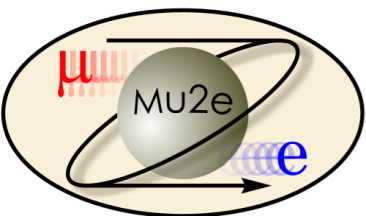# Mu2e Magnetic Field Mapping
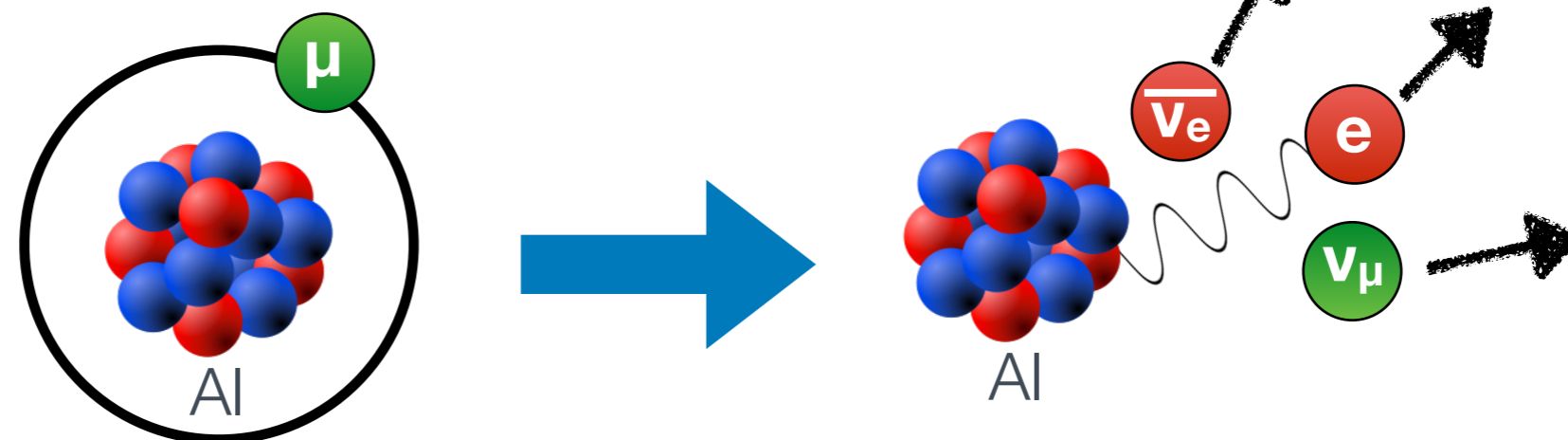
Brian Pollack, on behalf of the Mu2e Collaboration
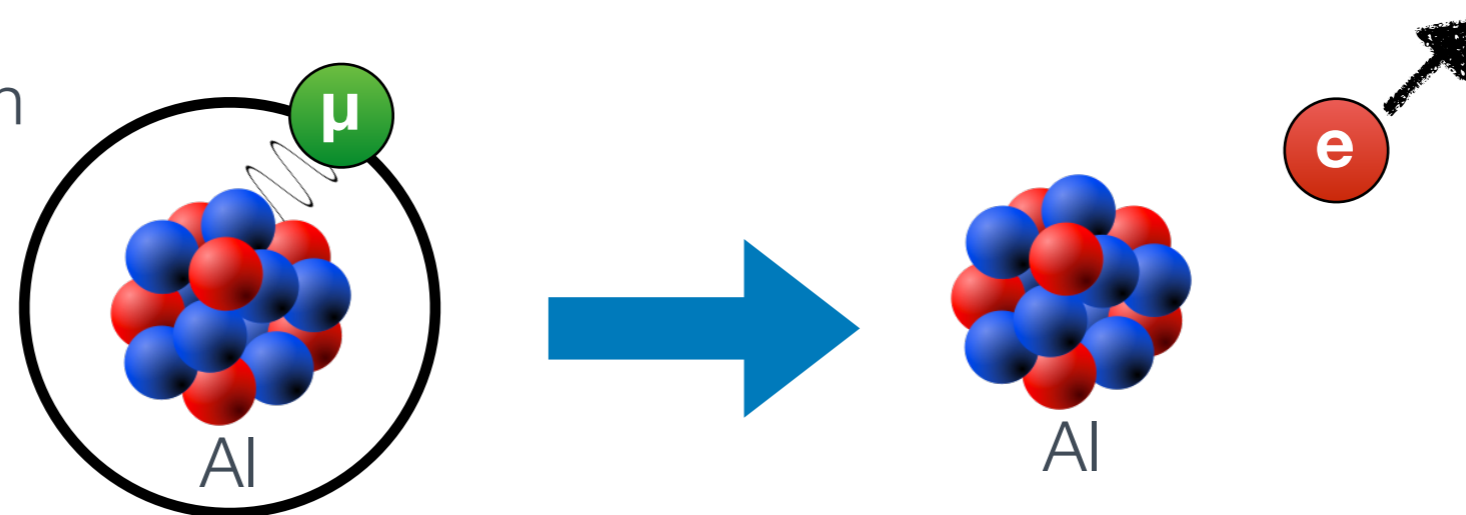
Northwestern University

8/2/17

Mu2e Processes

Decay-in-orbit
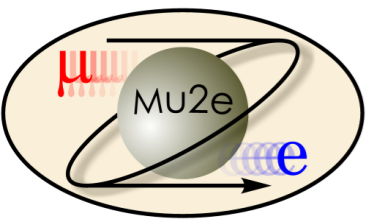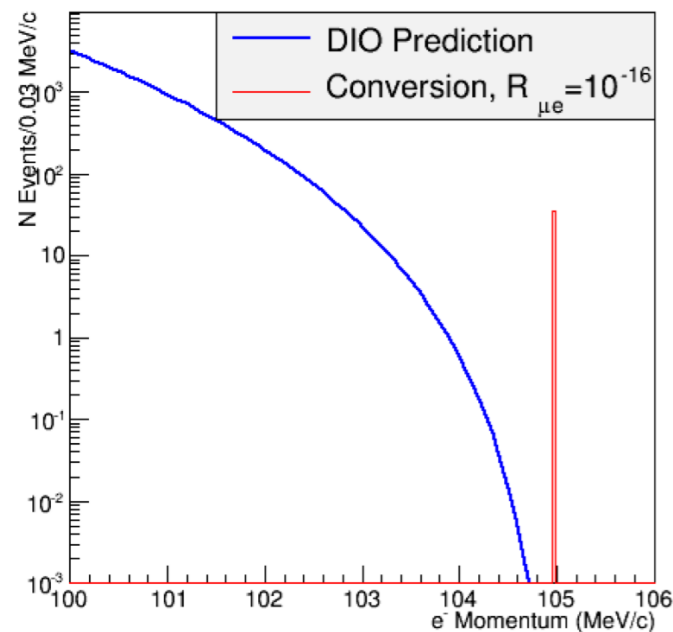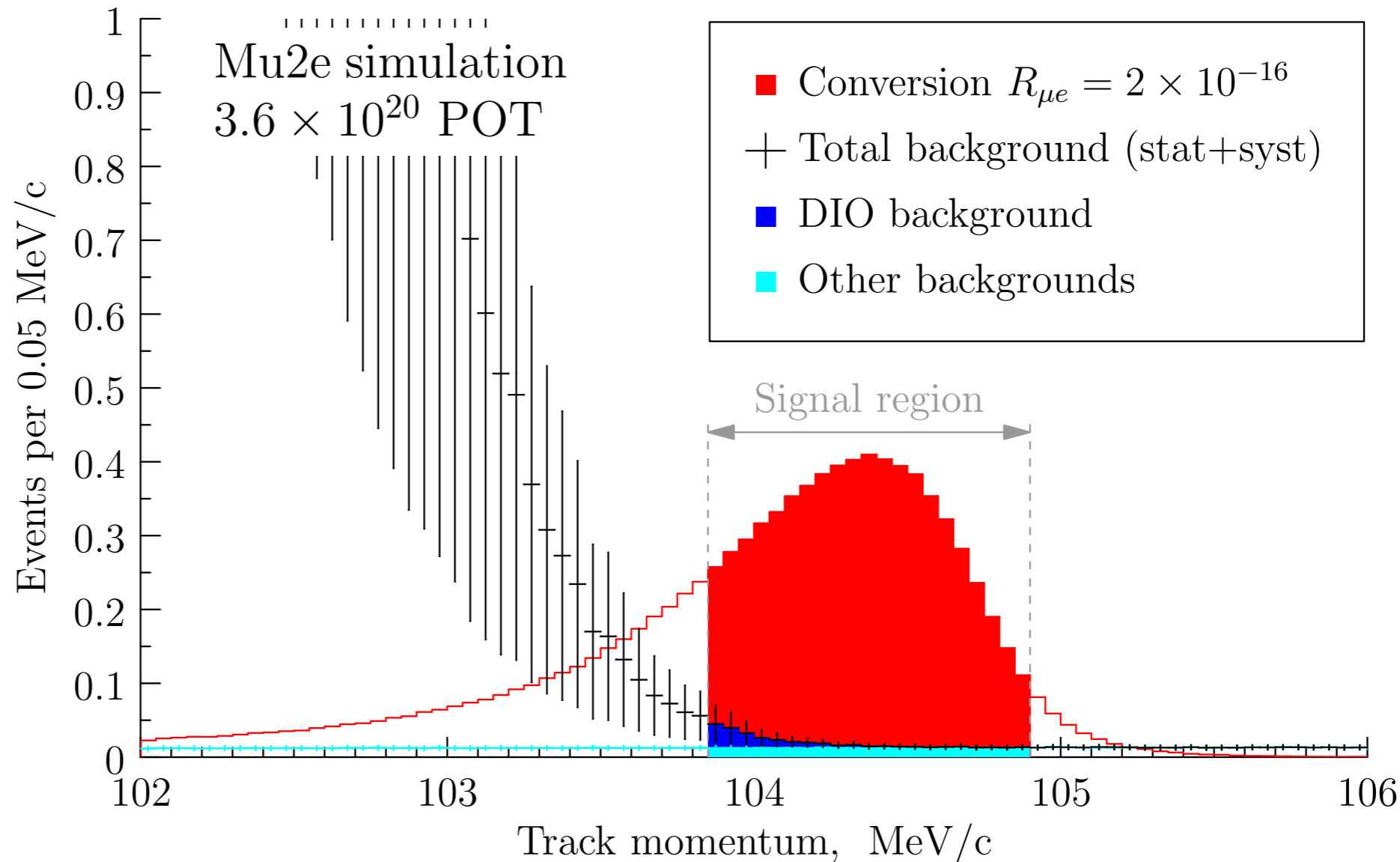(Background)

Neutrinoless Conversion
(Signal)
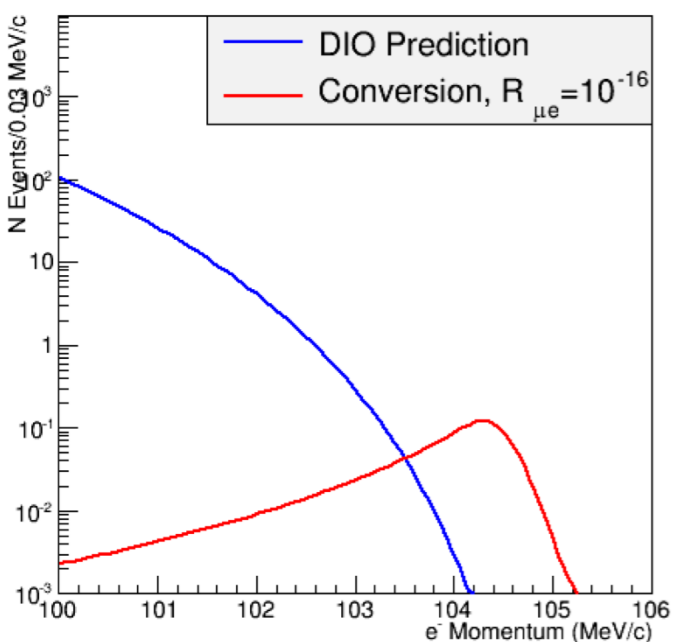
ΔB ≈ 1 G → Δp ≈ 10 keV/c

Uncertainty in field accuracy can shift momentum scale by tens of keV/c.

Better field accuracy → better sensitivity!

