# COMPASS++ / AMBER
# High-*E* muon-proton scattering: Systematics and NLO processes

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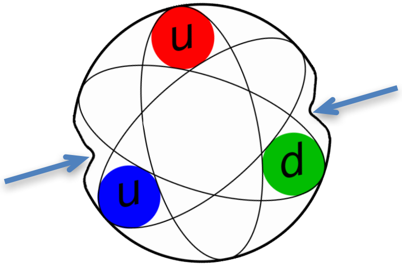
Technische Universität München



XIX International Conference
on Science, Arts and Culture

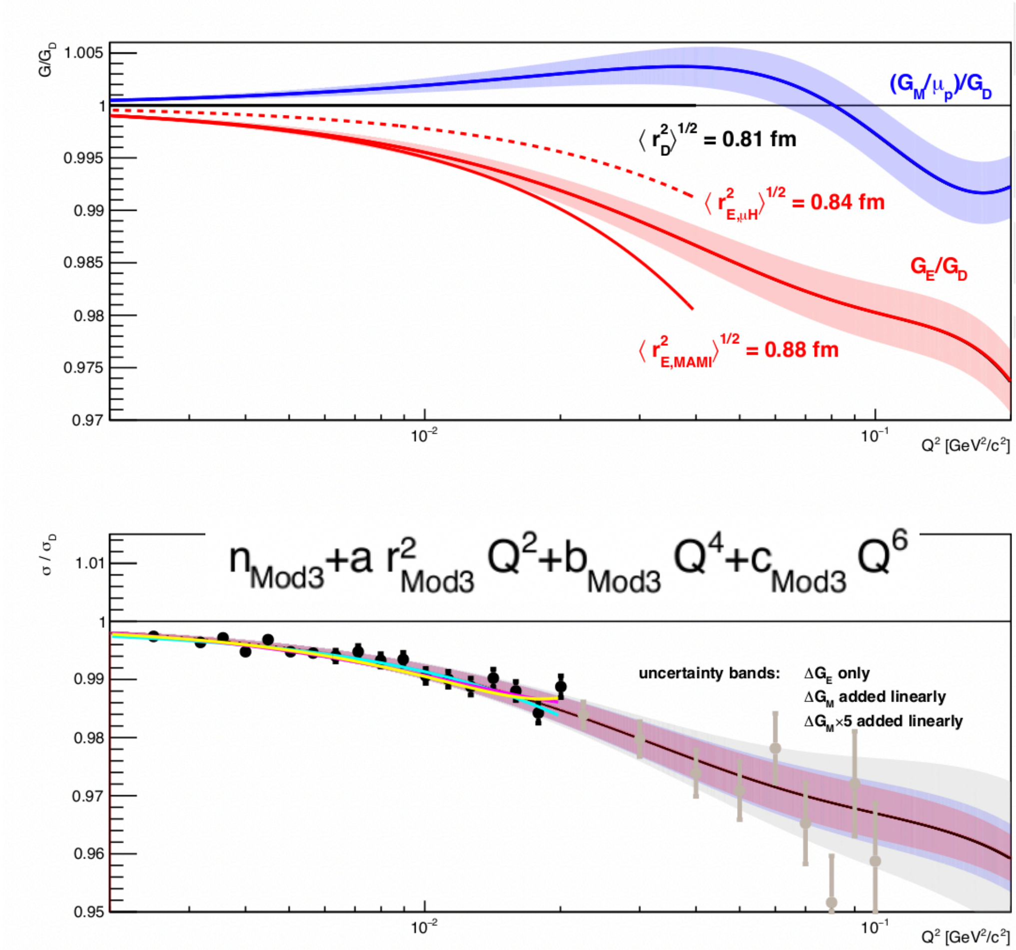
**THE PROTON RADIUS**

15 - 20 September 2019
Veli Lošinj, Croatia

ECSAC
European Centre for Science Arts and Culture

18. September 2019

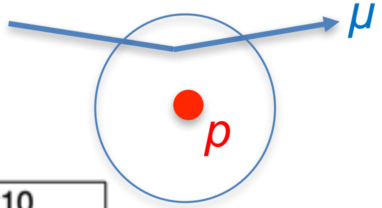
# Elastic lepton-proton cross section

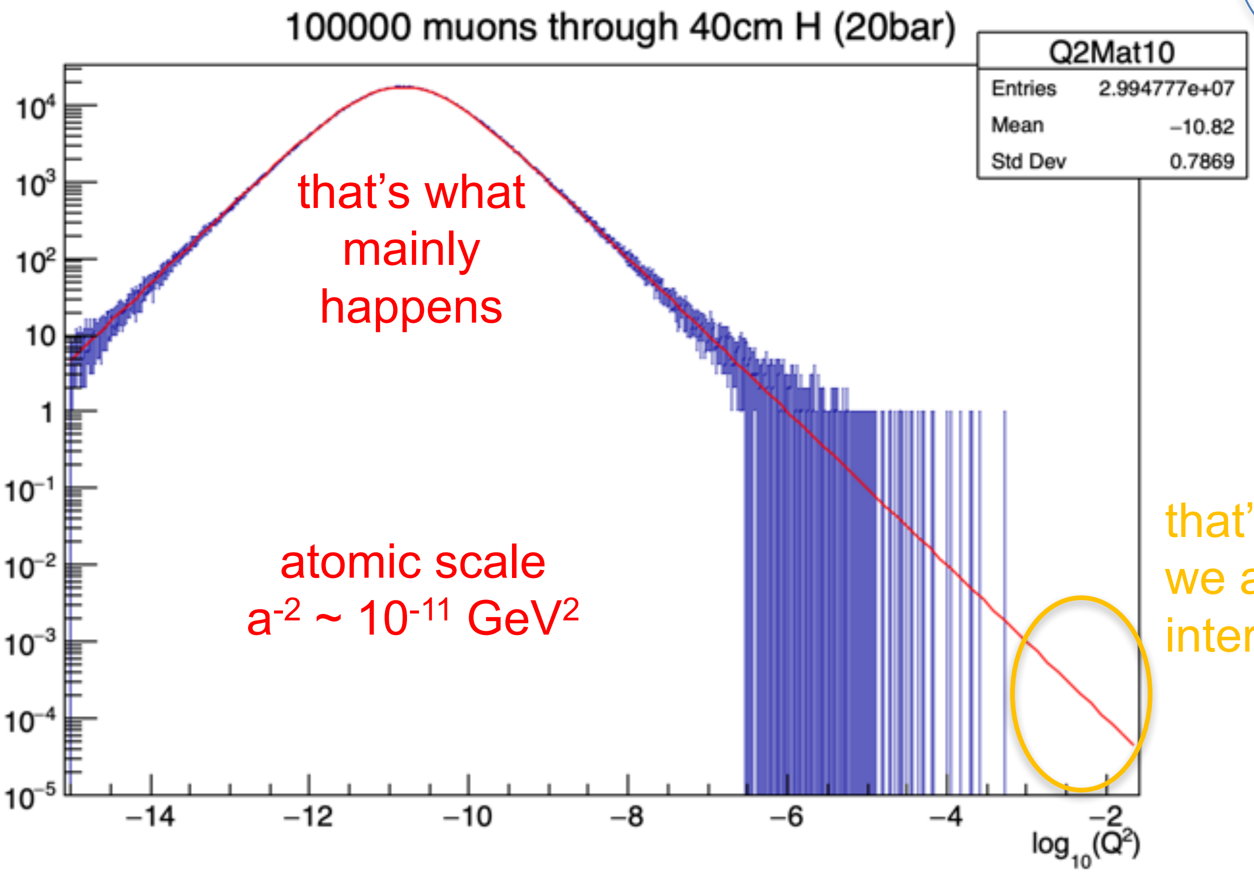


Only the low-$Q^2$ points in black were used in the various fits (polynomial in $Q^2$) to the pseudo-data shown as magenta (linear), purple (quadratic) and yellow (3rd order) curves. Pseudo-data points in grey require a different detector setup and are shown here for completeness. Only statistical uncertainties are shown as expected to dominate the systematic point-to-point uncertainty.

# Cross-section behavior

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





that's what mainly happens

atomic scale
$a^{-2} \sim 10^{-11}$ GeV$^2$

that's what we are interested in

# Cross-section behavior

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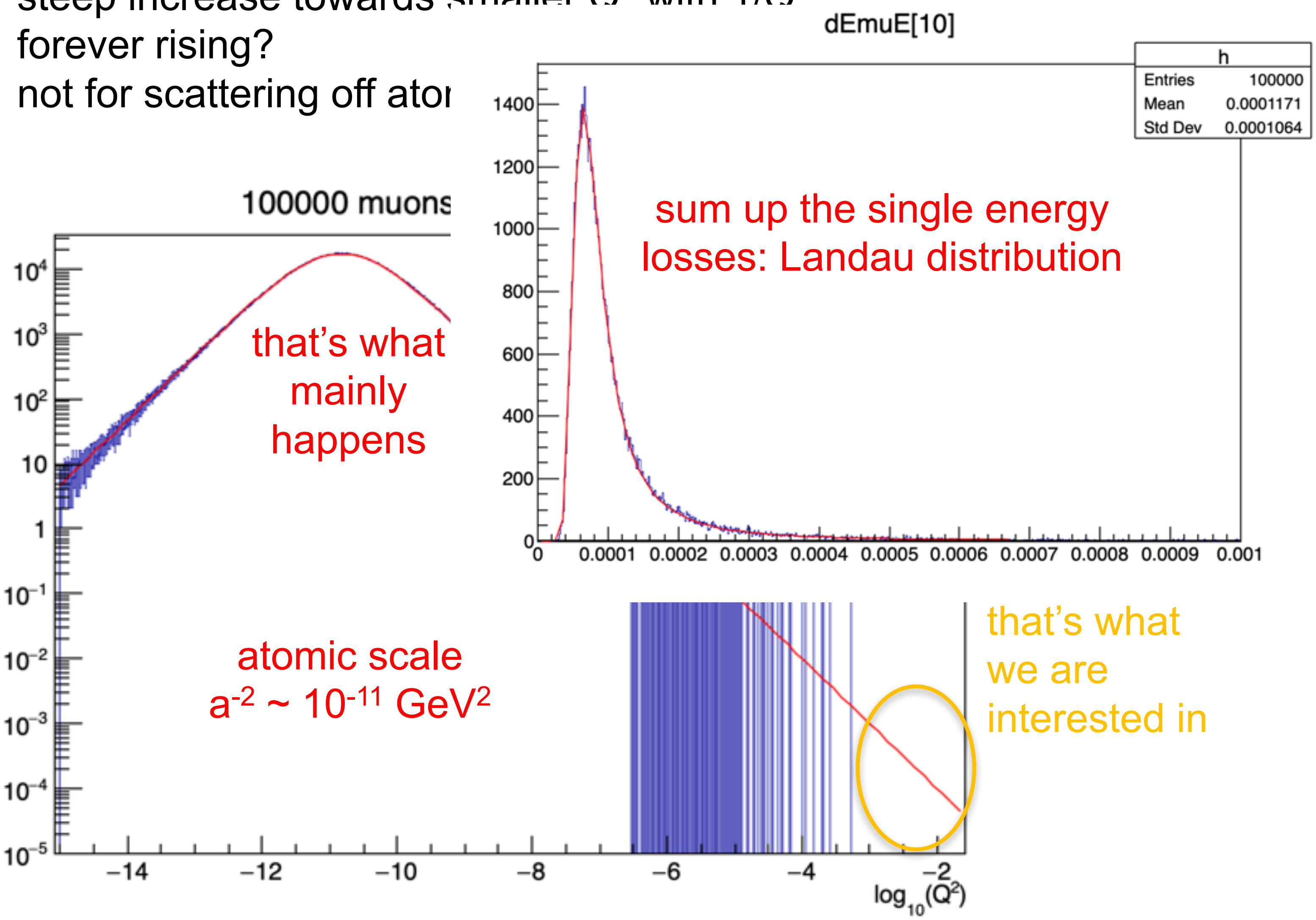
- not for scattering off ato



