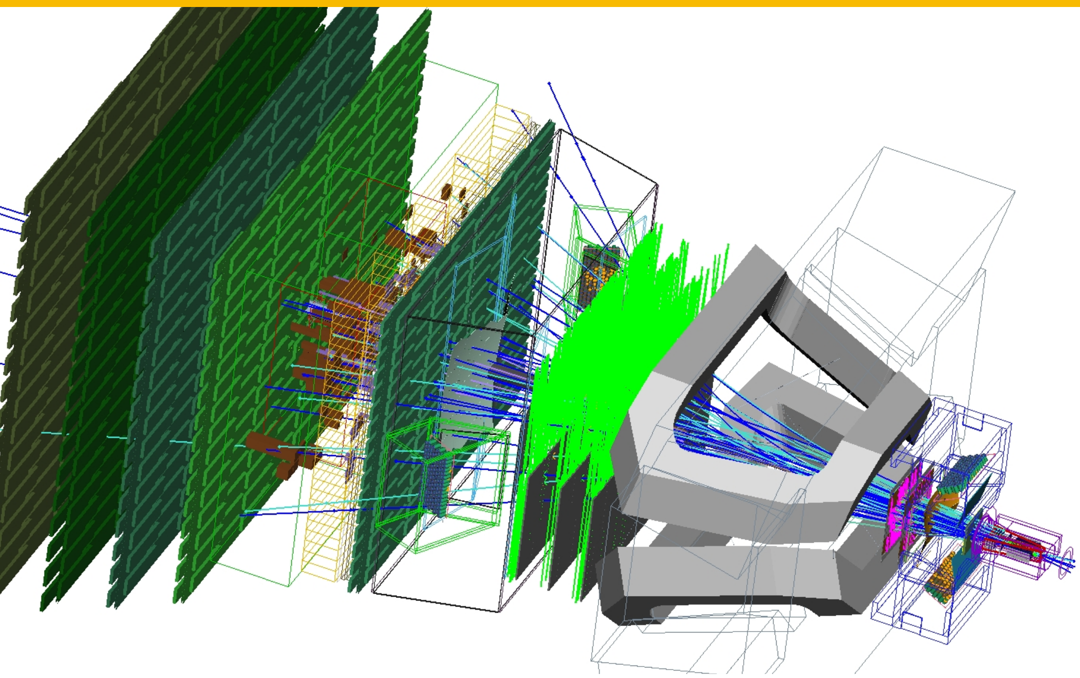
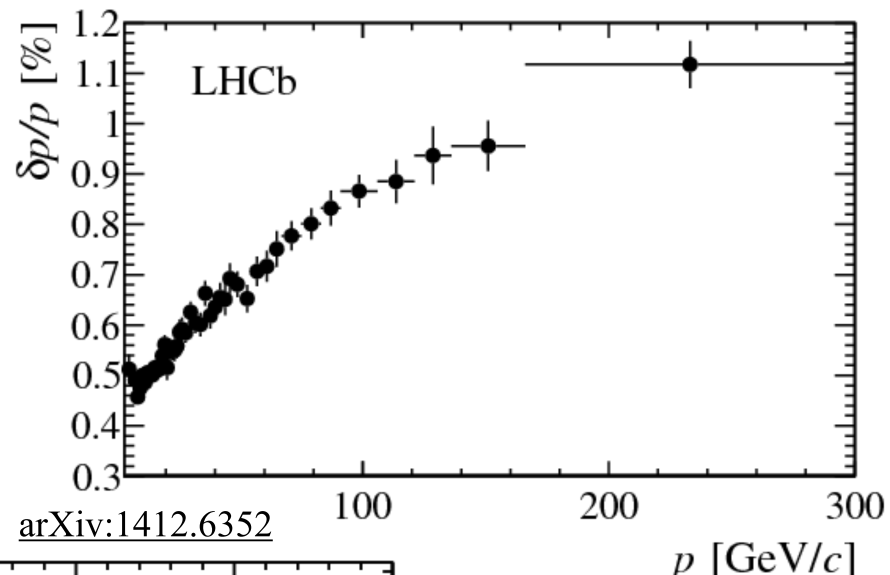
The LHCb magnetic field map

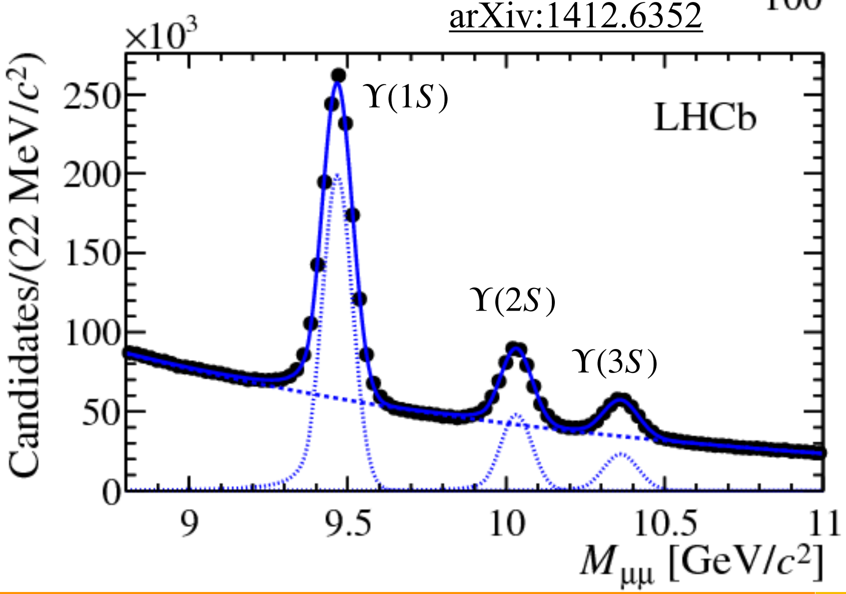
Procedure and updates

Track reconstruction at LHCb





arXiv:1412.6352



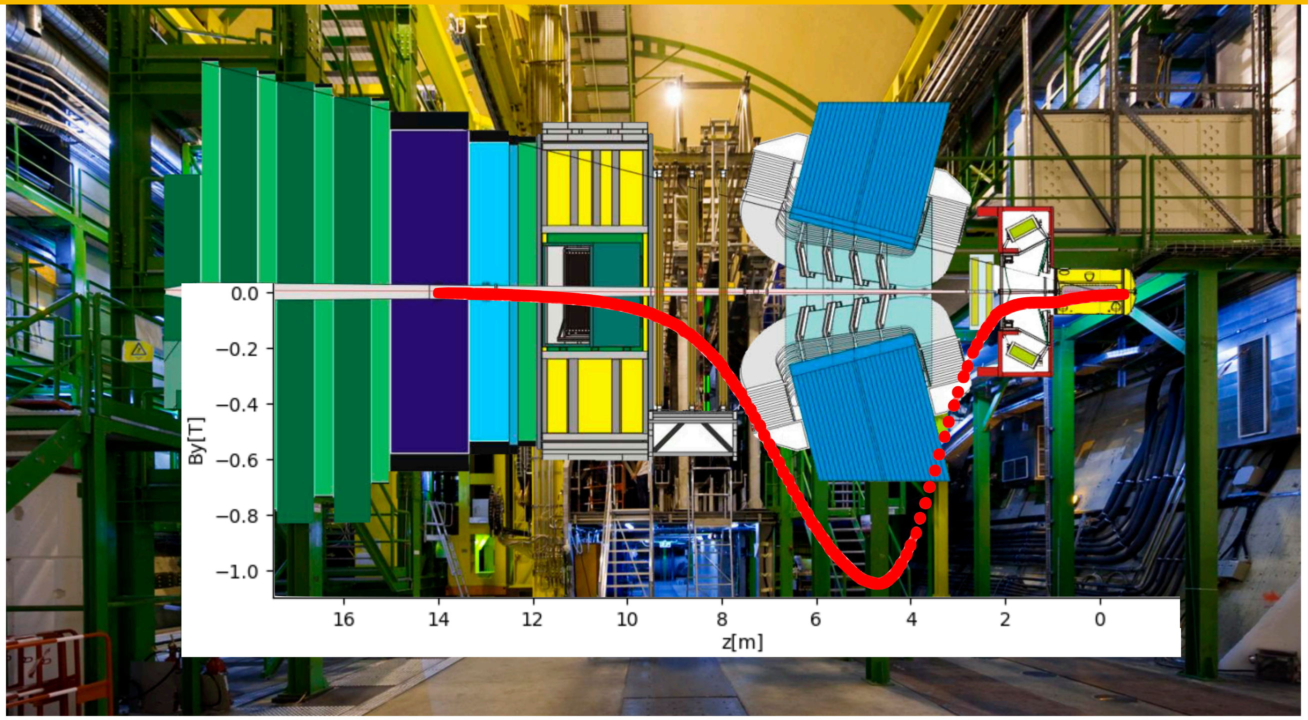
- Charge, momentum and direction of particles from collisions can be reconstructed using
  - Tracking stations
  - A magnetic field to bend the particle tracks
  - Reconstruction algorithm(s)

