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Geant4 simulation for the TREK experiment at J-PARC

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Overview

- Introduction
- Physics Motivation
- Test of Lepton Flavor Universality
- Search for Heavy Sterile neutrino (N)
- Search for Light U(1) gauge boson
- Implementation of Geant4 Framework
  - Geometry
  - Optimization of magnetic field
- Further Study

What Is Trek?

- Time Reversal violation Experiment with Kaons
  - **Measurement of T-violating transverse muon polarization (P_T) in $K^+ \rightarrow \pi^0\mu^+\nu$ decays**
- E36 (Lepton Universality & Sterile Neutrino Search)
  - **Measurement of $\Gamma(K^+ \rightarrow e^+\nu)/\Gamma(K^+ \rightarrow \mu^+\nu)$ and search for heavy sterile neutrinos using the TREK detector system**
  - Use TREK apparatus with stopped kaons to search for:
    - Lepton Flavor Universality
    - Heavy Sterile Neutrino
    - U(1) Boson

Physics Motivation

- Search for new physics beyond the Standard Model (SM)
- SM effective low energy description, new physics lies at ~1TeV and:
  - Dark matter (~23%) & dark energy (72%) cannot be explained
  - Baryogenesis cannot be derived from the SM
  - Neutrino masses

Test Lepton Flavor Universality

Lepton Flavor Universality

- e, μ and τ: Have different masses, same gauge couplings

$$\Gamma(K_{l2}) = g_l^2\,(G^2/8\pi)\, f_K^2 m_K m_l^2 \{1-(m_l^2/m_K^2)\}^2$$

→ $g_e = g_\mu$

- Branching ratio of Leptonic K^+ decay

$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r)$$

- Hadronic form factors cancel
- SM prediction is highly precise
  - $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Lepton Flavor Universality cont...

- High sensitivity to LFV beyond SM
  - MSSM with charged-Higgs SUSY-LFV
  - Can strongly be enhanced by emission of τ neutrino (ν_τ)

$$R_K^{LFV} = R_K^{SM}\left(1 + \frac{m_K^4}{M_{H^+}^4}\cdot\frac{m_\tau^2}{m_e^2}\Delta_{13}^2\tan^6\beta\right)$$

$\sim R_K^{SM}(1 \pm 0.013)$

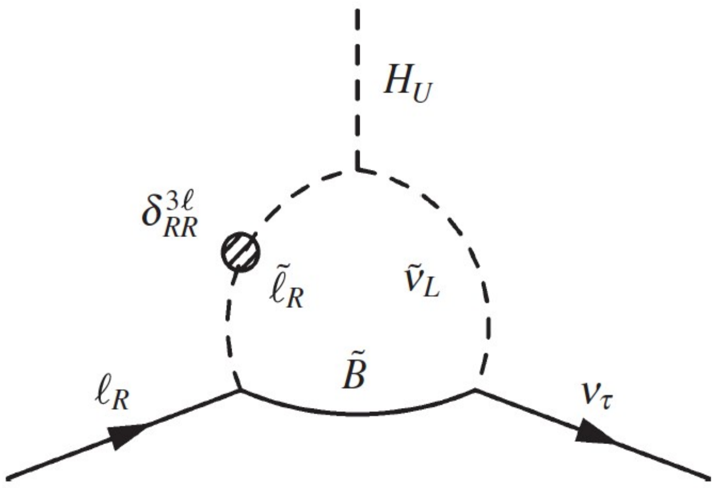


FIG. 1. Contribution to the effective $\bar{\nu}_\tau \ell_R H^+$ coupling.

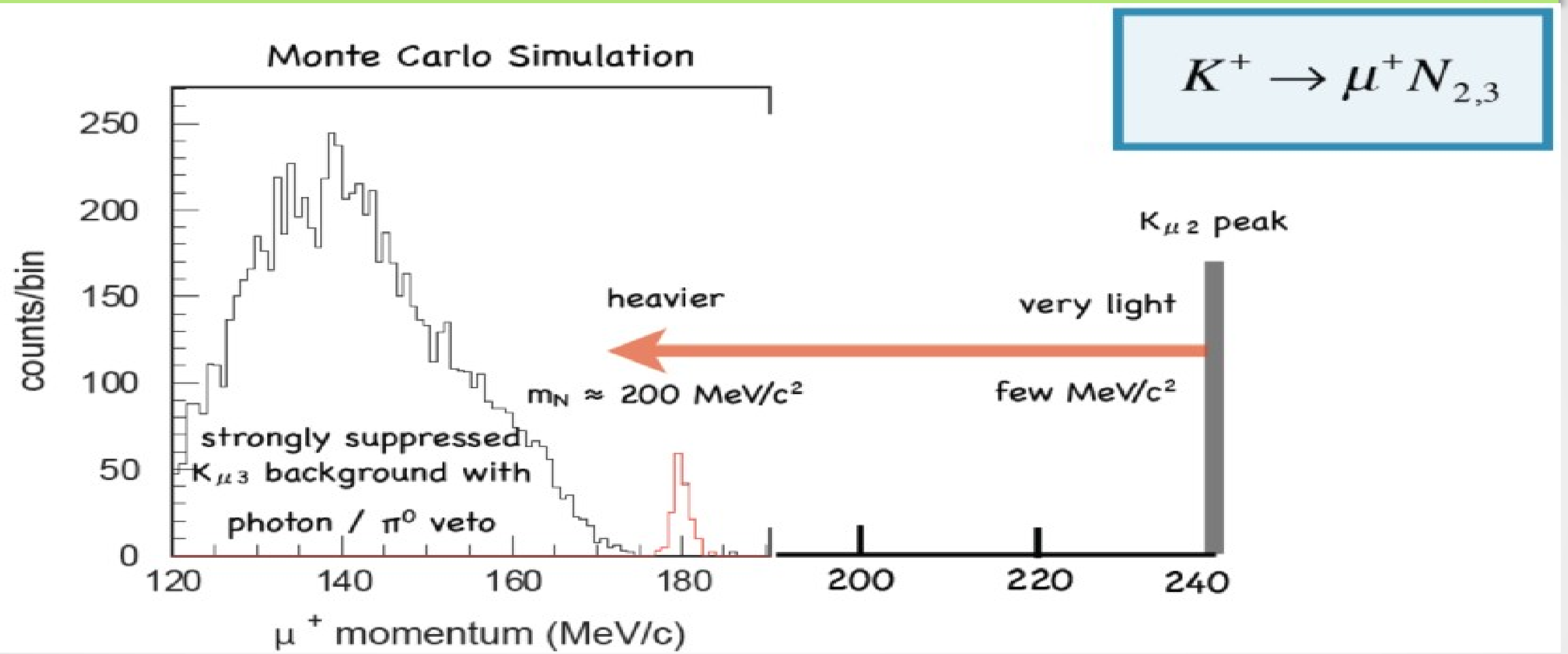
J. Girrbach and U. Nierste, arXiv:1202.4906;

A. Masiero, P. Paradisi, and R. Petronzio, Phys. Rev. D 74, 011701 (2006); JHEP11, 042 (2008)

- Current Experimental Precision (KLOE, NA62)
  - $R_K=(2.488\pm0.010)\times10^{-5}$, $\Delta R_K/R_K=0.4\%$

- Improve precision to 0.25% (0.20%stat.+0.15% sys.)

