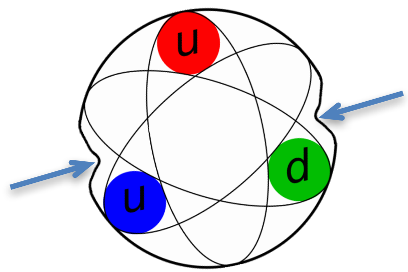
COMPASS++ / AMBER and the Proton Radius Puzzle

Jan Friedrich
Technische Universität München

on behalf of the COMPASS collaboration
and the COMPASS++/AMBER working group



28. February 2019

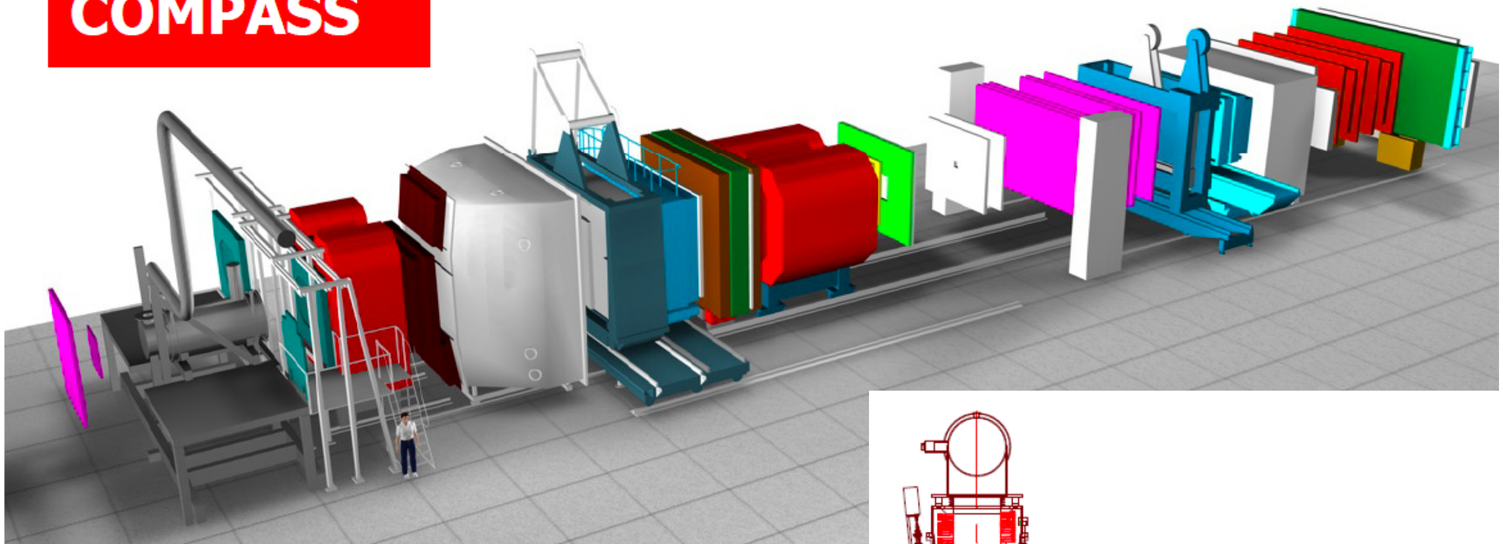
COMPASS QCD facility at CERN (SPS)

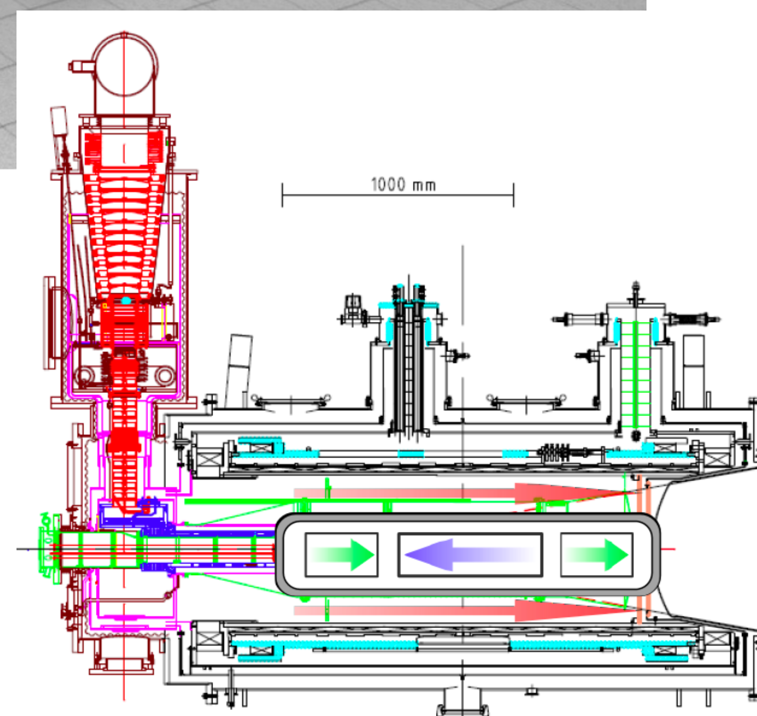
COmmon Muon Proton Apparatus for Structure and Spectroscopy

~220 physicists, 12 countries + CERN, 24 institutions

Reminder of the COMPASS physics program

COMPASS

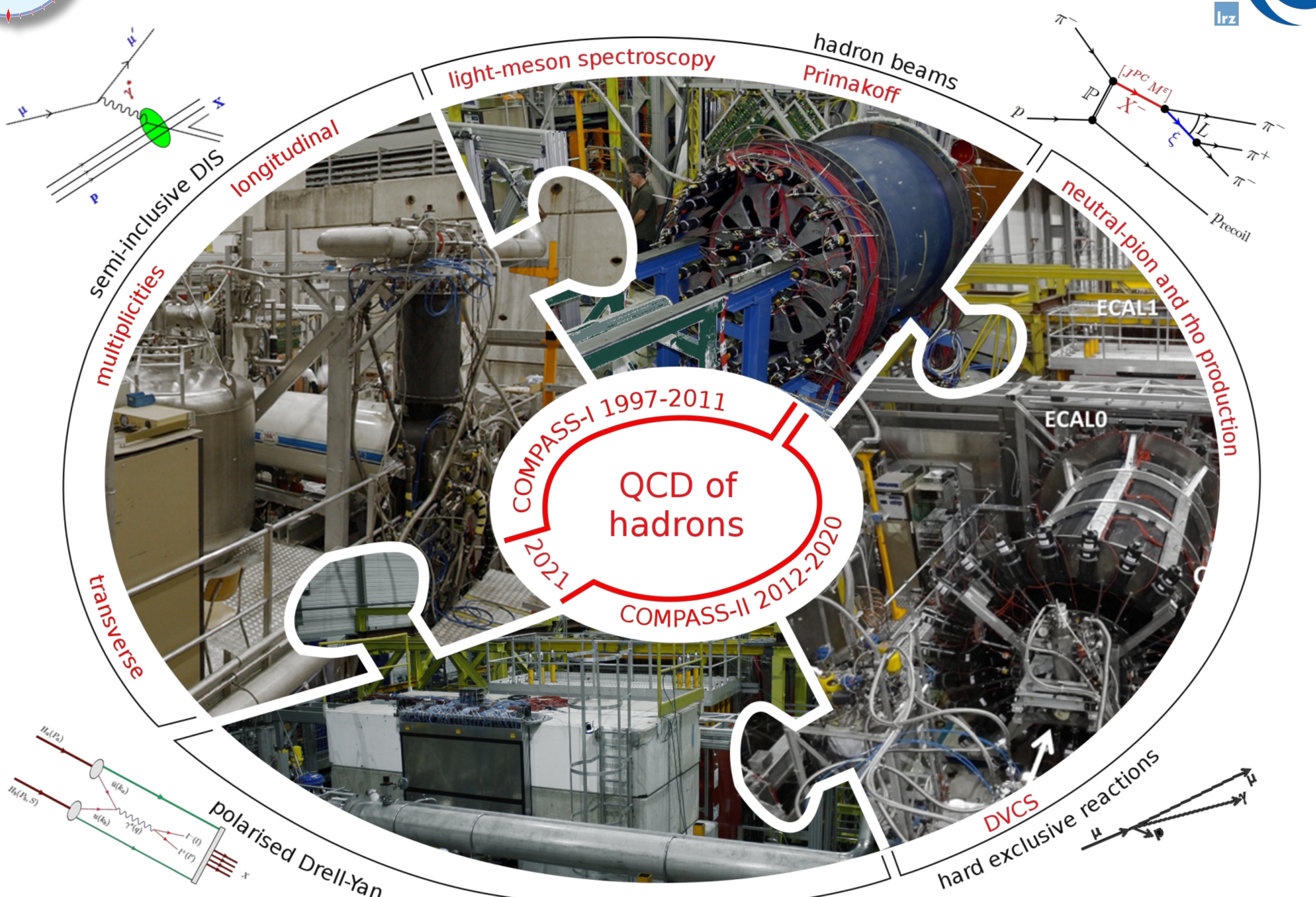




Versatile apparatus to investigate QCD:
Two-stage COMPASS Spectrometer

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 ^{6}LiD), liquid hydrogen and nuclear targets
3. Powerful tracking (350 planes) and PID systems (Muon Walls, Calorimeters, RICH)

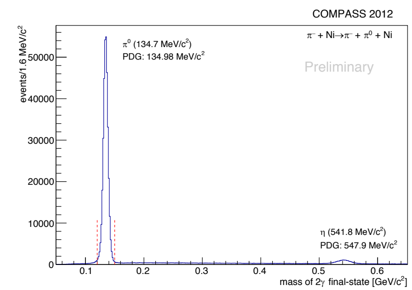
Reminder: COMPASS QCD facility secondary hadron and lepton beams



Analysis of COMPASS data

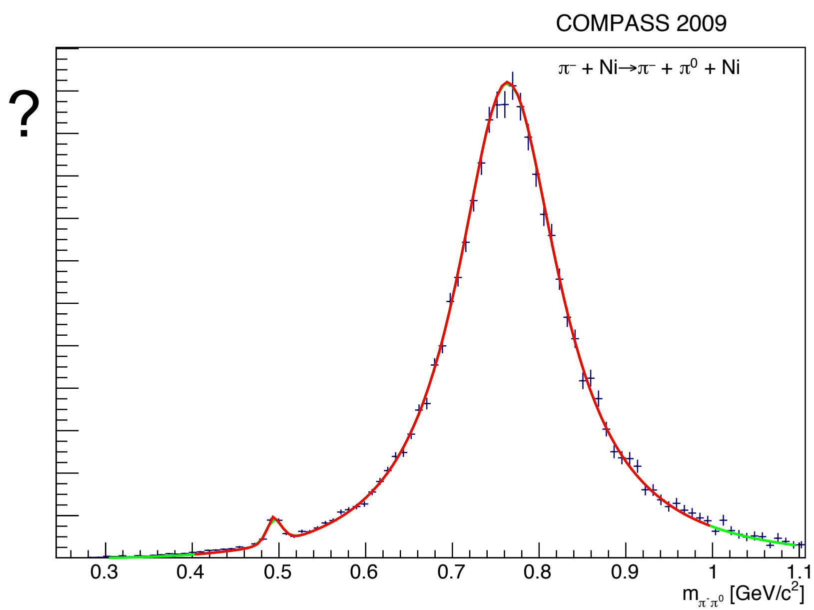
cf. talks yesterday

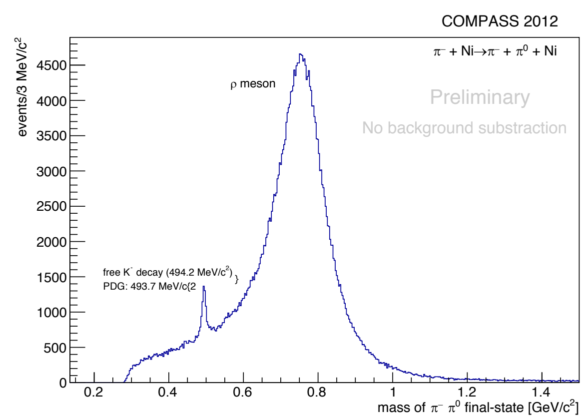
- Misha Mikhasenko, meson spectroscopy COMPASS / JPAC
- Dima Ryabchikov, PWA common analysis COMPASS / VES
- Bernhard Ketzer, spectroscopy overview and future



ongoing work on Primakoff reactions $\pi^-\gamma \to \pi^-\pi^0$

- get chiral anomaly $F_{3\pi}$ and radiative width of rho(770)
- luminosity normalization through beam K- decay rate
- goal: total uncertainty <5%





theory: Kubis, Hoferichter 2012

Envisaging future opportunities, EPSS, PBC-QCD

COMPASS beyond 2020 Workshop

21 Mar 2016, 08:05 → 22 Mar 2016, 17:10 Europe/Zurich

222-R-001 (CERN)

