Progress report on secondary vertex reconstruction from CMS using ZEUS tlite library

summer student project

by Laura van der Schaaf, University of Amsterdam
supervised by Achim Geiser and Andrii Gizhko

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1 Introduction to the project

The ZEUS detector at HERA measured deep inelastic scattering (DIS) of an electron and a proton from 1992 until 2007. The data allowed a precise test of QCD and measurement of the proton structure function F_2 [1][2]. The obtained results required a rigorous (secondary) vertex reconstruction [4]. Like ZEUS, the Compact Muon Solenoid detector (CMS) at the large hadron collider (LHC) relies on a well-working tracking system [6]. Therefore it makes sense to use the ZEUS analysis code on the low energy CMS data to get better statistics for low energy B mesons.

The goal of my summer student project is to adapt the ZEUS vertex reconstruction code such that it can reconstruct from CMS. The problem splits naturally into two subproblems. The first is the different track parametrizations used by the ZEUS and CMS collaborations. A simple basis change as presented in section 3 allows the use of ZEUS code for the CMS data without a lot of modifications. The second part concerns the used tracks to reconstruct the vertices. The original ZEUS vertex finding code uses jet tracks as input; however, there are some major differences between CMS and ZEUS jets. As a result it is not possible to use the CMS jets for the vertex finding code as elaborated in subseciton 2.3. During my project I investigated whether high transverse momentum tracks can be used as jet axes to choose input tracks for the code. The reconstruction methods are outlined in 4. Unfortunately, there are no results, yet.

2 Introduction to the ZEUS and CMS detectors

The event reconstruction depends on the characteristics of the detector as well as the source. This section gives a brief overview of the main parts of the ZEUS and CMS detectors focusing on the tracking part, and compares the two. The comparison of the two environments motivates the use of high transverse momentum tracks as input for the vertex reconstruction algorythm, outlined in subsection 2.3

2.1 ZEUS detector

The ZEUS detector was situated at HERA (Hadron-Elektorn-Ring-Anlage), an ep-collider with a design center of mass energy of $\sqrt(s) = 134$ GeV. It's main aim was the understanding of the constiutuents of the proton, and their interactions through DIS [3]. The data allowed a precise test of QCD and the most precise measurement of the proton structure function F_2 so far [1][2].

In the following, some detector components are described (compare fig.1). As this project focuses on the vertex reconstruction the working principle of the inner tracking detectors is emphasized.

The inner tracking system consists of the vertex detector (VXD), the central drift chamber (CTD), the forward and rear tracking detectors (FDET and RTD) and the micro vertex detector (MVD, replacing the VXD in a detector upgrade in 2001 and therefore not indicated in fig.1) [5][3].

- **VTX**: cylindrical drift chamber used to measure the event vertex and possible secondary vertices.
- **MVD**: silicon strip detector used to measure primary and possible secondary vertices.
- **CTD**: central drift chamber used for particle identification; the momentum and energy loss of charged particles is measured with high precision.
- **FDET** and **RTD**: forward and rear tracking detector. The drift cells cover the very forward and backward region.

Fig. 1 also shows the calorimeters: the high resolution uranium calorimeter (CAL), a backing calorimeter (BAC) and the hadron electron separator (HES). The muons are detected in the rear (RMUON), barrel (BMUON) and forward (FMUON) muon detectors. The VETO wall signals particles that enter the detector from the rear side and the C5 counter measures beam arrival times, it is situated at the proton entrance to the detector. An interesting side remark is that the radioactivity of the CAL allowed to calibrate the calorimeter without inserting a source. For more information see [3].

2.2 CMS detector

The Compact Muon Solenoid detector (CMS) is situated at the Large Hadron Collider (LHC) at CERN. LHC is a pp-collider constructed for a center of mass energy of 14TeV (so far data has been taken up to 7TeV). The CMS