Search For Heavy Sterile Neutrinos



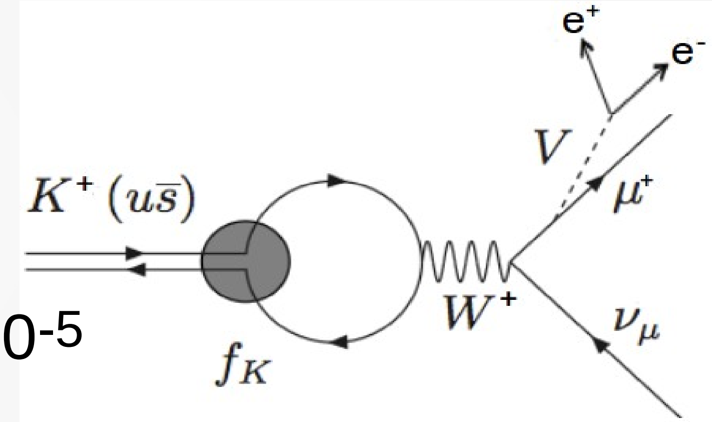
- ν Minimal Standard Model (νMSM)
  - Explanation of DM and BAU
  - Possibility of $M_N \leqq M_K$
- monochromatic peaks in $K^+ \to \mu^+ N$, $K^+ \to e^+ N$

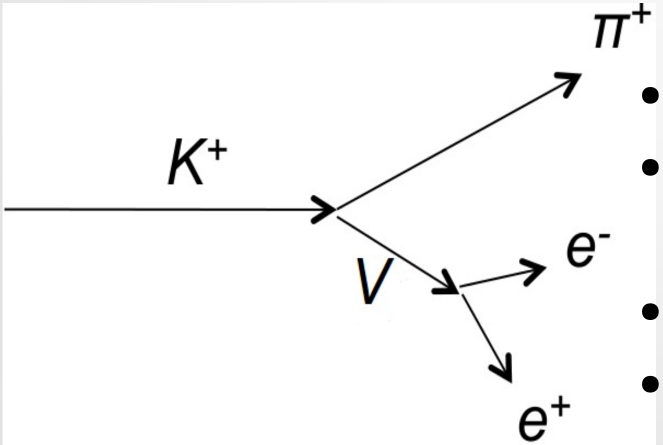
D. Gorbunov and M. Shaposhnikov, JHEP0710, 015 (2007)

Search for Dark Photon/U(1) Boson

- Full reconstruction of final state
  - Detection of all charges particles with good resolution

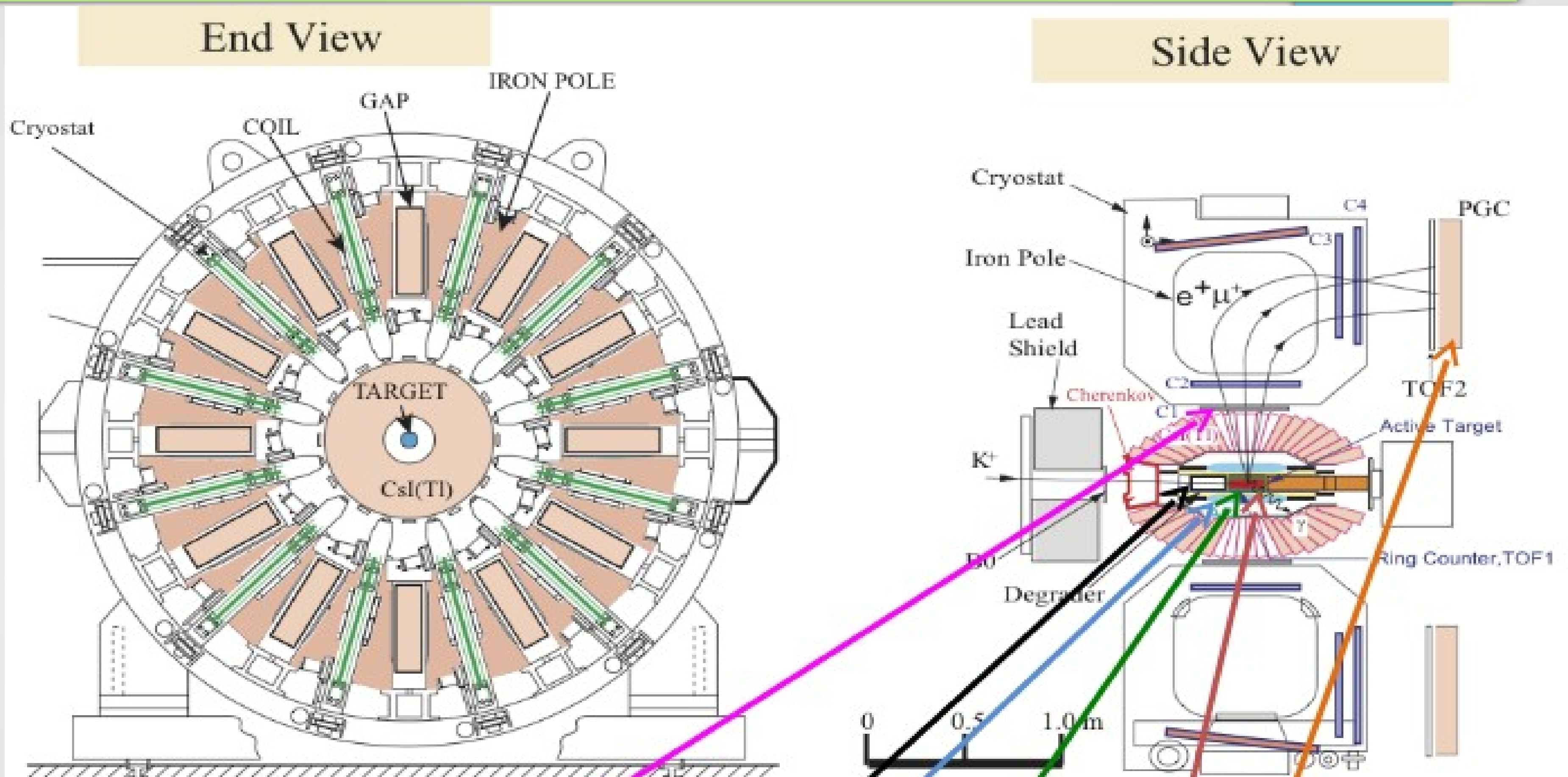
- Channel: $K^+ \rightarrow \mu^+ \nu e^+e^-$
- Search for narrow peak in (ee) invariant mass spectrum: $V \rightarrow e^+e^-$
- Sensitivity: $Br(K^+ \rightarrow \mu^+\nu V) \sim 10^{-8}$
- Background: $Br(K^+ \rightarrow \mu^+ \nu e^+e^-) \sim 2.5 \times 10^{-5}$