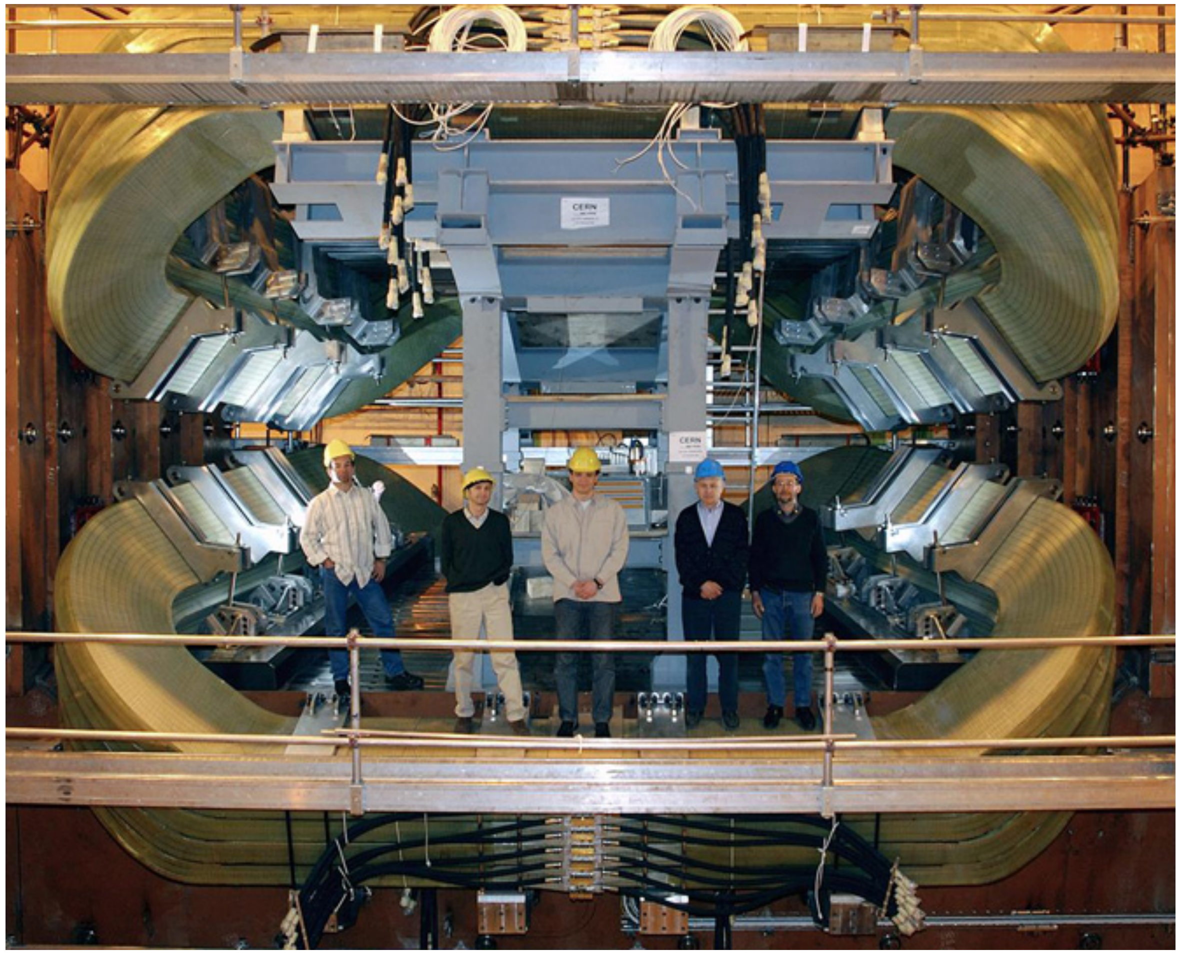
At LHCb, obtain relative momentum resolution of 0.5 - 1 %

- Need precise knowledge of the magnetic field for reconstruction and simulation

The LHCb magnet

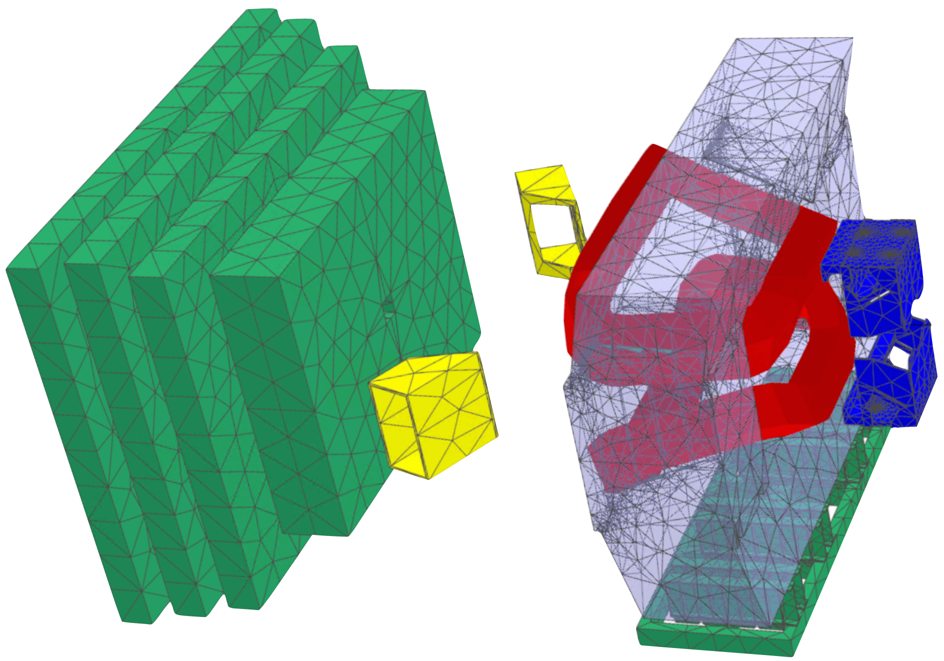
- ✦ Warm dipole magnet with water cooling
- ✦ Two 25-ton coils with 5.8kA current in a 1450-ton steel yoke
- ✦ Sloping poles: magnet "opens"
- ✦ Maximal field density > 1 T
- ✦ Integrated field density (bending power): ~4 Tm
- ✦ Field map from LHC Run 1 was updated for Run 2
- ✦ This work: further improvements for the Run 3 map



