Inclusive $Z(\nu\bar{\nu})\gamma$ full Run2 analysis report

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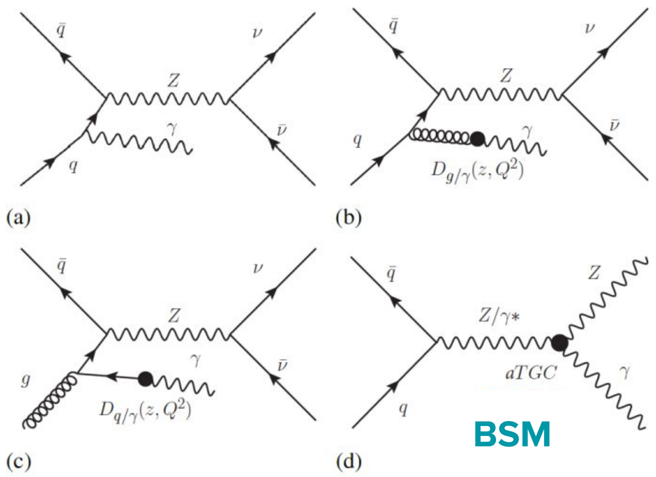
Motivation: general part

- Measuring the parameters of the Standard Model (SM) to very high precision is a pillar of the physics program of the LHC. Precision measurements provide a critical test of the consistency and limits of validity of the SM.
- Other LHC program is the search for new physics predicted by the beyond SM (BSM) theories. BSM theories predict the existence of new particles, which may be too massive to be produced at the LHC, but their quantum behaviour could help spot them.



- Precision measurements of triple and quartic gauge couplings are sensitive to BSM physics. One of these processes is Z(νν)γ process, which the group has been working on for a long time.
- The neutral decay channel of the Z boson has a higher branching ratio, but a worse resolution compared to the decay into charged leptons. So it can be used for combinations to increase the statistics. The hadron channel has even higher branching ratio, but it is difficult to work on it.

[Z→qq (69.91%), Z→ee (3.36%), Z→μμ (3.37%), Z→νν (20.00%)]

Motivation: goals

➢ Standard Model:

It is planned to calculate integral and differential in $\mathbf{E_T^{\gamma}}$, $\mathbf{N_{jets}}$, $\mathbf{p_T^{miss}}$, $\mathbf{\Delta\phi[\gamma, p_T^{miss}]}$, $\mathbf{p_T(Z\gamma)}$, $\mathbf{\eta_\gamma}$ cross-sections and compare the results with the theory predictions including NNLO QCD and NLO EWK corrections.

➢ Beyond SM:

One of the goals is to obtain the strongest up-to-date limits on anomalous neutral triple gauge-boson couplings (aTGCs) using vertex functions and EFT formalisms ➜ **interpretation**.

★ Combination of the EFT limits between Zγ and ZZ + ratio of Zγ/ZZ cross-sections.

Glance: ANA-STDM-2018-54

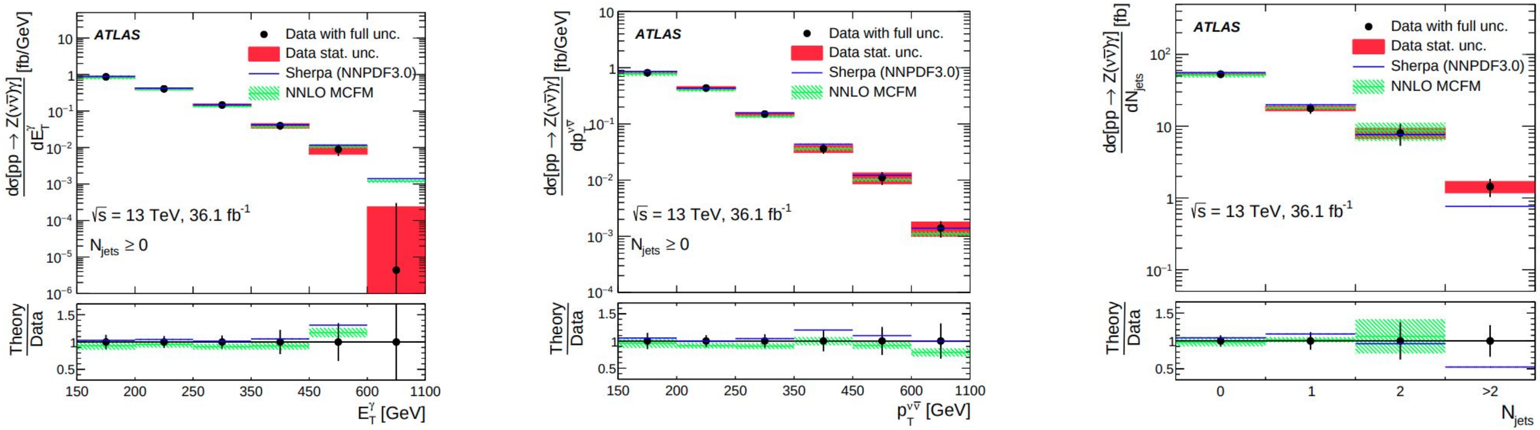
Motivation: previous Z(νν)γ analysis

Previous Z(νν)γ analysis was done using 36.1 fb^{-1} data.

- ★ Integrated cross-section:

$\sigma^{\text{ext.fid.}}$ [fb] Measurement	$\sigma^{\text{ext.fid.}}$ [fb] NNLO MCFM Prediction
$N_{\text{jets}} \geq 0$	
$83.7^{+3.6}_{-3.5}$ (stat.)$^{+6.9}_{-6.2}$ (syst.)$^{+1.7}_{-2.0}$ (lumi.)	78.1 ± 0.2(stat.)± 4.7(syst.)
$N_{\text{jets}} = 0$	
$52.4^{+2.4}_{-2.3}$ (stat.)$^{+4.0}_{-3.6}$ (syst.)$^{+1.2}_{-1.1}$ (lumi.)	55.9 ± 0.1(stat.)± 3.9(syst.)

- ★ *First differential cross-sections*, but as a function of $\mathbf{E_T^{\gamma}}$, $\mathbf{N_{jets}}$, $\mathbf{p_T^{miss}}$ only.
- ★ NNLO QCD corrections.



Motivation: previous Z(νν)γ analysis

★ Observed and expected one-dimensional 95% CL limits on h_3^γ, h_3^Z, h_4^γ and h_4^Z:

Parameter	Limit 95% CL	
	Measured	Expected
h_3^γ	$(-3.7\times10^{-4}, 3.7\times10^{-4})$	$(-4.2\times10^{-4}, 4.3\times10^{-4})$
h_3^Z	$(-3.2\times10^{-4}, 3.3\times10^{-4})$	$(-3.8\times10^{-4}, 3.8\times10^{-4})$
h_4^γ	$(-4.4\times10^{-7}, 4.3\times10^{-7})$	$(-5.1\times10^{-7}, 5.0\times10^{-7})$
h_4^Z	$(-4.5\times10^{-7}, 4.4\times10^{-7})$	$(-5.3\times10^{-7}, 5.1\times10^{-7})$

★ Observed and expected one-dimensional 95% CL limits on the $C_{\tilde{B}W}/\Lambda^4$, C_{BW}/Λ^4, C_{WW}/Λ^4 and C_{BB}/Λ^4 EFT parameters:

Parameter	Limit 95% CL	
	Measured [TeV^{-4}]	Expected [TeV^{-4}]
$C_{\tilde{B}W}/\Lambda^4$	(−1.1, 1.1)	(−1.3, 1.3)
C_{BW}/Λ^4	(−0.65, 0.64)	(−0.74, 0.74)
C_{WW}/Λ^4	(−2.3, 2.3)	(−2.7, 2.7)
C_{BB}/Λ^4	(−0.24, 0.24)	(−0.28, 0.27)

Motivation: Z(ℓℓ)γ analysis

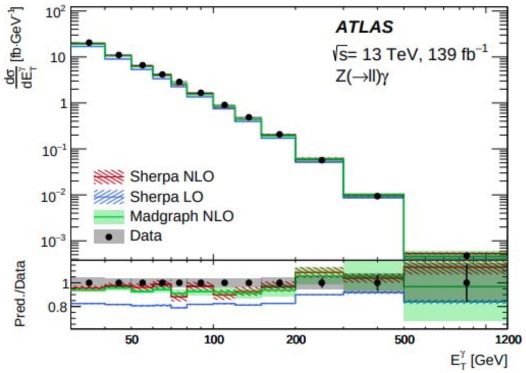
- Z(ℓℓ)γ 139 fb^{-1} analysis
- Integrated cross-section:

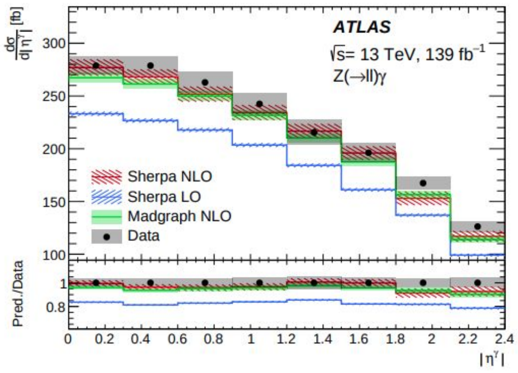
	Cross-section [fb]		
$e^+e^-\gamma$	530.4	± 9.0 (uncorr)	± 11.7 (corr) ± 9.0 (lumi)
$\mu^+\mu^-\gamma$	535.0	± 6.1 (uncorr)	± 11.5 (corr) ± 9.1 (lumi)
$\ell^+\ell^-\gamma$	533.7	± 5.1 (uncorr)	± 11.6 (corr) ± 9.1 (lumi)
Sherpa LO	438.9	± 0.6 (stat)	
Sherpa NLO	514.2	± 5.7 (stat)	
MadGraph NLO	503.4	± 1.8 (stat)	
Matrix NLO	444.2	± 0.1 (stat)	± 4.3 (C_{theory}) ± 8.8 (PDF) $^{+16.8}_{-18.9}$ (scale)
Matrix NNLO	518.9	± 2.0 (stat)	± 5.1 (C_{theory}) ± 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)
Matrix NNLO × NLO EW	513.5	± 2.0 (stat)	± 2.7 (C_{theory}) ± 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)
Matrix NNLO + NLO EW	518.3	± 2.0 (stat)	± 2.7 (C_{theory}) ± 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)

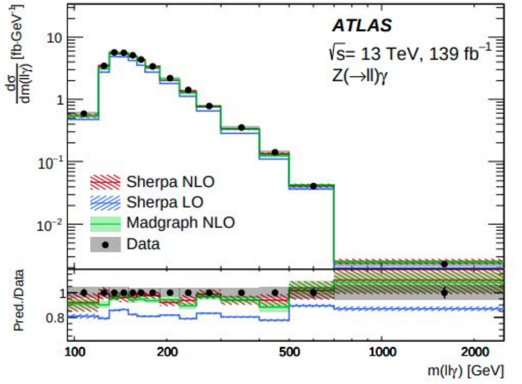
- Differential cross-sections as a function of E_T^γ, $|\eta_\gamma|$, m(ℓℓγ), $p_T^{\ell\ell\gamma}$, $p_T^{\ell\ell\gamma}$/m(ℓℓγ), and Δφ(ℓℓ, γ).

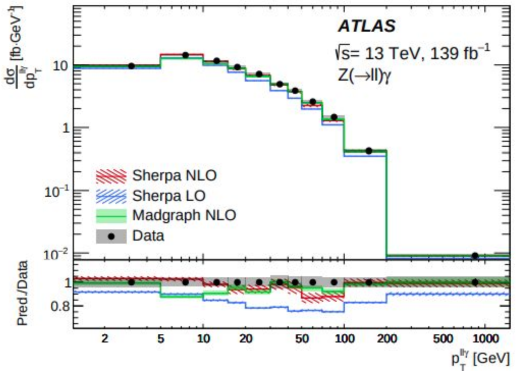
Motivation: Z(ℓℓ)γ analysis

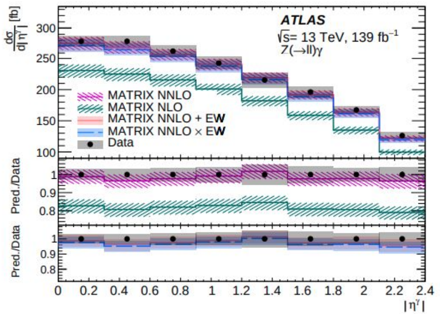
★ NNLO QCD and NLO EWK corrections.