- Channel: $K^+ \rightarrow \pi^+ e^+e^-$
- Search narrow peak in (ee) invariant mass spectrum: $V \rightarrow e^+e^-$
- Sensitivity: $Br(K^+ \rightarrow \pi^+V) \sim 10^{-8}$
- Background: $Br(K^+ \rightarrow \pi^+ e^+e^-) \sim 2.5 \times 10^{-7}$

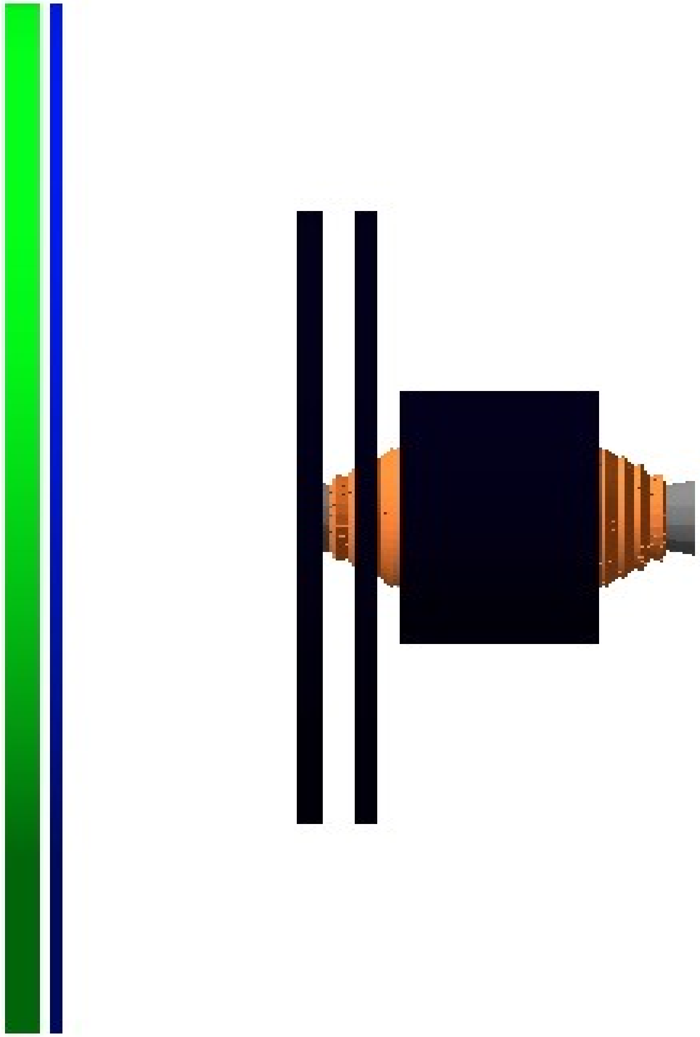
The TREK apparatus for E36



Toroid from E-246 @ KEK-PS

- C1 GEM
- Aerogel Cherenkov (AC)
- K+ stopping target
- TOF
- Lead Glass (PGC)
- SciFi tracker