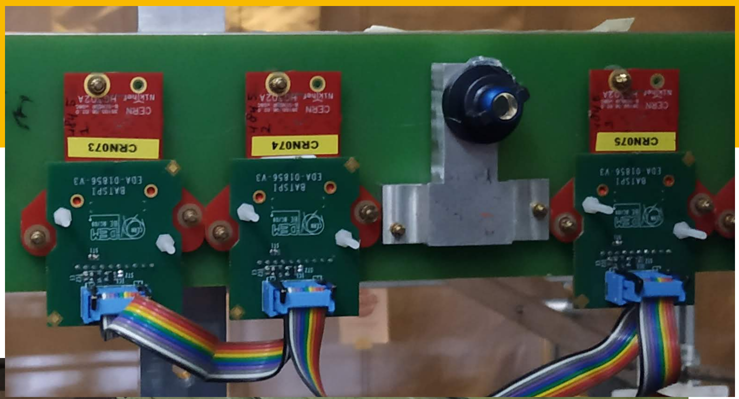


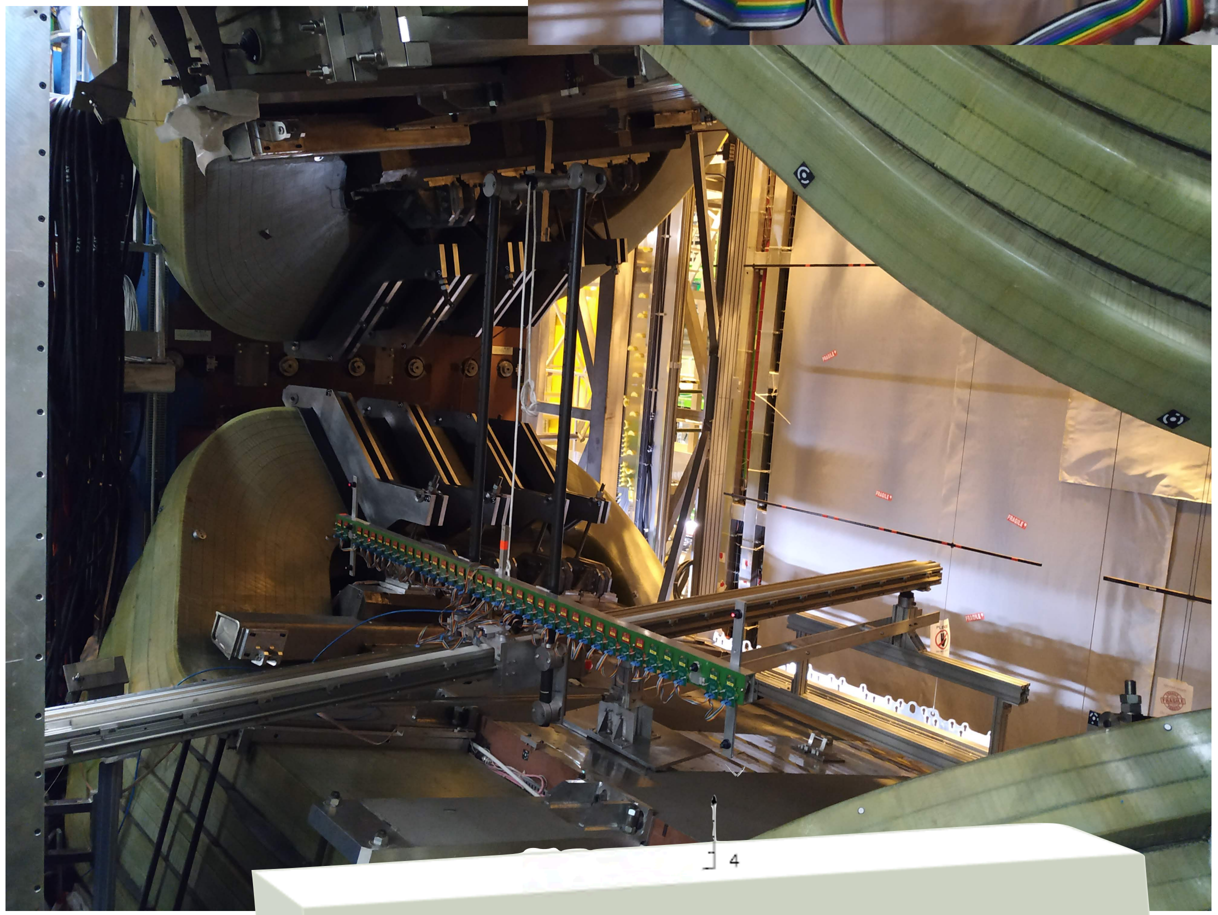
How to make a field map

- Want: field values B_x, B_y, B_z on a 10cm spaced cubic grid
- Can measure field components with Hall probes, but cannot cover all grid points
- Non-trivial coil and yoke geometry necessitate sophisticated simulation
- Solve Maxwell's equations using finite element modelling with OPERA (TOSCA)
- Use input from field measurements too!
- Adapt simulation model
  - To more closely resemble the real detector
  - For better matching of the field with measured values

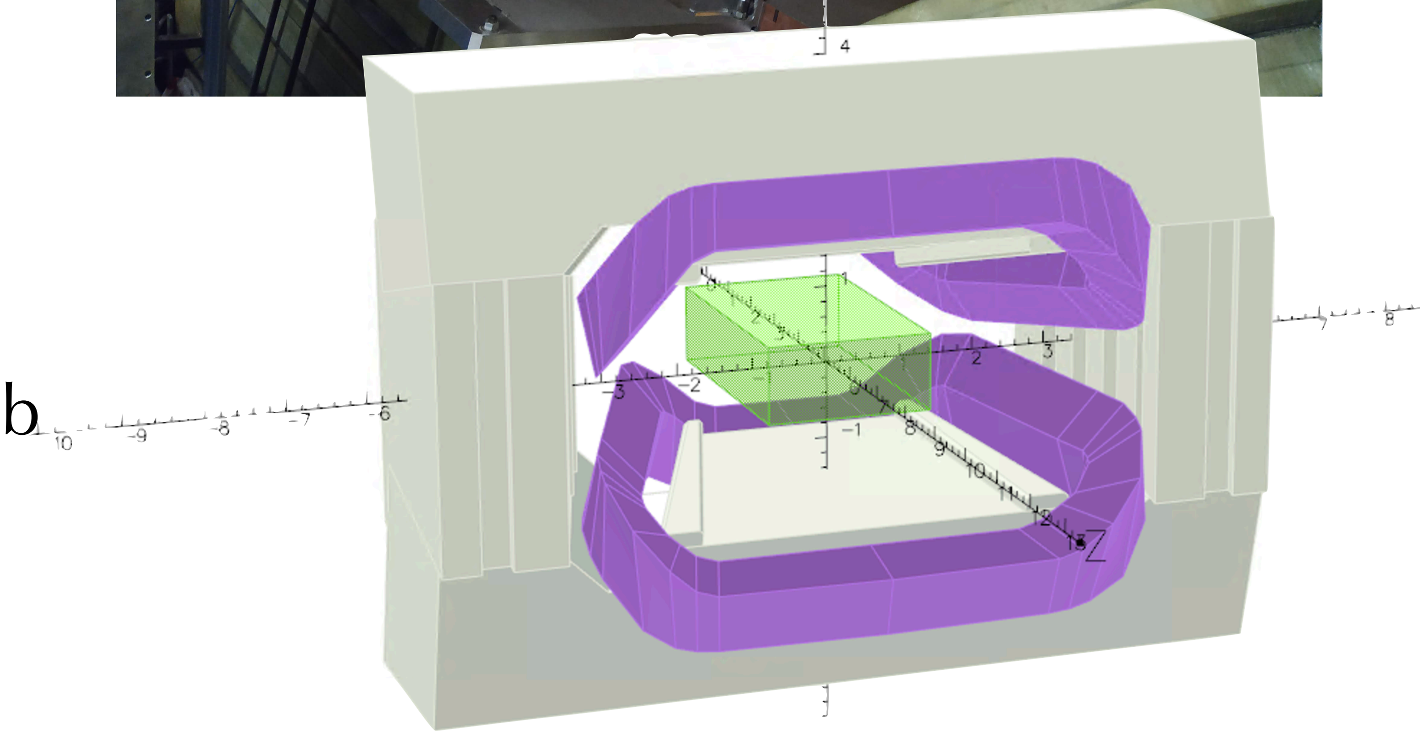


Field measurements in situ





- ✦ Measurements made by the CERN group
- ✦ 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 $y \in [-0.5m, 0.5m]$
- ✦ Positive and negative polarity (coil current reversed → field reversed)
- ✦ Survey of target positions in situ
  + detailed measurements of bar in lab
  = precise location of each sensor at each point, rotation of bar



