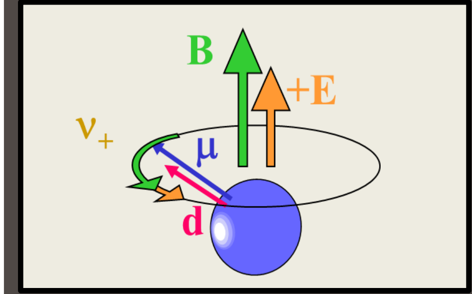
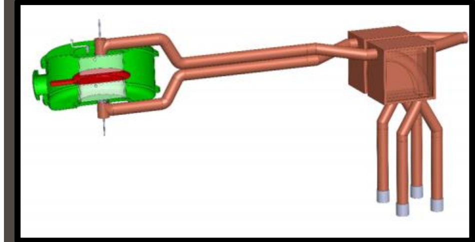
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

Monte Carlo EDM Simulations for the UCN Experiment at TRIUMF

February 18, 2017

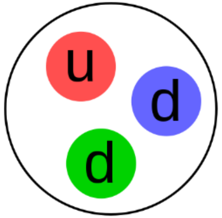
Sanmeet Chahal | University of Ottawa | TRIUMF





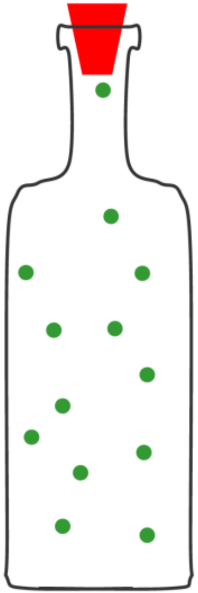
Project Overview

Goal: Measure the **electric dipole moment** (EDM) of the **neutron** (nEDM). Precision goal: 10^{-27} e•cm.



Motivation: Explain **matter/antimatter asymmetry**
Physics **beyond** the **Standard model**

Neutron type	Mean Energy (ev)	Velocity (m/s)	Temperature (K)
Fast	$> 500 \cdot 10^3$	$> 10^7$	$> 10\,000$
Thermal	$25 \cdot 10^{-3}$	2200	300
Ultracold	$\mathbf{< 300 \cdot 10^{-9}}$	$\mathbf{< 10}$	$\mathbf{< 0.002}$



Outline

1. EDM Measurement

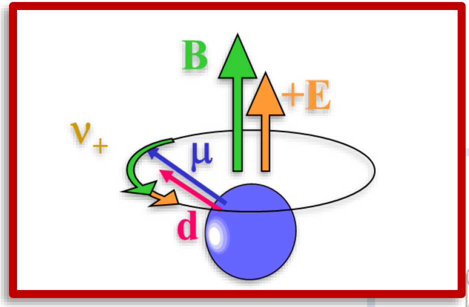
- Precession and EDM
- Ramsey Cycle
- Simulation Requirements

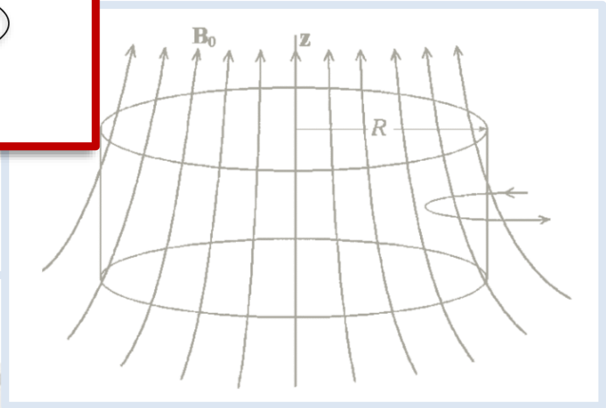
2. Simulation program

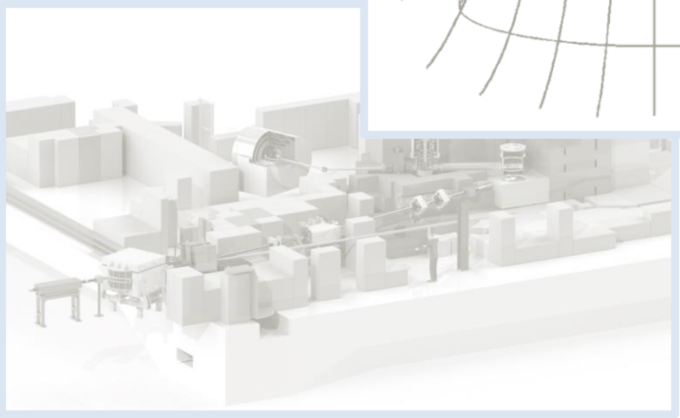
- PENTrack
- B0 and E fields
- Geometric phase effect
- Benchmark tests

3. Cell Orientation Study

- Method
- Results







Precession and EDM

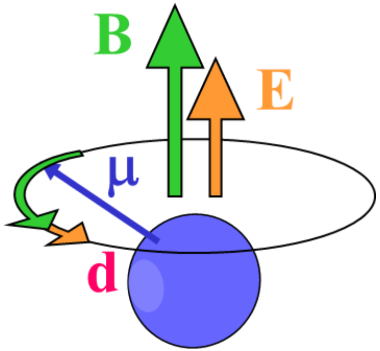
d_n = 0 e·cm

↓

Apply **Electric (E)** fields

↓

No change in ν!



$d_n \neq$ 0 e·cm

Parallel E field

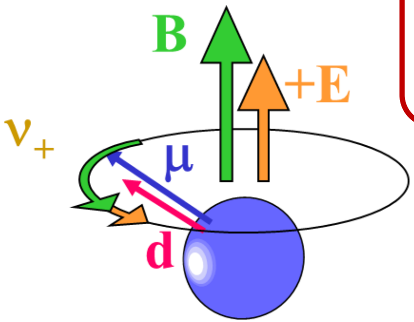
↓

Precession (ν_+) is **faster**

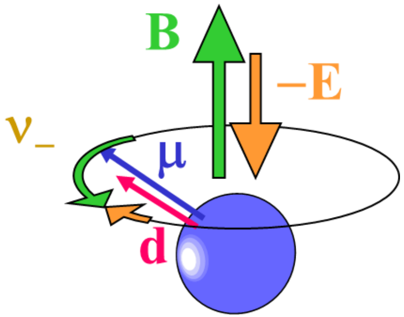
Anti-parallel E field

↓

Precession (ν_-) is **slower**



$$\mathbf{d_n} = \frac{h}{4E}\Delta\nu_\pm$$



Ramsey Cycle

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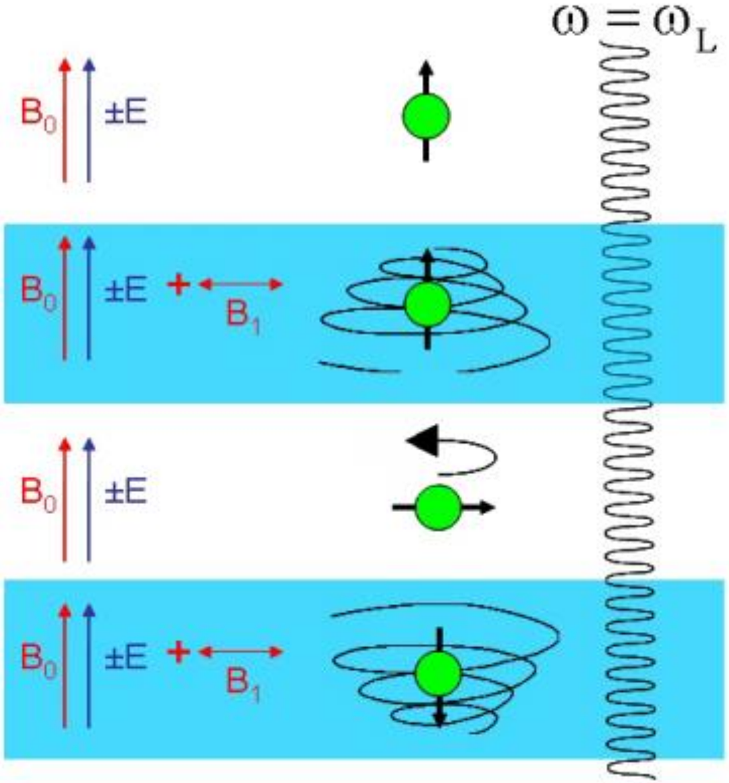
1. **Polarized** n & **constant** B_0 field.

2. B_1 pulse → **π/2 spin flip**.

3. **Free precession** in transverse plane.

3. Second B_1 pulse → **π/2 spin flip**.

4. **Count** neutrons' **spin state** → flip **E field**.



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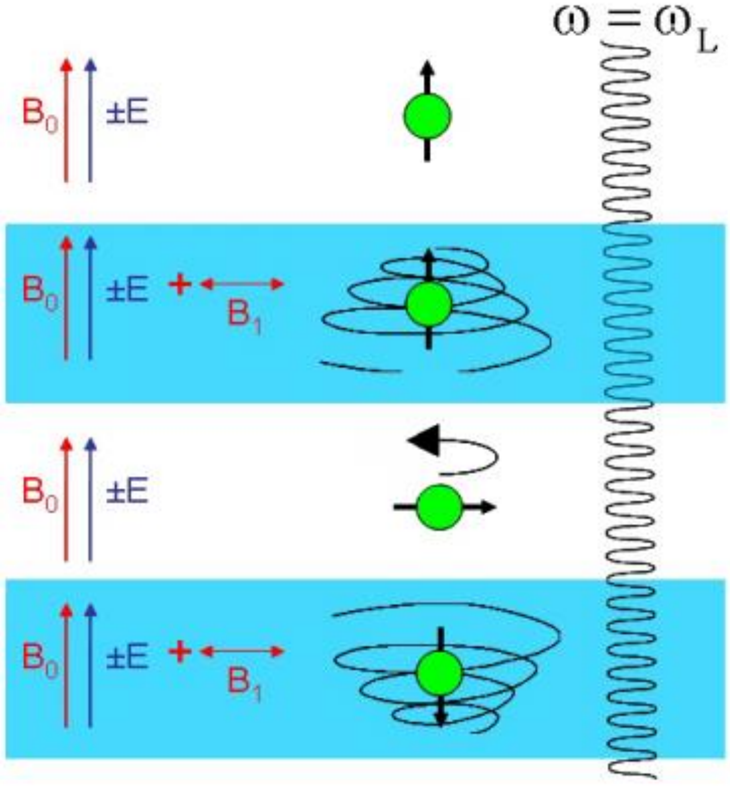


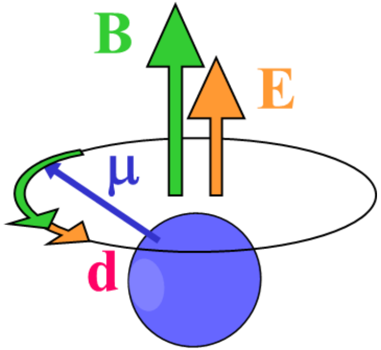
EDM Simulation Requirements

Fields

B_0 field – **starting** polarization

B_1 field – Do **spin flip**.

E field – **Changes ν**

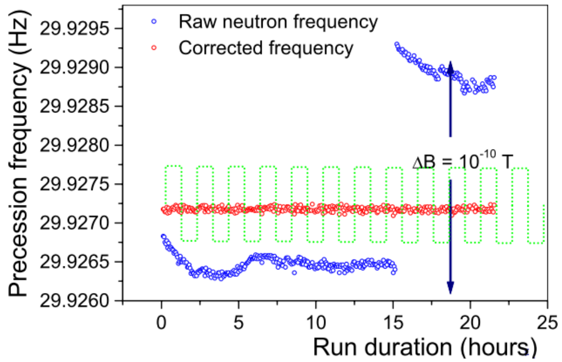


Other features

vxE effect : SR → **mot. B field**

$$B_v = \frac{E \times v}{c^2}$$

Comagnetometer atoms – reduce $\Delta d_{f,n}^{sys}$



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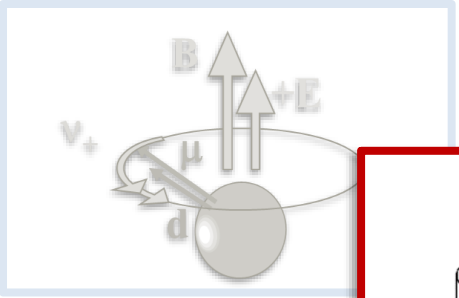
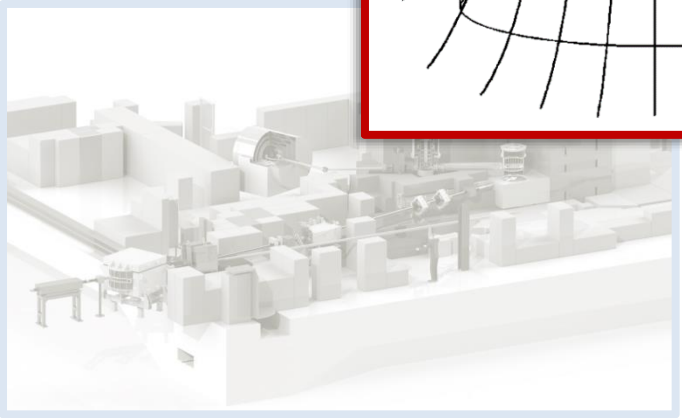
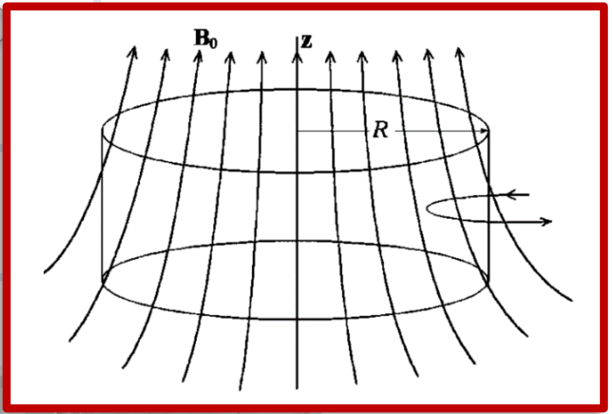
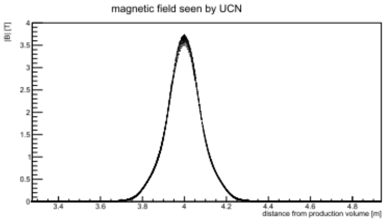




