New fitting concept in ATLAS muon tracking for the LHC Run II.

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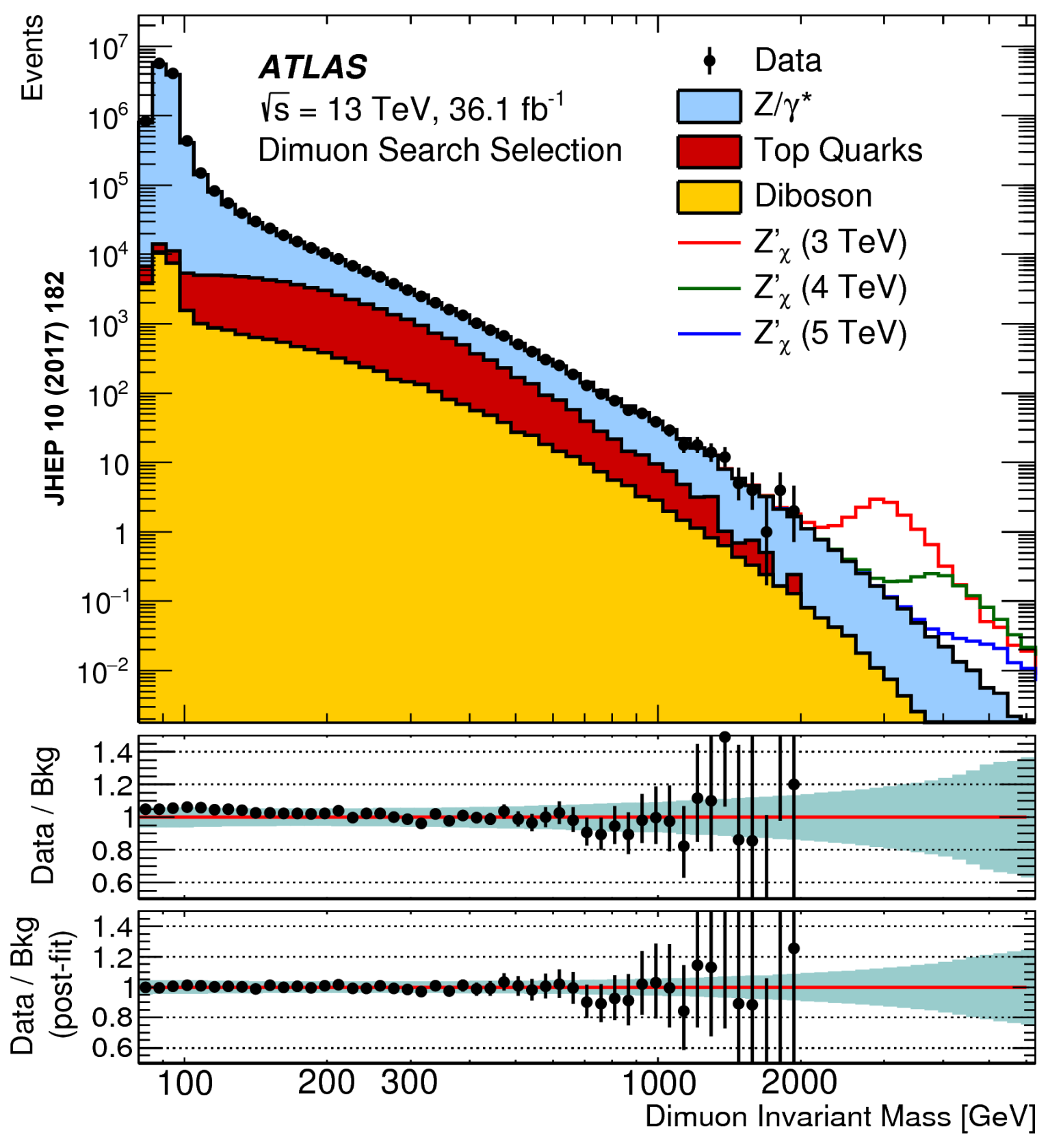
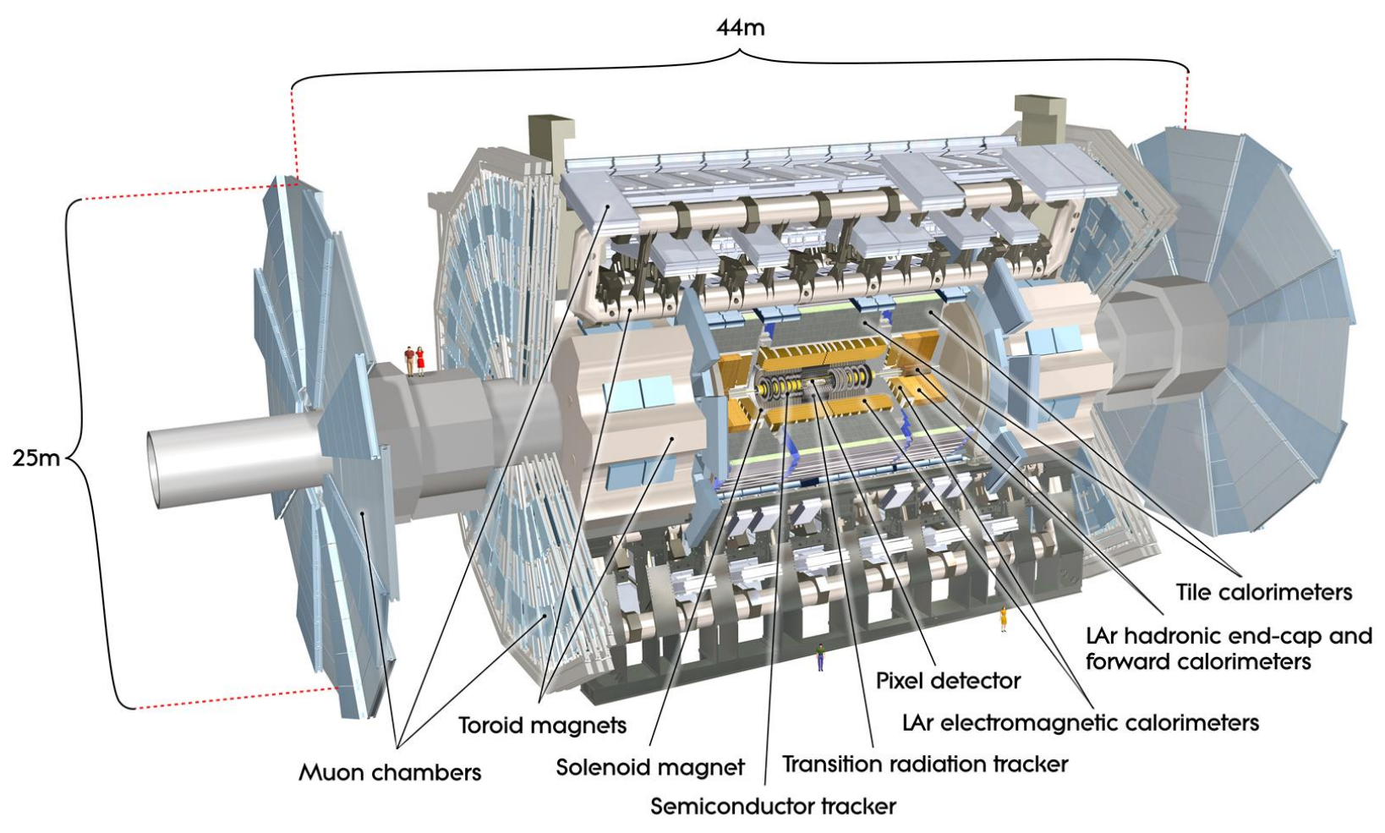
High-p_T muon signatures

