COMPASS++/AMBER

A New QCD Facility at the M2 Beam Line of the CERN SPS

Boris Grube

Institute for Hadronic Structure and Fundamental Symmetries
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Garching, Germany

12th International Workshop on the Physics of Excited Nucleons
Bonn University, 14. June 2019

The M2 Beam Line at the CERN SPS

World-wide unique high-intensity beams

- Secondary hadron beams ($p/\bar{p}$, $\pi^{\pm}$, and $K^{\pm}$)
- Tertiary polarized muon beams ($\mu^{\pm}$)
- Wide energy range: 20 to 280 GeV

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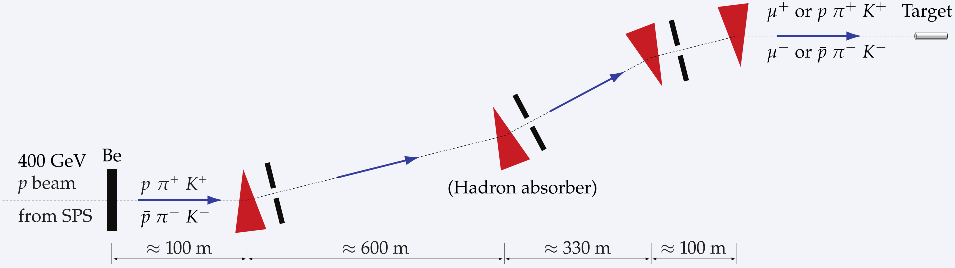
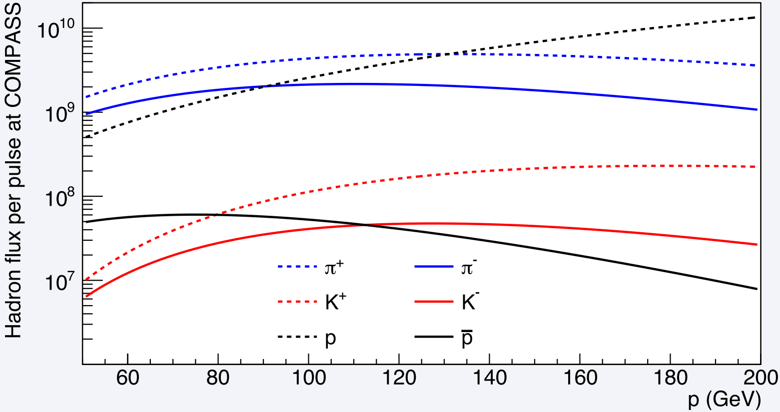


The M2 Beam Line at the CERN SPS

Flux of Secondary Hadron Beams



Typical SPS supercycle

- 10 s pulse length
- 48 s cycle duration

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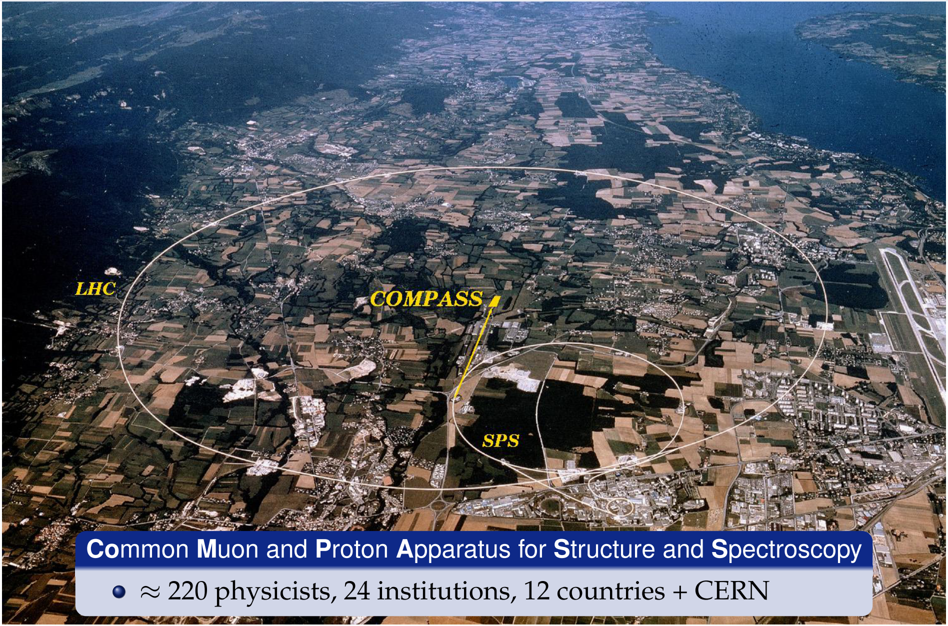
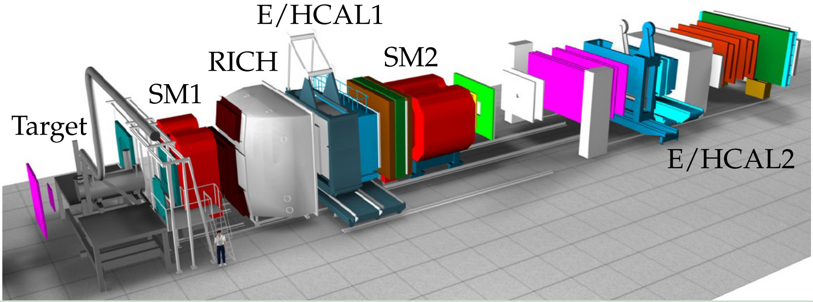


Common **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

- $\approx$ 220 physicists, 24 institutions, 12 countries + CERN

The COMPASS QCD Facility at the M2 Beam Line

Versatile Experimental Setup



- Large-acceptance two-stage spectrometer
- Precise tracking ($\approx$ 350 planes) and PID (CEDAR, RICH, calorimeters, muon system)
- Various targets
  - Polarized solid-state NH_3 or ^6LiD
  - Liquid H_2
  - Solid-state nuclear targets (e.g. Ni, W, Pb)

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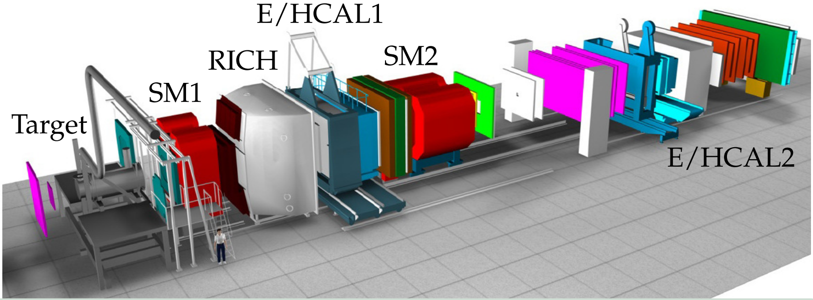

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The COMPASS QCD Facility at the M2 Beam Line

Broad Physics Program

Chiral dynamics

- $\pi^{\pm}$ polarizabilities
- Chiral anomaly $F_{3\pi}$

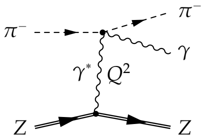
Hadron spectroscopy

- Excitation spectrum of hadrons
- Exotic hadrons

Nucleon structure

- Helicity and transversity PDFs
- $k_{\perp}$-dependent PDFs
- Generalized PDFs

$\pi\gamma$ reactions (Primakoff)



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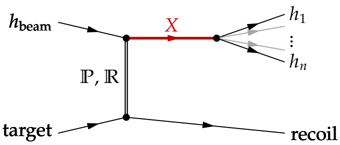
Diffraction



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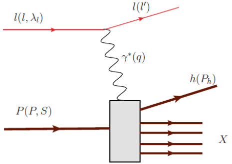
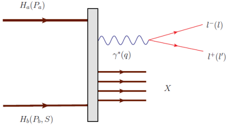


Polarized Drell-Yan



Great variety of planned measurements addressing fundamental QCD questions

Phase 1: after Long Shutdown 2 of LHC (2022 to 2024)

- Elastic μp scattering: precision measurement of proton charge radius
- Drell-Yan and charmonium production: determination of pion PDFs
- Measurement of p-induced $\bar{p}$ production cross sections for indirect dark matter searches

Phase 2: after Long Shutdown 3 of LHC (from 2026 on)

- RF-separated kaon and antiproton beams
- Kaon diffraction: high-precision kaon spectroscopy
- K-induced Drell-Yan, charmonium, and prompt-photon production: determination of kaon PDFs
- K-induced Primakoff reactions: electric polarizability of the kaon
- $\bar{p} + N^{\Uparrow}$ Drell-Yan: nucleon transverse-momentum-dependent PDFs
- …

COMPASS++/AMBER Project

Apparatus for **M**eson and **B**aryon **E**xperimental **R**esearch

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Developed within CERN's Physics Beyond Colliders (PBC) initiative

- `http://pbc.web.cern.ch`
- QCD physics working group
  - Report: *arXiv:1901.04482*
- Conventional beams working group

Embedded into the

- `http://europeanstrategyupdate.web.cern.ch`
- Positive feedback at *Granada Symposium* in May (project summary available *here*)

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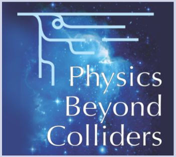

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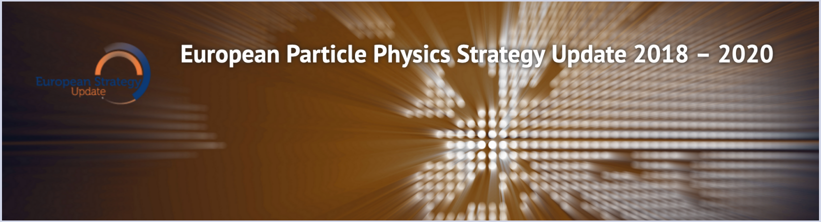

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Website: *https://nqf-m2.web.cern.ch*

Letter of Intent [arXiv:1808.00848]

- Signed by 265 authors

Proposal for phase 1 (2022 to 2024) [CERN-SPSC-2019-022]

- Signed by 240 authors
- Presented to SPS and PS Experiments Committee on 13. Jun 2019