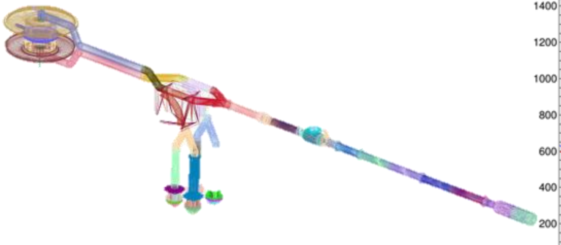


PENTrack

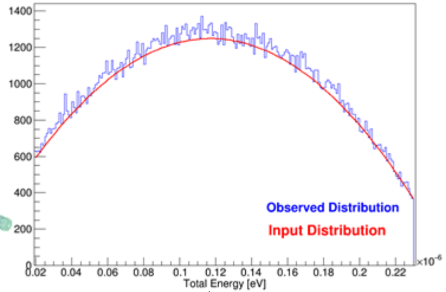
B & E **Fields**



Geometry



Energy **spectrum**



Equation of Motion

$$\ddot{\mathrm{x}} = \frac{1}{\gamma m}\left(1 - \frac{1}{c^2}\dot{\mathbf{x}} \otimes \dot{\mathbf{x}}\right)\left(P\mu\nabla|\mathbf{B}| - mg\mathbf{e_z} + q(\mathbf{E} + \dot{\mathbf{x}} \times \mathbf{B})\right)$$

PENTrack

Snapshot log | Hit log | End log | Spin log | Track log

Spin log → Time, Spin → $\Delta\nu_{\pm}$ → $\mathbf{d_n}$

B_0 Field

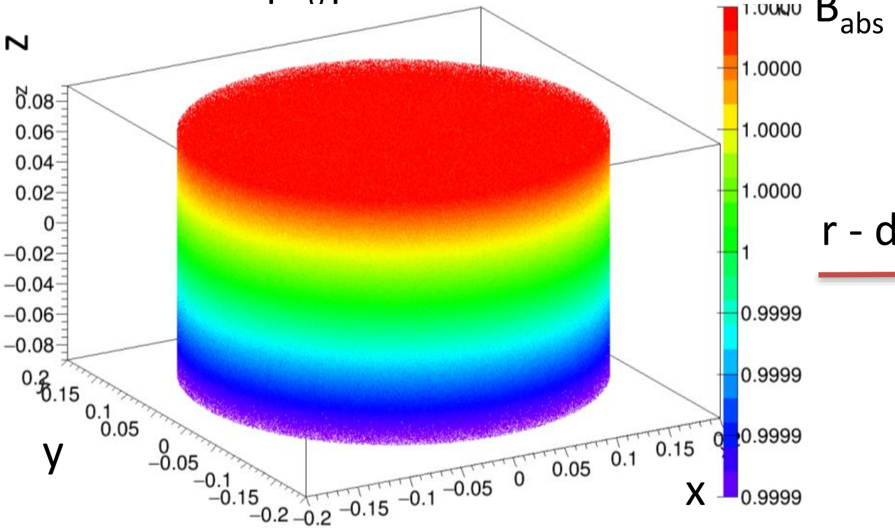
Axially **symmetric**, **static B_0** field & **Maxwell** equations.

$$\nabla \cdot B = 0$$
$$(\nabla \times B)_{\phi} = 0$$

$$B_z(r, z) \approx B_z(0, z) + \frac{\partial B_z(0, z)}{\partial z}$$

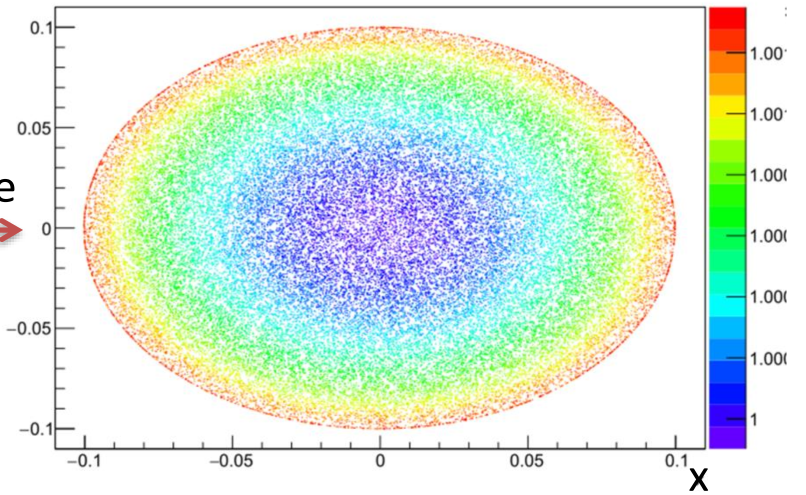
$$B_r(r, z) \approx -\frac{r}{2}\frac{\partial B_z(0, z)}{\partial z}$$

$|B_0|$ in EDM cell



r - dependence

$|B_0|$ in x-y plane



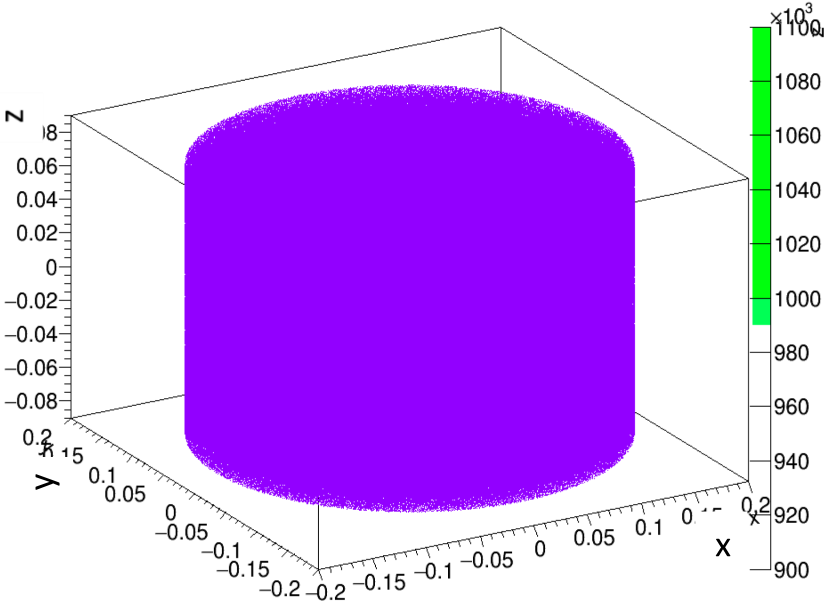
E Field and vxE

Ideal Model

- Static
- z-aligned
- Homogenous field (no gradient)
- vxE added

$$\mathbf{E} = \begin{bmatrix} 0 \\ 0 \\ x \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 10^6\ \mathrm{V/m} \end{bmatrix}$$

|E_z| in EDM cell



Geometric Phase Effect

$B_{xy} \rightarrow$ **shift** in ω_L

$$B_{xy} = \underbrace{B_{0xy}}_{\text{Gradient}} + \underbrace{B_v}_{\text{vxE}} = -\frac{r}{2}\frac{\partial B_{0z}}{\partial z} + \frac{E \times v}{c^2}$$

$$\Delta\omega \; \alpha \; \omega_{xy}^2$$

Geometric Phase Effect

$B_{xy} \rightarrow$ **shift** in ω_L

$$B_{xy} = B_{0xy} + B_v = -\frac{r}{2}\frac{\partial B_{0z}}{\partial z} + \frac{E \times v}{c^2}$$

Gradient vxE

$$\Delta\omega \ \alpha \ \omega_{xy}^2$$

$$\omega_{xy}^2 = \left(-\gamma B_{xy}\right)^2$$

$$\omega_{xy}^2 = \gamma^2 \left(\frac{r}{2}\frac{\partial B_{0z}}{\partial z}\right)^2 + \left(\frac{E \times v}{c^2}\right)^2 + r\frac{E \times v}{c^2}\frac{\partial B_{0z}}{\partial z}$$

Geometric Phase Effect

$B_{xy} \rightarrow$ **shift** in ω_L

$$B_{xy} = \underbrace{B_{0xy}}_{\text{Gradient}} + \underbrace{B_v}_{\text{vxE}} = -\frac{r}{2}\frac{\partial B_{0z}}{\partial z} + \frac{E \times v}{c^2}$$

$$\Delta\omega \;\; \alpha \;\; \omega_{xy}^2$$

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Linear in E $\rightarrow$ mimics real EDM

Benchmark Tests

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False EDM:

$$d_{f,n} = -\frac{\hbar}{4}\left(\frac{\left\langle\frac{\partial B_z(0,z)}{\partial z}\right\rangle_V}{B_{0z}^2}\right)\frac{\mathbf{v_{xy}^2}}{c^2}\left[1-\frac{\omega_r^{*2}}{\omega_0^2}\right]^{-1} \rightarrow d_{f,n} = -\frac{\hbar}{4}\left(\frac{\left\langle\frac{\partial B_z(0,z)}{\partial z}\right\rangle_V}{B_{0z}^2}\right)\frac{\mathbf{v_{xy}^2}}{c^2}\left[1-\frac{\omega_r^{*2}}{\omega_0^2}\right]^{-1}$$

Constant

Variable

Pendelbury et al. :

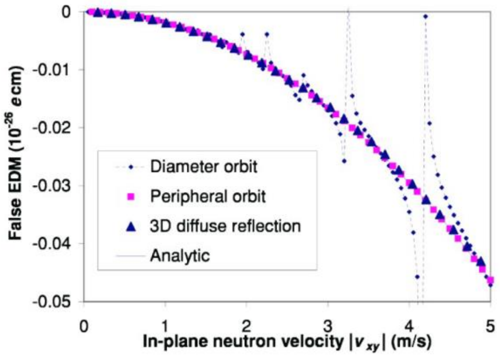
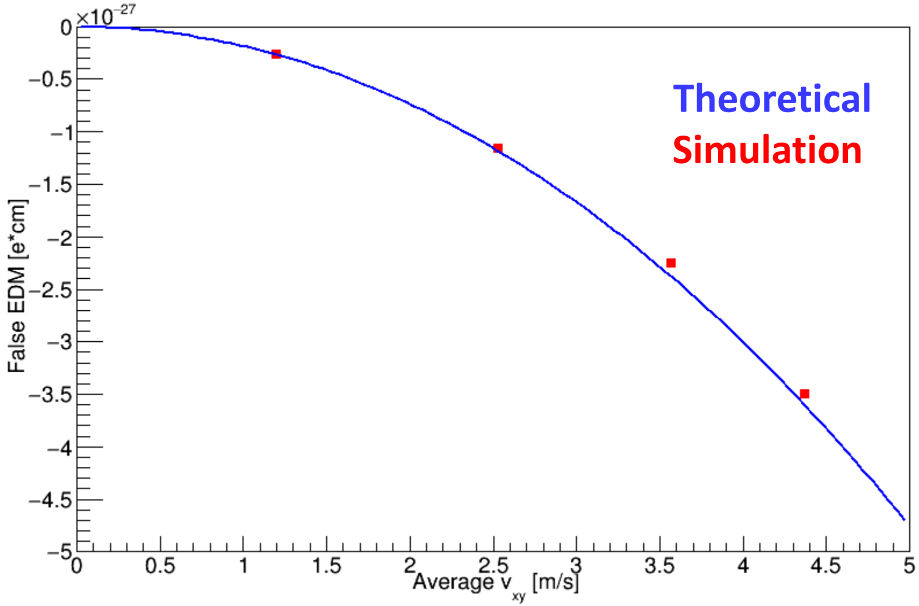


FIG. 11. (Color online) False EDM's obtained by computer simulation in the $|\omega_r|<|\omega_0|$ case. The results shown are for 2D specular reflection following peripheral and diameter orbits and for 3D diffuse reflection. The analytic result of Eq. (29) is shown as a smooth curve. Other parameters were $\partial B_{0z}/\partial z=1$ nT/m and $B_0=1$ μT.

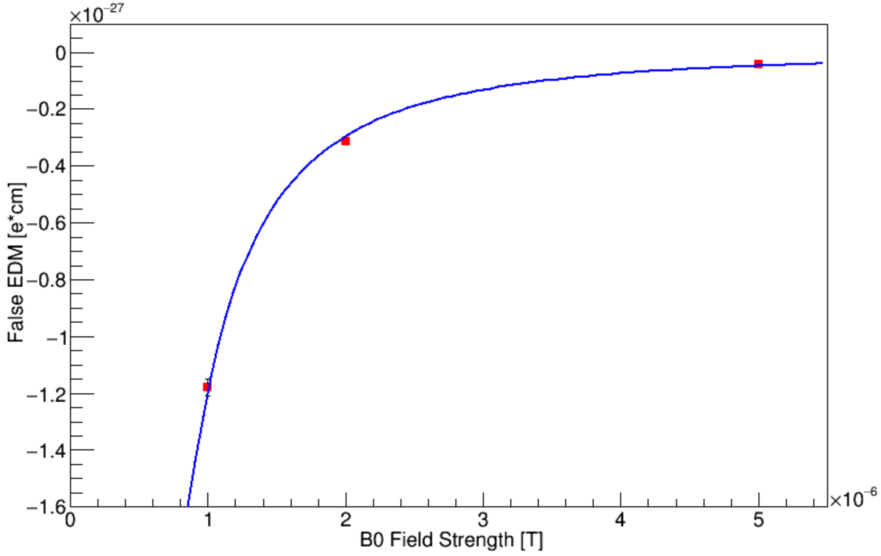
Chahal:



Benchmark Tests

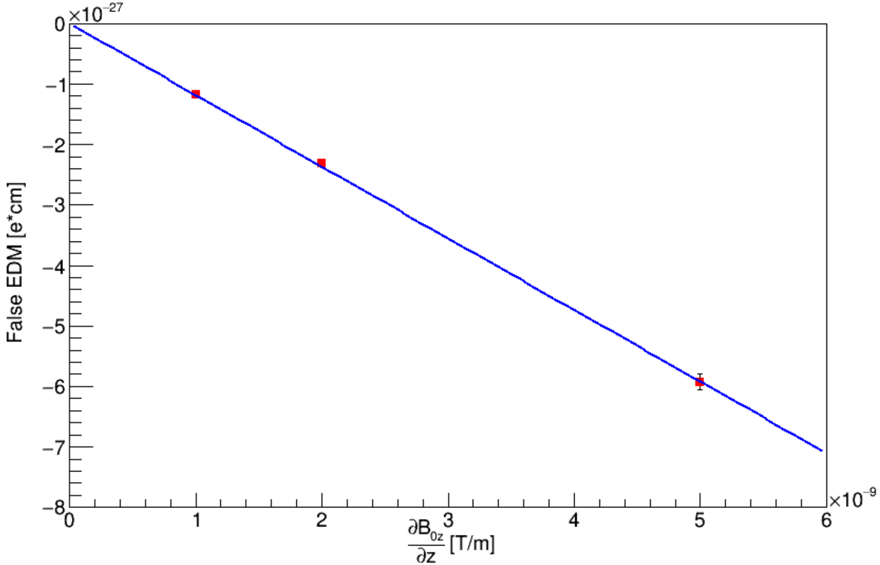
$$d_{f,n} = -\frac{\hbar}{4}\left(\frac{\left\langle \frac{\partial B_z(0,z)}{\partial z} \right\rangle_V}{\mathbf{B_{0z}^2}}\right)\frac{v_{xy}^2}{c^2}\left[1-\frac{\omega_r^{*2}}{\omega_0^2}\right]^{-1}$$