Description The goal of the workshop is to explore hadron physics opportunities for fixed-target COMPASS-like experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). The programme comprises

- Reviews of the various physics domains: TMDs, GPDs, FFs, spectroscopy, exotics, tests of ChPT, astrophysics

CERN Accelerating science europeanstrategyupdate.web.cern.ch Sign in

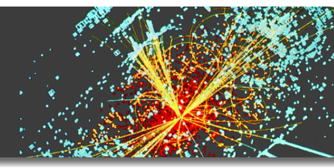
European Particle Physics Strategy Update 2018 – 2020

European Strategy Update

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 th[e] called upon the particle physics community across universities, laboratorie[s] written input by 18 December 2018 to prepare the discussions on the Strate[gy]

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



Call for input
157 proposals submitted

Physics Beyond Colliders

CERN-PBC-REPORT-2018-008

Physics Beyond Colliders QCD Working Group Report

arXiv:1901.04482 (85 pages)

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]

COMPASS

Apparatus for Meson and Baryon Experimental Research

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN

January 12, 2019

arXiv 1808.00848

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

[hep-ex] 12 Jan 2019

Letter of Intent:

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

COMPASS++†/AMBER‡

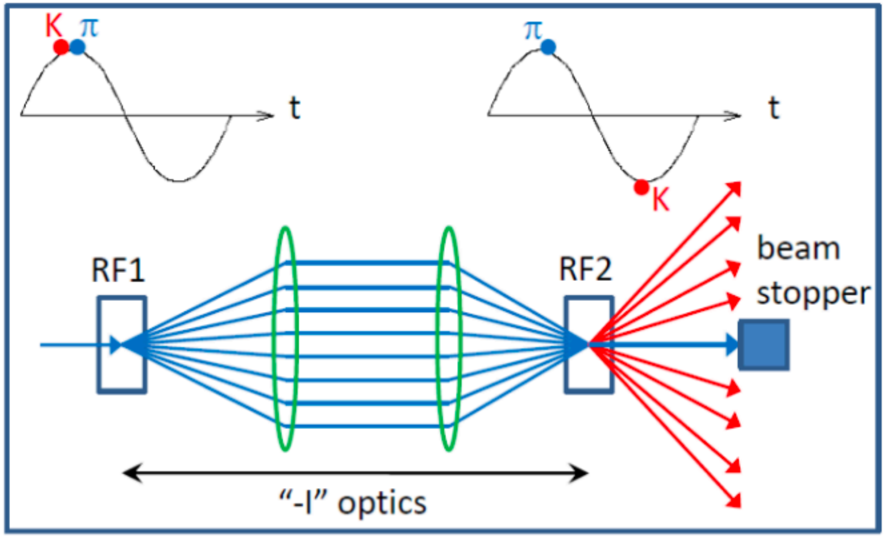
B. Adams[13,12], C.A. Aidala[1], R. Akhunzyanov[14], G.D. Alexeev[14], M.G. Alexeev[41], A. Amoroso[41,42],

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.

RF separated beam



- Deflection with 2 cavities
- Relative phase $= 0 \rightarrow$ 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:

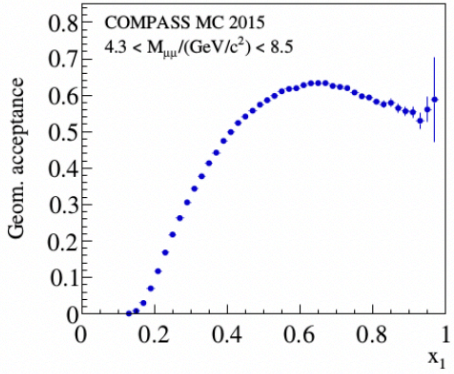
L should increase as p^2 for a given f $\rightarrow$ limits the beam momentum

Initial expectations before further *R&D*:

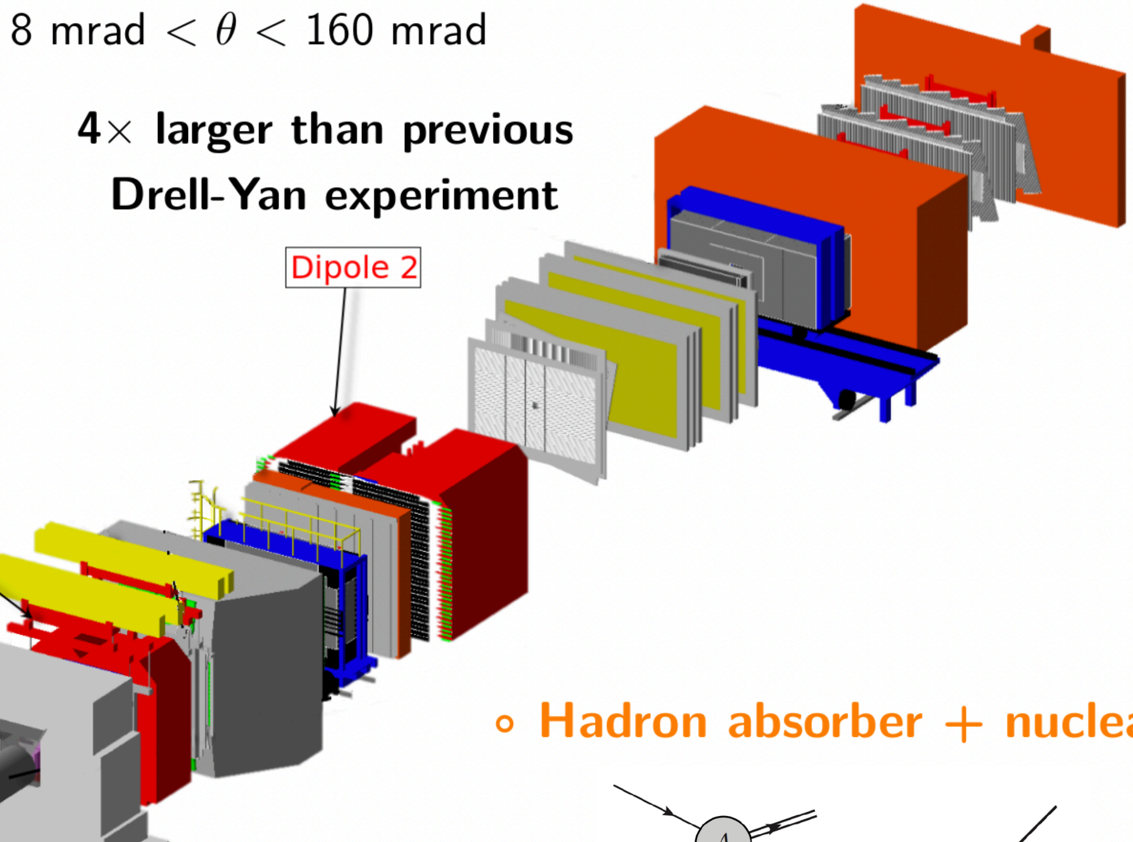
$\sim$ 80 GeV Kaon beam
$\sim$ 110 GeV Anti-proton beam

Conventional-beam physics: Drell-Yan

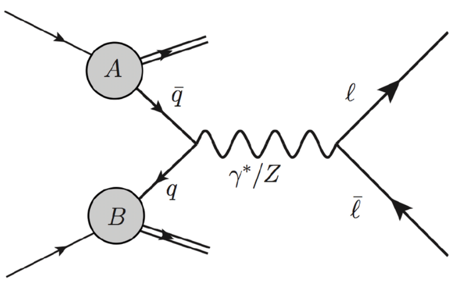
- **Large acceptance:** 8 mrad $< \theta <$ 160 mrad



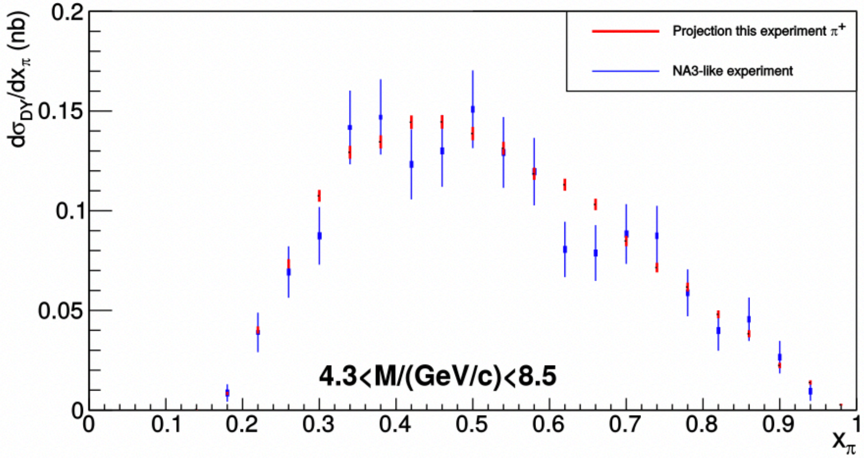
4× larger than previous Drell-Yan experiment



- **Hadron absorber + nuclear targets**



Conventional-beam physics: Drell-Yan

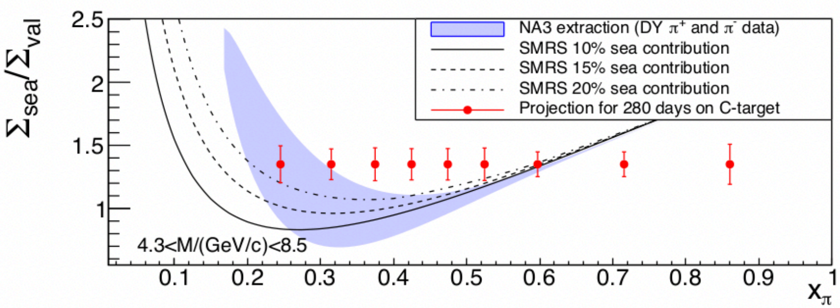


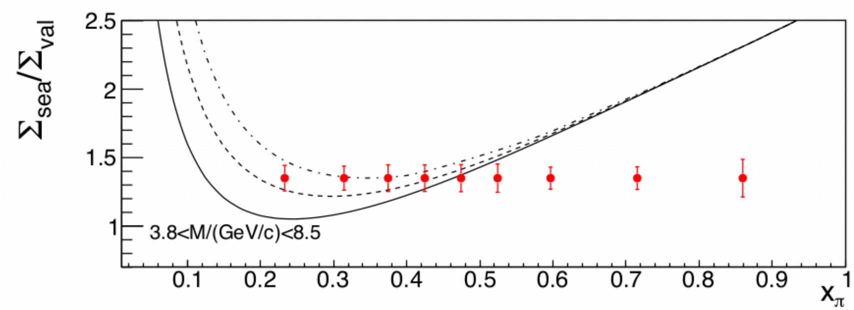
Expected accuracy compared to NA3 result

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

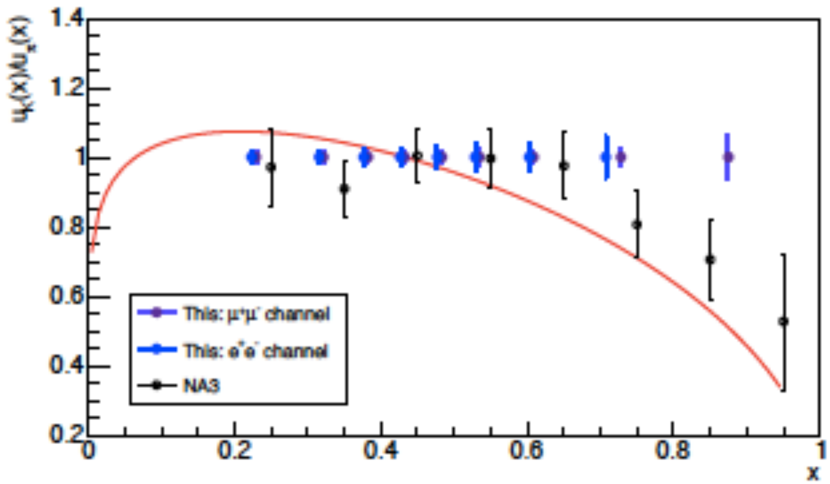
$\Sigma_{val} = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence

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





RF separated hadron beam
Meson structure study in DY and PP processes
Valence u-quarks in Kaon compared to pion



Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	DY events e^+e^-
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700	0
This exp.	100 cm C	K^-	2.1×10^7	80	4.0 – 8.5	25,000	13,700
				100	4.0 – 8.5	40,000	17,700
				120	4.0 – 8.5	54,000	20,700
		K^+	2.1×10^7	80	4.0 – 8.5	2,800	1,300
				100	4.0 – 8.5	5,200	2,000
				120	4.0 – 8.5	8,000	2,400
This exp.	100 cm C	π^-	4.8×10^7	80	4.0 – 8.5	65,500	29,700
				100	4.0 – 8.5	95,500	36,000
				120	4.0 – 8.5	123,600	39,800

Table 6: Achievable statistics of the new experiment, assuming 2×140 days of data taking with equal time sharing between the two beam charges. For comparison, the collected statistics from NA3 is also shown.

