# Application of linear and non-linear constraints in a brute-force-based alignment approach for CBM

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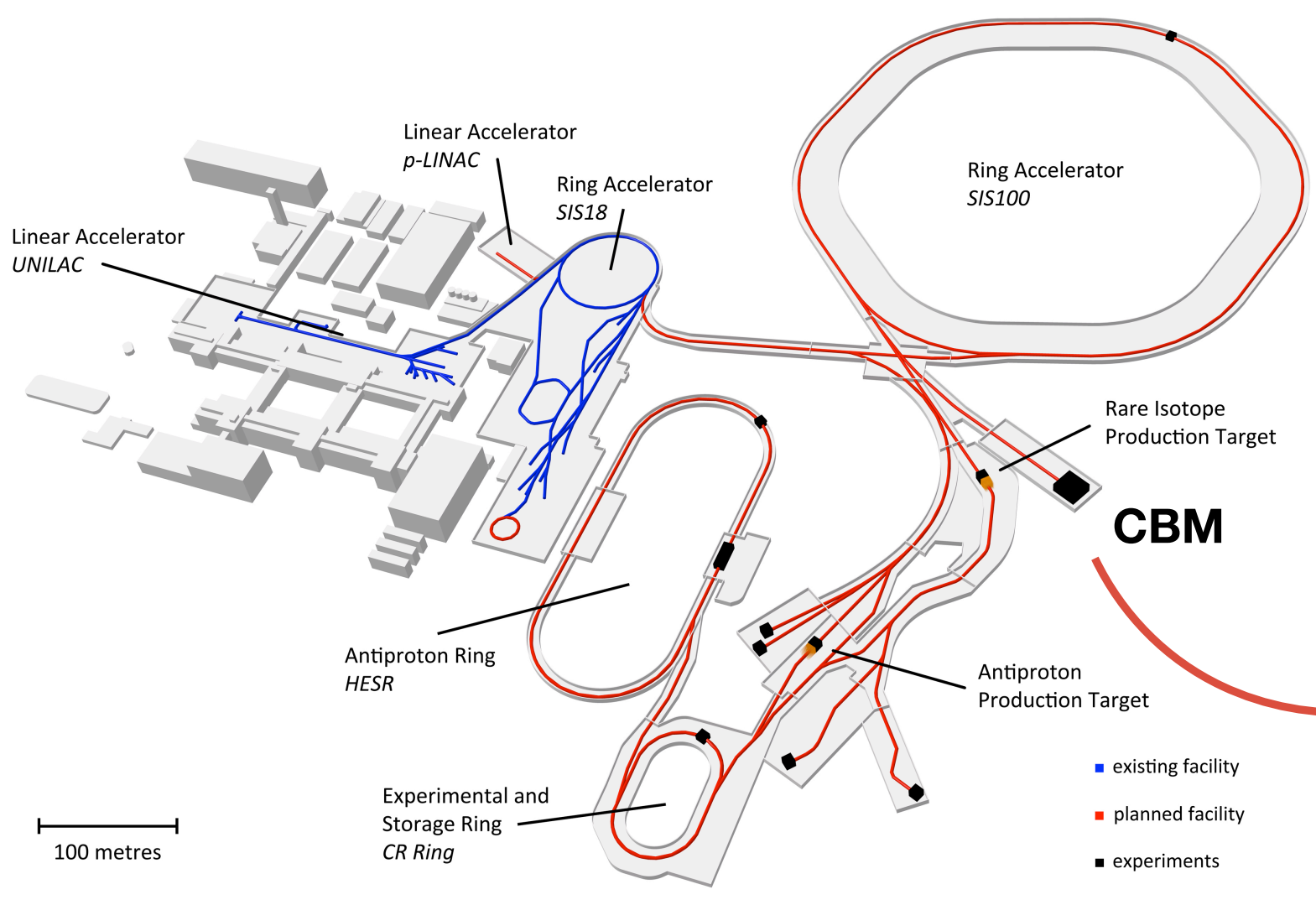
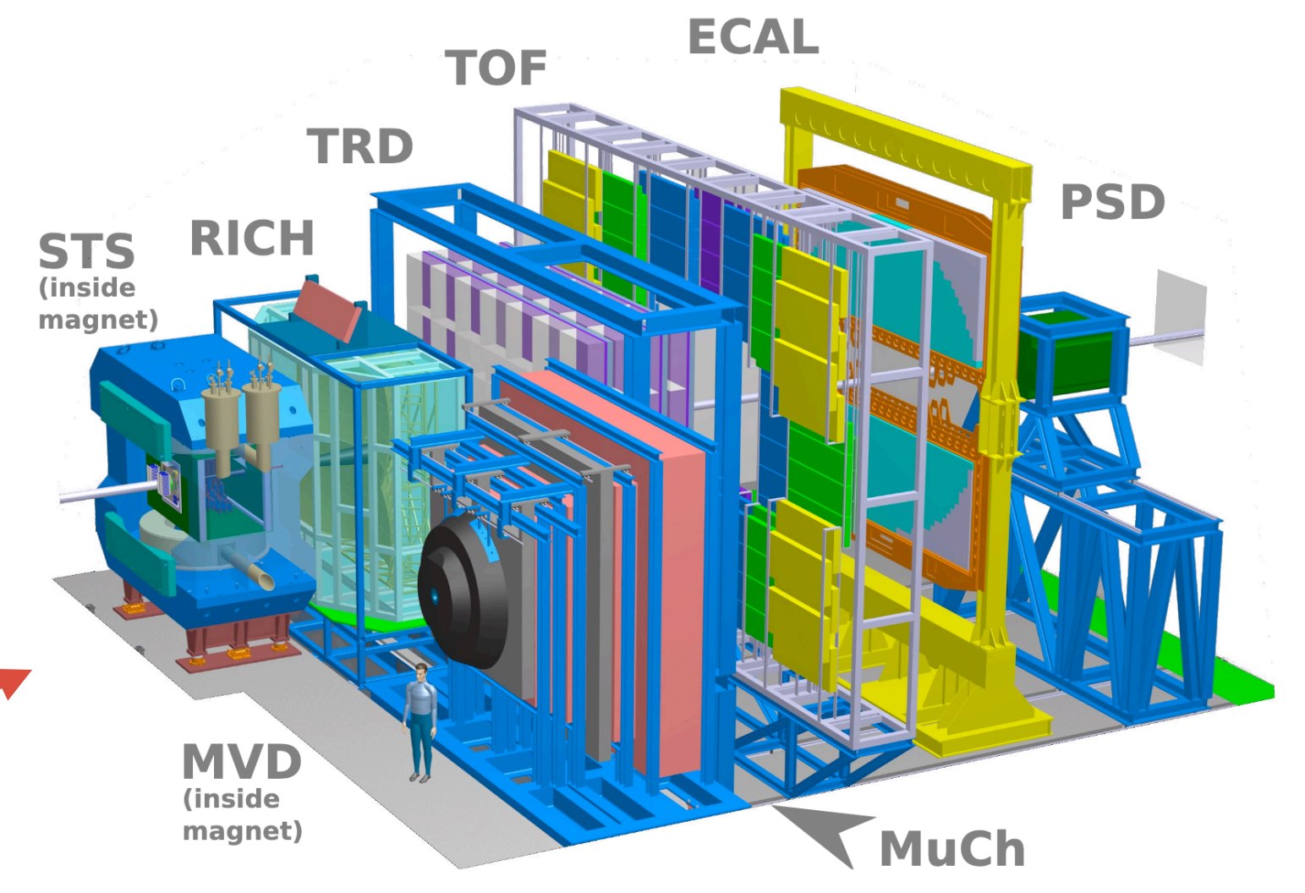
## The CBM experiment