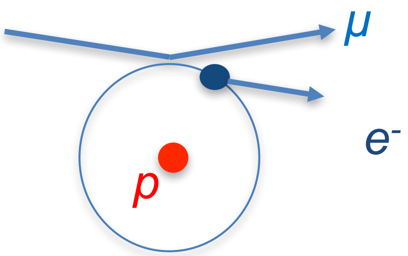
that's what mainly happens

atomic scale $a^{-2} \sim 10^{-11}$ GeV$^2$

sum up the single energy losses: Landau distribution

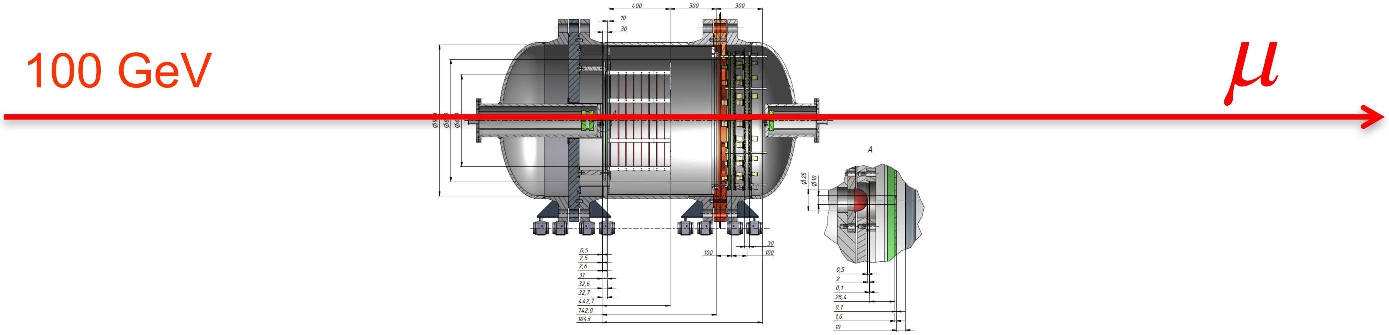
that's what we are interested in

# Landau tail



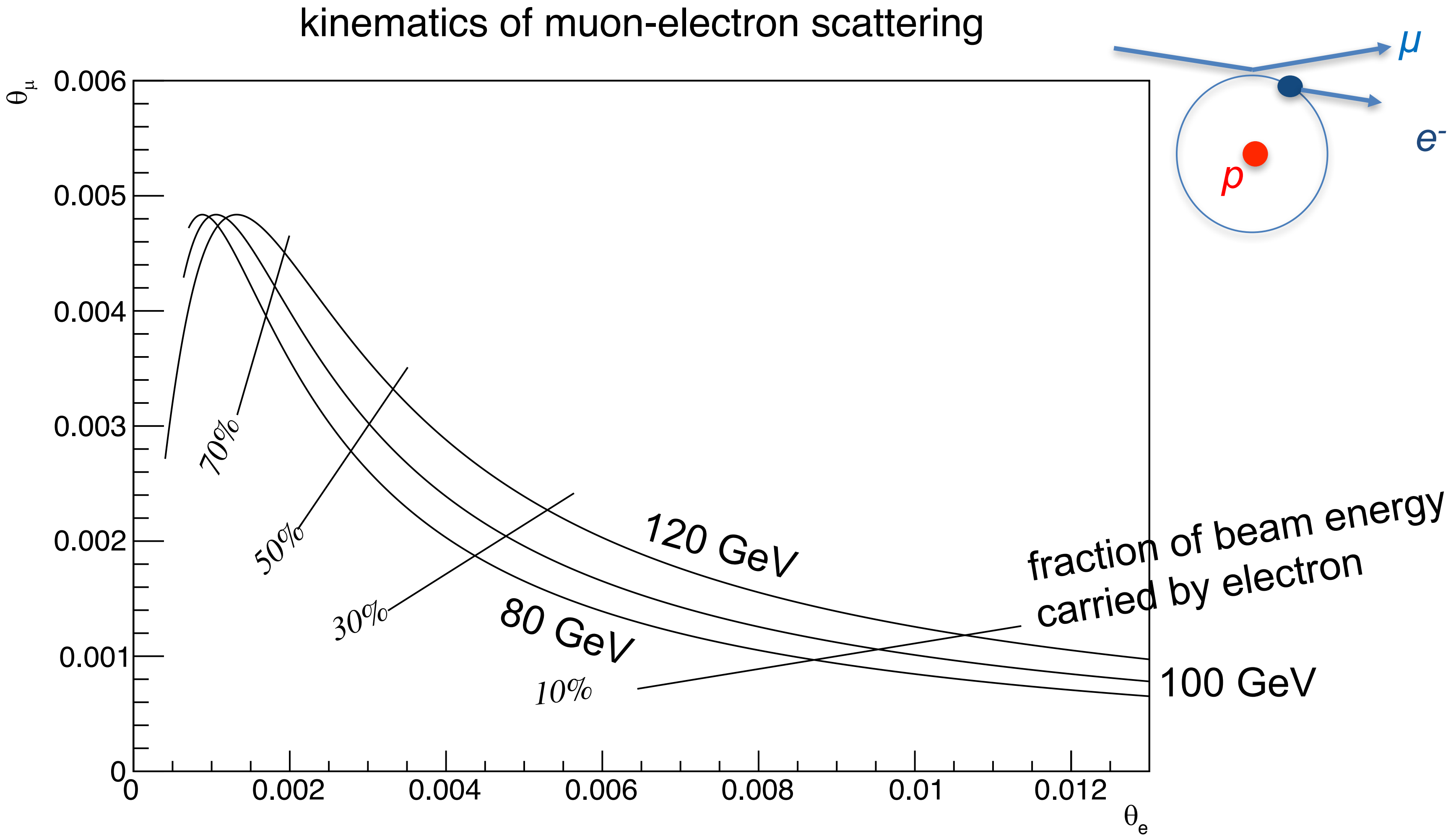
- near ionization threshold: binding important
- higher energies: scattering off quasi-free electrons
- at the end of the full TPC setup:
  - 2% of muons accompaigned by an electron >10 MeV
  - 0.3% with electron >50 MeV
- secondary processes need to be accounted for
  - overlap with proton recoils
  - fake recoil signals

# Recoil energy calibration

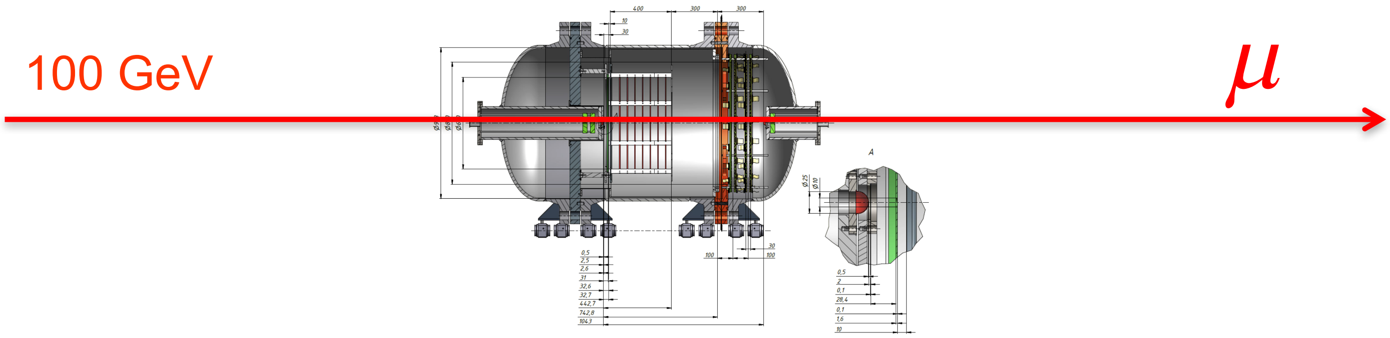


- precise determination of the momentum transfer $Q^2$ depends on energy calibration of the TPC signal
- possibly known from Mainz setup
- may not account *e.g.* for variations in time
- calibration in situ by measurement of elastic mu-e scattering

# Landau tail: “delta-electrons”



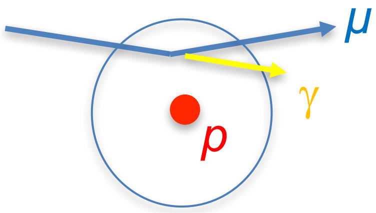
# Recoil energy calibration



- measurement of only the angles of muon and electron allows to determine the beam energy
- vertex can be constrained to narrow structures (windows, readout planes, detectors)
- kinematics *e.g.* for $E_e$=0.1$E_{beam}$=10 GeV: $\theta_\mu$=1mrad, $\theta_e$=10mrad
- sensitivity $\Delta E_{beam}/\Delta\theta_\mu$=1GeV/5µrad, $\Delta E_{beam}/\Delta\theta_e$=1GeV/50µrad
- good statistics, similar to elastic mu-p events (a few per sec)
- goal of the precision, assuming alignment precise to 0.1µrad: $\Delta E_{beam}$ ~100 MeV
- *i.e.* $\Delta Q^2_{shift} / Q^2 \sim 2 \cdot 10^{-4}$

NB. π-e scattering?

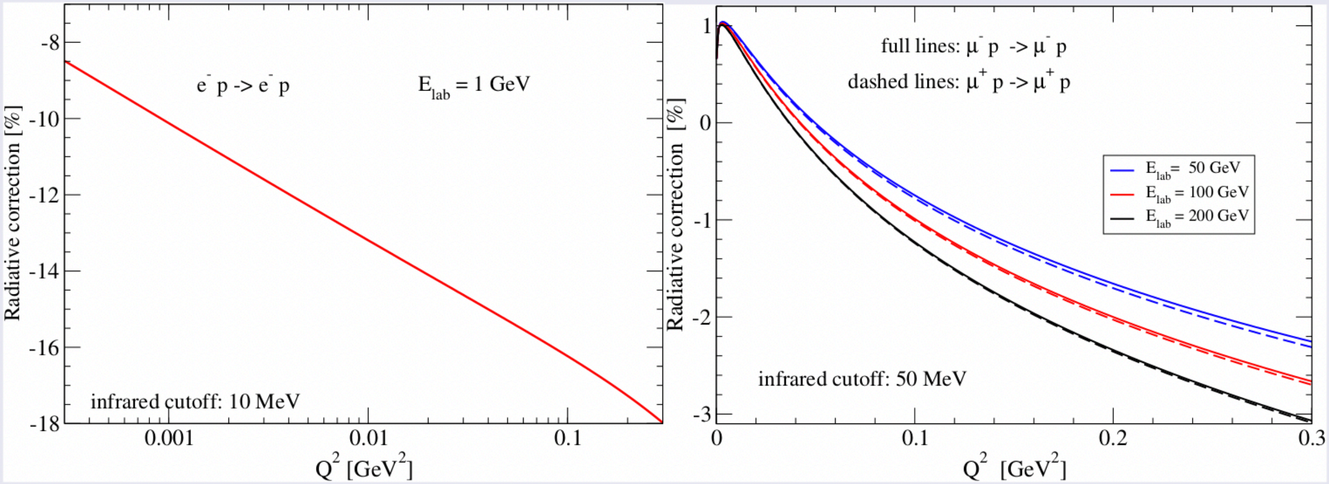
# NLO process: emission (and exchange) of a real (virtual) photon



- emission of photons strongly forward peaked
- energy spectrum ~1/$E_\gamma$
- measure forward photons with calorimeter?
- correction in the order 1%, uncertainty ~$10^{-3}$

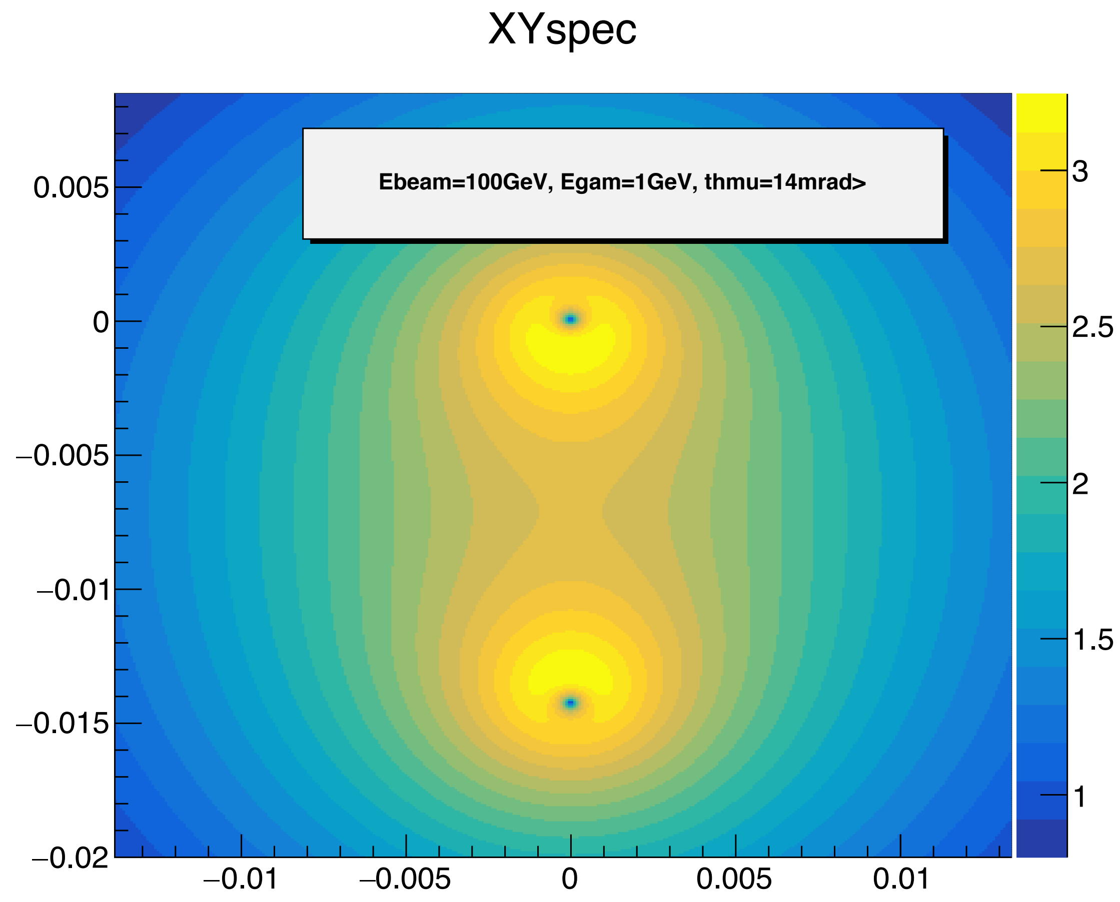
# Radiative corrections for electron and muon scattering

