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2008 J. Phys.: Conf. Ser. 119 032013

(http://iopscience.iop.org/1742-6596/119/3/032013)

The global χ^2 track fitter in ATLAS

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Abstract. While many high energy experiments use track fitting software that is based solely on the Kalman Filter technique, the ATLAS offline reconstruction also has several global track fitters available. One of these is the `GlobalChi2Fitter`, which is based on the scattering angle formulation of the track fit. One of the advantages of this method over the Kalman fit is that it can provide the scattering angles and related quantities (e.g. the residual derivatives) to the alignment algorithms. The algorithm has been implemented in the new common tracking framework in ATLAS, the philosophy of which is to improve the modularity and flexibility of the tracking software. This flexibility has proven crucial for the understanding of the data from the testbeam and cosmic runs. An overview of recent results will be presented, in particular the results from the combined tracking with the inner detector and the muon spectrometer using the cosmics data.

1. Introduction

During the past few years, a new framework for the ATLAS track reconstruction software has been developed, called 'New Tracking' [1]. The aim of this framework is to make the reconstruction software more flexible and maintainable, by delegating each reconstruction step to a dedicated software module. For each reconstruction step, the user can select and switch between different modules at runtime since they all have to implement the same abstract interface that is associated with that step. The modules communicate through a common Event Data Model (EDM) [2, 3], which, like many of the modules themselves, is designed to be applicable both in the Inner Detector and in the Muon Spectrometer. This article will cover the `GlobalChi2Fitter` software module, which implements the `Trk::ITrackFitter` interface for track fitters. The algorithm is based on the scattering angle formulation of the track fit[1] [4], which has a number of advantages:

- It only needs an initial estimate of the track parameters, not of their errors. The initialization of the covariance matrix is a delicate point in the Kalman fit.
- It can (optionally) solve the left/right ambiguities in drift circle hits.

[1] Previous implementations of a global track fitter with a scattering angle formulation in ATLAS are for example described in Ref. [5].

Journal of Physics: Conference Series **119** (2008) 032013 doi:10.1088/1742-6596/119/3/032013

- The global χ^2 fit yields the scattering angles on the track, which can e.g. be used in alignment procedures.

On the other hand, the global track fit typically needs to invert much larger matrices than the Kalman fit, which makes it desirable to limit the number of track parameters.

In the spirit of the common tracking framework, the `GlobalChi2Fitter` package delegates a number of subtasks to other modules that are also part of the framework. For example, the propagation from one measurement to another is performed using a `Propagator` tool, which also provides the derivatives that are required in the fit. Material effects are taken into account by using the `DynamicLayerCreator`, the `MultipleScatteringUpdator` and `EnergylossUpdator` tools. The `DynamicLayerCreator` delivers the material layers that are traversed by a given track, while the other two tools give an estimate of the material effects in a given layer. The `DynamicLayerCreator` gets the material information from a common source, called Tracking Geometry [6].

2. Implementation

General least squares fitting theory in track fitting is discussed in several texts (e.g. [7]). In the case of the global track fit, the χ^2 function to be minimized is:

$$\chi^2 = \sum_{meas} \frac{r_{meas}^2}{\sigma_{meas}^2} + \sum_{scat} \left(\frac{\theta_{scat}^2}{\sigma_{scat}^2} + \frac{(\sin\theta_{loc})^2 \phi_{scat}^2}{\sigma_{scat}^2} \right) + \sum_{Eloss} \frac{(\Delta E - \overline{\Delta E})^2}{\sigma_{Eloss}^2}. \quad (1)$$

Where r_{meas} is a residual, i.e. the difference between a measurement and the track prediction, θ_{scat} and ϕ_{scat} are the scattering angles at a scattering layer (i.e. the difference in angle between the incoming and outgoing track), and ΔE is the fitted energy loss at a material layer. The expected energy loss $\overline{\Delta E}$ can be obtained from the material description (parametrized energy loss), or, in the case of a muon traversing the calorimeter, it can be the energy loss as measured by the calorimeter[8]. The latter can improve the momentum resolution for high energy muons ($p > 100$ GeV) that often suffer from catastrophic energy losses that are not well predicted by the parametrized energy loss.

The fit parameters in this model are: the track parameters at the vertex (impact parameter, direction and momentum), the scattering angles (two for each scattering plane), and the energy losses. The energy loss in a material layer only needs to be fitted if the energy loss fluctuations cannot be ignored. Such is the case for muons that traverse the calorimeter. On the other hand, the material layers in the Inner Detector are so thin that it is sufficient to just lower the momentum by the expected amount in the algorithm. The number of fit parameters can be very large: the `DynamicLayerCreator` delivers around 15 material layers for an Inner Detector track, leading to a total of about 35 fit parameters. Fortunately, fast matrix inversion algorithms exist such that the execution speed of the track fit is still competitive. The matrix inversion is performed using the Bunch-Kaufman method, implemented in the `CLHEP` framework. In practice, the algorithm requires about twice as much CPU time as the Kalman Fitter.