- Currently under construction at FAIR (Darmstadt, Germany)
- Investigation of strongly interacting matter at high baryon densities
- Fixed target experiment
- High interaction rates: $10^5$ - $10^7$/s
- Self-triggered front-end electronics with free-streaming read-out
- Modular detector setup



The FAIR complex



CBM setup

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Latest CBM rendering

## Track-based software alignment

### Motivation

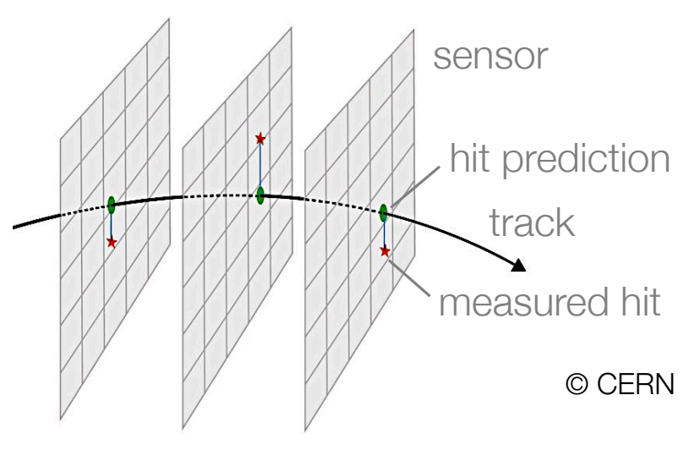
The experiment data analysis relies on the high measurement accuracy provided by high-resolution sensors. To exploit this high intrinsic resolution, the sensors' exact positions and orientations must be known. The experimental setup is never 100% precise, so corrections must be found and applied. Common analytical methods are based on a linearized relationship between corrections and imprecision. This, and the need to reformulate the analytical relationships for each application motivated the development of a complementary brute-force approach.

### Alignment objects

- Rigid bodies, e.g., sensors or stations
- Each with 6 degrees of freedom (translation and rotation)
- Alignment parameters: Corrections to translation vectors and rotations matrices
- $\vec{p}_{\text{rigid body}} = (\Delta x, \Delta y, \Delta z, \Delta\alpha, \Delta\beta, \Delta\gamma)^T$

### $\chi^2$ Minimization

- Discrepancy between measurements and hit predictions (according to track model)
- $\chi^2$ of residuals depends on alignment parameters $\vec{p}$ and the track parameters $\vec{t}$
- $\min\limits_{\vec{p}} \chi^2 = \min\limits_{\vec{p}} \sum\limits_{\text{tracks}} \sum\limits_{\text{hits}} \frac{(\text{hit} - \text{hitmodel}(\vec{p}, \vec{t}))^2}{\sigma^2}$



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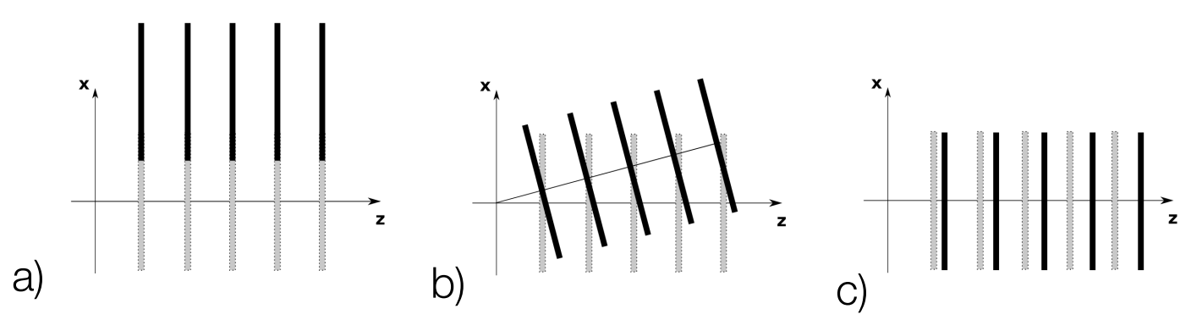
Deviations of hit predictions from measurements

