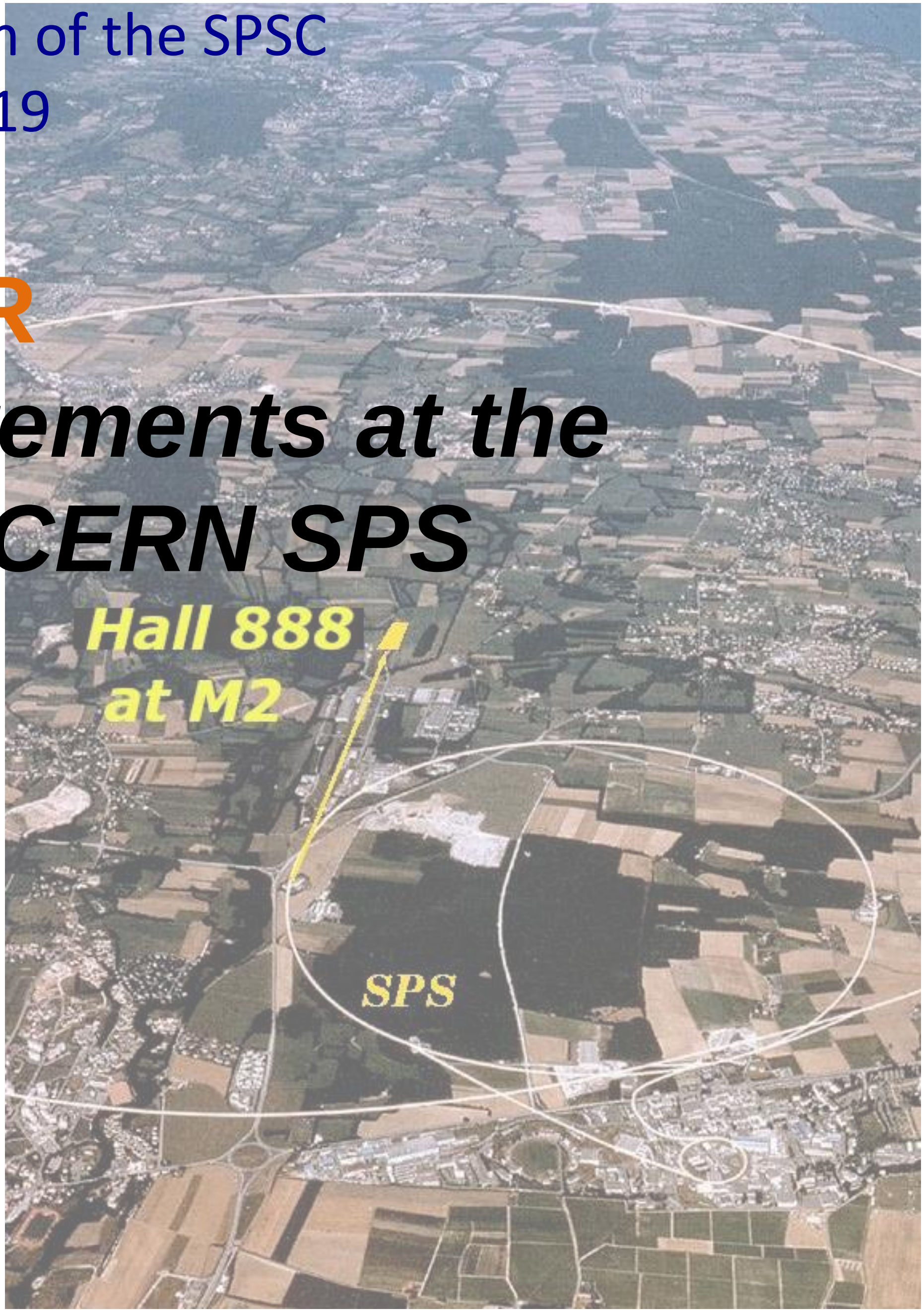
CERN Open Session of the SPSC
13.6.2019

COMPASS++/AMBER

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

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

Jan Friedrich
TU Munich
on behalf of the proto-Collaboration representatives



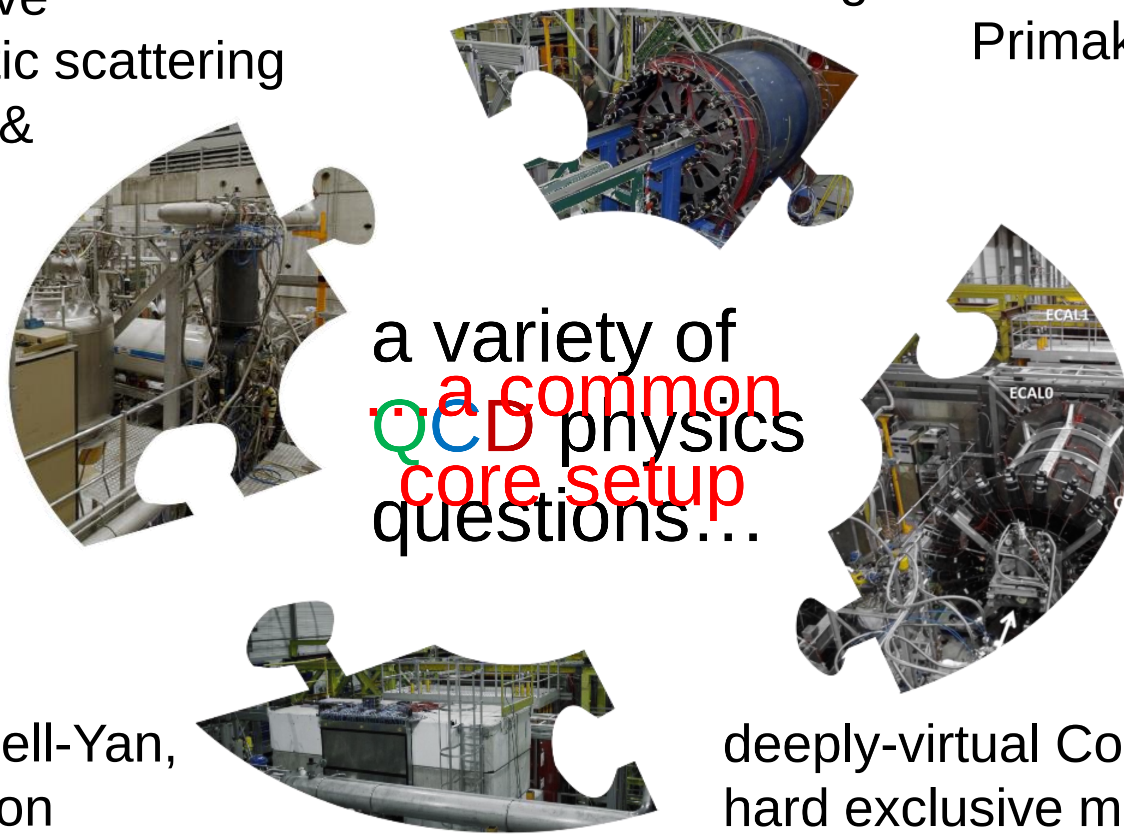
Outline

1. The steps so far towards a new Collaboration
2. A New QCD facility at CERN SPS: COMPASS++/AMBER
3. Beam time requests and time lines of phase-1
4. Hardware developments
5. Summary

The COMPASS programme

semi-inclusive
deep inelastic scattering
longitudinal &
transverse
polarised,
unpolarised

light-hadron spectroscopy
Primakoff reactions



a variety of QCD physics questions…

… a common core setup

polarised Drell-Yan,
J/ψ production

deeply-virtual Compton scattering
hard exclusive meson production

completion in 2021 with transverse deuteron run

A NQF@M2 beam line of the SPS CERN
COMPASS++/AMBER Letter of Intent

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019–003
SPSC-I-250
January 25, 2019

http://arxiv.org/abs/1808.00848

Apparatus for Meson and Baryon Experimental Research

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],

COMPASS++/AMBER
the full "LoI" programme

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
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Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: 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	$\sim$100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 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
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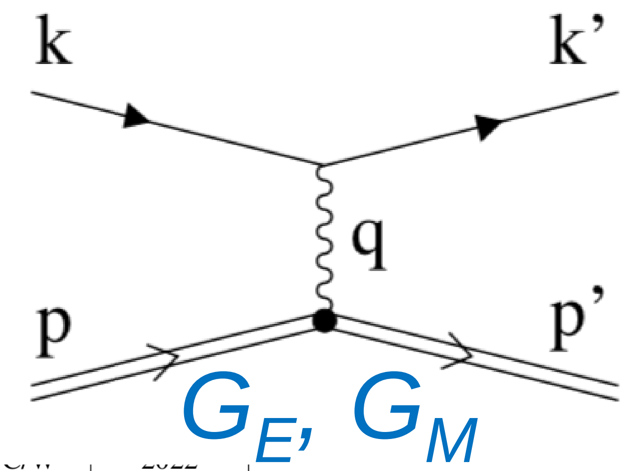

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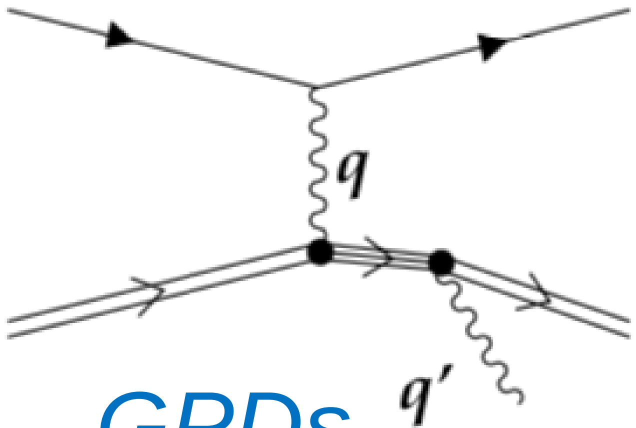

GPDs

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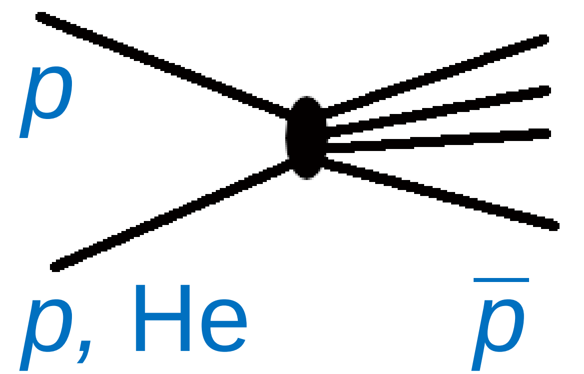

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$\overline{p}$-induced spectroscopy	Heavy quark exotics	[illegible], 20	$5 \cdot 10^7$	25	$\overline{p}$	[illegible]	[illegible]	[illegible]
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	[illegible]	[illegible]	[illegible]
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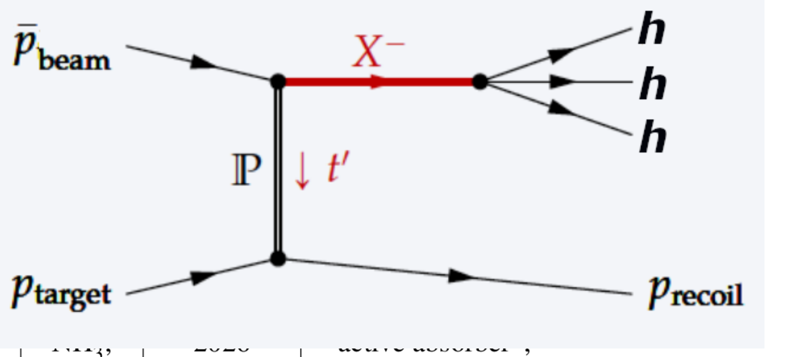

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spectroscopy	exotics	12, 20	$5 \cdot 10^7$	25				
Drell-Yan	Pion PDFs	[illegible]	$7 \cdot 10^7$	25				
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	K			
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 10			1 year	
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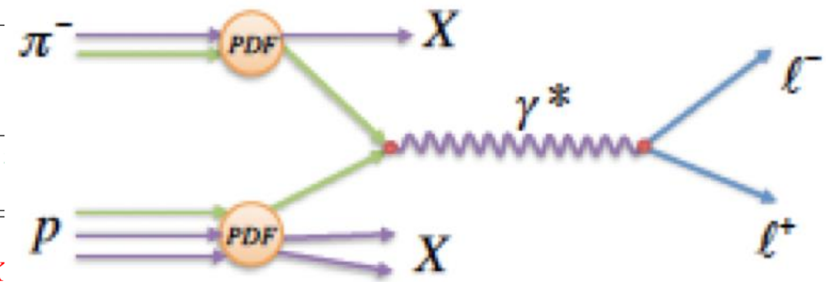

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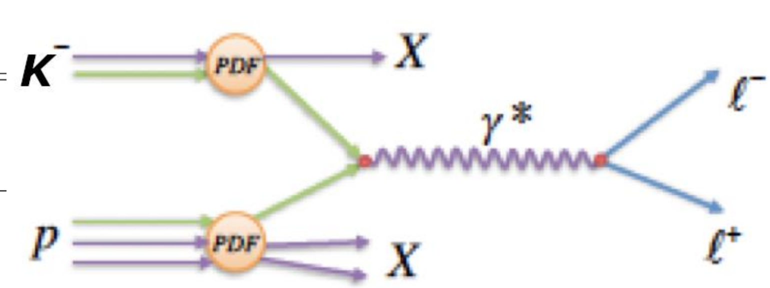

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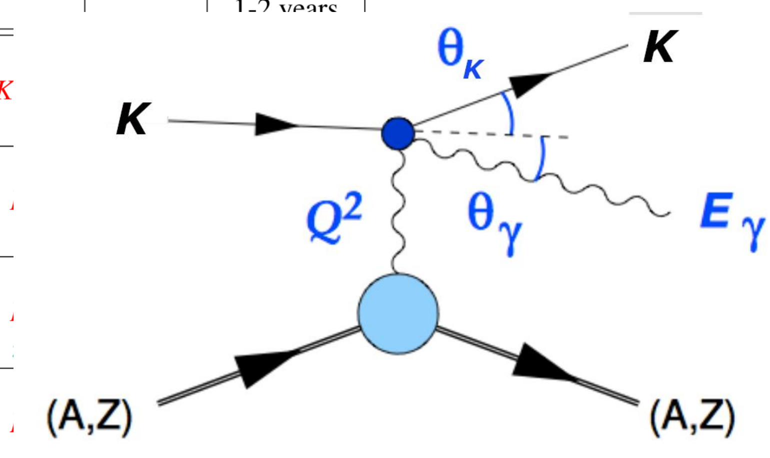

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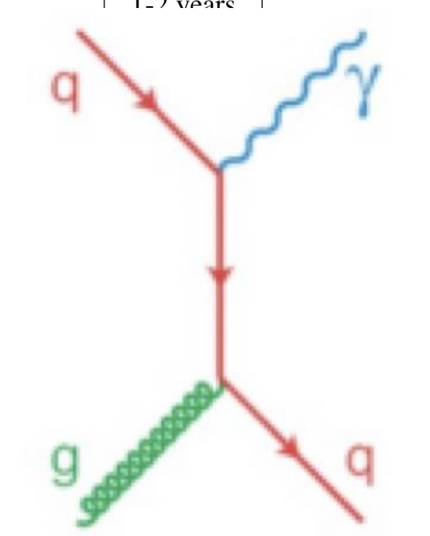

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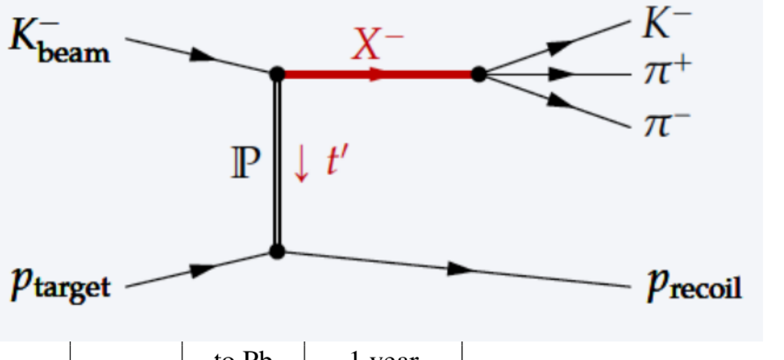

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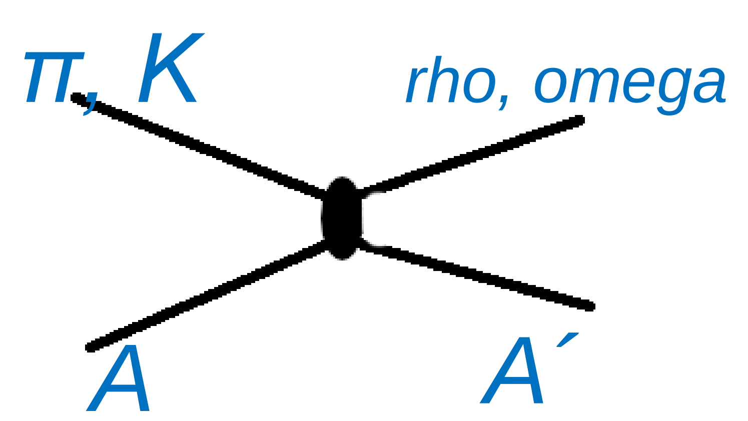

Two-stage program:

First stage (shorter term) – existing extracted beams
Second stage (longer term) – RF-separated extracted kaon and antiproton beams

focus on Run3 (2021-2024)

Proposal phase-1

measurements that can be realized before LS3

* Proton radius
* Antiproton production cross sections
* Pion-induced Drell-Yan and charmonium production mechanisms

A NQF@M2 beam line of the SPS CERN
COMPASS++/AMBER – Proposal Phase-1

CERN-SPSC-2019-022 / SPSC-P-360
31/05/2019

Proposal for Measurements at the M2 beam line of the CERN SPS
Phase-1: 2022-2024

COMPASS++[*]/AMBER[†]

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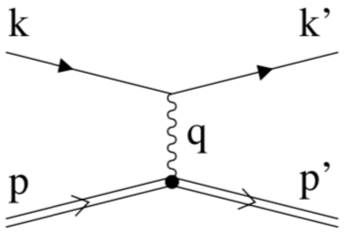
COMPASS++/AMBER – Proposal phase-I tentative running scheme

Year	Activity	Duration	Beam
2021	Proton radius test measurement	20 days	μ
2022	Proton radius measurement Antiproton production test measurement	120 (+40) days 10 days	μ p
2023	Antiproton production measurement Proton radius measurement	20(+10) days 140 (+10) days	p μ
2024 2024+	Drell-Yan: pion PDFs and charmonium production mechanism	$\lesssim$ 2 years	$p, K^+, \pi^+,$ $\bar{p}, K^-, \pi^-$

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 with precision better than 0.01 fm
- competitive to JLab, MAMI, MUSE



