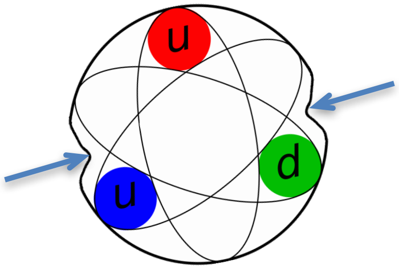
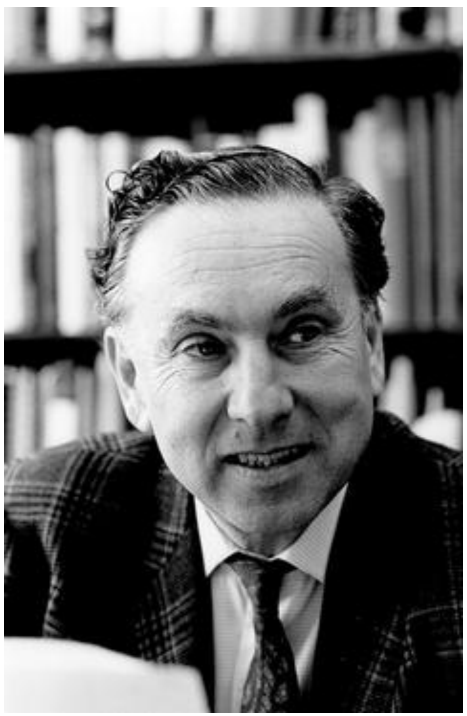
COMPASS++ / AMBER
and a Measurement of the Proton Radius
in High-Energy μp Scattering



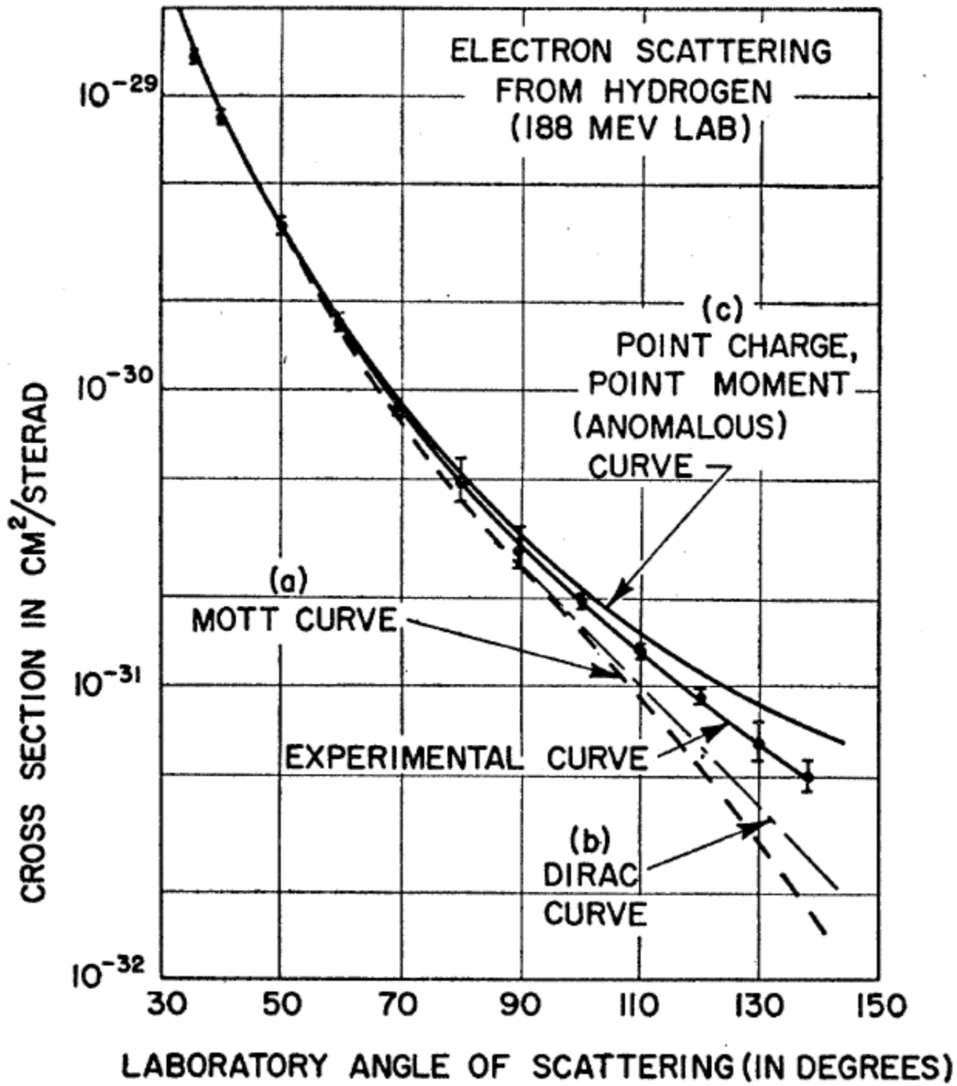
- The quest for hadron structure at Brookhaven and around the world: a few triggers
- An unusual approach to precision low-Q^2 physics using a high-energy muon beam
- COMPASS and a Letter of Intent for the long-range future: highlights from a broad physics program
- some test setup results

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



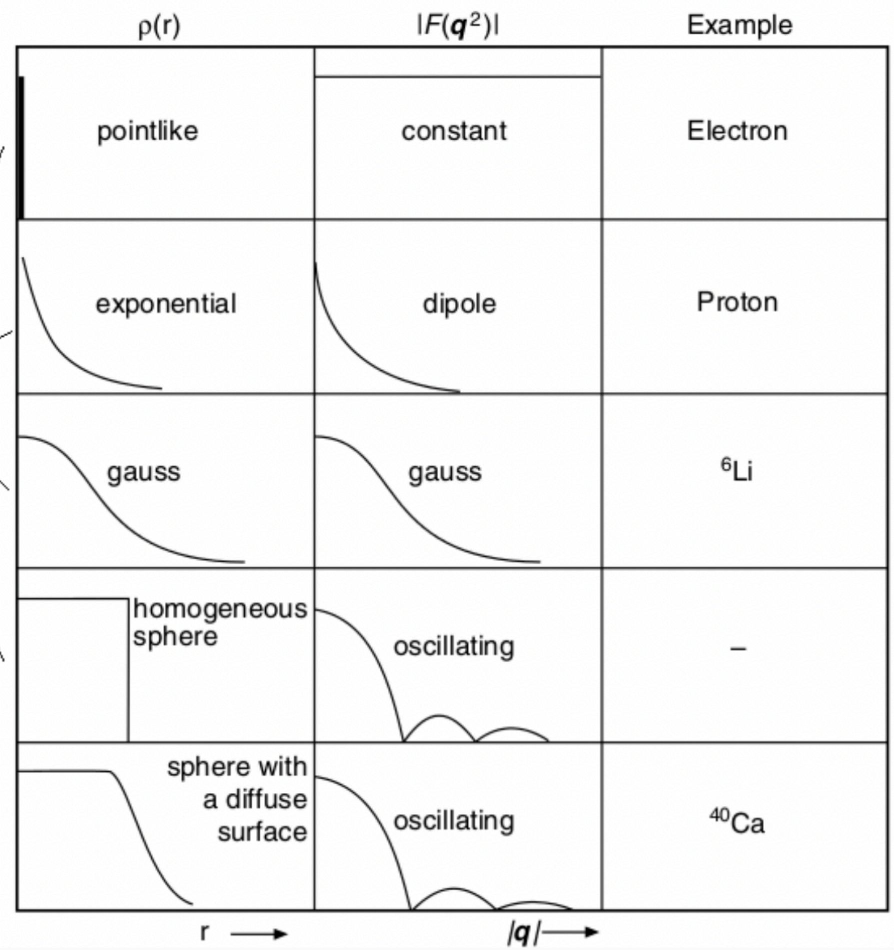
R. Hofstadter



Fourier transform of the charge distribution

Charge distribution $f(r)$	Form Factor $F(\boldsymbol{q}^2)$
$\delta(r)/4\pi$	1
$(a^3/8\pi)\cdot\exp(-ar)$	$\left(1+\boldsymbol{q}^2/a^2\hbar^2\right)^{-2}$
$\left(a^2/2\pi\right)^{3/2}\cdot\exp\left(-a^2r^2/2\right)$	$\exp\left(-\boldsymbol{q}^2/2a^2\hbar^2\right)$
$\begin{cases} 3/4\pi R^3 & \text{for } r \le R \\ 0 & \text{for } r > R \end{cases}$	$3\,\alpha^{-3}\,(\sin\alpha-\alpha\cos\alpha)$ with $\alpha=\lvert\boldsymbol{q}\rvert R/\hbar$

from: B. Povh, Particles and Nuclei



Extension of charge and magnetization is related to form factor $F(q^2)$

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 on dispersion theory and on a strong pion-pion interaction. The model is a synthesis of several theoretical ideas proposed by Frazer and Fulco,[1] Nambu,[2] and Chew.[3]

Let us first of all summarize some general properties of the nucleon form factors. We write the interaction of the nucleon with the electromagnetic field in the form:

$$\langle p'|j_\mu|p\rangle A_\mu = i\bar{u}(p')[G_1(t)\gamma_\mu + G_2(t)\sigma_{\mu\nu}k_\nu]u(p)A_\mu, \quad (1)$$

where p', p, and k are the four-momenta of the final nucleon, initial nucleon, and photon, respectively, and $t=k^2=(p'-p)^2$. The G_i still are operators in the isospin space:

$$G_i = G_i^S + G_i^V\tau_3,$$

and so

$$G_i^p = G_i^S + G_i^V; \quad G_i^n = G_i^S - G_i^V.$$

functions tend to the static charge and magnetic moment of the nucleon:

$$G_1^p(0)=e, \quad G_1^n(0)=0,$$

$$G_2^p(0)=\mu_p=eg_p/2M, \quad G_2^n(0)=\mu_n=eg_n/2M,$$

$$G_1^S(0)=G_1^V(0)=e/2,$$

$$G_2^S(0)=(\mu_p+\mu_n)/2=eg_S/2M,$$

$$G_2^V(0)=(\mu_p-\mu_n)/2=eg_V/2M,$$

$$g_p=1.79, \quad g_n=-1.91,$$

$$g_S=-0.06, \quad g_V=1.85, \quad (2)$$

The functions $G(t)$ are related to the usual Hofstadter form factors $F(t)$ by the following definitions:

$$G_i^{p,n}(t)=G_i^{p,n}(0)F_i^{p,n}(t). \quad (3)$$

Theory of the time – 1958ff

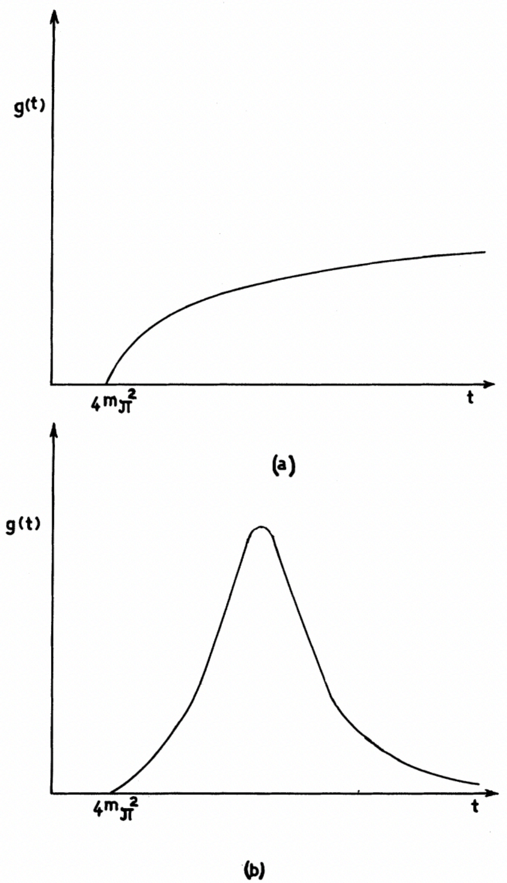


FIG. 1. Schematic representations of $g(t)$ in arbitrary scale. (a) Uncorrelated pions; (b) strong pion-pion resonance.

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 $t_R \simeq 22 m_\pi{}^2$:

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

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

By taking this attitude, the resonant state at $E_R \simeq 4.7 m_\pi$ 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 resonance. 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

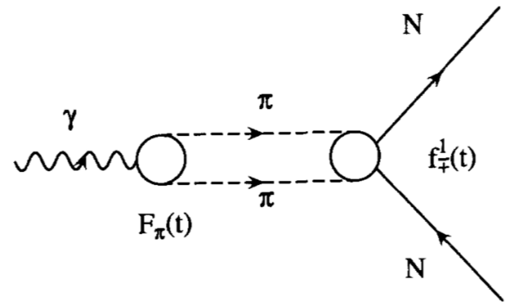
Dispersion-theoretical analysis of the nucleon electromagnetic form factors ★

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

accurate values from a few-parameter fit to all-Q² 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 $\langle r_E^2\rangle_p$,

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

low-Q² 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 $Q^2 \simeq 5$ GeV². This allowed to reconstruct the

Side remark: discovery of the ρ(770) resonance

VOLUME 6, NUMBER 11 PHYSICAL REVIEW LETTERS JUNE 1, 1961

PION-PION INTERACTION IN PION PRODUCTION BY π^+-p COLLISIONS*

D. Stonehill, C. Baltay, H. Courant, W. Fickinger, E. C. Fowler, H. Kraybill, J. Sandweiss, J. Sanford,† and H. Taft

Yale University, New Haven, Connecticut and Brookhaven National Laboratory, Upton, New York

(Received May 12, 1961)

Since the first conjectures[1] that rise in the total π^--p cross section between 300 and 600 Mev might be caused by a pion-pion interaction, this subject has received considerable attention. Theoretical analysis[2] of high-energy electron scattering on protons and neutrons has predicted a resonance in the pion-pion interaction at a total di-pion energy (ω) of 4 to 5 pion masses, with isotopic spin and angular momentum both equal to one. Several analyses of π^--p experiments[3] in the 1-Bev energy range have tended to confirm this prediction, and application[4] of the Chew-Low method has indicated a steep rise in the pion-pion cross section above $\omega = 4$. Recent work[5] with 1.9-Bev π^--p collisions shows a peak in the pion-pion interaction at $\omega \sim 5.5$. We report here evidence of pion-pion interaction in π^+-p collisions at three separate energies, which show striking effects attributable to a pion-pion resonance with ω of about 5.5 pion masses.

the final identification. Cross sections for the various reactions, based upon the first compilation of these events, are shown in Table I.

The influence of pion-pion interaction will appear most readily in the single pion production processes: $\pi^+ + p \to p + \pi^+ + \pi^0$ and $\pi^+ + p \to n + \pi^+ + \pi^+$.