## QED radiative corrections

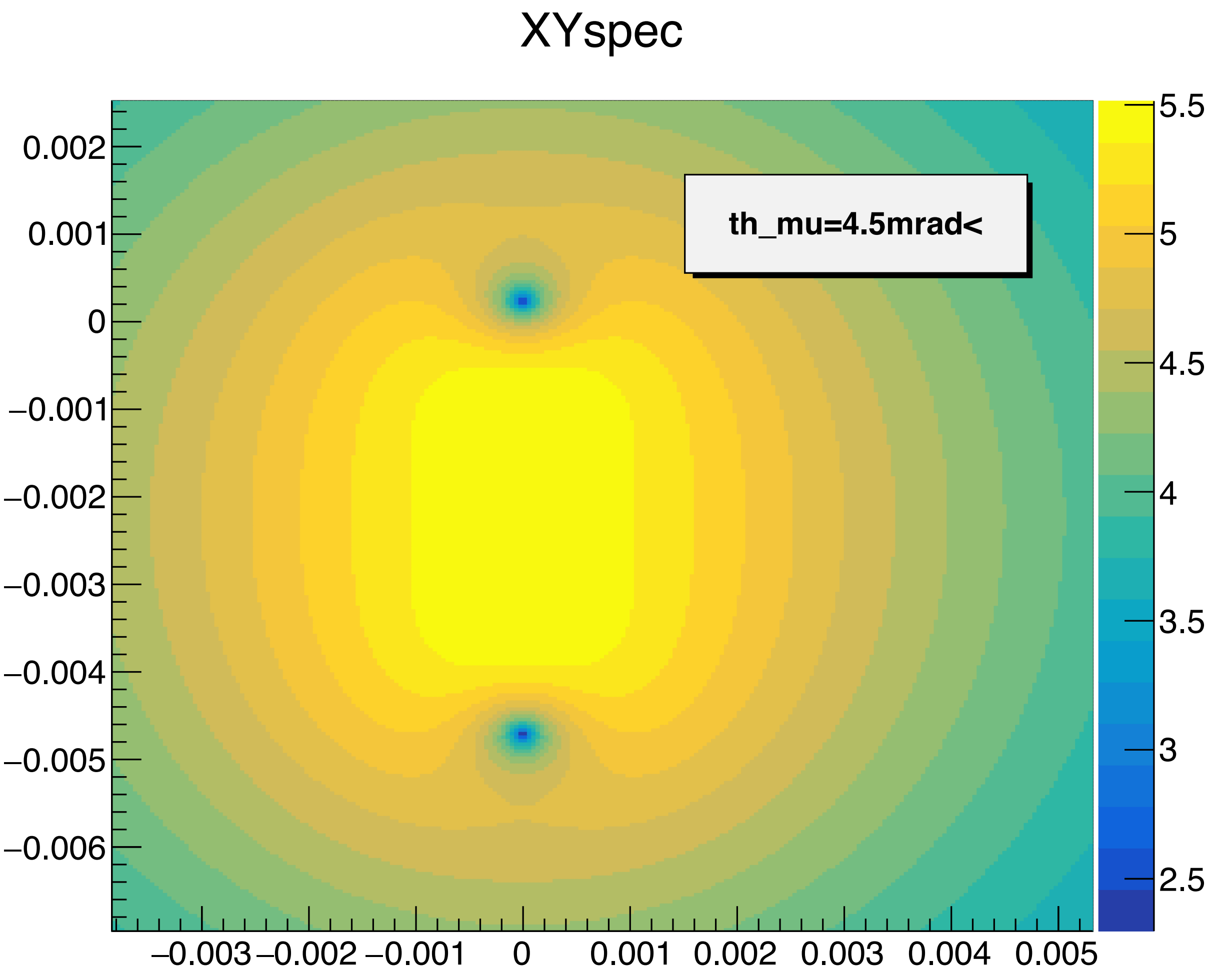


- for soft bremsstrahlung photon energies ($E_\gamma/E_{beam} \sim 0.01$), QED radiative corrections amount to $\sim$ 15-20% for electrons, and to $\sim$ 1.5% for muons
- important contribution to the uncertainty of elastic scattering intensities: *change* of this correction over the kinematic range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

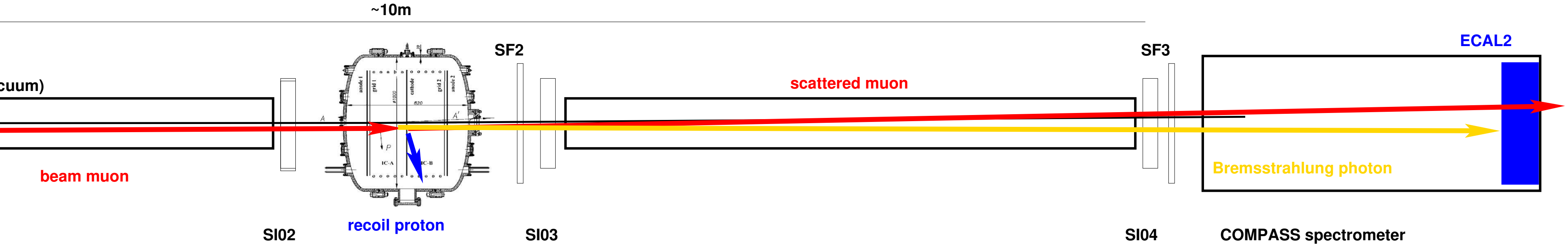
# Bremsstrahlung emission angle, E=100GeV



# Bremsstrahlung emission angle, E=100GeV

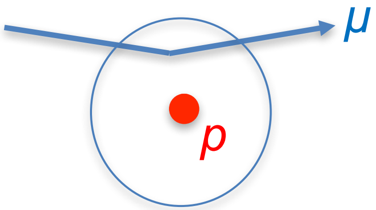


# Bremsstrahlung: real-photon emission along the muon-proton scattering



- Bremsstrahlung is emitted along the elastic process
- photon energy $E_\gamma$ exhibits roughly spectrum $1/E_\gamma$ ('infrared divergence')
- angular spectrum strongly focussed to approximately cone around lepton direction (relativistic case, opening angle $1/\gamma$ [Lorentz factor])
- Probability of Bremsstrahung emission for 100GeV beam and photon energies between 50MeV and 5GeV, relative to elastic cross section at $\theta_\mu$ =0.3mrad ($Q^2$=0.001): 5e-4
  - cross-checked with N. Kaiser on 20-30% level, differences to be settled
- For targeted 7e7 elastic events in $Q^2$=0.001…0.04 $GeV^2/c^2$ the number of Bremsstrahlung events is in the order of 38000 events

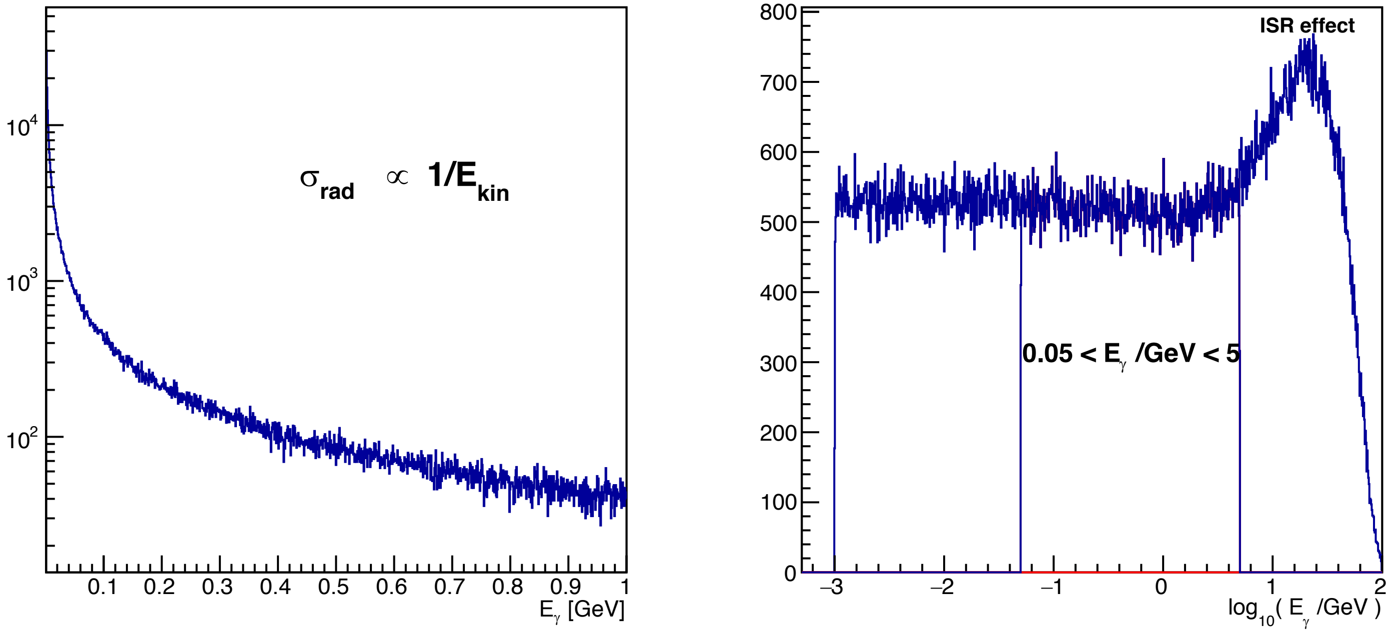
# (Incomplete) summary



- the muon-proton elastic scattering experiment at COMPASS aims at a determination of the proton electric form factor in the range $Q^2 < 0.04$ GeV$^2$ with a point-to-point precision of $10^{-3}$
- allows determination of the proton radius with a precision <1%
- for a sufficient statistical precision, 70 million events
- model / extrapolation / fitting uncertainty: *cf.* Thomas' talk
- further systematics
  - calibration of the kinetic energy of the recoil proton (*i.e.* $Q^2$) with a precision <0.2%
  - $Q^2$-dependence of radiative corrections, <0.1%
  - Monte-Carlo simulation of acceptance / efficiency correction <0.5%

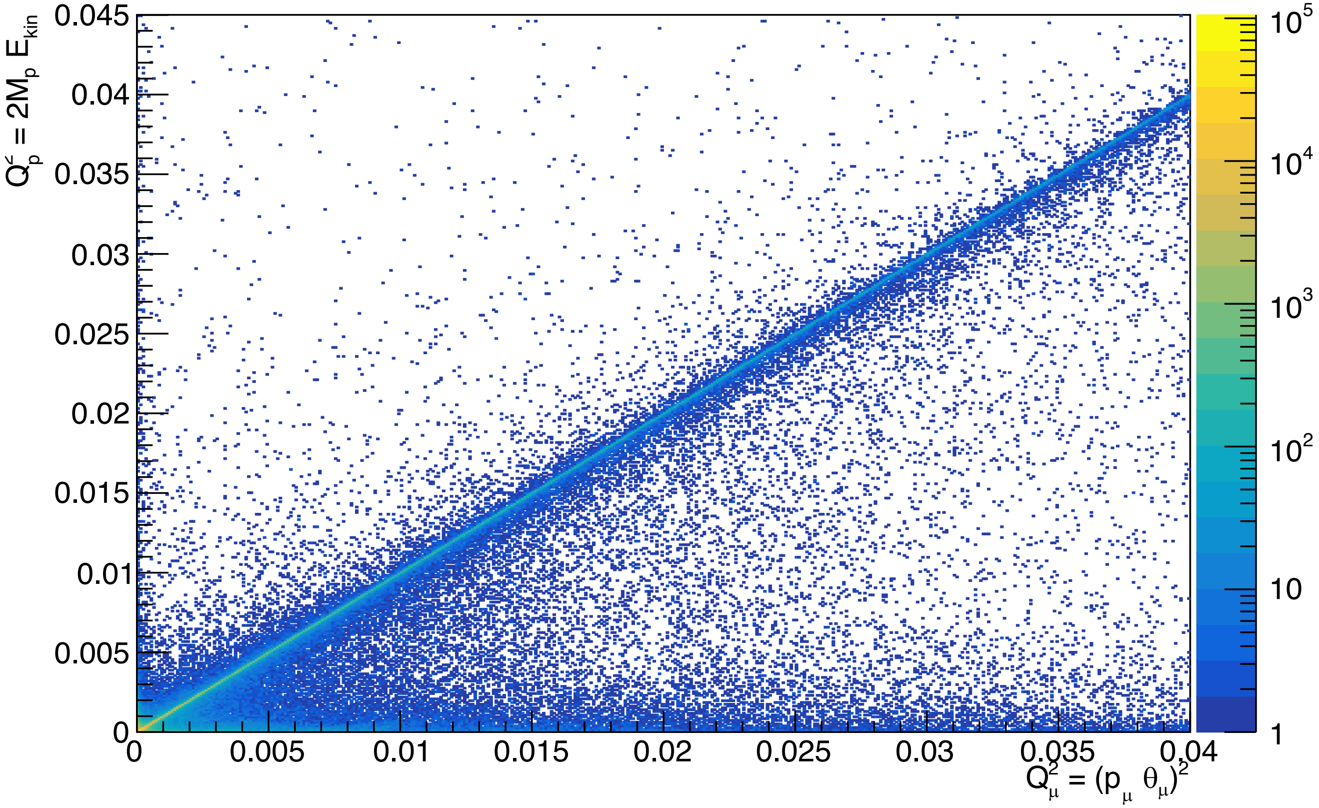
# real-photon energy spectrum

MC simulation of 500k events in $\theta_\mu$ =0.3 … 2 mrad, $E_\gamma$ > 1 MeV
(new development, theory [traced ME] from Norbert Kaiser)



