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A Fundemental Study on Photon Isolation

Summer Research Report

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Contents

1 Introduction

In Quantum Electrodynamics (QED), splitting refers to a process where a high-energy particle emits or dacays a daughter particle and undergoes a change in its state. This process is governed by the principles of QED, which is the quantum field theory describing the electromagnetic force.

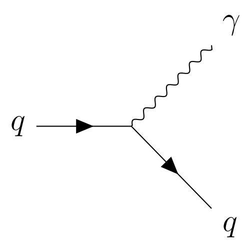


Figure 1: Feynman diagram for $q \to q\gamma$.

Here we are interested in $q \to q\gamma$ process (Fig. 1). Which refers to the quark undergoing a transition where it emits a photon. The emission of a photon by a quark can occur in various high-energy processes, and it contributes to the dynamics of particle interactions in experiments such as those conducted at particle colliders.

The probability for a quark to radiate a photon with some angle θ_γ and momentum fraction z_γ is given by:

$$\mathrm{d}P_{q\to q\gamma} = \frac{\alpha_e e^2}{2\pi}\frac{\mathrm{d}\theta_\gamma}{\theta_\gamma}P(z_\gamma)\mathrm{d}z_\gamma, \quad P(z) = \left(\frac{1+(1-z)^2}{z}\right)_+, \tag{1}$$

where $P(z)$ is the (regularized) QED splitting function [1]. The QED splitting function gives the probability density for a quark to emit a photon with a certain fraction of its energy. The quark can lose energy by emitting a photon, and the splitting function characterizes the likelihood of this energy loss. The form of the QED splitting function depends on the specific process under consideration and is derived using perturbation theory. QED splitting function plays an important role in high energy experiments thus we put a great emphasis on it. In this study, we use soft drop isolation to explore the QED splitting function in $q \to q\gamma$ process.

2 Grooming

Jet grooming refers to a set of techniques used to improve the reconstruction and analysis of jets. Jets can be affected by various effects, such as soft radiation and pileup, which can lead to a broader or less well-defined jet structure. Grooming methods help mitigate these effects and enhance the precision of jet measurements.

Soft radiation, characterized by low momentum particles, can significantly impact the structure of jets, making them broader and less well-defined. Grooming techniques, such as trimming, pruning, and soft drop, are designed to remove soft radiation from jets, providing a more accurate measurement of the core jet properties. And grooming methods improve the discrimination between jets originating from hard-scattering processes (signal) and those influenced by soft radiation or pileup (background). By removing wide-angle and soft radiation components, grooming helps to enhance the purity of the signal sample, making it easier to identify. Also, different experimental conditions, such as varying center-of-mass energies and detector configurations, can impact the performance of jet algorithms. Grooming methods provide a way to adapt to these conditions, improving the robustness and consistency of jet measurements across different experimental setups.

Grooming is widely used in experiments at high-energy colliders like the Large Hadron Collider (LHC) at CERN, where the production of jets is abundant.

2.1 Soft Drop Algorithm

Soft Drop is a grooming algorithm that involves recursively declustering a jet into two subjets and rejecting the subjet with the lower momentum if certain conditions are not met. It is designed to be sensitive to both soft radiation and wide-angle radiation.

Soft drop declustering is used to identify hard subjets within a jet that satisfy the condition:

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \geq z_{\text{cut}} \left(\frac{R_{12}}{R_0} \right)^{\beta}, \tag{2}$$

where p_{Ti} are the transverse momenta of the subjets, R_{12} is their pairwise angular separation, R_0 is the jet radius parameter, and z_{cut} and β are the parameters of the soft drop algorithm. The two parameters control the sensitivity of the Soft Drop algorithm to soft radiation and wide-angle radiation. A smaller z_{cut} enhances the removal of soft radiation, while β controls the angular scaling.

Soft drop isolation is a method derives from soft drop declustering and it inverts the condition of soft drop declustering, thereby selecting “photon jets” with no appreciable substructure.

3 Photon Isolation

3.1 Procedure

The photon isolation procedure is a combination of soft drop declustering and soft drop isolation.

First we start with a jet with radius $R = 0.4$ which is obtained by ankt-k_T algorithm. Then first we apply soft drop declustering with $z_{\text{cut}} = 0.1$, $\beta = 0$, $R_0 = R = 0.4$ to the jet. Thus we have two prongs and then it comes to soft drop isolation.

For soft drop isolation, we set $z_{\text{cut}} = 0.1$, $\beta = 2$, $R_0 = R_{12}/2$. Only if we go through all the declustering and we don't find a splitting that passes the cut and at the same time the last particle in the declustering is a photon, we regard it as an isolated photon subjet.

