GEM-based polarimeter detector for proton EDM measurement

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Outline

1. About proton EDM experiment
2. GEM detector for pEDM measurement
3. MC simulation results on proton scattering on carbon target
4. Summary and future plans

EDM and spin precession

- **The existence of a permanent electric dipole moment** of an elementary particles would violate parity(P) and time reversal(T) symmetry. Thus, under the assumption of CPT invariance, a non-zero EDM **would signal CP violation**.
- **The CP violation could explain the matter and antimatter asymmetry of our universe.**

- **Spin dynamics (with EDM and MDM) in magnetic+electric field**

$$\frac{d\vec{s}}{dt}=\vec{\mu}\times\vec{B}+\vec{d}\times\vec{E} \qquad \mu = g(e\hbar/4mc),\ d=\eta(e\hbar/4mc)$$

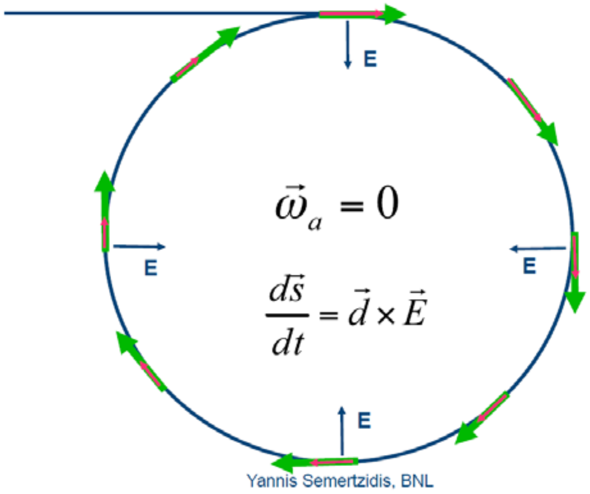
$$with\ \vec{\beta}\cdot\vec{E}=\vec{\beta}\cdot\vec{B}=0$$

$$\vec{\omega}=-\frac{e}{m}\left[\underbrace{a\vec{B}}_{\text{MDM in B-field}}+\underbrace{\left(\frac{1}{\gamma^2-1}-a\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\text{MDM in induced B-field}}+\eta\underbrace{\left(\frac{\vec{E}}{c}+\vec{\beta}\times\vec{B}\right)}_{\text{EDM term}}\right],\ a=\frac{g-2}{2}$$

All electric ring

- Why does the spin precesses in the horizontal plane even without B field in the vertical direction?
  - ✓ In the co-moving frame of a particle with nonzero velocity, the radial E-field partially transforms into a vertical magnetic field the amplitude of which depends on the particle's velocity (Lorentz transform of field).
  - ✓ That B-field acts on the particle's magnetic moment.

$$\vec{\omega}_a = \frac{e}{m}\left(a - \left(\frac{m}{p}\right)^2\right)\vec{\beta}\times\vec{E} \quad \leftarrow \text{MDM}$$



The spin precession is zero at "magic" momentum only with positive anomaly (a=0.8 for proton, **0.7 GeV/c** for protons, 3.1GeV/c for muons,…)

$$p = \frac{m}{\sqrt{a}}, \text{ with } a = \frac{g-2}{2}$$

$$at\ magic\ momentum\ with\ B = 0,\ \vec{\omega}_a = 0 \rightarrow \frac{d\vec{s}}{dt} = \vec{d}\text{x}\vec{E}$$

If the EDM vector d is not zero, the particle spin will precess out of plane as a function of storage time due to the radial E-field ($\vec{\omega}_e$).

$$\vec{\omega}_a : g - 2\ precess, \vec{\omega}_e : EDM\ precess$$

pEDM signals

11.1 Expected signal of the pEDM experiment

The expected EDM signal, assuming the spin is along the momentum, is estimated by

$$\frac{d\vec{s}}{dt} = \vec{d}\times\vec{E} \Rightarrow \frac{1}{2}\hbar\omega = dE \Rightarrow \frac{d\theta}{dt} = \frac{2dE}{\hbar} \Rightarrow$$
$$\theta(t) = \theta_0 + \frac{2dE}{\hbar}t, \qquad (11.1)$$

where d, E are assumed to be orthogonal to each other. For E=10.5 MV/m, 95% E-field coverage of the ring, and an EDM of d=10^{-29} e·cm, the rate of change in the vertical spin component is

$$\theta(t) = \theta_0 + \frac{2dEc}{\hbar c}t = \theta_0 + \frac{2\times10^{-31}\,\mathrm{e\cdot m}\times 10.5\,\mathrm{MV/m}\times 0.95\times 3\times10^{8}\,\mathrm{m/s}}{197\ \mathrm{MeV\ fm}}t \Rightarrow$$
$$\theta(t) = \theta_0 + 3\frac{\mathrm{nrad}}{\mathrm{s}}t. \qquad (11.2)$$

We can make the following observations from equations (11.1) and (11.2):

*see pEDM proposal for details

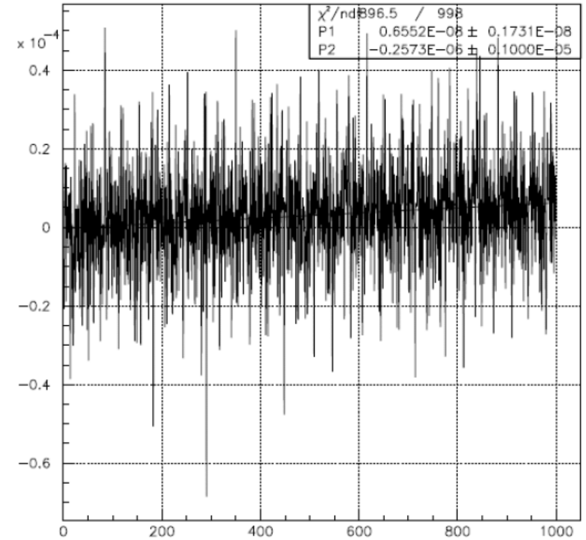


Figure 11.1: (L-R)/(L+R) vs. time [s], is as well as the fit results to two parameters (slope and dc offset). The total counts used are 4×10^{12}, with P_0=0.8, and A=0.6. The slope is estimated with 3.8 sigma statistical accuracy. The fit results confirm the result of eq. (11.3).