QCD facility – future fixed target experiment at M2
Spectrometer upgrades

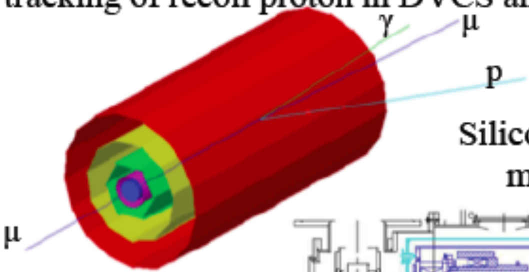
- **New type of FEE and trigger logic compatible with trigger-less readout**
  - FPGA-based TDC with time resolution down to 100 ps (iFTDC)
- Higher trigger rates: **90-200 kHz** (factor of 2.5-5)
- Digital trigger
- First tests in 2018

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?

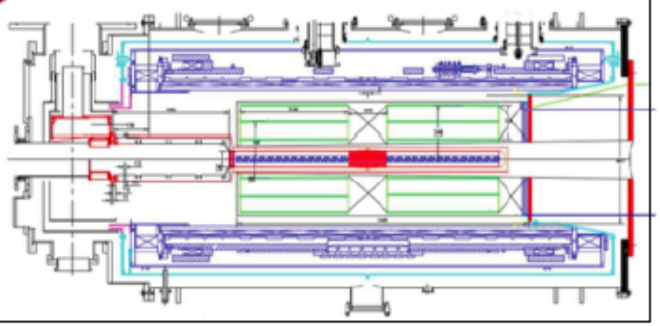
Could be Large-Area Picosecond Photo-Detectors based on micro-channel plates with time resolution < 50 ps, spatial resolution ~ 0.5 mm. LAPPD™ by IncomInc.

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

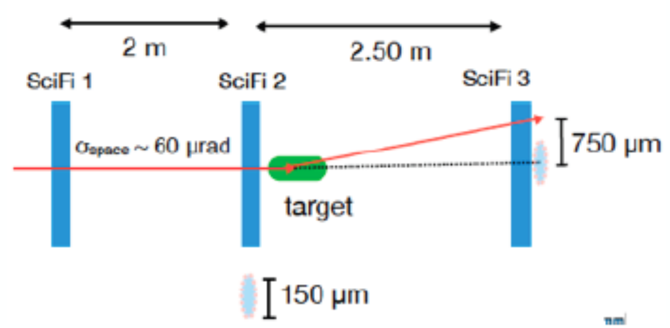
GPD E: 3-layer silicon detector at very low temperature for tracking of recoil proton in DVCS and PID via dE/dx.



Silicon detector inside existing modified target magnet.

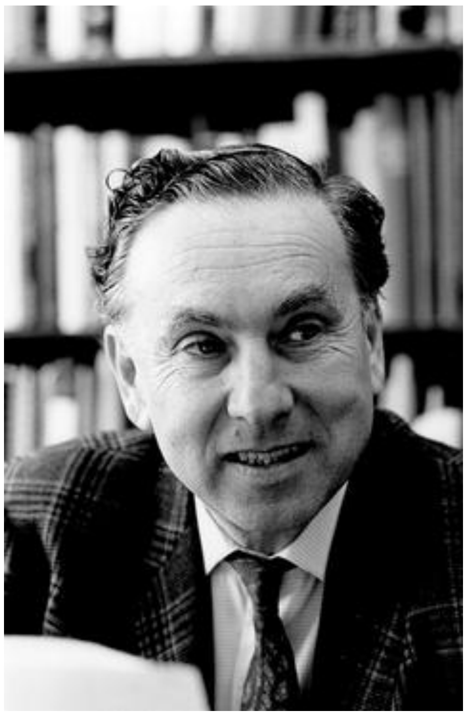


Proton radius:
- **High-pressure active TPC target or hydrogen tube** surrounded by SciFi, 4-8 layers with U/V projections
- **SciFi trigger system** on scattered muon
- Silicon trackers

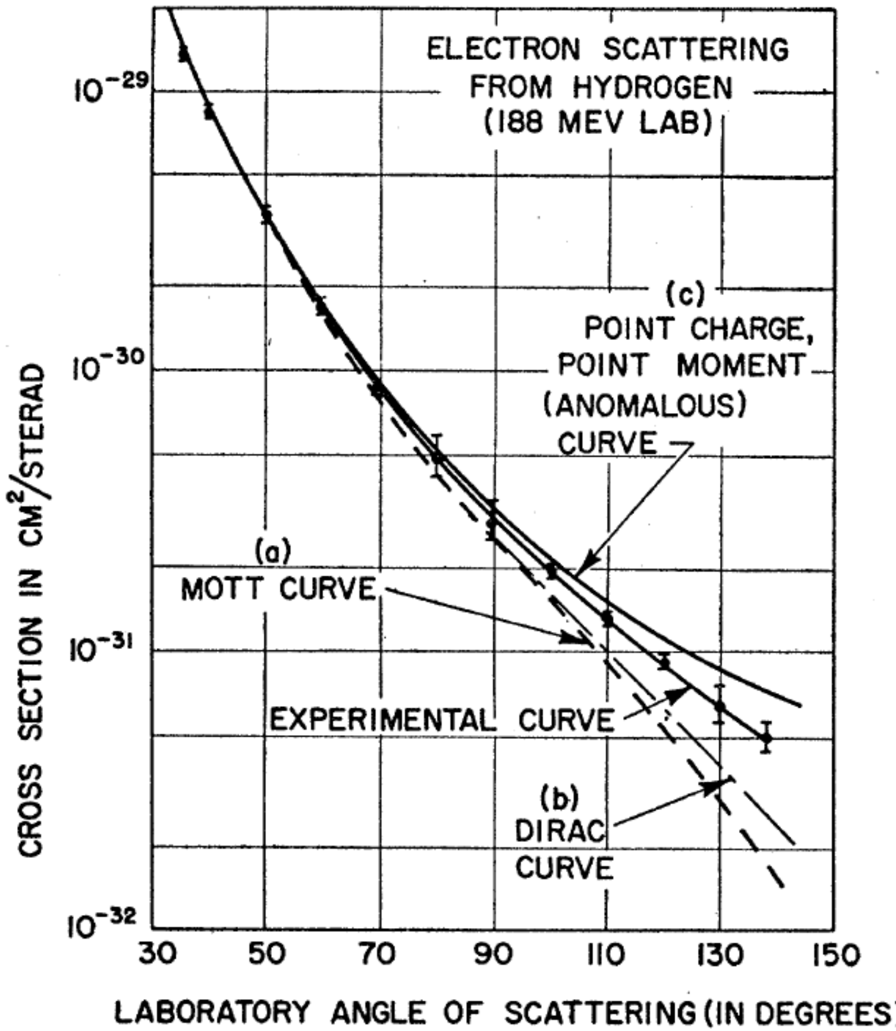


Measurement of the Proton Radius in ep-Scattering

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

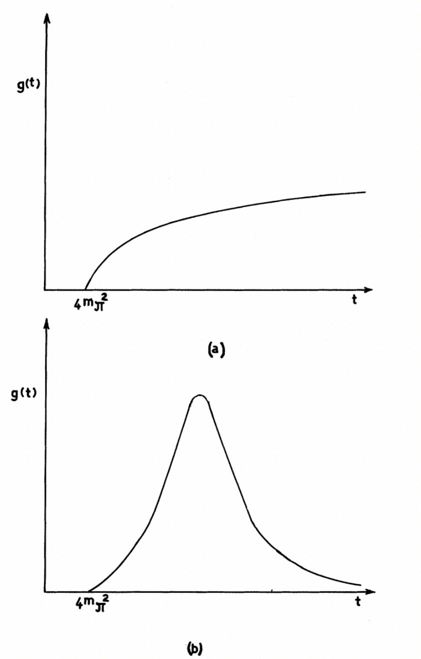


FIG. 1. Schematic representations of $g(t)$ in arbitrary scale. (a) Uncorrelated pions; (b) strong pion-pion resonance.

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

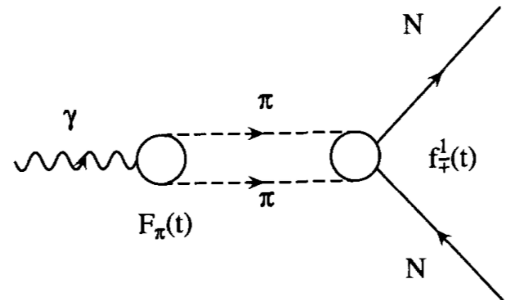
Dispersion-theoretical analysis of the nucleon electromagnetic form factors ★

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

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

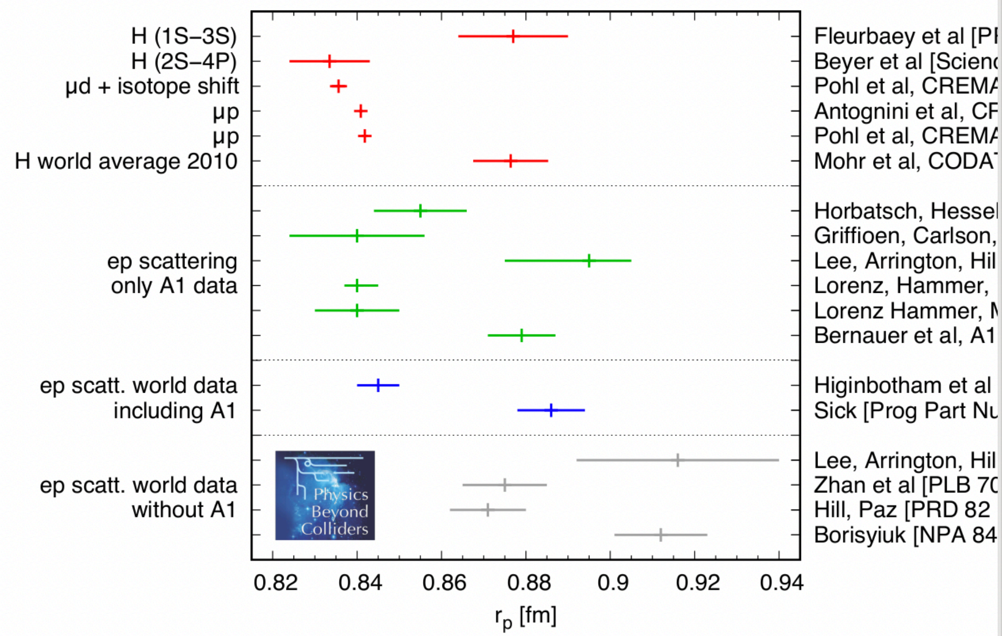
With that constraint, the authors of Ref. [15] performed a four-pole fit (with two masses fixed at $M_\rho = 0.765$ GeV and $M_{\rho'} = 1.31$ GeV) to the available data for the proton electric and magnetic form factors up to $Q^2 \simeq 5$ GeV^2. This allowed to reconstruct the

