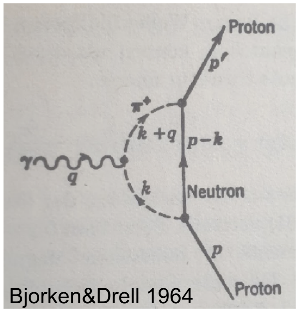
Overview of Proton Radius Measurements

Jan Friedrich



P. Mergell et al./Nuclear Physics A 596 (1996) 367–396

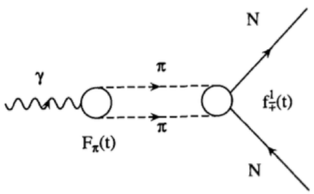
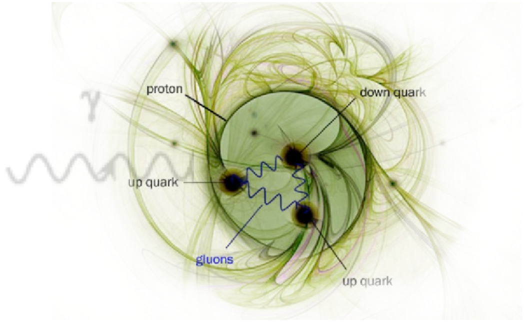


Fig. 1. Two-pion cut contribution to the isovector nucleon form factors.



18 November 2020
IWHSS2020 Trieste/zoom

The quest for the extension of the proton – a look at the origins

PHYSICAL REVIEW VOLUME 79, NUMBER 4 AUGUST 15, 1950

High Energy Elastic Scattering of Electrons on Protons

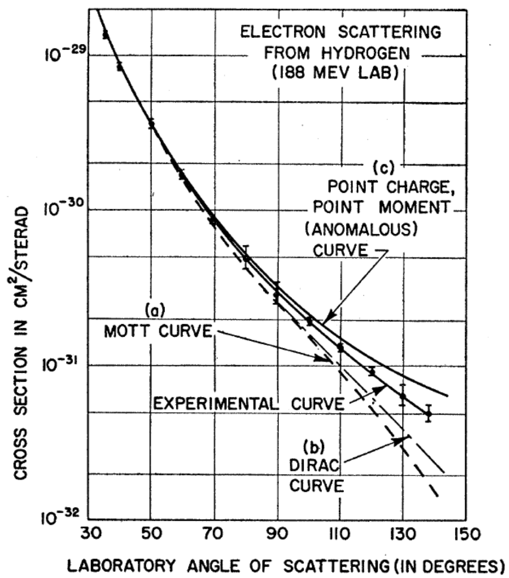
M. N. ROSENBLUTH
Stanford University, Stanford, California

(Received March 28, 1950)

The theory of the elastic scattering of electrons on protons at very high energies is discussed in detail. A formula is given for the cross section. This formula contains certain parameters which depend on the action of the virtual photon and meson fields. In particular, curves have been calculated on the assumption of scalar and pseudoscalar meson theory. While these perturbation theory calculations are not very trustworthy, and the results depend on the choice of coupling constants, it is felt that qualitative features can be checked with experiment. It is concluded that at low relativistic energies ($E<50$ Mev) the experiment provides a valuable check on quantum electrodynamics. At higher energies it should yield data on the nature of the meson cloud of the proton.

Measurement of the Proton Radius in *ep*-Scattering

1956: $r_p \approx 0.8$ fm



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

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

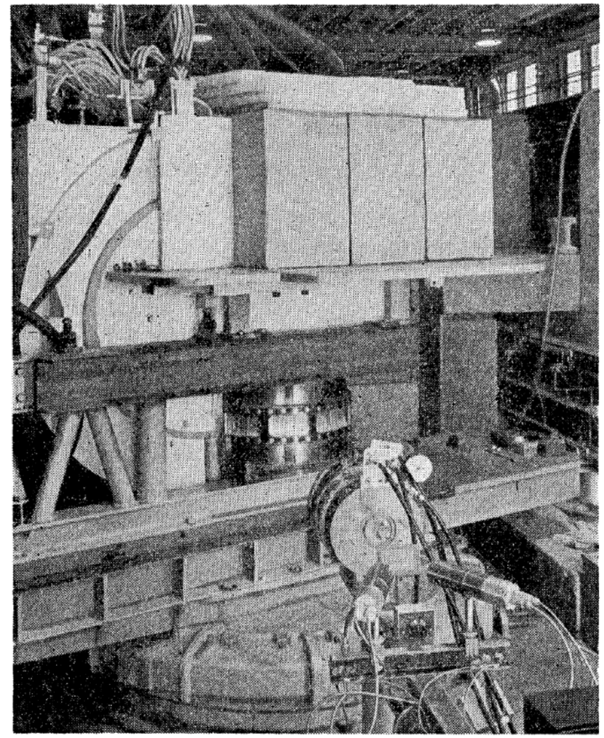


FIG. 15. The semicircular 190-Mev spectrometer, to the left, is shown on the gun mount. The upper platform carries the lead and paraffin shielding that encloses the Čerenkov counter. The brass scattring chamber is shown below with the thin window encircling it. Ion chamber monitors appear in the foreground.

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

the story goes on

1950 formalism for high-energy ep scattering (Rosenbluth)

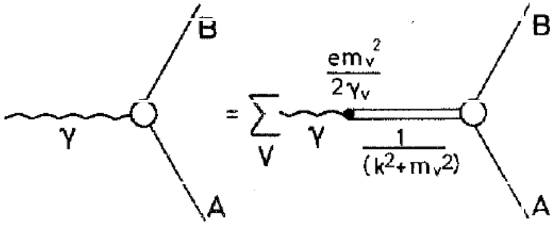
1956 first measurements: $r_p = 0.80$ fm (Hofstadter)

1957-59 dispersion relations (DR) are introduced (Nambu, Goldberger *et al.*)

1960 $J^P = 1^- \; \pi\pi$ resonance at $m \approx 630$MeV (vector meson) is postulated to explain the proton radius (Frazer&Fulco, Bergia *et al.*)

1961 the $\rho(770)$ is found (Erwin, Stonehill *et al.*)

1966 Hofstadter high$-Q^2$data: dipole form factor



1975 Borkowski data fit: $r_p = 0.88$ fm

1976 Höhler DR fit: $r_p = 0.836$ fm

1980 Mainz low$-Q^2$ precision data (1): $r_p = 0.862$ fm (Simon *et al.*)

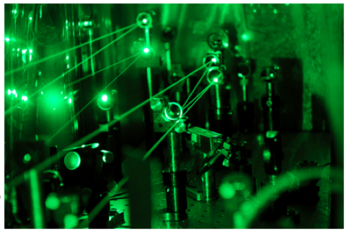
1995 Mergell, Meißner, Drechsel DR fit: $r_p = 0.847$ fm