- In pEDM experiment, spin processes on the vertical plane.
- The storage time will be 1000 s.

How to measure spin precession

- Store polarized beam in the storage ring
- Extract the beam slowly(in 1000s for pEDM experiment) by scattering the particles on the unpolarized nuclei
  - ✓ Carbon target
- Due to L-S coupling between incoming polarized particle(proton, deuteron, etc..) and target nuclei, the scattering occurs asymmetrically on the left and right for the vertically polarized(vertical component of the polarization vector) beam and up and down asymmetry for the horizontally polarized beam.
- Measure the asymmetry using a polarimeter

- For spin 1/2 particle

Differential cross section for proton

$$\sigma(\theta) = \sigma_{unpol}(\theta) = [1 + p_y A_y(\theta)]$$

$$P_y = \frac{1}{A_y}\epsilon_{LR} = \frac{1}{A_y}\frac{L-R}{L+R}.$$

A_y: analyzing power
P_y: vector polarization

Vertical component of vector polarization ← **L-R asymmetry**

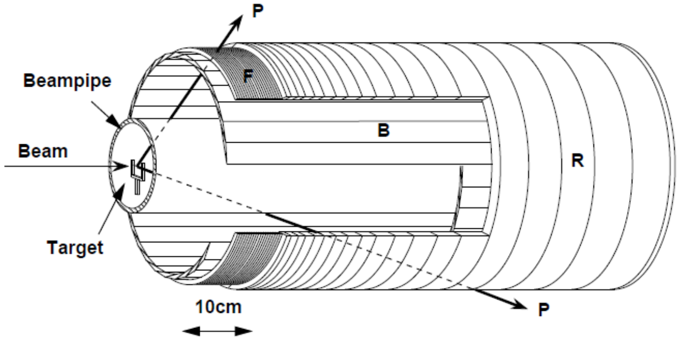
COSY storage ring and EDDA detector

❖ **COSY: The COoler Synchrotron**

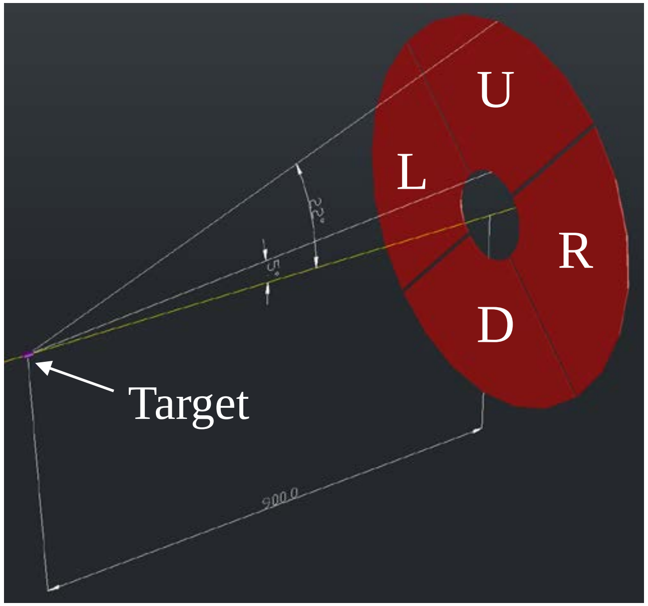
- Forschungszentrum Jülich, Germany
- For proton and deuteron storage
- Circumference of 184m
- Designed for momentum of between 0.3 GeV/c and 3.7 GeV/c.
- The number of particles per fill is about 10^{10} for polarized and 10^{11} for unpolarized particles.
  - ✓ About 10^{6} in the 2014 summer run
- Detector: EDDA, scintillation detector
- An advantage of COSY is the beam phase space controlling (dipole, qudropole, sextupole magnets).
  - ✓ momentum below 0.6 GeV/c: electron cooling
  - ✓ momentum of above 1.5 GeV/c: stochastic cooling