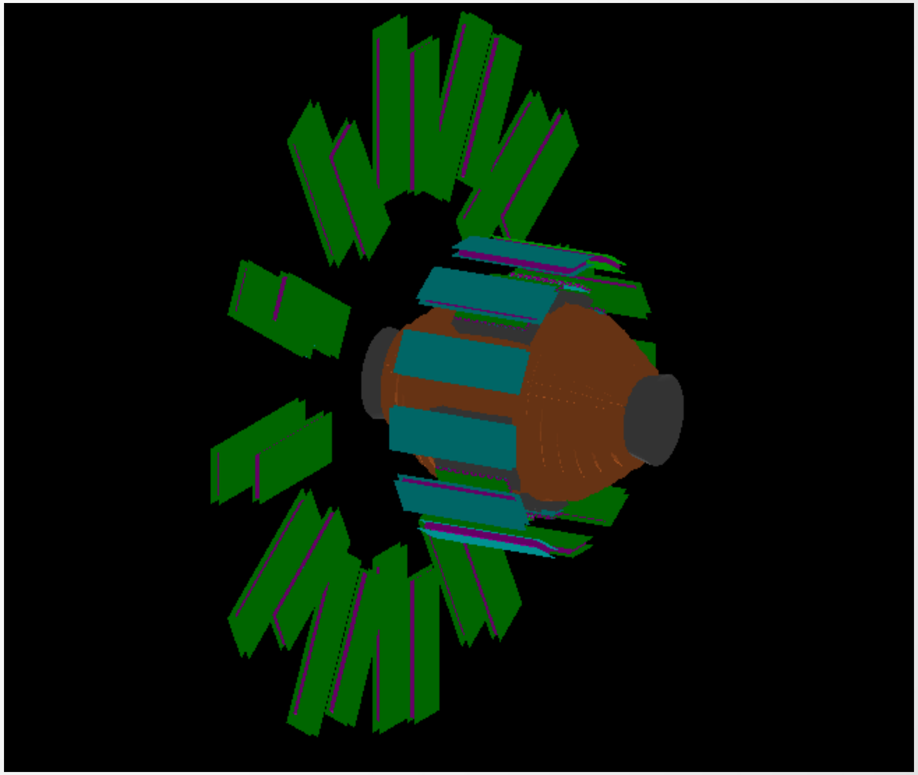
Implementation of Geant4 framework



Regions of sensitive detectors

Geometry of tracking elements

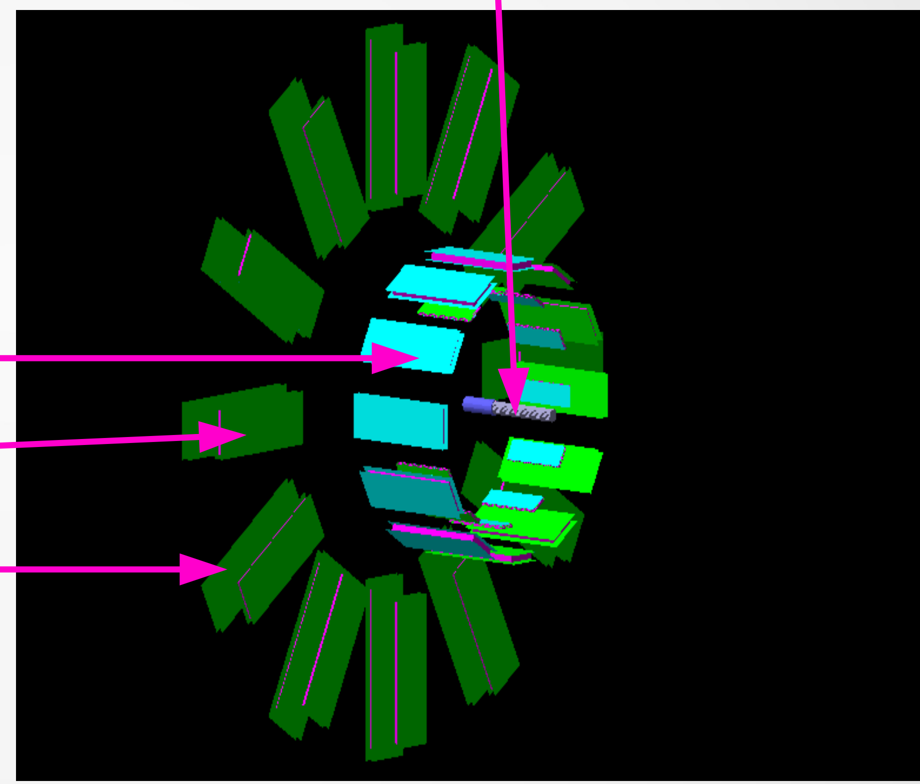
- Qt well suited for real-time fast visualization and demonstration.
  - Mouse control (rotation and zoom)
  - Save scene as vector or pixel graphics
- Qt generated geometry
  - SciFiber Target
  - CsI Barrel
  - GEMs
  - MWPCs



Tracking Element Geometry cont...

- Same Geometry
  - Removed CsI Barrel to expose SciFiber target
  - C2
  - C3
  - C4