Constant
Variable



$$d_{f,n} = -\frac{\hbar}{4}\left(\frac{\mathbf{\left\langle \frac{\partial B_z(0,z)}{\partial z} \right\rangle_V}}{B_{0z}^2}\right)\frac{v_{xy}^2}{c^2}\left[1-\frac{\omega_r^{*2}}{\omega_0^2}\right]^{-1}$$

Constant
Variable



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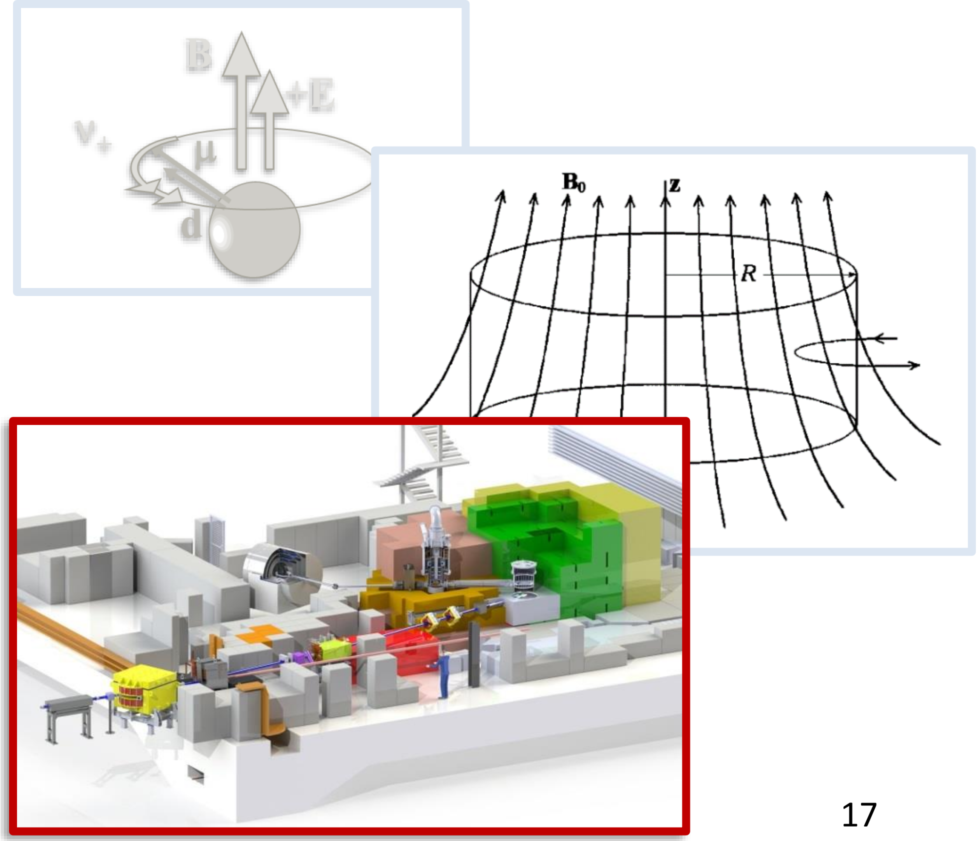
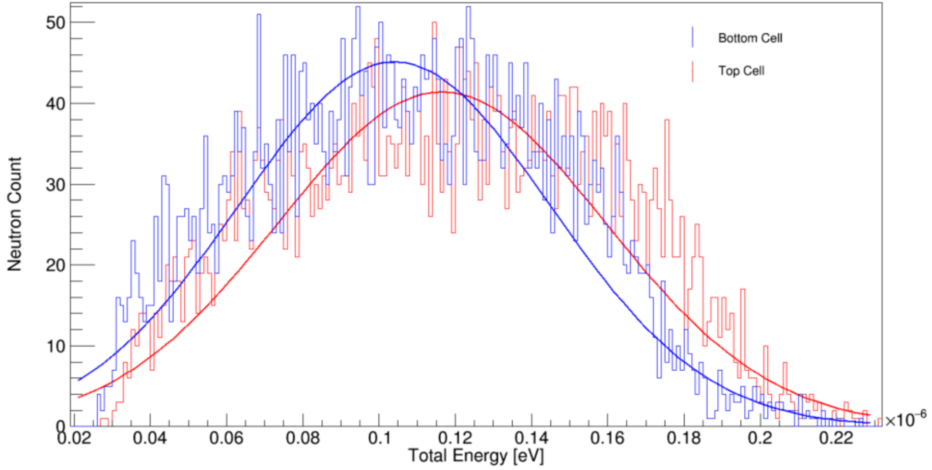
   - Description
   - Results

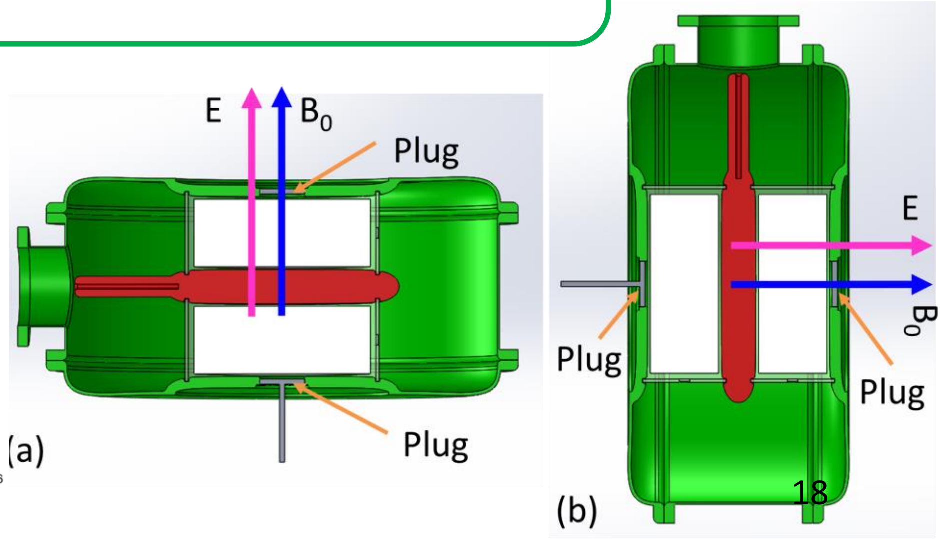


Optimum cell orientation

Goal: Determine effect of cell orientation on the $d_{f,n}$.

Procedure: 1. Energy spectrum from filling efficiency simulation.
2. Determine $d_{f,n}$ in both orientations.





Results

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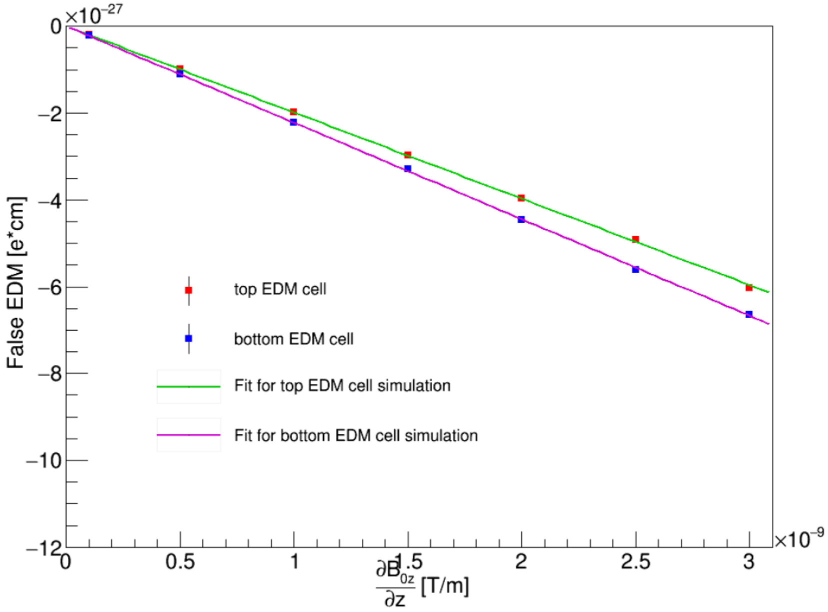
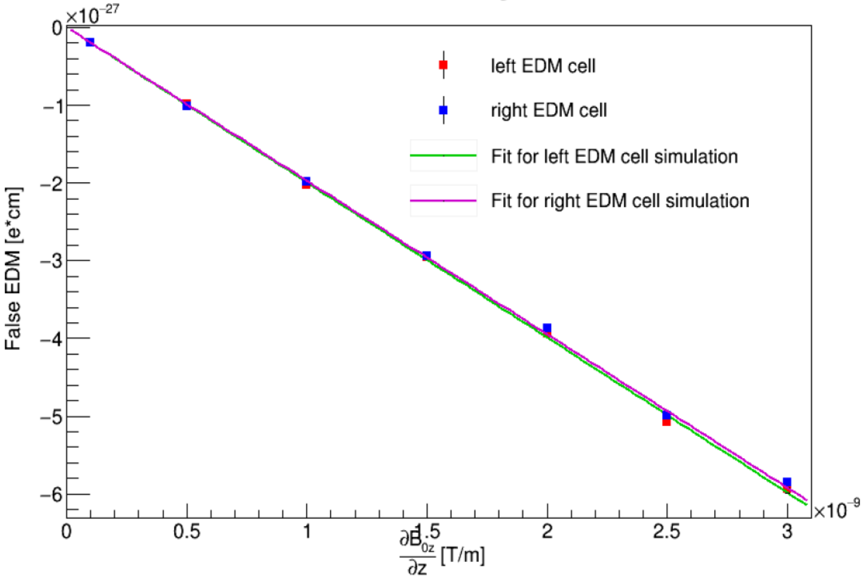
Vertical orientation



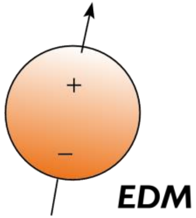
Horizontal orientation

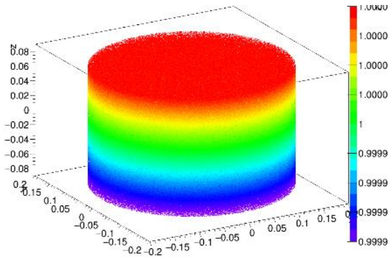


N. Christopher. “An amalgamation of work on the UCN source and nEDM experiment at TRIUMF”. Vancouver, TRIUMF, 2016.

Summary

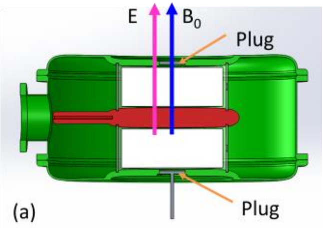
Basic nEDM simulation **requirements in place**





Implementation **benchmarked with published results**

Utility demonstrated with cell orientation study



Thank you! Questions?

TRIUMF: Alberta | British Columbia | Calgary | Carleton | Guelph | Manitoba | McMaster | Montréal | Northern British Columbia | Queen’s | Regina | Saint Mary’s | Simon Fraser | Toronto | Victoria | Winnipeg | York

References

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[15] Lloyd, E. *Guide Topologies Parameters.* Vancouver: TRIUMF, 2014.

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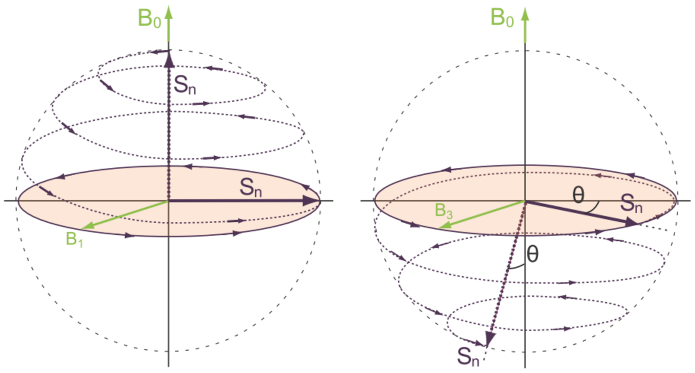
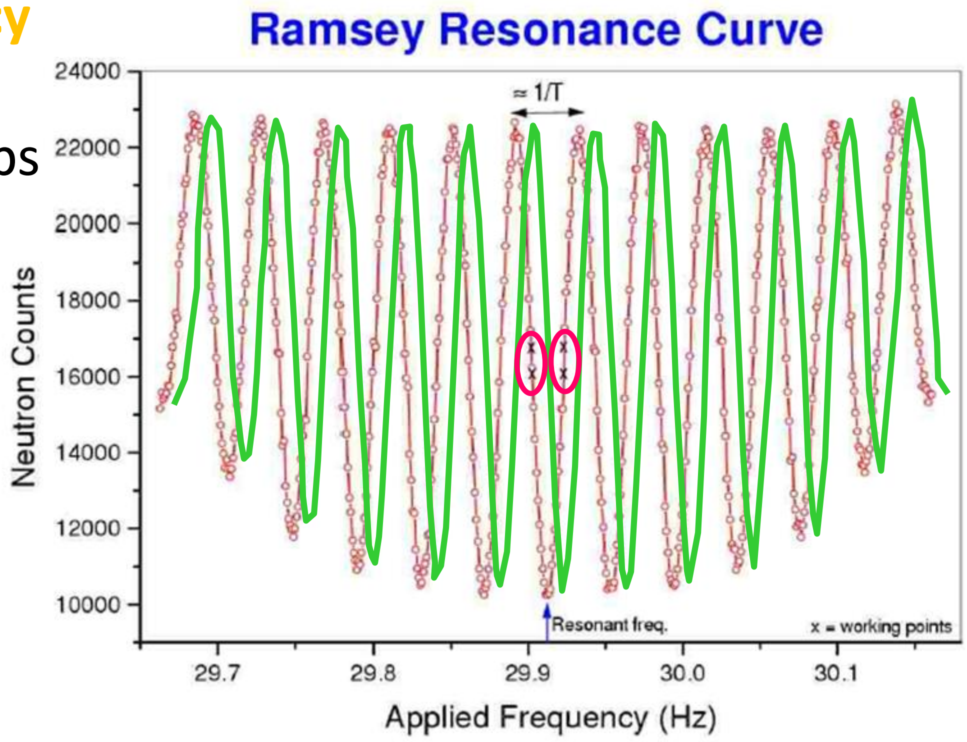
Backup Slides