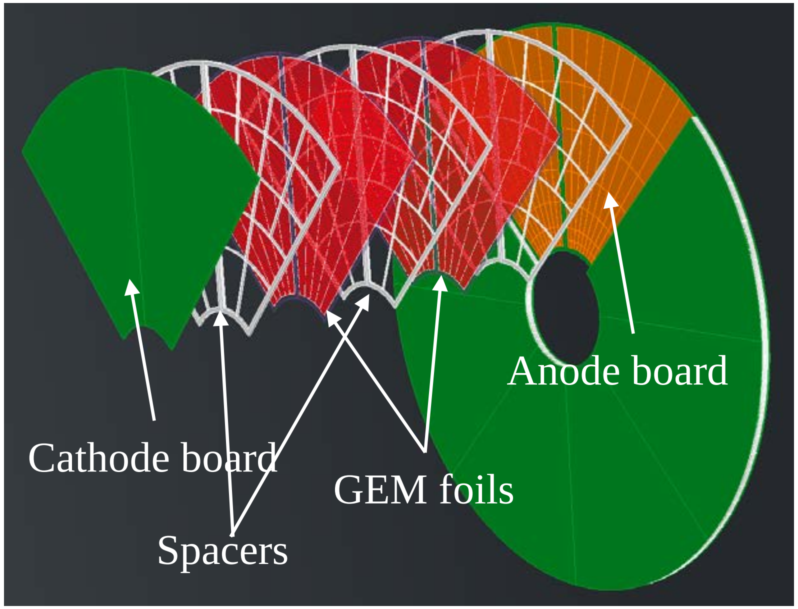
❖ **EDDA detector**

- 32 scintillation bars for azimuthal angle measurement
- 8 rings for the polar angle measurement covering about 9~15 degrees
- Target: Graphite, l=17 mm, above beam center by 4 mm
- Beam extraction is carried out by applying white noise on the beam path
- Beam momentum dispersion $\Delta P/p \sim 10^{-4}$ without electron cooling, with electron cooling 10^{-6}



GEM-based polarimeter detector Concept

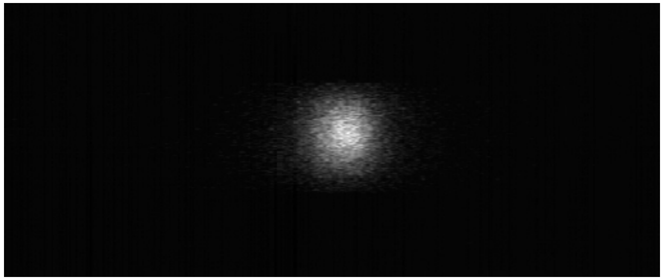




- ❖ Use 4 segmented GEM layers to measure L/R, U/D asymmetry
- ❖ Measure the proton hit locations directly from the anode pad signals
- ❖ Use multichannel readout ASIC instead of scintillators and PMTs
  - ✓ CERN SRS system?
- ❖ High spatial resolution is attainable (~50 μm)
- ❖ High radiation hardness

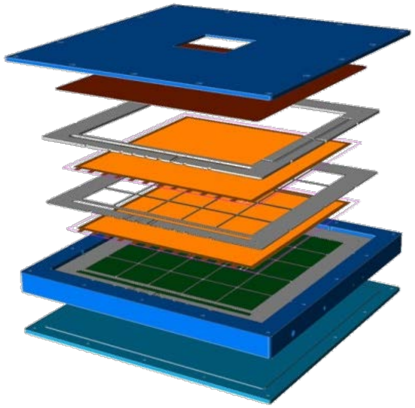
Experiences on GEM detectors

X-ray imaging device

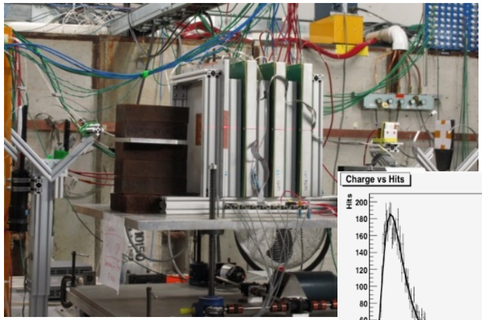


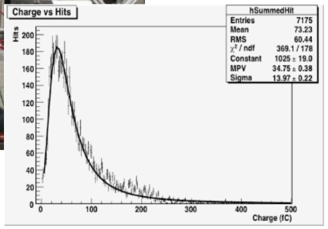
54,528 pixel image out of **512 channels**