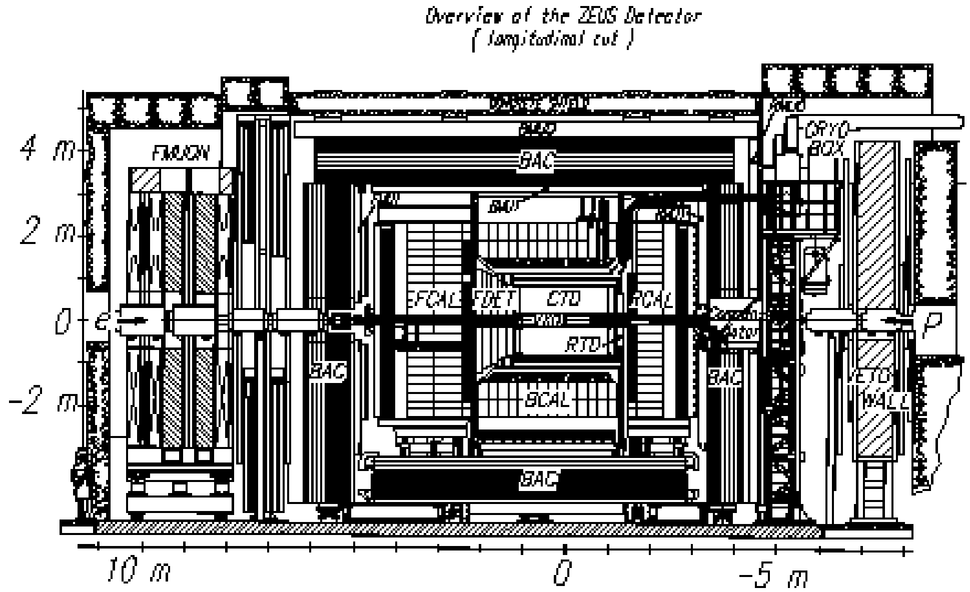

Figure 1: Schematic of the ZEUS detector along the beamline, figure taken from [5]. The MVD is not indicated, it replaced the VXD during a detector upgrade in 2001.

detector is designed to investigate the new energy regime with a focus on the electroweak symmetry breaking mechanism [6]. The last missing particle in the standard model, the Higgs boson, was found in July 2012 by the CMS and ATLAS (A Toraoidal LHC Apparatus) collaborations [8][9].

In the following the inner tracking detector of the CMS detector is described. The other components of the CMS detector can be seen in fig.2 and further information can be found in [6][7]. In case of the CMS detector, the inner tracking system consists of silicon pixel and strip detectors. It consists of the following subdetectors, see fig.3:

- **PIXEL**: tracking system closest to the interaction point. The precision of the track reconstruction in the pixel detectors gives the precision of the reconstructed secondary vertices. The pixel tracking system consists of three hybrid pixel detector layers around the beamline and two discs of pixel modules on each side.
- **TIB** and **TID**: the tracking inner barrel and disks are silicon micro strip detectors, the TIB detector has stripes parallel to the beamline and the TID in radial direction

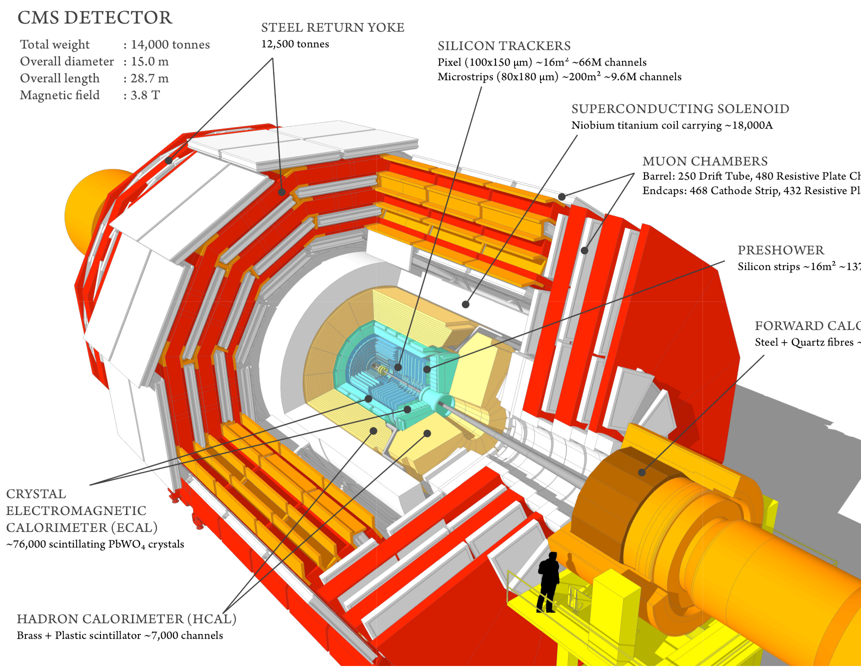

Figure 2: Schematic of the CMS detector, figure taken from [7].