### Weak modes

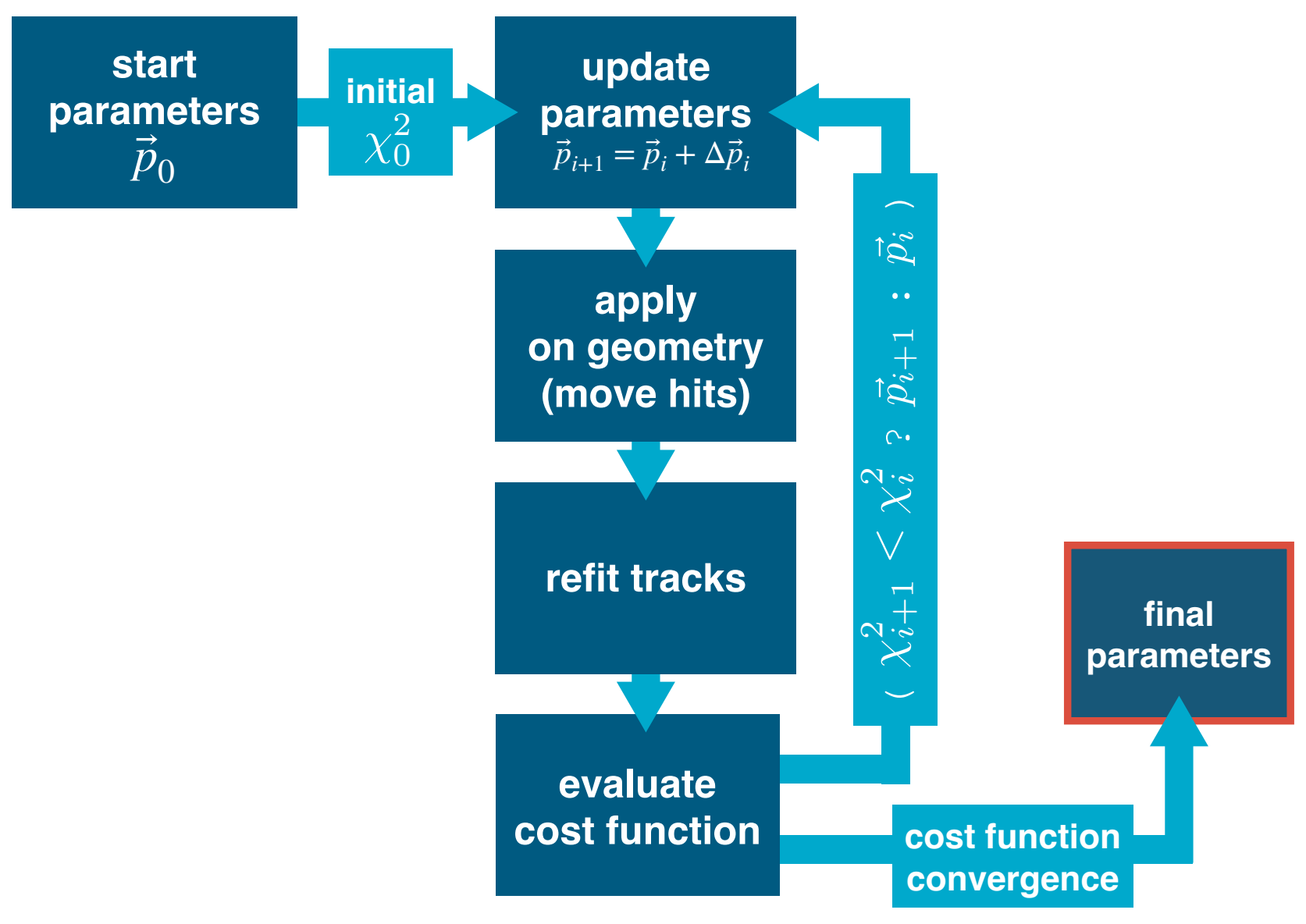
A particular challenge in alignment is the mitigation of weak modes. These correspond to changes in alignment parameters that do not affect the $\chi^2$ value. In other words, the cost function has no unique minimum.