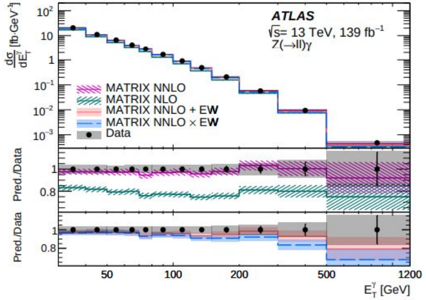


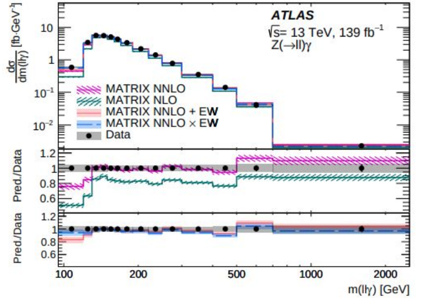






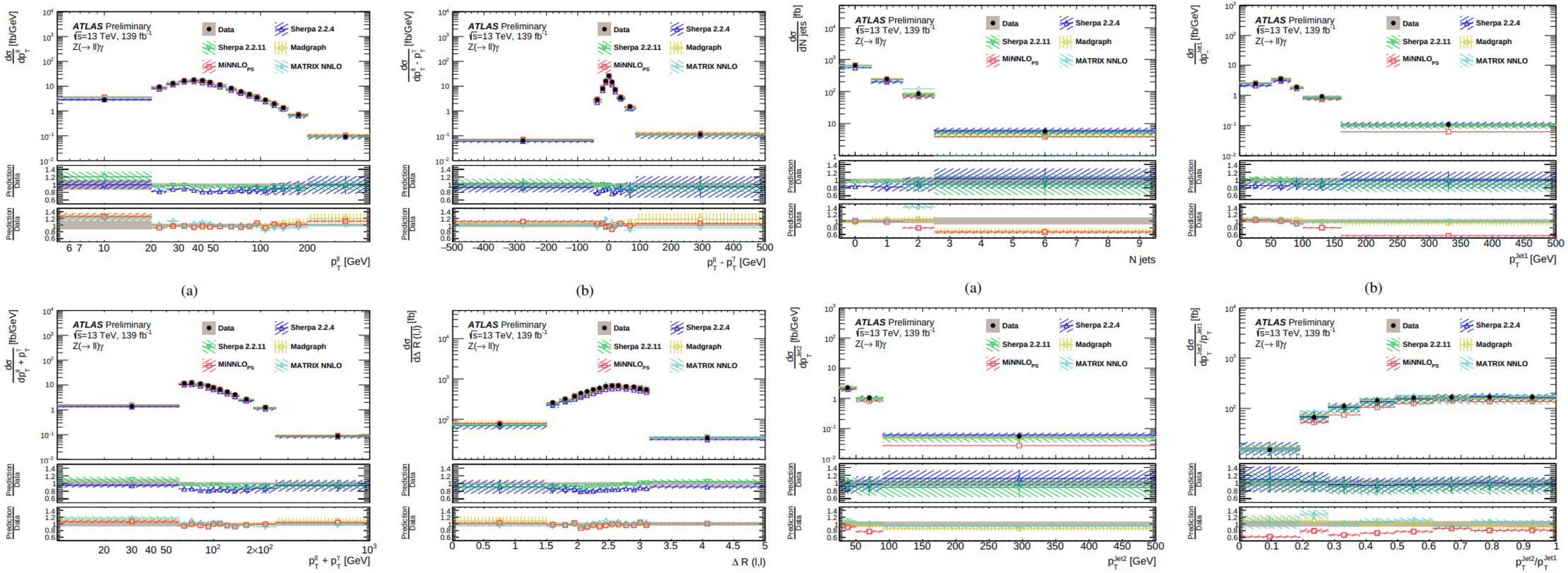






Motivation: Z(ℓℓ)γ+jets analysis

- ★ Z(ℓℓ)γ+jets 139 fb^{-1} analysis
- ★ Differential cross-sections as a function of $p_T^{\ell\ell}$, $p_T^{\ell\ell} - p_T^{\gamma}$, $p_T^{\ell\ell} + p_T^{\gamma}$, $\Delta R(\ell, \ell)$, N_{Jets}, p_T^{Jet1}, p_T^{Jet2}, p_T^{Jet2}/p_T^{Jet1}, m_{jj}, $m_{\ell\ell\gamma}$, H_T, $p_T^{\gamma}/\sqrt{H_T}$, $\Delta\phi(Jet, \gamma)$, $p_T^{\ell\ell\gamma j}$, ϕ_{CS},$\cos\theta_{CS}$, $p_T^{\ell\ell\gamma}/m(\ell\ell\gamma)$.



Selection optimisation: multivariate method

Topology: high-energetic γ + high missing transverse momentum p_T^{miss}

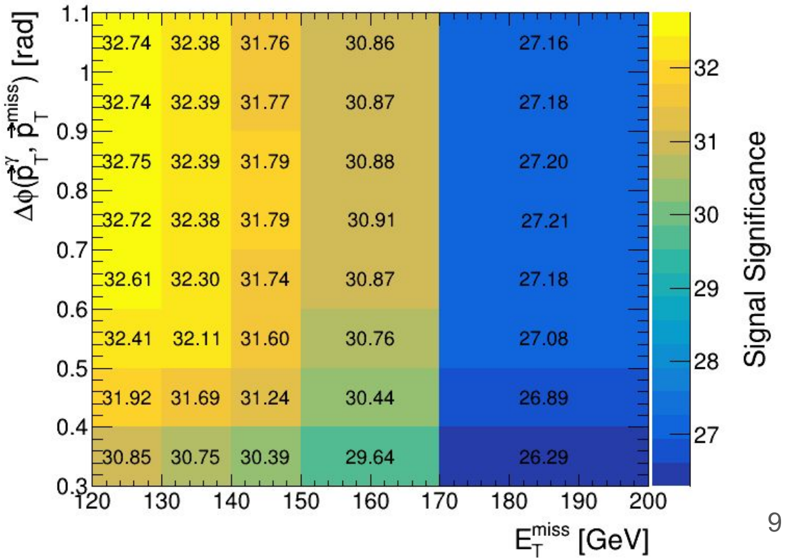
Preselections	Cut Value
E_T^{miss}	> 120 GeV
E_T^{γ}	> 150 GeV
Number of tight isolated photons	$N_\gamma = 1$
Lepton veto	$N_e = 0,\ N_\mu = 0$

Multivariate (MV) method of the selection optimisation takes into account the signal significance *Z* as a function of the threshold values of the variables:

$$Z = N_{\text{signal}} / \sqrt{N_{\text{signal}} + N_{\text{bkg}}}$$

The output of the MV optimisation procedure is a vector of threshold values of the variables at which the maximum *Z* is reached.

2D illustration:



Selection optimisation: increase in statistical significance

Signal region (SR) definition with the thresholds obtained by MV selection optimisation method:

	Selections	Cut Value
SR	E_T^{miss}	> 130 GeV
	E_T^{miss} significance	> 11
	$\|\Delta\phi(\vec{p}_T^{miss}, \gamma)\|$	> 0.6
	$\|\Delta\phi(\vec{p}_T^{miss}, j_1)\|$	> 0.4

Impact of the used variables on the number of signal and background events and statistical significance (at the bottom of the table the results are for the case when the cut is not applied):

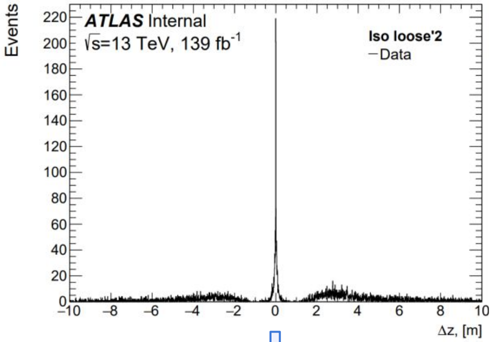
Selections	N_{signal}	$N_{bkg}, \cdot 10^3$	Z
Preselections	12380 ± 9	77.6 ± 0.7	41.3 ± 0.2
Selections	9843 ± 8	15.5 ± 0.5	61.8 ± 0.6
- $E_T^{miss} > 130$ GeV	9939 ± 8	16.2 ± 0.5	61.5 ± 0.6
- E_T^{miss} significance > 11	11261 ± 8	33.1 ± 0.6	53.5 ± 0.3
- $\|\Delta\phi(\vec{p}_T^{miss}, \gamma)\| > 0.6$	9858 ± 8	16.0 ± 0.5	61.4 ± 0.6
- $\|\Delta\phi(\vec{p}_T^{miss}, j_1)\| > 0.4$	10016 ± 8	17.6 ± 0.5	60.3 ± 0.6

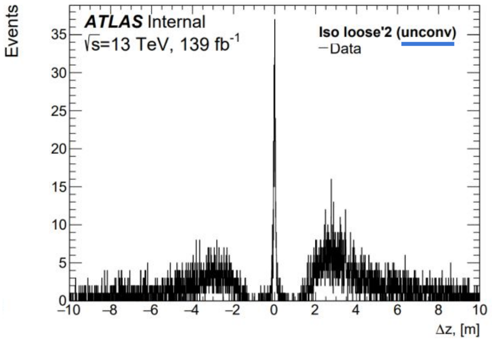
Moreover, there is no significant increase in statistical significance with using $N_{b\text{-}jets}$ and $p_T^{SoftTerm}$ variables.

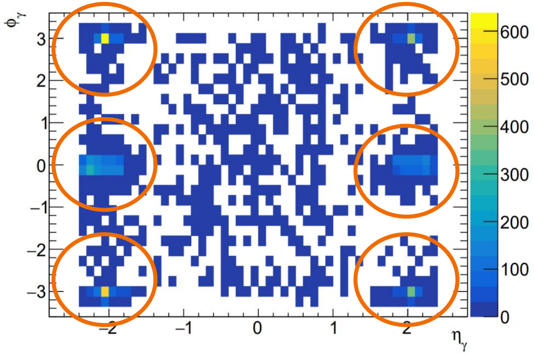
Photon pointing: beam-induced background (BIB)

- Muons from pion and kaon decays in hadronic showers, induced by beam losses in non-elastic collisions with gas and detector material, deposit large amount of energy in calorimeters through radiative processes (= **fake jets**).
- The characteristic peaks of the fake jets due to BIB concentrate at **± π** and **0** (mainly due to the bending in the horizontal plane that occurs in the D1 and D2 dipoles and the LHC arc).

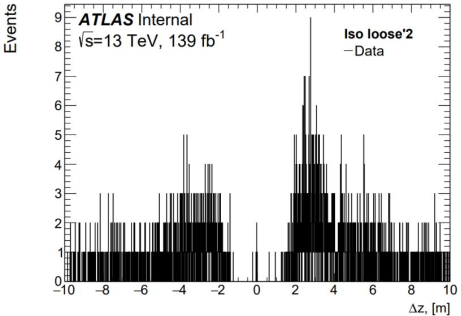
$$\Delta z = z_\gamma - z_{\text{vtx}}$$

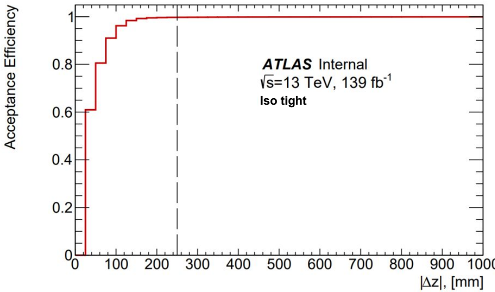


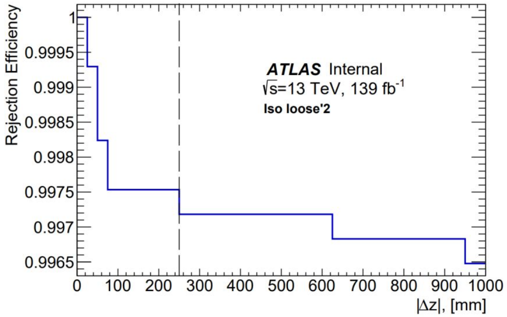




Cuts: |φ| < 0.2, |φ| ∈ [2.9; 3.2] and |η| > 1.7







|Δz| < 250 mm

Rejection efficiency: (100 ± 3)%

Acceptance efficiency: (99.7 ± 0.9)%

Background composition

Percentage of the total predicted background

Background composition for Z(νν)γ:

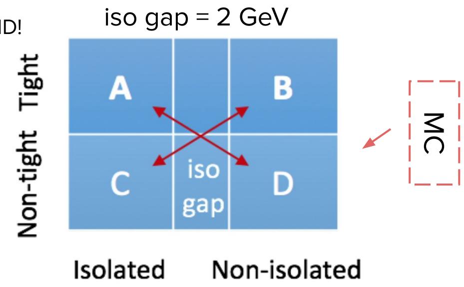
- 35 % — γ+jets – via MC → ABCD method based on E_T^{miss}-significance and additional variable
- 27 % — W(lν)γ – fit to data in additional CR based on N_{lep} (shape from MC)
- 21 % — e→γ – fake-rate estimation using Z-peak (tag-n-probe) method
- 14 % — jet→γ – ABCD method based on γ ID and isolation
- 1.9 % — $Z(l^+l^-)\gamma$ – via MC
- 1.5 % — ttγ – via MC

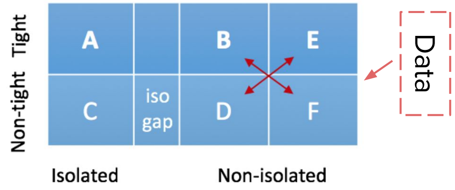
jet→γ misID background: correlation factor

Background is estimated from data using **2D-sideband method**:
<u>Photon isolation and identification variables</u> are used to construct the sidebands.

Isolation should not correlate with non-tight ID!

$$\frac{N_{A}^{jet\to\gamma}}{N_B} = \frac{N_C}{N_D}$$





Correlation is measured in data and MC by $R = \frac{N_A N_D}{N_B N_C}$.

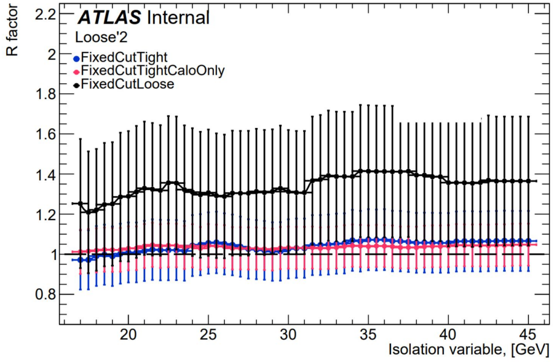
Non-tight: at least one of the cuts on the following variables should fail in these:

- *loose'2*: w_{s3}, F_{side}
- *loose'3*: $w_{s3}, F_{side}, \Delta E$
- *loose'4*: $w_{s3}, F_{side}, \Delta E, E_{ratio}$
- *loose'5*: $w_{s3}, F_{side}, \Delta E, E_{ratio}, w_{tot}$

FixedCutTightCaloOnly:

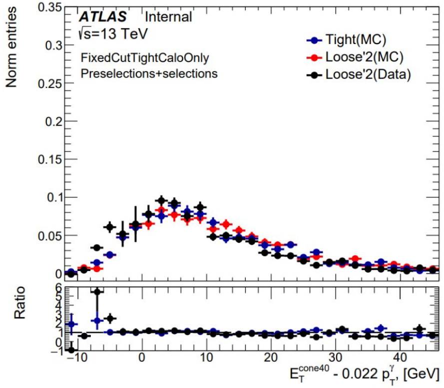
A: tight, $E_T^{cone40} - 0.022\, p_T^{\gamma} < 2.45$ [GeV]
B: tight, $2.45 + gap < E_T^{cone40} - 0.022\, p_T^{\gamma}$ [GeV]
C: non-tight, $E_T^{cone40} - 0.022\, p_T^{\gamma} < 2.45$ [GeV]
D: non-tight, $2.45 + gap < E_T^{cone40} - 0.022\, p_T^{\gamma}$ [GeV]

R factor	loose'2	loose'3	loose'4	loose'5
FixedCutTight (w/o upper cut)				
MC	1.05 ± 0.15	1.14 ± 0.15	1.19 ± 0.14	1.39 ± 0.17
Data-driven	1.4 ± 0.3	1.3 ± 0.3	1.3 ± 0.3	1.3 ± 0.3
FixedCutTight (upper cut = 25.45 GeV)				
MC	1.06 ± 0.15	1.15 ± 0.16	1.21 ± 0.15	1.40 ± 0.17
Data-driven	1.01 ± 0.18	1.02 ± 0.18	1.01 ± 0.18	1.01 ± 0.17
FixedCutTight (track inversion + upper cut = 25.45 GeV)				
MC	1.01 ± 0.12	1.15 ± 0.12	1.29 ± 0.13	1.58 ± 0.16
Data-driven	1.07 ± 0.12	1.13 ± 0.12	1.09 ± 0.10	1.12 ± 0.10
FixedCutTightCaloOnly				
MC	1.06 ± 0.10	1.14 ± 0.11	1.22 ± 0.10	1.40 ± 0.12
Data-driven	1.07 ± 0.10	1.13 ± 0.10	1.15 ± 0.10	1.15 ± 0.10



FixedCutTightCaloOnly

Data-driven				
Cut	loose'2	loose'3	loose'4	loose'5
9.45	1.08 ± 0.11	1.14 ± 0.11	1.12 ± 0.10	1.13 ± 0.10
9.95	1.07 ± 0.10	1.13 ± 0.10	1.15 ± 0.10	1.15 ± 0.10
10.45	1.09 ± 0.10	1.14 ± 0.10	1.14 ± 0.10	1.15 ± 0.10
10.95	1.18 ± 0.11	1.23 ± 0.11	1.21 ± 0.10	1.22 ± 0.10
11.45	1.23 ± 0.11	1.27 ± 0.11	1.22 ± 0.10	1.22 ± 0.10



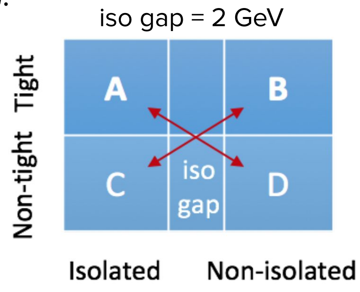
jet→γ misID background: uncertainties

➢ Statistical uncertainty:

- The event yields of four regions in data and non jet → γ background are varied by ±1σ independently **(4%)**.
- The statistical uncertainty on the signal leakage parameters is negligible.

