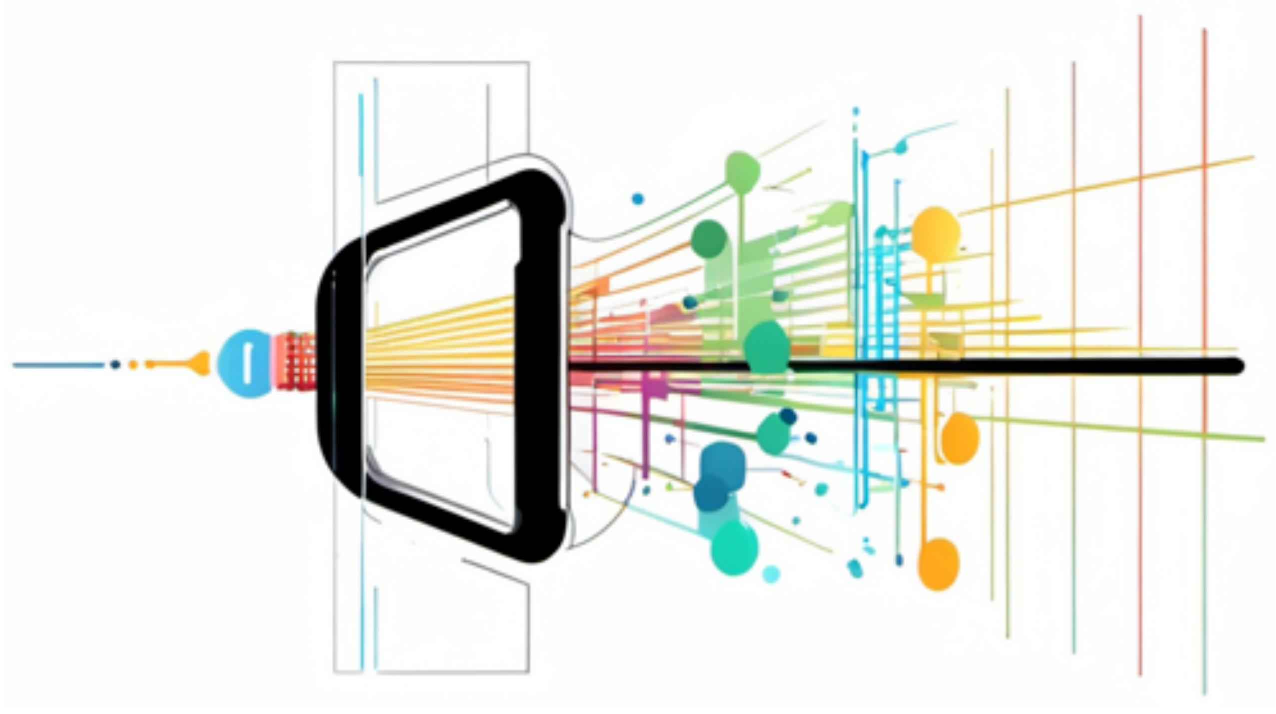
Updates to the magnetic field map

M. Bachmayer, F. Blanc, R. Quagliani, A. Venkateswaran

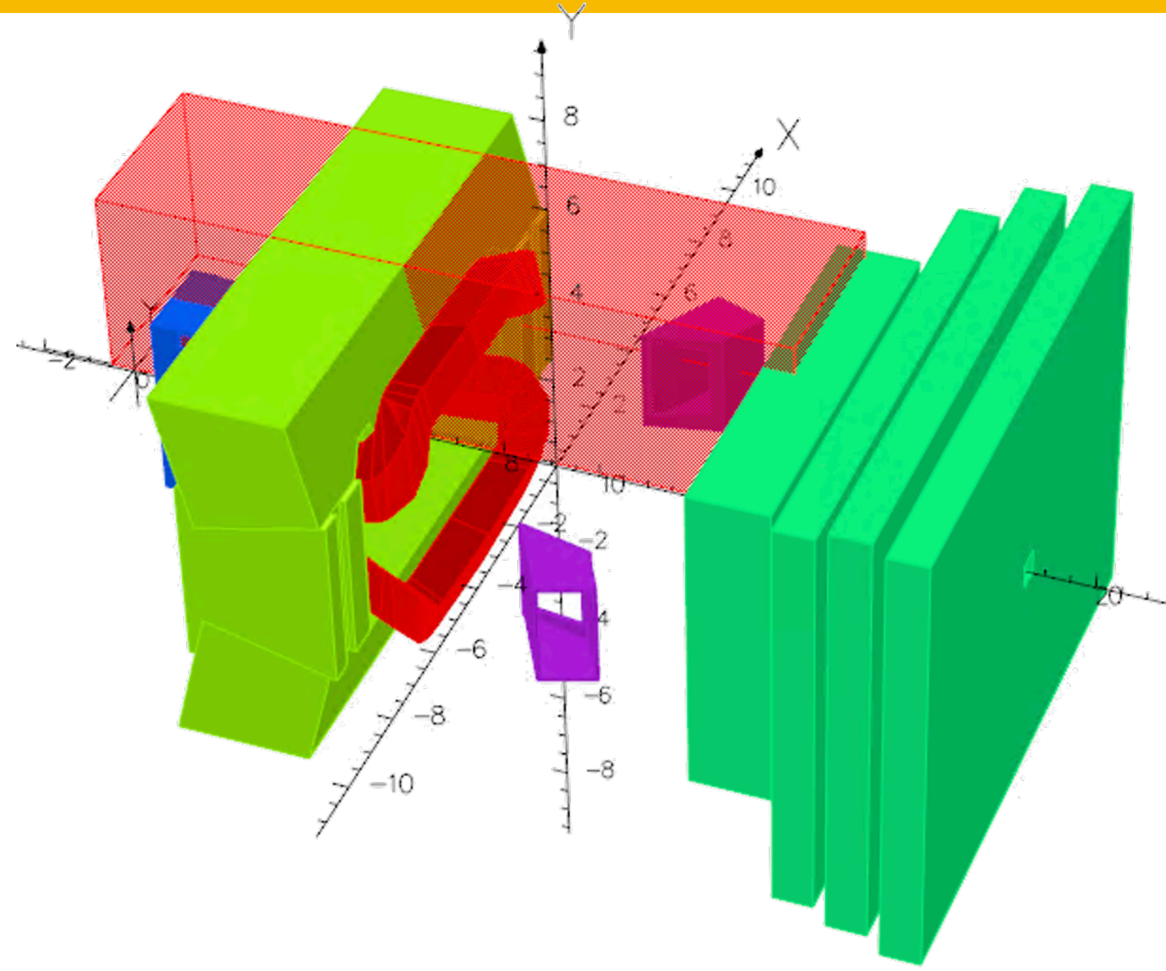


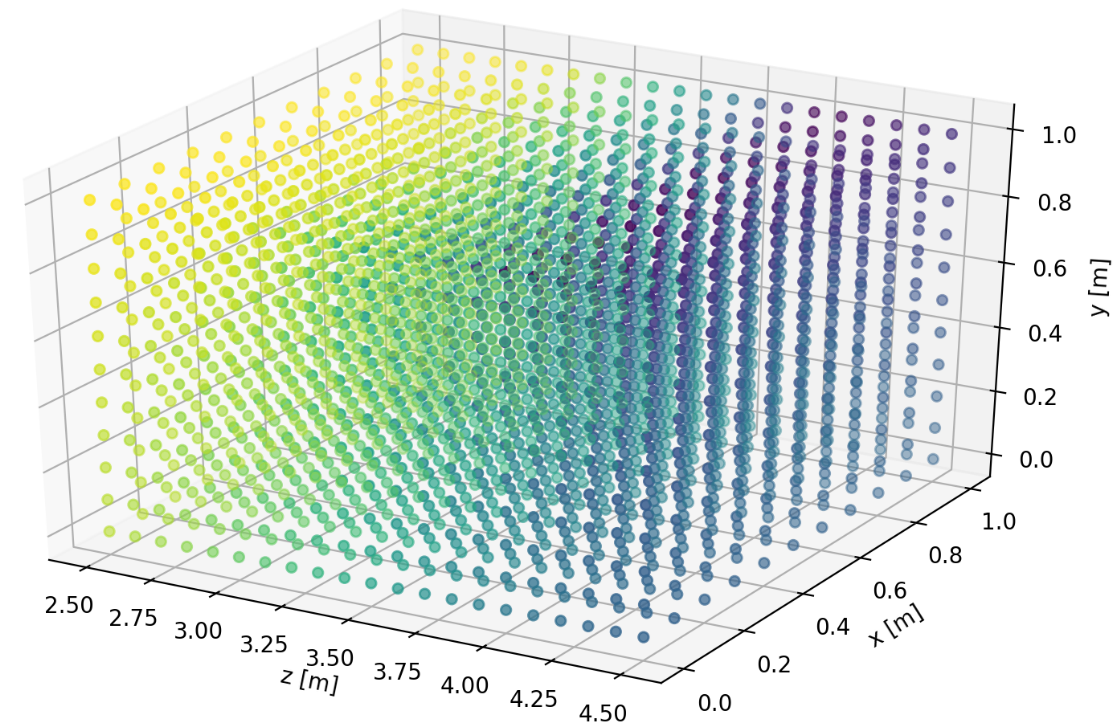
Outline

- Introduction: the magnetic field map - format and applications
- How to make a field map
- Ferromagnetic material in the detector environment
- Field map validation on data: strategies, results, and limitations
- U2 studies: removing the RICH1 shielding

The B field map

- ✦ Grid of 10cm x 10cm x 10cm of Bx, By, Bz values
- ✦ One map per quadrant from (x,y,z) = (0, 0, -0.5m) to (4m, 4m, 14m)
- ✦ 4 maps à 41 x 41 x 146 points
- ✦ Same maps (*-1) for MagUp and MagDown
- ✦ In simulation/reconstruction: linear interpolation of field components from surrounding points





The simulation suite

- OPERA is a a suite of multiphysics analysis programs that use finite element discretisation
- TOSCA / TOSCAMAGN is (the old name for) OPERA magnetostatic solver
- The first LHCb field maps were partly based on OPERA simulations
- Received an Opera model file from David Websdale, which is the basis of the current nominal model

Field map history

- The first LHCb field maps were partly based on OPERA (TOSCA) simulations

- Subsequent maps were made by fitting translations, rotations and scale factors to fit the field from simulation to measured field values

- We used the CAD model from those first maps as the basis of the current nominal model

- Aim: make simulation model correspond more closely to the real detector, so as to need fewer corrections

