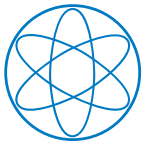
Future Measurement of the Proton Radius at the M2 beamline

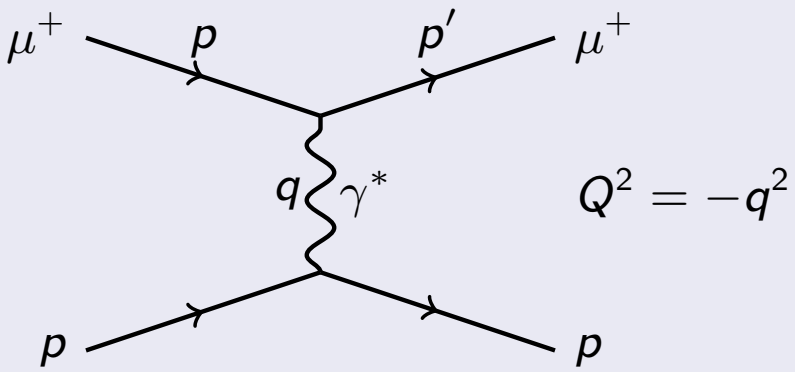
Sebastian Uhl

Physik Department E18
Technische Universität München



IWHSS 2018 Bonn
March 2018

scattering experiments



$$\frac{d\sigma}{dQ^2} = \frac{\pi\alpha^2}{Q^4 m_p^2 \vec{p}_\mu^{\,2}} \left[\left(G_E^2 + \tau G_M^2 \right) \frac{4E_\mu^2 m_p^2 - Q^2(s - m_\mu^2)}{1+\tau} - G_M^2 \frac{2m_\mu^2 Q^2 - Q^4}{2} \right]$$

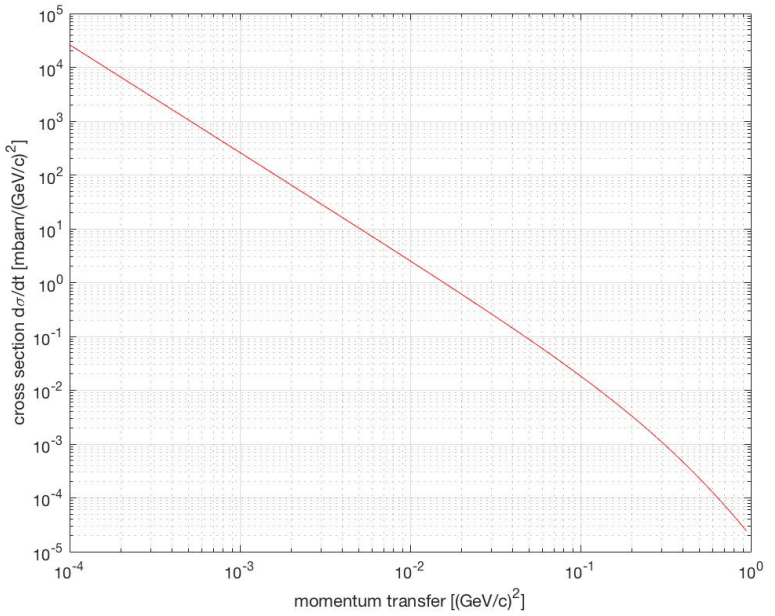
$$\text{with } \tau = Q^2/(4m_p^2)$$

mean squared charge-radius

$$\langle r_E^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

scattering experiments

$$G_E\left(Q^2\right) \approx G_M\left(Q^2\right)/\mu_p \approx$$
$$G_D\left(Q^2\right) = \left(1 + Q^2/a^2\right)^{-2}$$