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

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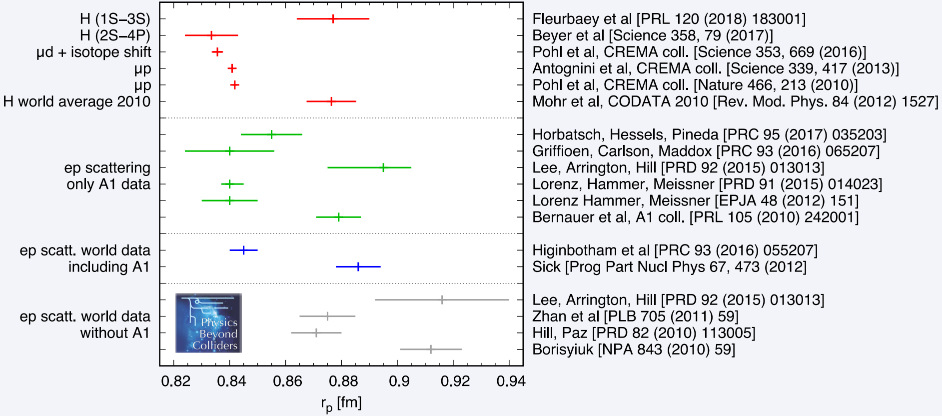
Phase 1

Precision Measurement of the Proton Charge Radius

The Proton-Radius Puzzle

proton charge radius from spectroscopy or ep scattering

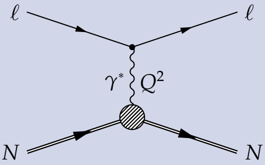


Contradictory proton-radius values from

- finite-size effects in spectroscopy of ordinary and muonic hydrogen
- slope of form-factor measured in elastic *ep* scattering

The Proton Charge Radius from Lepton Scattering

- Response of proton to external electromagnetic fields encoded in electric form factor G_E and magnetic form factor G_M



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with $\mu_p = 2.79$ and $a^2 = 0.71\,\text{GeV}^2$

- Taylor expansion of G_E for spherically symmetric charge distribution

$$\langle r_E^2 \rangle = -6\hbar \left. \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2} \right|_{Q^2=0}$$

- At high energy and low Q^2

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} \propto G_E^2 + \tau\, G_M^2 \quad \text{with} \quad \tau = Q^2/(4m_p^2) \quad \text{small}$$

$\Rightarrow$ contribution from G_M small $\Rightarrow$ can be modelled

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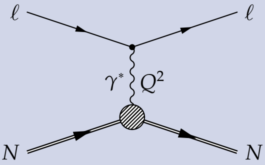

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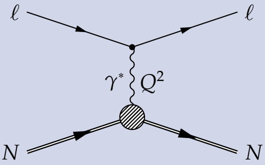

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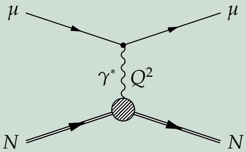
COMPASS++/AMBER Proposal

Precision measurement of proton charge radius in high-energy elastic μp scattering



- Advantageous/complementary systematics compared to other techniques
- Provides new and independent proton-radius value

Goals

- Cover range $10^{-3} < Q^2 < 0.04\,\text{GeV}^2$
- Statistical precision of 0.01 fm or smaller
- Could rule out lepton-flavor effects as explanation for proton-radius puzzle

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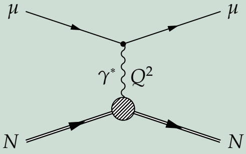

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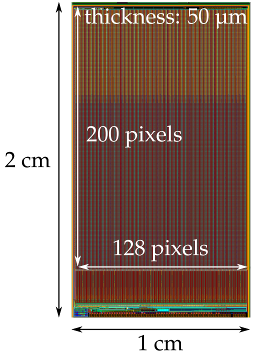
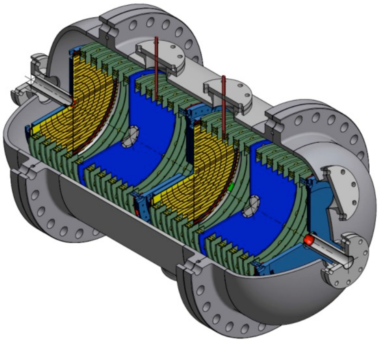
COMPASS++/AMBER Experimental Setup

Challenging measurement

- 100 GeV muon beam with high-intensity $2 \times 10^6\,\mathrm{s}^{-1}$
- High Q^2 resolution down to $Q^2 = 10^{-3}\,\mathrm{GeV}^2$
  - Simultaneous measurement of scattered muon and recoil proton
  - High-precision forward tracking (MuPix8 silicon pixel detector)
  - Active-target high-pressure (20 bar) hydrogen TPC





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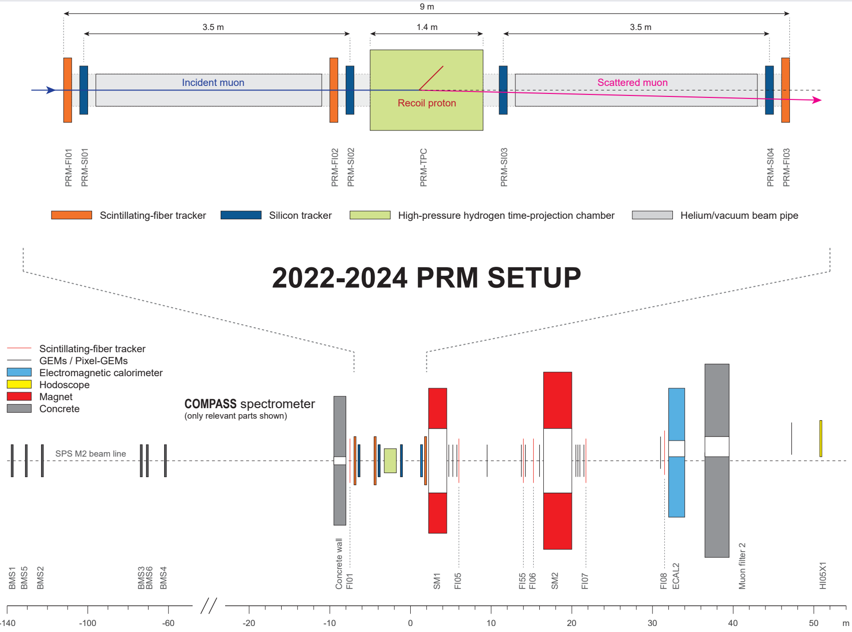
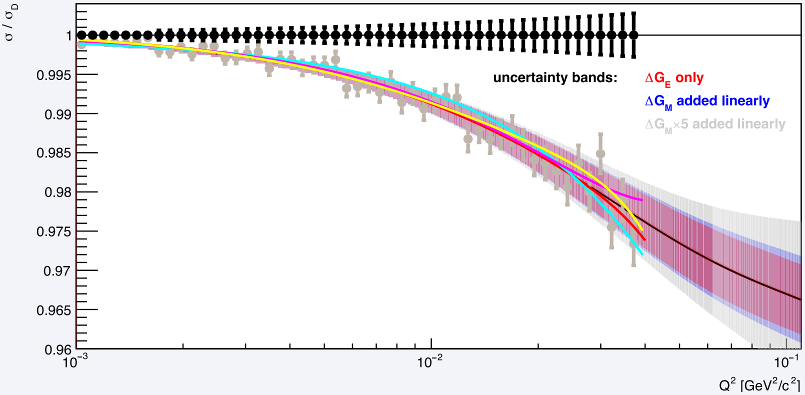


COMPASS++/AMBER Projected Performance (2 Years)

- 1 % statistical precision of radius value requires 70×10^6 elastic events
- Resolution $\Delta Q^2 / Q^2 \approx 15\,\%$ at $Q^2 = 10^{-3}\,\mathrm{GeV}^2$



Running or Planned Lepton Scattering Experiments

MUSE (PSI)

- Low-energy elastic μp scattering
- $E_\mu = 140\,\mathrm{MeV} \Rightarrow$ substantial correction (percent level) due to Coulomb distortion of wave function of non-relativistic muon
- Correction for pion contamination in beam

Electron scattering experiments

- PRad (JLab)
- Two experiments at Mainz Microtron
  1. Initial-state radiation
  2. Simultaneous detection of scattered electron (forward tracker) and recoil proton (active-target TPC)
- Low-energy ep scattering
  - MAGIX at MESA (Mainz)
  - JPARC

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Phase 1

Determination of Pion Parton Distribution Functions

Motivation

- Pion is lightest hadron and Nambu-Goldstone boson of spontaneous breaking of chiral symmetry
- Explaining properties and structure of pion is cornerstone of understanding non-perturbative QCD
- Not enough data to directly constrain all pion PDFs ⇒ need sum rules, models
- More data needed

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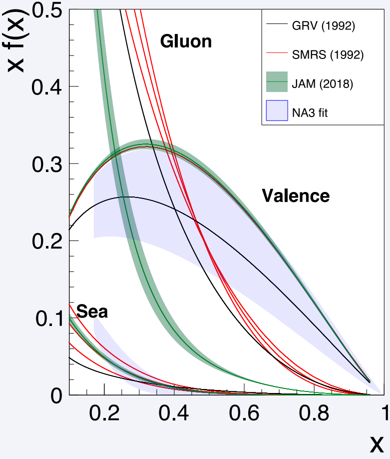


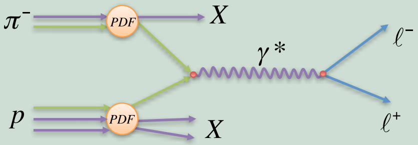
GRV: M. Glück *et al.*, ZPC **53** (1992) 651

SMRS: P. J. Sutton *et al.*, PRD **45** (1992) 2349

JAM: P. C. Barry *et al.*, PRL **121** (2018) 152001

COMPASS++/AMBER Proposal

Measurement of pion-induced Drell-Yan dimuon production



- Isoscalar target: ^{12}C to minimize nuclear effects
- π^+ and π^- beams: separation of valence and sea-quark contributions

$$\Sigma_{\text{val}} = \sigma_{\pi^-} - \sigma_{\pi^+} \qquad \text{only valence-valence}$$

$$\Sigma_{\text{sea}} = 4\sigma_{\pi^+} - \sigma_{\pi^-} \qquad \text{no valence-valence}$$