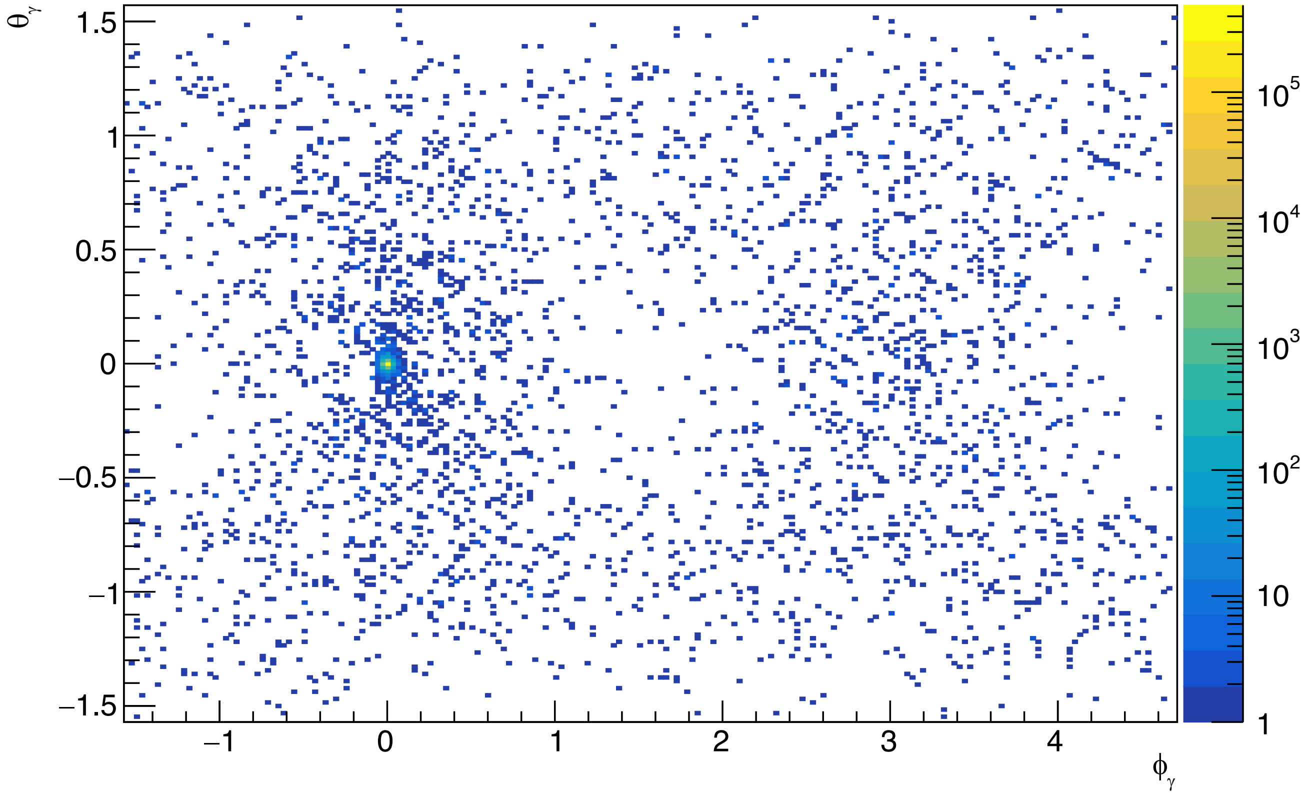
ISR effect: if incoming muon loses much of its energy, the scattering off the proton happens on lower average Q2 and accordingly larger cross section

# impact on Q2 reconstruction



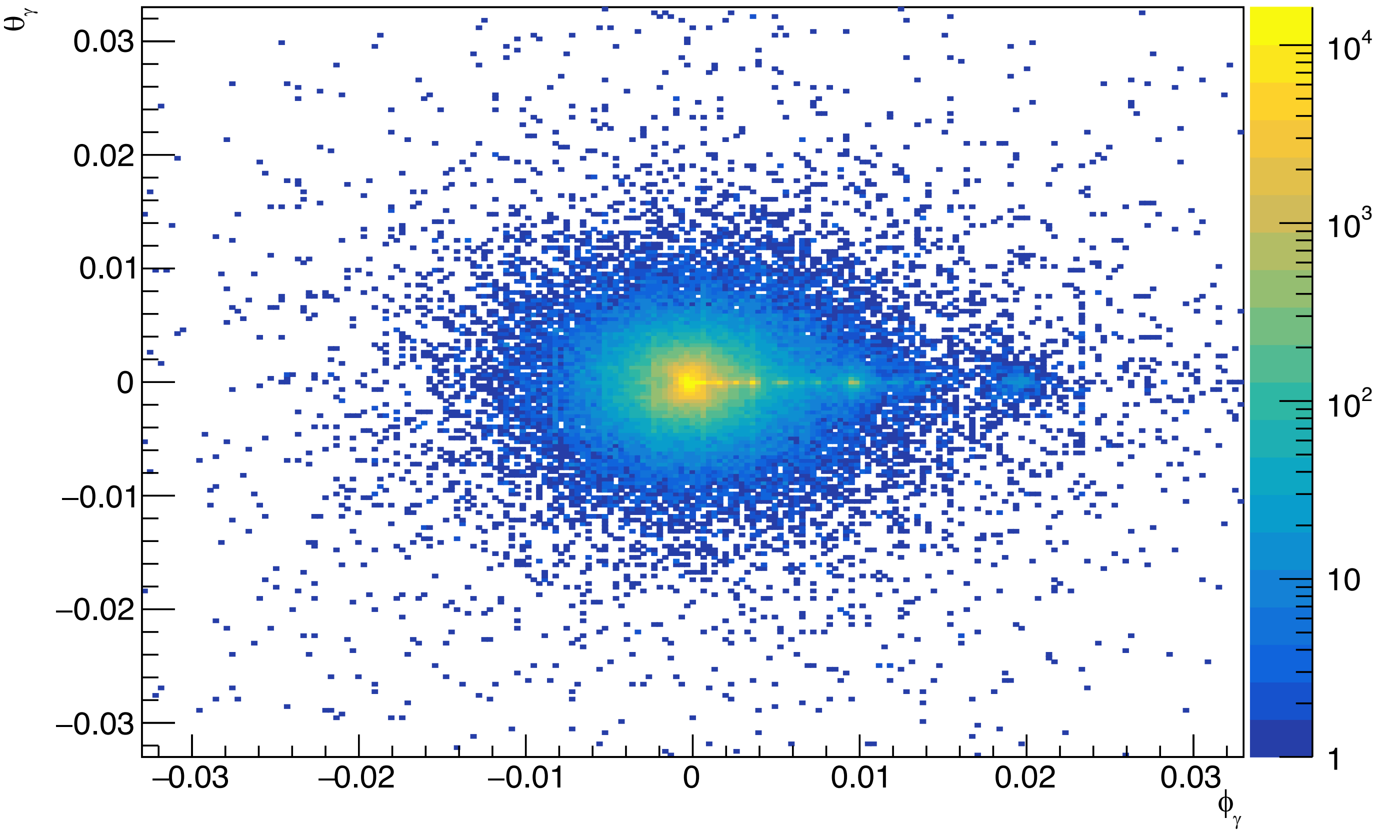
real-photon emission distorts the kinematics, correlation of reconstruction from muon and recoil proton becomes blurred

# photon angular spectrum



$\theta_\gamma$ is ‚out-of-plane‘ angle $\theta_\gamma = 0$ is the muon scattering plane
$\phi_\gamma = 0$ is forward kinematics (emission along incoming muon direction)
$\phi_\gamma = \pi$ is backward kinematics

# photon angular spectrum



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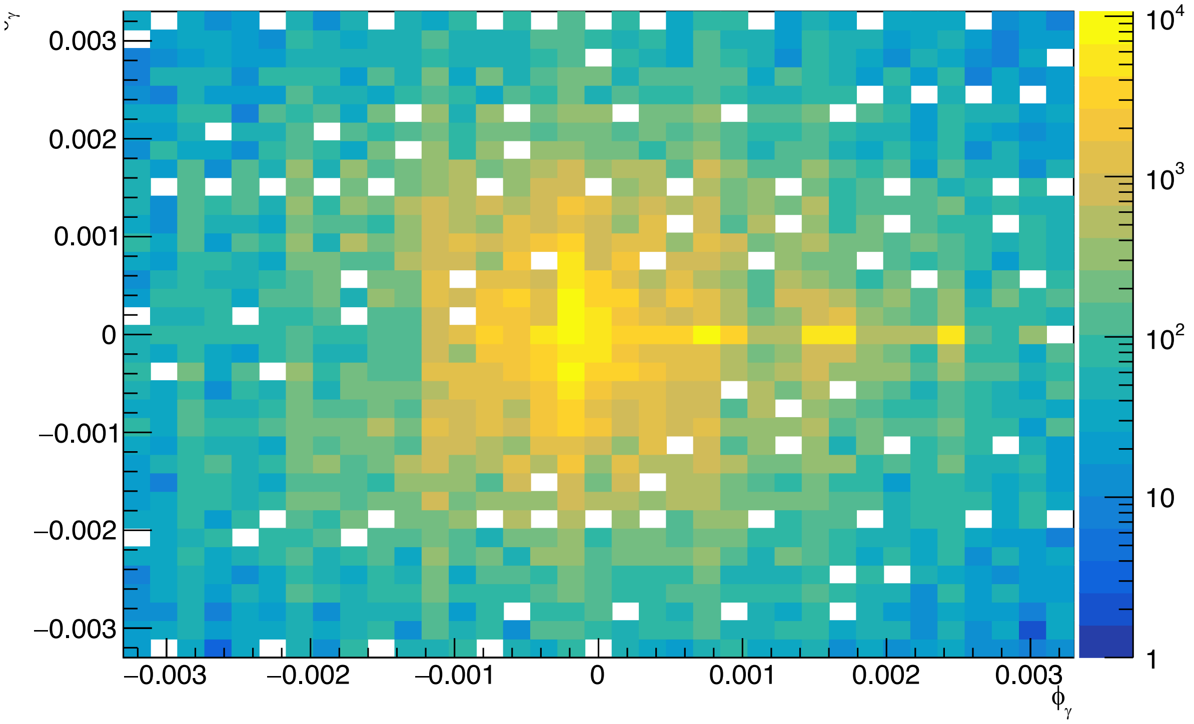
# photon angular spectrum



One ECAL2 cell (3.9cm/30m) corresponds to 1.3 mrad, so the majority of photons lies in the innermost ca. 100 cells

usage of ECAL2 is interesting to control the radiative corrections for the Proton Radius Measurement

# Summary table – beam requirements

| Program | Physics Goals | Beam Energy [GeV] | Beam Intensity [$s^{-1}$] | Trigger Rate [kHz] | Beam Type | Target | Earliest start time, duration | Hardware Additions |
|---|---|---|---|---|---|---|---|---|
| $\mu p$ elastic scattering | Precision proton-radius measurement | 100 | $4\cdot10^6$ | 100 | $\mu^\pm$ | high-pr. H2 | 2022<br>1 year | active TPC<br>SciFi trigger<br>silicon veto |
| Hard exclusive reactions | GPD $E$ | 160 | $10^7$ | 10 | $\mu^\pm$ | $NH_3^\uparrow$ | 2022<br>2 years | recoil silicon, modified PT magnet |
| Input for DMS | $\overline{p}$ production cross-section | 20-280 | $5\cdot10^5$ | 25 | $p$ | LH2, LHe | 2022<br>1 month | LHe target |
| $\overline{p}$-induced Spectroscopy | Heavy quark exotics | 12, 20 | $5\cdot10^7$ | 25 | $\overline{p}$ | LH2 | 2022<br>2 years | target spectr.: tracking, calorimetry |
| Drell-Yan | Pion PDFs | 190 | $7\cdot10^7$ | 25 | $\pi^\pm$ | C/W | 2022<br>1-2 years | |
| Drell-Yan (RF) | Kaon PDFs<br>Nucleon TMDs | ∼100 | $10^8$ | 25-50 | $K^\pm, \overline{p}$ | $NH_3^\uparrow$, C/W | 2026<br>2-3 years | ”active absorber”, vertex det. |
| Primakoff (RF) | Kaon polarizibility & pion life time | ∼100 | $5\cdot10^6$ | $> 10$ | $K^-$ | Ni | n/e<br>2026<br>1 year | |
| Prompt Photons (RF) | Meson gluon PDFs | $\geq 100$ | $5\cdot10^6$ | 10-100 | $K^\pm$<br>$\pi^\pm$ | LH2, Ni | n/e<br>2026<br>1-2 years | hodoscope |
| $K$-induced Spectroscopy (RF) | High-precision strange-meson spectrum | 50-100 | $5\cdot10^6$ | 25 | $K^-$ | LH2 | 2026<br>1 year | recoil TOF forward PID |
| Vector mesons (RF) | Spin Density Matrix Elements | 50-100 | $5\cdot10^6$ | 10-100 | $K^\pm, \pi^\pm$ | from H to Pb | 2026<br>1 year | |

Table 5: Requirements for future programs at the M2 beam line after 2021. Standard muon beams are in blue, standard hadron beams in green, and RF-separated hadron beams in red.