The Mu2e Experiment

Proton Beam

Production Solenoid

Detector Solenoid

Transport Solenoid

Production Target

Calorimeter

Tracker

Muon
Stopping Target
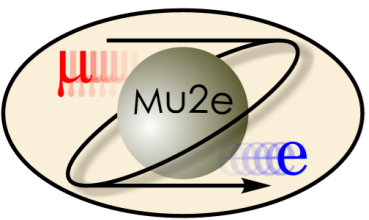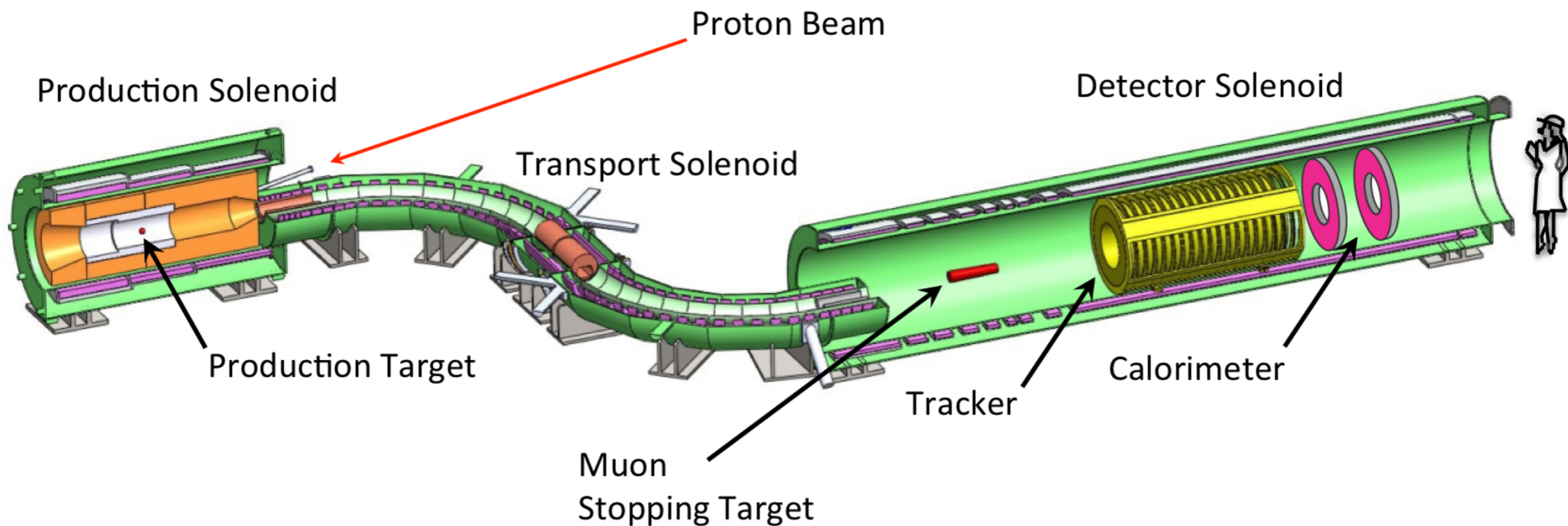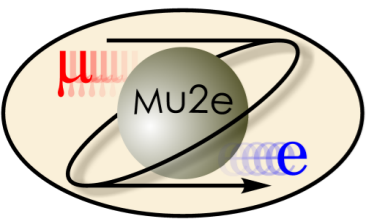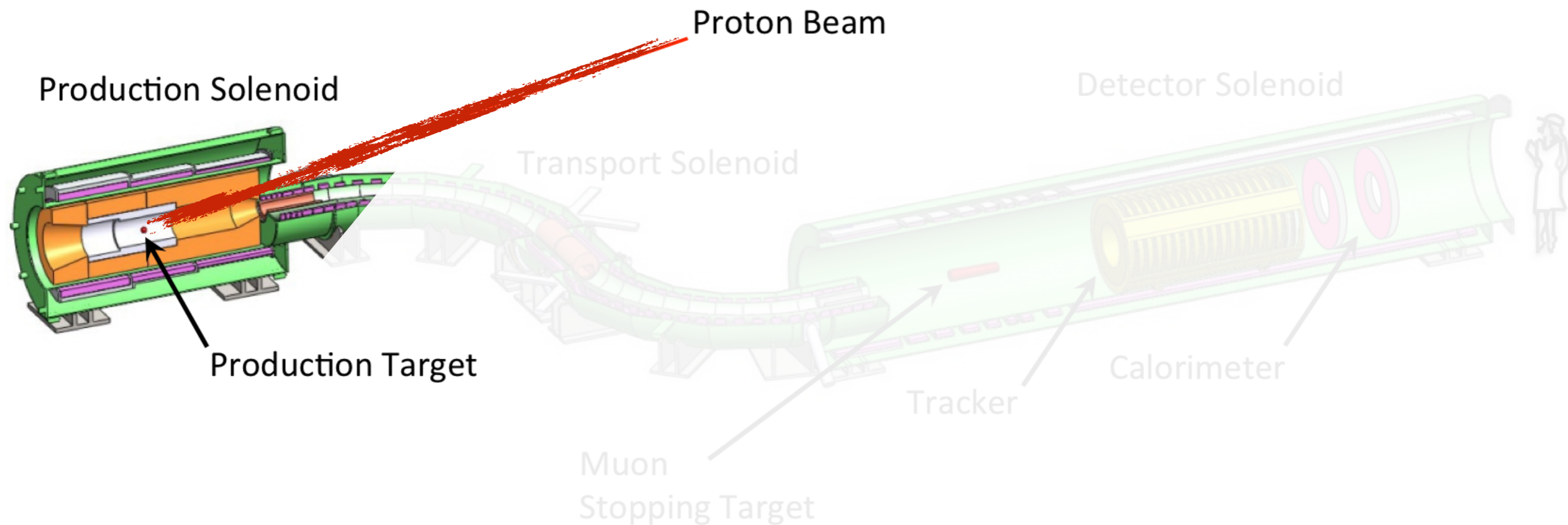
1. Proton collides with production target.

The Mu2e Experiment

Production Solenoid

Proton Beam

Detector Solenoid

Transport Solenoid

Production Target

Calorimeter

Tracker

Muon
Stopping Target

1. Proton collides with production target.
2. Pions back-scatter into transport solenoid.

The Mu2e Experiment

1. Proton collides with production target.
2. Pions back-scatter into transport solenoid.
3. Muons and pions transported to detector solenoid.

The Mu2e Experiment

Proton Beam

Production Solenoid

Detector Solenoid

Transport Solenoid

Production Target

Calorimeter

Tracker

Muon
Stopping Target

1. Proton collides with production target.

2. Pions back-scatter into transport solenoid.

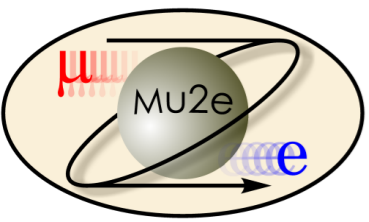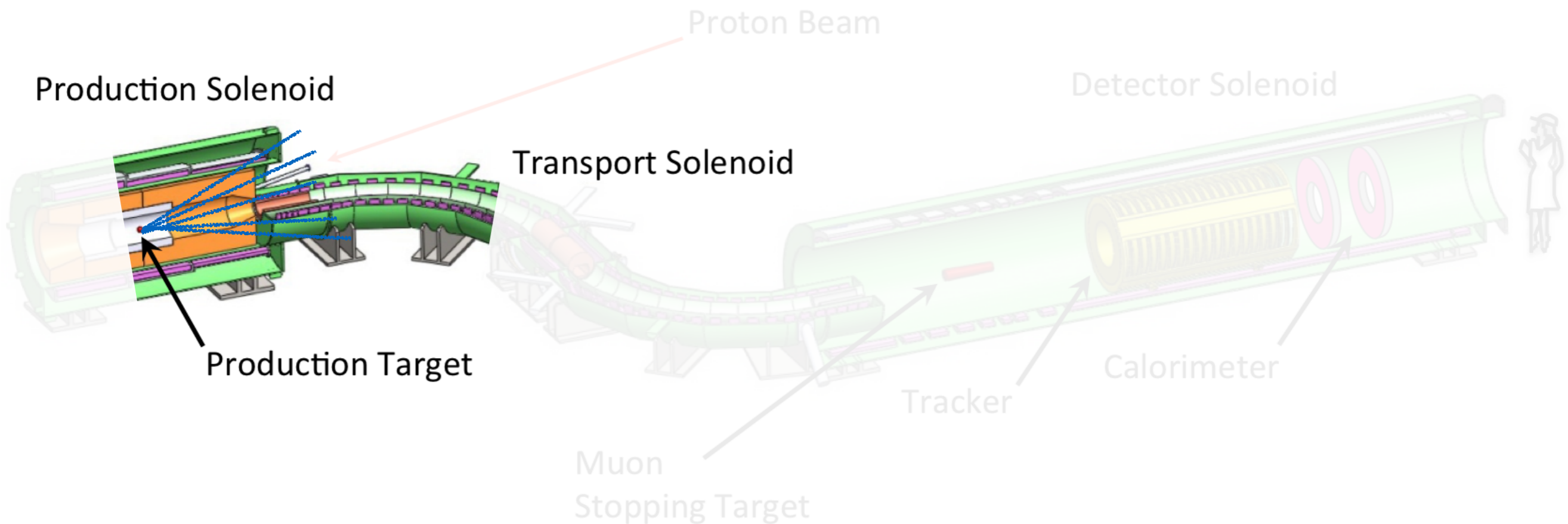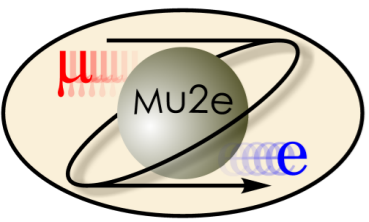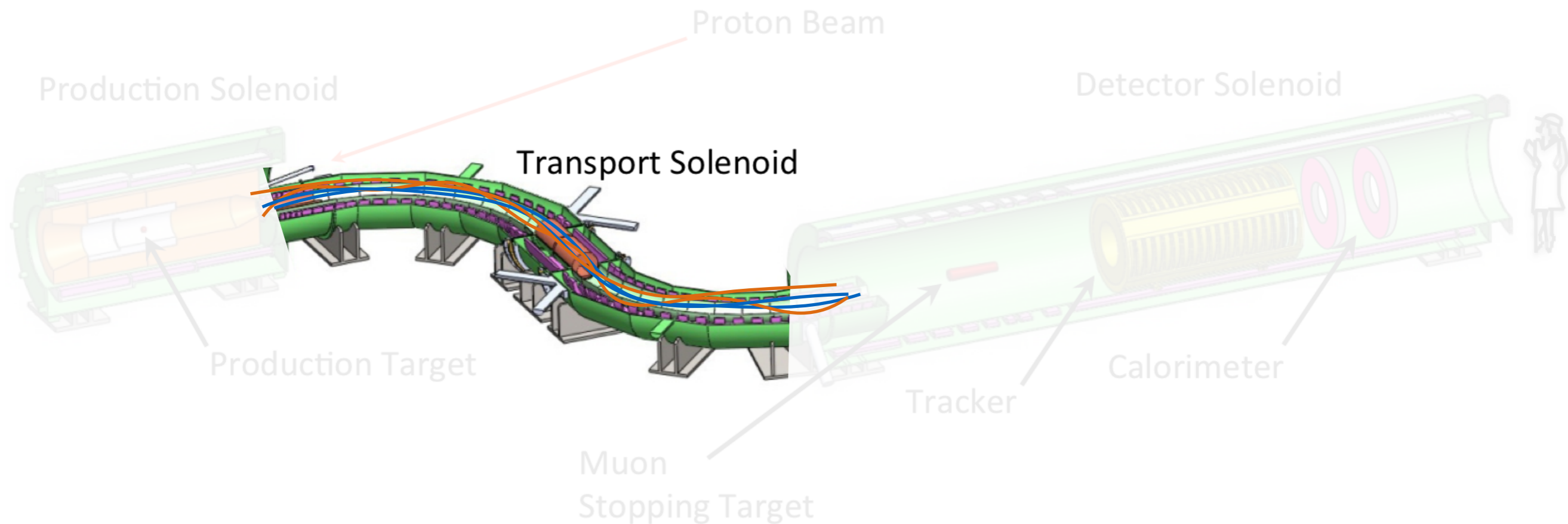3. Muons and pions transported to detector solenoid.