Goals

- Collect $10\times$ more data than currently available
- First precise and direct measurement of the sea contribution in the pion

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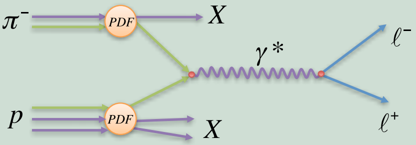

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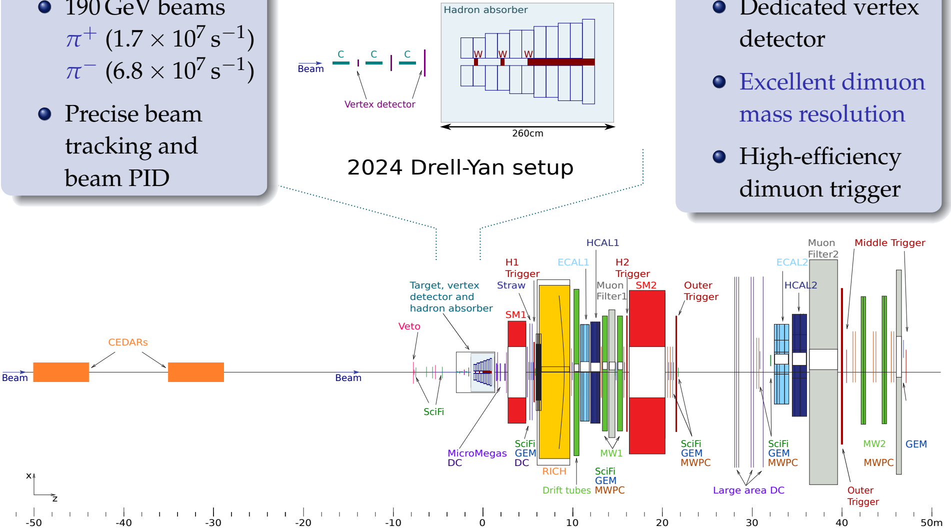
COMPASS++/AMBER Experimental Setup

- 190 GeV beams
  π^+ $(1.7 \times 10^7\,\mathrm{s}^{-1})$
  π^- $(6.8 \times 10^7\,\mathrm{s}^{-1})$
- Precise beam tracking and beam PID

- Dedicated vertex detector
- Excellent dimuon mass resolution
- High-efficiency dimuon trigger



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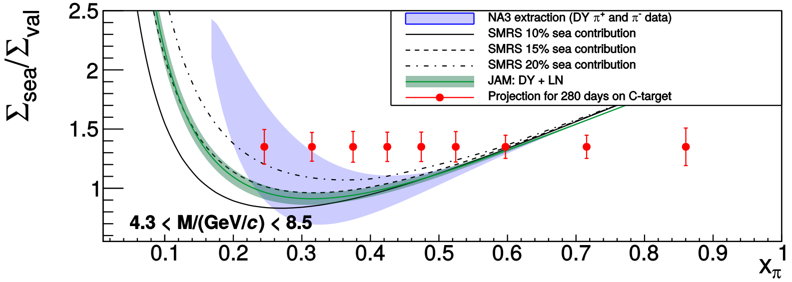

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- $\approx$ 25 000 Drell-Yan events
- Dimuon mass resolution $\approx$ 100 MeV
  - Extension of analyzed range to $4.0 < M_{\mu\mu} < 8.5$ GeV possible
  - 35 % larger sample

COMPASS++/AMBER Proposal

Study of charmonium production

- Drell-Yan samples
  - $\pi + \mathrm{C}$: 1.2×10^6 J/ψ
  - $\pi + \mathrm{W}$: 0.75×10^6 J/ψ
  - Similar amounts for $p + \mathrm{C}$ and $p + \mathrm{W}$
  - $\psi(2S)$ cross section $10\times$ lower
- Low-p_T region dominated by $q\bar{q}, gg \to J/\psi$
- Polarization of colliding partons directly transferred to J/ψ
- Test theory of quarkonium production in low-p_T domain
  - Verify hadronization model
  - Constrain pion PDFs

COMPASS++/AMBER Proposal

Study of charmonium production

- Drell-Yan samples
  - $\pi + \text{C}$: 1.2×10^6 J/ψ
  - $\pi + \text{W}$: 0.75×10^6 J/ψ
  - Similar amounts for $p + \text{C}$ and $p + \text{W}$
  - $\psi(2S)$ cross section $10\times$ lower
- Low-p_T region dominated by $q\bar{q}, gg \to J/\psi$
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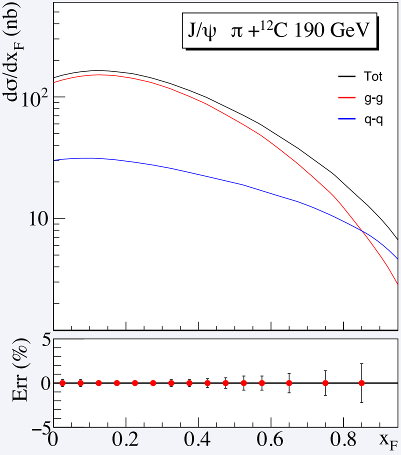
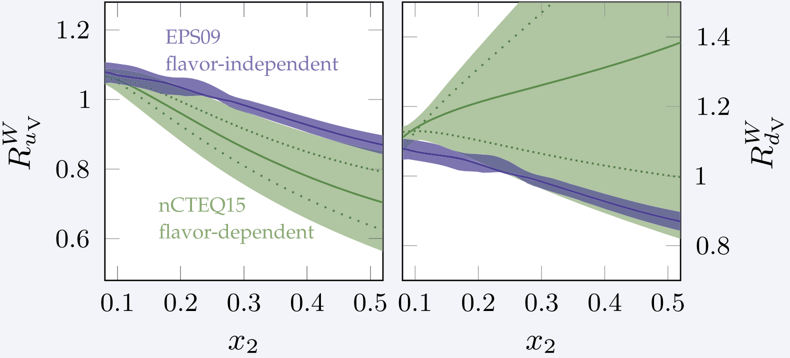


V. Cheung *et al.*, PRD **98** (2018) 114029

COMPASS++/AMBER Proposal

Study of nuclear dependence

- *Open question:* flavor dependence of modification of nuclear PDFs w.r.t. nucleon PDFs
- *Ideal tool:* Drell-Yan dimuon production with π^+ and π^- beams



P. Paakkinen *et al.*, PLB **768** (2017) 7

nCTEQ15: K. Kovarik *et al.*, PRD **93** (2016) 085037

EPS09: K. Eskola *et al.*, JHEP **04** (2009) 065

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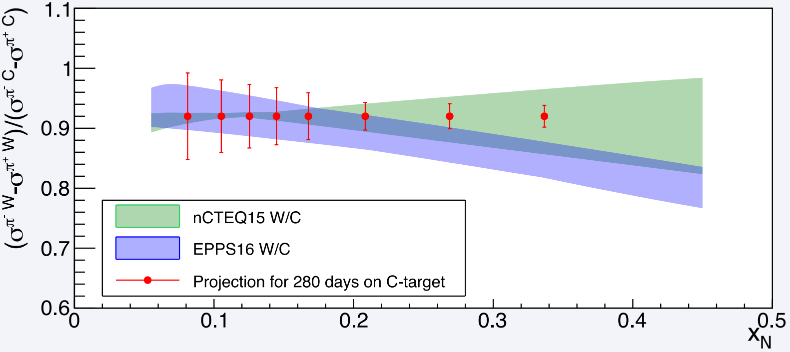


nCTEQ15: K. Kovarik *et al.*, PRD **93** (2016) 085037

EPPS16: K. Eskola *et al.*, EPJC **77** (2017) 163

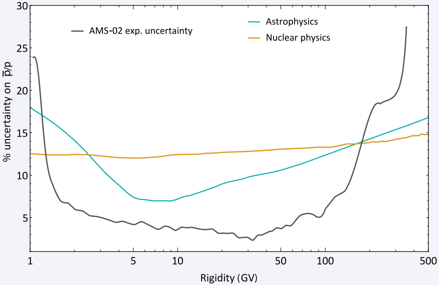
Phase 1

Measurement of p-Induced $\bar{p}$ Production Cross Section

COMPASS++/AMBER Proposal

Measurement of p-induced $\bar{p}$ production cross section

- AMS-02: precise data on cosmic antiparticle flux
- Sources: standard model processes and annihilation of dark matter particles
- *Limiting factor:* prediction of standard model contribution to antiproton flux
    - Dominant processes: $\bar{p}$ production in scattering of p and ^{4}He
- $p + p \to \bar{p} + X$ cross section: several measurements
- $p + {}^4\text{He} \to \bar{p} + X$ cross section: only LHCb at 4 TeV and 6.5 TeV



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Goals

- Measure cross section for $p + p$ and $p + {}^4\text{He} \to \bar{p} + X$ in 10 bins in $\bar{p}$ momentum and rapidity
- Statistical uncertainty of $\approx 0.5\,\%$ per data point
- Systematic uncertainty $\approx 5\,\%$
- p beam energies: 60, 100, 150, 200, and 280 GeV

Phase 2

Large Variety of Proposed Measurements

Proposed COMPASS++/AMBER Phase-2 Measurements

Pion beam

- Direct measurement of π^0 lifetime
- Color-screening effects in vector-meson production off nuclei

Muon beam and transversely polarized target

- Measurement of GPD E in deeply virtual Compton scattering
- Measurements of deeply virtual exclusive meson production

Low-energy antiproton beam

- Heavy-quark meson spectroscopy

RF-separated antiproton beam

- Drell-Yan with transversely polarized target: nucleon transverse-momentum-dependent PDFs

RF-separated kaon beam

- Drell-Yan, charmonium, and prompt-photon production: determination of kaon PDFs
- Primakoff reactions: electric polarizability of the kaon
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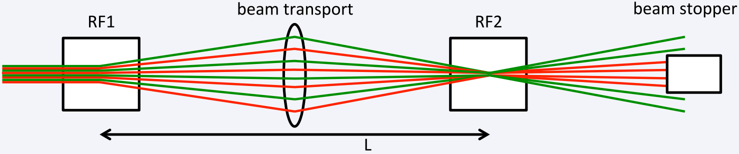
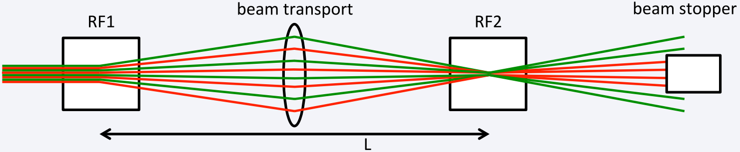
RF-Separated Kaon and Antiproton Beams