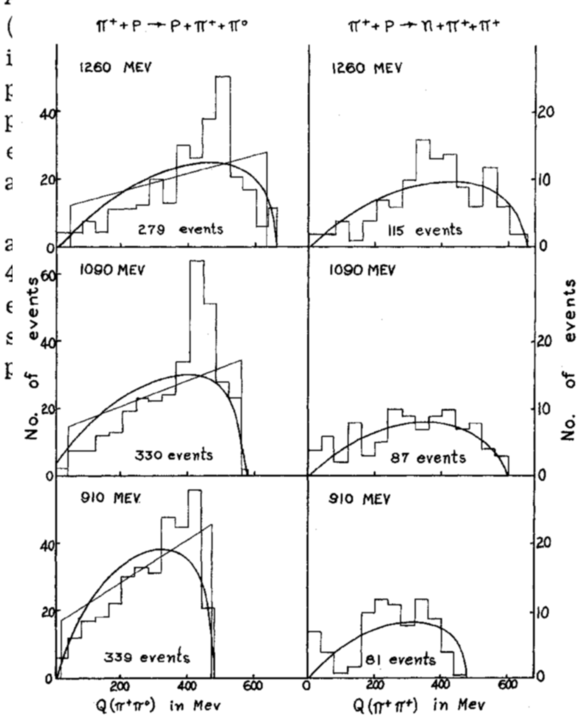


FIG. 1. Distribution of pion-pion Q values (that is, kinetic energy of the two outgoing pions in their mutual center-of-momentum system) for the reactions $\pi^+ + p \to p + \pi^+ + \pi^0$ and $\pi^+ + p \to n + \pi^+ + \pi^+$ at 910-Mev, 1090-Mev, and 1260-Mev laboratory kinetic energy of the incident pion. The curved lines are the Q distribution resulting from uniform distribution of the secondary particles in momentum space. The straight lines give the Q distribution resulting from isotropic decay of a pion-proton isobar of unique mass 1230 Mev.

Side remark: discovery of the ρ(770) resonance

VOLUME 6, NUM

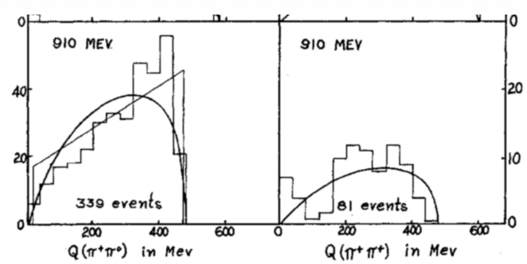
Yale U

Since the fir
π^--p cross se
be caused by a
has received
analysis[2] of hi
protons and n
in the pion-pi
ergy (ω) of 4
and angular m
analyses of π^-
range have te
application[4] o
a steep rise i
$\omega = 4$. Recent
shows a peak
We report her
in π^+-p collisi
which show st
pion resonanc

Emilio Gino Segrè

"The antiproton discovery [1956] was followed by studies of its properties and interactions, as well as those of the antineutron. In subsequent experiments Chamberlain and Wiegand worked independently of Segrè, with Chamberlain rejoining the Segrè group after a few years but on an equal footing in what became the Segrè-Chamberlain group. In the early 1960s Ypsilantis, with Wiegand and students, mounted an ambitious counter experiment to study pion-pion interactions through pion production by pions. Theorists had described the electromagnetic form factors of the proton and neutron in terms of a spin-one resonance between pions with an energy in the range of 500-600 MeV. The experiment was designed to find such a resonant state. In the end the resonance proved to be at 760 MeV, near the upper limit of the apparatus. The discovery of the rho meson, as the state was called, was accomplished by others using hydrogen bubble chambers. The counter experiment confirmed the bubble chamber results but could add little. Segrè blamed the theorists for their incorrect prediction of the resonant energy." (from: J. David Jackson, "Emilio Gino Segrè 1905 – 1989")

-pion Q values (that is,
ing pions in their mutual
for the reactions $\pi^+ + p$
π^+ at 910-Mev, 1090-Mev,
c energy of the incident
Q distribution resulting
e secondary particles in
t lines give the Q distri-
decay of a pion-proton
v.

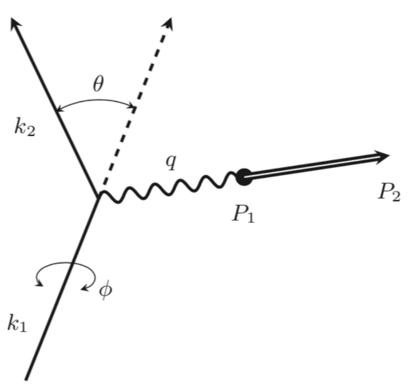


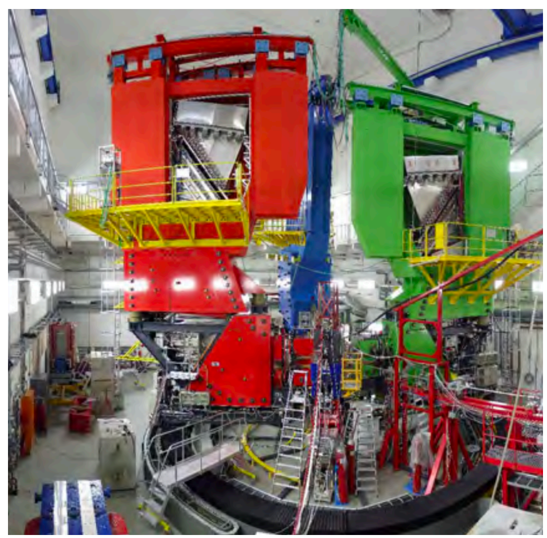
In the footsteps of Hofstadter: electron scattering at the Mainz Microtron MAMI

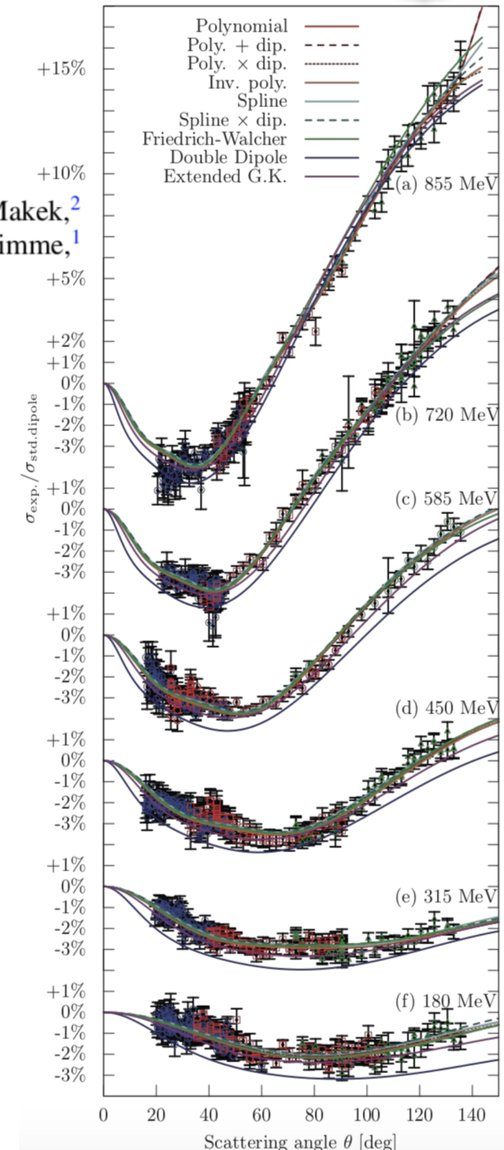
PHYSICAL REVIEW C **90**, 015206 (2014)

Electric and magnetic form factors of the proton

J. C. Bernauer,[1,*] M. O. Distler,[1,†] J. Friedrich,[1] Th. Walcher,[1] P. Achenbach,[1] C. Ayerbe Gayoso,[1] R. Böhm,[1] D. Bosnar,[2] L. Debenjak,[3] L. Doria,[1] A. Esser,[1] H. Fonvieille,[4] M. Gómez Rodríguez de la Paz,[1] J. M. Friedrich,[5] M. Makek,[2] H. Merkel,[1] D. G. Middleton,[1] U. Müller,[1] L. Nungesser,[1] J. Pochodzalla,[1] M. Potokar,[3] S. Sánchez Majos,[1] B. S. Schlimme,[1] S. Širca,[3,6] and M. Weinriefer[1]
(A1 Collaboration)
[1]*Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
[2]*Department of Physics, University of Zagreb, 10002 Zagreb, Croatia*
[3]*Jožef Stefan Institute, Ljubljana, Slovenia*
[4]*LPC-Clermont, Université Blaise Pascal, CNRS/IN2P3, F-63177 Aubière Cedex, France*
[5]*CERN, CH-1211 Geneva 23, Switzerland, on leave of absence from Physik-Department, Technische Universität München, 85748 Garching, Germany*
[6]*Department of Physics, University of Ljubljana, Slovenia*
(Received 26 July 2013; revised manuscript received 24 March 2014; published 29 July 2014)



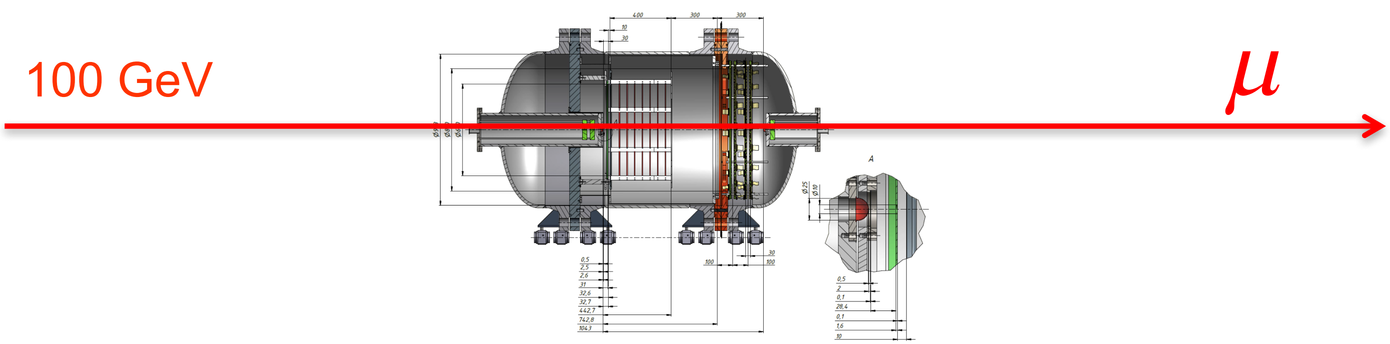




In the footsteps of Hofstadter: ideas for measurement of the low-momentum transfer region

- initial-state radiation (ISR) of the MAMI electron beam: broad ranges of equivalent beam energy and momentum transfer are accessed in the same data
- PRad at Jefferson Lab: electron scattering at 1.1 and 2.2 GeV
- MAMI: detect lowest proton recoil energies, down to 0.5 MeV (i.e. Q^2=0.001GeV^2), within the target gas: active high-pressure TPC, development by PNPI (St. Petersburg) / GSI
- MUSE at PSI: low-energy muon scattering

proposed now: use the high-pressure TPC with the high-energy COMPASS muon beam



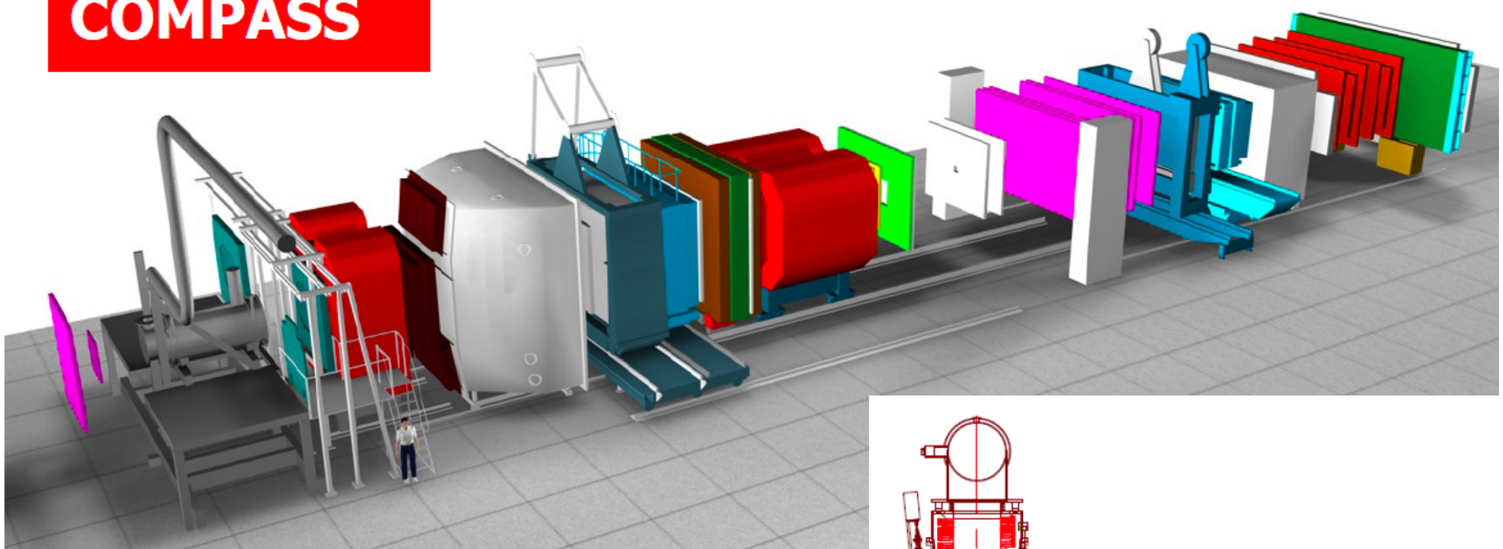
COMPASS QCD facility at CERN (SPS)

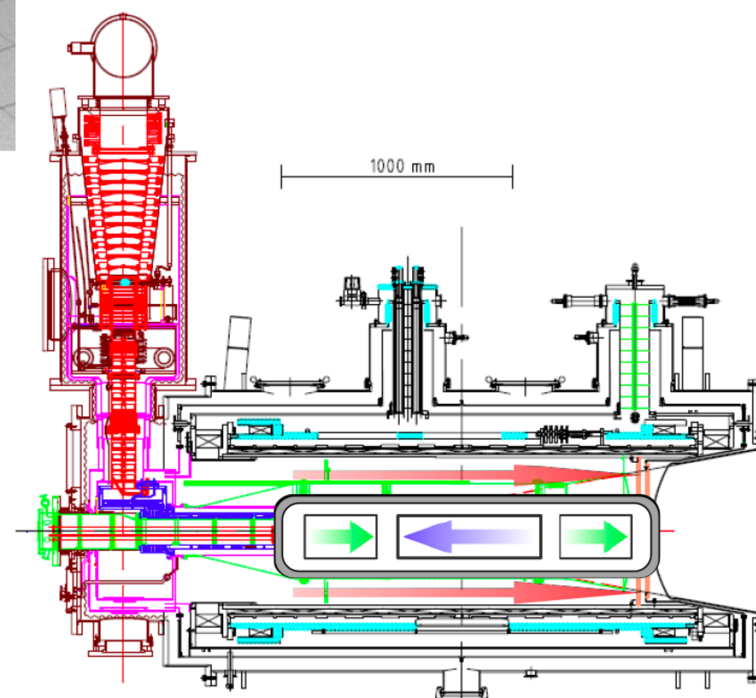
COmmon Muon Proton Apparatus for Structure and Spectroscopy