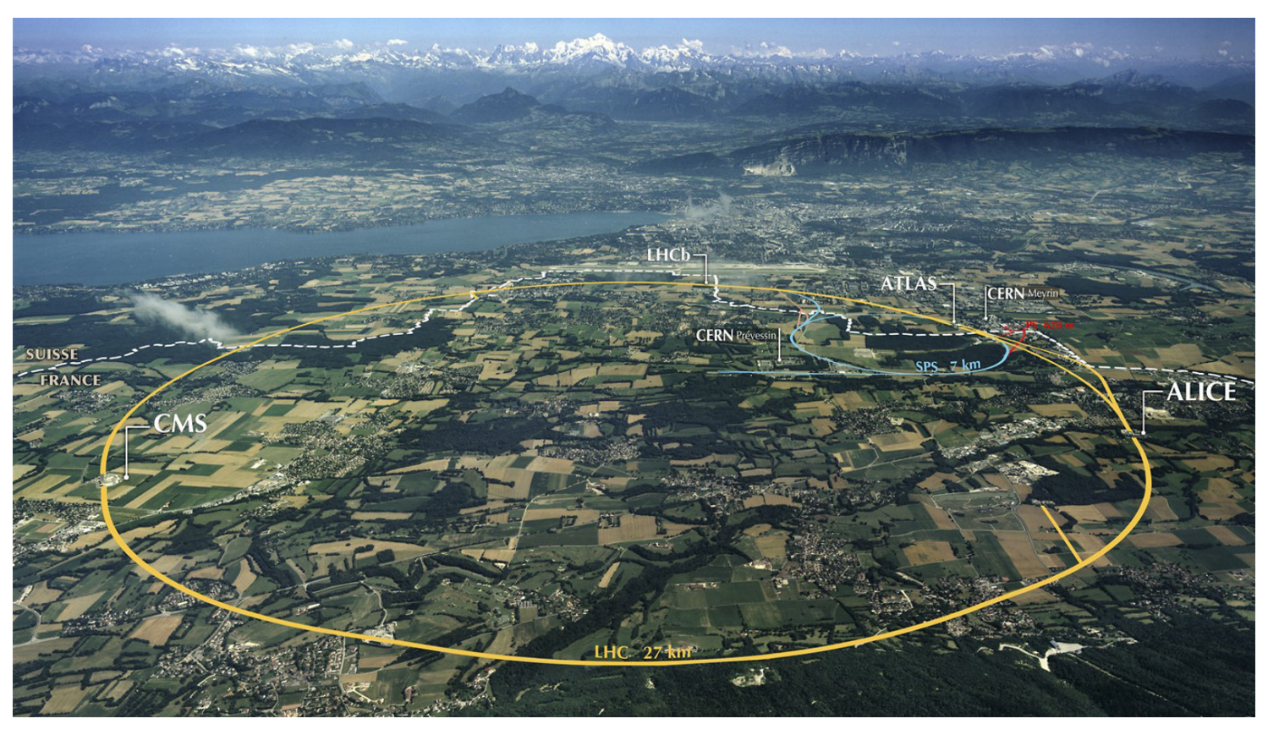


High p_T muons are essential signatures for a number of proposed expansions to the Standard Model (SM). Many such extensions feature additional U(1) symmetries with heavy spin-1 bosons, usually referred to as Z', which could be observed through a narrow resonance in the dimuon mass spectrum: at the masses currently being probed, accurate measurements of muons with p_T over 1 TeV are essential.