G_E, G_M

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

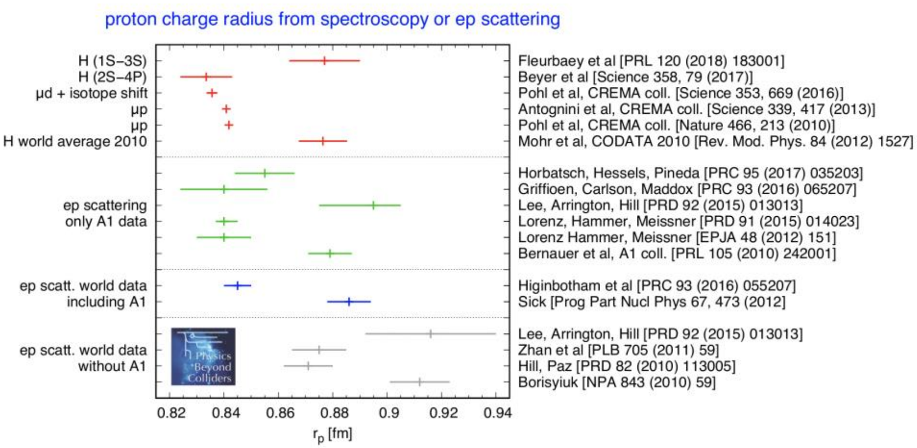
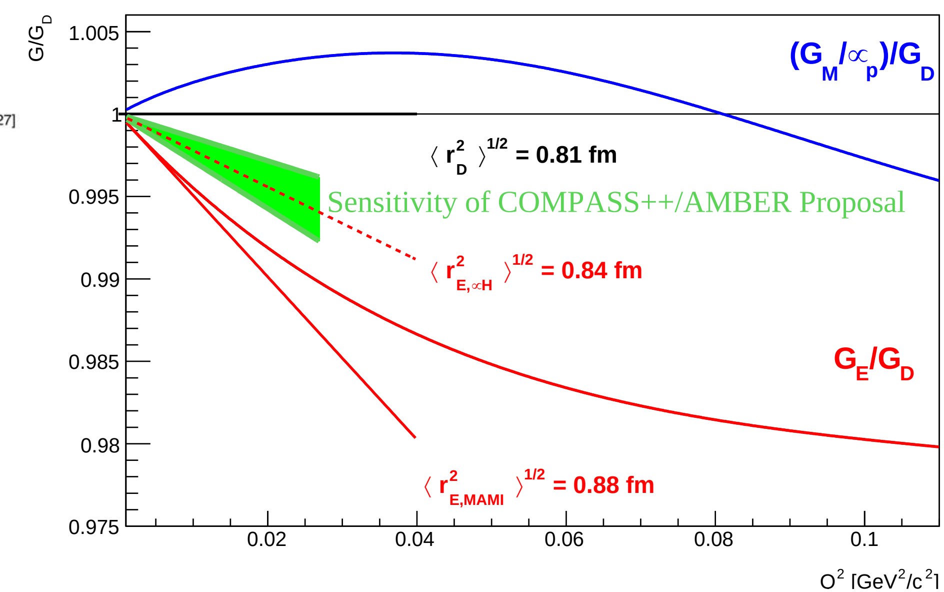
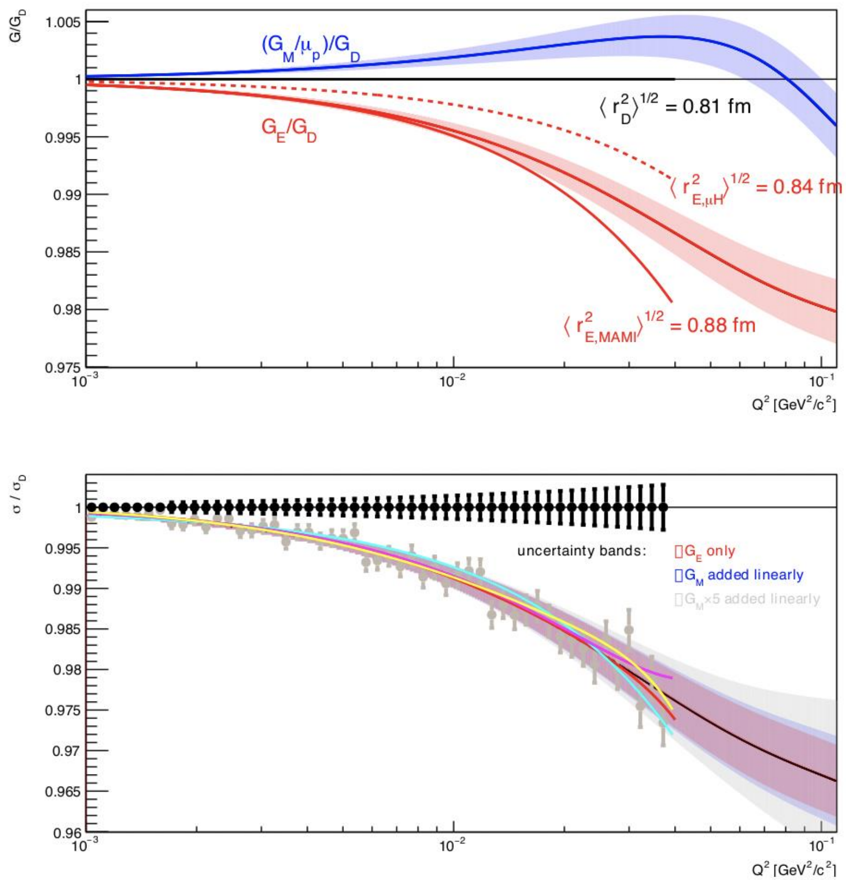


Figure 2: Compilation of the proton radius puzzle, figure taken from [7].



Proton radius measurement from muon-proton high-energy scattering

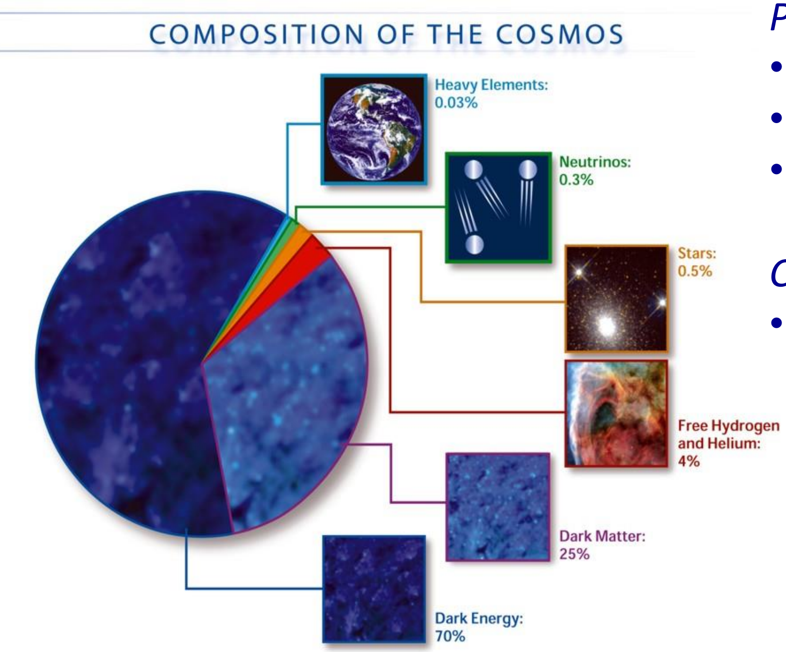


COMPASS++/AMBER proposal:

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

Proton beam: Search for Dark Matter

Absolute cross section measurement p+He $\rightarrow \overline{p}$+X



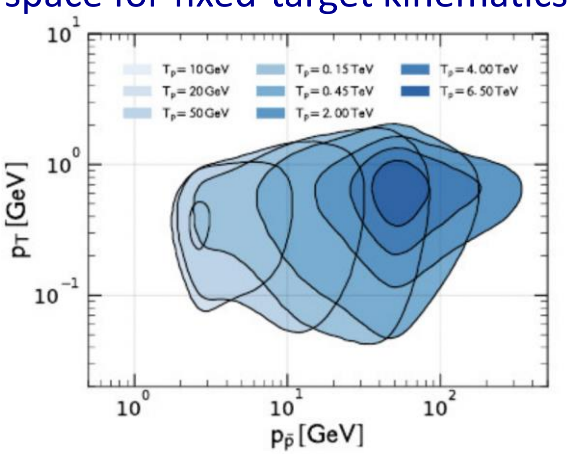
Physics case:

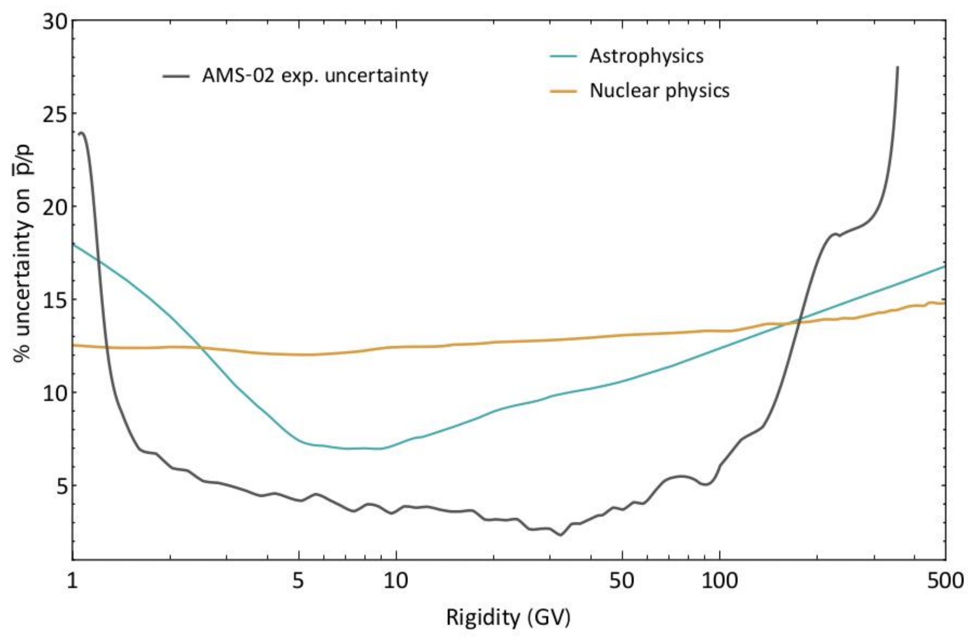
- precise data on cosmic antiparticle flux from AMS2 data
- possible sources: standard model and dark matter processes
- limiting factor for MC simulations: production cross sections, currently only known to 30-50%

COMPASS++/AMBER proposal:

- measure inclusive antiproton production cross sections in *pp* and *p*He collisions over a wide beam range of 50…250 GeV

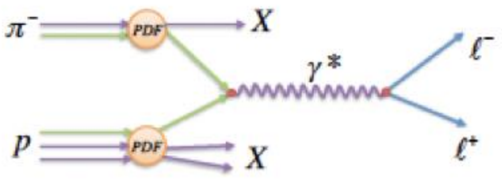
parameter space for fixed-target kinematics





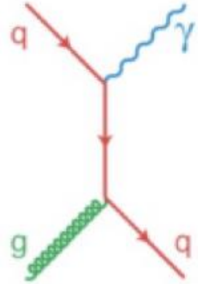
Learning about the partonic structure of pions

Drell-Yan:



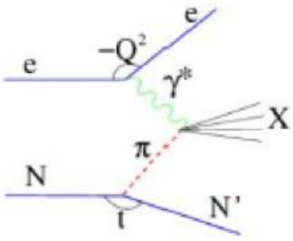
- 90's: NA3, NA10, E615
- 10's: COMPASS-II
- 20's: New Experiment

Prompt photon production:



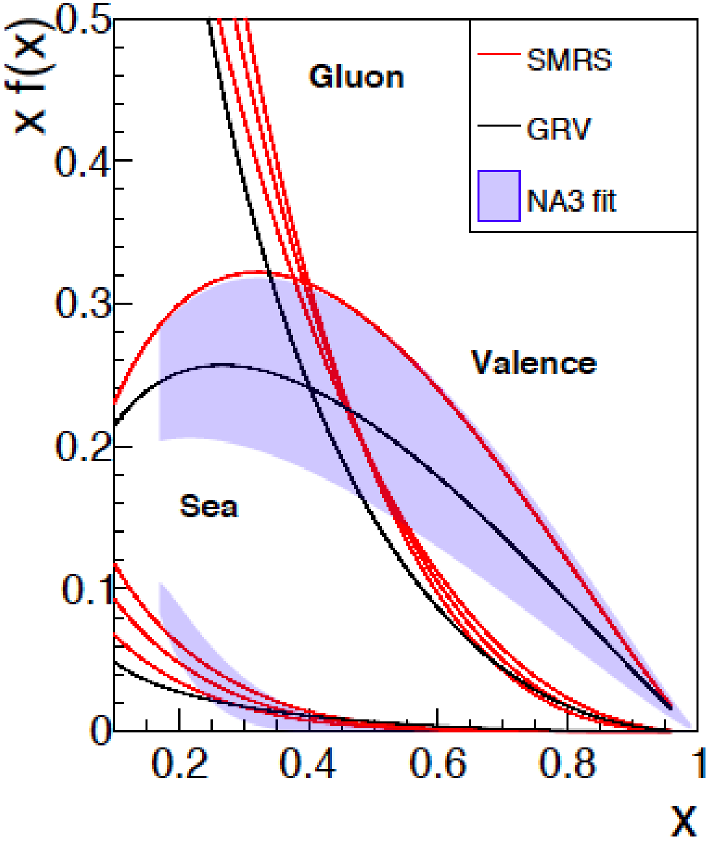
- 90's NA24, W70
- 20's New experiment

DIS with leading N:



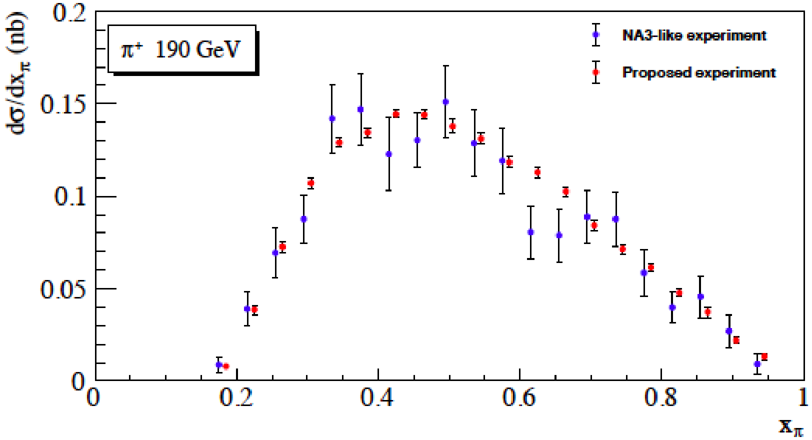
- 90's: H1, ZEUS
- 10's: JLAB TDIS
- 30's: EIC

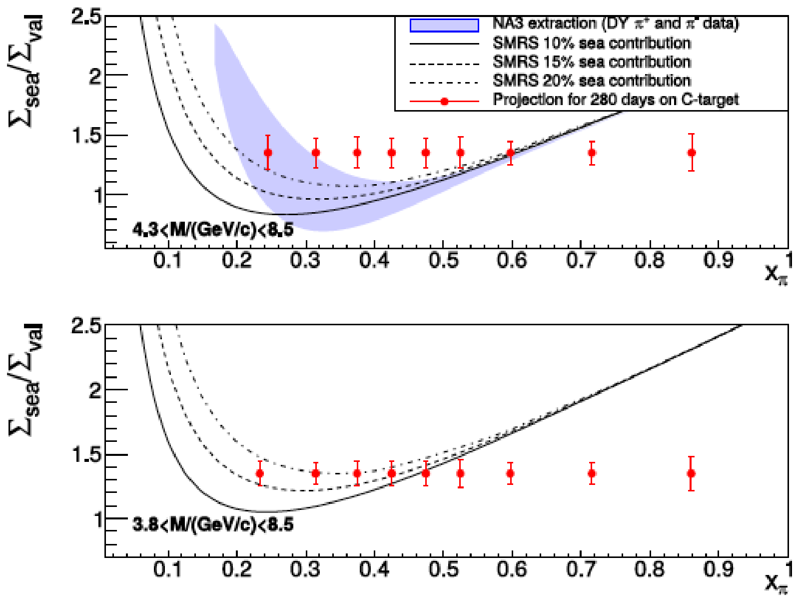
Existing hadron beam
Drell-Yan (I): pion structure



- valence, sea and gluon distributions in the pion in different models
- experimental result (NA3) with large uncertainties

Existing hadron beam
Drell-Yan (II): competitiveness

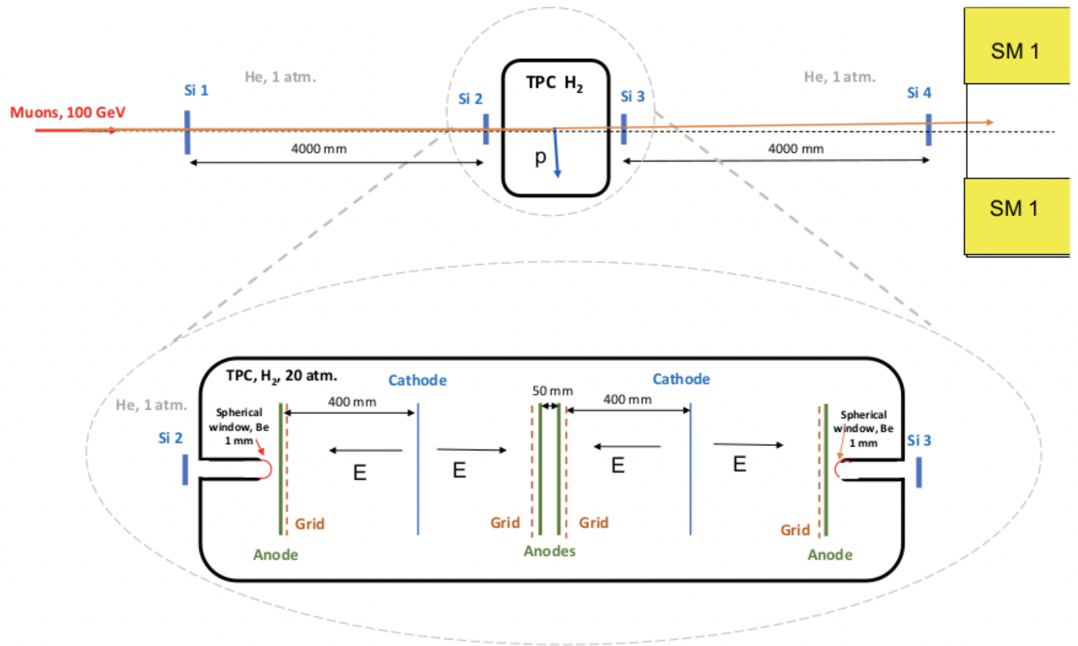




Expected accuracy as compared to NA3

- $\Sigma_V = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence
- $\Sigma_S = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$: no valence-valence
- Collect at least a **factor 10 more statistics** than presently available
- Minimize nuclear effects on target side
  - Projection for 2×140 days of Drell-Yan data taking
  - π^+ to π^- 10:1 time sharing
  - 190 GeV beams on Carbon target $(1.9\lambda^{\pi}_{int})$
  - Improvement of shielding to double the intensity is under investigation