Data-driven corrections to measured field values

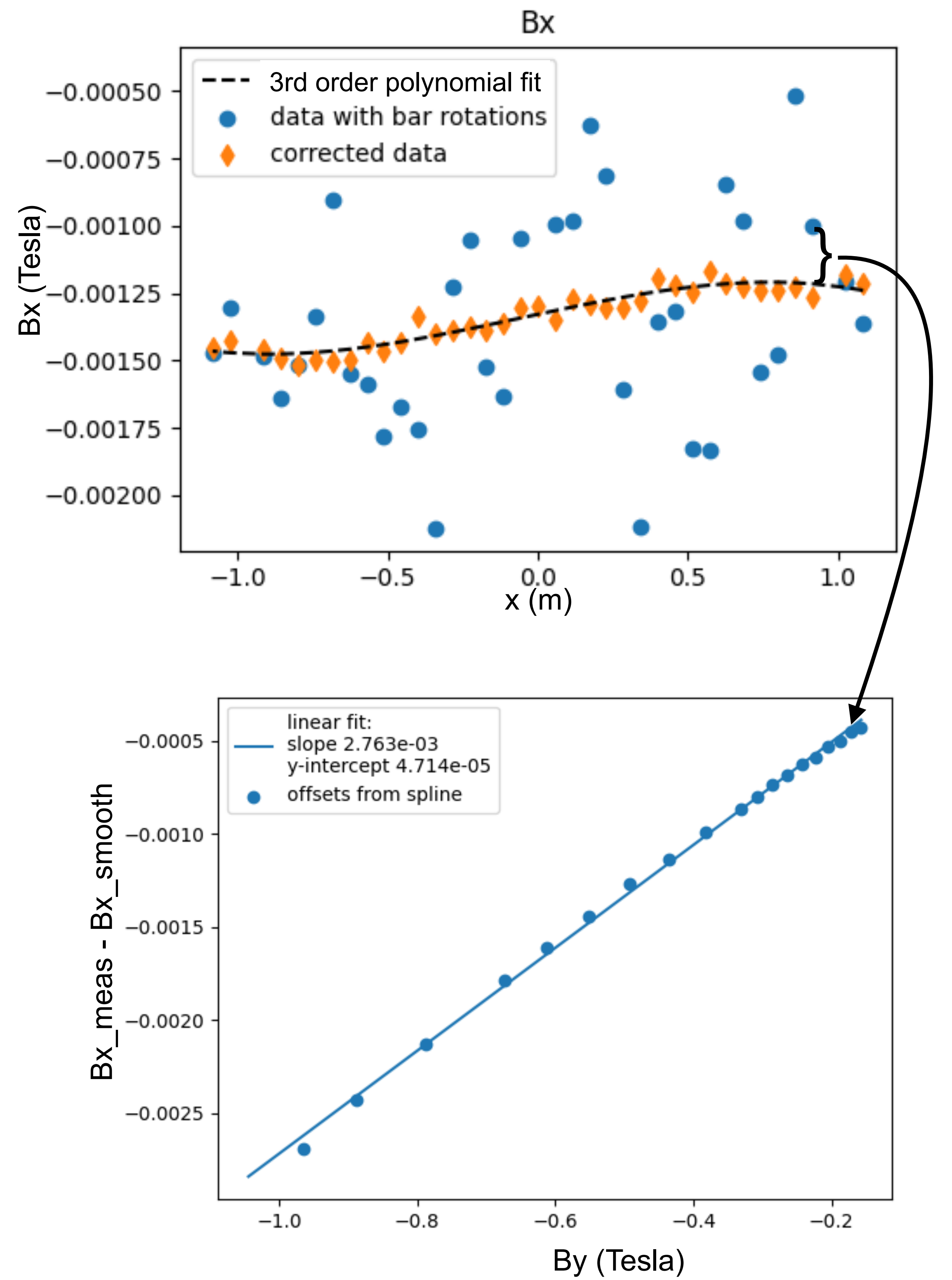
- Hall sensors can be rotated slightly with respect to each other
- Field in measurement region is mostly vertical: $B_y \gg B_x$, B_z
- A rotated sensor would pick up systematically more of B_y with its B_x probe than its neighbour
- Fit smooth field progression in B_x and B_z along the bar of sensors
- Deviation from smoothness is linear with B_y for each probe
- Apply first-order correction:

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

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

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

- Thanks to Natalia Feliks for important contributions to these studies



Adapting the model

- Adjustments to bring model closer to real LHCb detector
  - Iron support under magnet yoke
  - Pole faces orientation
  - Clamps holding coils
- Crucially, new map does not assume symmetry of detector layout
- Adjustments to improve matching with measurements
  - Translation of magnet in space by a few cm
  - Rotation $\mathcal{O}(1\mathrm{mrad})$
  - Scaling of coil current (factor 1.0018)