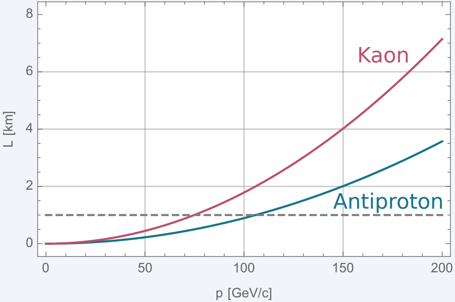
Panofsky-Schnell Method

P. Bernard *et al.*, CERN-1968-029



- Beam momentum limited by length of beam line
- Estimated intensities
  - Kaon: $5 \times 10^6\,\mathrm{s}^{-1}$
  - Antiproton: $5 \times 10^7\,\mathrm{s}^{-1}$
- More detailed studies needed to determine beam parameters more precisely
- Requires major investment





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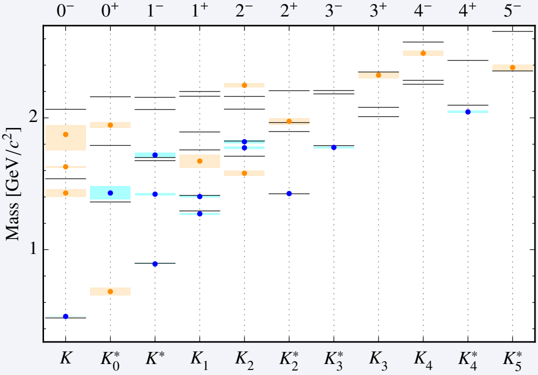
Kaon Spectroscopy at COMPASS++/AMBER

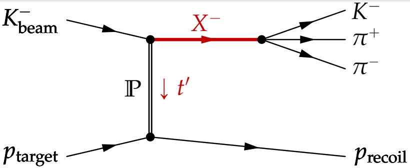
PDG 2016: 25 kaon states below 3.1 GeV / c^2

- Only 12 kaon states in summary table, 13 need confirmation
- Most PDG entries more than 30 years old
- Since 1990 only 4 kaon states added to PDG (only 1 to summary table)



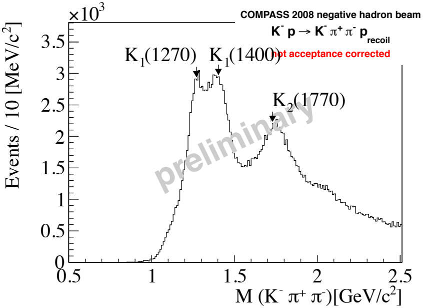
[Courtesy S. Wallner, TUM]

Example: Diffractive Production of $K^-\pi^+\pi^-$ Final State



COMPASS

$0.07 < t' < 0.7\,(\text{GeV}/c)^2$



WA03 (CERN)

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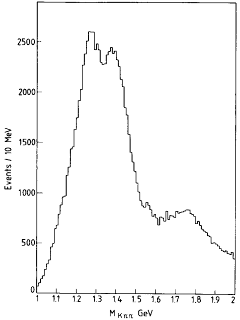

ACCMOR, NPB **187** (1981) 1

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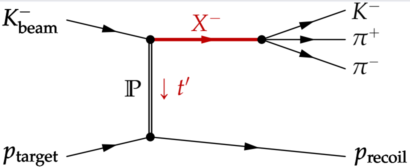

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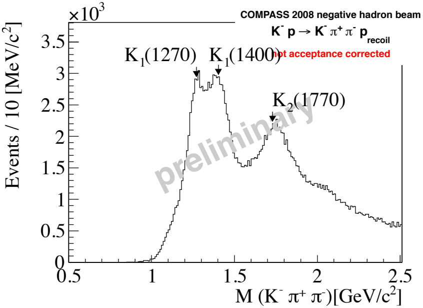

COMPASS data

- Only subset of available sample
- Total sample ≈ 700 000 events (3.5× WA03)

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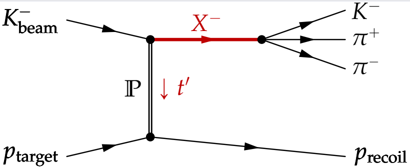

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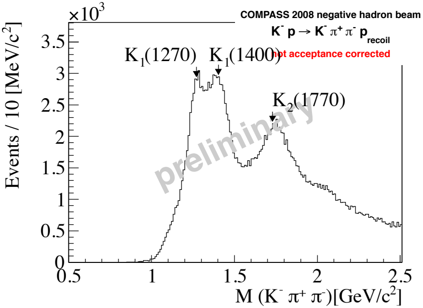

COMPASS++/AMBER goal

- $> 10 \times 10^6\ K^-\pi^+\pi^-$ events
- Apply partial-wave analysis methods developed for COMPASS
- High-precision kaon spectroscopy
  - Complete flavor multiplets
  - Look for partners of non-strange exotic states

3 Measurements proposed for phase 1 (2022-24)

1. Proton radius in high-energy muon-proton scattering
2. Pion PDFs in pion-induced Drell-Yan
3. Antiproton production in pp and pHe collisions

- Formation of a new collaboration is on track
- Various hardware developments and upgrades are ongoing

Phase 2 (after LS3)

- Broad physics program using conventional and RF-separated beams

New ideas and collaborators are welcome!

https://nqf-m2.web.cern.ch

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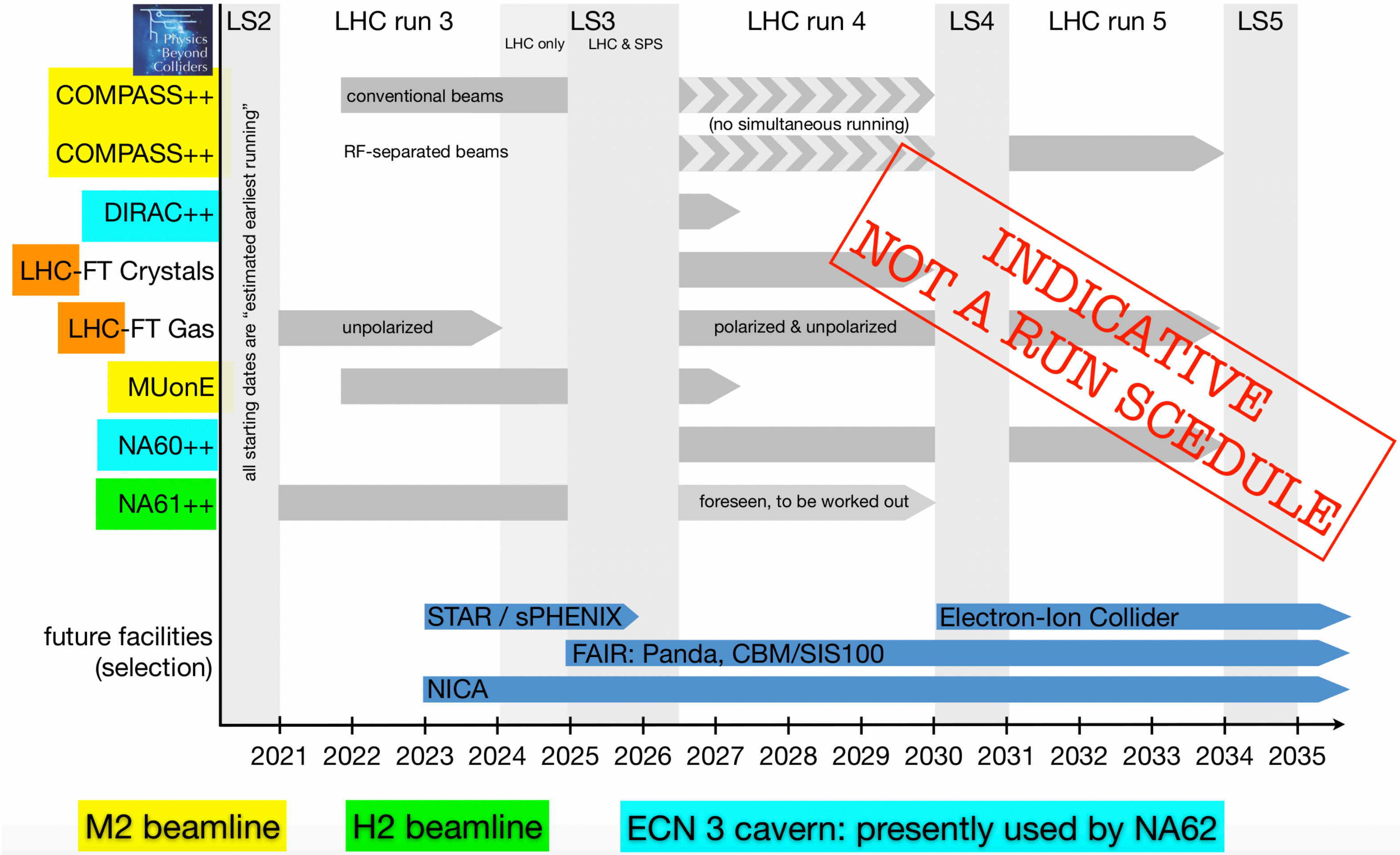
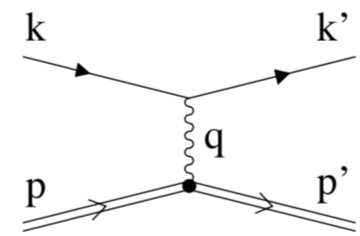
Spares

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

Proton radius measurement from muon-proton high-energy scattering

- contradictory findings for the proton radius 0.84…0.88 fm from different experimental and theoretical approaches on the 5% level
- direct determination as slope of the electric form factor G_E at Q^2 near zero
- proposed experiment reaches a precision 0.01 fm
- competitive to JLab, MAMI, MUSE



