Proton Radius with COMPASS++/AMBER

Proposed precision measurement
of elastic μp scattering at high energy and low Q^2
at the CERN M2 beamline

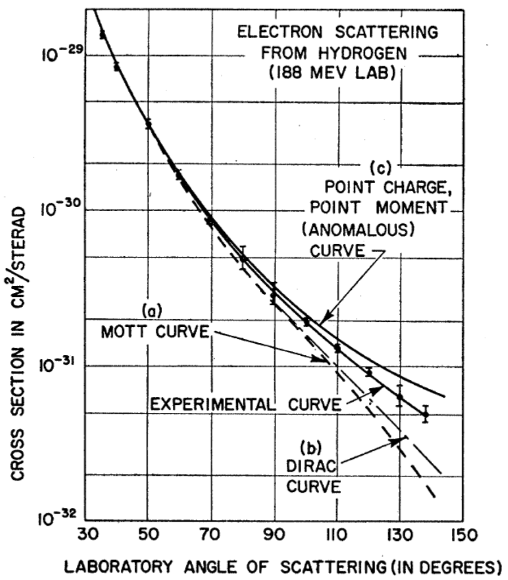
Jan Friedrich

5 February 2020
Mainz, remotely

TPC workshop Mainz

Measurement of the Proton Radius in *ep*-Scattering

1956: $r_p \approx 0.8$ fm



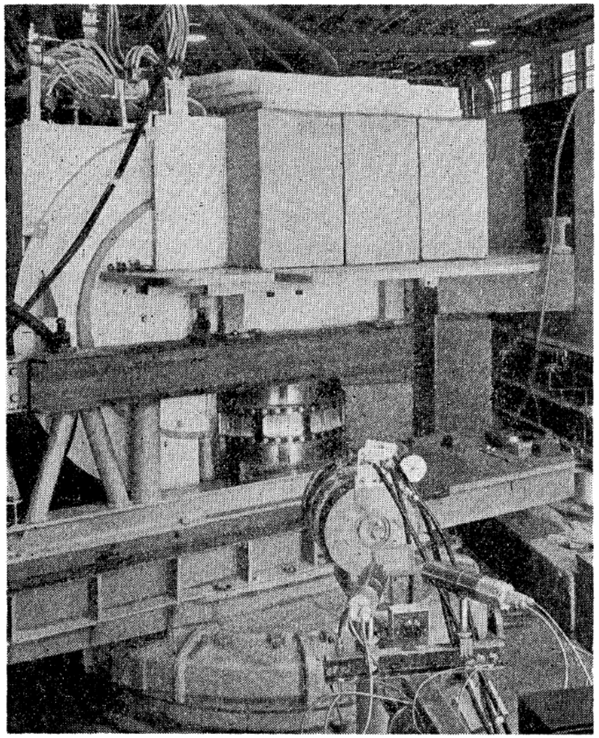


FIG. 15. The semicircular 190-Mev spectrometer, to the left, is shown on the gun mount. The upper platform carries the lead and paraffin shielding that encloses the Čerenkov counter. The brass scattring chamber is shown below with the thin window encircling it. Ion chamber monitors appear in the foreground.

If qa is small, where a is the root-mean-square radius, all form factors reduce to the simple expansion

$$F = 1 - (q^2a^2/6) + \cdots. \quad (19)$$

REVIEWS OF MODERN PHYSICS VOLUME 28, NUMBER 3 JULY, 1956

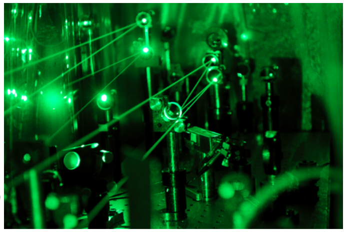
Electron Scattering and Nuclear Structure*

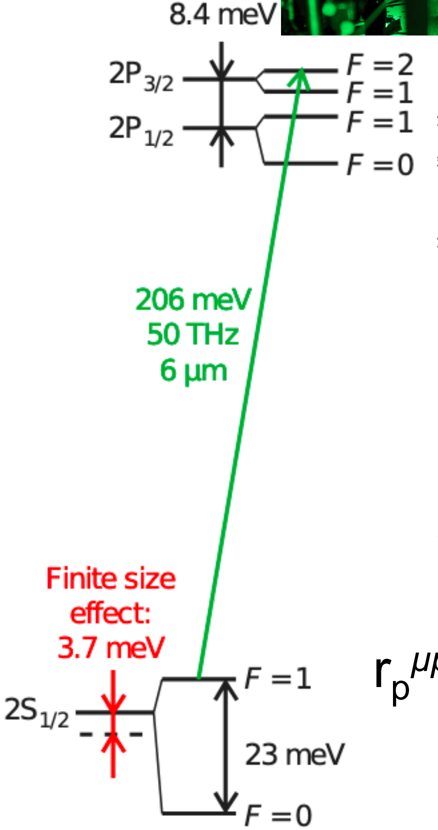
ROBERT HOFSTADTER
Department of Physics, Stanford University, Stanford, California

The low background has been achieved with the spectrometer, detector, and shield now to be described. A photograph of the apparatus is given in Fig. 15. It

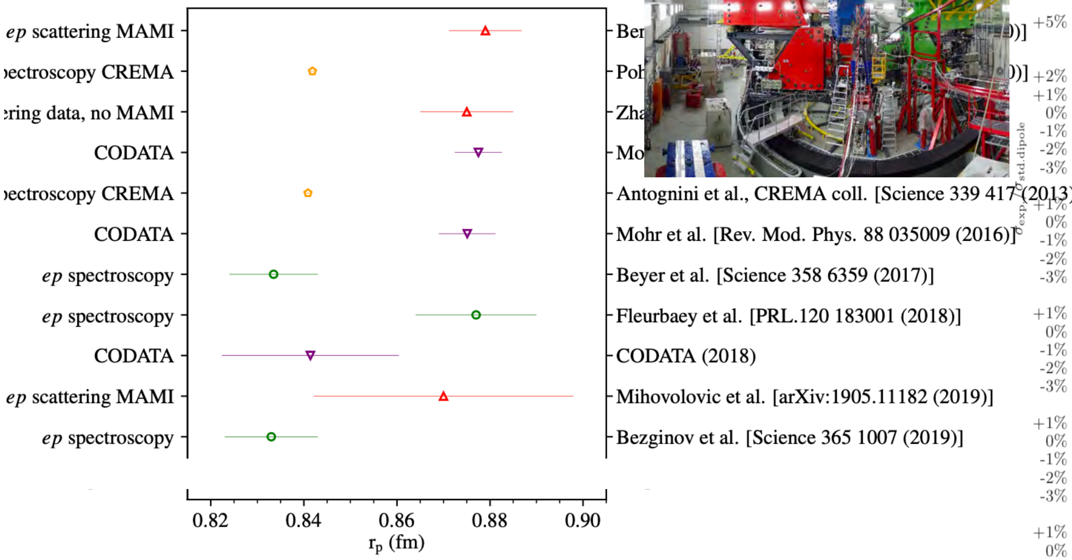
Measurement of the Proton Radius in *ep*-Scattering

CREMA 2010

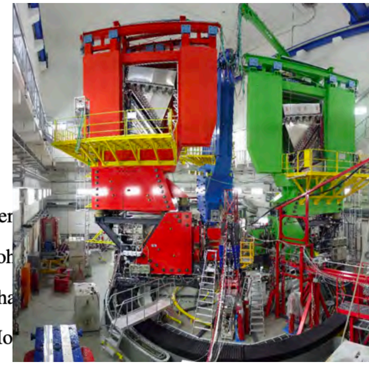


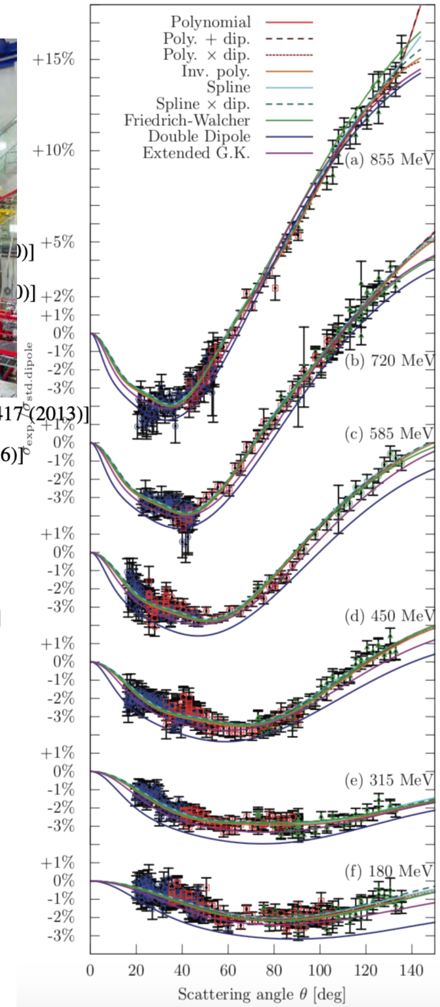


status October 13, 2019



MAMI 2010





$r_p^{\mu p\ Lamb} \approx 0.84$ fm

$r_p^{elastic\ ep} \approx 0.88$ fm

what to add?
how clarify what the true proton radius is and where the difference comes from?

Planned, ongoing, recent scattering experiments of the proton form factor

The discrepancy between the results – the proton radius puzzle - triggered many new proposals and experiments:

- ***e⁻*** scattering radiative: ISR electron scattering at MAGIX-MESA
- ***e⁻*** scattering at medium *E* with active-target TPC at MAMI
- ***e⁻*** scattering at higher *E*: PRad at Jefferson Lab

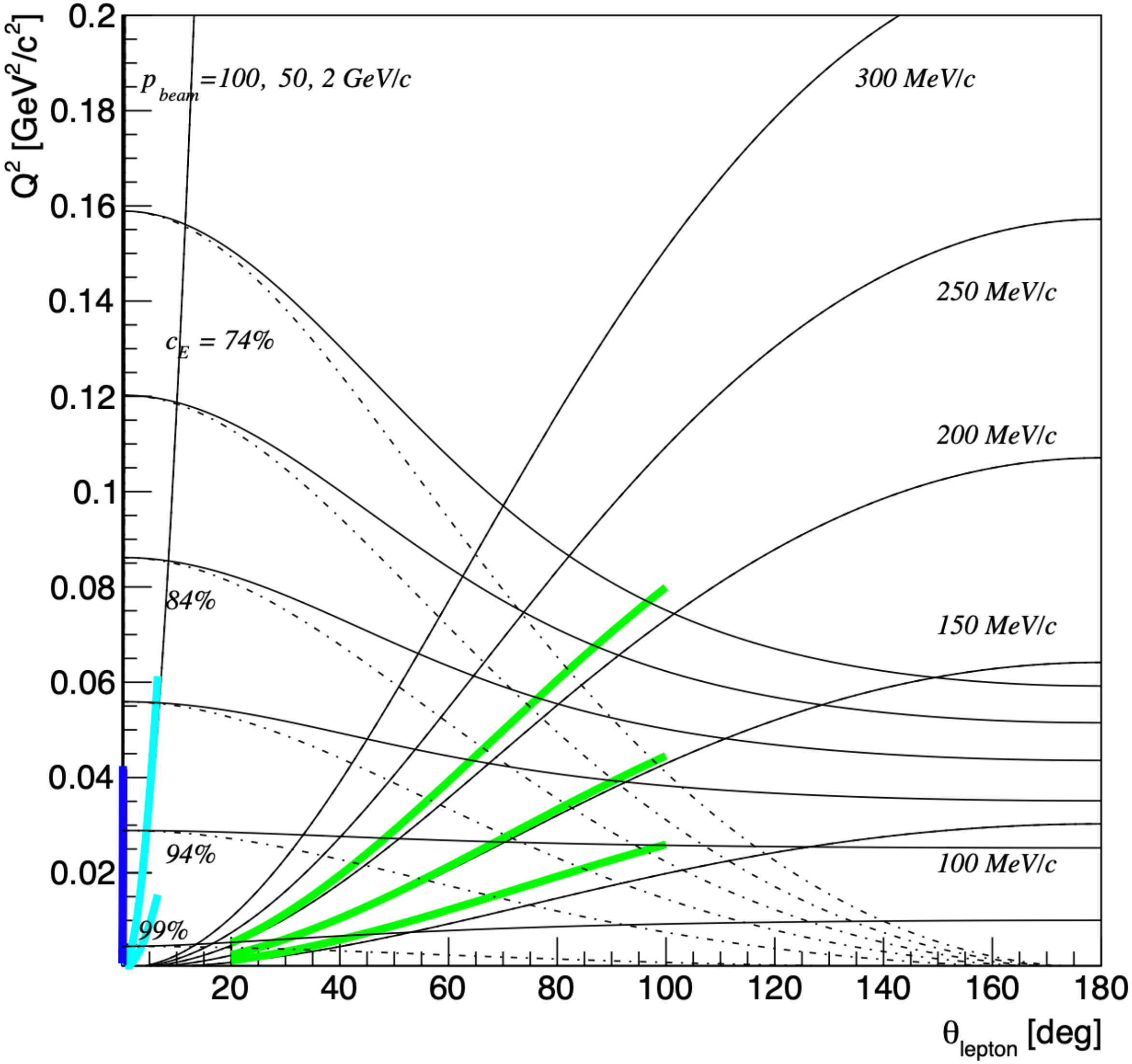
- $\mu^{+/-}$, $e^{+/-}$ scattering at low energy: MUSE / PSI