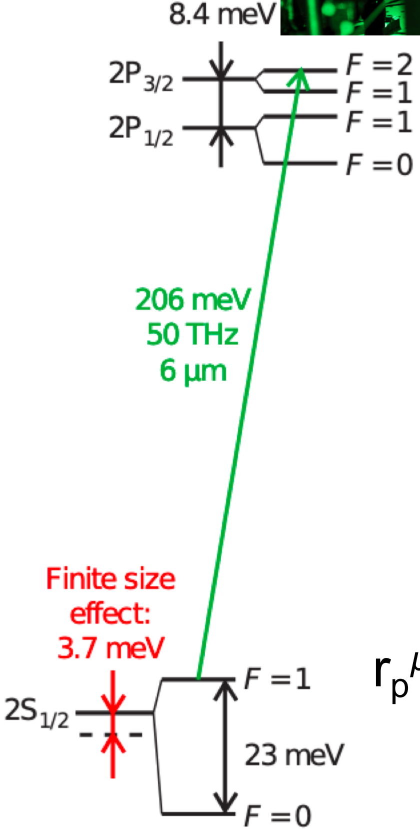
2010 Mainz low$-Q^2$ precision data (2): $r_p = 0.879$ fm (Bernauer *et al.*)
μH line splitting: $r_p = 0.841$ fm (Pohl *et al.*)

>2010 dozens of papers on fitting procedures, systematic effects etc.

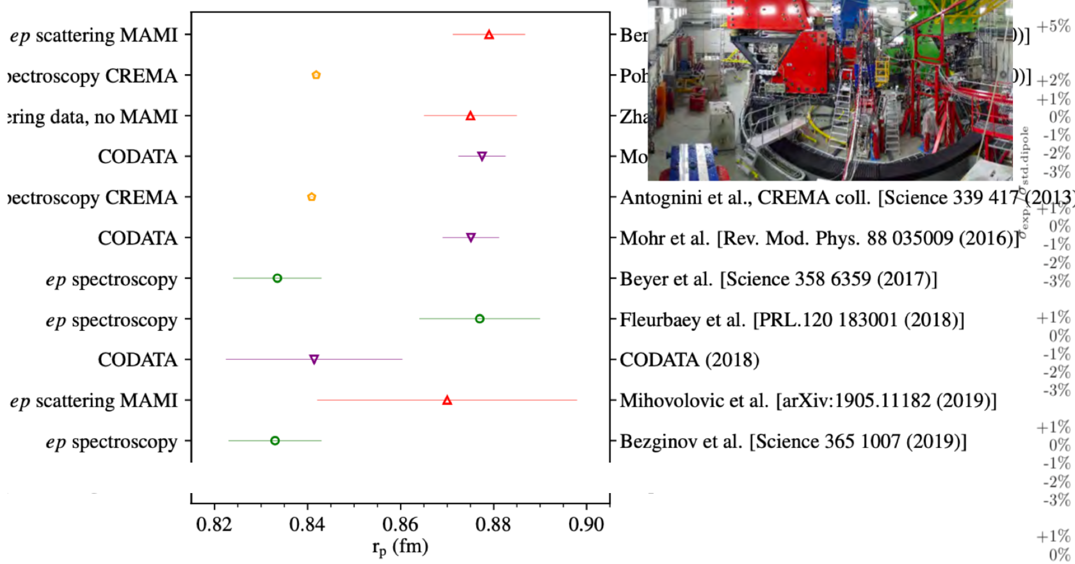
Measurements of the Proton Radius in 2010

CREMA 2010

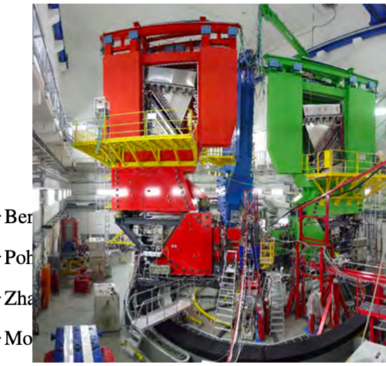


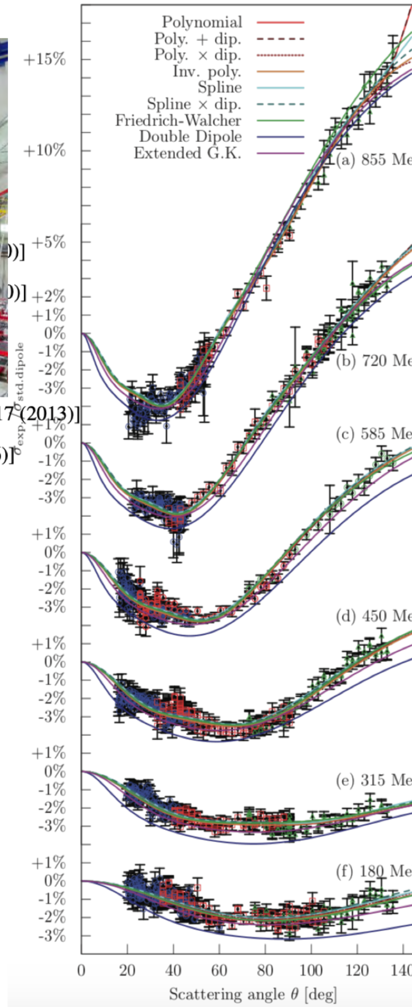


status October 13, 2019



MAMI 2010





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

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

The "Proton Radius Puzzle"

