Preliminary Conceptual Design of Proton Charge Radius Experiment Using Future Muon Beam at CiADS

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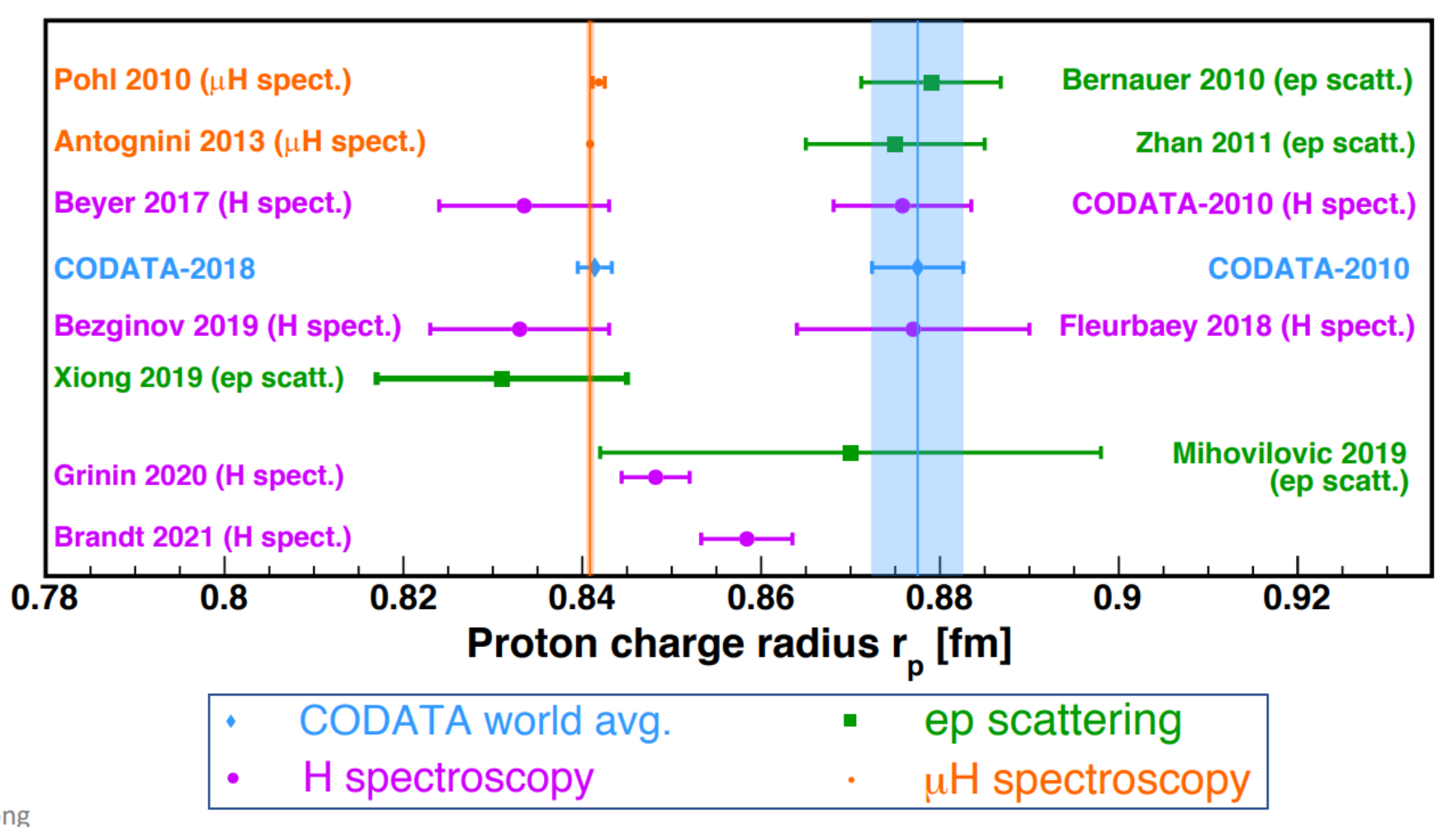
Motivation and Introduction

- Muonic hydrogen spectroscopy experiment yielded a proton charge radius result 7σ smaller than previous ordinary hydrogen spectroscopy and elastic e-p scattering.
- This unexpected discrepancy is often referred to as the "**proton charge radius puzzle**".