~220 physicists, 12 countries + CERN, 24 institutions

Reminder of the COMPASS physics program

COMPASS

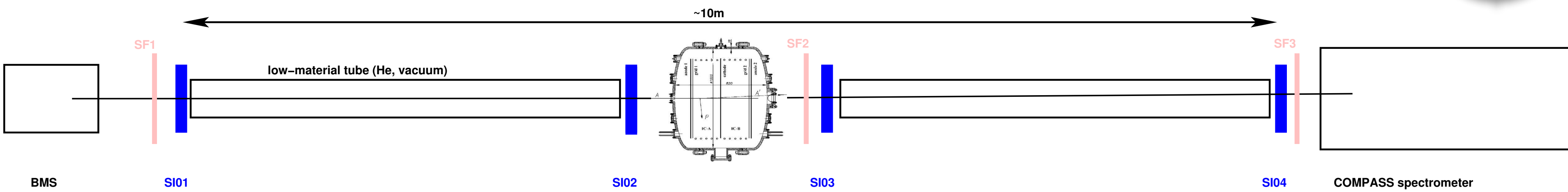




Versatile apparatus to investigate QCD:
Two-stage COMPASS Spectrometer

1. Muon, electron and hadron beams with momenta 20-250 GeV and intensities up to 10^8 particles per second
2. Solid-state polarised (NH_3 or ^6LiD), liquid hydrogen and nuclear targets
3. Powerful tracking (350 planes) and PID systems (Muon Walls, Calorimeters, RICH)

Proton Radius Measurement: Proposed Setup

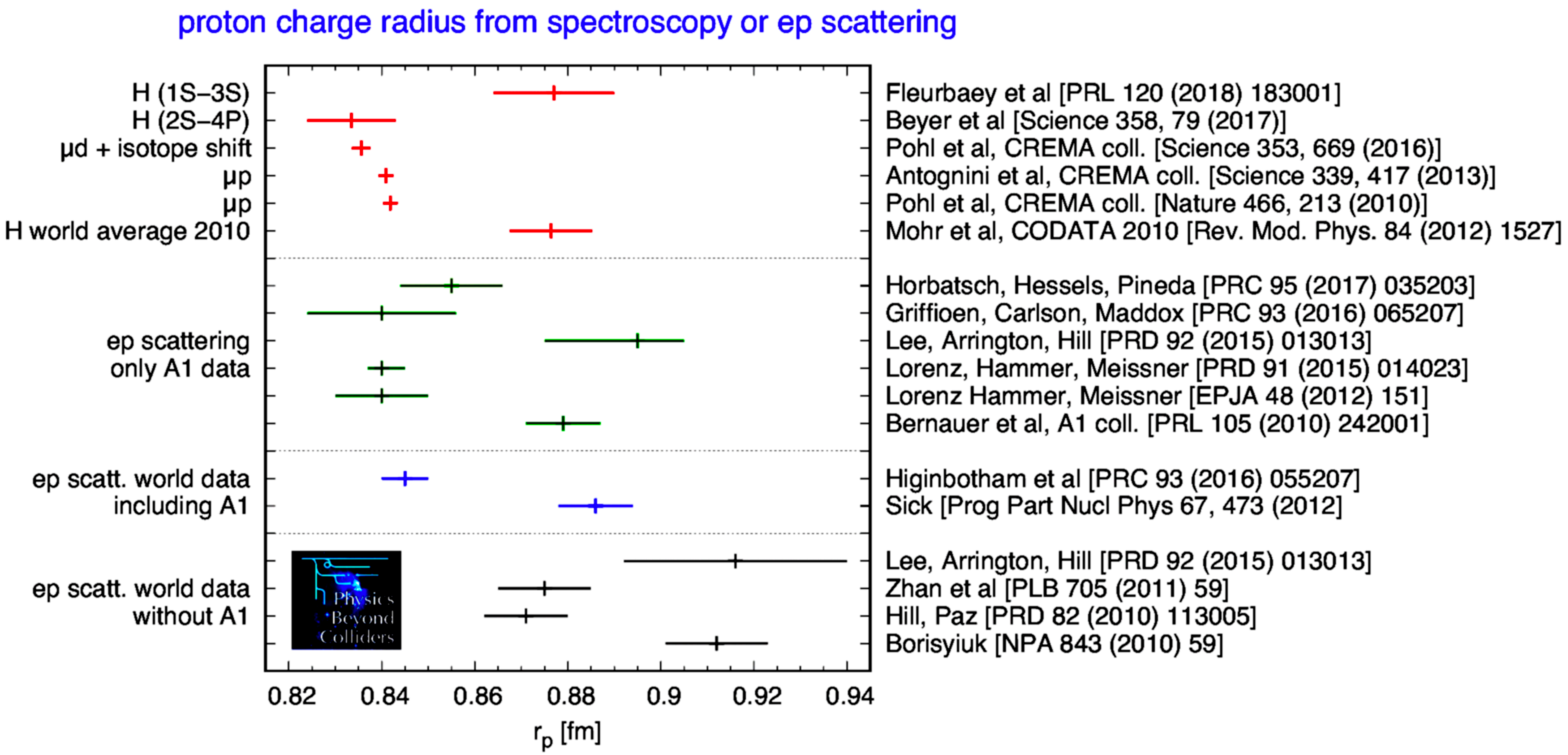


- muon scattering angles 0.3 (Q^2=0.001GeV^2) … 2 mrad (Q^2=0.04GeV^2)
  (100 GeV beam, minimal kinematic range, better larger)
- side kick over 5m base line: 1.5 … 10 mm
- sufficiently large, high-resolution Si detectors, Δx<=10μm, x>=50mm
- pressurized active high-purity H_2 target
- corresponding track lengths a few cm
- TPC readout on two sides
- beam intensity >= 2e6 muons/second, one year of running

All details are to be fixed employing a realistic Monte-Carlo simulation, including state-of-the-start (?!) event generator

⟷ Jan Bernauer's work for the MAMI experiment

Summary of the present physics case



from the CERN future document "PBC summary", December 2018

ESPP and PBC

CERN Accelerating science
europeanstrategyupdate.web.cern.ch
Sign in
European Strategy Update
European Particle Physics Strategy Update 2018 – 2020
The European Strategy for Particle Physics provides a clear prioritisation of European ambitions in advancing the particle physics science. The Strategy is due to be updated by May 2020 to guide the direction of the field to the mid-2020s and beyond.
To optimally inform all participants in the process, the Secretariat of the European Strategy Group (ESG) called upon the particle physics community across universities, laboratories and national institutes to submit written input by 18 December 2018 to prepare the discussions on the Strategy Update which will take place in 2019.
UPDATES
Call for Input
157 proposals submitted
Home
About
Process
Submit input
Organisation
Resources

CERN Council Open Symposium on the Update of
European Strategy for Particle Physics
13-16 May 2019 - Granada, Spain

PBC-QCD

CERN-PBC-REPORT-2018-008

Physics Beyond Colliders
QCD Working Group Report

A. Dainese[1], M. Diehl[2,*], P. Di Nezza[3], J. Friedrich[4], M. Gaździcki[5,6] G. Graziani[7], C. Hadjidakis[8], J. Jäckel[9], M. Lamont[10] J. P. Lansberg[8], A. Magnon[10], G. Mallot[10], F. Martinez Vidal[11], L. M. Massacrier[8], L. Nemenov[12], N. Neri[13], J. M. Pawlowski[9,*], S. M. Puławski[14], J. Schacher[15], G. Schnell[16,*], A. Stocchi[17], G. L. Usai[18], C. Vallée[19], G. Venanzoni[20]

arXiv:1901.04482
(85 pages)

Contents

1 Overview 3
1.1 Proposals and physics topics 4

2 Proposals 10
2.1 LHC Fixed Target 10
2.1.1 Physics motivation 10
2.1.2 LHCb-FT 16
2.1.3 LHCSpin 19
2.1.4 ALICE-FT 21
2.2 LHC-FT: crystals 22
2.3 COMPASS++ 25
2.3.1 μp elastic scattering and the proton charge radius 26
2.3.2 Pion PDFs from Drell-Yan production 31
2.3.3 Kaon polarisability from the Primakov reaction 33
2.3.4 Strange meson spectroscopy with kaon beams 35
2.3.5 Selected other COMPASS++ measurements and summary 37
2.4 MUonE 37
2.5 NA60++ 42
2.6 NA61++ 46
2.7 DIRAC++ 49

3 Summary of heavy-ion measurements 52

4 Measurements for cosmic-ray physics and for neutrino experiments 53

5 Compatibility of COMPASS++ and MUonE at the M2 beam line 60

6 Conclusions 68

List of Figures 70

List of Tables 73

References 74

QCD Conveners' Introduction

Markus Diehl, Jan Pawlowski, Gunar Schnell

Physics Beyond Colliders Annual Workshop
CERN, 16 to 17 January 2019

	LHC FT gas				LHC FT	COMPASS++	MUonE	NA61++	NA60++	DIRAC++
	ALICE	LHCb	LHCSpin	AFTER@LHC	crystals					
proton PDFs	×	×		×						
nuclear PDFs	×	×		×		×				
spin physics	×		×	×		×				
meson PDFs						×				
heavy ion physics	×			×				×	×	
elast. μ scattering						×	×			
chiral dynamics						×				×
magnet. moments					×					
spectroscopy						×				
measurements for cosmic rays and neutrino physics	×	×		×		×		×		

Table 1. Schematic overview of the physics topics addressed by the studies presented in the QCD working group.

A NQF (COMPASS++/AMBER) summary for ESPP

A New QCD Facility at the M2 beam line of the CERN SPS

Document for the 2020 update of the European Strategy for Particle Physics

Abstract

This document summarises the physics interest, sensitivity reach and competitiveness of a future general-purpose fixed-target facility for Particle Physics research. Based upon the versatile M2 beam line of the CERN SPS, a great variety of measurements is proposed to address fundamental issues of Quantum Chromodynamics. In phase-1 of the project, operating with muons a complementary result on the average charged proton radius will be obtained and the elusive General Parton Distribution function E can be accessed, operating with pions the quark structure of the pion will be revealed, operating with antiprotons completely new results in the search of exotic XYZ states are expected, and operating with protons the antiproton production cross section will be measured as important input for future Dark Matter searches. Upgrading the M2 beam line in phase-2 of the project will provide unrivalled radio-frequency separated high-intensity and high-energy beams. Operating with kaons the virgin field of high-precision strange-meson spectroscopy becomes accessible, the Primakoff process will be used for a first measurement of the kaon polarisability, and the Drell-Yan process opens access to the

Apparatus for Meson and Baryon Experimental Research

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

January 12, 2019

arXiv 1808.00848
CERN-SPSC-2019-003 (SPSC-I-250)

Letter of Intent:

A New QCD facility at the M2 beam line of the CERN SPS[*]

COMPASS++[†]/AMBER[‡]

B. Adams[13,12], C.A. Aidala[1], R. Akhunzyanov[14], G.D. Alexeev[14], M.G. Alexeev[41], A. Amoroso[41,42],

LoI content: Physics

Contents

Executive Summary 1

1 Introduction 6

2 Hadron physics using the muon beam 8

2.1 Proton radius measurement using muon-proton elastic scattering . . . 8

2.1.1 Experiments targeting the proton radius puzzle: the M2 beam line case . . . 8

2.1.2 Formalism of elastic lepton-proton scattering . . . 10

2.1.3 Measurement at the CERN M2 beam line . . . 11

2.2 Hard exclusive reactions using muon beam and transversely polarised target . . . 12

2.2.1 Motivations for a measurement of the GPD E . . . 12

2.2.2 Measurements of Deeply Virtual Compton Scattering . . . 13

2.2.3 Measurements of Deeply Virtual Meson Production . . . 15

3 Hadron physics using conventional hadron beams 17

3.1 Drell-Yan and charmonium production using conventional hadron beams . . . 17

3.1.1 Introduction: Meson structure and the origin of nuclear mass . . . 17

3.1.2 Separation of valence and sea-quark contributions in the pion . . . 18

3.1.3 J/ψ production mechanism and the gluon distribution in the pion . . . 21

3.1.4 Nuclear dependence studies: Flavour-dependent valence modifications . . . 23

3.1.5 Drell-Yan and J/ψ angular distributions . . . 24

3.1.6 Run plan: physics goals and required beam time . . . 24

3.1.7 Worldwide competition . . . 26

3.2 Spectroscopy with low-energy antiprotons . . . 27

3.2.1 Physics case . . . 27

3.2.2 Beam line . . . 29

3.2.3 Measurements . . . 31

3.2.4 Experimental requirements . . . 31

3.3 Measurement of antiproton production cross sections for Dark Matter Search . . . 32

3.3.1 Physics case . . . 32

3.3.2 Feasibility of the measurement . . . 35

3.3.3 Competitiveness and complementarity . . . 40

4 Hadron physics with RF-separated beams 42

4.1 Beam line . . . 42

4.2 Spectroscopy of kaons . . . 43

4.2.1 Physics case . . . 43

4.2.2 Previous measurements . . . 45

4.2.3 Novel analysis techniques . . . 45

4.2.4 Future measurements at the SPS M2 beam line . . . 46

4.2.5 Planned or proposed measurements at other facilities . . . 46

4.3 Drell-Yan physics with high-intensity kaon and antiproton beams . . . 47

4.3.1 Studies of the spin structure of the nucleon with an antiproton beam . . . 47

4.3.2 Valence-quark distributions in the kaon . . . 49

4.3.3 Separation of valence and sea-quark contributions in the kaon . . . 50

4.3.4 The J/ψ production mechanism and the gluon distribution in the kaon . . . 51

4.3.5 Other experiments . . . 52

4.3.6 Run plan: physics goals and required beam time . . . 53

4.4 Study of the gluon distribution in the kaon via prompt-photon production . . . 53

4.4.1 Gluon PDFs for mesons . . . 53

4.4.2 Prompt photons . . . 54

4.4.3 Prompt-photon production in COMPASS kinematics . . . 54

4.5 Primakoff Reactions . . . 57

4.5.1 Kaon polarisability . . . 57

4.5.2 Direct measurement of the lifetime of the neutral pion . . . 58

4.6 Vector-meson production off nuclei by pion and kaon beams . . . 59

4.6.1 Physics case . . . 59

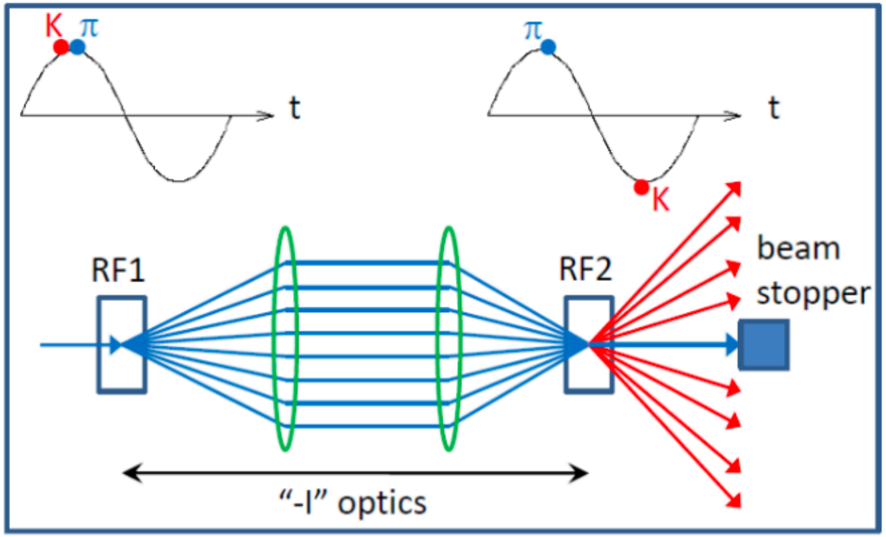
4.6.2 The proposed measurement . . . 61

10 projects currently, at first stage with the available hadron/muon beams, at second: RF separated kaon and antiproton beam.