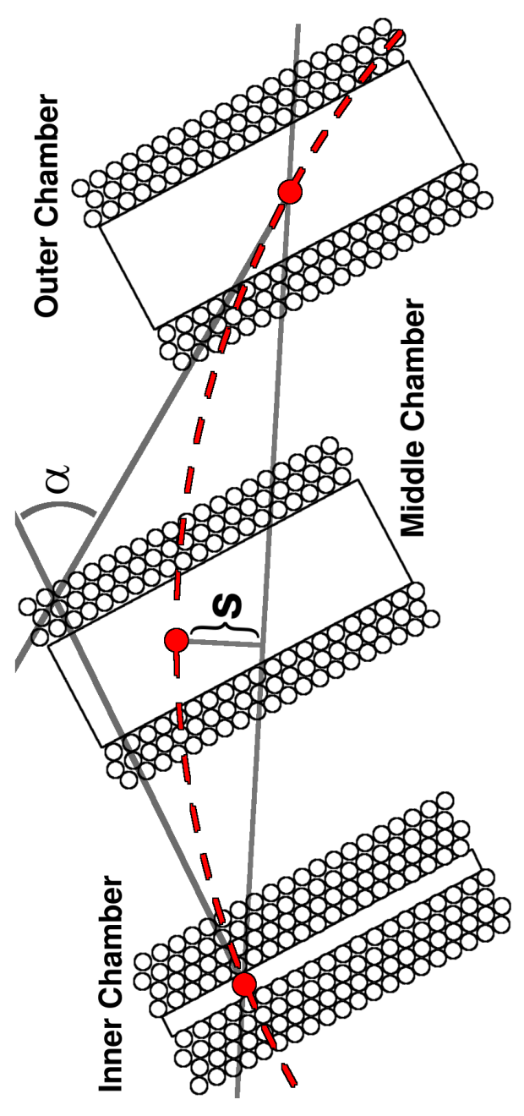
The ATLAS Detector at the LHC

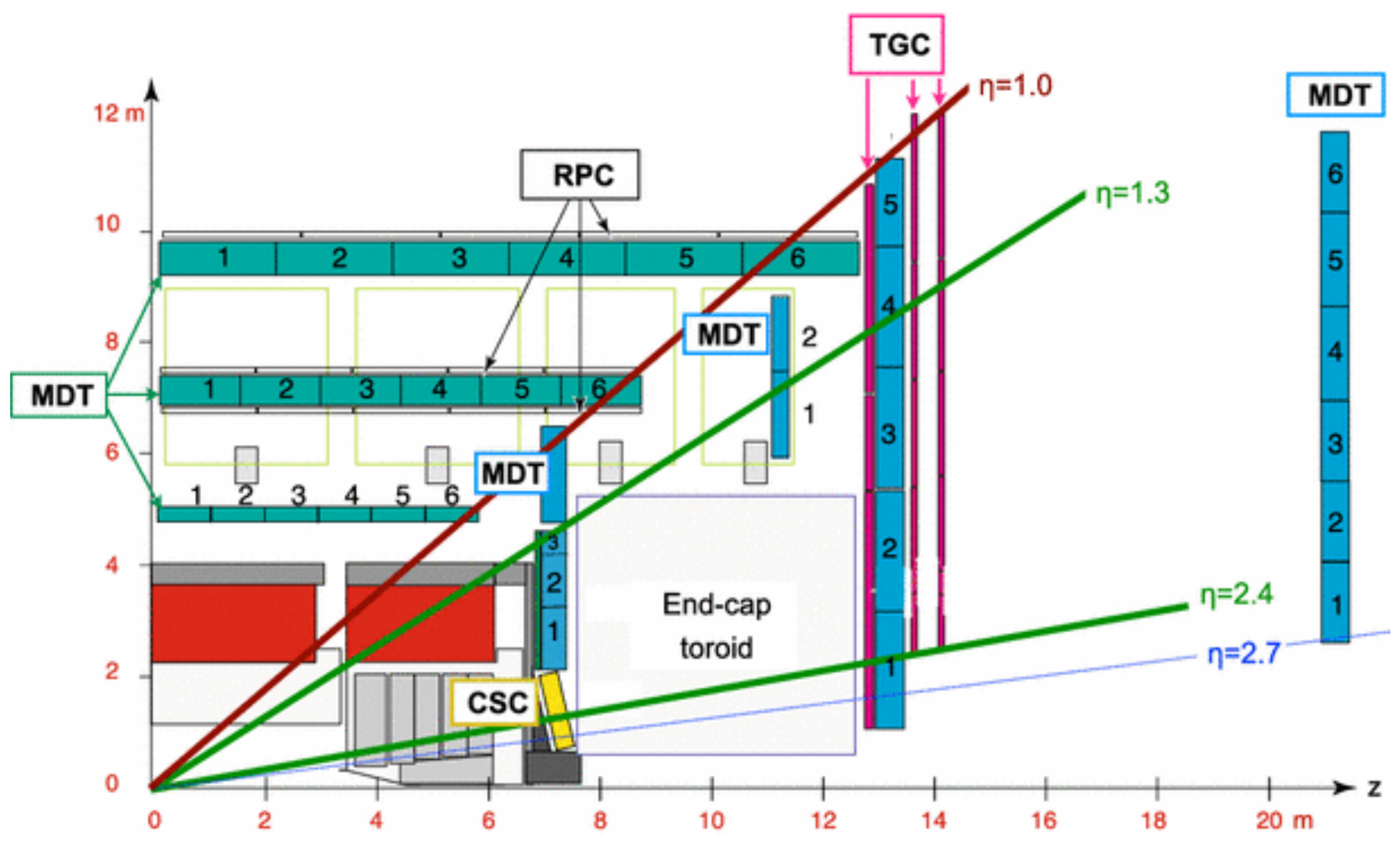


ATLAS is an all-purpose particle reconstruction detector at the LHC. During the ongoing Run II, the LHC provides proton-proton collisions at a center-of-mass energy of 13 TeV.



Measuring muons in the ATLAS Muon Spectrometer





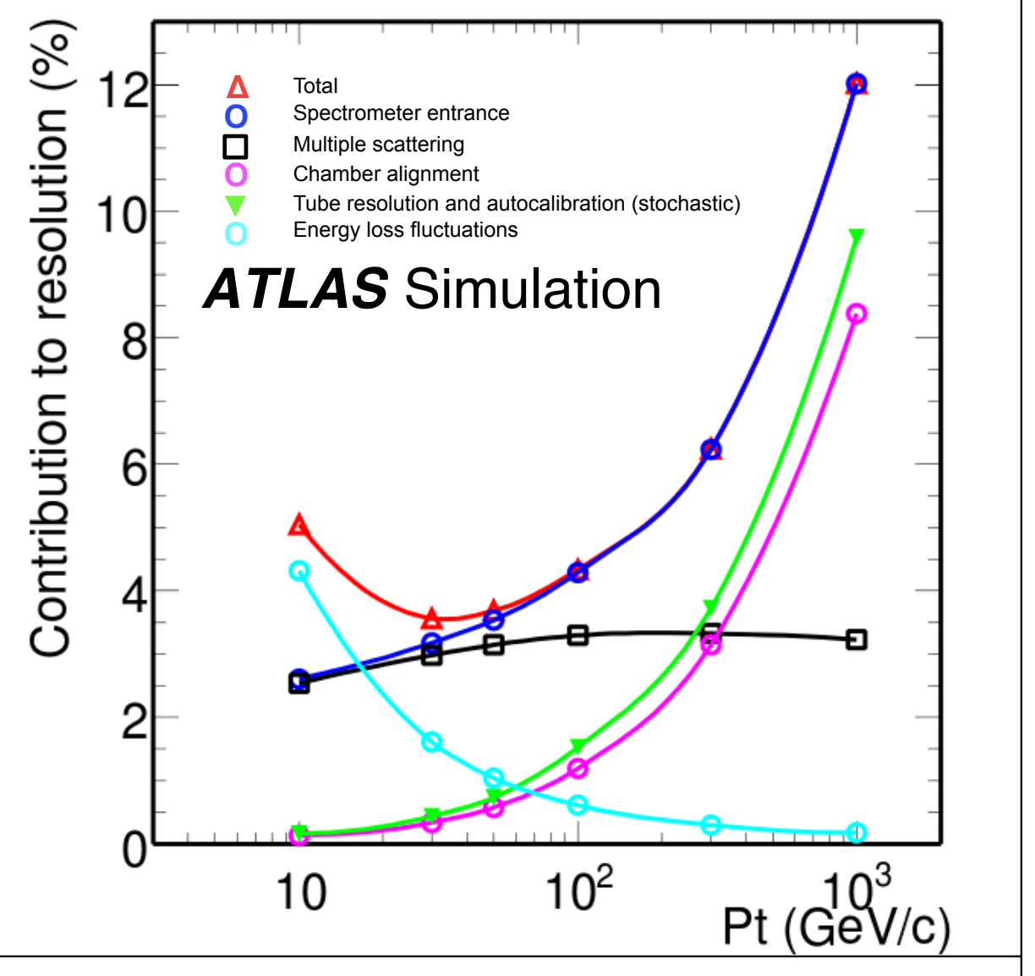
The ATLAS Muon Spectrometer

Precision measurements in the bending plane are made over most of the range of |η|<2.7 by Monitored Drift Tube (MDT) chambers. Each tube consists of a gas-filled cylinder with a central wire; chambers are made from multiple layers of MDTs. At the highest values of |η| in the innermost endcap layer, the flux is too large for MDTs and Cathode Strip Chambers (CSC) are used instead. Triggering and measurements in φ are provided by Resistive Plate Chambers (RPC) in the barrel and Thin Gap Chambers (TGC) in the endcap. Toroidal magnetic fields provide bending for momentum measurements.

Muon tracking and reconstruction

Muons are reconstructed first in the spectrometer, and then combined with tracks reconstructed separately in the Inner Detector (ID). A combined track-fit of all measurements is done with a χ^2 minimization process, taking into account energy loss and multiple scattering.