- Most recent measured field values from January 2021

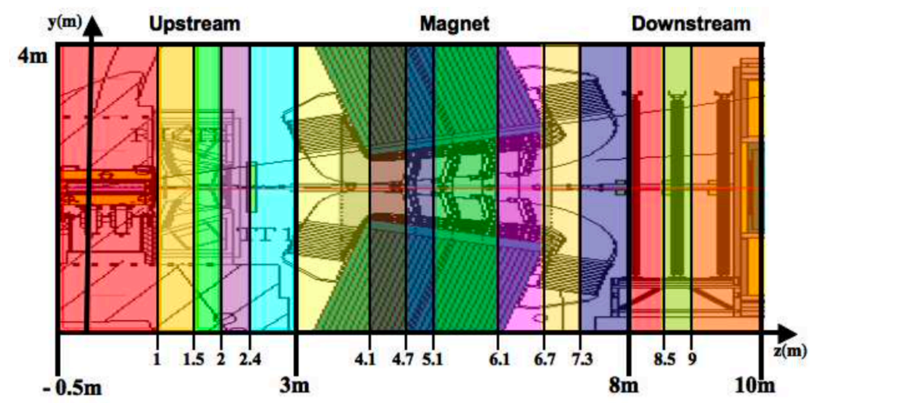
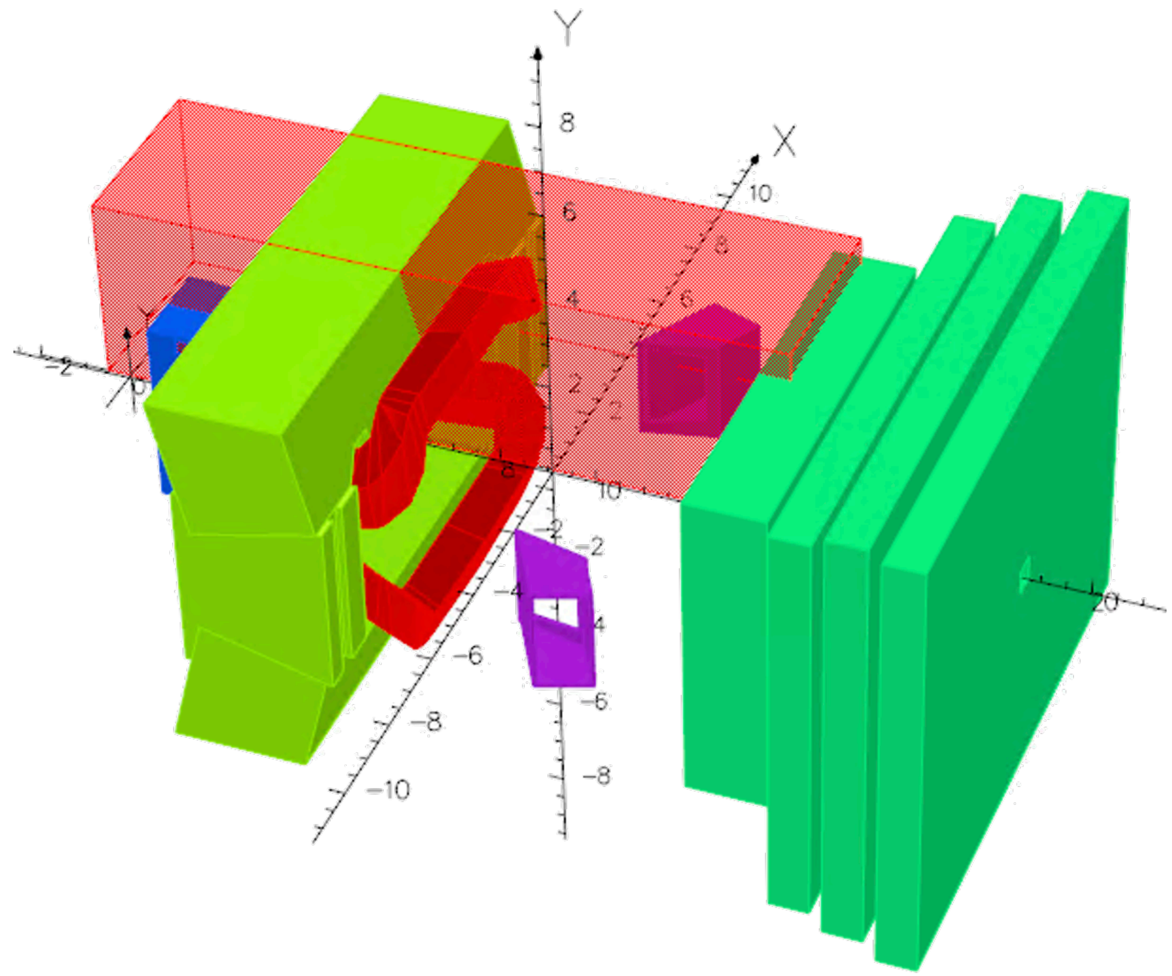
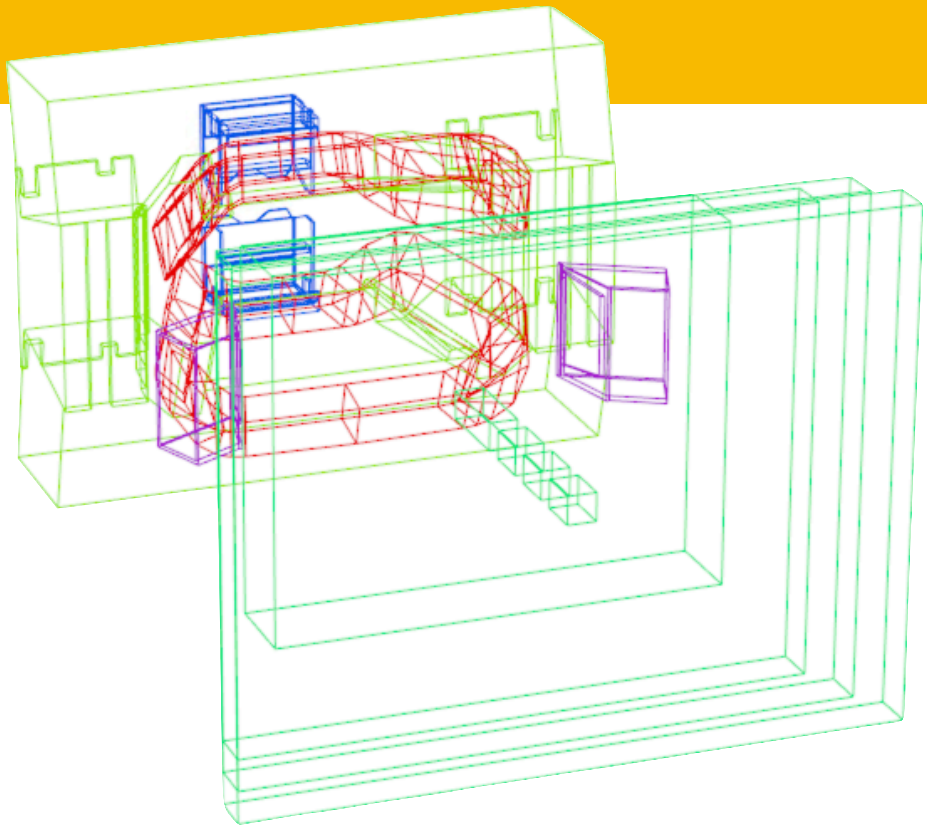


Figure 1 Set of cuttings along the LHCb z coordinate (black lines at z=100, 150, 200, 240, 300, 410, 470, 510, 610, 670, 730, 800, 850 and 900cm) delimiting fifteen regions, in which the B_x, B_y and B_z component behaviours are independently described by analytic parameterizations.

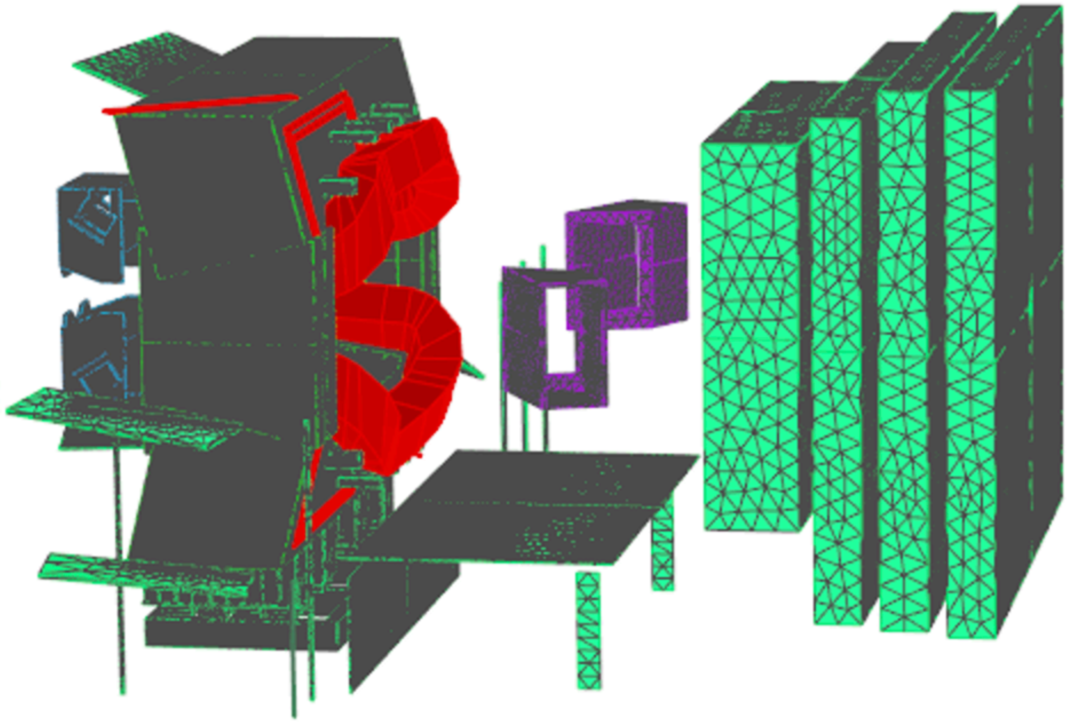
from LHCb-2007-093



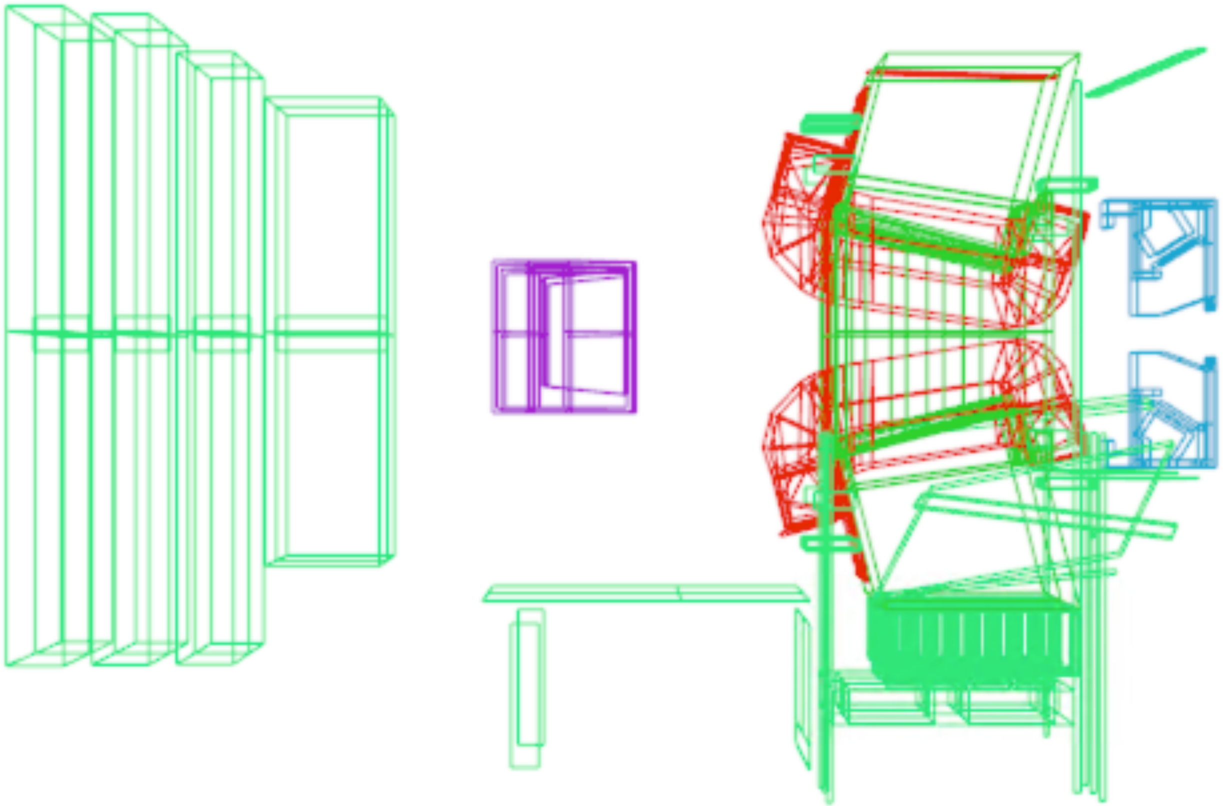
Changes to the simulation



- Basic Opera model file from David Websdale includes Coils and magnet yoke, RICH1 & RICH2, HCAL, and Muon stations
- Important changes made to simulation / model:
  - Using all four quadrants
  - Smaller mesh size, especially in magnet region
  - Iron yoke under magnet
  - Bunker (steel-reinforced concrete)
  - "Clamps" holding coils
  - Scaffolding material in environment
  - Orientation of pole faces based on survey results
  - Make coil current uniform + correct current value
  - Current lines that feed coils
  - Coils "opening" due to field