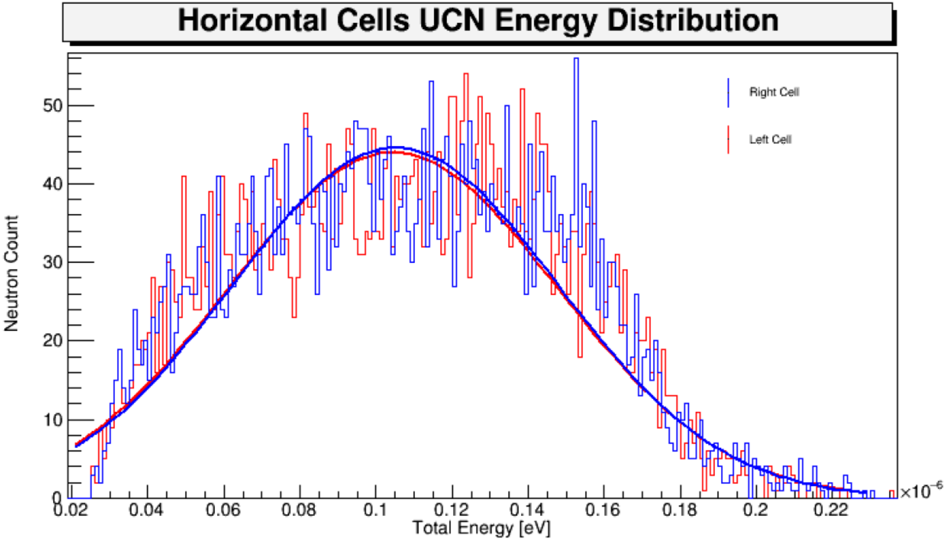
Ramsey Resonance Curve

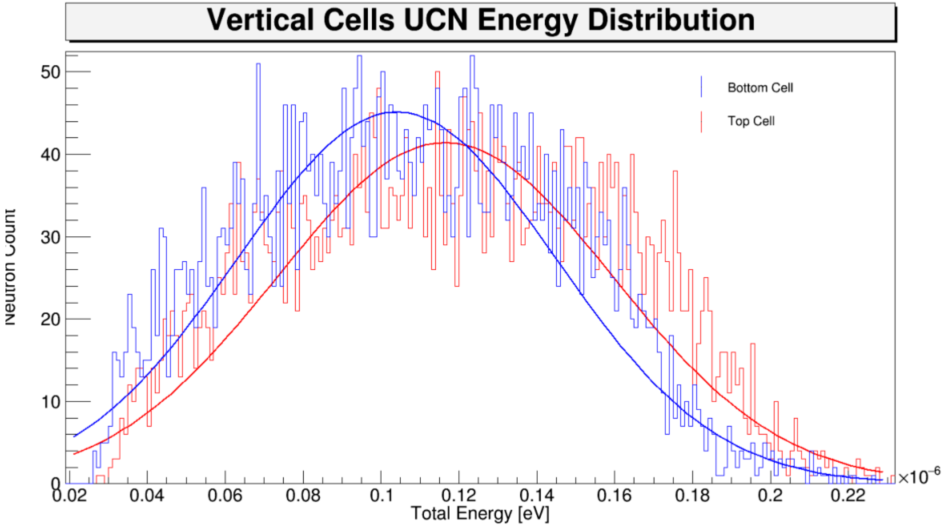
1. B_1 pulse at **non-resonance frequency**
2. **Probability of spin flip** ≠ 1.
3. At **resonance** = **max** # of neutron flips
4. **Fit** to **Ramsey curve** to find ν_+ or ν_-
5. Use $d_n = \frac{h}{4E}\Delta\nu_\pm$





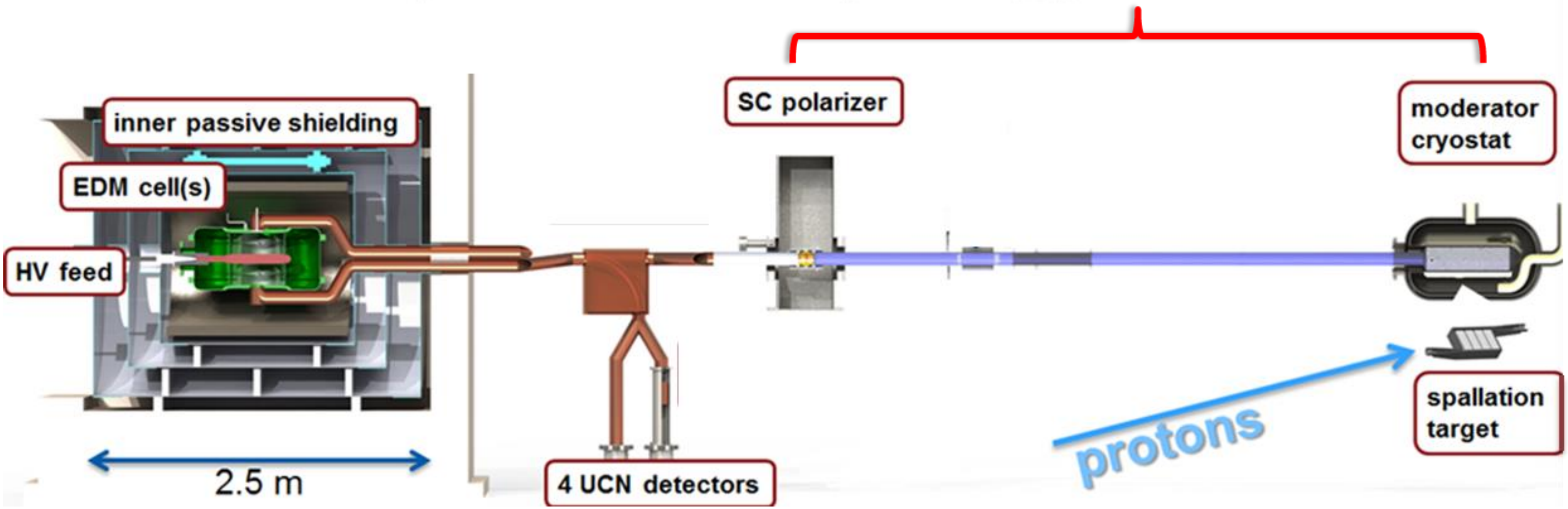
Total Energy Distribution



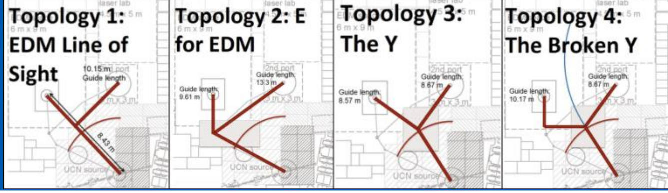


UCN Experiment

UCN produced in **UCN source**

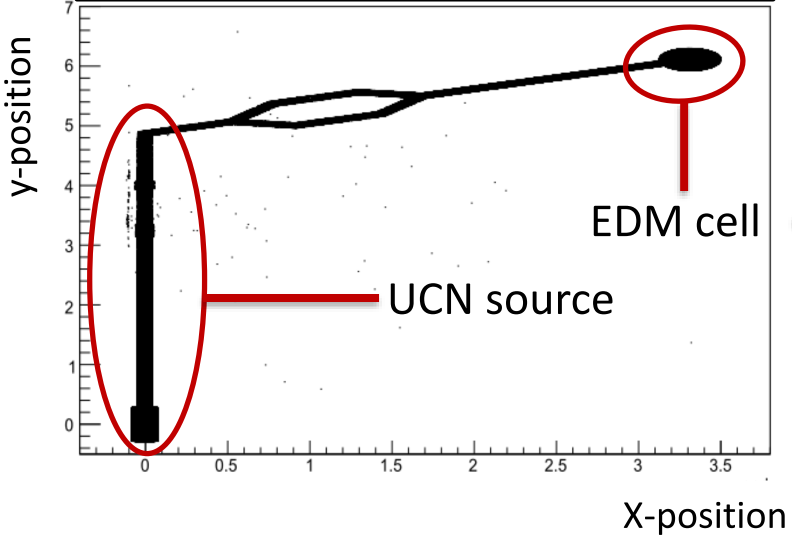


Procedure

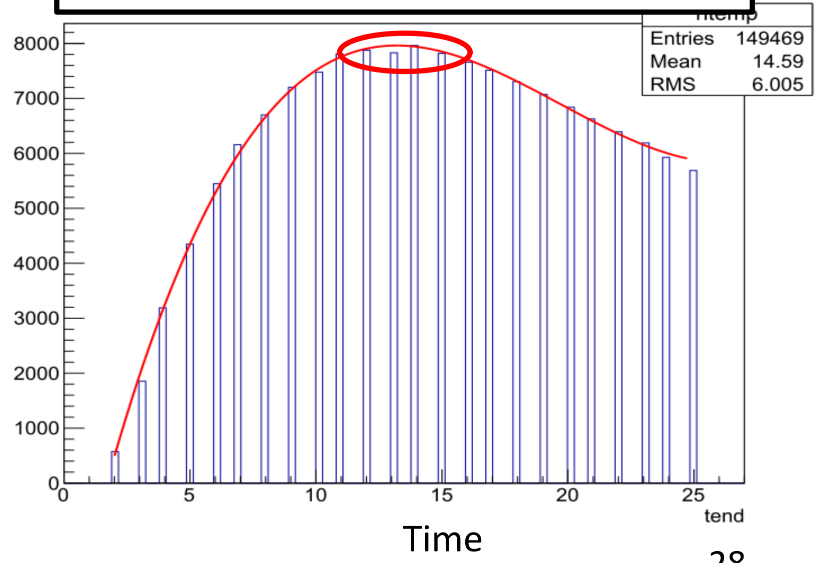


PENTrack → **Snapshot** of neutron **positions** → Histogram **neutron count** in **EDM cell** → Find **maximum**, **Compare** all layouts

Layout 3 Neutron Positions



Neutrons in EDM cell over time



Simulation Purpose

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"Determine **optimum** guide layout"

Want: High **neutron densities**

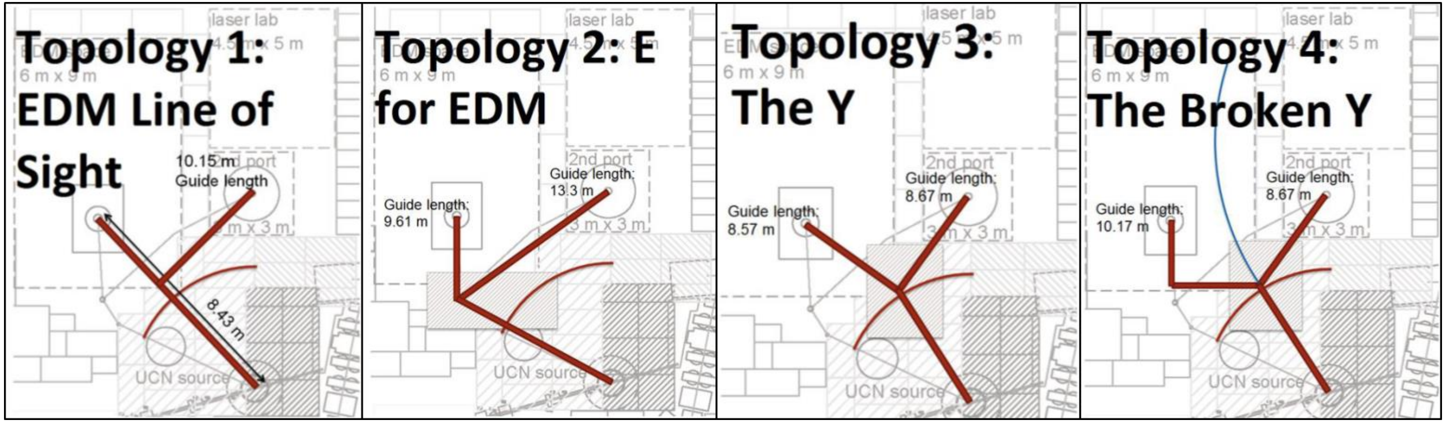
$$\sigma_{EDM} = \frac{\hbar}{2\alpha T E\sqrt{N}}$$

α – visibility
T – observation time
E – Electric field
N – number of neutrons

Don't want: High **radiation** in experimental area.

↓

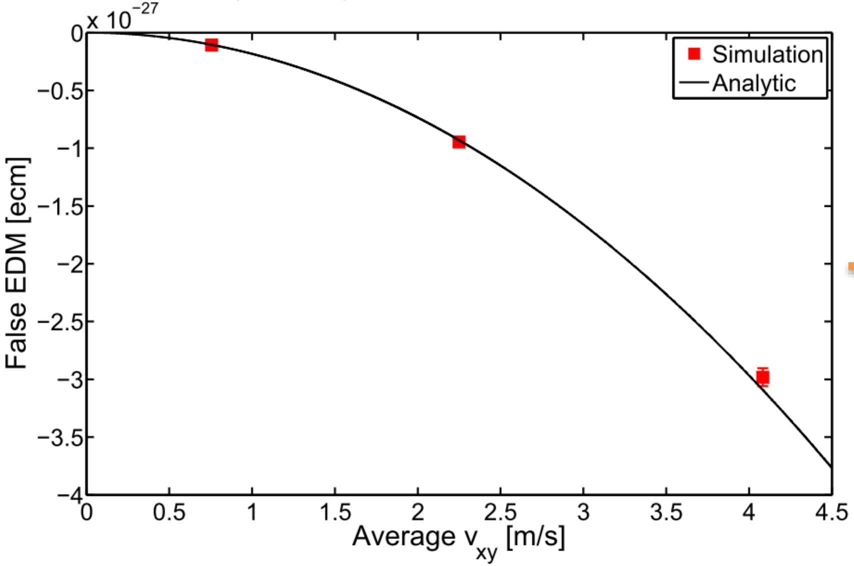
No access to experiment.