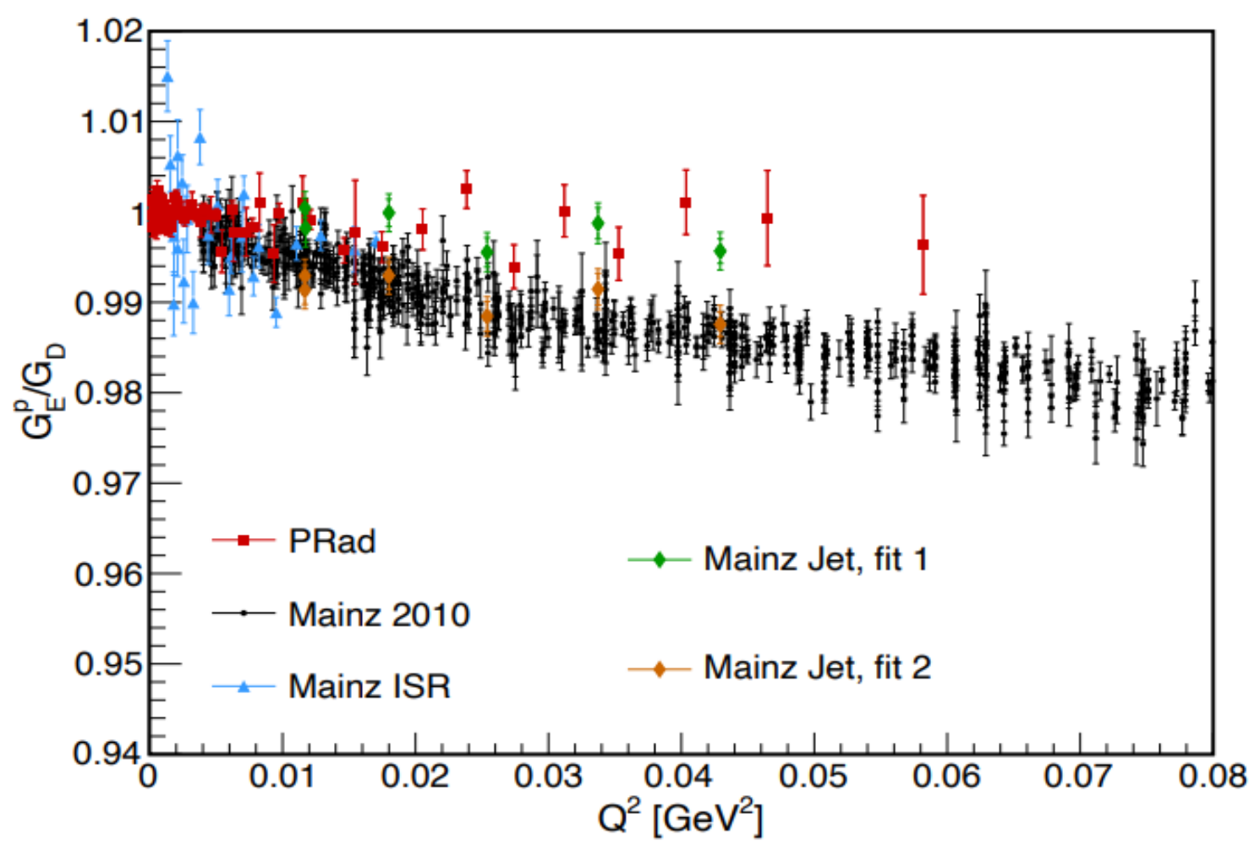
Current Status on Proton Charge Radius



Weizhi Xiong

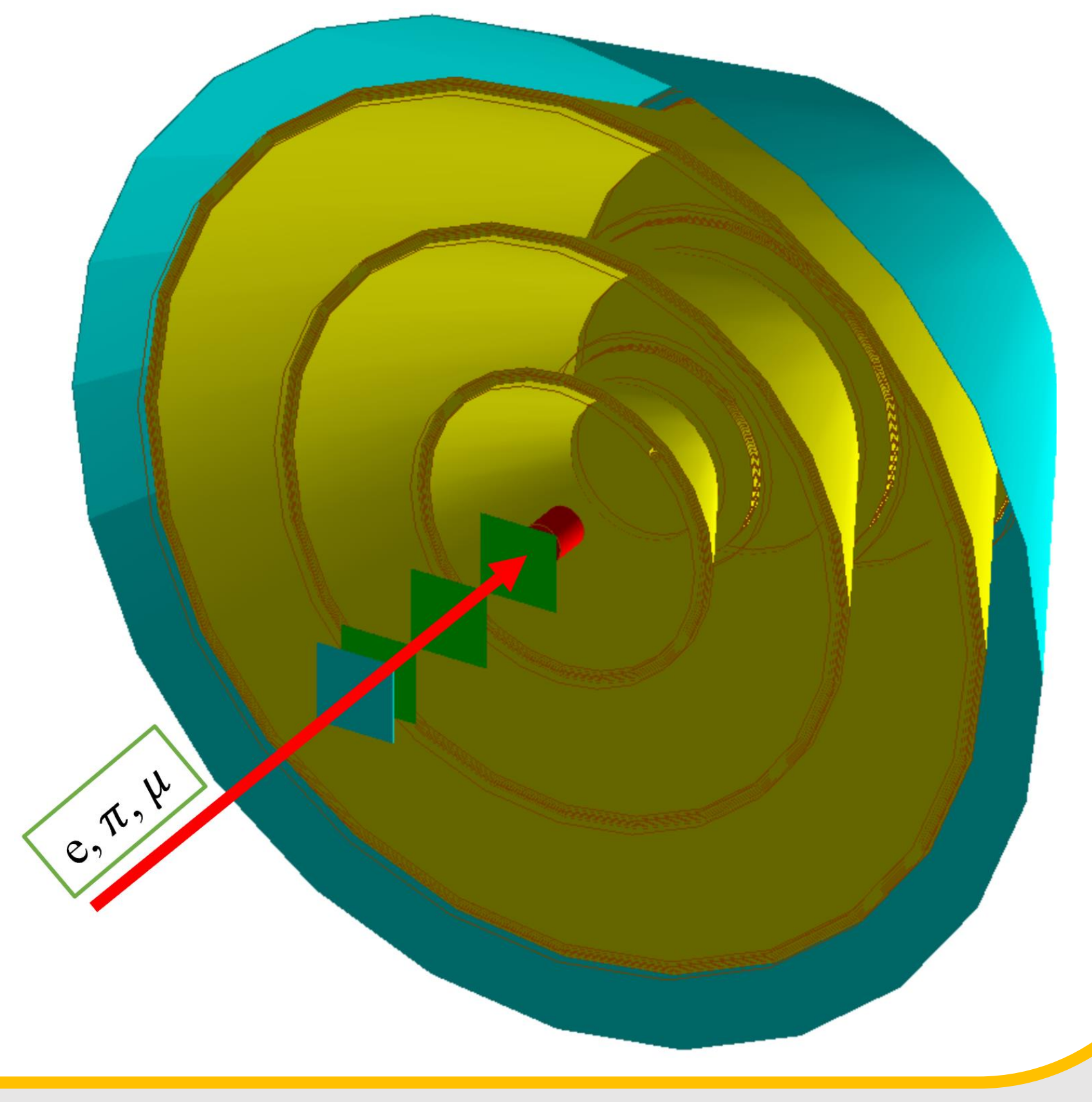
- In the past decade, significant progress has been made in both experiment and theory, yet many problems remain.
- E.g. , the inconsistent G_E^p form factor between PRad and Mainz experiments.