All beams we are going to use are unique worldwide

RF separated beam

- Deflection with 2 cavities
- Relative phase $= 0 \to$ dump
- Deflection of wanted particle given by $\Delta\phi \approx \frac{\pi f L}{c} \frac{m_w^2 - m_u^2}{p^2}$



To keep good separation:

L should increase as p^2 for a given $f \to$ limits the beam momentum

Initial expectations before further $R\&D$:

$\sim$ 80 GeV Kaon beam
$\sim$ 110 GeV Anti-proton beam

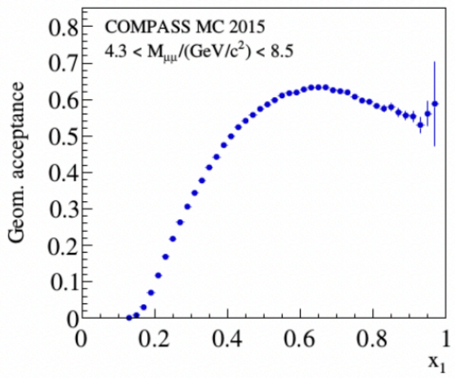
Summary table – beam requirements

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

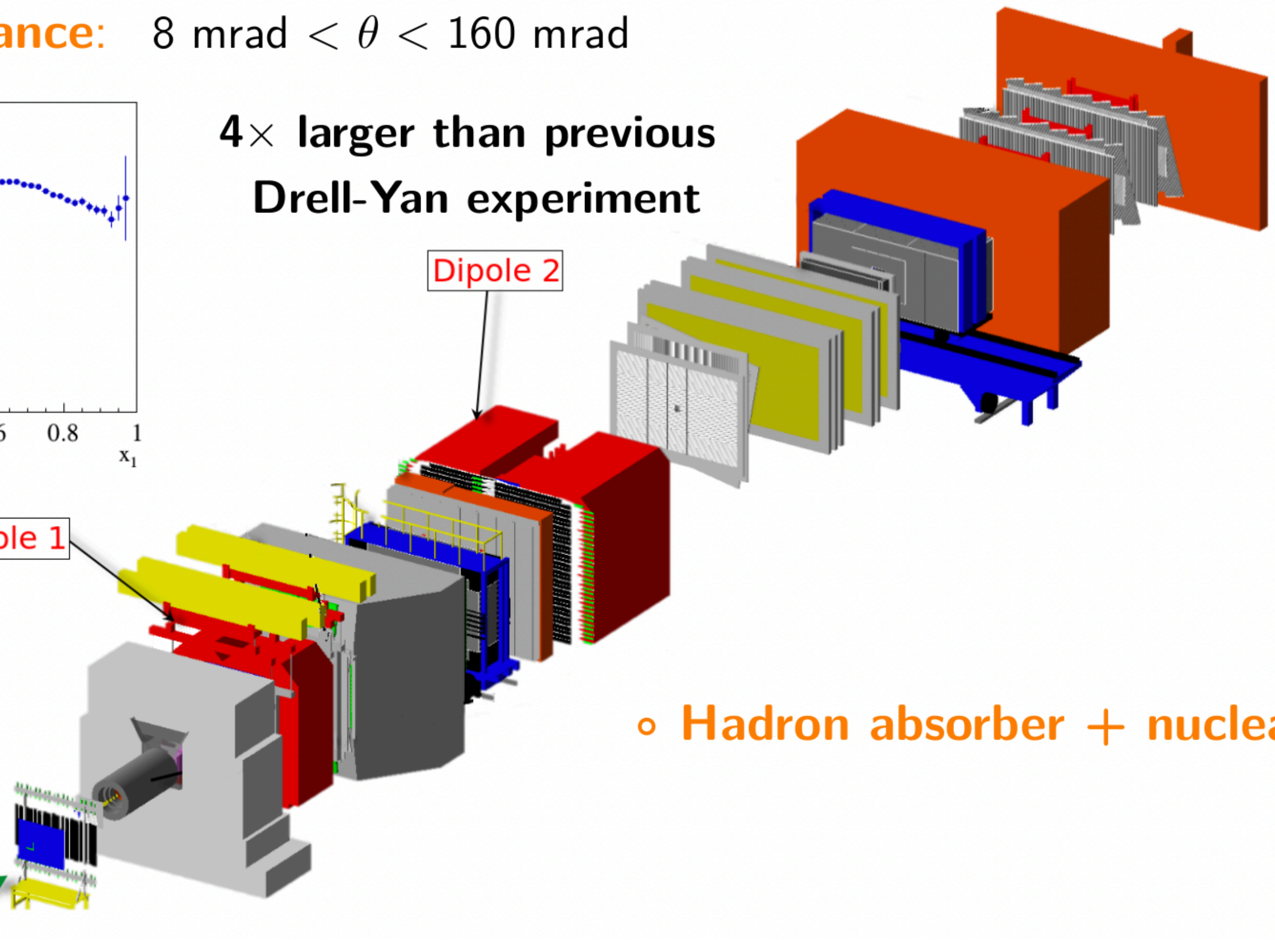
Table 5: Requirements for future programs at the M2 beam line after 2021. Standard muon beams are in blue, standard hadron beams in green, and RF-separated hadron beams in red.

Other conventional-beam physics: Drell-Yan

- **Large acceptance**: 8 mrad $< \theta <$ 160 mrad

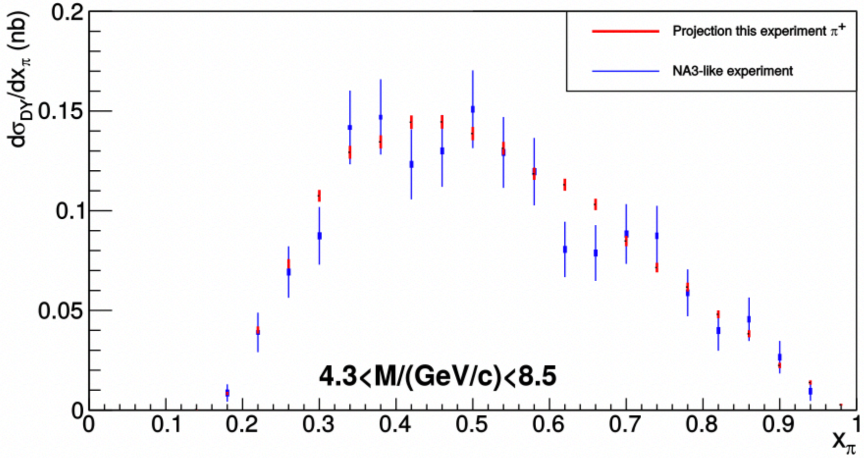


4× larger than previous Drell-Yan experiment



- **Hadron absorber + nuclear targets**

Other conventional-beam physics: Drell-Yan

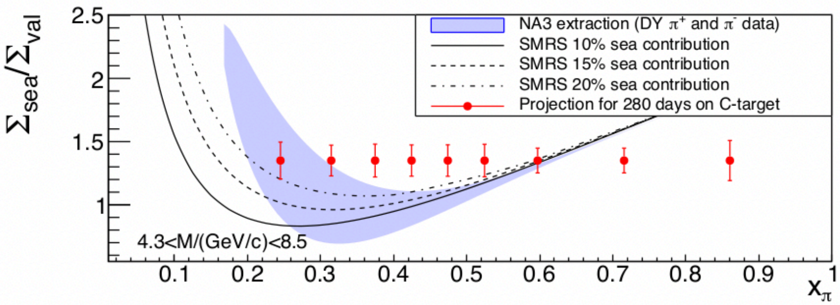


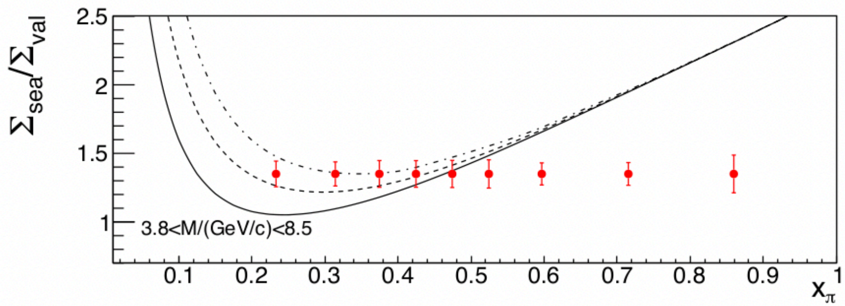
Expected accuracy compared to NA3 result

- Collect at least a **factor 10 more statistics** than presently available
- Aim at the first precise direct measurement of the pion sea contribution

$\Sigma_{val} = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence

$\Sigma_{sea} = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$: no valence-valence

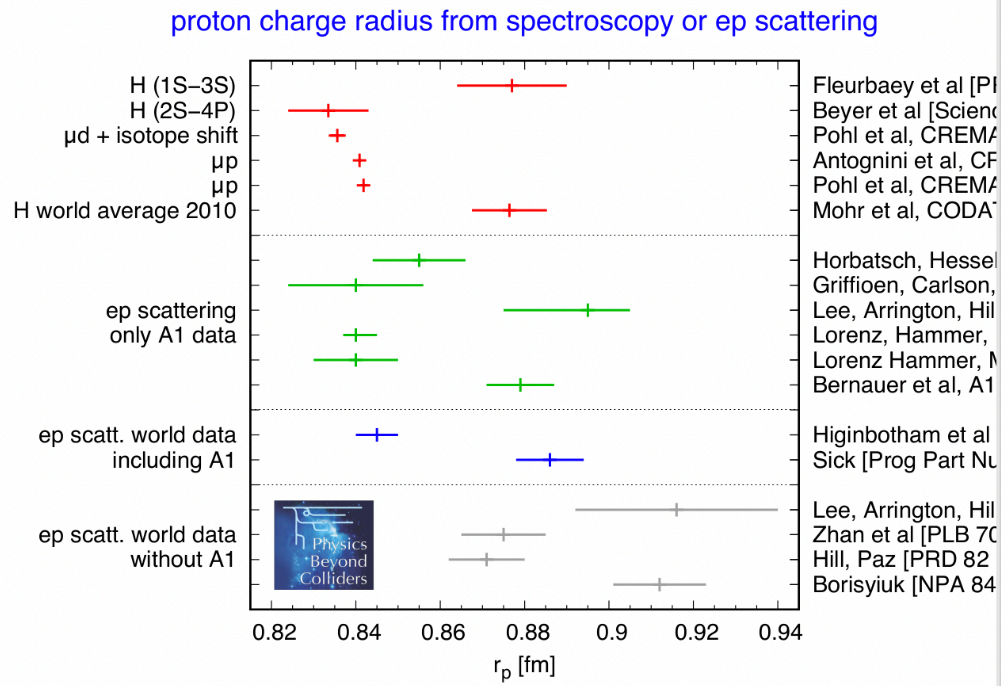




back to proton radius:
from the PBC-QCD convener's summary

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

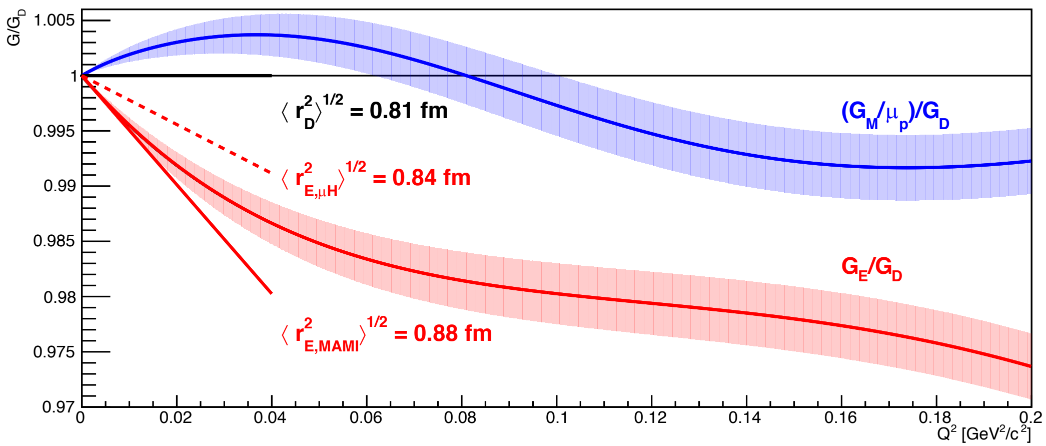


★ advantages over ep scatt:

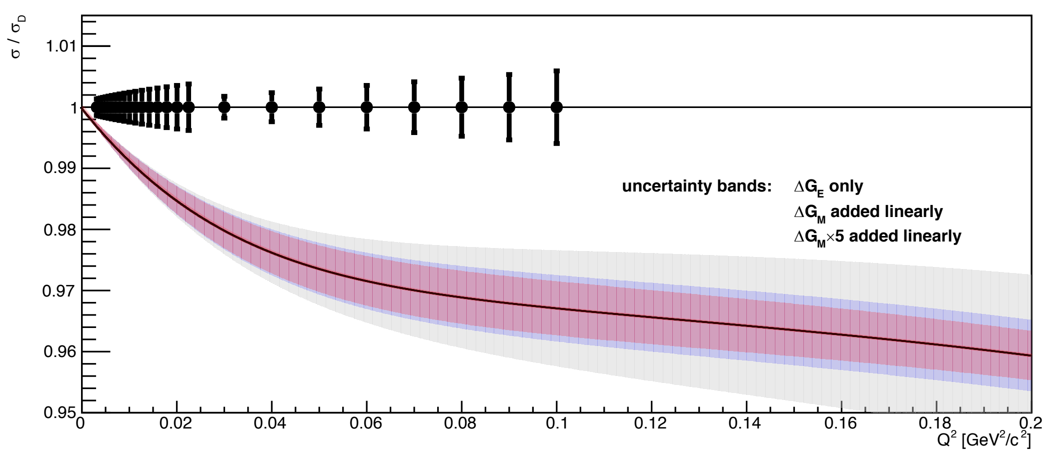
- ✦ smaller QED radiative corrections
- ✦ very small contamination from magnetic form factor