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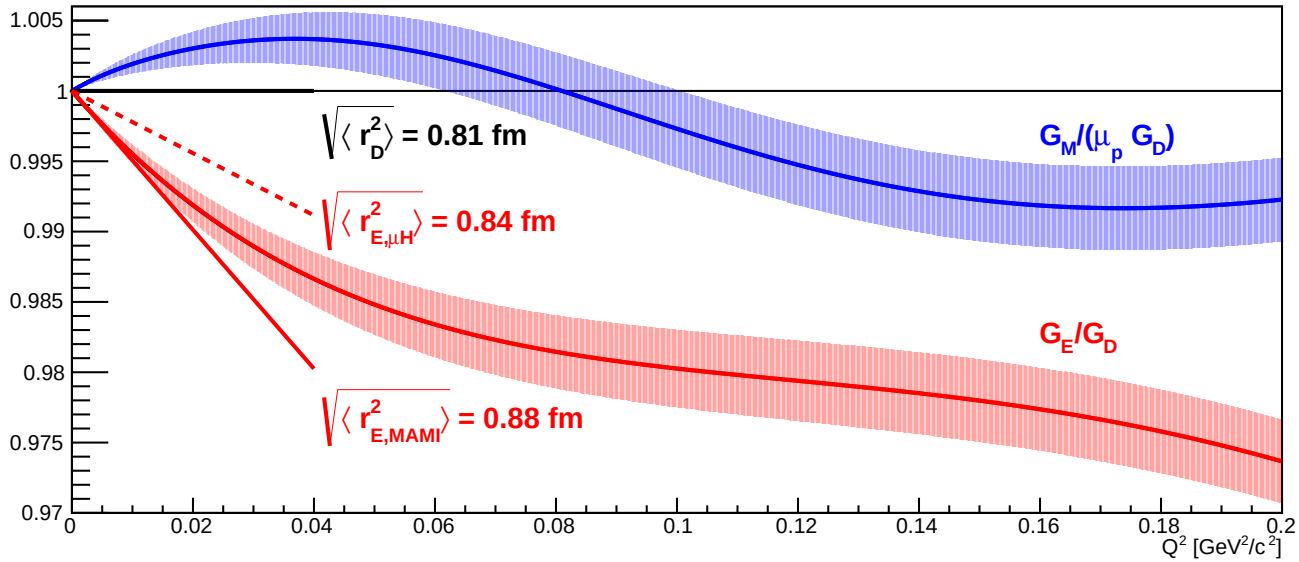
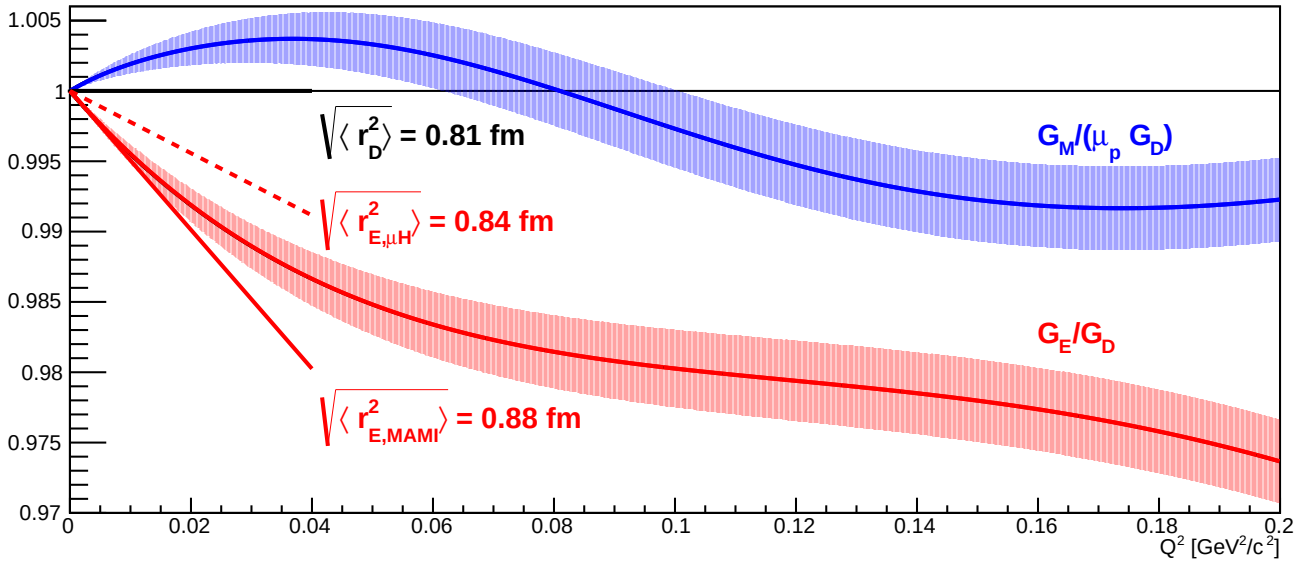
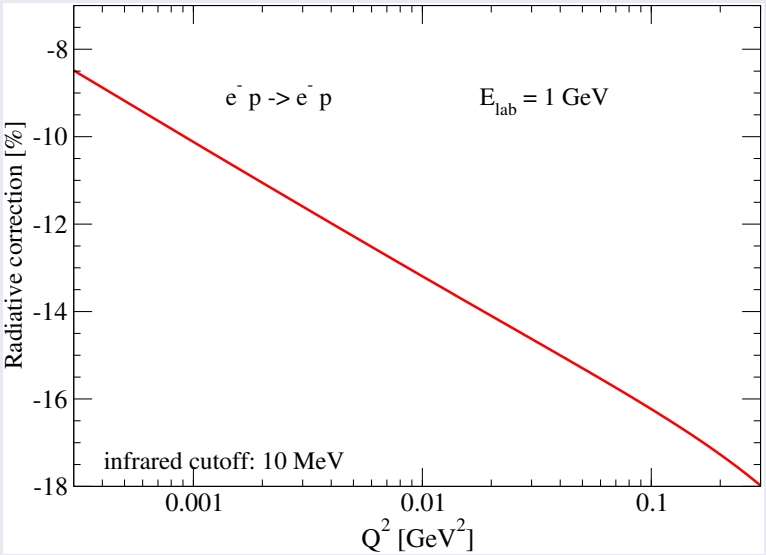