Total statistics: 4%.

Central value	1960±83
loose'3	–334
loose'4	–397
loose'5	–472
Isolation gap +0.15 GeV	+33
Isolation gap –0.15 GeV	–22



➢ Systematic uncertainty:

- Anti-tight definition and isolation gap choice – variations of ABCD regions determination for ±1σ changes in data yield (**24%**).
- Uncertainty coming from the signal leakage parameters is obtained via using different generators and parton shower models (**9%**).

Signal leakage parameters	MadGraph+Pythia8, Sherpa 2.2	MadGraph+Herwig7, MadGraph+Pythia8	Relative deviation
c_B	0.0713 ± 0.0002	0.1000 ± 0.0011	29%
c_C	0.00879 ± 0.00007	0.0092 ± 0.0003	4%
c_D	0.00070 ± 0.00002	0.00099 ± 0.00010	29%
$jet \to \gamma$ est.	1960	1785	9%

- The iso/ID uncertainty on reconstruction photon efficiency $\delta_{eff}^{iso/ID}$ (**1.4%**):

  - $\sigma_{iso}^{c_B}(\text{relative}) = \delta_{iso}^{eff} * (c_B + 1)/c_B$
  - $\sigma_{ID}^{c_C}(\text{relative}) = \delta_{ID}^{eff} * (c_C + 1)/c_C$
  - $\sigma_{iso}^{c_D}(\text{relative}) = \delta_{iso}^{eff} * (c_B + 1)/c_B$
  - $\sigma_{ID}^{c_D}(\text{relative}) = \delta_{ID}^{eff} * (c_C + 1)/c_C$

$\delta^{eff}_{iso} = 0.013$
$\delta^{eff}_{iso/ID} = 0.013$

Total systematics: 26%.

★ **Total number of jet→γ events:** 1960 ± 80 ± 510. Z(νν)+jets and multi-jet MC predicts 1600 ± 1200 events.

e→γ misID background: Z-peak method

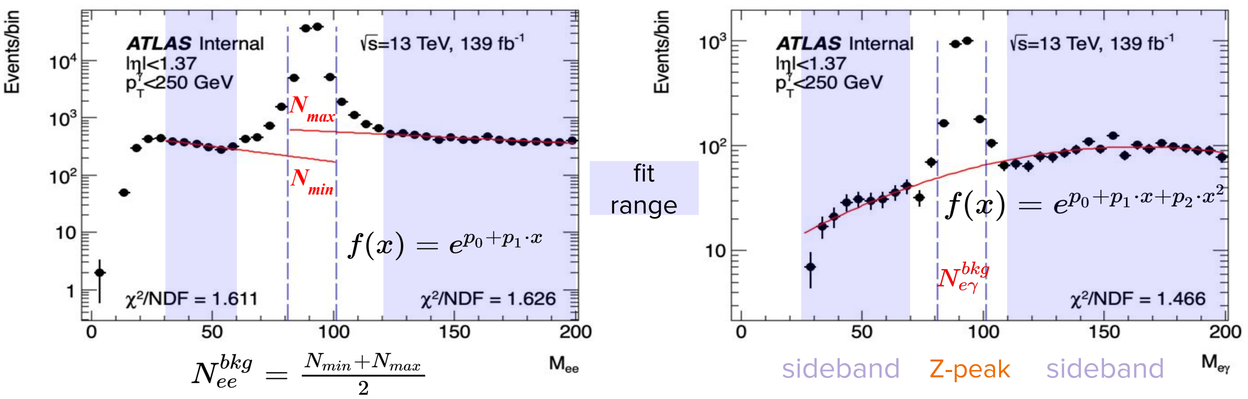
<u>Source</u>: W(lν), top and tt processes.

<u>Estimation procedure</u>:

1. estimating e➔γ fake rate as $rate_{e\to\gamma} = \frac{(N_{e\gamma} - N_{bkg})}{(N_{ee} - N_{bkg})}$,

where N_{ee}, $N_{e\gamma}$ – number of ee and eγ events in Z-peak mass window (M_Z – 10 GeV, M_Z + 10 GeV), N_{bkg} – background in Z-peak mass window extrapolated from sideband with exponential pol1 or pol2 fit.

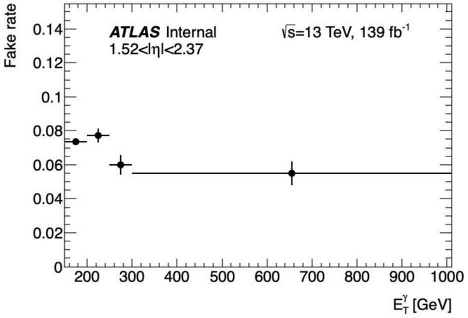
ee pairs **eγ pairs**

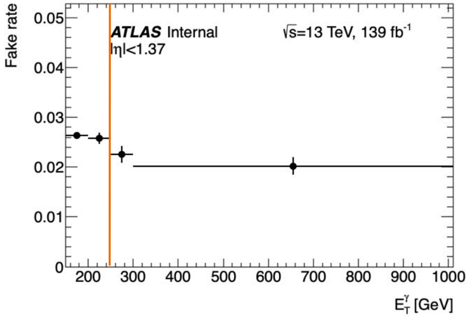


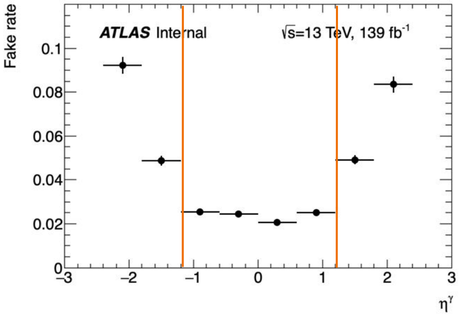
2. building e-probe CR (SR with electron instead of photon).

3. scaling data distributions from e-probe CR on fake rate.

e→γ misID background: uncertainties







Since e→γ fake rate depends on η и p_T, it is estimated in three regions.

$e \to \gamma$ fake rates		
	$150 < E_T^\gamma < 250$ GeV	$E_T^\gamma > 250$ GeV
$0 < \|\eta\| < 1.37$	$0.0240 \pm 0.0006 \pm 0.0009$	$0.0205 \pm 0.0013 \pm 0.0045$
$1.52 < \|\eta\| < 2.37$	$0.0696 \pm 0.0018 \pm 0.0072$	

Systematics:

1. *Fake-rate*:
   - Z-peak mass window variation (varies from 0.5% to 0.9%).
   - Background under Z-peak evaluation (varies from 2.2% to 10.4%).
   - Difference between "real fake rate" in Z(ee) MC and tag-and-probe method performed on Z(ee) MC (varies from 1.13% to 19.4%).

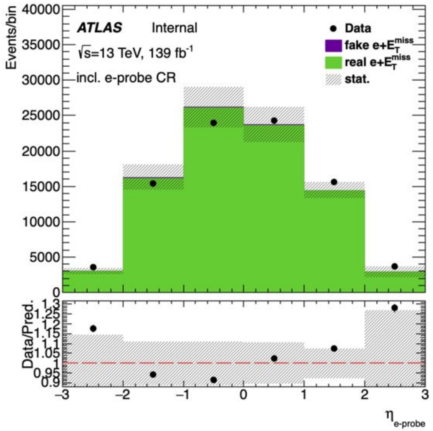
Total systematics on the fake-rate: 22%.

2. *E-probe CR*:
   - Impurity of the region (0.46%).

Total syst. on the background yield: 6%.

Contamination is determined as:

$$\frac{\text{fake } e{+}E_{\text{T}}^{\text{miss}}}{\text{real } e{+}E_{\text{T}}^{\text{miss}}}.$$



Total background (e-probe region scaled by fake-rate): 3070 ± 12 ± 187.

jet→E_T^{miss} misID background: estimation strategy

- Background originating from γ+jets processes is significantly reduced by applying selections on **E_T^{miss}** and **E_T^{miss}-significance**.

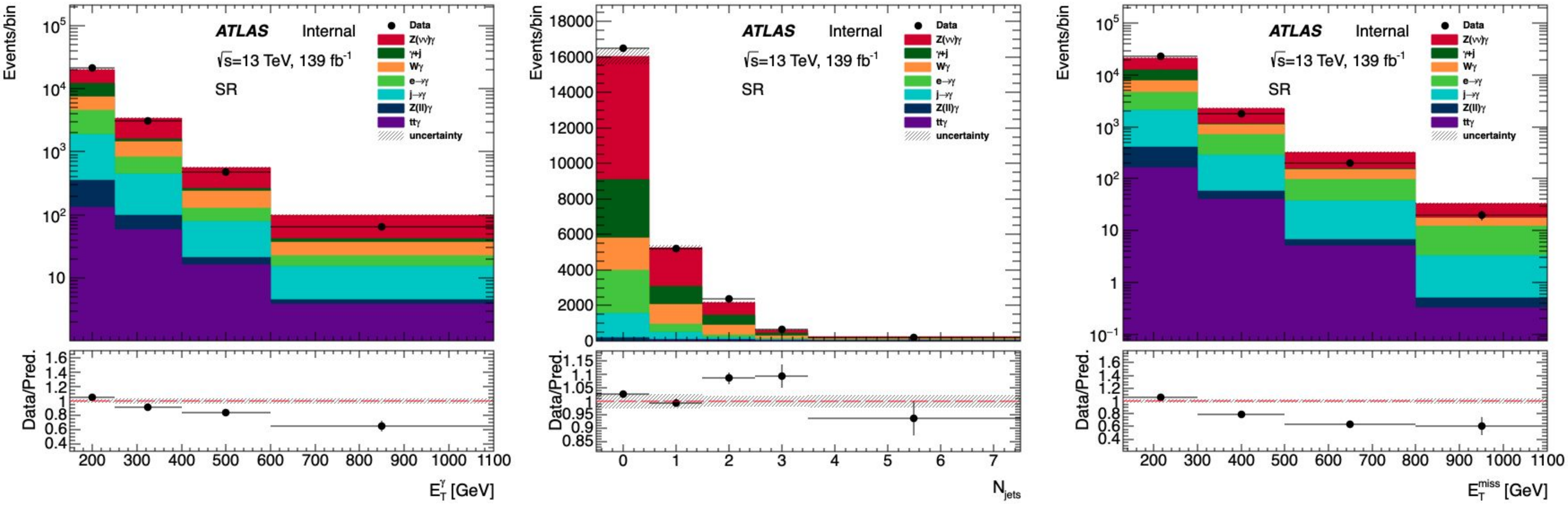
- For now, **MC simulation** is used to estimate this background.

- The MC normalisation is estimated from the CR constructed in **low-E_T^{miss}-significance range** (E_T^{miss}-significance < 11) with **E_T^{miss} selection relaxed** to $E_T^{miss} > 100$ GeV.

- Normalisation coefficient is equal to **0.66**, which is close to the normalisation factor obtained using 2D-sideband method in $Z(\nu\nu)\gamma$ EWK analysis (0.68).

- The plan is to estimate this background for each bin using **2D-sideband method**: E_T^{miss}-significance and other discriminative variable (e.g. $\Delta\phi[\gamma, p_T^{miss}]$ or $p_T^{SoftTerm}$) will be used to construct the sidebands.

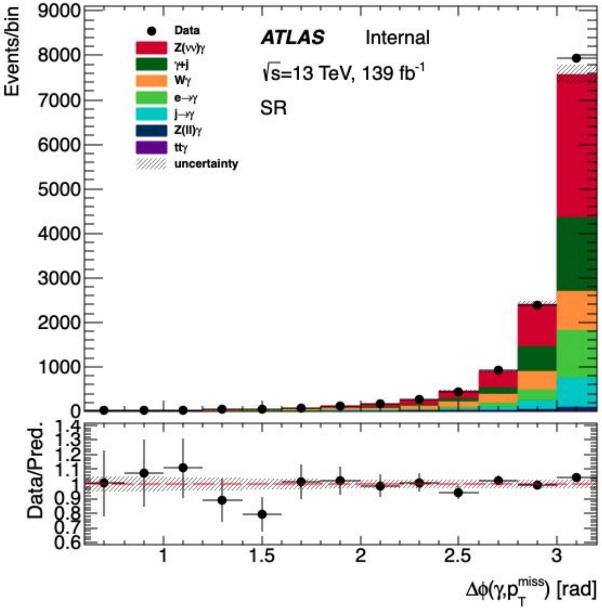
Control plots

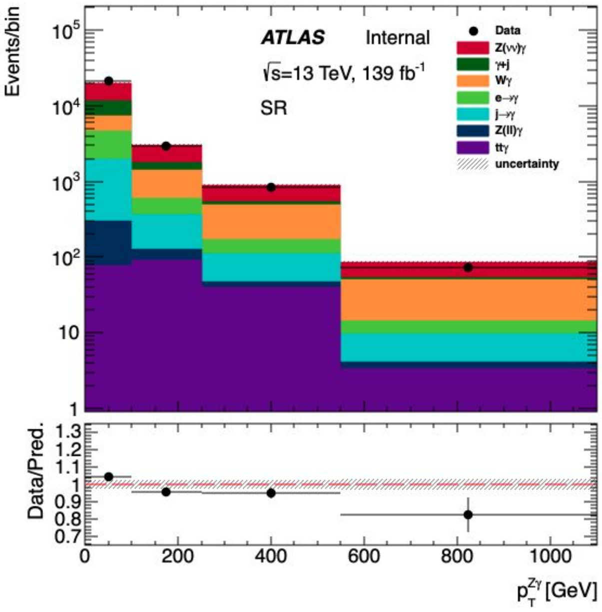


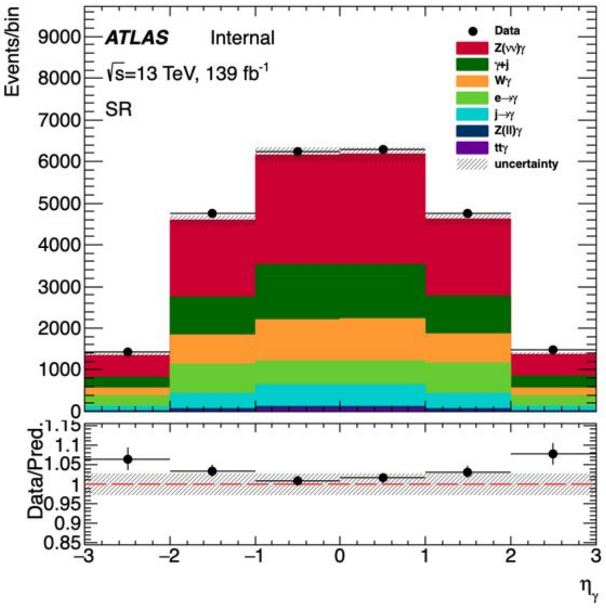
For jet→γ bkg, the shape is taken from Z(νν)γ QCD MC. γ+jet bkg has 0.66 normalisation. e→γ bkg: DD.