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



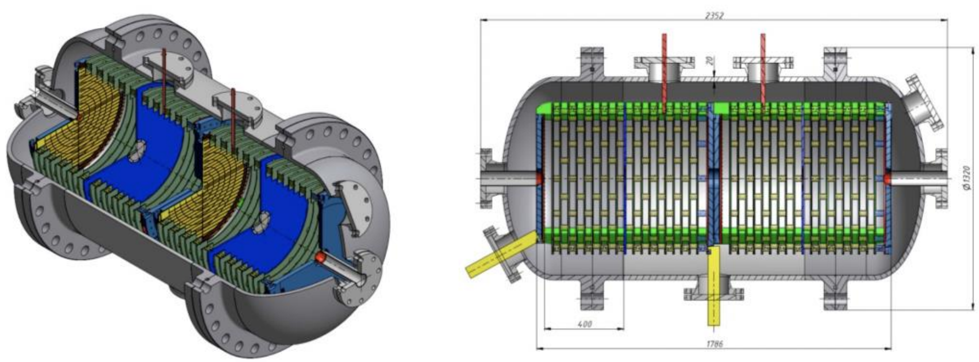
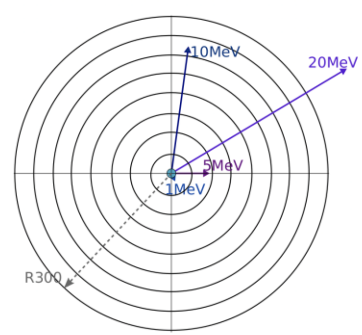
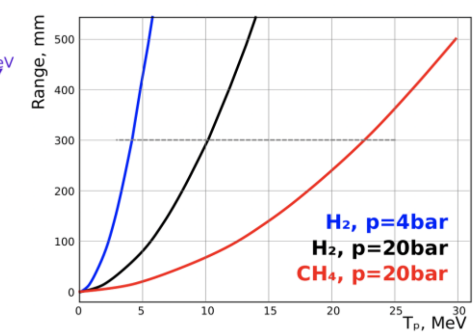
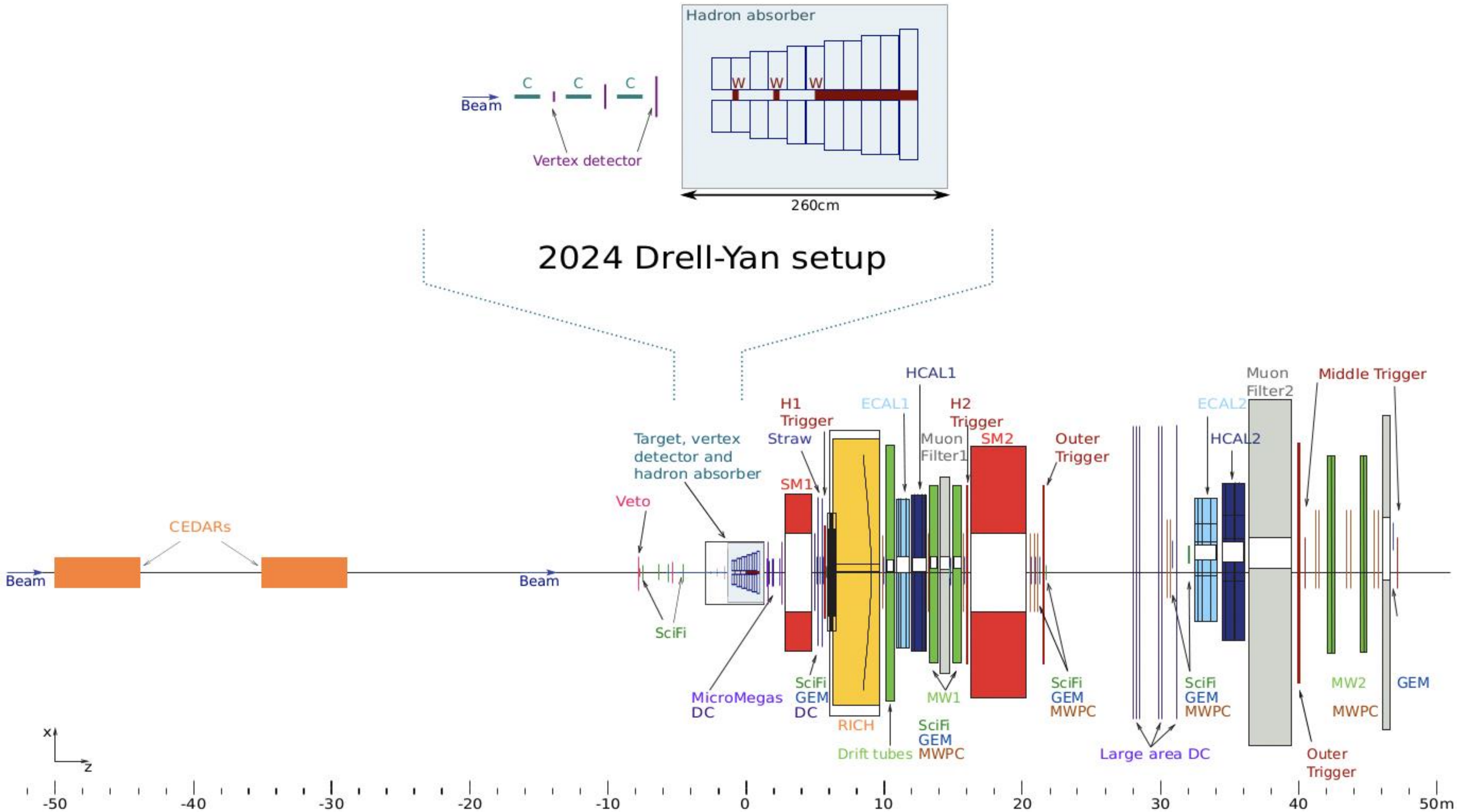


Figure 45: Engineering design for the four-cell hydrogen TPC.





New hardware: Vertex detector for the Drell-Yan experiment



New hardware: Trigger scheme

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

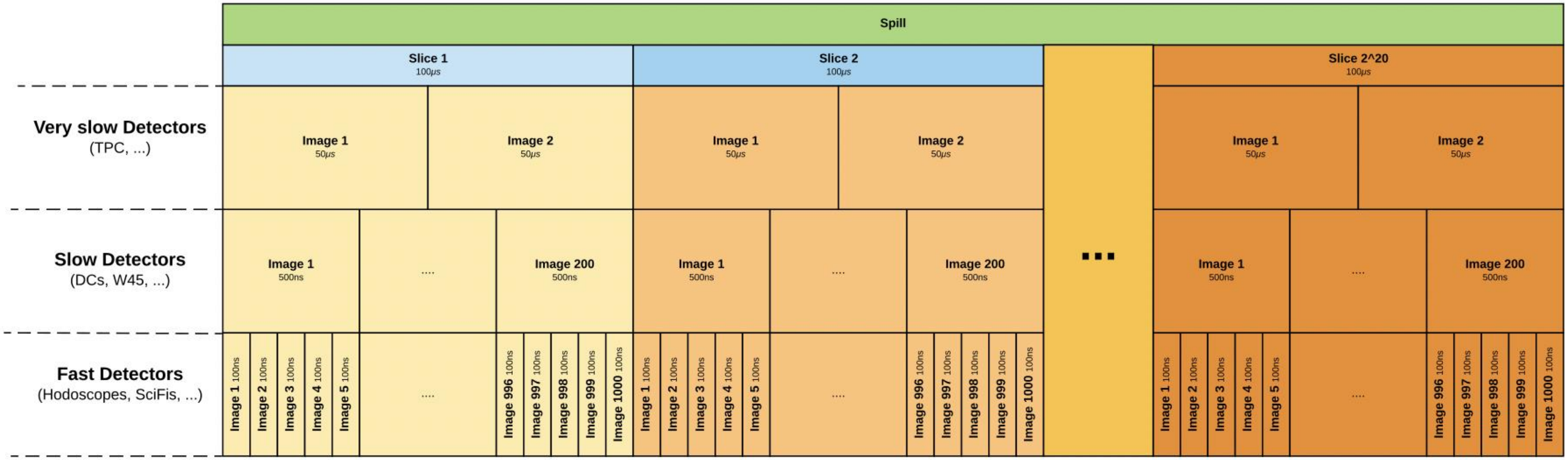
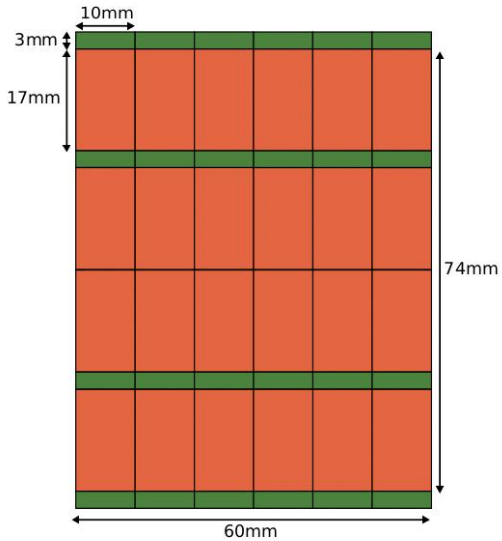


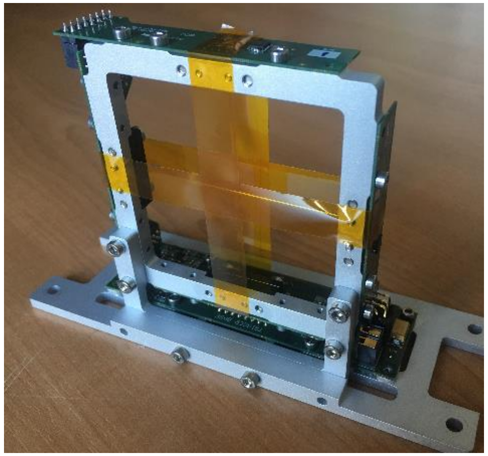
Figure 39: Overview for the time-slicing

more new planned hardware

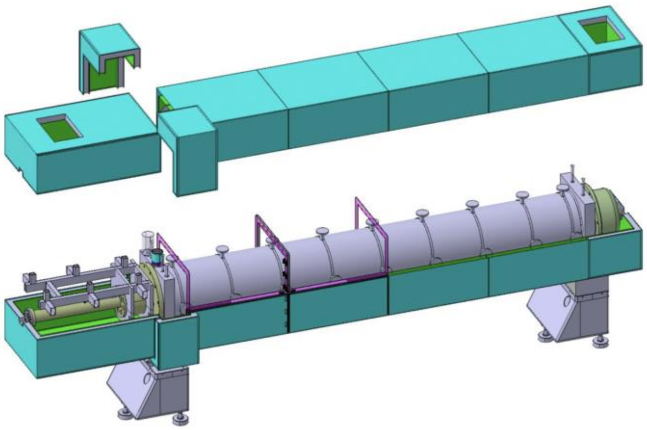
- silicon pixel detectors
- elastic muon-scattering kinematics with SciFi detectors
- upgrades: large-area pixelGEM and MPGD
- CEDARs at high rates
- Beam Momentum Station for proton radius measurement



MuPix8 detector array



SciFi prototype



thermally shielded CEDARs

Forming a new Collaboration

240 authors from
50 institutes,
interest from more
institutes expressed

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Summary

- COMPASS++/AMBER proposes to perform 3 measurements at the SPS M2 beam line 2022-24
  - Proton radius in high-energy muon-proton scattering
  - Antiproton production in *pp* and *p*He collisions
  - Pion-induced Drell-Yan
- formation of the new Collaboration is on track
- various hardware developments and upgrades are ongoing

phase-2 with RF-separated beam beyond LS3

Thank you!

Spares

COMPASS++/AMBER – Proposal phase-I Outlook

The **Outlook** of the proposal recapitulates the future plans of COMPASS++/AMBER, which reach far beyond phase-1, in accordance with what was already sketched in our Letter of Intent [1]. We propose to upgrade the M2 beam line after LS3, in order to also deliver radio-frequency (RF) separated hadron beams of high energy and high intensity. Such an upgrade is presently under study by CERN EN-EA in the framework of the Physics-beyond-Colliders Initiative. Once realised, it would make the CERN SPS M2 beam line absolutely unique in the world for many years to come.

As an overview, brief descriptions are provided of all presently available ideas for further experiments to be performed at the M2 beam line, either with RF-separated hadrons or with muons:

Drell-Yan physics and hadron spectroscopy with high-intensity kaon and antiproton beams

- Valence-quark distributions in the kaon
- Separation of valence and sea-quark contributions in the kaon
- J/ψ production mechanism and gluon distribution in the kaon
- Measurement of the electric polarisability of the kaon via the Primakoff reaction
- High-precision strange-meson spectroscopy
- Study of the gluon distribution in the kaon via prompt-photon production
- Studies of the spin structure of the nucleon with antiproton beam and a transversely polarised target
- Heavy-quark meson spectroscopy with low-energy antiprotons
- Direct measurement of the lifetime of the neutral pion
- Vector-meson production off nuclei by pion and kaon beams

Hard exclusive reactions with muon beam and transversely polarised target

- Measurement of the GPD E in Deeply Virtual Compton Scattering
- Measurements of Deeply Virtual Meson Production

COMPASS++/AMBER – Proposal phase-I
Input to SPSC EHN2 wg

1. amount of beam time:

2021: approved SIDIS Deuteron run of COMPASS (commissioning + 150 effective data taking days)
+ Proton Radius (PR) test (20 days in the beginning)
2022: (after NA64u beam test ~30): PR (120 + 40) + Antiproton Production (AP) test measurement (10)
2023: (after NA64u ~ 30): AP measurement (20) + PR (140+10)
2024 and beyond: ((after NA64u ~30): Drell-Yan ~ 2 full year of data taking

3. requirements on actual beam (energy, type, intensity)

SIDIS: 160 GeV muon beam, maximal intensity of ~ 3x10^7 per second
PR: 100 GeV muon beam, intensity 2x10^6 per second
AP: 50 - 250 GeV proton beam, intensity 5x10^6 per second
DY: 190 GeV h- and h+ beams, maximal hadron beam intensity of ~10^8 per second.

4. contingency plans: to be discussed separately.

5. infrastructural work required to be done beforehand (especially if it has to be done still during LS2):
NONE, apart of standard modifications of the M2 beam line for SIDIS, hadron and DY beam running

6. setup times:

SIDIS: longest set-up time (~4 months) taking into account COMPASS Polarised Target, setting up will be performed during LS2
PR: ~2-3 weeks
DY: ~2-3 weeks
AP: ~2-3 weeks

Backup – proposal p. 11

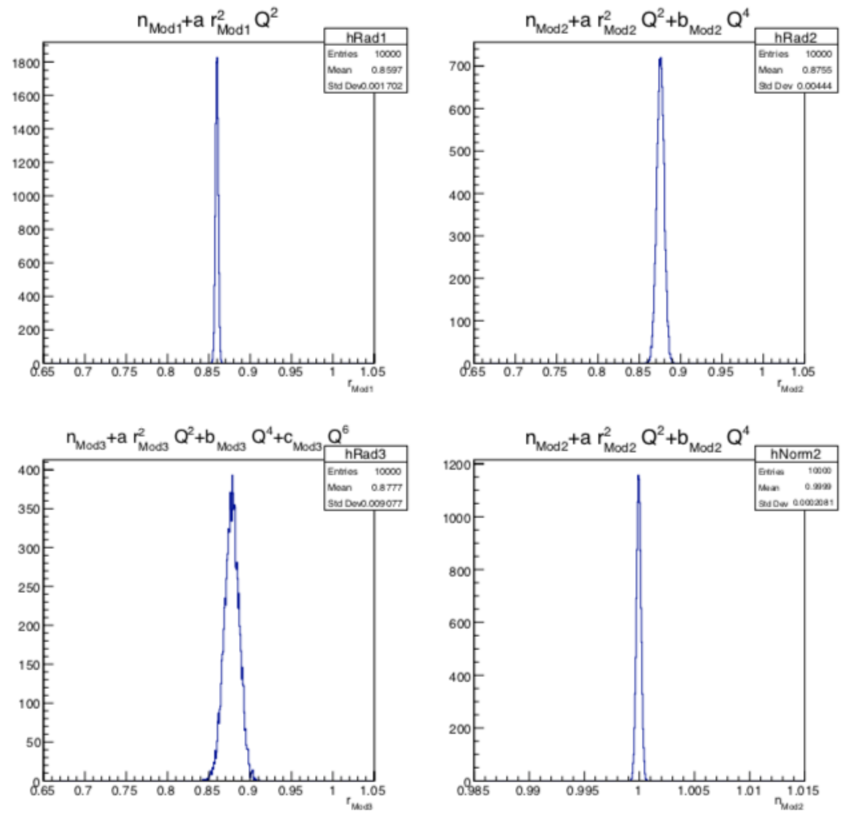


Figure 3: Statistical precision on the radius for different numbers of free parameters. Modn refers to fitting with a polynomial up to order Q^{2n}.

Backup – proposal p. 15

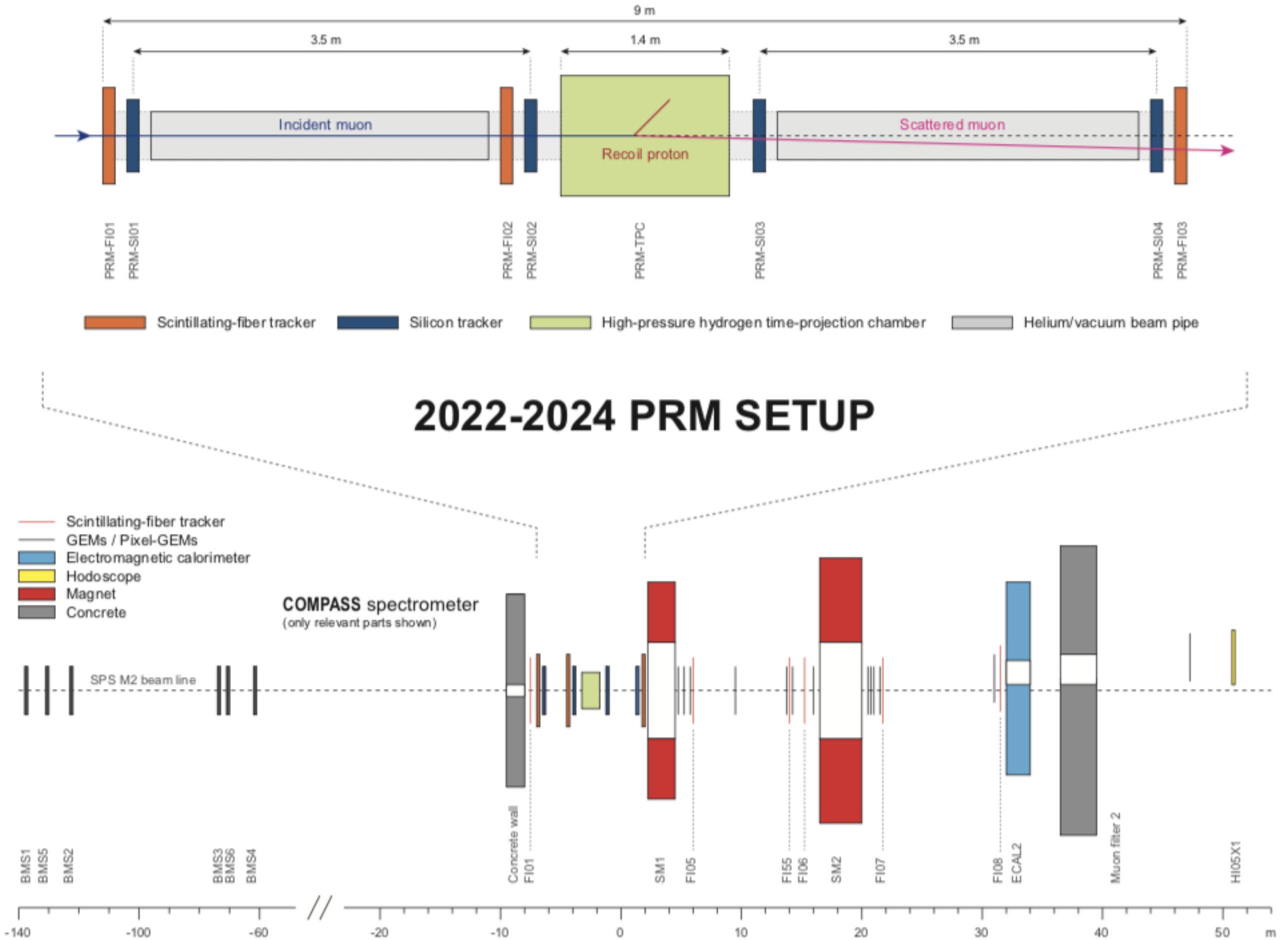


Figure 4: Layout of the experimental setup at the M2 beam line, highlighting the relevant parts of the COMPASS spectrometer and the additional detectors required for the proton radius measurement.