Prototype GEM detector for DHCAL

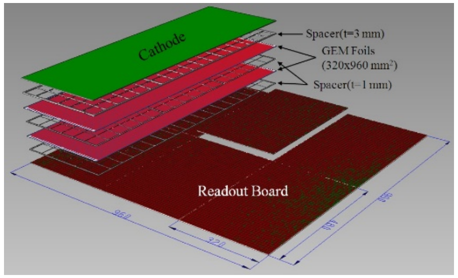


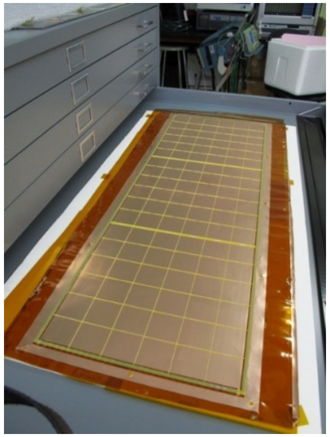
FNAL beam test





Large scale GEM foil design





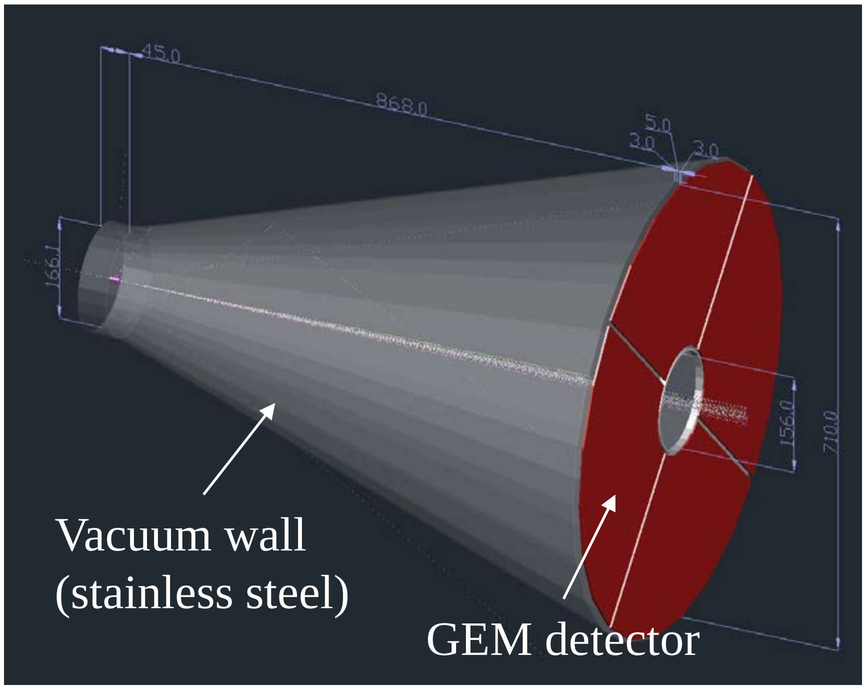
Geant4 simulation for proton scattering on carbon target

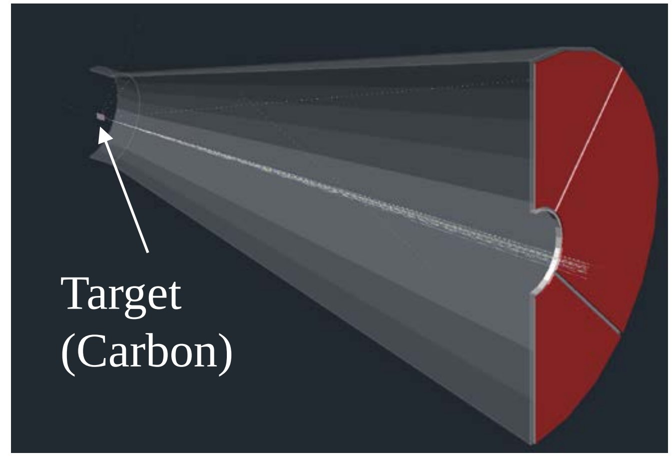
❖ Simulation setup

- Simulation tool: Geant4 v4.10.p02
- Physics list used for simulation: QGSP_BERT
- Input particle: 701 MeV/c, 1,000,000 POTs
  - ✓ P=701 MeV, β=0.6, K=230 MeV
- Target length: 15 ~ 75 mm (COSY target: 17 mm)
- Target dia.: 10 mm
- Target material: Graphite(C:N:O=99:0.7:0.3, 1.7*g/cm^3)
- Distance between target and detector: 900 mm
- Absorber: No
- Absorber thickness: 0
- Vacuum chamber wall: 3 mm stainless steel
- GEM detector: Ar:CO_2=80:20 mixture, 3 mm drift gap

Target and GEM detector

Four segmented GEM planes are arranged for measuring asymmetry(U/D,L/R).





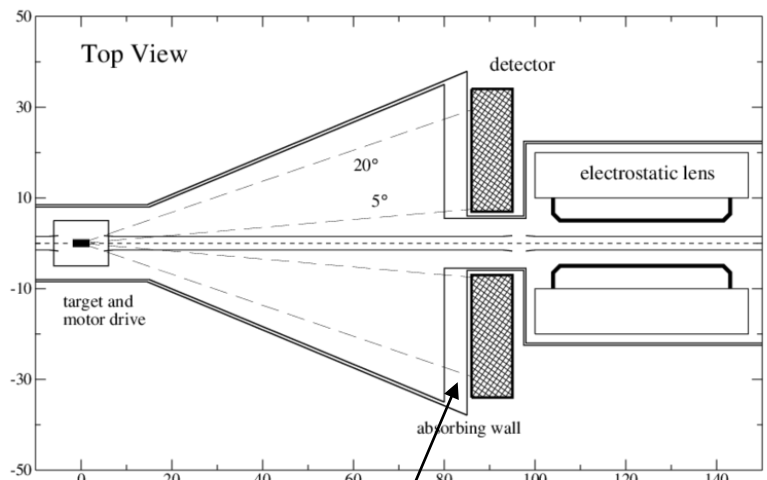
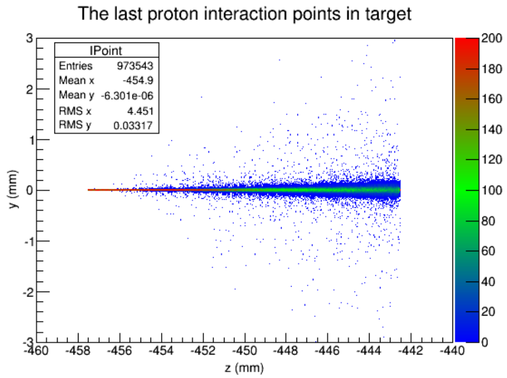