The total uncertainty includes the statistical uncertainty for all bkgs, while for jet→γ and e→γ bkgs there is also the systematic uncertainty.

Control plots







For jet→γ bkg, the shape is taken from Z(νν)γ QCD MC. γ+jet bkg has 0.66 normalisation. e→γ bkg: DD.

The total uncertainty includes the statistical uncertainty for all bkgs, while for jet→γ and e→γ bkgs there is also the systematic uncertainty.

Summary

- Several steps of the inclusive $Z(\nu\bar{\nu})\gamma$ Run2 analysis are already done: selection optimisation, data-driven estimation of jet→γ, e→γ and (preliminary) E_T^{miss}→jet misID backgrounds, control plots.
- Plans:
  - Re-optimise the SR after adding $Z(\nu\bar{\nu})\gamma$ and Wγ EWK samples + W(τν) samples with separation of lepton and hadron channels.
  - Estimate:
    - E_T^{miss}→jet background using 2D-sideband method.
    - pile-up background (expected to be negligible).
    - Wγ background.
  - Uncertainties.
  - Cross-section measurements.
  - Limits on aTGCs.
  - EB request till the end of the year.

Back-up

Object selections

Photon selection:

$E_T^{\gamma} > 10$ GeV, $|\eta| < 2.37$, crack region excluded, cluster quality cut, ambiguity cut, tight ID, FixedCutTightCaloOnly isolation, $\Delta R(\gamma, e/\mu) < 0.4$

Electron selection:

$p_T > 4.5$ GeV, $|\eta| < 2.47$, crack region excluded, loose ID, $\Delta R(e,\mu) < 0.1$

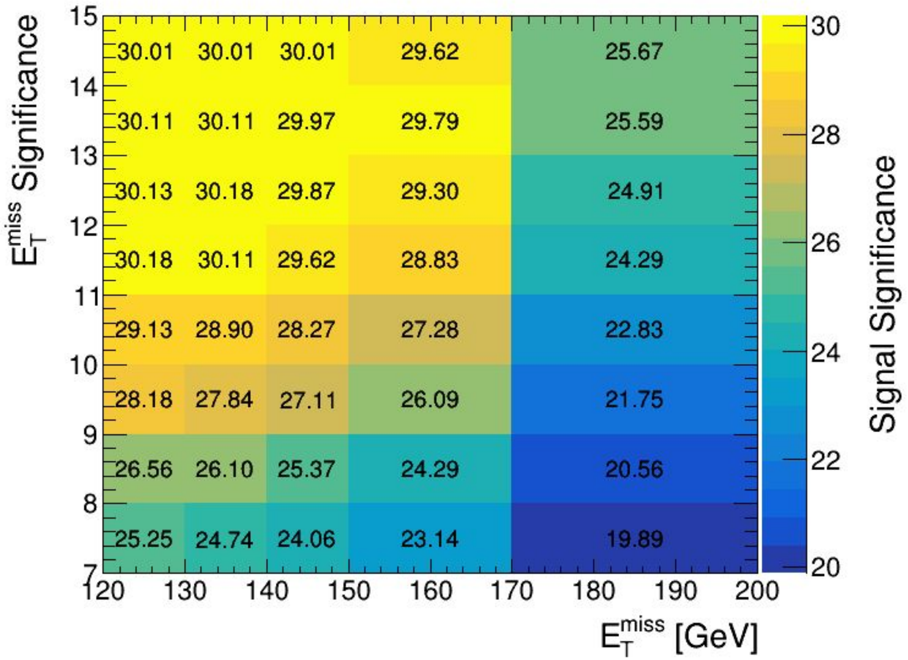
Muon selection:

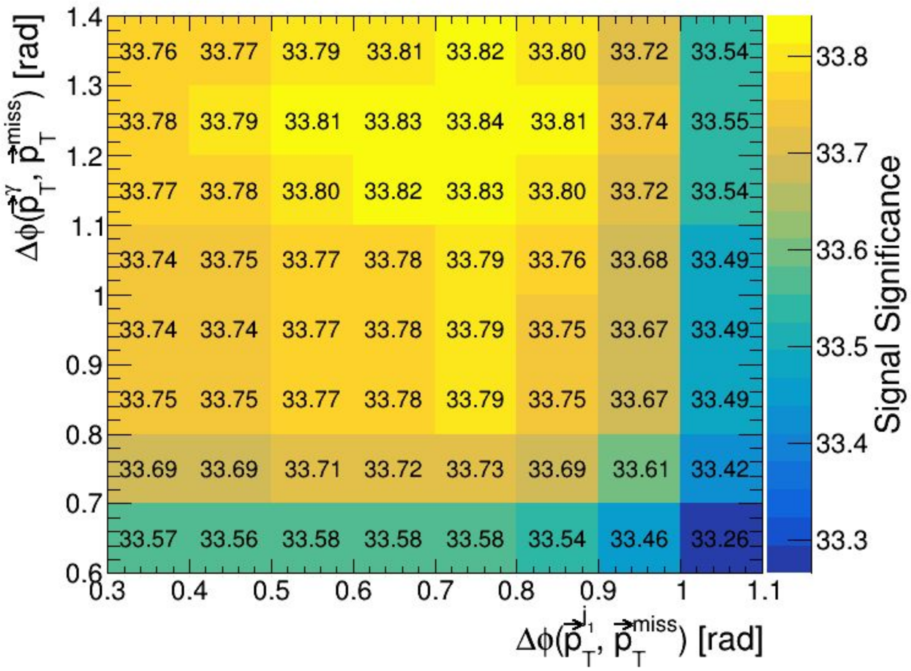
$p_T > 4$ GeV, $|\eta| < 2.47$, crack region excluded, loose ID, $|z_0 {}^* \sin\theta| < 0.5$ mm, d_0 signif. < 3

Jet selection:

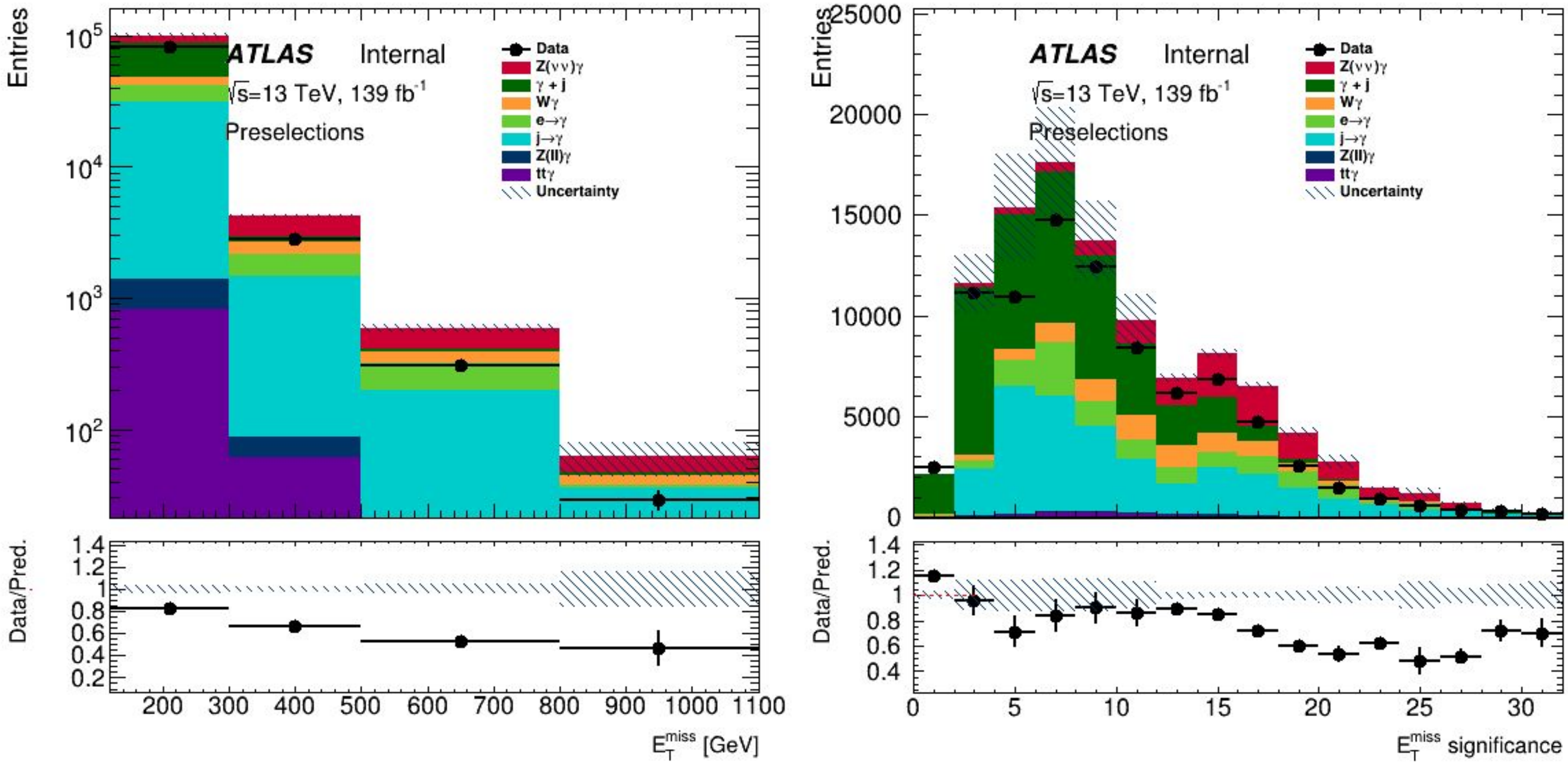
$E_T > 50$ GeV, $|\eta| < 4.5$,
AntiKt4EMPFlowJets,
tight JVT, $\Delta R(\text{jet}, e/\mu/\gamma) < 0.4$

Selection optimisation: multivariate method



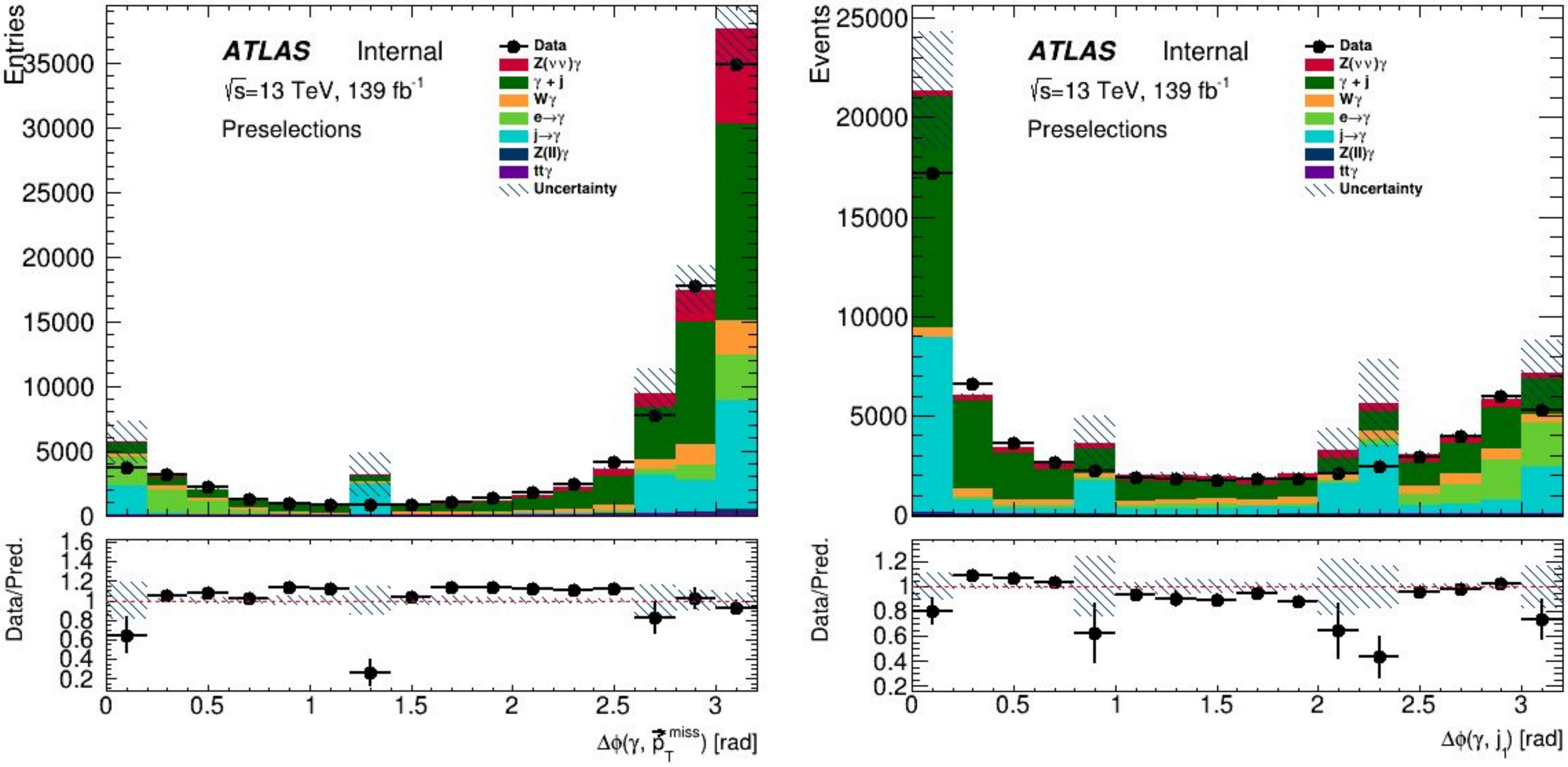


Selection optimisation: distributions



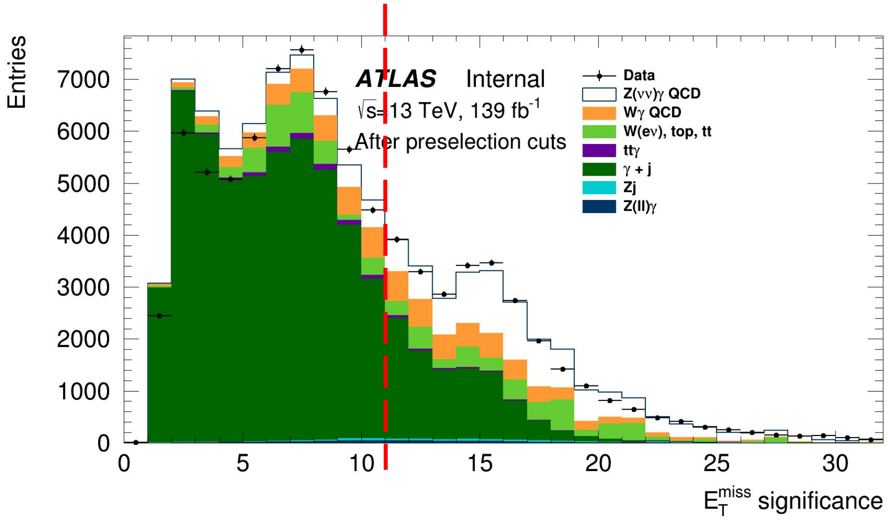
For jet→γ bkg, the shape is taken from Z(νν)+jets and multi-jet MC. γ+jet bkg has 0.66 normalisation. e→γ bkg: W(eν), W(τν), top, tt MC.

