Shining Light on Dark Matter, One Photon at a Time

by

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Abstract

A search is conducted for new physics in final states containing a photon and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV. The data collected by the CMS experiment at the CERN LHC correspond to an integrated luminosity of 35.9 inverse femtobarns. No deviations from the predictions of the standard model are observed. The results are interpreted in the context of dark matter production and limits on new physics parameters are calculated at 95% confidence level. For the two simplified dark matter production models considered, the observed (expected) lower limits on the mediator masses are both 950 (1150) GeV for 1 GeV dark matter mass.

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Title: Professor

Acknowledgments

This is the acknowledgements section. You should replace this with your own acknowledgements.

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Chapter 1

Global Event Reconstruction

In the previous chapter, we discussed the interactions of particles with the individual subdetectors and how these generate electrical signals. Now, we shall discuss the reverse process, namely reconstructing the individual particles or physics objects from the electrical signals recorded by the subdetectors.

Traditionally, each class of physics object was reconstructed using information from a single subdetector: muons from the muon chambers, isolated photons and electrons from the ECAL, jets and missing transverse energy from the HCAL, and secondary vertices from τ lepton and b quark decays from the tracker. However, as depicted in Figure 1-1, each type of particle interacts with multiple different subdetectors and this information is lost unless the information from all the subdetectors is combined into a single global event description.

The particle flow (PF) algorithm leverages the fine angular granularity of the calorimeters and the excellent momentum resolution of the inner tracker and muon chambers to greatly improve the reconstruction of physics objects and include soft particles that would otherwise be ignored. This is especially advantageous for jet energy measurements as roughly 62% of the jet energy is carried by charged hadrons, approximately 27% by photons, around 10% by neutral hadrons, and about 1.5% by neutrinos.

The distinguishing feature of the PF algorithm is to combine multiple detector signals together into a single PF candidate. The input detector signals are the tracks,

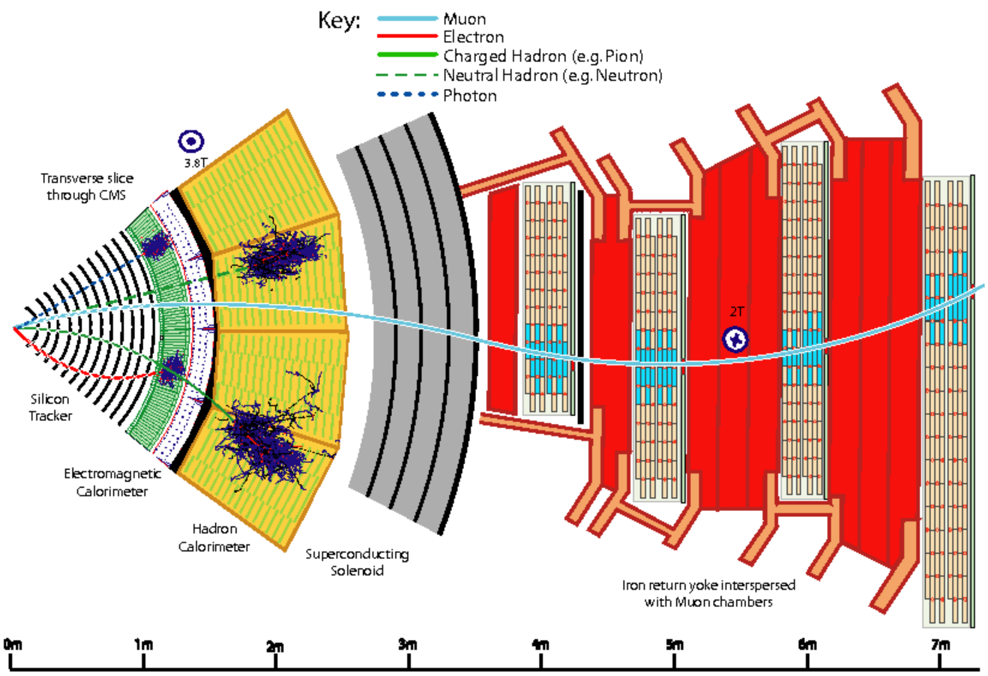

Figure 1-1: A sketch of a transverse slice of the CMS detector showing particle interactions from the interaction point to the muon detector. Reprinted from Reference [].

vertices, calorimeter clusters, and muon segments described in Section 1.1. Based on their proximity in the η-ϕ, these PF elements are combined into muons, electrons, and hadrons. Muon segments are combined with inner tracks to produce muons, inner tracks are combined with calorimeter clusters to produce electrons and charge hadrons, and calorimeter clusters are correlated to produce photons and neutral hadrons.

