Studies for the measurement of the $tt + \gamma$ process with ATLAS at LHC

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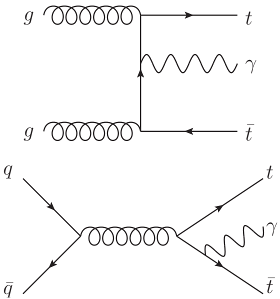
Why is $pp \to t\bar{t}\gamma$ interesting?

- sensitive to the electromagnetic coupling of the top quark $\to$ direct charge measurement
- sensitive to vertex structure (in differential measurements) $\to$ test of the Standard Model and possible clues to physics beyond the Standard Model



$$\Gamma^{\mu}\left(q^2\right) = -iQ_t e \gamma^{\mu}\left(F_1^V\left(q^2\right) + F_1^A\left(q^2\right)\gamma_5\right) - iQ_t e i \frac{\sigma^{\mu\nu}}{2m_t} q_{\nu}\left(F_2^V\left(q^2\right) + F_2^A\left(q^2\right)\gamma_5\right)$$

Precision measurements:

- possible background: charged hadrons that are misidentified as photons and photons from hadron decays

Photons at ATLAS

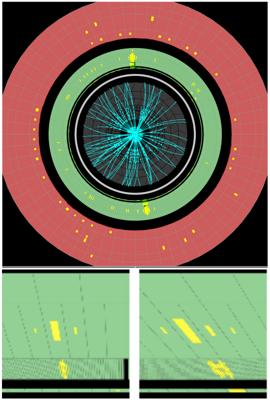
Reconstruction and identification

photons deposit energy mostly in the electromagnetic calorimeter:

- searching for energy clusters in the electromagnetic calorimeter
- reconstruction and matching of the tracks, photon conversion?
- possibly: reconstruction of conversion vertex
- depending on the matching: (un)converted photon or electron

Photon identification with hight signal efficiency and hight background rejection is required. Photon identification is based on cuts on discriminating variables that characterize:

- hadronic leakage
- lateral and longitudinal shower development
- energy ratios



Shower shapes

Variables and Position

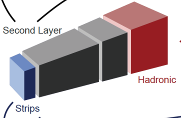
	Strips	2nd	Had.
Ratios	f_1, f_{side}	R_η*, R_ϕ	$R_{Had.}$*
Widths	$w_{s,3}$, $w_{s,tot}$	$w_{\eta,2}$*	-
Shapes	ΔE, E_{ratio}		

* Used in PhotonLoose.

Energy Ratios

$$R_\eta = \frac{E^{S2}_{3\times7}}{E^{S2}_{7\times7}} \qquad R_\phi = \frac{E^{S2}_{3\times3}}{E^{S2}_{3\times7}}$$

φ η



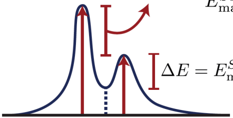
$$R_{Had} = \frac{E_T^{Had}}{E_T}$$

$$f_1 = \frac{E_{S1}}{E_{Tot.}}$$

$$f_{side} = \frac{E^{S1}_7 - E^{S1}_3}{E^{S1}_3}$$

Shower Shapes

$$E_{ratio} = \frac{E^{S1}_{max,1} - E^{S1}_{max,2}}{E^{S1}_{max,1} + E^{S1}_{max,2}}$$

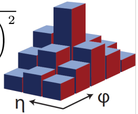


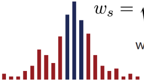
$$\Delta E = E^{S1}_{max,2} - E^{S1}_{min}$$

Widths

$$w_{\eta,2} = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left(\frac{\sum E_i \eta_i}{\sum E_i}\right)^2}$$

Width in a 3×5 (Δη×Δφ) region of cells in the second layer.





$$w_s = \sqrt{\frac{\sum E_i (i - i_{max})^2}{\sum E_i}}$$

ws3 = w_1 uses 3 strips in η;
wstot is defined similarly, but uses 20 strips.

Prompt Photons and Hadron Fakes

Prompt Photons

A prompt photons is a photon originating from the matrix element, the parton shower or the hadronisation.

Hadron fake

A hadron fake is either a hadron misidentified as photon or a photon from the hadron decay.

Data modelling

hadron fakes:

- based on dijet events
- e.g. $g + g \rightarrow g + g$
- final state gluons create jets
- some hadrons of these jets will be detected as photons

prompt photons:

- based on inclusive photon samples
- primarily events where $g + q \rightarrow \gamma + q$ via t-channel scattering (QCD-Compton)

Hadron Fakes

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High amount of hadronic fakes for $t\bar{t}\gamma$-processes (about 30 % at $\sqrt{s} = 7$ TeV). At $\sqrt{s} = 7$ TeV discrimination using discriminating variables e.g. p_T^{iso}.

The photon track-isolation variable p_T^{iso}...

... is defined as the scalar sum of the transverse momenta of selected tracks in a cone of $\Delta R = 0.2$ around the photon candidate.

p_T^{iso}-distribution of signal and background is simulated with templates. The templates are fitted to the data using a likelihood fit.

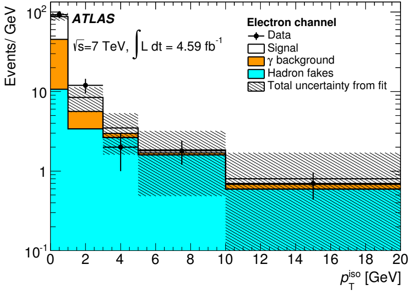

Figure: [2]Results of the combined likelihood fit using the track-isolation (p_T^{iso}) distributions as the discriminating variable for the electron channel.

[2]Phys.Rev.D 91:072007

Shower Shape Studies

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- check distributions of the shower shape variables for differences
- use differences to discriminate between hadron fakes and prompt photons
- use information about conversion

$$s = \frac{1}{2} \sum_{i \in \text{bins}} \frac{\left(s_i - b_i\right)^2}{\left(s_i + b_i\right)}$$

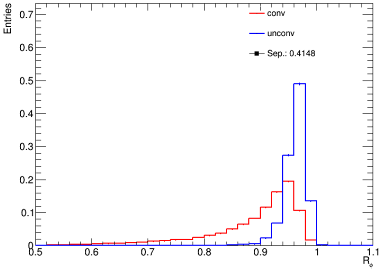


Figure: Comparison of R_ϕ between tight-ID converted and unconverted photons.

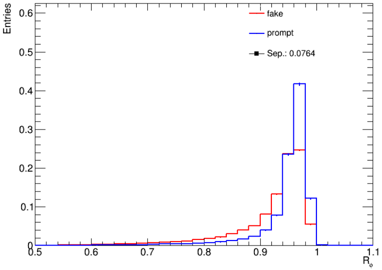


Figure: Comparison of R_ϕ between tight-ID prompt photons and fakes.