Reinforced concrete

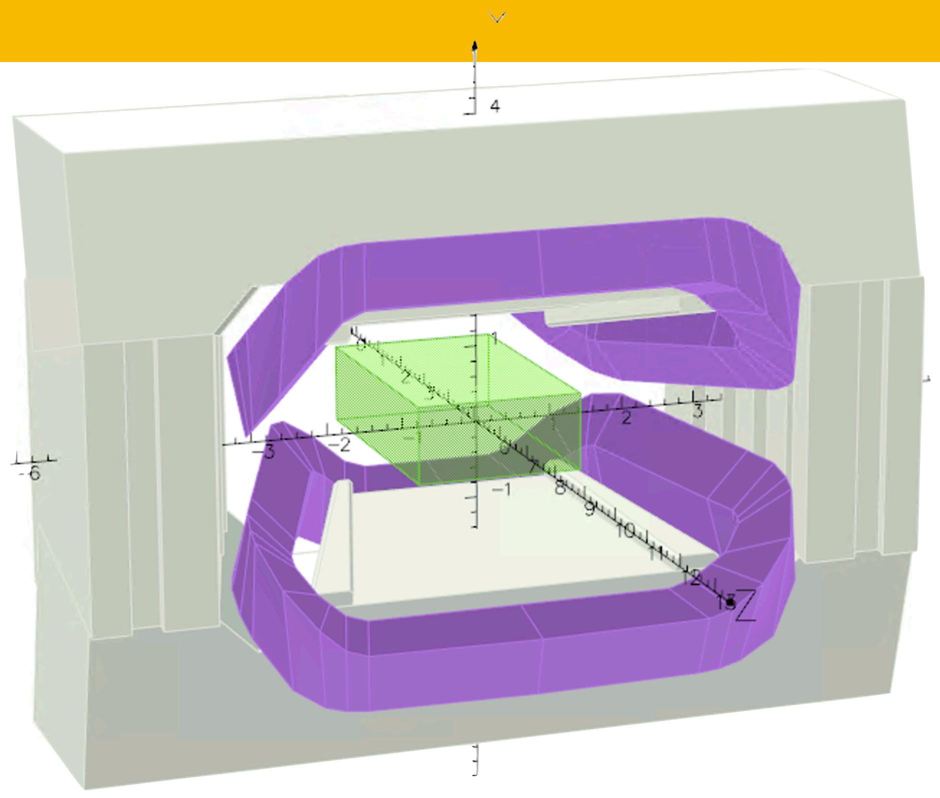


- UX85 cavern floor and walls are made of reinforced concrete, which generally contains about 2% steel
- Simulation studies show that this can influence the magnetic field
- Drawings of the cavern, Velo alcove, etc. often do not have information about the steel in the concrete
- Have this information for the bunker → included in simulation model

Post-simulation corrections

- Due to finite mesh size in the FEM simulation, the field values given by OPERA have fluctuations up to 1 mT
  - Get smoother field map from interpolation from surrounding field values
  - Using a Maxwell-compliant interpolation method developed by Pierre Billoir
- Grid points inside yoke may be used for tracks near acceptance boundaries - these are discontinuous with the field values in air
  - Assign extrapolated values from nearest cubes that are fully in air

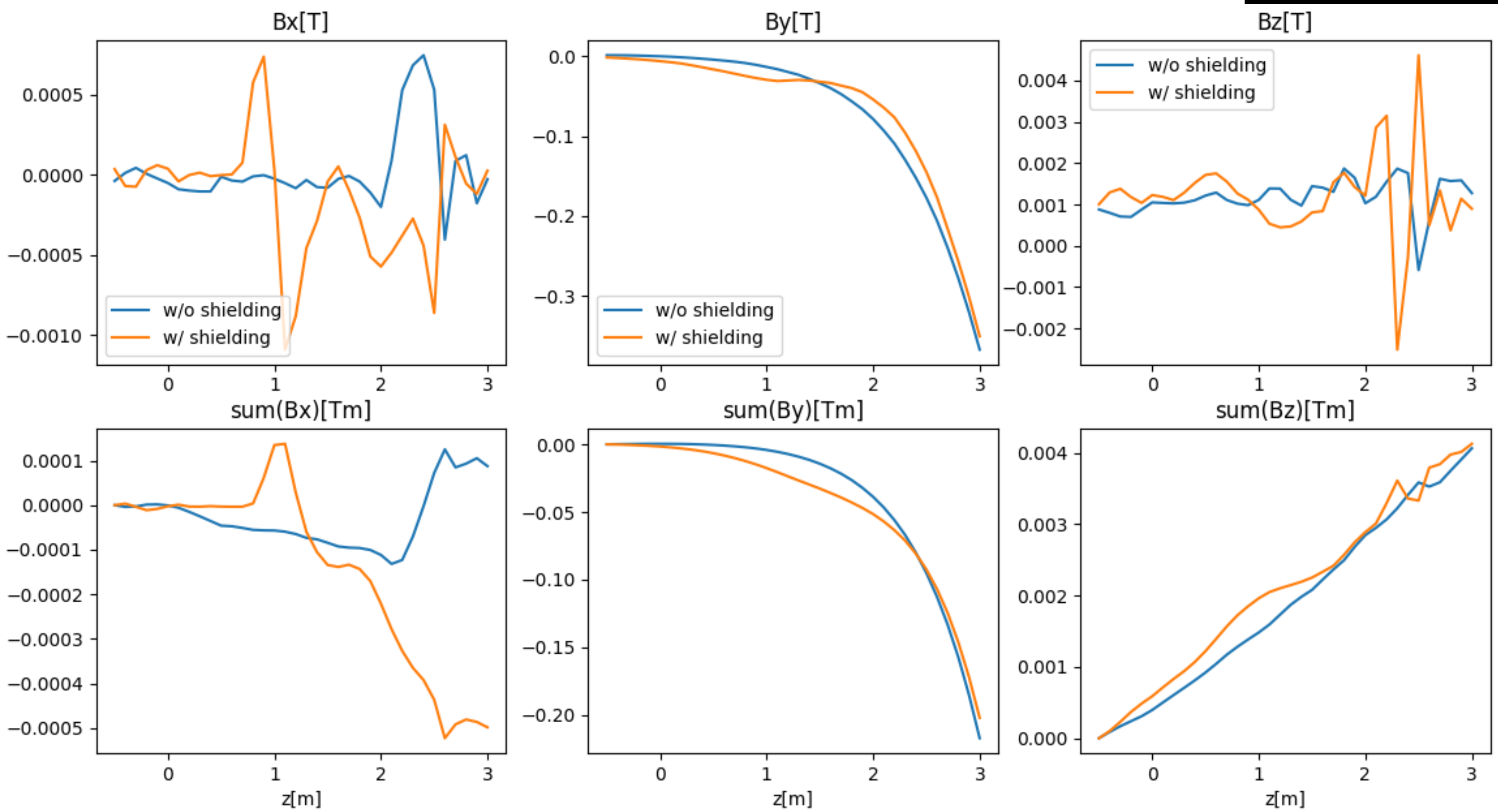
Data-driven adjustments



- Field measurements from Jan 2021 cover central region of magnet: x ∈ [-1m, 1m], y ∈ [-0.5m, 0.5m], z ∈ [2.5m, 6.02m]
- Minimise difference to simulated field by allowing a translation of the yoke and coils
    - Shift whole field virtually instead of re-simulating at every fit iteration
    - Fit yields a ~2cm downstream shift
    - Can also allow for scale factor of ~0.996, but should it be applied everywhere?
- More local: adjust field to match data, in central region only

Removing the RICH1 shielding (1)

Study by Renato Quagliani

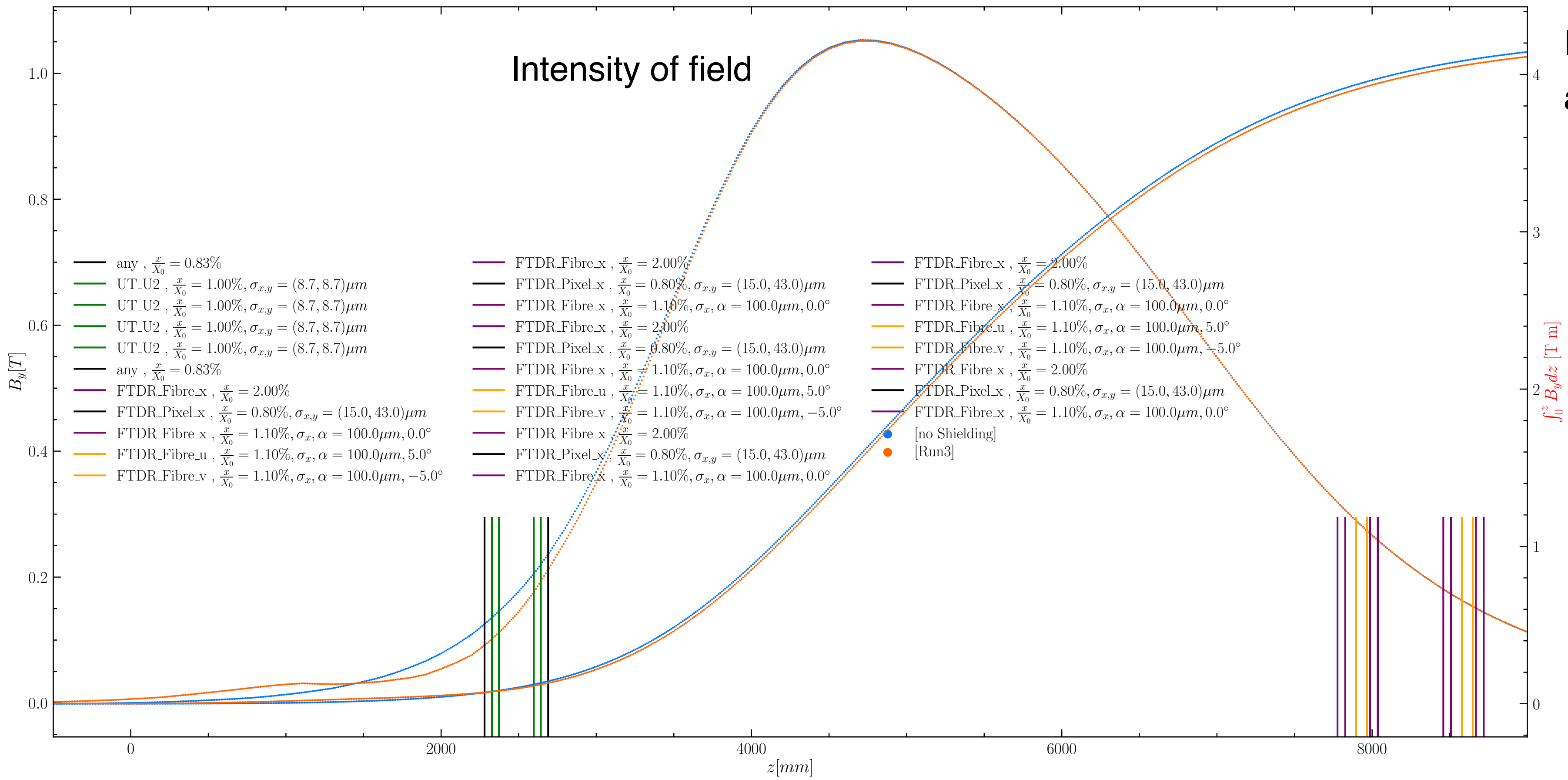


- Shielding guides field lines upstream
- Without shield, have
  - Lower field tails in Velo region
  - Smoother field in upstream region