Selection optimisation: distributions

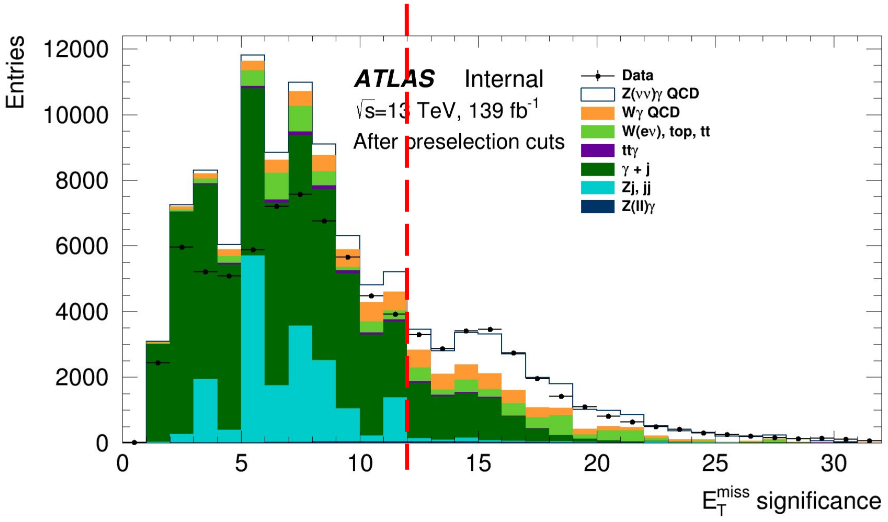


For jet→γ bkg, the shape is taken from Z(νν)+jets and multi-jet MC. γ+jet bkg has 0.66 normalisation. e→γ bkg: W(eν), W(τν), top, tt MC.

Selection optimisation: multi-jet problematic normalisation



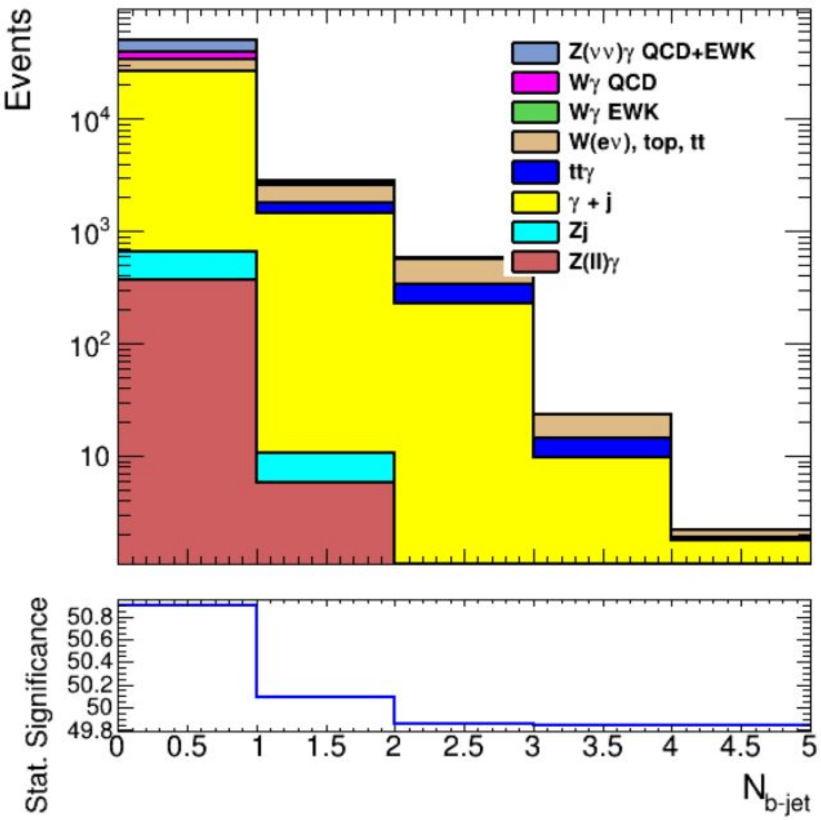
without multi-jet samples

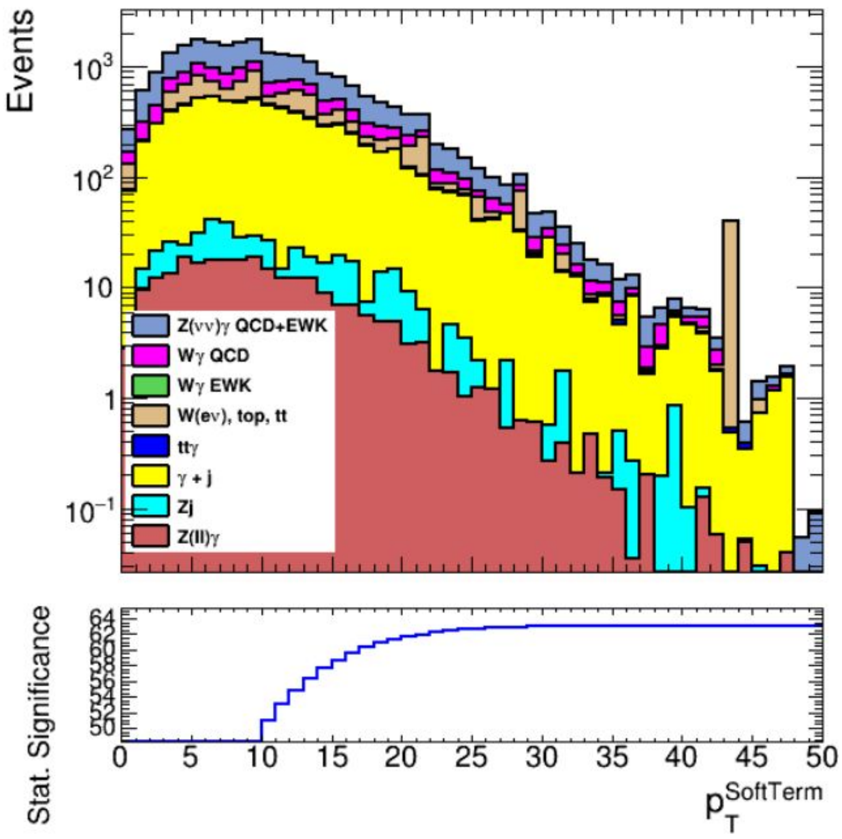


with multi-jet samples

Multi-jet samples are not used for the optimisation procedure due to their problematic normalisation.

Selection optimisation: $N_{b\text{-jet}}$ and $p_T^{SoftTerm}$





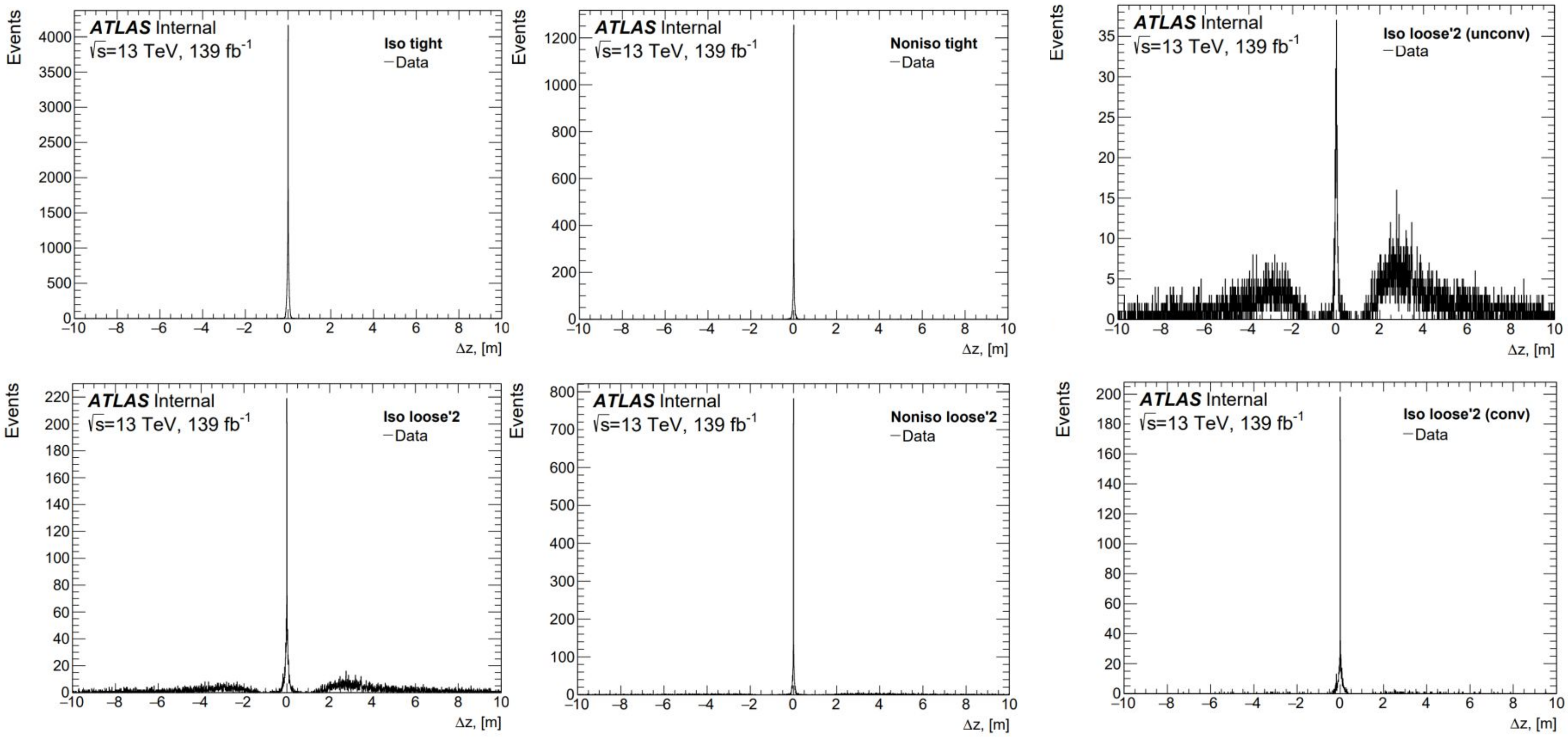
Selection optimisation: event yields

	FixedCutTight	FixedCutTightCaloOnly		
Variable	W/O MultiJet		With MultiJet	With MultiJet
E_T^{miss} *signif.*	>11	>11	>12	—
$\Delta\phi(E_T^{miss}, \gamma)$	>0.6	>0.7	>0.7	—
$\Delta\phi(E_T^{miss}, j_1)$	>0.4	>0.4	>0.4	—
E_T^{miss}, GeV	>130	>130	>130	—
Signal				
Z($\nu\nu$)γ QCD	9752 ±8	9840 ±8	9355 ±8	12380 ±9
Z($\nu\nu$)γ EWK	0 ±0	0 ±0	0 ±0	0 ±0
Total signal	9752 ±8	9840 ±8	9355 ±8	12380 ±9
Background				
Wγ QCD	3610 ±21	3645 ±22	3265 ±21	7456 ±30
Wγ EWK	0 ±0	0 ±0	0 ±0	0 ±0
tt, top, W(eν)	3128 ±447	3463 ±518	3328 ±512	9039 ±636
ttγ	210 ±3	213±3	165 ±3	888 ±6
γ+j	7501 ±78	7598 ±78	6261 ±71	59162 ±203
Zj	213 ±16	315 ±20	295 ±19	486 ±23
Z(ll)γ	266 ±4	270 ±4	242 ±4	608 ±7
MultiJet	—	1243.91 ± 1243.02	0.6+-0.4	18532±4645
Total bkg.	14928±455	15504±525	13558±518	96172 ±4693
Stat. signif.	62.1±0.6	61.8±0.6	61.8±0.6	37.6 ±