our Proposal:
CERN-SPSC-2019-022; SPSC-P-360; nqf-m2.web.cern.ch

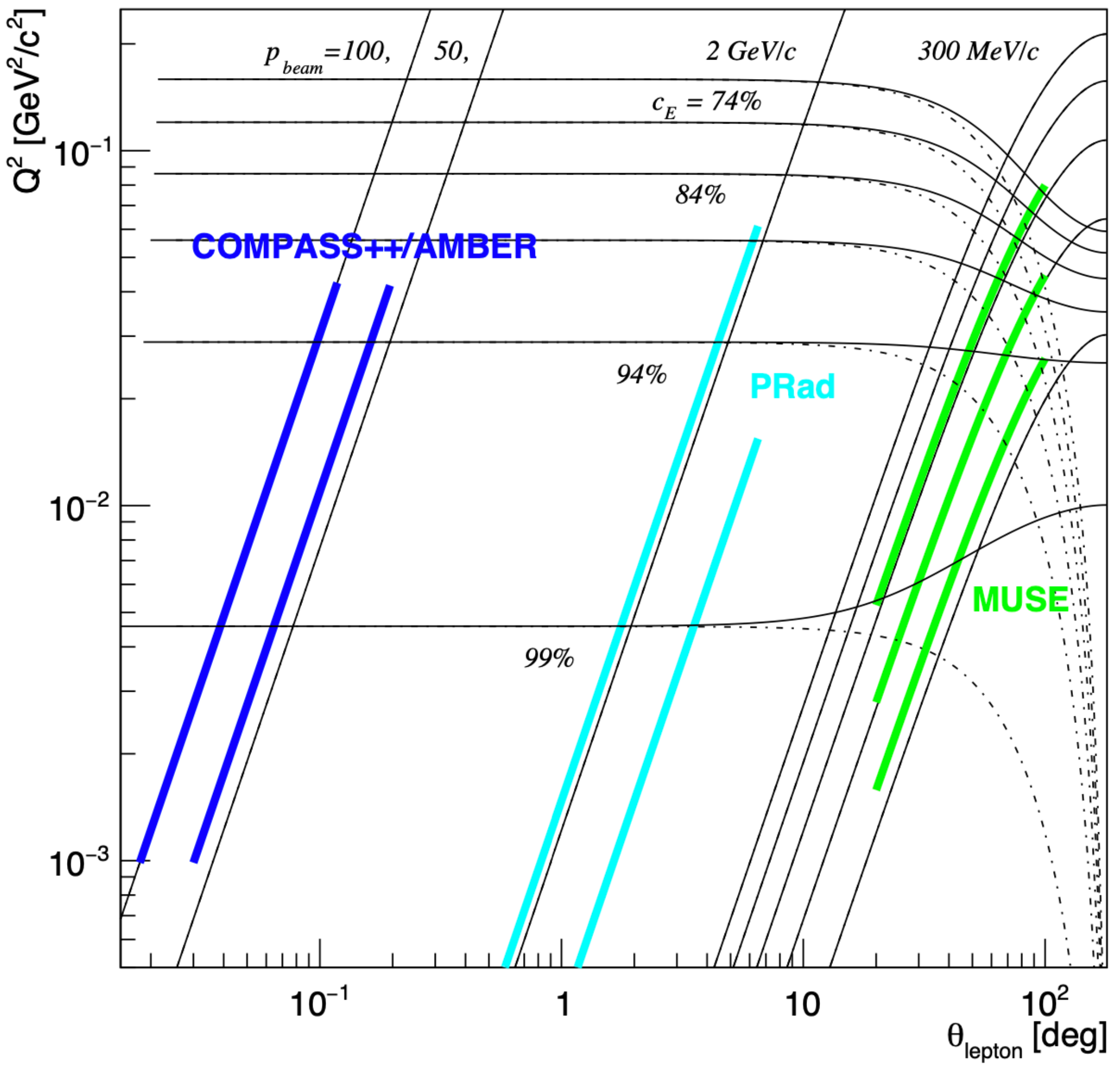
- $\mu^{+/-}$ at high *E* at CERN (COMPASS++/AMBER)

different, in several ways favorable systematics

Kinematic ranges

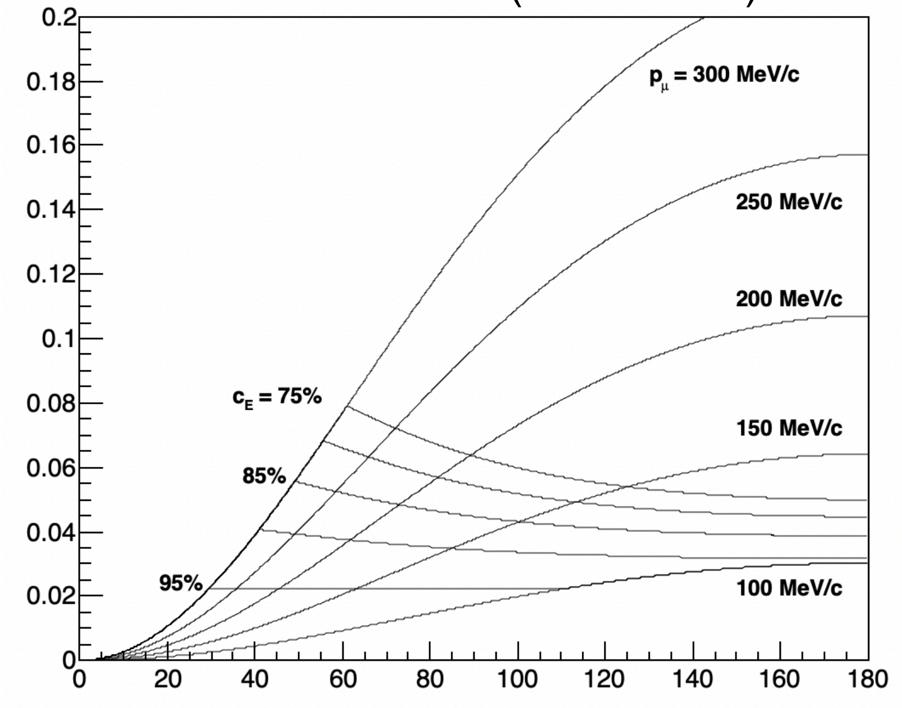


Kinematic ranges



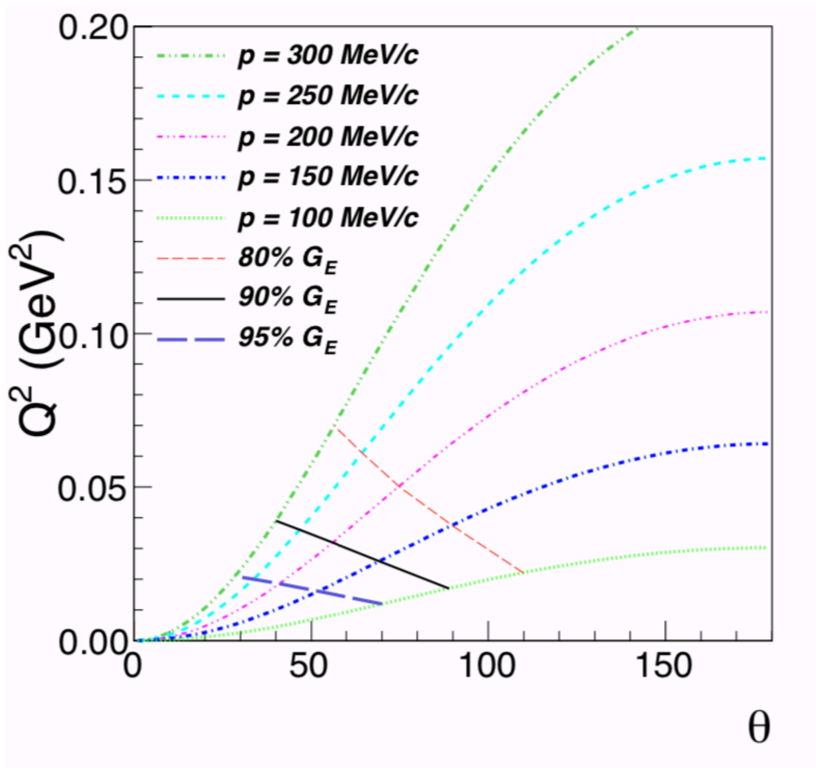
MUSE – kinematics of low-energy elastic muon scattering

our calculation (muon mass)