The residuals r_{meas} are obtained by propagating the track through the magnetic field to a measurement, and then calculating the distance between the measurement and the track. The propagation is performed by a `Propagator` tool, e.g. the `StraightLinePropagator` or the `RungeKuttaPropagator`. In addition to the residuals themselves, the global track fit also needs to know the derivatives of the residuals with respect to all the track parameters. The `RungeKuttaPropagator` provides the transport jacobian (i.e. the derivatives of the propagated track parameters with respect to the original track parameters) for each propagation from one measurement to another, simple matrix multiplication then yields the derivatives that are required by the track fit. The `RungeKuttaPropagator` uses the Bugge-Myrheim method to calculate the transport matrix, which is fully (semi-)analytic, and therefore fast. It is also robust: all the Inner Detector track fits and more than 99.8% of the Muon Spectrometer track fits succeed using these derivatives. The remaining 0.2% are recovered by switching to 'numerical' derivatives, i.e. by slightly varying each track parameter and calculating the resulting change in the residual. Since the numerical derivatives require an additional propagation along the track for each track parameter, it is clear that the analytical derivatives are preferred.

After the residuals and their derivatives have been calculated, the track parameters are updated using the update formula. This process continues until the track fit has converged, i.e. when there is no appreciable difference between the new and the old χ^2. Then, a track (`Trk::Track`) is written out which has the following information:

- The track parameters at the perigee (d_0, z_0, ϕ_0, θ_0, q/p) and their errors, accessible through `track->perigeeParameters()`
- The overall χ^2 and the number of degrees of freedom of the track, accessible through `track->fitQuality()`
- A list of measurements on the track (`Trk::MeasurementBase`), accessible through `track->measurementsOnTrack()`
- A list of track parameters at each measurement, including the track error in the local measurement coordinate.
- A list of scattering angles at each scattering center, including their variances. Stored in the `Trk::ScatteringAngleOnSurface` class.

By default the measurements that are stored in the track are just copied over from the original list of measurements, but the track fit has the option to recalibrate once more the measurements using the fitted estimate of the trajectory via a generic interface.

In addition to the information above, the track fit has the option to provide the full covariance matrix (i.e. including the covariances on the scattering angles), and a matrix holding all the residual derivatives. The methods to access this information are defined in the `Trk::IGlobalTrackFitter` interface, which extends the `Trk::ITrackFitter` interface. One client of these methods is the global χ^2 alignment algorithm, which needs the full covariance and derivative matrices, as well as the fitted scattering angles, to correct for multiple scattering in its alignment procedure [9]. Furthermore, the V-ATLAS event display [10] uses the scattering angle information to display the actual kinks in the tracks.

3. Applications

The `GlobalChi2Fitter` package has and is being applied in a wide range of scenarios. It is the default track fitter in `CTBTracking`, the reconstruction software for testbeam and cosmic ray events in the Inner Detector[11]. For full physics events, the package serves as a backup for the `KalmanFitter` which is the default track fitter in the Inner Detector. In the Muon Spectrometer, the `GlobalChi2Fitter` has been tested successfully in a new modularized muon reconstruction package. Furthermore, a `TrkRefitAlg` algorithm exists such that the common track fitters like the `GlobalChi2Fitter` can refit any other track, e.g. an Inner Detector track, a Muon Spectrometer track, or a combined track.

Figs. 1 and 2 show the resolutions of the `GlobalChi2Fitter` and the `KalmanFitter` on the impact parameter and the transverse momentum, as a function of transverse momentum, obtained by fitting simulated single muon tracks in the Inner Detector. The two algorithms achieve identical results, which is expected since both algorithms are mathematically based on χ^2 minimization. The resolution of the `GlobalChi2Fitter` on the transverse momentum in the muon system is satisfactory as well, as shown in Fig. 3.

An essential ingredient for the reconstruction of muons in ATLAS is the combined muon fit, which incorporates the measurements in the Inner Detector, the calorimeters and the Muon

Journal of Physics: Conference Series **119** (2008) 032013 doi:10.1088/1742-6596/119/3/032013

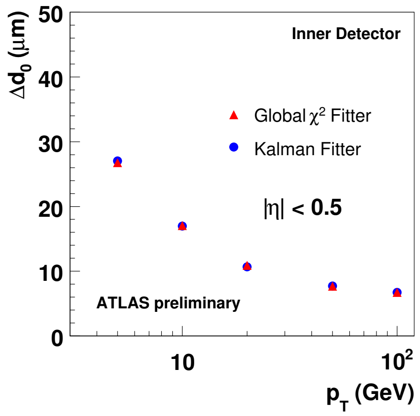

Figure 1. Resolution on the impact parameter of the KalmanFitter and the GlobalChi2Fitter.