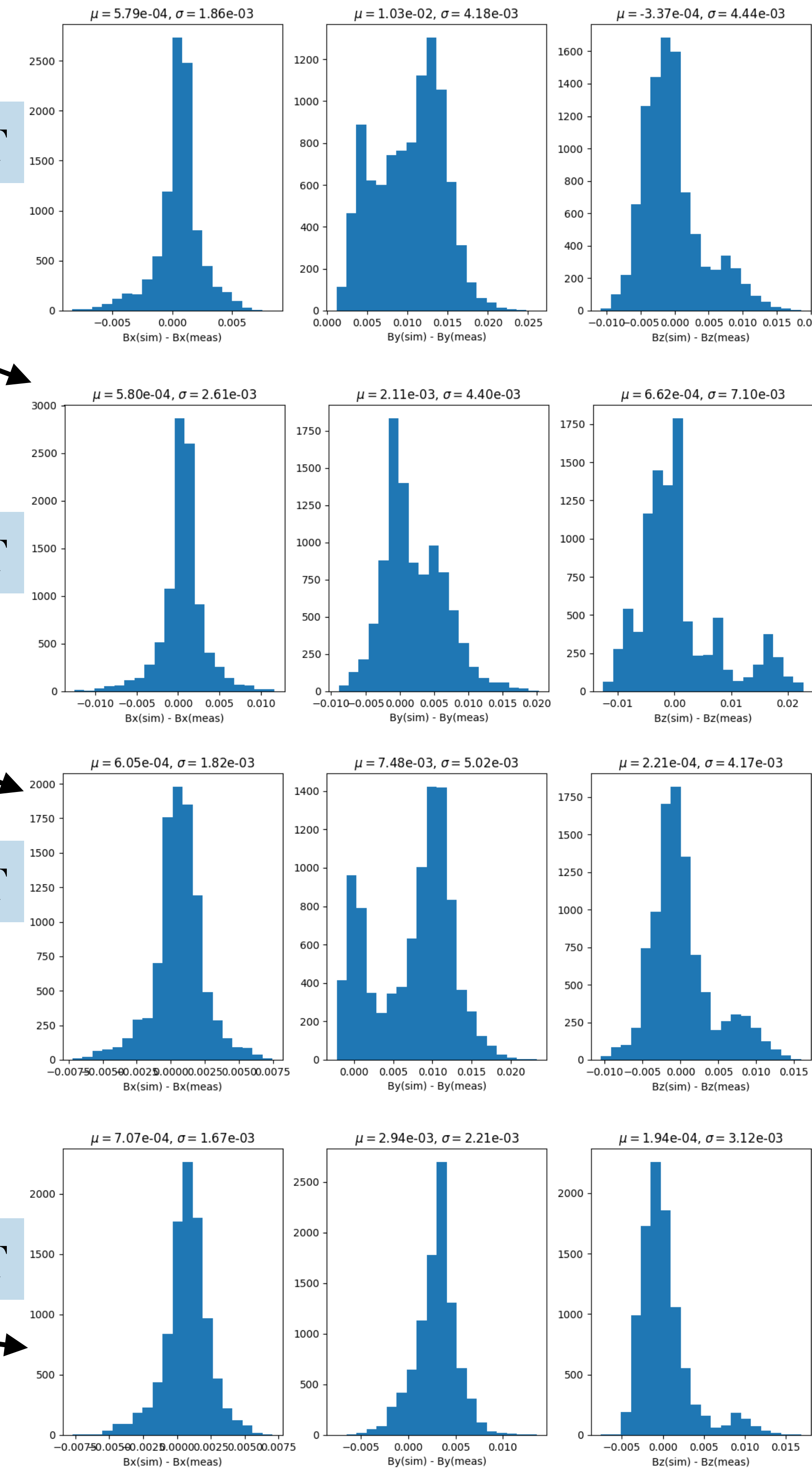
Simulated field – measured field

$\sigma_{\Delta B_y}$ = 4.2e-3 T

$\sigma_{\Delta B_y}$ = 4.5e-3 T

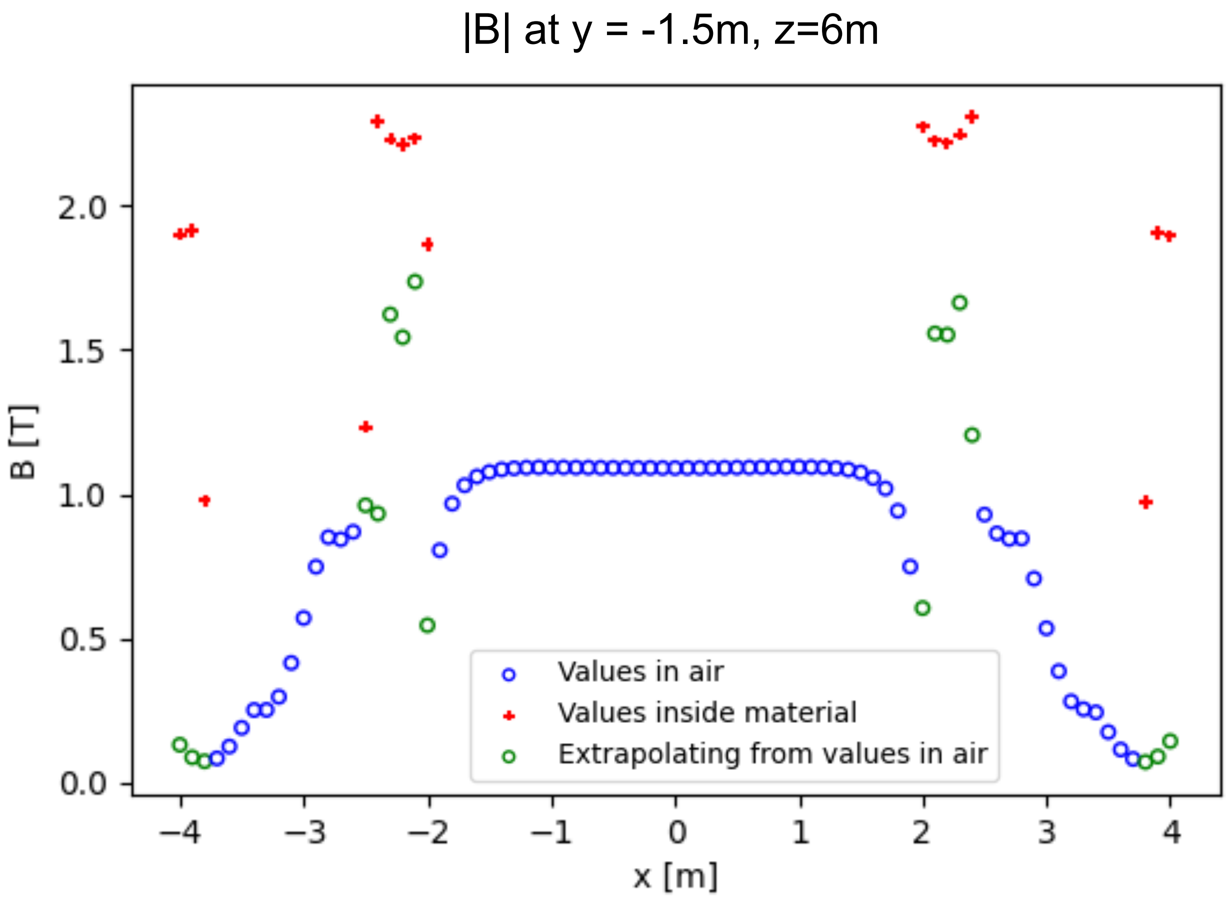
$\sigma_{\Delta B_y}$ = 5.0e-3 T

$\sigma_{\Delta B_y}$ = 2.2e-3 T



Smoothing of field values

- Fluctuations in simulated field values due to macroscopic size of FEM cells
  - Use interpolation from 5cm cube around each map grid point to even out these fluctuations
  - Interpolation done with 2nd order polynomials that are compliant with Maxwell's equations
- Fields in materials (in iron yoke) should not be used for interpolation of the fields in air
  - For map grid points near material boundaries and in material, extrapolate from points that are fully in air