Shower Shape Studies

Table: Comparison of separations between prompt photons and hadron fakes for different variables and conversion types.

	all	converted	unconverted	N_{bins}	x_{min}	x_{max}
R_η	0.0531	0.0462	0.0279	30	0.85	1.05
R_ϕ	0.0764	0.0344	0.0507	30	0.5	1.1
$w_{\eta 2}$	0.0232	0.0153	0.0091	30	0.004	0.016
f_{side}	0.0778	0.0332	0.0809	30	0	0.7
$w_{\eta 1}$	0.0464	0.0262	0.0321	30	0.4	0.85
w_{stot}	0.0484	0.0350	0.0391	30	0	4
R_{had}	0.0310	0.0354	0.0238	30	-0.2	0.25
R_{had_1}	0.0291	0.0368	0.0224	30	-0.05	0.06
E_{ratio}	0.0234	0.0286	0.0209	30	0.75	1.02
ΔE	0.0029	0.0052	0.0016	30	−25 GeV	300 GeV

BDT-Algorithm

BDT uses an ensemble of weak learners to create one strong learner. Models have form:

$$F(x) = \sum_{m=1}^{M} \gamma_m h_m(x)$$

$h_m(x)$ are called weak learners, we use decision trees. The model is build iterative:

$$F_m(x) = F_{m-1}(x) + \gamma_m h_m(x)$$

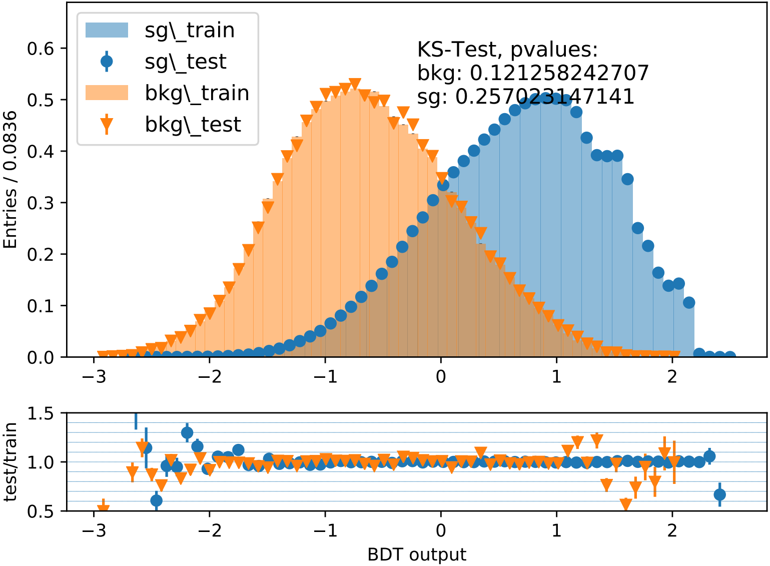
$h_m(x)$ is chosen so that the loss function L will be minimized:

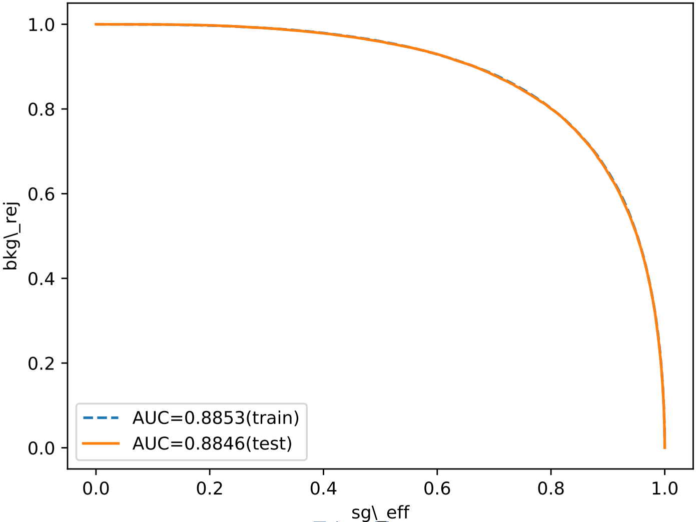
$$F_m(x) = F_{m-1}(x) + \arg\min_h \sum_{i=1}^{n} L\left(y_i, F_{m-1}(x_i) - h(x)\right)$$

Use learning rate ν to scale step length:

$$F_m(x) = F_{m-1}(x) + \nu\gamma_m h_m(x)$$

BDT
Kolmogorov-Smirnov Test





AUC=0.8853(train)
AUC=0.8846(test)
bkg_rej
sg_eff
0.0
0.2
0.4
0.6
0.8
1.0

Comparison of BDT results

Table: Comparison of AUC-values

	no conversion	converted	unconverted	conversion as feature
AUC-test	0.8829	0.8780	0.8761	0.8838
AUC-train	0.8840	0.8803	0.8805	0.8864

Table: Comparison AUC-values for exponential loss function

	no conversion	converted	unconverted	conversion as feature
AUC-test	0.8829	0.8784	0.8774	0.8846
AUC-train	0.8839	0.8811	0.8798	0.8853

Summary and Outlook

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Summary

- can use differences in shower shapes to discriminate between prompt photons and hadron fakes
- training two different BDTs for converted and unconverted photons does not improve performance
- increase in performance when using conversion as feature

Outlook

- studies of systematics
- optimization of BDT parameters
- comparison with other MVA-algorithms (e.g. neural network)

Thank you for your attention.

Backup

Implementation of BDT

Gradient Tree Boosting

- number of single trees = 120, maximum depth of trees = 3, learning rate = 0.1, subsample = 0.5
- loss function: $L = -2\,(yP - \log(1 + \exp(P)))$, where P is the log-odds
- train size: 0.8, test size: 0.2
- features: R_η, R_ϕ, $w_{\eta 2}$, f_{side}, $w_{\eta 1}$, w_{stot}, R_{had}, R_{had_1}, E_{ratio}, ΔE, (see appendix)

Decision Tree

- uses a set of decision rules to perform classification on a dataset
- training vectors $x_i \in \mathbb{R}^l,\ i = 1, ..., n$
- label vector $y_i \in \mathbb{R},\ i = 1, ..., n$
- n samples and l features
- data at node m represented by Q
- split candidates $\theta = (j, t_m)$ with feature j and threshold t_m
- data is split into two subsets $Q_{\text{left}}(\theta)$ and $Q_{\text{right}}(\theta)$:

$$Q_{\text{left}}(\theta) = \left\{(x_i, y_i) | x_i^j \leq t_m\right\}$$
$$Q_{\text{right}}(\theta) = Q \setminus Q_{\text{left}}$$

- x_i^j is the value of the i-th sample for the j-th feature
- impurity at node m is calculated for impurity function $H()$:

$$G(Q, \theta) = \frac{n_{\text{left}}}{N_m} H(Q_{\text{left}}(\theta)) + \frac{n_{\text{right}}}{N_m} H(Q_{\text{right}}(\theta))$$