The Proton Electric Form Factor of Mainz and PRad



- No μ-p elastic scattering proton radius result published until now.
- We propose a high precision measurement using future CiADS muon beam.
- Collect μ-p, e-p, as well as e-e elastic scattering simultaneously.
- Opportunity for direct test of lepton universality, help resolve the "proton charge radius puzzle".

The Figure of Proposed Experiment in This Poster



Physical Background

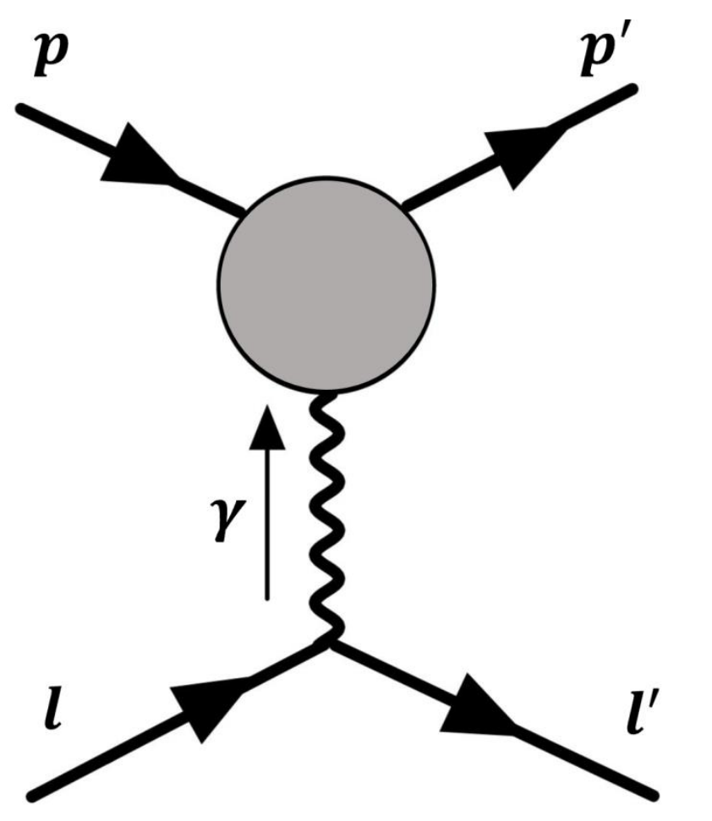
The **Rosenbluth formula**, describing the lepton-proton elastic scattering (one photon exchange):

$$\frac{d\sigma}{d\Omega}=\left(\frac{d\sigma}{d\Omega}\right)_{Mott}\frac{1}{1+\tau}\left[\left(G_E^p(Q^2)\right)^2+\frac{\tau}{\varepsilon}\left(G_M^p(Q^2)\right)^2\right]$$

In case of μ-p, the mass of μ can't be neglected:

$$Q^2=-(l-l')^2,\qquad \tau=\frac{Q^2}{4M^2}$$

$$\varepsilon=\left[1-2(1+\tau)\frac{2m^2-Q^2}{4E_lE_{l'}-Q^2}\right]^{-1}$$



The electric form factor and its Taylor expansion at low Q^2:

$$G_E^p(Q^2)=1-\frac{1}{6}\overline{r_E^{p\,2}}Q^2+\cdots$$

Derivative at low Q^2 limit:

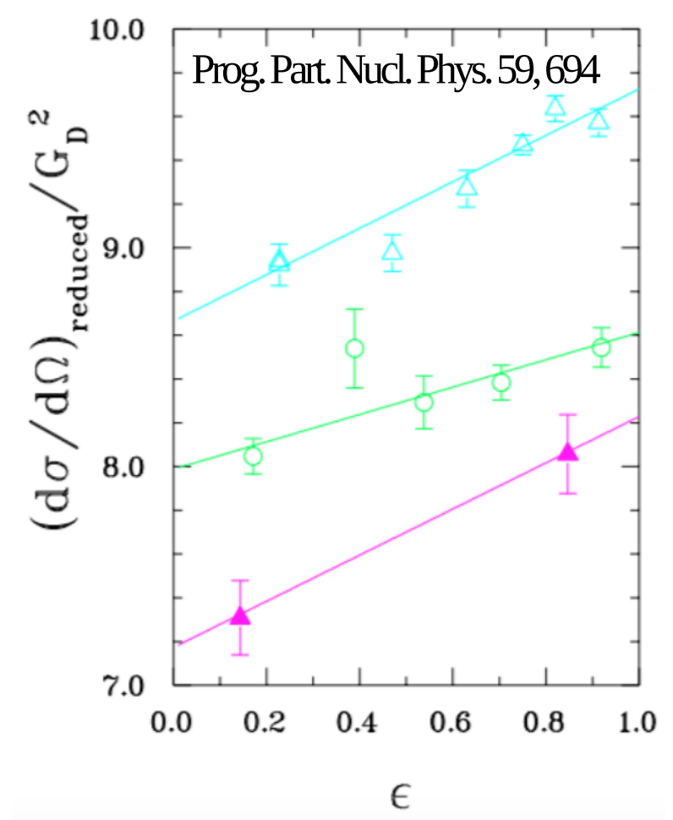
$$\overline{r_E^{p\,2}}\equiv-6\left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}$$

Radius Extraction

Classical Rosenbluth separation:

$$\left(\frac{d\sigma}{d\Omega}\right)_{reduced}=\left(G_M^p(Q^2)\right)^2+\frac{\varepsilon}{\tau}\left(G_E^p(Q^2)\right)^2$$

Measure at the same Q^2, different ε to separate the G_E^p and G_M^p, need minimum two beam energies.