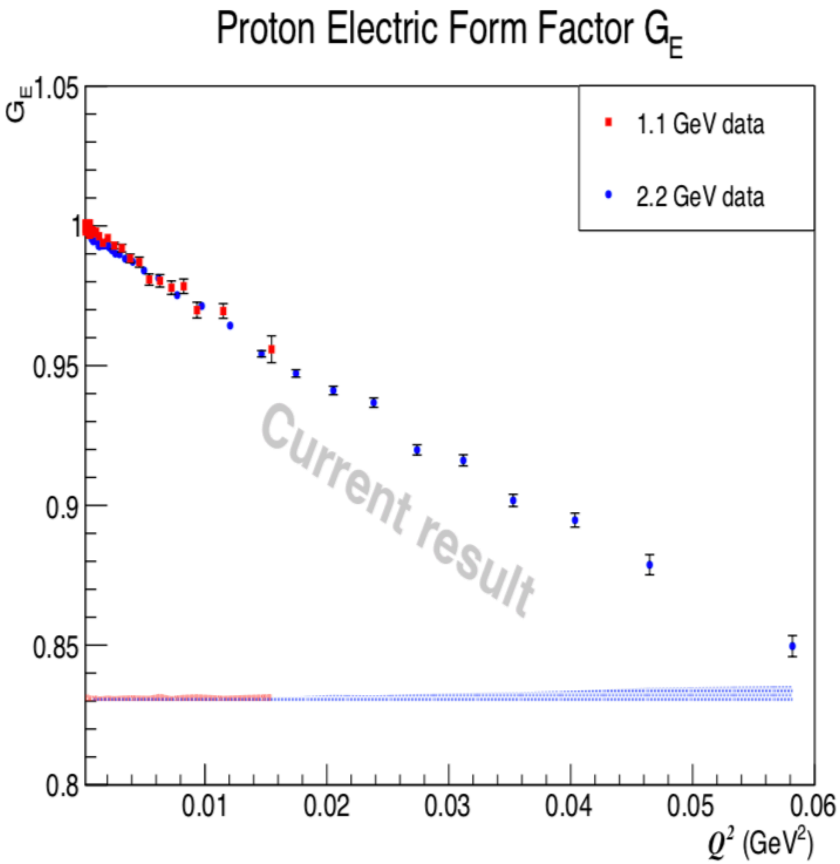


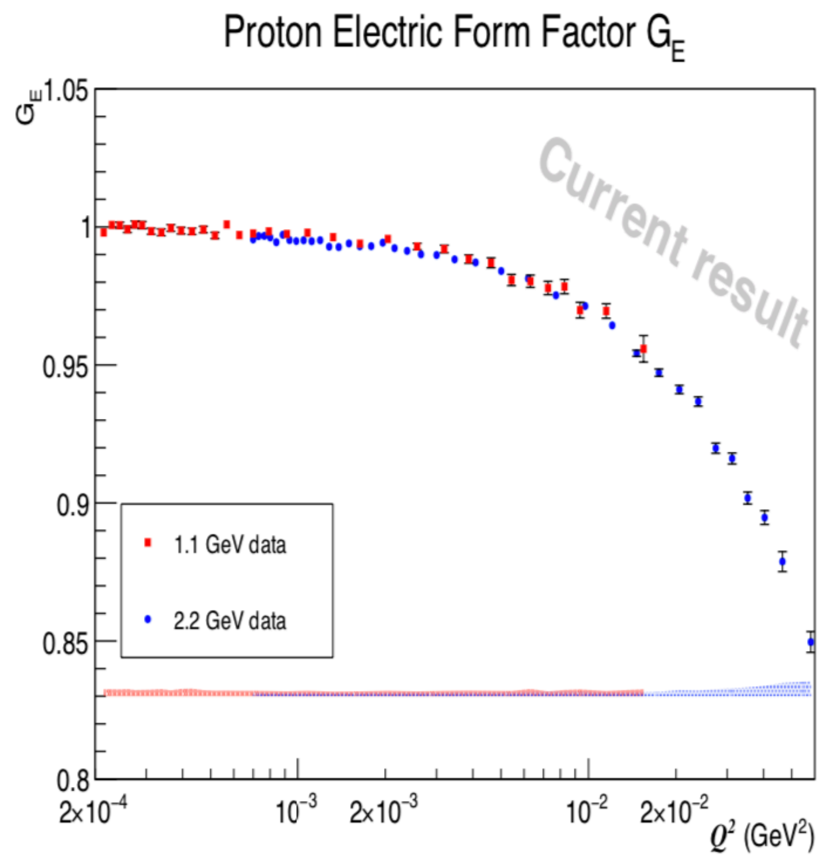
A Proposal for the Paul Scherrer Institute πM1 beam line

Studying the Proton "Radius" Puzzle with μp Elastic Scattering



PRad





Lowest Q^2 ever achieved from ep elastic scattering

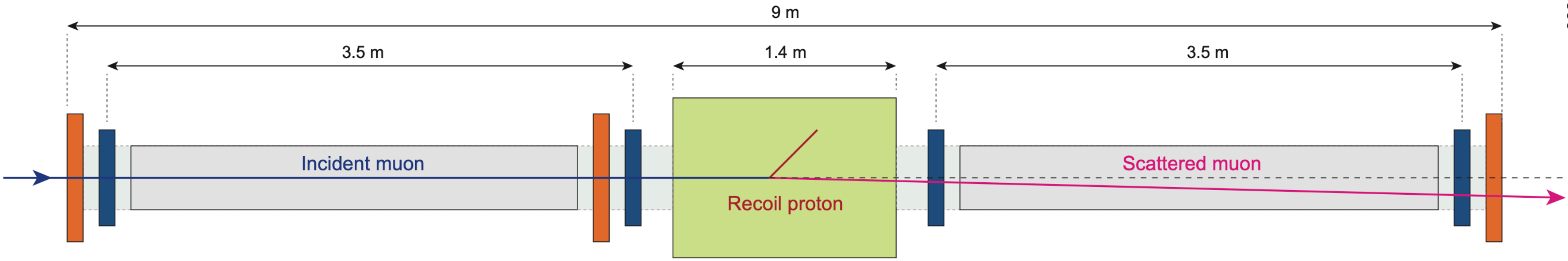
from: H. Gao, ICSAC2019, Losinj, Croatia

CERN-SPSC-2019-022; SPSC-P-360

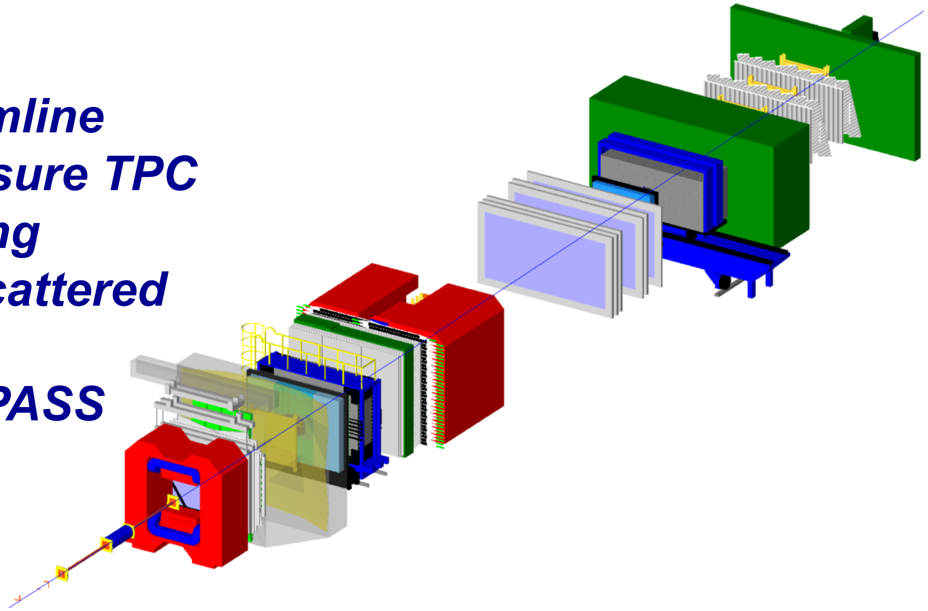
Proposal for Measurements at the M2 beam line of the CERN SPS

– Phase-1 –

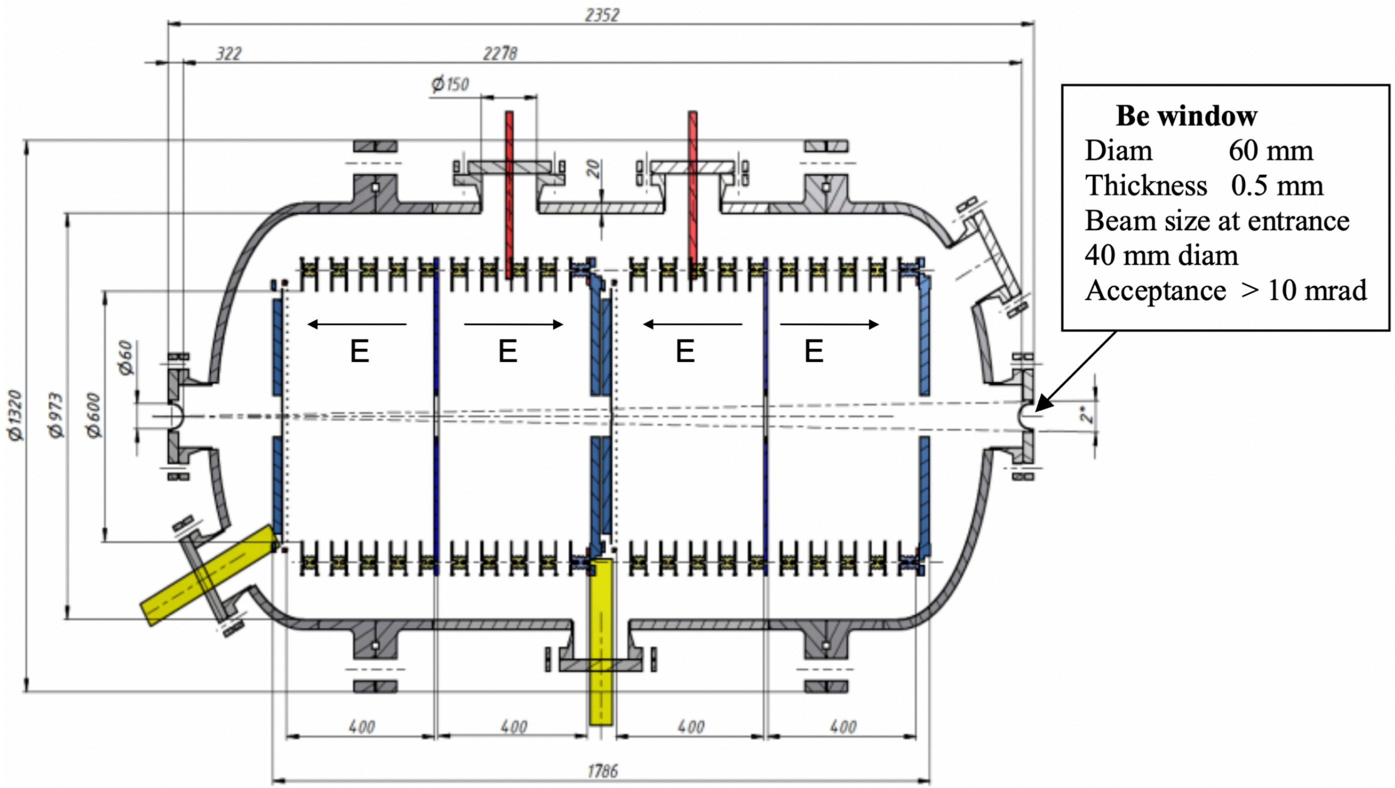
COMPASS++*/AMBER†



- ***100 GeV muons of the CERN M2 beamline***
- ***Protons in an active-target high-pressure TPC***
- ***Silicon detectors for precision tracking***
- ***200μm SciFi stations for trigger on scattered muons***
- ***inner tracking and ECAL of the COMPASS spectrometer***