4. Muons are captured at target.

The Mu2e Experiment

1. Proton collides with production target.
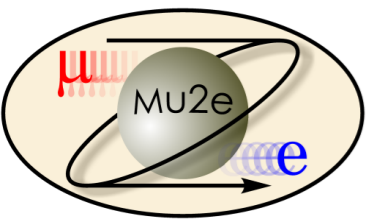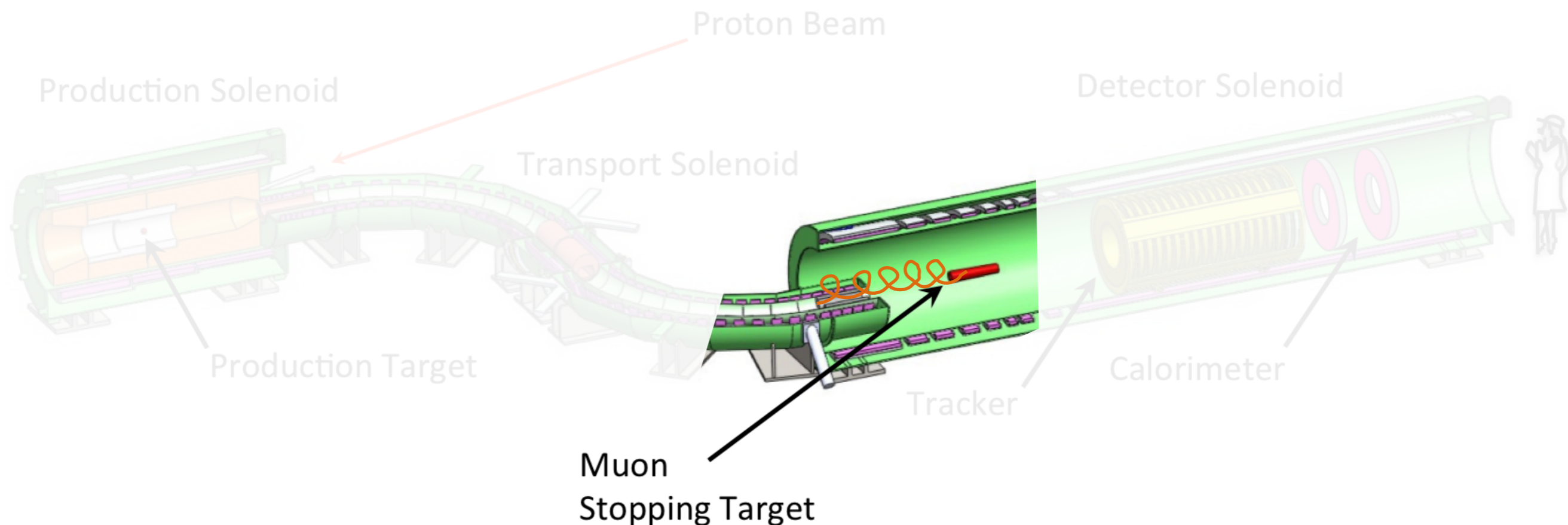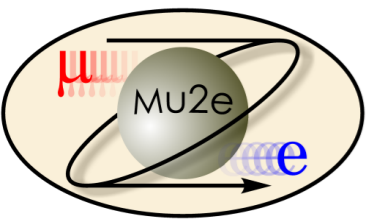2. Pions back-scatter into transport solenoid.
3. Muons and pions transported to detector solenoid.
4. Muons are captured at target.
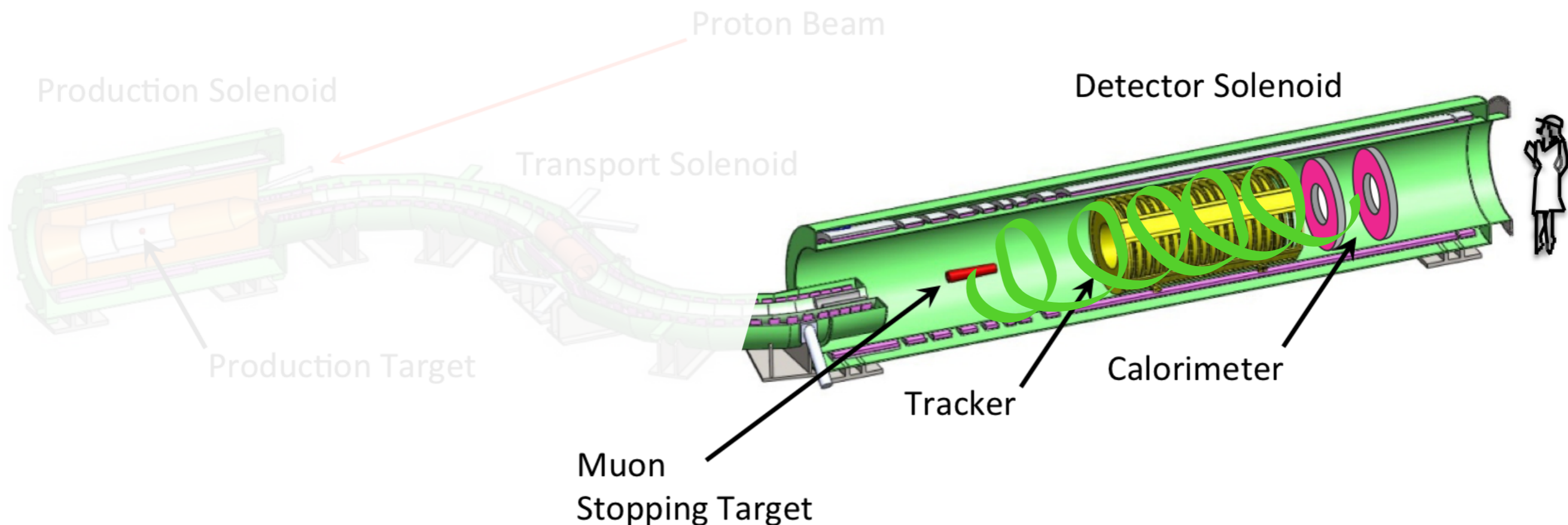5. Outgoing electrons pass through detector system.
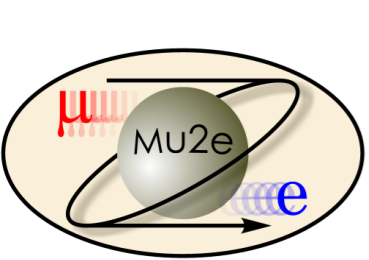
The Magnetic Field
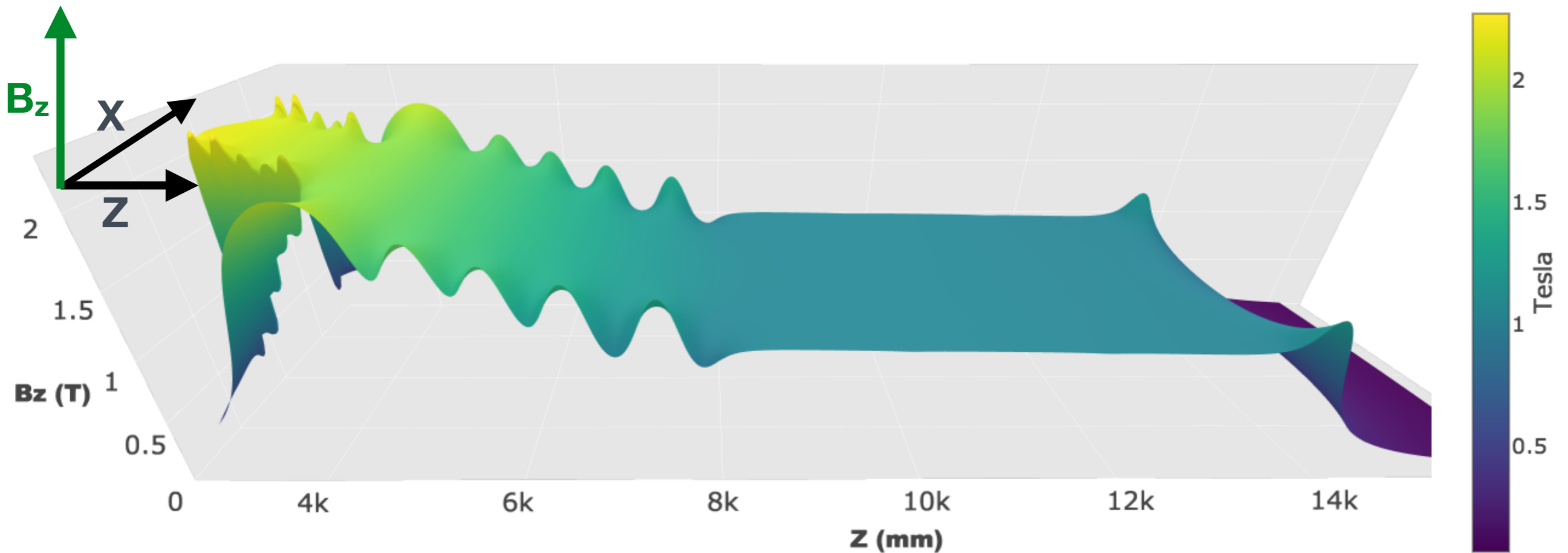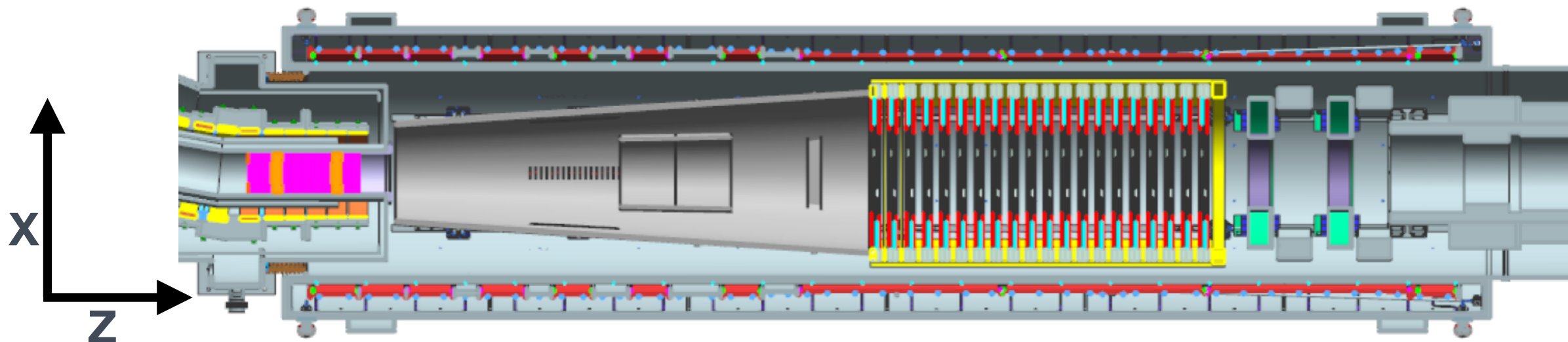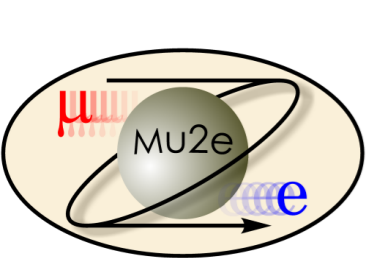
Detector Solenoid

The Magnetic Field

End of Transport Solenoid

and Collimator

Detector Solenoid

2T Field

Bz

Bz (T)

Z (mm)

Tesla

Detector Solenoid

Stopping Target

Muons are captured

X

Z

Gradient Region

2 to 1 T

B_z

X

Z

B_z (T)

2

1.5

1

0.5

0

4k   6k   8k   10k   12k   14k

Z (mm)

Tesla

2

1.5

1

0.5

The Magnetic Field

Detector Solenoid

Tracker planes   **Calorimeter**

X
Z

B_z X
Z

Uniform Region, 1T

Strictest requirements on field accuracy

B_z (T)

2

1.5

1

0.5

0

4k   6k   8k   10k   12k   14k

Z (mm)

2

1.5

1

0.5

Tesla

The Magnetic Field

Detector Solenoid

R<80 cm

~4m < Z < ~13m

Region mapped in upcoming slides

B_z

B_z (T)

Z (mm)

Tesla

5

Solenoid Field Mapper

★ **Field Mapper will take a sparse set of magnetic field measurements.**

  • Very demanding hardware requirements!
    (hall probe calibration, laser alignment, etc.)

★ **A continuous field will be reconstructed.**

★ **Measurement errors must be minimized and quantified.**

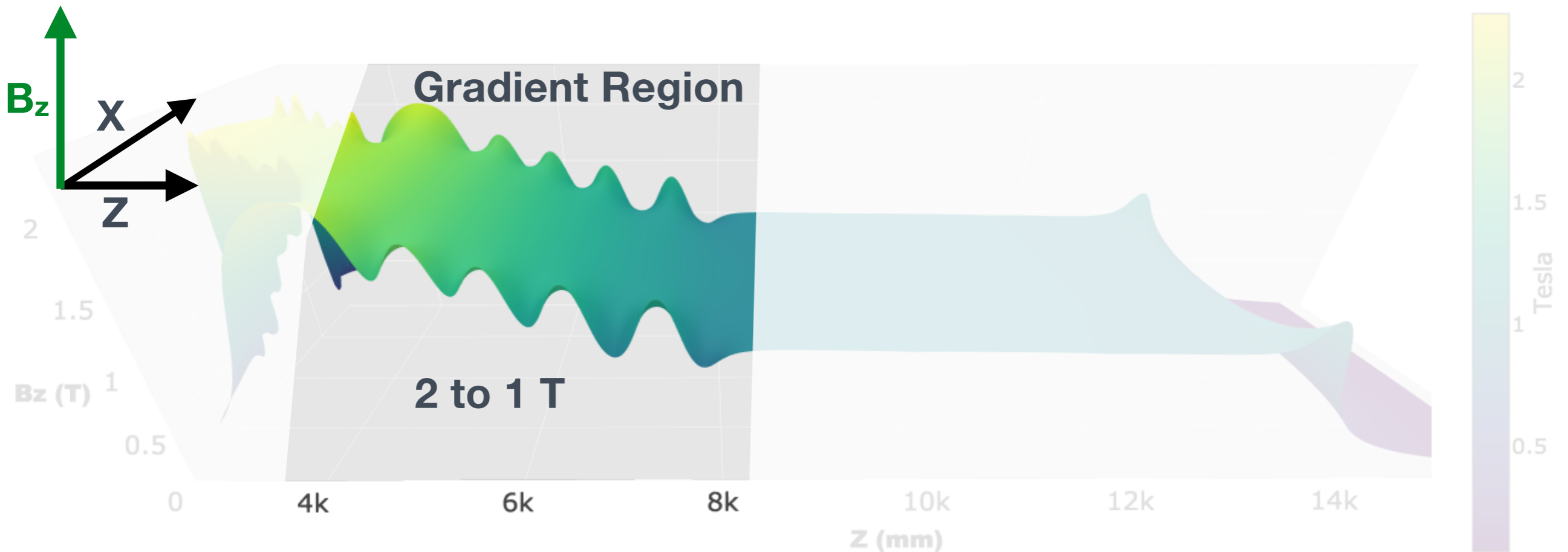 ★ Reconstructed field must be accurate to 1×10^{-4} w.r.t. true.

Need ~1 G accuracy for 1 T field.
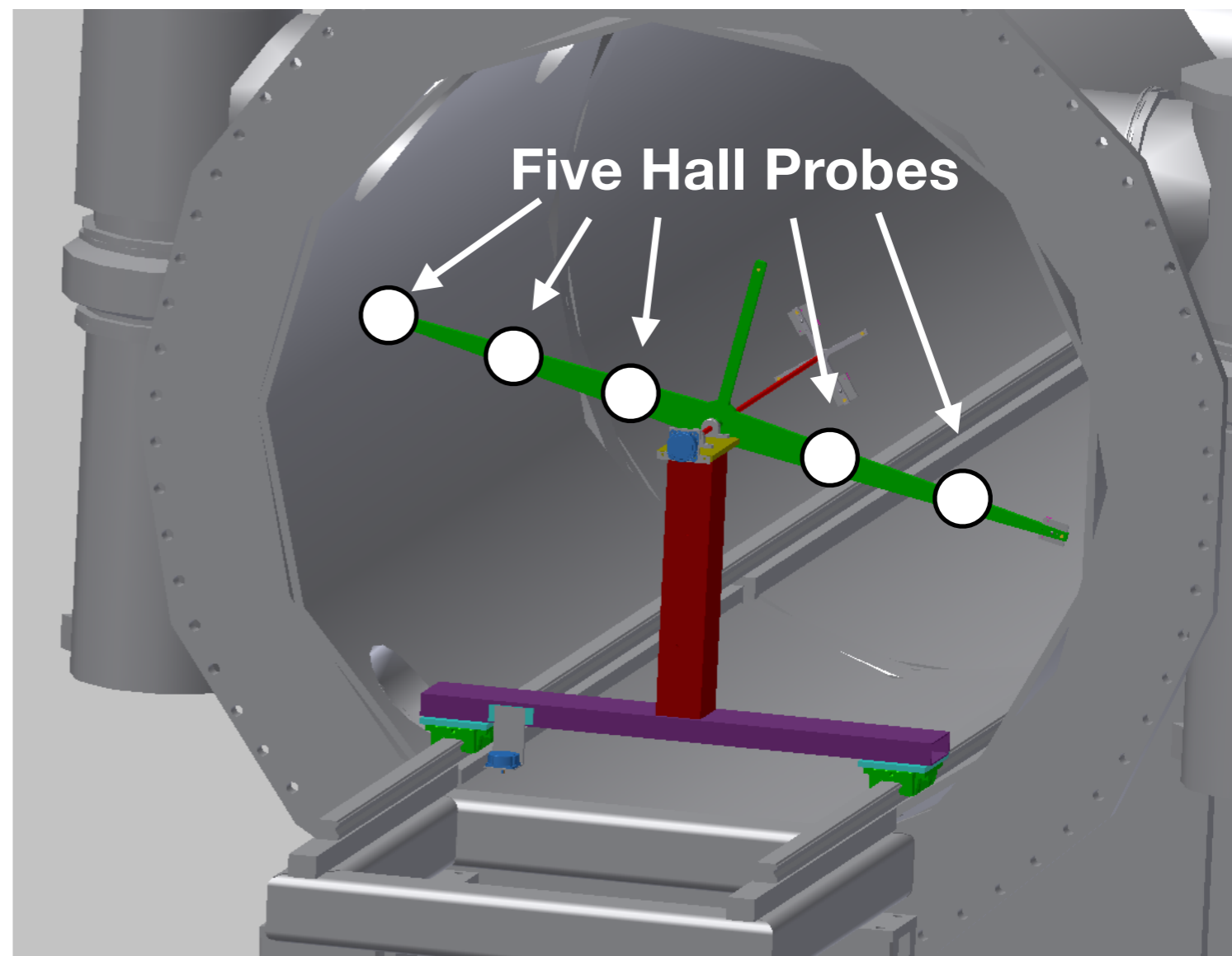
Five Hall Probes