Elastic lepton-proton cross section

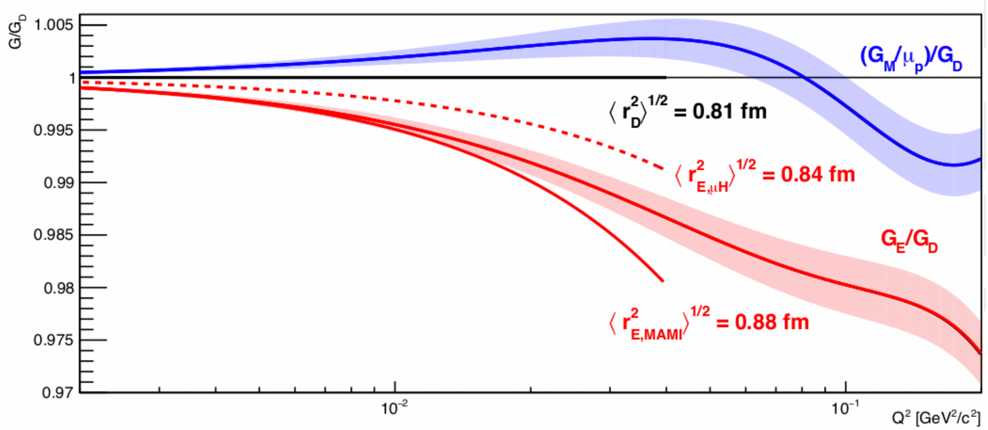
$$\frac{d\sigma^{\mu p\to\mu p}}{dQ^2} = \frac{\pi\alpha^2}{Q^4 m_p^2 \vec{p}_\mu^{\,2}}\left[\left(G_E^2+\tau G_M^2\right)\frac{4E_\mu^2 m_p^2 - Q^2(s-m_\mu^2)}{1+\tau} - G_M^2\frac{2m_\mu^2 Q^2 - Q^4}{2}\right]$$

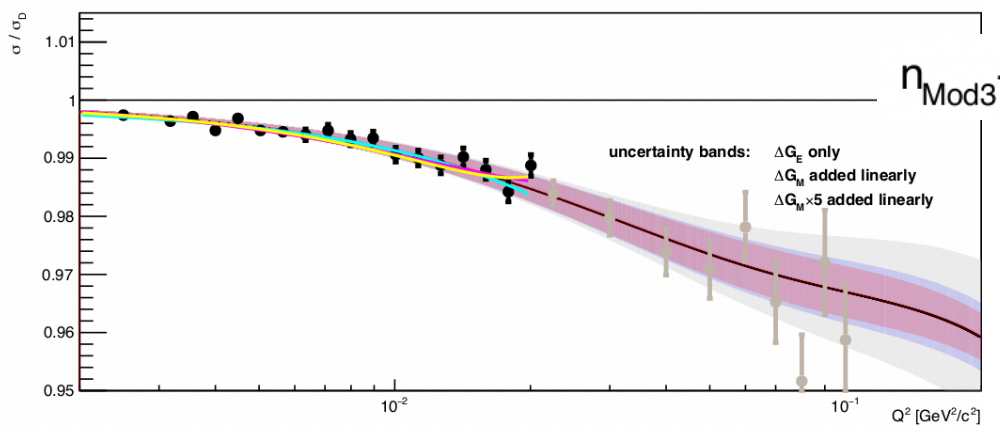


$$\frac{1}{6}r_p^2 = -\frac{d}{dQ^2}\bigg|_{Q^2=0} G_E(Q^2)$$



Elastic lepton-proton cross section





$n_{Mod3} + a\, r^2_{Mod3}\, Q^2 + b_{Mod3}\, Q^4 + c_{Mod3}\, Q^6$

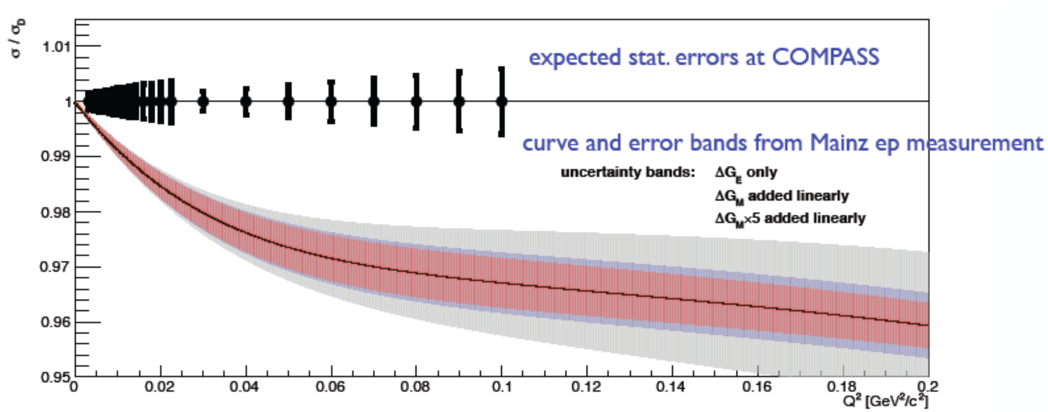
Only the low-Q^2 points in black were used in the various fits (polynomial in Q^2) to the pseudo-data shown as magenta (linear), purple (quadratic) and yellow (3^{rd} order) curves. Pseudo-data points in grey require a different detector setup and are shown here for completeness. Only statistical uncertainties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

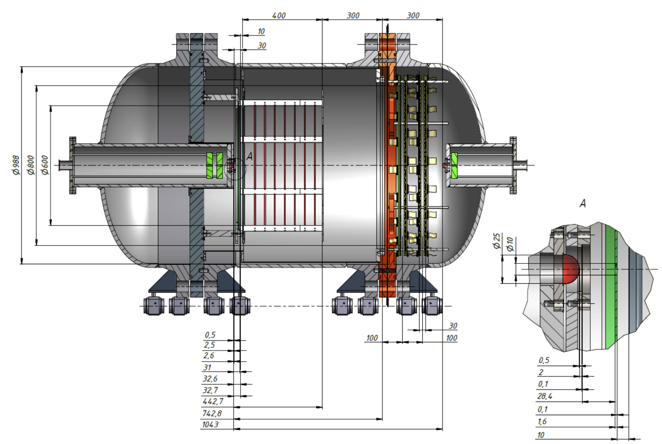
Proton Radius measurement

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

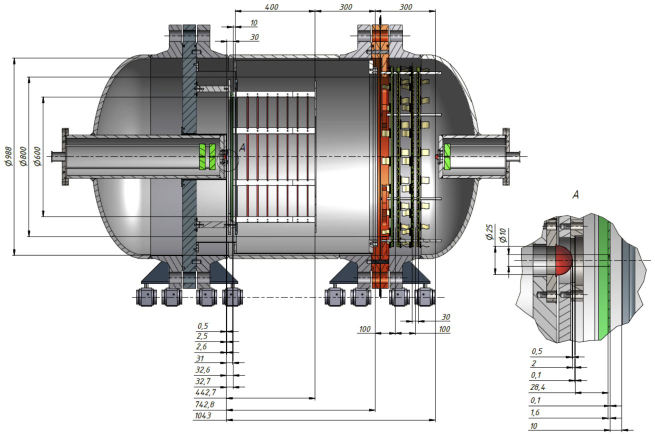
- 100 GeV SPS M2 muon beam
- high-pressure hydrogen TPC active-target cell (PNPI development)
- measure cross-section shape over broad Q^2 range $10^{-4}\ldots10^{-1}$
- fit from 10^{-3} … 2×10^{-2} the proton radius (slope of electric form factor)

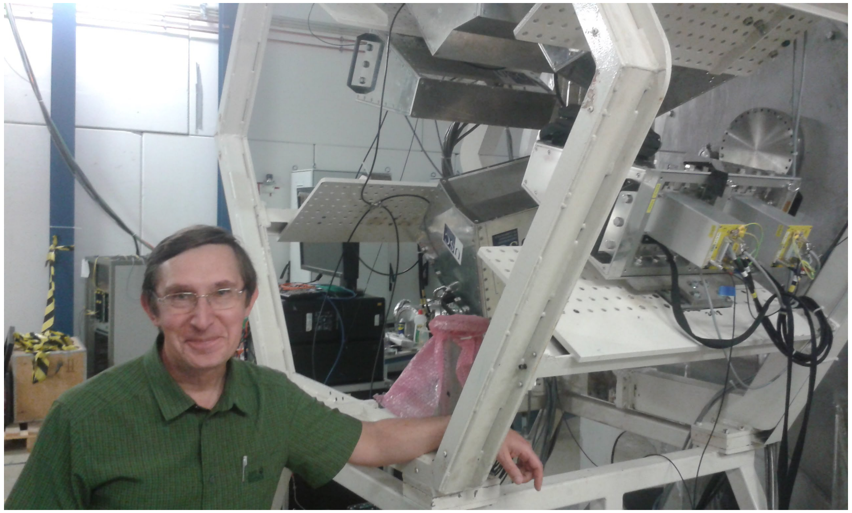




A high-pressure active target TPC

Alexey Vorobyov





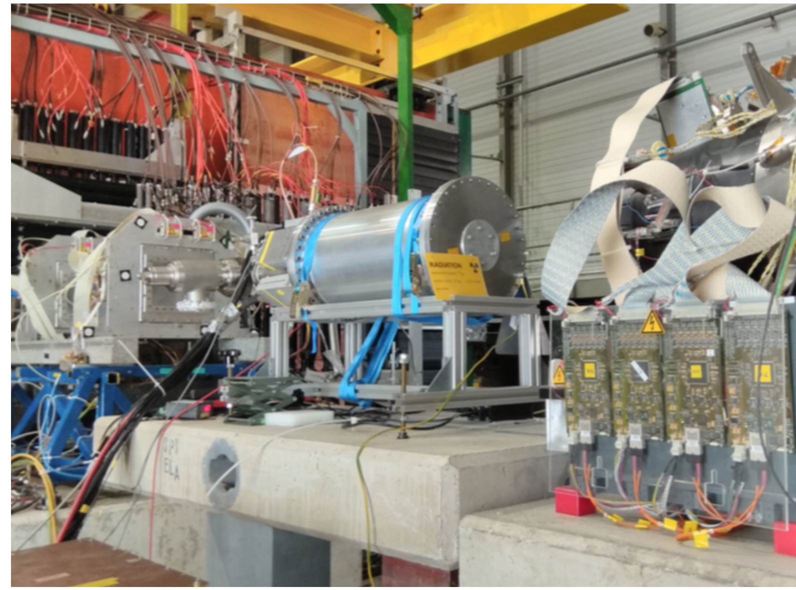
Oleg Kiselev, Evgeni Maev

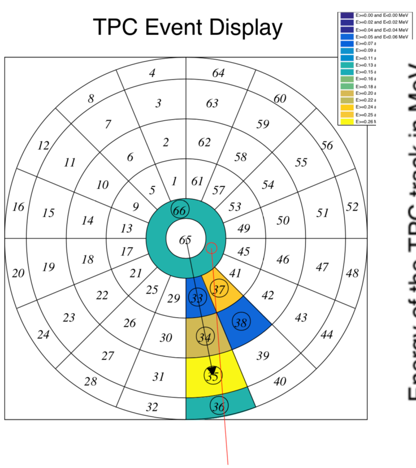
Alexander Inglessi

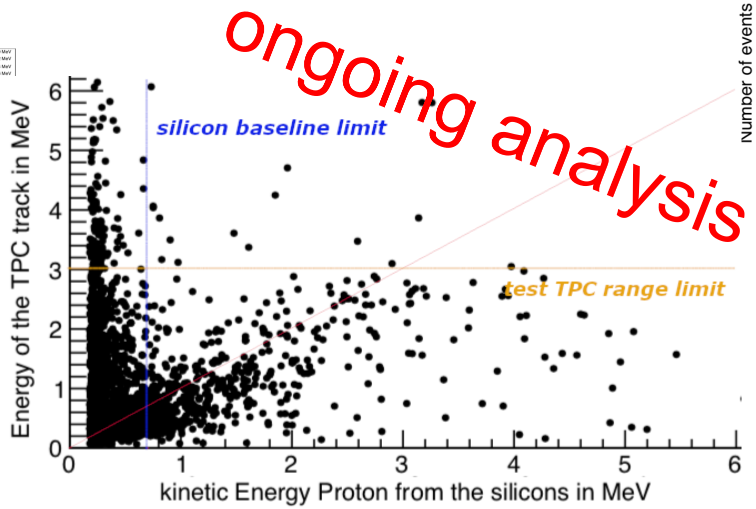
Test in 2018 for Proton Radius measurement

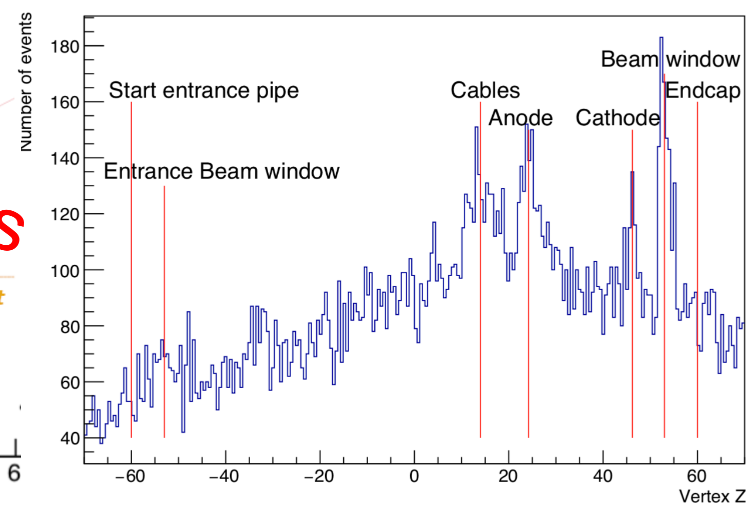
Test setup during 2018 DY run downstream COMPASS, check