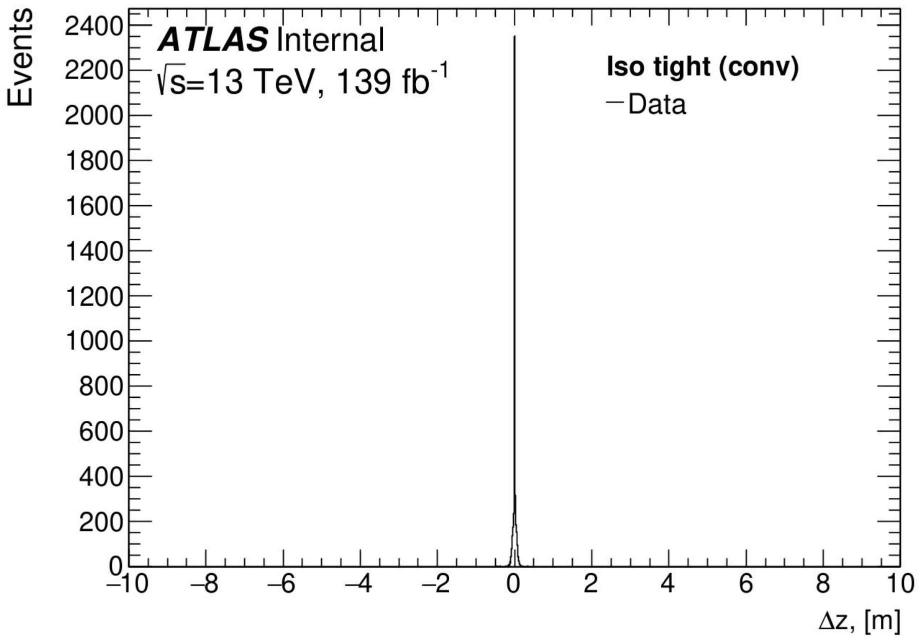
Selection optimisation: isolation checks

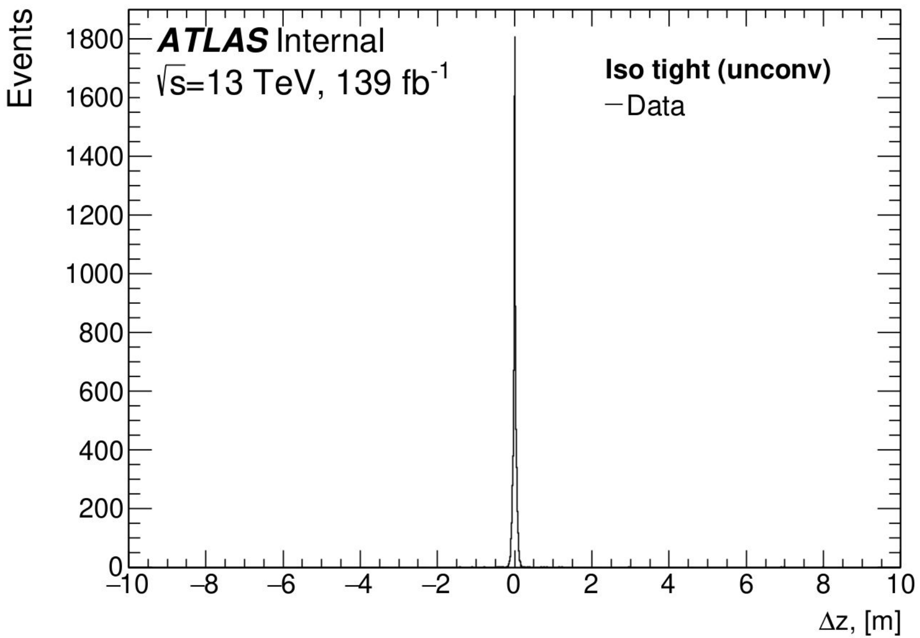
Isolation	FixedCutTight		FixedCutTightCaloOnly					
Multijet	–	+	–	+	–	+	+	+
Selections	+ E_T^{miss} sign > **11** + $\lvert\Delta\varphi(\gamma, E_T^{miss})\rvert$ > **0.6** + $\lvert\Delta\varphi(j_1, E_T^{miss})\rvert$> 0.4 + E_T^{miss} > 130		+ E_T^{miss} sign > **11** + $\lvert\Delta\varphi(\gamma, E_T^{miss})\rvert$ > **0.6** + $\lvert\Delta\varphi(j_1, E_T^{miss})\rvert$> 0.4 + E_T^{miss} > 130		+ E_T^{miss} sign > **11** + $\lvert\Delta\varphi(\gamma, E_T^{miss})\rvert$ > **0.7** + $\lvert\Delta\varphi(j_1, E_T^{miss})\rvert$> 0.4 + E_T^{miss} > 130		–	+ E_T^{miss} sign > **12** + $\lvert\Delta\varphi(\gamma, E_T^{miss})\rvert$ > **0.7** + $\lvert\Delta\varphi(j_1, E_T^{miss})\rvert$> 0.4 + E_T^{miss} > 130
Signal	9752 ± 8	9752 ± 8	9843 ± 8	9843 ± 8	9840 ± 8	9840 ± 8	12381 ± 9	9355 ± 8
Background	14928 ± 455	16172 ± 1324	15520 ± 525	16764 ± 1349	15505 ± 525	16749 ± 1349	96172 ± 4693	13558 ± 518
Significance	62.1 ± 0.6	60.6 ± 1.5	61.8 ± 0.6	60.3 ± 1.5	61.8 ± 0.6	60.3 ± 1.5	37.6 ± 0.8	61.8 ± 0.7
	↑ multivariate method				↑ multivariate method			↑ multivariate method

Beam-induced background (BIB)

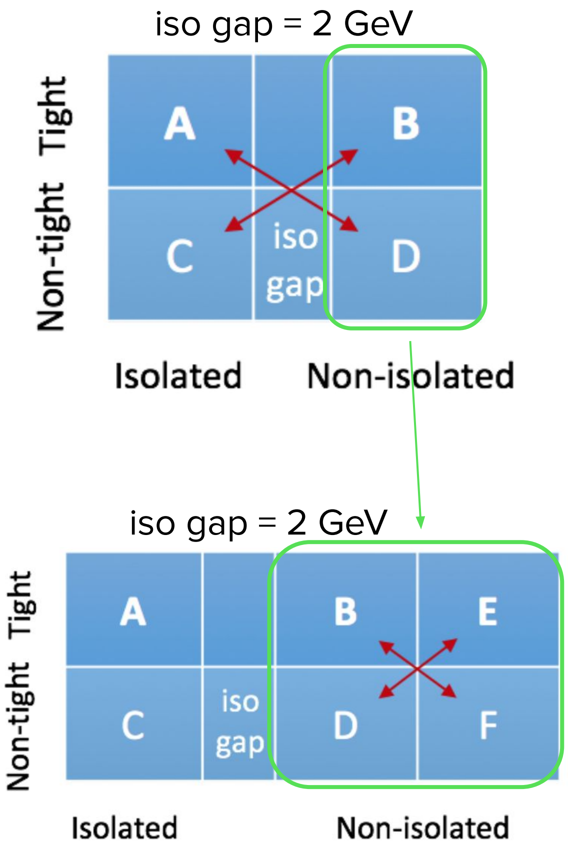


Beam-induced background (BIB)





jet→γ misID background: regions definition



FixedCutTightCaloOnly:

A: tight, $E_T^{cone40} - 0.022\ p_T^{\gamma} < 2.45$ [GeV]

B: tight, $2.45 + gap < E_T^{cone40} - 0.022\ p_T^{\gamma}$ [GeV]

C: non-tight, $E_T^{cone40} - 0.022\ p_T^{\gamma} < 2.45$ [GeV]

D: non-tight, $2.45 + gap < E_T^{cone40} - 0.022\ p_T^{\gamma}$ [GeV]

Non-tight: at least one of the cuts on the following variables should fail in these:

- *loose'2*: w_{s3}, F_{side}
- *loose'3*: $w_{s3}, F_{side}, \Delta E$
- *loose'4*: $w_{s3}, F_{side}, \Delta E, E_{ratio}$
- *loose'5*: $w_{s3}, F_{side}, \Delta E, E_{ratio}, w_{tot}$

FixedCutTightCaloOnly:

B-E: tight, $4.45 < E_T^{cone40} - 0.022\ p_T^{\gamma} < 9.95$ [GeV]

D-F: non-tight, $4.45 < E_T^{cone40} - 0.022\ p_T^{\gamma} < 9.95$ [GeV]

E: tight, $9.95 < E_T^{cone40} - 0.022\ p_T^{\gamma}$ [GeV]

F: non-tight, $9.95 < E_T^{cone40} - 0.022\ p_T^{\gamma}$ [GeV]

jet→γ misID background: isolation working point

- Isolation: FixedCutTight, without upper cut

FixedCutTight, (w/o upper cut)				
MC				
	loose'2	loose'3	loose'4	loose'5
R-factor	1.05 ± 0.15	1.14 ± 0.15	1.19 ± 0.14	1.39 ± 0.17

Data-driven				
Cut	loose'2	loose'3	loose'4	loose'5
7.95	1.6 ± 0.3	1.5 ± 0.3	1.4 ± 0.3	1.4 ± 0.3
8.45	1.5 ± 0.3	1.5 ± 0.3	1.4 ± 0.3	1.4 ± 0.3
8.95	1.4 ± 0.3	1.3 ± 0.3	1.3 ± 0.3	1.3 ± 0.3
9.45	1.6 ± 0.4	1.5 ± 0.4	1.5 ± 0.4	1.5 ± 0.3
9.95	1.6 ± 0.4	1.5 ± 0.4	1.7 ± 0.4	1.6 ± 0.4

- Isolation: FixedCutTight, with upper cut 25.45 GeV

FixedCutTight, (upper cut = 25.45 GeV)				
MC				
	loose'2	loose'3	loose'4	loose'5
R-factor	1.06 ± 0.15	1.15 ± 0.16	1.21 ± 0.15	1.40 ± 0.17

Data-driven				
Cut	loose'2	loose'3	loose'4	loose'5
8.45	1.1 ± 0.2	1.1 ± 0.2	1.03 ± 0.18	1.06 ± 0.18
8.95	0.96 ± 0.18	0.97 ± 0.17	0.96 ± 0.17	0.97 ± 0.16
9.05	1.01 ± 0.18	1.02 ± 0.18	1.01 ± 0.18	1.01 ± 0.17
9.45	1.08 ± 0.19	1.10 ± 0.19	1.10 ± 0.19	1.12 ± 0.18
9.95	1.03 ± 0.18	1.03 ± 0.18	1.16 ± 0.19	1.16 ± 0.19
10.45	1.1 ± 0.2	1.1 ± 0.2	1.2 ± 0.2	1.2 ± 0.2
10.95	1.2 ± 0.2	1.2 ± 0.2	1.3 ± 0.2	1.3 ± 0.2

- Isolation: FixedCutTight and track inversion

FixedCutTight (inversion), (w/o upper cut)				
MC				
	loose'2	loose'3	loose'4	loose'5
R-factor	1.01 ± 0.12	1.15 ± 0.12	1.29 ± 0.13	1.58 ± 0.16

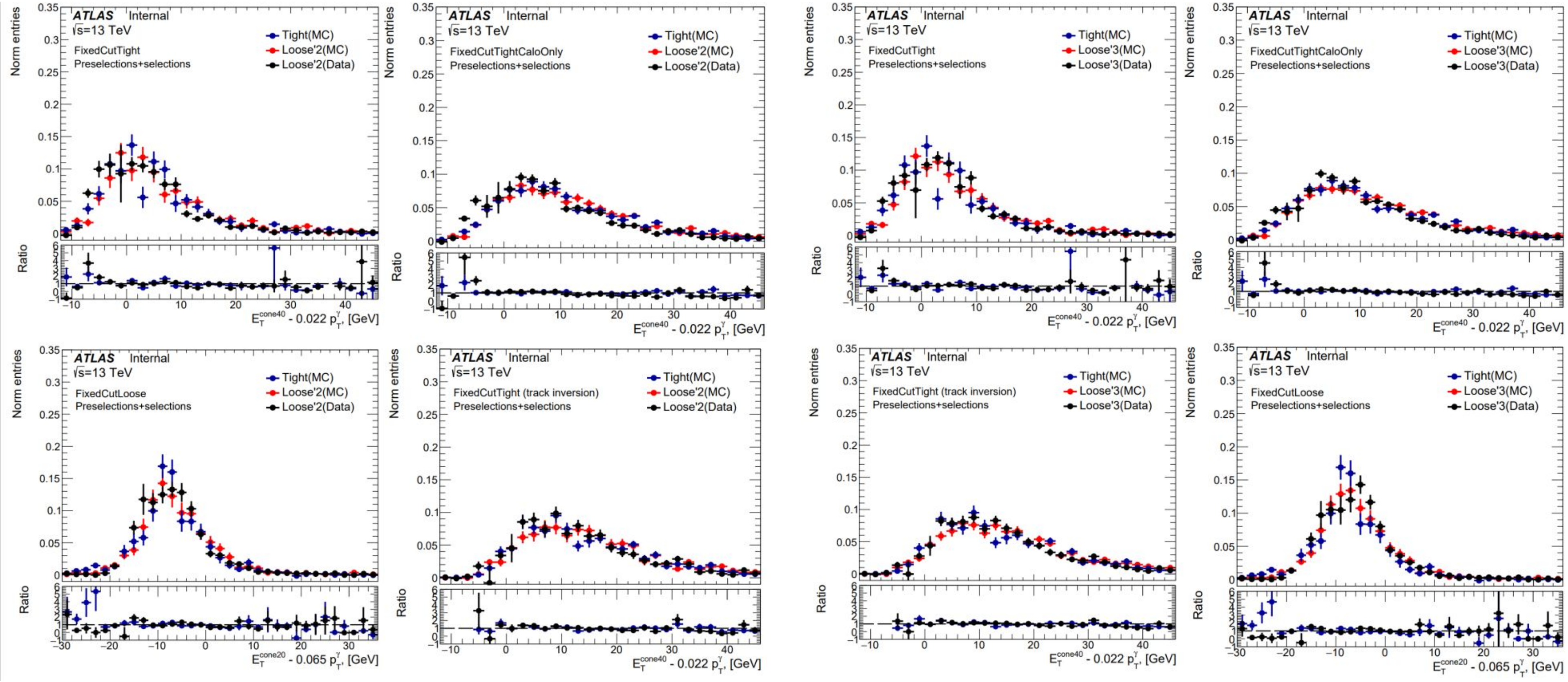
Data-driven				
Cut	loose'2	loose'3	loose'4	loose'5
9.45	1.09 ± 0.13	1.15 ± 0.13	1.09 ± 0.11	1.13 ± 0.11
9.95	1.08 ± 0.12	1.16 ± 0.12	1.11 ± 0.11	1.13 ± 0.10
10.20	1.07 ± 0.12	1.13 ± 0.12	1.09 ± 0.10	1.12 ± 0.10
10.45	1.09 ± 0.12	1.14 ± 0.12	1.10 ± 0.10	1.14 ± 0.10
10.95	1.18 ± 0.13	1.23 ± 0.12	1.17 ± 0.10	1.20 ± 0.10

- Isolation: FixedCutTightCaloOnly, without upper cut

FixedCutTightCaloOnly, (w/o upper cut)				
MC				
	loose'2	loose'3	loose'4	loose'5
R-factor	1.06 ± 0.10	1.14 ± 0.11	1.22 ± 0.10	1.40 ± 0.12

