Proton Radius with COMPASS++/AMBER

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

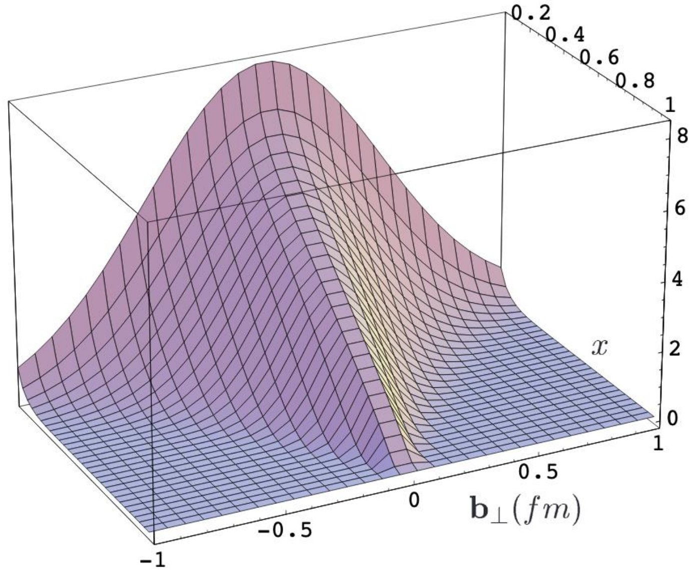
Jan Friedrich

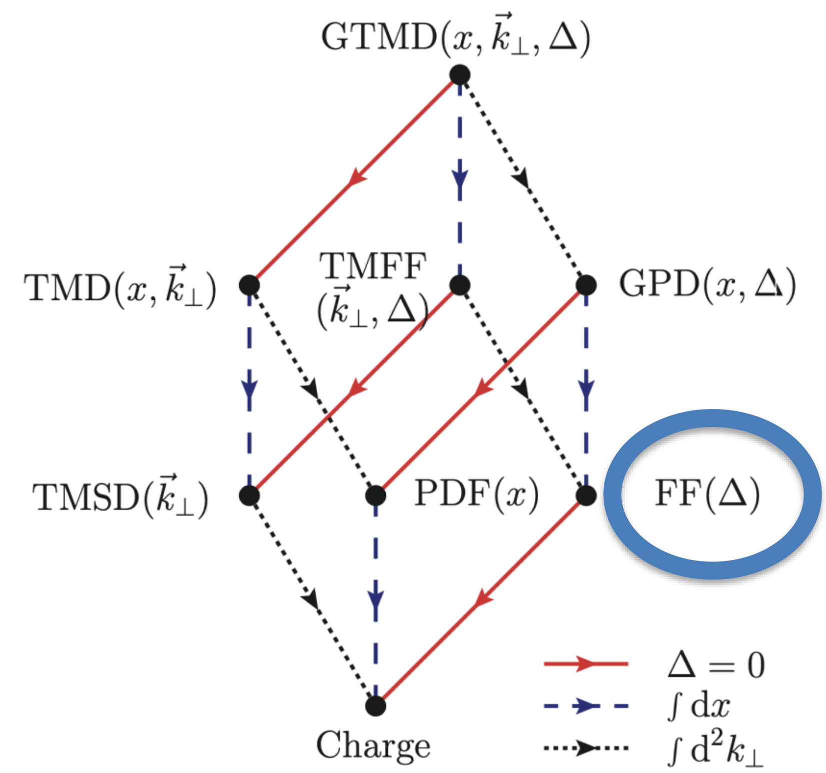
5 February 2020
CERN

Correlations in Partonic and Hadronic Interactions - 2020 (CPHI-2020)

Structure of the Nucleon

transverse extension *correlating* with the parton momentum distribution





from: **IMPACT PARAMETER SPACE INTERPRETATION FOR GENERALIZED PARTON DISTRIBUTIONS**

MATTHIAS BURKARDT

International Journal of Modern Physics A | Vol. 18, No. 02, pp. 173-207 (2003)

from:

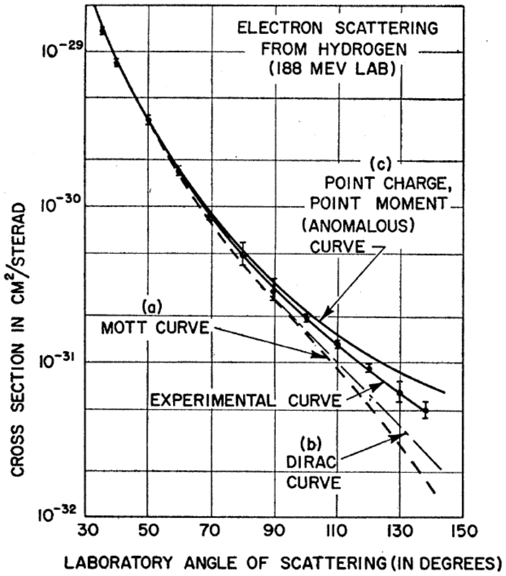
Models for TMDs and numerical methods

B. Pasquini (Pavia U. and INFN, Pavia), C. Lorce' (IPN and LPT, Orsay)

Proc.Int.Sch.Phys.Fermi 180 (2012)

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

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

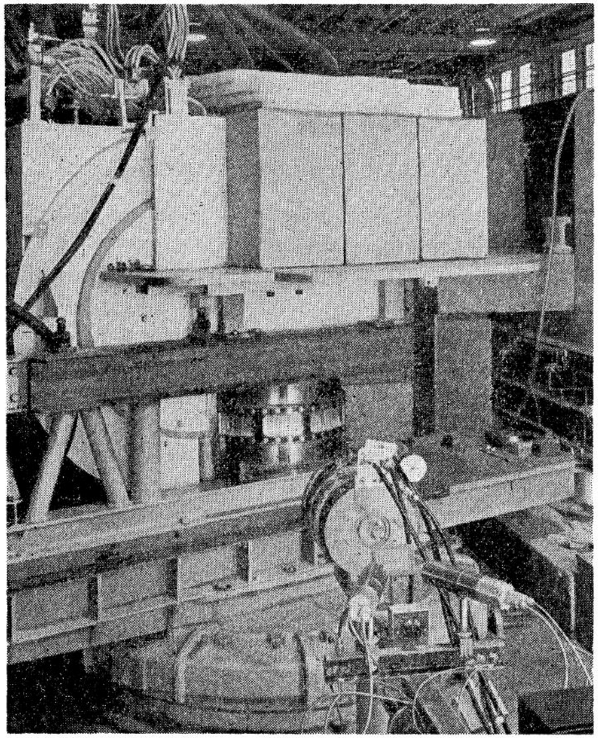


FIG. 15. The semicircular 190-Mev spectrometer, to the left, is shown on the gun mount. The upper platform carries the lead and paraffin shielding that encloses the Čerenkov counter. The brass scattering chamber is shown below with the thin window encircling it. Ion chamber monitors appear in the foreground.

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

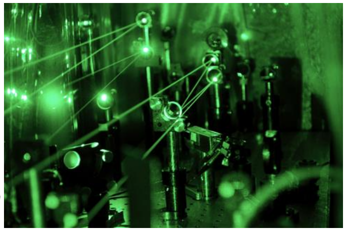
Electron Scattering and Nuclear Structure*

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

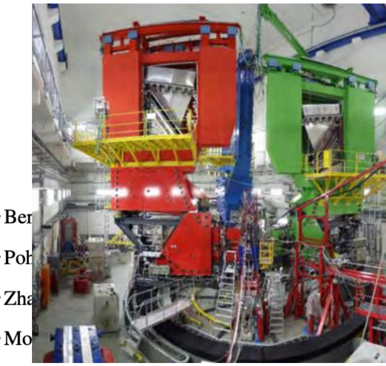
The low background has been achieved with the spectrometer, detector, and shield now to be described. A photograph of the apparatus is given in Fig. 15. It