G_E, G_M

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

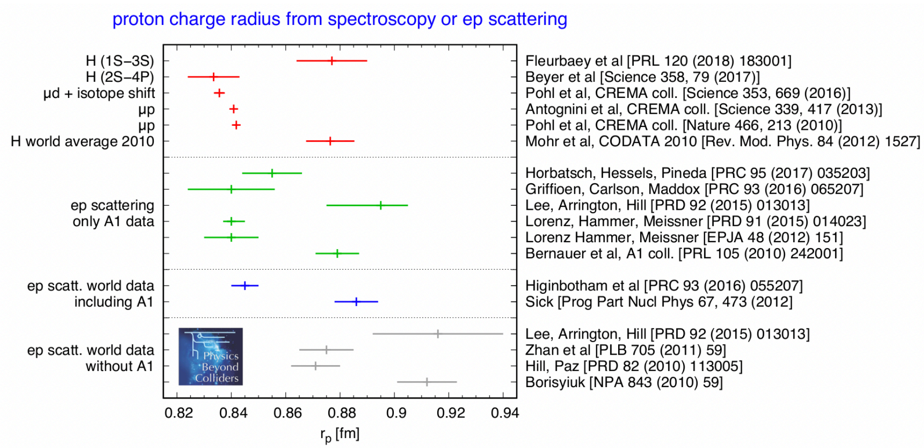
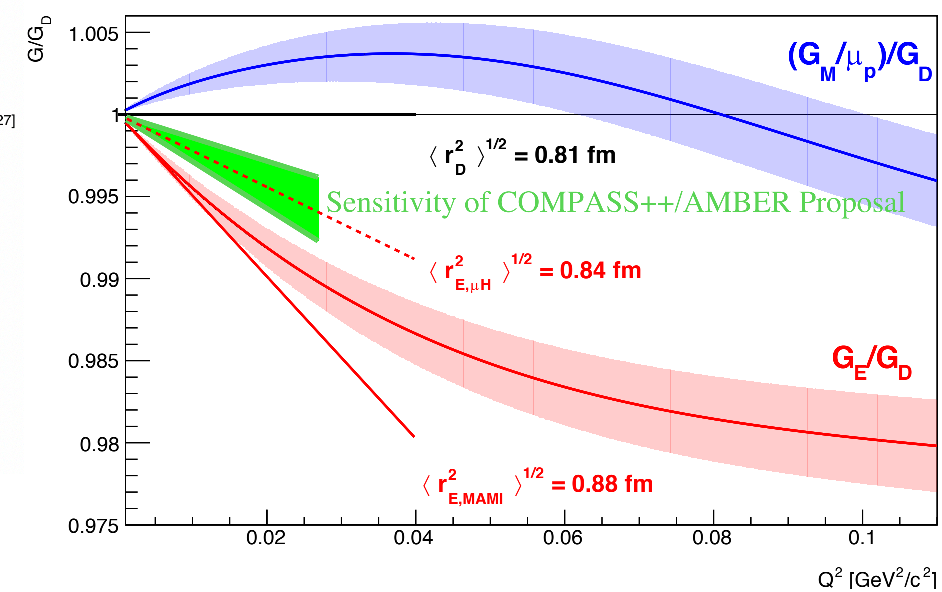
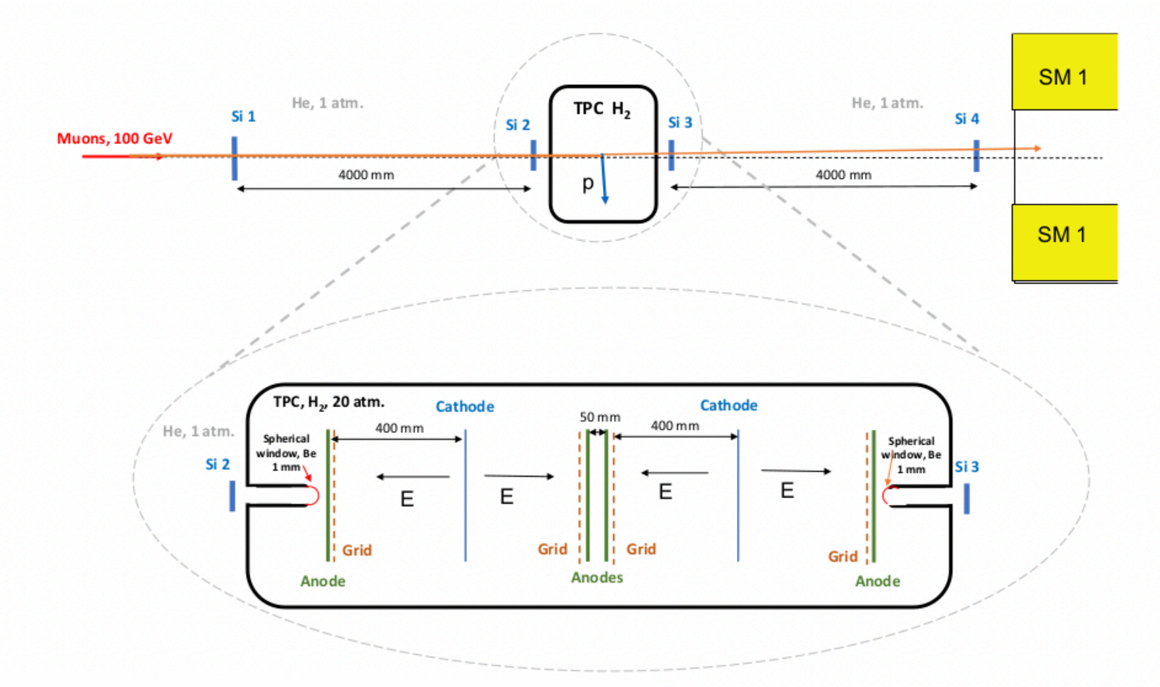


Figure 2: Compilation of the proton radius puzzle, figure taken from [7].



New hardware: The active-target TPC for the proton radius measurement



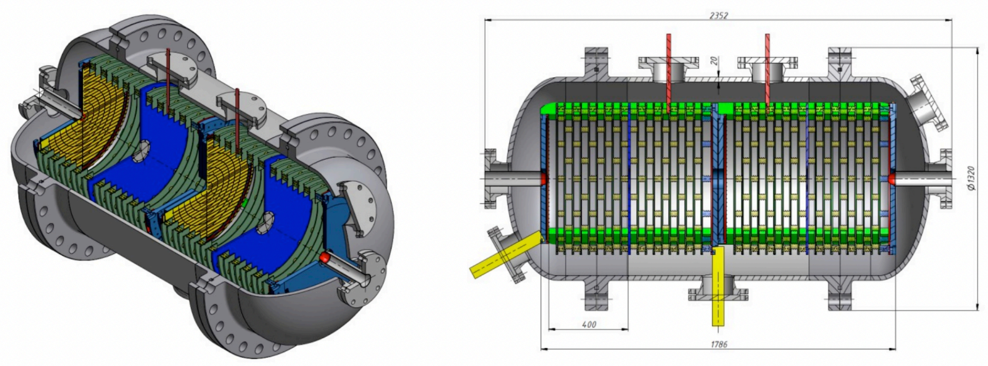
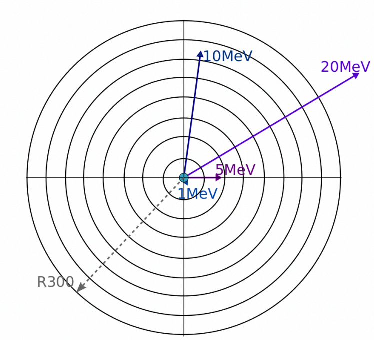
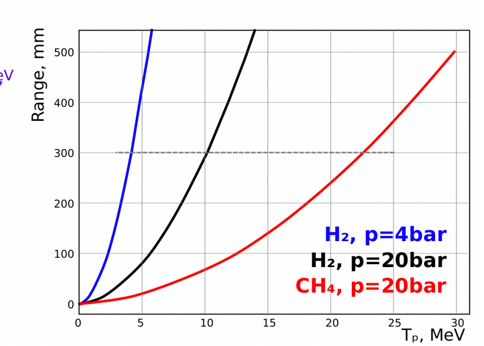


Figure 45: Engineering design for the four-cell hydrogen TPC.

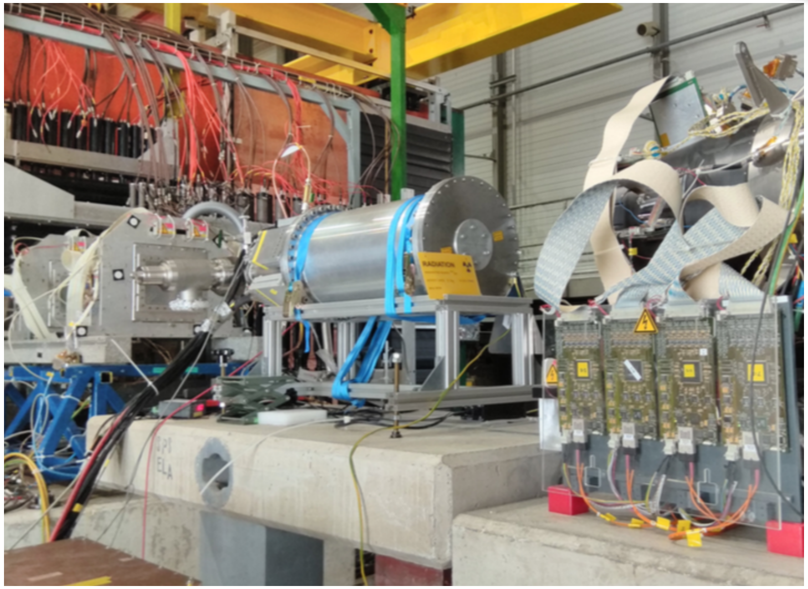


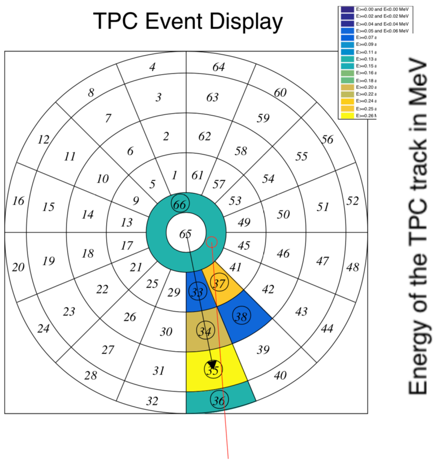


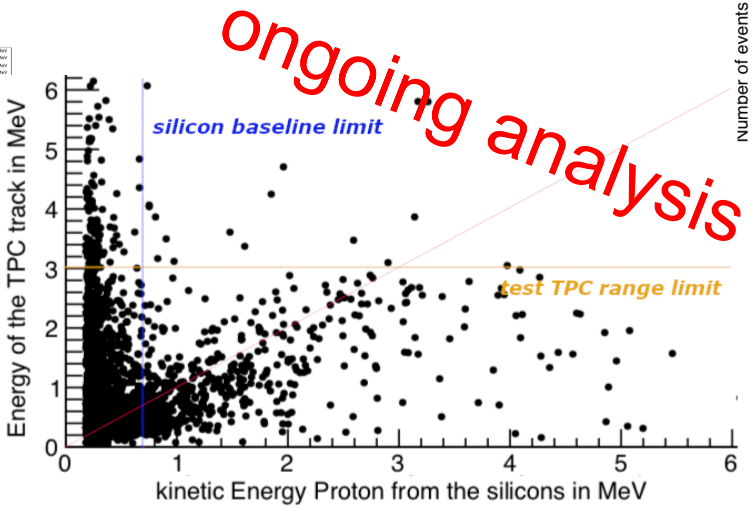
Test in 2018 for Proton Radius measurement