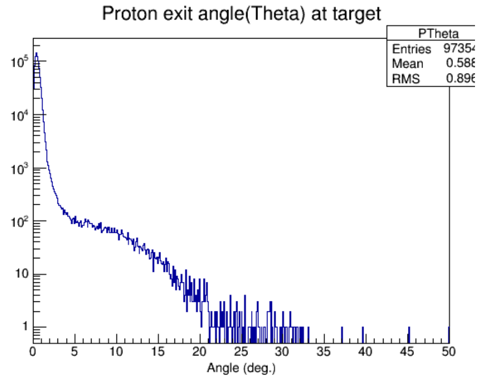
Fig: from Proton EDM proposal

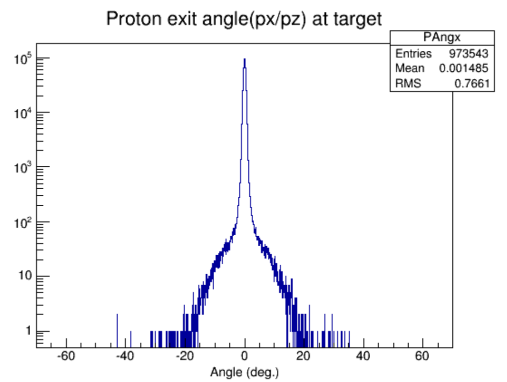
Absorber was removed in this simulation

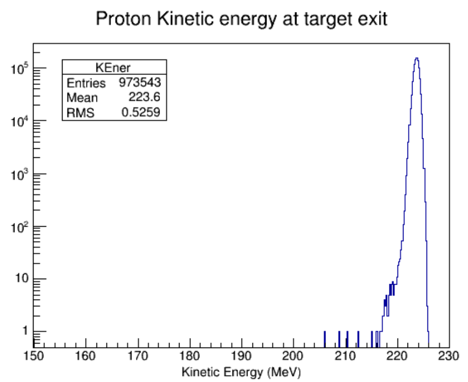
* Pictures from Geant4 visualization

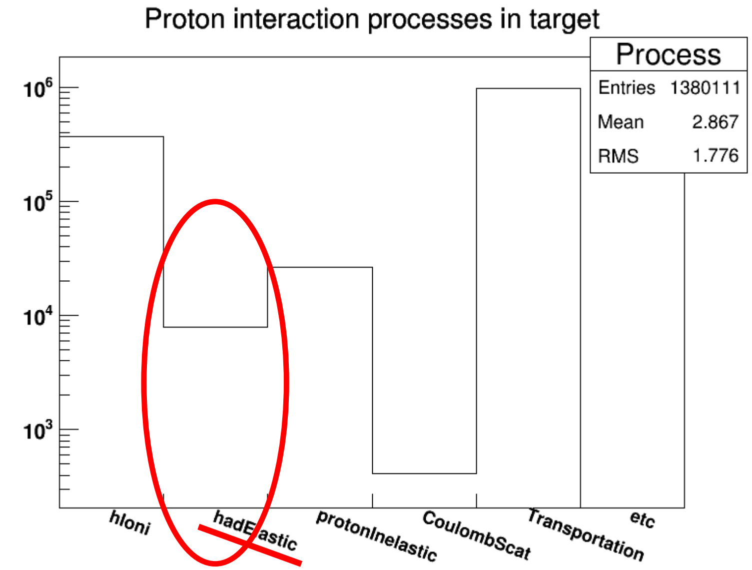
Proton interaction in carbon target

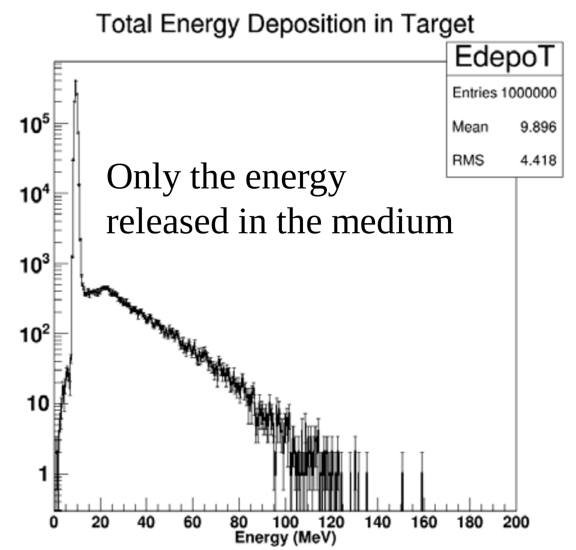












* Target length is 15 mm

- 26,457 protons out of 1000000 are lost in the target.(**2.6457%**)
- Proton detection efficiency(on detector cover area, 5~22^{o}): 0.5814 %
- **Portion of hadElastic: 1.95219 %**