Measurement of the Proton Radius in *ep*-Scattering

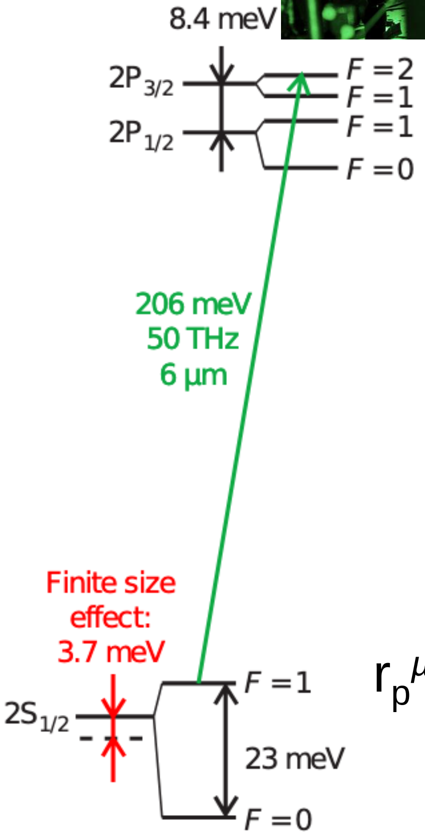
CREMA 2010

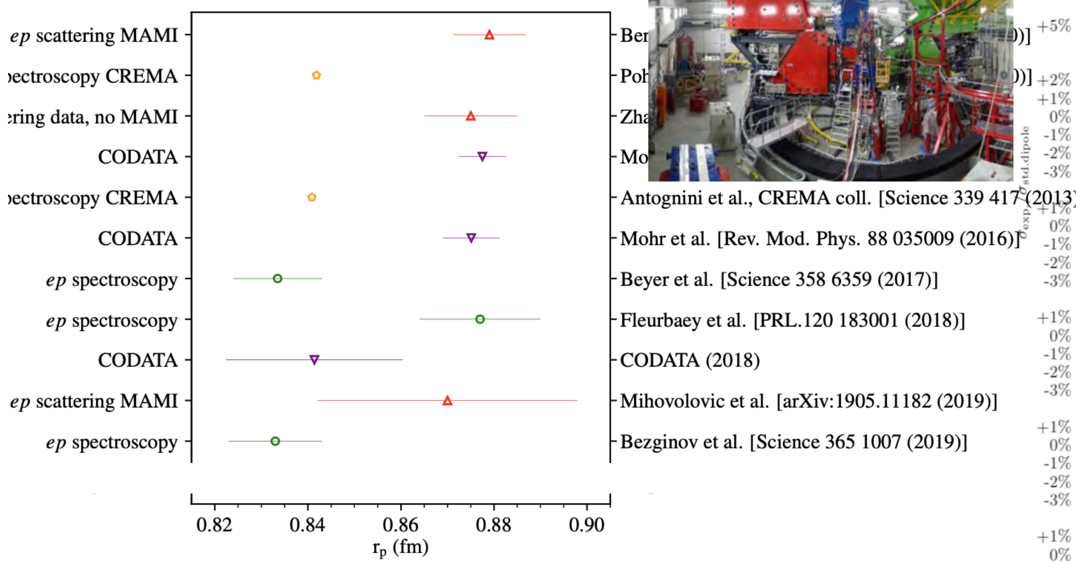


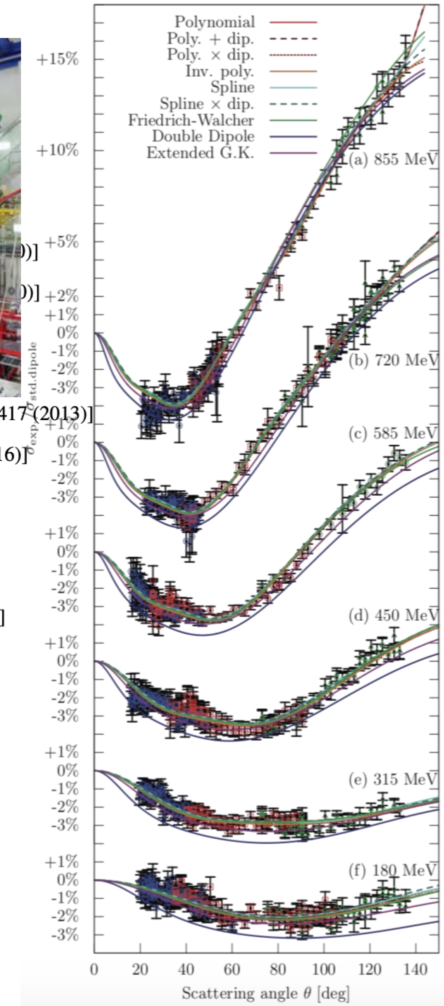
MAMI 2010



status October 13, 2019







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

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

different, in several ways favorable systematics

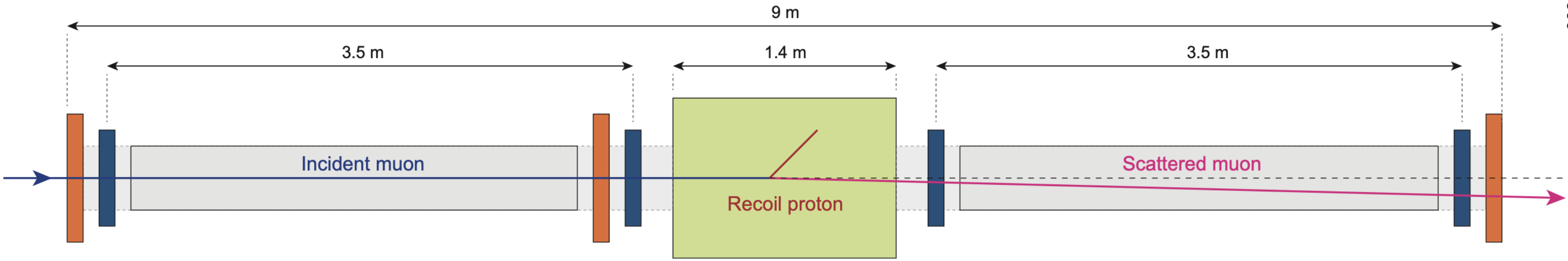
CERN-SPSC-2019-022; SPSC-P-360

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

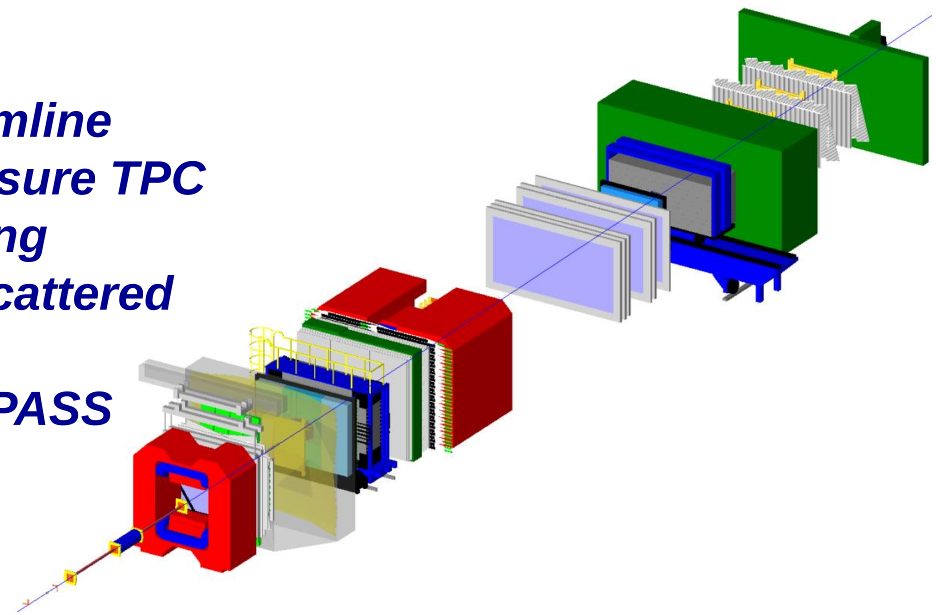
– Phase-1 –

COMPASS++*/AMBER†

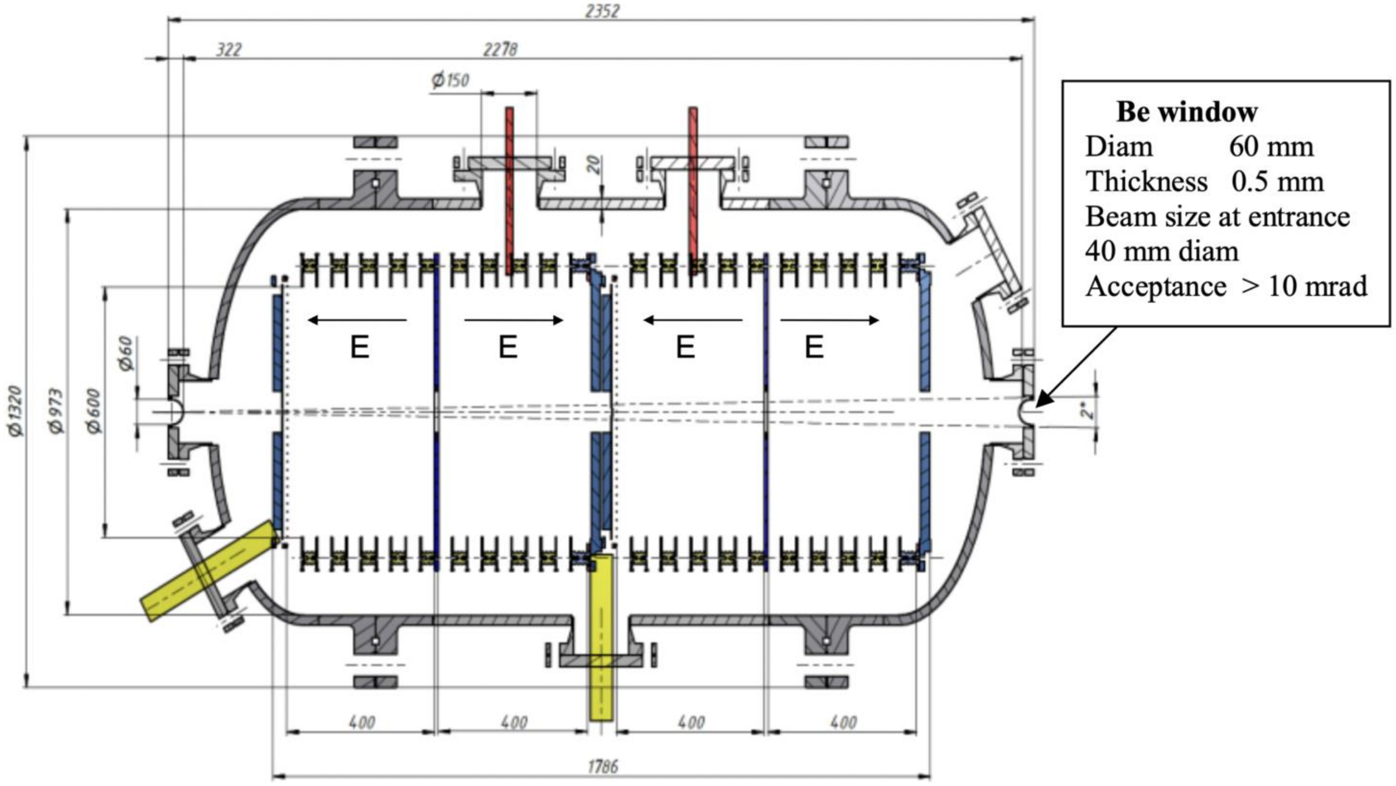
other parts: cf. talks of Marcia (Drell-Yan), Alexey (prompt photons), Psi$^{(\prime)}$ production (Igor)



- ***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***

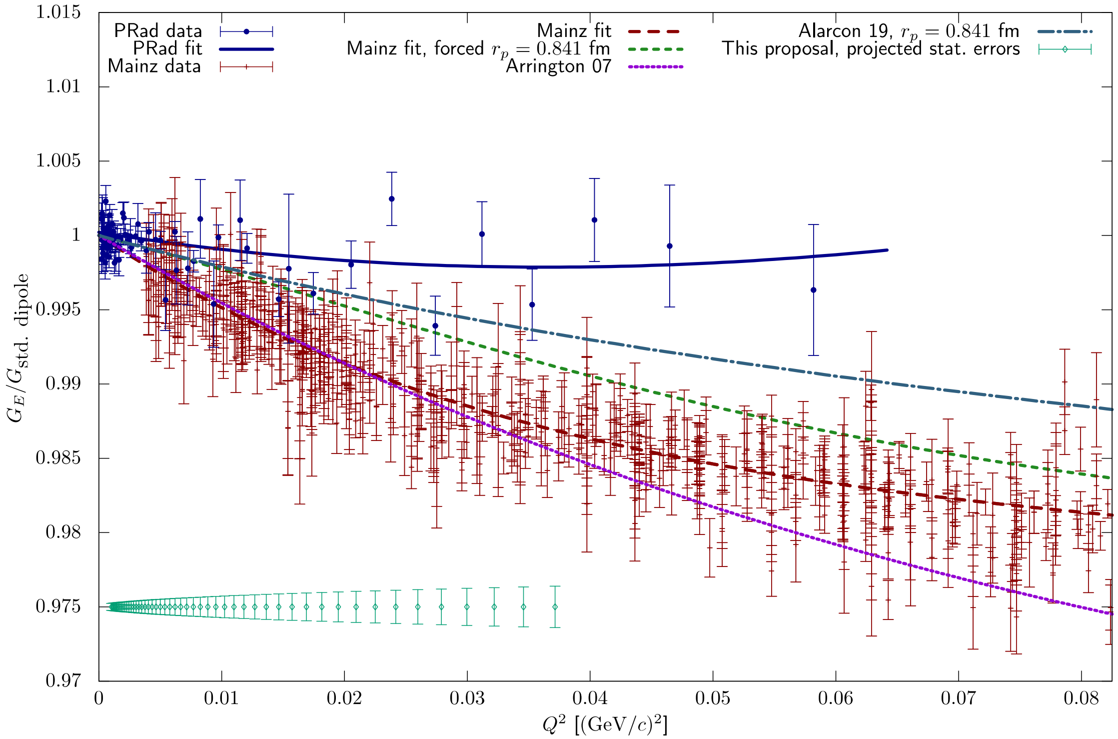


Active target: high-pressure TPC



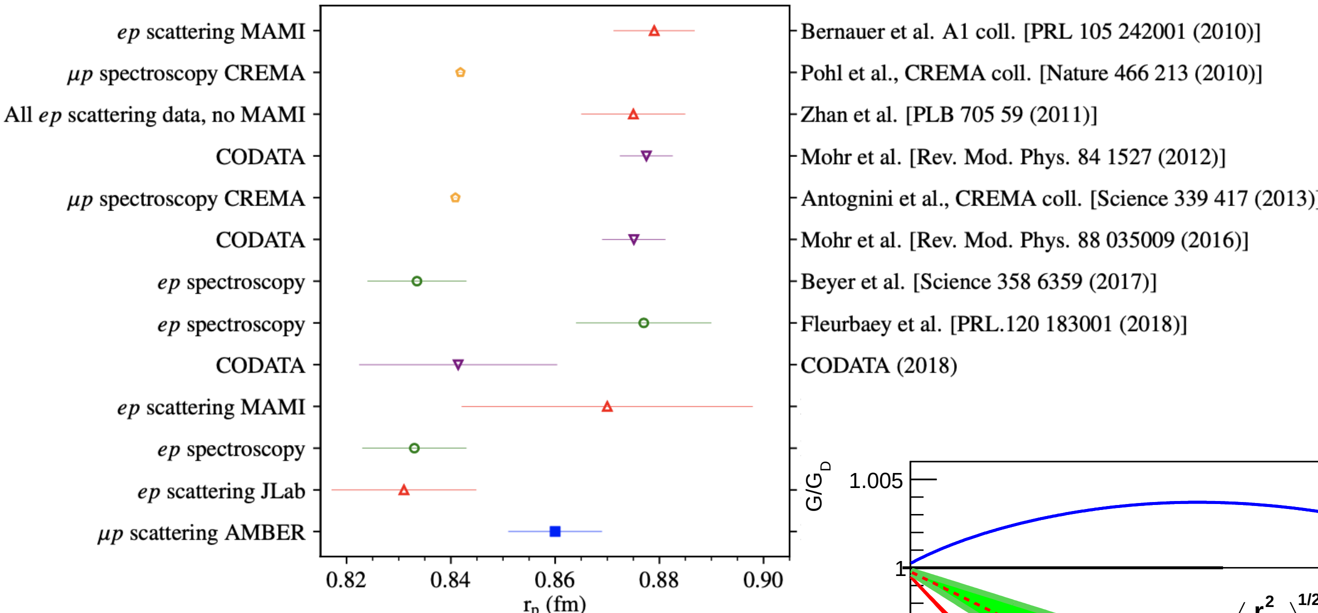
- up to 20 bar pressure
- 600mm diameter of active volume
- reconstruction of recoil energy 0.5-20 MeV (10^{-3}…$4x10^{-2}$ GeV^2)