Backup – proposal p. 18-20

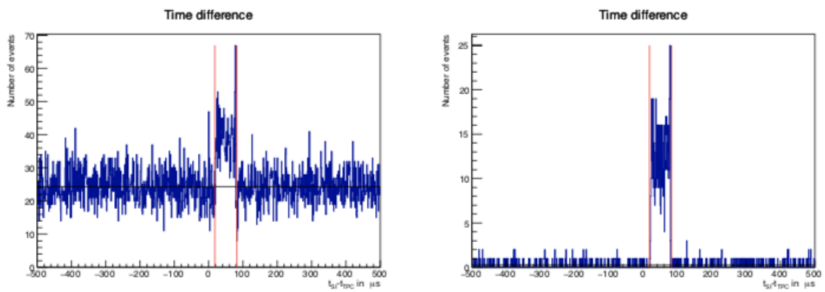


Figure 5: Difference between the time stamps of the silicon detectors and the TPC only with θ and radial cut (left) and with additional cuts on the z coordinate (along the beam) of the vertex within the active area of the TPC and the condition that central TPC anode pads were hit. There is a correlation in time between 18 and 82 μs, which corresponds well to the expected maximum drift time in the TPC of around 60 μs.

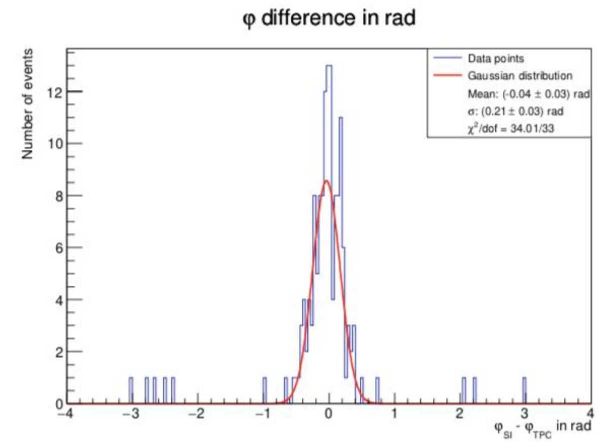


Figure 6: The difference in the polar angle φ between the tracks measured with the silicon detectors and the ones reconstructed with the TPC. The width of the peak originates mainly from the $\pi/8$ segmentation in single pads of the TPC anode.

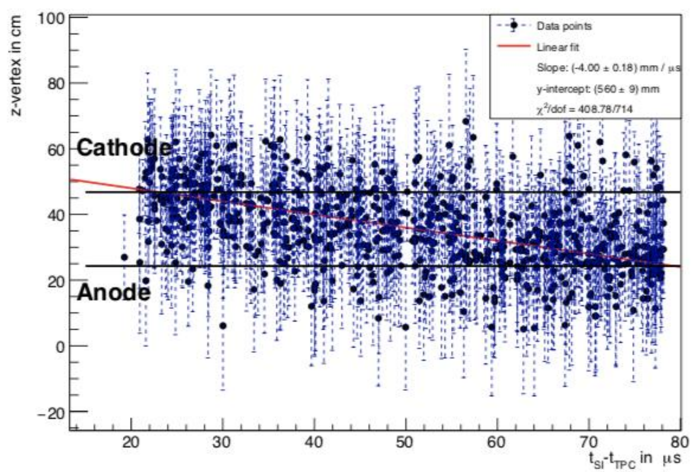


Figure 8: z coordinate of the vertex versus time difference of the TPC and silicon data. The linear fit determines the drift velocity which is slightly larger than the one expected from simulations (taking into account mainly properties of the hydrogen gas)

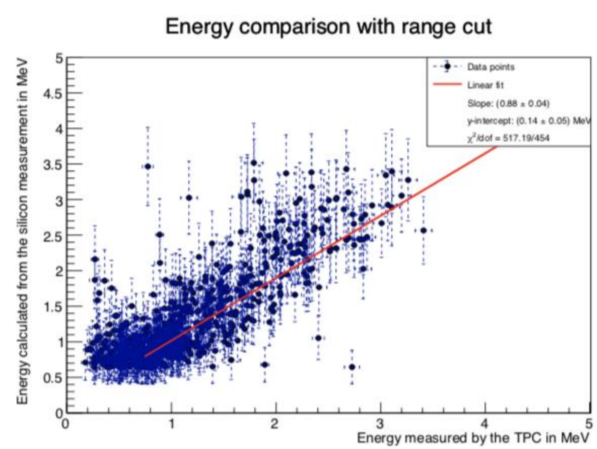


Figure 7: The energy of the recoil proton calculated from the scattering angle θ measured by the silicon trackers versus the energy deposit measured in the TPC.

Backup – proposal p. 25

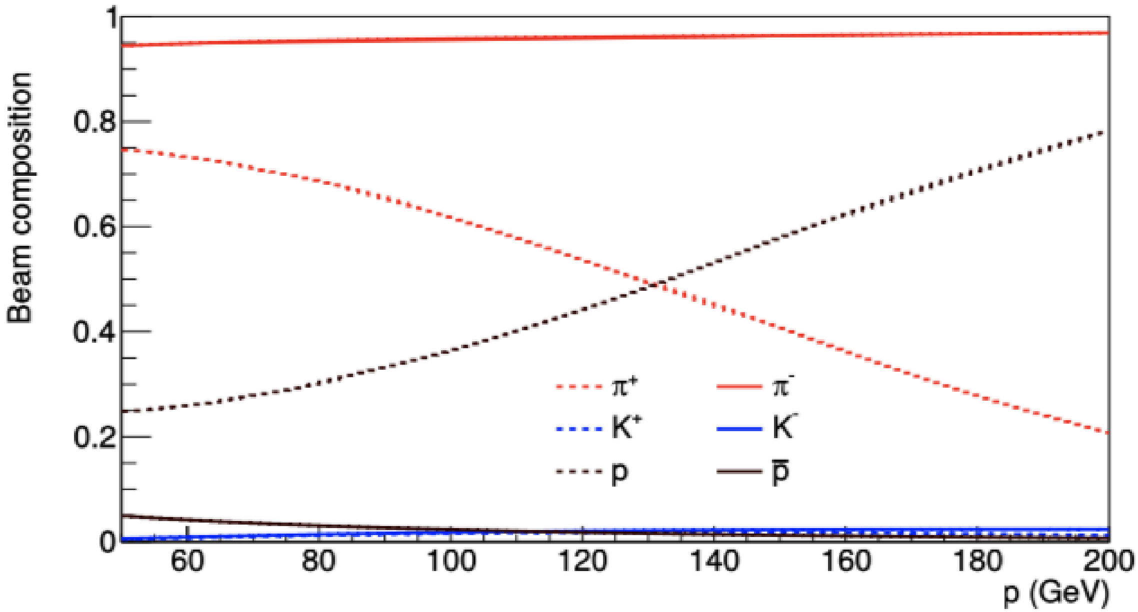


Figure 10: Dependence of the hadron-beam composition on the momentum at the EHN2 location of the M2 beam line.

Backup – proposal p. 26-27

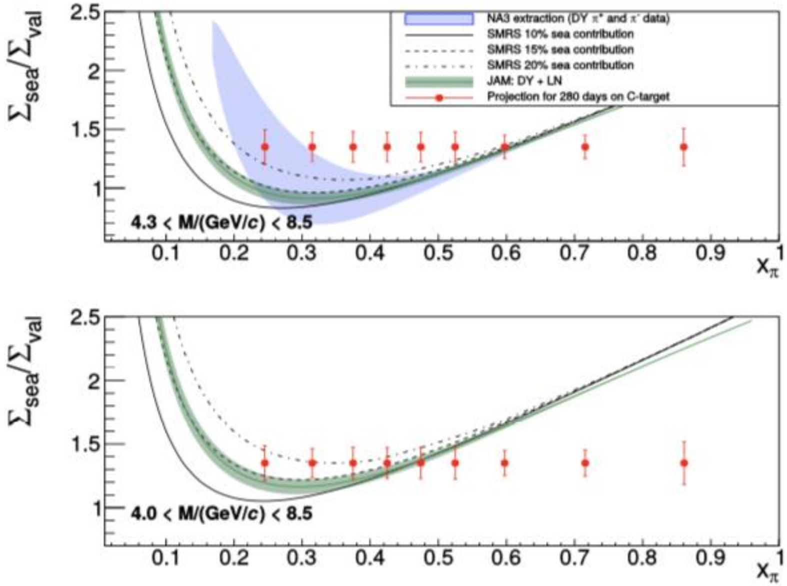


Figure 11: The ratio $\Sigma_{sea}/\Sigma_{val}$ as a function of x_π, using three different sea-quark distributions from [48] for two mass ranges. The ratio is also calculated with the sea-quark distribution from [53], which includes leading-neutron DIS data from ZEUS [51] and H1 [52]. The shown statistical accuracy is expected when using the data-taking conditions presented in the text. The blue shaded area is the uncertainty derived from the statistics quoted in the NA3 paper [37].

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120 cm D_2	286 140	π^-	65×10^7	4.2 – 8.5 4.35 – 8.5	7800 3200
	12 cm W	286 194 140	π^-	65×10^7	4.2 – 8.5 4.07 – 8.5 4.35 – 8.5	49600 155000 29300
COMPASS 2015 COMPASS 2018	110 cm NH_3	190	π^-	7.0×10^7	4.3 – 8.5	35000 52000
This exp	75 cm C	190	π^+	1.7×10^7	4.3 – 8.5 4.0 – 8.5	26000 37000
		190	π^-	6.8×10^7	4.3 – 8.5 4.0 – 8.5	25000 34000
	12 cm W	190	π^+	0.2×10^7	4.3 – 8.5 4.0 – 8.5	10000 14000
		190	π^-	1.0×10^7	4.3 – 8.5 4.0 – 8.5	9000 12000

Table 4: Statistics collected by earlier experiments (top rows), compared with the achievable statistics of the proposed experiment (bottom rows), in 255 days (π^+ beam) + 25 days (π^- beam).

Backup – proposal p. 28-30

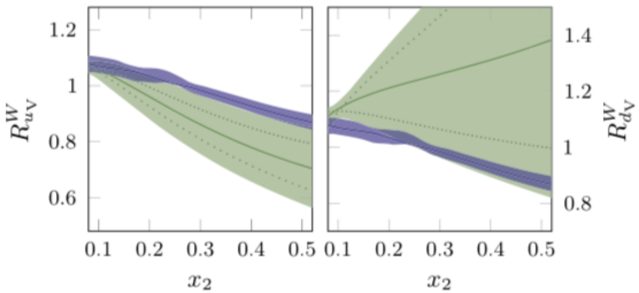


Figure 12: The modification of u_v (left) and d_v (right) distributions in tungsten, as obtained by the nCTEQ15 global fit in green, and by the EPS09 global fit in blue. Figure from Paakkinen et al. [62]. While nCTEQ15 allows for different up and down-quark modifications in tungsten without data to constrain the flavour-dependence hypothesis, EPS09 constrains these modifications to be flavour independent.

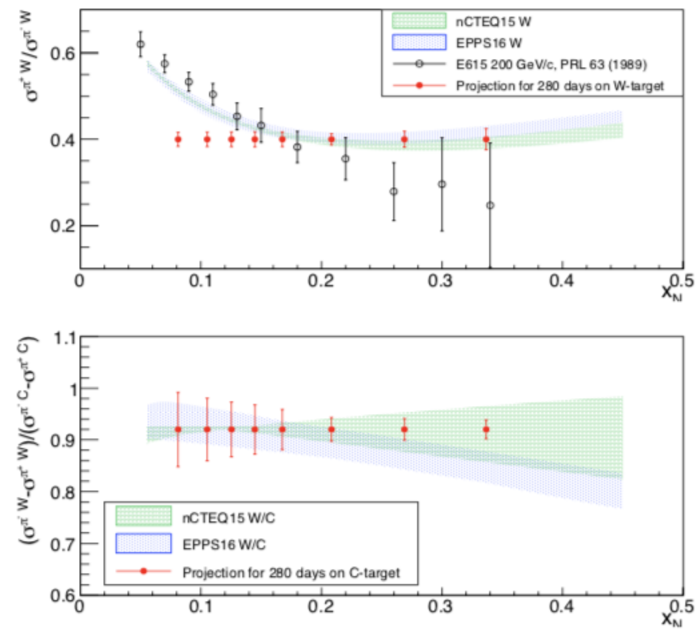


Figure 13: Top panel: Drell-Yan cross-section ratio for positive-over-negative pion beam polarity, shown *vs.* x_N. The expected statistical uncertainties from the proposed experiment (shown as full red dots) are compared to E615 results and two sets of nuclear PDFs. Bottom panel: Drell-Yan ratio of the cross-section beam-charge differences for tungsten over carbon, shown *vs.* x_N. The expected accuracy of the proposed experiment is shown together with two sets of nuclear PDFs.

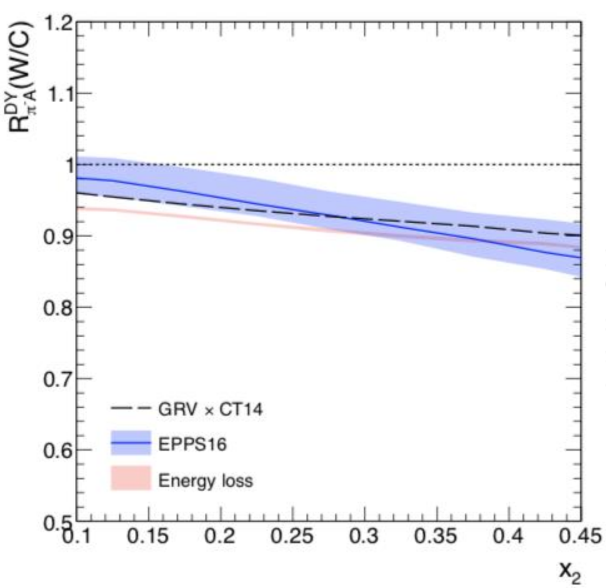
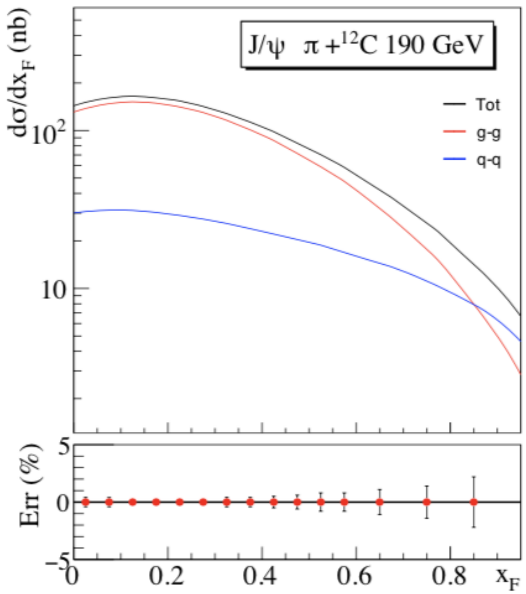


Figure 14: Drell-Yan cross-section ratio tungsten-over-carbon as a function of x_2 and the predicted parton-energy-loss effect under the conditions of the proposed Drell-Yan measurement. The figure is provided by the authors of ref. [70].

Backup – proposal p. 32-33



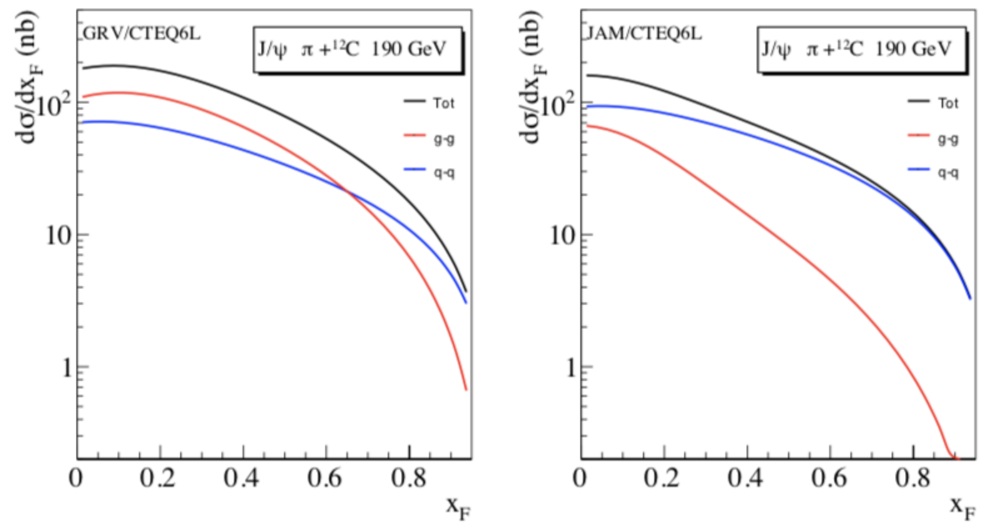


Figure 16: Pion-induced J/ψ production cross sections computed with the ordinary CEM model using the CTEQ6L nucleon PDFs and the GRV-NLO fit for the pion PDFs (left panel) or the JAM18 pion PDFs (right panel).

Figure 15: Top panel: Pion-induced J/ψ cross section prediction for a ^{12}C target computed with the ICEM model of Ref. [87] (black line). The red and blue lines show the $q\bar{q}$ and gg contributions, respectively. Bottom panel: estimated relative uncertainties in the proposed experiment.