Removing the RICH1 shielding (2)

Study by Renato Quagliani

Scan over z of fields from maps with/without shielding

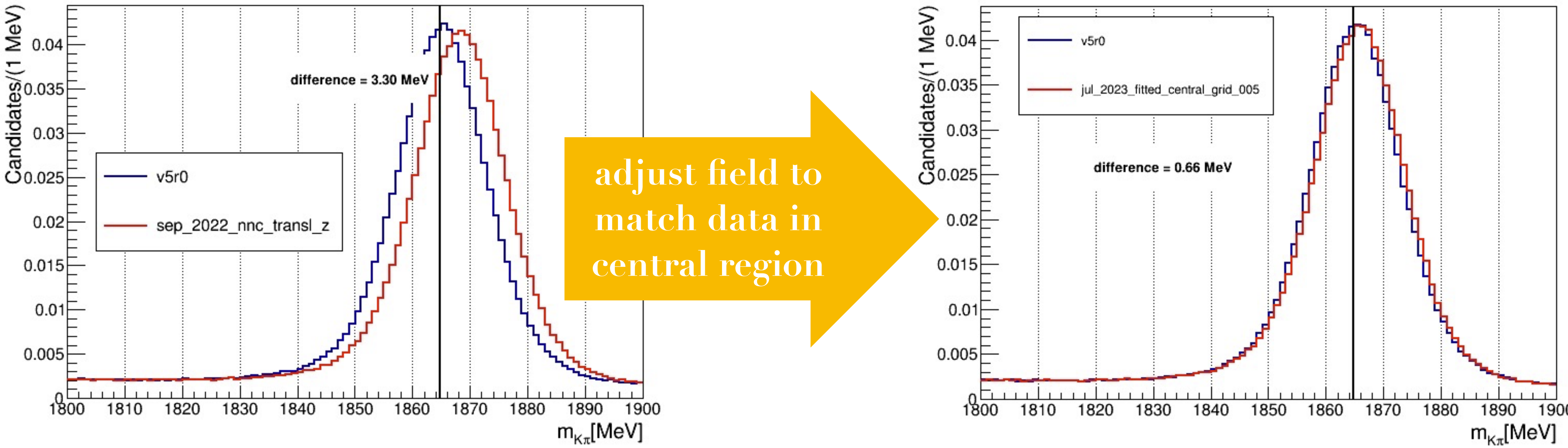


Integral of field along z for xy=(0,0)

- Study impact on track states resolutions using parametric geometry to describe multiple scattering, but no energy loss
- Forwarding track states: small improvement in p-resolution of Velo-UT exit tracks (15% rather than 20%)
- More smooth field, lower in Velo, higher in UT

Testing the new map on data

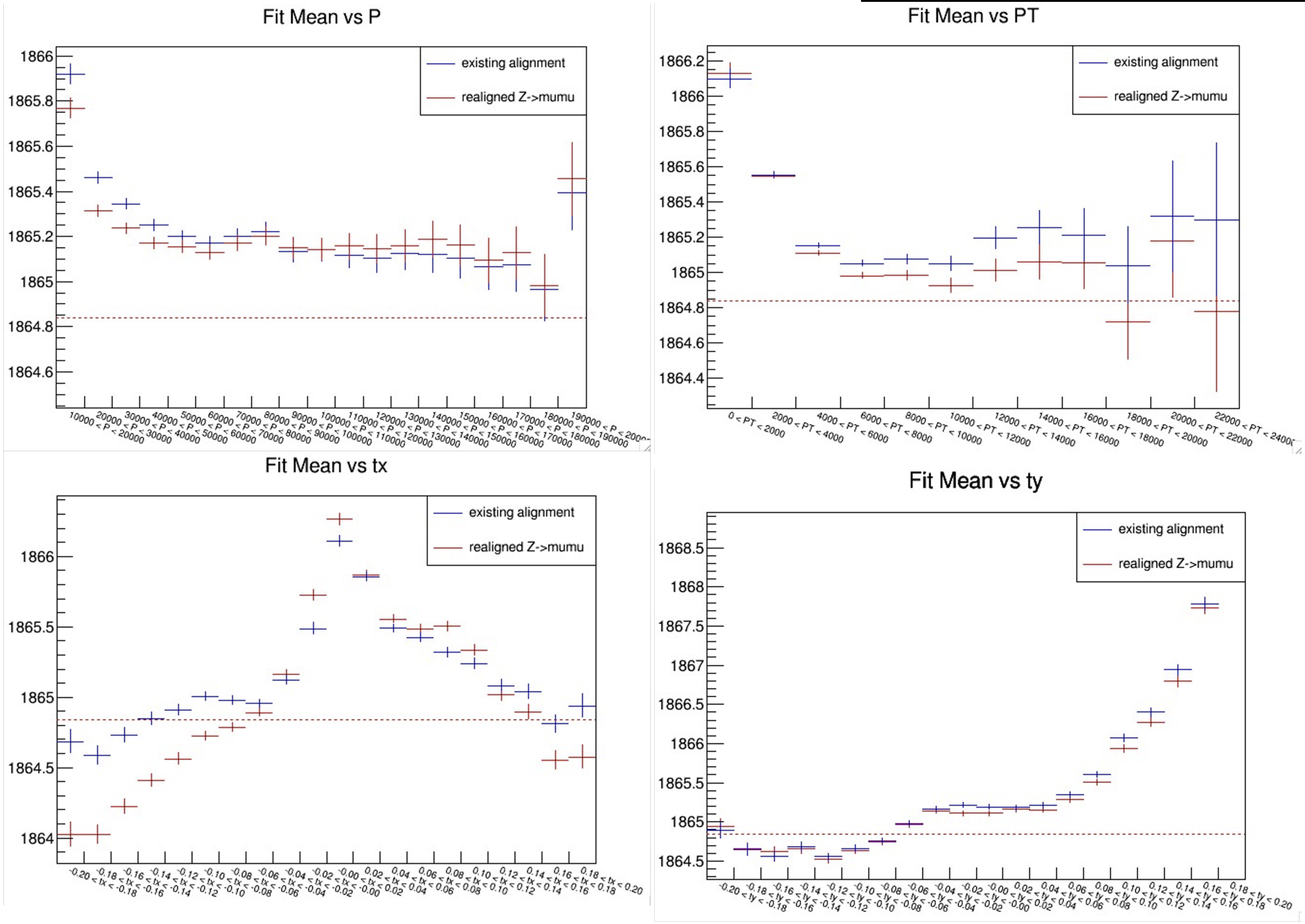
Work by Arvind Venkateswaran



- Field map validation on fully reconstructed data
- Compare with most recent LHCb field map (v5r0)
- Draw conclusions on field regions that need better description, global/local scale factor, etc.
- Need to be careful with (re-)aligment