1.005
1
0.995
0.99
0.985
0.98
0.975
0.97
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Q^2 [GeV^2/c^2]
$\sqrt{\langle r_D^2 \rangle}$ = 0.81 fm
$\sqrt{\langle r_{E,\mu H}^2 \rangle}$ = 0.84 fm
$\sqrt{\langle r_{E,MAMI}^2 \rangle}$ = 0.88 fm
$G_M/(\mu_p G_D)$
G_E/G_D

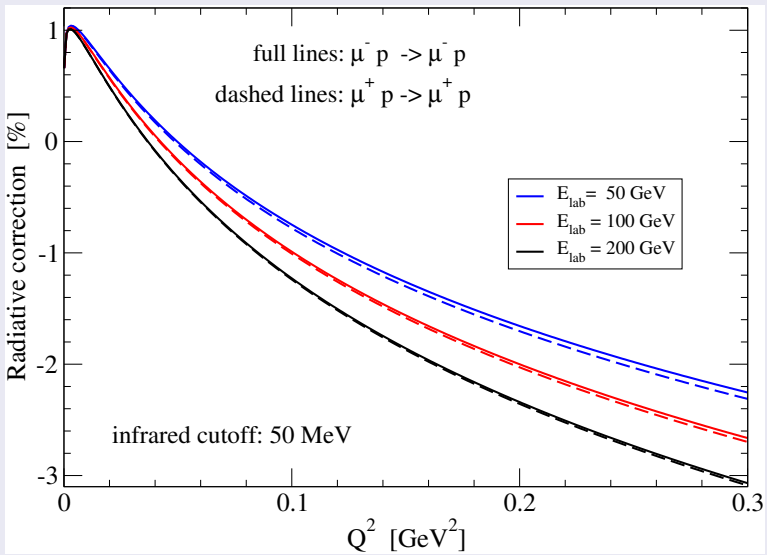


opportunity for new generation experiment at M2 beam line

- scatter muon beam off proton target
- measure cross-section dependence on Q^2
- obtain combination of electric and magnetic form factor $G_E^2 + \tau G_M^2$
  - form factors cannot be separated due to high beam energy