Backup – proposal p. 34

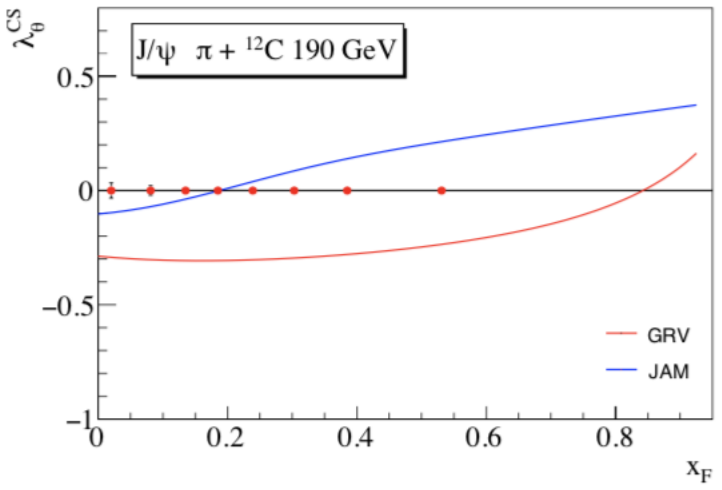


Figure 17: Pion-induced J/ψ polarization as a function of x_F. The polarization was computed assuming the ICEM average polarization values of 0.4 for the $q\bar{q}$ and -0.6 for the gg contributions (Cheung and Vogt, priv. comm.). The pion PDFs are those of GRV (red curve) and JAM (blue curve) parametrizations. The data points indicate the statistical accuracy achievable with the experimental assumptions described in the text.

Backup – proposal p. 43

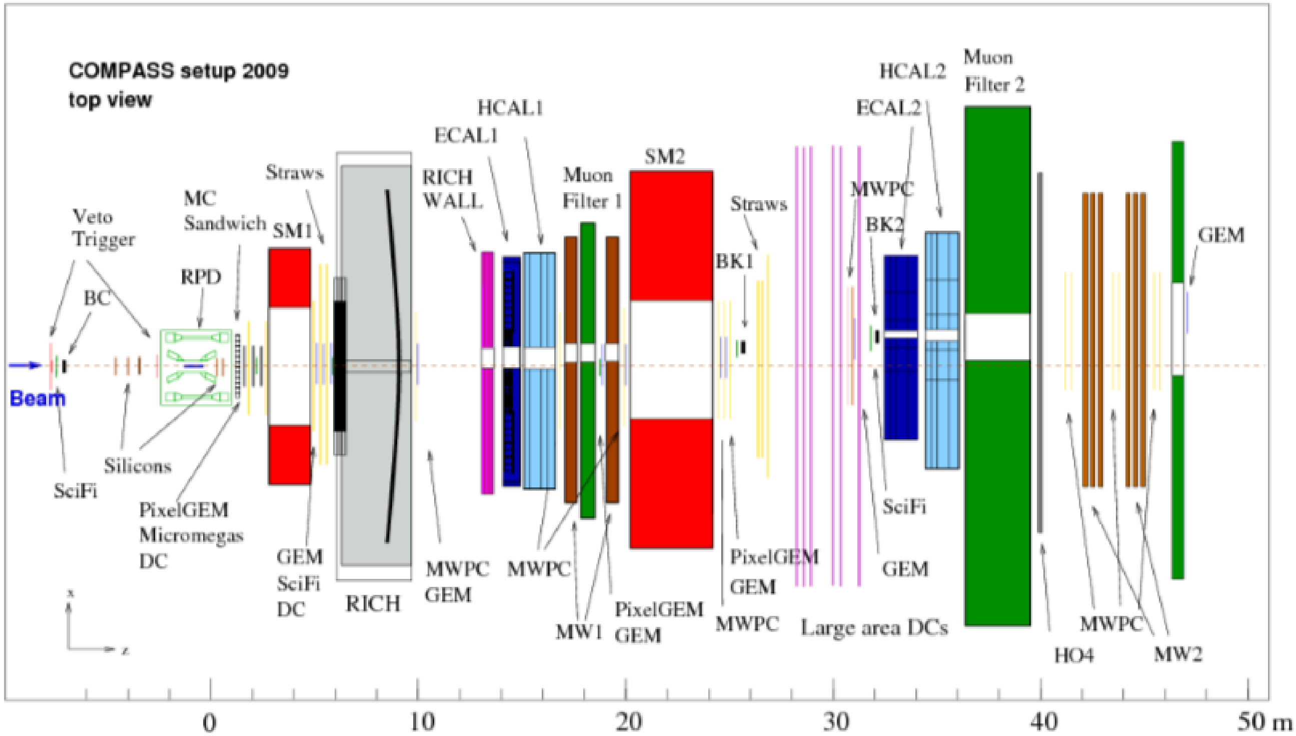


Figure 20: Top view of the 2009 Compass spectrometer setup for data taking with hadron beams.

Beam Mom [GeV/c]	π^+	K^+	p
60	64.6 ± 0.8	9.7 ± 0.2	23.4 ± 0.6
120	42.8 ± 0.5	7.2 ± 0.08	49.0 ± 0.7
200	17.5 ± 0.5	3.44 ± 0.10	79.0 ± 0.9
300	2.01 ± 0.04	0.641 ± 0.012	97.3 ± 0.5

Table 5: Particle content, in percent, of the beam leaving the 500 mm thick primary Beryllium production target [133].

Backup – proposal p. 44

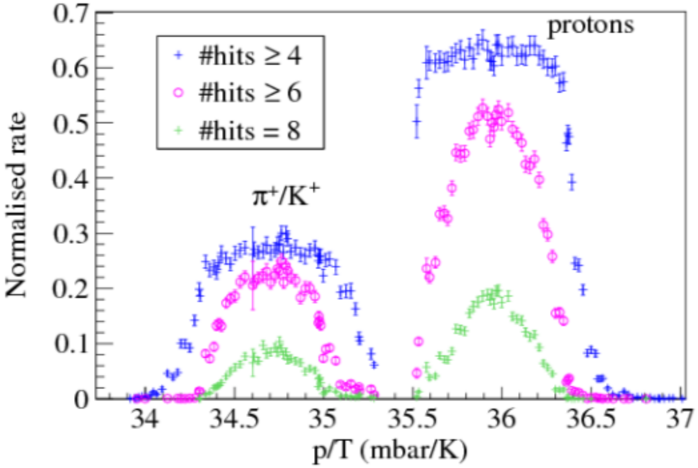


Figure 21: Pressure scan with CEDAR1 for a positive hadron beam with at least 4, 6 or 8 PMTs in coincidence, obtained at COMPASS in 2009 for a 190 GeV/c proton beam with a nominal intensity of $5 \cdot 10^6$ p/s.

Backup – proposal p. 46-47

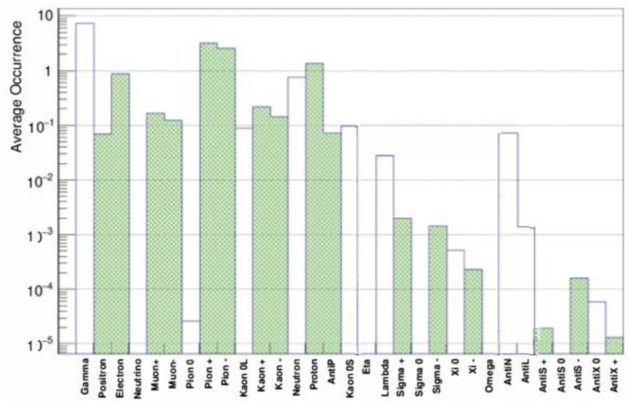


Figure 22: Particle type abundance in $p + p$ interactions at 190 GeV/c.

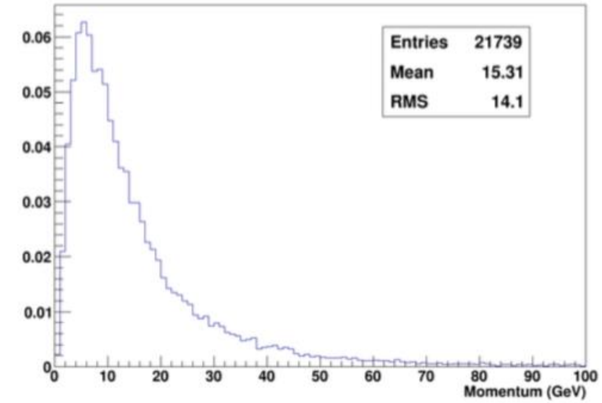


Figure 24: Momentum spectrum of $\overline{p}$ produced in $p + p$ interactions at 190 GeV/c

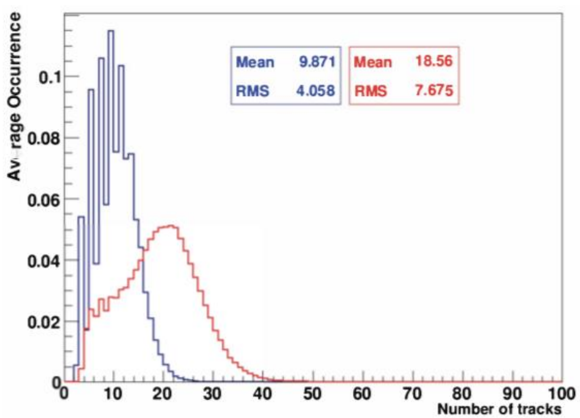


Figure 23: Track multiplicity in $p + p$ interactions at 190 GeV/c: in blue the charged tracks, in red all tracks.

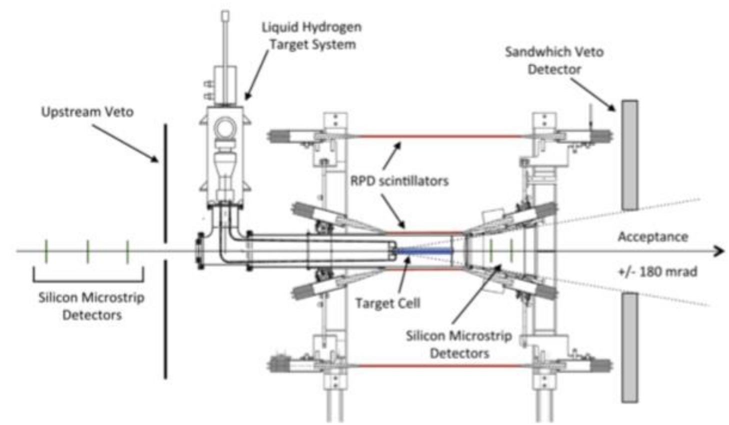


Figure 25: Longitudinal section of the COMPASS liquid H_2 target.

Backup – proposal p. 48-49

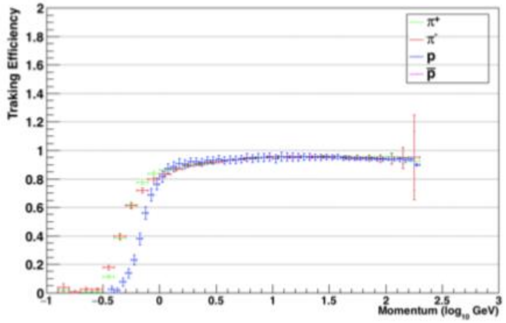


Figure 26: Tracking efficiency as a function of the particle momentum, for π^+ (green), π^- (red), p (blue).

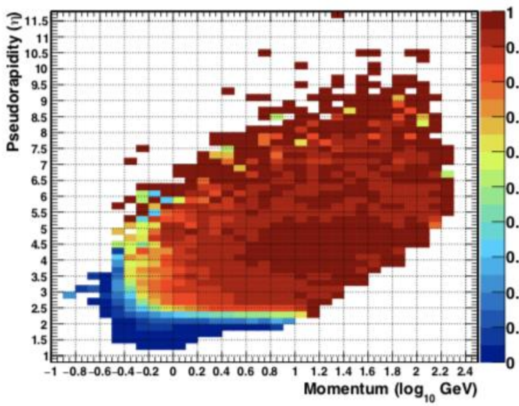


Figure 27: Double differential (η,$log_{10}(p)$) reconstruction efficiency for negative pions produced in 190 GeV/c $p+p$ interactions.

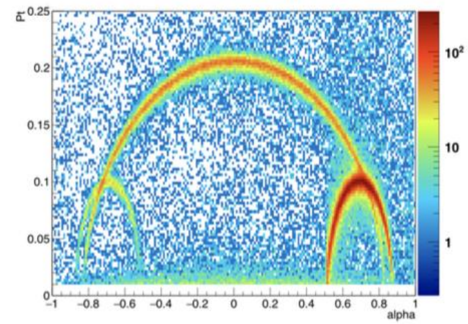


Figure 28: Armenteros plot for the selected neutral secondary vertices. It is possible to spot the main arch corresponding to K^0 and $\bar{K}^0$ decays and the smaller left and right arches corresponding to $\bar{\Lambda}_0$ and Λ_0 decays, respectively.

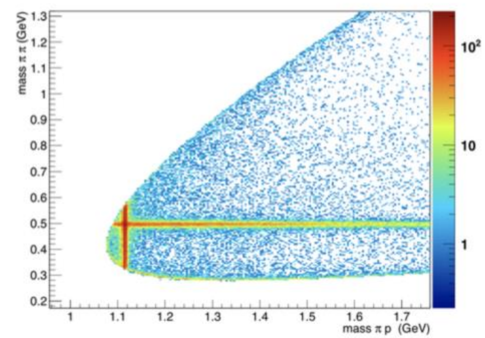


Figure 29: Invariant mass in the $\pi\pi$ hypothesis vs the $p\pi$ hypothesis. The vertical and horizontal bands correspond to Λ_0 and K^0 decays respectively.

Backup – proposal p. 50-51

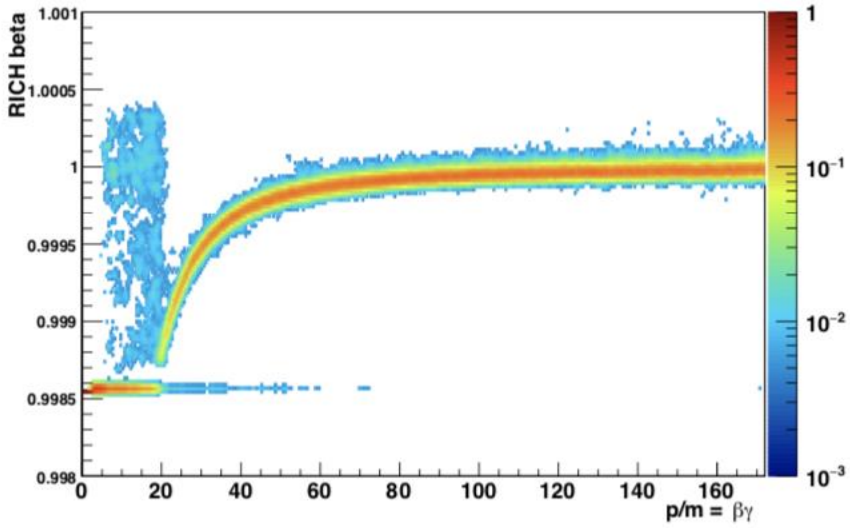


Figure 30: Each column in this scatter plot represents the p.d.f for the RICH-measured beta, for the corresponding particle with $\beta\gamma = p/m$.

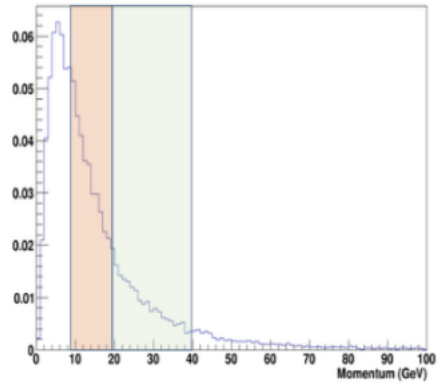


Figure 31: Expected $\bar{p}$ momentum spectrum for 190 GeV p primaries on LH_2. The two shaded areas represent the ranges where the $\bar{p}$ identification with RICH is effective. In the orange one $\bar{p}$ are identified in veto mode, in the green one the $\bar{p}$ identification is direct.

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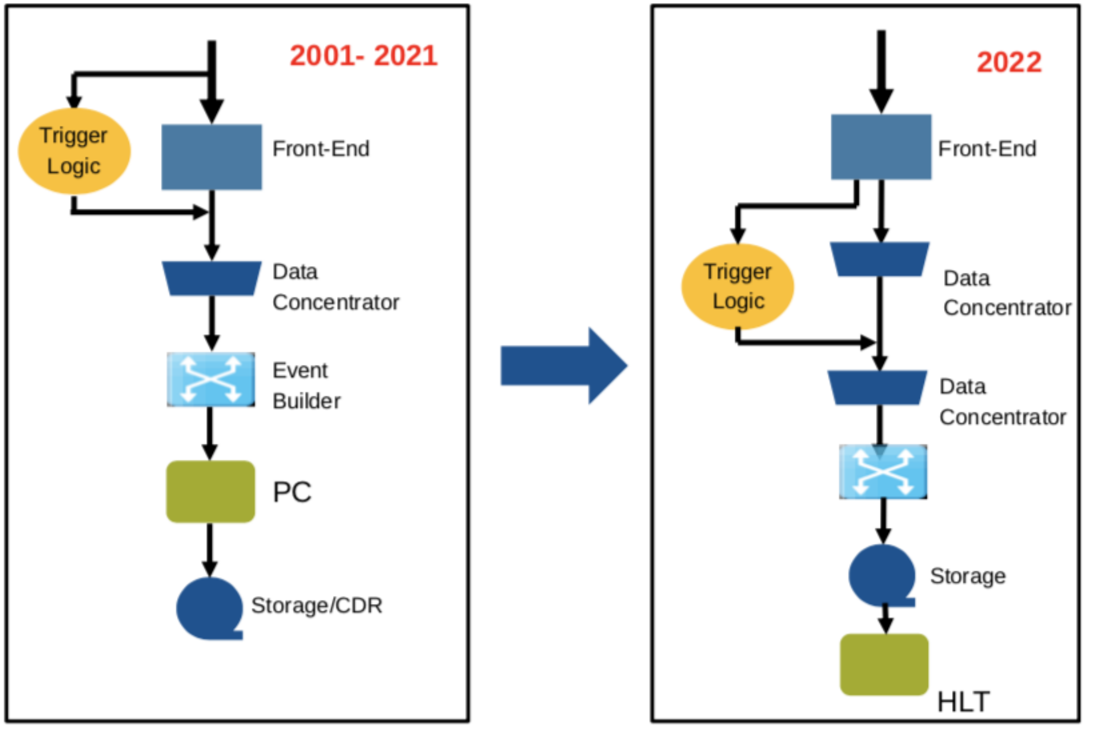