talk by Randolf Pohl

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

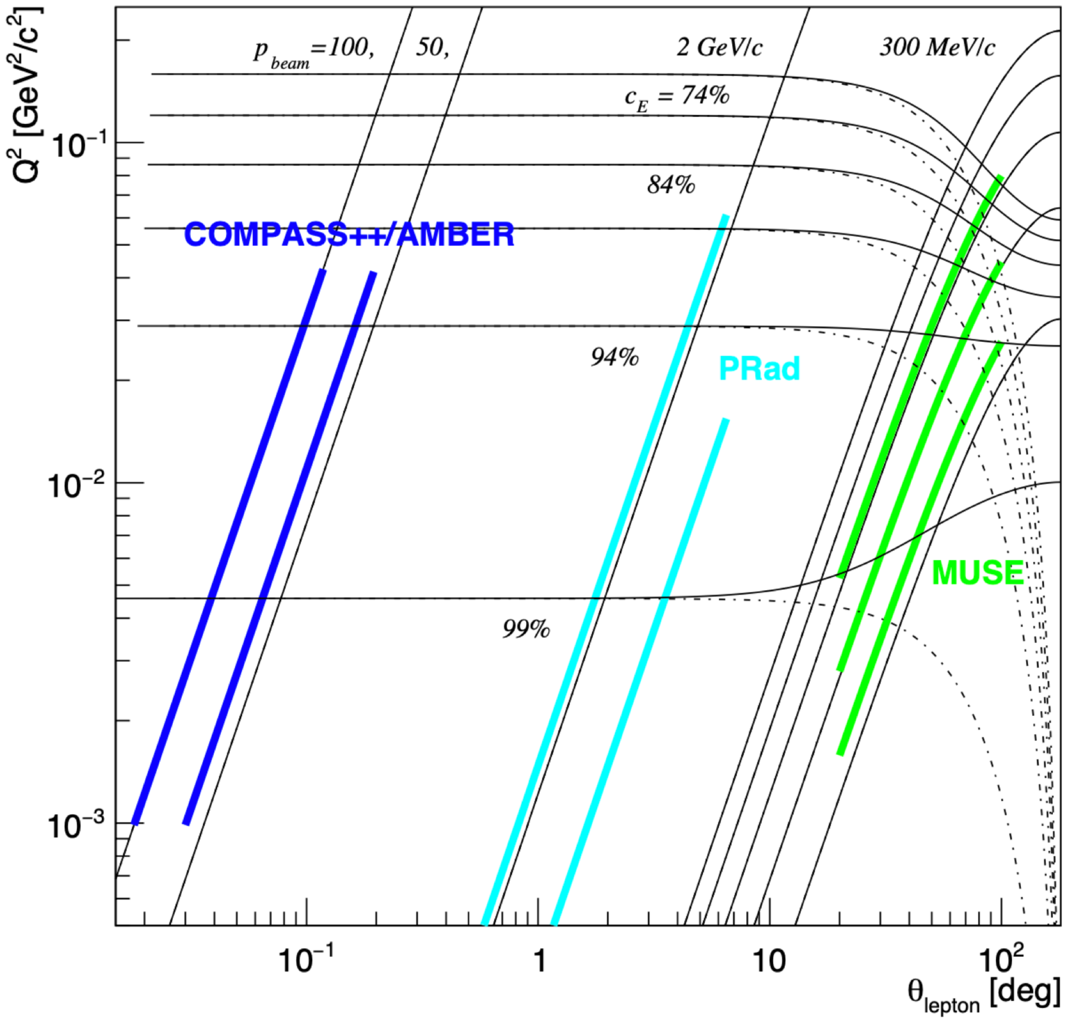
New data from lepton-proton scattering

Several proposed, preparing, ongoing experiments to solve the puzzle in the next years

- **PRad**: electron-proton with E_e = 1.1/2.2 GeV
  → Recent publication of results: smaller value
  → PRad2: detector upgrade planned *talk by Ashot Gasparian*
- **MAMI**: electron-proton with E_e < 750 MeV
  → Two new experiments in preparation
- **MAGIX-MESA**: electron-proton with E_e < 150 MeV
  → Electric and magnetic form factor
  → New accelerator - start in 2024
- **MUSE**: muon/electron-proton with $E_{e,\mu}$ < 140 MeV
  → Comparison of electron and muon scattering
  → Start of data taking in 2019 *talk by Ronald Gilman*
- **OLYMPUS**: electron/positron-proton with E_e = 2-3 GeV
  → Ratio of e^+/e^- c.s. gives access to 2-photon exchange
- **COMPASS++/AMBER**: muon-proton, E_μ ~100 GeV
  → Data for high-energy elastic μ-proton scattering
  → Different systematics compared to other

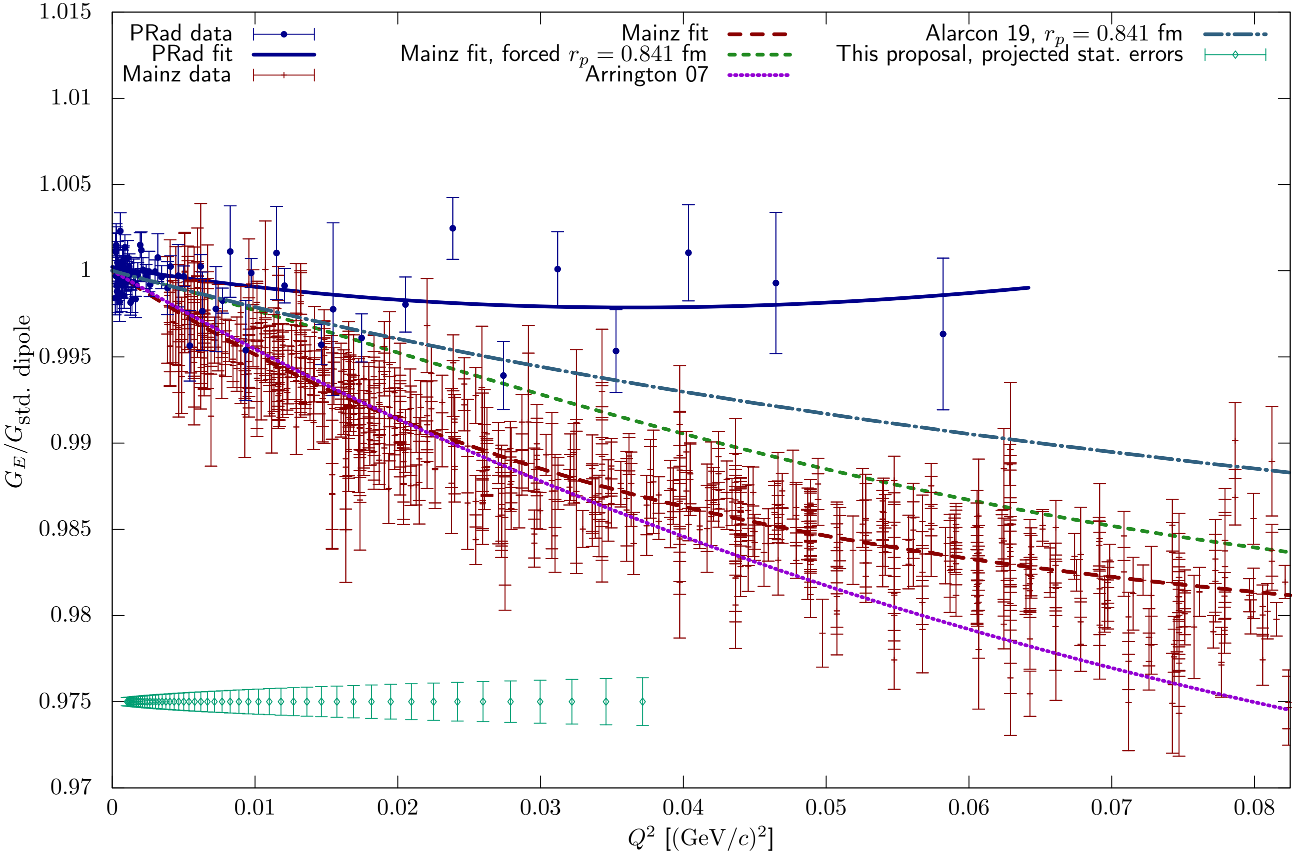
Proton Radius Experiment at Jefferson Lab