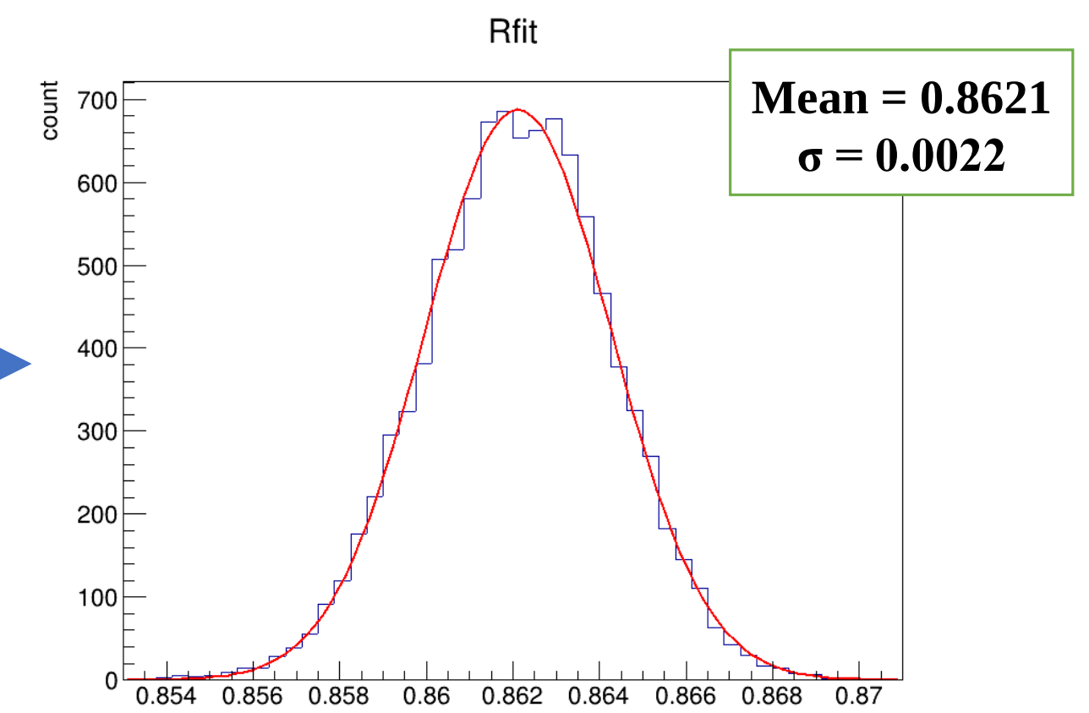
Or, fit the cross section:

Parameterized G_E^p and G_M^p in Rosenbluth formula, e.g. rational(1,1):

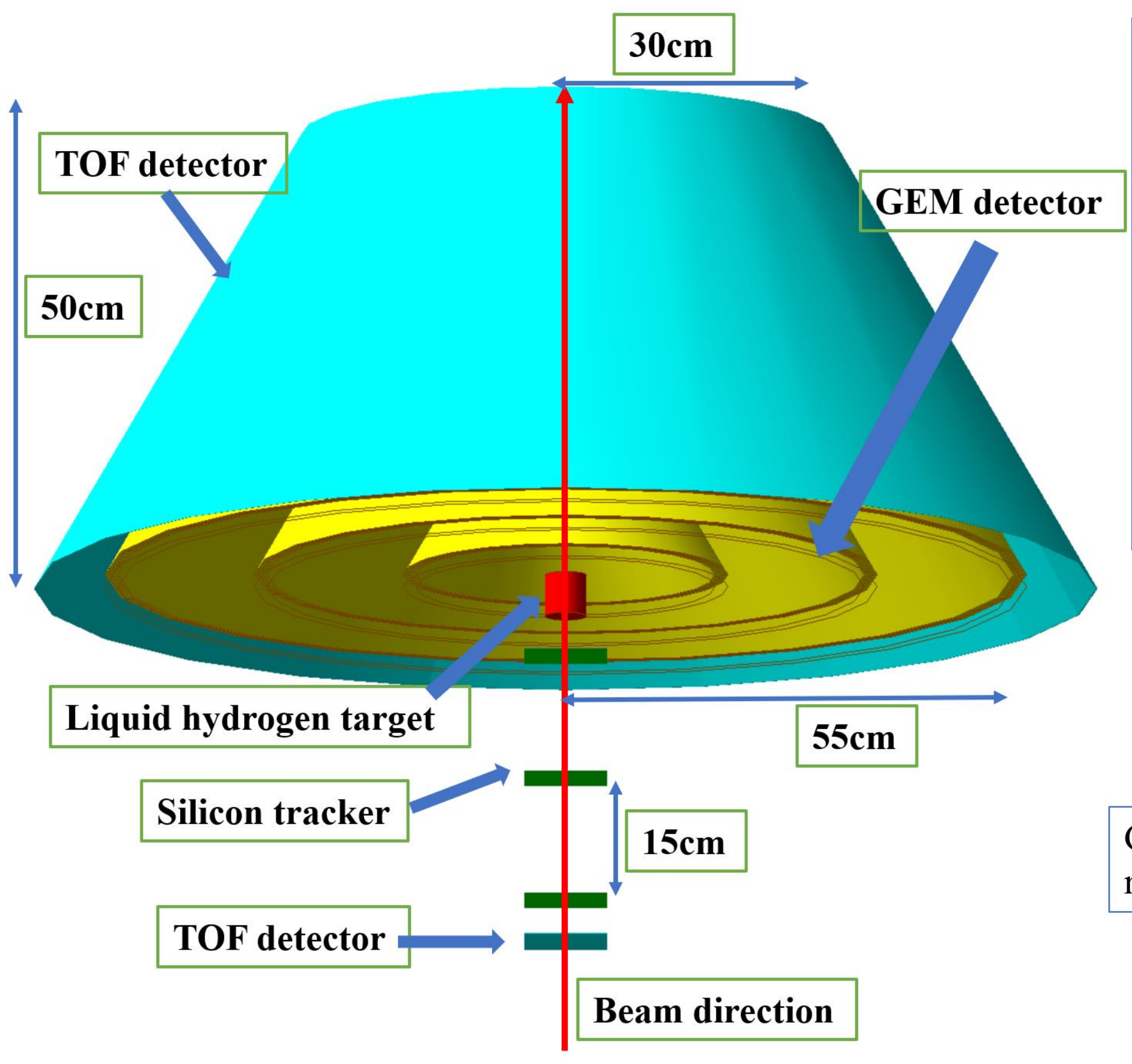
$$G_E^{p,fit}(Q^2)=\frac{1+p_E^aQ^2}{1+p_E^bQ^2},\quad G_M^{p,fit}(Q^2)=\mu_p\frac{1+p_M^aQ^2}{1+p_M^bQ^2}.$$