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



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)
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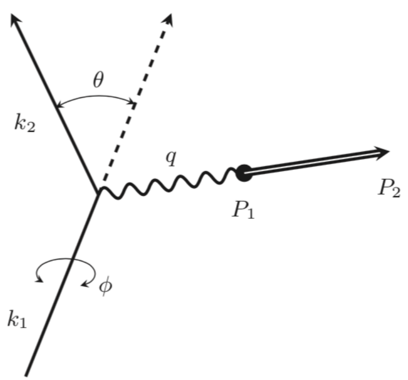
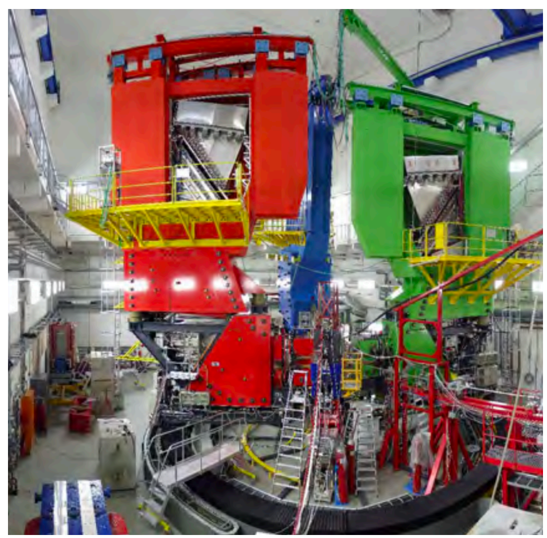
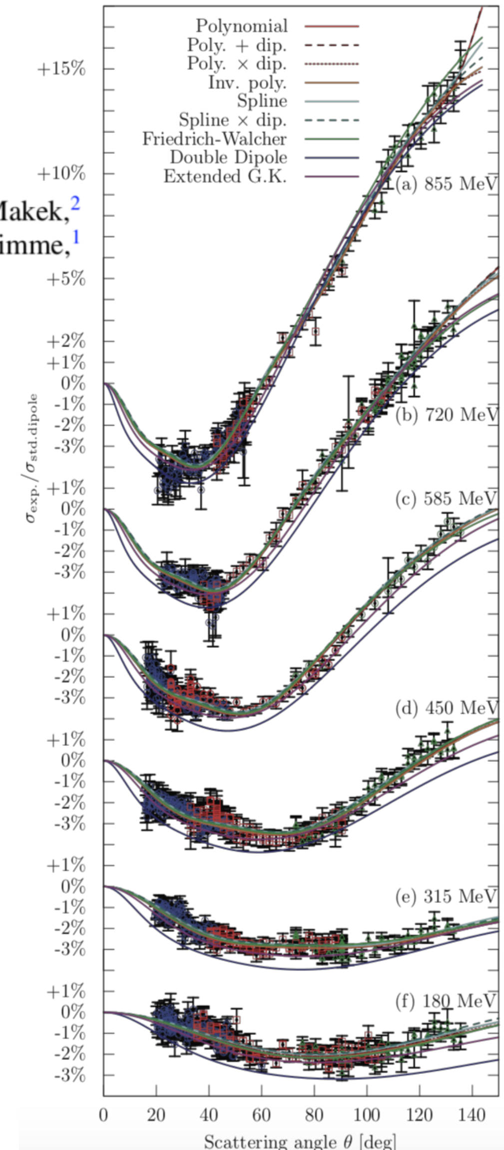
[2] *Department of Physics, University of Zagreb, 10002 Zagreb, Croatia*
[3] *Jožef Stefan Institute, Ljubljana, Slovenia*
[4] *LPC-Clermont, Université Blaise Pascal, CNRS/IN2P3, F-63177 Aubière Cedex, France*
[5] *CERN, CH-1211 Geneva 23, Switzerland, on leave of absence from Physik-Department, Technische 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)





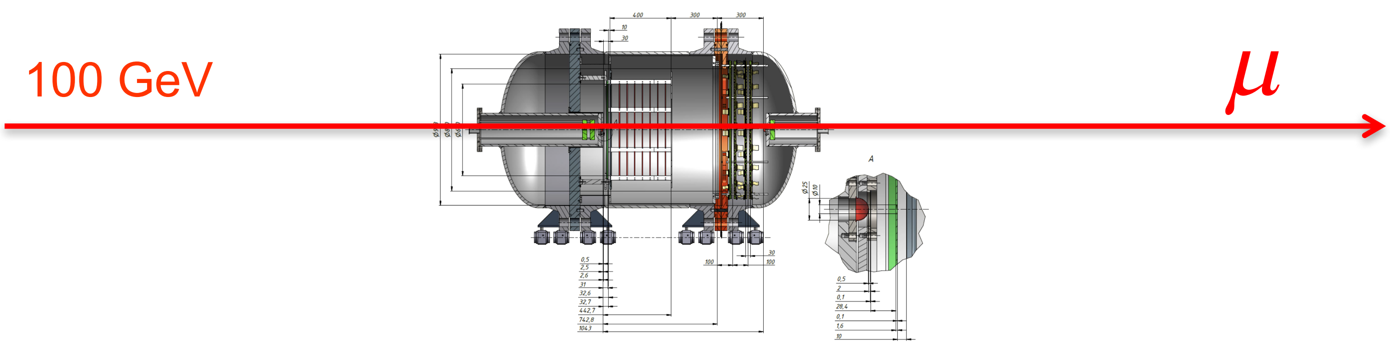


In the footsteps of Hofstadter: ideas for measurement of the low-momentum transfer region

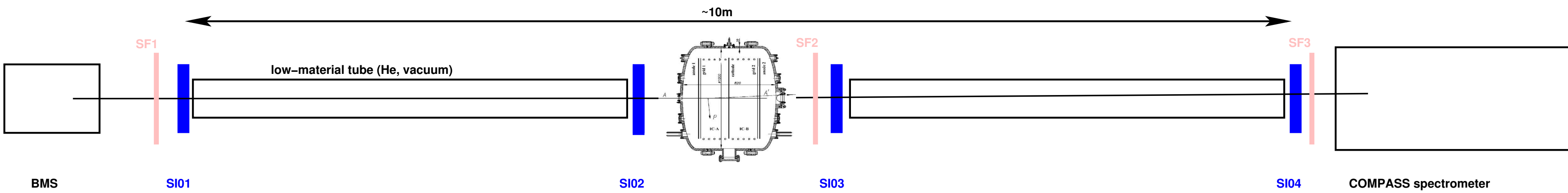
- initial-state radiation (ISR) of the MAMI electron beam
- PRad at Jefferson Lab: electron scattering at 1.1 and 2.2 GeV

- 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



Proton Radius Measurement: Proposed Setup



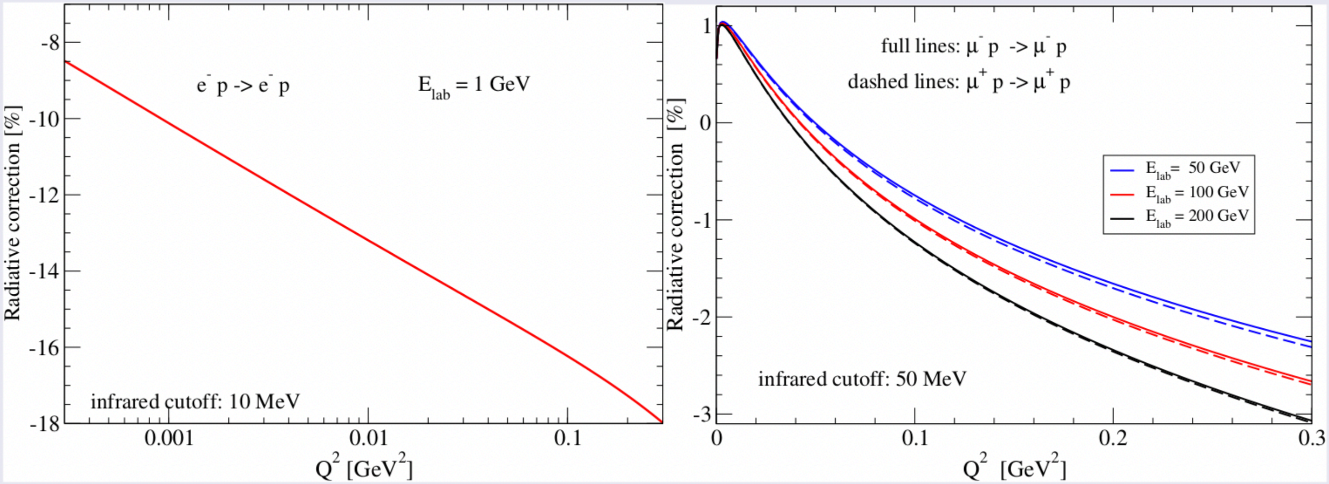
- muon scattering angles 0.3 (Q^2=0.001GeV^2) … 2 mrad (Q^2=0.04GeV^2)
  (100 GeV beam, minimal kinematic range, better larger)
- side kick over 5m base line: 1.5 … 10 mm
- sufficiently large, high-resolution Si detectors, Δx<=10μm, x>=50mm

- 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
- precision on proton radius <= 0.013 fm (no full simulation yet)

Radiative corrections for electron and muon scattering

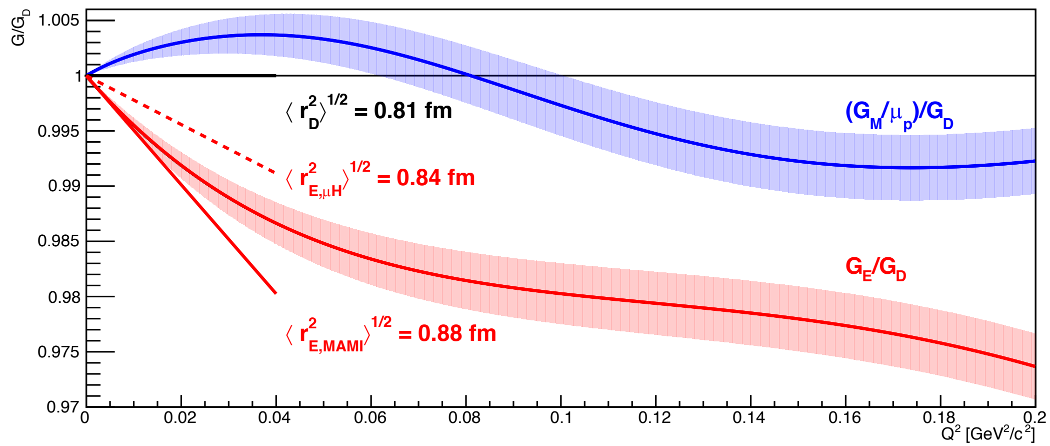
QED radiative corrections



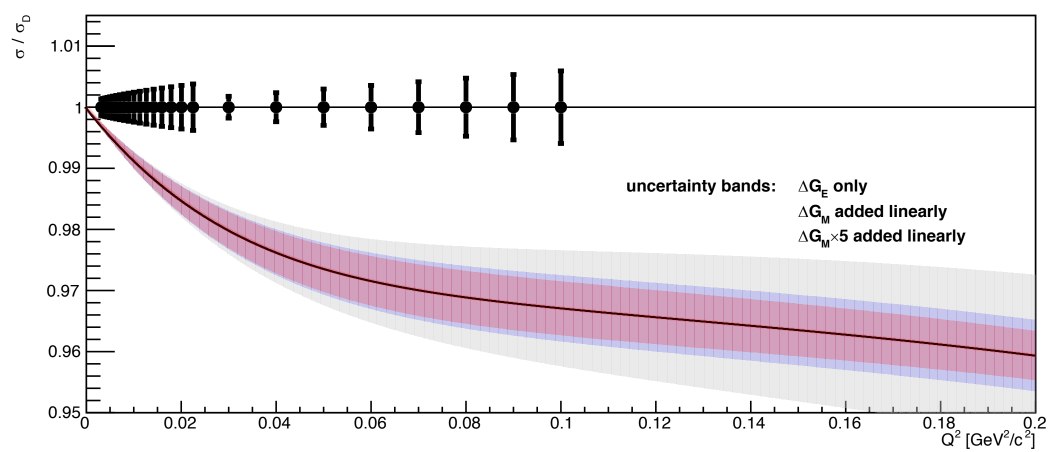
- for soft bremsstrahlung photon energies ($E_\gamma/E_{beam} \sim 0.01$), QED radiative corrections amount to $\sim$ 15-20% for electrons, and to $\sim$ 1.5% for muons
- important contribution to the uncertainty of elastic scattering intensities: *change* of this correction over the kinematic range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