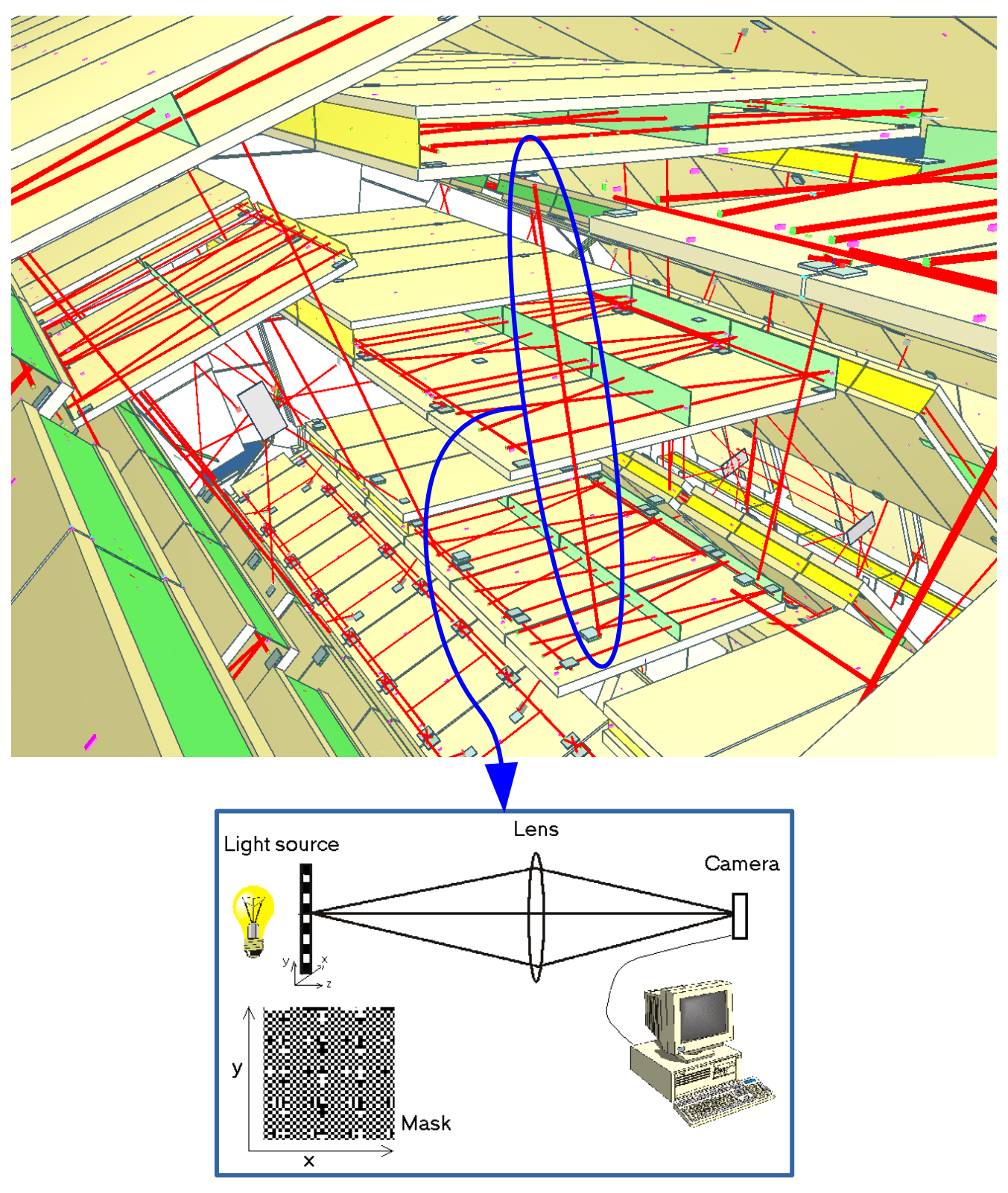
At low p_T, energy loss and multiple scattering dominate the resolution, but at high p_T precision knowledge of the detector becomes more important. In particular, to achieve a 10% resolution at 1 TeV the chamber position needs to be known to a precision of ~40 μm.

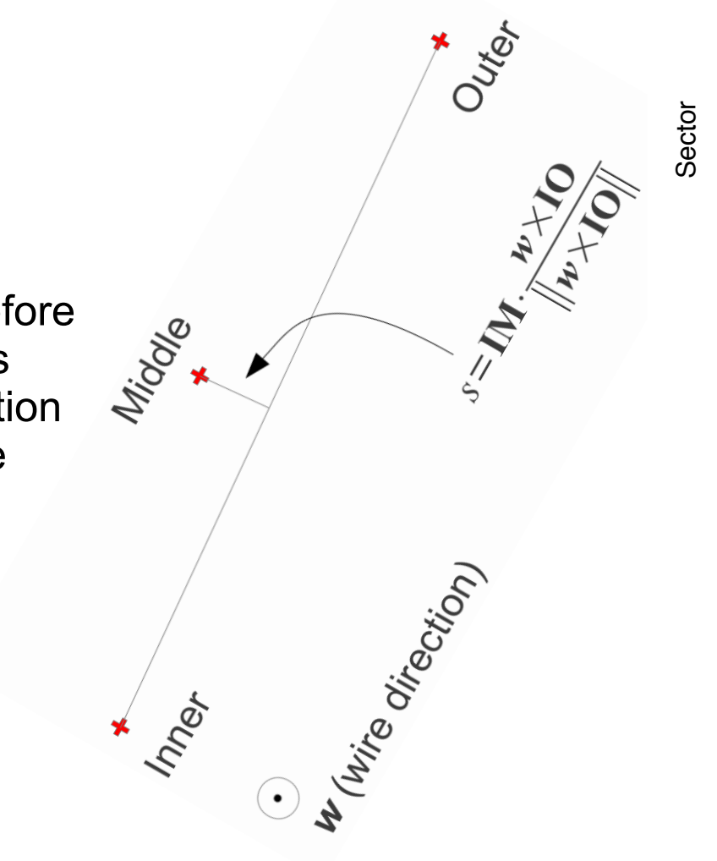


Alignment in the ATLAS Muon Spectrometer

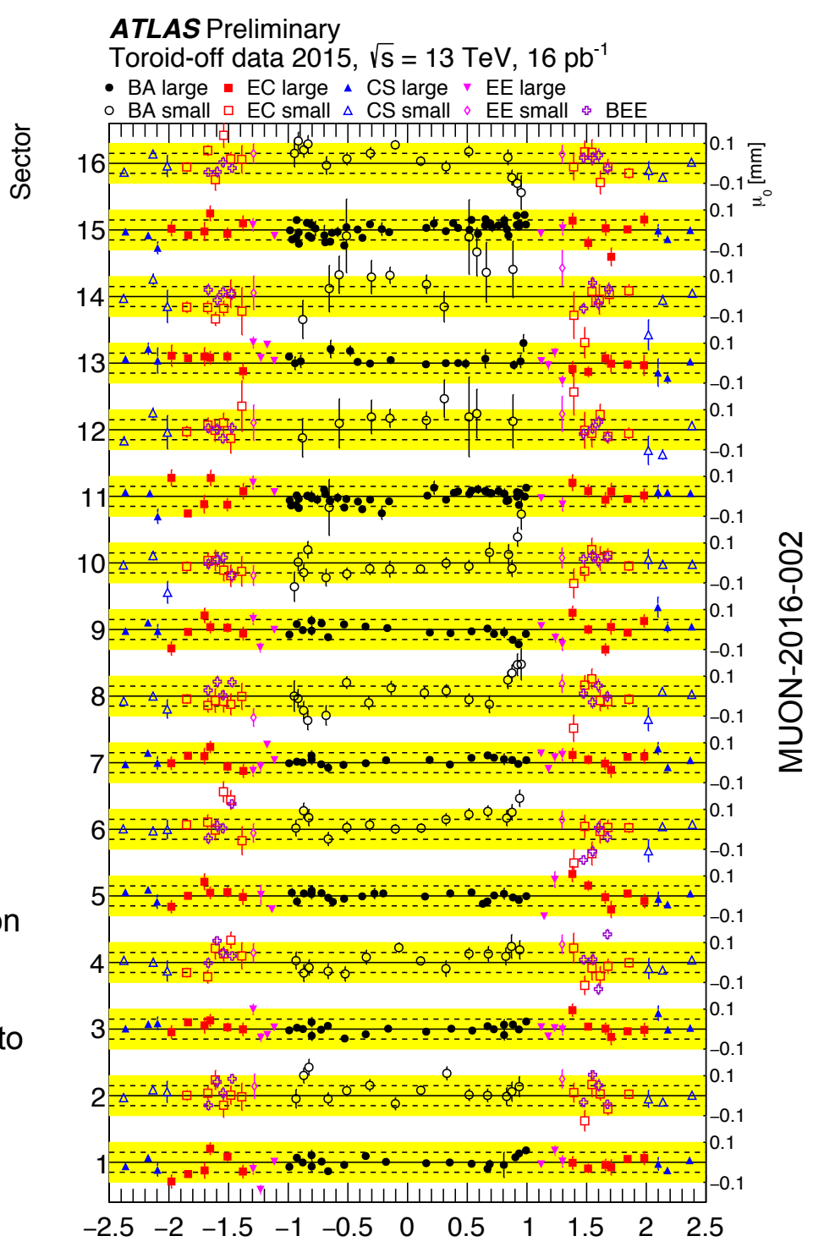
Optical Alignment using the RASNIK system

The position of installed chambers can be surveyed only to a precision of a few mm, and will move or deform over time. Therefore an optical alignment system consisting of three-point straightness monitors (known as RASNIKs) is used to measure chamber position relative to this survey. A large number of these systems measure displacements (and deformations) of the chambers in different directions in order to constrain their positions.