Field mapper in solenoid

Hall Probes

Large Propeller

Small Propeller
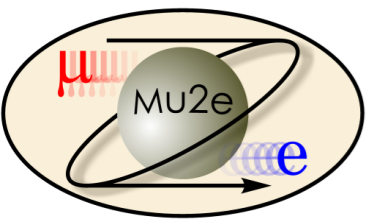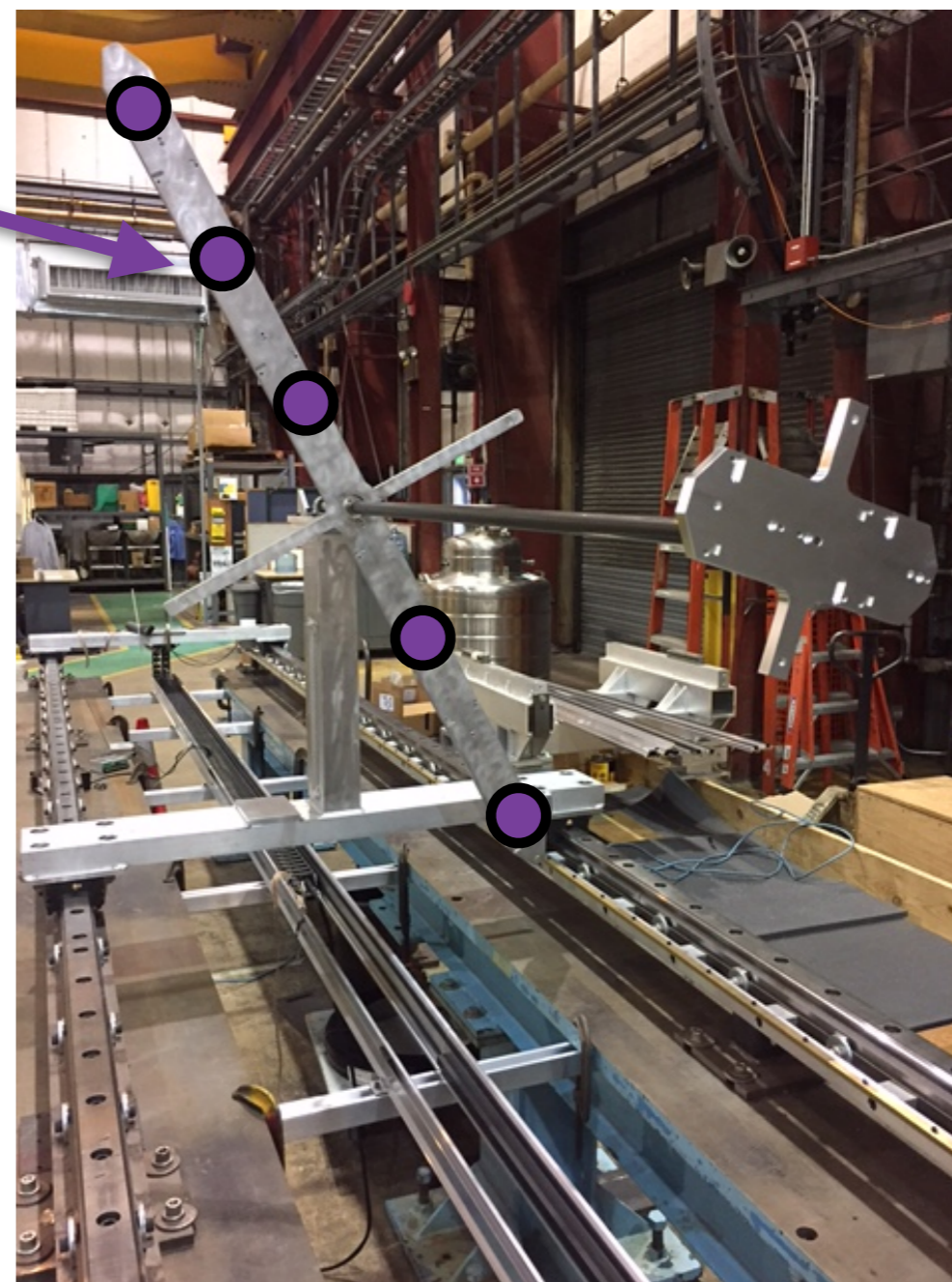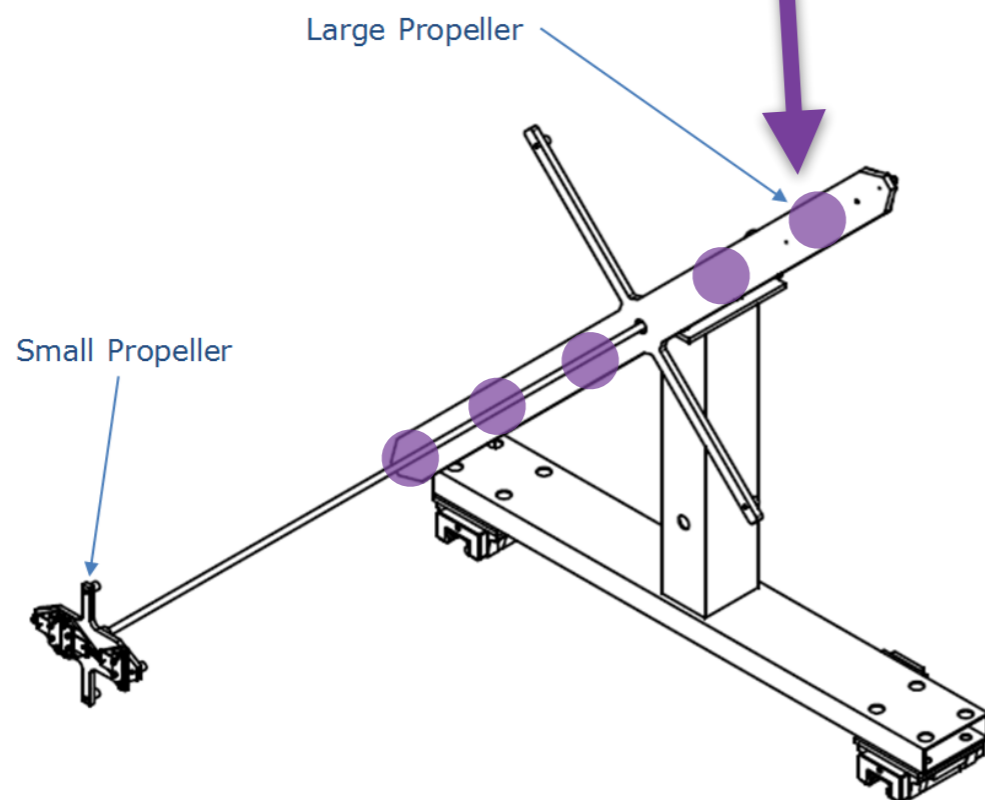
How do we turn discrete measurements into a continuous field?
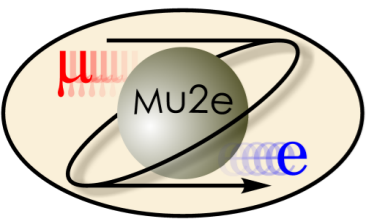
Maxwell's Equations

★ **Maxwell's equations for the fiducial region:**

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \text{and} \qquad \vec{\nabla} \times \vec{B} = 0$$

★ **The B-field can be expressed as gradient of scalar potential:**

$$\vec{B} = -\vec{\nabla}\Phi$$

★ **In cylindrical coordinates, a series solution for Φ using modified Bessel's functions:**

$$\Phi = \sum_{n,m} A_{nm} e^{\pm in\phi} e^{\pm ik_{nm}z} I_n(k_{nm}\rho)$$

★ **Will measure field components B_ρ and B_z and B_ϕ, _not_ Φ.**

★ **Measurements determine coefficients through a χ^2 fit.**
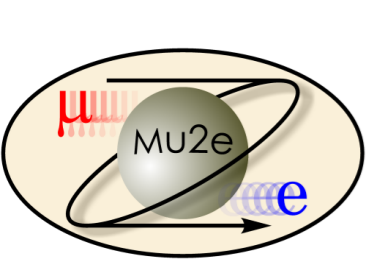
Analytical Model

★ **Derived from solutions to Maxwell's Equations for a generic solenoid:**

$$B_r = \sum_{n,m} \cos(n\phi + \delta_n) k_{nm} I_n'(k_{nm} r) [A_{nm} \cos(k_{nm} z) + B_{nm} \sin(-k_{nm} z)]$$

$$B_z = \sum_{n,m} -\cos(n\phi + \delta_n) k_{nm} I_n(k_{nm} r) [A_{nm} \sin(k_{nm} z) + B_{nm} \cos(-k_{nm} z)]$$

$$B_\phi = \sum_{n,m} -\frac{n}{r} \sin(n\phi + \delta_n) I_n(k_{nm} r) [A_{nm} \cos(k_{nm} z) + B_{nm} \sin(-k_{nm} z)]$$

★ **All field components fit simultaneously.**

★ **Fit expanded to ~200 terms, ~400 free parameters.**
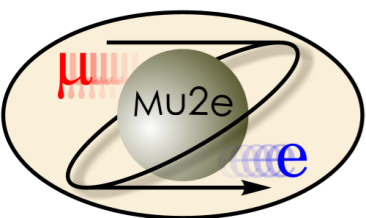
Fit Results

2D Slice Range:

4 m ≤ Z ≤ 13 m

R ≤ 80 cm
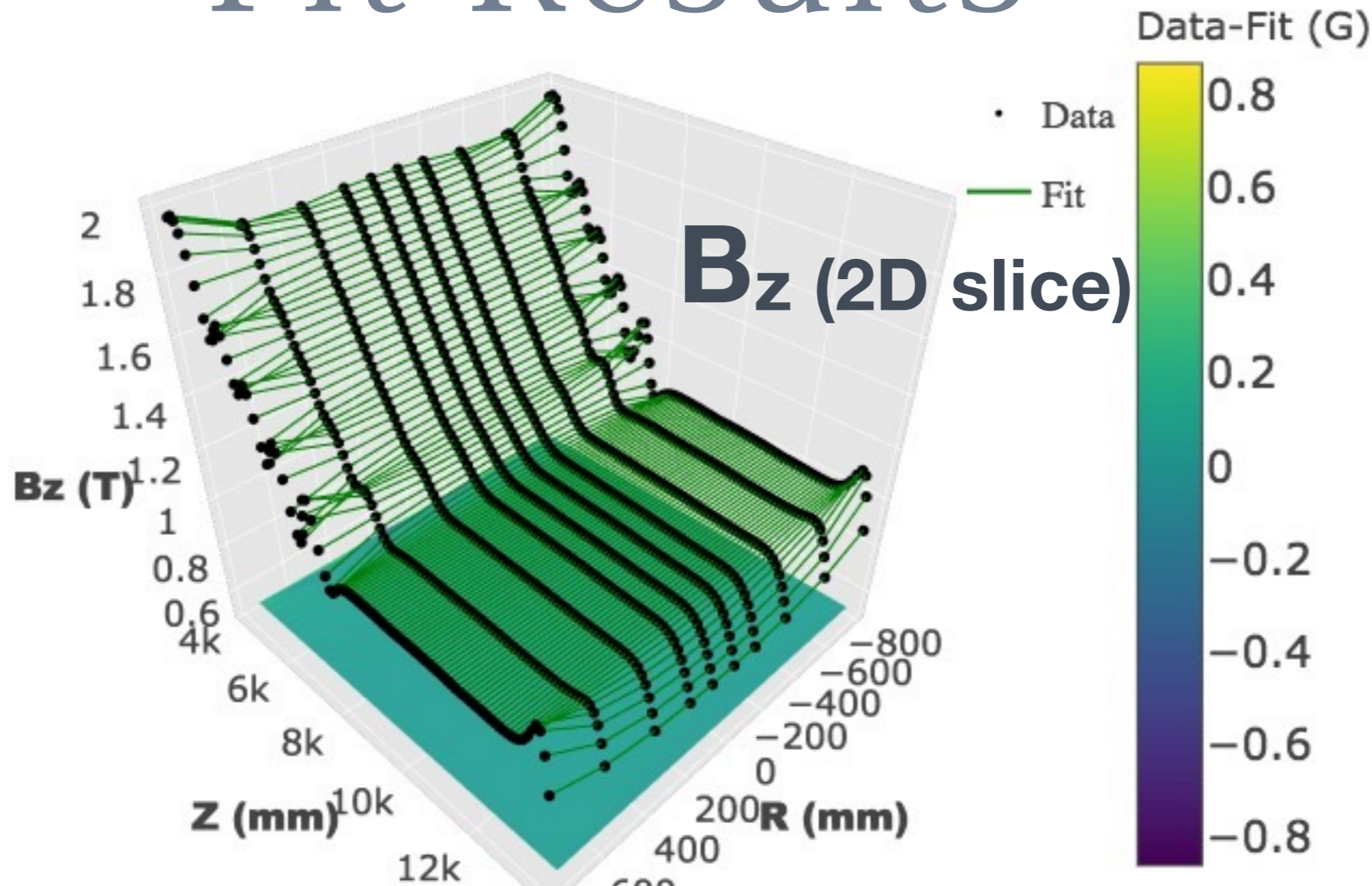
Black dots: Sim data points

Green mesh: Fit

Surface: Residuals

(Data-Fit, in units of Gauss)

-Agreement with simulation at **R<800 mm is excellent.**

-Level of disagreement is <u>still</u> on the order of 10^{-5} - 10^{-6} **(~0.01 Gauss)**

-Extrapolation of field is accurate within **~5 Gauss for 800<R<900 mm**

Systematic Errors

★ **Hall probes will be subject to systematic errors based on positional and measurement accuracy.**

- Requirements for Detector Solenoid:

  ✦ *Measurement*: $\sigma|\mathbf{B}|/|\mathbf{B}| \leq 0.01\%$ *(Shown in next slide)*

  ✦ *Position*: σ position $\leq$ 1mm

  ✦ *Orientation*: $\sigma\phi \leq 0.1$ mrad

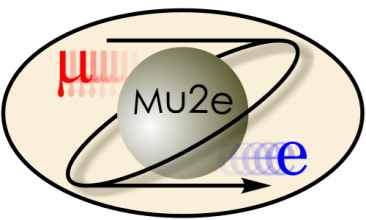★ **These effects will translate into slight mis-measurements, which in turn will affect field map.**

★ **Procedure:**

- Modify hall probe measurements with systematic errors.