Decision Tree

- the parameters that minimize the impurity are chosen:

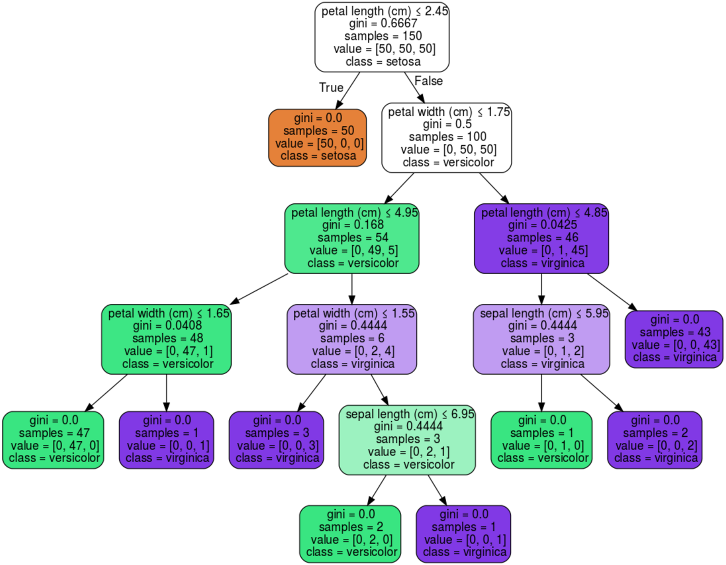
$$\theta^* = \arg\min_\theta G(Q, \theta)$$

- recuse for $Q_{\text{left}}(\theta^*)$ and $Q_{\text{right}}(\theta^*)$.
- possible measure for impurity is GINI:

$$H(X_m) = \sum_k p_{mk}(1 - p_{mk}),$$
$$p_{mk} = \frac{1}{N_m} \sum_{x_i \in R_m} I(y_i = k)$$

- p_{mk} is the proportion of class k in node m.

Example for a decision tree using the iris dataset



BDT-Algorithm

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$h_m(x)$ is chosen so that the loss function L will be minimized:

$$F_m(x) = F_{m-1}(x) + \arg\min_h \sum_{i=1}^{n} L\left(y_i, F_{m-1}(x_i) - h(x)\right)$$

Use learning rate ν to scale step length:

$$F_m(x) = F_{m-1}(x) + \nu\gamma_m h_m(x)$$

General idea of MVA implementation and training procedure

- learn some properties of a data set and apply them to new data
- split data into training set and testing set
- train MVA algorithm using the training set
- test algorithm on testing set

Data

Signal

- based on inclusive photon samples
- primarily events where $g + q \rightarrow \gamma + q$ via t-channel scattering (QCD-Compton)
- `/eos/atlas/atlascerngroupdisk/perf-egamma/InclusivePhotons/v12/v12_01/PyPt17_inf_mc15c_v12_PIDuse.root`

Background

- based on dijet events
- e.g. $g + g \rightarrow g + g$
- final state gluons create jets
- some hadrons of these jets will be detected as photons
- `/eos/atlas/atlascerngroupdisk/perf-egamma/InclusivePhotons/v12/v12_01/Py8_jetjet_mc15c_v12_PIDuse.root`

Shower shape variables

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Normalised hadronic leakage

$$R_{\mathrm{had}} = \frac{E_{\mathrm{T}}^{\mathrm{had}}}{E_{\mathrm{T}}}$$

The transverse energy deposited in the hadronic calorimeter $E_{\mathrm{T}}^{\mathrm{had}}$ in a window of $\Delta\eta \times \Delta\phi = 0.24 \times 0.24$ behind the photon cluster, normalized to the total transverse energy E_{T}

Normalised hadronic leakage in first layer

$$R_{\mathrm{had}_1} = \frac{E_{\mathrm{T}}^{\mathrm{had},1}}{E_{\mathrm{T}}}$$

The transverse energy deposited in the first layer of the hadronic calorimeter $E_{\mathrm{T}}^{\mathrm{had},1}$ in a window of $\Delta\eta \times \Delta\phi = 0.24 \times 0.24$ behind the photon cluster, normalized to the total transverse energy E_{T}

Definitions from Eur. Phys. J. C 76 (2016) 666

Middle η energy ratio

$$R_\eta = \frac{E^{S2}_{3\times 7}}{E^{S2}_{7\times 7}}$$

The ratio of the sum of the energy $E^{S2}_{3\times 7}$ in a rectangle of 3×7 calorimeter cells in the second layer, to the sum of the energies $E^{S2}_{7\times 7}$ in a 7×7 rectangle, centred around the cluster seed.

Middle ϕ energy ratio

$$R_\phi = \frac{E^{S2}_{3\times 3}}{E^{S2}_{3\times 7}}$$

The ratio of the sum of the energy $E^{S2}_{3\times 3}$ in a rectangle of 3×3 calorimeter cells in the second layer, to the sum of the energies $E^{S2}_{3\times 7}$ in a 3×7 rectangle, centred around the cluster seed.

Shower shape variables

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Middle lateral width

$$w_{\eta 2} = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left(\frac{\sum E_i \eta_i}{\sum E_i}\right)^2}$$

Measures the lateral width of the shower in the second layer of the electromagnetic calorimeter in a window of $\eta \times \phi = 3 \times 5$ cells. E_i is the energy deposited in each cell and η_i the η position of the cell.

Front side energy ratio

$$F_{\text{side}} = \frac{E(\pm 3) - E(\pm 1)}{E(\pm 1)}$$

Measures the lateral containment of the shower in η. $E(\pm n)$ is the energy in the $\pm n$ strips around the strip with the highest energy.

Shower shape variables

Front lateral width (3 strips)

$$w_{s3} = \sqrt{\frac{\sum E_i \left(i - i_{\max}\right)^2}{\sum E_i}}$$

Measures the width of the shower in η using three strip cells centred on the strip with the highest energy. i is the strip identification number, $i_{\max}$ identifies the strip with the highest energy and E_i is the energy deposited in each strip.

Front lateral width (total)

$w_{s\,\mathrm{tot}}$ measures the width of the shower in η using alls cells in a window of $\Delta\eta \times \Delta\phi = 0.0625 \times 0.196$, approximately 20×2 strip cells. $w_{s\,\mathrm{tot}}$ is computed as w_{s3}.

Shower shape variables

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Front second maximum energy difference

$$\Delta E = \left[E^{S1}_{2^{\text{nd}}\text{max}} - E^{S1}_{\text{min}}\right]$$

The difference between the energy of the strip cell with the second largest energy $E_{2^{\text{nd}}\text{max}}$ and the energy of the cell with the lowest energy found between the largest and the second largest energy E^{S1}_{min}. If there is no second maximum $\Delta E = 0$.