$$\chi^2=\sum_i\left(\frac{\sigma_{measure}(Q_i^2)-\sigma_{fit}(Q_i^2)}{\Delta\sigma_{measure}}\right)^2$$

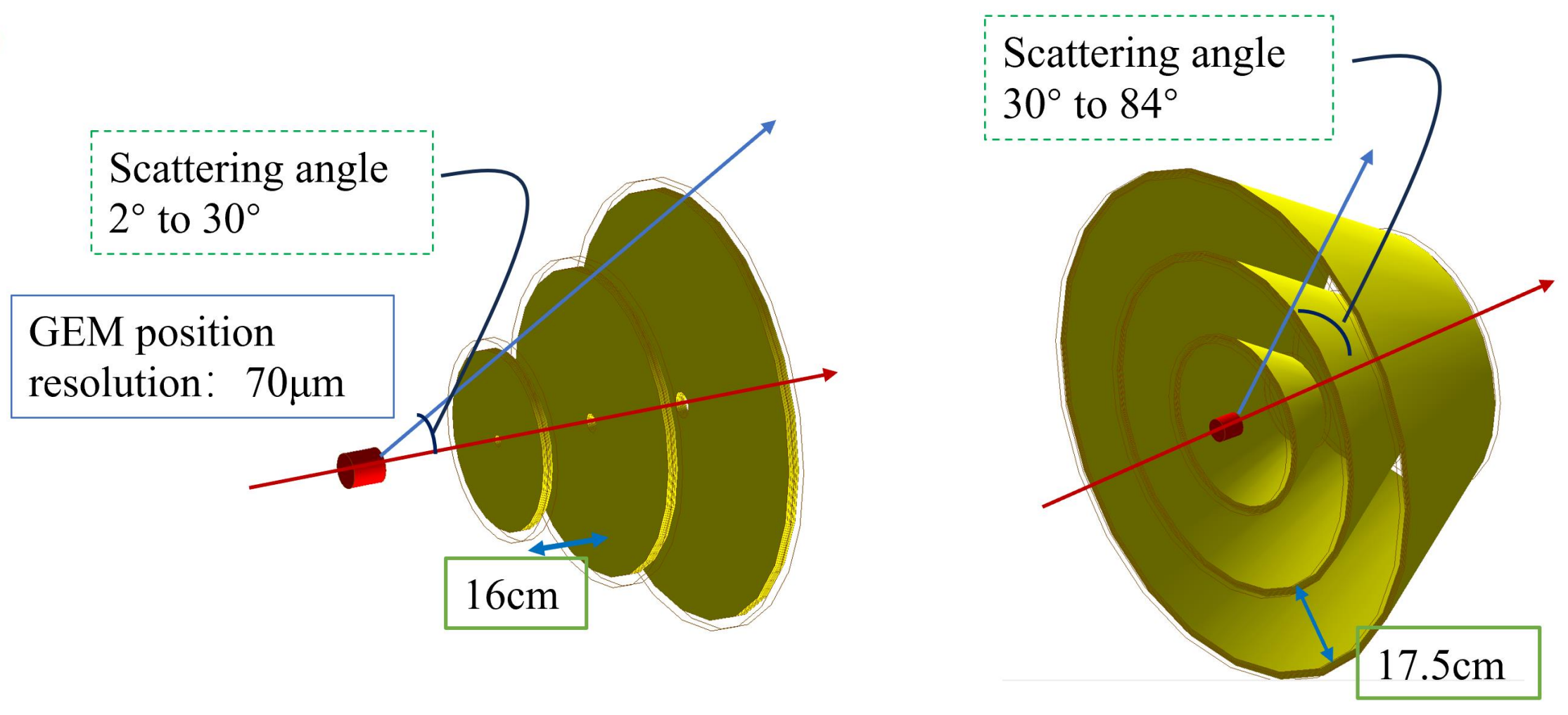
- Pseudo-data with projected stat. uncertainties (μ-p) generated based on the Kelly model.
- Fitting algorithm tested by extracting a consistent result with the input radius(0.863 fm).