- **Fit** function to **modified** probe values.

- Compare resulting map to **true** field.
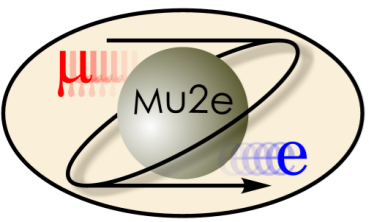
★ **A scale factor representing a miscalibration of each probe measurement, satisfying B$_{measured}$ is within 0.01% of B$_{true}$.**
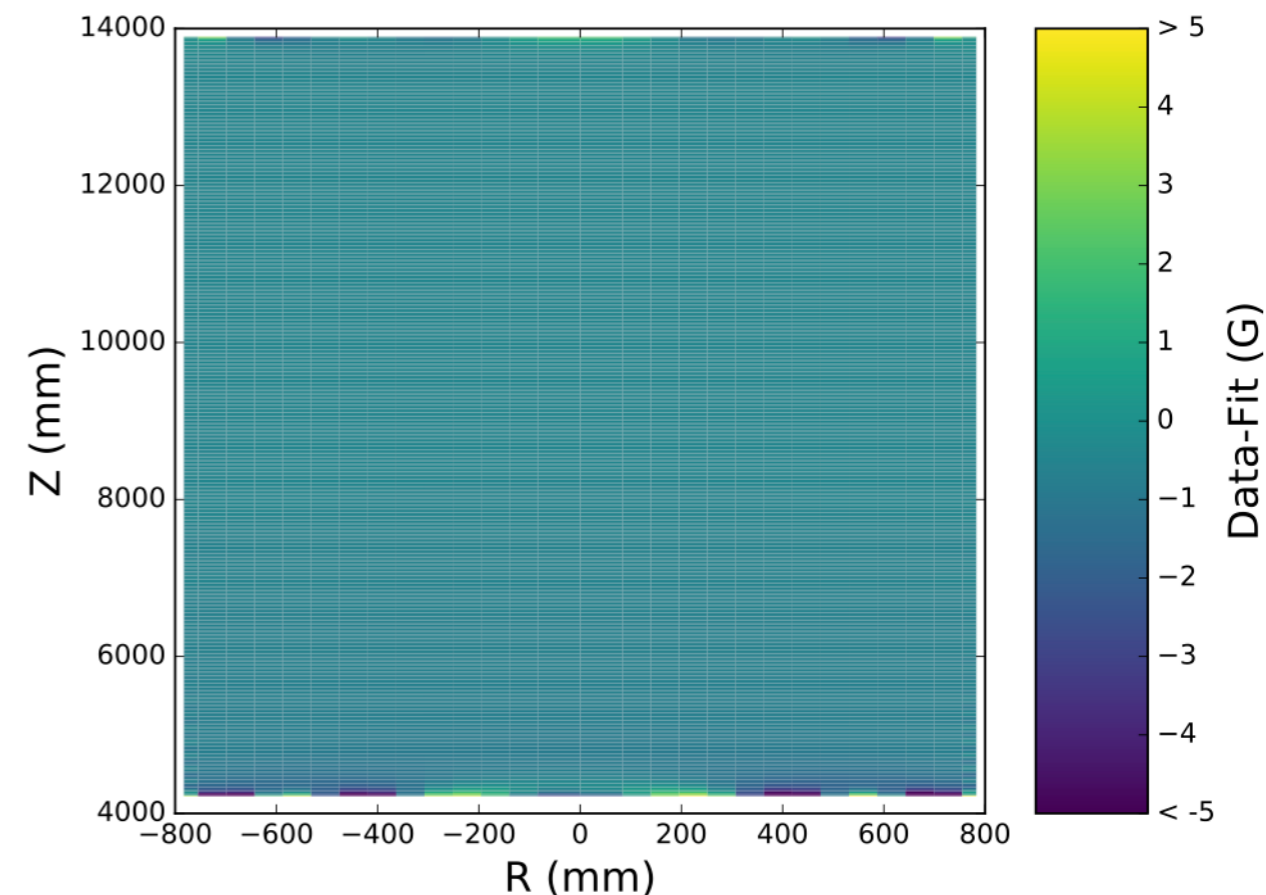
- e.g., B → B*(1+ε) where -0.0001<"ε"<0.0001

- Represents <u>correlated</u> systematic effect, not random error

**Bz Residuals
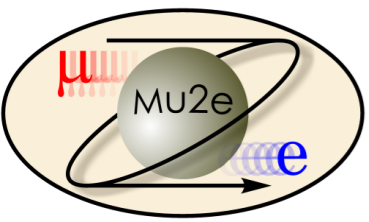Fit vs Miscalibrated Probes**
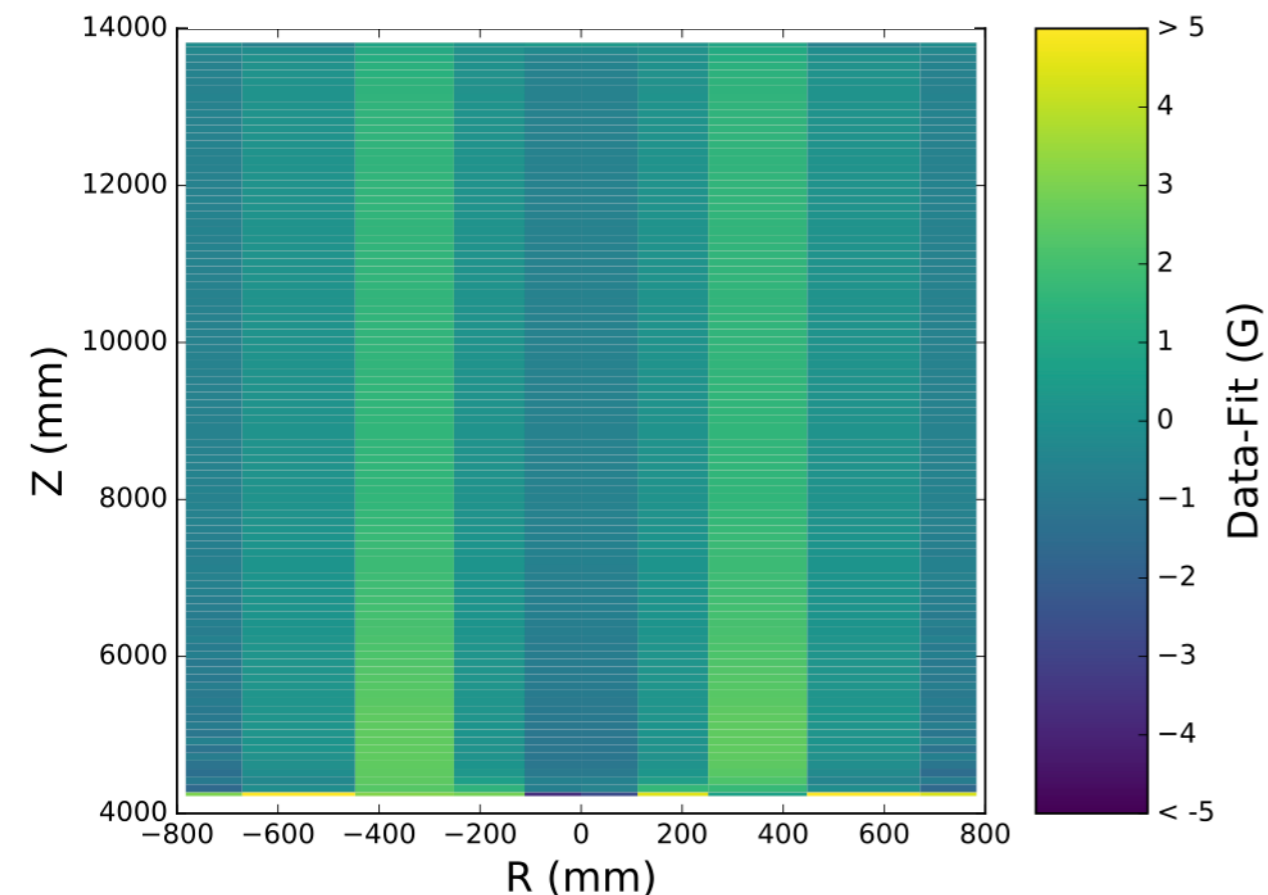
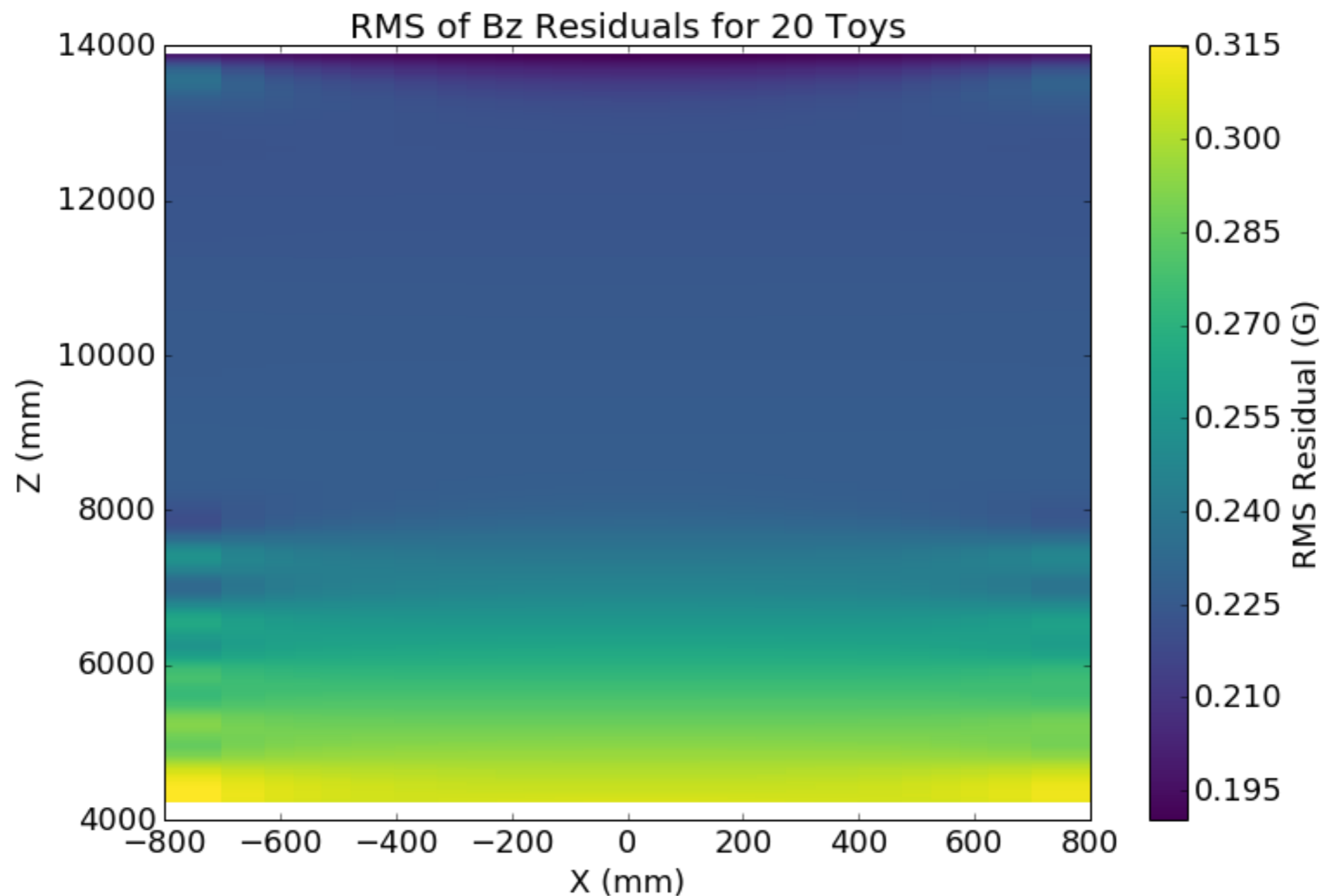**Bz Residuals
Fit vs True Field**

Fit function resists miscalibration, more accurate

than simple interpolation!

RMS of Residuals

Simulation of systematic errors re-run 20 times, results compiled:

RMS of Bz Residuals for 20 Toys

The spread of expected residuals is ~0.25 G, which corresponds to a relative error better than 5×10^{-5}.
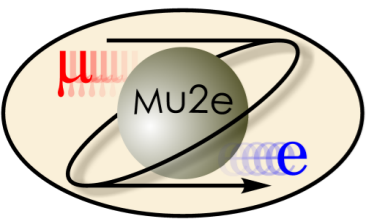
Software Implementation

★ **All data manipulation, fitting, and visualization software written in Python with popular open source packages:**

- Numpy, Scipy, pandas, lmfit, matplotlib, plotly…
- Easy to integrate results into any software framework.