advantage of μ beam

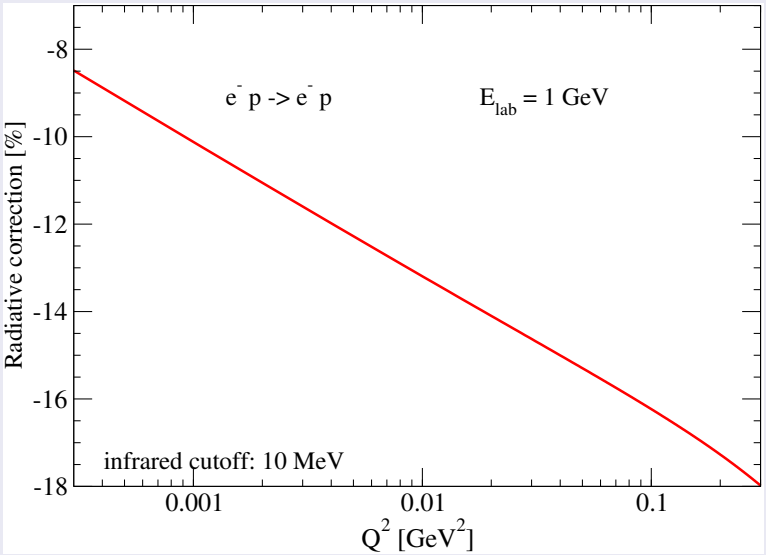


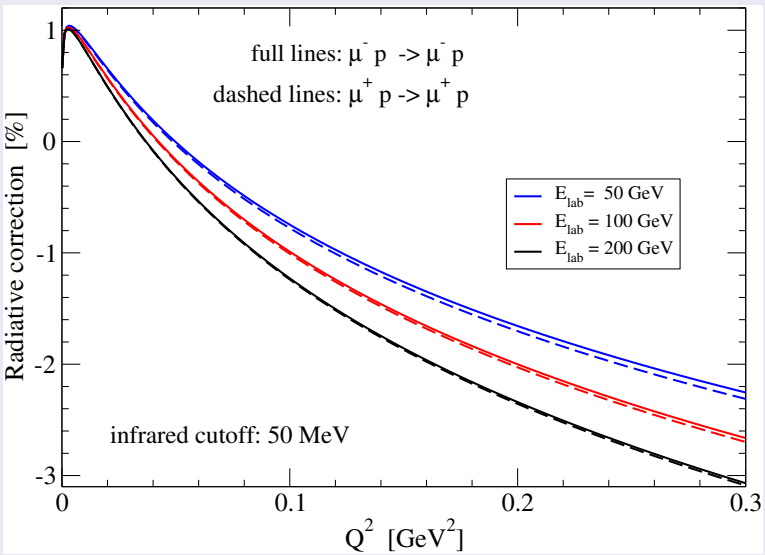


$$d\sigma = d\sigma_{1\gamma}\,(1+\delta)$$

- compared to e^- beam: smaller radiative corrections for μ beam

advantage of μ beam





$$d\sigma = d\sigma_{1\gamma}\,(1+\delta)$$

- compared to e^- beam: smaller radiative corrections for μ beam
- measuring recoil proton will integrate over radiative tails
- uncertainty on remaining corrections
- will not reduce impact on overall cross-section measurement

advantage of high-energy μ beam

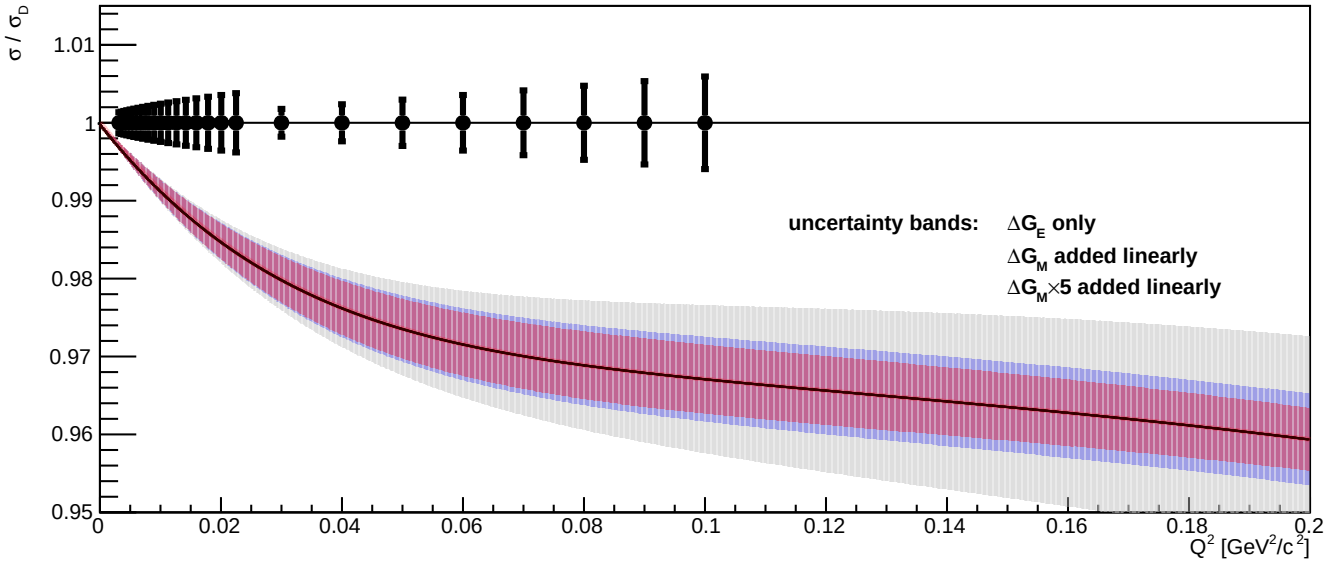
Coulomb corrections

- required corrections depend on scattering angle

$$\delta = Z\alpha\pi \frac{\sin\frac{\theta}{2} - \sin^2\frac{\theta}{2}}{\cos^2\frac{\theta}{2}}$$

- smaller scattering angle at higher energies

compared to μ beam at low energies: smaller corrections



requirements for measurement

assuming one year of data taking

- goal: uncertainty on $\sqrt{\langle r_E^2 \rangle} \approx 0.01\,\text{fm}$
- systematics: $Q^2 \gtrapprox 1 \cdot 10^{-3}\ (\text{GeV}/c)^2$
- uncertainty on G_M: $Q^2 \lessapprox 0.2\ (\text{GeV}/c)^2$

experimental challanges

identify elastic reactions

- measurement of recoil proton
- measurement of scattering angle of muon

measurement of recoil proton

- high-pressure hydrogen target
- wide range of recoil energies $\mathcal{O}\,(100\,\mathrm{keV})$ to $\mathcal{O}\,(100\,\mathrm{MeV})$
- required energy resolution $\mathcal{O}\,(50\,\mathrm{keV})$