Front maxima relative energy ratio

$$E_{\text{ratio}} = \frac{E^{S1}_{1^{\text{st}}\text{max}} - E^{S1}_{2^{\text{nd}}\text{max}}}{E^{S1}_{1^{\text{st}}\text{max}} + E^{S1}_{2^{\text{nd}}\text{max}}}$$

The relative difference between the energy of the strip with the highest energy $E^{S1}_{1^{\text{st}}\text{max}}$ and the energy of the strip with the second highest energy $E^{S1}_{2^{\text{nd}}\text{max}}$. If there is no second maximum $E_{\text{ratio}} = 1$

Shower Shape Studies

Table: Comparison of separations between converted and unconverted photons for different variables for all photons, prompts and hadron fakes

	all	prompt	fake	N_{bins}	x_{min}	x_{max}
R_η	0.0891	0.0608	0.0830	30	0.85	1.05
R_ϕ	0.4148	0.3930	0.4035	30	0.5	1.1
$w_{\eta 2}$	0.0996	0.0831	0.0974	30	0.004	0.016
f_{side}	0.1195	0.1643	0.0748	30	0	0.7
$w_{\eta 1}$	0.1266	0.1288	0.1091	30	0.4	0.85
w_{stot}	0.0820	0.0808	0.0707	30	0	4
R_{had}	0.0104	0.0051	0.0087	30	-0.2	0.25
R_{had_1}	0.0060	0.0030	0.0052	30	-0.05	0.06
E_{ratio}	0.0059	0.0060	0.0060	30	0.75	1.02
ΔE	0.0033	0.0035	0.0034	30	-25 GeV	300 GeV

Separation

Separation:

$$s = \frac{1}{2} \sum_{i \in \text{bins}} \frac{(s_i - b_i)^2}{(s_i + b_i)}$$

R_η

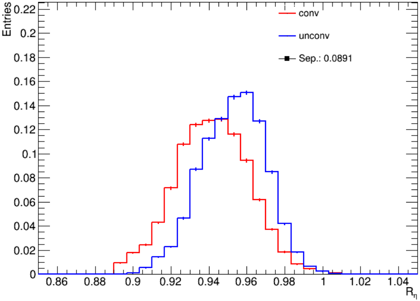


Figure: Comparison of R_η between tight-ID converted and unconverted photons.

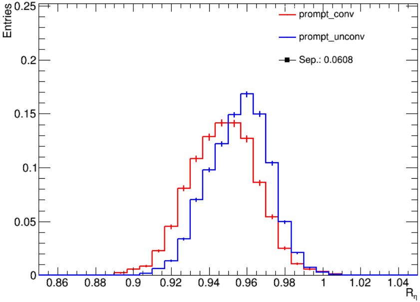


Figure: Comparison of R_η between tight-ID converted and unconverted prompt photons.

R_η

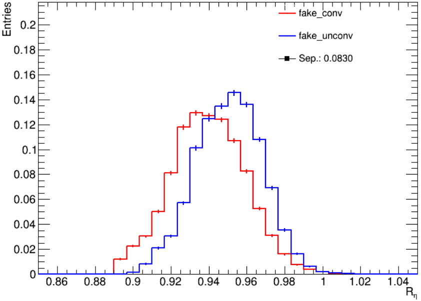


Figure: Comparison of R_η between tight-ID converted and unconverted fake photons.

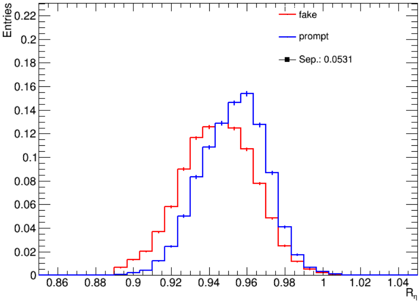


Figure: Comparison of R_η between tight-ID prompt photons and fakes.

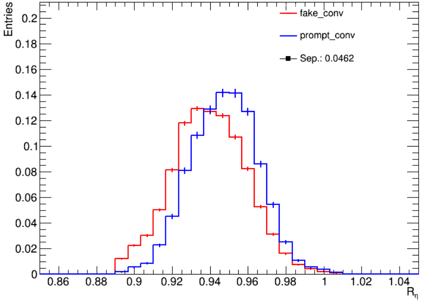


Figure: Comparison of R_η between tight-ID converted prompt photons and fake photons.

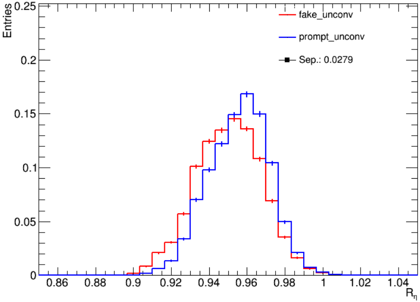


Figure: Comparison of R_η between tight-ID unconverted prompt photons and fake photons.

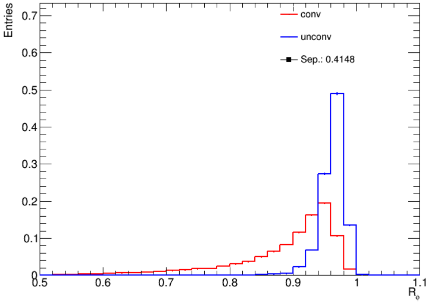


Figure: Comparison of R_ϕ between tight-ID converted and unconverted photons.

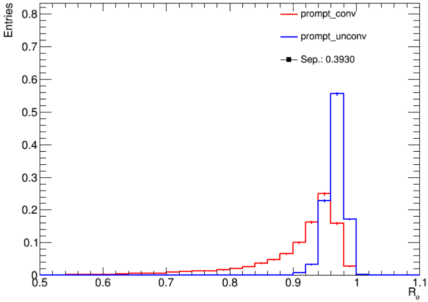


Figure: Comparison of R_ϕ between tight-ID converted and unconverted prompt photons.

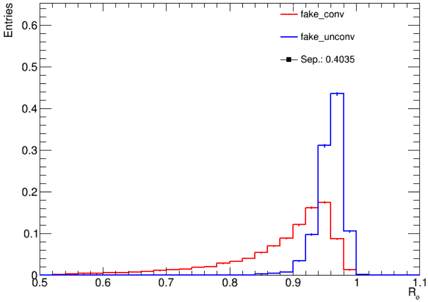
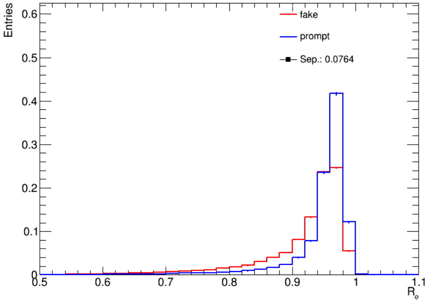


Figure: Comparison of R_ϕ between tight-ID converted and unconverted fake photons.