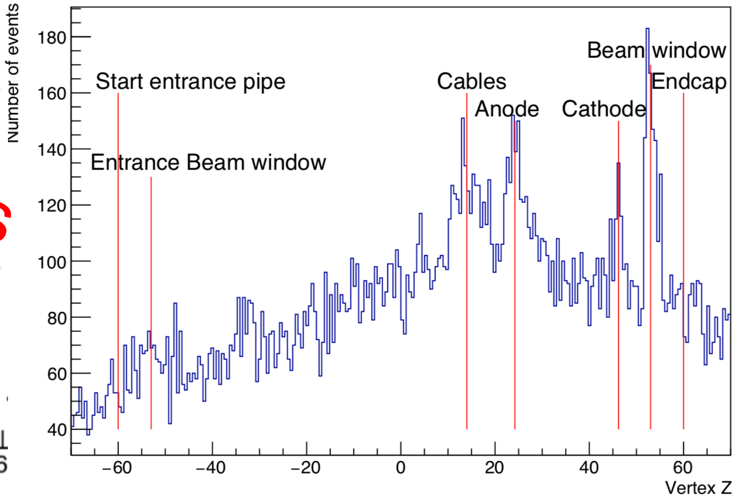
Test setup during 2018 DY run downstream COMPASS, check

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

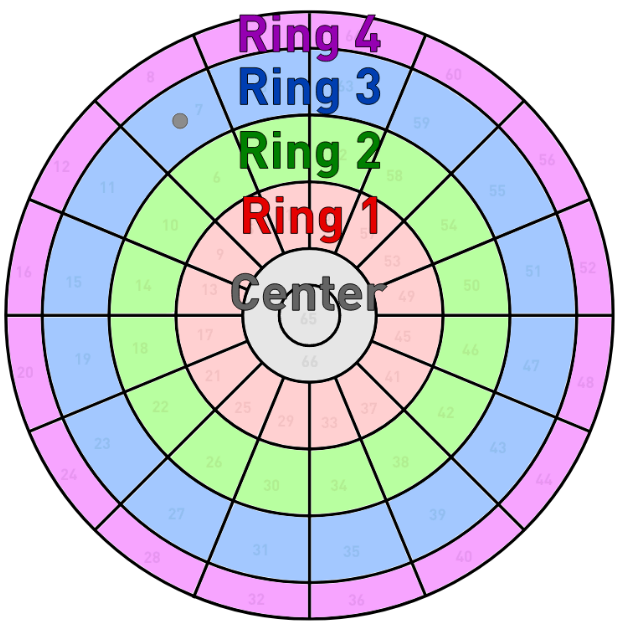


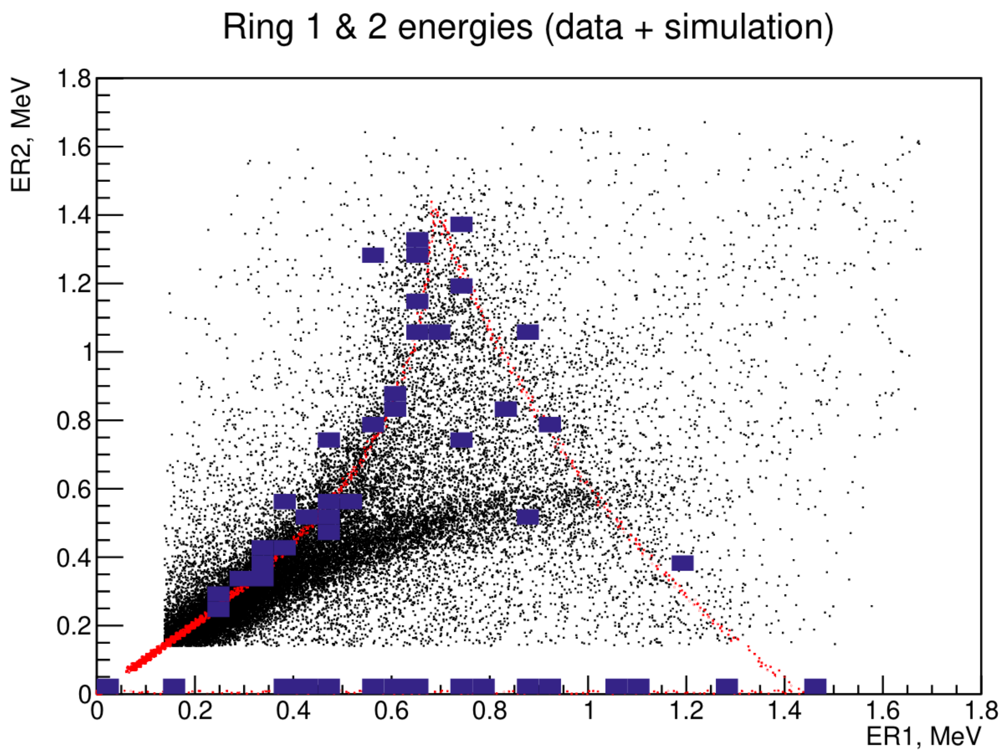




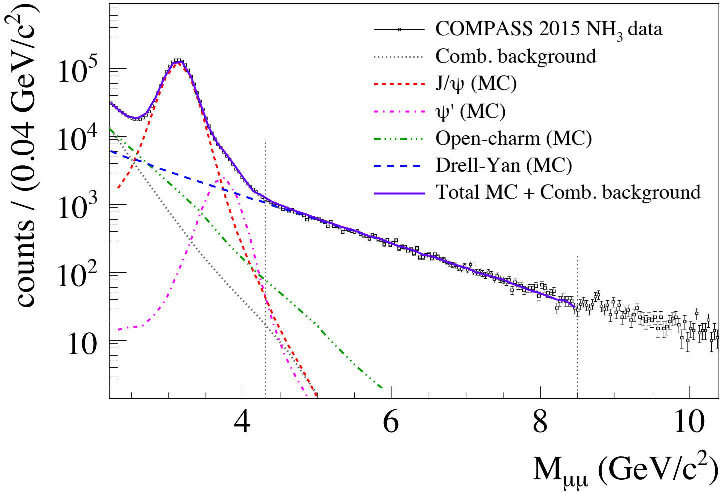


Ring energies — matched events





Mass spectrum

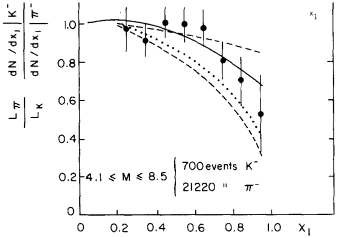


Background less than 4% in $4.3 < M_{\mu\mu}/(GeV) < 8.5$

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

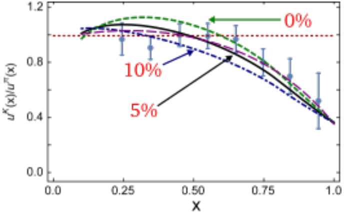


Interesting observation: At hadronic scale gluons carry only 5% of K's momentum *vs* ~30% in π

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

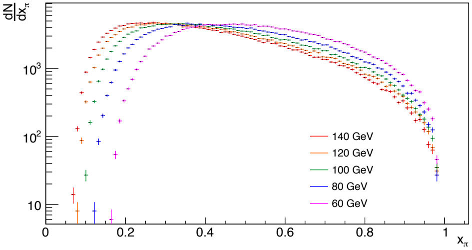
How to improve the situation?