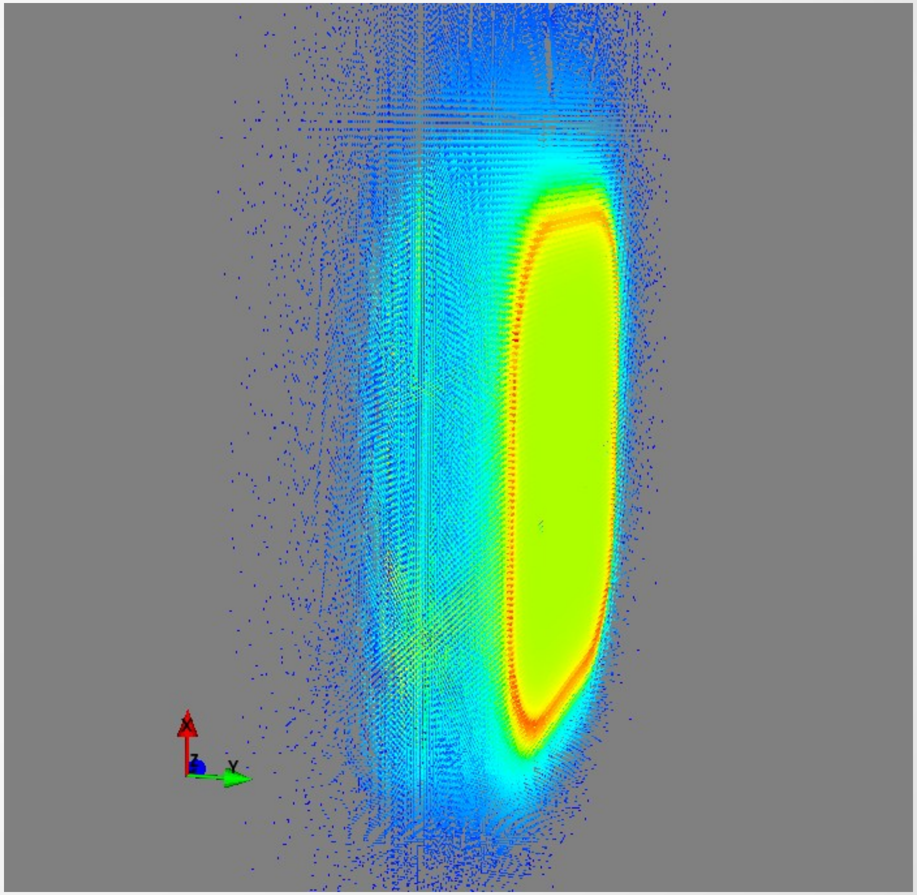
Target



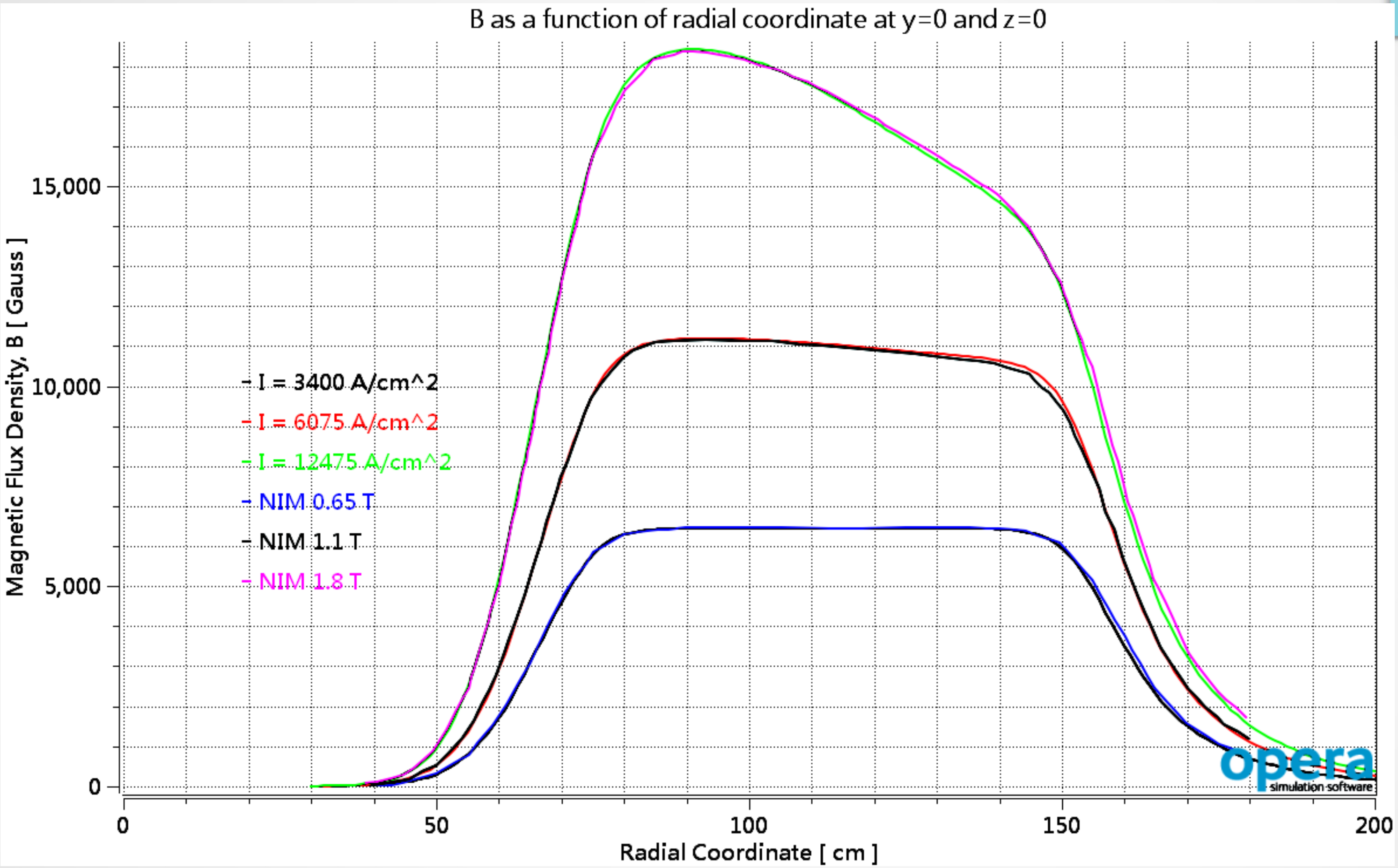
Magnetic field

- TOSCA generated magnetic field (P. Monaghan)
  - 1/8 sector field map
- Needed to generate a full sector field map
  - Used ROOT script with following symmetry

$$-y : B_x \to -B_x, B_y \to +B_y, B_z \to -B_z$$
$$-z : B_x \to +B_x, B_y \to +B_y, B_z \to -B_z.$$



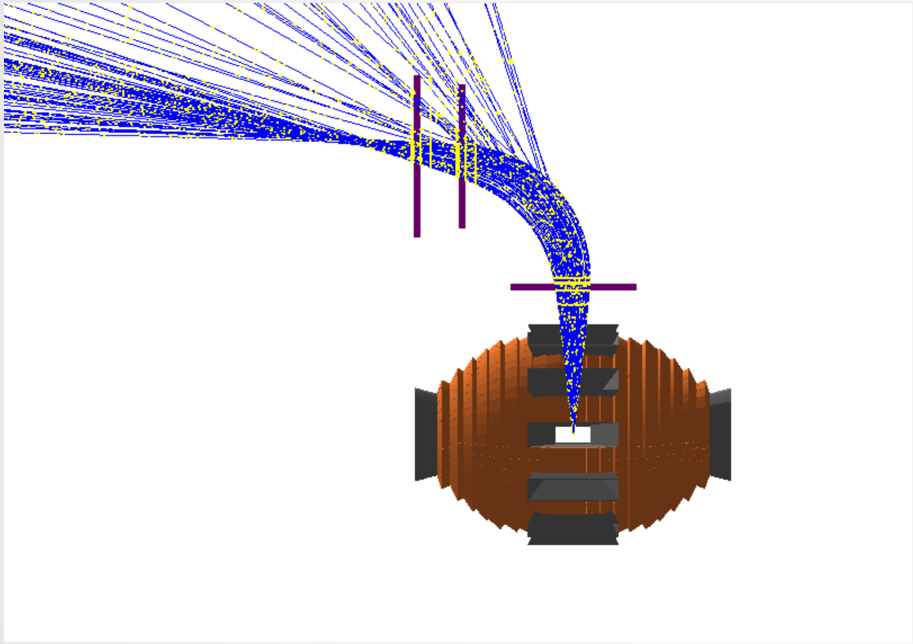
Magnetic field cont



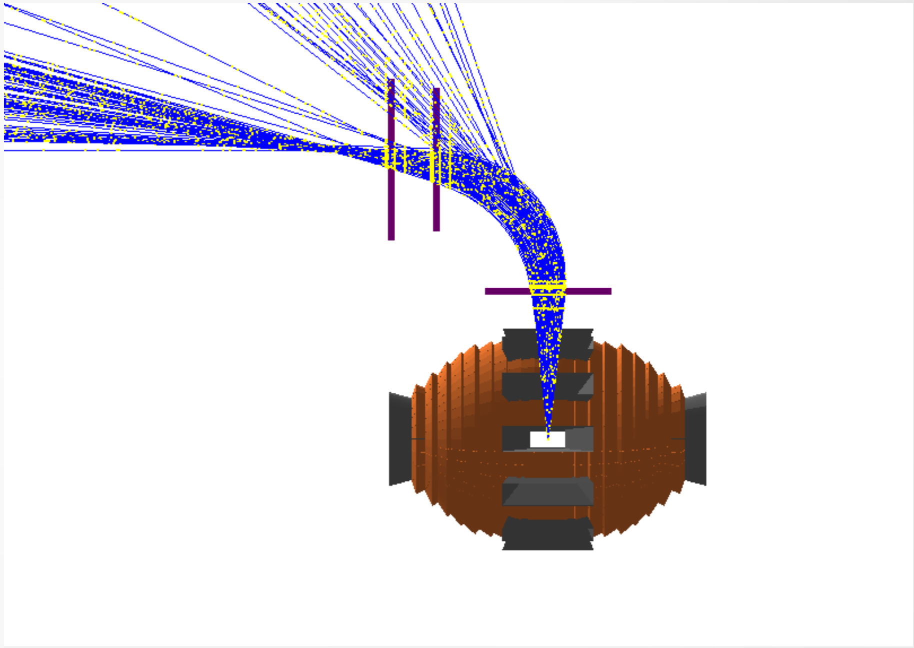
- Comparison of TOSCA field to NIM field
  - Very good agreement