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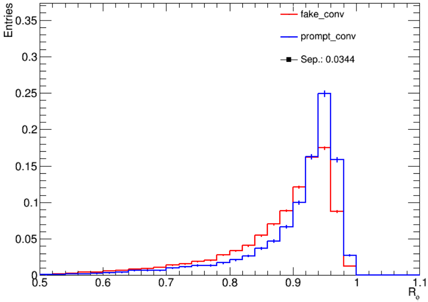

Figure: Comparison of R_ϕ between tight-ID converted prompt photons and fake photons.

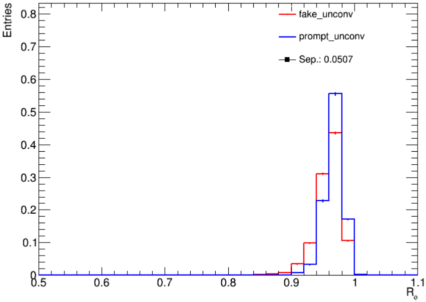

Figure: Comparison of R_ϕ between tight-ID unconverted prompt photons and fake photons.

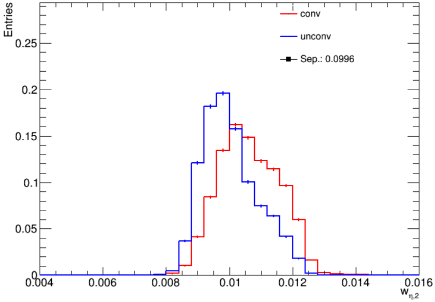

Figure: Comparison of $w_{\eta 2}$ between tight-ID converted and unconverted photons.

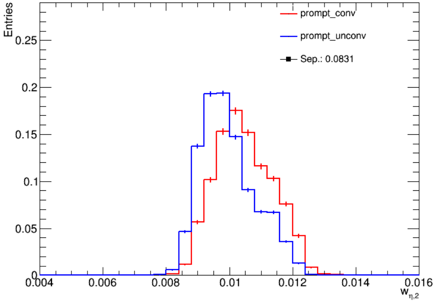

Figure: Comparison of $w_{\eta 2}$ between tight-ID converted and unconverted prompt photons.

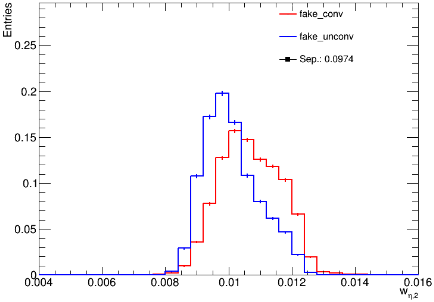

Figure: Comparison of $w_{\eta 2}$ between tight-ID converted and unconverted fake photons.

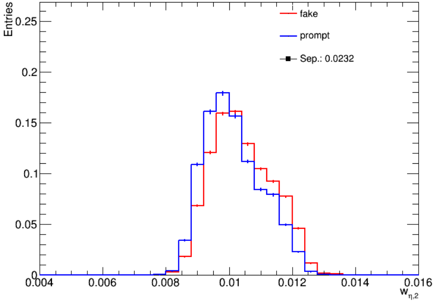

Figure: Comparison of $w_{\eta 2}$ between tight-ID prompt photons and fakes.

$w_{\eta 2}$

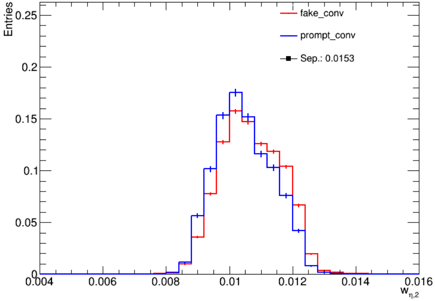

Figure: Comparison of $w_{\eta 2}$ between tight-ID converted prompt photons and fake photons.

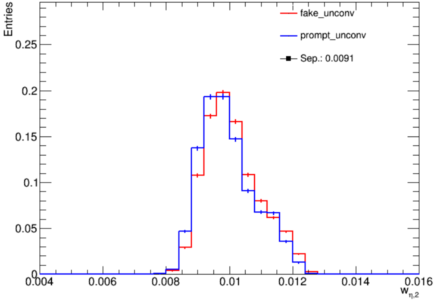

Figure: Comparison of $w_{\eta 2}$ between tight-ID unconverted prompt photons and fake photons.

f_{side}

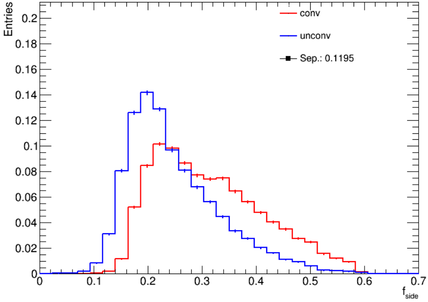

Figure: Comparison of f_{side} between tight-ID converted and unconverted photons.

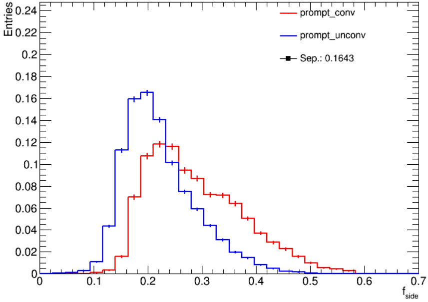

Figure: Comparison of f_{side} between tight-ID converted and unconverted prompt photons.

f_{side}

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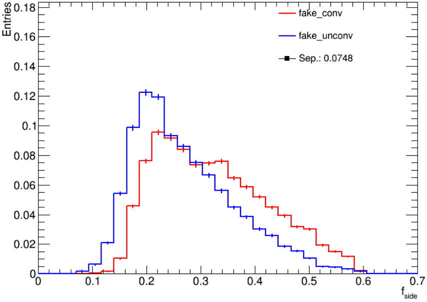

Figure: Comparison of f_{side} between tight-ID converted and unconverted fake photons.

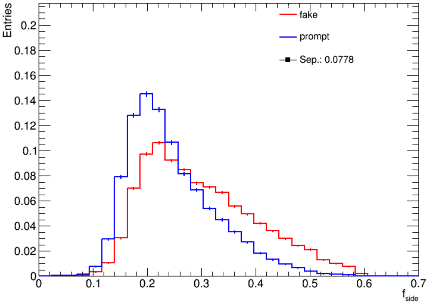

Figure: Comparison of f_{side} between tight-ID prompt photons and fakes.