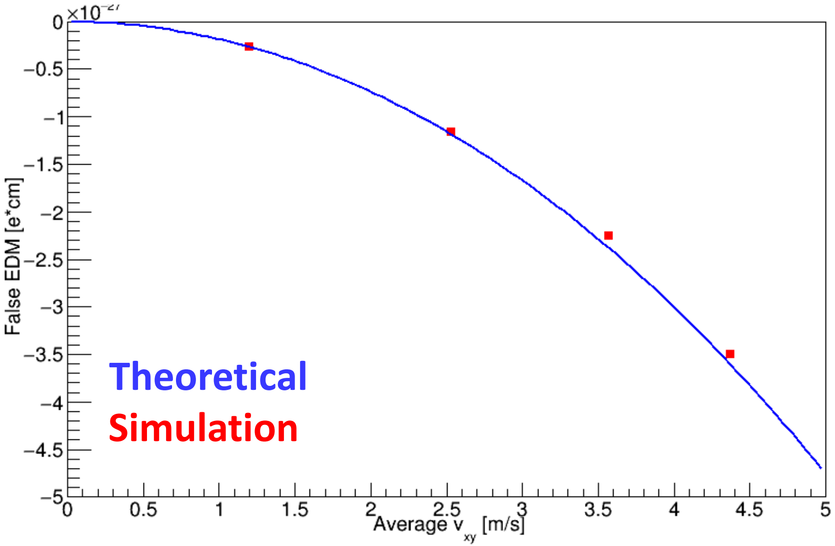
Benchmark Test

False EDM vs. average planar velocity

Knecht (2009):

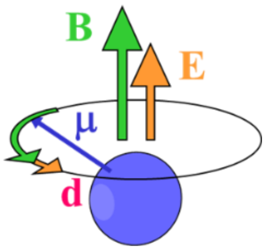


Chahal (2015):



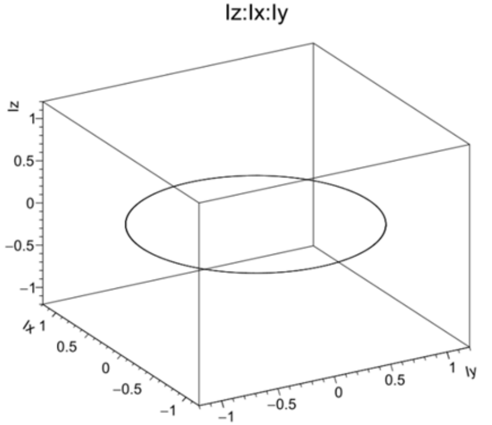
Neutron Precession Test

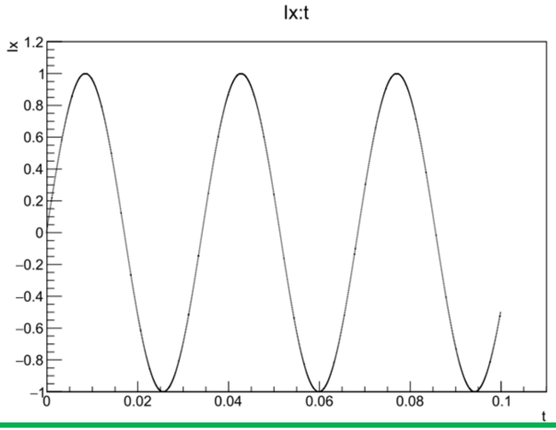
Axially **symmetric**, **static B_0** field & **Maxwell** equations.

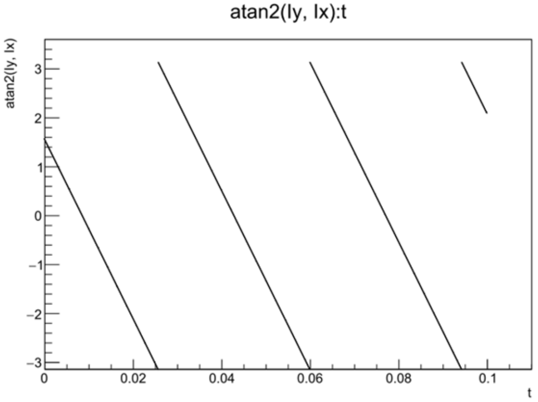


$$B_z(r,z) \approx B_z(0,z) + \frac{\partial B_z(0,z)}{\partial z}$$

$$B_r(r,z) \approx -\frac{r}{2}\frac{\partial B_z(0,z)}{\partial z}$$





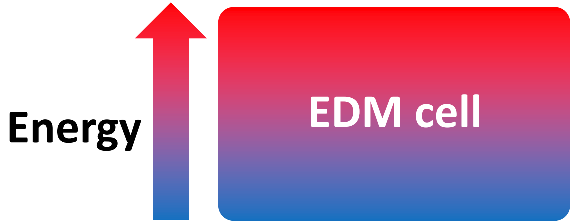


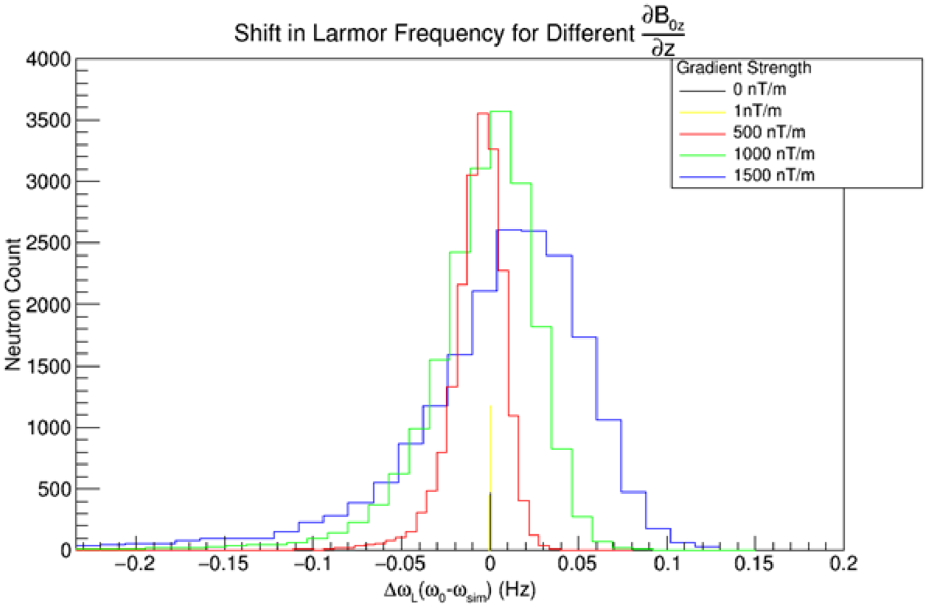
$$\Delta\omega_{L,sim} = 72.2 \pm 3.5\ \text{pHz} \ \rightarrow \text{for } d_n = 10^{-27}\ e \cdot cm \ \textbf{need } \Delta\omega_L < 9\ \text{nHz}$$

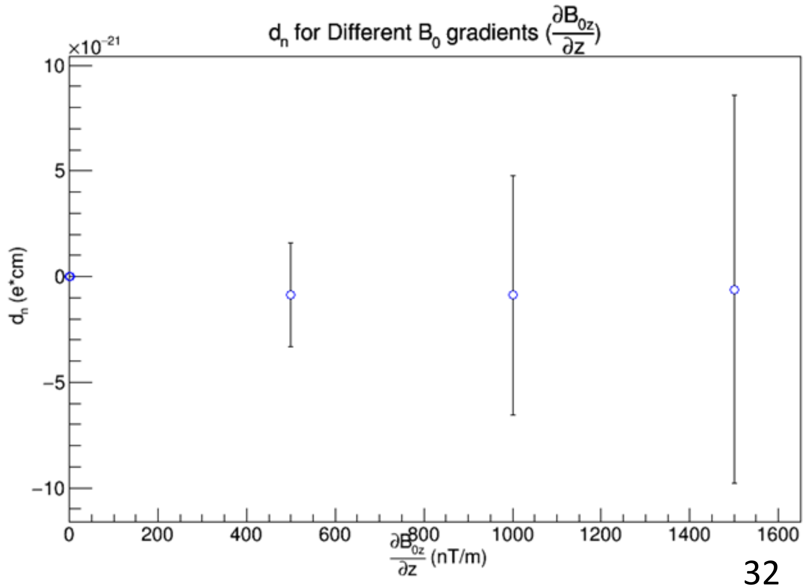
Gradient Comparison

Test $\Delta\nu$ in different **gradients**

low energy n → **lower in cell** → **lower B_0** → $\Delta\nu < 0$







B_0 Field Formulas

B_x

$$B_x(x,y,z) = -\frac{x}{2}\frac{\partial B_z(0,0)}{\partial z}$$

$$\frac{\partial B_x}{\partial x} = -\frac{1}{2}\frac{\partial B_z(0,0)}{\partial z}$$

$$\frac{\partial B_x}{\partial y} = 0, \qquad \frac{\partial B_x}{\partial z} = 0$$

B_y

$$B_y(x,y,z) = -\frac{y}{2}\frac{\partial B_z(0,0)}{\partial z}$$

$$\frac{\partial B_y}{\partial x} = 0\,, \frac{\partial B_y}{\partial z} = 0$$

$$\frac{\partial B_y}{\partial y} = -\frac{1}{2}\frac{\partial B_z(0,0)}{\partial z}$$

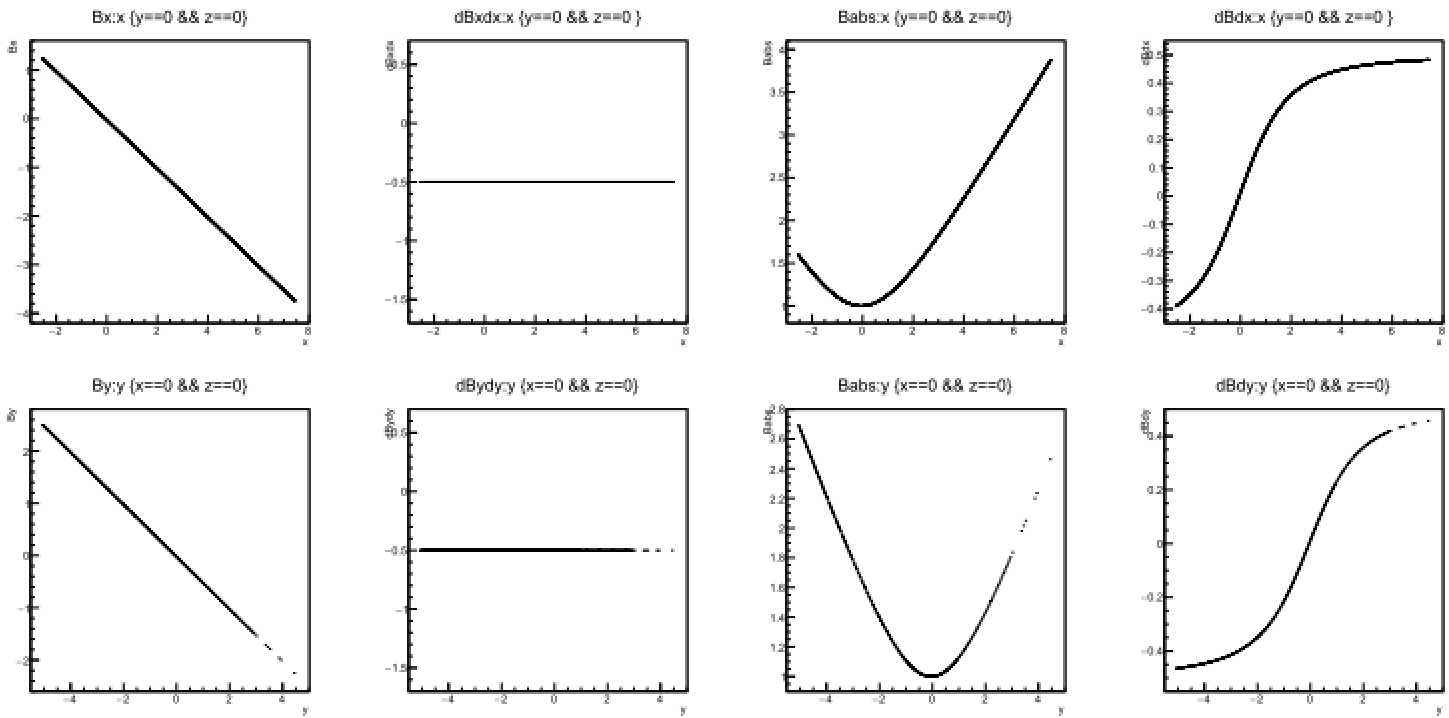
B_z

$$B_z = B_z(0,0) + \frac{\partial B_z(0,0)}{\partial z} z$$

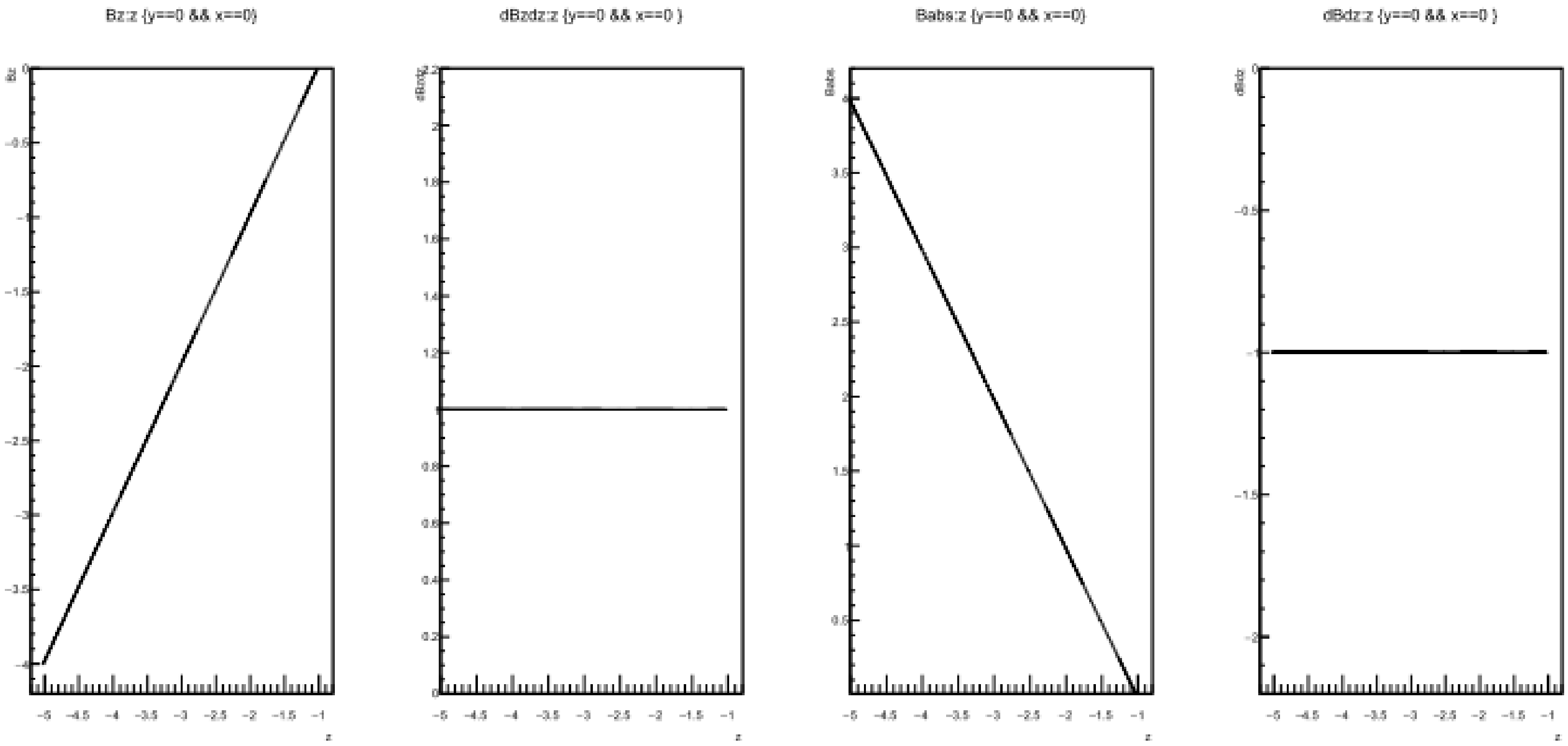
$$\frac{\partial B_z}{\partial x} = \frac{\partial B_z}{\partial y} = 0$$