Kawachi et al., NIMA416 (1998) 253

Magnetic field optimization studies: Geant4



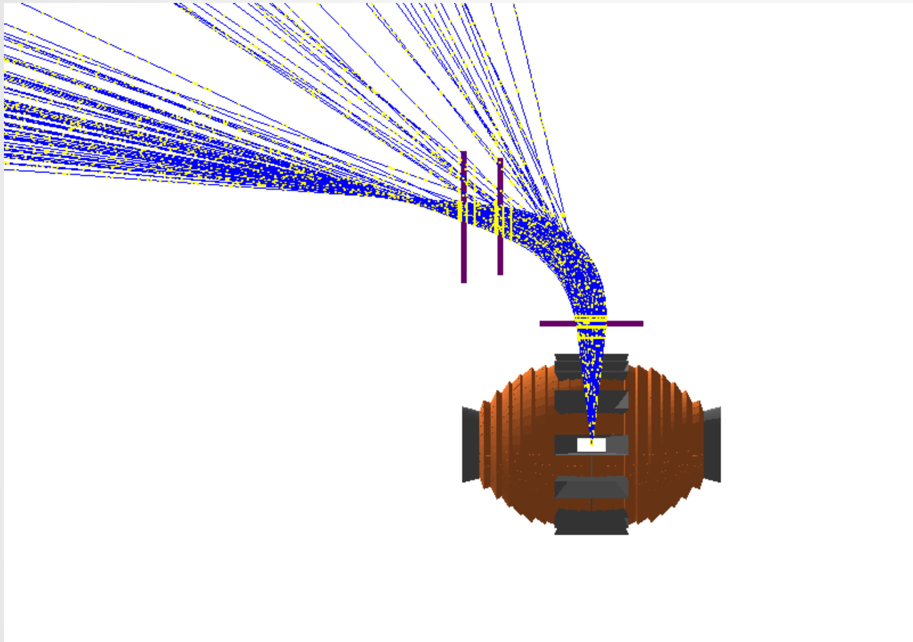
0.65T TOSCA field scaled to 1.4T



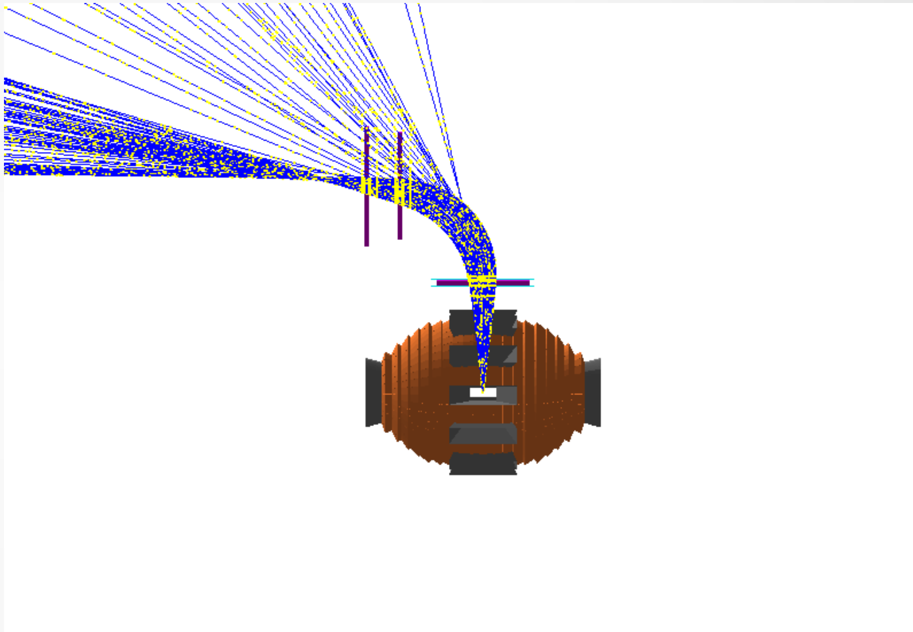
0.65T E236 field scaled to 1.4T

- Randomized generation angles of μ^+ – tracks 236MeV/c

Magnetic field optimization studies: Geant4 cont...