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

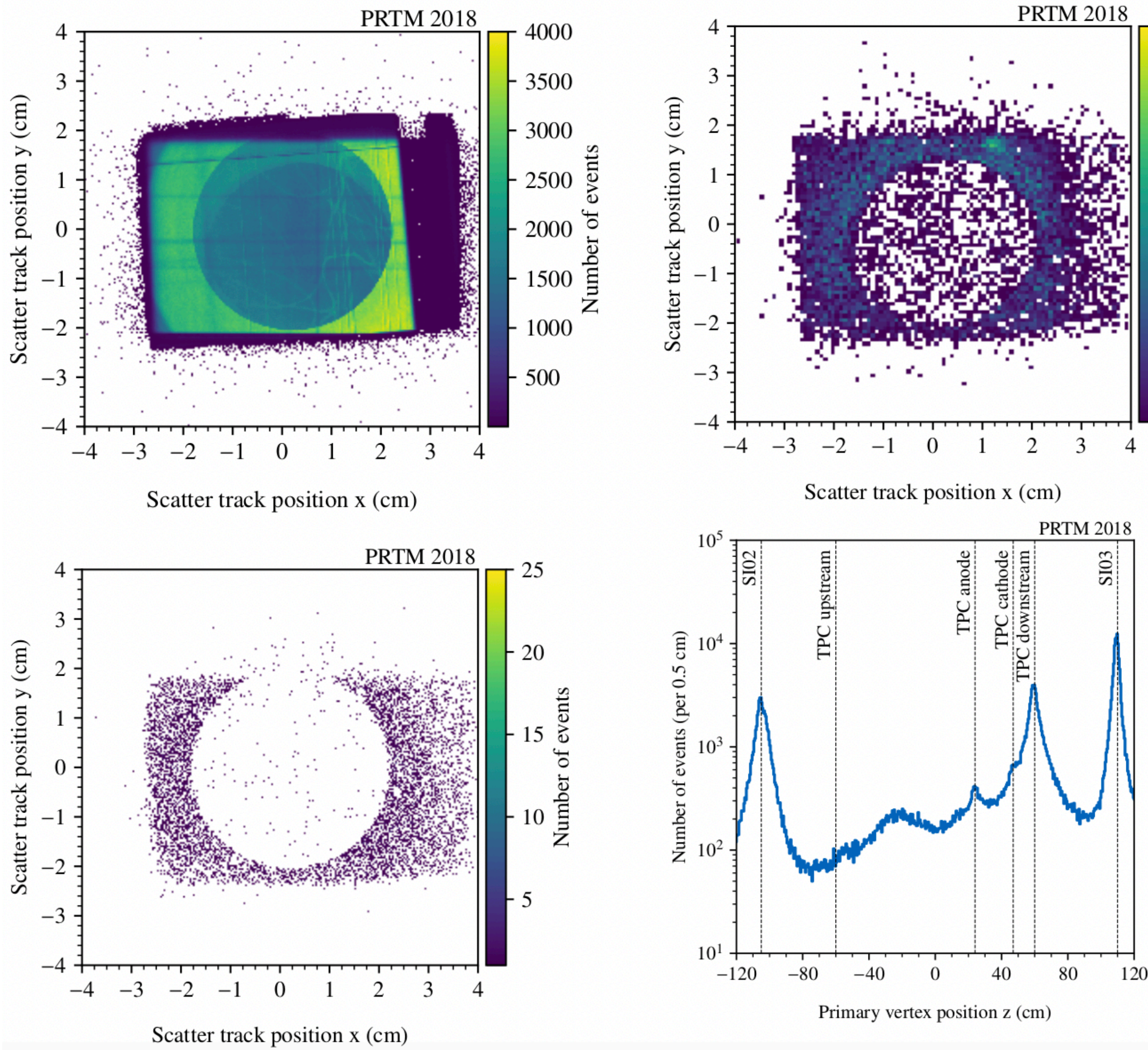






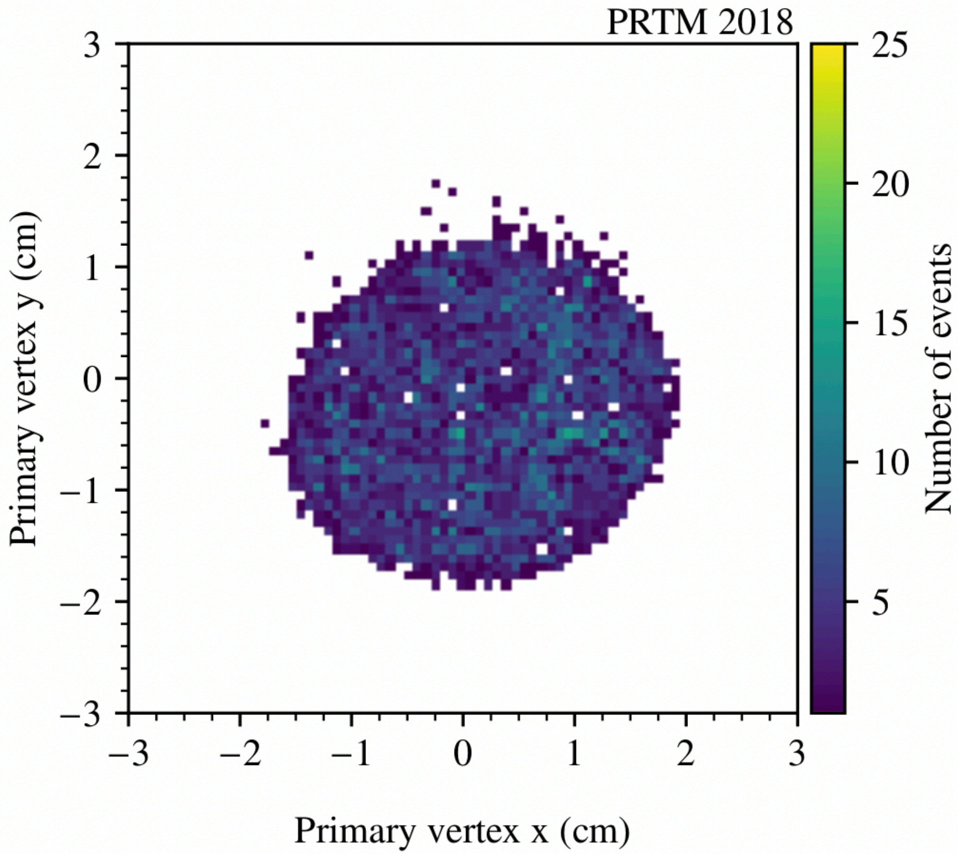


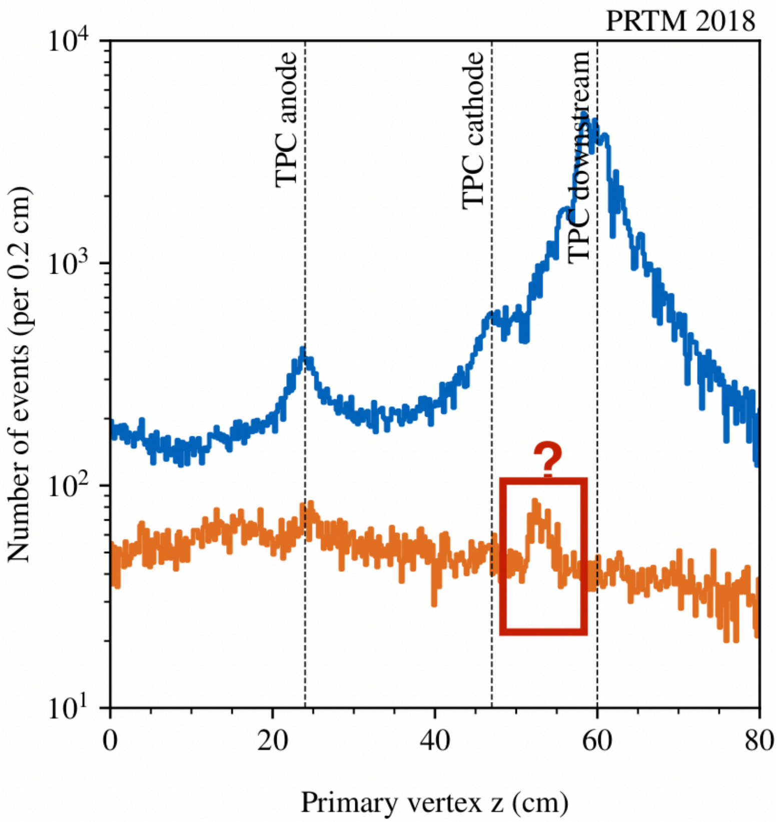
Test in 2018 – vertex reconstruction



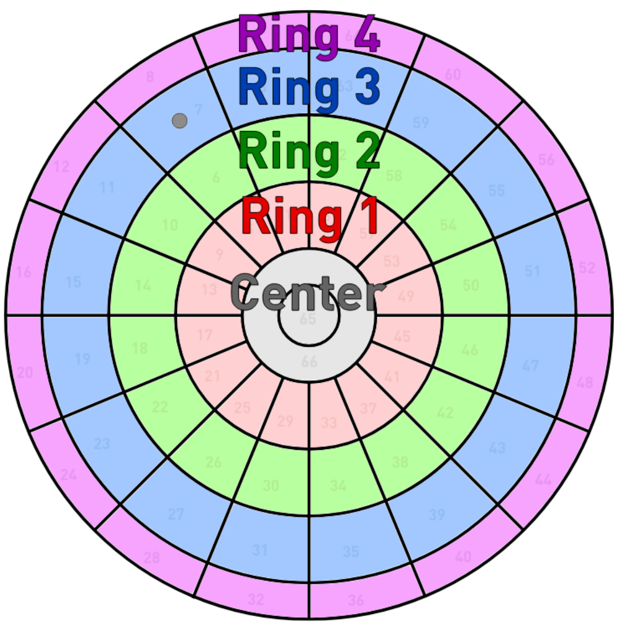
cathode (z = +47 cm)

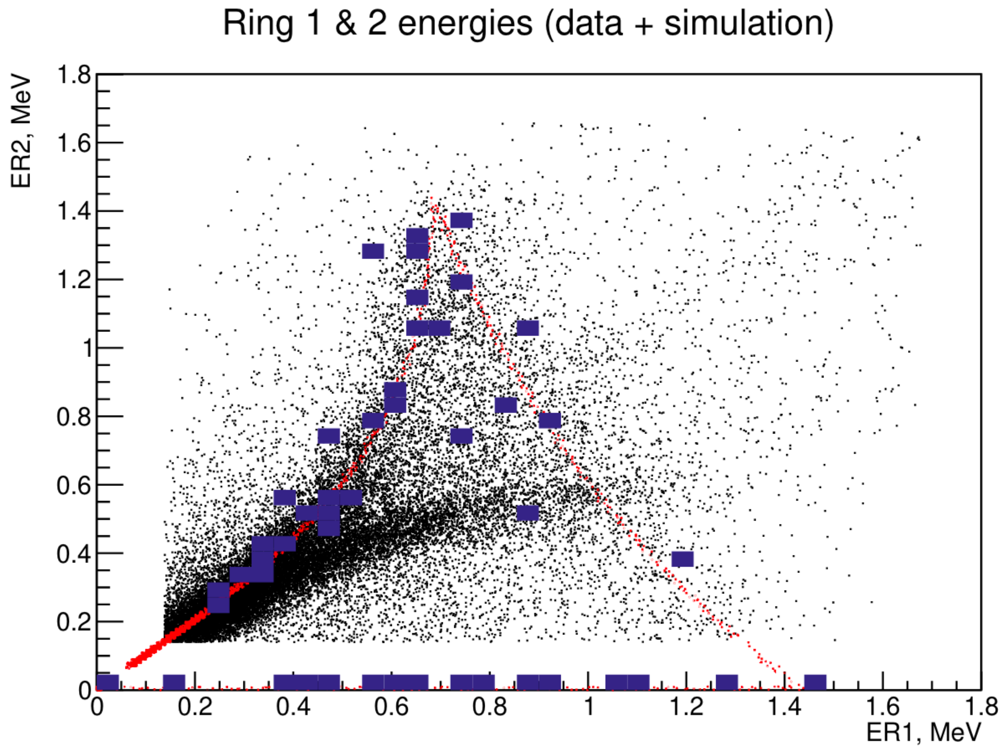
Test in 2018 – vertex reconstruction





Ring energies — matched events





Summary

- COMPASS++ / AMBER is getting on track to 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 enter a new phase, collaboration with SBU on event generator?

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

COMPASS++/AMBER HOME DOCUMENTS WORKSHOPS TIMELINES I AM INTERESTED

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!

Backup

Partonic structure of the pion

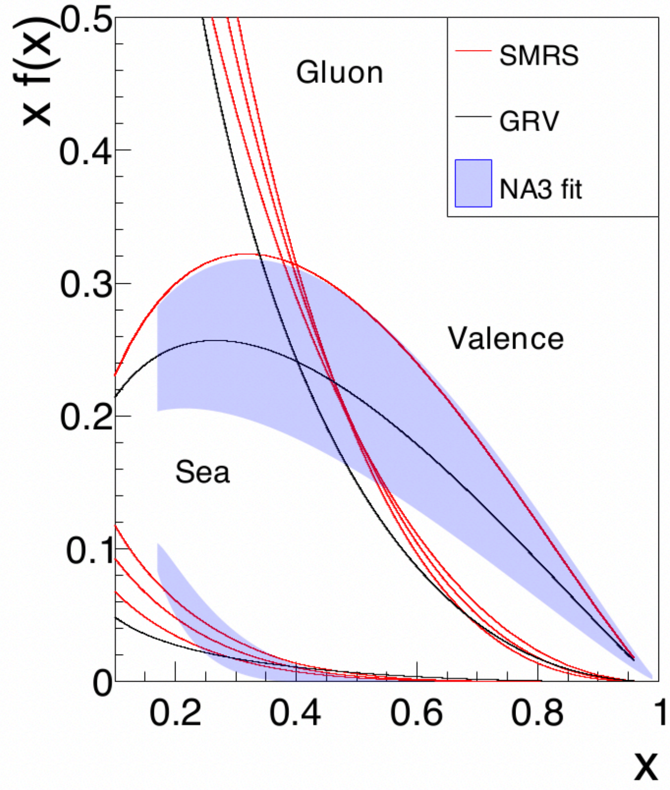
GRV: M. Gluck et al, Z.Phys.C **53** (1992) 651-655

SMRS: P.J. Sutton et al, Phys.Rev.D **45** (1992) 2349–2359

Example with three fits:

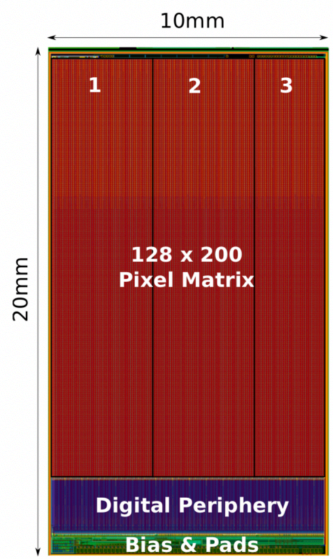
- Large untainties or not even at all
- Not enough data to directly constrain all PDFs → use of: Momentum Sum rules, constituent quark model...
- Sea no direct constraints

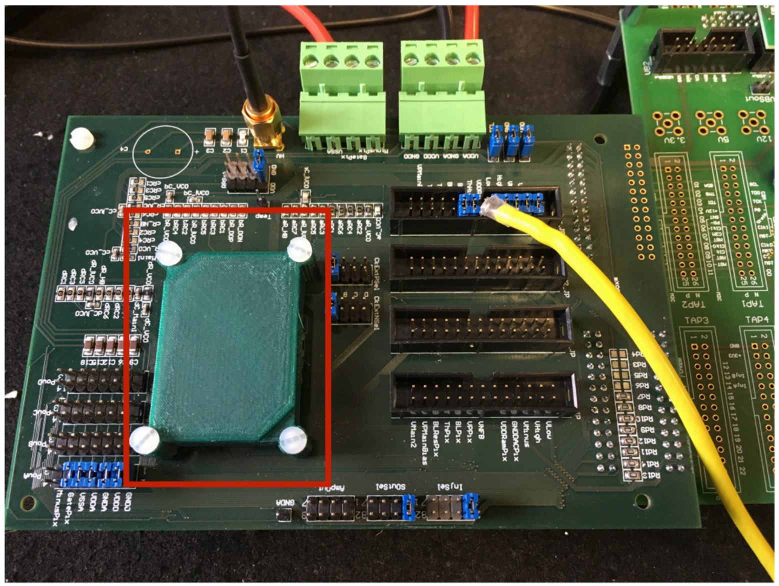
More data is needed, with better control of uncertainties, and full error treatment.