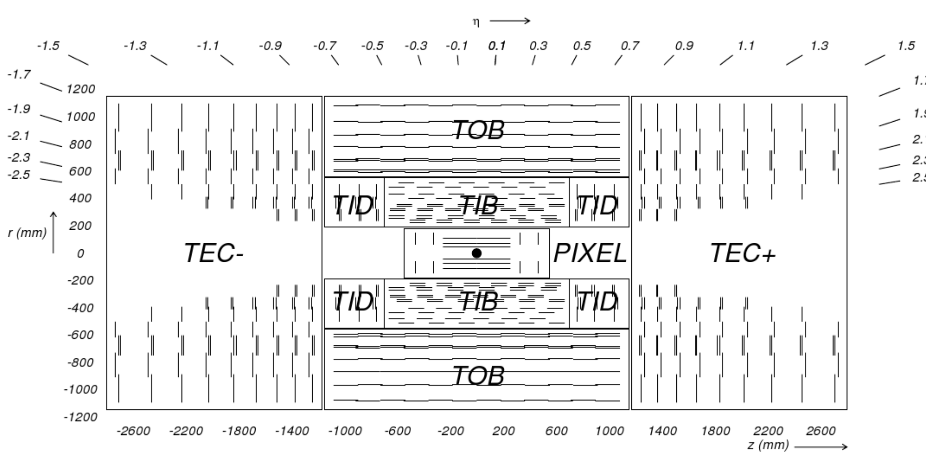

Figure 3: Schematic of the CMS tracker, figure taken from [6].

- **TOB**: the tracker outer barrel consists of six silicon micro strip detectors with the stripes along the beam axis.
- **TEC-** and **TEC+**: the tracker end cap detectors consists of nine discs with 7 silicon strips respectively aligned in the radial direction.

2.3 Comparison of the two detectors and the implications for the vertex finding algorythm input

The initial particles in case of CMS are two protons; ZEUS, on the other hand, observes collisions with only one proton in the initial state. As a result more jets can be observed in a typical CMS event than in a typical ZEUS event. Furthermore, CMS runs at higher energies, therefore an average CMS jet is of higher energy, too. The energy cut used for CMS jets lies above the typical jet energies of ZEUS events (for ZEUS the cut is at 500MeV, for CMS some typical cuts are reported in [10]) and the lower energy CMS jets cannot be reconstructed with calorimeter data due to overlap [10]. To use both data sets in the same energy region, jets need to be reconstructed from tracking information alone. Using high transverse momentum tracks with enough space between the respective tracks seems to be a good first guess for replacing the jet axes in the reconstruction code. How I intended to check this is discussed in section 4. Unfortunately, there are no trustworthy results, yet.

3 Track parametrization in ZEUS and CMS

The two collaborations ZEUS and CMS decided upon two different track parametrizations. In order to use the ZEUS code on CMS data the tracks and the covariance matrix have to be reparametrized. In this section the two parametrizations and the reparametrization are described.

3.1 The two parametrizations

In fig.4 the used helix parameters are drawn. On the left hand the ZEUS parameters are represented, $\overrightarrow{a} = (\phi_0, Q/R, QD_0, z_0, \mathrm{cotan}\Theta_0)$:

- ϕ_0: angle between the x-direction and the helix momentum in point $\overrightarrow{D_0}$