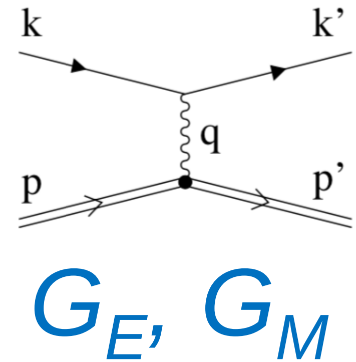
Proposed running 2022

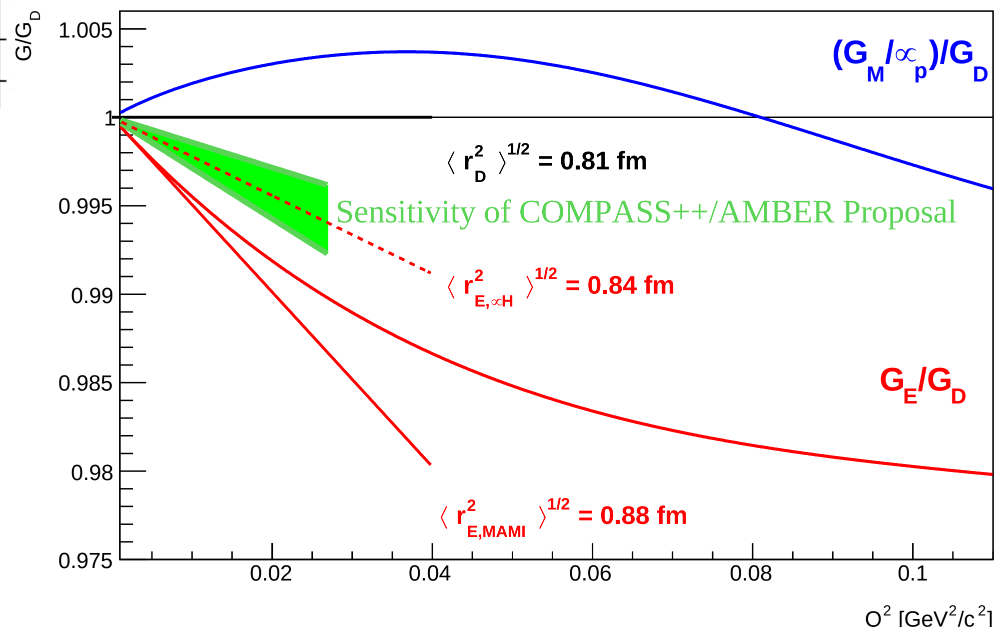


- program for 200 days of beam
- precision on the proton radius < 0.01 fm

Precision in the context of the puzzle







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

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

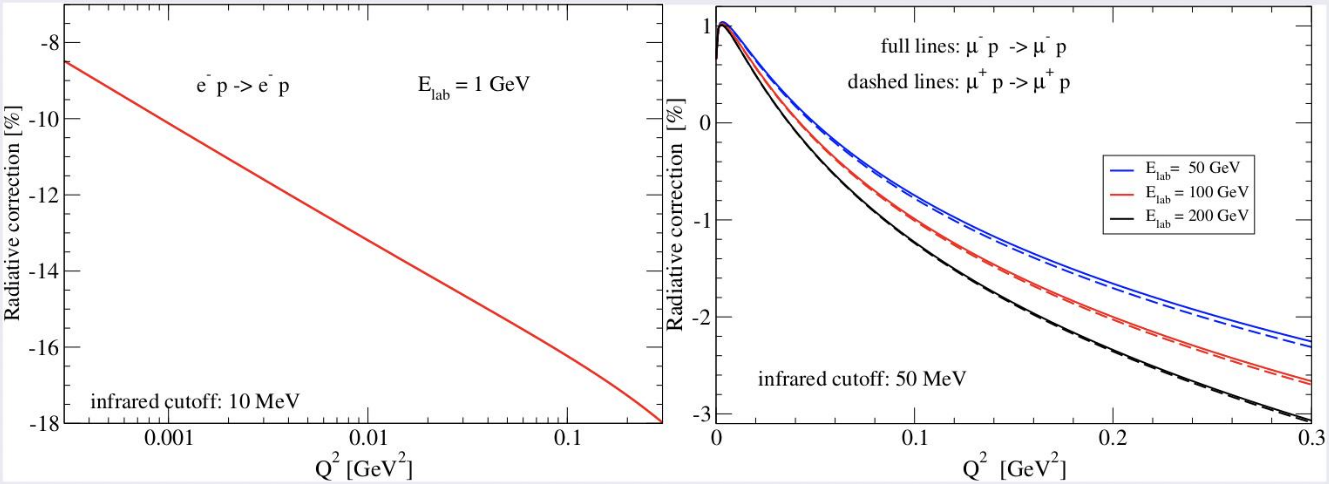
- elastic scattering experiments provide data for G_E at non-vanishing Q^2 and thus require an extrapolation procedure towards zero
  $\to$ mathematical ansatz may take more or less bounds into account (physics/theory/whatever motivated)
- Any approach (Padé, CF, DI, CM,...) *must* boil down to a series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

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

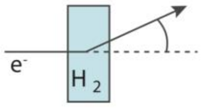
  introducing possibly very different assumptions on the coefficients c_i
- recipe for experimenters: measure a sufficiently large range of Q^2 down to values as small as possible and as precise as possible

Radiative corrections for electron and muon scattering

QED radiative corrections

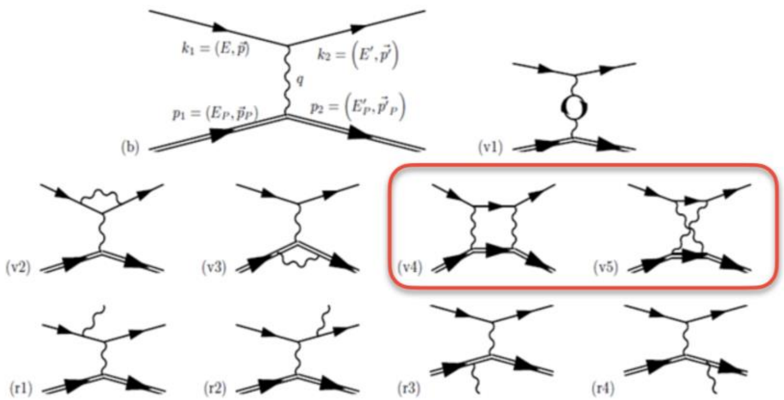


- for soft bremsstrahlung photon energies ($E_\gamma / E_{beam} \sim 0.01$), QED radiative corrections amount to $\sim$ 15-20% for electrons, and to $\sim$ 1.5% for muons
- important contribution to the uncertainty of elastic scattering intensities: *change* of this correction over the kinematic range 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

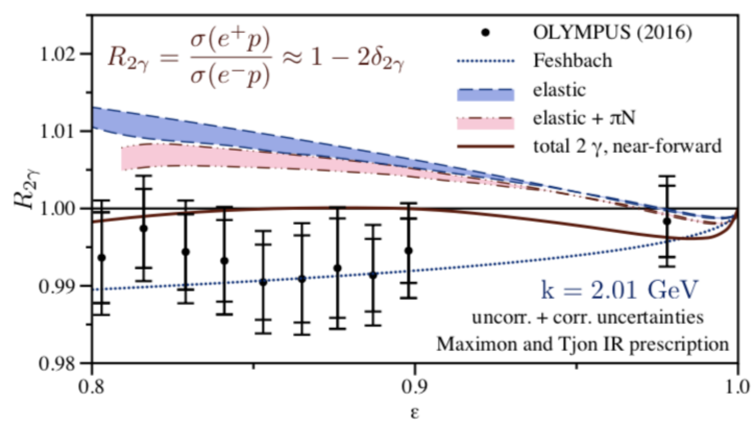


e⁻-p scattering

Radiative corrections



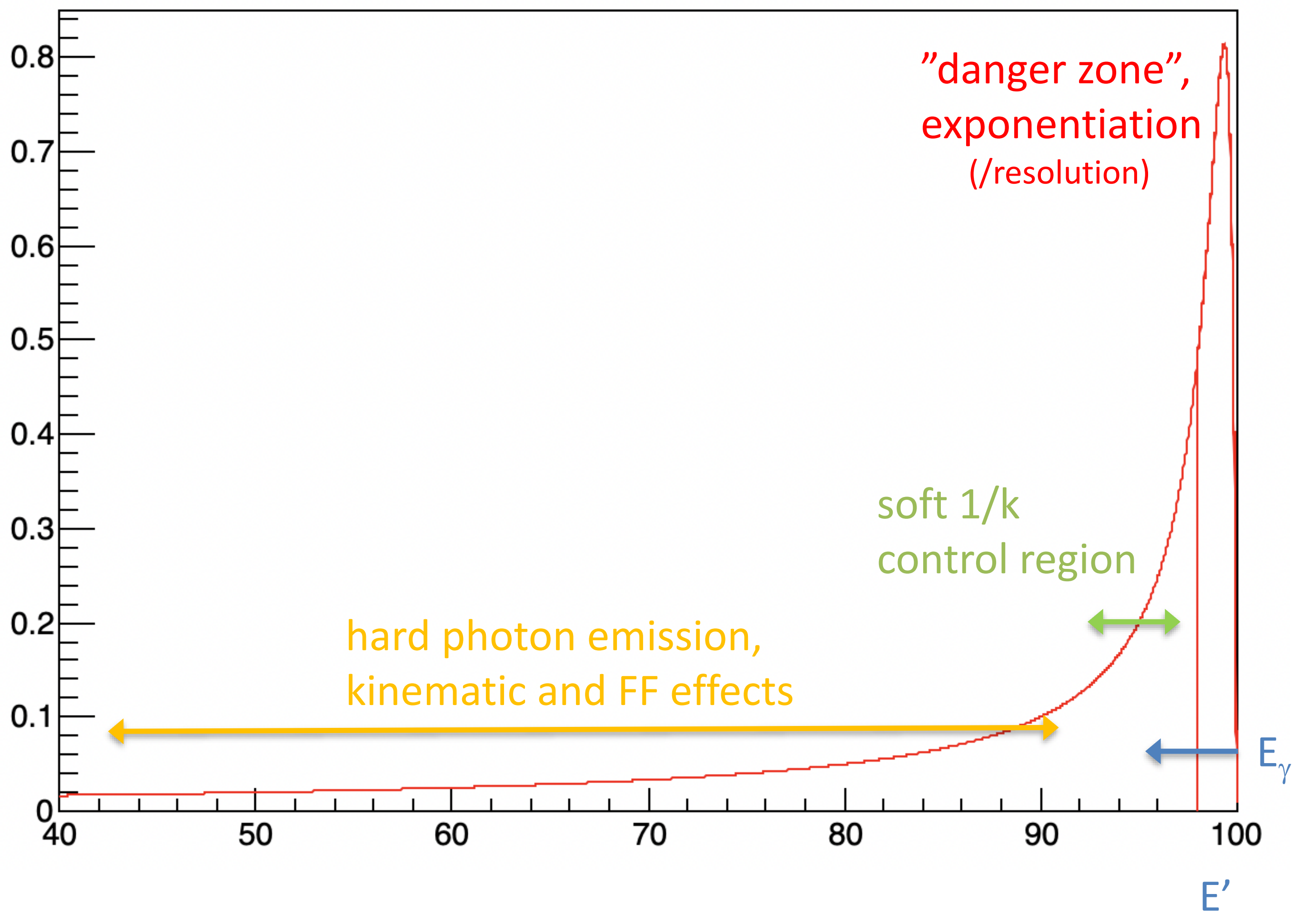
$$\sigma^{exp} \equiv \sigma_{1\gamma}(1 + \delta_{soft} + \delta_{2\gamma})$$



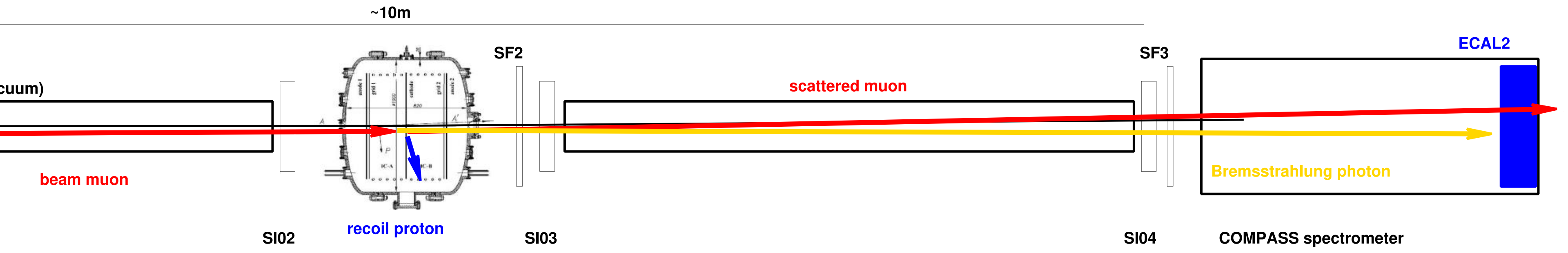
near-forward 2ɣ agree with data
multi-particle 2ɣ, e.g. ππN, is important

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

Shape of the elastic peak



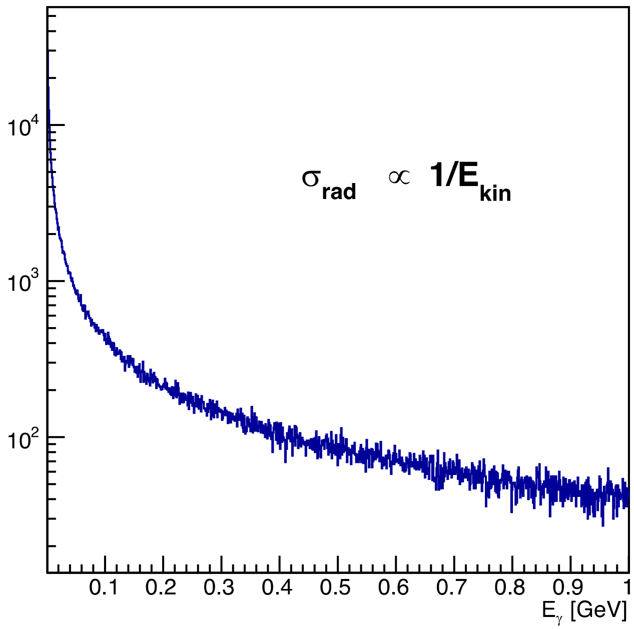
Bremsstrahlung: real-photon emission along the muon-proton scattering