M Deissenroth 2010, Dissertation, University of Heildelberg

Weak mode examples
a) and b) overall movements. c) scaling

## A brute-force-based alignment approach



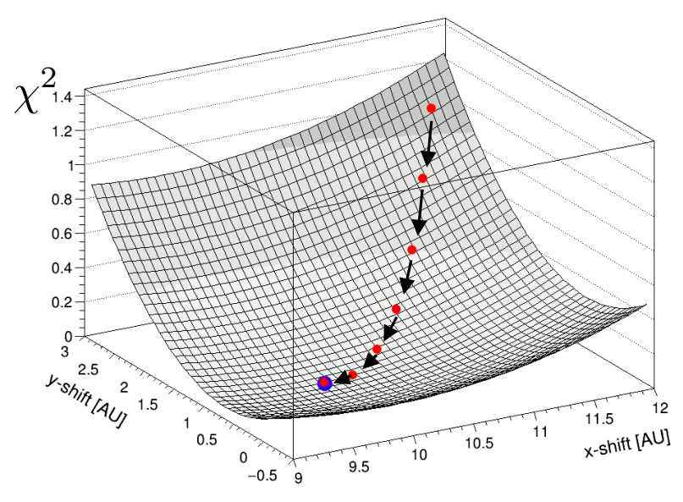
The brute-force alignment procedure

### Iterative trial and error procedure

- Ideal geometry as start parameter set
- The parameter space is probed with a cost function ($\chi^2$ of the hit residuals)
- In each iteration $\Delta\vec{p}$ is determined within the parameter validity interval
- New $\vec{p}$ values are kept if $\chi^2$ improves and discarded otherwise

### How to find next $\vec{p}$

- Small steps in parameter space following the gradient
- Conjugate gradient descent
- Quadratic approximation
- …



2D example

### Prerequisites

- Start values for parameters (best guesses)
- Validity range of parameters (according to setup accuracy)
- Min and max step size
- Cost function $\chi^2$
- Well-defined geometry
- A set of high-quality tracks

## Linear constraints

### Straightforward constraints

- **Fixing stations:** Respective parameters are not included in the alignment
- **Setting the sum of all shifts in one dimension to zero:** After each iteration cycle, the constrained parameters are simultaneously reset around their axis

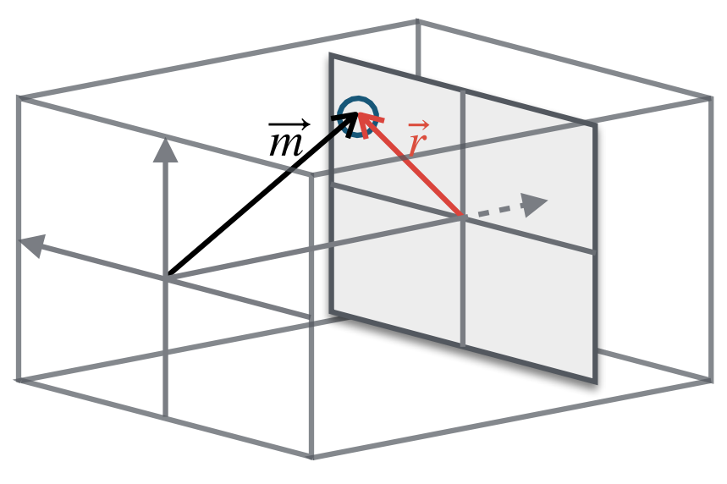
### Validity range

- The setup accuracy defines a validity range for each parameter
- All steps $\Delta\vec{p}$ are restricted to the validity range
- Parameter space is only scanned in a narrow interval corresponding to the validity range
- Mitigates the weak mode of overall shifts of the entire detector