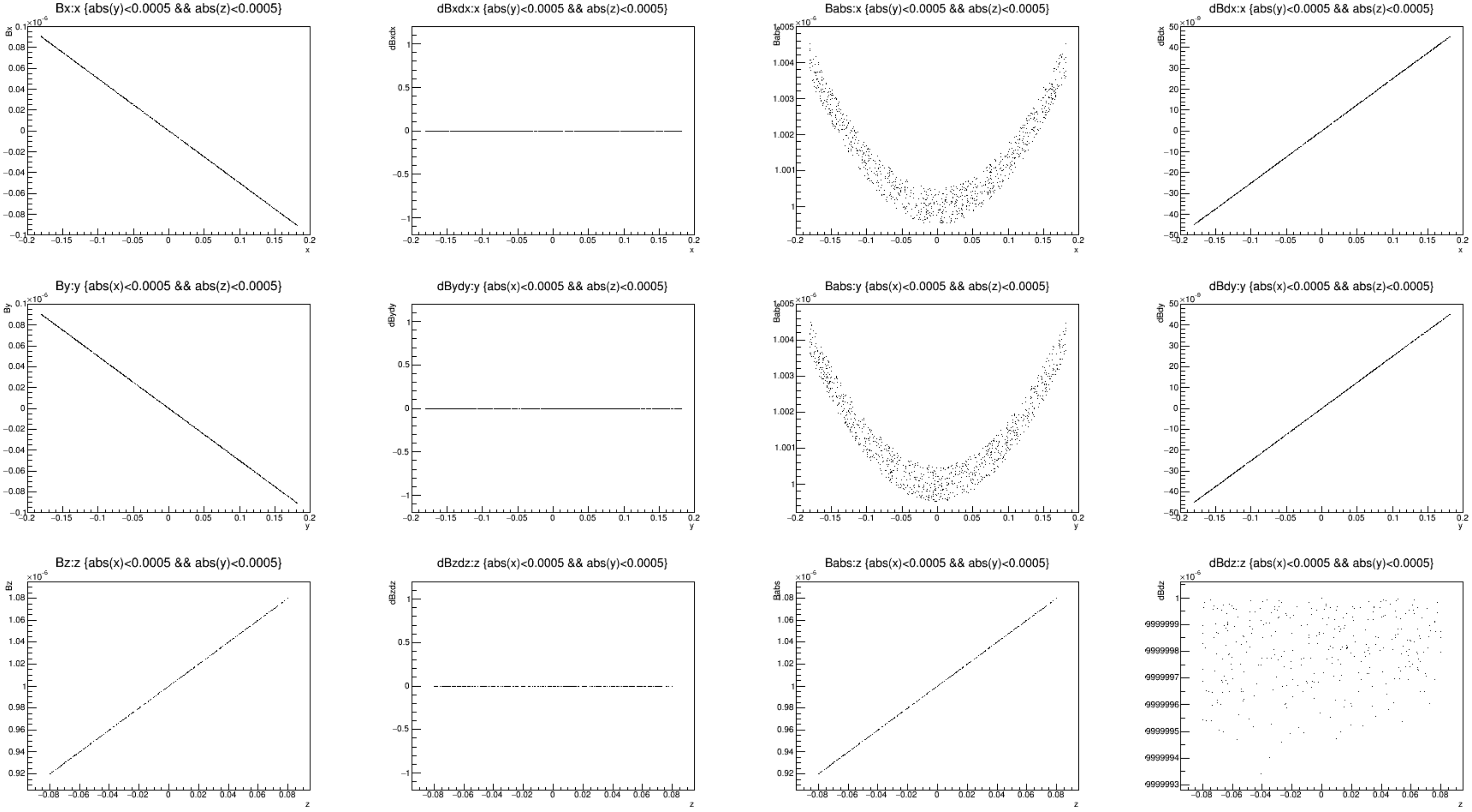
$$\frac{\partial B_z}{\partial z} = \frac{\partial B_z(0,0)}{\partial z}$$

Single Variable B_0 field Tests

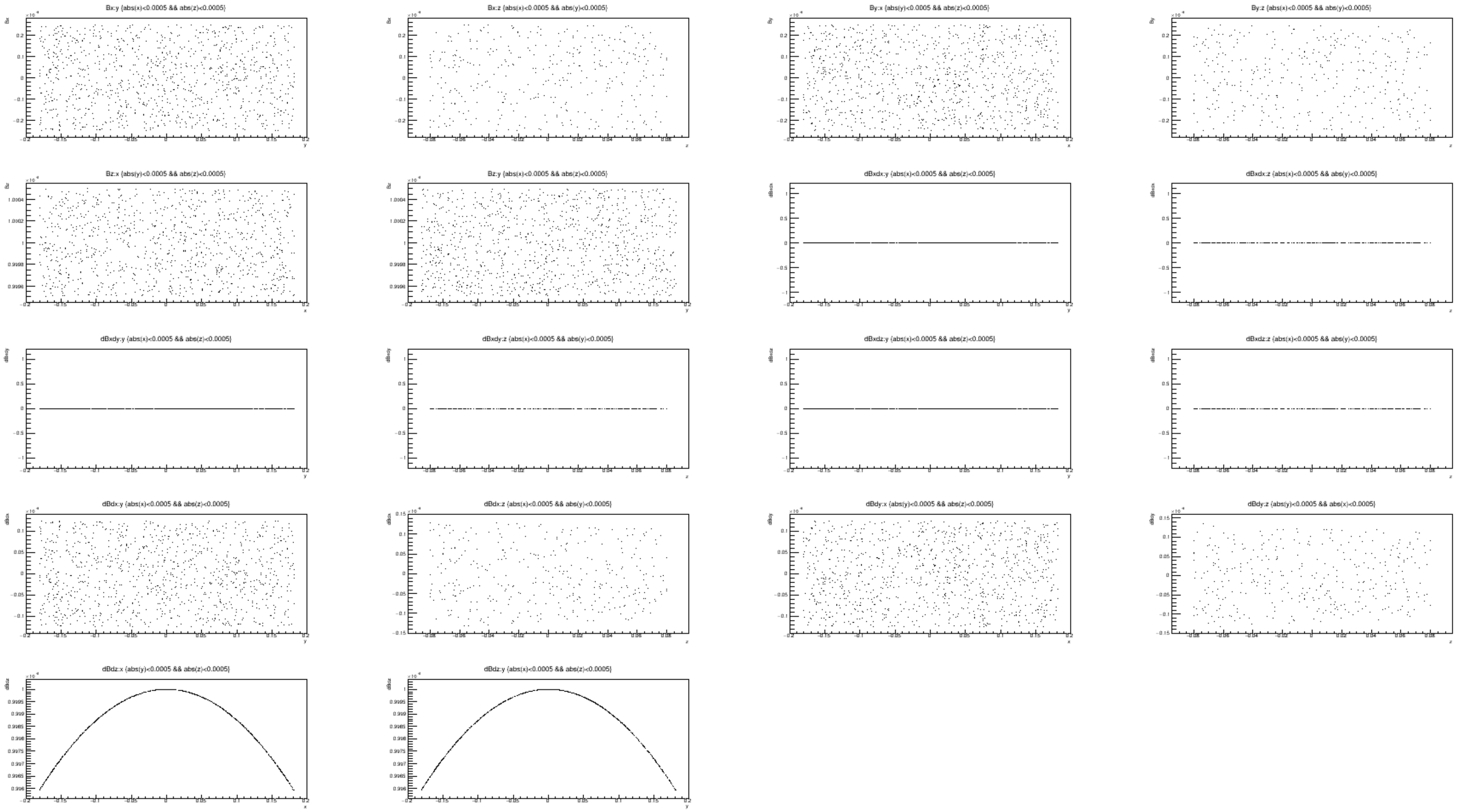


Single Variable B_0 field





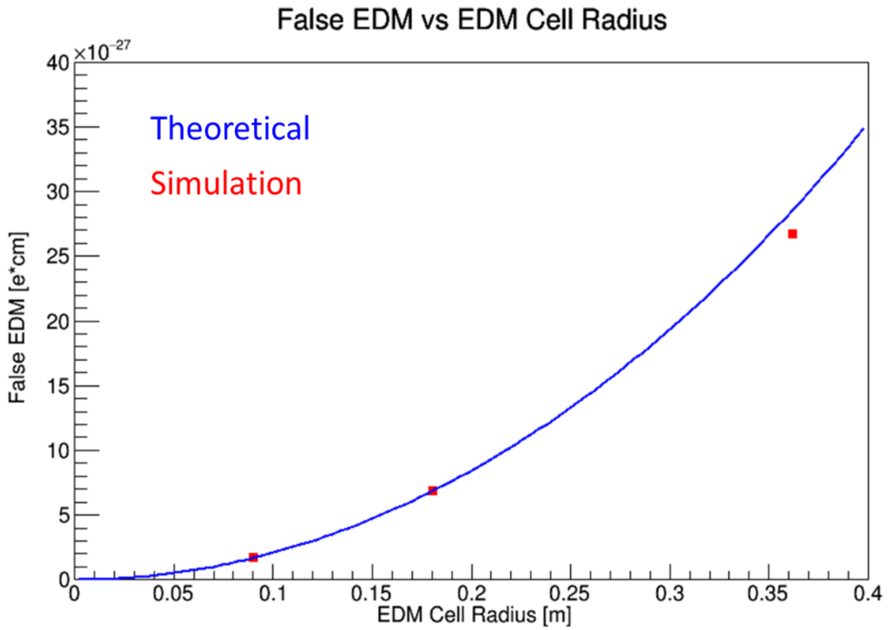
Bx:x {abs(y)<0.0005 && abs(z)<0.0005}
Bx
x
dBxdx:x {abs(y)<0.0005 && abs(z)<0.0005}
dBxdx
x
Babs:x {abs(y)<0.0005 && abs(z)<0.0005}
Babs
x
dBdx:x {abs(y)<0.0005 && abs(z)<0.0005}
dBdx
x
By:y {abs(x)<0.0005 && abs(z)<0.0005}
By
y
dBydy:y {abs(x)<0.0005 && abs(z)<0.0005}
dBydy
y
Babs:y {abs(x)<0.0005 && abs(z)<0.0005}
Babs
y
dBdy:y {abs(x)<0.0005 && abs(z)<0.0005}
dBdy
y
Bz:z {abs(x)<0.0005 && abs(y)<0.0005}
Bz
z
dBzdz:z {abs(x)<0.0005 && abs(y)<0.0005}
dBzdz
z
Babs:z {abs(x)<0.0005 && abs(y)<0.0005}
Babs
z
dBdz:z {abs(x)<0.0005 && abs(y)<0.0005}
dBdz
z



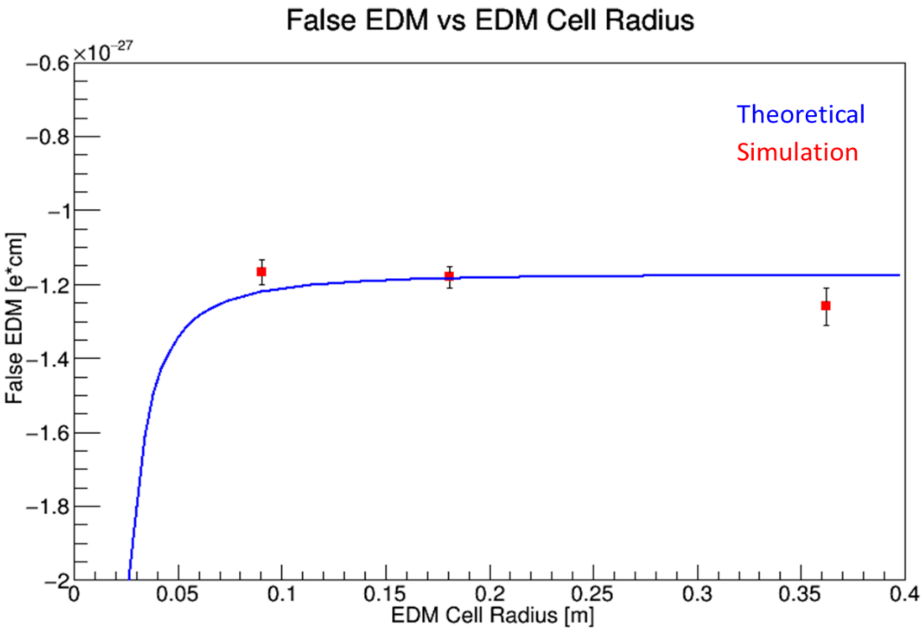
Bx:y {abs(x)<0.0005 && abs(z)<0.0005}
Bx:z {abs(x)<0.0005 && abs(y)<0.0005}
By:x {abs(y)<0.0005 && abs(z)<0.0005}
By:z {abs(x)<0.0005 && abs(y)<0.0005}
Bz:x {abs(y)<0.0005 && abs(z)<0.0005}
Bz:y {abs(x)<0.0005 && abs(z)<0.0005}
dBxdx:y {abs(x)<0.0005 && abs(z)<0.0005}
dBxdx:z {abs(x)<0.0005 && abs(y)<0.0005}
dBxdy:y {abs(x)<0.0005 && abs(z)<0.0005}
dBxdy:z {abs(x)<0.0005 && abs(y)<0.0005}
dBxdz:y {abs(x)<0.0005 && abs(z)<0.0005}
dBxdz:z {abs(x)<0.0005 && abs(y)<0.0005}
dBdx:y {abs(x)<0.0005 && abs(z)<0.0005}
dBdx:z {abs(x)<0.0005 && abs(y)<0.0005}
dBdy:x {abs(y)<0.0005 && abs(z)<0.0005}
dBdy:z {abs(y)<0.0005 && abs(x)<0.0005}
dBdz:x {abs(y)<0.0005 && abs(z)<0.0005}
dBdz:y {abs(x)<0.0005 && abs(z)<0.0005}