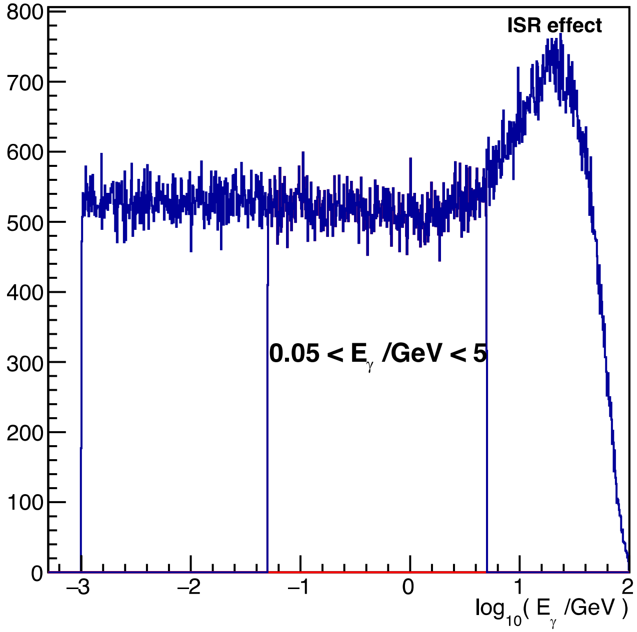


- Bremsstrahlung accompanies the elastic process
- for low-energy photons roughly $1/E_{\gamma}$ (‘infrared divergence‘)
- angular spectrum: peaking in the relativistic case, opening angle $1/\gamma$ [Lorentz factor]
- 100 GeV beam: E_{γ} between 50 MeV and 5 GeV emission probability at θ_{μ} =0.3mrad (Q^2=0.001): 5 x10^{-4}
- Bremsstrahlung events in Q^2=0.001…0.04 GeV^2/c^2 about 38000

Real-photon energy spectrum

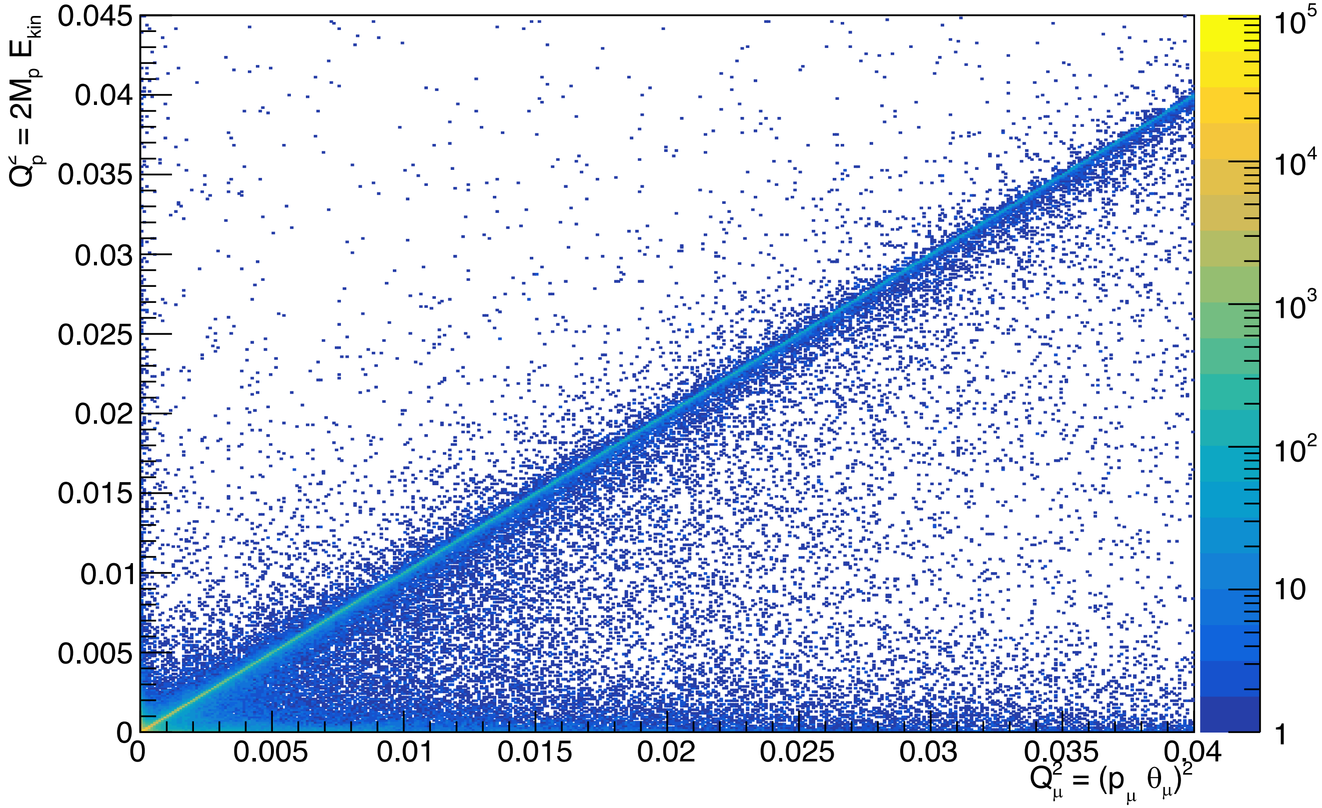
MC simulation of 500k events in θ_μ =0.3 … 2 mrad, E_γ > 1 MeV





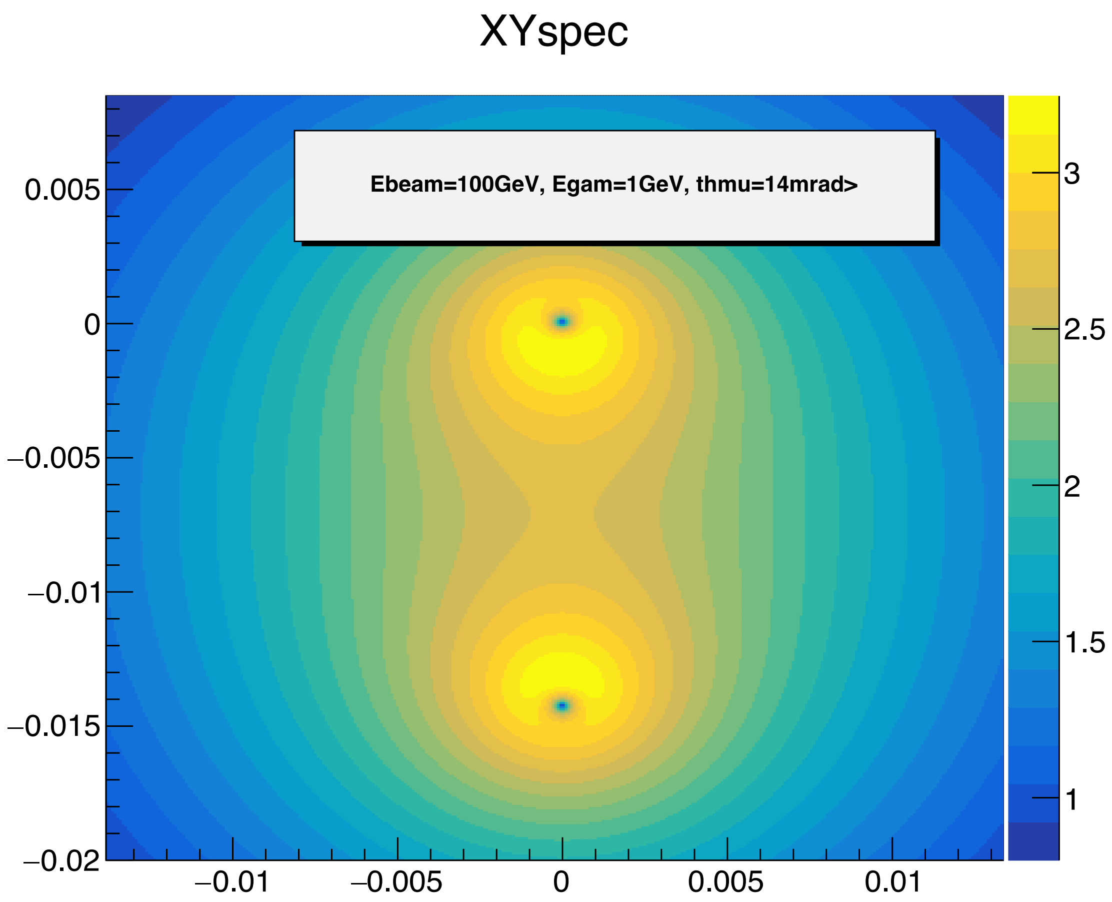
ISR effect: if incoming muon loses much of its energy, the scattering off the proton under a specific scattering angle happens at lower average Q^2 and accordingly a larger cross section

Impact on Q2 reconstruction

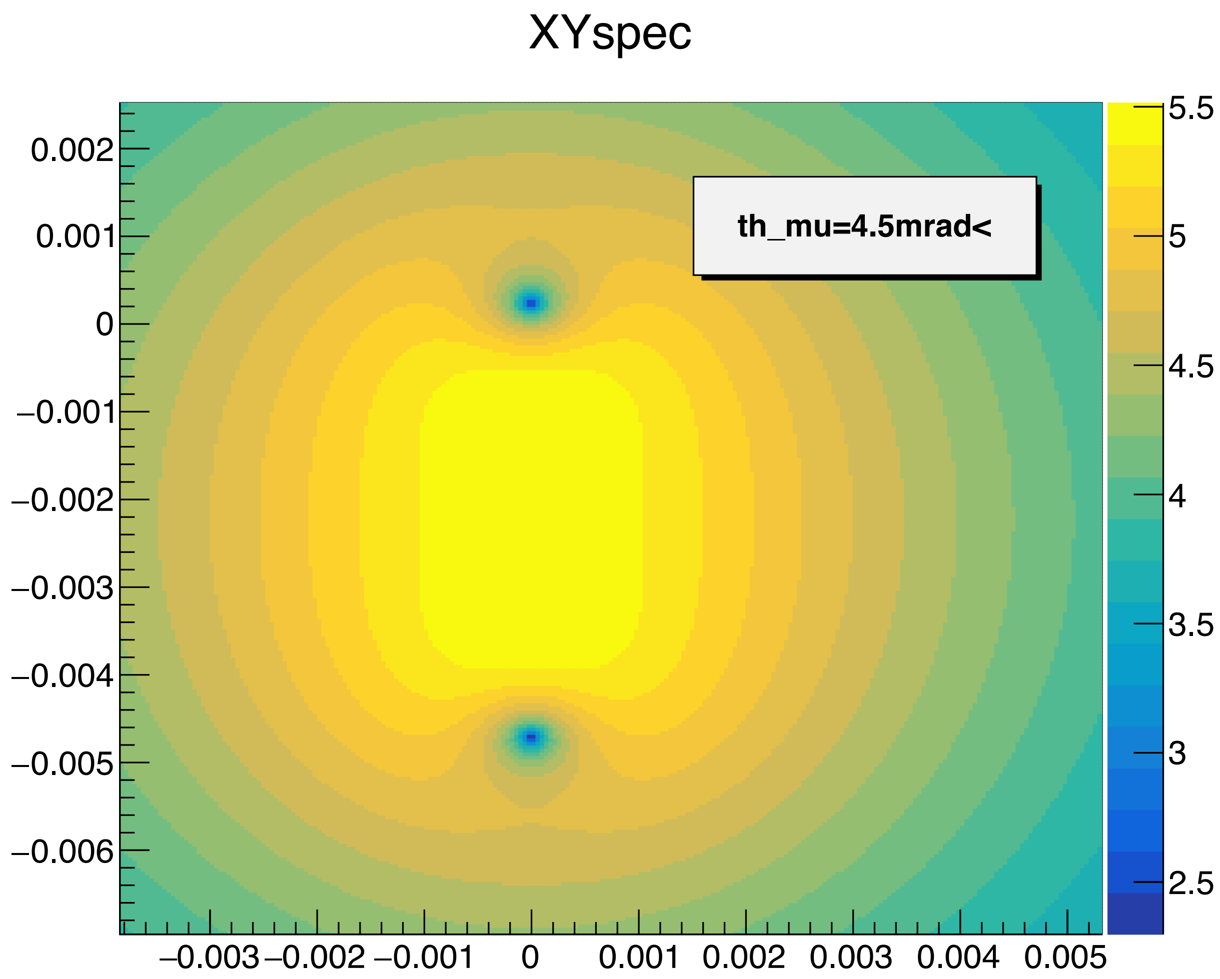


real-photon emission distorts the kinematics, correlation of reconstruction from muon and recoil proton becomes blurred