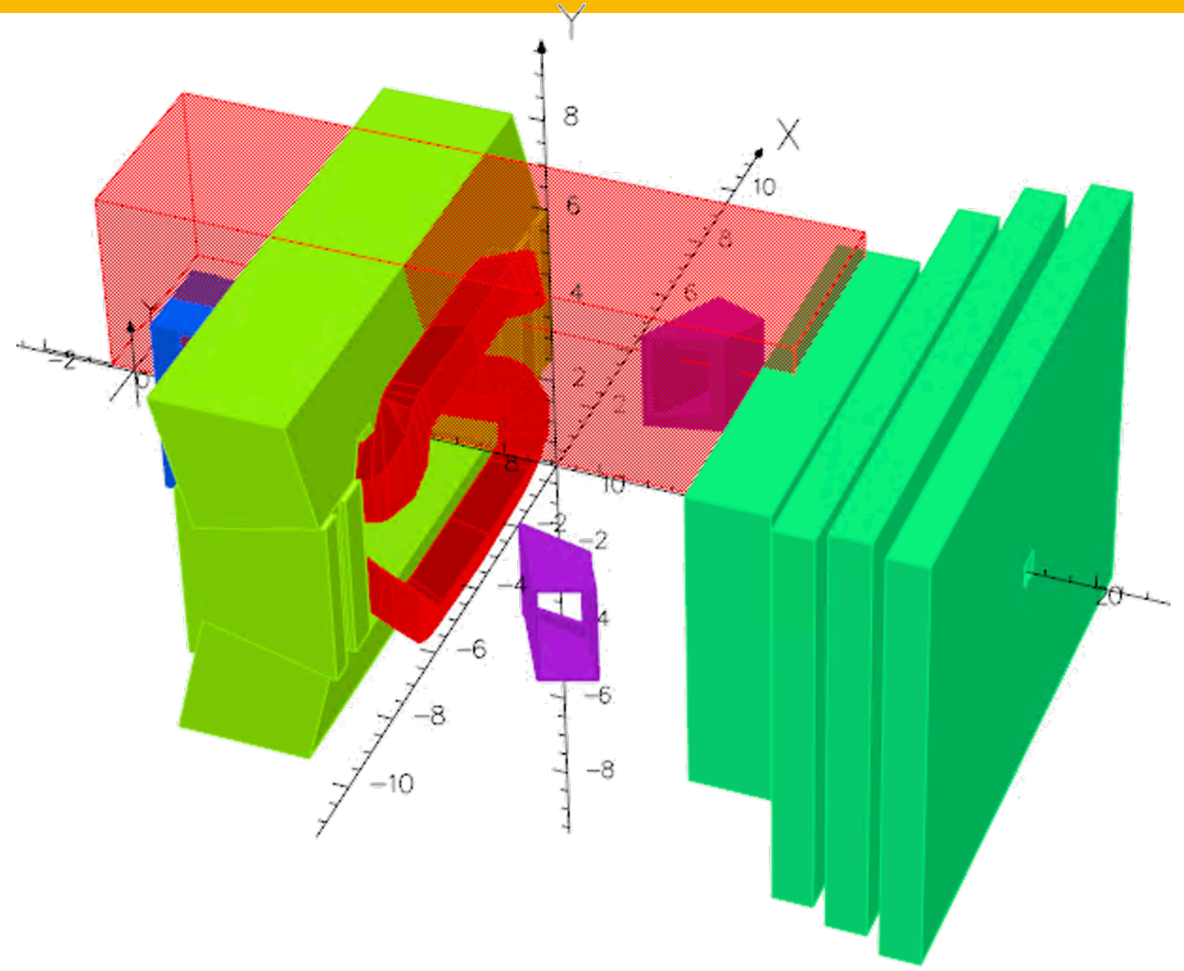


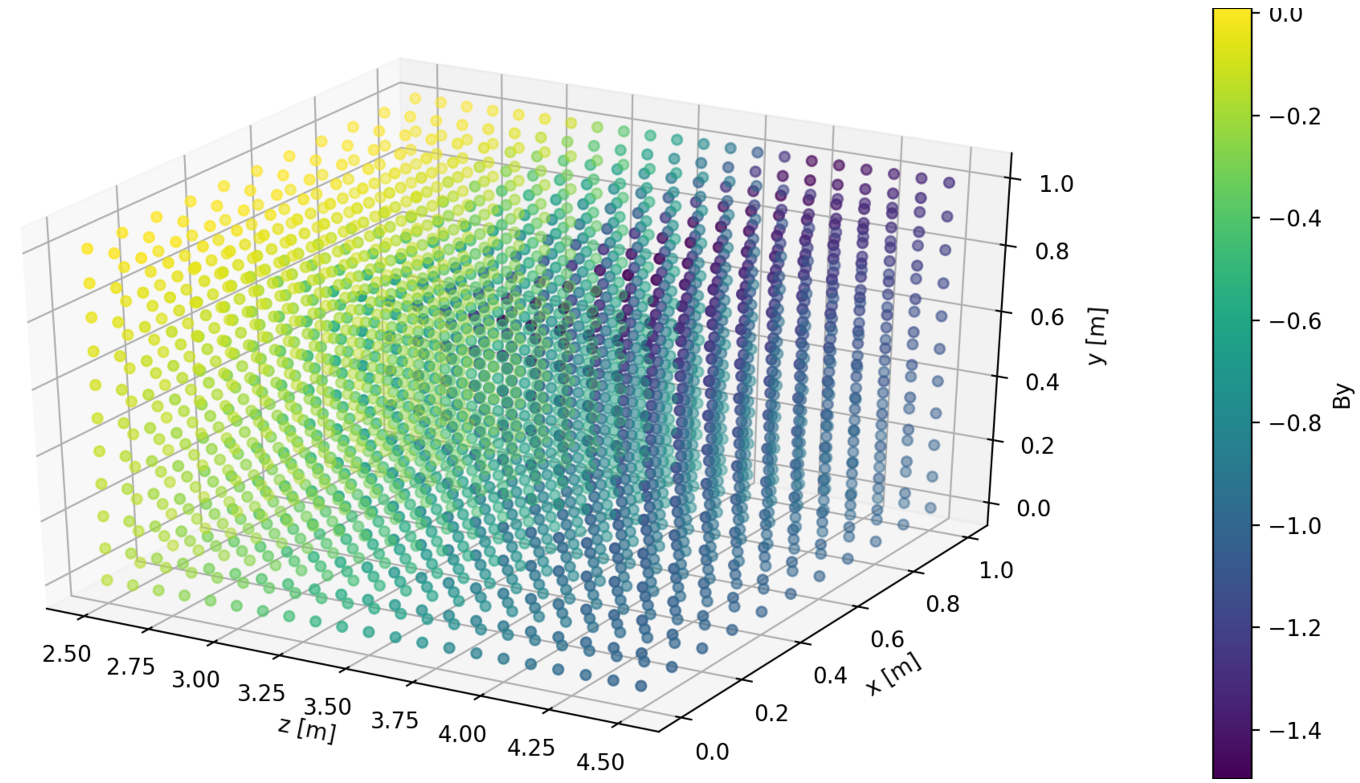
Conclusion

- The magnetic field map of the LHCb dipole has been updated
- Developed correction procedure for the rotation of the Hall probes w.r.t. each other
- More realistic detector model used in simulation
- Simulation no longer assumes symmetry of detector
- Magnet moved in simulation based on fit to field measurements
- Extrapolation from air for more accurate field values near material boundaries
- Next step: validation of new map, incl. momentum (invariant mass) resolution