measurement of recoil proton

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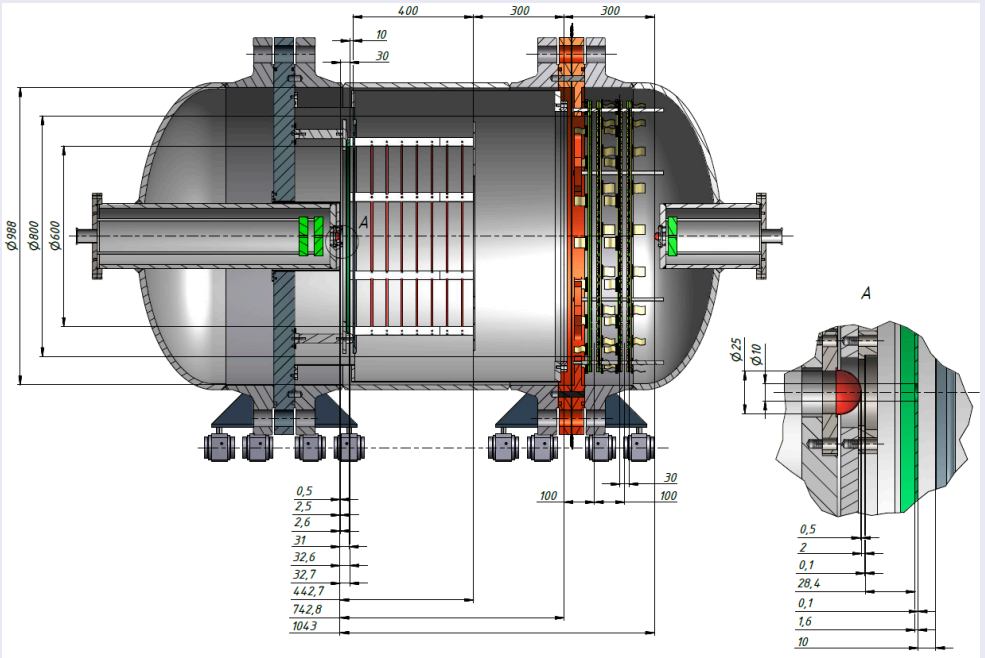
TPC as active target



- high luminosity requires long target
  - long drift time might be an issue
- not all protons might be stopped inside TPC

measurement of scattering angle of muon

position detectors

- small scattering angles $\mathcal{O}(100\,\mu\text{rad})$
  - excellent spatial resolution required
- high intensity
  - fast detectors

measurement of scattering angle of muon

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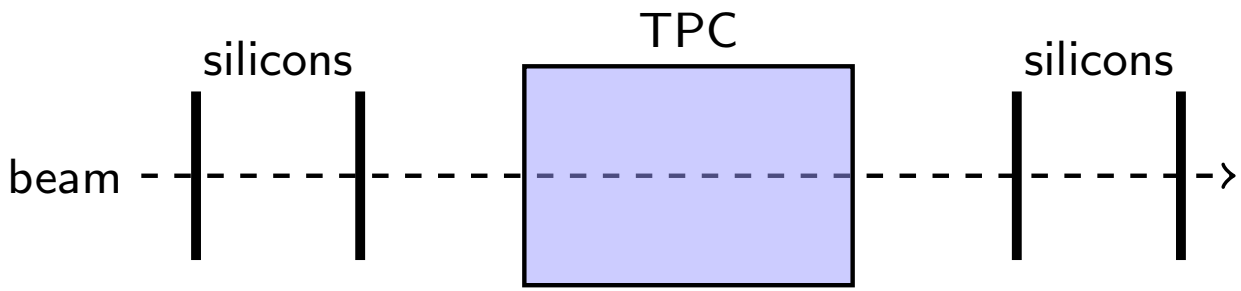
silicon tracking detectors

- strip
  - for current silicon detectors required performance has been shown
- pixel



proposed set-up

- hydrogen TPC acting as active target
  - measurement of energy of recoil proton
  - between 0.5 and 100 MeV
  - required resolution: $\Delta \approx 60\,\mathrm{keV}$
- silicon telescopes up- and downstream of target
  - measurement of muon scattering angles
  - 300 μrad at $Q^2 \approx 10^{-3}\ (\mathrm{GeV}/c)^2$
  - required resolution $\sigma \lessapprox 100\,\mu\mathrm{rad}$