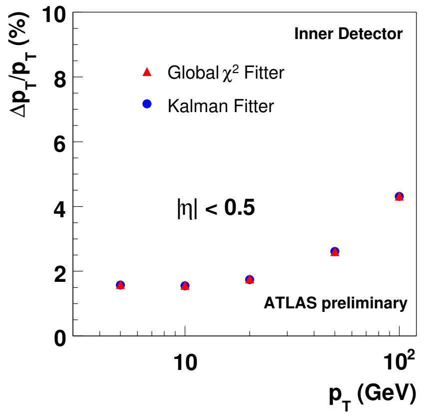

Figure 2. Resolution on the transverse momentum of the KalmanFitter and the GlobalChi2Fitter.

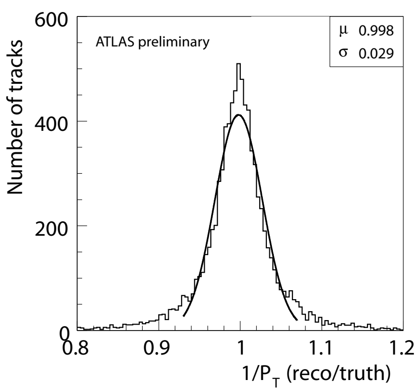

Figure 3. Resolution on the transverse momentum of the ATLAS muon reconstruction.

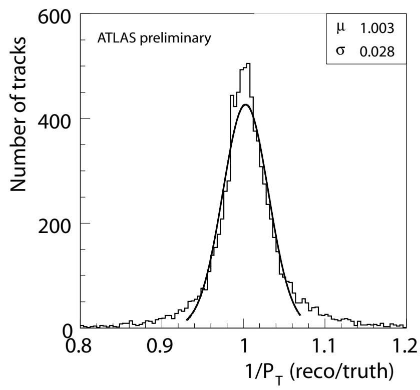

Figure 4. Resolution on the transverse momentum, after refitting with the GlobalChi2Fitter.

Spectrometer into a single track fit. The integration of the calorimeter material effects into the common tracking framework has not yet been finalized at the time of writing. Prototypes of the required interfaces exist, which allow the combined fit to be performed. Fig. 5 shows the momentum resolution of the combined fit as a function of p_T. A clear improvement is seen compared to the stand-alone track fits, especially when the Inner Detector and the Muon Spectrometer contribute roughly equally to the momentum resolution. The combined fit has also been attempted using real cosmic ray data, as shown in Fig. 6.

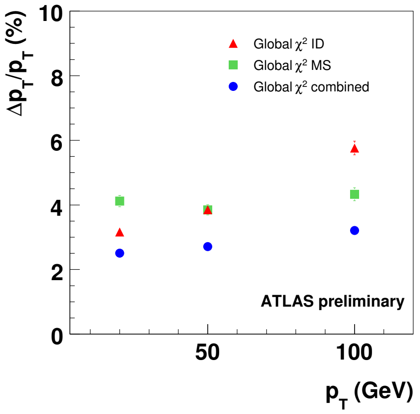

Figure 5. Resolution on the transverse momentum of the GlobalChi2Fitter, in combined and in stand-alone mode.

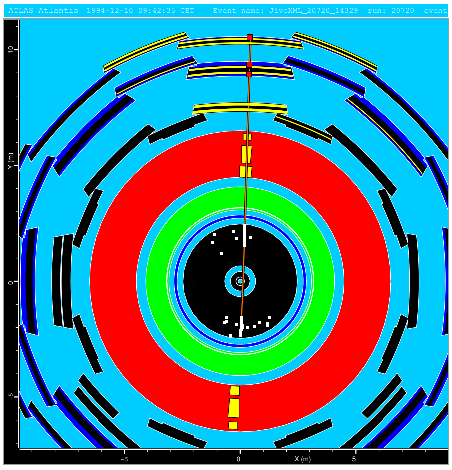

Figure 6. Event display of a cosmic muon track in the ATLAS detector, fitted using the GlobalChi2Fitter.

4. Conclusions

The global track fit has been successfully implemented in the ATLAS tracking framework. Originally intended as a simple track fitter for testbeam events, the `GlobalChi2Fitter` is now a solution that fully exploits the physics potential of ATLAS. While not as fast as the `KalmanFitter`, the `GlobalChi2Fitter` offers some unique features, such as the explicit calculation of the scattering angles. The algorithm also serves as a reference for other track fitters, and as a test bed for new developments in the ATLAS common tracking project.

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