Geometrical parameters for detector

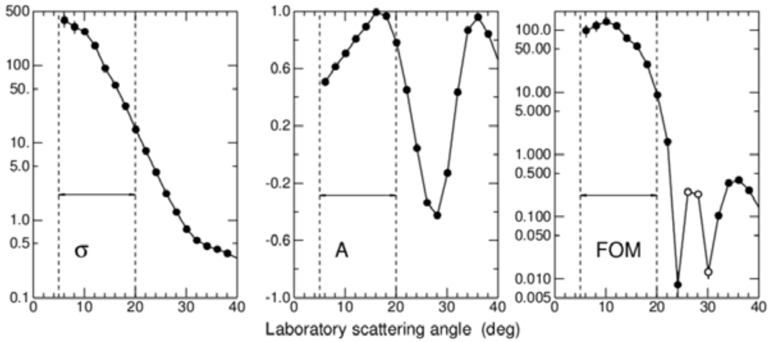
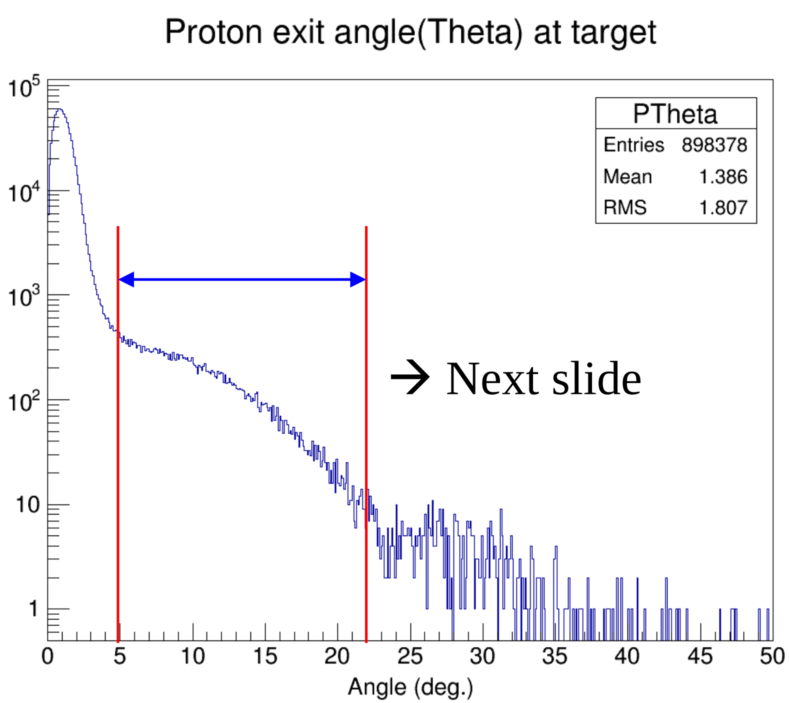
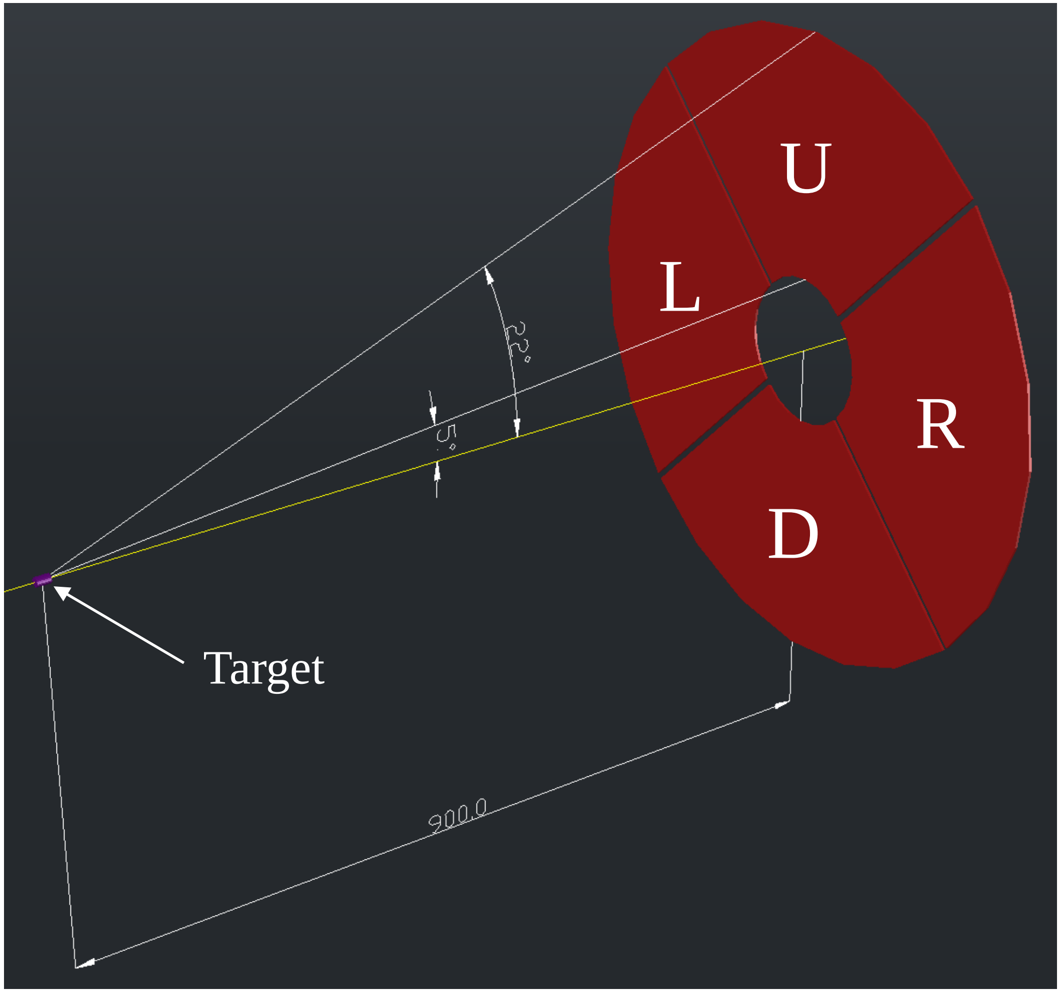
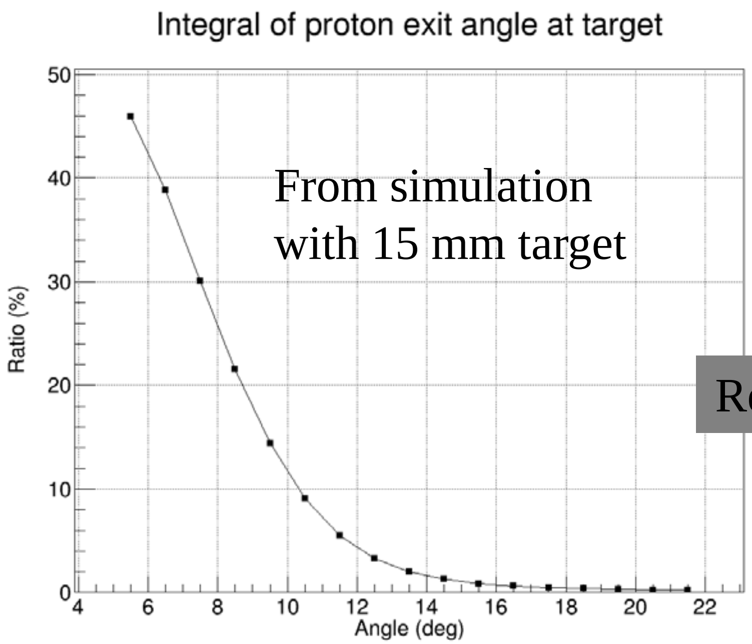