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



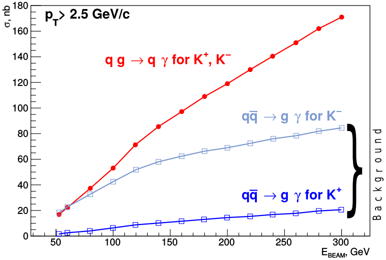
Kaon RF separated

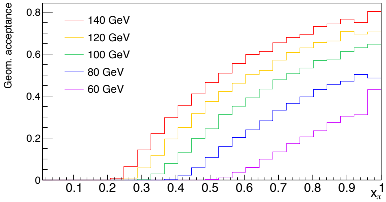
DY cross-section



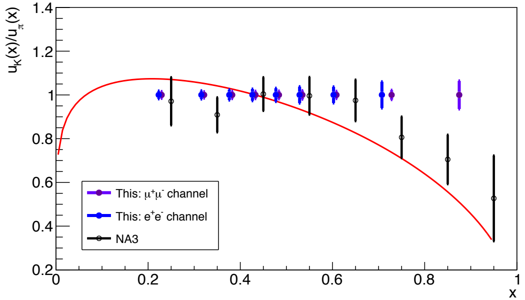
- Highest beam energy to access low x
- Highest beam energy to increase signal/bgd ratio
- Favorable also COMPASS-like apparatus

Prompt photon cross-section





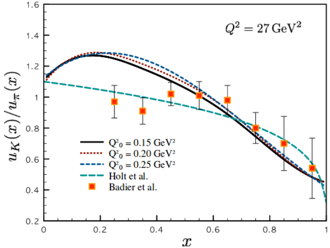
Projections for Kaon structure



- More data points and more precise compared to NA3
- Discriminating power between models
- 1 year with $2 \times 10^7\ s^{-1}$ 100 GeV K^- beam
- π taken simultanously

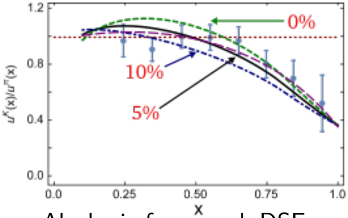
Unique and Promising

S-i. Nam PRD 86, 074005, 2012



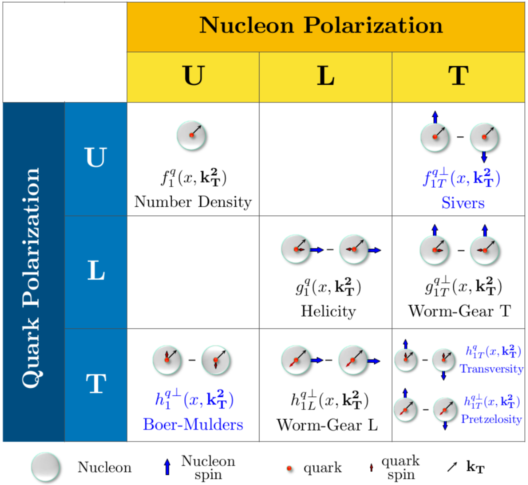
Gauge-invariant nonlocal chiral-quark model

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



Algebraic framework DSE

So far, I talked only about mesons but what about the nucleon?



At LO QCD, the nucleon can be decomposed into 8 twist-2 TMD PDFs.

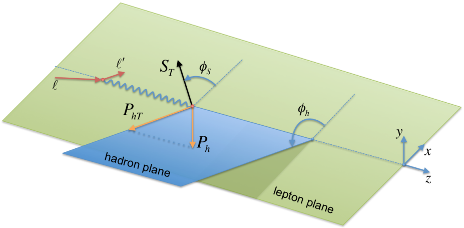
Using a transversally polarised target, one can access in SIDIS as well as in Drell-Yan:

- Sivers
- Transversity
- Pretzelosity

Drell-Yan and SIDIS cross-section modulations

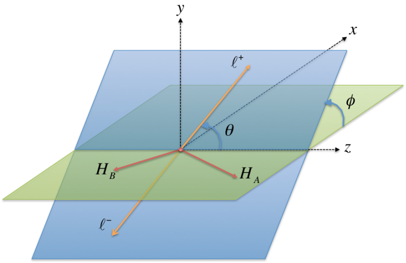
SIDIS:

$$\frac{d\sigma}{dxdydzd\phi_S d\phi_h dP^2_{hT}} \overset{\text{LO}}{=} \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1\frac{\gamma^2}{2x}\right)\hat{\sigma_U}\Big\{1+\epsilon A_{UU}^{\cos(2\phi_h)}\cos(2\phi_h)$$
$$+S_T\Big[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)+\epsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h-\phi_S)$$
$$+\epsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\Big]$$
$$+S_T P_l\left[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)A_{LT}^{\cos\phi_h-\phi_S}\right]\Big\}$$



DY:

$$\frac{d\sigma}{d^4qd\Omega} \overset{\text{LO}}{=} \frac{\alpha^2}{Fq^2}\hat{\sigma_U}\Big\{\left(1+\cos^2(\theta)+\sin^2(\theta)A_{UU}^{\cos(2\phi)}\cos(2\phi)\right)$$
$$+S_T\Big[(1+\cos^2(\theta))A_{UT}^{\sin(\phi_S)}\sin(\phi_S)$$
$$+\sin^2(\theta)\left(A_{UT}^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)+A_{UT}^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\right)\Big]\Big\}$$



Synergy DY *vs* SIDIS

DY:						SIDIS:		
$A_{UU}^{\cos(2\phi)}$	$\propto h_{1,h}^{\perp q}$	$\otimes$	$h_{1,p}^{\perp q}$	Boer-Mulders	$A_{UU}^{\cos(2\phi_h)}$	$\propto h_{1,p}^{\perp q}$	$\otimes$	$H_{1q}^{\perp h}$
$A_{UT}^{\sin(\phi_S)}$	$\propto f_{1,h}^{q}$	$\otimes$	$f_{1T,p}^{\perp q}$	Sivers	$A_{UT}^{\sin(\phi_h-\phi_S)}$	$\propto f_{1T,p}^{\perp q}$	$\otimes$	D_{1q}^{h}
$A_{UT}^{\sin(2\phi-\phi_S)}$	$\propto h_{1,h}^{\perp q}$	$\otimes$	$h_{1,p}^{q}$	Transversity	$A_{UT}^{\sin(\phi_h+\phi_S)}$	$\propto h_{1,p}^{q}$	$\otimes$	$H_{1q}^{\perp h}$
$A_{UT}^{\sin(2\phi+\phi_S)}$	$\propto h_{1,h}^{\perp q}$	$\otimes$	$h_{1T,p}^{\perp q}$	Pretzelosity	$A_{UT}^{\sin(3\phi_h-\phi_S)}$	$\propto h_{1T,p}^{\perp q}$	$\otimes$	$H_{1q}^{\perp h}$

TMD PDFs are **universal** but
final state interaction (SIDIS) *vs.* initial state interaction (DY) $\rightarrow$ **Sign flip** for naive T-odd TMD PDFs

$$f_{1T}^{\perp q}\,|_{\text{SIDIS}} = -f_{1T}^{\perp q}\,|_{\text{DY}}$$
$$h_{1}^{\perp q}\,|_{\text{SIDIS}} = -h_{1}^{\perp q}\,|_{\text{DY}}$$

Crucial test of TMD framework in QCD

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

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

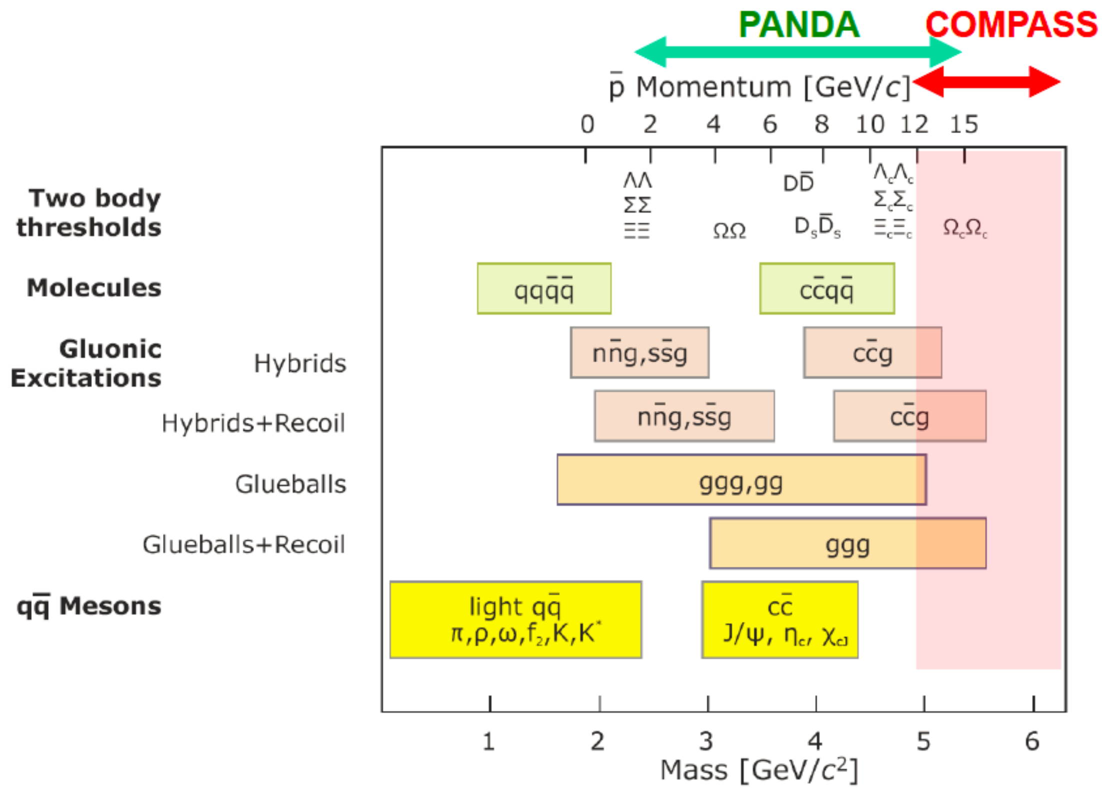
Method: antiproton-proton annihilation

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

Complementary to LHCb

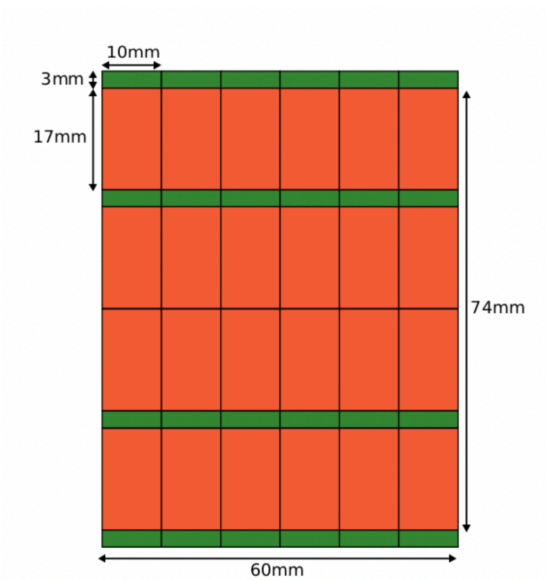
(p-pbar annihilation – gluon rich environment and it allows high spin states)