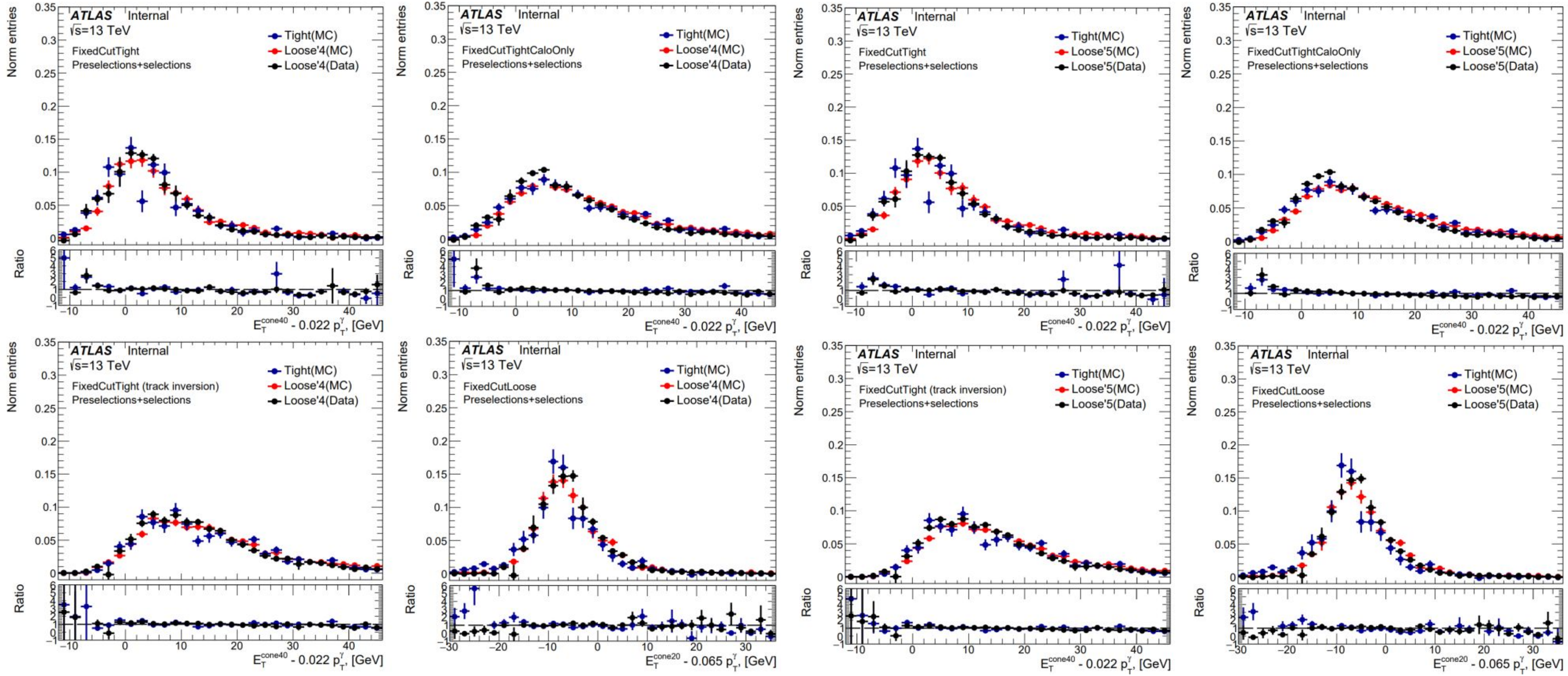
Data-driven				
Cut	loose'2	loose'3	loose'4	loose'5
9.45	1.08 ± 0.11	1.14 ± 0.11	1.12 ± 0.10	1.13 ± 0.10
9.95	1.07 ± 0.10	1.13 ± 0.10	1.15 ± 0.10	1.15 ± 0.10
10.45	1.09 ± 0.10	1.14 ± 0.10	1.14 ± 0.10	1.15 ± 0.10
10.95	1.18 ± 0.11	1.23 ± 0.11	1.21 ± 0.10	1.22 ± 0.10
11.45	1.23 ± 0.11	1.27 ± 0.11	1.22 ± 0.10	1.22 ± 0.10

jet→γ misID background: isolation working point



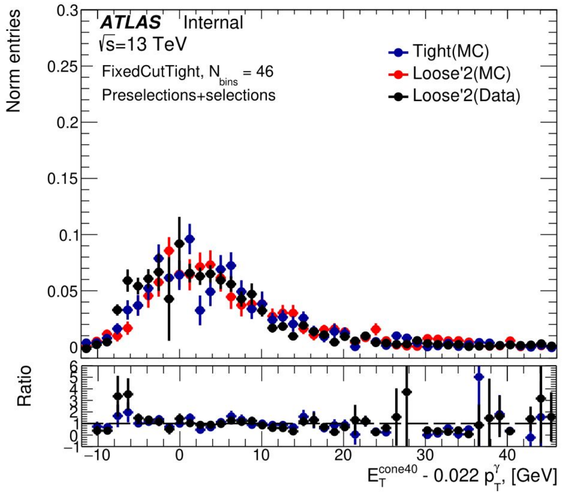
loose'2 ***loose'3***

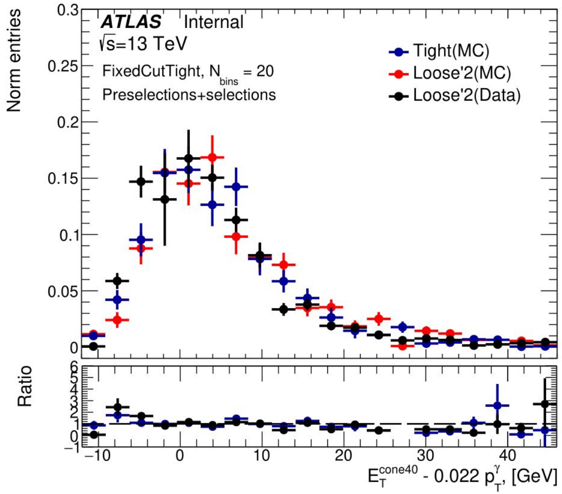
jet→γ misID background: isolation working point

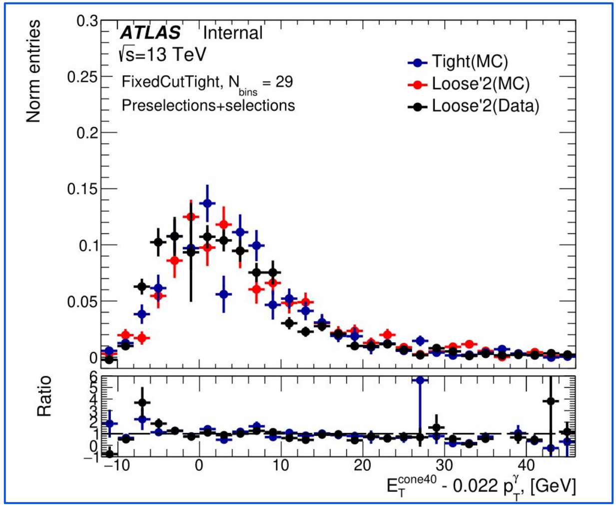


loose'4 *loose'5*

jet→γ misID background: isolation working point







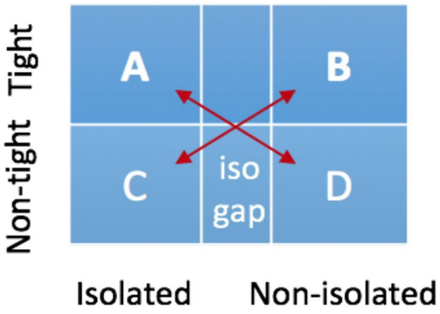
For blue point in 20 bin: 0.0144971 +- 0.00474881
For black point in 20 bin: 0.00177925 +- 0.00131052
For red point in 20 bin: 0.00257787 +- 0.00238254
Ratio in 20 bin: 5.62366 +- 5.51433

$$\Delta\left(\frac{x}{y}\right) = \sqrt{\left(\frac{\Delta x}{y}\right)^2 + \left(\frac{x\Delta y}{y^2}\right)^2}$$

For blue point in 28 bin: -0.00022147 +- 0.00140026
For black point in 28 bin: 0.00342036 +- 0.0014042
For red point in 28 bin: 0.000896954 +- 0.00102111
Ratio in 28 bin: -0.246913 +- 1.58623 (blue point), 3.81331 +- 4.6148 (black point)

jet→γ misID background: estimation technique

iso gap = 2 GeV



The number of events arising in each of the regions:

$$N_A = N_A^{\text{sig}} + N_A^{\text{bkg}} + N_A^{\text{jet}\to\gamma};$$
$$N_B = c_{\text{B}} N_A^{\text{sig}} + N_B^{\text{bkg}} + N_B^{\text{jet}\to\gamma};$$
$$N_C = c_{\text{C}} N_A^{\text{sig}} + N_C^{\text{bkg}} + N_C^{\text{jet}\to\gamma};$$
$$N_D = c_{\text{D}} N_A^{\text{sig}} + N_D^{\text{bkg}} + N_D^{\text{jet}\to\gamma};$$

The signal leakage parameters:

$$c_i = \frac{N_i^{\text{sig}}}{N_A^{\text{sig}}}$$ MC

$$\widetilde{N}_i = N_i - N_i^{\text{bkg}}$$

$$N_{\text{A}}^{\text{sig}} = \widetilde{N}_{\text{A}} - R(\widetilde{N}_{\text{B}} - c_{\text{B}} N_{\text{A}}^{\text{sig}}) \frac{\widetilde{N}_{\text{C}} - c_{\text{C}} N_{\text{A}}^{\text{sig}}}{\widetilde{N}_{\text{D}} - c_{\text{D}} N_{\text{A}}^{\text{sig}}}$$

$$\begin{cases} a = c_D - R c_B c_C; \\ b = \widetilde{N}_{\text{D}} + c_D \widetilde{N}_{\text{A}} - R(c_B \widetilde{N}_{\text{C}} + c_C \widetilde{N}_{\text{B}}); \\ c = \widetilde{N}_{\text{D}} \widetilde{N}_{\text{A}} - R \widetilde{N}_{\text{C}} \widetilde{N}_{\text{B}}. \end{cases}$$

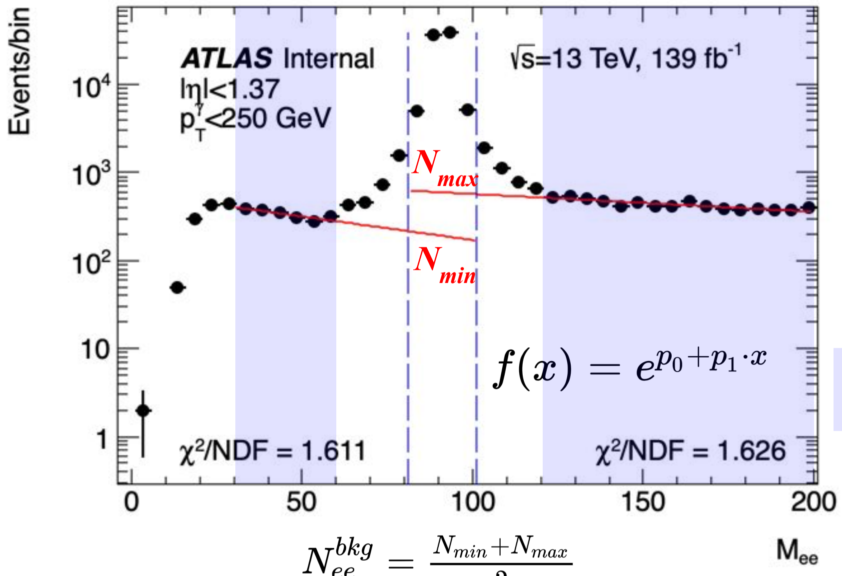
$$N_{\text{A}}^{\text{sig}} = \frac{b - \sqrt{b^2 - 4ac}}{2a}$$

$$N_{\text{A}}^{\text{jet}\to\gamma}$$

	Data	Wγ QCD	Wγ EWK	W($e\nu$), *top*, *tt*	*tt*γ	γ + jet	*Z*(*ll*)γ
A	24946 ± 158	3655 ± 22	145.9 ± 0.7	3070 ± 12	213 ± 3	5016 ± 52	270 ± 4
B	5163 ± 72	337 ± 8	14.1 ± 0.2	140.9 ± 0.5	21.9 ± 1.0	161 ± 9	15.1 ± 1.3
C	1586 ± 40	32 ± 2	1.42 ± 0.07	41.92 ± 0.14	2.2 ± 0.3	36 ± 4	2.4 ± 0.4
D	2805 ± 53	3.0 ± 0.6	0.21 ± 0.03	0 ± 0	0.82 ± 0.19	0.8 ± 0.4	0.19 ± 0.11