Elastic lepton-proton cross section

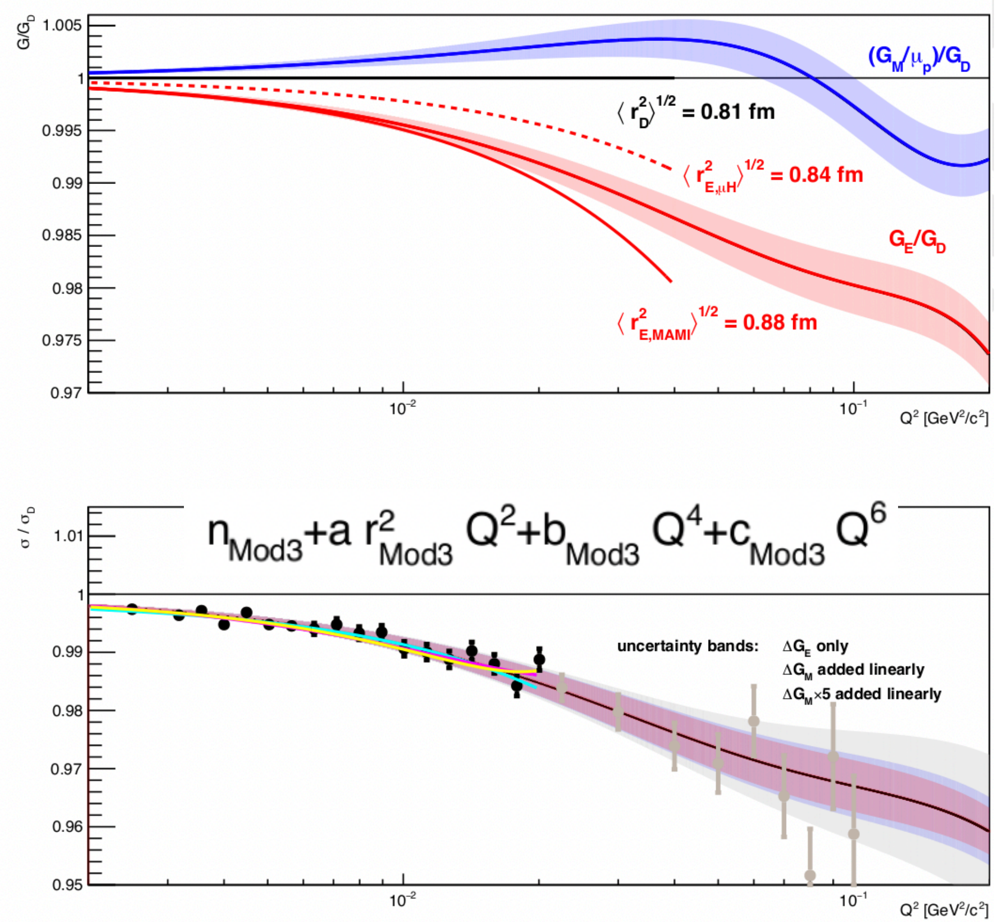
$$\frac{d\sigma^{\mu p\to\mu p}}{dQ^2} = \frac{\pi\alpha^2}{Q^4 m_p^2 \vec{p}_\mu^{\,2}}\left[\left(G_E^2+\tau G_M^2\right)\frac{4E_\mu^2 m_p^2 - Q^2(s-m_\mu^2)}{1+\tau} - G_M^2\,\frac{2m_\mu^2 Q^2 - Q^4}{2}\right]$$



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



Elastic lepton-proton cross section

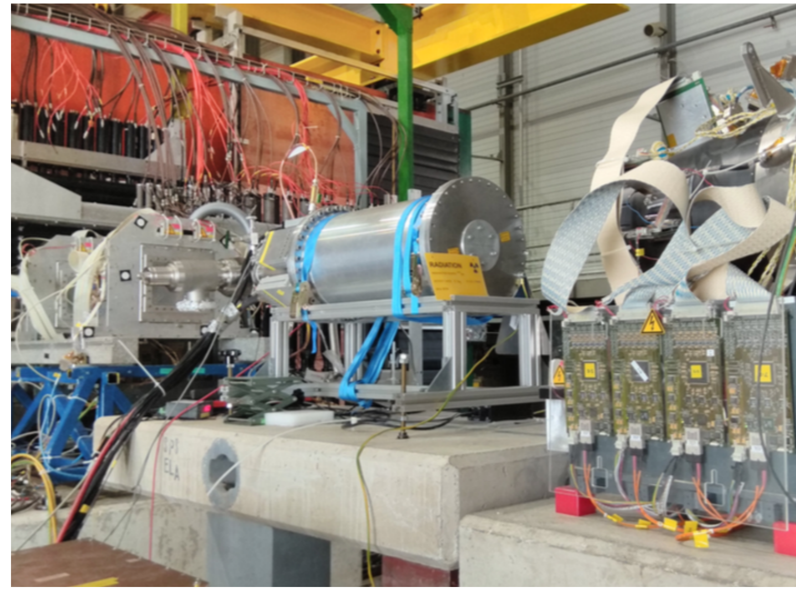


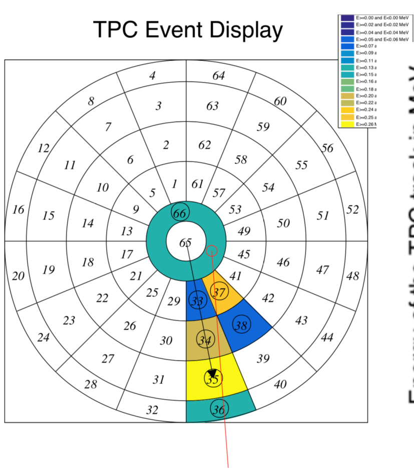
Only the low-Q^2 points in black were used in the various fits (polynomial in Q^2) to the pseudo-data shown as magenta (linear), purple (quadratic) and yellow (3^{rd} order) curves. Pseudo-data points in grey require a different detector setup and are shown here for completeness. Only statistical uncertainties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

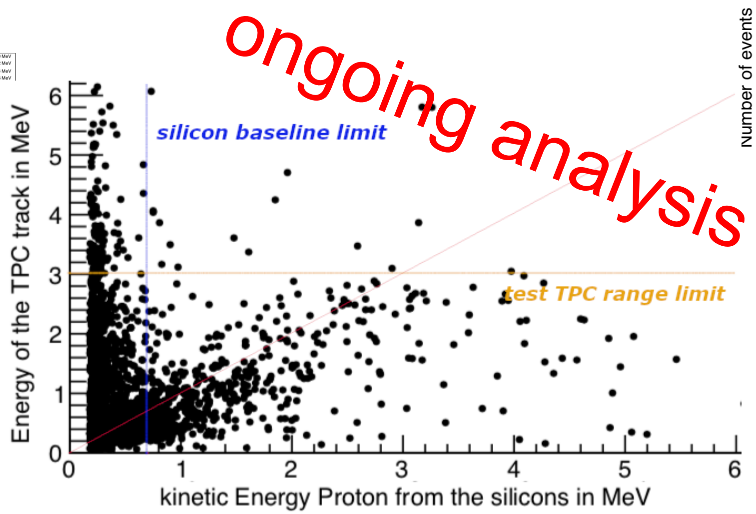
Test in 2018 for Proton Radius measurement

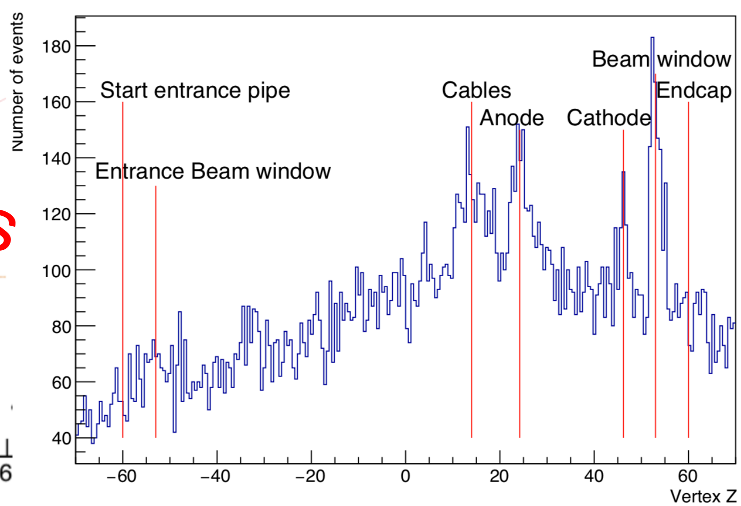
Test setup during 2018 DY run downstream COMPASS, check

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

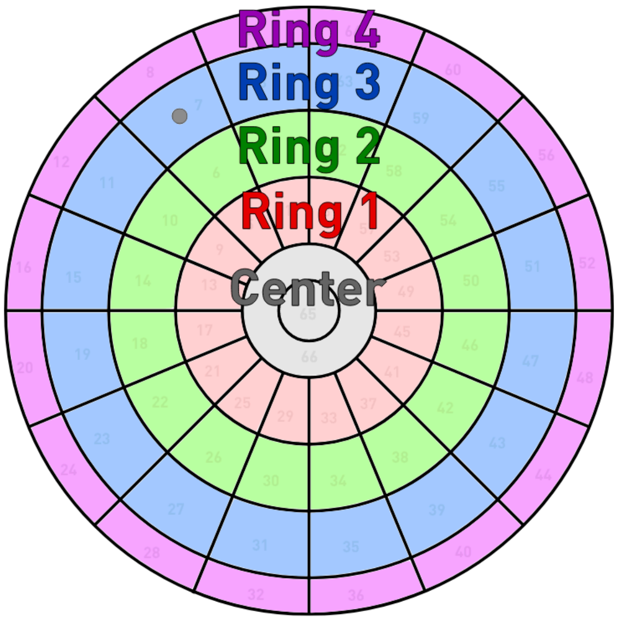


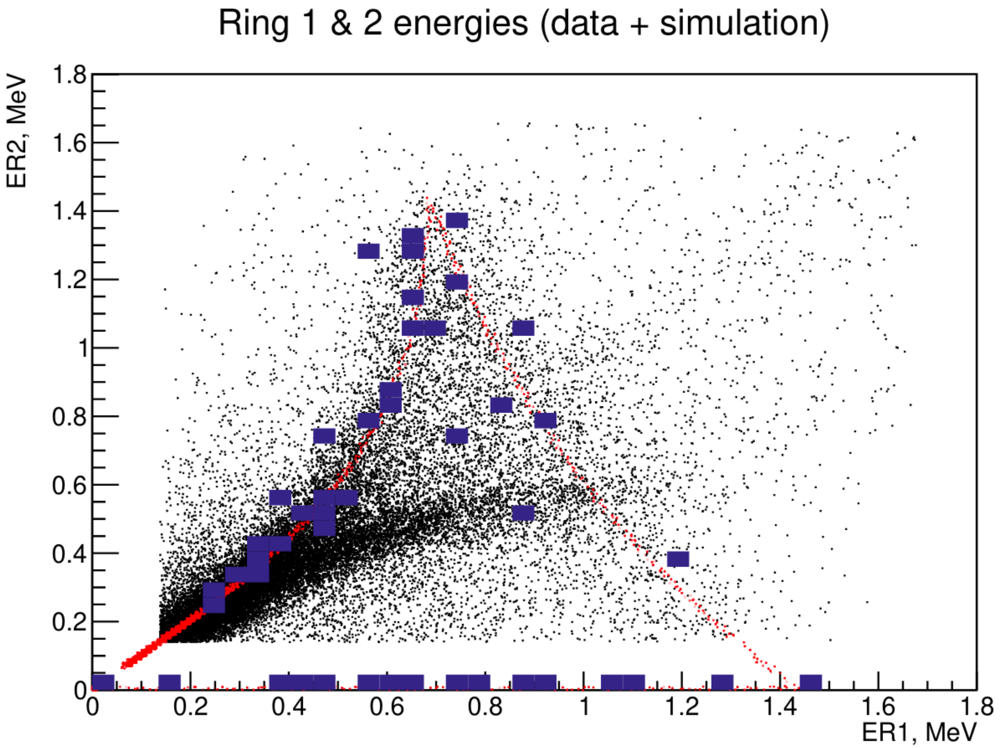






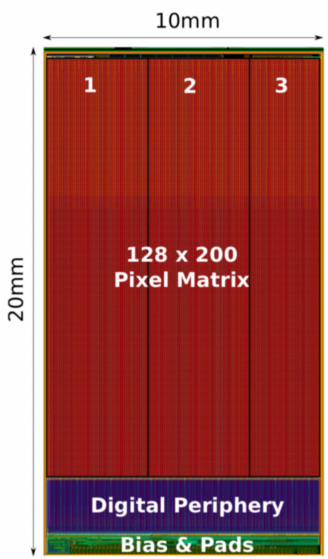
Ring energies — matched events

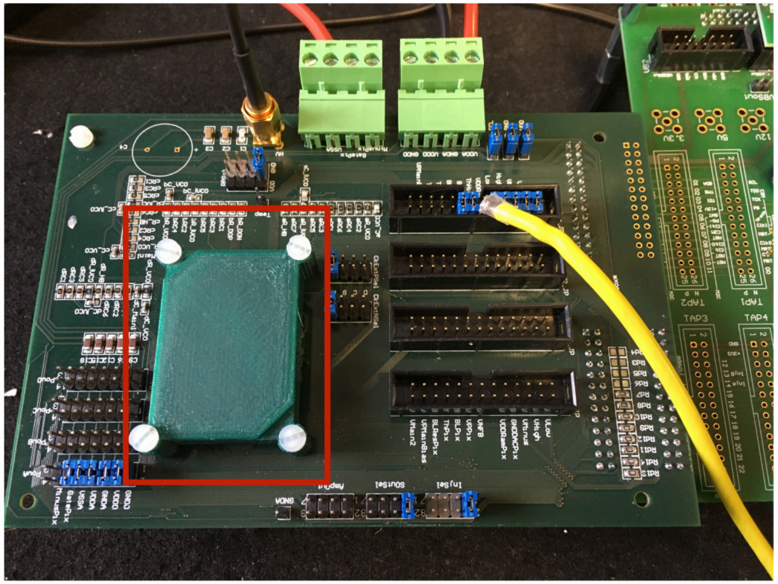




New ideas for silicon detectors ready for continuous readout –Igor and team

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!