## A non-linear constraint

### Point measurement constraint

- Reference point $\vec{r}$ with fixed local coordinates with respect to a sensor or station
- Measured global coordinates $\vec{m}$ of $\vec{r}$ with measurement error $\sigma$
- During alignment $\vec{r}_{\text{global}}$ changes according to the alignment parameters of the sensor
- In each iteration over the sensor parameters ensure: $|\vec{m} - \vec{r}_{\text{global}}| \leq 3.5\sigma$



Point coordinates are fixed to a measurement

## Prealignment

### Using photometric survey data

A desirable feature is to include precise measurement information in the alignment process mitigate weak modes. For example, photometric surveys deliver global coordinates of known points in the detector setup.

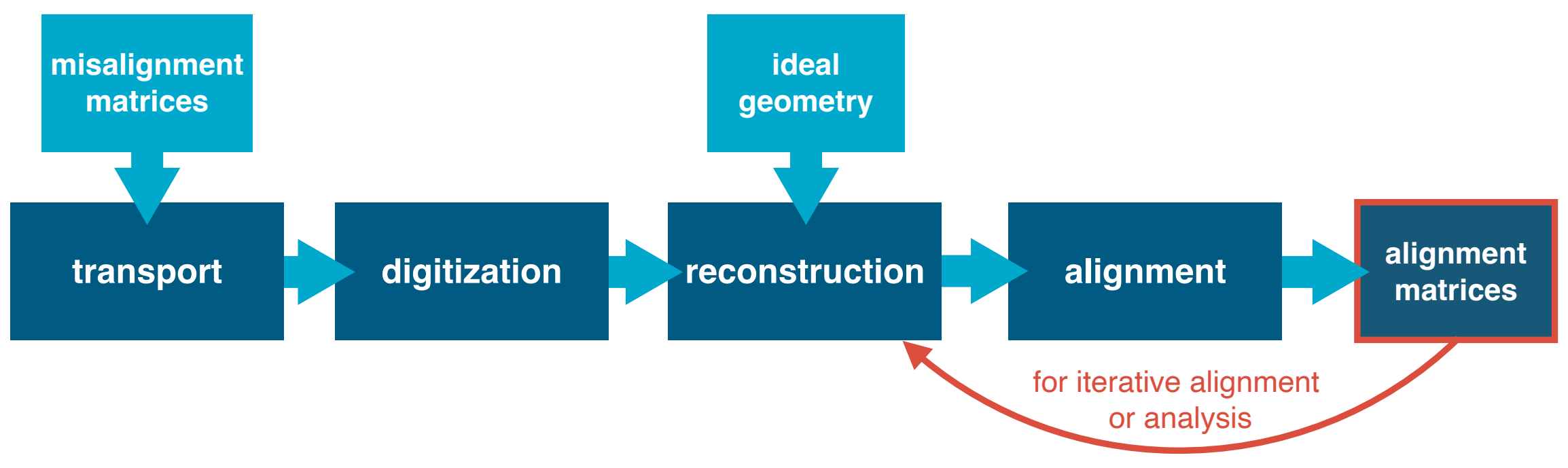
During the brute-force-based alignment procedure, these points can be pinned to the respective coordinates using the point measurement constraint.

## Advantages

- Individual parameter treatment
- Non-linear constraints
- Inequality constraints
- Non-linearized cost function $\chi^2$
- Combination of different optimization methods
- Parallelizable
- Potentially linear runtime scaling

## Next step

- Work towards interfaces for a full alignment test chain in CBMROOT simulations



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