The bias on the sagitta s is measured based on the straight track assumption and then broken down into three components, a constant term (plotted at right vs. η and ϕ sector) and terms to measure its variation with respect to θ and ϕ.



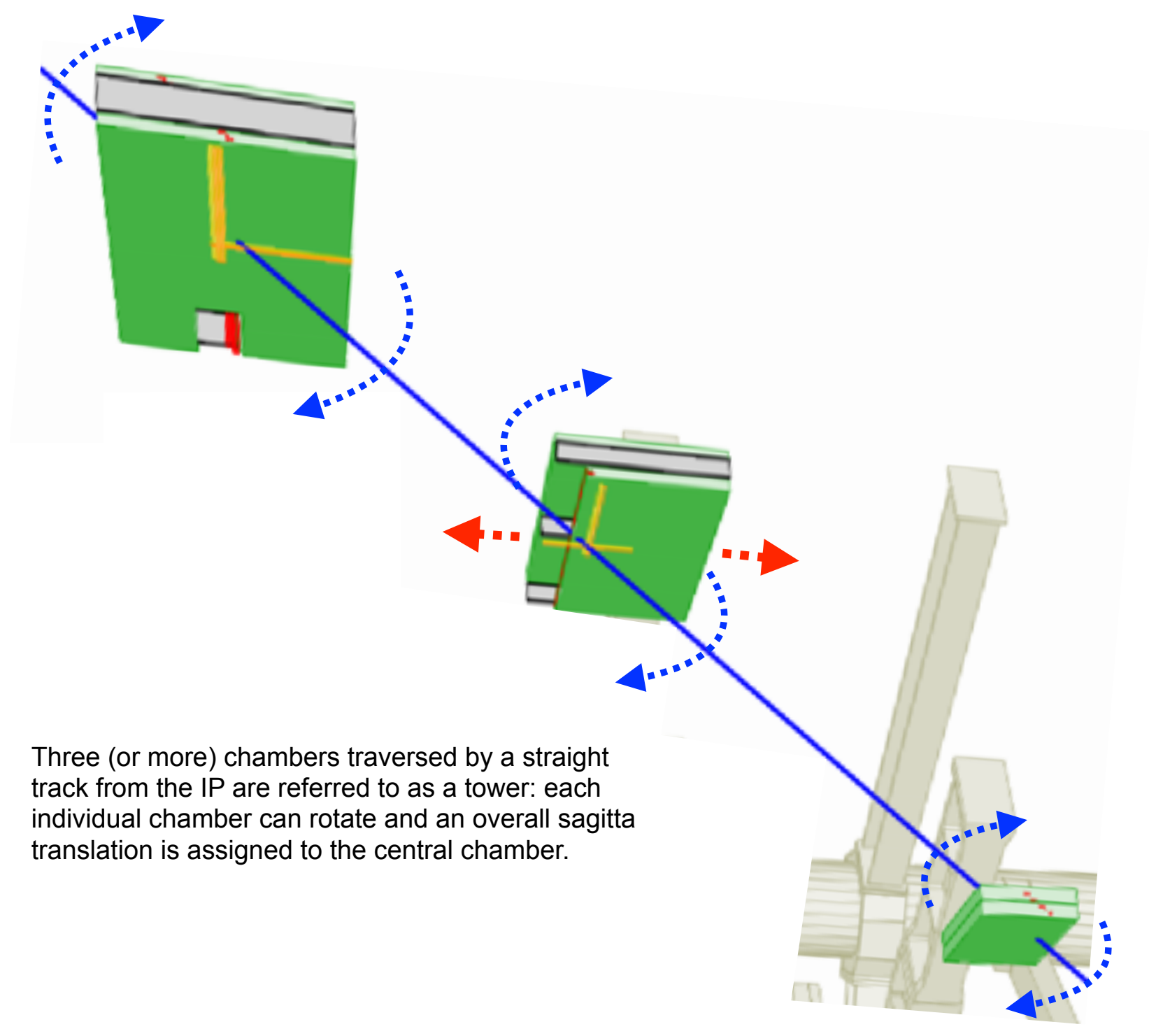
Track-based Alignment

In order to achieve the ultimate resolution, the optical alignment is supplemented by further measurements which compensate for its weaknesses:
> Alignment sensor locations can only be known to their mounting precisions
> Some chambers are only partially integrated into the optical alignment system
> There is no connection between the separate optical alignment systems of the barrel and endcap
> There is no connection between the optical alignment of the MS and the ID

The necessary additional data is taken during special runs in which the toroidal magnetic fields are turned off. Deviations from straight-line tracks are found by comparing to expected positions. The results are combined with the optical alignment to obtain a set of parameters describing the amount of misalignment of each chamber using the model: $\mu_0 + \frac{\theta-<\theta>}{\mathrm{RMS}(\theta)}\mu_\theta + \frac{\phi-<\phi>}{\mathrm{RMS}(\phi)}\mu_\phi$

Where θ and ϕ are the polar and azimuthal angles and the RMS is taken over the track sample.