Otherwise no competitors for the next at least 10 years

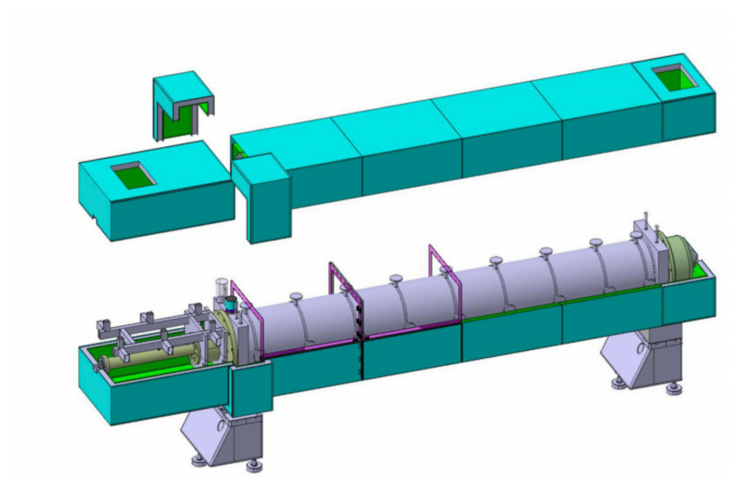


more new planned hardware

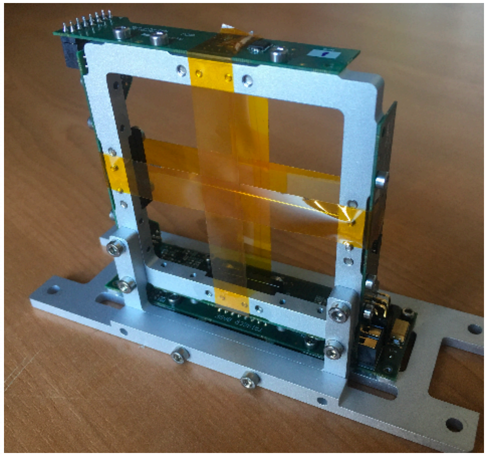
- silicon pixel detectors
- upgrades: large-area pixelGEM and MPGD
- CEDARs at high rates
- Beam Momentum Station for proton radius measurement
- elastic muon-scattering with SciFi detectors



MuPix8 detector array



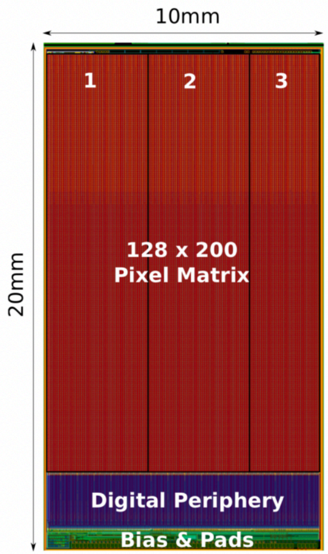
thermally shielded CEDARs

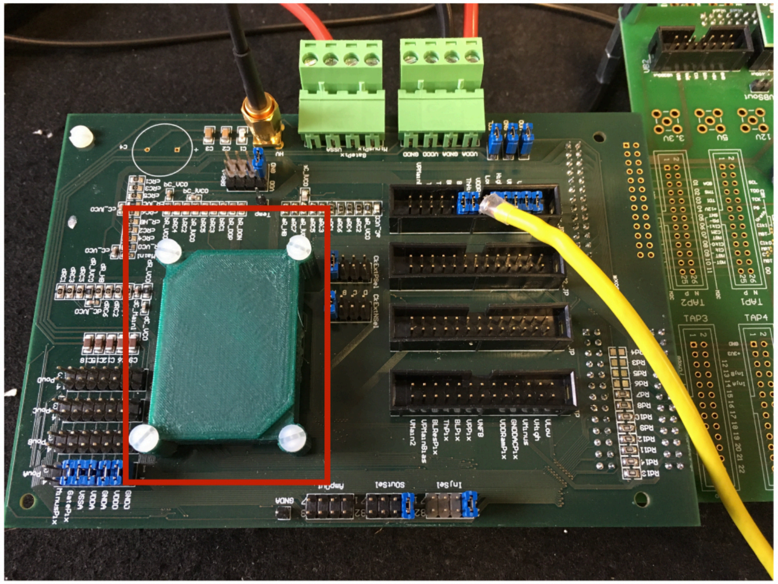


SciFi prototype

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

QCD facility – future fixed target experiment at M2
Spectrometer upgrades

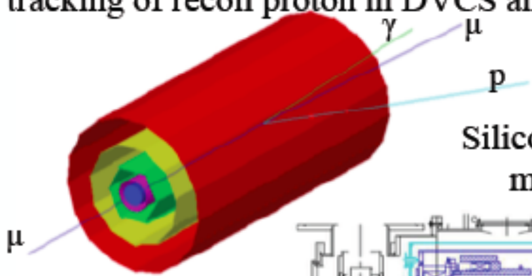
- **New type of FEE and trigger logic compatible with trigger-less readout**
  - FPGA-based TDC with time resolution down to 100 ps (iFTDC)
- Higher trigger rates: **90-200 kHz** (factor of 2.5-5)
- Digital trigger
- First tests in 2018

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?

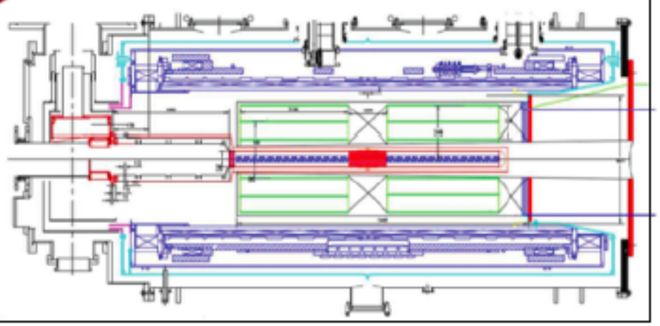
Could be Large-Area Picosecond Photo-Detectors based on micro-channel plates with time resolution < 50 ps, spatial resolution ~ 0.5 mm. LAPPD™ by IncomInc.

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

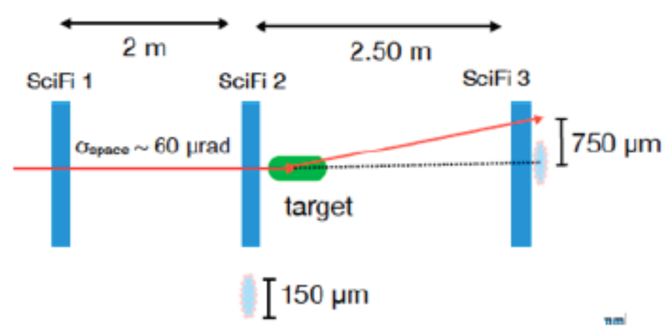
GPD E: 3-layer silicon detector at very low temperature for tracking of recoil proton in DVCS and PID via dE/dx.



Silicon detector inside existing modified target magnet.



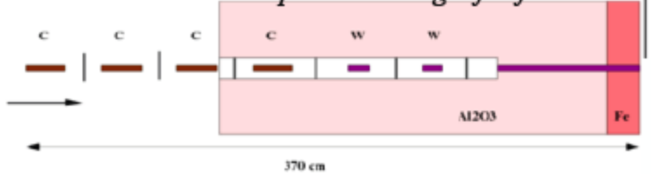
Proton radius:
- **High-pressure active TPC target or hydrogen tube** surrounded by SciFi, 4-8 layers with U/V projections
- **SciFi trigger system** on scattered muon
- Silicon trackers



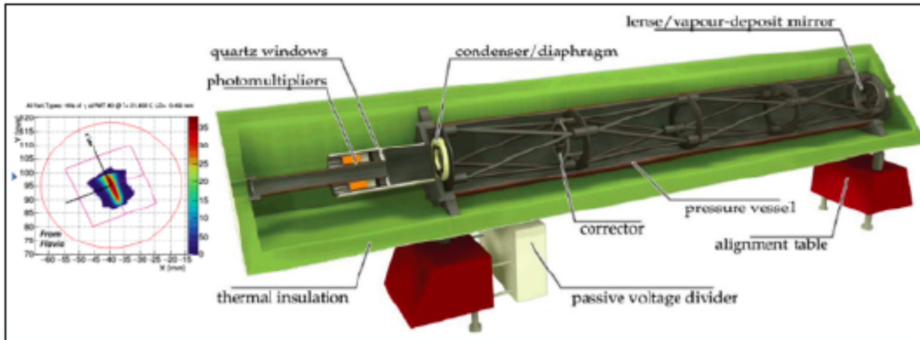
QCD facility – future fixed target experiment at M2
Spectrometer upgrades

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

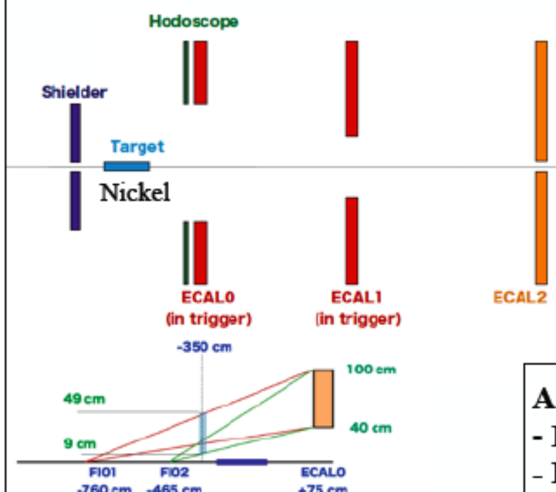
unpolarized target for future DY



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?

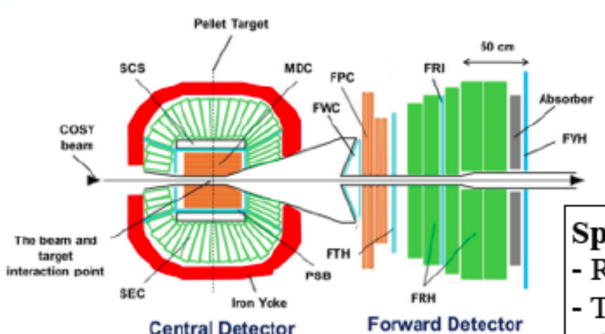


CEDAR upgrade 2018



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

Improvement of acceptance

Requirements: Active absorber

- Trackers
- Magnetic field
- Good resolution for vertexing
- Large area
- Capabilitity to collect e^+e^- DY pairs

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