Backup - B field map details

- 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





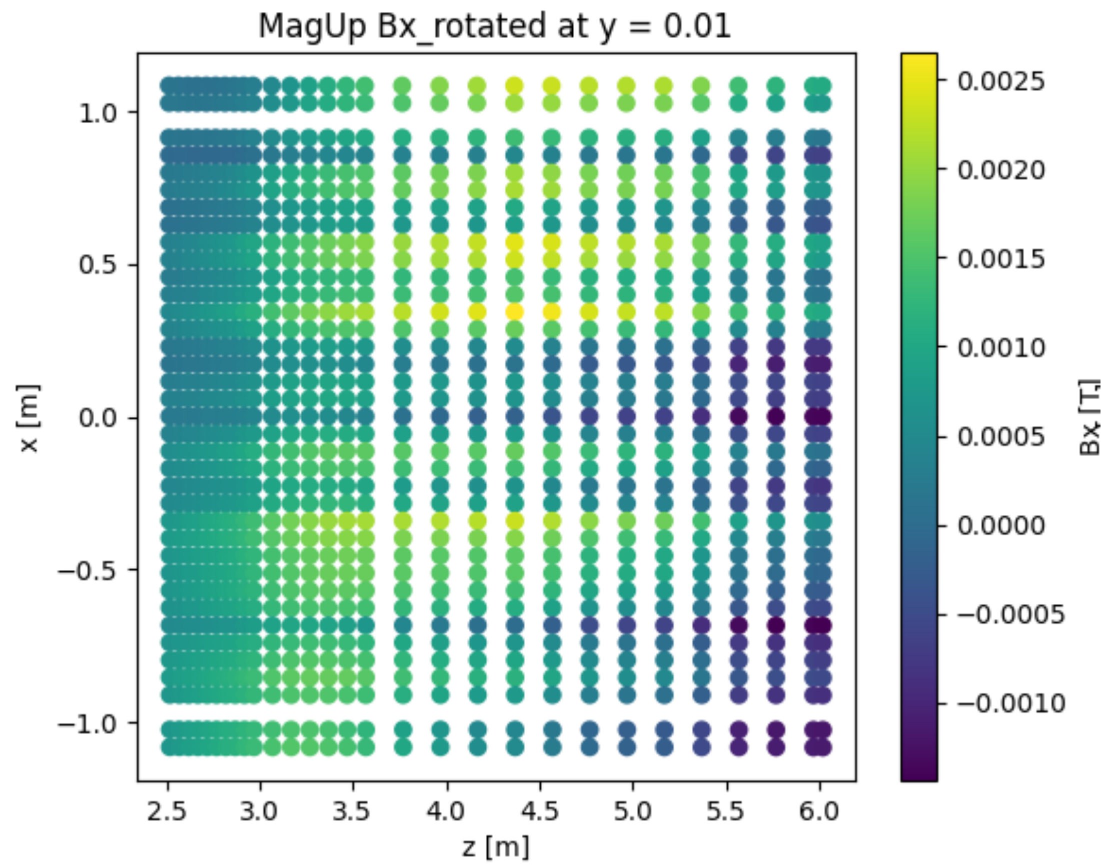
Backup - data-driven corrections

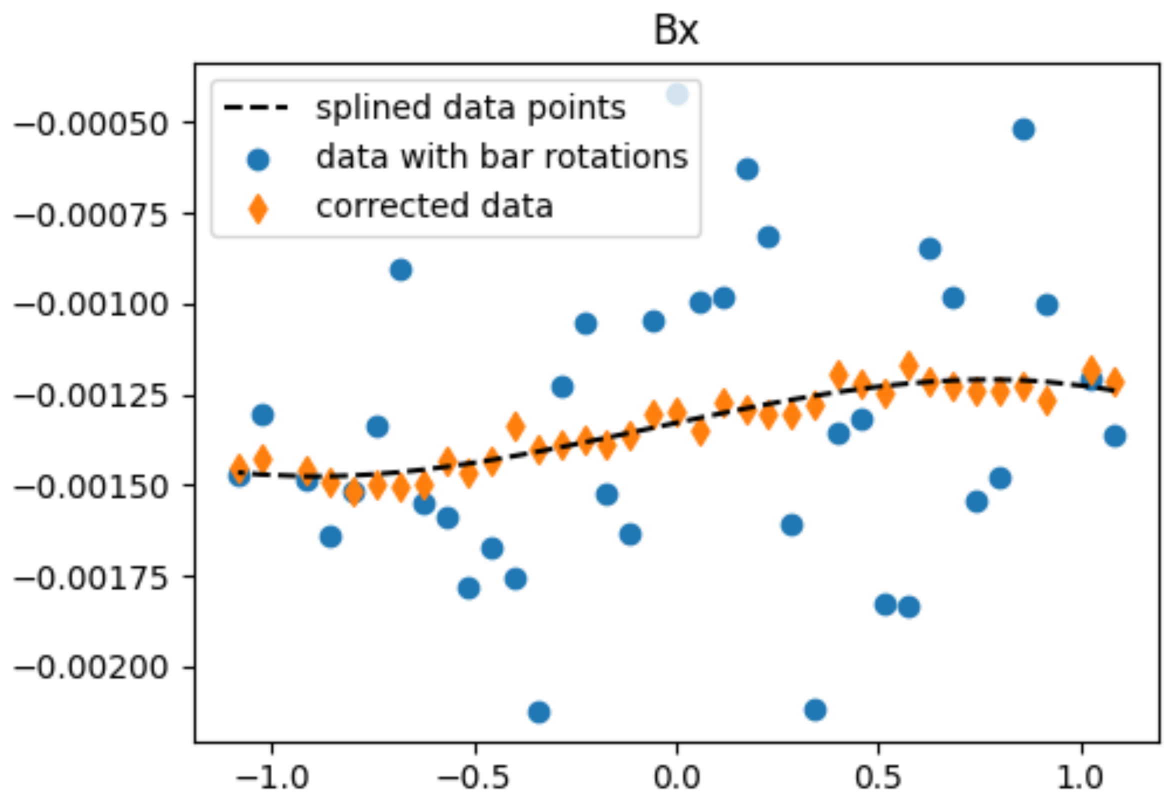
- First-order correction:

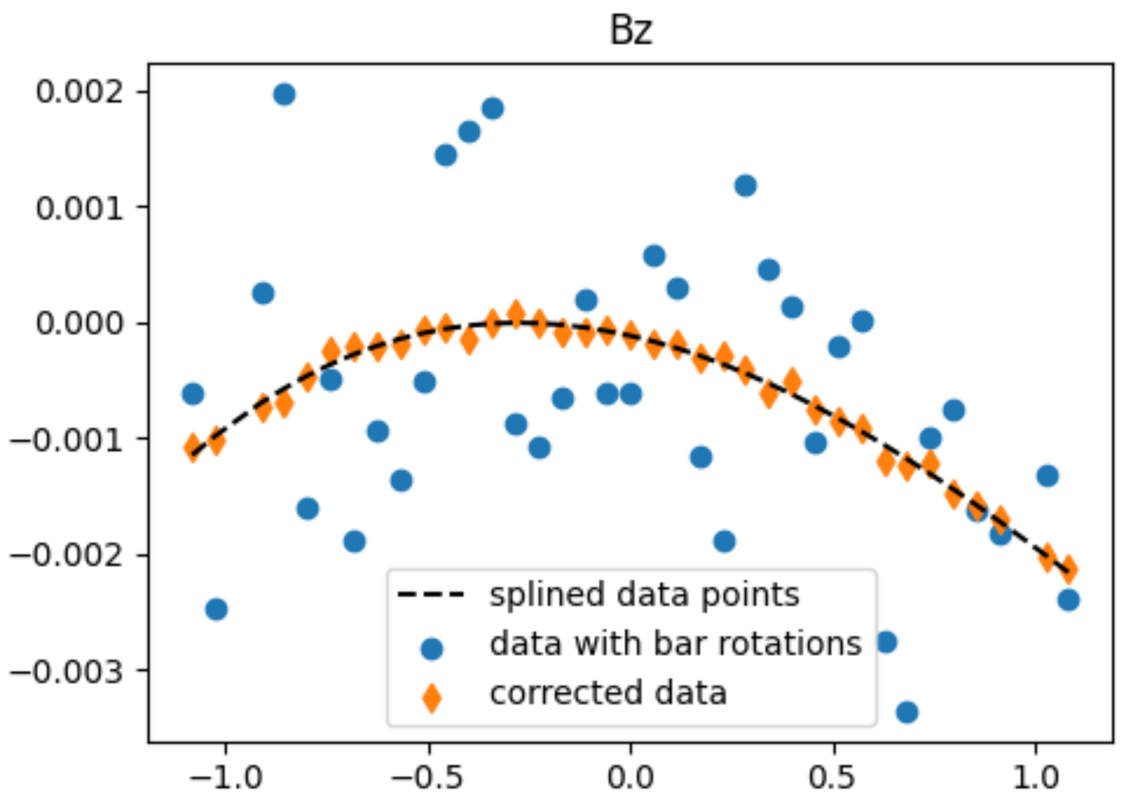
$$B_x^{\text{corr}} = B_x^{\text{meas}} - c_x B_y^{\text{meas}}$$