★ **Minimization time is good:**

- ~500 parameter fit run over ~20,000 data points takes ~30 min on an i7 laptop.
- Using numba (with CUDA for GPU acceleration), time reduced by 2x-10x using current-gen GPU.
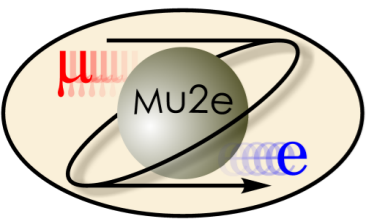
Summary

★ **Mu2e will improve current CLFV sensitivity by over 4 orders of magnitude.**

  • Great discovery potential!

★ **Demanding performance requires precise and accurate knowledge of magnetic field.**

  • Novel hardware and software solutions needed.

★ **Leveraging magnetostatics and modern-day computing, semi-analytic fitting technique can produce continuous, accurate maps, even in non-ideal scenarios.**

Backup
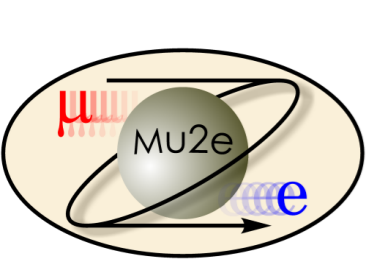
★ **Lepton Flavor Violation (LFV) is a well known and defining phenomena in the neutrino sector.**
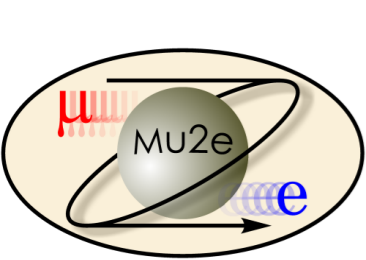
★ **But what about Charged Lepton Flavor Violation (CLFV)?**

- Has not yet been detected → only limits have been placed.
- Greatly suppressed in SM (BR < 10^{-50}).

★ **Mu2e is designed to probe CLFV with 10,000 times the sensitivity of previous experiments!**

★ **If a single signal event is observed, it will be a clear sign of New Physics.**

Neutrinos don't conserve flavor…

ν_e ↔ ν_μ

ν_τ
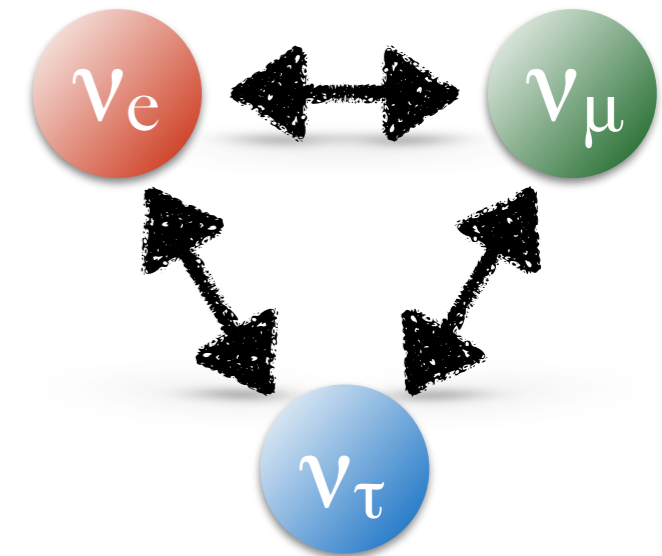
…do charged leptons?

e ↔ μ

?

τ
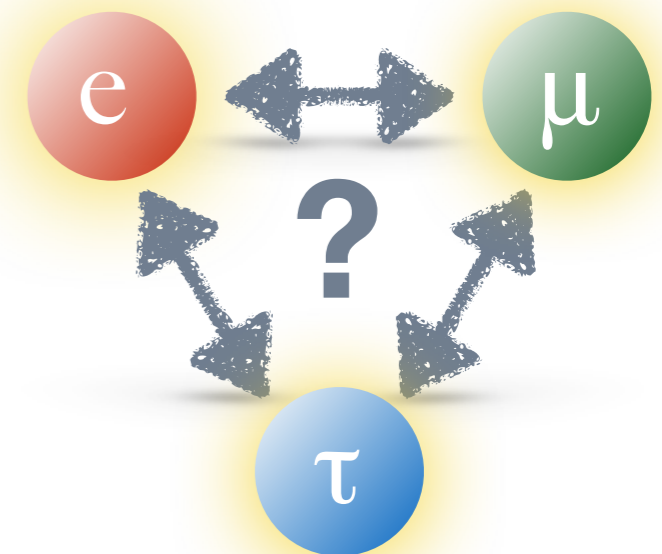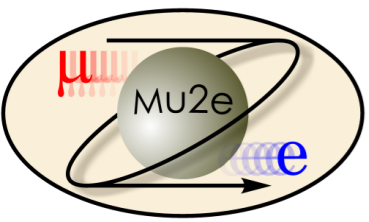
The Experiment Goal

Key Metric : $R_{\mu e} = \dfrac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$.

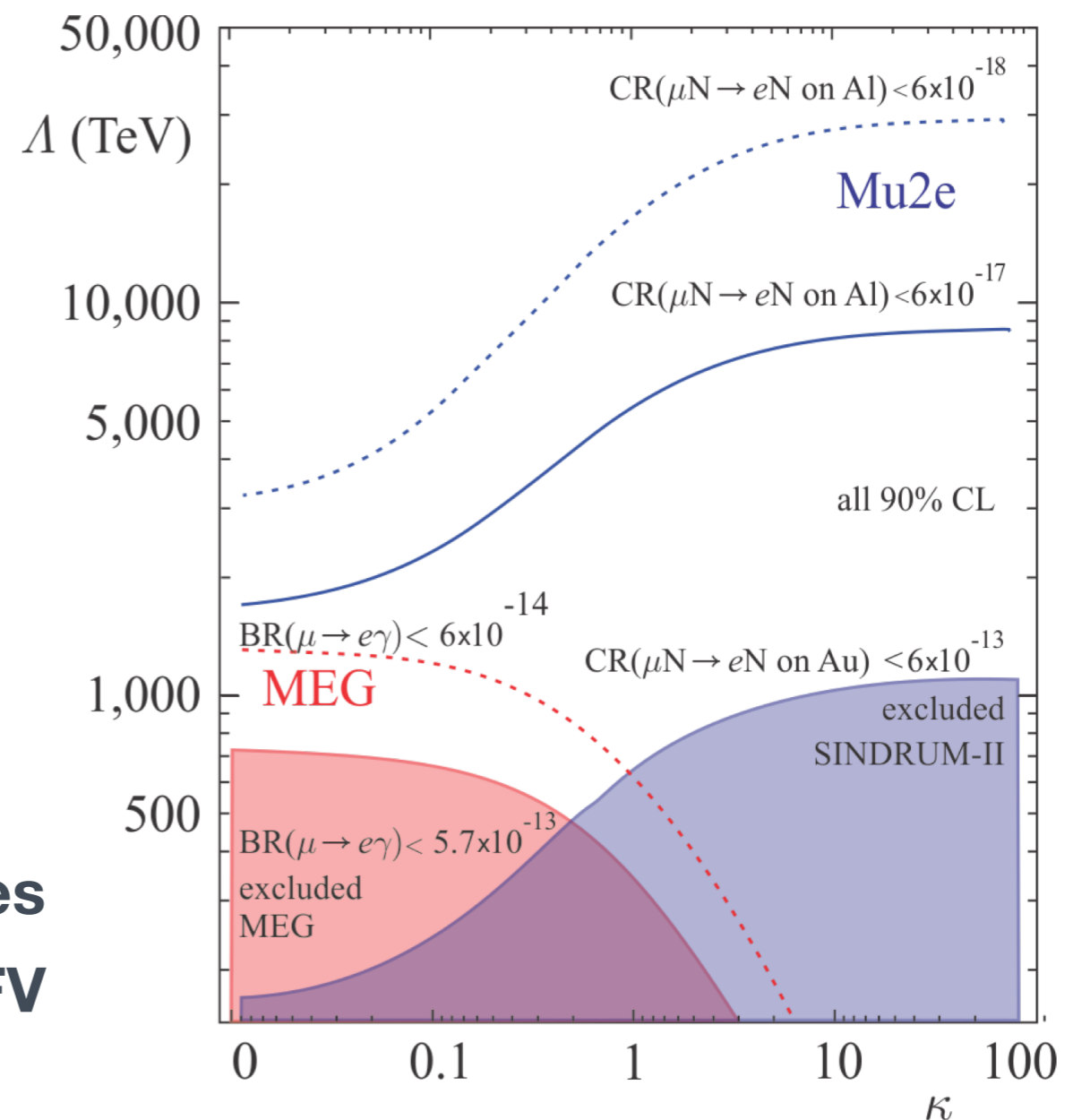**(Rate of neutrinoless conversion)**

(Rate of ordinary muon capture)

Model Independent Effective Lagrangian:

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}_L \gamma^\mu q_L \right).$$

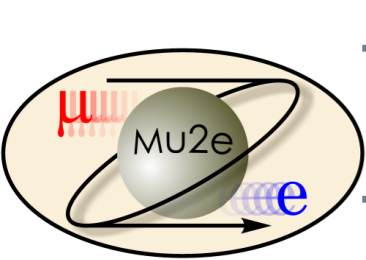**Magnetic moment interactions** | **Four-fermion interactions**

Λ: New Physics mass scale

κ: Dimensionless relative contribution scale

Mu2e will be sensitive to new physics scales up to ~10,000 TeV, and to both types of CLFV operators.
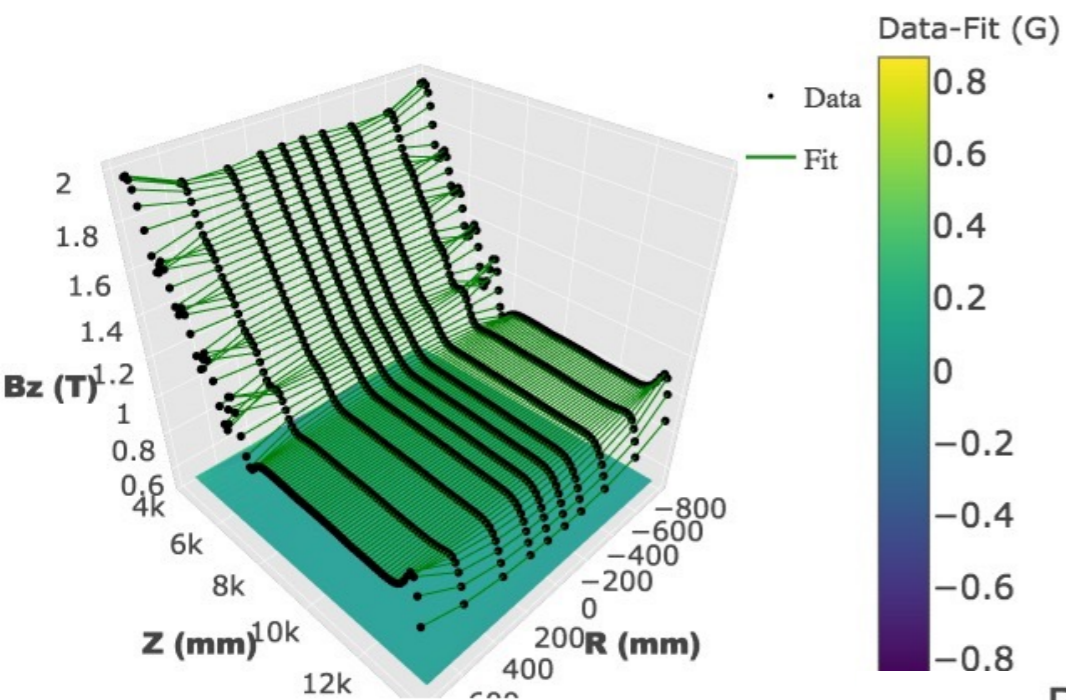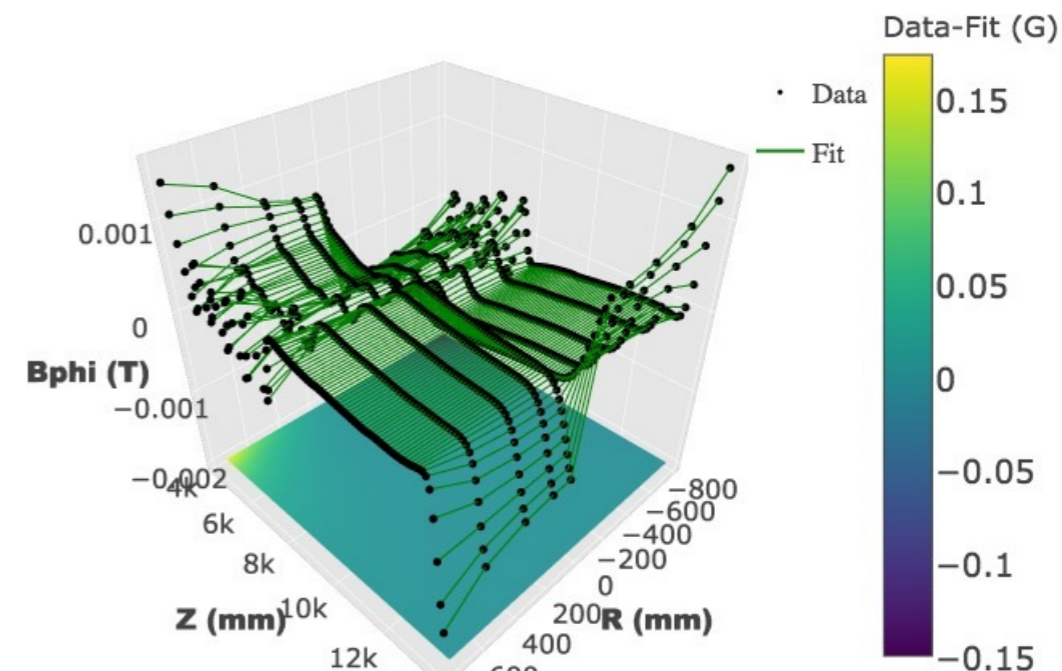

André de Gouvêa, NU

Fit Results (Sparse)