# QCD facility – future fixed target experiment at M2
## Spectrometer upgrades

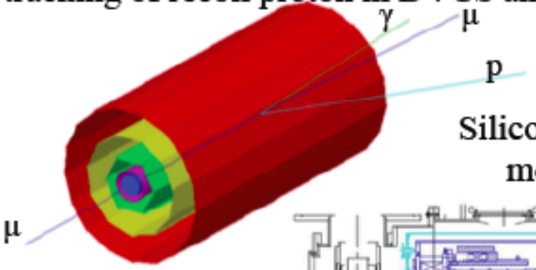
- **New type of FEE and trigger logic compatible with trigger-less readout**
  - FPGA-based TDC with time resolution down to 100 ps (iFTDC)
- Higher trigger rates: **90-200 kHz** (factor of 2.5-5)
- Digital trigger
- First tests in 2018

General upgrades of COMPASS-II apparatus:
- New large-size **PixelGEMs**
- **GEMs** or **Micromegas** to replace aging MWPCs
- High-aperture "**RICH0**" for some programs, $p <$ 10-15 GeV?

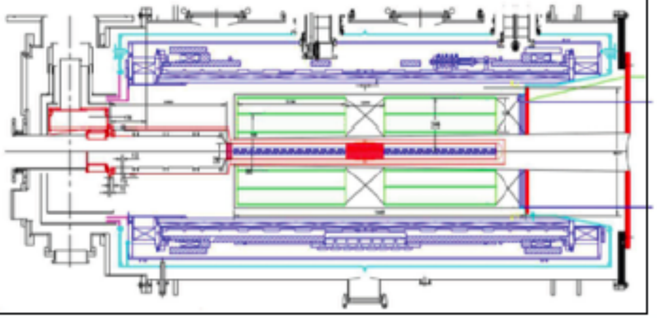
*Could be Large-Area Picosecond Photo-Detectors based on micro-channel plates with time resolution < 50 ps, spatial resolution ~ 0.5 mm. LAPPD™ by IncomInc.*

- High-rate-capable **CEDARs** for beam PID for all hadron programs.

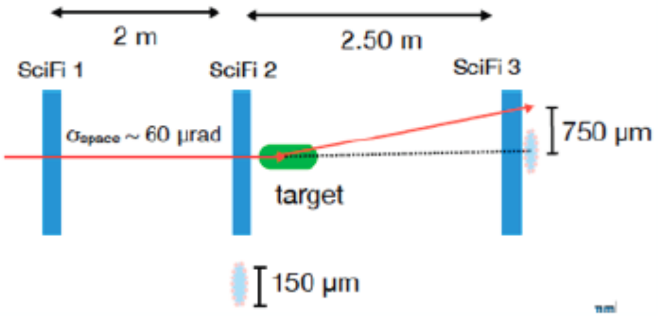
**GPD E**: 3-layer silicon detector at very low temperature for tracking of recoil proton in DVCS and PID via dE/dx.



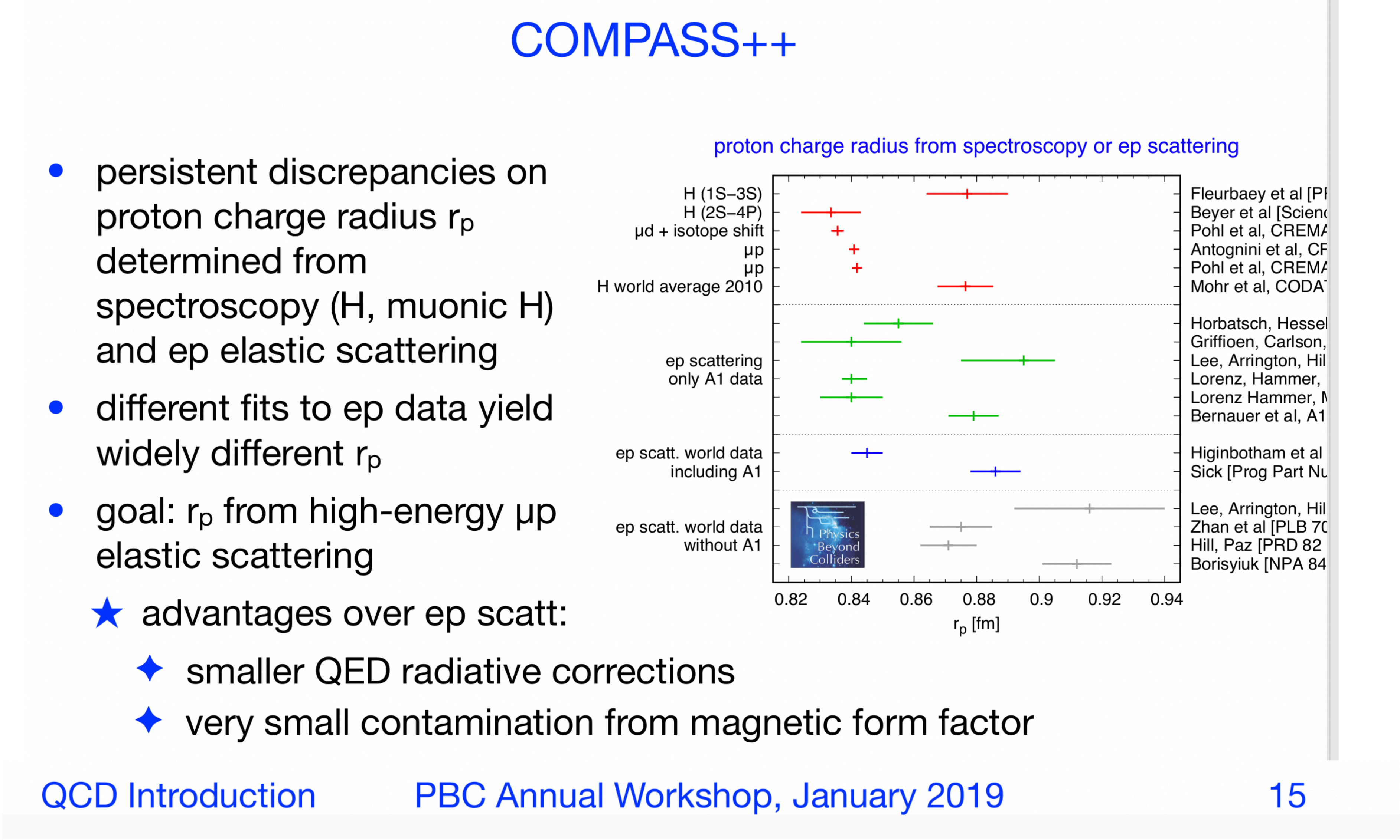
Silicon detector inside existing modified target magnet.



**Proton radius:**
- **High-pressure active TPC target or hydrogen tube** surrounded by SciFi, 4-8 layers with U/V projections
- **SciFi trigger system** on scattered muon
- Silicon trackers



# from the PBC-QCD convener's summary



## 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

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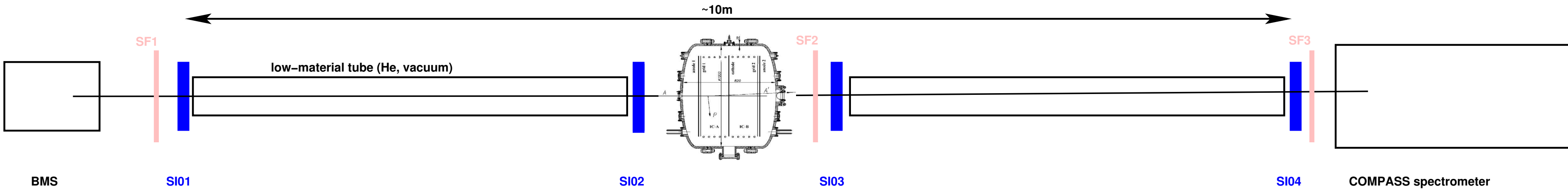
# Proton Radius Measurement: Proposed Setup



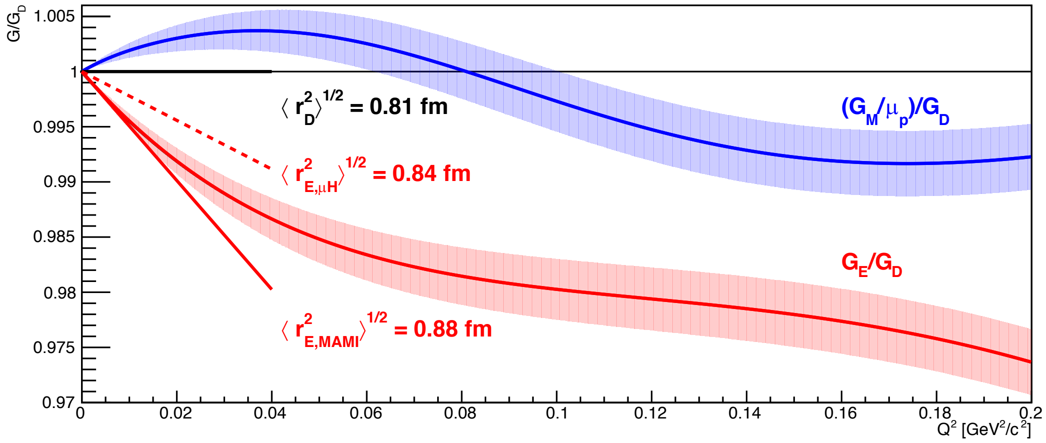
- muon scattering angles 0.3 ($Q^2$=0.001GeV$^2$) … 2 mrad ($Q^2$=0.04GeV$^2$) (100 GeV beam, minimal kinematic range, better larger)
- side kick over 5m base line: 1.5 … 10 mm
- sufficiently large, high-resolution Si detectors, $\Delta x$<=10$\mu$m, x>=50mm

- pressurized active high-purity $H_2$ target
- corresponding track lengths a few cm
- TPC readout on two sides

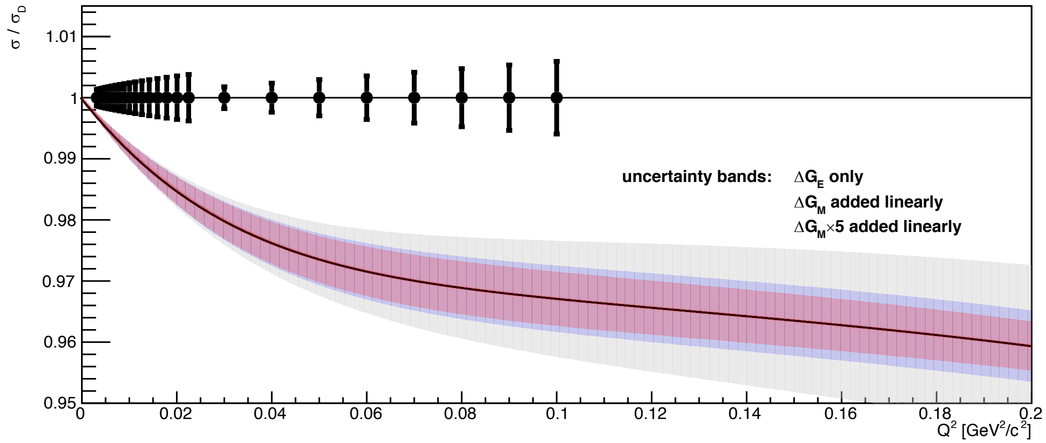
- beam intensity >= 2e6 muons/second, one year of running
- precision on proton radius <= 0.013 fm (no full simulation yet)

# Elastic lepton-proton cross section

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



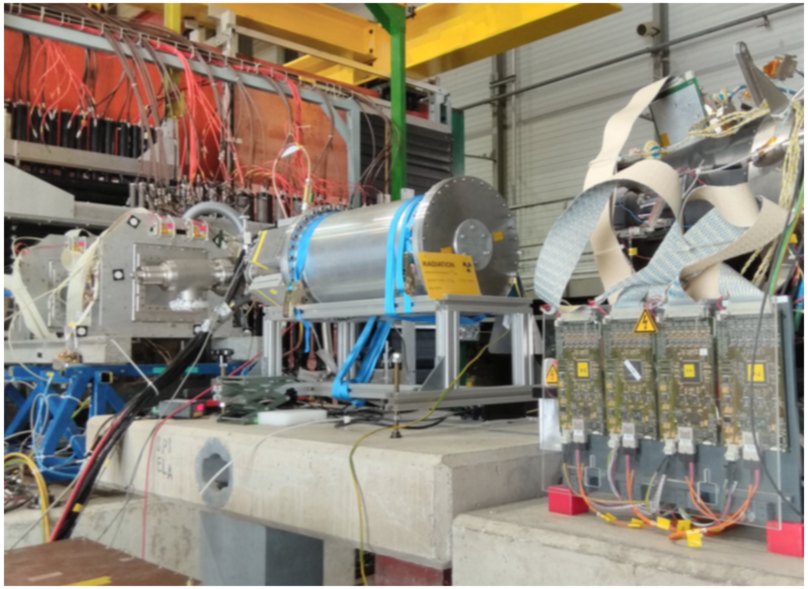
$$\frac{1}{6}r_p^2 = -\frac{d}{dQ^2}\Big|_{Q^2=0} G_E(Q^2)$$