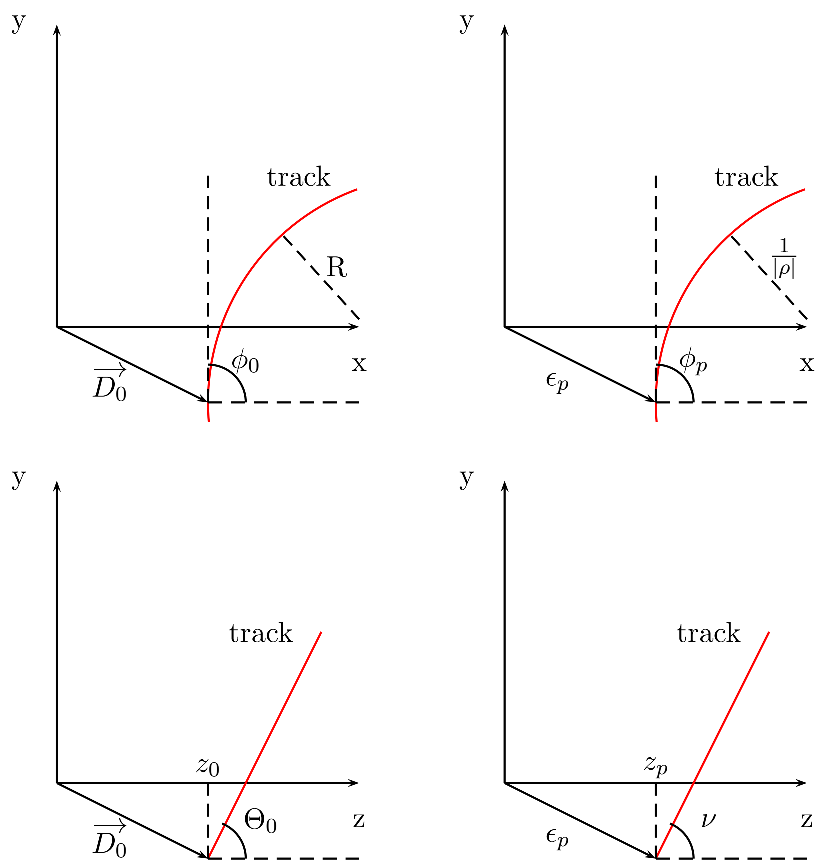

Figure 4: On the left side the ZEUS parametrization is shown and on the right side the respective CMS parametrization. The upper panels show the xy- and the lower panels the yz-plane.

- Q/R: charge of the track divided by the radius of the helix in the xy-plane
- QD_0: charge of the track multiplied by the projection on the xy-plane of the closest distance between the reference point and the track
- z_0: z-coordinate of the closest distance between the reference point and the track
- cotanΘ_0: polar angle of the track

On the right hand side of fig.4 the respective CMS parameters are indicated, $\overrightarrow{a} = (\epsilon_p, z_p, \nu, \phi_p, \rho)$:

- ϵ_p: projection on the xy-plane of the closest distance between the reference point and the track, the signature is positive if the reference point is on the left
- ν: polar angle of the track
- ϕ_p: angle between the x-direction and the helix momentum in point ϵ_p
- ρ: signed curvature of the track

3.2 How to get from CMS to ZEUS parameters

The change of helix parameters:

- $\phi_0 = \phi_p$
- $Q/R = \rho$
- $QD_0 = \frac{\rho}{|\rho|}\epsilon_p$
- $z_0 = z_p$
- cotanΘ_0 = cotan(ν)

The covariance matrix can be adapted with the formula for tensor transformation (in our case x represents the ZEUS parameters and y the CMS parameters, T is the covariance matrix in the respective basis):

$$T^{\mu\nu}(x) = \frac{\partial x^\mu}{\partial y^\sigma}\frac{\partial x^\nu}{\partial y^\rho}T^{\sigma\rho}(y) \tag{1}$$

In eqn.1 the Einstein summation convention is used. Plugging in the change of parameters, the following covariance matrix can be obtained. The matrix is written in the ZEUS basis with CMS parameters and σ_{ij} represents the ij-component of the CMS covariance matrix.

$$\begin{pmatrix} \sigma_{33} & \sigma_{34} & \frac{\rho}{|\rho|}\sigma_{03} & \sigma_{13} & \frac{2}{\cos 2\nu - 1}\sigma_{23} \\ \sigma_{34} & \sigma_{44} & \frac{\rho}{|\rho|}\sigma_{04} & \sigma_{14} & \frac{2}{\cos 2\nu - 1}\sigma_{24} \\ \frac{\rho}{|\rho|}\sigma_{03} & \frac{\rho}{|\rho|}\sigma_{04} & \sigma_{00} & \sigma_{01} & \frac{2}{\cos 2\nu - 1}\sigma_{02} \\ \sigma_{13} & \sigma_{14} & \sigma_{01} & \sigma_{11} & \frac{2}{\cos 2\nu - 1}\sigma_{12} \\ \frac{2}{\cos 2\nu - 1}\sigma_{23} & \frac{2}{\cos 2\nu - 1}\sigma_{24} & \frac{2}{\cos 2\nu - 1}\sigma_{02} & \frac{2}{\cos 2\nu - 1}\sigma_{12} & (\frac{2}{\cos 2\nu - 1})^2\sigma_{22} \end{pmatrix}$$

4 Vertex reconstruction

After the reconstruction of the tracks, primary and secondary vertices can be reconstructed. The true vertices indicate the location of particle interactions and thus give information on the lifetime of particles. The number of tracks that emerge from a vertice and the momentum (including direction) of the produced particles allow the reconstruction of the momentum end energy of the mother particle. Vertices are thus a very useful tool to understand particle interactions [3][4].