The PF algorithm reconstructs particles in the blocks described in Section 1.2 and after each block any PF elements associated to a PF candidate are not considered by the following blocks. For example, clusters associated with photons will not be used when reconstructing neutral hadrons. After all PF candidates are identified, they can be combined into event-wide variables such as jets and the missing transverse energy as described in Section 1.3.

1.1 Particle Flow Elements

1.1.1 Tracks

The Combinatorial Track Finder software is used to reconstruct tracks in an iterative inside-out process. Initial interations search for tracks that are easy to find, e.g. those with high p_{T}, and hits associated with these tracks are removed for later iterations, reducing the combinatorial complexity and simplifying the search for more difficult tracks, e.g. greatly displaced ones.

The first step is to form seeds based on pixel hits, double strip hits containing 3D information, and an estimate of the beam spot. Earlier iterations require three pixel hits while later iterations gradually loosen the requirements. The final iterations specifically target increased muon tracking efficiency by including information from the muon chambers.

Next, a Kalman filter is used to find additional hits consistant with the evolution of the track seeds through the rest of the tracker, accounting for the magnetic field, energy loss due to ionization, and multiple scattering. The five parameters used for the helical trajectory evolution are the curvature ρ, the azimuthal angle ϕ_0, the transverse impact parameter d_0 , the longitudinal impact parameter z_0 , and $\lambda = \cot\theta$, where θ is the polar angle.

After propagating the track through all layers of the detector and finding all associated hits, a Kalman fitter and smoother is used to refit the overall trajectory while a fourth-order Runge-Kutta method is used to extrapolate the trajectory between successive hits. To reduce the fraction of fake tracks, various quality requirements concerning the number of missing hits, the reduced χ^2 of the fit, and compatibility with a primary vertex are applied before proceeding to the next iteration.

Track reconstruction for electrons is more complicated as the Kalman filter is not a good description because of the high rate of non-Gaussian energy loss due to brehmsstrahlung these tracks experience within the tracker. To improve the electron reconstruction efficiency, the electron seed collection is filled both by looking outside-in for ECAL superclusters (see Section 1.1.4) consistant with track seeds and inside-out track seeds consistent with superclusters. A Gaussian Sum Filter (GSF) defined to approximate the Bethe-Heitler energy-loss distribution is used to fit the trajectory of electron tracks.

1.1.2 Primary Vertexing

A deterministic annealing (DA) algorithm is used to associate tracks to primary vertices. Tracks must pass additional requirements on the transverse impact parameter d_0, the number of strip and pixel hits, and the reduced χ of the trajectory fit to be considered when finding primary vertices. The most probable vertex positions at an artifical temperature T are determined by the minimization of the "free energy"

$$F = -T \sum_{i}^{N_T} \ln \sum_{j}^{N_V} p_{ij} \rho_j \exp \left[-\frac{1}{T} \left(\frac{z_i^T - z_j^V}{\sigma_i^z} \right)^2 \right] \tag{1.1}$$

where the z_j^V are the vertex positions with weights ρ_j, the z_i^T and σ_i^z are the longitudinal impact parameters and the corresponding uncertainties of the tracks, and the p_{ij} are the probabilities of assigning the track i of N_T to the vertex j of N_V.

The DA algorithm starts with a single vertex at a very high temperature that is gradually decreased. The free energy F is minimized with respects to z_j^K at each new temperature and a vertex is split in two whenever T falls below its criticial temperature

$$T_C^j = 2 \sum_i \frac{p_i p_{ij}}{(\sigma_i^z)^2} \left(\frac{z_i^T - z_j^V}{\sigma_i^z} \right)^2 \Big/ \sum_i \frac{p_i p_{ij}}{(\sigma_i^z)^2}. \tag{1.2}$$

The annealing procedure with vertex splitting continues down to $T = 4$ and the final assignment of tracks to vertices is performed at $T = 1$ without any further splitting. The vertex designated as *the* primary vertex of the hard scattering is the one which maximizes

$$\sum_i (p_{\mathrm{T}}^i)^2 + (p_{\mathrm{T}}^{\mathrm{miss}})^2, \tag{1.3}$$

where p_{T}^i is the transverse momentum of a track assigned to the vertex and $p_{\mathrm{T}}^{\mathrm{miss}}$ is the magnitude of the momentum imbalance in the transverse plane for the vertex.

1.1.3 Secondary Vertexing

1.1.4 Calorimeter Clusters

1.2 Particle Identification

1.2.1 Muons

1.2.2 Electrons and Isolated Photons

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