Benchmark Test

Mercury



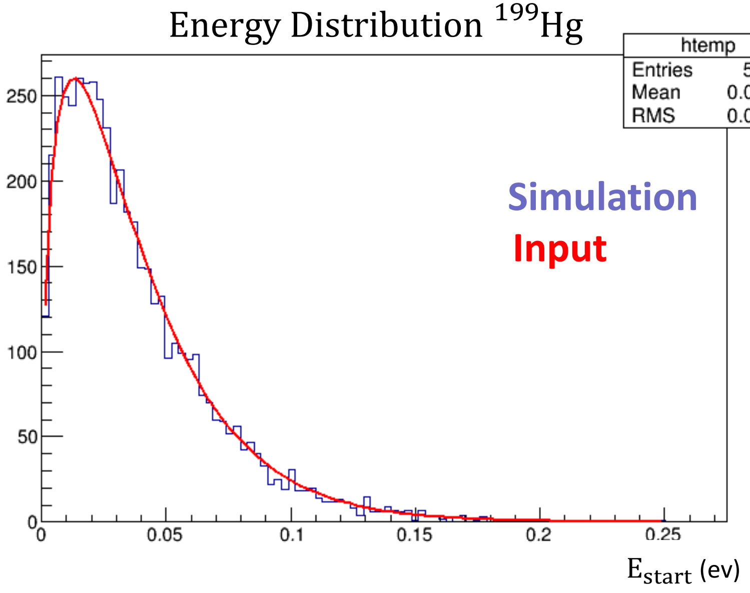
Neutron



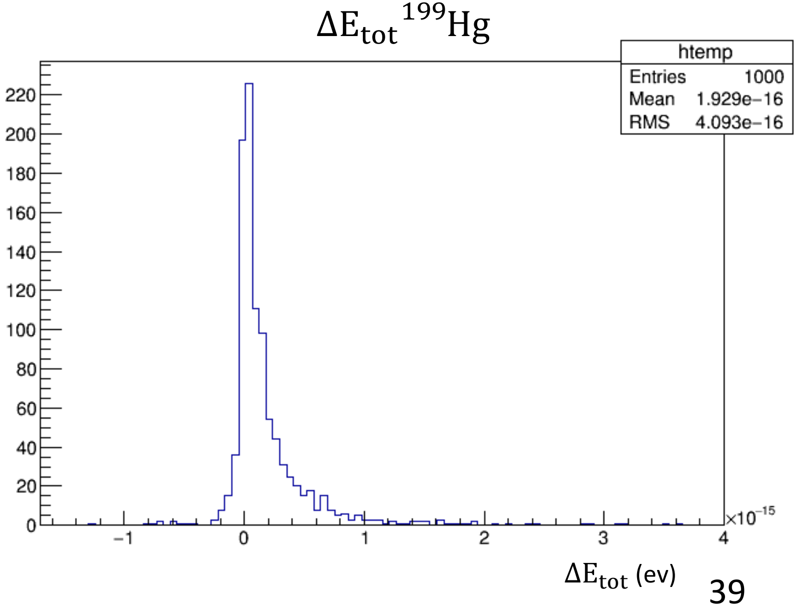
Comagnetometers (^{199}Hg)

PENTrack: **only p^+, e^-, and n** → Add **xenon** and **mercury** atoms

Maxwell-Boltzmann Energy Spectrum



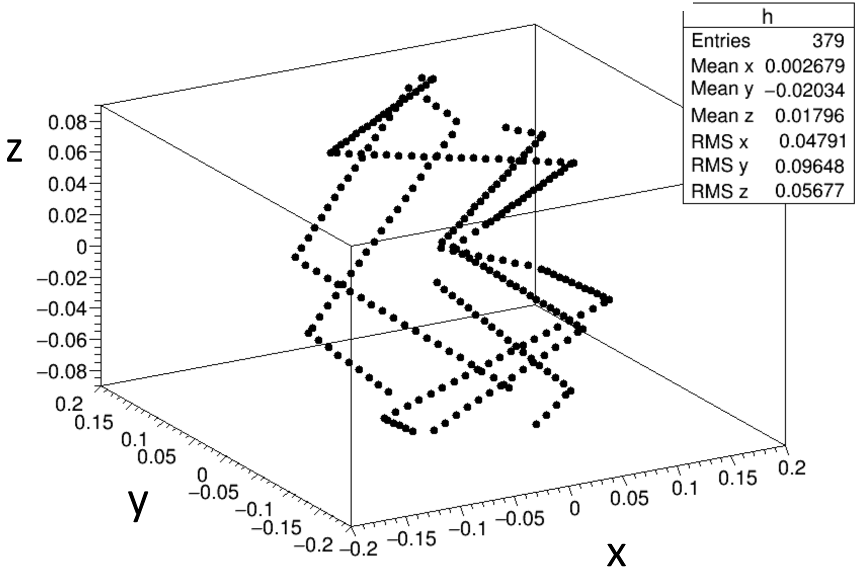
Energy conservation: $\frac{\Delta E}{E} \cong 10^{-12}$ eV ✔



Comagnetometers (^{129}Xe)

Trajectory check

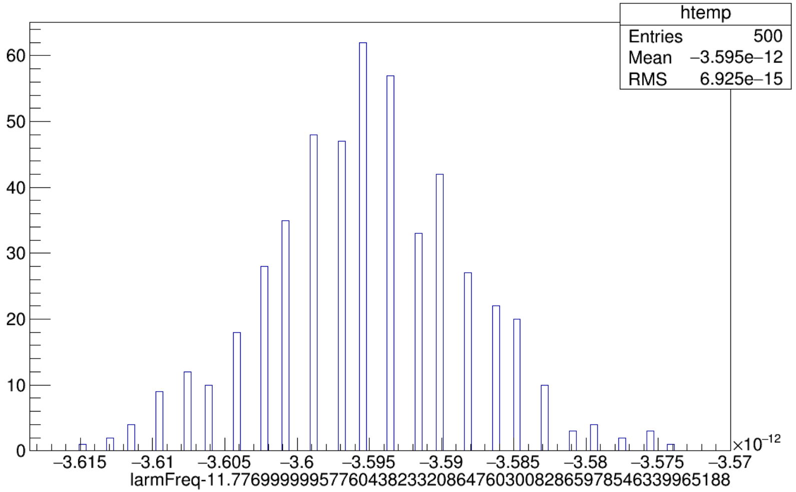
^{129}Xe specular trajectory



Larmor Precession Frequency Test

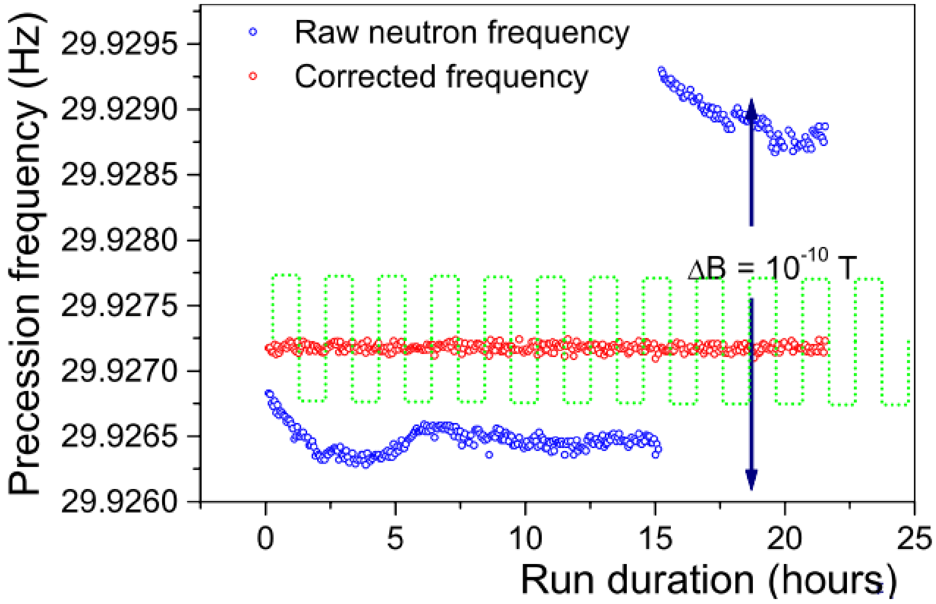
$\Delta\omega_{L,Xe}$ < **3.59 pHz** with **500 atoms**

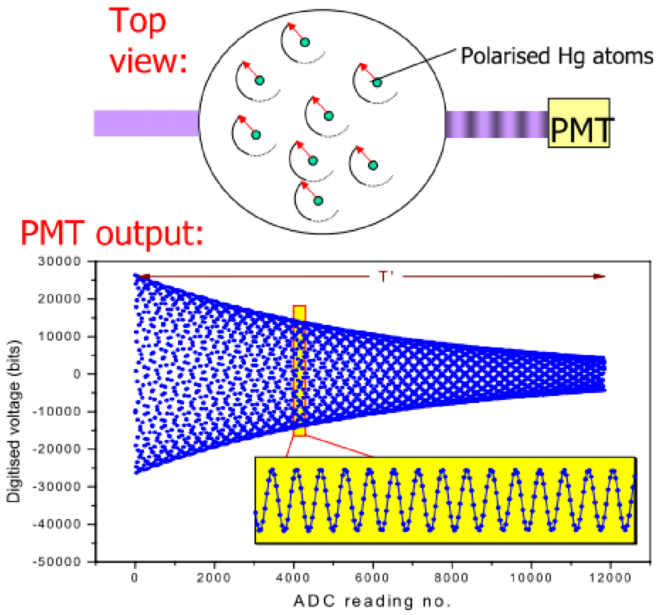
$\Delta\omega_L$ ^{129}Xe



Dual Comagnetometer

- Hg-199 and Xe-129 occupy cell volume
- Monitor changes in $\mathbf{B_0}$ $\rightarrow$ reduce systematic error





Comagnetometer Wall Interactions

Current Status

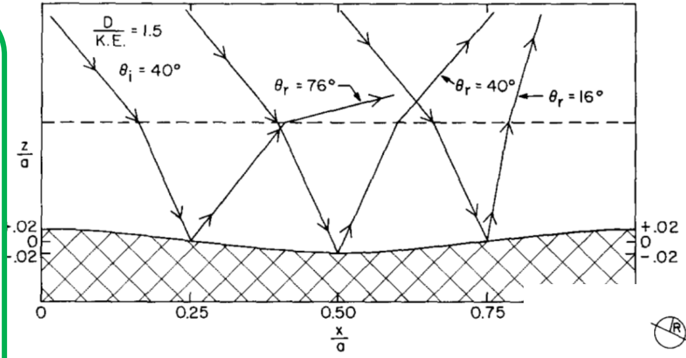
Specular and **diffuse** reflection model

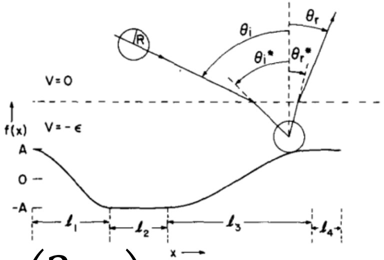
↓ **Valid**

Pendlebury: "…**no dependence of the results on surface reflection law**"

↓ **Future**

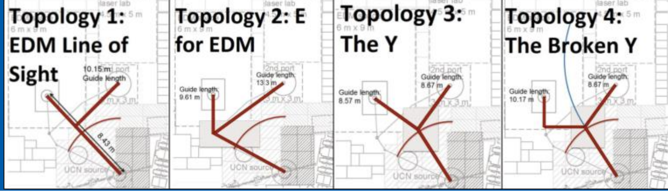
Implement **corrugated wall model** + **sticking time**

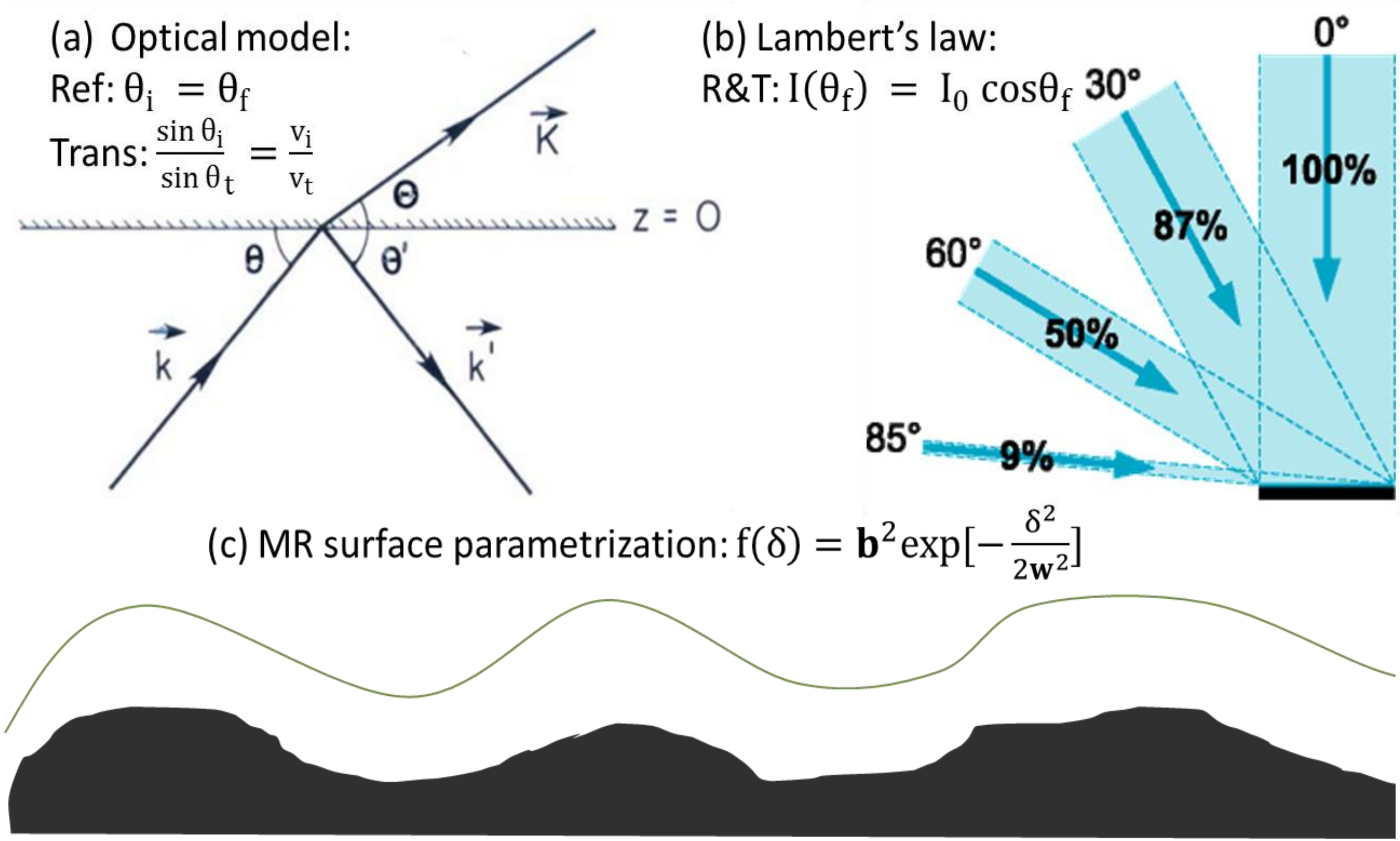




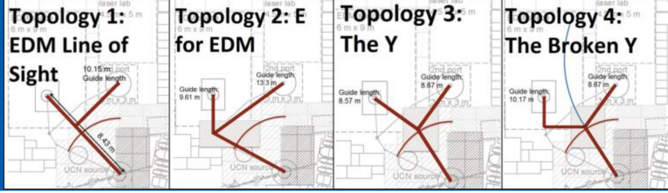
$$V = \begin{cases} 0 & z > z_0 \cos\left(\frac{2\pi x}{a}\right) \\ \infty & z \leq z_0 \cos\left(\frac{2\pi x}{a}\right) \end{cases}$$