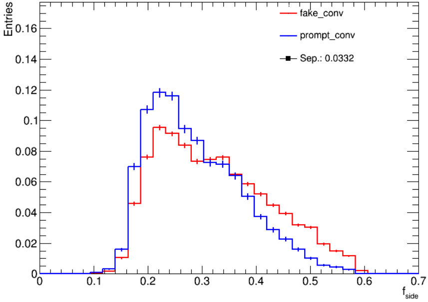

Figure: Comparison of f_{side} between tight-ID converted prompt photons and fake photons.

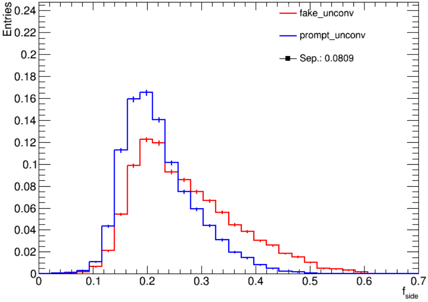

Figure: Comparison of f_{side} between tight-ID unconverted prompt photons and fake photons.

$w_{\eta 1}$

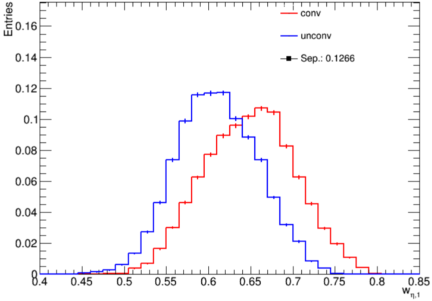

Figure: Comparison of $w_{\eta 1}$ between tight-ID converted and unconverted photons.

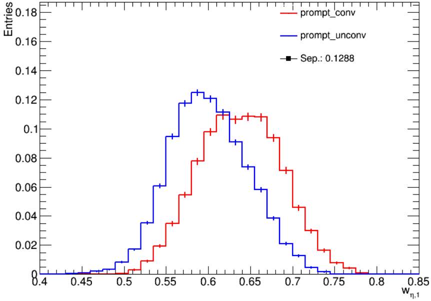

Figure: Comparison of $w_{\eta 1}$ between tight-ID converted and unconverted prompt photons.

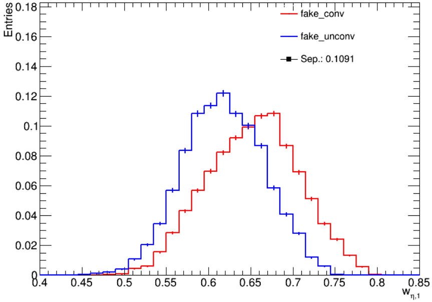

Figure: Comparison of $w_{\eta 1}$ between tight-ID converted and unconverted fake photons.

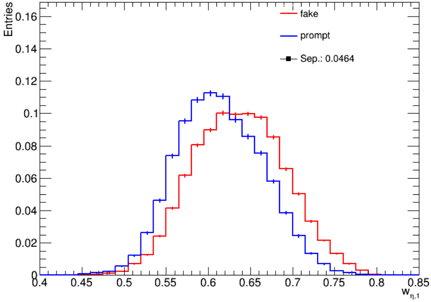

Figure: Comparison of $w_{\eta 1}$ between tight-ID prompt photons and fakes.

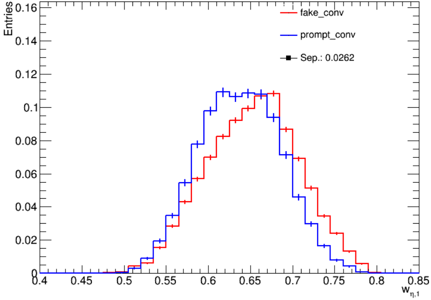

Figure: Comparison of $w_{\eta 1}$ between tight-ID converted prompt photons and fake photons.

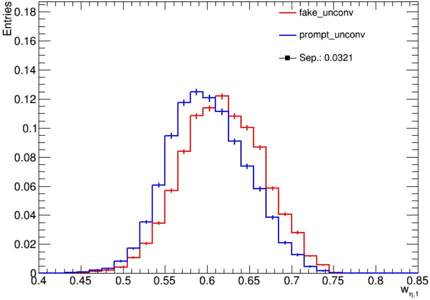

Figure: Comparison of $w_{\eta 1}$ between tight-ID unconverted prompt photons and fake photons.

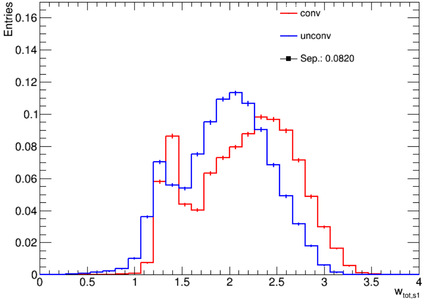

Figure: Comparison of $w_{\mathrm{tot},s1}$ between tight-ID converted and unconverted photons.

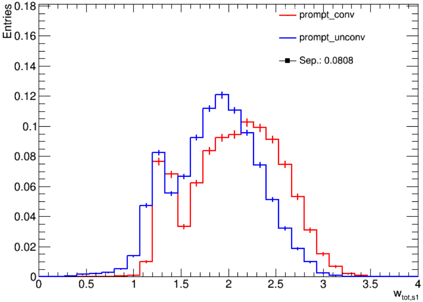

Figure: Comparison of $w_{\mathrm{tot},s1}$ between tight-ID converted and unconverted prompt photons.

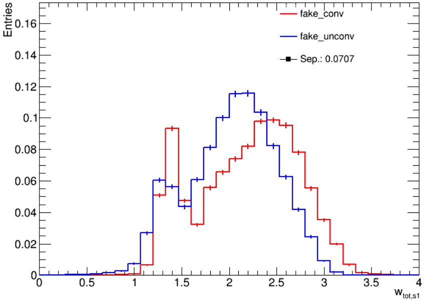

Figure: Comparison of $w_{\mathrm{tot},s1}$ between tight-ID converted and unconverted fake photons.

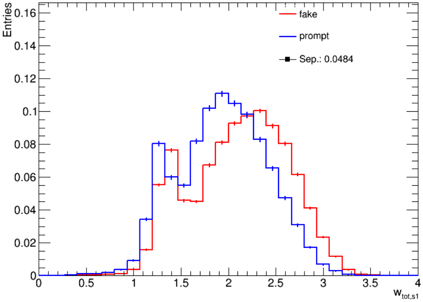

Figure: Comparison of $w_{\mathrm{tot},s1}$ between tight-ID prompt photons and fakes.

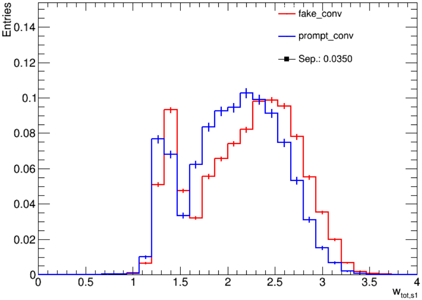

Figure: Comparison of $w_{\text{tot},s1}$ between tight-ID converted prompt photons and fake photons.