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

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

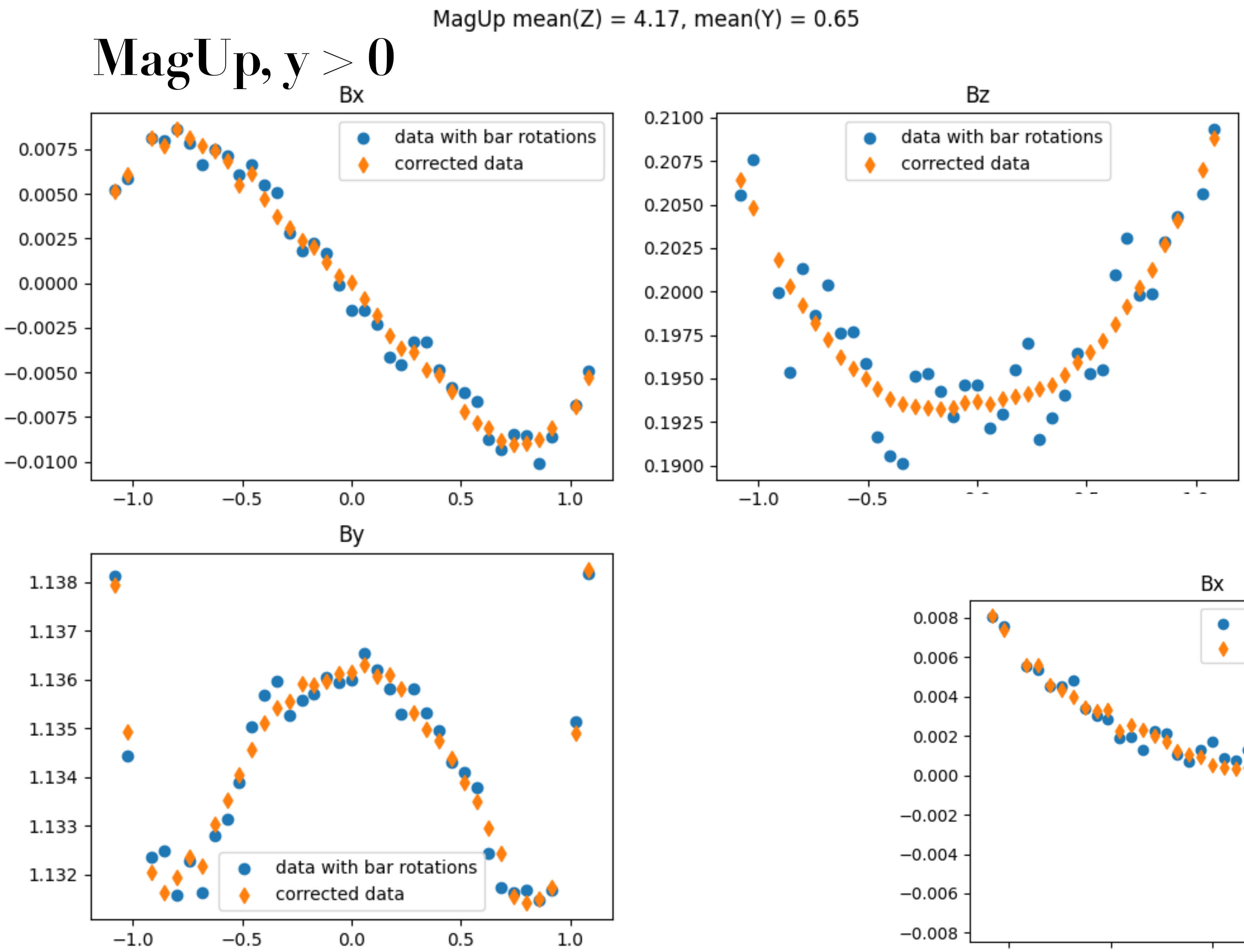




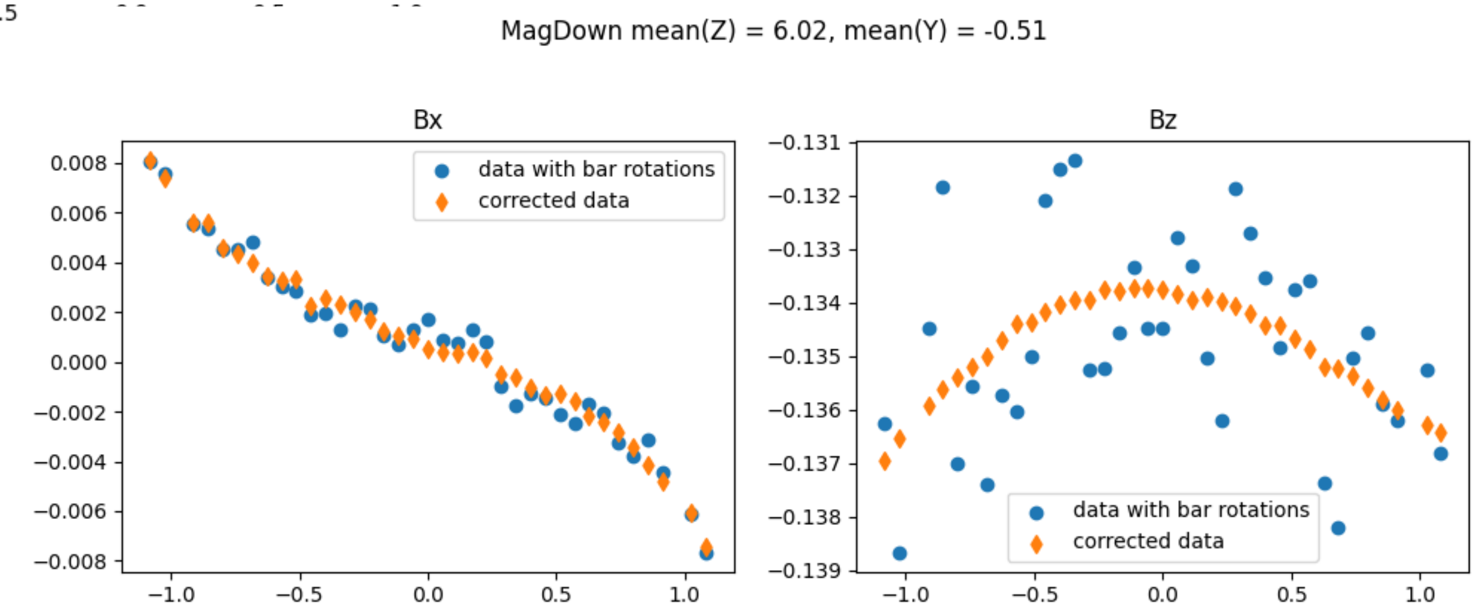


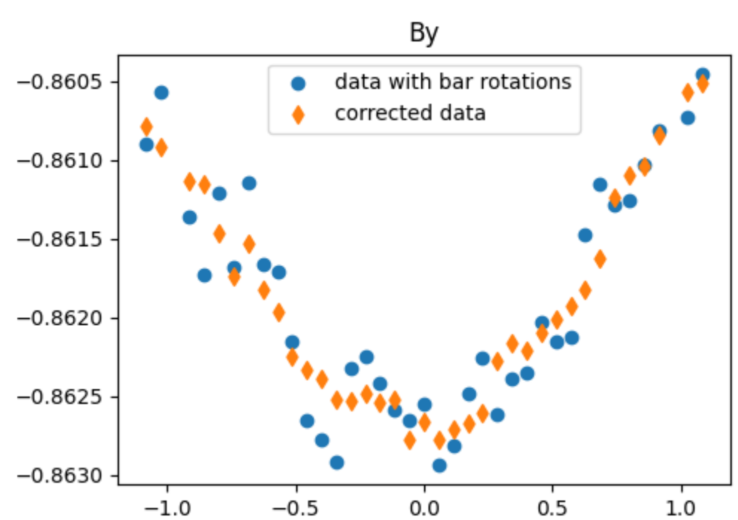
Backup - data-driven corrections (2)

MagUp, y > 0



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





z > 4.2m, y < 0

Backup - Maxwell-compliant interpolation

- Formalism developed by Pierre Billoir

- Use cubic grid: values (B_x, B_y, B_z) at evenly spaced nodes

- Interpolate values within each cube from the field values on the cube corners

- Approximate B fields as second-degree polynomials in the coordinates (x, y, z):

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

- Polynomial coefficients over-constrained by Maxwell's equations in vacuum and the field values on the corners

$$\nabla \cdot B = 0 \qquad \nabla \times B = 0$$

Backup - extrapolation / smoothing