Bremsstrahlung emission angle, E=100GeV



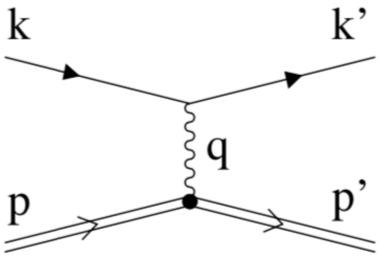
Bremsstrahlung emission angle, E=100GeV

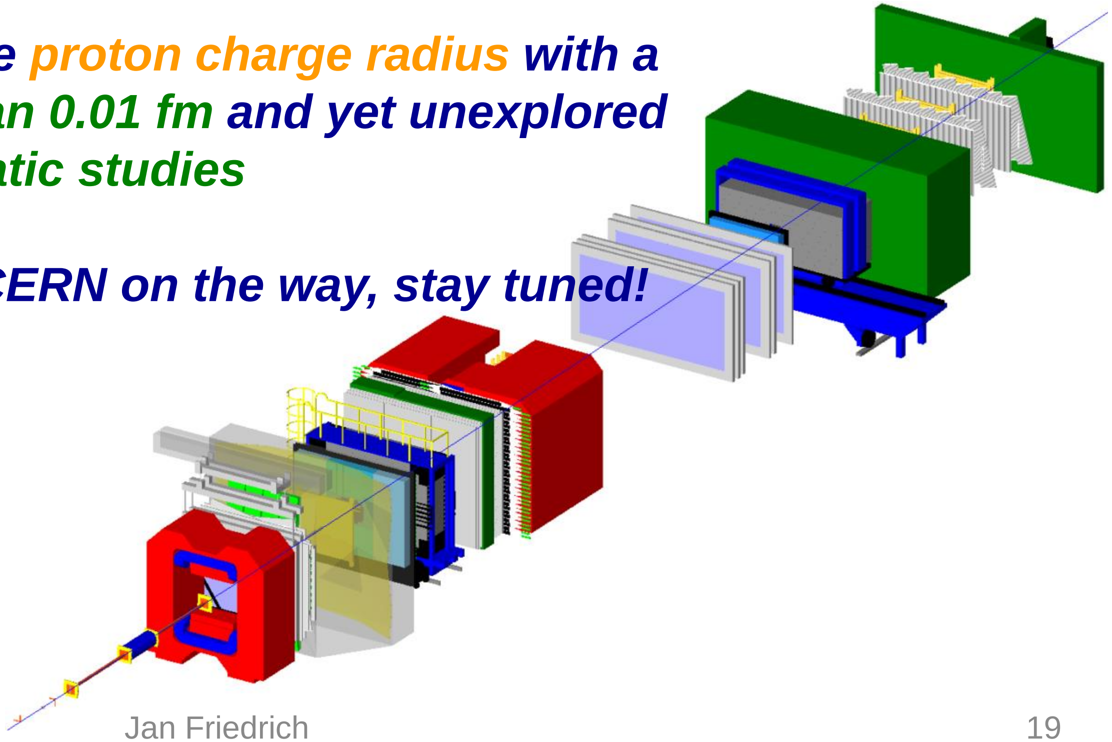


Summary and Outlook

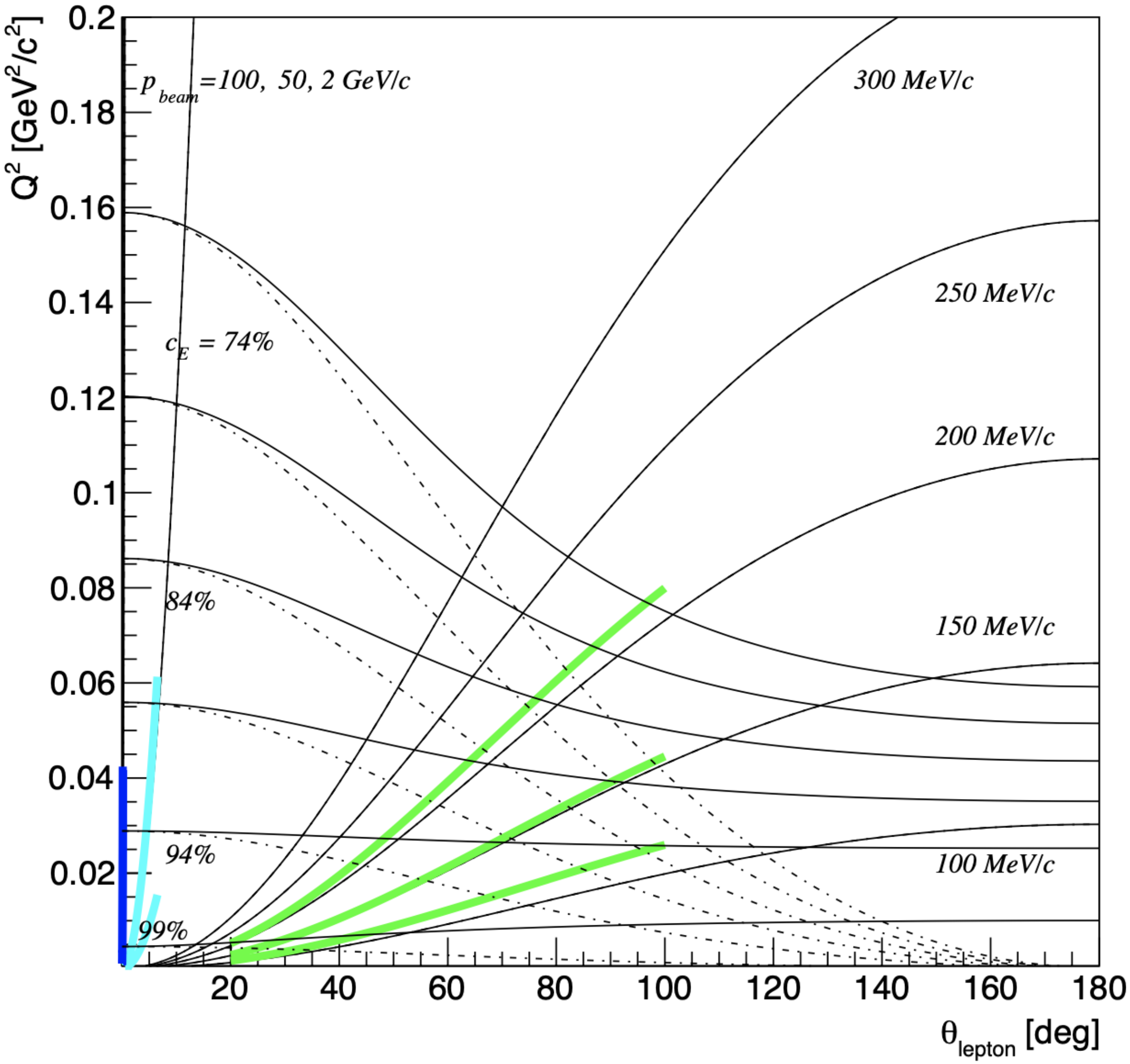
- *COMPASS++/AMBER* ***proposes high-energy elastic muon-proton scattering for the***
- ***determination of*** $G_{E,p}$ ($10^{-3} < Q^2 < 4\ 10^{-2}$) ***with relative point-to-point precision < 10^{-3} and the***
- ***measurement of the** proton charge radius **with a precision better than 0.01 fm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

approval by CERN on the way, stay tuned!

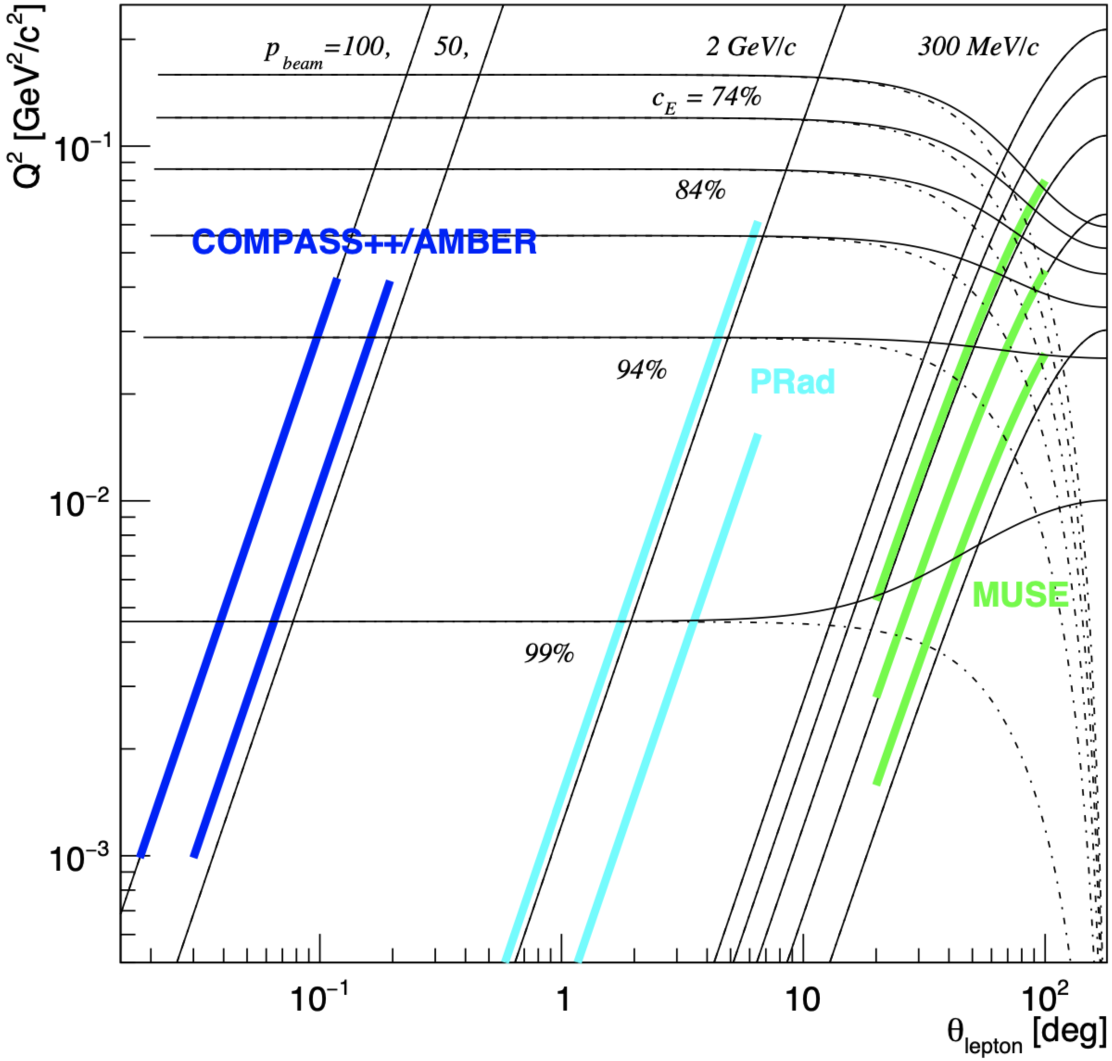




Kinematic ranges



Kinematic ranges



Models for the Nucleon Form Factors employing Dispersion Relations

Nuclear Physics A 596 (1996) 367–396

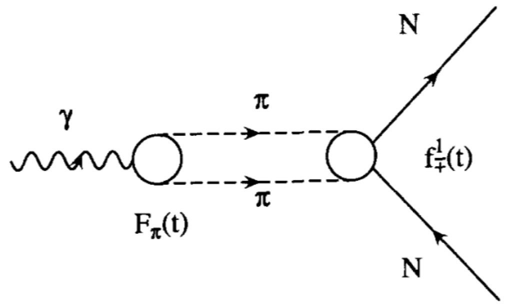
Dispersion-theoretical analysis of the nucleon electromagnetic form factors ⋆

P. Mergell [a,1], Ulf-G. Meißner [b,2], D. Drechsel [a,3]

[a] *Universität Mainz, Institut für Kernphysik, J.-J.-Becher Weg 45, D-55099 Mainz, Germany*

[b] *Universität Bonn, Institut für Theoretische Kernphysik, Nussallee 14-16, D-53115 Bonn, Germany*

Received 21 June 1995



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

Table 2
Proton and neutron radii

accurate values from a few-parameter fit to all-Q^2 data

	r_E^p [fm]	r_M^p [fm]	r_M^n [fm]	r_1^p [fm]	r_2^p [fm]	r_2^n [fm]
Best fit	0.847	0.836	0.889	0.774	0.894	0.893
Ref. [21]	0.836	0.843	0.840	0.761	0.883	0.876

For the data in the low-energy region, the contribution of the Q^4 term to the proton electric form factor is marginal (< 0.3%). This leads to an rather accurate value for $\langle r_E^2 \rangle_p$,