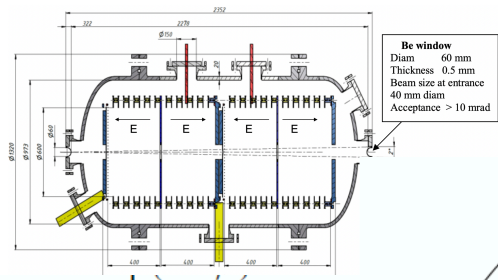


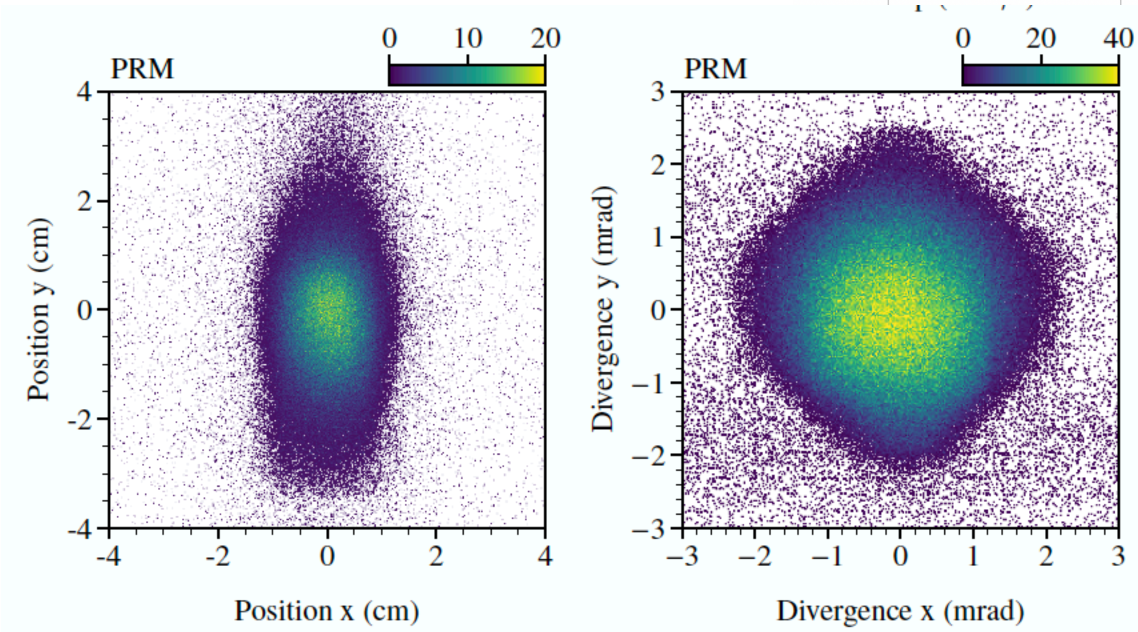
Active target: high-pressure TPC

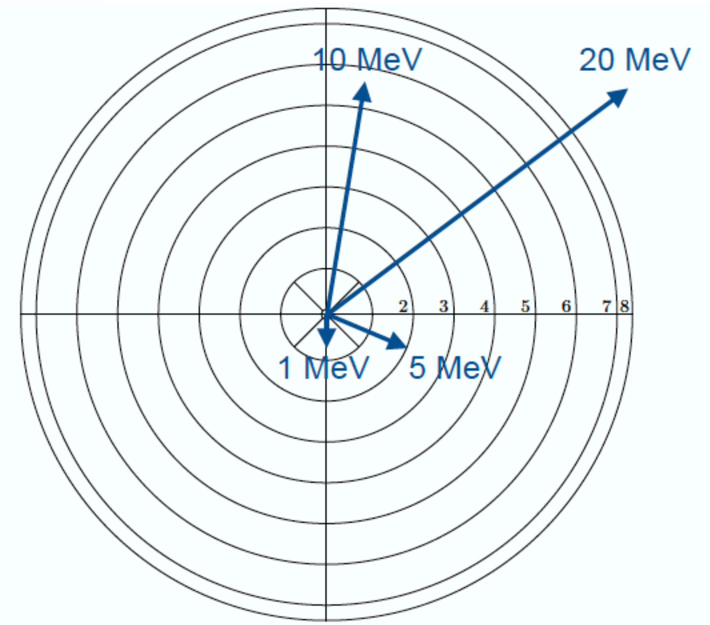


- up to 20 bar pressure
- 600mm diameter of active volume, 4-fold segmentation
- reconstruction of recoil energy 0.5-20 MeV (10^{-3}…$4x10^{-2}$ GeV^2)

High-pressure TPC readout structure

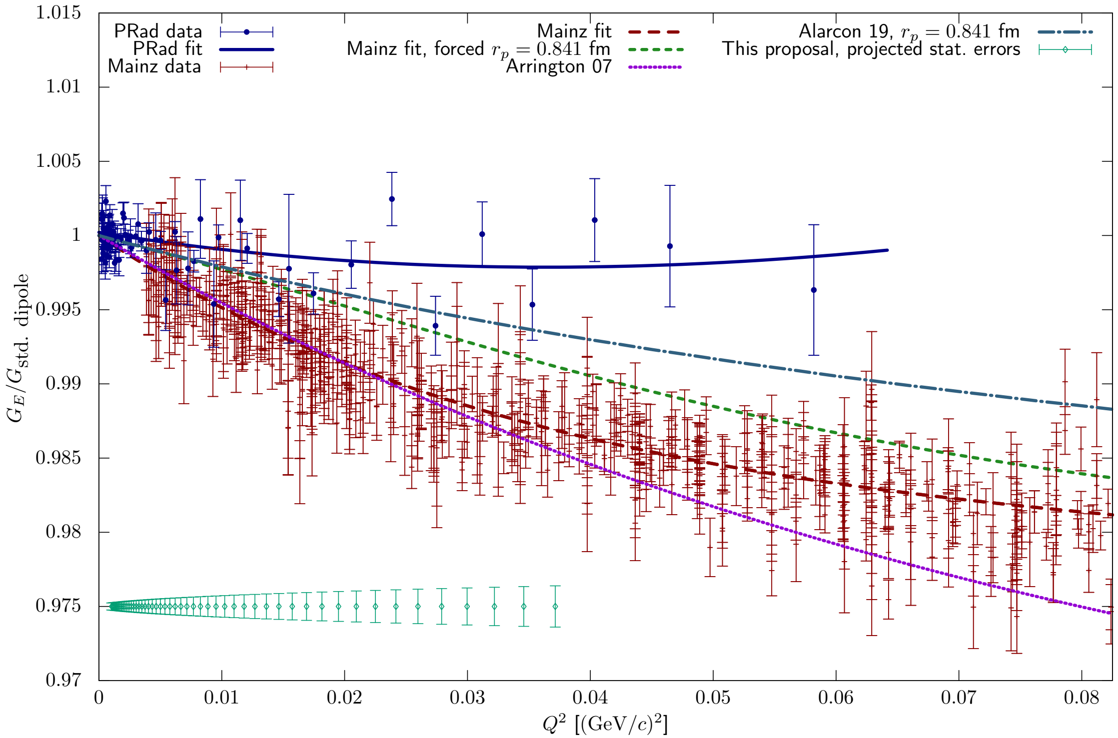






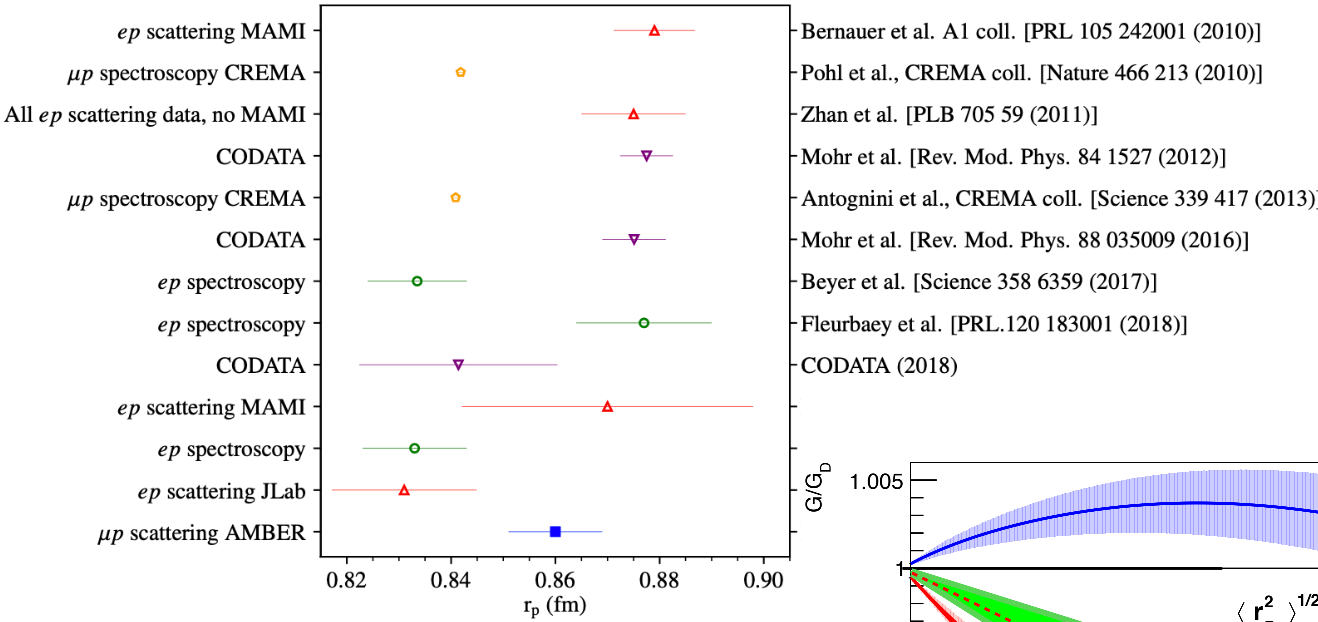
- muon beam characteristics at M2 beamline
- fine segmentation of TPC readout in the beam spot region can be of use to disambiguate the correlation with the beam muon
- flux $2 \cdot 10^6$ /s (increased intensity would be possible if TPC allows)

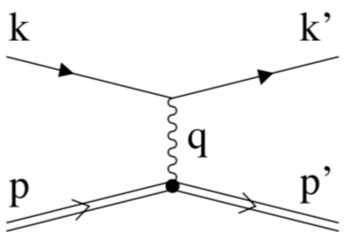
Proposed running 2022



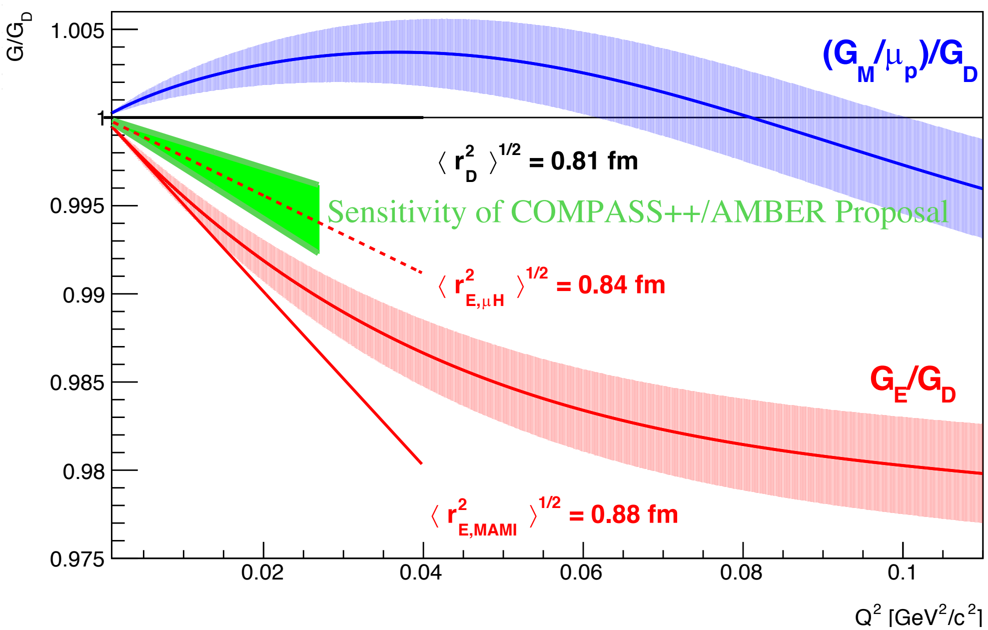
- program for 200 days of beam
- precision on the proton radius < 0.01 fm

Precision in the context of the puzzle





G_E, G_M



Charge radius: definition and model dependence

Determination of the rms radius from a form factor measurement

- the rms radius of a charge distribution seen in lepton scattering is *defined* as the slope of the electric form factor at vanishing momentum transfer Q^2

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

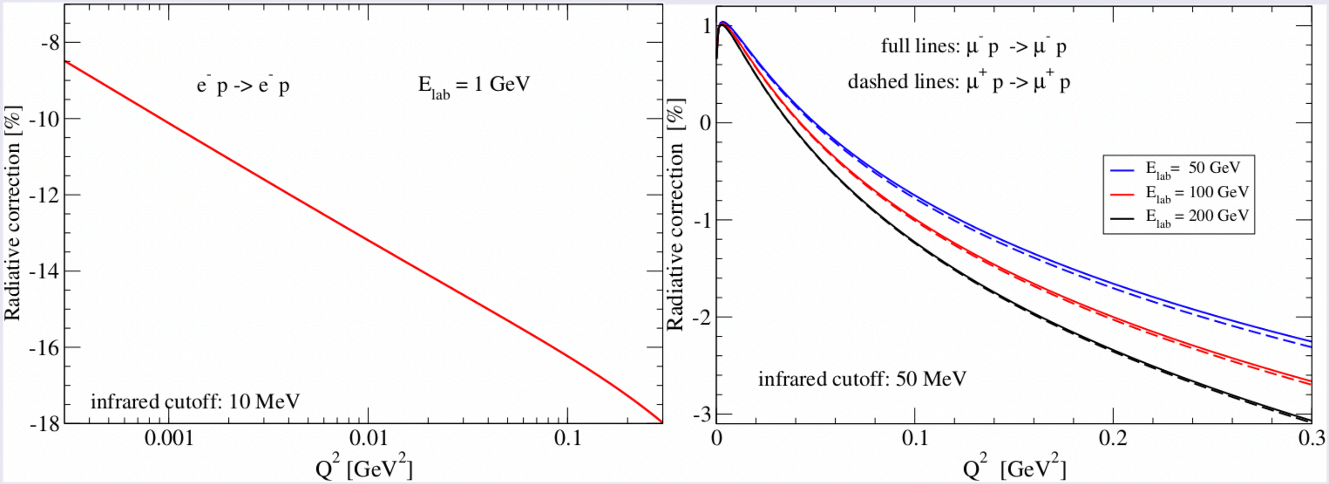
- elastic scattering experiments provide data for G_E at non-vanishing Q^2 and thus require an extrapolation procedure towards zero
  $\rightarrow$ mathematical ansatz may take more or less bounds into account (physics/theory/whatever motivated)
- Any approach (Padé, CF, DI, CM,...) *must* boil down to a series expansion

$$G_E(Q^2) = 1 + c_2 Q^2 + c_4 Q^4 + \ldots$$

  introducing possibly very different assumptions on the coefficients c_i
- recipe for experimenters: measure a sufficiently large range of Q^2 down to values as small as possible and as precise as possible