Experiment Setup



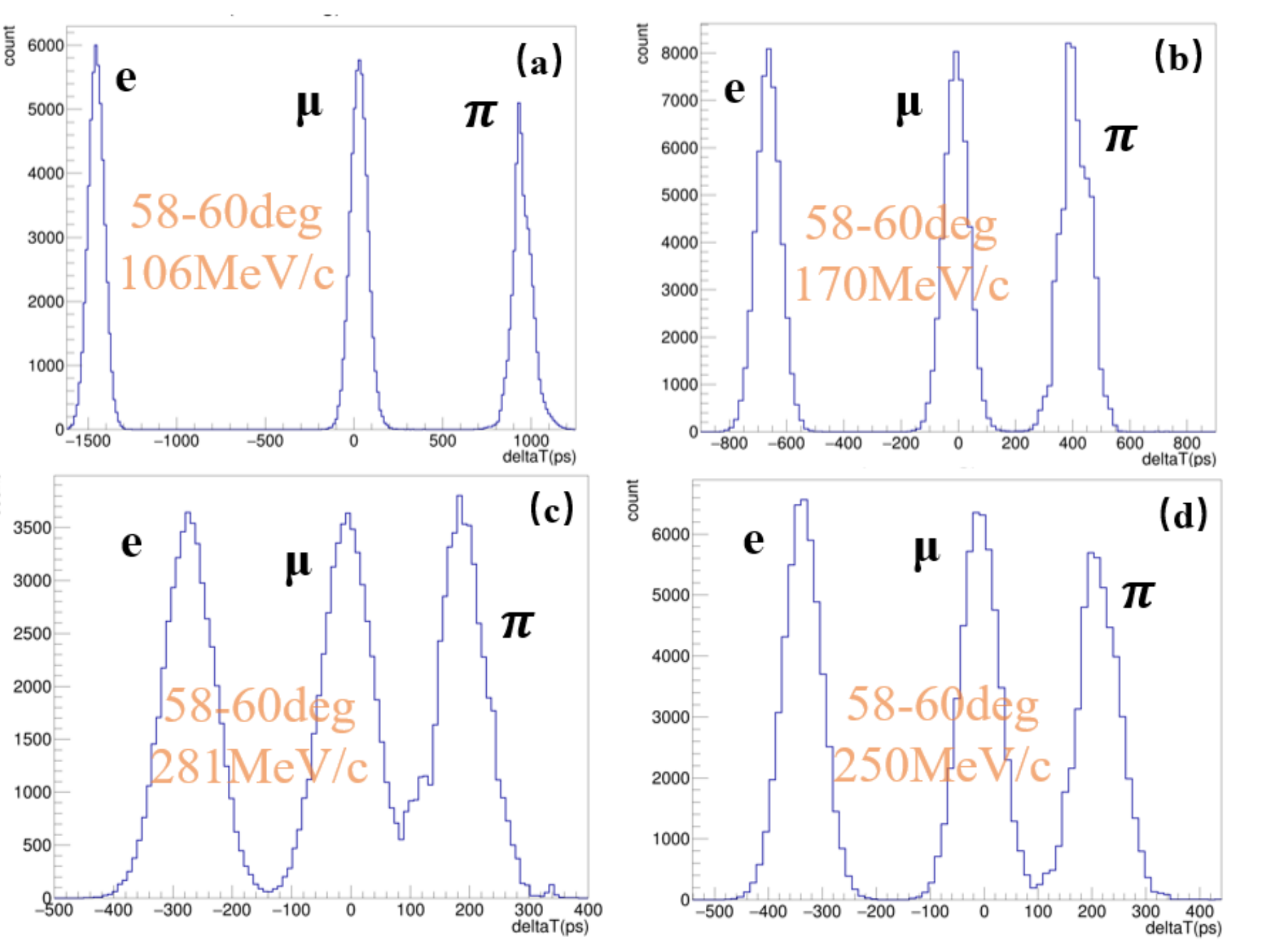
- 5 cm long LH2 target with 5 cm diameter
- Three silicon trackers to measure incoming particle
- Three GEMs for scattered particle tracking
- Tow timing detector to measure time-of-flight(TOF)



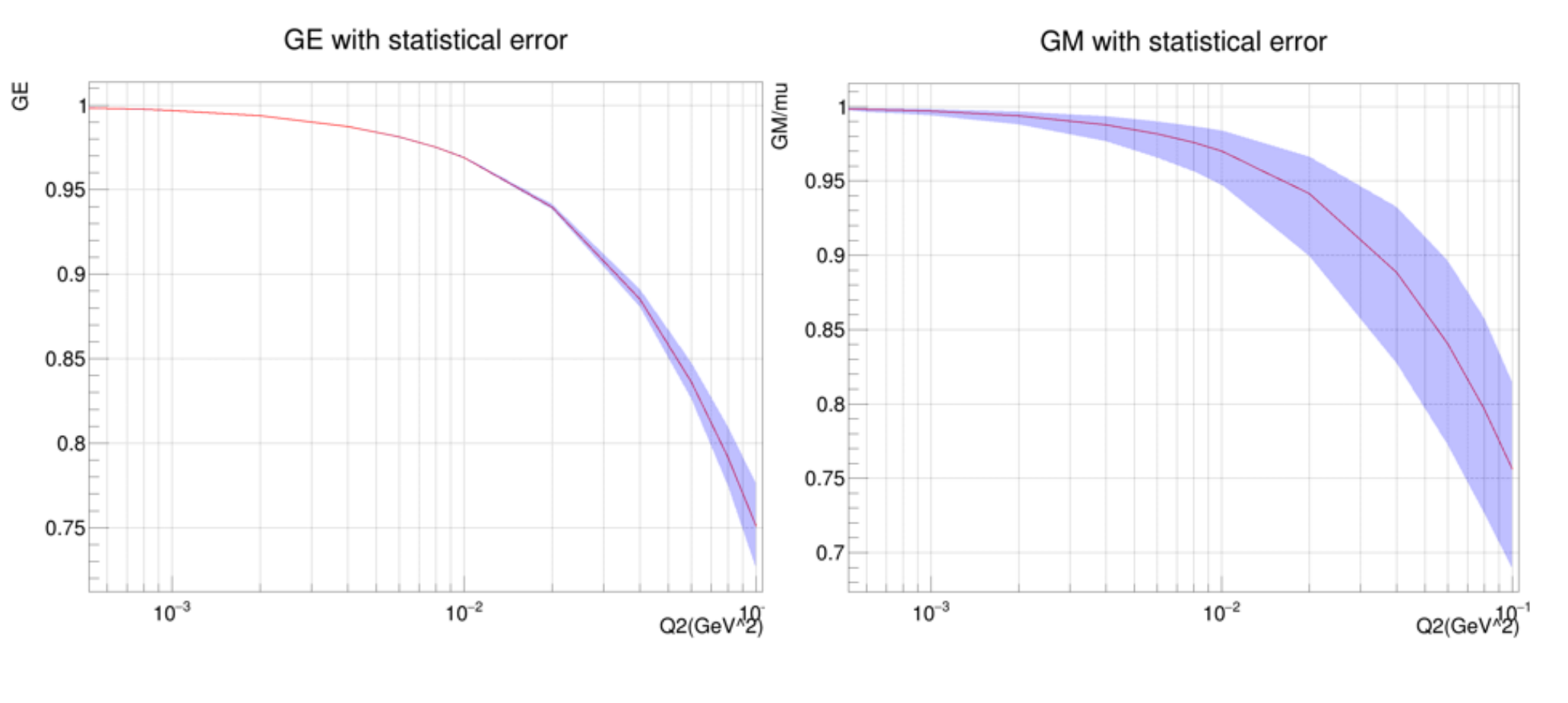
Quantity	Projected Coverage/Value
Beam Momentum	106, 170, 281 MeV/c
Scattering Angle	2 – 84 degrees
Q^2 Range for e	About 1e-4(1e-5) to 0.1114 $(GeV/c)^2$
Q^2 Range for μ	About 1e-4(1e-5) to 0.1098 $(GeV/c)^2$
Silicon Tracker Resolution	5 μm
GEM Resolution	70 μm
Time Detector Resolution	<= 30 ps
Beam Time(μ-p) (Luminosity$2.11\times10^{29}Hz\cdot\mathrm{cm}^{-2}$)	4 weeks
Statistical Precision	0.002 fm
Systematic Precision	Aim: no more than 0.01fm