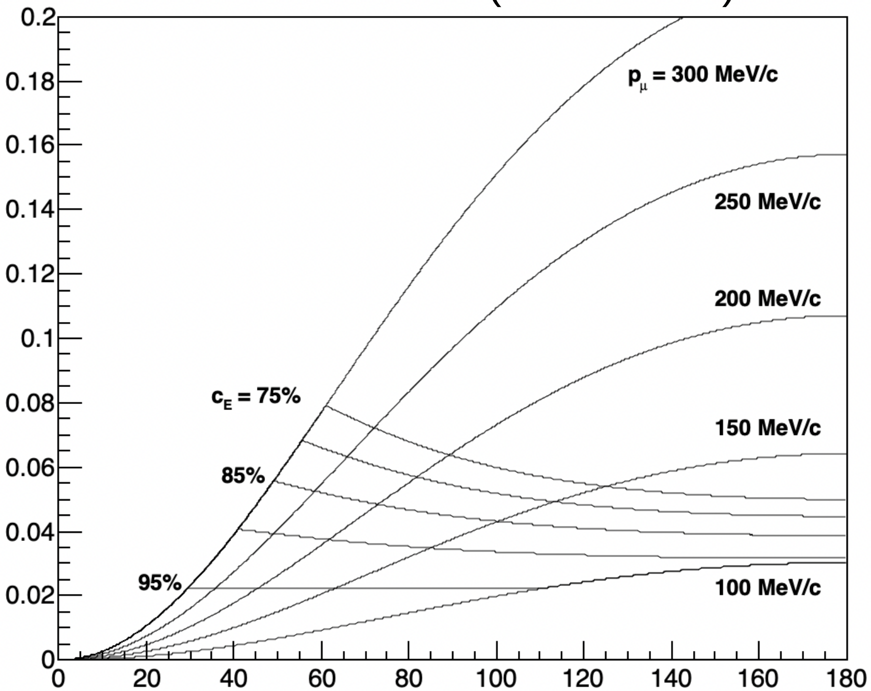
$$\langle r_E^2 \rangle_p = (0.862 \pm 0.012)^2 \mathrm{fm}^2 . \qquad (29)$$

low-Q^2 experimental of-the-time value discussed

With that constraint, the authors of Ref. [15] performed a four-pole fit (with two masses fixed at $M_\rho = 0.765$ GeV and $M_{\rho'} = 1.31$ GeV) to the available data for the proton electric and magnetic form factors up to $Q^2 \simeq 5$ GeV^2. This allowed to reconstruct the

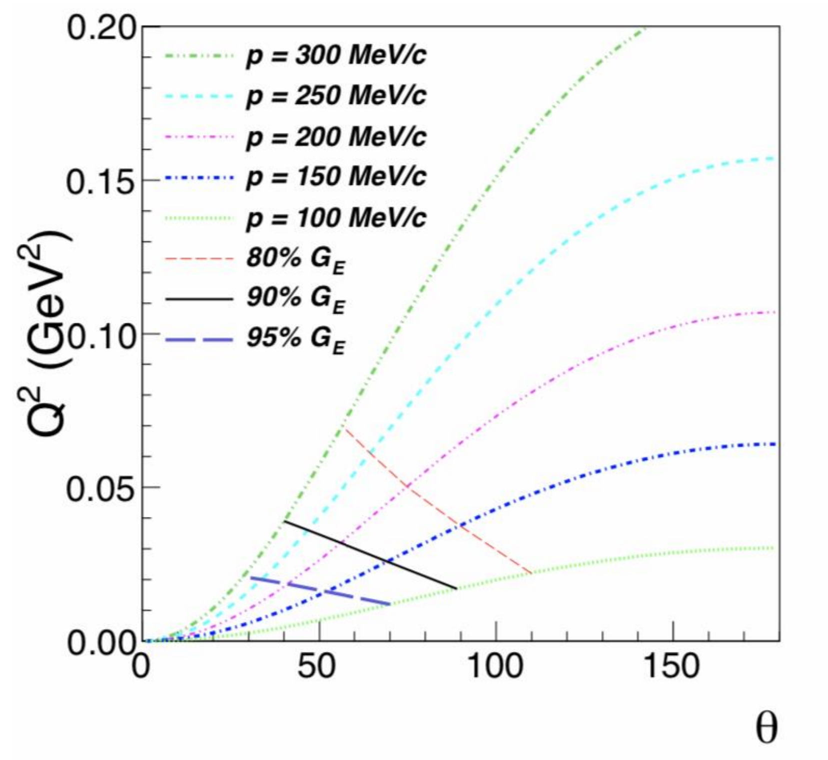
MUSE – kinematics of low-energy elastic muon scattering

our calculation (muon mass)

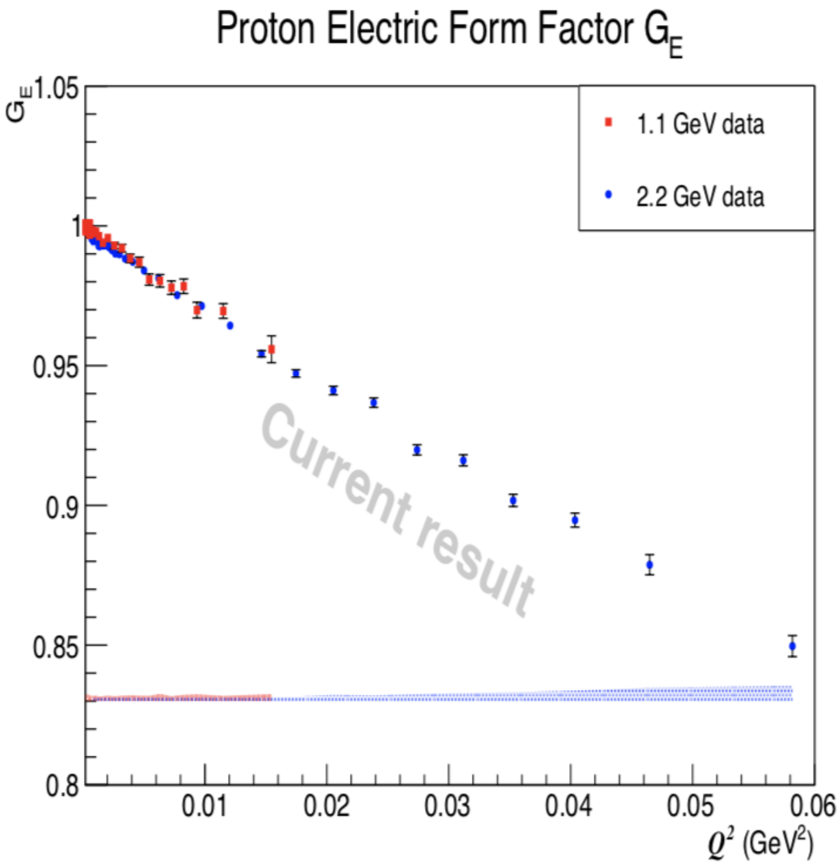


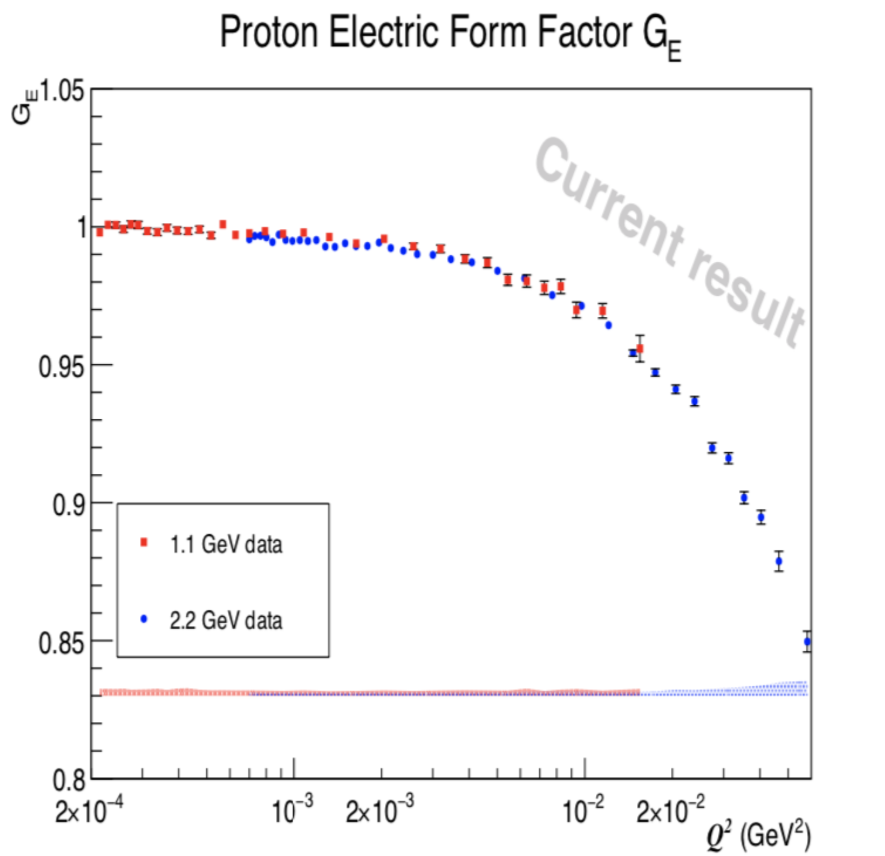
A Proposal for the Paul Scherrer Institute πM1 beam line

Studying the Proton "Radius" Puzzle with μp Elastic Scattering



PRad





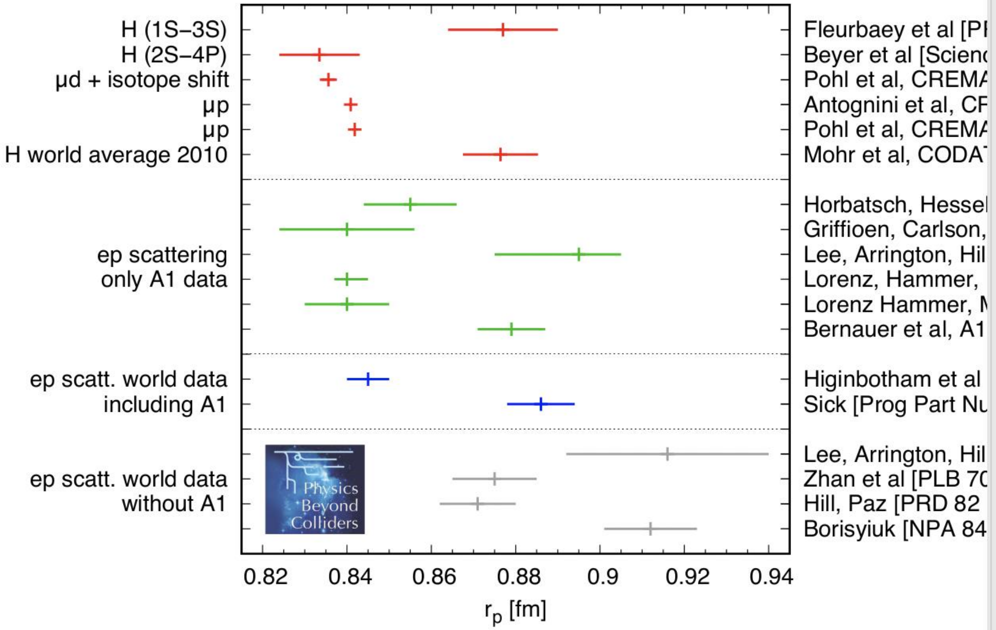
Lowest Q^2 ever achieved from ep elastic scattering

from: H. Gao, ICSAC2019, Losinj, Croatia

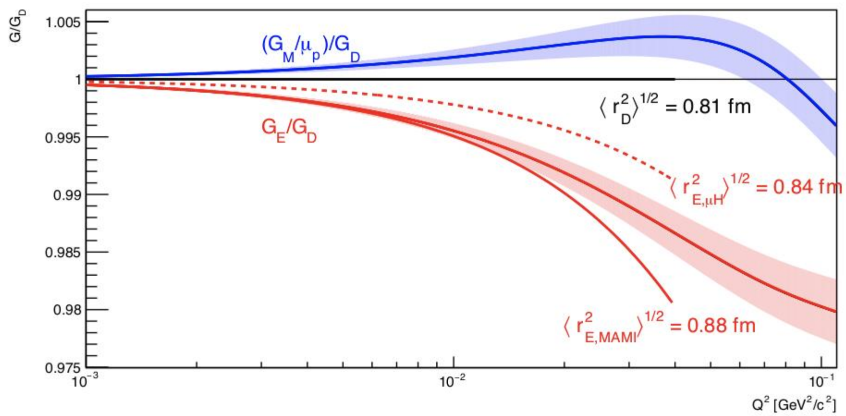
COMPASS++

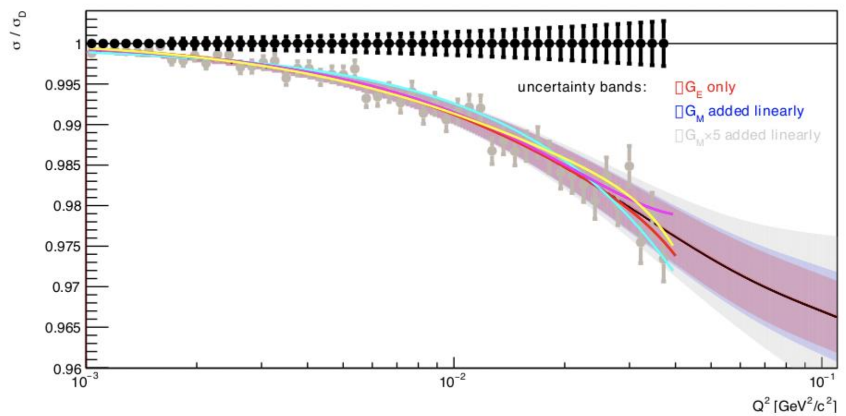
- persistent discrepancies on proton charge radius r_p determined from spectroscopy (H, muonic H) and ep elastic scattering
- different fits to ep data yield widely different r_p
- goal: r_p from high-energy μp elastic scattering
  - ★ advantages over ep scatt:
    - ✦ smaller QED radiative corrections
    - ✦ very small contamination from magnetic form factor