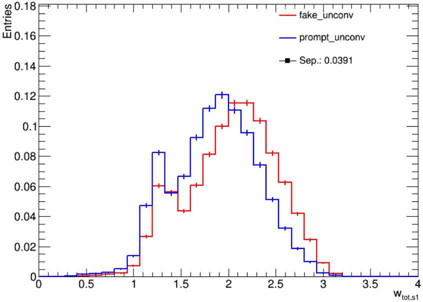

Figure: Comparison of $w_{\text{tot},s1}$ between tight-ID unconverted prompt photons and fake photons.

R_{had}

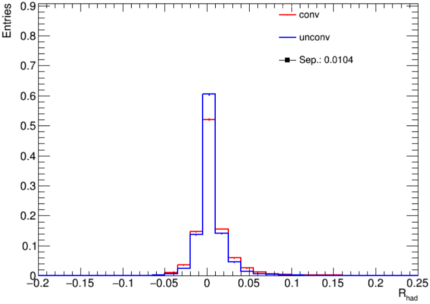

Figure: Comparison of R_{had} between tight-ID converted and unconverted photons.

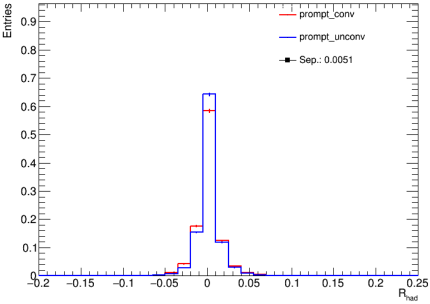

Figure: Comparison of R_{had} between tight-ID converted and unconverted prompt photons.

R_{had}

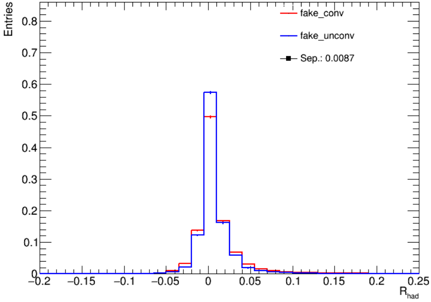

Figure: Comparison of R_{had} between tight-ID converted and unconverted fake photons.

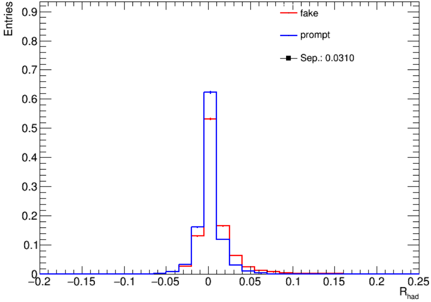

Figure: Comparison of R_{had} between tight-ID prompt photons and fakes.

R_{had}

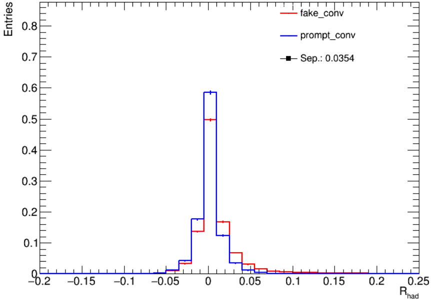

Figure: Comparison of R_{had} between tight-ID converted prompt photons and fake photons.

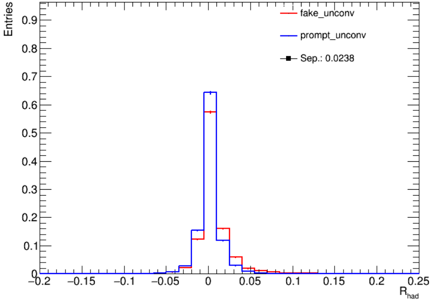

Figure: Comparison of R_{had} between tight-ID unconverted prompt photons and fake photons.

R_{had_1}

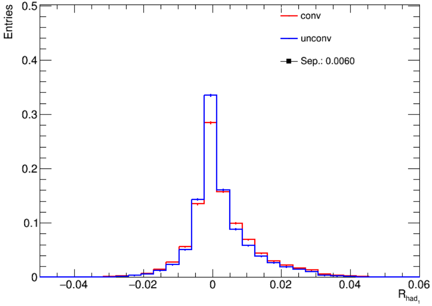

Figure: Comparison of R_{had_1} between tight-ID converted and unconverted photons.

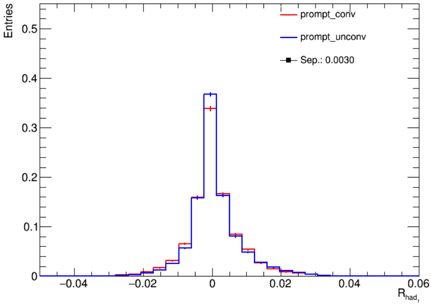

Figure: Comparison of R_{had_1} between tight-ID converted and unconverted prompt photons.

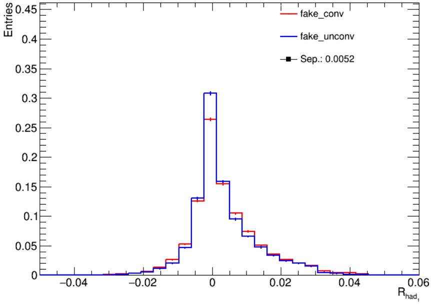

Figure: Comparison of R_{had_1} between tight-ID converted and unconverted fake photons.

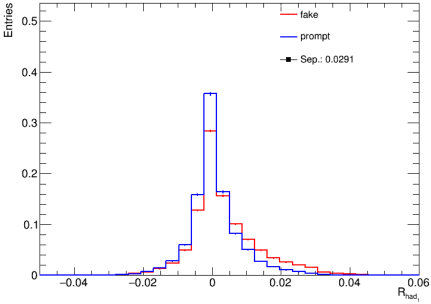

Figure: Comparison of R_{had_1} between tight-ID prompt photons and fakes.

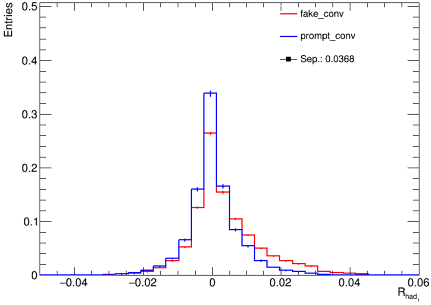

Figure: Comparison of R_{had_1} between tight-ID converted prompt photons and fake photons.