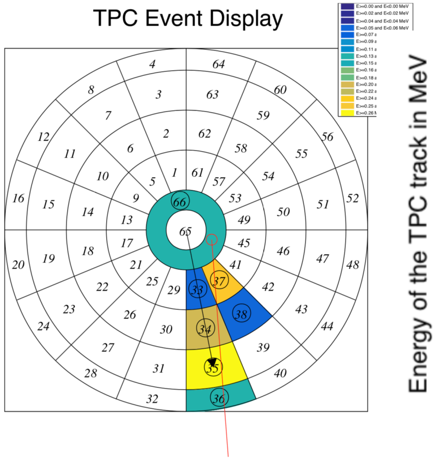


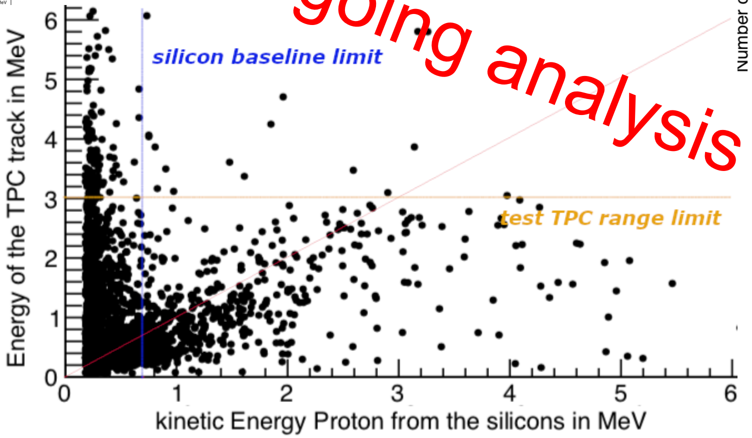
# Test in 2018 for Proton Radius measurement

Test setup during 2018 DY run downstream COMPASS, check

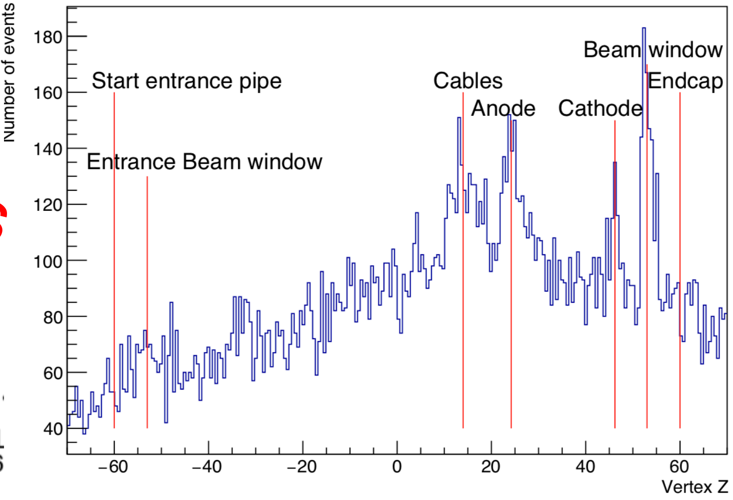
- TPC operation in muon beam ✅
- vertex reconstruction with silicon telescopes ✅
- coincidence detection of scattered muon and recoiling proton ✅



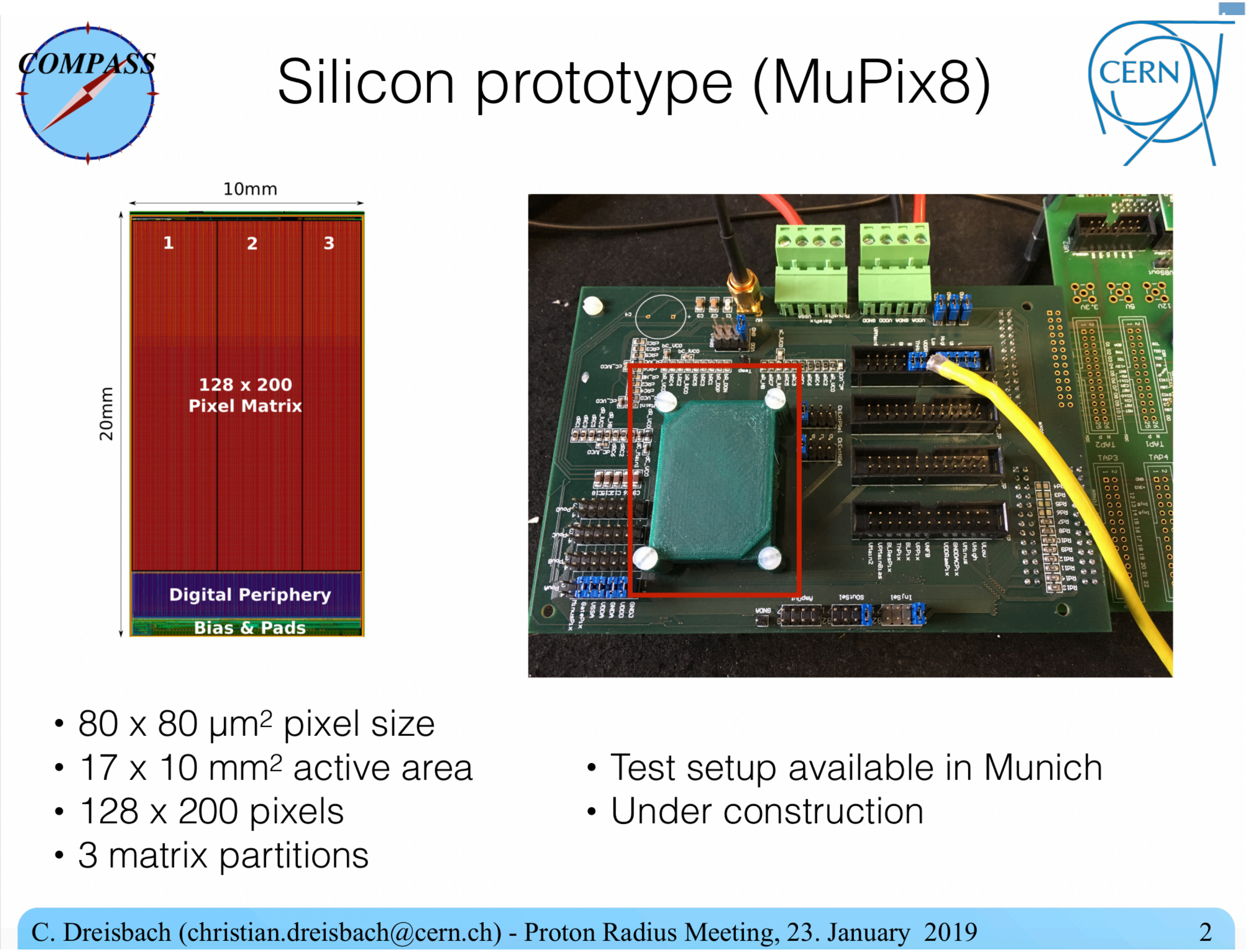

TPC Event Display



ongoing analysis



# New ideas for silicon detectors ready for continuous readout –Igor and team



## Silicon prototype (MuPix8)

- 80 x 80 μm² pixel size
- 17 x 10 mm² active area
- 128 x 200 pixels
- 3 matrix partitions

- Test setup available in Munich
- Under construction

C. Dreisbach (christian.dreisbach@cern.ch) - Proton Radius Meeting, 23. January 2019 2

# Summary

- COMPASS++ / AMBER is getting on track as a future QCD facility at the CERN M2 beam line with a broad physics program

- tests in 2018 for a proton radius measurement with a high-energy muon beam promising
- preparations for the measurement in 2021/22 take up momentum

stay connected: nqf-m2.web.cern.ch -- new ideas & collaborators welcome!

List of workshops where a New QCD facility at the M2 beam line of the CERN SPS was discussed.

10. **Mapping Parton Distribution Amplitudes and Functions", ECT***

10. 9. 2018 - 14. 9. 2018, https://indico.ectstar.eu/event/22/overview

- Studying meson and proton structure at the CERN M2 beam line, V. Andrieux https://indico.ectstar.eu/event/22/contributions/502/attachments/390/535/Andrieux_Trento10092018.pdf

9. **MiniWorkshop on A New QCD Facility at the SPS (CERN) after 2021**

20. 6. 2018, CERN, https://indico.cern.ch/event/737176/

8. **PBC Working Group Meeting**

13. 6. 2018 - 14. 6. 2018, CERN, https://indico.cern.ch/event/706741/

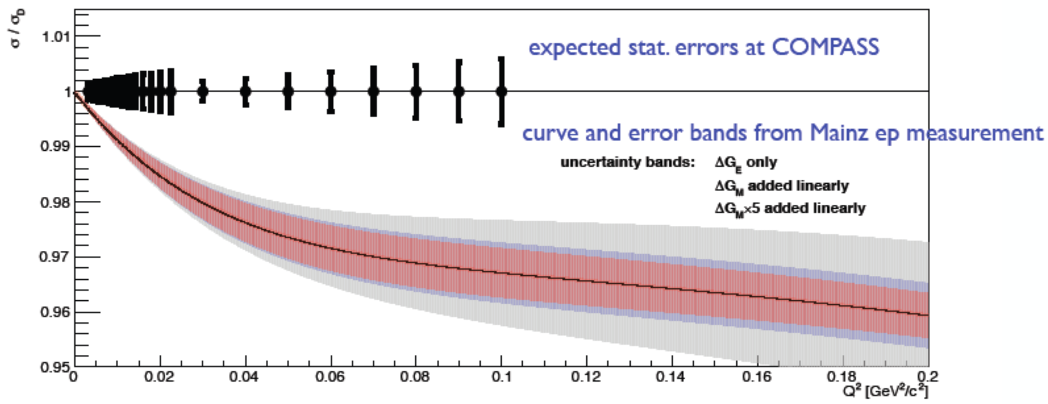
# Thank you for your attention!