Kinematic ranges



- Relative contribution c_E of the electric form factor G_E to c.s. is practically constant for lepton beam energies > 1GeV (Rosenbluth separation not possible)
- At small Q^2 the contribution of G_M is very small and its impact can be safely estimated (even with assuming large uncertainty on G_M)
- Differences due to lepton mass only at small beam energy / large scattering angles

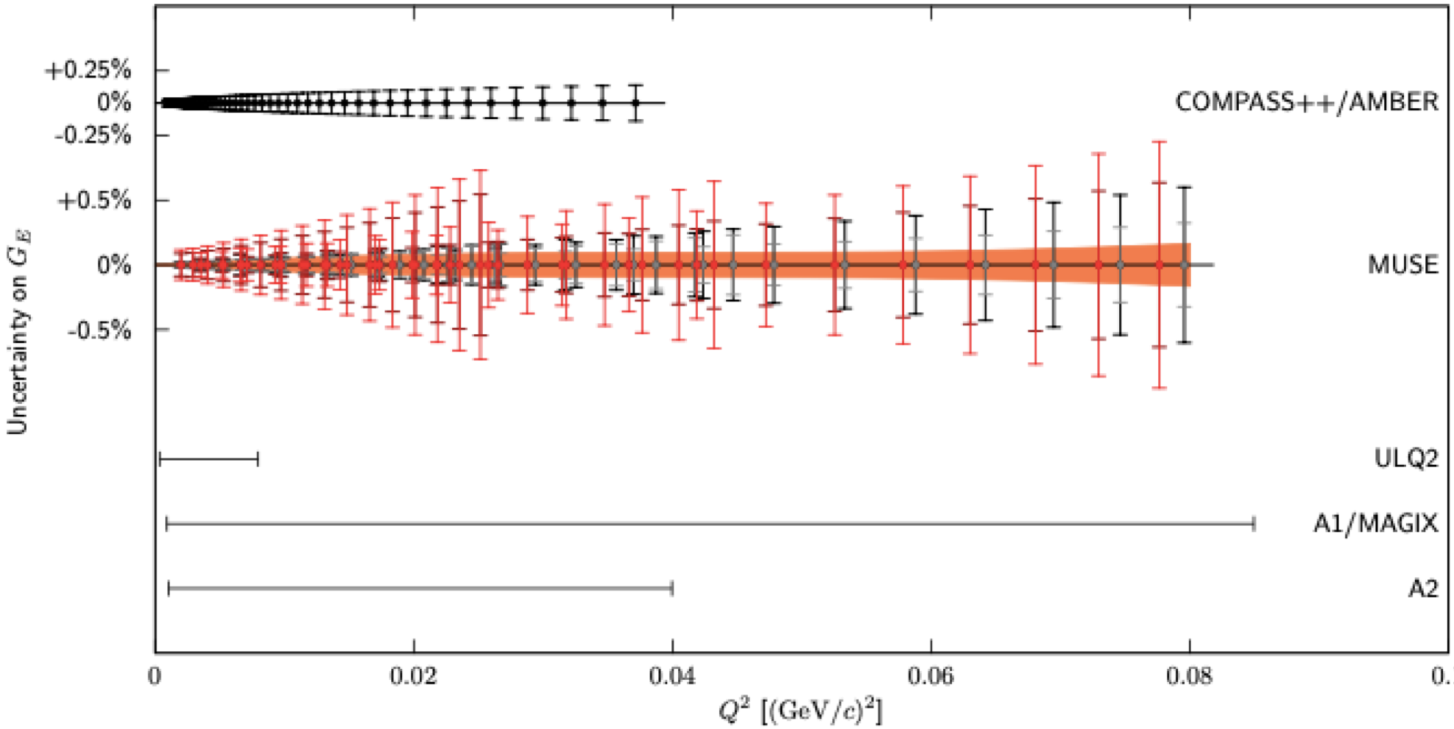
Mainz vs. JLab data



uncertainties for the COMPASS++/AMBER proposal

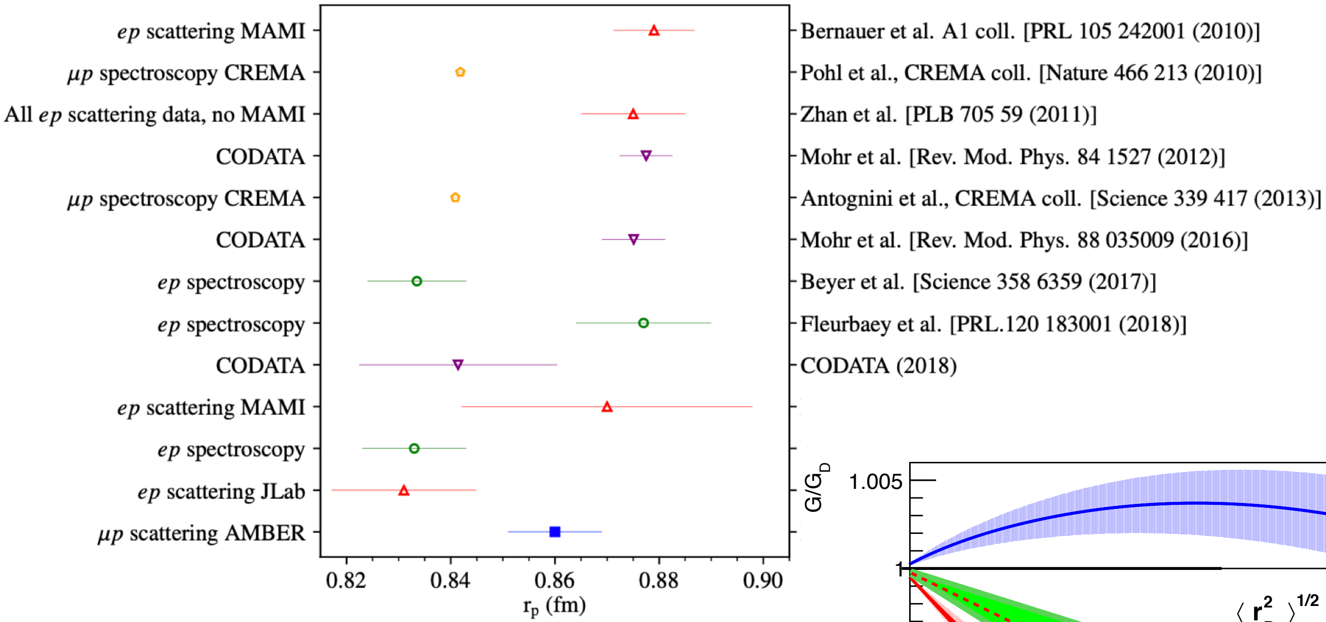
- program for 200 days of beam
- precision on the proton radius < 0.01 fm

