A Momentum Correction Factor to Recalculate LHCb Data

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Introduction

The Large Hadron Collider (LHC) of the research organization CERN (Geneva, Switzerland) is the largest and most powerful particle accelerator in the world. The LHC uses accelerators to get protons circulating at nearly the speed of light in the 27-km loop and then aim them to crash into each other at four places in the loop. Detectors are placed around these collision points to track the resulting shower of particles. We measure information about a particle (such as momentum and type) by combining measurements from the detector parts. Using the principles of conservation of energy and momentum we can use information from the shower of particles to indirectly probe what happened at the collision.

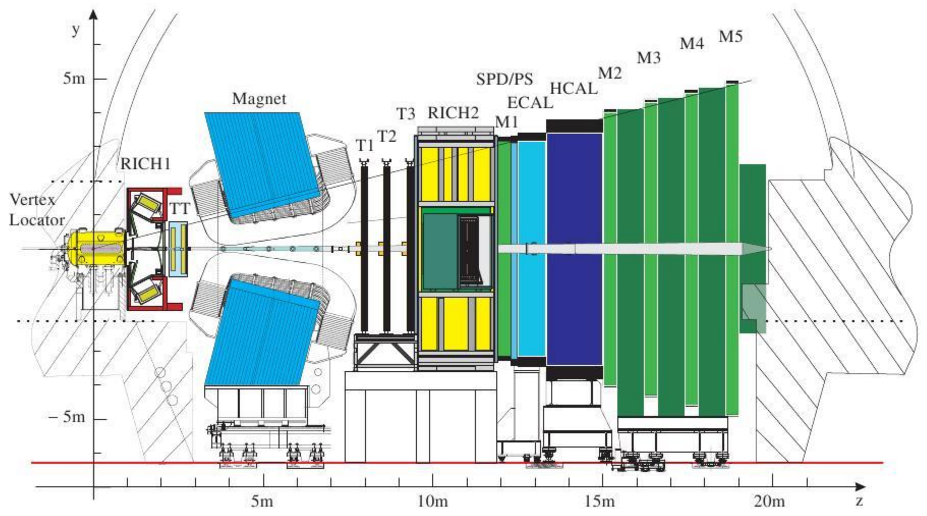


Fig. 1: Diagram of the LHCb detector with axes to show scale. Each separate part of the detector has been labeled .

Purpose

Regardless of the momentum, location, trajectory, and charge a particle will always have the same invariant mass (sometimes called a "rest" mass). However, recent data recorded by the LHCb detector have shown inconsistent particle masses. The measured masses are inconsistent between positive/negative charges, location in the detector, and momentum of the particle. The average mass is also very different from the world average. This bias affects nearly all of the analyses in the LHCb collaboration and is a critical issue to resolve. Our goal is to parameterize and develop a correction to this bias in order to recalibrate the data.

Theory

The famous $E = mc^2$ equation applies only when the particle is at rest. When the particle is moving, the relation becomes the Einstein mass-energy equivalence formula:

Eq. 1 $$E = \sqrt{(mc^2)^2 + (pc)^2}$$

where E is the total energy of a particle (MeV), m is invariant mass (MeV/c^2), and p is the momentum (MeV/c). This describes the amount of total energy a particle has, both invariant mass and kinetic energy.

When a particle decays into daughter particles, we can add the momenta of the daughters to obtain the mother's momenta (and therefore the mass).

We combine these two ideas and rearrange equations to break down the mass calculation so that the mass of the mother M can be calculated from the mass m, momentum p, and angle θ between trajectories of each daughter:

Eq. 2 $$M^2 = \Sigma(m_i^2) + \Sigma(m_i^2\left(\frac{p_j}{p_i}\right) + m_j^2\left(\frac{p_i}{p_j}\right) + p_i p_j \theta_{ij}^2)$$

Assuming that the detector is incorrectly measuring the momentum of the particles, we add a correction factor to the momentum of the form $p_i' = p_i(1 + \epsilon + \alpha p_{xz})$, where ϵ is a correction to the overall momentum, and α is a correction proportional to the bending of the particle's path by the magnets. We insert this corrected momentum value p_i' into Eq. 2 and find the difference between world data and LHCb data as shown in Eq. 3.

Eq. 3 $$M'^2 - M^2 \approx \Sigma_{i<j}((m_i^2\left(\frac{p_j}{p_i}\right) - m_j^2\left(\frac{p_i}{p_j}\right))(\delta_j - \delta_i) + p_i p_j(\delta_i + \delta_j)\theta_{ij}^2)$$

This difference of masses from LHCb and world data can be used to determine the correction coefficient for p_i'.