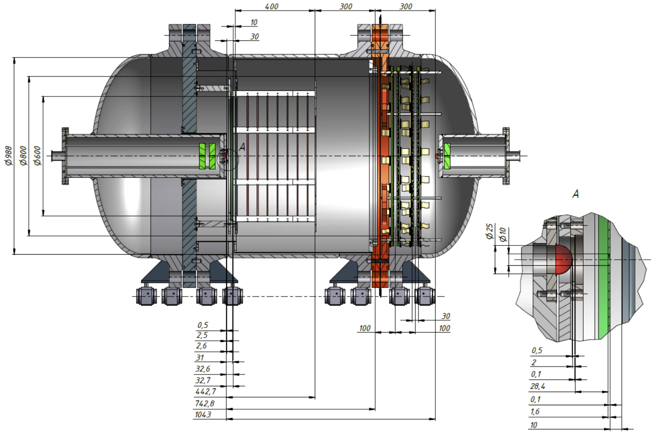
# Proton Radius measurement

## Physics case: determine the proton radius in high-energy muon-proton scattering

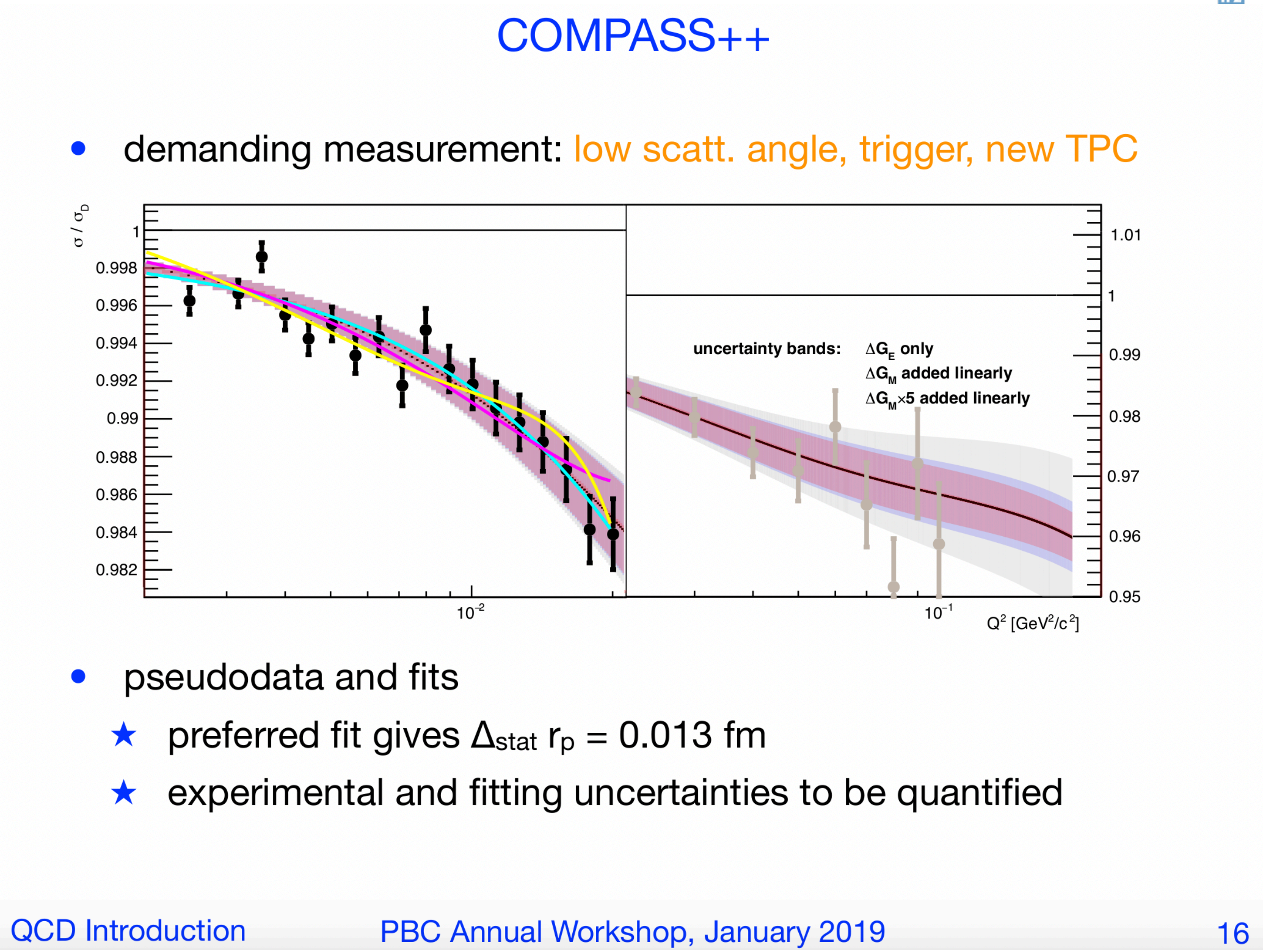
- elastic μp scattering at low $Q^2$
- key advantages over ep
  - measure electric form factor $G_E$, essentially no contribution from magnetic one $G_M$ (high E)
  - much smaller QED rad. corr. (muon mass)
- remains: theory uncertainty from fitting the form factor slope

- 100 GeV SPS M2 muon beam
- high-pressure hydrogen TPC active-target cell (PNPI development)
- measure cross-section shape over broad $Q^2$ range $10^{-4} \ldots 10^{-1}$
- fit from $10^{-3}$ … $2\times10^{-2}$ the proton radius (slope of electric form factor)





# Feedback from PBC QCD working group



## COMPASS++

- demanding measurement: low scatt. angle, trigger, new TPC

- pseudodata and fits
  - ★ preferred fit gives $\Delta_{\mathrm{stat}}\, r_p = 0.013$ fm
  - ★ experimental and fitting uncertainties to be quantified

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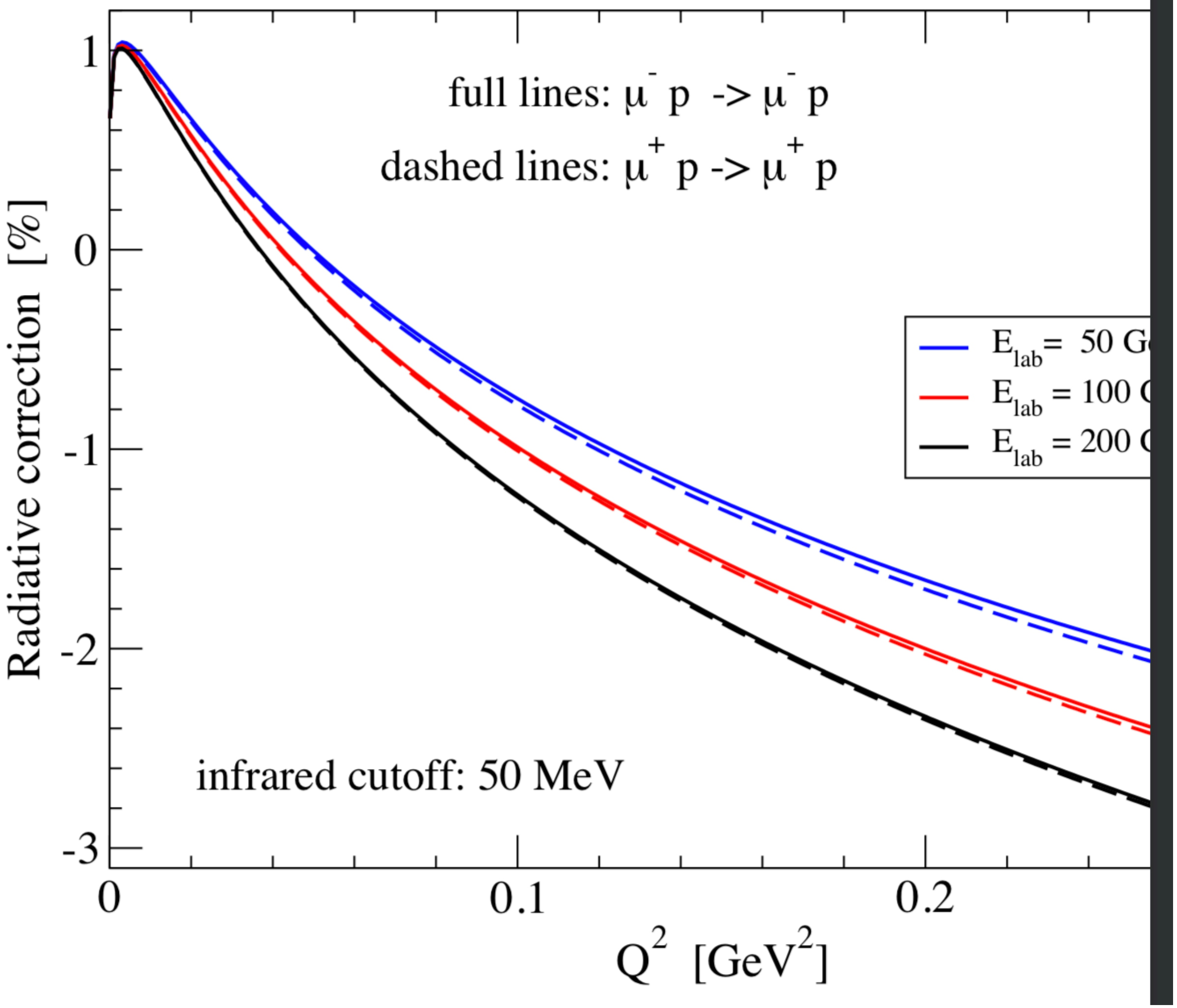

full lines: μ⁻ p -> μ⁻ p
dashed lines: μ⁺ p -> μ⁺ p
E_lab = 50 G
E_lab = 100 G
E_lab = 200 G
infrared cutoff: 50 MeV
Radiative correction [%]
1
0
-1
-2
-3
0
0.1
0.2
Q² [GeV²]

# 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 $Q^2$

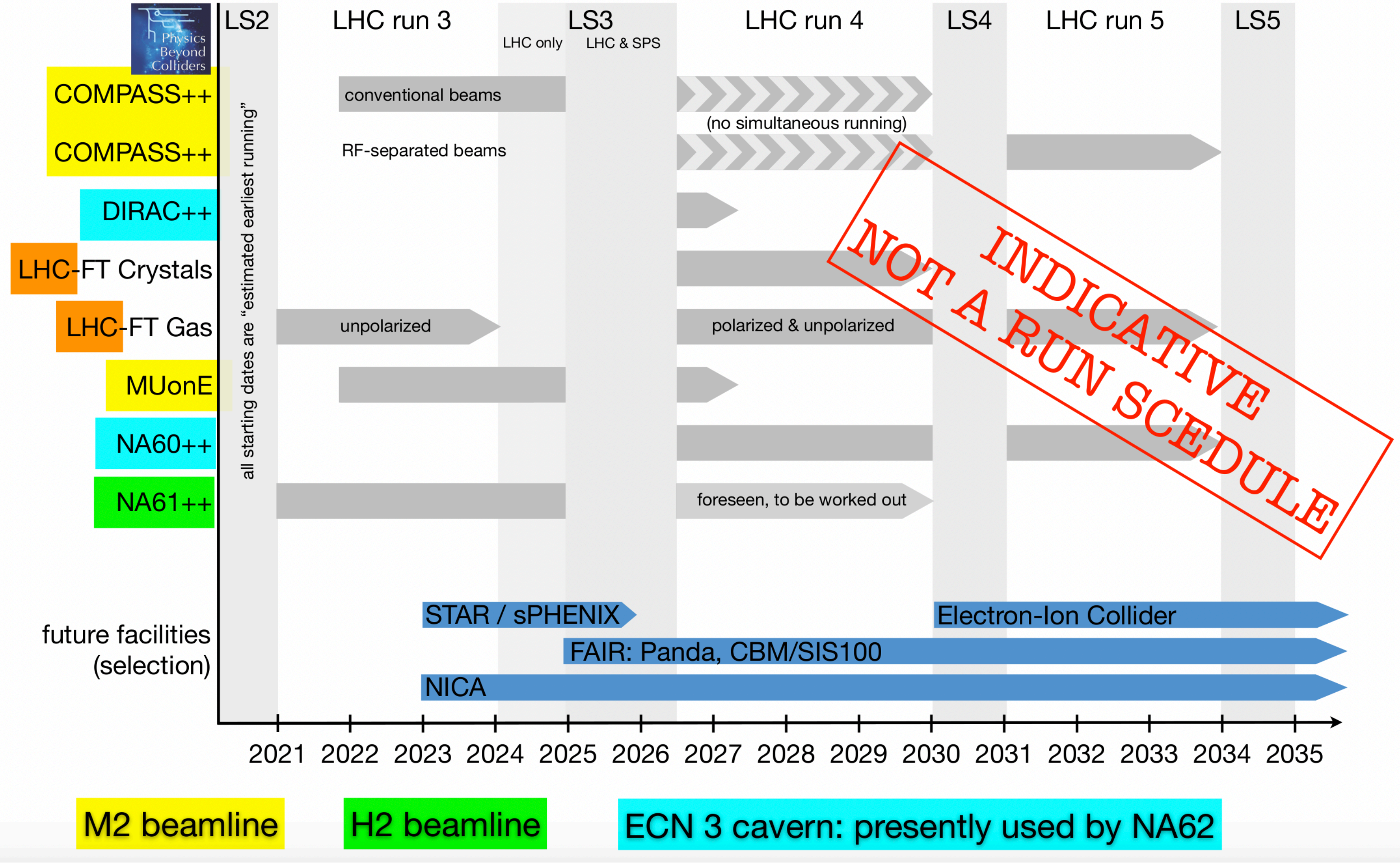
$$\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{dG_E(Q^2)}{dQ^2} \right|_{Q^2 \to 0}$$

- elastic scattering experiments provide data for $G_E$ at non-vanishing $Q^2$ and thus require an extrapolation procedure towards zero
  → 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

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

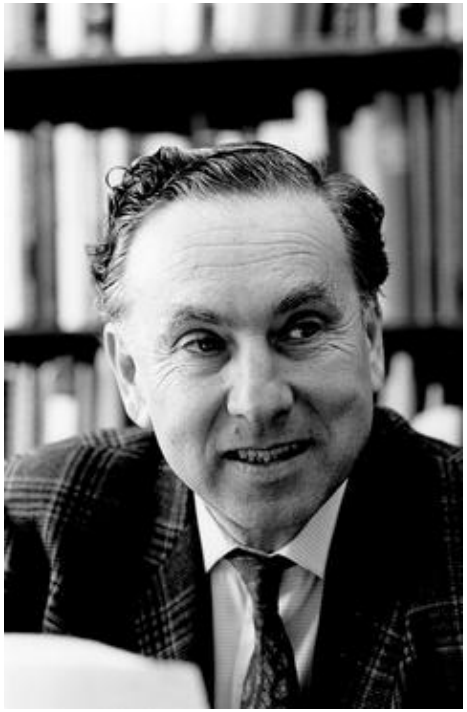
  introducing possibly very different assumptions on the coefficients $c_i$
- recipe for experimenters: measure a sufficiently large range of $Q^2$ down to values as small as possible and as precise as possible