Incorporating alignment effects via gaussian constraints on hit ensembles

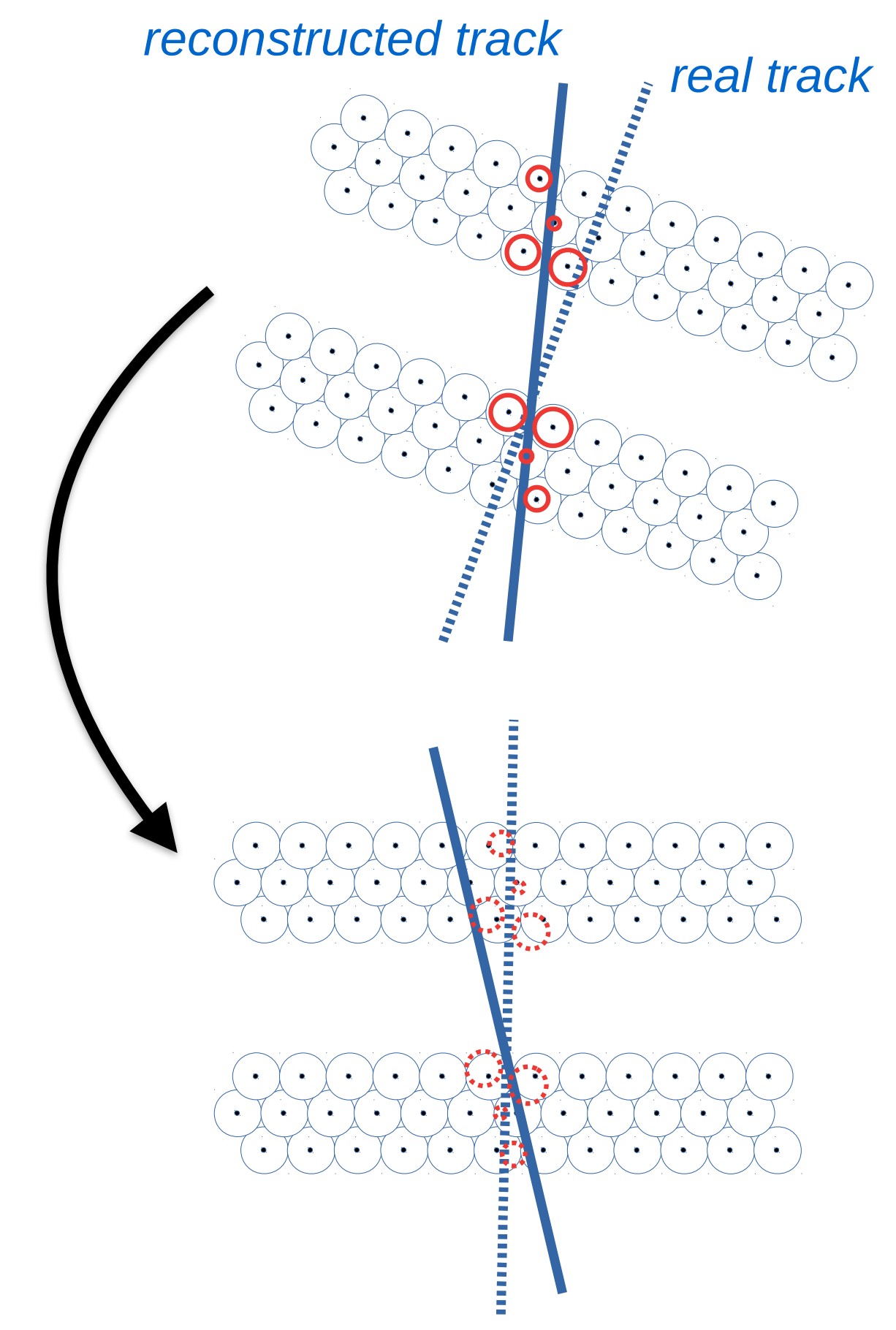


Three (or more) chambers traversed by a straight track from the IP are referred to as a tower: each individual chamber can rotate and an overall sagitta translation is assigned to the central chamber.

Misalignment means that the real detector position and orientation is different than it is in the geometry assumed by the tracking.

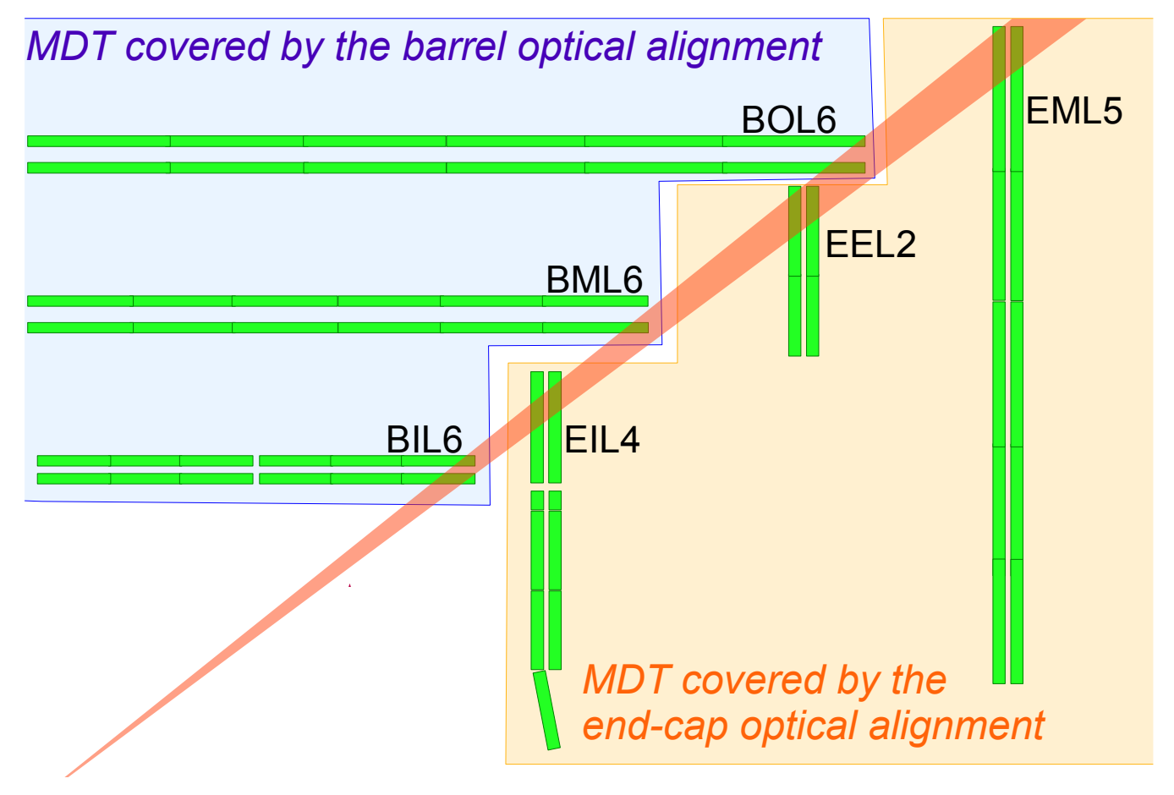
Previously this was incorporated by inflating the single hit uncertainties. However, this means that the uncertainty of the final χ^2 fit does not reflect the reality. Additionally, this neglects the fact that in the case of misalignment individual hits will move together, rather than separately.

Instead, a method involving gaussian constraints applied to ensembles of hits in a single chamber was adopted.