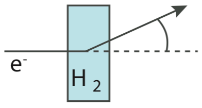
Radiative corrections for electron and muon scattering

QED radiative corrections

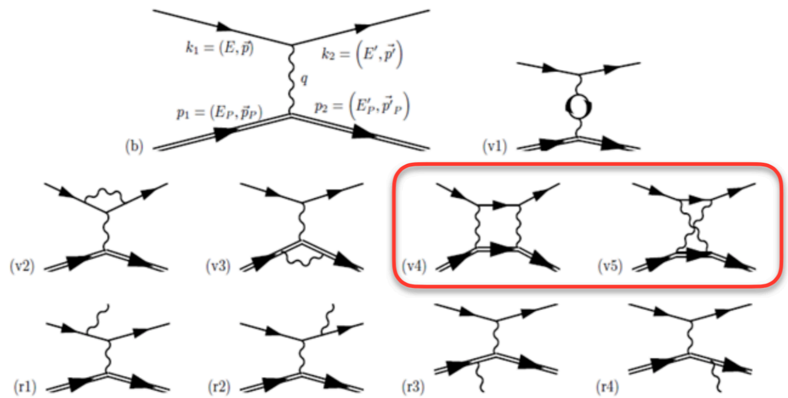


- for soft bremsstrahlung photon energies ($E_\gamma/E_{beam} \sim 0.01$), QED radiative corrections amount to $\sim$ 15-20% for electrons, and to $\sim$ 1.5% for muons
- important contribution to the uncertainty of elastic scattering intensities: *change* of this correction over the kinematic range of interest
- check: impact of exponantiation procedure (stricty valid only for vanishing photon energies): e^-: $2-4\%$, μ^-: 0.1%
- integrating the radiative tail out to large fraction of beam energy: shifts the correction to smaller values, but only *increases* the uncertainty

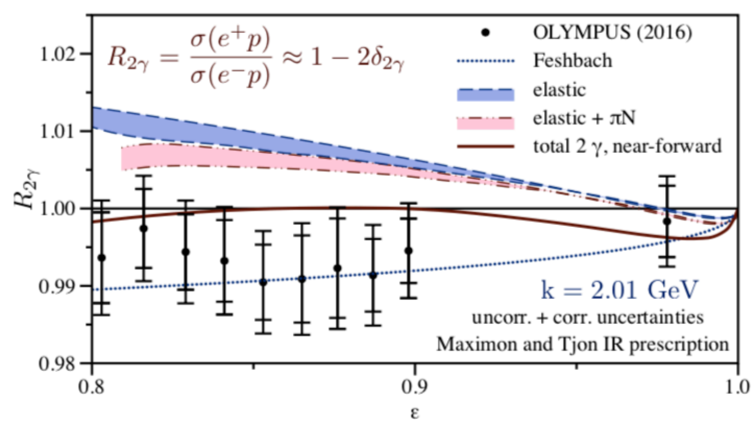
Radiative corrections



e⁻-p scattering



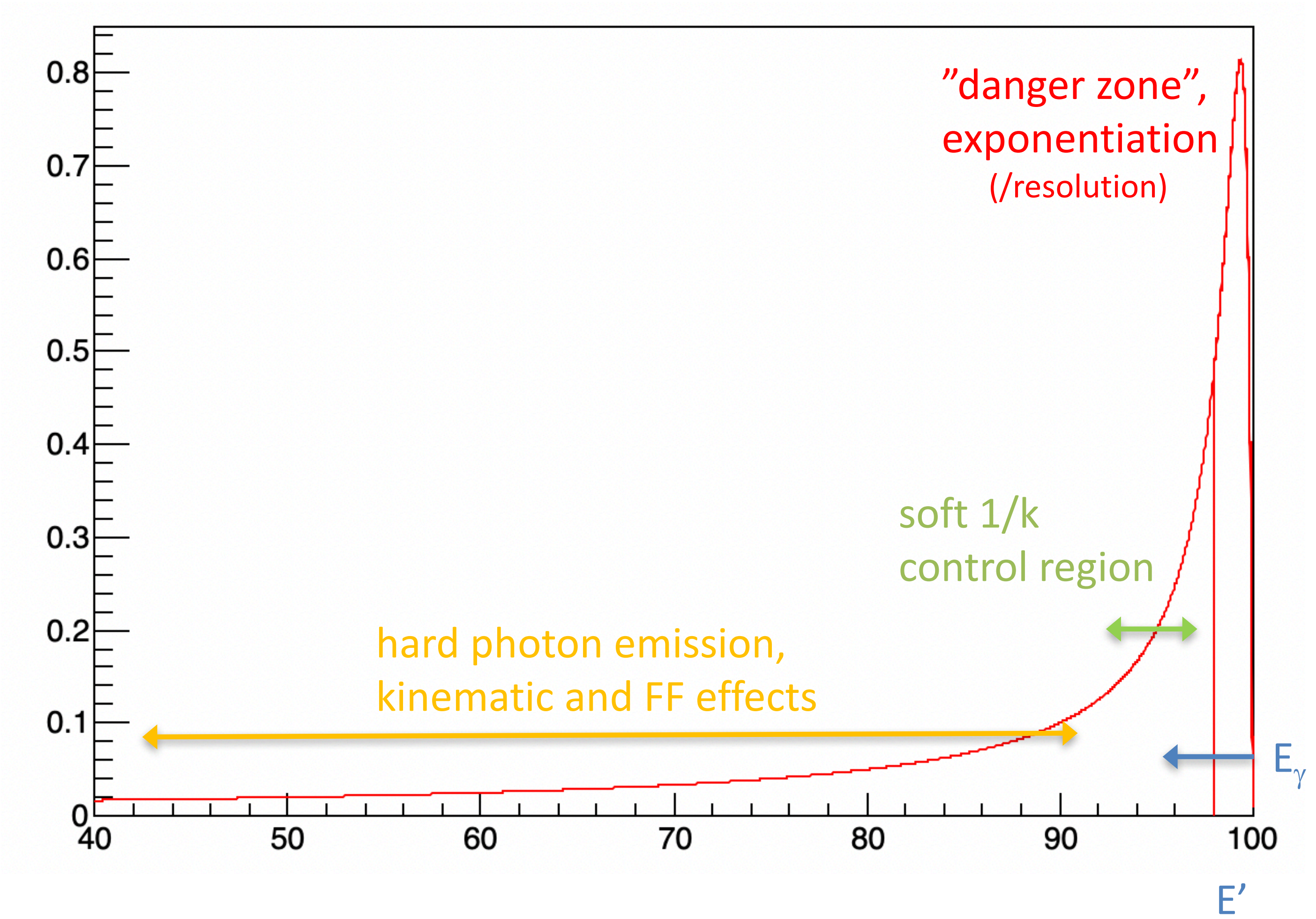
$$\sigma^{exp} \equiv \sigma_{1\gamma}(1 + \delta_{soft} + \delta_{2\gamma})$$



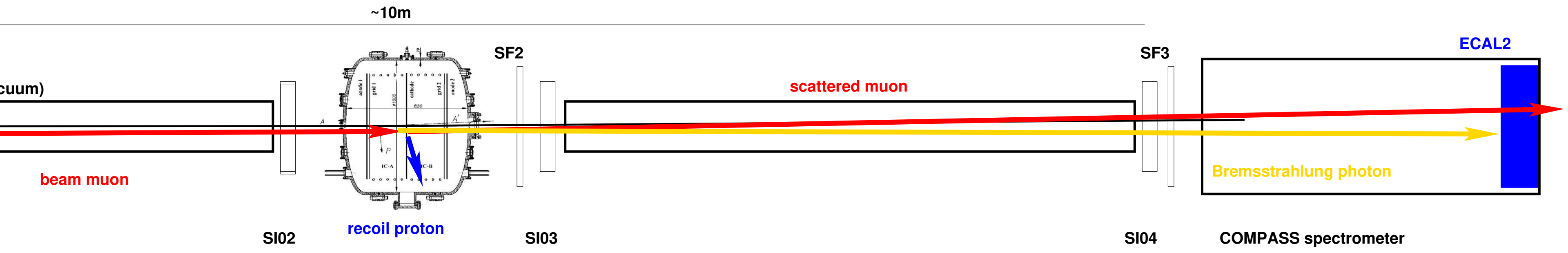
near-forward 2γ agree with data
multi-particle 2γ, e.g. ππN, is important

Tomalak, Pasquini, Vdh (2017)
Pasquini, Vdh, Ann.Rev.Nucl.Part.Sci(2018)

Shape of the elastic peak



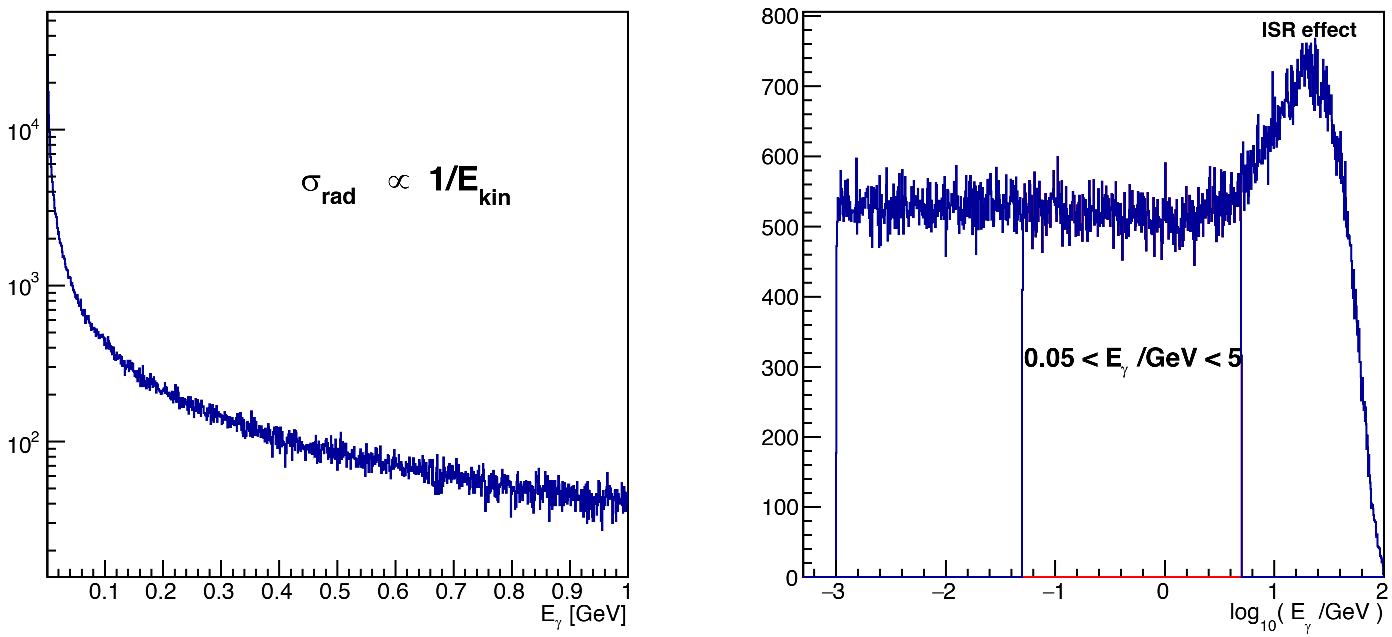
Bremsstrahlung: real-photon emission along the muon-proton scattering