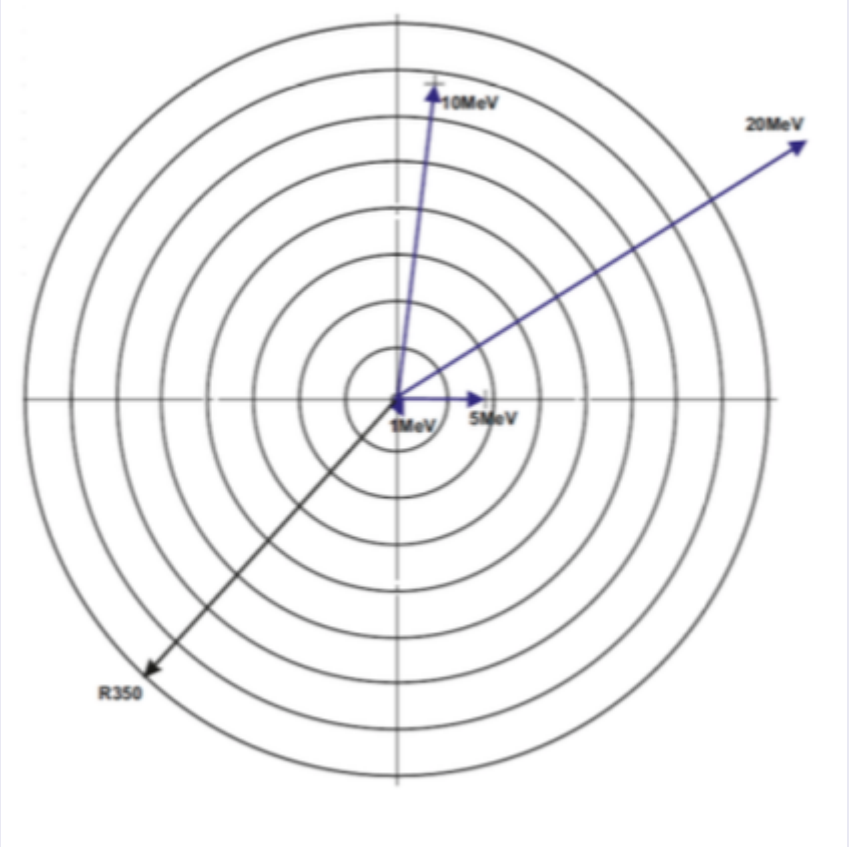
combination of TPC and silicon detectors

- in simulation: required resolution achieved down to small Q^2

combination of TPC and silicon detectors

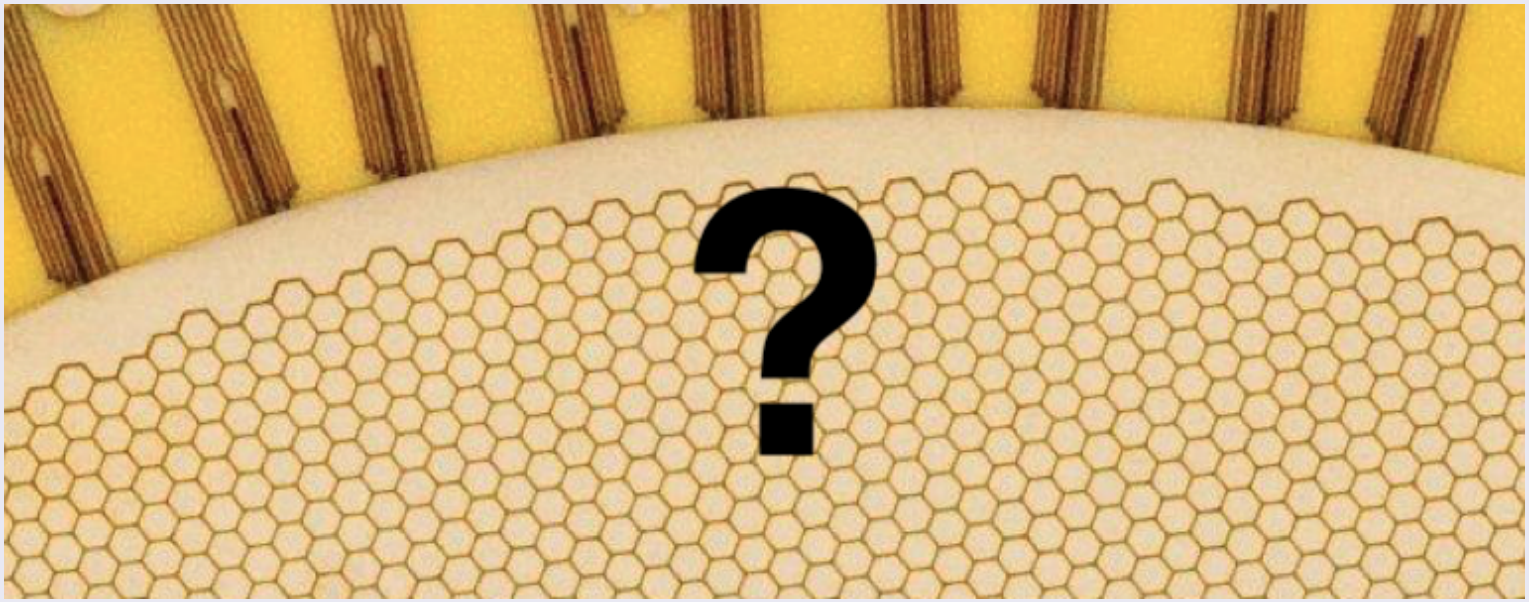
- in simulation: required resolution achieved down to small Q^2
- test beam this year