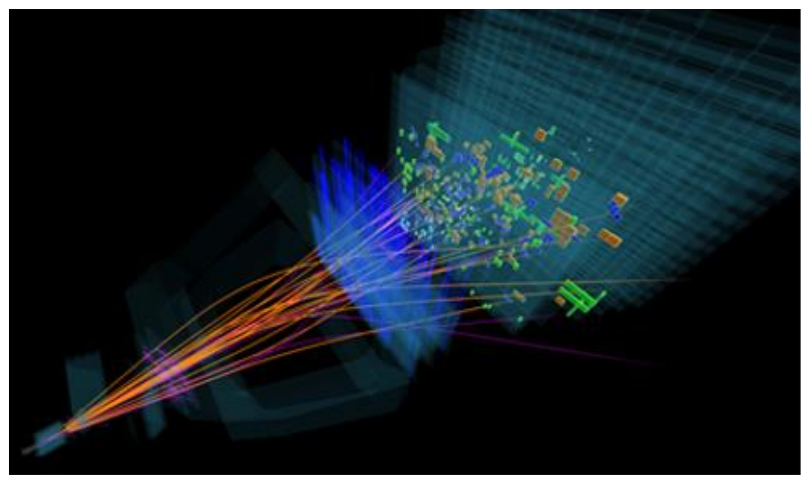
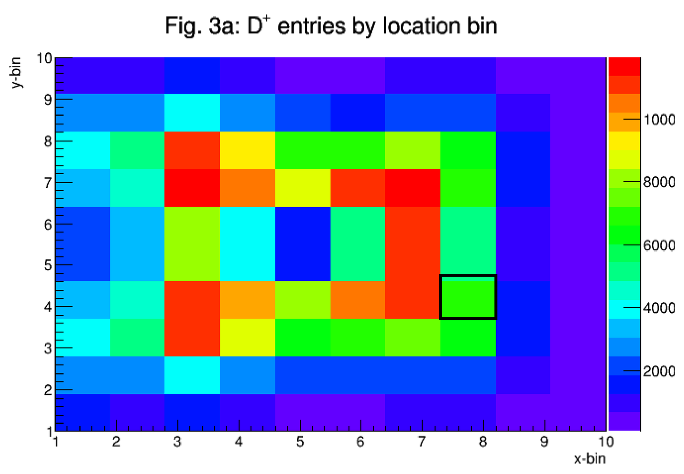


Fig. 2: Image of an LCHb track reconstruction. This includes the calculated paths of daughters in red, some detector parts in blue and teal, and collision sites with the detector in green

Method

We began our analysis by studying the decay mode $D^+ \rightarrow K^-\pi^+\pi^+$. The parent and daughter particles of this decay mode are well-studied and have precisely measured masses from world data. We applied our decay mode to Eq. 3 to do our calculations.

To account for a possible bias in terms of where the particle physically hits the detector, we divided one of the planes in the LHCb detector into a ten by ten grid of bins shown in Fig. 3a. The x and y axes represent the location of the particle in the particular cross-section of the detector and the color on the z axis represents how many entries a bin has received.



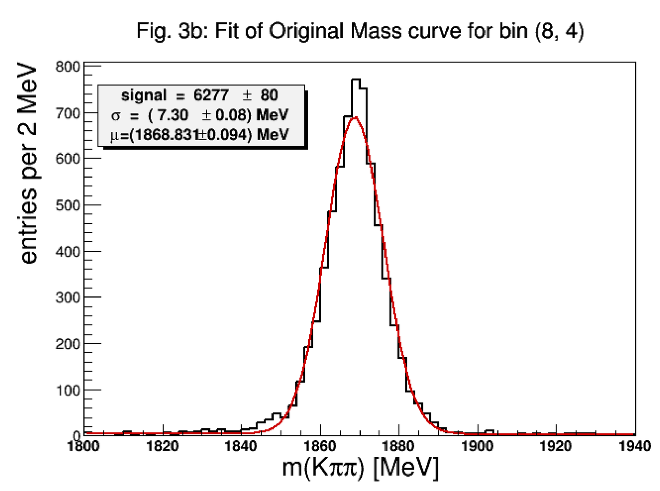


Fig. 3a: A ten-by-ten grid of bins by location with the number of entries in color on the z-axis. Bin (8,4) is boxed.
Fig 3b: The mass histogram of D⁺ candidates before correction for bin (8,4) with a fit curve in red.

I have chosen to use bin (8, 4) as the representative example of other bins on the grid.

To identify trends or patterns we can look at the fitted mass across columns or rows of the grid. Fig. 4 shows the fitted mass for D⁺ and D⁻ candidates before our correction in the column x = 4. There is a dramatic disagreement with the world average as we approach the edges of the detector.