- Bremsstrahlung accompanies the elastic process
- for low-energy photons roughly $1/E_\gamma$ (‘infrared divergence‘)
- angular spectrum: peaking in the relativistic case, opening angle $1/\gamma$ [Lorentz factor]
- 100 GeV beam: E_γ between 50 MeV and 5 GeV emission probability at θ_μ =0.3mrad (Q^2=0.001): 5 $\times 10^{-4}$
- Bremsstrahlung events in Q^2=0.001…0.04 GeV^2/c^2 about 38000

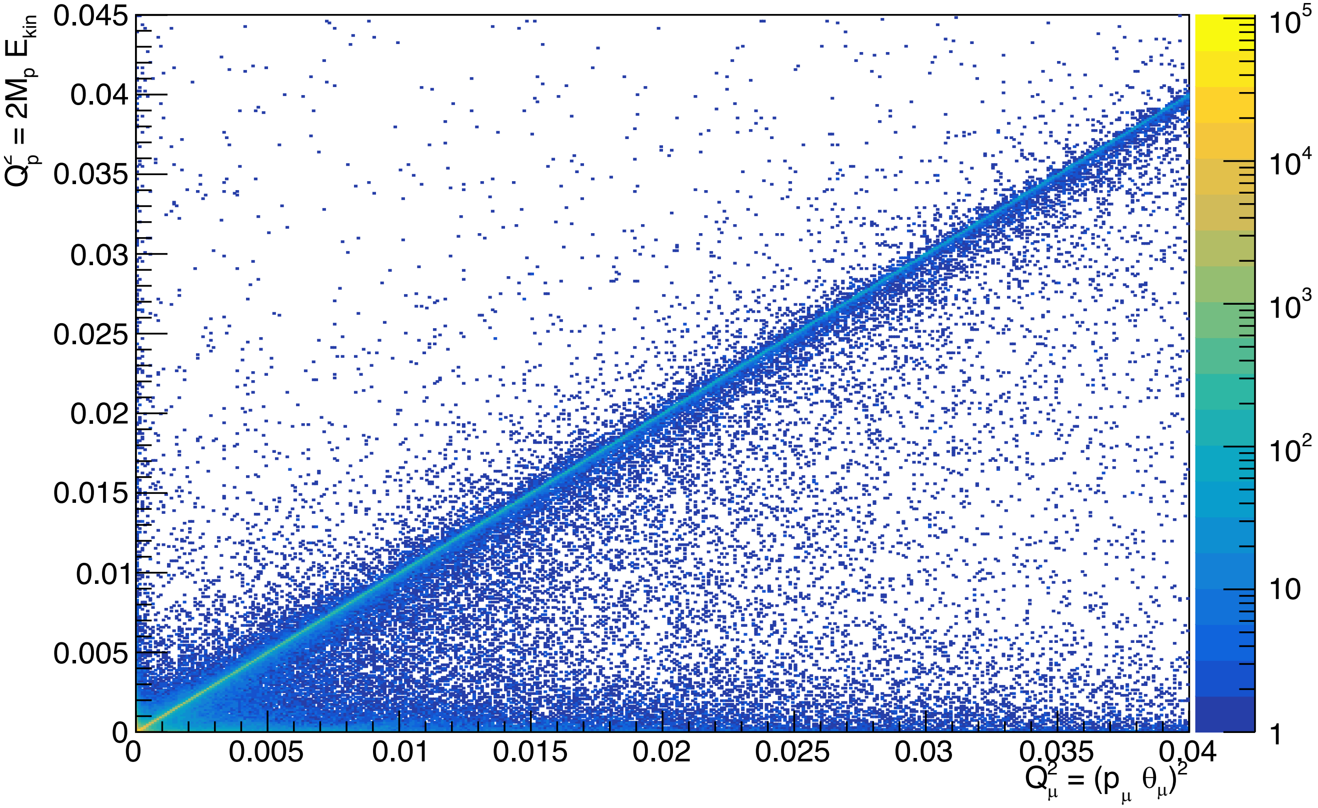
Real-photon energy spectrum

MC simulation of 500k events in θ_μ =0.3 … 2 mrad, E_γ > 1 MeV



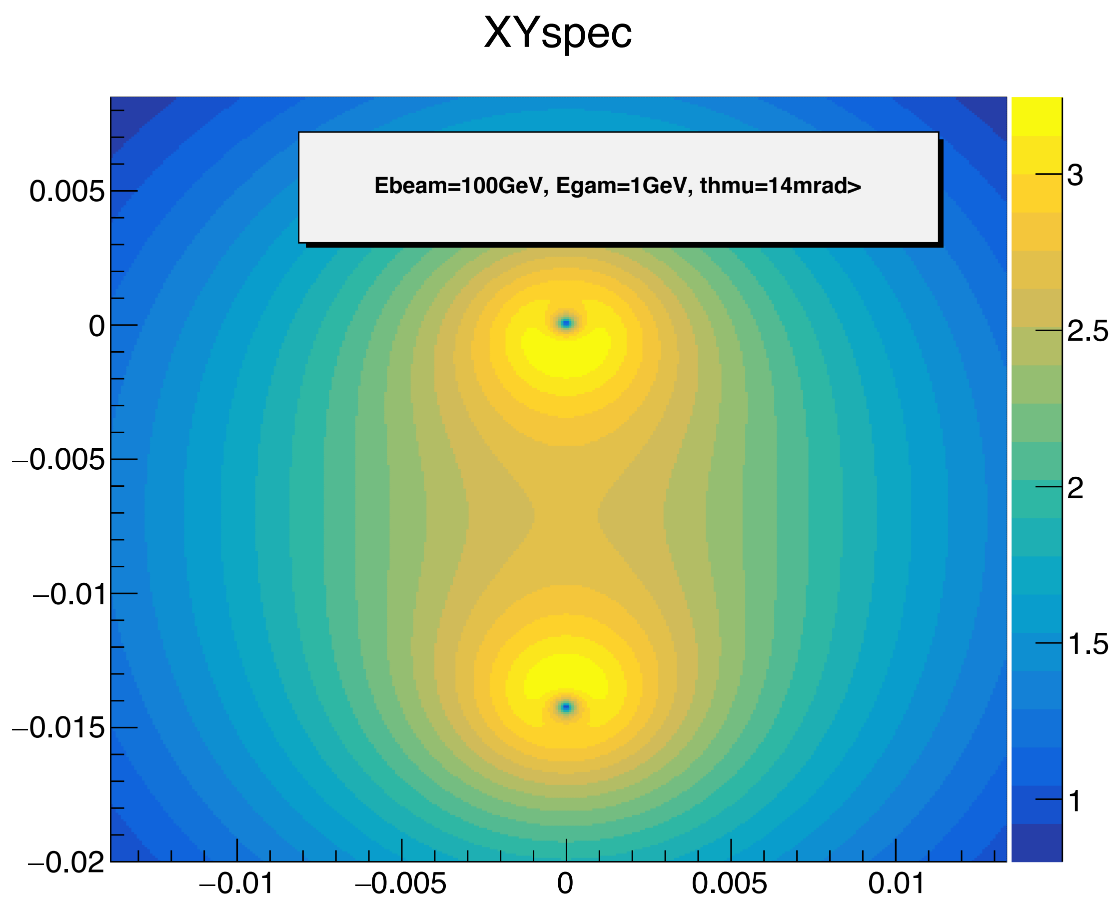
ISR effect: if incoming muon loses much of its energy, the scattering off the proton under a specific scattering angle happens at lower average Q^2 and accordingly a larger cross section

Impact on Q2 reconstruction

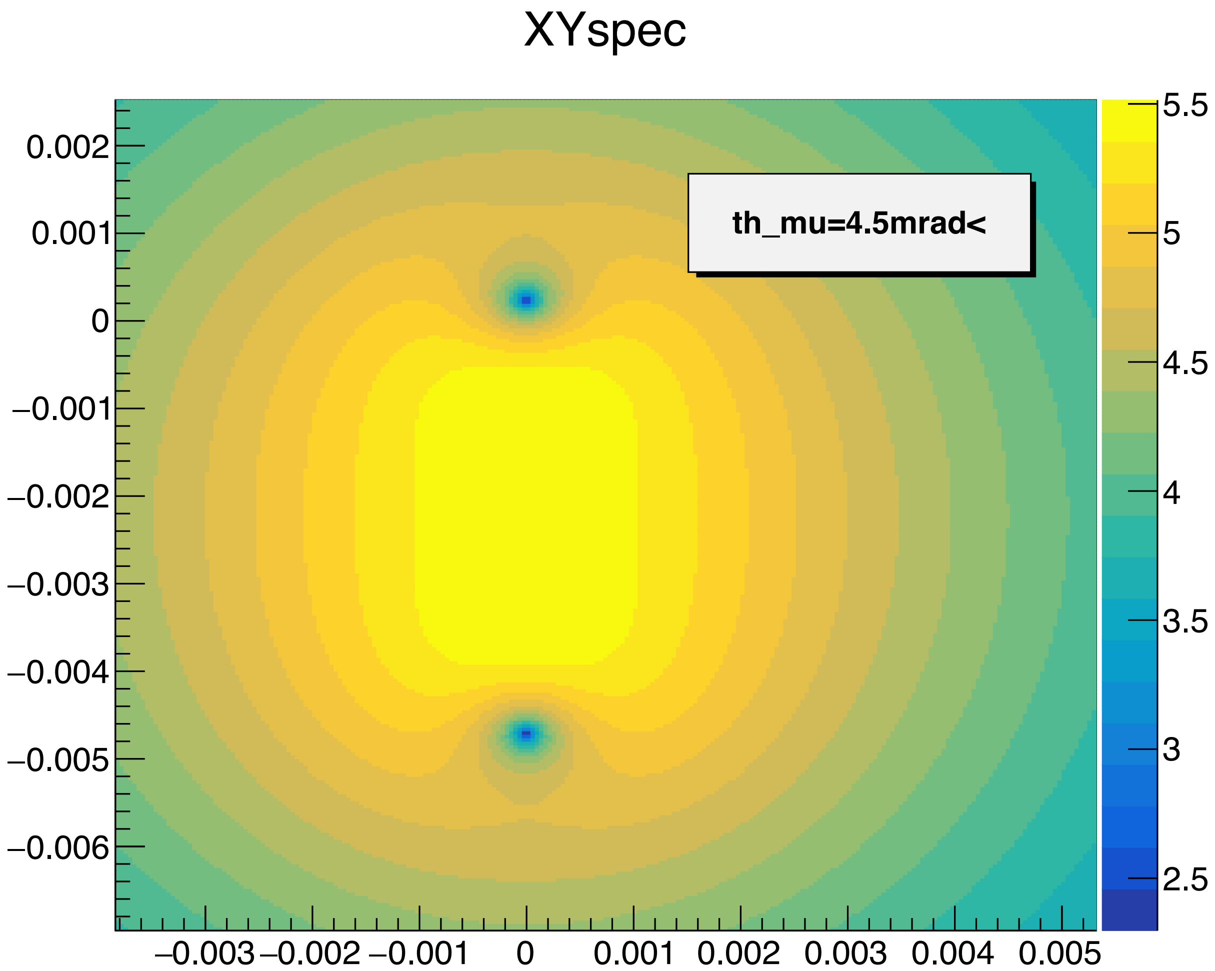


real-photon emission distorts the kinematics, correlation of reconstruction from muon and recoil proton becomes blurred