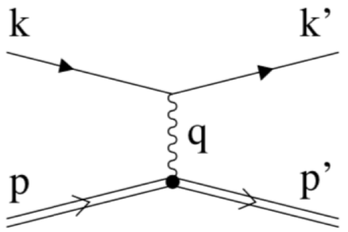
Q^2 coverage and precision for different lepton scattering experiments



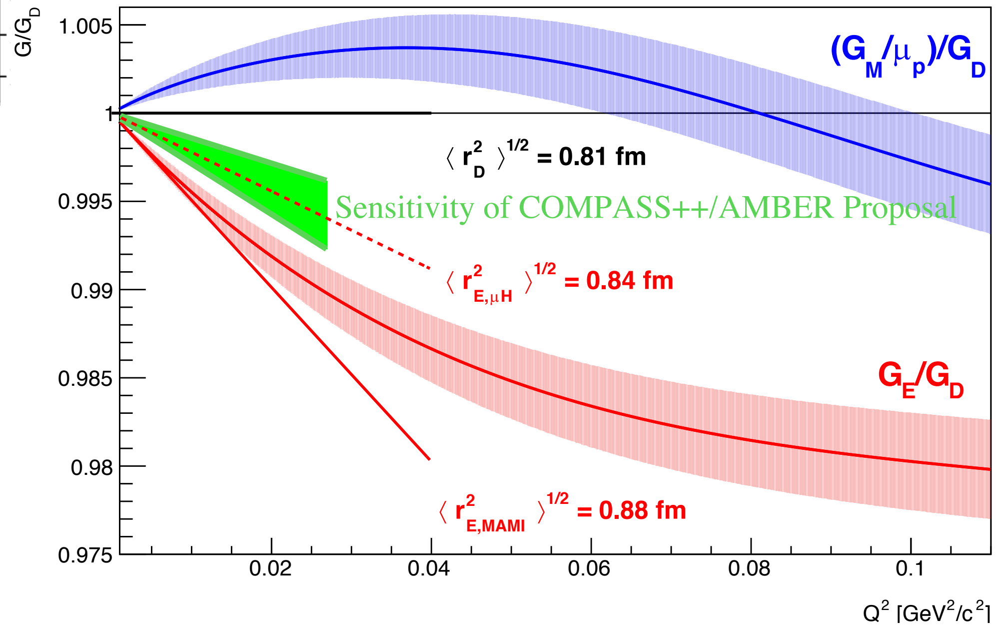
courtesy: J. Bernauer, Proc's FCCP2019

Precision in the context of the puzzle





G_E & G_M



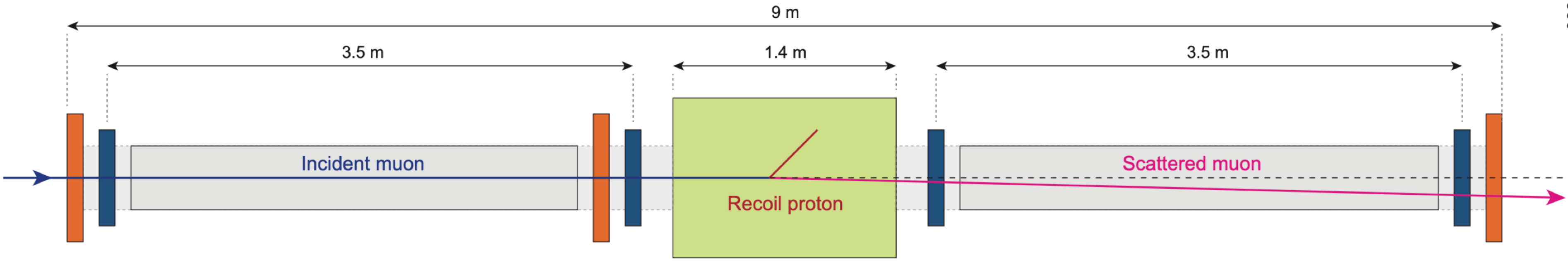
CERN-SPSC-2019-022; SPSC-P-360

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

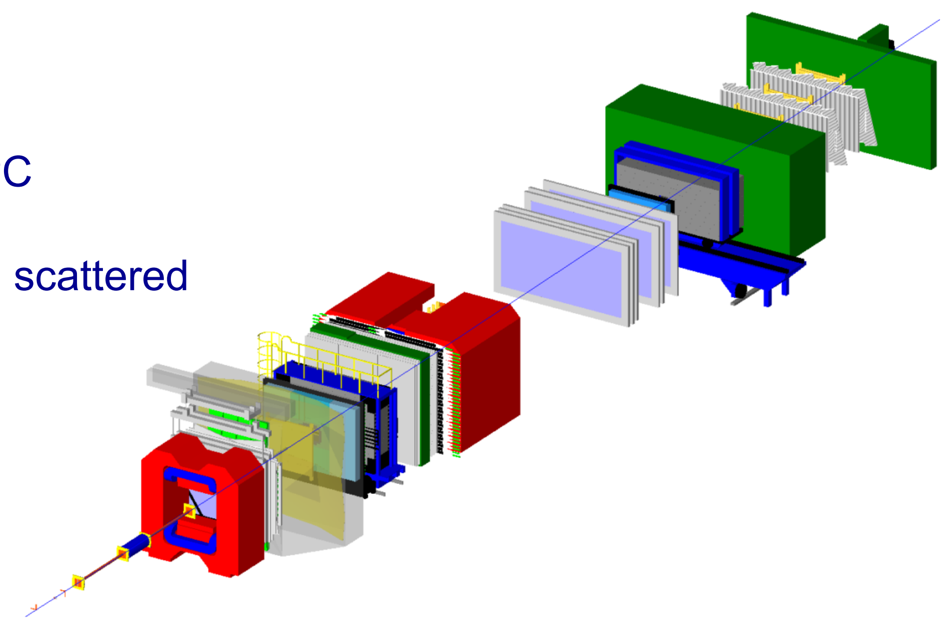
– Phase-1 –

COMPASS++*/AMBER†

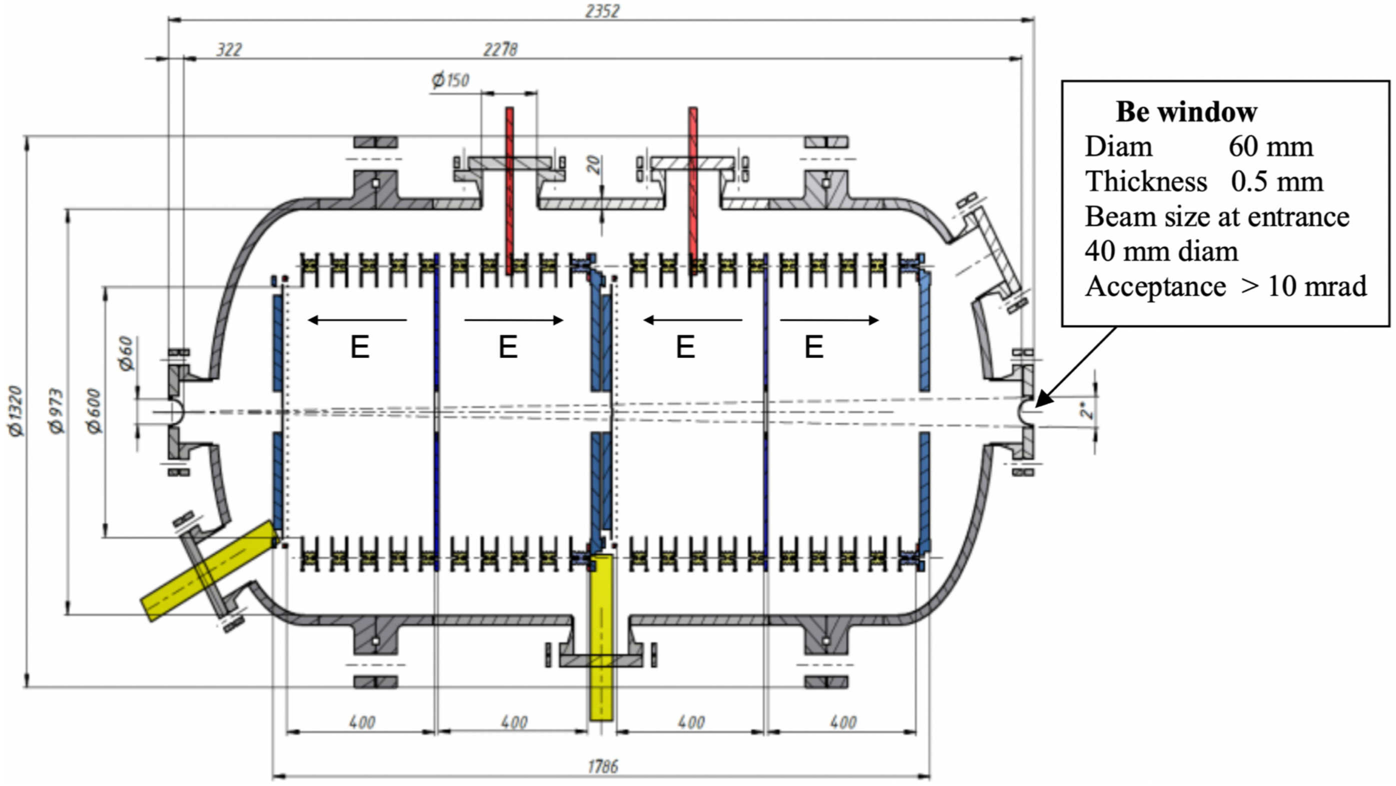
Physics program recommended by the CERN SPSC in Oct 2020



- 100 GeV muons of the CERN M2 beamline
- Protons in an active-target high-pressure TPC
- Silicon detectors for precision tracking
- 500µm SciFi stations for trigger/timing of the scattered muons
- inner tracking and ECAL of the COMPASS spectrometer



Active target: high-pressure TPC



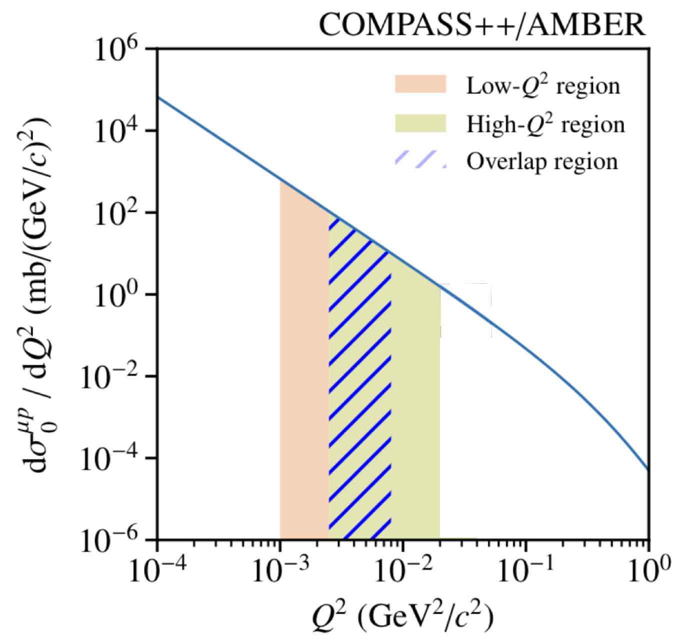
- up to 20 bar pressure
- 600mm diameter of active volume
- reconstruction of recoil energy 0.5-20 MeV (10^{-3}…$4x10^{-2}$ GeV^2)