# PBC-QCD

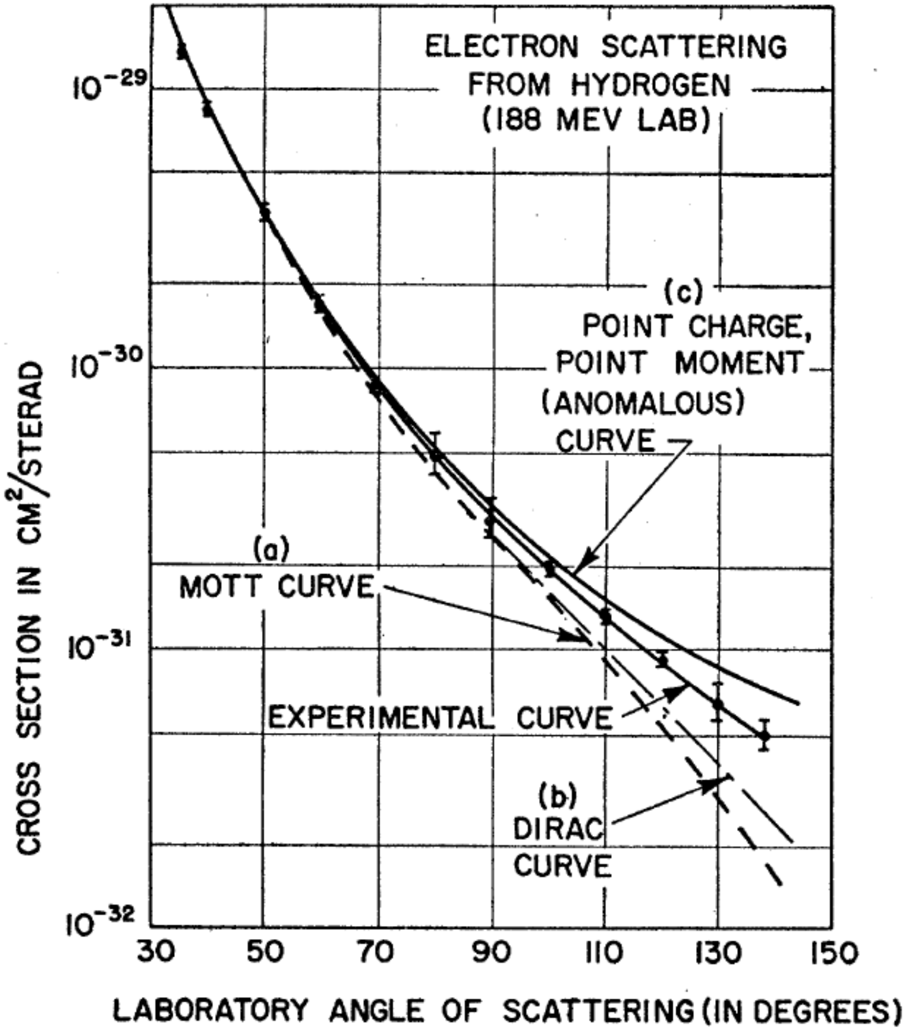

Physics Beyond Colliders
LS2
LHC run 3
LS3
LHC only
LHC & SPS
LHC run 4
LS4
LHC run 5
LS5
COMPASS++
COMPASS++
DIRAC++
LHC-FT Crystals
LHC-FT Gas
MUonE
NA60++
NA61++
all starting dates are "estimated earliest running"
conventional beams
(no simultaneous running)
RF-separated beams
unpolarized
polarized & unpolarized
foreseen, to be worked out
INDICATIVE
NOT A RUN SCEDULE
future facilities
(selection)
STAR / sPHENIX
Electron-Ion Collider
FAIR: Panda, CBM/SIS100
NICA
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
M2 beamline
H2 beamline
ECN 3 cavern: presently used by NA62

# Measurement of the Proton Radius in ep-Scattering

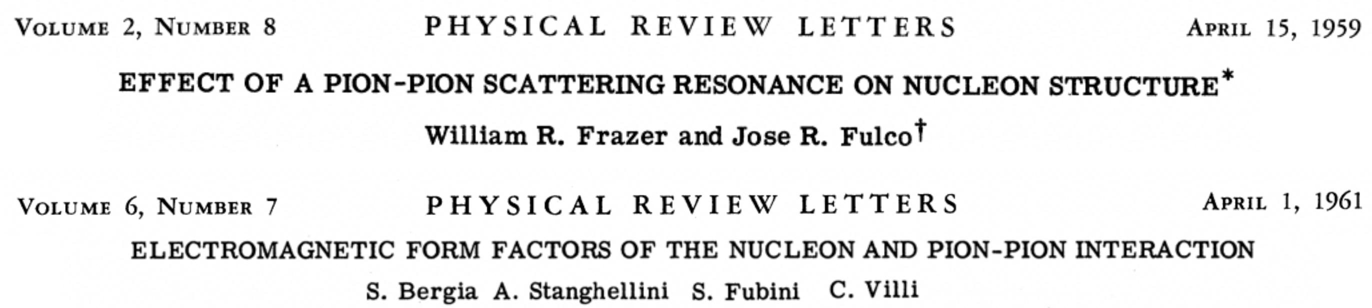
1956 at SLAC
Measurement of elastic e-p scattering shows first structure effect, $\langle r_p \rangle \approx 0.8$ fm



R. Hofstadter



# Theory of the time – 1958ff



VOLUME 2, NUMBER 8 PHYSICAL REVIEW LETTERS APRIL 15, 1959

**EFFECT OF A PION-PION SCATTERING RESONANCE ON NUCLEON STRUCTURE***

**William R. Frazer and Jose R. Fulco†**

VOLUME 6, NUMBER 7 PHYSICAL REVIEW LETTERS APRIL 1, 1961

**ELECTROMAGNETIC FORM FACTORS OF THE NUCLEON AND PION-PION INTERACTION**

**S. Bergia A. Stanghellini S. Fubini C. Villi**

We wish to propose a simple model for the electromagnetic structure of the nucleon, based

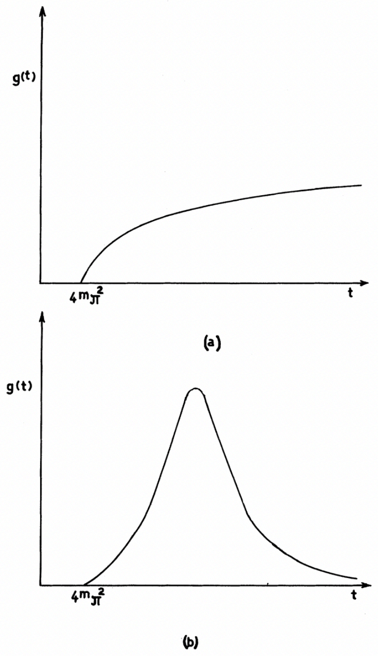
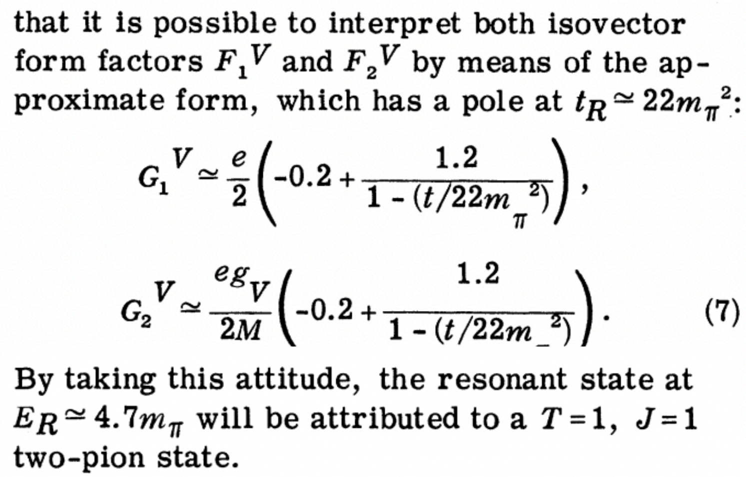


FIG. 1. Schematic representations of $g(t)$ in arbitrary scale. (a) Uncorrelated pions; (b) strong pion-pion resonance.



that it is possible to interpret both isovector form factors $F_1^V$ and $F_2^V$ by means of the approximate form, which has a pole at $t_R \simeq 22m_\pi^2$:

$$G_1^V \simeq \frac{e}{2}\left(-0.2+\frac{1.2}{1-(t/22m_\pi^2)}\right),$$

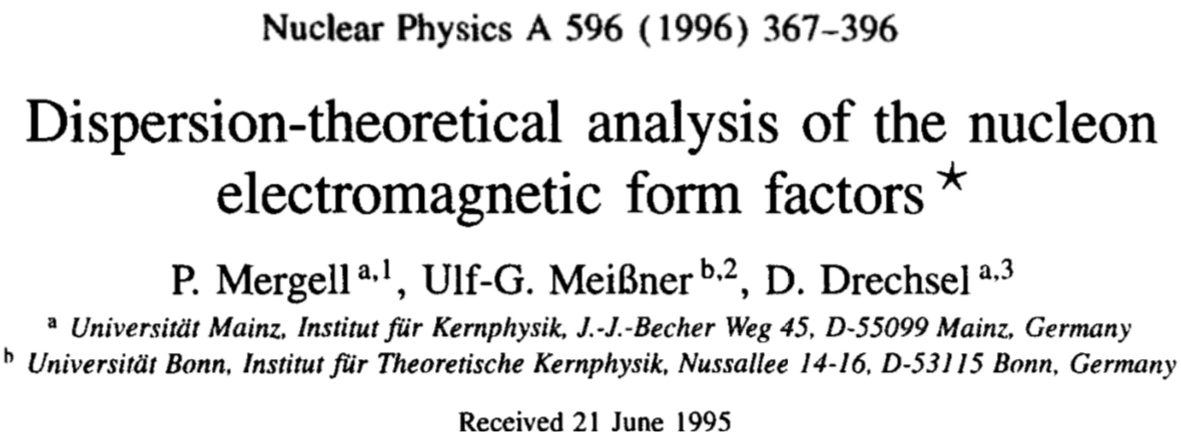
$$G_2^V \simeq \frac{eg_V}{2M}\left(-0.2+\frac{1.2}{1-(t/22m_\pi^2)}\right). \qquad (7)$$

By taking this attitude, the resonant state at $E_R \simeq 4.7m_\pi$ will be attributed to a $T=1$, $J=1$ two-pion state.

This is the first version of a vector-meson dominance (VMD) model for the nucleon form factors, including only the rho. Later

- 1974 Höhler
- 1995 Mergell, Meißner, Drechsel
- 2014 Lorenz, Meißner

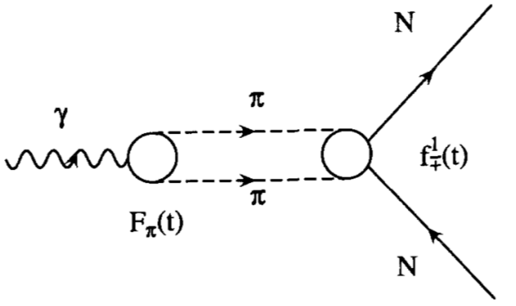
# Models for the Nucleon Form Factors employing Dispersion Relations


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.

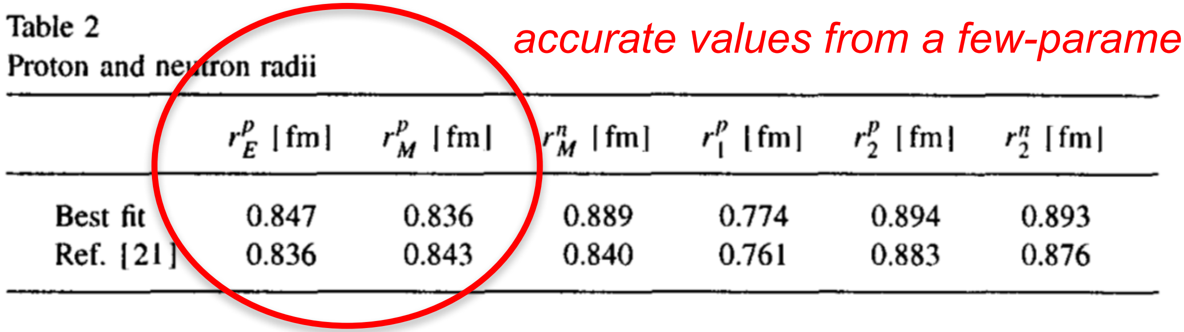
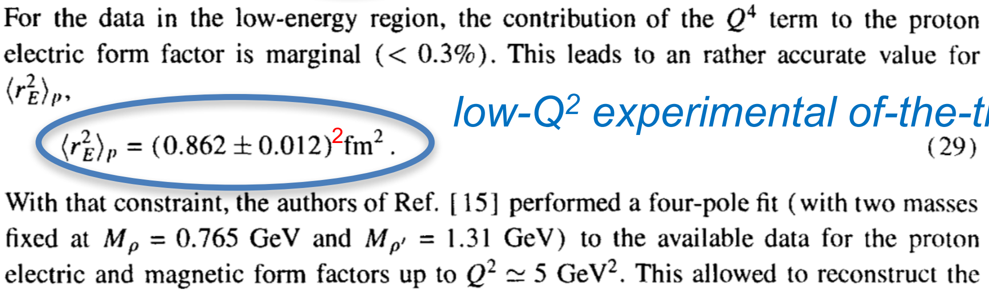


Table 2
Proton and neutron radii

| | $r_E^p$ [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 |

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


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 $\langle r_E^2 \rangle_p$,

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

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

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