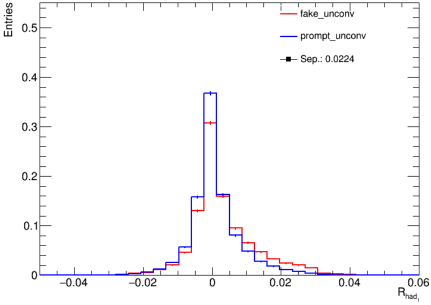

Figure: Comparison of R_{had_1} between tight-ID unconverted prompt photons and fake photons.

E_{ratio}

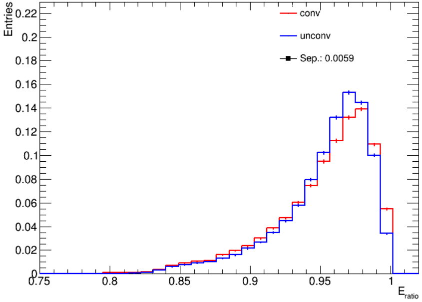

Figure: Comparison of E_{ratio} between tight-ID converted and unconverted photons.

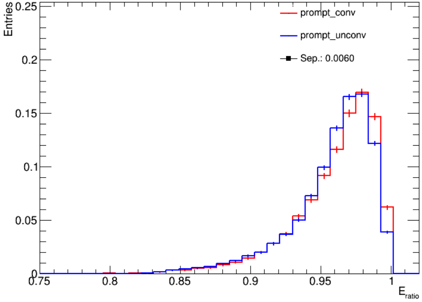

Figure: Comparison of E_{ratio} between tight-ID converted and unconverted prompt photons.

E_{ratio}

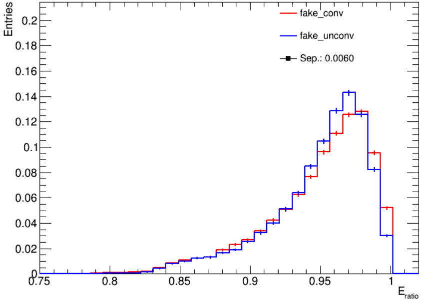

Figure: Comparison of E_{ratio} between tight-ID converted and unconverted fake photons.

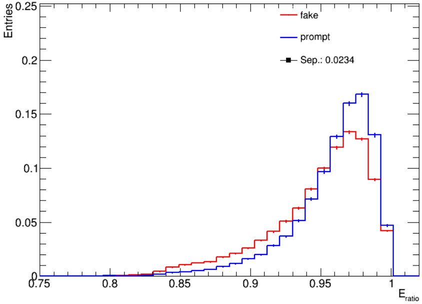

Figure: Comparison of E_{ratio} between tight-ID prompt photons and fakes.

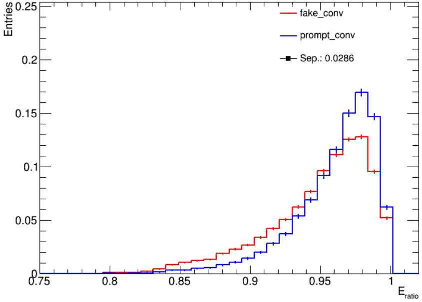

Figure: Comparison of E_{ratio} between tight-ID converted prompt photons and fake photons.

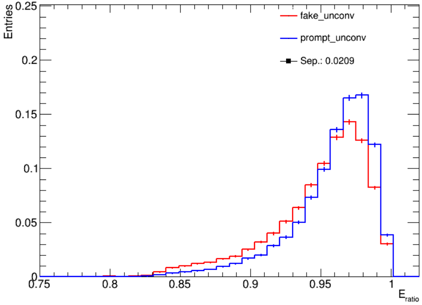

Figure: Comparison of E_{ratio} between tight-ID unconverted prompt photons and fake photons.

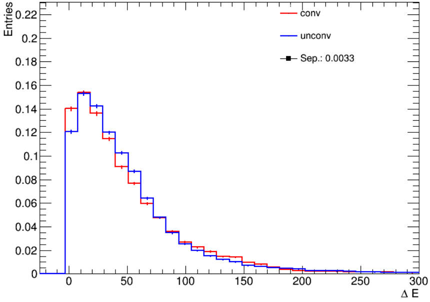

Figure: Comparison of ΔE between tight-ID converted and unconverted photons.

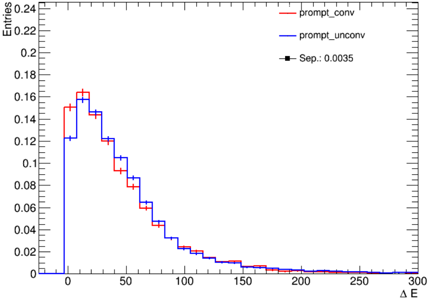

Figure: Comparison of ΔE between tight-ID converted and unconverted prompt photons.

ΔE

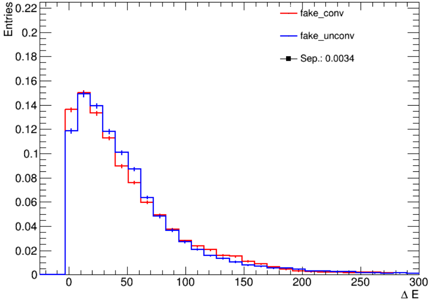

Figure: Comparison of ΔE between tight-ID converted and unconverted fake photons.

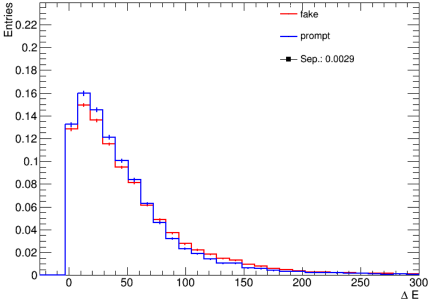

Figure: Comparison of ΔE between tight-ID prompt photons and fakes.

ΔE

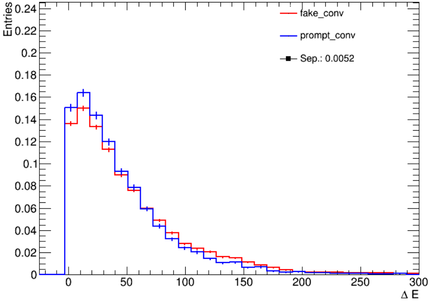

Figure: Comparison of ΔE between tight-ID converted prompt photons and fake photons.

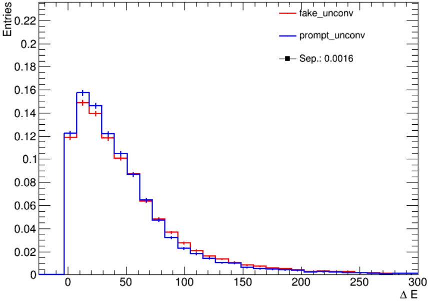

Figure: Comparison of ΔE between tight-ID unconverted prompt photons and fake photons.