Mass profiles in map v5r0

Work by Arvind Venkateswaran



- Difficult to disentangle field map and alignment effects

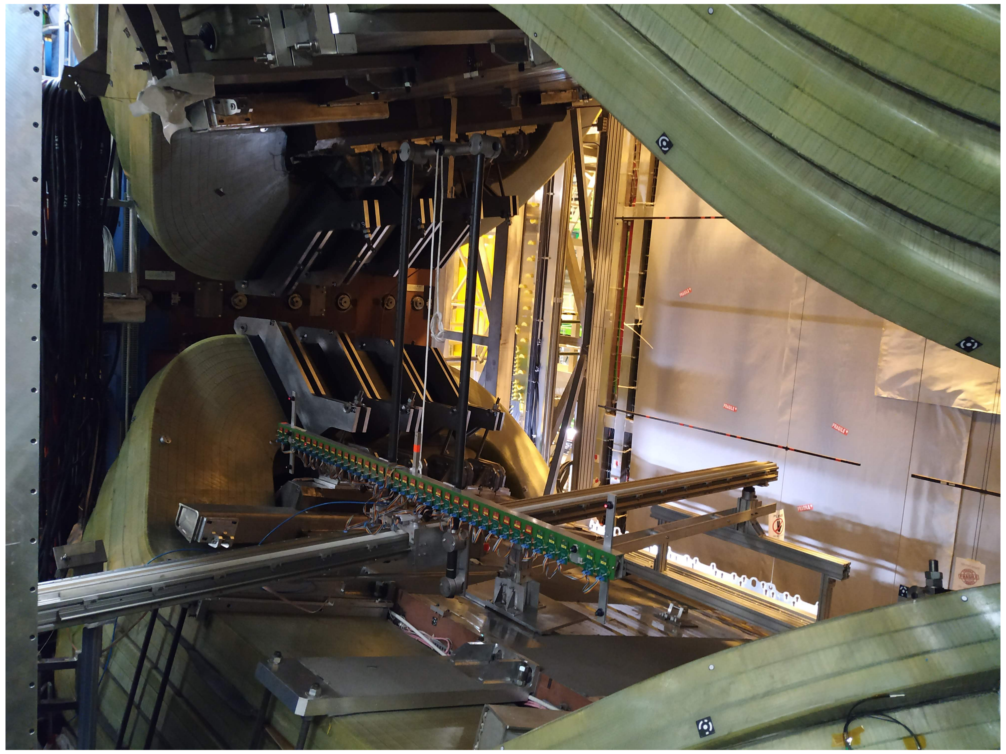
Conclusion & plans

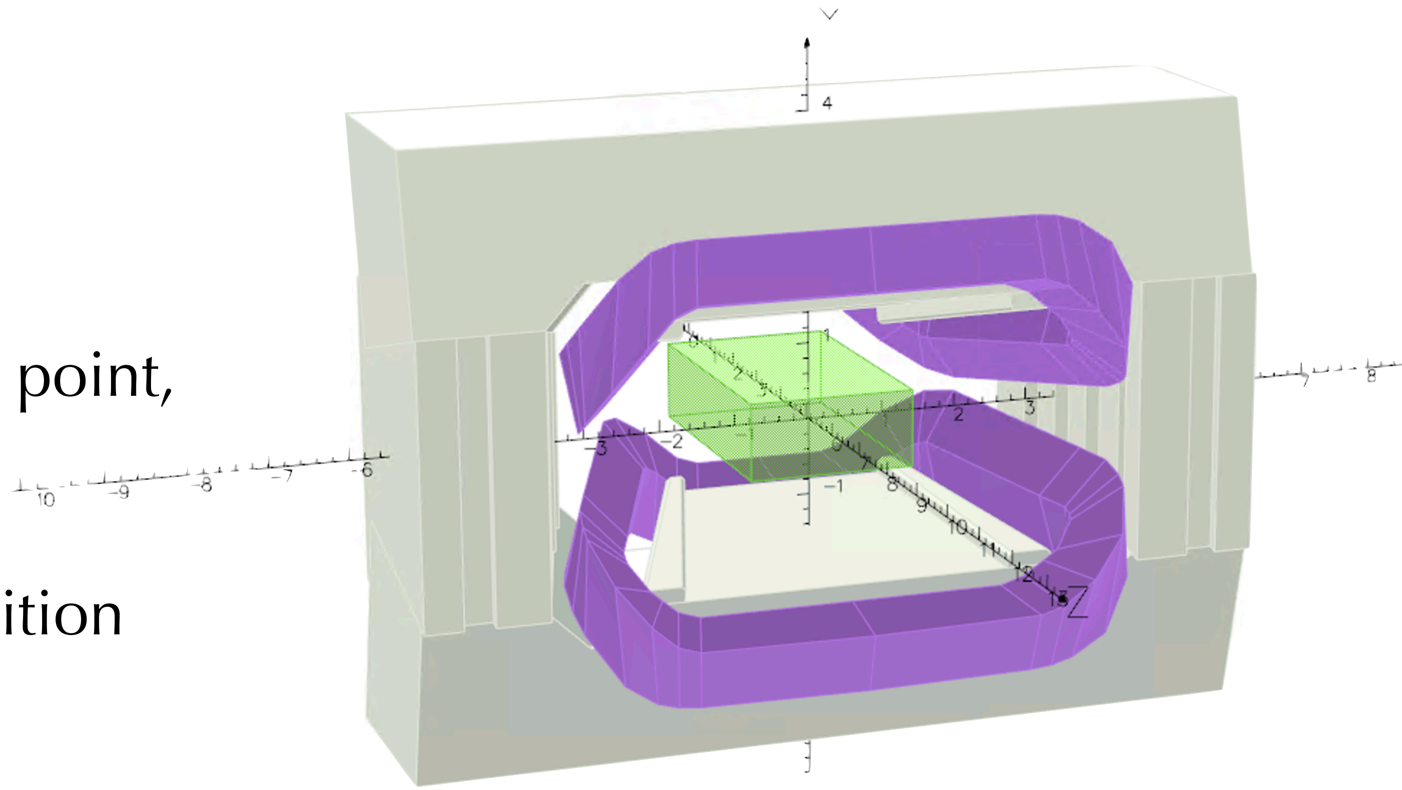
- Opera simulation + field measurement data → adjusted field map
- Reinforced concrete?
- Further input from collision data: mass profiles in x, y, tx, ty, p
- Alignment ⇄ magnetic field
- U2 studies: removing the RICH1 shielding smooths upstream field
- Currently: adding latest model changes, testing diff. field correction methods on collision data

BACKUP

Measurements of the field in situ (January 2021)

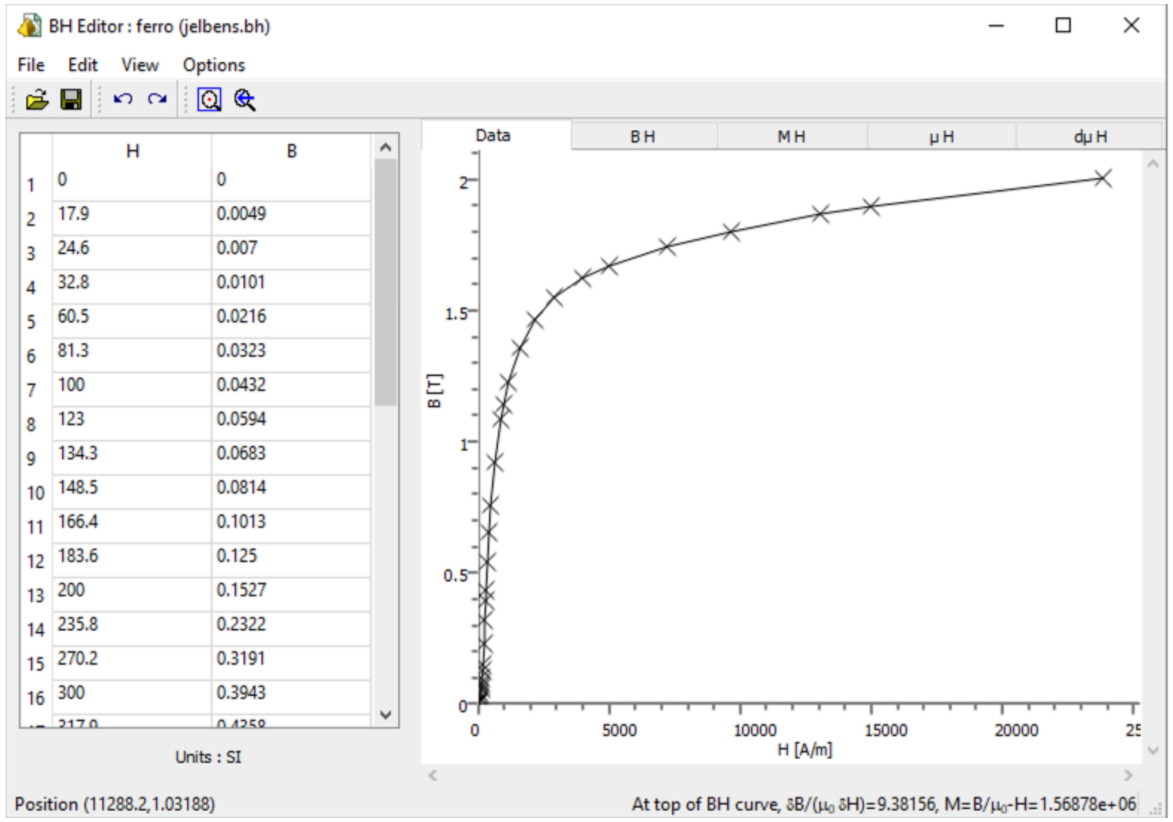
- Measurements made by the CERN group:
  R. Dumps, F. Garnier, P.-A. Giudici, N. Pacifico, P. Sainvitu, H. Schindler, A. Zemanek
- Positive and negative polarity
- 37 * 3 Hall probes mounted on bar in x-direction: $x \in [-1m, 1m]$
- 29 positions in z: $z \in [2.5m, 6.02m]$
- 3 - 5 steps in $y \in [-0.5m, 0.5m]$
- Survey of target positions in situ
  + detailed measurements of bar in lab
  = precise location of each sensor at each point, rotation of bar
- Recorded B field values 10 times per position (once every 5s)



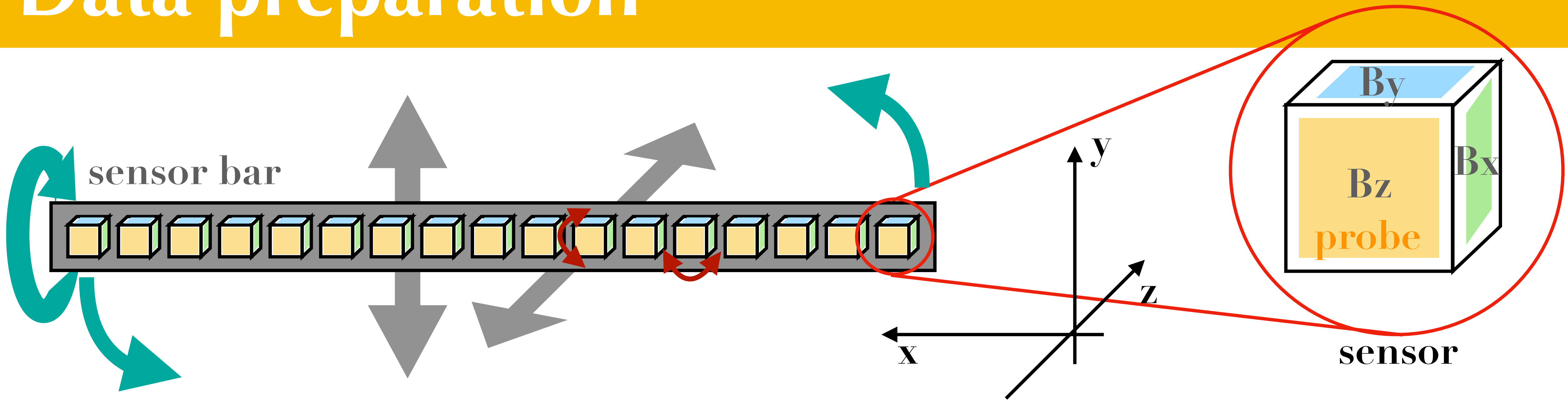


Simulation parameters

- Materials defined by B-H curve: one for magnet and Hcal/Muon and one for RICH
- Adjustables:
  - Mesh
    - Element size
    - Maximum angle
    - Surface tolerance
    - Algorithm
  - Material properties (nonlinear, isotropic)
  - Field calculation method (nodal interpolation, magnetization integral)
  - And *many* more