CERN 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/

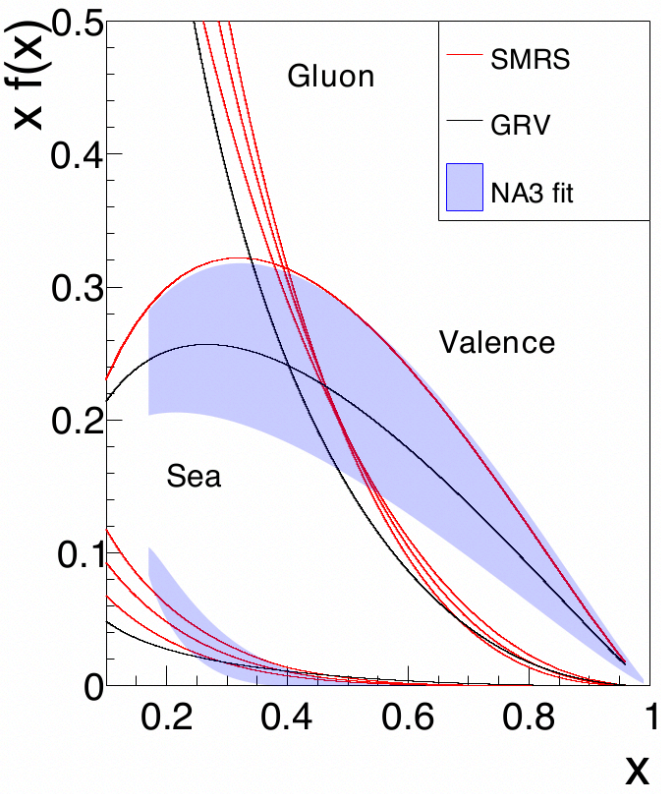
Thank you for your attention!

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

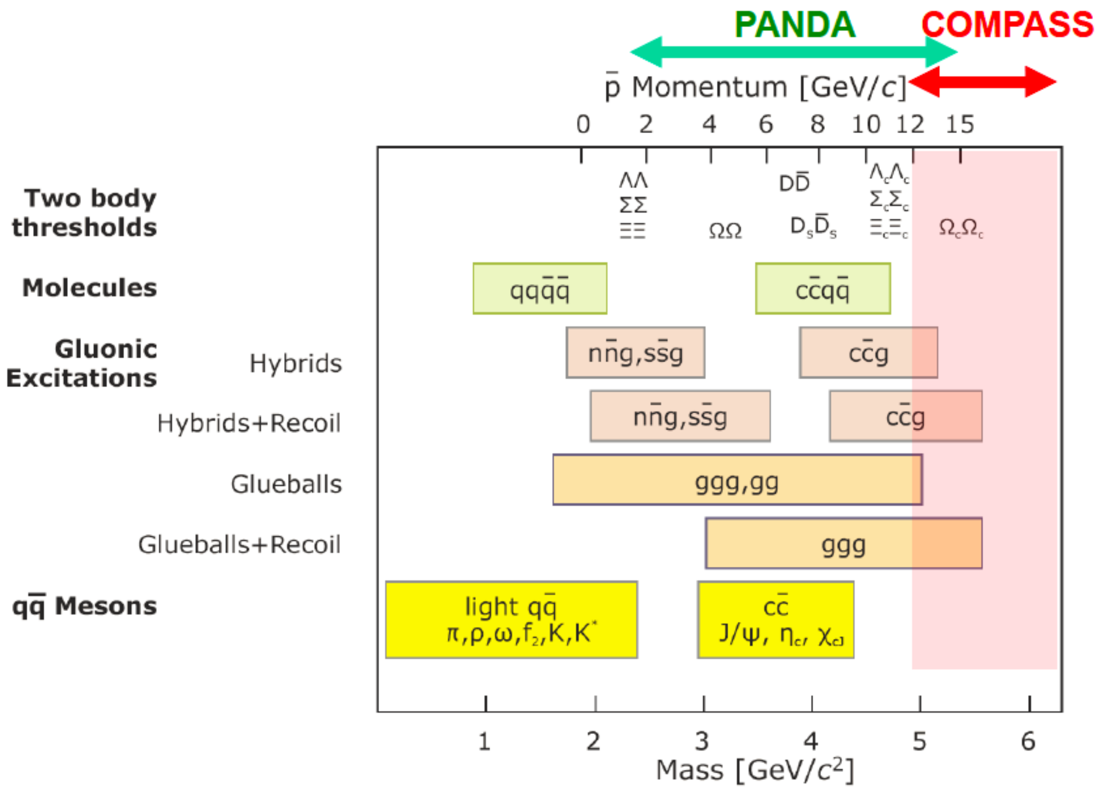
More data is needed, with better control of uncertainties, and full error treatment.

Existing beam line, antiproton-enriched beam
Charmonium-like mesons

M2 SPS beam line has to be retuned to extract
Antiproton beam (momentum ~ 20 GeV)

Method: antiproton-proton annihilation

Goal: charmed hybrids and exotics study in the mass range higher than reachable in PANDA



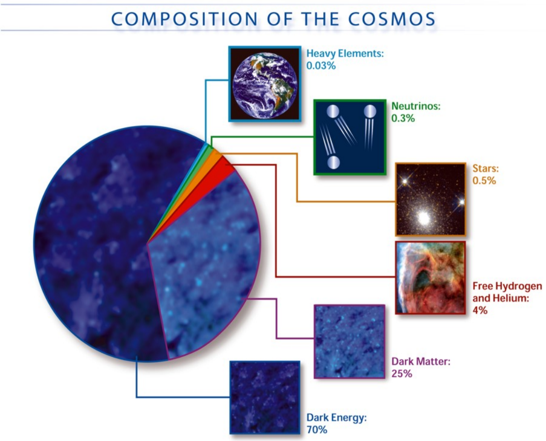
Complementary to LHCb

(p-pbar annihilation – gluon rich environment and it allows high spin states)

Otherwise no competitors for the next at least 10 years

Existing proton beam: Search for Dark Matter

Absolute cross section measurement p+He--> pbar+X



-New AMS(2) data – the antiparticle flux is well known now (few % pres.) (http://dx.doi.org/10.1103/PhysRevLett.117.091103)

- Two type of processes contribute – SM interactions (proton on the ISM with the production for example antiprotons in the f.s.) and contribution from dark particle – antiparticle annihilation;
- In order to detect a possible excess in the antiparticles flux a good knowledge of inclusive cross sections of p-He interaction with antiparticles in the f.s. is a must, currently the typical precision is of 30-50%.

COMPASS++ from a few tens of GeV/c up to 250 GeV/c, in the pseudorapidity range $2.4 < h < 8$.

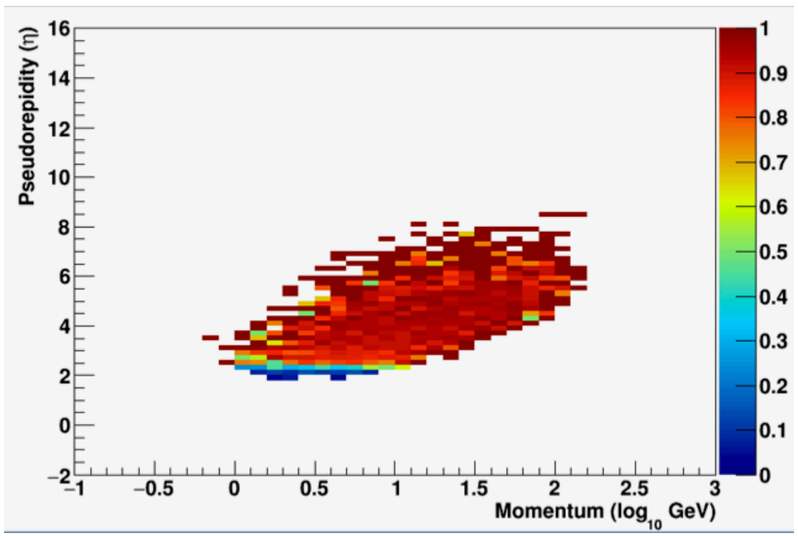
We performed simulation with TGEANT (GEANT4 based COMPASS MC), using FLUKA generator or the internal TGEANT generator:

2009 COMPASS hadron setup, 190 GeV beam.

New tCOMPASS associated members for this project:

AMS: Paolo Zuccon (MIT), Nicolò Masi (Bologna)

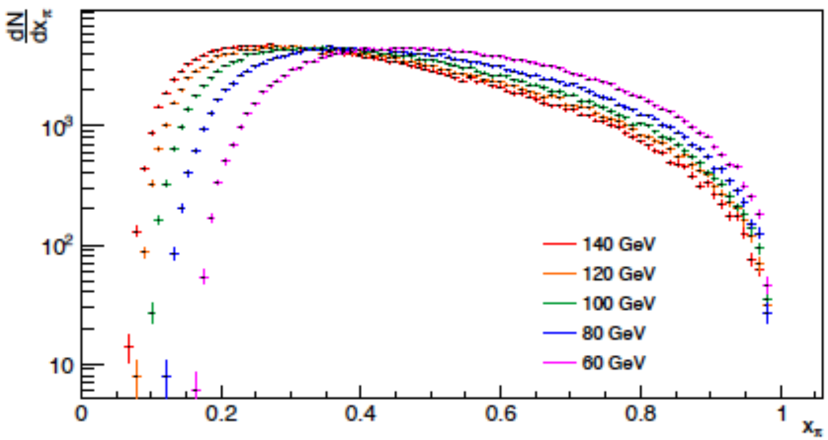
Theoretical Physicist: Fiorenza Donato (Torino)



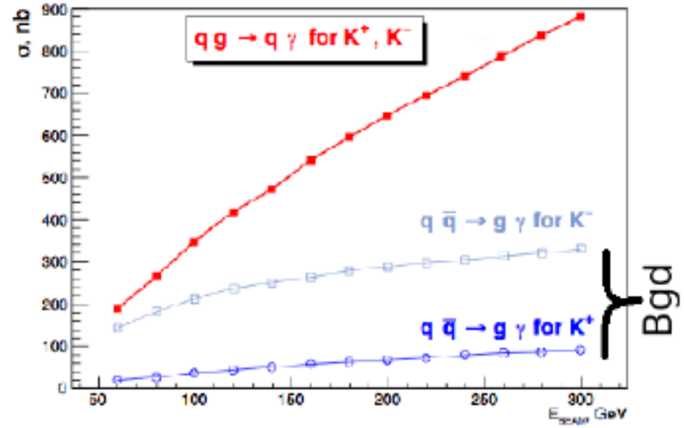
Goal is to measure the double differential (momentum and pseudorapidity) anti-p cross production from p+p and p+He at different proton momenta (50, 100, 190, 250 GeV/c).

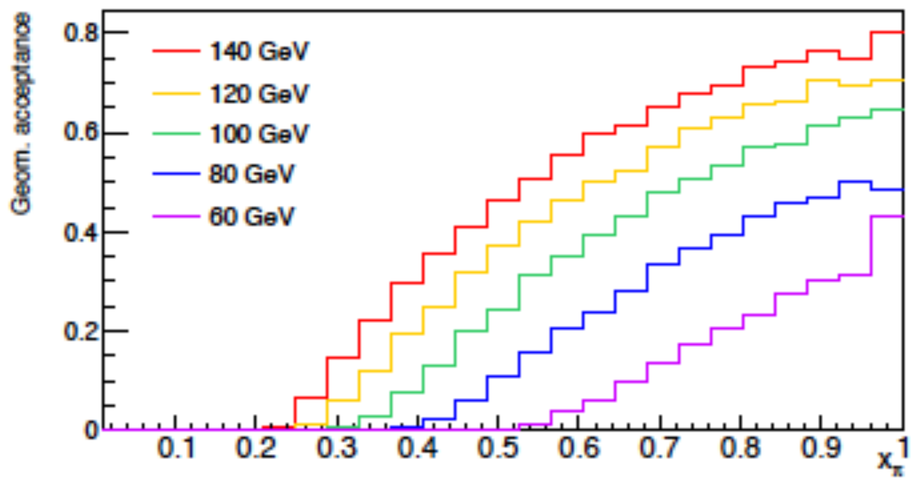
RF separated hadron beam
Meson structure study in DY and PP processes

DY cross-section



Prompt photon cross-section





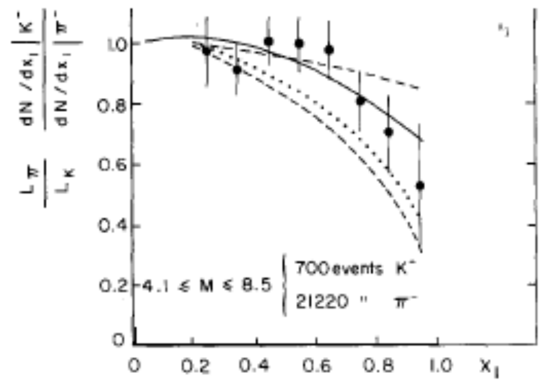
Highest possible beam momentum is Essential for both Drell-Yan and Prompt Photons program

What do we know about kaon structure?