3.2 Some Observables

3.2.1 z_{iso}

The QED splitting function describes the probability distribution of the momentum sharing z between the photon and the quark. We define the isolated photon momentum sharing as

$$z_{\text{iso}} = \frac{p_{T\gamma-\text{sub}}}{p_{T\gamma-\text{sub}} + p_{T\text{had}-\text{sub}}}. \tag{3}$$

Where $p_{T\gamma-\text{sub}}$ is the transverse momentum of the isolated photon subjet and $p_{T\text{had}-\text{sub}}$ is the transverse momentum of the other (hadronic) subjet.

3.2.2 θ

θ denotes the angular distance between two objects in the $\eta - \phi$ plane, where η is the pseudorapidity and ϕ is the azimuthal angle. For the two subjets in soft drop,

$$\Delta R_{12} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}. \tag{4}$$

For the soft drop algorithm, after each declustering step, the angular separation ΔR_{12} between the two subjets is calculated, and this separation is used in the soft drop condition. The condition ensures that the soft radiation and wide-angle radiation within the jet are treated appropriately.

The ΔR_{12} term in the denominator is normalized by the jet radius R to make it dimensionless and is raised to the power of β to control the angular scaling. The soft drop condition ensures that the softer subjet is not too collinear with the harder subjet, effectively removing soft radiation from the jet.

4 Parton Shower Study

We perform a parton shower study in Pythia 8.309 [2] [3] and generate 100 million events from proton-proton collisions. Jet clustering and photon isolation were performed using FastJet 3.4.1 [4].

We firt make a brief introduction to Pythia and FastJet, and then we discuss the result.

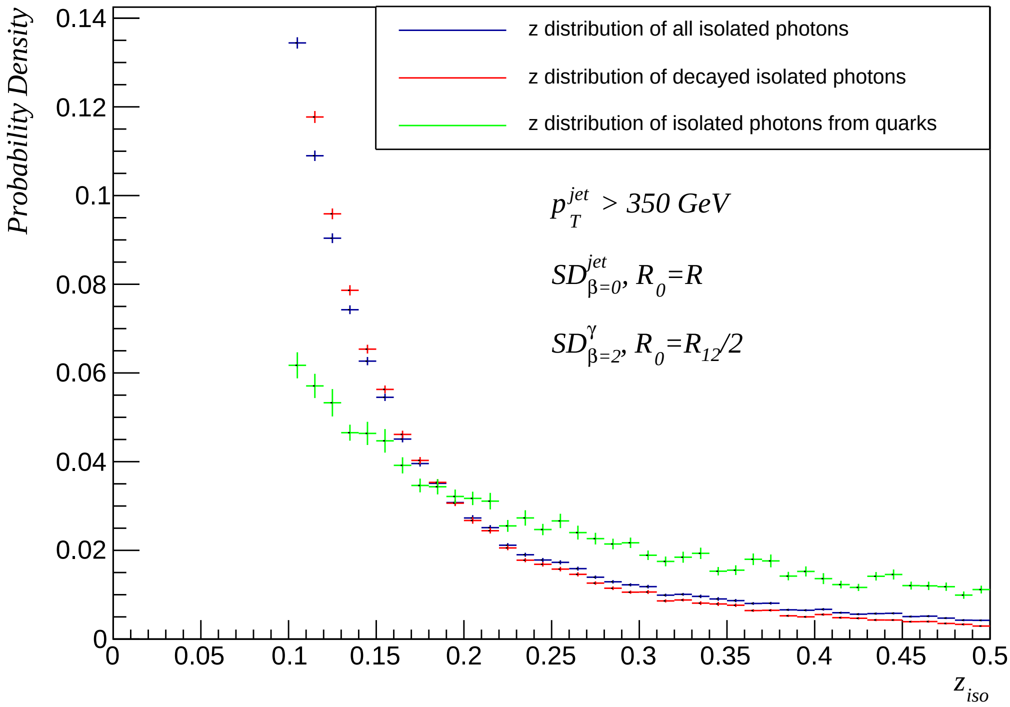


Figure 2: All isolated photons without $\theta_{\rm cut}$

4.1 Pythia

PYTHIA is a program for the generation of high-energy physics collision events, i.e. for the description of collisions at high energies between electrons, protons, photons and heavy nuclei. It contains theory and models for a number of physics aspects, including hard and soft interactions, parton distributions, initial- and final-state parton showers, multiparton interactions, fragmentation and decay. It is largely based on original research, but also borrows many formulae and other knowledge from the literature. As such it is categorized as a general purpose Monte Carlo event generator.