Bremsstrahlung emission angle, E=100GeV



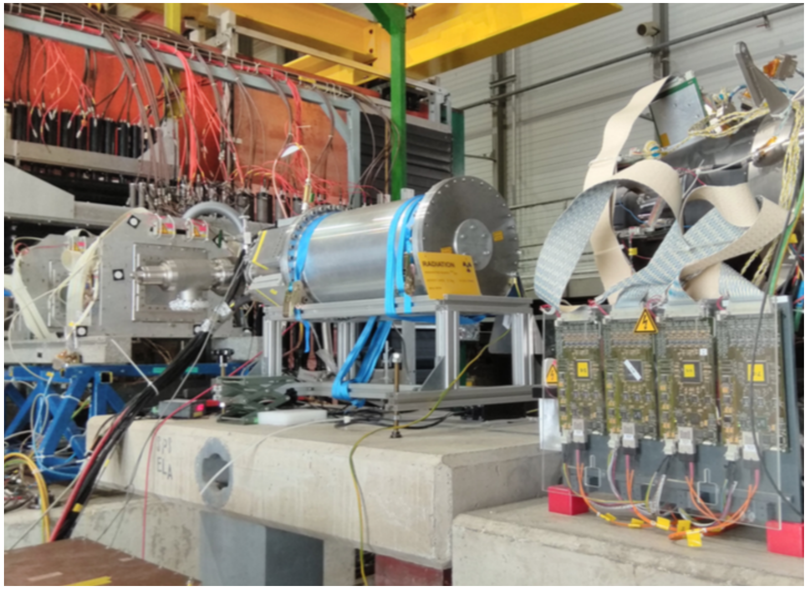
Bremsstrahlung emission angle, E=100GeV

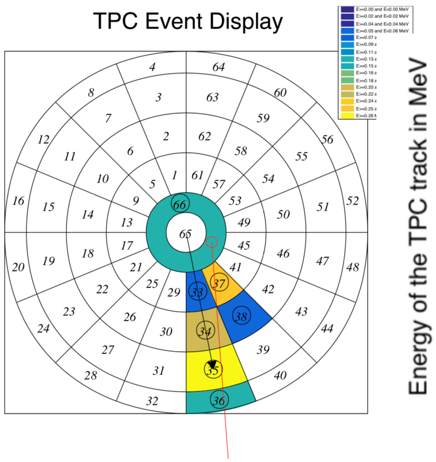


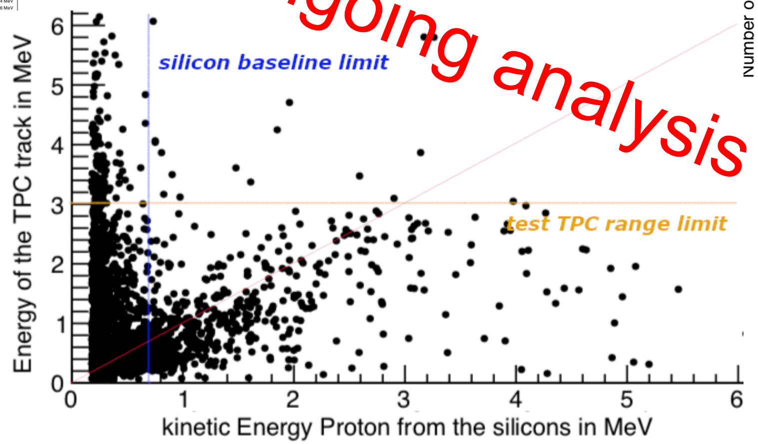
Test in 2018 for Proton Radius measurement

Test setup during 2018 DY run downstream COMPASS, check

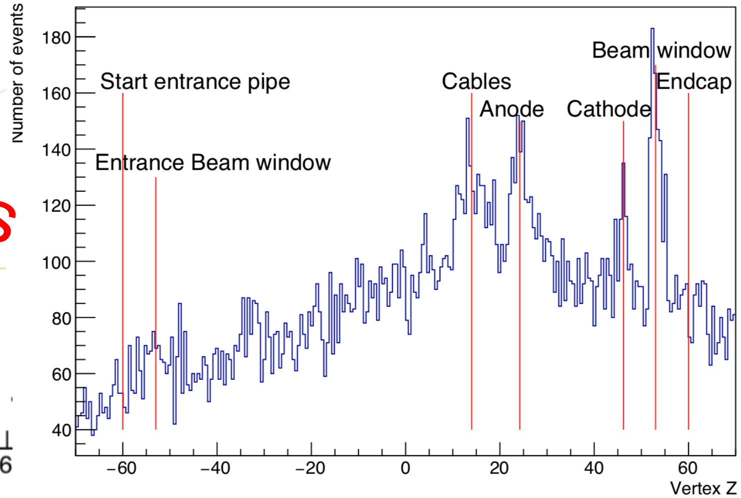
- TPC operation in muon beam ✅
- vertex reconstruction with silicon telescopes ✅
- coincidence detection of scattered muon and recoiling proton ✅

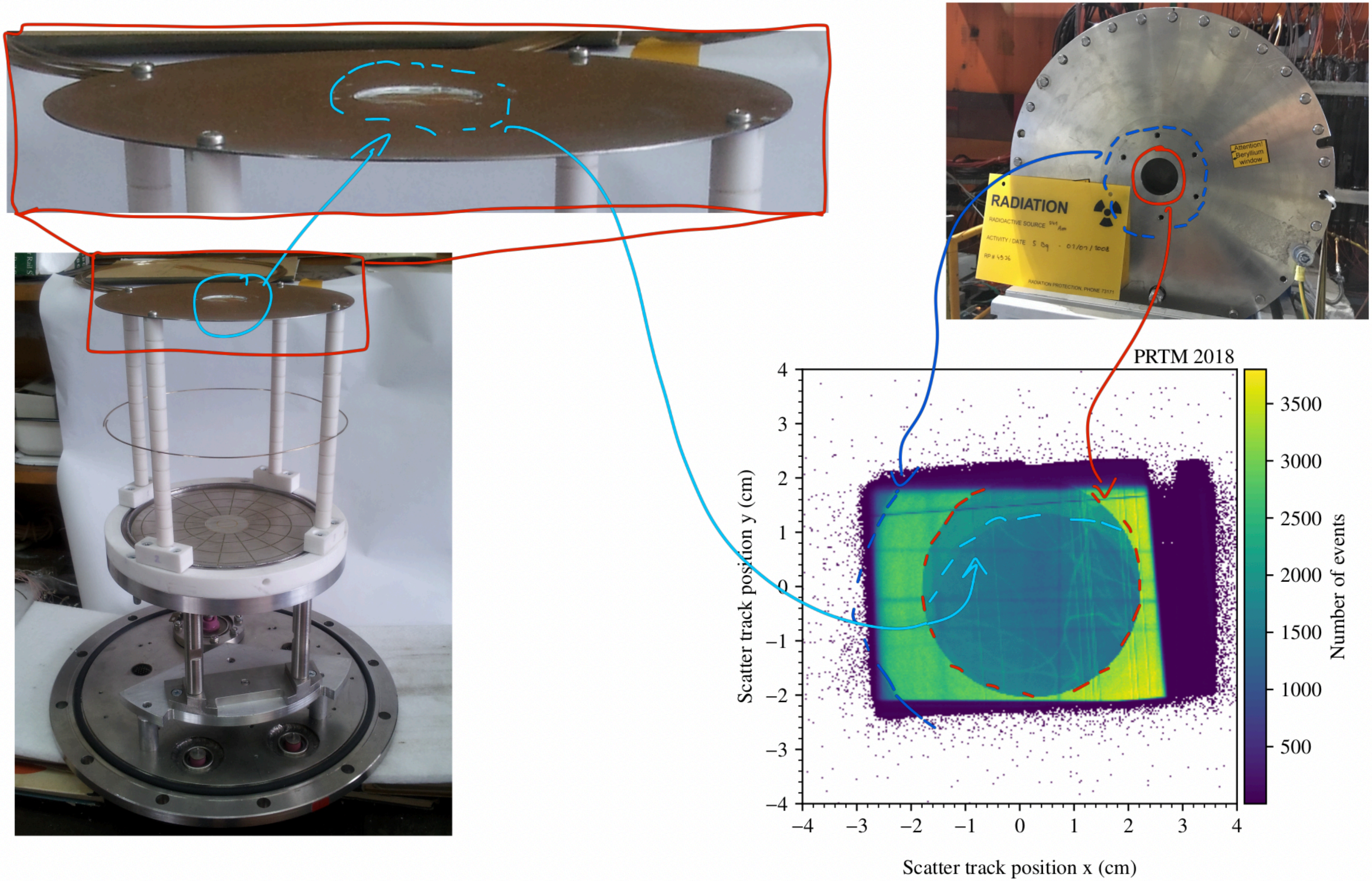






ongoing analysis




RADIATION
RADIOACTIVE SOURCE
ACTIVITY / DATE
RADIATION PROTECTION PHONE 73171
Attention! Beryllium window
PRTM 2018
Scatter track position y (cm)
Scatter track position x (cm)
Number of events
−4
−3
−2
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500
1000
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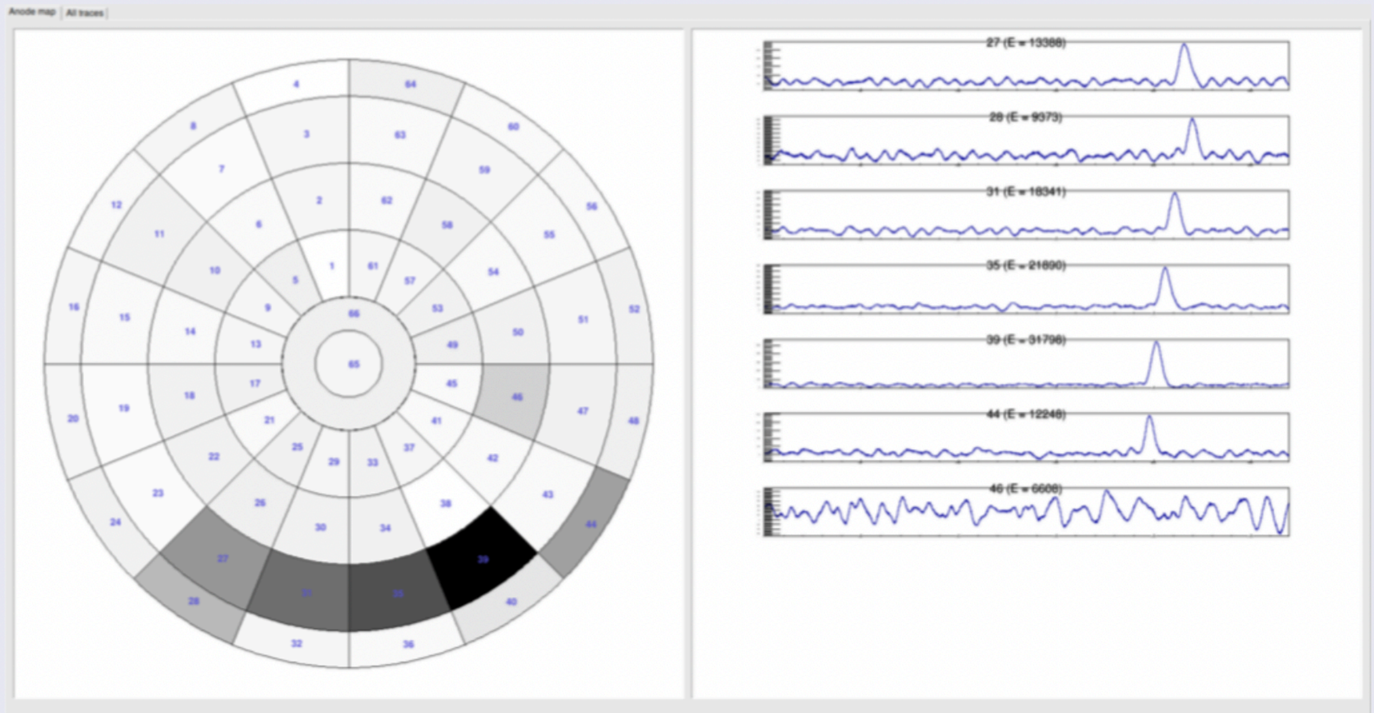
TPC signals

performance of TPC



- recoil protons with muon beam observed

New hardware: Trigger scheme

- Free-running DAQ approach with continuous ‘triggerless’ front-end readout
- image-slicing according to detector response time
- online trigger marks images for higher-level readout