For the ZEUS reconstruction of secondary and primary vertices, the deterministic annealing filter (DAF) is used [4]. The first step is to choose tracks which are used for the vertex fit. For the ZEUS analysis the jet axes are used as reference axes. Tracks are associated to the closest jet, the group of tracks associated with one jet is then used as input for the vertex fit. Two cuts are introduced:

- The first cut takes care of the geometrical distance between the tracks:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1 \tag{2}$$

  where $\eta = -\ln \tan\frac{\Theta}{2}$ is the pseudo rapidity and $\Delta\eta = \eta^{\text{track}} - \eta^{\text{jet}}$ respectively $\Delta\phi = \phi^{\text{track}} - \phi^{\text{jet}}$

- The second cut takes care of the transverse energy content of the jet:

$$p_T^{\text{track}} > 500\text{MeV} \tag{3}$$

For more information on the (secondary) vertex fit I refer to [4].

During my summer student project I added the possibility to use high transverse momentum tracks as the reference axes, instead of the jet axes. For every event, up to 10 reference tracks are chosen with the only constriction that the high p_T axes should not be too close, i.e. eqn.2 should not be valid for two reference axes. If 2 is valid for two high p_T tracks the track with higher transverse momentum is used as reference axes. If there are not enough high p_T tracks with sufficient distance to each other, less than 10 tracks are used as reference axes. There is no equivalent cut to eqn.3 implemented so far.

In the following, the parameters that were chosen to compare the results with the two different vertex reconstruction inputs are discussed. The chosen parameters give either information on the fit quality or were studied in detail in earlier reconstructions, thus allowing for comparison with earlier results. Due to a bug the actual comparison could not be done so far.

- **Vertex location**: The secondary vertices are expected around the beam axes, a bulk of vertices far off the beamline indicates bad fitting. The vertex location can be used as a cut parameter to improve the fit quality.
- **Chi squared**: the chi squared distribution gives information on the precision of the fit. Assuming that the error on the tracks is normally distributed, a chi squared of about one is expected.
- **Projected decay length**: The decay length of a particle is an indicator for it's state. The decay length is computed in the following manner: the decay length was calculated as the difference between the beam spot and the secondary vertex in the xy-plane, $\overrightarrow{L}$. The projected decay length, L_{XY}, gives information about the mass of the mother particle and is determined by taking the scalar product of the decay length and the jet axis, $\overrightarrow{j}$, as a formula:

$$L_{XY} = \overrightarrow{L} \cdot \frac{\overrightarrow{j}}{|\overrightarrow{j}|} \tag{4}$$

  Heavier particles (as for example charmed or B-mesons) result in an asymetric decay length distribution, prefering positive signs, whereas ligther quarks result in an almost symmetric distribution around $L_{XY} = 0$ [4]. The decay length significance is defined as the fraction of the projected decay length and it's error. This quantity allows an event to be better distinguished between heavy and light mesons [4].

- **Number of vertices per event**: A comparison of the number of vertices found per event by the algorithms for the different inputs indicates if there are a lot of non-fitted vertices or if there are vertices fitted that do not exist.
- **Number of tracks per vertex**: Can be used for consistency checks, the number of vertices per event and the number of tracks per vertex should give the number of tracks per event, a known number.

5 Conclusion

The code to use high transverse momentum tracks instead of jets for secondary vertex reconstruction is implemented and is technically working. Whether the code can be used for secondary vertex reconstruction for CMS data is not clear, yet. In a next step the results for the reconstruction with high p_T tracks and jets have to be compared to each other for ZEUS MC data. It is however clear, that the general idea of using CMS data for ZEUS code can be implemented.

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References

[1] J.Turnau, *Precision QCD measurements at HERA*, (2013)

[2] P.Belov, *Proton structure and PDFs from HERA*, (2013)

[3] S.Bentvelsen, *Measurement of the proton structure function at HERA using the ZEUS detector*, PhD thesis (1994)

[4] S.Roloff, *Measurement of CHarm and Beauty Production in Deep Inelastic Scattering at HERA*, PhD thesis (2011)

[5] *http://www.nikhef.nl/pub/departments/mt/projects/zeus/vertex/website.html* (22-8-2013)

[6] CMS collaboration, JINST3 S08004 (2008)

[7] *http://cms.web.cern.ch/news/cms-detector-design* (23-8-2013)

http://cms.web.cern.ch/news/tracker-detector (23-8-2013)

http://cms.web.cern.ch/news/silicon-pixels (23-8-2013)

http://cms.web.cern.ch/news/silicon-strips (23-8-2013)

[8] CMS collaboration, *Observation of a new boson at a mass of 125GeV with the CMS experiment at the LHC*, (17-9-2012)

[9] ATLAS collaboration, *Observation of a new particle in the search of the Standard Model Higgs boson with the ATLAS detector at the LHC*, (July 2012)

[10] CMS collaboration, *Determination of jet energy calibration and transverse momentum resolution in CMS*, (2011)