Analysis and Simulation

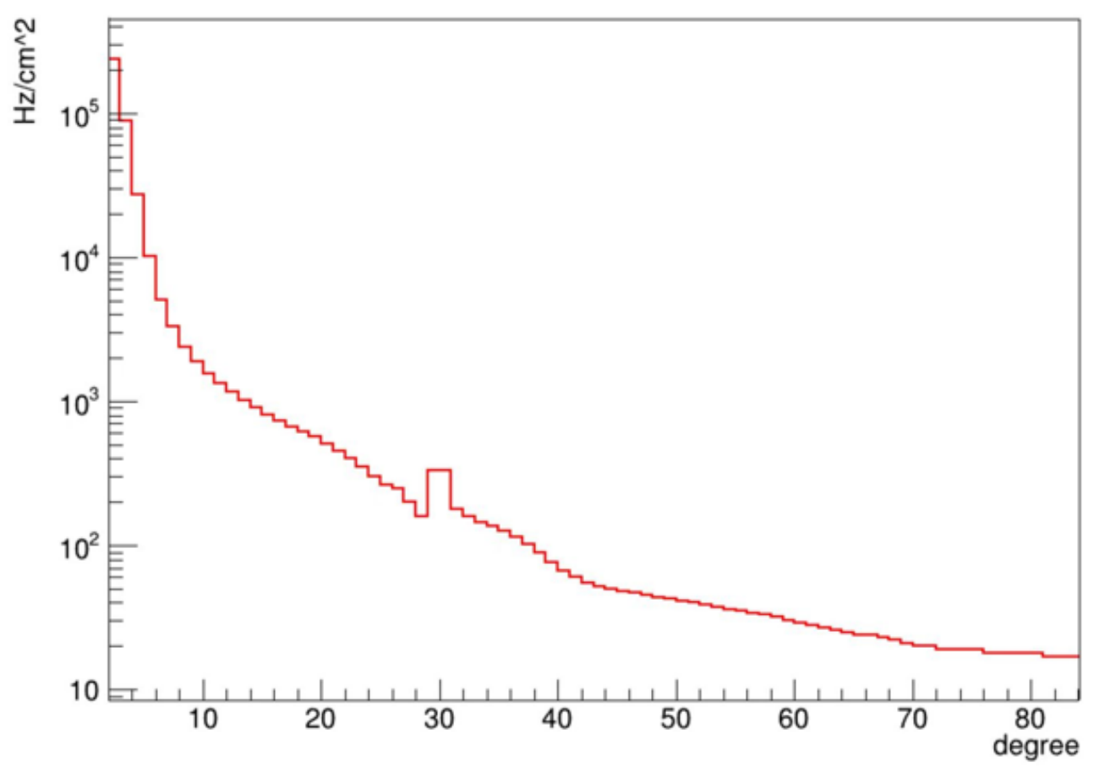
G4 Simulation for PID Using TOF at Different Beam Momentum



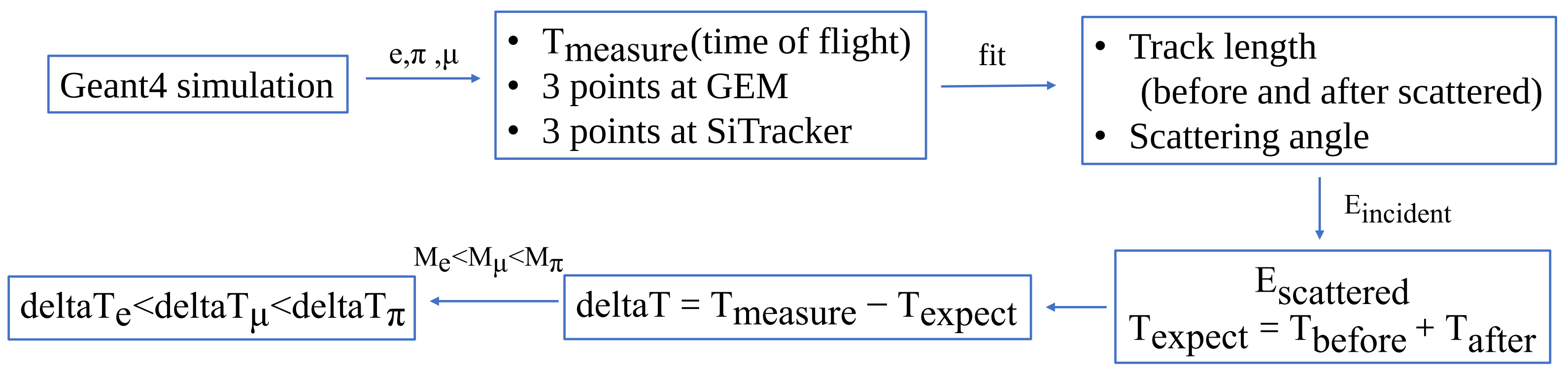
- TOF reso. ($30\sqrt{2}$ ps) sufficient for PID at low momenta in (a) and (b).
- But in (c), 3% π will be misidentified as μ. As π's cross section is bigger than μ, the ratio may too high.
- Improve TOF reso. (30 ps), reduce the momentum in (c), 0.2% π will be misidentified as μ in (d).