Bz vs R and Z for DS
Z>4200, Z<13900, Phi==0.46

Bphi vs R and Z for DS
Z>4200, Z<13900, Phi==0.46

Br vs R and Z for DS
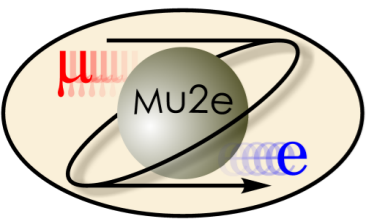Z>4200, Z<13900, Phi==0.46
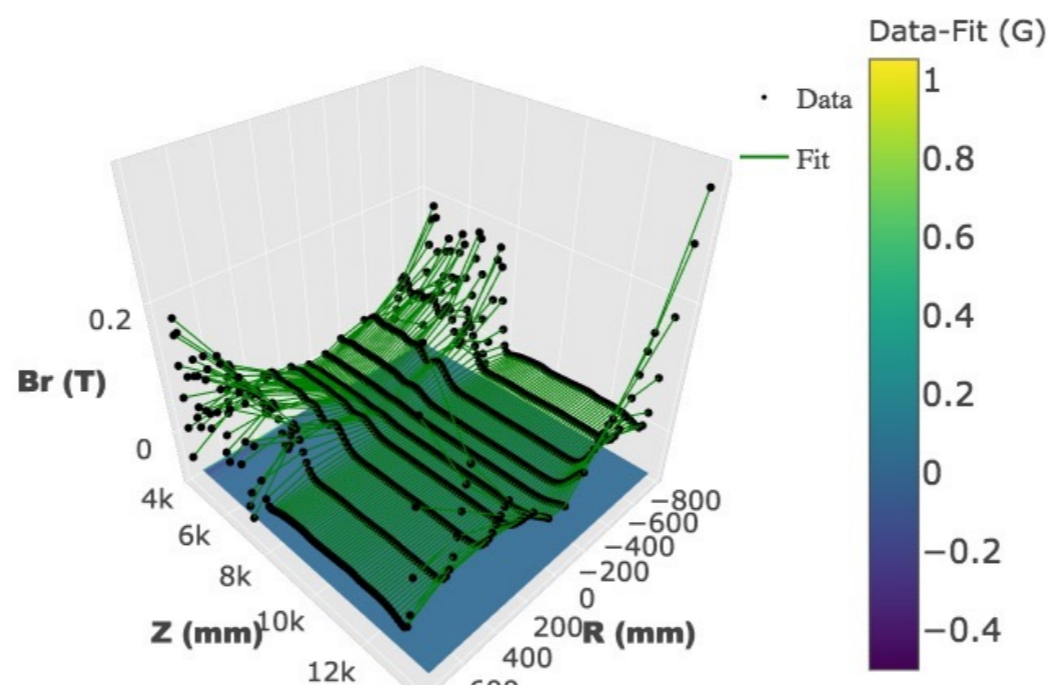
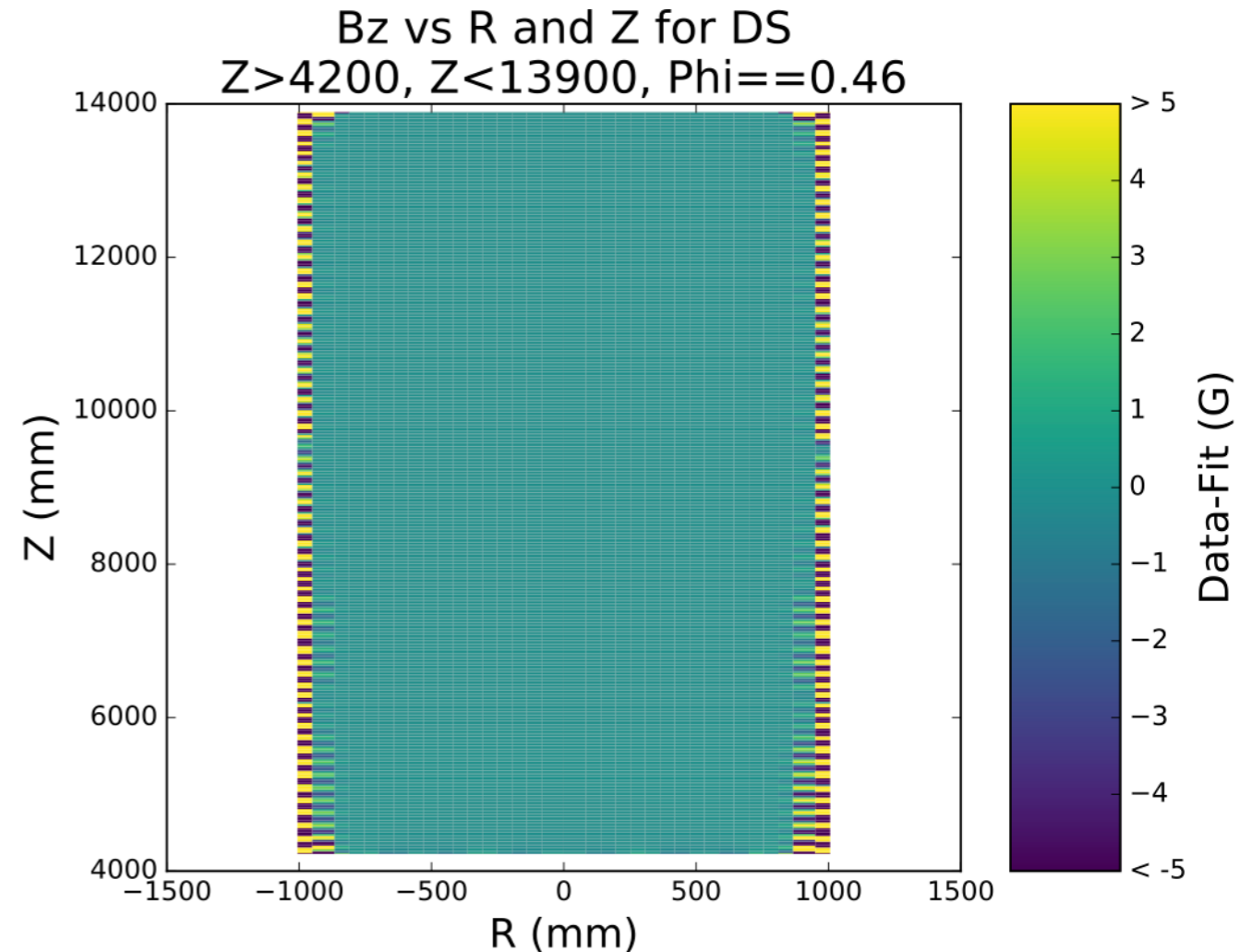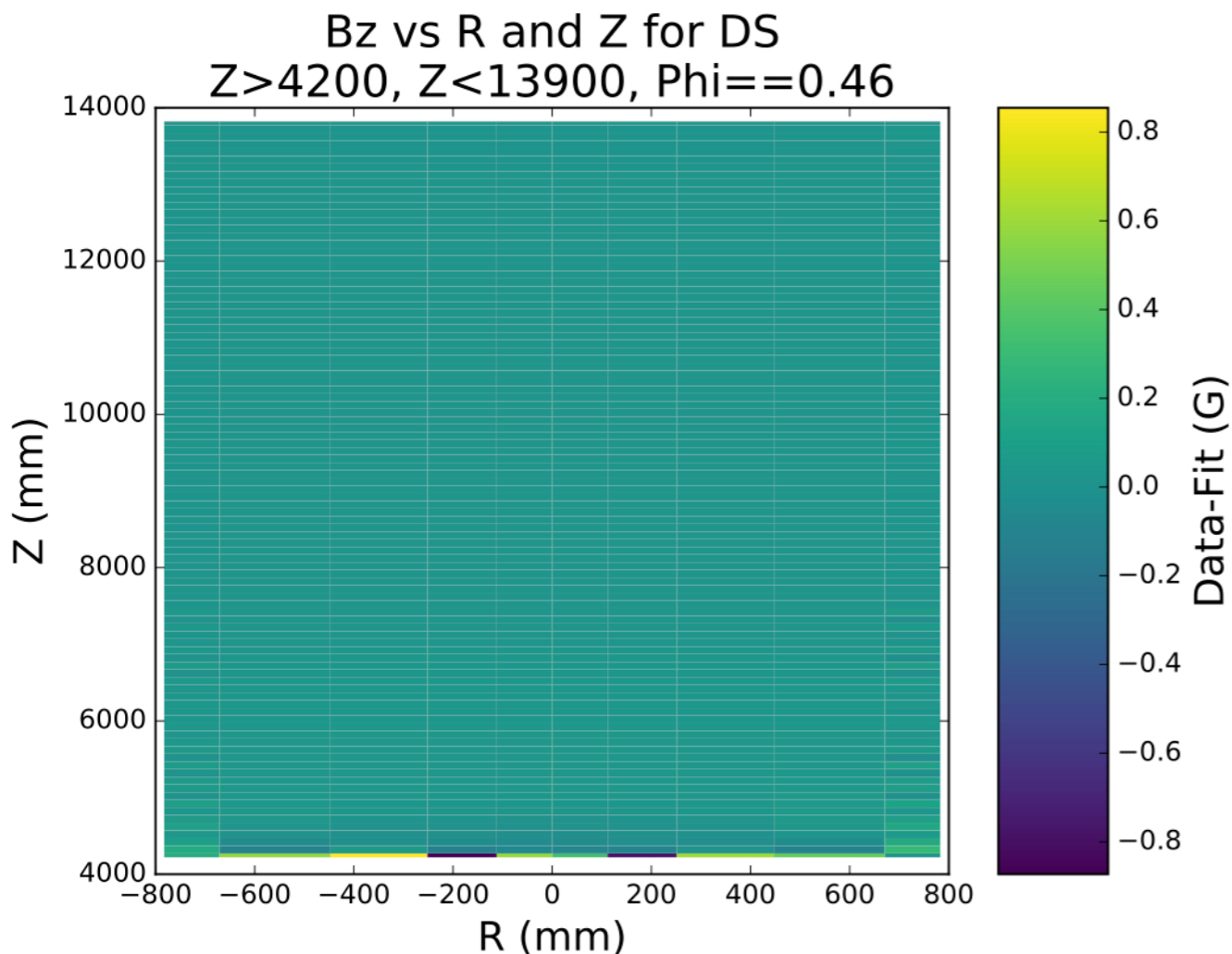**Black dots: Data points**

Green mesh: Fit

Surface: Residuals

(Data-Fit, in units of Gauss)

This is an example for a single 2D slice of the magnetic field. All slices and components are fit simultaneously.

Map Results (Dense)

Bz vs R and Z for DS
Z>4200, Z<13900, Phi==0.46

Bz vs R and Z for DS
Z>4200, Z<13900, Phi==0.46

Residual compared to probes (sparse sample).

Residual compared to dense sample.

- Agreement with simulation at **R<800 mm is excellent.**

- Level of disagreement is <u>still</u> on the order of **10^{-5} - 10^{-6} (~0.01 Gauss)**