Proposed Q^2-Range at COMPASS++/AMBER

Measurement of elastic μ-p-scattering

Active-target pressurized hydrogen TPC combined with tracking and *COMPASS* spectrometer.

- Direct measurement of recoil-proton energy:
  $0.001 \leq Q^2 / (\mathrm{GeV}^2/c^2) \leq 0.02$
- Conservative scenario:
  → Low-Q^2: $0.001 \leq Q^2 / (\mathrm{GeV}^2/c^2) \leq 0.0025$
  → High-Q^2: $0.0025 \leq Q^2 / (\mathrm{GeV}^2/c^2) \leq 0.02$
- Data taking of 150 days - Phase II:
  → 43 days - low-Q^2 at 4 bar
  → 107 days - high-Q^2 at 20 bar
- Data set with $33 \cdot 10^6$ events:
  → stat. prec. on $\langle r^2 \rangle$: 1.6 %
  → fixed $\langle r^6 \rangle$ term: 0.7 %
  (values from simulation)



Stat. Prec.	fixed $< r^6 >$	Q^2 (GeV$^2/c^2$)	Statistics	Pressure	Comment
0.9 %	0.5 %	0.0010 - 0.04	70 mio.	20 bar	150 days
1.2 %	0.6 %	0.0025 - 0.04	37 mio.	20 bar	150 days
1.6 %	0.7 %	0.0010 - 0.04	6 + 27 mio.	4 + 20 bar	43 + 107 days
1.4 %	0.7 %	0.0010 - 0.04	12 + 27 mio.	4 + 20 bar	86 + 107 days