proton charge radius from spectroscopy or ep scattering



Proton radius measurement from muon-proton high-energy scattering



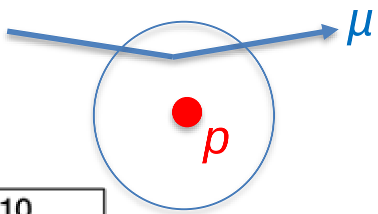


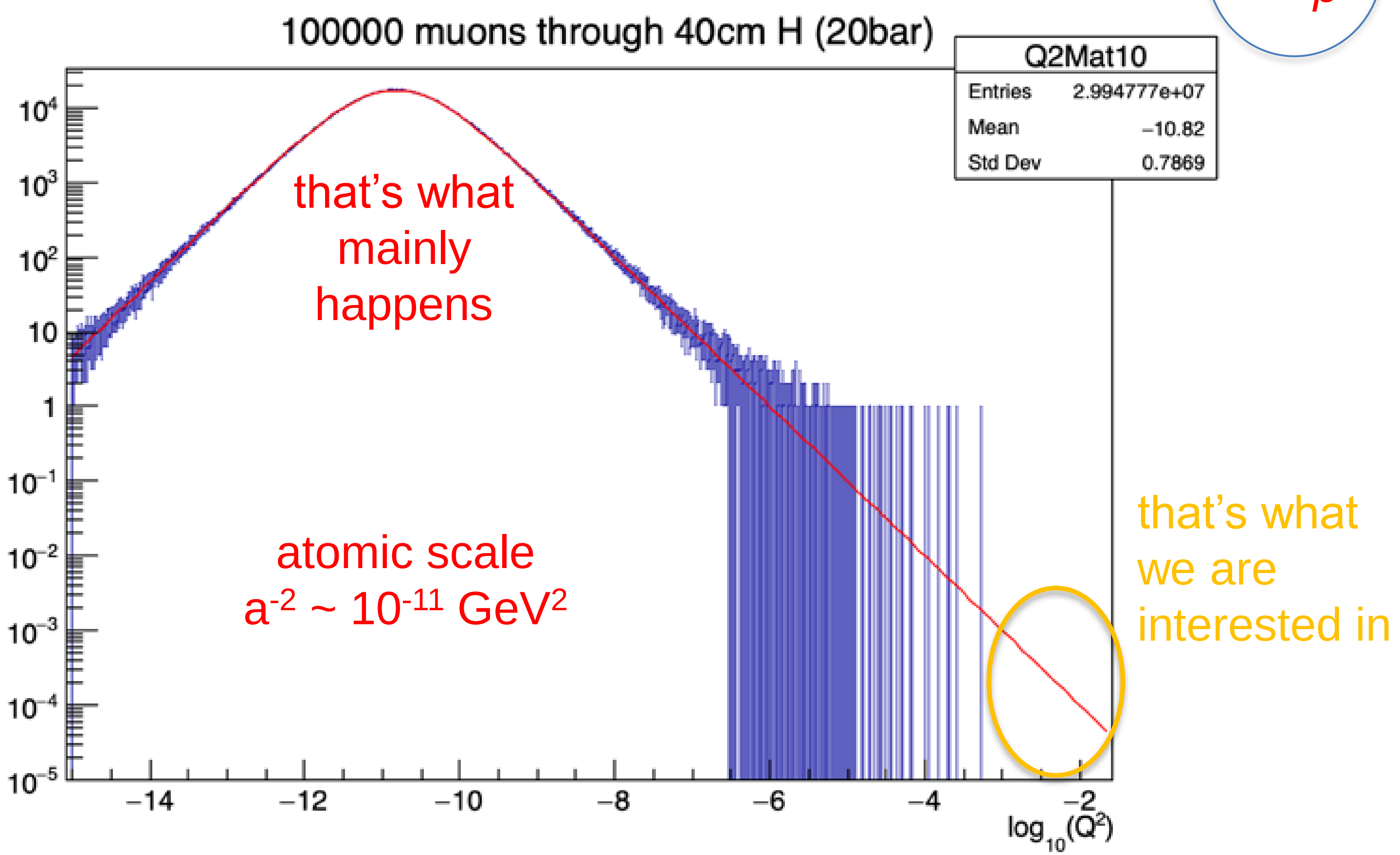
COMPASS++/AMBER proposal:

- precise measurement of recoiling proton in a pressurized active-target H_2 cell with TPC readout
- in coincidence with the scattered muon kinematics at 100 GeV beam energy
- reach a point-to-point precision of 10^{-3}
- Q^2 range $10^{-3} – 4x10^{-2}$ GeV^2
- fit with free parameters up to terms in Q^4 gives <r^2> with the desired precision
- advantegous / complementary systematics compared to the other experimental approaches

General cross-section behavior

- steep increase towards smaller Q^2 with $1/Q^4$
- forever rising?
- not for scattering off atoms / molecules:





Cross-section behavior

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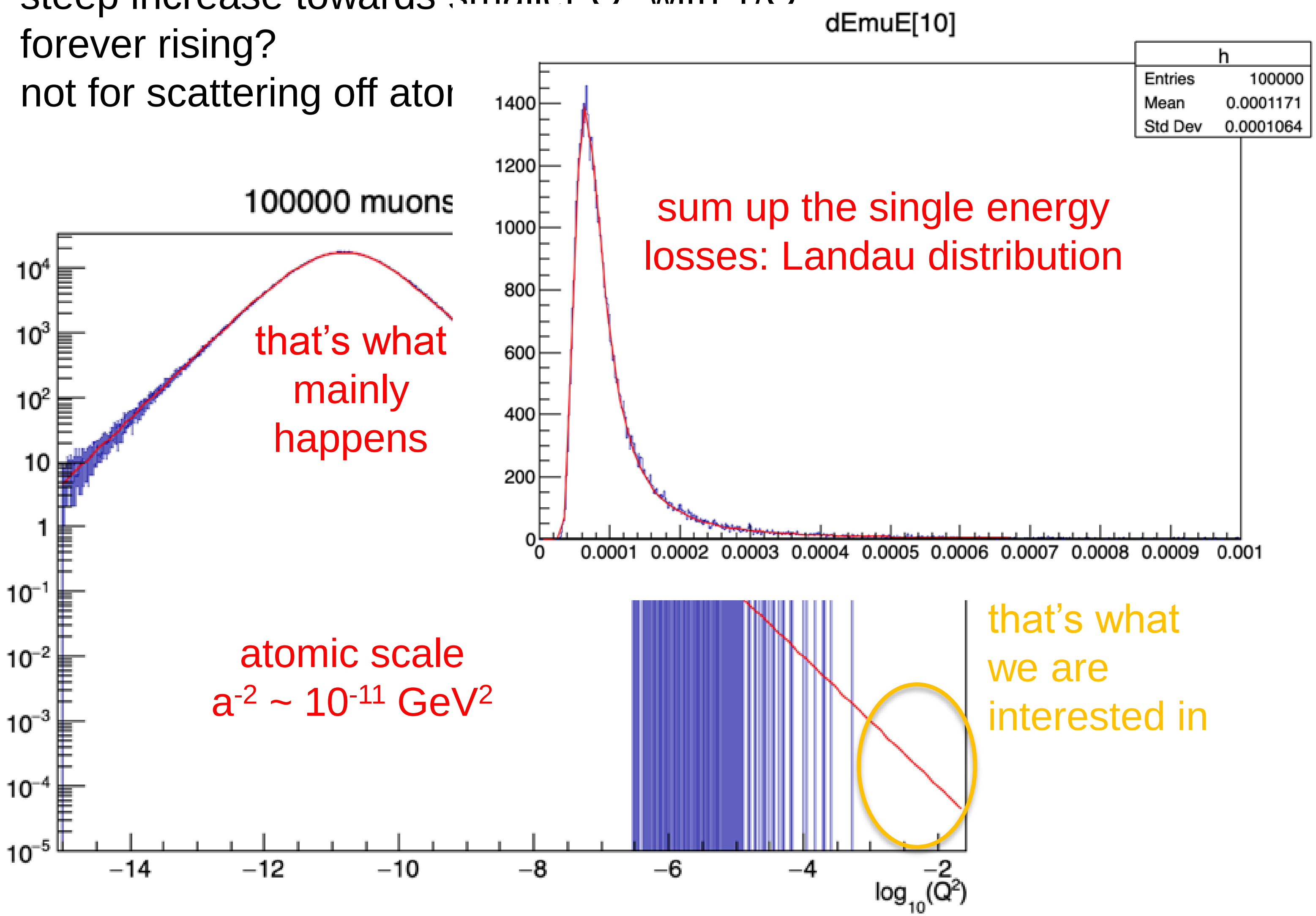
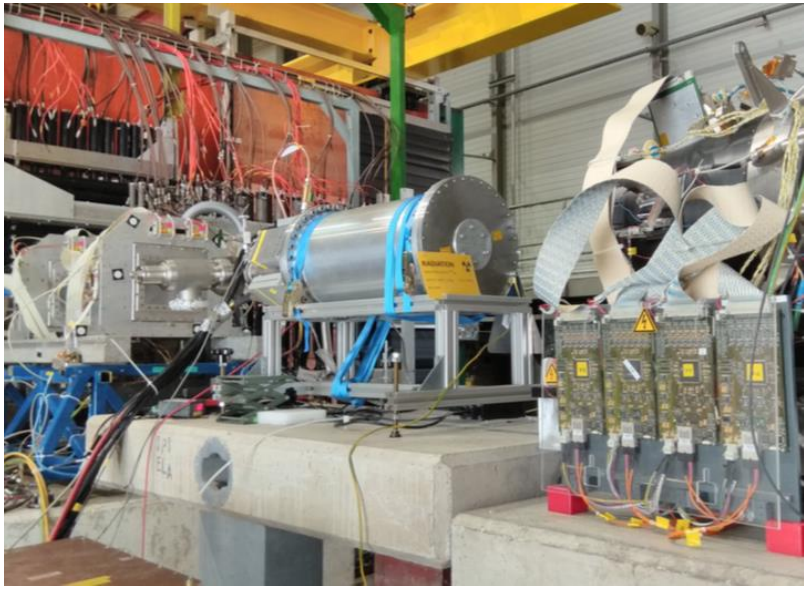
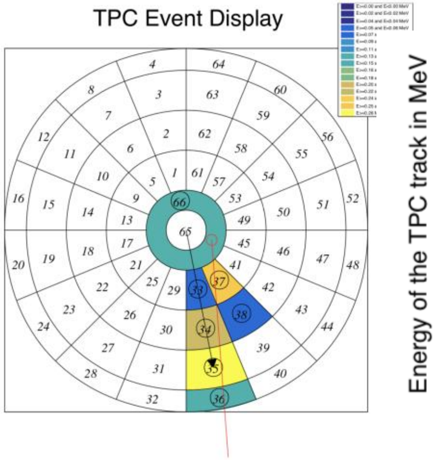


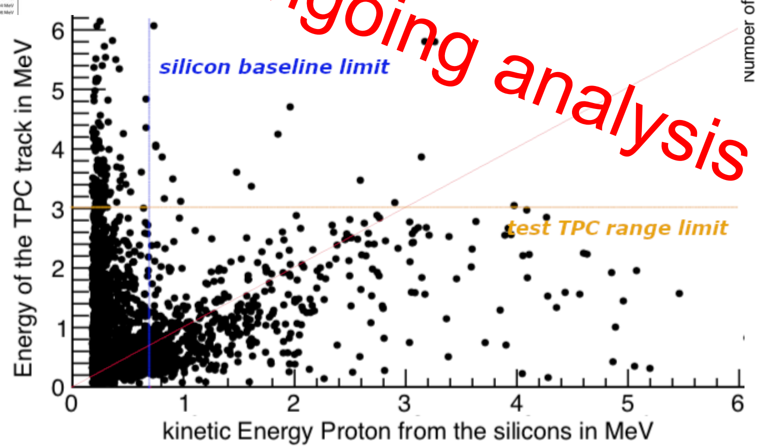
Test in 2018 for Proton Radius measurement