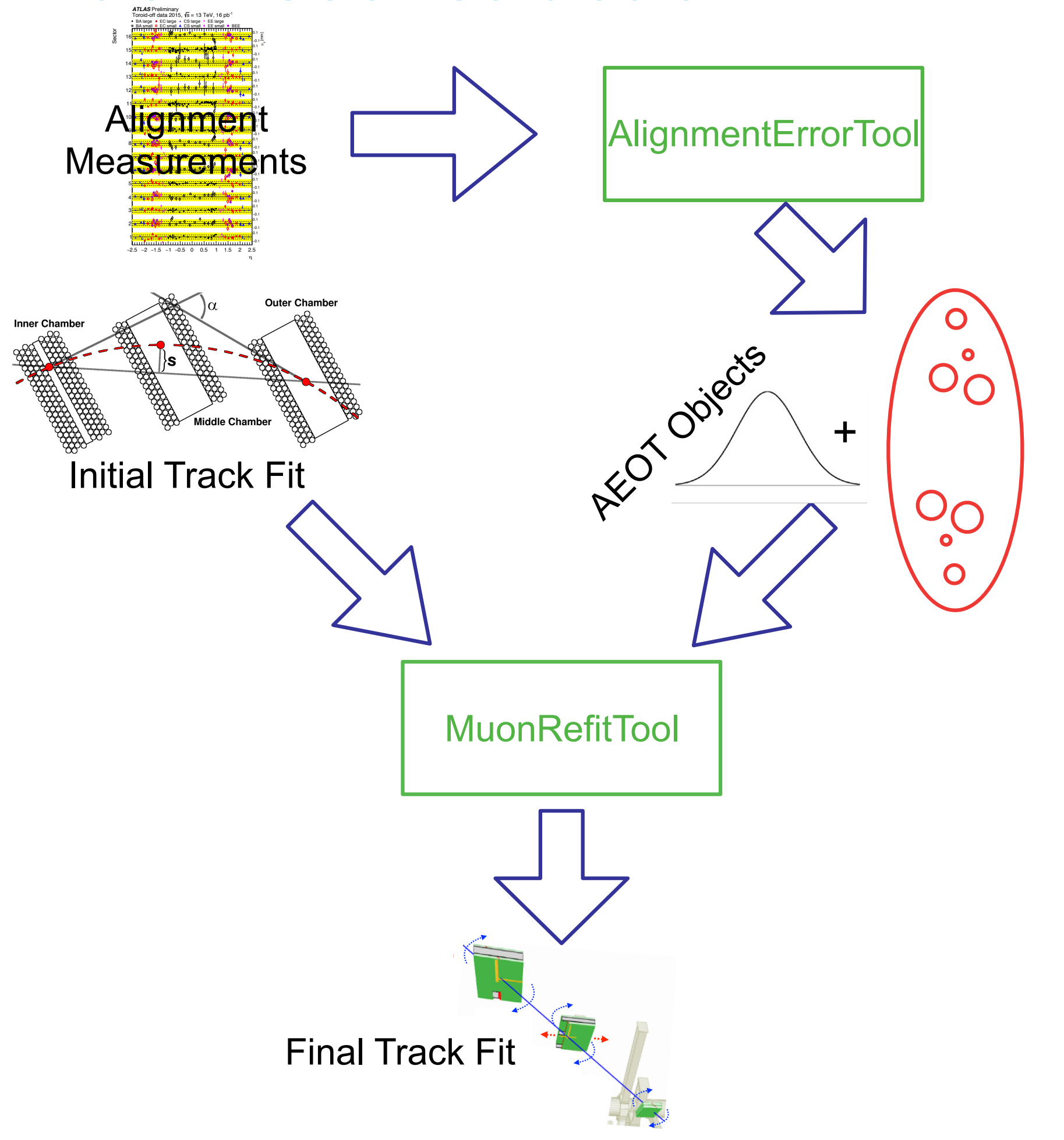
The width of the constraints are obtained from misalignment calculations: in the case of little to no misalignment, nominal values of 10 μm (translations) and 1 μrad (rotations) are used.

In the example shown here, the chamber is rotated, so the gaussian constraint associated to this chamber is given a width accordingly. Hits which have previously been fit together into a segment in the chamber (here in red) are all assigned the same constraint, allowing them to rotate together.



This same method is used for tracks that go through regions with independent alignment systems (barrel-endcap, as above, or large-small). In such cases the gaussian constraint is applied to all of the hits from one of the alignment systems, allowing them to move with respect to the other hits based on the measured misalignment between the two systems.

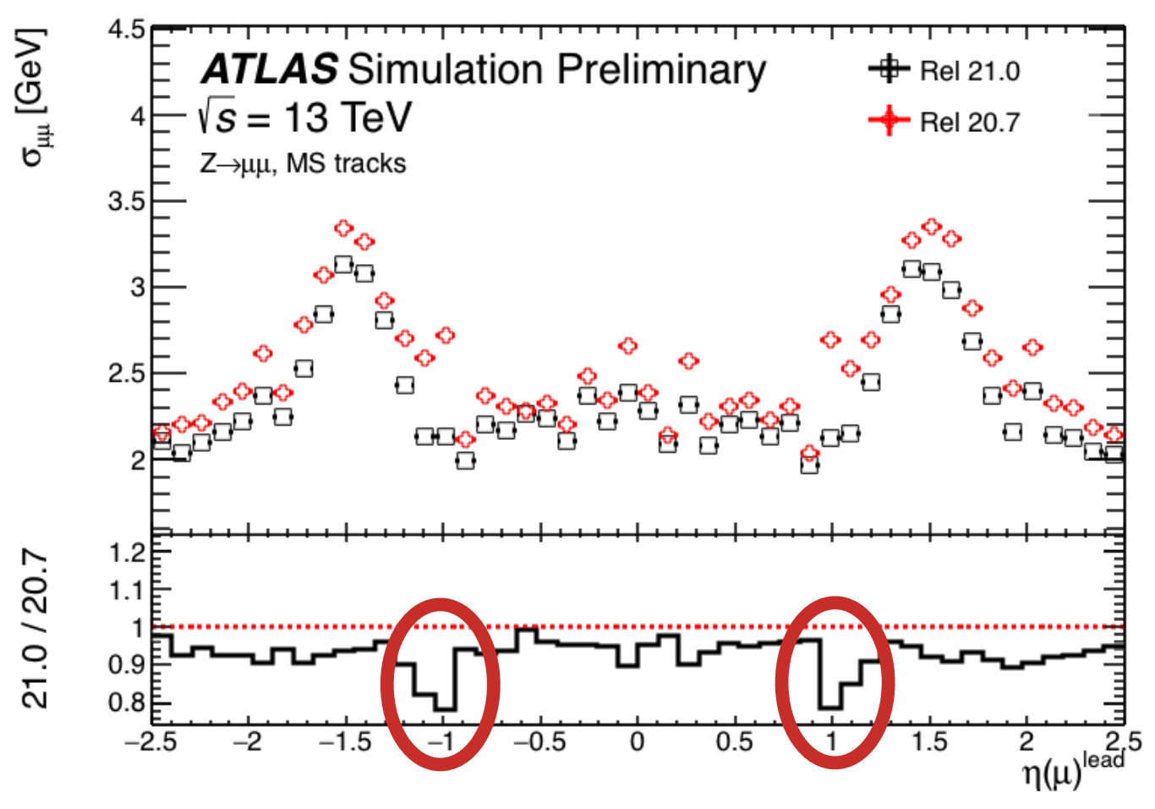
Implementation in the muon reconstruction