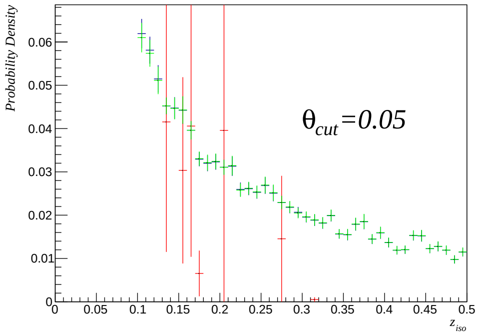
4.2 FastJet

FASTJET is a software package for jet finding in pp and e^+e^- collisions. It includes fast native implementations of many sequential recombination clustering algorithms, plugins for access to a range of cone jet finders and tools for advanced jet manipulation. It provides a fast implementation of several longitudinally invariant sequential recombination jet algorithms, in particular the longitudinally invariant kt jet algorithm, the inclusive longitudinally invariant version of the Cambridge/Aachen jet-algorithm, and the inclusive anti-kt algorithm.

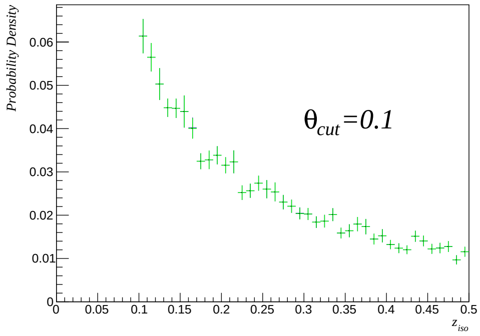
4.3 Result

For event selection, we require $p_{T\rm jet} > 350$ GeV as a defult setting. In Fig. 2, we show the z distribution of all isolated photons ($p_{T\rm jet} > 350$ GeV), which is, including photons from quarks and photons from measons' (η and π_0) decay.

In Fig. 3a, we set a $\theta_{\rm cut}$ to be 0.05, that is, only the splittings whose $\Delta R_{12} >$



(a)



(b)

Figure 3: z distribution with θ_{cut}

θ_{cut} are shown on the plot. Obviously many splittings from decay vanish. And when increase the θ_{cut} to 0.1, there are no splittings from meson decay.

The angular separation ΔR is used to identify and classify particles. A small ΔR indicates particles that are close together, possibly originating from a common parent. A larger ΔR suggests particles that are more widely separated, possibly from distinct origins. In the decay of mesons, which are composite particles formed by a quark and an antiquark bound together by the strong force, the close proximity of daughter particles arises from the fundamental characteristics of the strong force and the behavior of quarks. The strong force, acting over short ranges, binds quarks tightly, and the phenomenon of color confinement ensures that quarks are always found within bound states. When a meson undergoes decay, the quark and antiquark experience interactions dictated by the strong force, leading to daughter particles that are close together, which makes them have a small angular separation.

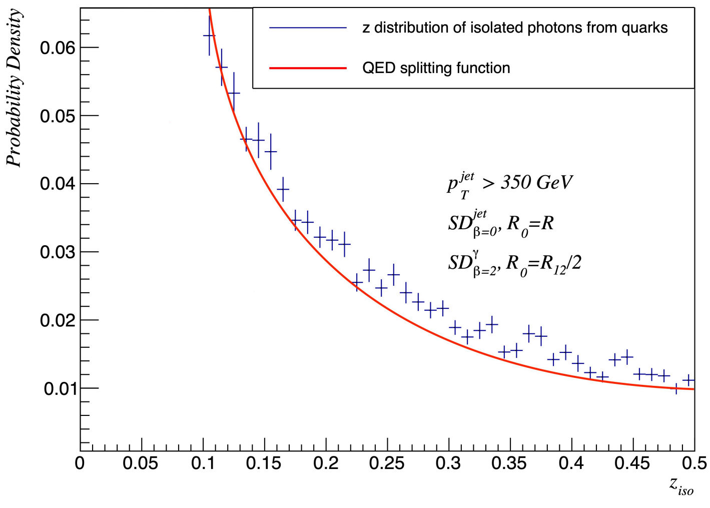


Figure 4: QED splitting function and isolated photons from quarks

Here in Fig. 4, we plot the QED splitting function with z distribution of quark photons. The similarity in shape between the QED splitting function and the z distribution of quark photons in the plot suggests a correlation between the probability distribution of momentum sharing (described by the QED splitting function) and the actual observed momentum distribution (represented by the z values). This correlation indicates that the characteristics of photon emissions in the quark-to-photon process (such as how the momentum is shared between the quark and the emitted photon) are in line with the theoretical expectations set by Quantum Electrodynamics (QED). This congruence is crucial for validating the theoretical framework and enhances our understanding of the underlying physics in high-energy processes involving quarks and photons.

5 Acknowledgments

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