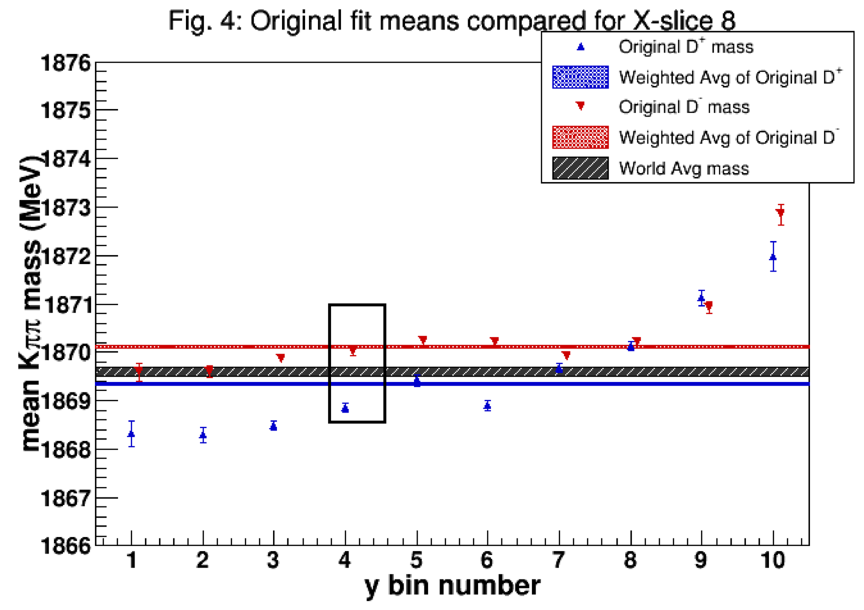
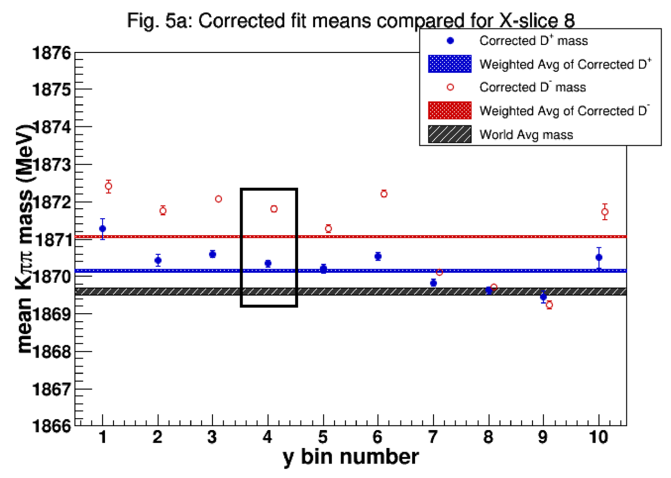


Fig 4: The uncorrected mass for D⁺ (blue) and D⁻ (red) candidates for each bin in column x = 4 of Fig 3a. The average of each data set is shown with ± 1σ uncertainty as the corresponding colored rectangles. The world average D⁺ mass with ± 1σ uncertainty is shown as the black shaded rectangle.

Results & Discussion

Using the bins of mass data and Eq. 3, we determined the correction coefficients ϵ and α. A properly functioning correction should shift the $D^\pm$ data sets in Fig. 4 to be closer together, flatter, and agree with the precisely measured world mass average.



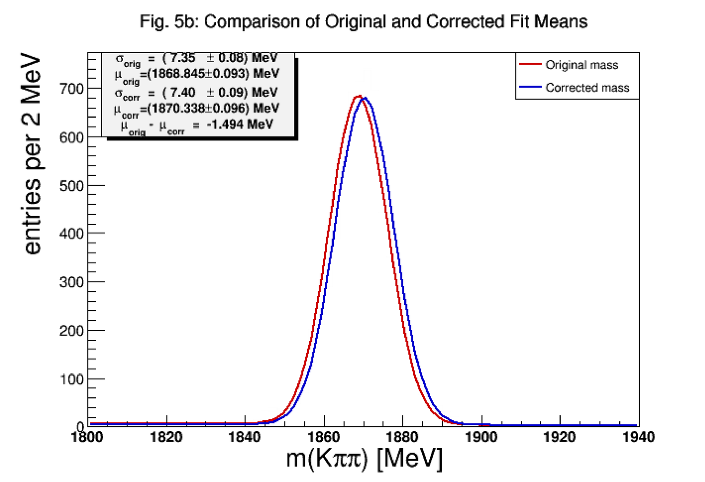


Fig 5a: The corrected mass for D⁺ (blue) and D⁻ (red) candidates for each bin in column x = 4 of Fig 3a. The average of each data set is shown with ± 1σ uncertainty as the corresponding colored rectangles. The world average D+ mass with ± 1σ uncertainty is shown as the black shaded rectangle.
Fig 5b: Comparison of the fit to D⁺ candidates in bin (8,4) before (red) and after (blue) correction.

Comparing Fig 4 and Fig 5a shows that the correction has improved the agreement near the edge and brought average D- mass closer to the world average. However, the correction shifted a number of bins away from the world average. The average D+ mass disagrees more strongly after applying the correction. Fig. 5b shows bin (8,4) was shifted by 1.5 MeV which moved it further from the world average.

We can conclude from our work that this process is not sufficient for correcting mass data from the LHCb. The next iteration of the correction procedure will need to reduce the approximations and include additional degrees of freedom. For example, we should use different correction coefficients for kaons and pions.

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