Reflection Models

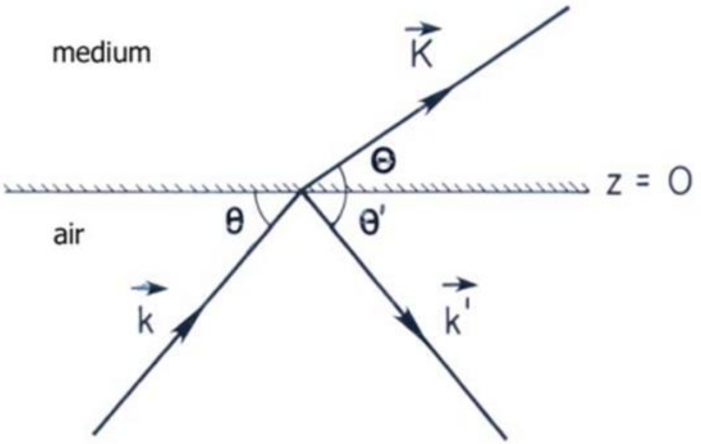




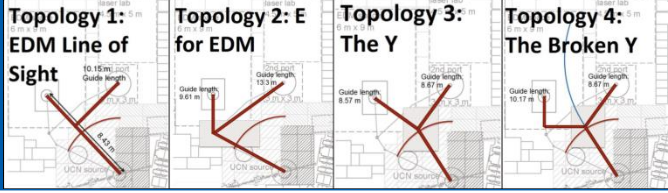
Specular Model



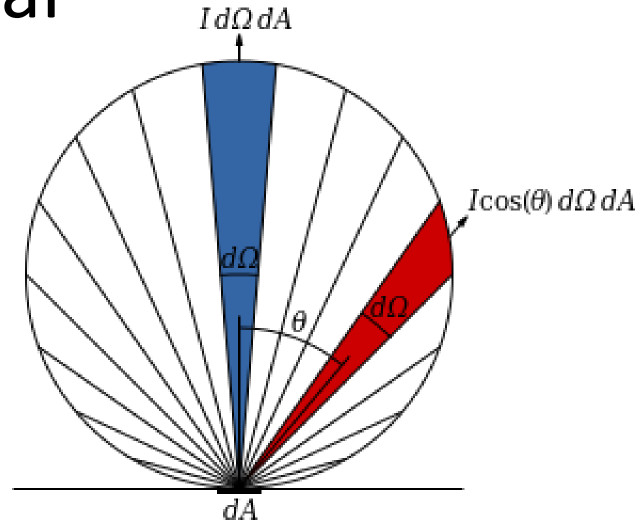
- Definition of model:
  - Ideal surface
  - Law of Reflection: $\theta_f = \theta_i$
  - Snells' law: $n \cong 1 - \frac{\lambda^2 N}{2\pi}\sqrt{{b_c}^2 - (\frac{\sigma_r}{2\lambda})^2} + i\frac{\lambda N \sigma_r}{4\pi}$
    - » n = index of refraction
    - » N = nuclei number density
    - » b_c = scattering length
    - » σ_r = total loss cross section
    - » λ = neutron de Broglie wavelength



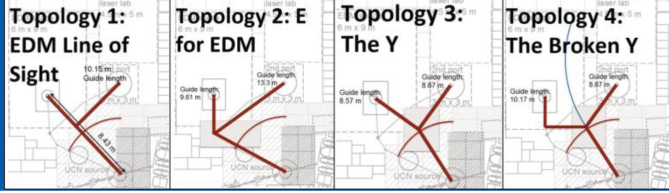
Lambert’s Model



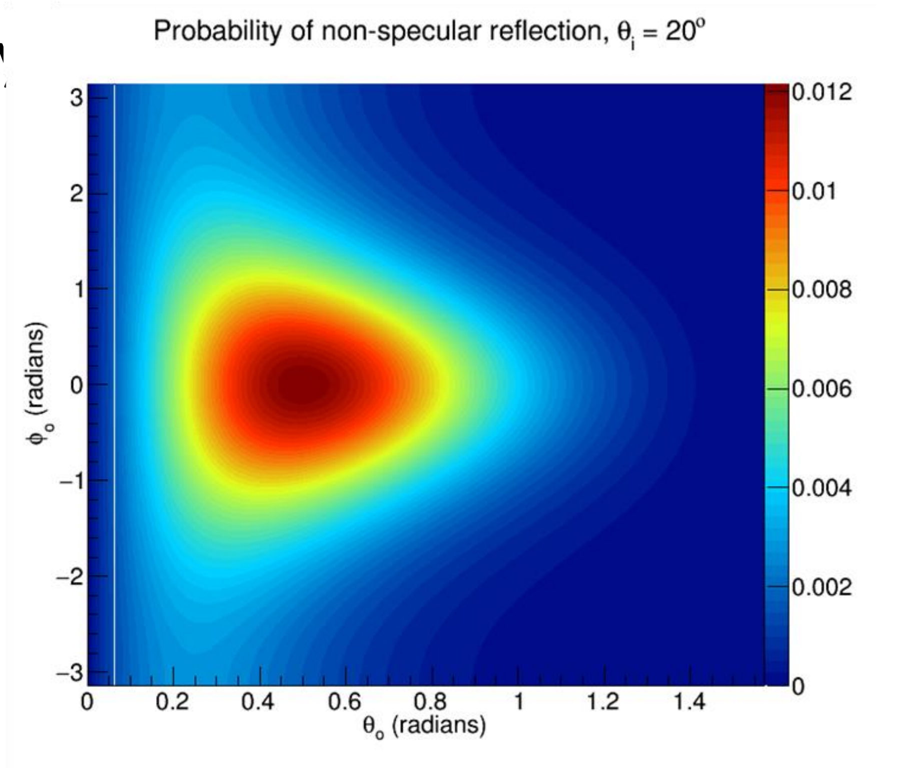
- “Radiant intensity observed any angle is directly proportional to cosine of the direction of incidence and the normal”
- $I(\theta_f) = I_0 \cdot \cos(\theta_f)$



Micro-roughness Model

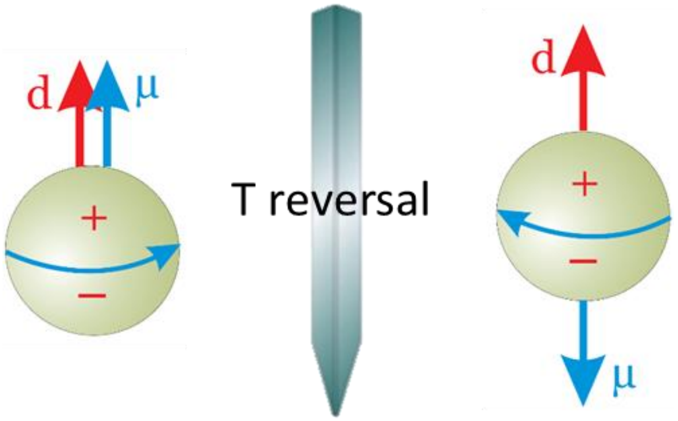


- Surface roughness modelled by Guassian peaks with Gaussian distribution
  - $f(\vec{r}) = f(r) = b^2 \exp[-\frac{r^2}{2w^2}]$
- Dependent on θ_i
- Energy dependent
- Material dependent



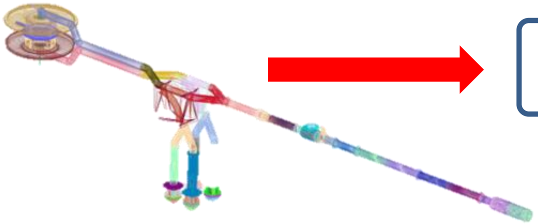
Neutron and CP violation

1. Consider neutron with d_n and μ → apply time reversal
2. d_n remains unchanged but μ reverses
3. T-symm. violated → CP violated

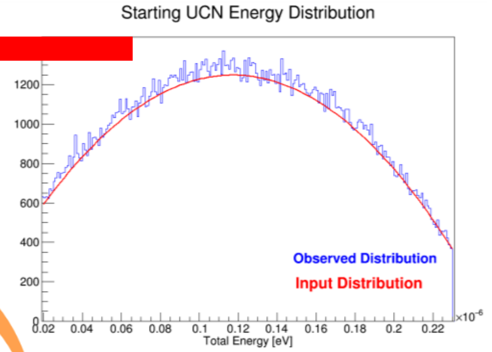


Monte Carlo (MC) Simulations

"Use **random numbers** to **sample** different **probability distributions**."



Create neutrons: **position** & **velocity***



$$\ddot{x} = \frac{F}{m}$$

Integrate **equation of motion**# $\times\ N_{particle}$

$$\ddot{\mathrm{x}} = \frac{1}{\gamma m}\left(1 - \frac{1}{c^2}\dot{\mathrm{x}} \otimes \dot{\mathrm{x}}\right)\left(P\mu\nabla|\mathbf{B}| - mg\mathbf{e}_z + q(\mathbf{E} + \dot{\mathrm{x}} \times \mathbf{B})\right)$$

On hit (reflect, transmit, absorb) and **decay***

* = MC step
# = Deterministic

Example of Monte Carlo Step

TRIUMF

On hit (reflect or transmit)

Analytically calculate probability of **transmission** (Ex: **0.10**)

Generate **random number** with **uniform distribution** (Ex: **0.25**)

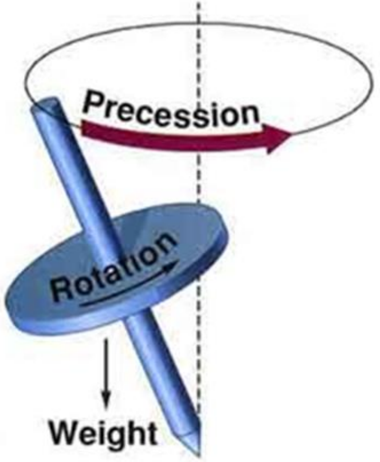
Rand ≤ T → Transmission!

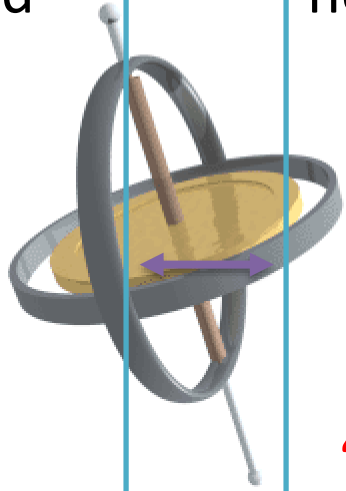
Rand > T → **Reflection!**

Precession

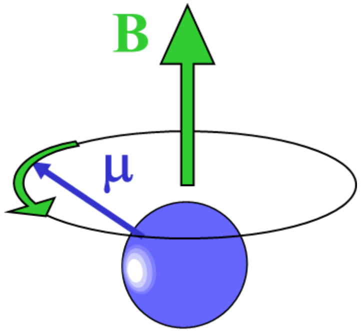
"**Rotation** of the **axis of rotation**"

Gyroscope – **gravity** field





neutron **spin** – **magnetic field**

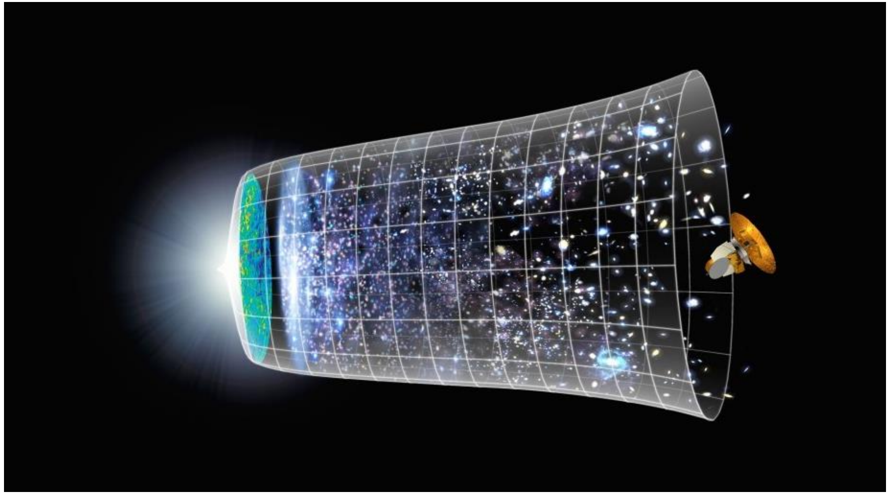


"Larmor" Precession: $\omega_L = -\gamma B$

Stronger field → **Faster** precession (ν)

Motivation

Explanation for **matter/antimatter asymmetry**



Evidence for physics **beyond** the **Standard model**