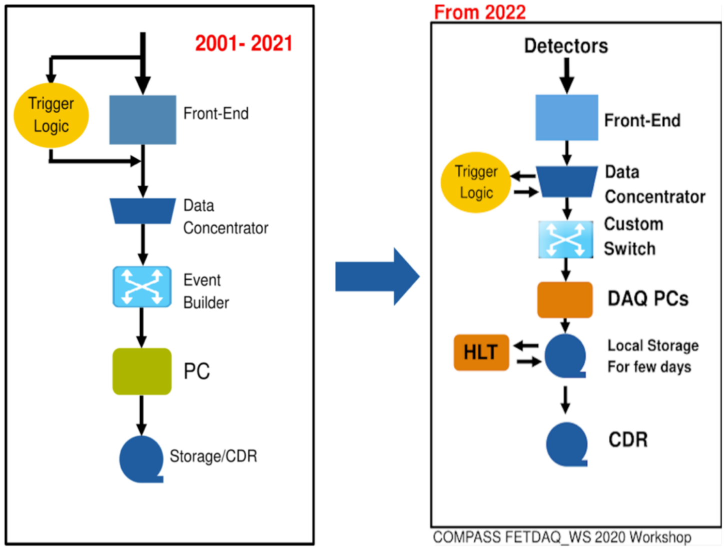
Fitting procedures and theory input: talk by Christian Weiss

New Technology, one aspect: Trigger-less DAQ System

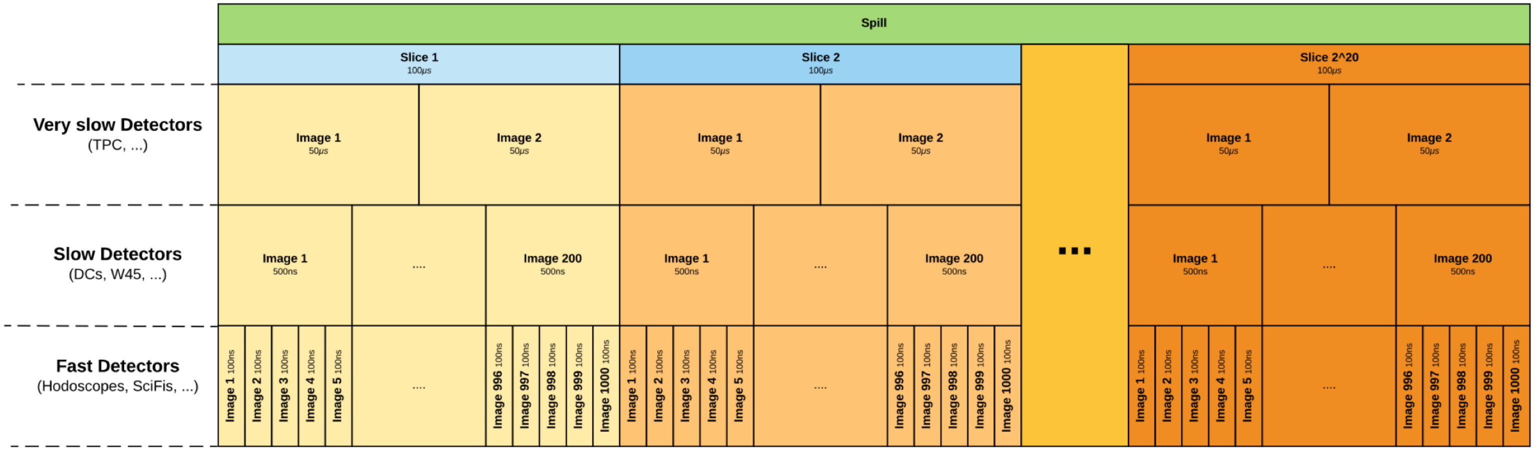
New DAQ development

A concept applying continuous DAQ based on the following principals:

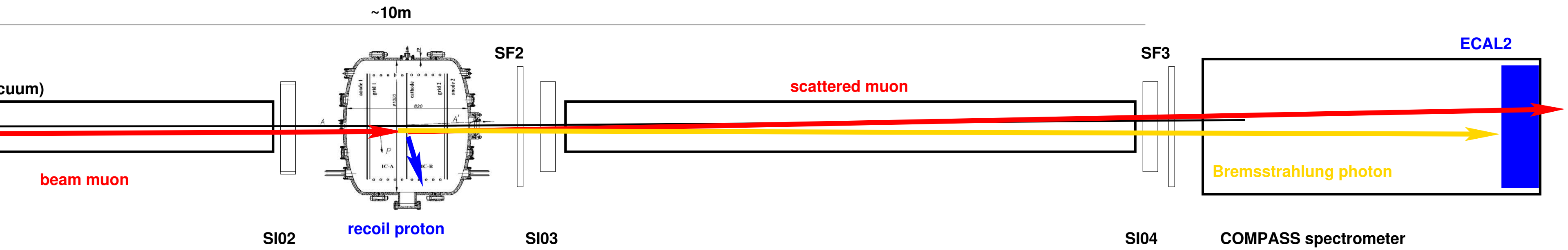
- Continuously delivering front-end electronics
- Front-end data can be forwarded to trigger processors
- Hardware event builder stores data until trigger decision
- Status and Plans:
  → Adaption of DAQ firmware and software (within 2020)
  → Increase of data rate capability (2/10 GB/s 2022/2023)
  → Development of digital trigger (iFTDC card since 2019)