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

Silicon prototype (MuPix8)





- 80 x 80 μm^2 pixel size
- 17 x 10 mm^2 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

Test in 2018 for Proton Radius measurement

- demonstrated the measurement principle employing the active TPC and silicon detectors
- Q^2 range was limited by geometry
  - lower limit ca. $3x10^{-3}$ due to short SI detector baseline and high beam energy (ca. 180 GeV)
  - upper limit ca. $6x10^{-3}$ due to proton range in 8bar H_2
- observed event rate and structure roughly within expectations, calibrations and data analysis ongoing

a hot physics topic – this experiment should run in 2022 at M2 and needs soon CERN support statement for realization

Proton Radius Measurement – Feedback from PBC

- physics reach of the proposed measurement acknowledged
- regarding the Q^2 range of the measurement 10^{-3} … $2x10^{-2}$ GeV^2 it is encouraged to extend this range, especially to lower values, for a better control of the „fit ambiguities“

our answer:

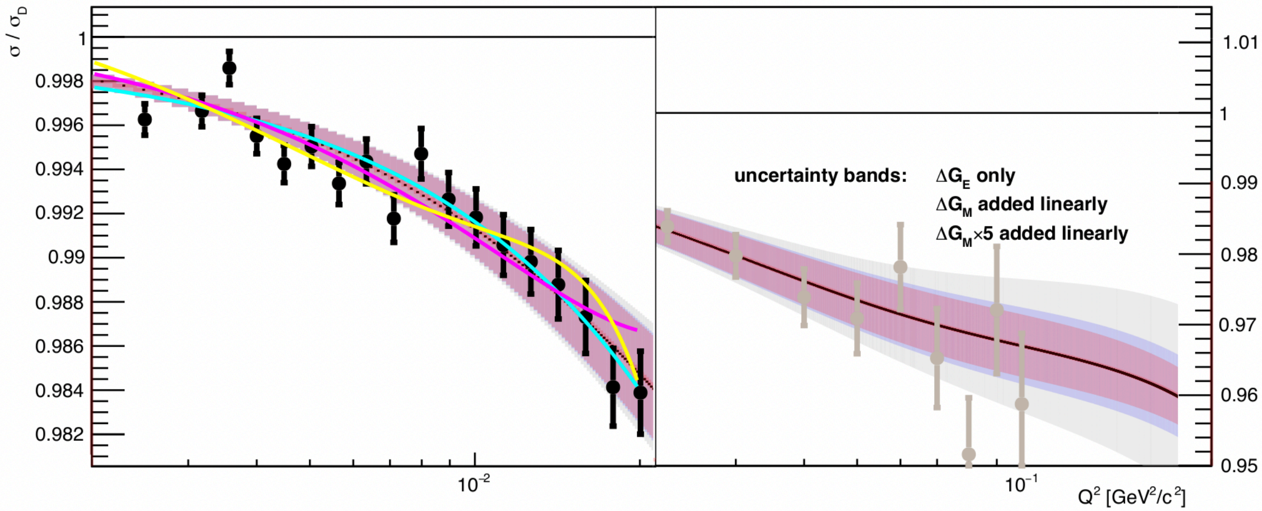
- yes, extending the experimental sensitivity to as-low-as possible Q^2 values (beyond 10^{-3}) is to be taken into account in the design of the set-up (will require ~10m target region for the silicon telescopes)
- low-Q^2 data points will be useful and meaningful in terms of systematics control
- the expected form factor impact on the cross-section is below 0.1% in that region, and thus of a similar size as other expected (experimental) systematic effects. Accordingly, those points are of limited use in terms of discriminating theoretical uncertainties (except for excluding unrealistic scenarios)

all in all positive feedback from PBC,
SPSC to be awaited – expected soon!

Feedback from PBC QCD working group

COMPASS++

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



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

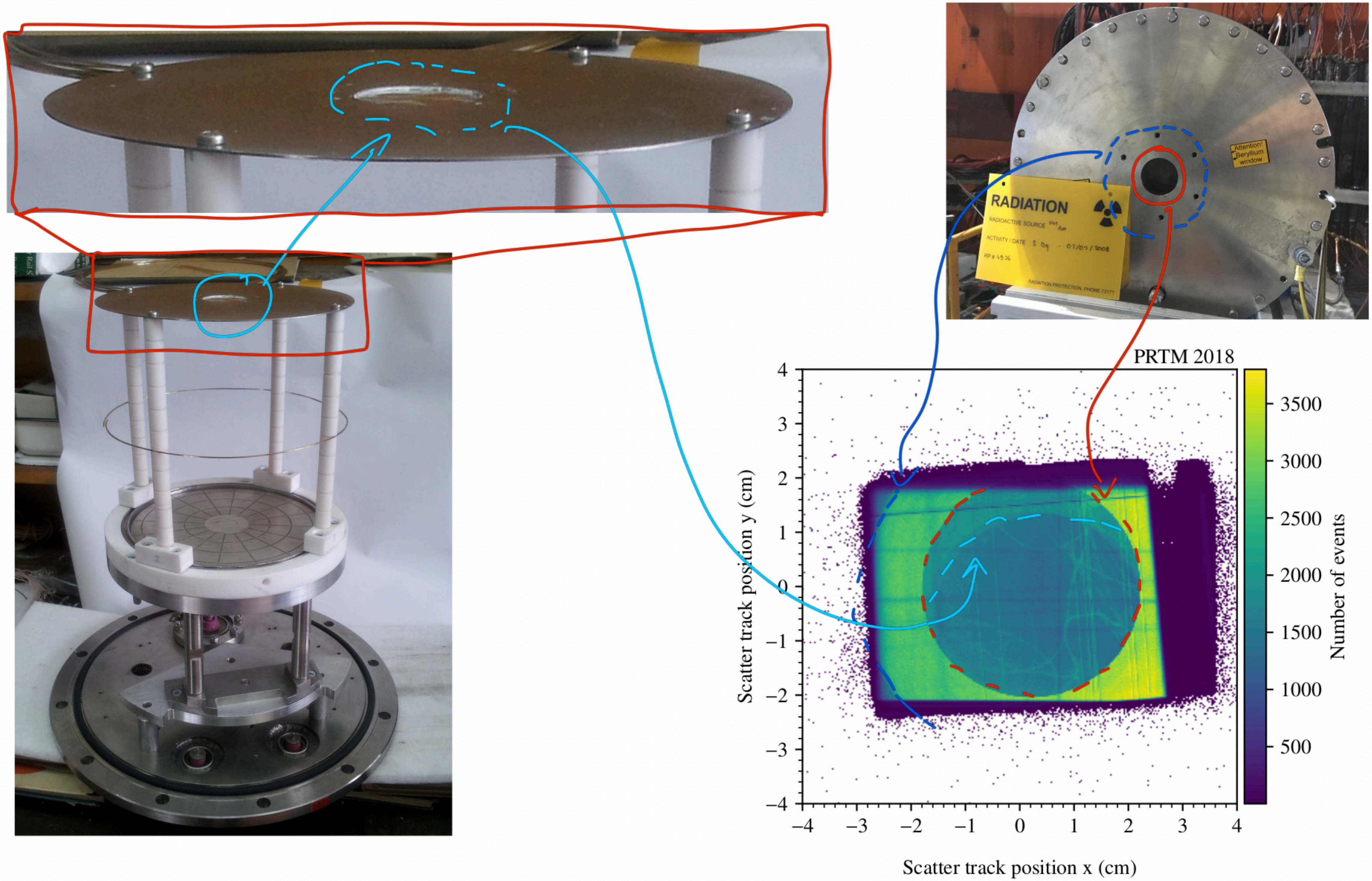
COMPASS in 2021/22

- For 2021, COMPASS has proposed a transverse-deuteron run with muon beam
- Recommended by SPSC and approved by the research board in 2018 for a beam time (of 150 days, as specified in the proposal assuming standard efficiencies for SPS and COMPASS)
- In 2010, this was achieved by using the full available beam of the year
- In 2021, SPS and the spectrometer have to restart after a 2-year break
- Possible competition from the NA64mu proposal and MUonE test, aim at muon beam in 2021

we should get prepared for readiness of the proton radius experiment for starting in 2021

Many thanks are due to
COMPASS Proton Radius Enthusiasts
TUM team
PNPI team
GSI team
Bonn team
COMPASS

Thank you!


RADIATION
RADIOACTIVE SOURCE
ACTIVITY / DATE
RADIATION PROTECTION PHONE 73171
Attention! Beryllium window
PRTM 2018
Scatter track position x (cm)
Scatter track position y (cm)
Number of events
−4 −3 −2 −1 0 1 2 3 4
500 1000 1500 2000 2500 3000 3500

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

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

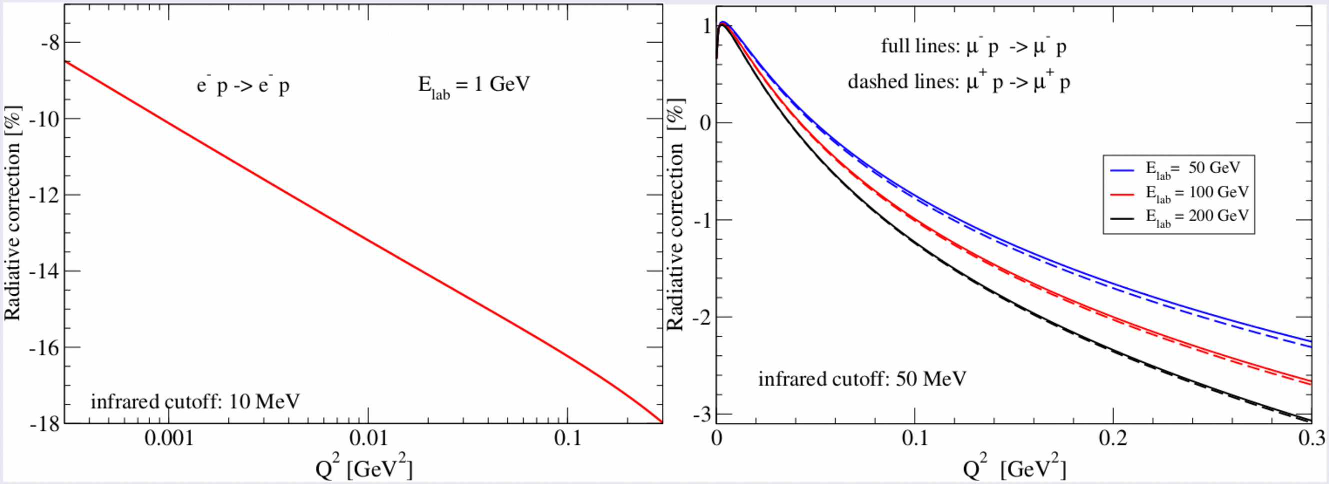
- elastic scattering experiments provide data for G_E at non-vanishing Q^2 and thus require an extrapolation procedure towards zero
  $\rightarrow$ mathematical ansatz may take more or less bounds into account (physics/theory/whatever motivated)
- Any approach (Padé, CF, DI, CM,...) *must* boil down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

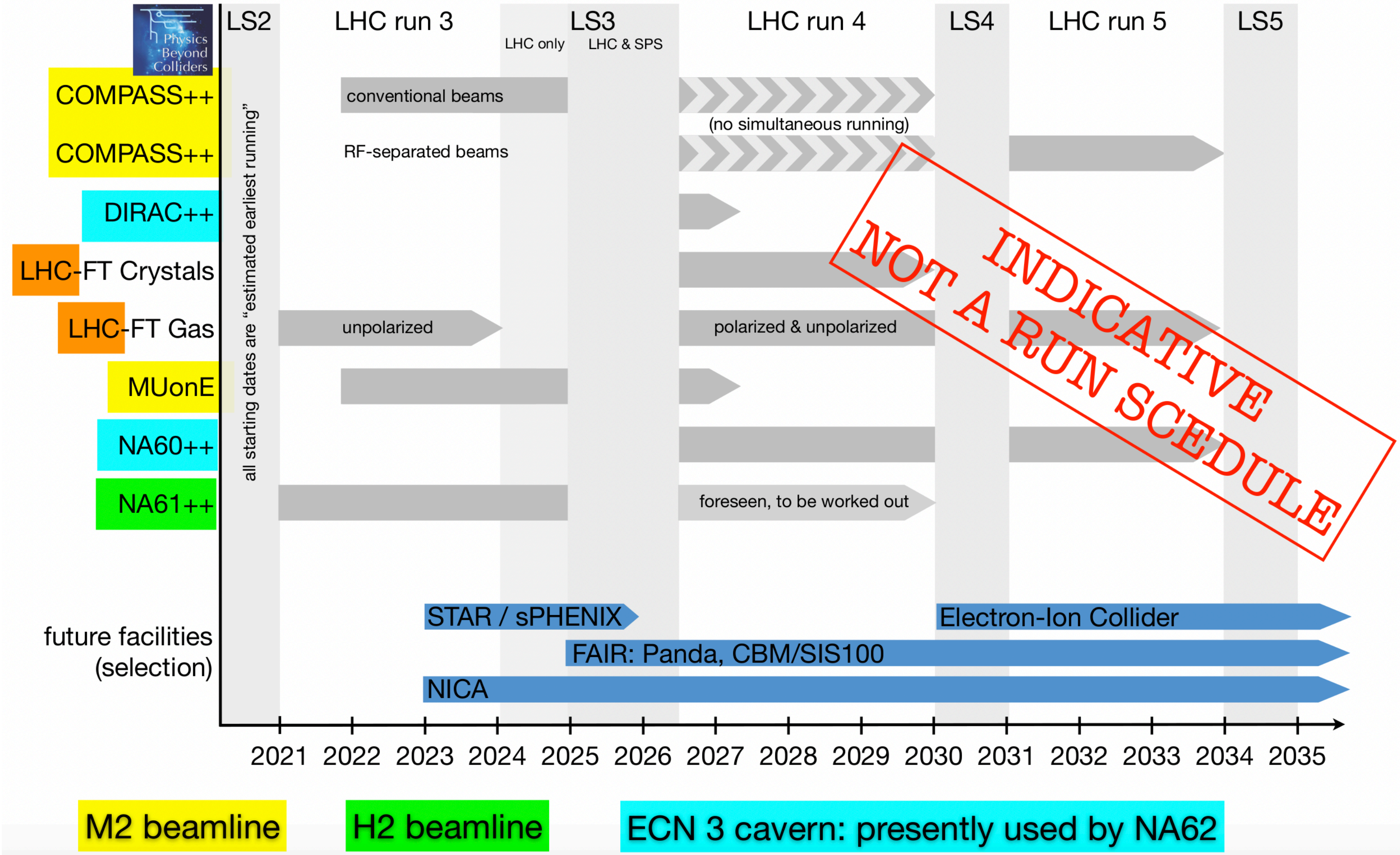
Radiative corrections for electron and muon scattering