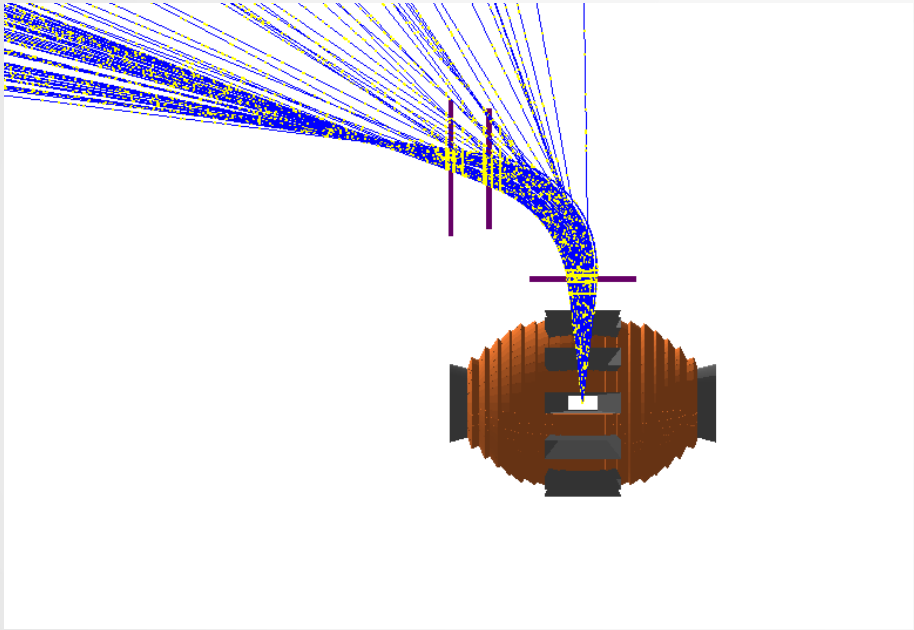
1.4T TOSCA field

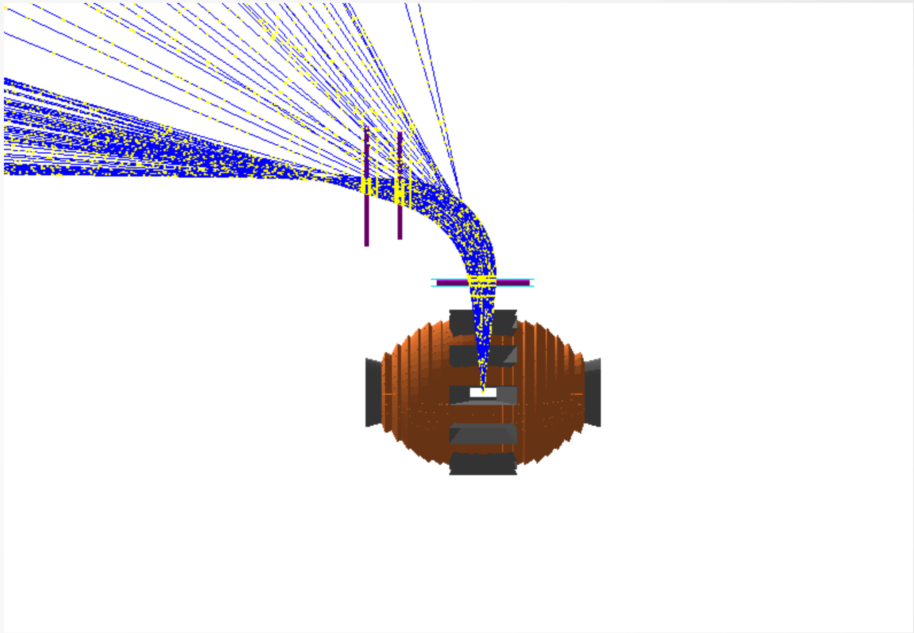


0.65T E246 field scaled to 1.4T

- Randomized generation angles of μ^+ – tracks 236MeV/c

Magnetic field optimization studies: Geant4 cont...