Fig: from Proton EDM proposal

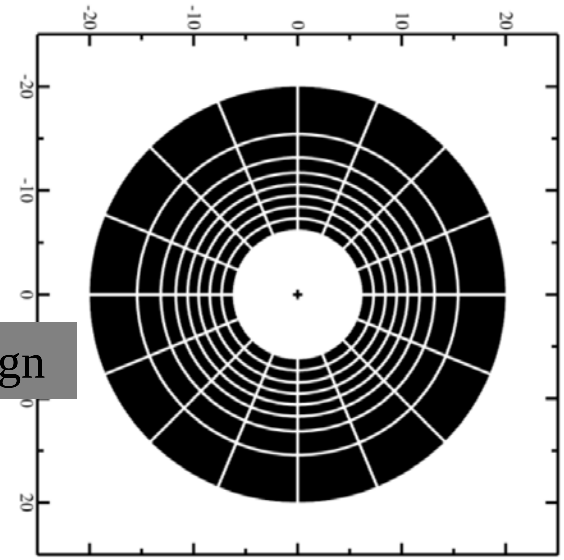




Detector anode pad design from scattering data



Readout pad design

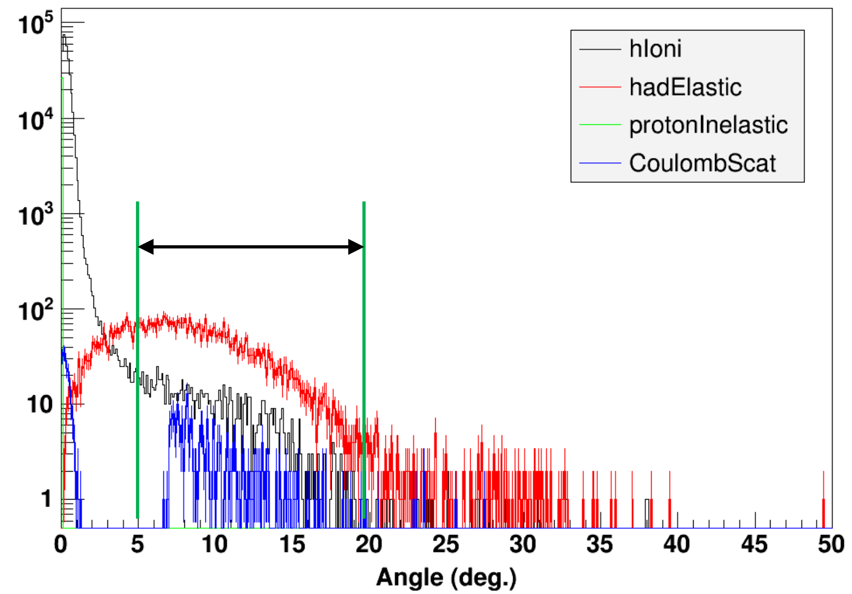


Example of equal rate readout pads

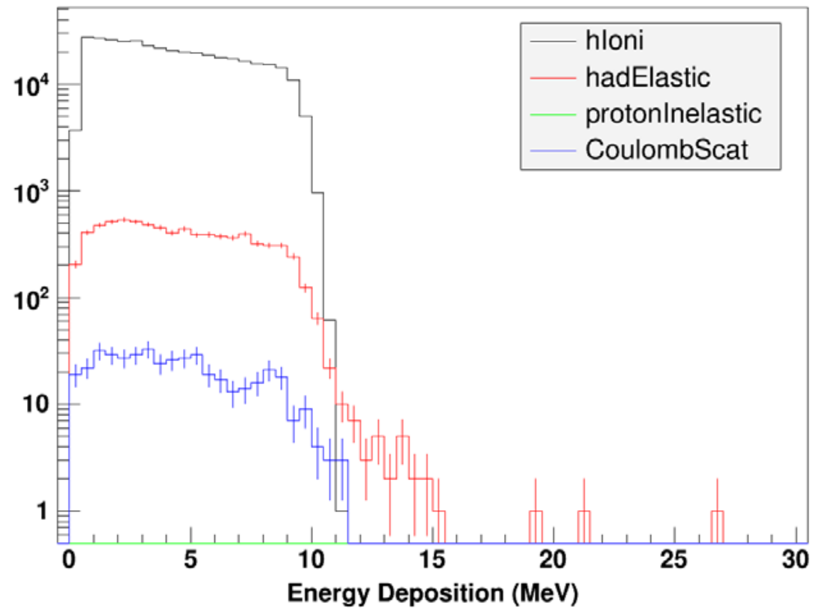
- Each point represents the ratio of integrated angle distribution.
- The integration was done by 1 degree interval and divided by the total area measured in the range of 5~22 degrees.