Sole measurement from NA3

J. Badier *et al.*, PLB93 354 (1984)

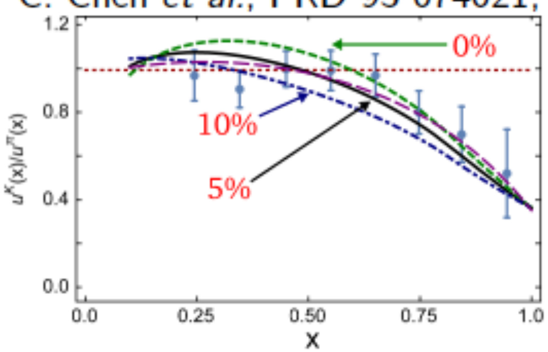
- Limited statistics: 700 events with K^-
- Sensitivity to $SU(3)_f$ breaking
- Mostly only model predictions
- No predictions from lattice - waiting for data!



Interesting observation:At hadronic scale gluons carry only 5% of K's momentum *vs* ~30% in π

- Scarce data on u-valence
- No measurements on gluons
- No measurements on sea quarks

C. Chen *et al.*, PRD 93 074021, 2016



PBC-QCD

QCD Conveners' Introduction

Markus Diehl, Jan Pawlowski, Gunar Schnell

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

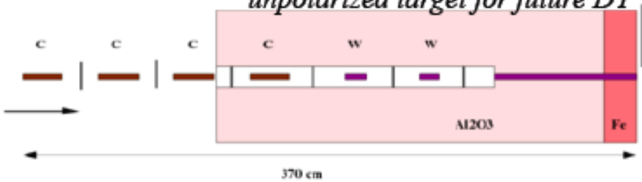
	LHC FT gas				LHC FT crystals	COMPASS++	MUonE	NA61++	NA60++	DIRAC++
	ALICE	LHCb	LHCSpin	AFTER@LHC						
proton PDFs	×	×		×						
nuclear PDFs	×	×		×		×				
spin physics	×		×	×		×				
meson PDFs						×				
heavy ion physics	×			×				×	×	
elast. μ scattering						×	×			
chiral dynamics						×				×
magnet. 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.

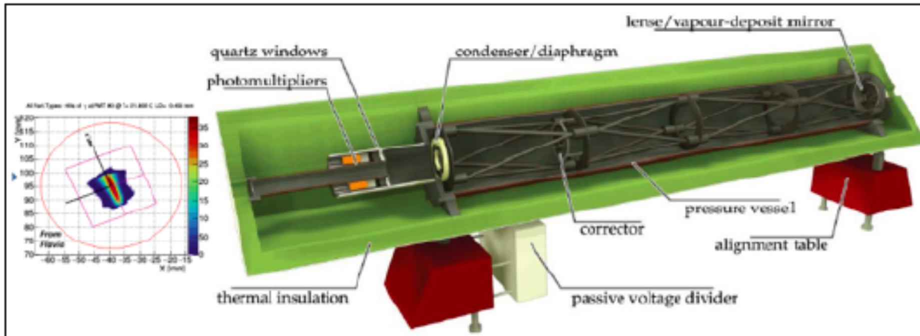
QCD facility – future fixed target experiment at M2
Spectrometer upgrades

Drell-Yan general:
- High-purity and efficiency di-muon trigger
- Dedicated precise luminosity measurement
- Dedicated vertex-detection system
- Beam trackers

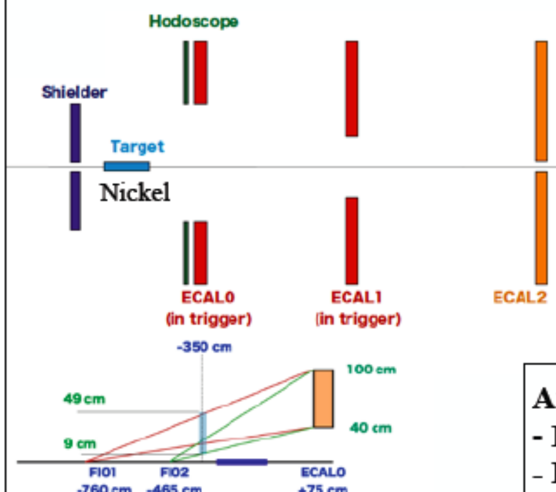
unpolarized target for future DY



Drell-Yan RF separated beams:
- Due to lower beam energy, need wide aperture ± 200 mrad
- High-rate and high-multiplicity capability
- Active absorber (magnetic field, calorimetry?)
- TPCs?
- GEMs?

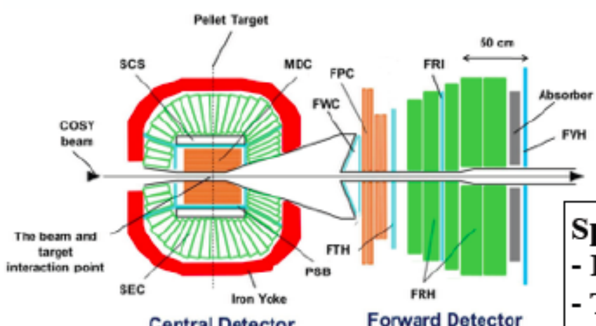


CEDAR upgrade 2018



Prompt Photons
- Shielder (20-30cm steel) upstream of target
- New hodoscope upstream of ECal0
- Transparent setup

Anti-matter cross section
- LH2 and LHe targets
- RICH0 for lower momentum to ID anti-protons?

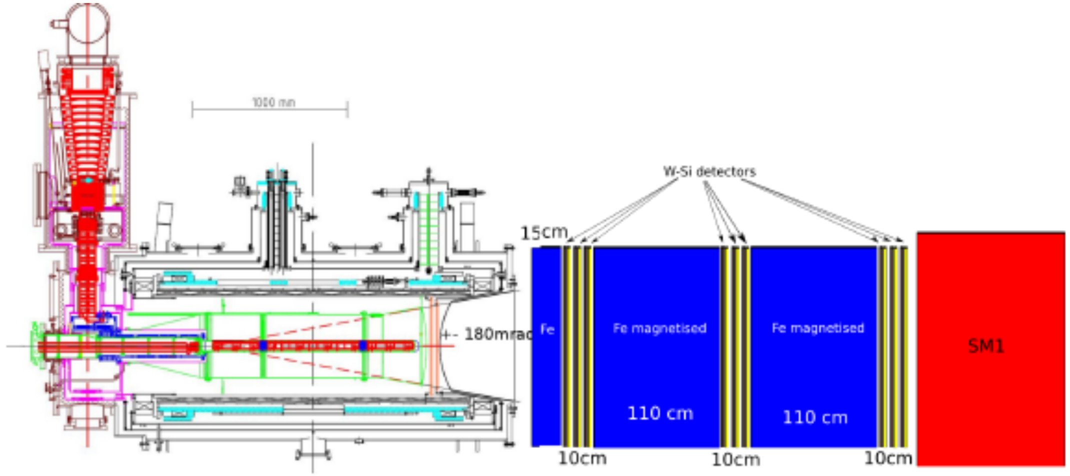


WASA detector with target spectrometer

Spectroscopy with low-anergy anti-p:
- RICH & CEDAR, RICH0 for low p?
- Target spectrometer (tracking, barrel calorimeter) similar to WASA

Spectroscopy with high-energy K—:
- RICH & CEDAR
- Uniform acceptance, ECals
- Good vertexing
- Recoil TOF detector

QCD facility – future fixed target experiment at M2 Spectrometer upgrades for Drell-Yan measurements with RF-separated beam



- Investigate the possibility to use W-Si detectors, a la PHENIX (NCC, MPC-EX)
- Dead zone with radius of 9 cm (12 cm) for angles below 90 mrad (120 mrad)
- Outter radius: 112 cm for angles up to 300 mrad

Initial detector consideration:

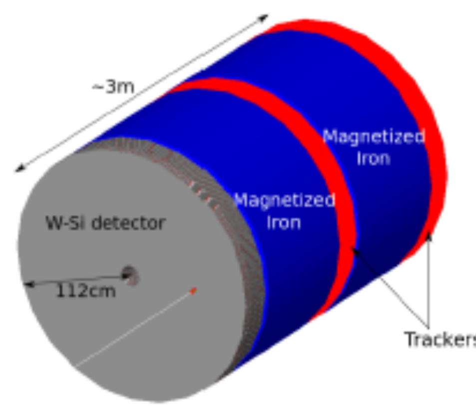
Combination of

- Baby-Mind detector

  M. Antonova *et al.* arXiv:1704.08079

- W-Si detectors, a la BNL

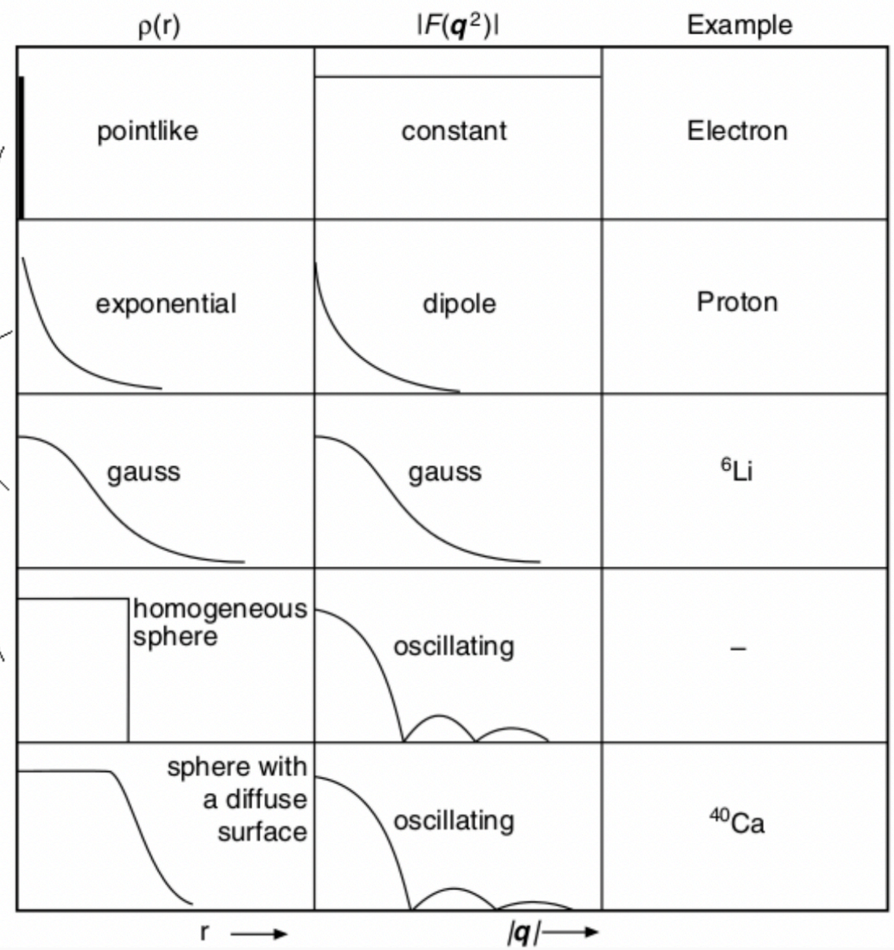
  AnDY | Phenix MPCEX | Phenix NCC



Fourier transform of the charge distribution

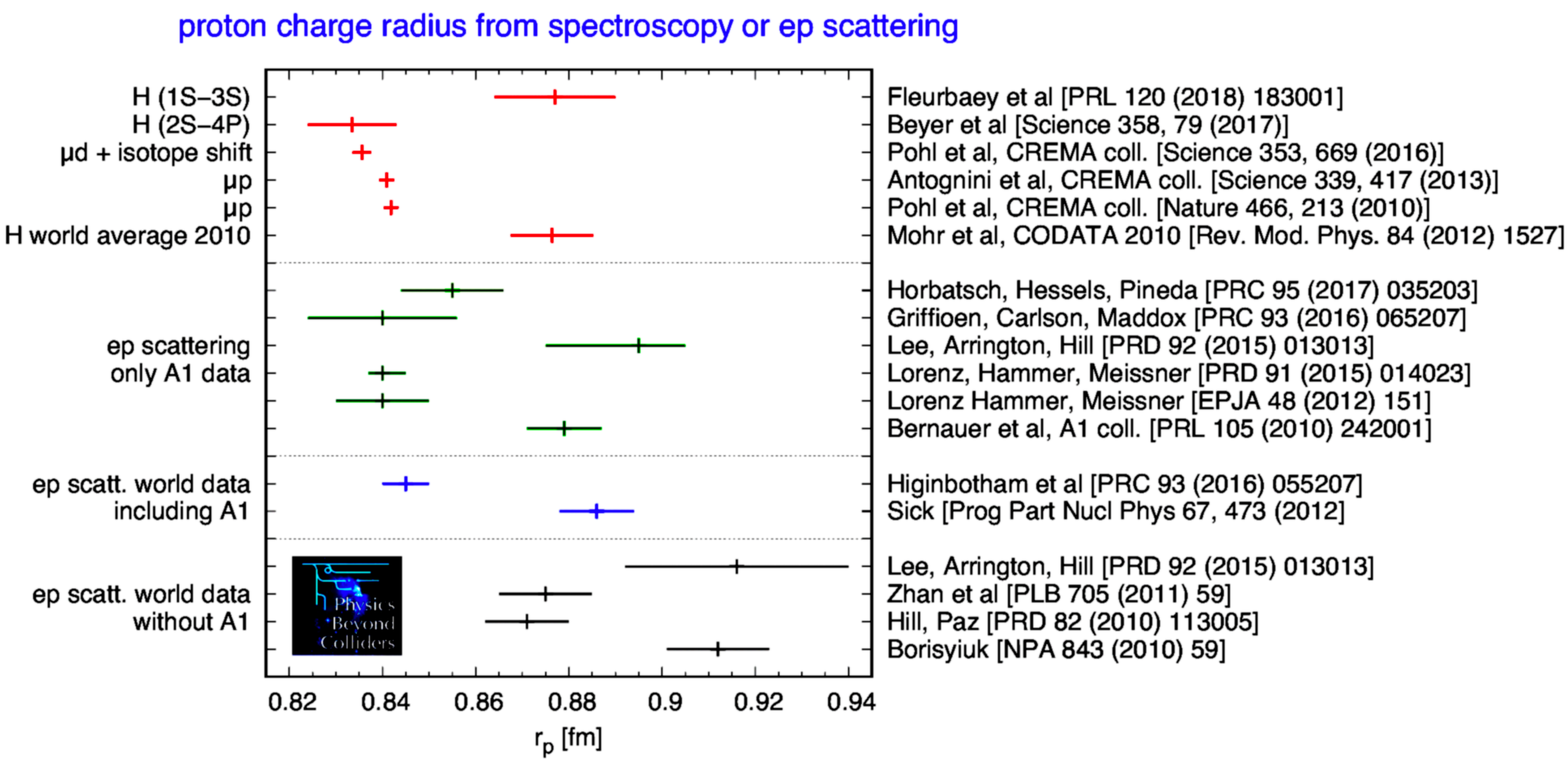
Charge distribution $f(r)$	Form Factor $F(\boldsymbol{q}^2)$
$\delta(r)/4\pi$	1
$(a^3/8\pi)\cdot\exp(-ar)$	$(1+\boldsymbol{q}^2/a^2\hbar^2)^{-2}$
$(a^2/2\pi)^{3/2}\cdot\exp(-a^2r^2/2)$	$\exp(-\boldsymbol{q}^2/2a^2\hbar^2)$
$\begin{cases} 3/4\pi R^3 & \text{for } r \le R \\ 0 & \text{for } r > R \end{cases}$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

from: B. Povh, Particles and Nuclei



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

Summary of the present physics case



from the CERN future document “PBC summary”, December 2018

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

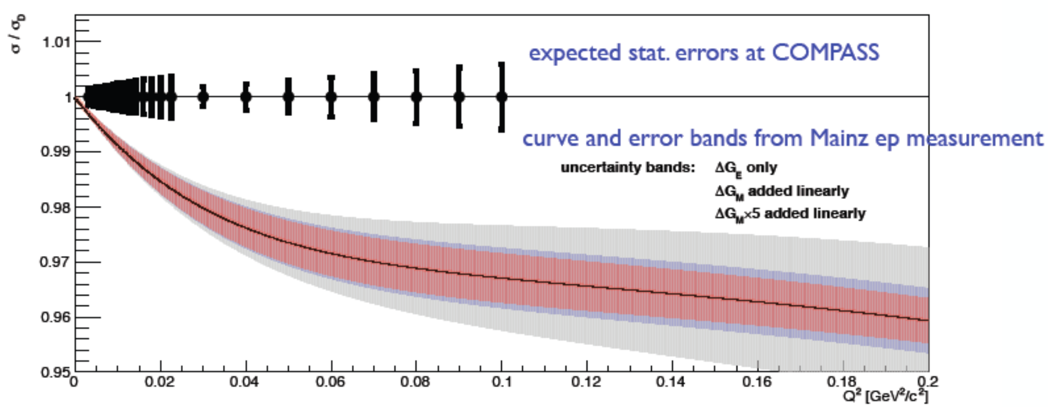
This document summarises the physics interest, sensitivity reach and competitiveness of a future general-purpose fixed-target facility for Particle Physics research. Based upon the versatile M2 beam line of the CERN SPS, a great variety of measurements is proposed to address fundamental issues of Quantum 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

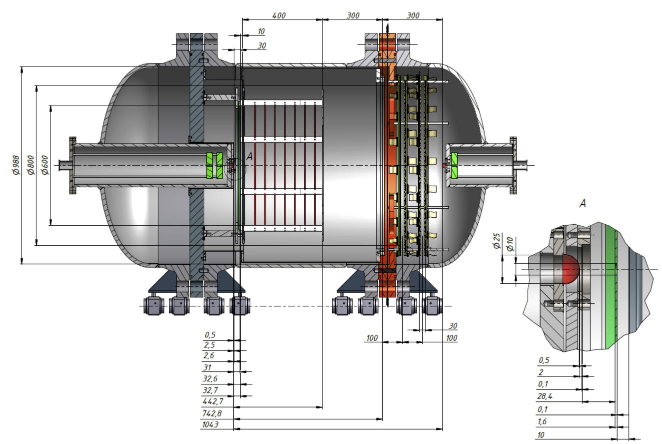
Proton Radius measurement

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} … $2\text{x}10^{-2}$ the proton radius (slope of electric form factor)

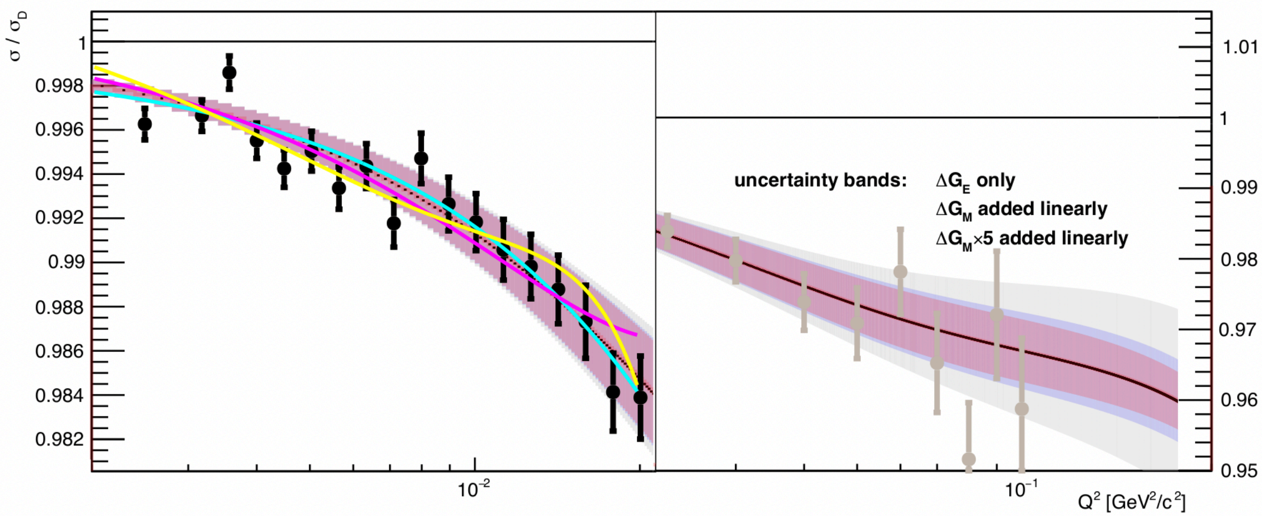




Feedback from PBC QCD working group

COMPASS++

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



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

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

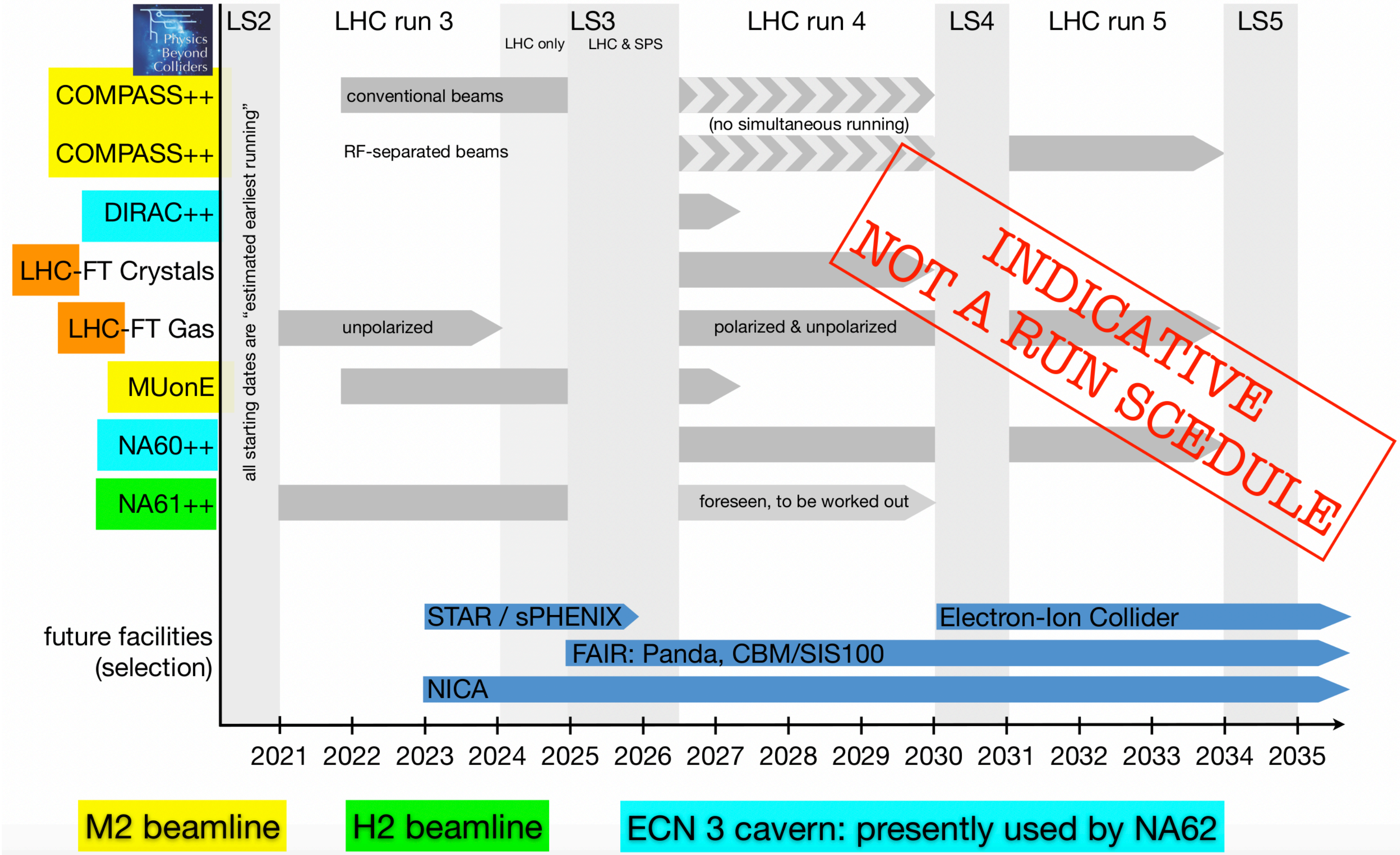
$$\langle r_E^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

- 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

PBC-QCD



Physics Beyond Colliders
LS2
LHC run 3
LHC only
LS3
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