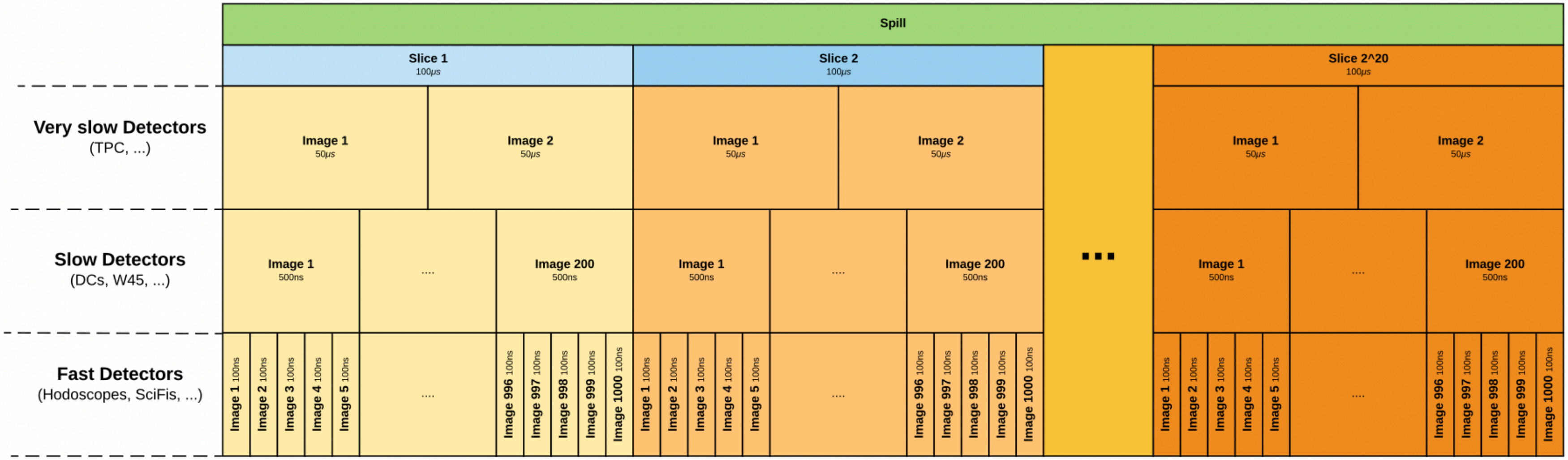
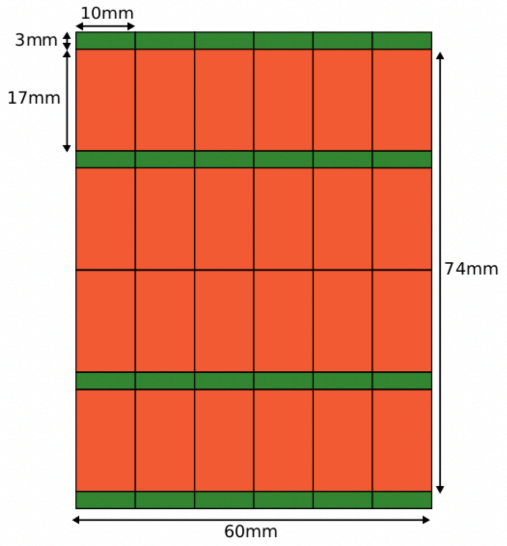


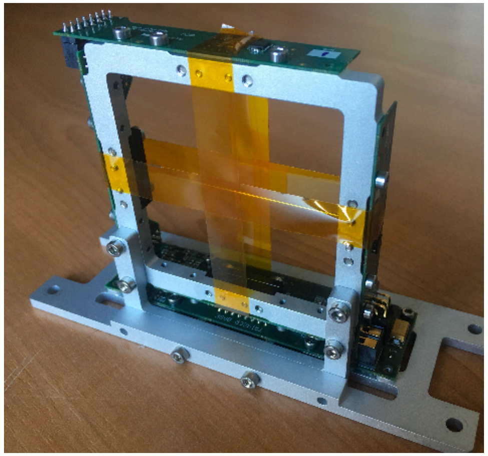
Figure 39: Overview for the time-slicing

more new planned hardware

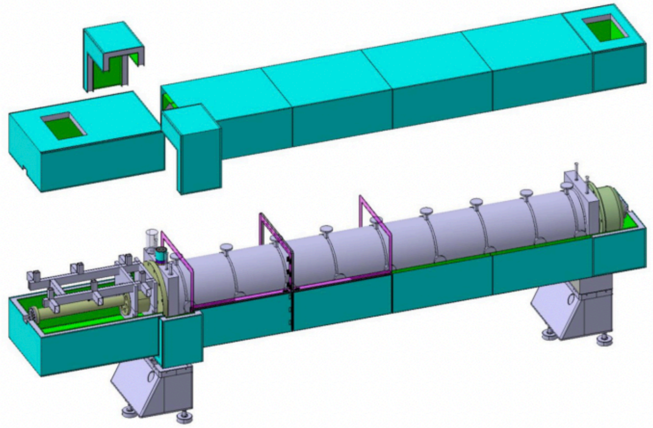
- silicon pixel detectors
- elastic muon-scattering kinematics with SciFi detectors
- upgrades: large-area pixelGEM and MPGD
- CEDARs at high rates
- Beam Momentum Station for proton radius measurement



MuPix8 detector array



SciFi prototype



thermally shielded CEDARs

Schedule 2021 and 2022

Beam time of 20 days in 2021 for pilot run

- proof-of-principle of the employed detector techniques, based on readiness of the subsystems in two charges at the beginning and towards the end of the 2021 COMPASS run
- silicon pixel detectors: currently two main options
  - MUPIX10 or ATLASpix3, fast, pixel size 50-80 μm
  - ALICE ALPIDE, slow (5-10μs), pixel size 28 μm
- SciFi detectors accordingly: 200μm or 2mm ?
- test-TPC (IKAR) upon availability
  - faster FADC readout
  - anode structure?

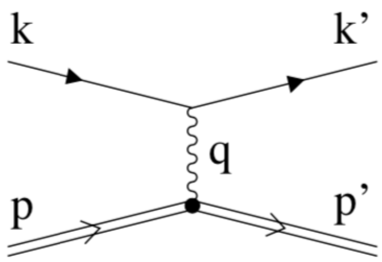
Beam time in 2022: Applied for the first year of running

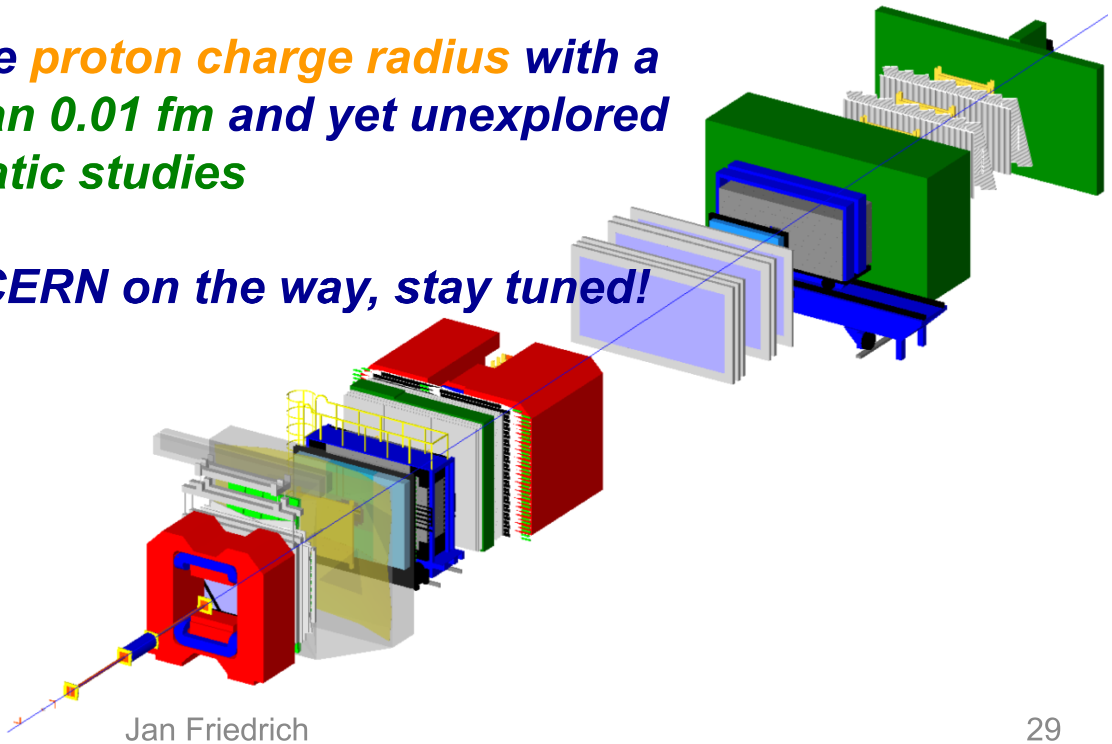
MuPix8 detector array SciFi prototype thermally shielded CEDARs

Summary and Outlook

- *COMPASS++/AMBER proposes high-energy elastic muon-proton scattering for the*
- *determination of $G_{E,p}$ ($10^{-3} < Q^2 < 4\ 10^{-2}$) with relative point-to-point precision $< 10^{-3}$ and the*
- *measurement of the proton charge radius with a precision better than 0.01 fm and yet unexplored territory of systematic studies*

approval by CERN on the way, stay tuned!





fitting with a truncated series for small Q^2

$$n\,(1 + a_2\,Q^2 + a_4\,Q^4 + a_6\,Q^6 + a_8\,Q^8 + \ldots)$$

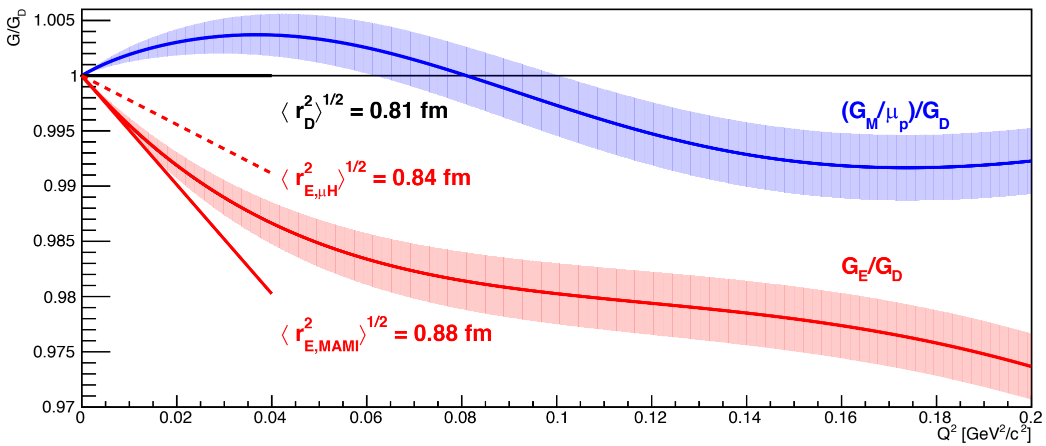
- 3 free parameters n, a_2, a_4 (sys 0.0035, stat 0.0040 fm)
- 4 free parameters n, a_2, a_4, a_6 (sys <0.0020, stat 0.0090 fm)

choice of higher-order terms:

- $a_i = 0$ for $i \geq 6$ or 8
- fix e.g. $a_i = a_D$ for $i \geq 6$ or 8 according to some model

Elastic lepton-proton cross section

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



$$\frac{1}{6}r_p^2 = -\left.\frac{d}{dQ^2}\right|_{Q^2=0} G_E(Q^2)$$