- Projected form factor value with 68.3% confidence intervals.
- Red line is the Kelly form factor value.



- GEM hit rate from Geant4 beam-on-target simulation. Assume beam flux: total 21MHz, e:μ:π=10:1:10.



Geant4 simulation

e,π ,μ

- $T_{measure}$(time of flight)
- 3 points at GEM
- 3 points at SiTracker

fit

- Track length (before and after scattered)
- Scattering angle

$E_{incident}$

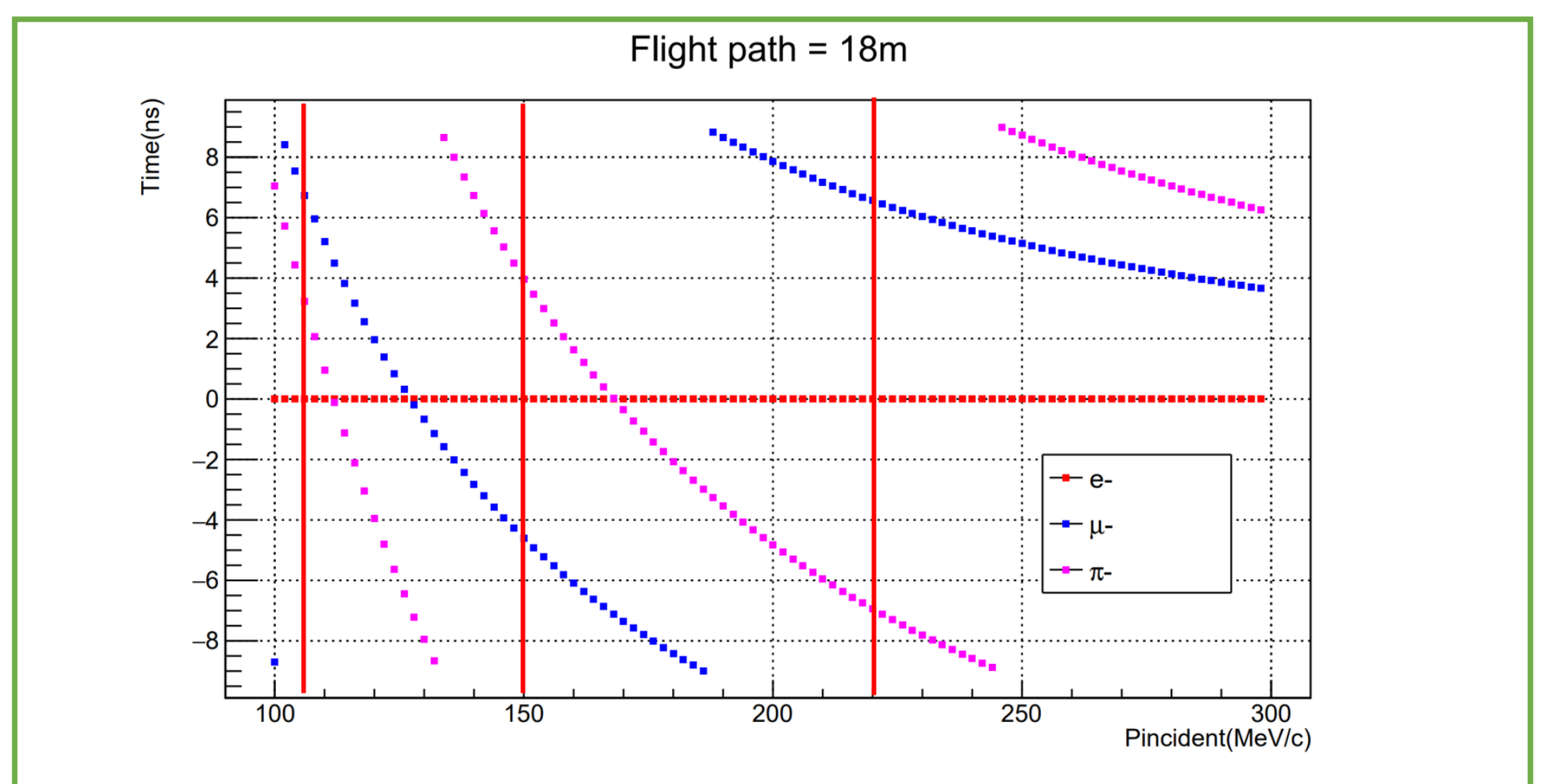
$E_{scattered}$
$T_{expect} = T_{before} + T_{after}$

deltaT = $T_{measure} - T_{expect}$

$M_e<M_\mu<M_\pi$

deltaT$_e$<deltaT$_\mu$<deltaT$_\pi$

- Method of particle identification(PID) using TOF.



- Beam PID method learning from MUSE.
- Beam particle's time distribution relative to accelerator RF signal.
- RF period at CiADS, shown here as -9 to 9 ns.
- Time difference of e, μ, π should bigger than 3 ns.

Future Work

- Other systematic errors need to study in detail.
- More realistic material and detectors in G4.
- Select and study more appropriate detector types.
- Explore lower Q^2 range.
- Work on e-e, μ-e elastic scattering measure.