test beam set-up



- performance of TPC in muon beam

test beam set-up



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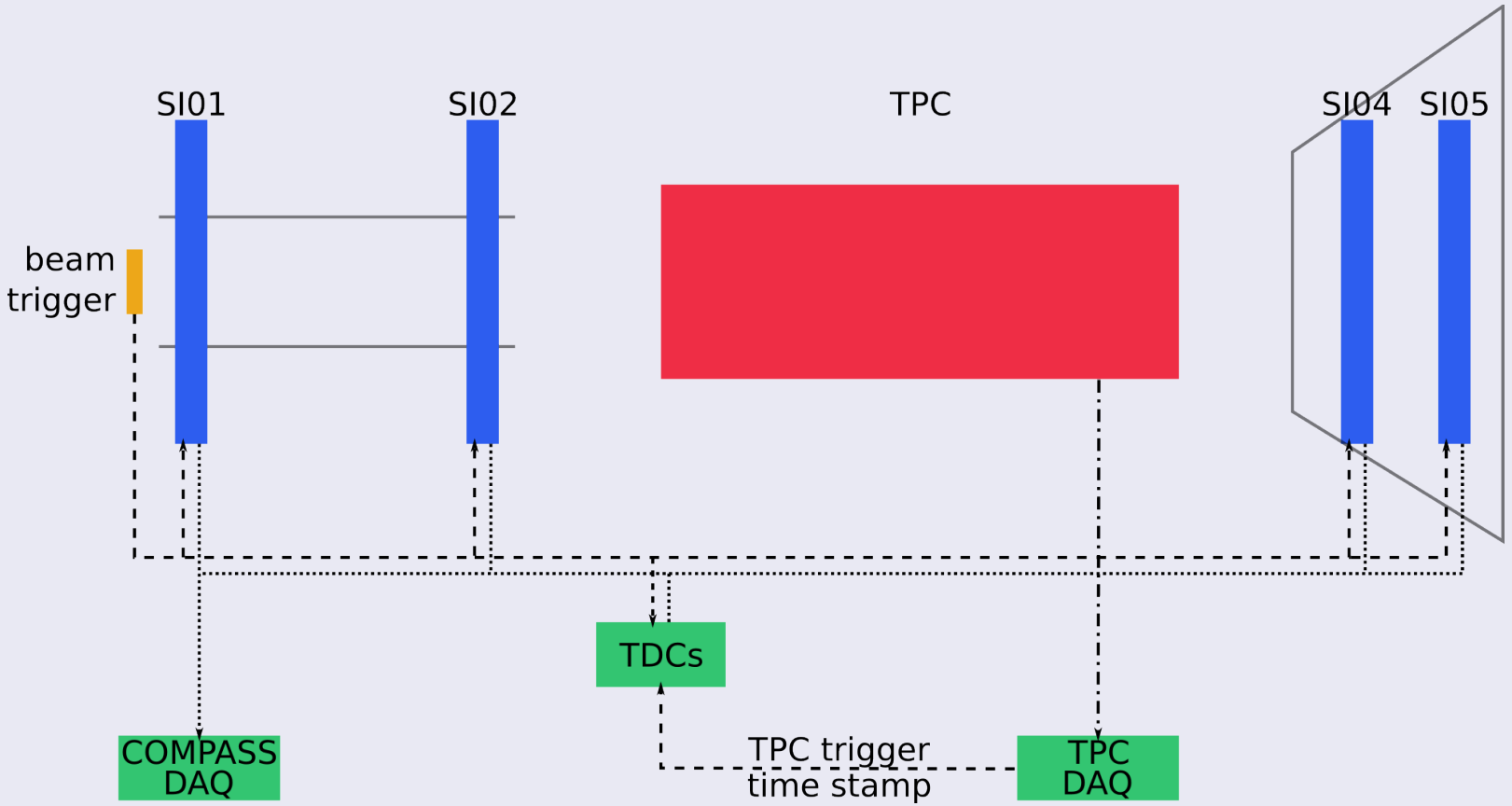
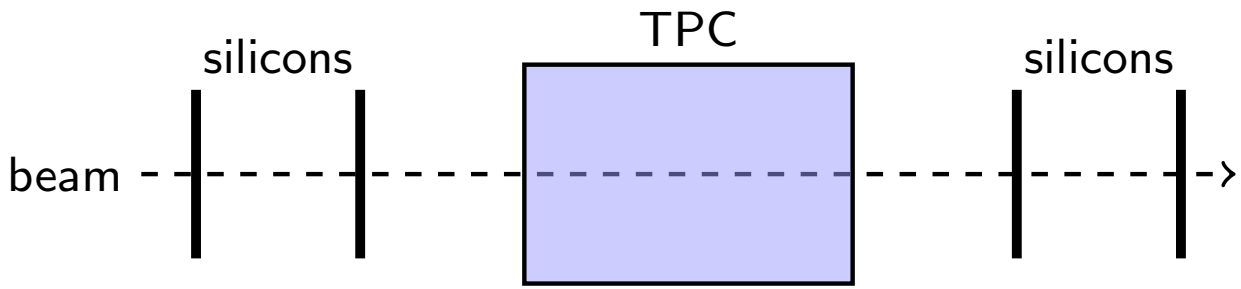
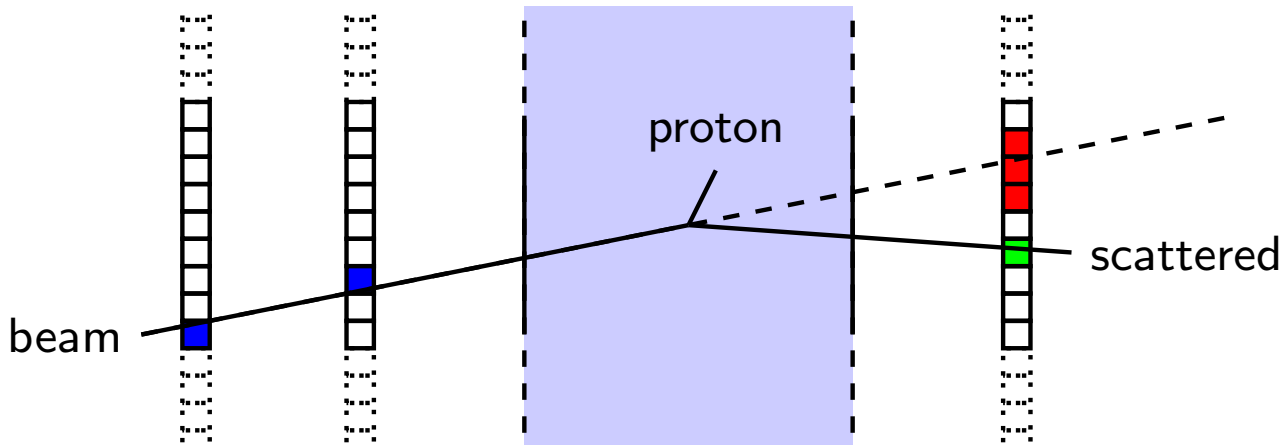