Figure 37: Evolution of iFDAQ

Backup – proposal p. 60

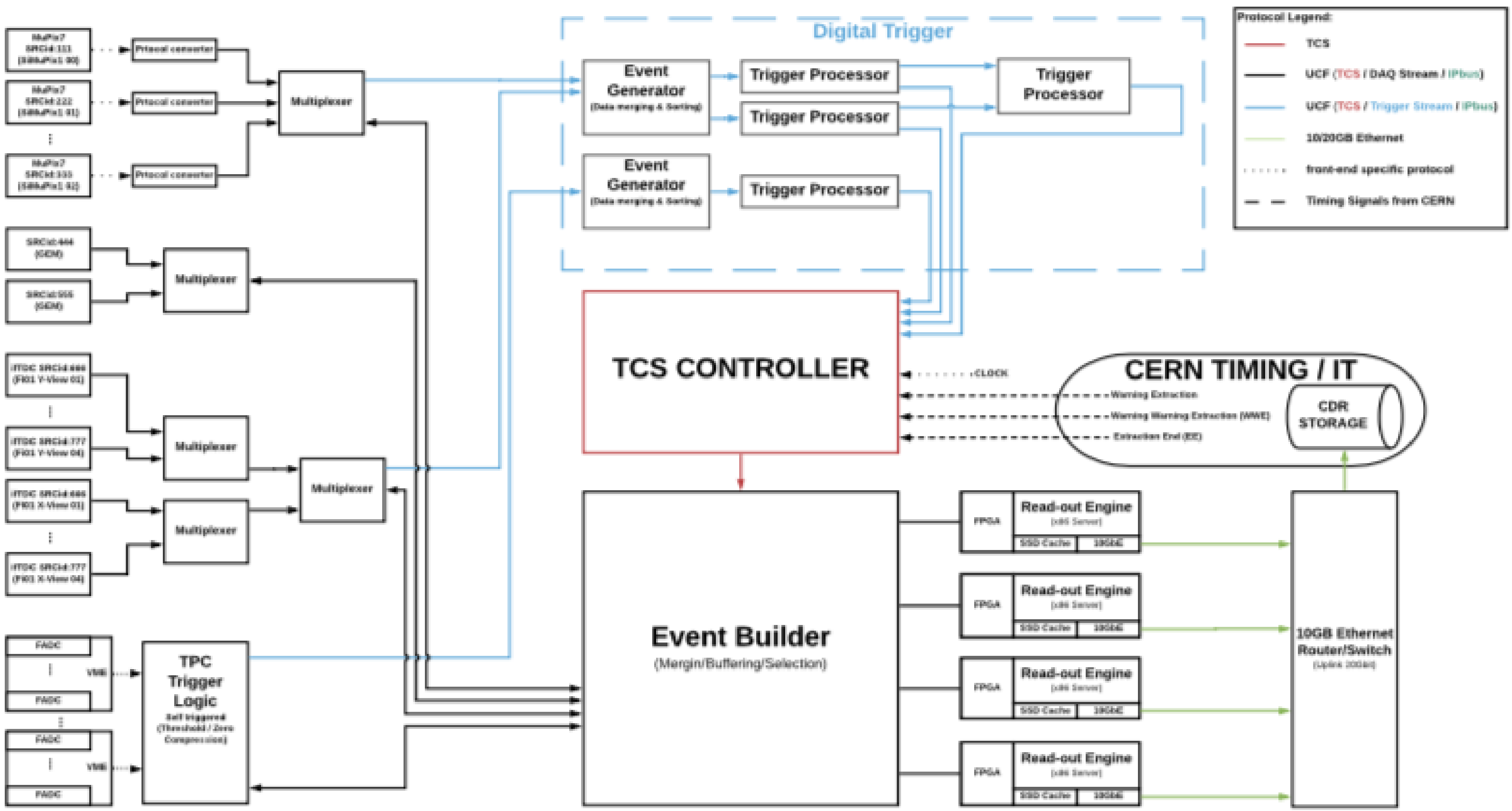


Figure 38: Logical scheme of the different components of the future DAQ system

Backup – proposal p. 61

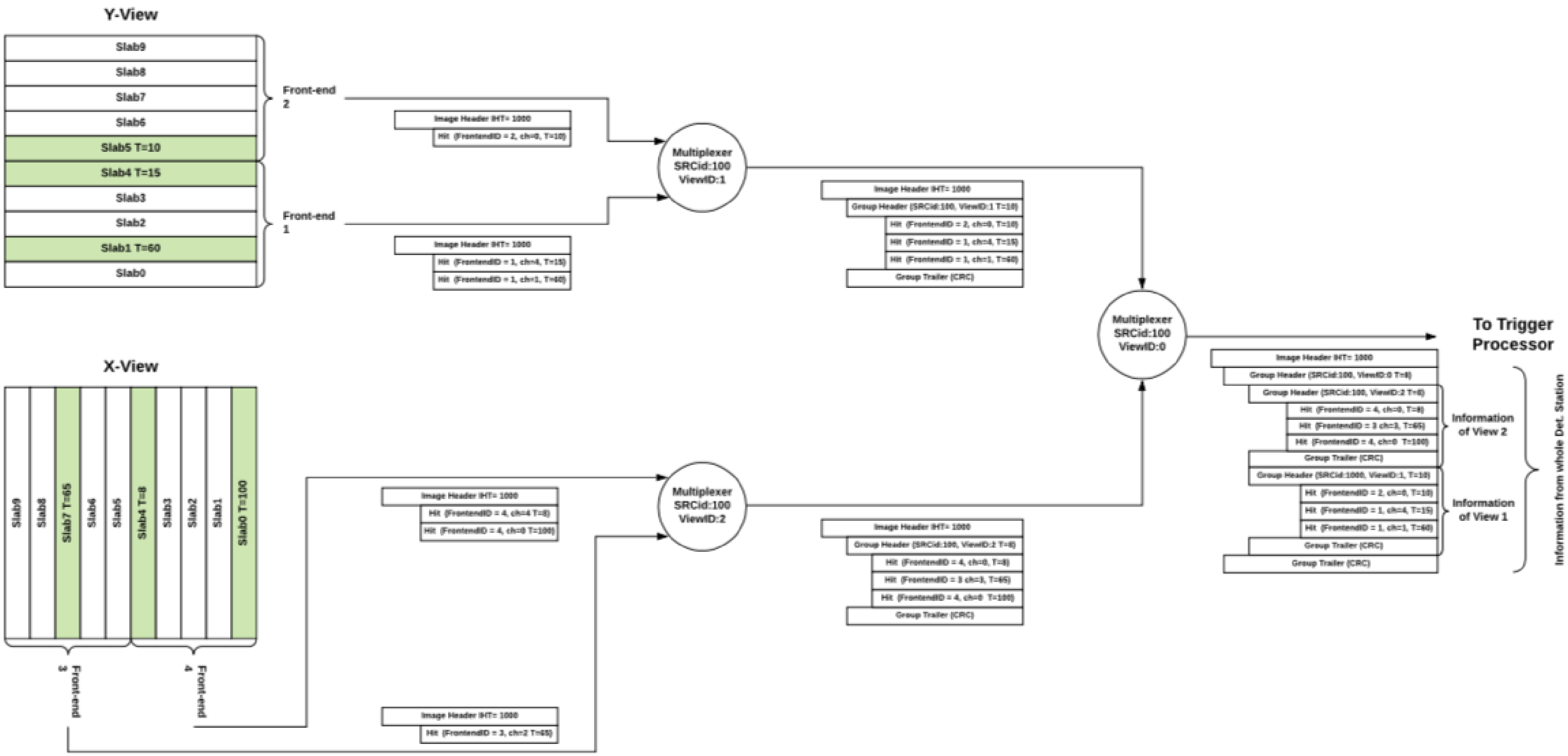


Figure 40: Data-flow through the DAQ of hit information of one Image. Front-ends sent only hit information with image header. These front-end data streams are concentrated in the multiplexer and a group header/trailer pair is added to indicated the origin of the hits before the combined data stream is further sent to the Trigger Processor.

Backup – proposal p. 63

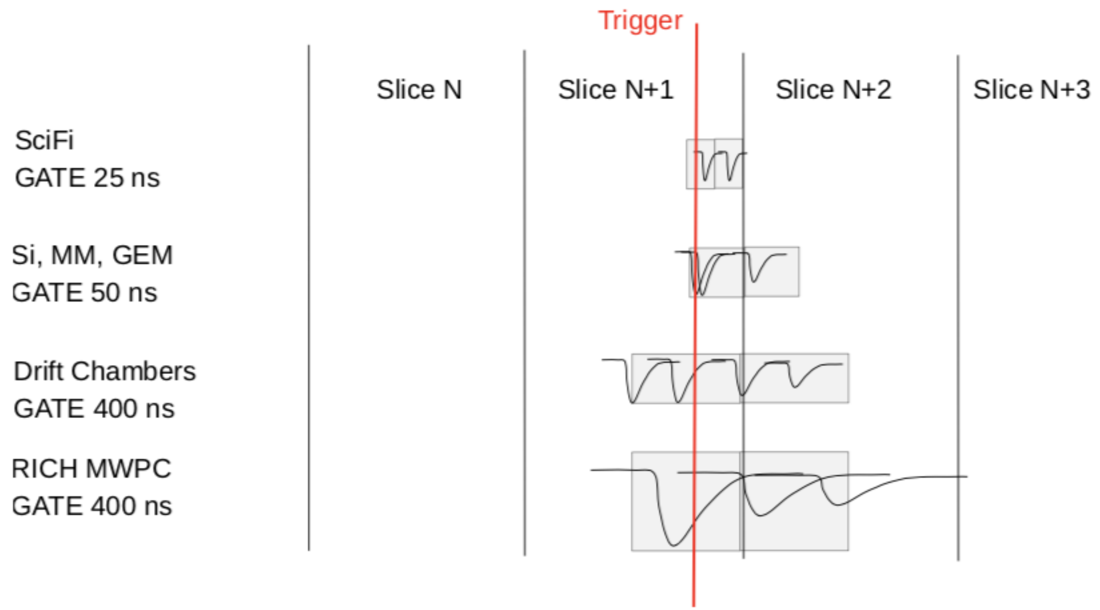


Figure 41: Selection of data which is stored to disk after a trigger is issued.

Backup – proposal p. 72

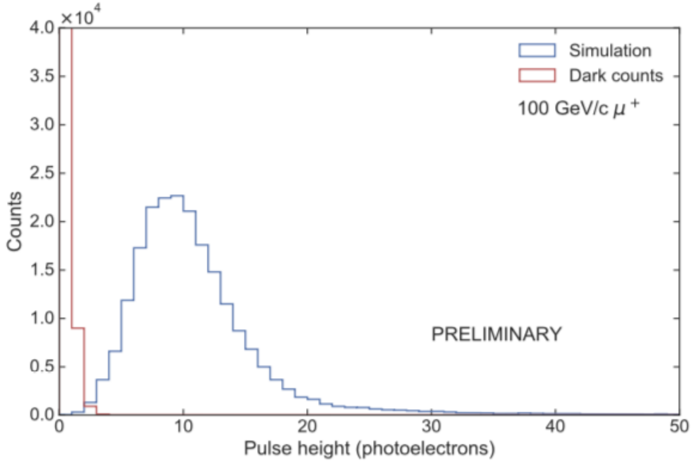


Figure 47: Simulated pulse-height spectrum (blue) for 100-GeV/c muons in a 200-μm scintillating-plastic fiber, generated with a simulation framework tuned to reproduce experimental data. Also shown is the dark-count spectrum of a KETEK PM1125-WB SiPM at room temperature (red).

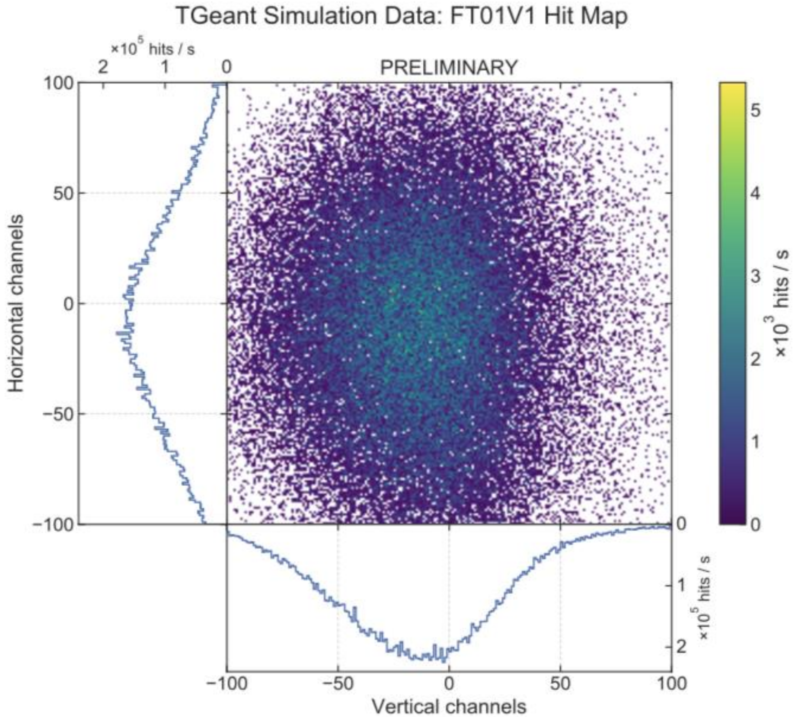


Figure 48: Hit map of one SciFi tracking layer (one vertical layer, one horizontal layer) with a pixel size of $200 \times 200\,\mu\text{m}^2$, simulated with TGeant. Each detector consists of two tracking layers shifted by 100 μm in each direction relative to each other.

Backup – proposal p. 76

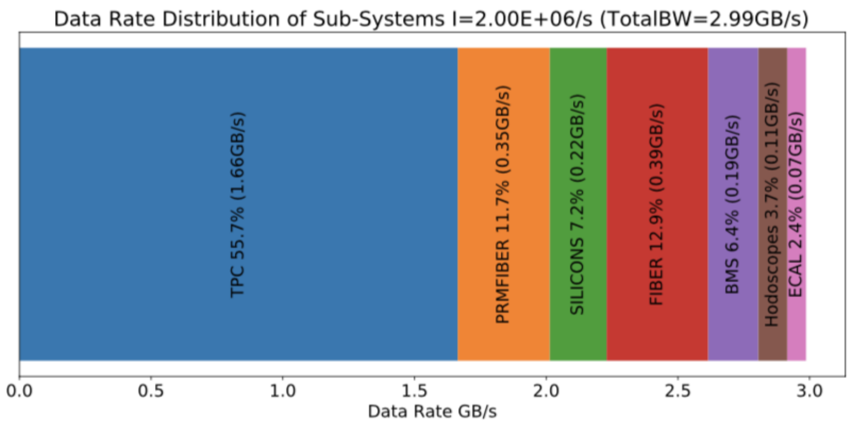


Figure 51: Distribution of data rate for different detector systems for an beam intensity of 2E6.

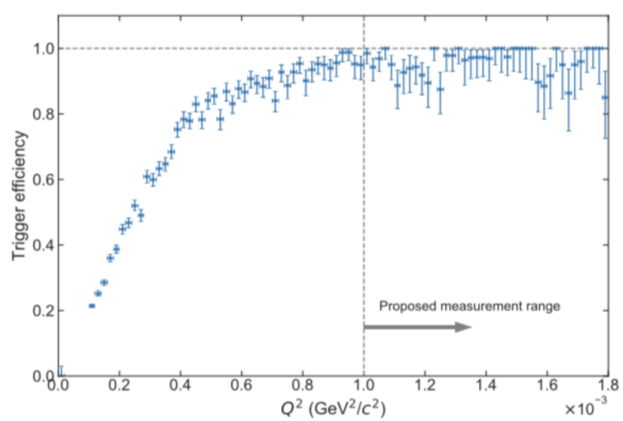


Figure 52: Predicted efficiency of the elastic-muon trigger for the proton radius measurement, which is about 97 % for the proposed measurement range ($0.001 < Q^2/(\mathrm{GeV}^2/c^2) < 0.04$). The increased uncertainties at larger Q^2-values are due to the limited size of the data set at the moment used for this graph.

Backup – proposal p. 77

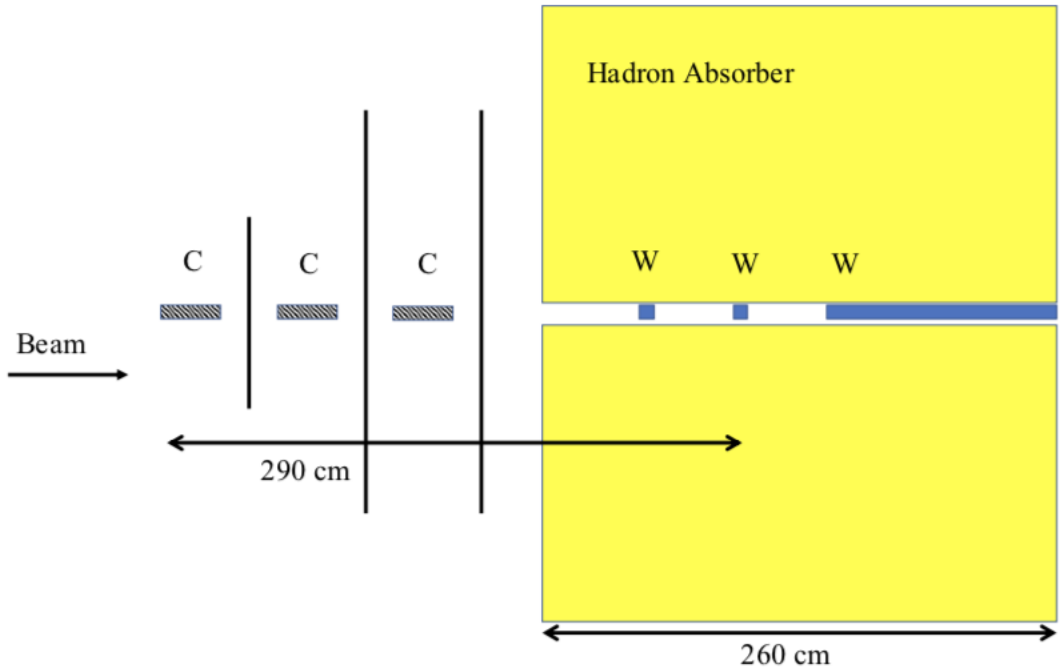


Figure 53: Conceptual representation of the Drell-Yan target system, showing the three 25 cm carbon sections interspersed with tracking detector planed, followed by the two 6 cm tungsten targets and the tungsten plug inside the hadron absorber.

Backup – proposal p. 80

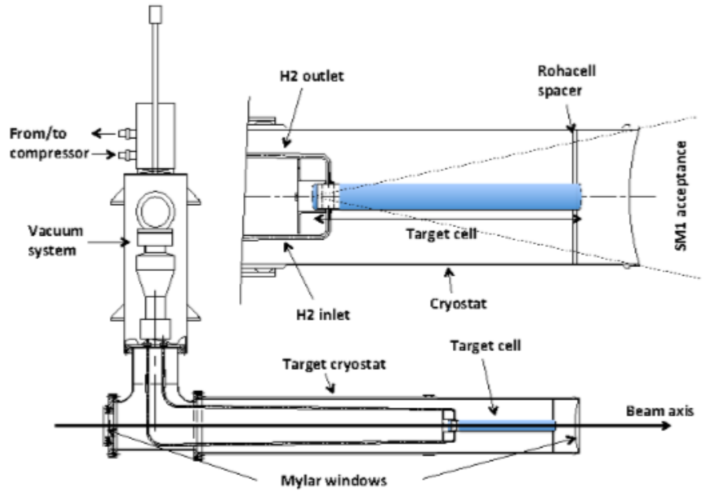


Figure 55: Side view of the liquid hydrogen target system. A closer view of the cylindrical Mylar cell and hydrogen piping is shown in the inset.