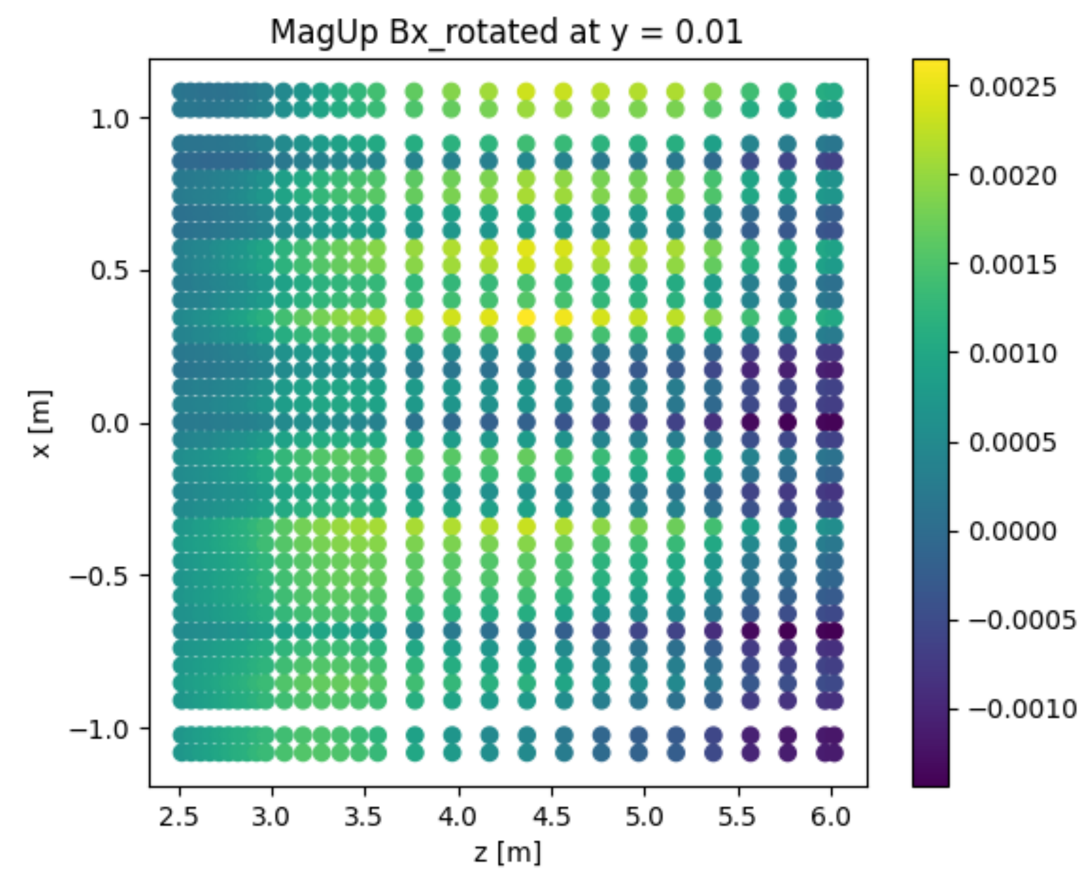
Data preparation

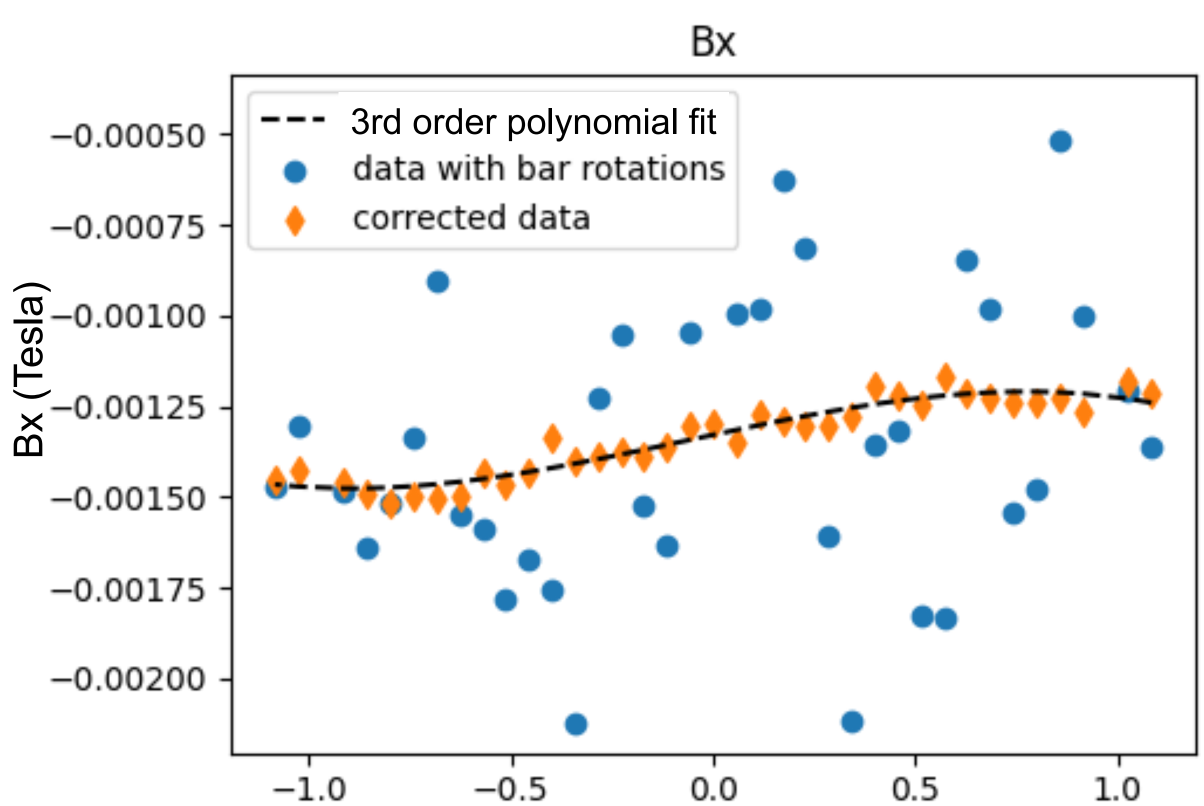


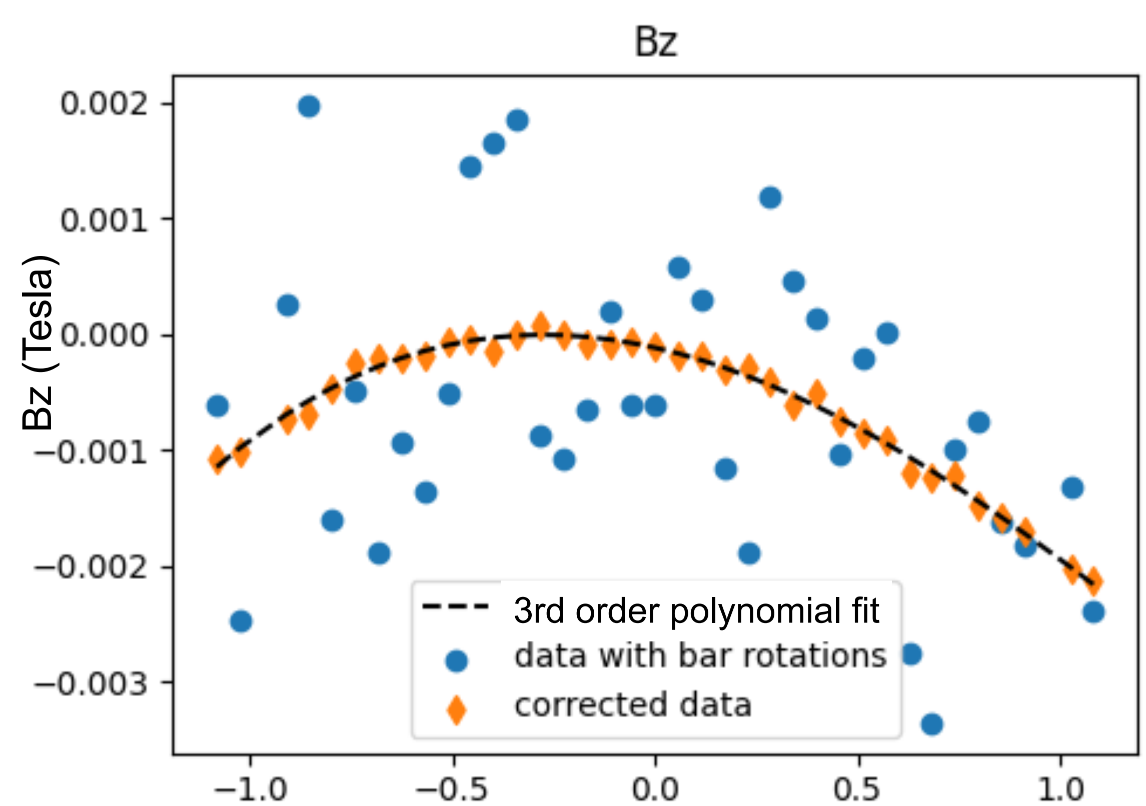
- 37 sensors mounted on bar which can be moved in y and z
- 3 probes per sensor glued onto cube
- Probes were calibrated by the CERN group; accuracy O(2 Gauss)
- Survey of target positions in situ
  + detailed measurements of bar in lab
  = precise location of each sensor at each point, rotation of bar
- Survey supplied rotation parameters for the bar
- Data-driven correction applied to data to decrease influence from sensor rotations with respect to each other - NB: method not sensitive to global rotation
- Semester project with Natalia Feliks in 2021

Correction of measurement values

- Survey included rotation of whole bar, but sensors can be rotated with respect to each other
- Sensor A would pick up systematically more of By with its Bx probe than sensor B
- Fit smooth field progression in Bx and Bz along the bar
- Deviation from smoothness is linear with By for each probe







Correction of measurement values (2)

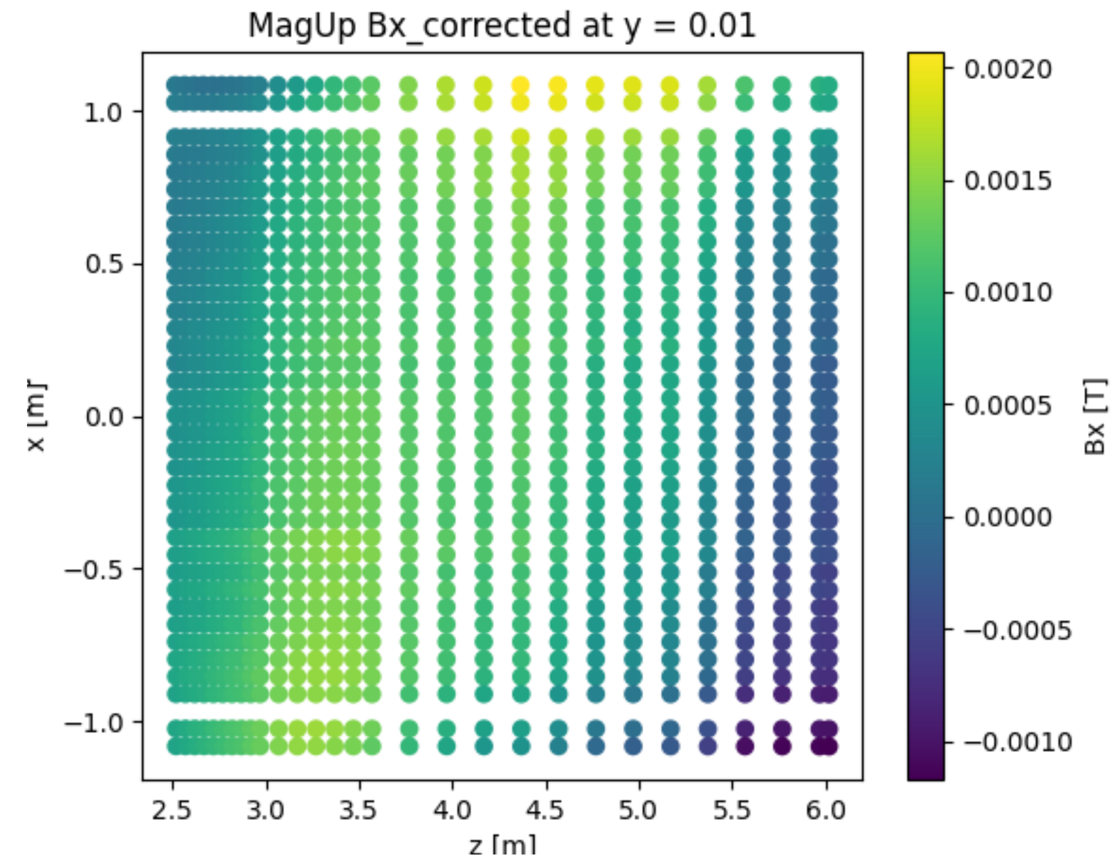
- Apply first-order correction:

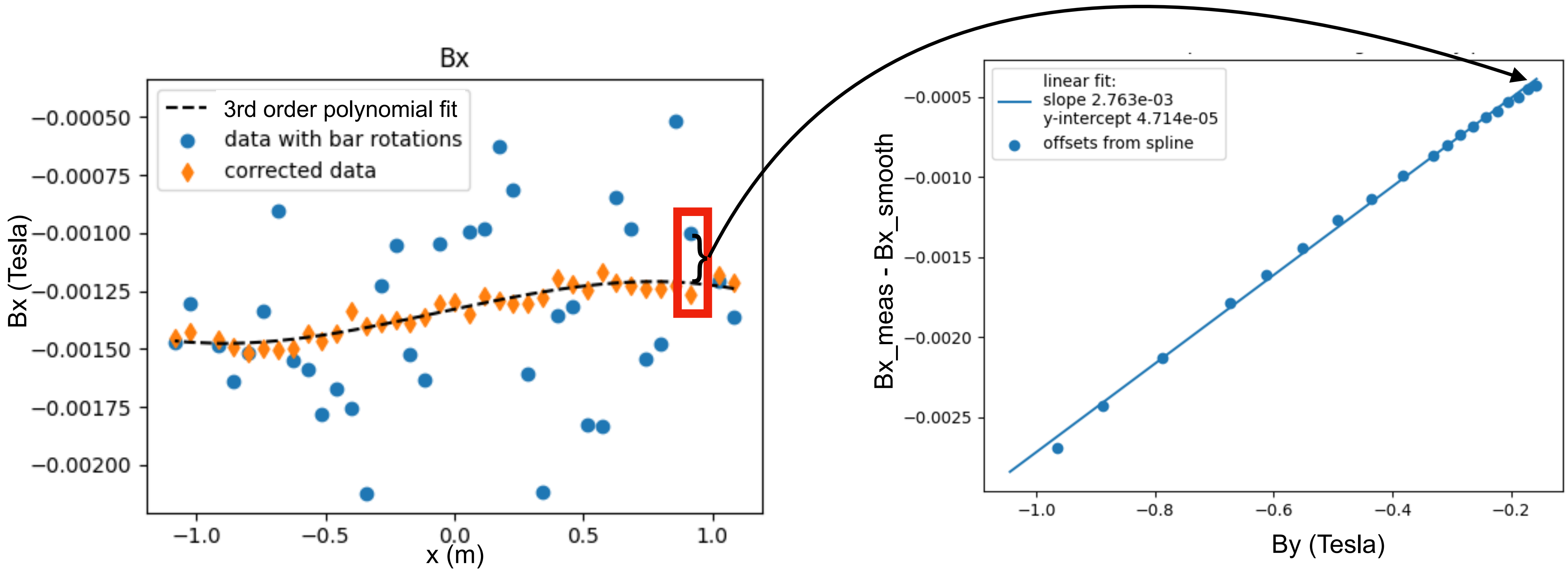
$$B_x^{\text{corr}} = B_x^{\text{meas}} - c_x B_y^{\text{meas}}$$

$$B_z^{\text{corr}} = B_z^{\text{meas}} - c_z B_y^{\text{meas}}$$

$$B_y^{\text{corr}} = B_y^{meas} + c_x B_x^{\text{meas}} + c_z B_z^{\text{meas}}$$

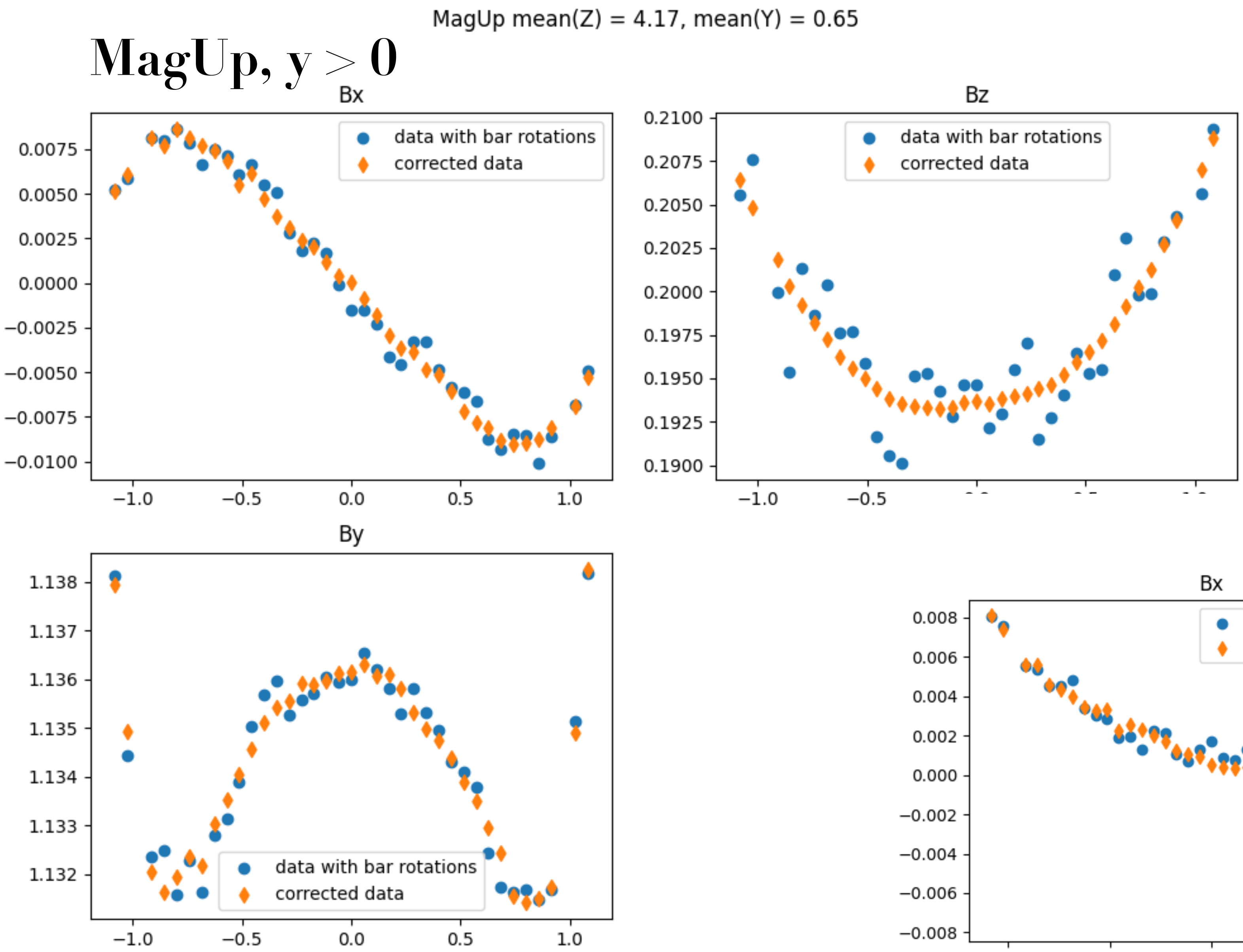
- Thanks to Natalia Feliks for important contributions to these studies



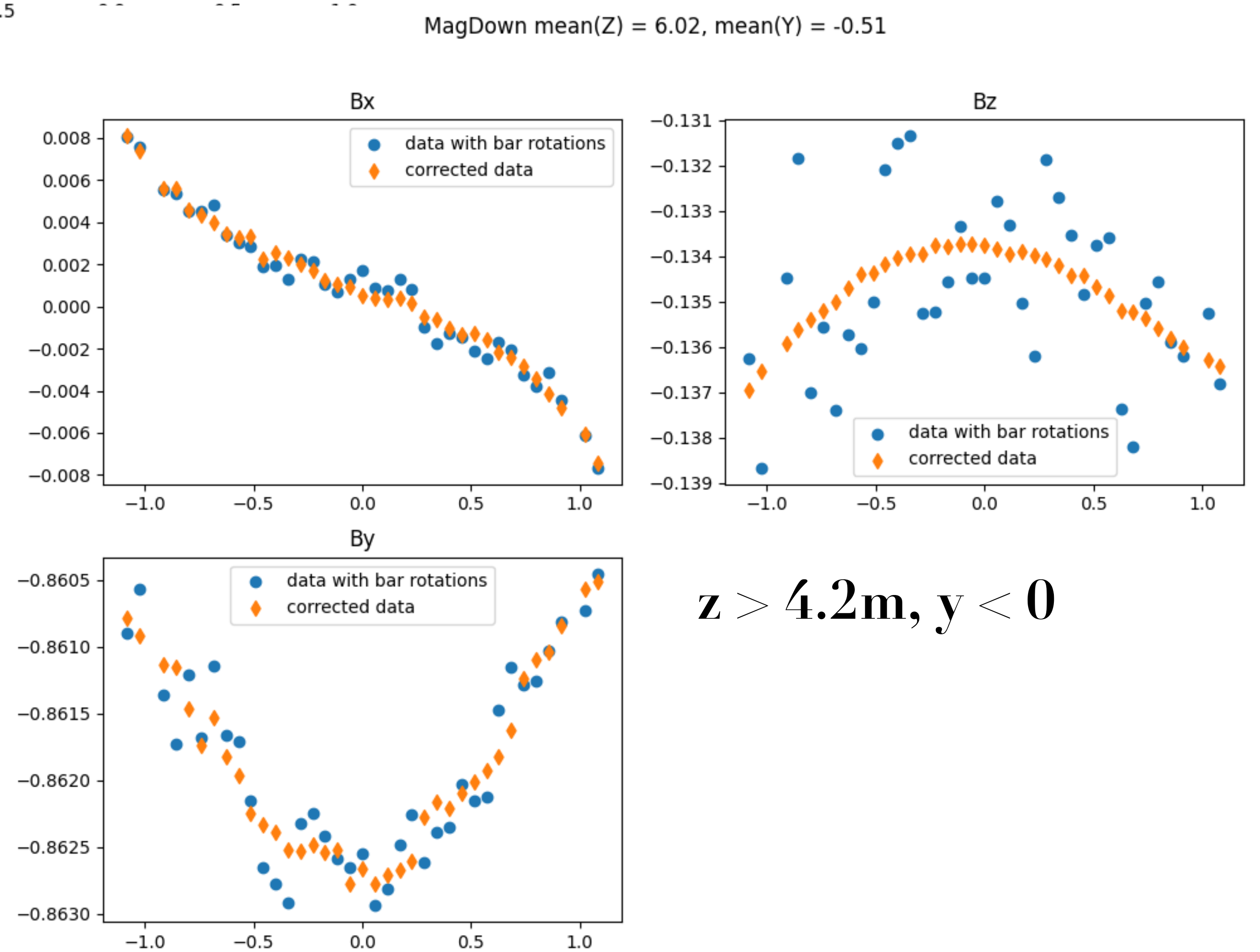


Correction of measurement values (3)