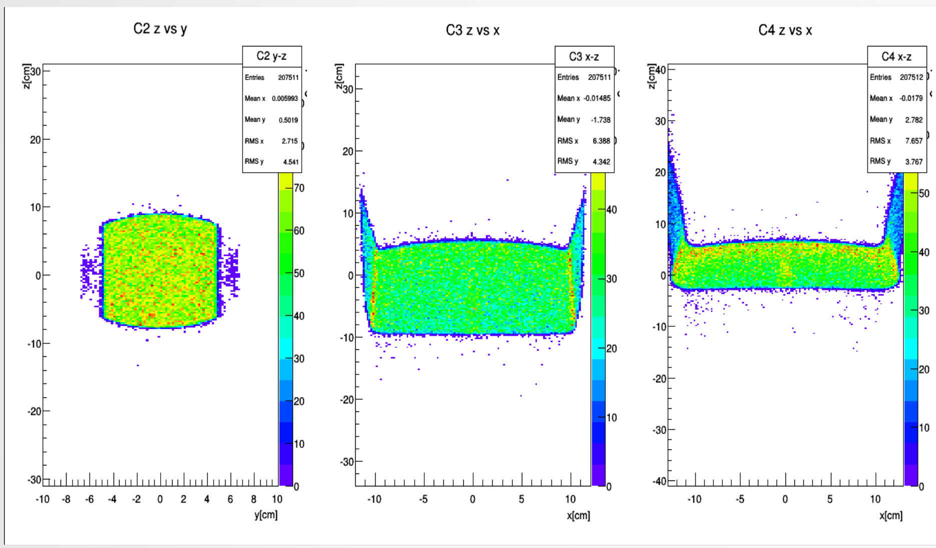


1.6T TOSCA field scaled to 1.4T

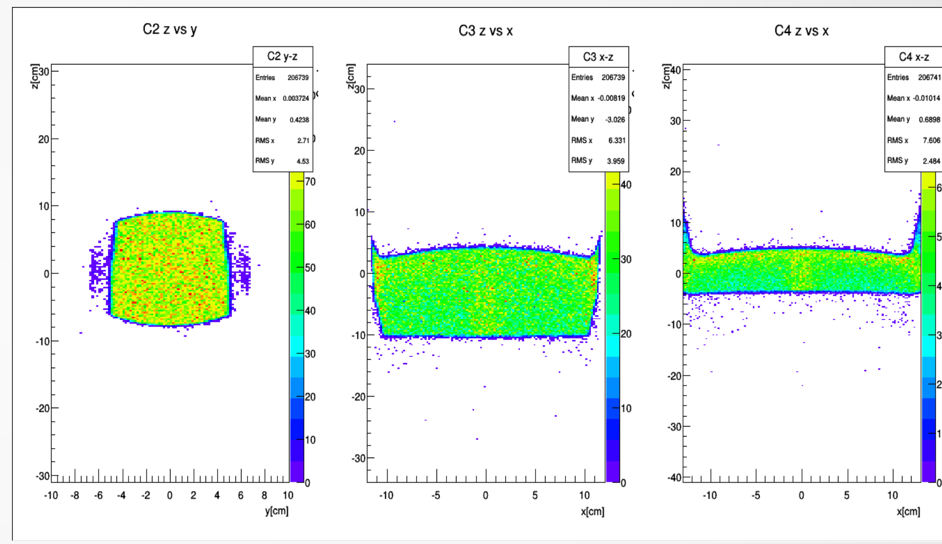
0.65T E246 field scaled to 1.4T

- Randomized generation angles of μ^+ – tracks 236MeV/c

Magnetic field optimization studies: ROOT



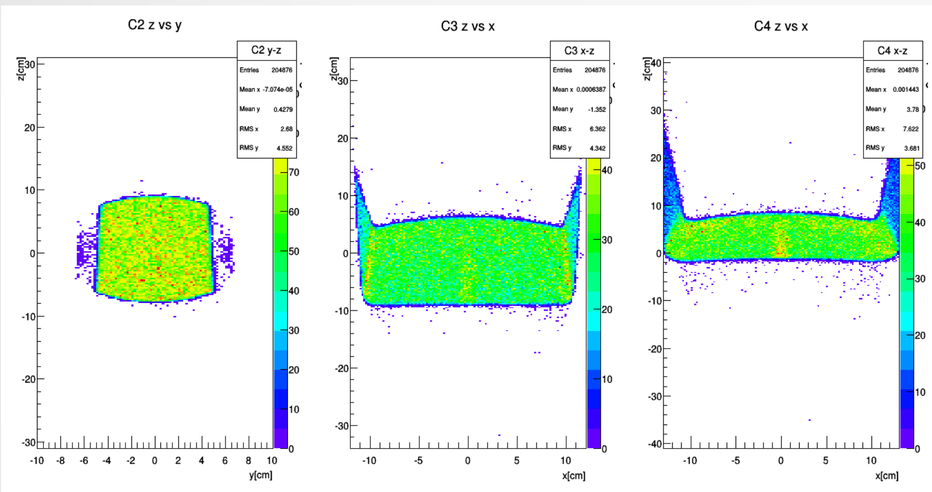
<u>0.65T TOSCA field scaled to 1.4T</u>



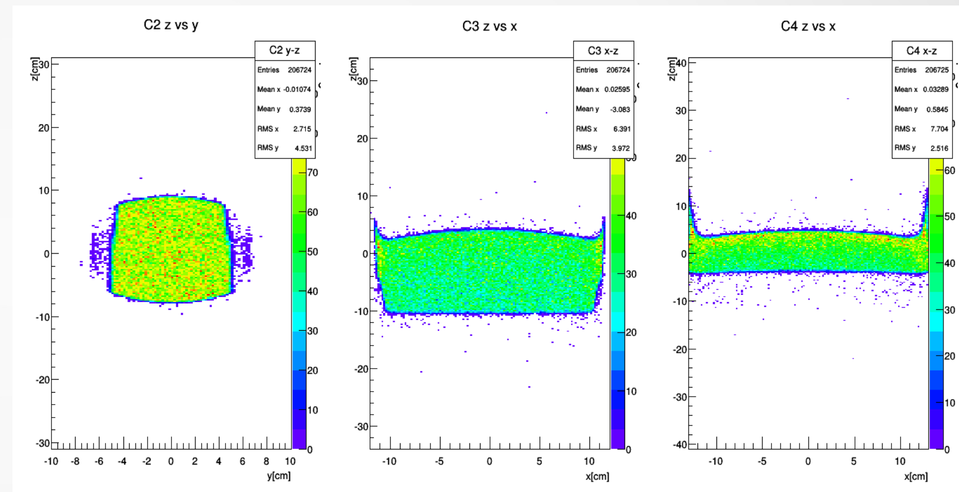
<u>0.65T E246 field scaled to 1.4T</u>

- Randomized generation angles of μ^+ – tracks 236MeV/c

Magnetic field optimization studies: ROOT cont...



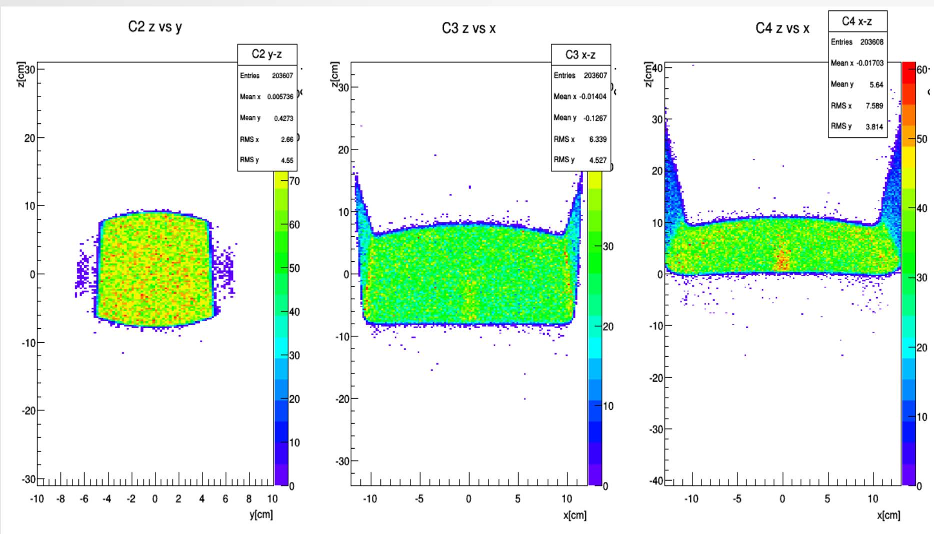
1.4T TOSCA field

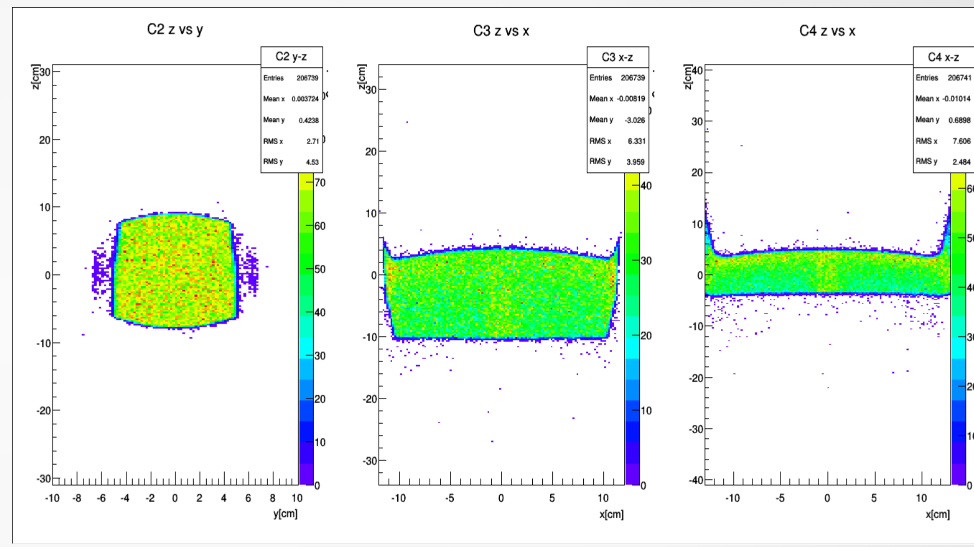


0.65T E246 field scaled to 1.4T

- Randomized generation angles of μ^+ – tracks 236MeV/c

Magnetic field optimization studies: ROOT cont...





<u>1.6T TOSCA field scaled to 1.4T</u>

<u>0.65T E246 field scaled to 1.4T</u>

- Randomized generation angles of μ^+ – tracks 236MeV/c

Conclusion and further study

- Very good agreement between TOSCA calculation and NIM field
- Notice similarities for 0.65T fields
  - Differences between them are evident
- Saturation reduces bending power of the magnetic field at 1.4T and 1.6T
- Study differences in hit location event by event using the same seed number
- Add Silicon Fiber Tracker to Geant4 geometry
- Port C++ code to GDML
  - Enable me to incorporate already existing OLYMPUS codes