Backup – proposal p. 82

Equipment	Responsible (tentative)	Status
Beam	CERN	new/existing
BMS	Bonn	existing
CEDAR	CERN, Warsaw	existing/upgrad
Luminosity measurement	Freiburg, Mainz	upgrade
C/W target	Lisbon	new
LH_2,LHe_2 target	CERN, Czech G., Virginia, Yamagata	existing/new
DY vertex detector		new
Silicon detectors	Munich, Torino	new/existing
TPC and pressure tank	Gatchina, GSI	new
TPC gas system	Gatchina	new
TPC RO	Bonn, Freiburg, Gatchina, GSI	new
SciFi target	Munich	new
SciFi tracker	Bonn	existing
GEM	Bonn	refurbish
Micromegas		existing
Straws	Illinois	existing
MWPC	JINR, Torino	upgrade
DC	Illinois	existing
RICH	Atlanta, Calcutta, Czech G., Trieste	existing/upgrade/new
RICHWALL	JINR, Torino	existing
HCAL1	JINR	existing
HCAL2	IHEP Protvino	existing
ECAL1	IHEP Protvino	existing
ECAL2	IHEP Protvino	existing
MW1	JINR	existing
MW2	IHEP Protvino	existing
W45	CERN	existing
DAQ/Computing	Czech Group, Munich, Tomsk, Warsaw	upgrade
Trigger	Bonn, Mainz	upgrade
PRM Trigger	Mainz, Munich	new
Front-end		upgrade
Slow control	Lisbon	existing
Infrastructure	CERN	existing

Table 14: Tentative responsibilities for detector construction/upgrades, operation and maintenance. The assignments are still preliminary and subject to change according to funding. The new components concern predominantly the phase-1 presented in this document, several developments, such as the new DAQ, are however in view of the complete future running plan. Several major detector developments that are presently envisaged for measurements beyond phase-1 are omitted here. This table will be updated along with forthcoming proposals for further measurements at the COMPASS++/AMBER facility.

Backup – proposal p. 83-84

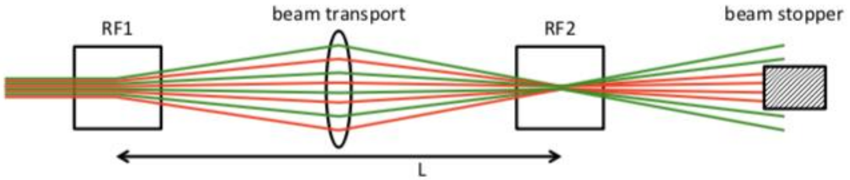


Figure 56: Panofsky-Schnell method for RF-separated beams. The unwanted particles (red) are stopped by a beam stopper while the wanted particles (green) receive a net deflection by the combination of the RF1 and RF2 dipole RF cavities out of the central axis, which is sufficient to go around the stopper.

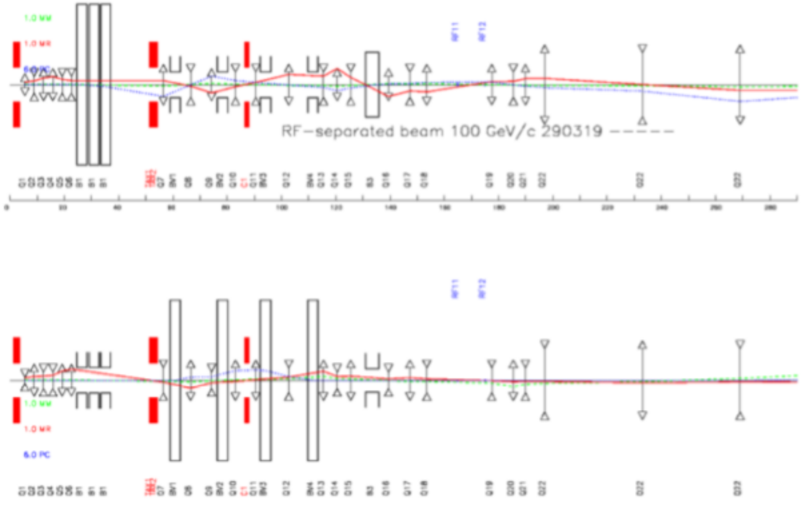


Figure 57: First outcome of optics studies for an RF-separated beam in the M2 beam line. The beam momentum selection will be achieved by including a vertical achromat comprising four strong dipole magnets (BV1-BV4).

fitting with a truncated series for small Q^2

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

- 3 free parameters n, a_2, a_4 (sys 0.0035, stat 0.0040 fm)
- 4 free parameters n, a_2, a_4, a_6 (sys <0.0020, stat 0.0090 fm)

choice of higher-order terms:

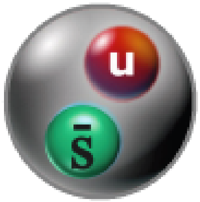
- $a_i = 0$ for $i \geq 6$ or 8
- fix e.g. $a_i = a_D$ for $i \geq 6$ or 8 according to some model

Motivations

Pion

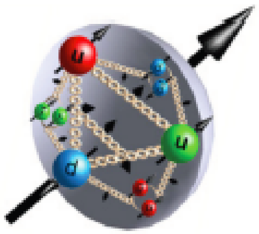
- $M_{\pi} \sim 140$MeV
- Spin 0
- 2 light valence quarks
- 2 TMD PDFs at LT.

Kaon



- $M_{K} \sim 490$MeV
- Spin 0
- 1 light and 1 "heavy" valence quarks
- 2 TMD PDFs at LT.

Proton



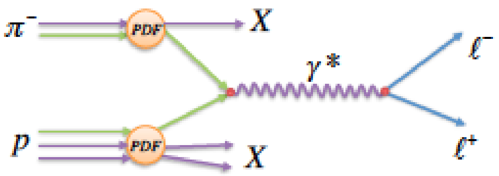
- $M_{p} \sim 940$MeV
- Spin 1/2
- 3 light valence quarks
- 8 TMD PDFs at LT.

3 QCD objects, different structures, different properties, understanding differences and similarities teaches us about QCD

Existing hadron beam
We learned very little so far about meson structure

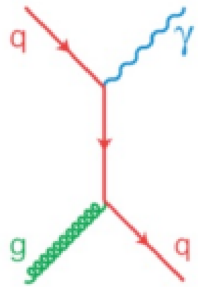
How to access meson structure

Drell-Yan:



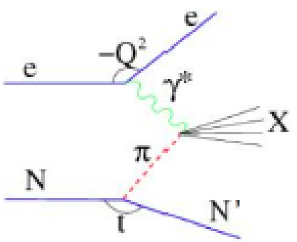
- 90's: NA3, NA10, E615
- 10's: COMPASS-II
- 20's: New Experiment

Prompt photon production:



- 90's NA24, W70
- 20's New experiment

DIS with leading N:



- 90's: H1, ZEUS
- 10's: JLAB TDIS
- 30's: EIC

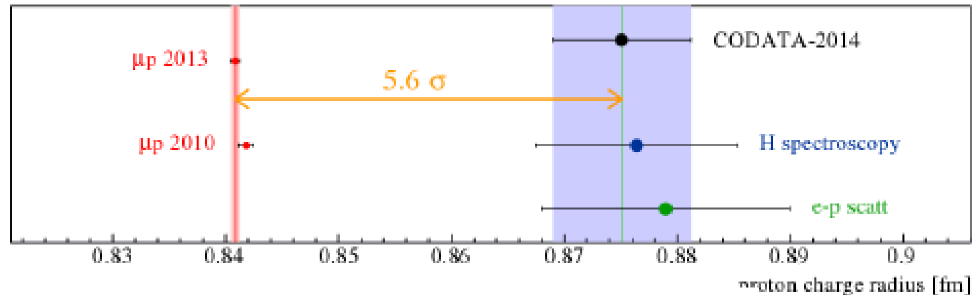
Existing muon beam:
Proton radius measurement in elastic mu-p scattering

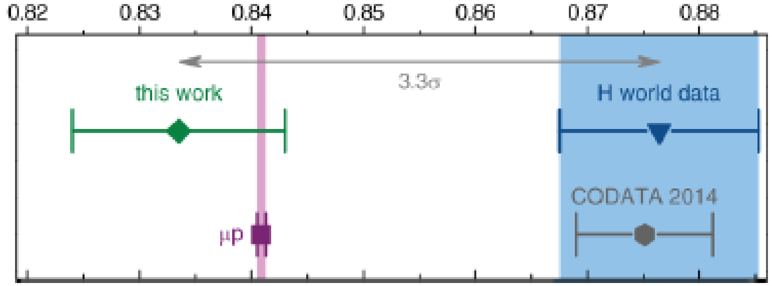
from: Krauth et.al. Arxiv:1706.00696

Proton radius puzzle since 2010
(Pohl et al, Nature 466, 213)

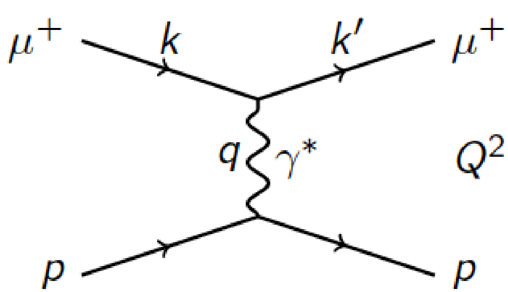
Laser spectroscopy of muonic hydrogen data are rather in agreement now with electronic hydrogen spectroscopy data (new determination of the Rydberg constant can be used to reinterpret all electronic hydrogen data) and e-p scattering data.

New experiment on μ-p scattering is a missing ingradient in proton radius puzzle





Science 358, 79 (October 2017)



$$Q^2 = -q^2$$

- elastic scattering of muons off a proton target
- measure Q^2 spectrum over wide range: 10^{-4} to $10^{0}\,\mathrm{GeV}^2/c^2$
  - extract radius from its shape

challange: identify elastic reactions

- muon scattering angle between 100 μrad and 10 mrad
- recoil proton energy between 100 keV and 500 MeV

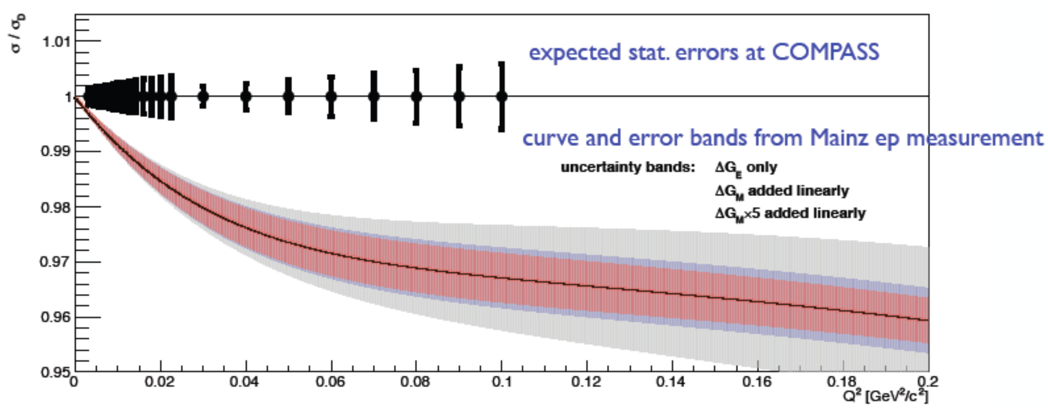
both information are required

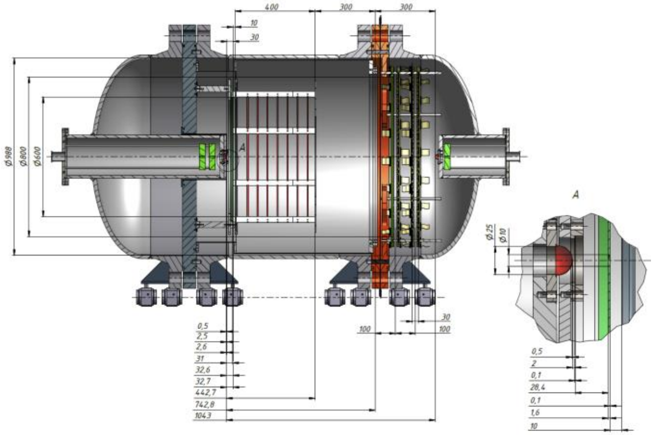
Proton Radius measurement

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

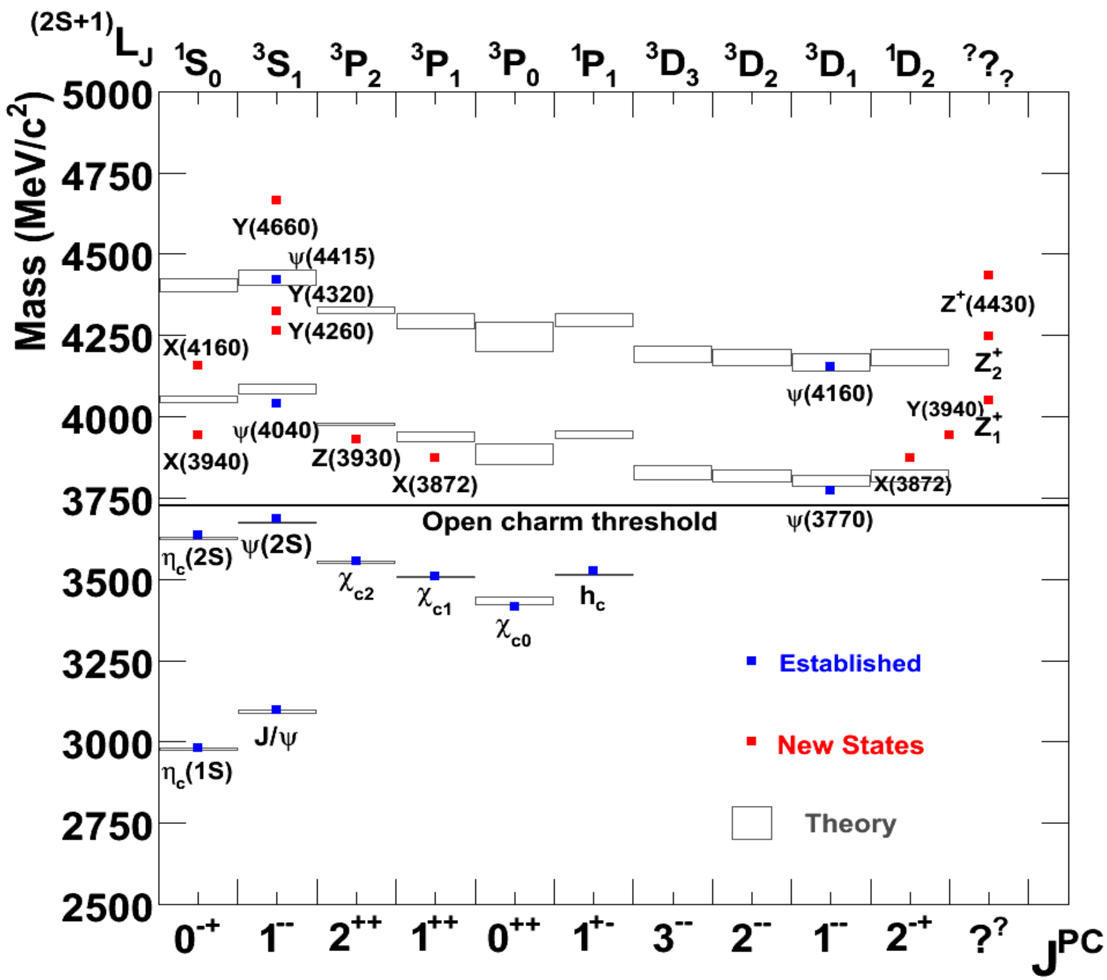
- elastic μp scattering at low Q^2
- key advantages over ep
  - measure electric form factor G_E, essentially no contribution from magnetic one G_M (high E)
  - much smaller QED rad. corr. (muon mass)
- remains: theory uncertainty from fitting the form factor slope

- 100 GeV SPS M2 muon beam
- high-pressure hydrogen TPC active-target cell (PNPI development)
- measure cross-section shape over broad Q2 range $10^{-4} \ldots 10^{-1}$
- fit from 10^{-3} … 2×10^{-2} the proton radius (slope of electric form factor)





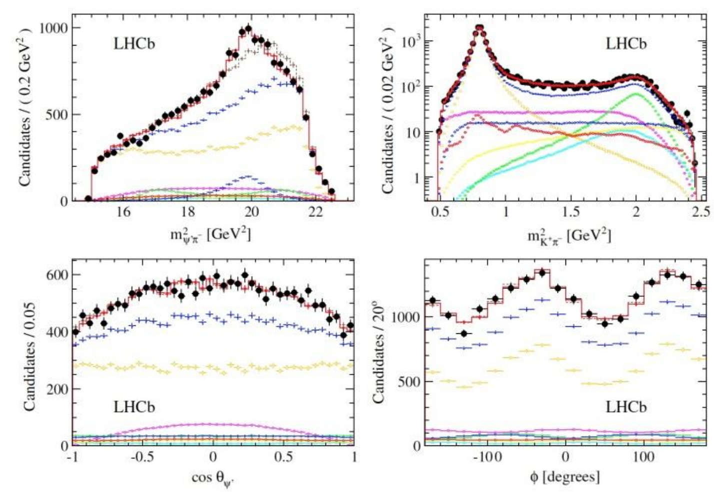
Existing beam line, antiproton-enriched beam
Charmonium spectra



[V. Santoro, Hadron 2015]

- Many new (narrow) states discovered in recent years
- Assignment not clear
- Some definitively not charmonium-like

LHCb: $Z(4430)^-$: 13.9 σ



[LHCb, PRL 112, 222002 (2014)]