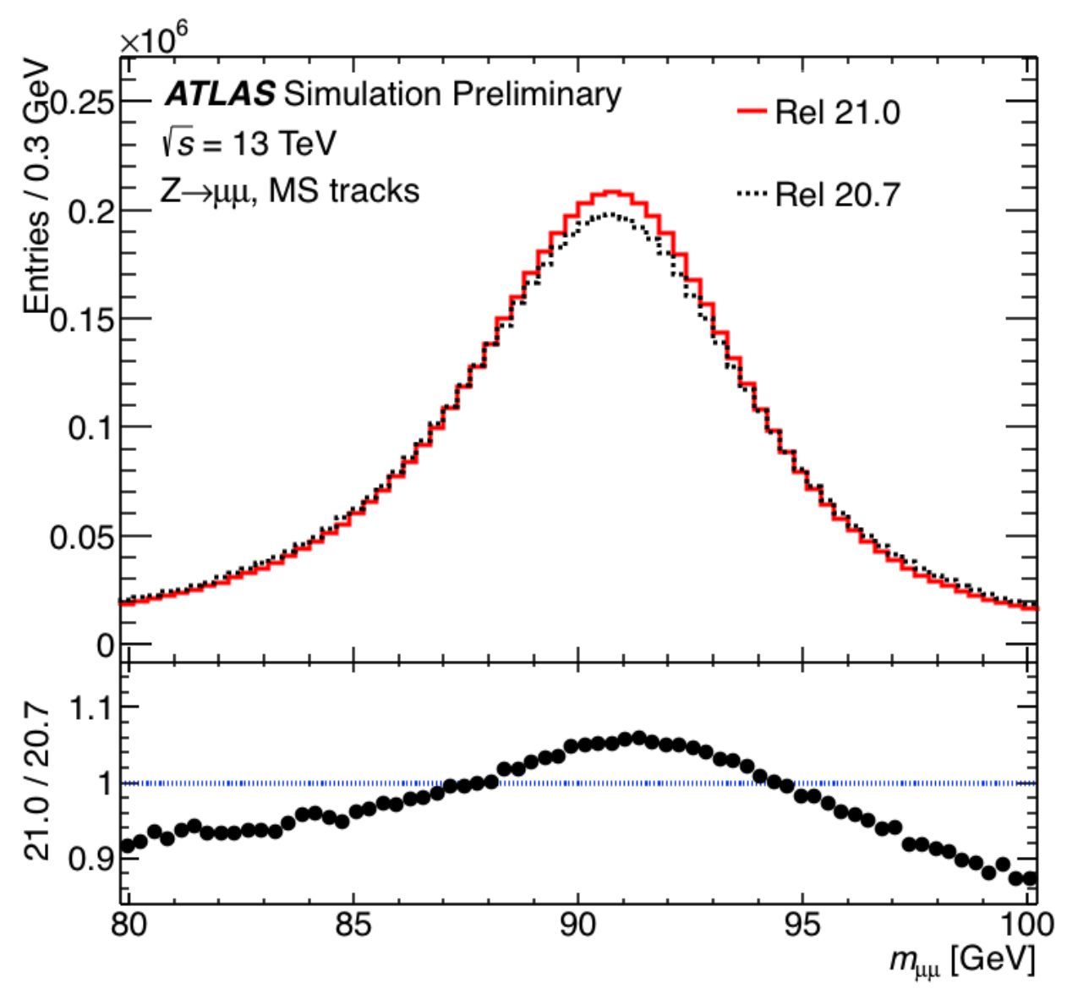


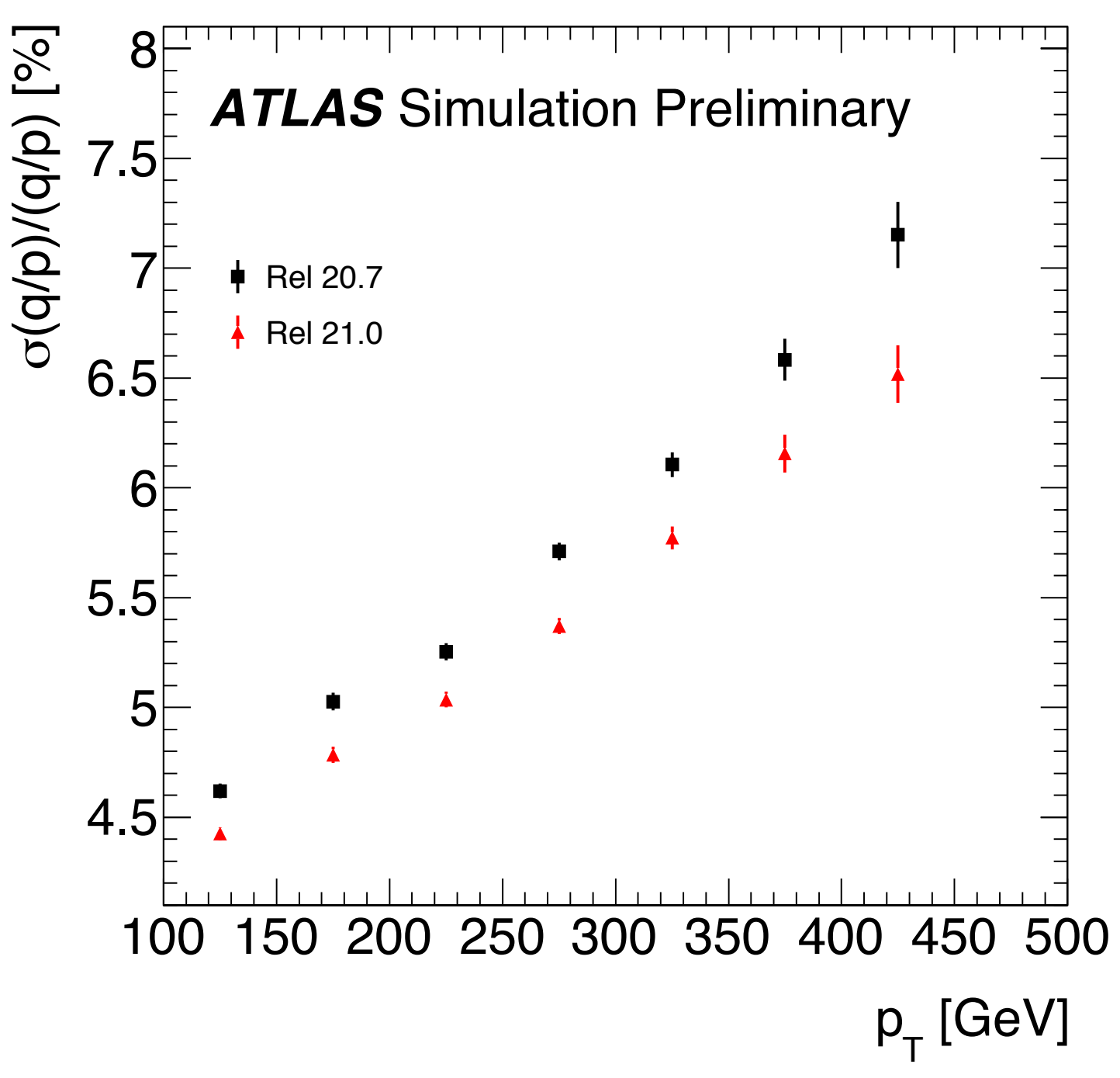
The Alignment Effect on Track (AEOT)

This object is the basis of the implementation: it contains the gaussian constraints and a list of the hits they are to be applied to. AEOT's are directly included in the vector of measurements and the derivative matrix that is used to define the χ^2 of the fit.

Performance gains







A considerable improvement in the resolution is observed in simulated Z decays, for the di-muon mass (top left), the Z peak (top right), and for individual muons (lower left). Release 21 includes AEOT's, while release 20.7 does not: there are other changes as well, but the AEOTs will drive the change in the resolution. This can be seen from the fact that the greatest improvement is observed near |η|=1, in the region where the barrel and endcap overlap. Previously all hits in either the barrel or endcap would have their uncertainties inflated; with AEOTs this is not necessary and the resolution improves accordingly.

Additionally, the fact that muons now have realistic errors makes it possible to use those errors to evaluate the quality of muons, with those with large errors discarded for analyses where precision is required. This yields an increase in efficiency compared to simply vetoing regions (such as that near |η|=1) where all tracks would have their single hit uncertainties inflated.

Future work

As mentioned above, the Inner Detector has its own independent alignment system that is not connected to the Muon Spectrometer one. Currently the degree of misalignment between the two is treated as a constant average value: it is implemented as a scatterer with X_0=0, so that the track can change direction without losing energy. Using an AEOT to describe this misalignment instead would allow for additional realism and greatly improve the granularity with which the misalignment is described.

Additionally, it is important to work to streamline and clean up and the code to keep the CPU penalty to a minimum. An increase in CPU consumption is inevitable due to the increased size of the matrix that must be inverted; a simultaneous switch to a new linear algebra library resulted in total CPU consumption remaining roughly unchanged, but if the use of AEOT's is to be expanded again it will be necessary to keep the additional CPU consumption to a minimum.