Proton direction and energy deposition at interaction points in target

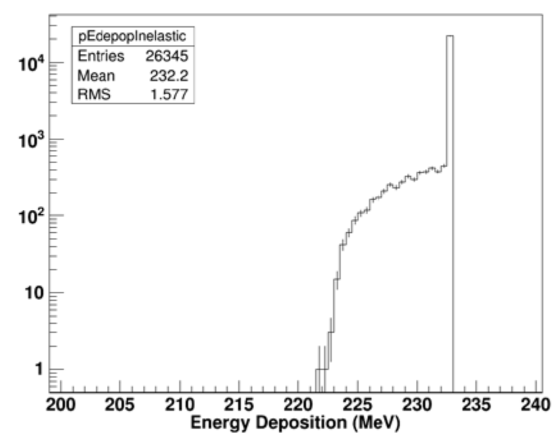
Proton angles at interaction points in target



Proton energy deposition in each process



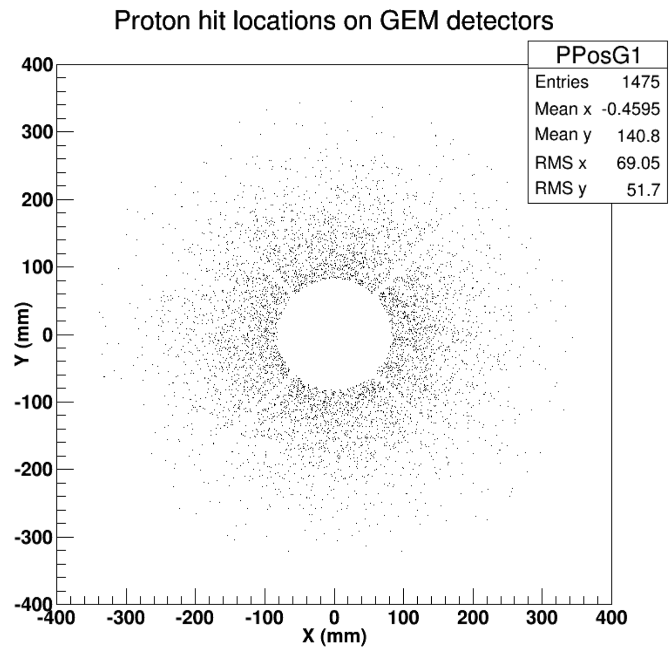
Energy deposition in protonInelastic process in target

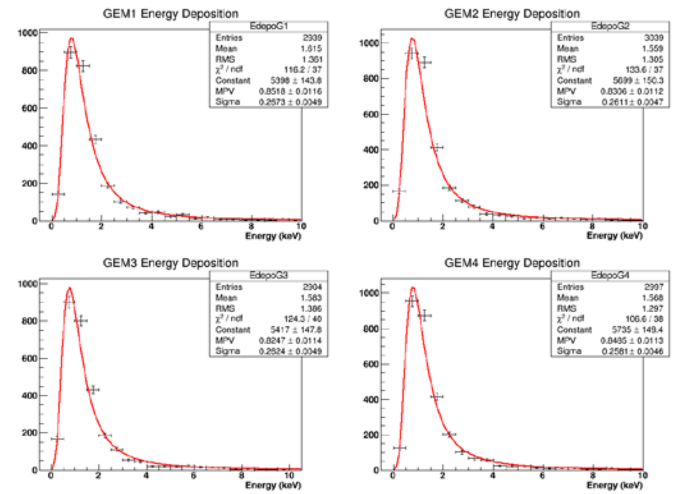


* Target length is 15 mm

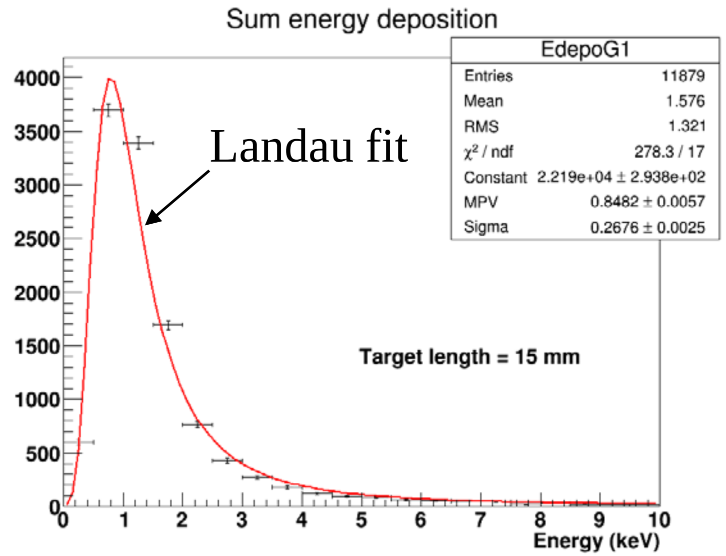
- 26,457 protons out of 1000000 are lost in the target through inelastic process.(**2.6457%**)
- **Portion of hadElastic: 1.95219 %**

Proton hit locations and energy deposition in GEM detectors





Add all 4 histograms



MPVs

T_l=15mm: 0.848 ± 0.006

T_l=30mm: 0.892 ± 0.004

T_l=45mm: 0.924 ± 0.004

T_l=60mm: 1.059 ± 0.002

T_l=75mm: 1.074 ± 0.002

Summary and future plans

- About proton EDM experiment
- GEM detector as polarimeter detector
- Preliminary MC simulation study for detector design
- Currently collecting equipment and materials for detector construction and test
- Detector design will be began once we finalize the geometrical dimensions of the GEM chamber and anode board