- performance of TPC in muon beam
- correlate events in silicon detectors with events in TPC



proposed set-up

- trigger on recoil proton signal
  - drift time in TPC $\mathcal{O}(100\,\mu\text{s})$
  - trigger-less readout of all detectors
  - online event reconstruction to correlate proton and muon signals

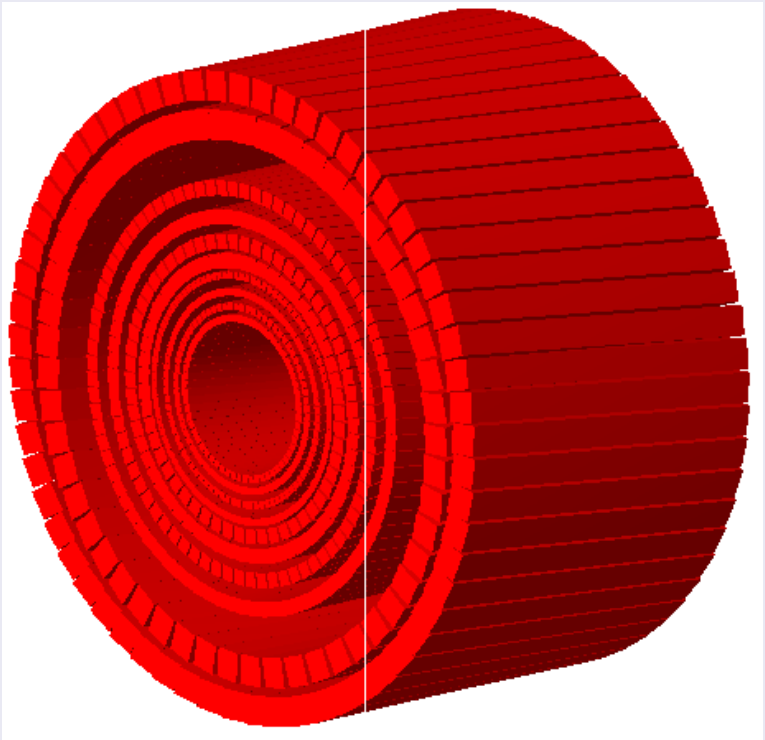


proposed set-up

- trigger on recoil proton signal
  - drift time in TPC $\mathcal{O}(100\,\mu\text{s})$
  - trigger-less readout of all detectors
  - online event reconstruction to correlate proton and muon signals
- trigger on small kink in muon track

higher Q^2

- recoil protons not stopped inside hydrogen volume
- replace hydrogen TPC by hydrogen volume surrounded by scintillator barrel



- stop protons in layers
- measure energy via Bragg peak
- faster trigger decision

- measurement of proton charge-radius with high-energy muon beam
  - unique opportunity to verify results from electron scattering
  - smaller corrections required
- first test measurement this year
  - compatibility of TPC with “broad” muon beam
  - correlation of proton and muon signals