MagUp, $y > 0$



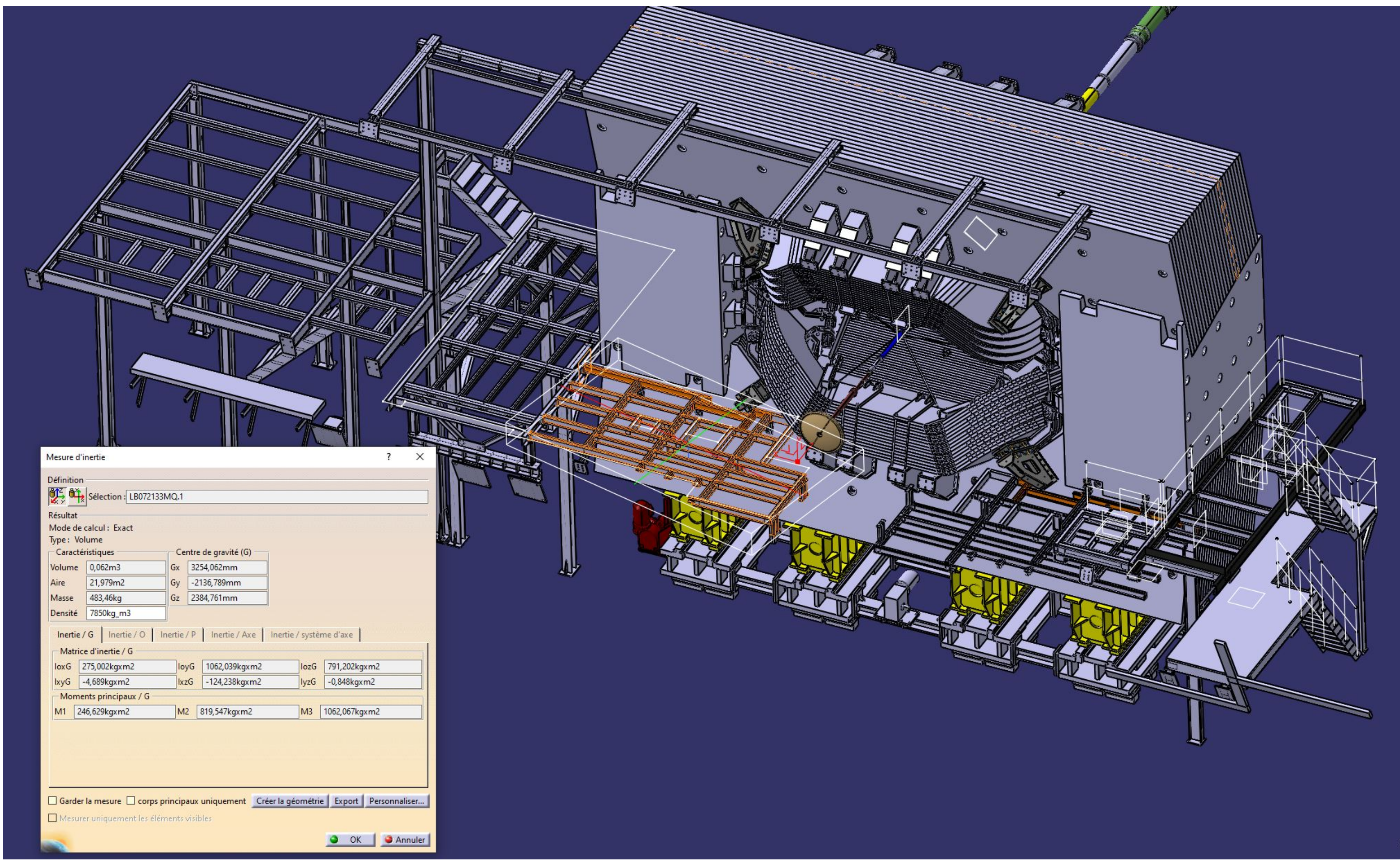
These data are outside the region used to calculate the correction coefficients

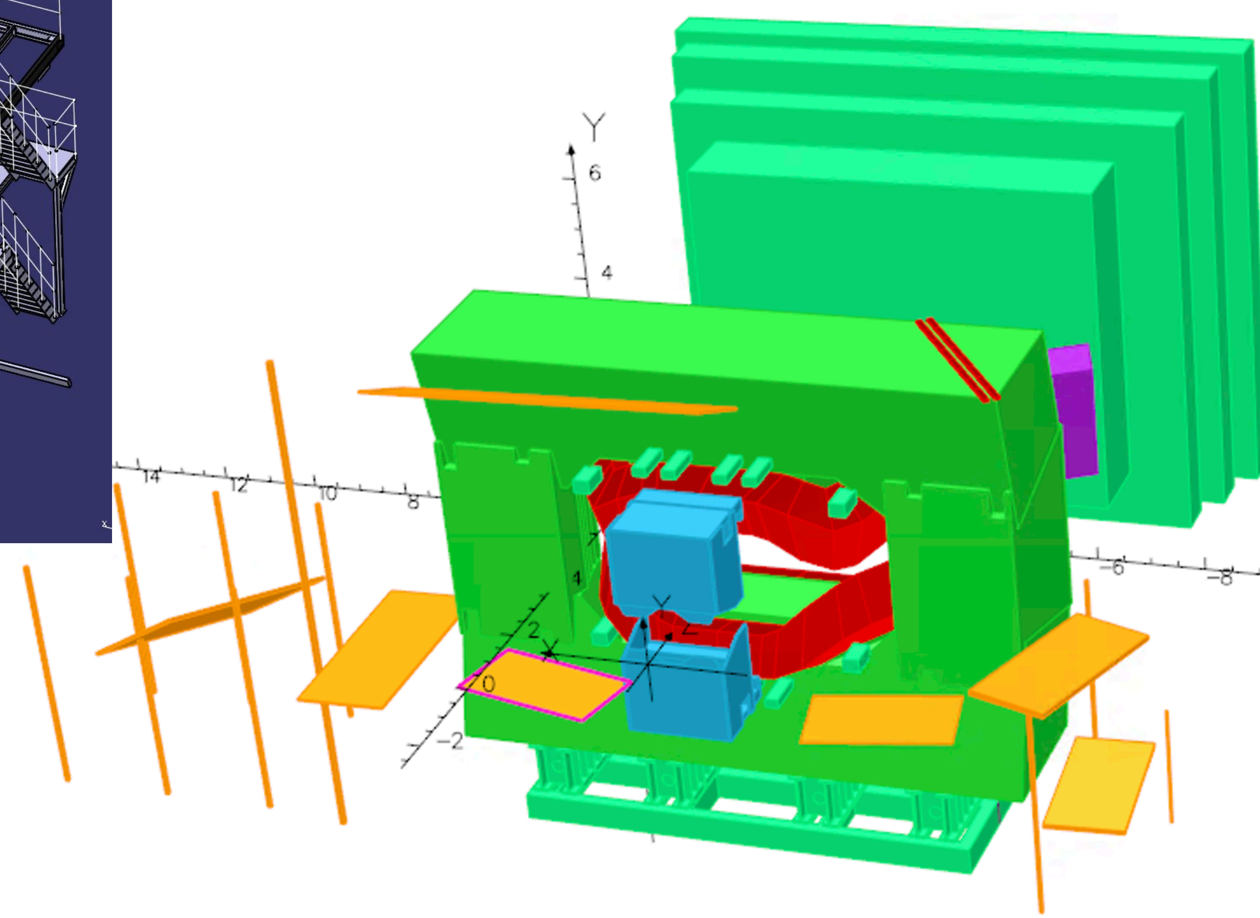


$z > 4.2m, y < 0$

Scaffolding

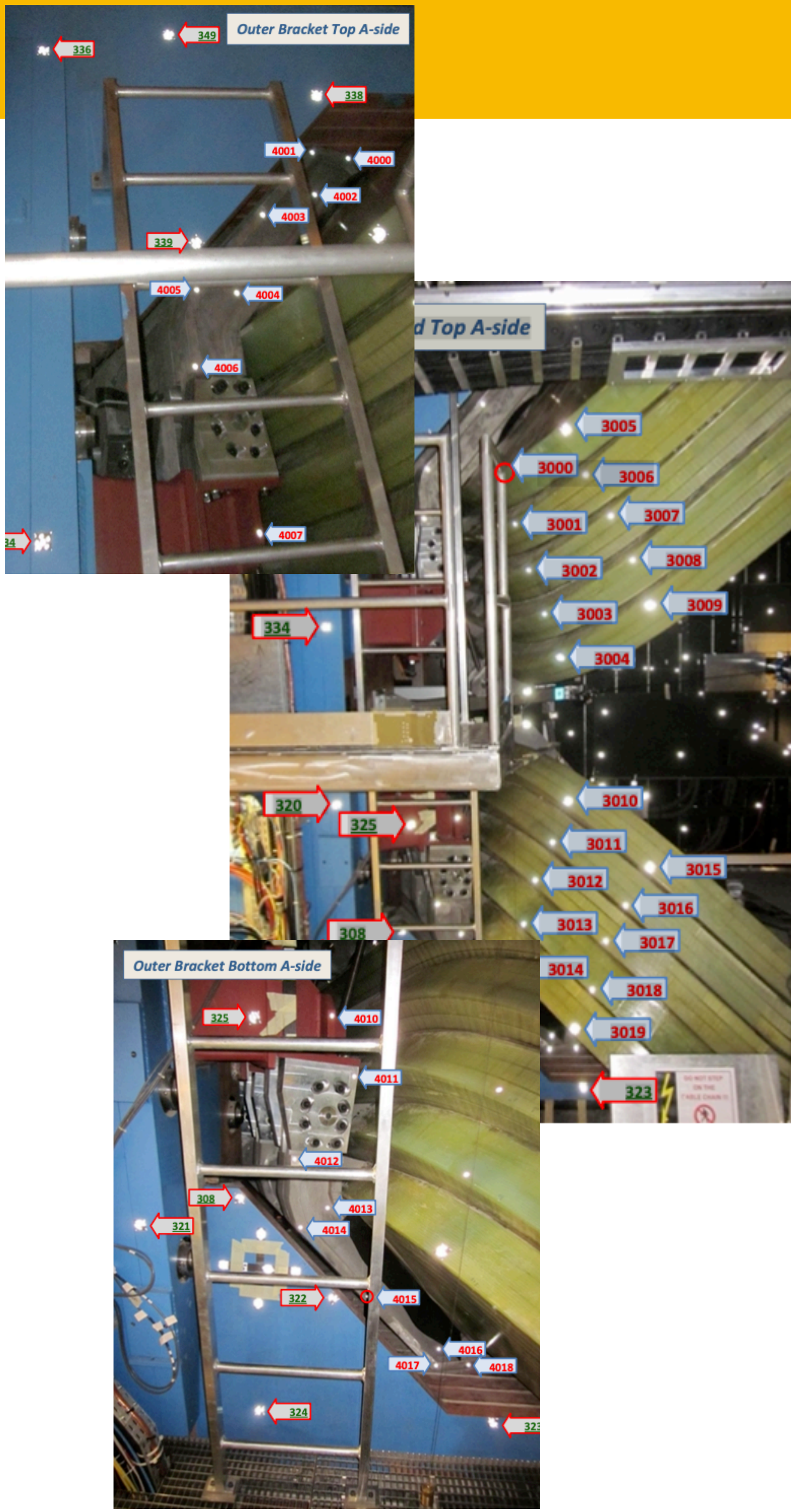
- Simplified description of each component so that volume, center of mass, and moments of inertia match





Coil opening

- From document Dipol_Magnetic_25062012 / EDMS N° 1231521 / Dipol_Photogrametry_25062012.pdf
- Points on coils, on yoke and on brackets
- Brackets not in sim, looking at coils and yoke
- Coils shift/open by several mm, in magnetic field, yoke by <1mm
- Neglect yoke shift
- Note: coil shift is significantly in z direction
    - Only have measurements of coil on IP side - should the z shift be an extension or a global shift of the coils wrt the yoke?
    - Inner brackets have some shift in z too, and extension makes little sense to me -> assume global shift



Backup: interpolation / smoothing

Given a field map is defined as a set of values (B_x, B_y, B_z) over a cubic grid of spacing L in the three directions x, y, z, we want to obtain the best second degree approximation over the eight points of an elementary cube, obeying the Maxwell equations in a non magnetic region:

$\partial B_x/\partial x + \partial B_y/\partial y + \partial B_z/\partial z = 0$

$\partial B_x/\partial y - \partial B_y/\partial x = \partial B_y/\partial z - \partial B_z/\partial y = \partial B_z/\partial x - \partial B_x/\partial z = 0.$

Setting the origin at the center of the cube and using the reduced coordinates $X = x/L$, $Y = y/L$, $Z = z/L$, we want to express the field components as:

$$B_x(x,y,z) = B_x^0 + B_x^x\,X + B_x^y\,Y + B_x^z\,Z + B_x^{xx}\,X^2 + B_x^{yy}\,Y^2 + B_x^{zz}\,Z^2 + B_x^{xy}\,XY + B_x^{xz}\,XZ + B_x^{yz}\,YZ$$

From Pierre Billoir's interpolation note

- Field values at grid points directly from Opera are subject to fluctuations $\mathcal{O}(10^{-4}$ T): intrinsic precision of simulation
- P. Billoir developed method for Maxwell-compliant interpolation of field values on cubic grid
- Will use this interpolation to smooth the field values on the grid points for the final map

Extrapolation