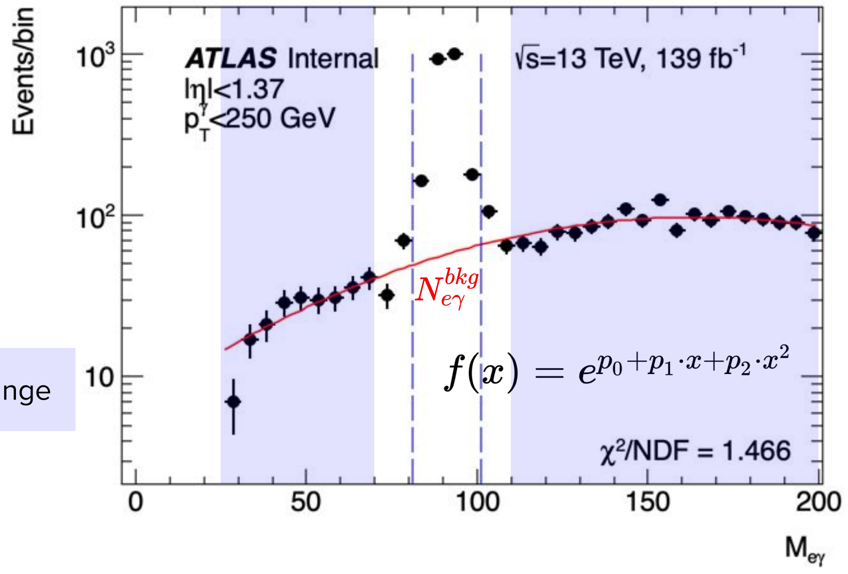
e→γ misID background: background under Z peak

ee pairs



$$N_{ee}^{bkg} = \frac{N_{min}+N_{max}}{2}$$

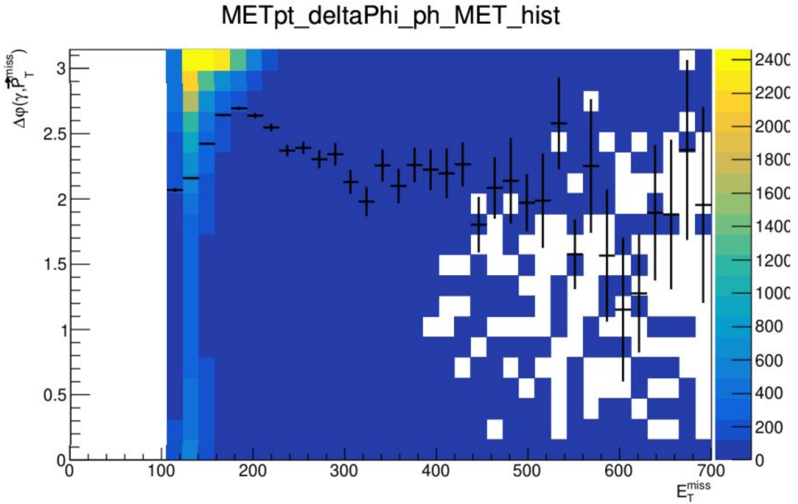
eγ pairs

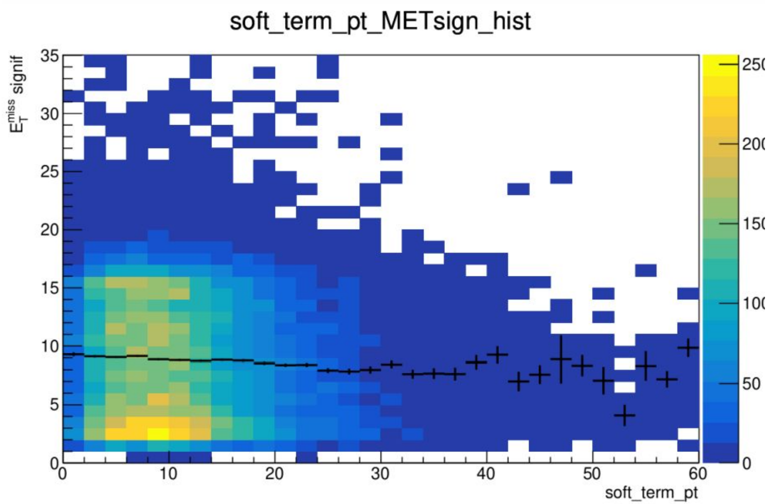


fit range

- ➢ Systematics on bkg estimation under Z peak are evaluated by variation of N^{bkg} values in ee and eγ pairs.
- ➢ N_{min} and N_{max} values are used as variations of N_{ee}^{bkg}. In eγ pairs extrapolation function parameters are varied by their statistical uncertainties one by one. Resulting integral of the function is used for variation of $N_{e\gamma}^{bkg}$.
- ➢ Sum in quadrature of the largest variations of $N_{e\gamma}^{bkg}$ and N_{ee}^{bkg} is taken as systematics.

E_T^{miss}→jet misID background: estimation strategy



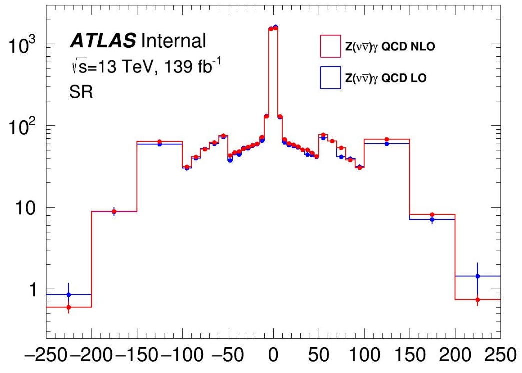


var1 var2	E_T^{miss}signif >11 $p_T^{SoftTerm} < 16$	1.3101
var1 var2	E_T^{miss}signif >11 && $\Delta\phi$(jet_lead, p_T^{miss}) > 0.4 $p_T^{SoftTerm} < 16$	1.24685
var1 var2	E_T^{miss}signif >11 && $\Delta\phi$(jet_lead, p_T^{miss}) > 0.4 && $\Delta\phi(\gamma, p_T^{miss}) > 0.6$ $p_T^{SoftTerm} < 16$	1.24627

R for variables configurations w/o soft term is very bad (>>1)

Pile-up background

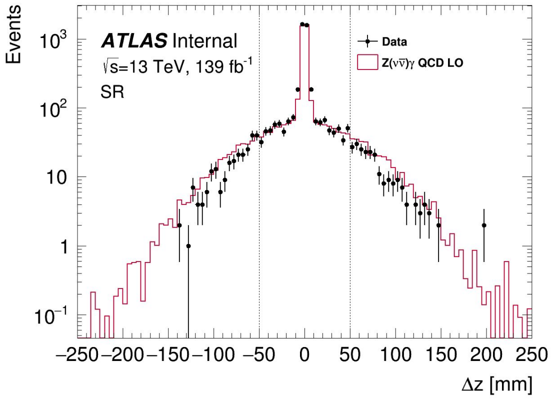
- In full Run2 Z(ll)γ inclusive analysis it was found that events with Z and photon from different primary vertices have non-negligible probability (up to **5%** of the total event yield)
- Since our final state assumes high energetic photons, E_T^{miss}, probability of such events should be much smaller.



- Fraction of pile-up background is calculated as:

$$f_{PU} = \frac{N^{|\Delta z|>50mm}_{\text{data, 2-track Si}} - N^{|\Delta z|>50mm}_{\text{single pp, 2-track Si}}}{N_{\text{data, 2-track Si}} \times 0.32}, \quad N^{|\Delta z|>50mm}_{\text{single pp, 2-track Si}} = SF_1 \times SF_2 \times N^{|\Delta z|>50mm}_{\text{MC, 2-track Si}}$$

- SF_1 is equal to the ratio of events in data to events in Sherpa MC sample near |Δz| around zero (4.61±0.07)
- SF_2 – normalization factor taking into account the mismodelling in the tails of |Δz| distribution (it was calculated for Sherpa Zγ QCD by Z(ll)γ inclusive team using events with FSR photons) (1.5±0.3)



f_{PU}= -(58±11)%

R factor data-driven optimization (I/IV)

- Optimization without W(τν) and with $|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \gamma)|$ > 0.6, except FCLoose (cut 0.7)

FixedCutLoose (inverted), w/o upper cut

MC				
	loose'2	**loose'3**	**loose'4**	**loose'5**
R-factor	1.06 ± 0.10	1.19 ± 0.11	1.30 ± 0.11	1.56 ± 0.13
Data-driven				
Cut	**loose'2**	**loose'3**	**loose'4**	**loose'5**
8.95	1.14 ± 0.12	1.08 ± 0.10	1.00 ± 0.08	0.97 ± 0.08
9.45	1.10 ± 0.11	1.04 ± 0.10	0.96 ± 0.08	0.94 ± 0.07
9.95	1.08 ± 0.11	1.03 ± 0.09	0.96 ± 0.08	0.95 ± 0.07
10.45	1.03 ± 0.10	0.99 ± 0.09	0.92 ± 0.07	0.91 ± 0.07
10.95	1.08 ± 0.11	1.01 ± 0.09	0.93 ± 0.07	0.93 ± 0.07
11.45	1.09 ± 0.11	1.00 ± 0.09	0.94 ± 0.07	0.92 ± 0.07

FixedCutTight (inversion), (w/o upper cut)

MC				
	loose'2	**loose'3**	**loose'4**	**loose'5**
R-factor	1.01 ± 0.12	1.15 ± 0.12	1.29 ± 0.13	1.58 ± 0.16
Data-driven				
Cut	**loose'2**	**loose'3**	**loose'4**	**loose'5**
9.45	1.10 ± 0.08	1.16 ± 0.07	1.12 ± 0.06	1.17 ± 0.06
9.95	1.12 ± 0.06	1.17 ± 0.07	1.13 ± 0.06	1.17 ± 0.06
10.20	1.09 ± 0.07	1.14 ± 0.07	1.12 ± 0.06	1.16 ± 0.06
10.45	1.10 ± 0.07	1.15 ± 0.07	1.13 ± 0.06	1.17 ± 0.06
10.95	1.16 ± 0.07	1.22 ± 0.07	1.18 ± 0.06	1.22 ± 0.06

FixedCutTight, (upper cut = 25.45 GeV)

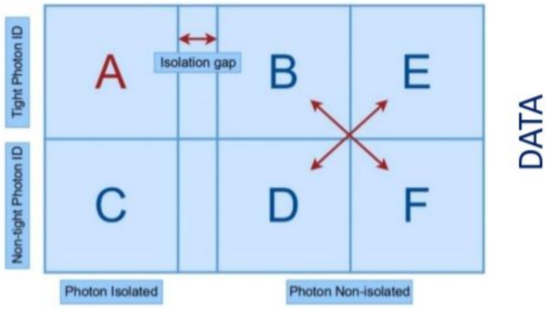
MC				
	loose'2	**loose'3**	**loose'4**	**loose'5**
R-factor	1.06 ± 0.15	1.15 ± 0.16	1.21 ± 0.15	1.40 ± 0.17
Data-driven				
Cut	**loose'2**	**loose'3**	**loose'4**	**loose'5**
8.45	1.15 ± 0.13	1.16 ± 0.12	1.16 ± 0.11	1.21 ± 0.11
8.95	1.11 ± 0.13	1.11 ± 0.12	1.14 ± 0.11	1.17 ± 0.11
9.45	1.20 ± 0.14	1.22 ± 0.13	1.27 ± 0.13	1.30 ± 0.12
9.95	1.16 ± 0.14	1.17 ± 0.13	1.23 ± 0.12	1.28 ± 0.12
10.45	1.19 ± 0.14	1.20 ± 0.14	1.22 ± 0.12	1.26 ± 0.12

FixedCutTightCaloOnly, (w/o upper cut)

MC				
	loose'2	**loose'3**	**loose'4**	**loose'5**
R-factor	1.06 ± 0.10	1.14 ± 0.11	1.22 ± 0.10	1.40 ± 0.12
Data-driven				
Cut	**loose'2**	**loose'3**	**loose'4**	**loose'5**
9.45	1.16 ± 0.07	1.21 ± 0.06	1.20 ± 0.06	1.23 ± 0.06
9.95	1.15 ± 0.06	1.20 ± 0.06	1.20 ± 0.05	1.22 ± 0.05
10.45	1.16 ± 0.06	1.21 ± 0.06	1.20 ± 0.06	1.22 ± 0.05
10.95	1.22 ± 0.07	1.27 ± 0.06	1.24 ± 0.06	1.26 ± 0.06

R' estimation for data-driven regions

- R' is the correlation factor for MC in regions B-E, E, D-F, F
- M_{cut} is the separation point of B-E and E regions, U_{cut} is the upper cut on the isolation



R'	M_{cut}, GeV	U_{cut}, GeV	loose'2	loose'3	loose'4	loose'5
FCTight	8.95	25.45	1.02 ± 0.16	1.13 ± 0.18	1.11 ± 0.16	1.26 ± 0.18
FCTight (invers.)	10.20	—	1.6 ± 0.3	1.7 ± 0.2	1.57 ± 0.18	1.68 ± 0.19
FCCaloOnly	9.95	—	1.17 ± 0.12	1.32 ± 0.12	1.34 ± 0.11	1.51 ± 0.12
FCLoose (invers.)	10.45	—	1.35 ± 0.15	1.37 ± 0.13	1.32 ± 0.11	1.42 ± 0.12

Regions definition

Selections	Cut Value
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 120 GeV
E_{T}^{γ}	> 150 GeV
Number of tight isolated photons	$N_{\gamma} = 1$
Number of jets	$N_{\mathrm{jets}} \geq 2$
Lepton veto	$N_{\mathrm{e}} = 0$, $N_{\mu} = 0$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	> 12
$\lvert\Delta\phi(\gamma, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})\rvert$	> 0.4
$\lvert\Delta\phi(j_1, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})\rvert$	> 0.3
$\lvert\Delta\phi(j_2, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})\rvert$	> 0.3
$p_{\mathrm{T}}^{\mathrm{SoftTerm}}$	< 16 GeV

Table 2: Event selection criteria for $Z(\nu\bar{\nu})\gamma jj$ candidate events.

Region	Var1	Var2
A	($E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 12 AND $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, j_1) > 0.3$ AND $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, j_2) > 0.3$ AND $N_{jets} > 1$)	($p_{\mathrm{T}}^{\mathrm{SoftTerm}} < 16$ GeV AND $p_{\mathrm{T}}^{\mathrm{cone20}}/p_{\mathrm{T}} < 0.05$)
B	($E_{\mathrm{T}}^{\mathrm{miss}}$ significance < 12 OR $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, j_1) < 0.3$ OR $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, j_2) < 0.3$ OR $N_{jets} \leq 1$)	($p_{\mathrm{T}}^{\mathrm{SoftTerm}} < 16$ GeV AND $p_{\mathrm{T}}^{\mathrm{cone20}}/p_{\mathrm{T}} < 0.05$)
C	($E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 12 AND $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, j_1) > 0.3$ AND $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, j_2) > 0.3$ AND $N_{jets} > 1$)	($p_{\mathrm{T}}^{\mathrm{SoftTerm}} > 16$ GeV OR $p_{\mathrm{T}}^{\mathrm{cone20}}/p_{\mathrm{T}} > 0.05$)
D	($E_{\mathrm{T}}^{\mathrm{miss}}$ significance < 12 OR $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, j_1) < 0.3$ OR $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, j_2) < 0.3$ OR $N_{jets} \leq 1$)	($p_{\mathrm{T}}^{\mathrm{SoftTerm}} > 16$ GeV OR $p_{\mathrm{T}}^{\mathrm{cone20}}/p_{\mathrm{T}} > 0.05$)

Table 12: Definition of two boolean variables used to define ABCD regions. $p_{\mathrm{T}}^{\mathrm{SoftTerm}} < 60$ GeV requirement was applied to all regions.

Cuts definition

```
cut1 = (n_ph == 1) && (ph_pt > 150) && (metTST_pt > 120) && (fabs(ph_z_point) < 250);
cut2 = (n_e_looseBL == 0) && (n_mu == 0);
cut3 = (ph_isem == 0) && ((ph_iso_et40-0.022*ph_pt) < 2.45) && (soft_term_pt < 60);
cut4A = A_Selection();
cut4B = B_Selection();
cut4C = C_Selection();
cut4D = D_Selection();
```

Backup 1

reproc-27-11-20

```
total = 99947.6
cut1 applied = 97412.2
cut2 applied = 96476.4
cut3 applied = 56342.3
cut4A applied = 122.173
cut4B applied = 36598.8
cut4C applied = 52.228
cut4D applied = 16588.9
```

reproc-30-09-21

```
total = 79116.5
cut1 applied = 77523.2
cut2 applied = 72555.3
cut3 applied = 57115
cut4A applied = 437.691
cut4B applied = 41491.9
cut4C applied = 91.1535
cut4D applied = 12763
```