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

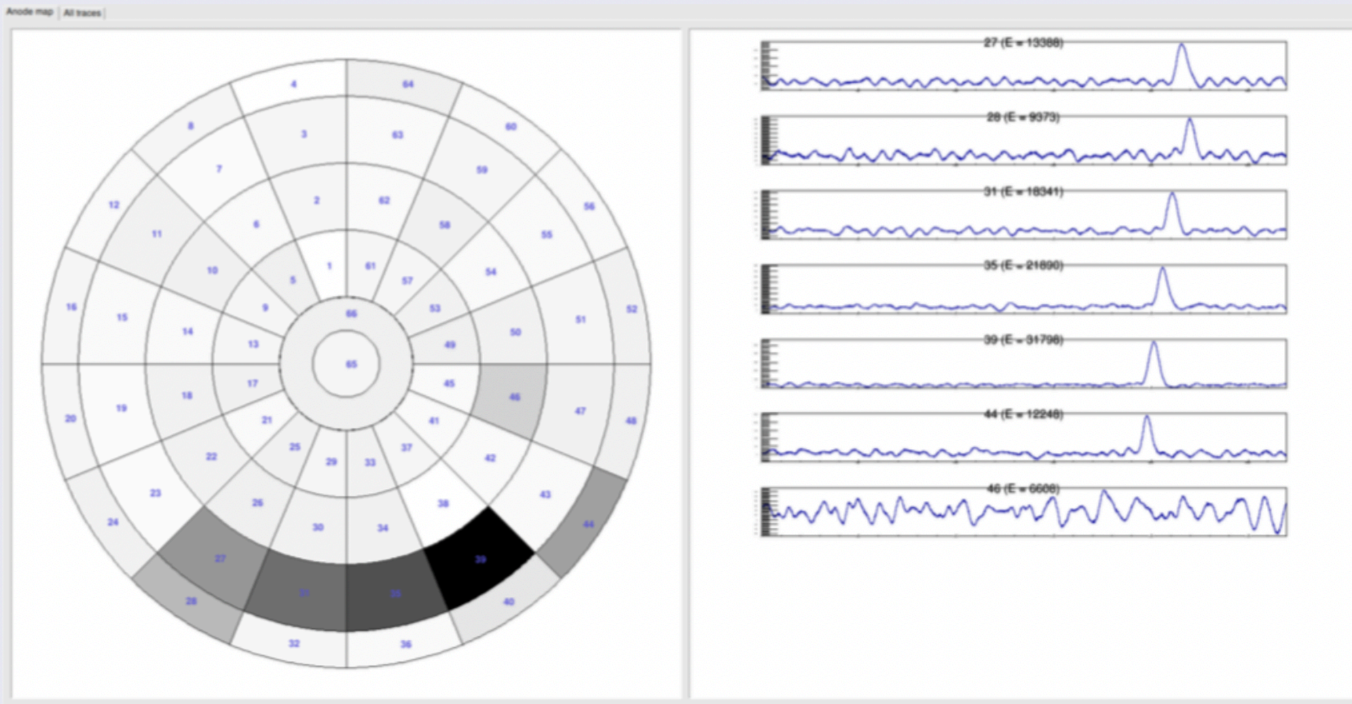
PBC-QCD



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

TPC signals

performance of TPC



- recoil protons with muon beam observed

LoI content: Instrumentation

5 Instrumentation 63

5.1 Summary table 63

5.2 General upgrades 64

5.2.1 Front-end electronics and DAQ 64

5.2.2 Large-area PixelGEM detectors 64

5.2.3 Large-area multi-pattern gaseous detectors (MPGD) 65

5.2.4 CEDARs at high rates 65

5.2.5 Hadron PID perspectives: RICH 66

5.3 Specific upgrades 66

5.3.1 Overview 66

5.3.2 High-pressure hydrogen TPC for proton-radius measurement 67

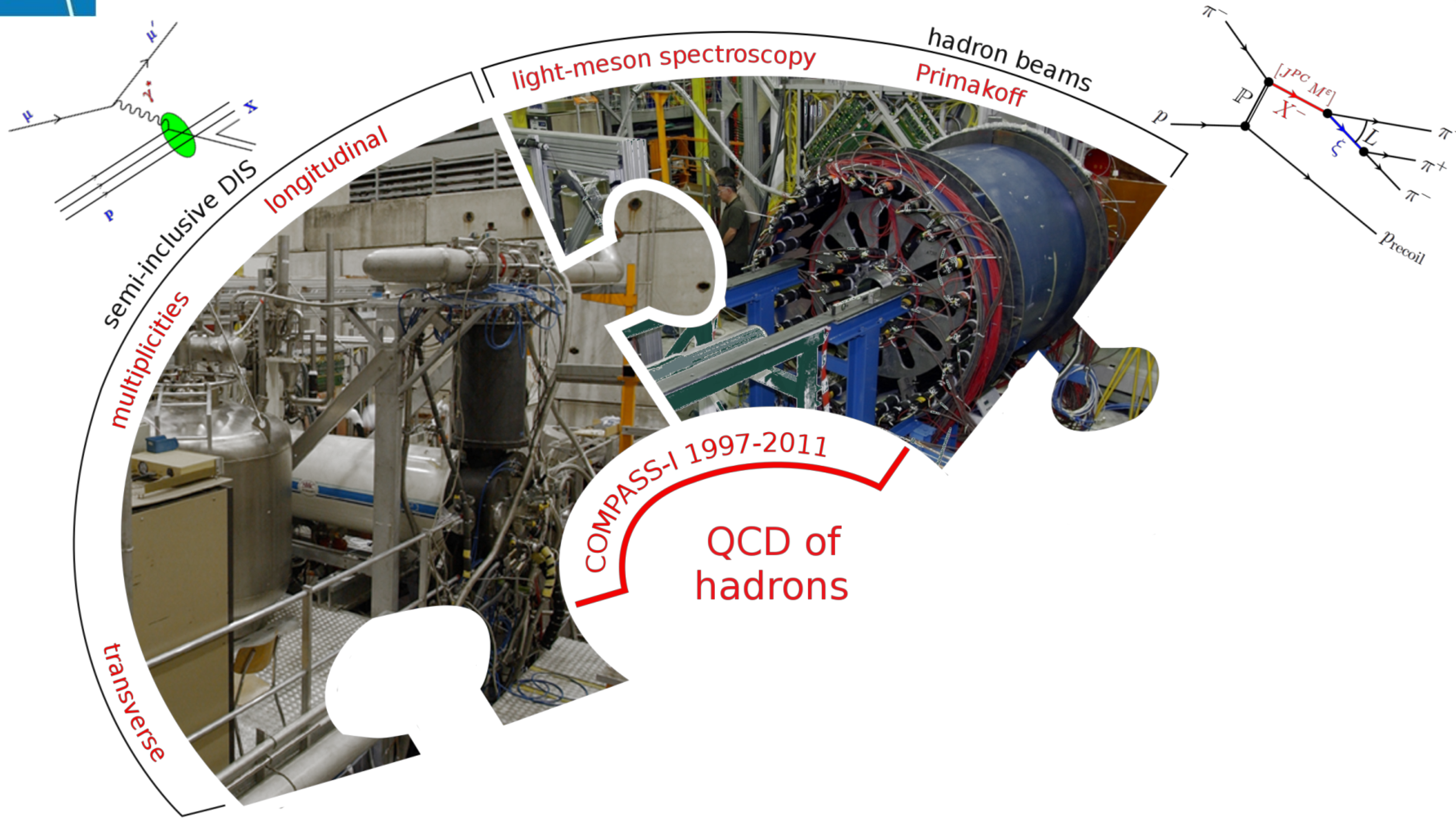
5.3.3 Recoil detector with polarised target 70

5.3.4 Target spectrometer for spectroscopy with low-energy antiprotons 71

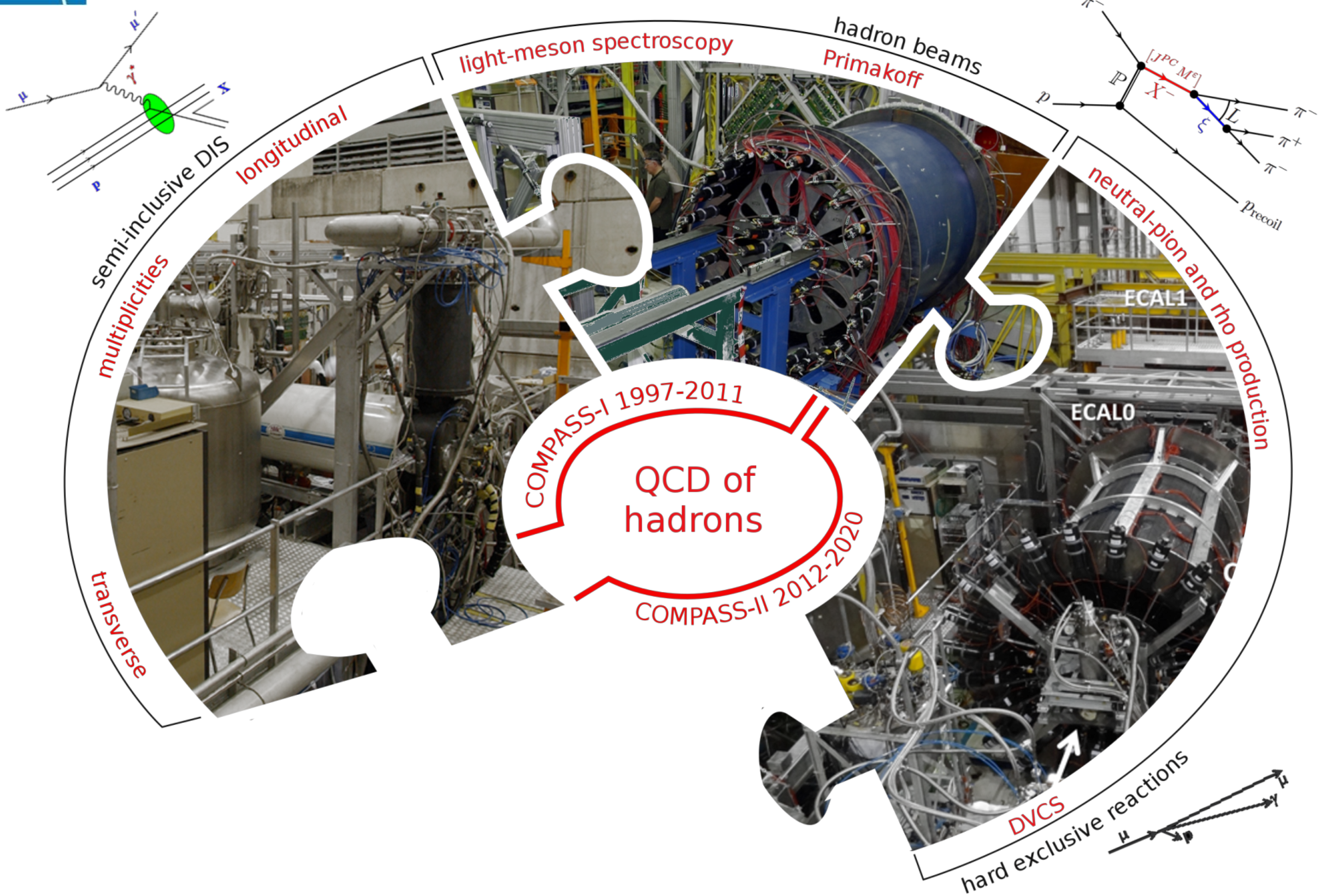
5.3.5 Active absorber for Drell-Yan measurements with an RF-separated hadron beam 73

It is difficult to give exact cost estimate right now: it stays in the range 10-20 MCHF

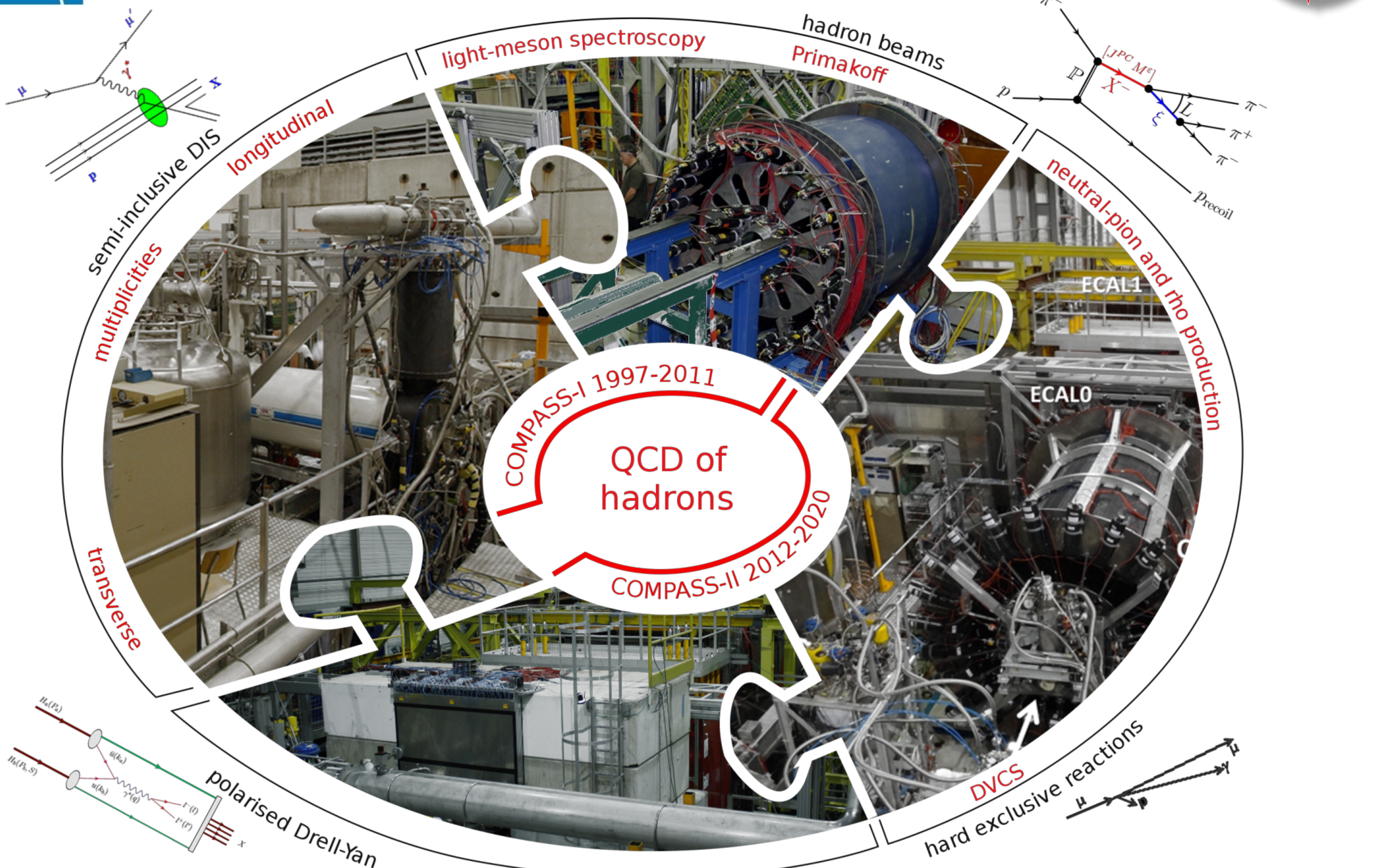
COMPASS QCD facility at SPS M2 beam line (CERN)
secondary hadron and lepton beams



COMPASS QCD facility at SPS M2 beam line (CERN) secondary hadron and lepton beams



COMPASS QCD facility at SPS M2 beam line (CERN) secondary hadron and lepton beams



COMPASS QCD facility at SPS M2 beam line (CERN) secondary hadron and lepton beams