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

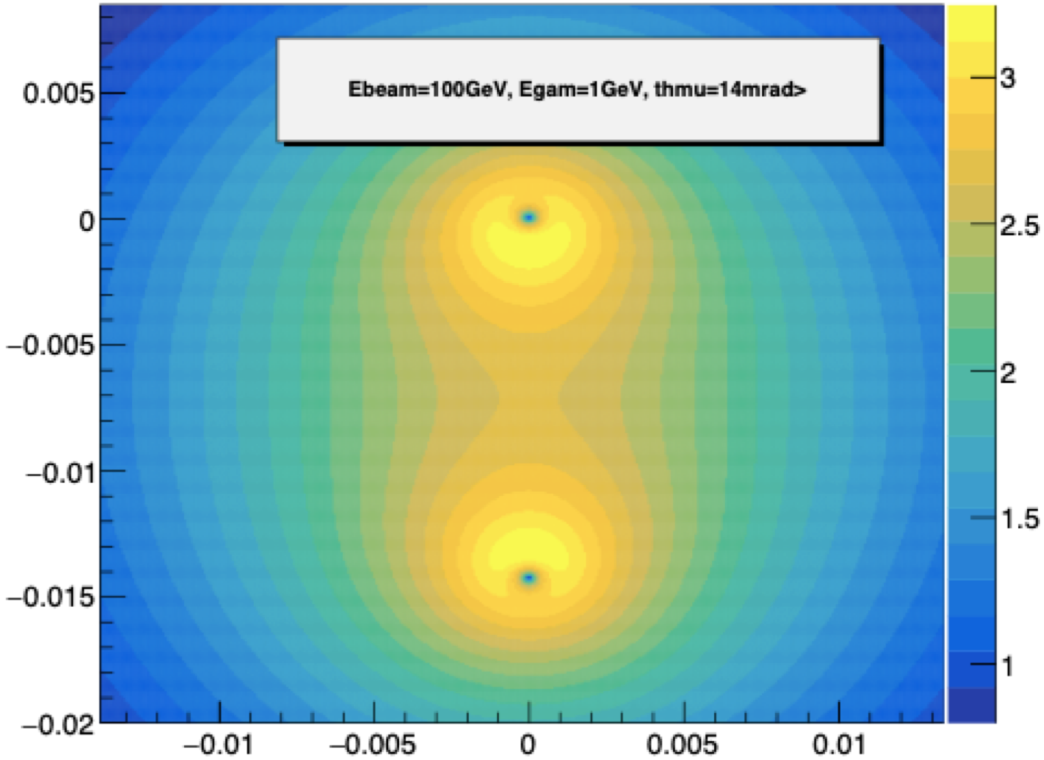


Bremsstrahlung: real-photon emission along the muon-proton scattering



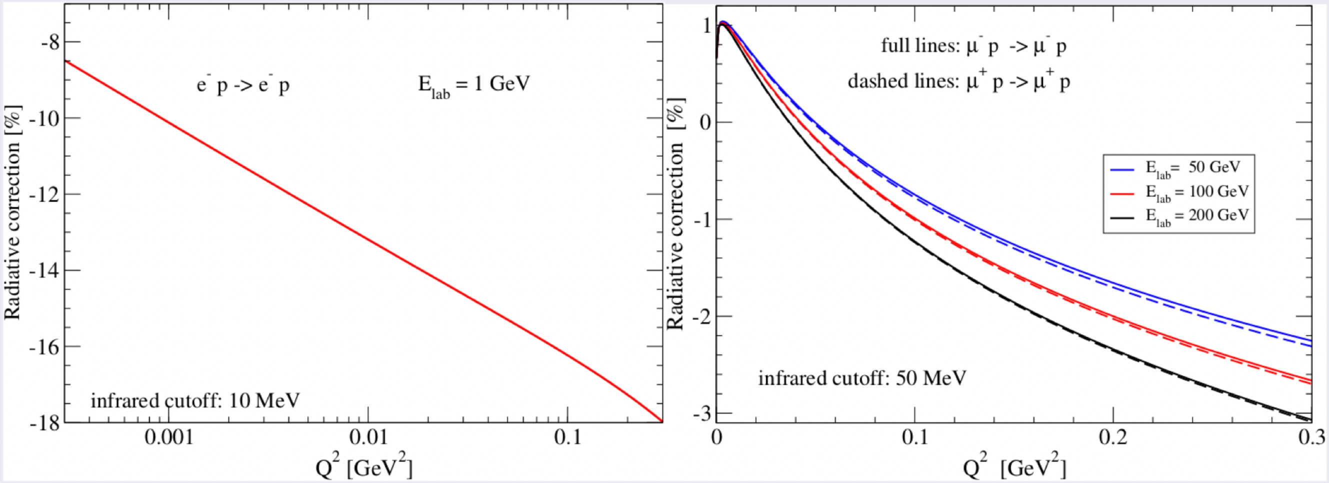
- Bremsstrahlung accompanies the elastic process
- for low-energy photons roughly $1/E_\gamma$ ('infrared divergence')
- angular spectrum: peaking in the relativistic case, opening angle $1/\gamma$ [Lorentz factor]
- 100 GeV beam: E_γ between 50 MeV and 5 GeV emission probability at θ_μ =0.3mrad (Q^2=0.001):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

Bremsstrahlung: angular emission spectrum for muon beam energy 100 GeV and scattering angle 14 mrad



Radiative corrections for electron and muon scattering

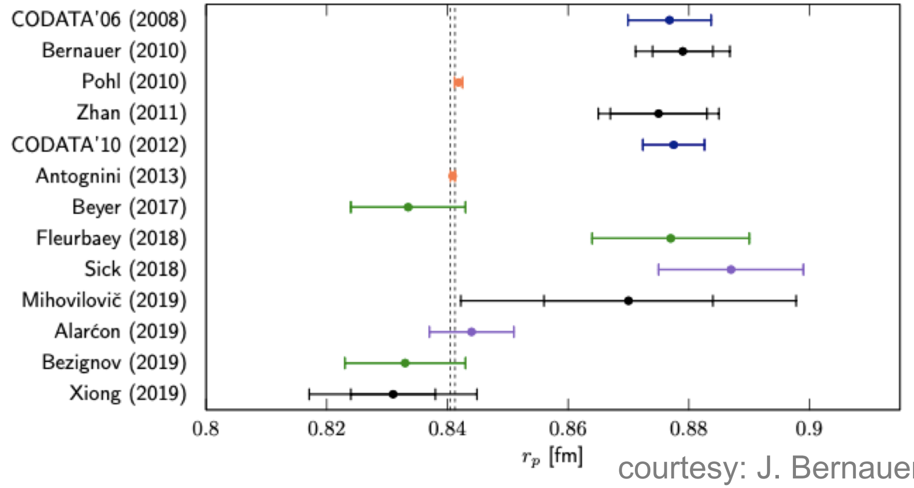
QED radiative corrections



- 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

Measurements of the Proton Radius: Summary

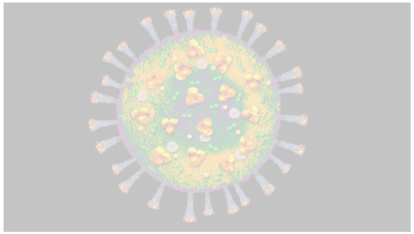
- *A large variety of experiments on both sides, atomic spectroscopy and lepton scattering are ongoing or planned*
- *Increasing evidence for the "small-radius scenario" $r_p \approx 0.84\ fm$, in line with established theory expectation*



courtesy: J. Bernauer, Proc's FCCP2019

- *Remains the question: did anything go wrong with the earlier electron scattering experiments? If yes, what?*
- *Promising approach: Scattering of muons with high statistical precision and yet unexplored territory of systematic studies*
- *Scattering experiments are needed to get the full picture, i.e. the full functional dependence $G_E(Q^2)$ and $G_M(Q^2)$*

…and what if the proton looks completely different from what we imagine? – *expect the unexpected*



Thank you