- Extrapolation of field is accurate within **~5 Gauss for 800<R<900 mm**
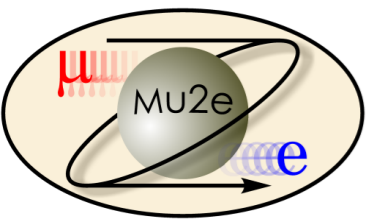
Position Systematic
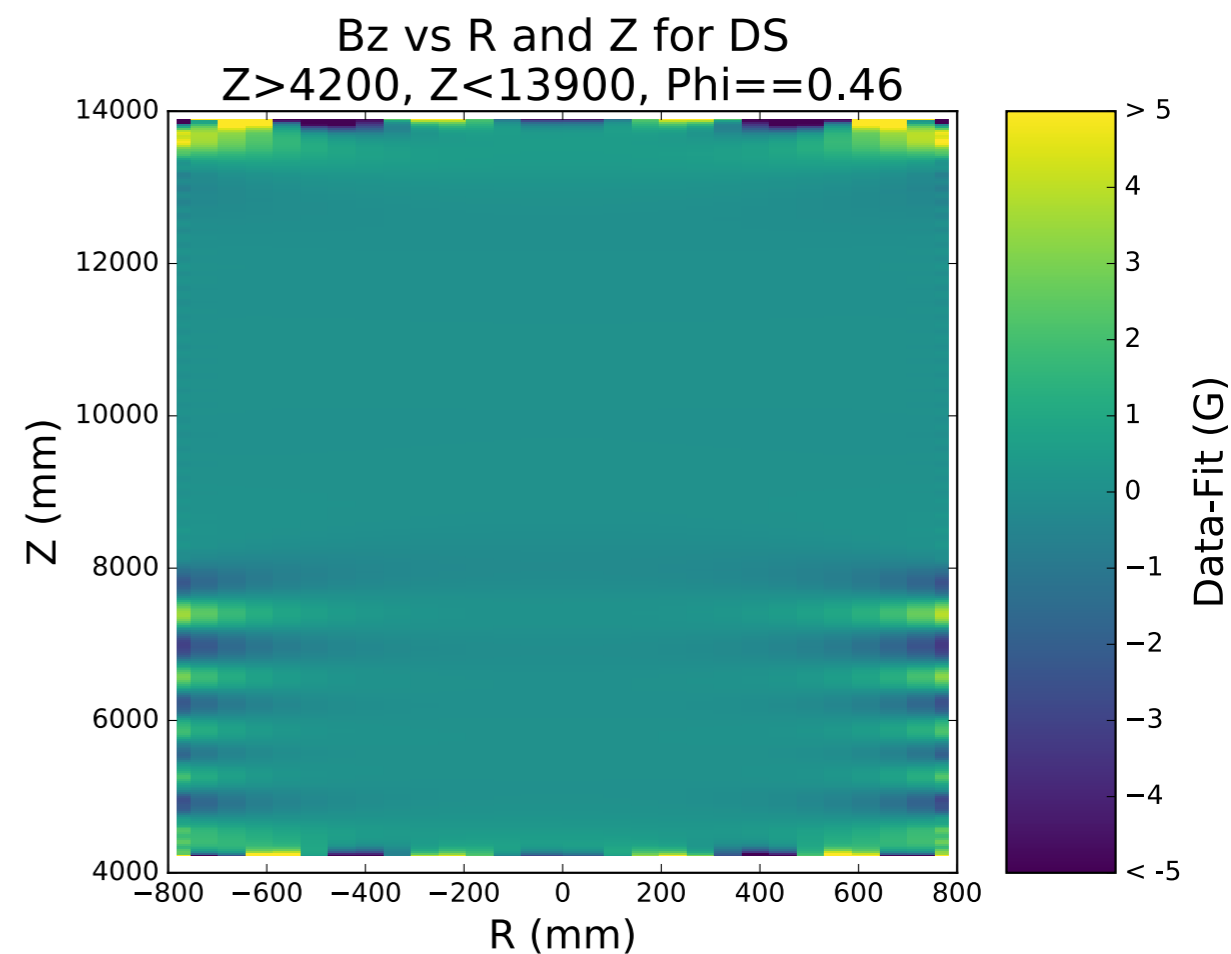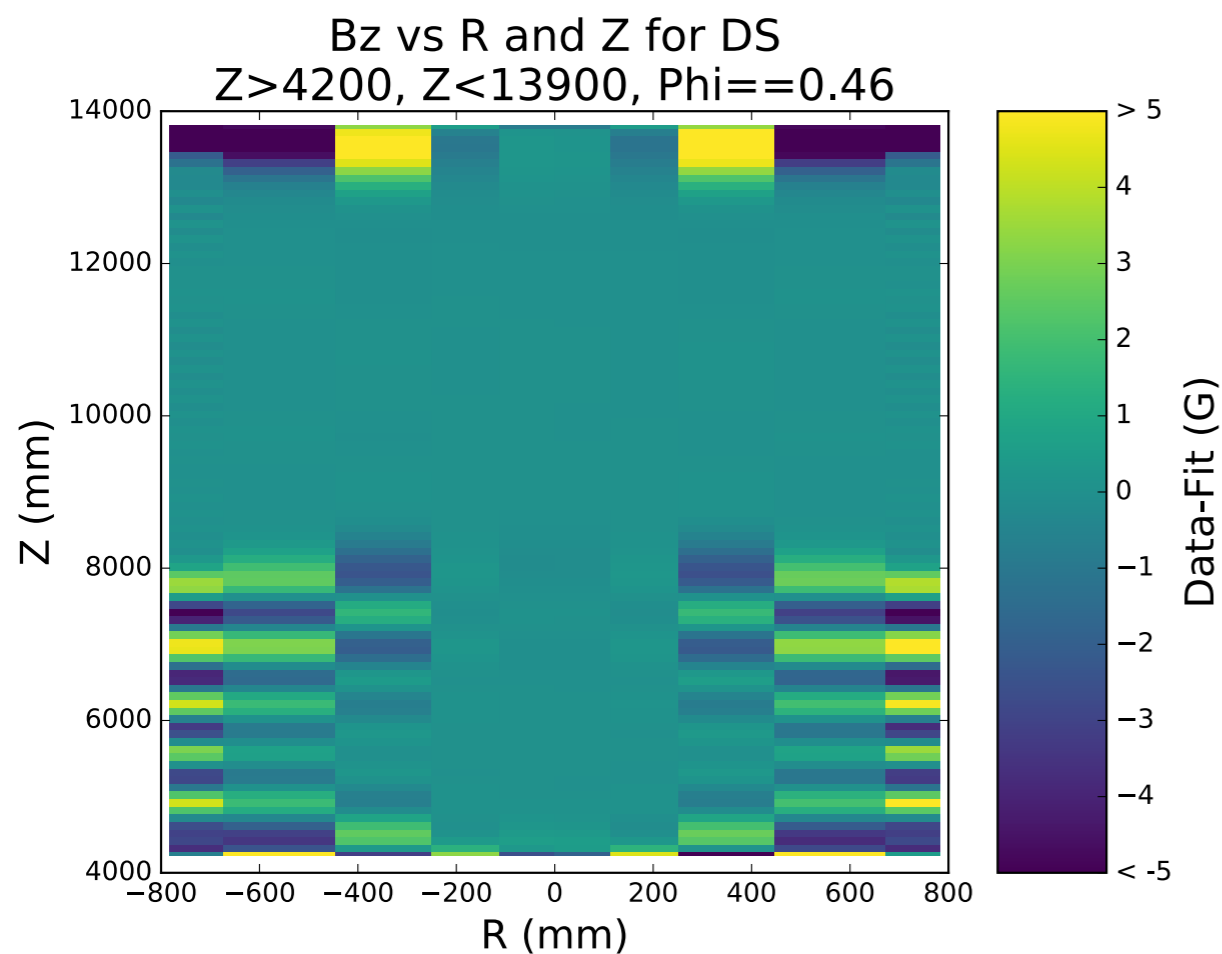
★ **Each probe position is shifted by an offset of ~±1 mm in the radial direction.**

★ **As, expected, greatest effects are in regions of high magnetic gradient w.r.t radial position.**

- Minimal effect in tracking region.

Fit compared to probe measurements

Fit compared to true field
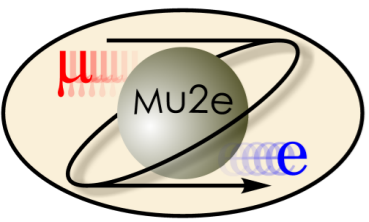
Orientation Systematic
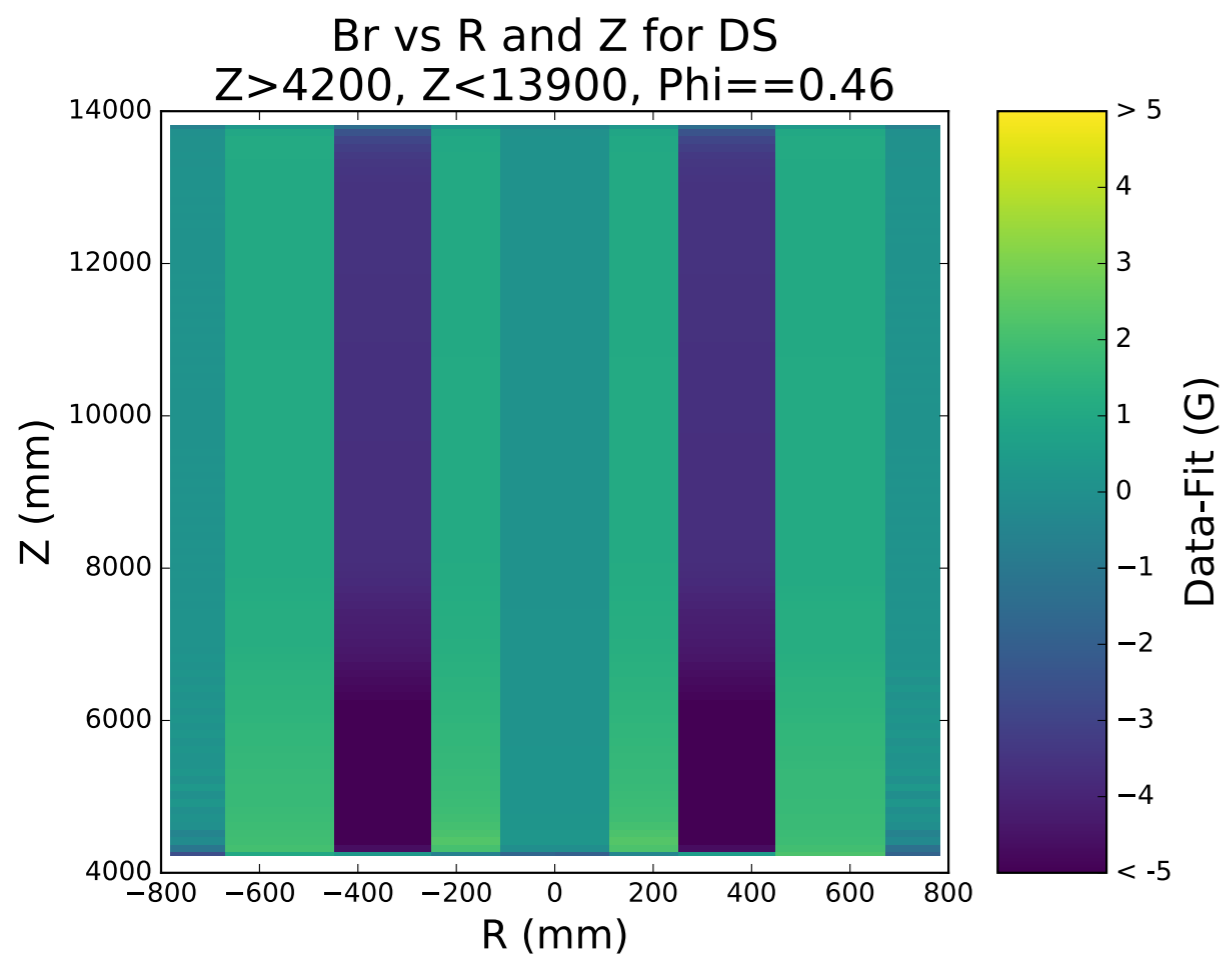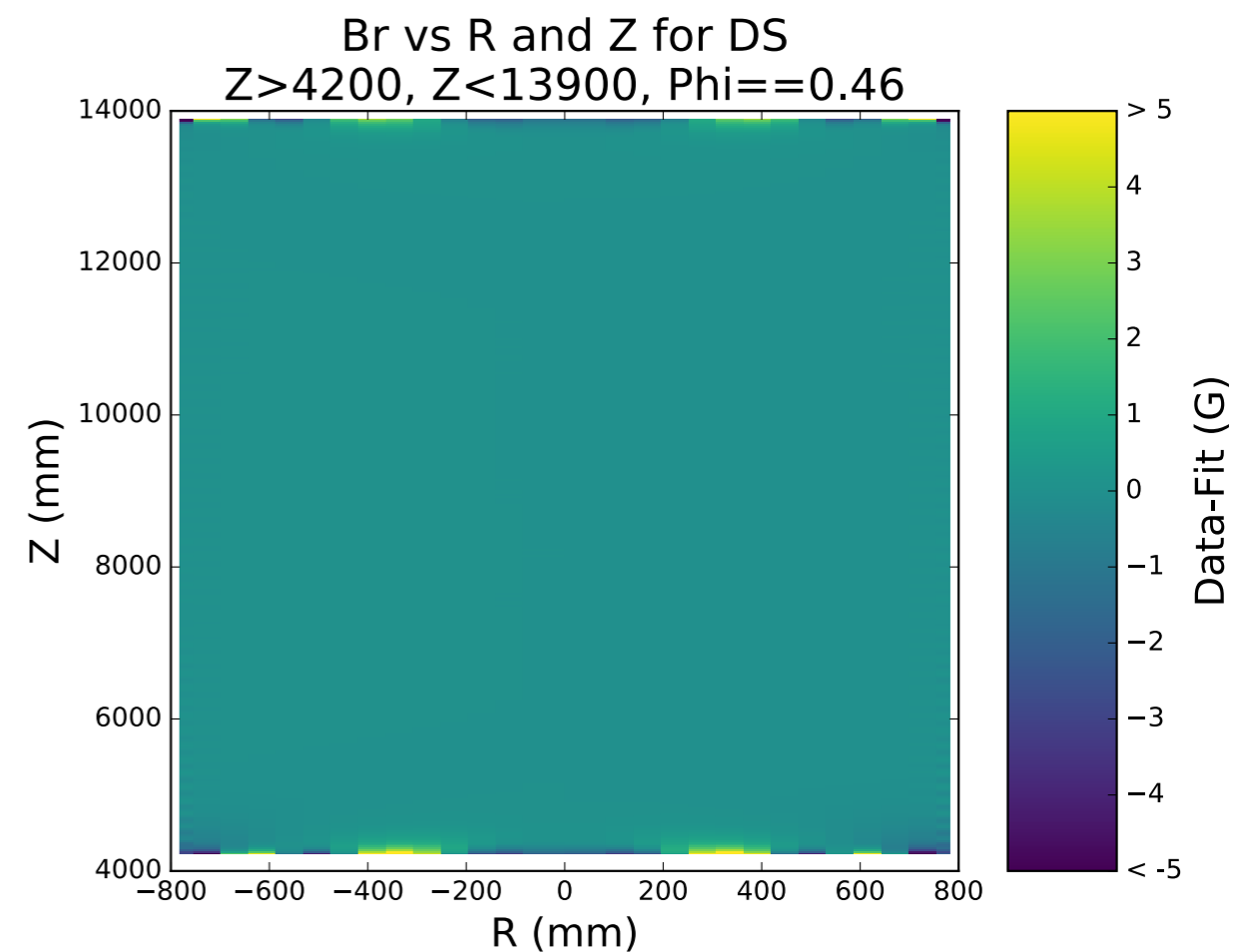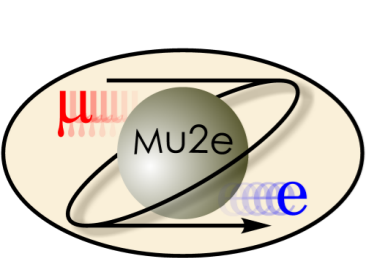
★ **Each probe is rotated by an angle of ~0.1 mrads in the R-Z plane**

• This mainly impacts the value of Br, as the Bz component is much larger.

★ **This mixing should always reduce the Z-component and increase the R-component.**

Fit compared to probe measurements

Fit compared to true field

Field Mapping System (FMS) Team

★ **Sandor Feher —** L3 Manager, Fermilab – TD/MSD Measurements and Analysis Group Leader, Mu2e Detector Solenoid (DS) L3 Manager

★ **Michael Lamm —** L3 CAM, Mu2e Solenoid System L2 manager

★ **Argonne National Laboratory team:**

- **Rich Talaga** and **Robert G. Wagner —** Senior Physicists

- **James Grudzinski** and **Jeffrey L. White —** Senior Mechanical Engineers

- **Allen Zhao —** Motion Control Expert, Senior Engineer

★ **Fermilab team:**

- **Luciano Elementi** and **Charles Orozco —** System Engineers

- **Horst Friedsam —** Geodicist

- **Thomas Strauss —** Associate Scientist

- **Jerzy Nogiec —** Computer Scientist

★ **Northwestern University:**

- **Michael Schmitt —** Physics Professor

- **Brian Pollack —** HEP Research Fellow

- **Thoth Gunter —** Graduate Student