Test setup during 2018 DY run downstream COMPASS, check

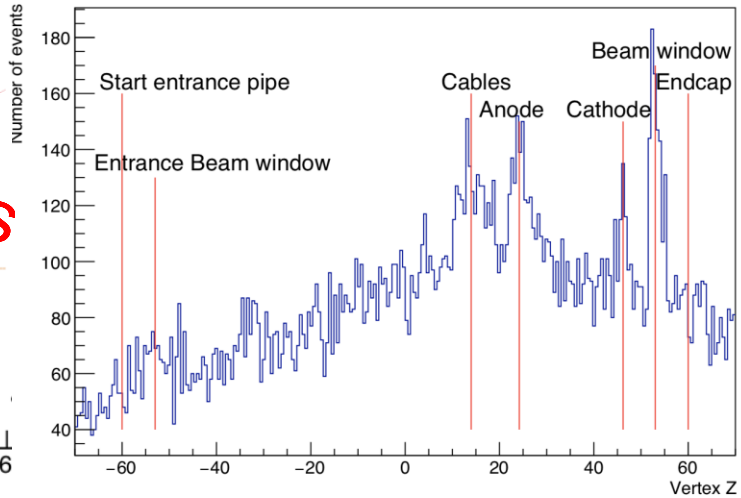
- TPC operation in muon beam ✓
- vertex reconstruction with silicon telescopes ✓
- coincidence detection of scattered muon and recoiling proton ✓







ongoing analysis



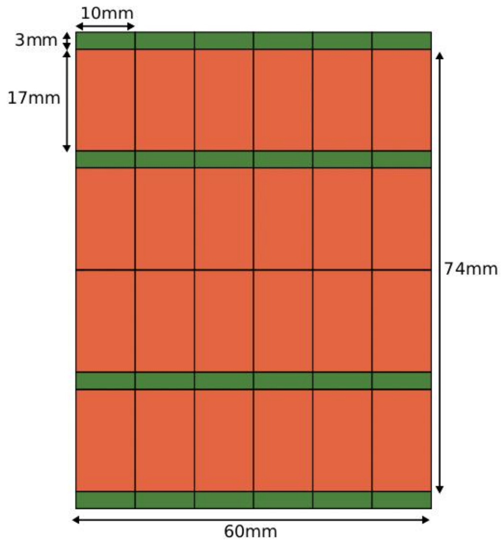
New hardware: Trigger scheme

- continuous ‘triggerless’ first-level readout
- time-slicing according to detector response time
- marking of slices for higher-level readout

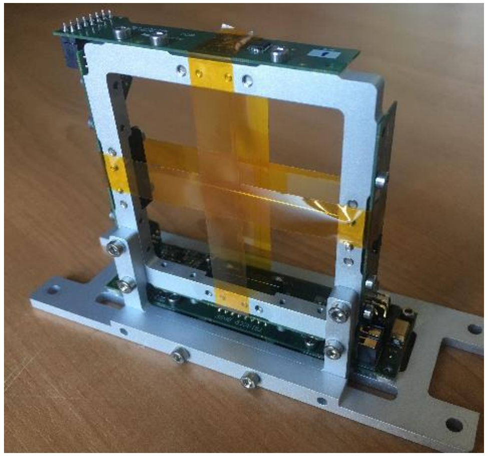
Figure 39: Overview for the time-slicing

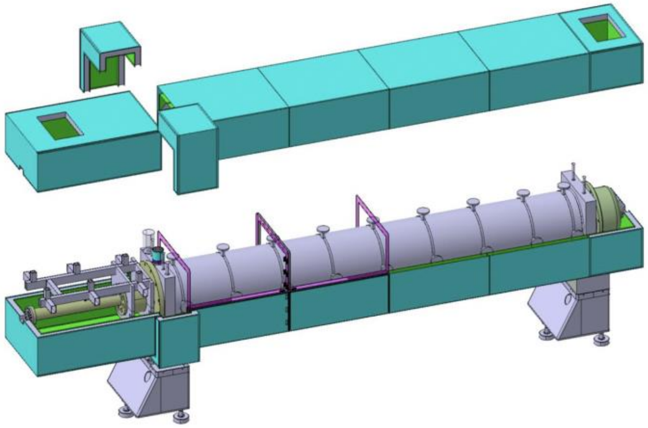
more new planned hardware

- 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

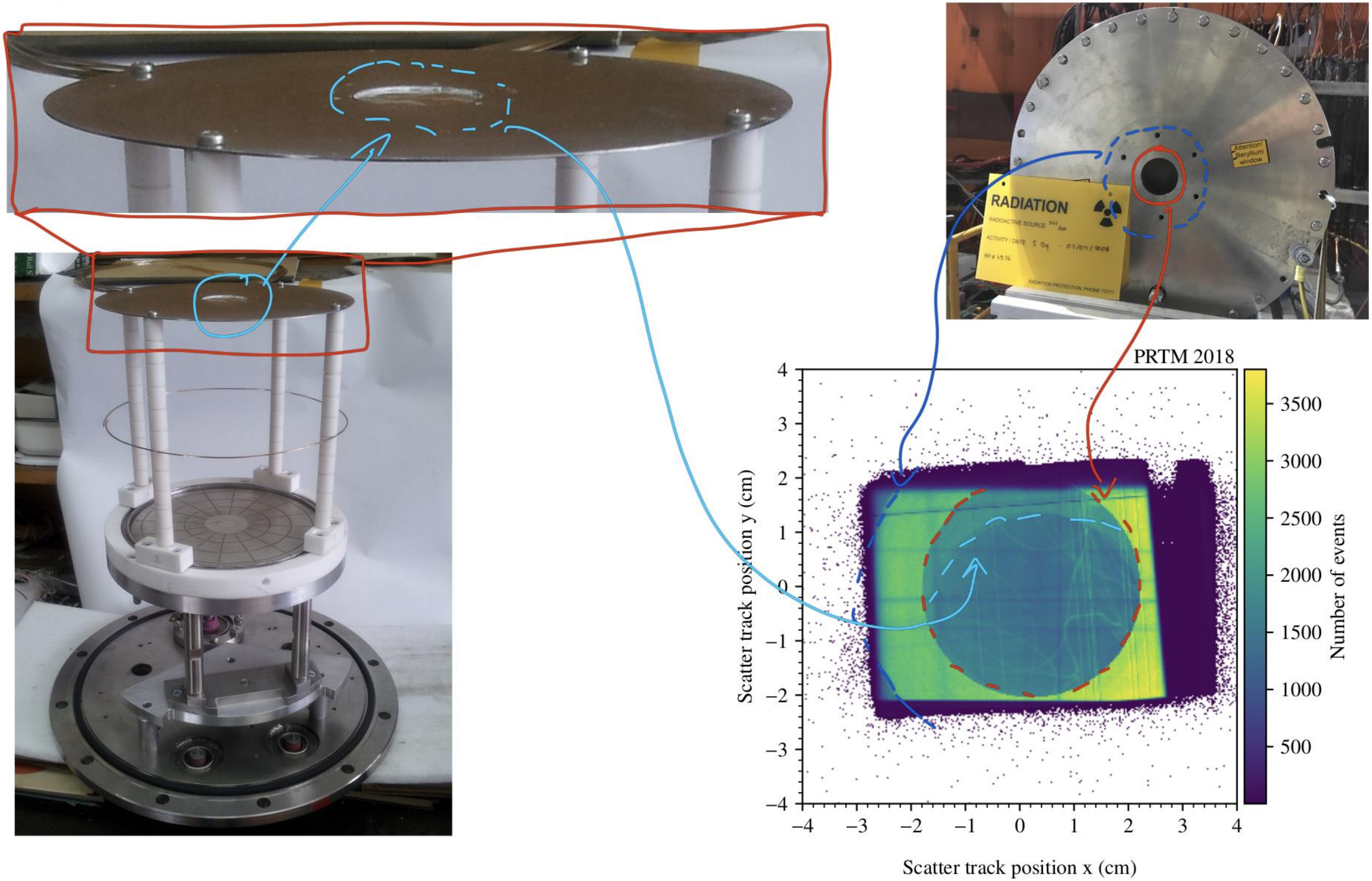
fitting with a truncated series for small Q^2

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

- 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)

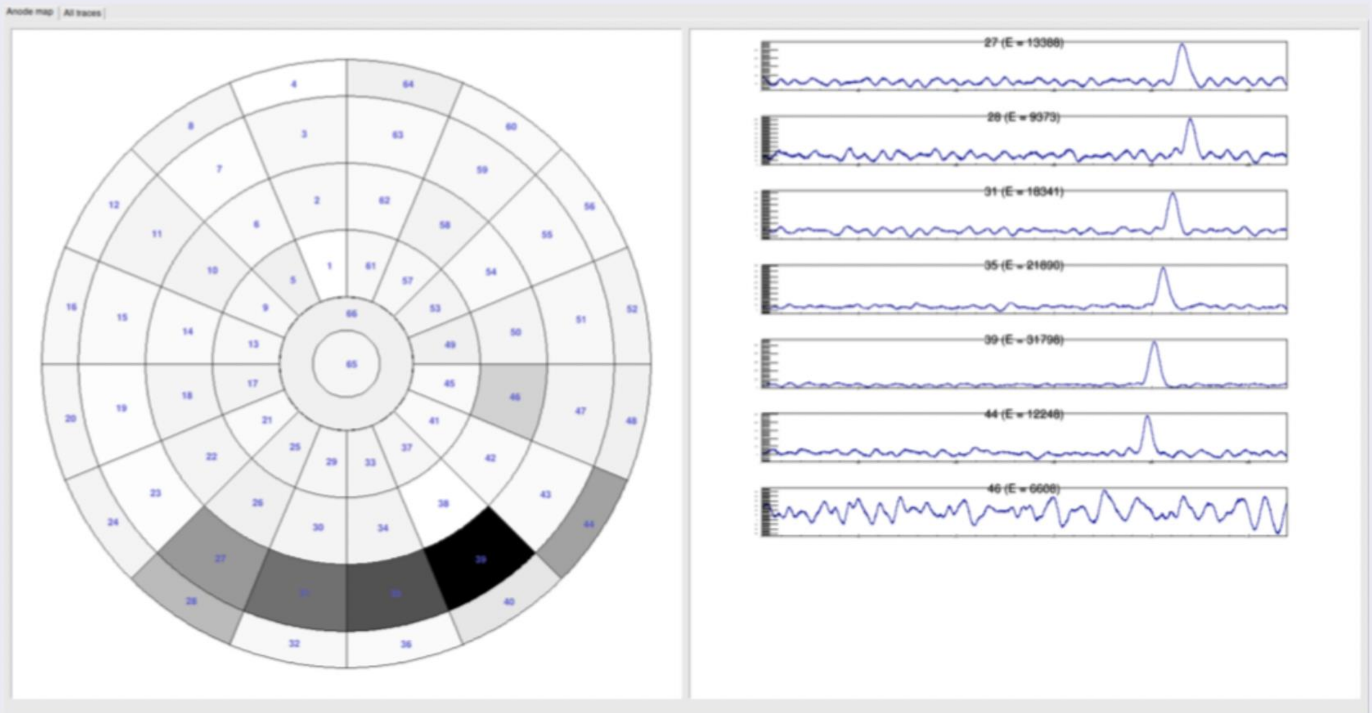
choice of higher-order terms:

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



RADIATION
RADIOACTIVE SOURCE
RADIATION PROTECTION
Attention! Beryllium window
PRTM 2018
Scatter track position y (cm)
Scatter track position x (cm)
Number of events
4
3
2
1
0
−1
−2
−3
−4
−4 −3 −2 −1 0 1 2 3 4
3500
3000
2500
2000
1500
1000
500

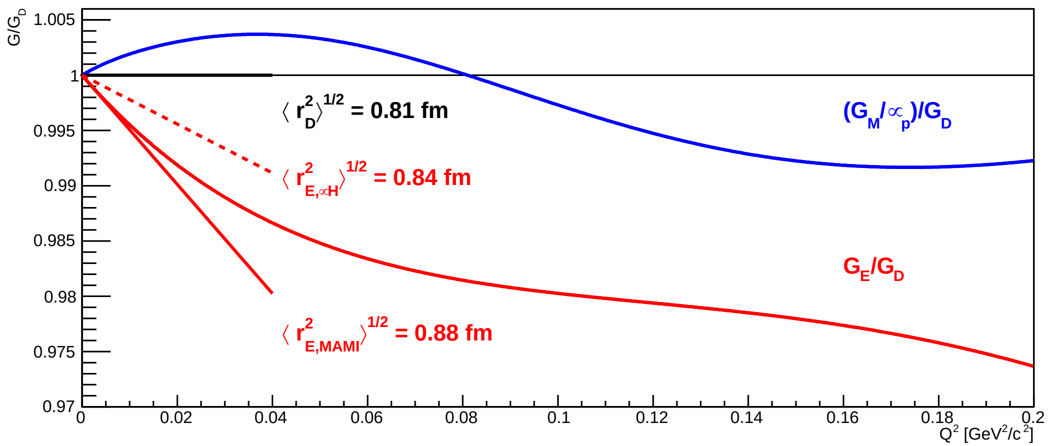
performance of TPC



- recoil protons with muon beam observed

Elastic lepton-proton cross section

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



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