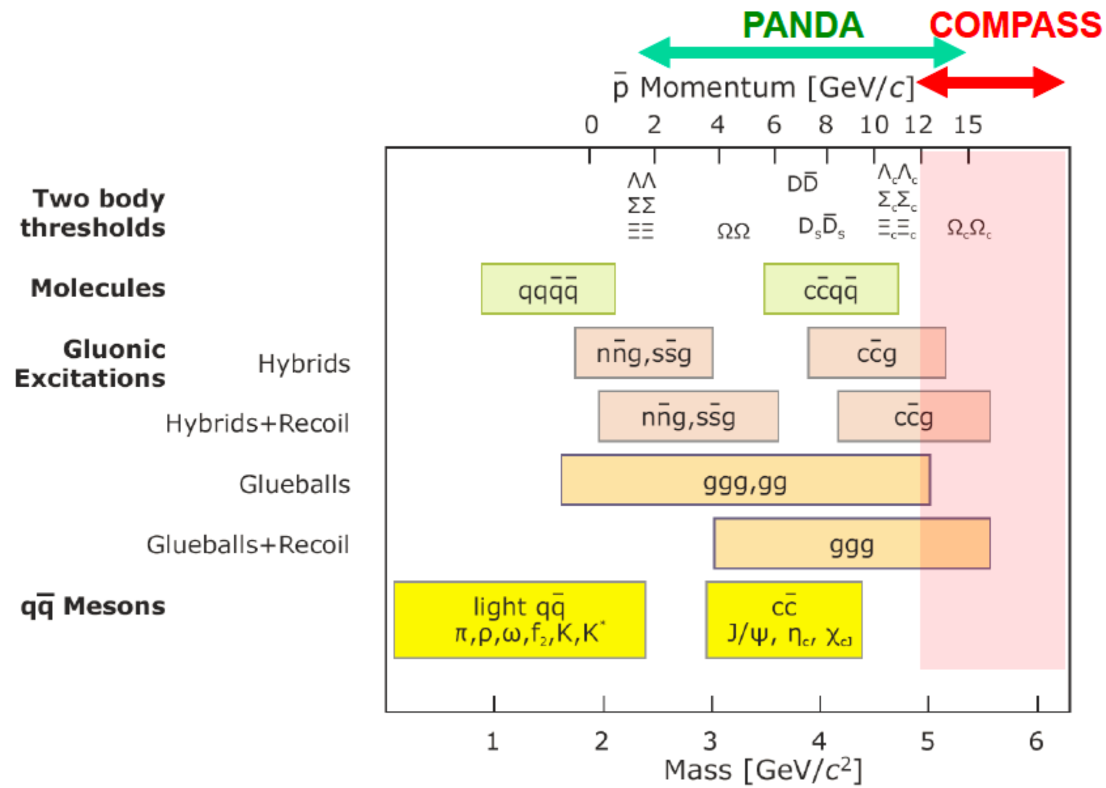
Existing beam line, antiproton-enriched beam
Charmonium-like mesons

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

Method: antiproton-proton annihilation

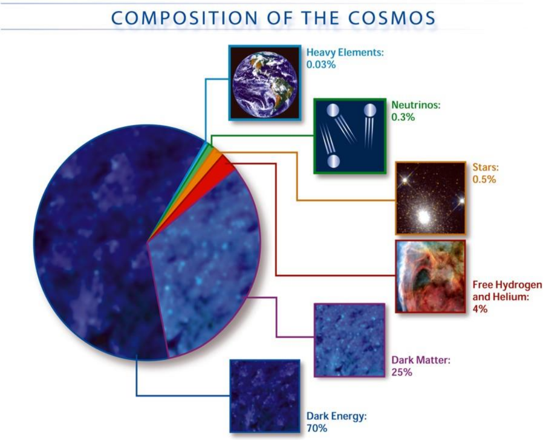
Goal: charmed hybrids and exotics study in the mass range higher than reachable in PANDA

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



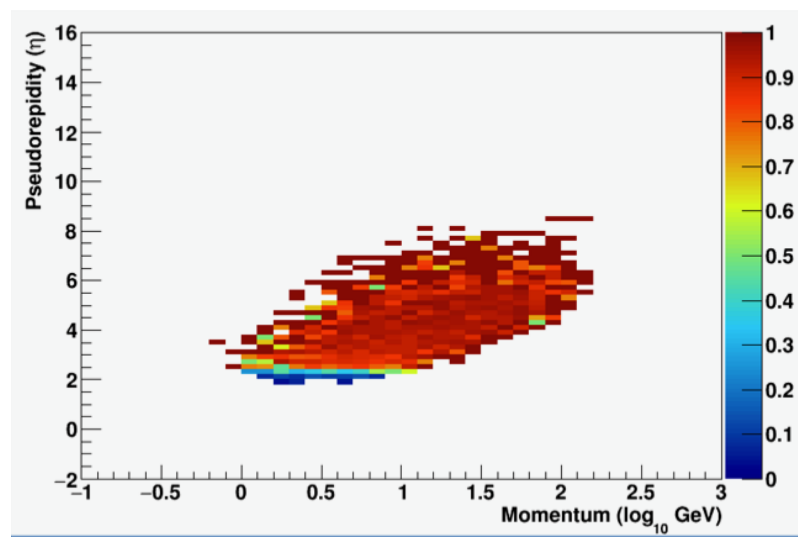
-New AMS(2) data – the antiparticle flux is well known now (few % pres.) (http://dx.doi.org/10.1103/PhysRevLett.117.091103)

- 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%.

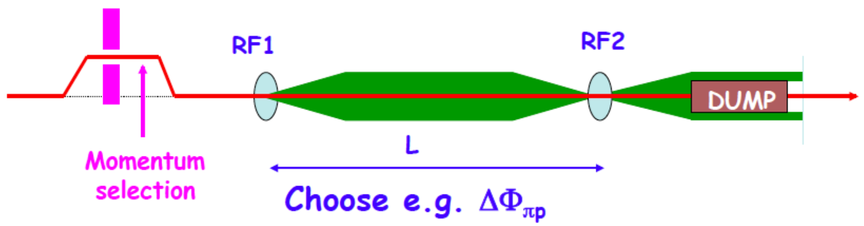
COMPASS++ from a few tens of GeV/c up to 250 GeV/c, in the pseudorapidity range 2.4 < h < 8.
We performed simulation with TGEANT (GEANT4 based COMPASS MC), using FLUKA generator or the internal TGEANT generator:
2009 COMPASS hadron setup, 190 GeV beam.

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 antiproton/kaon beam



$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$ with $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$

"Normal" h^- beam composition:
~97% (π) ~2.5%(K) ~0.5% (pbar)

Assumptions:

– 8×10^7 antiprotons for 10^{13} ppp (10 seconds) (optimistic estimate by Lau Gatignon);
– we assume here 4×10^{13} protons.

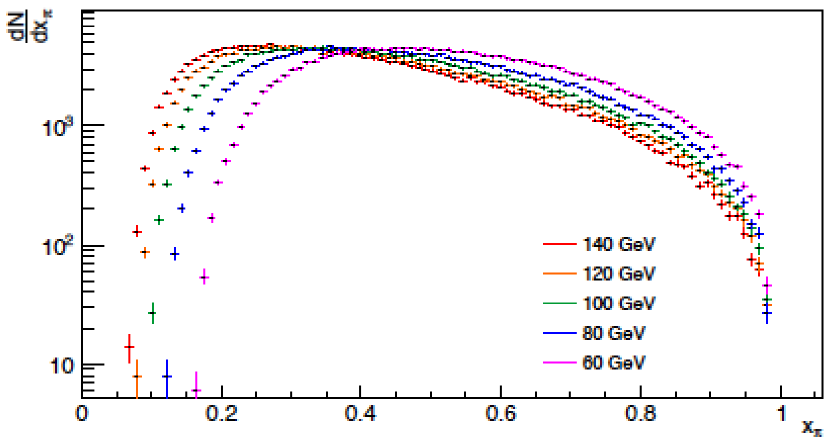
Antiprotons RF separated beam: 3.2×10^7 /s - Gain is a factor of 50 compared to the standard h^- beam for Drell-Yan experiment (~1% of h^- beam 6×10^7 /s dominated by π^-)

Using the same assumption for RF separated kaon beam, possible kaon beam intensity is 8×10^6 /s - Gain is a factor of 80 compared to to the standard "spectroscopy" h^- beam

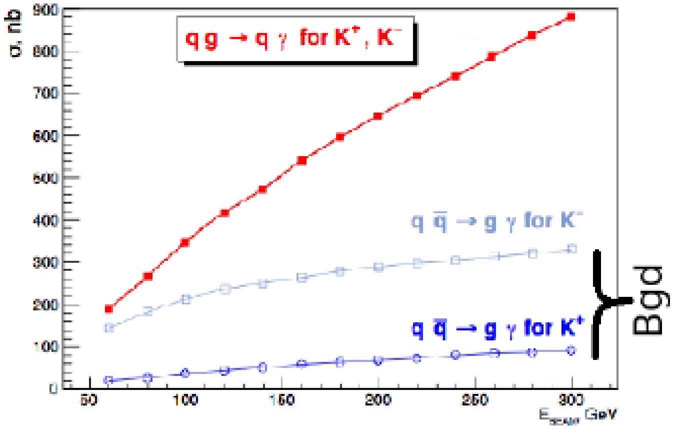
High intensity RF separated beam will provide unique opportunities for Hadron Spectroscopy and Drell-Yan physics

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

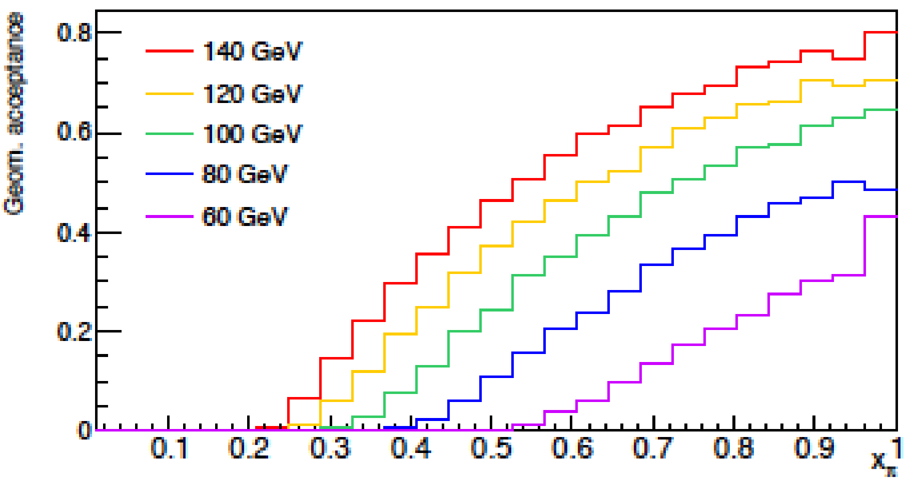
DY cross-section



Prompt photon cross-section



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

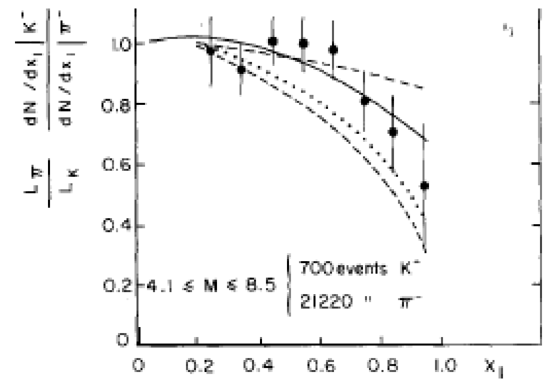


What do we know about kaon structure?

Sole measurement from NA3

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

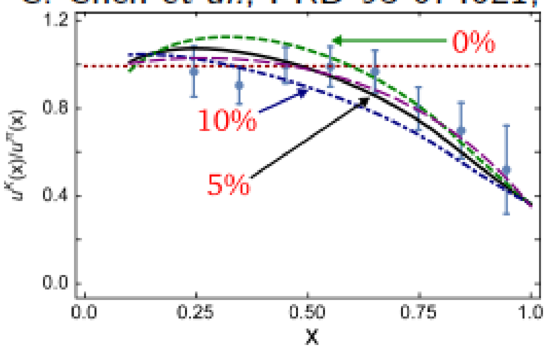
- Limited statistics: 700 events with K^-
- Sensitivity to $SU(3)_f$ breaking
- Mostly only model predictions
- No predictions from lattice - waiting for data!



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

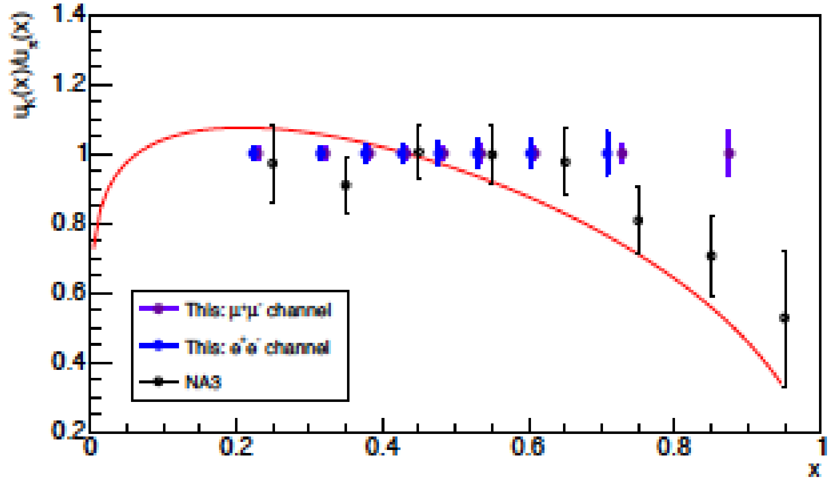
C. Chen *et al.*, PRD 93 074021, 2016



RF separated hadron beam

Meson structure study in DY and PP processes

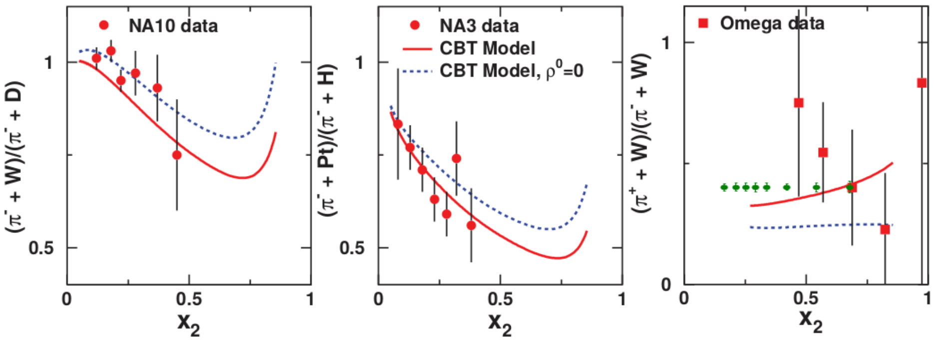
Valence u-quark quarks in Kaon compared to pion



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

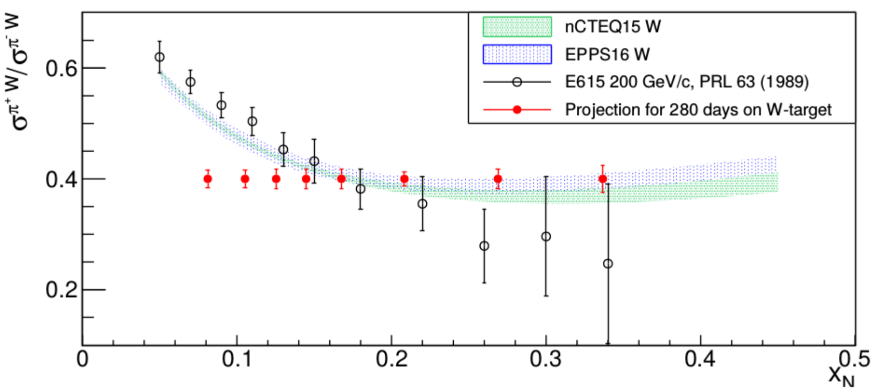
Table 6: Achievable statistics of the new experiment, assuming 2×140 days of data taking with equal time sharing between the two beam charges. For comparison, the collected statistics from NA3 is also shown.

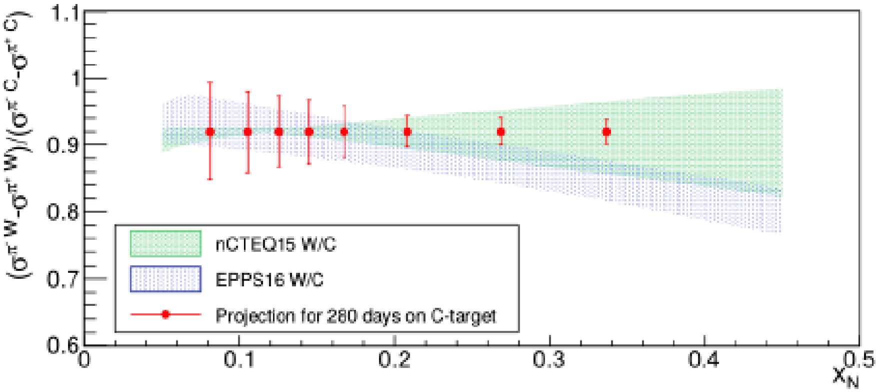
Existing hadron beam
Drell-Yan (III)



- Statistical uncertainties projections for COMPASS-like experiment (1 or 2 years of running depending on beam intensity: 7x10[7] or 1.4x10[8] /s)
- Time sharing 1:10 h^-/h^+ beam

1. sea/valence ratio in pion
2. EMC effect pion projectile (red - flavour dep.)
3. Nuclear PDFs (existing DY data already in)
4. Nuclear PDFs (valence)





RF separated hadron beam
Meson structure study in DY and PP processes
Projection for valence/sea quarks separation in Kaon

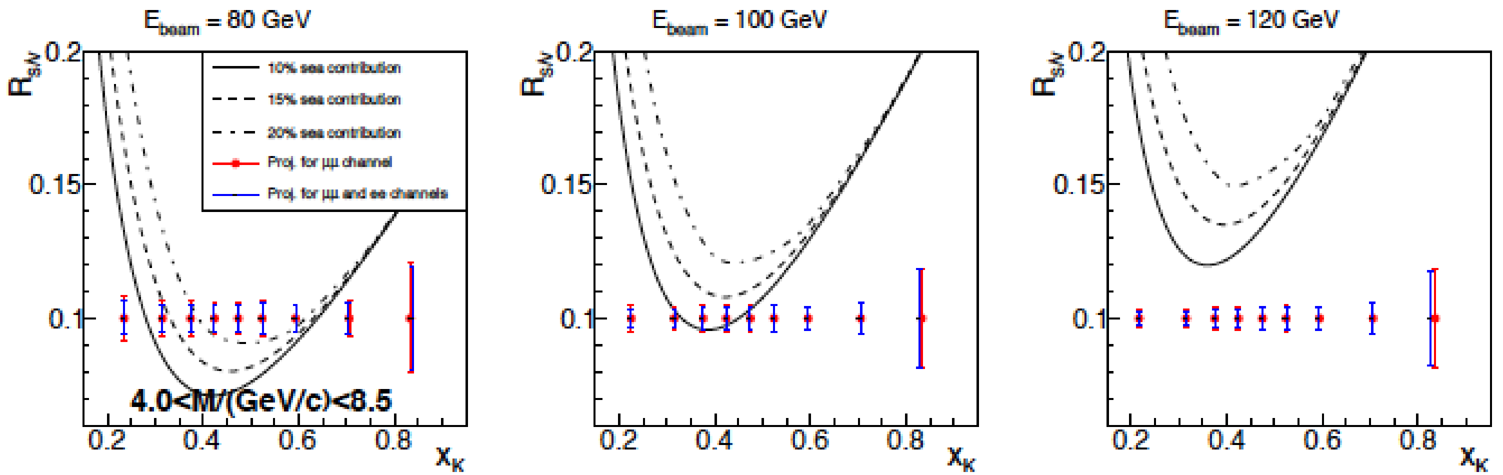


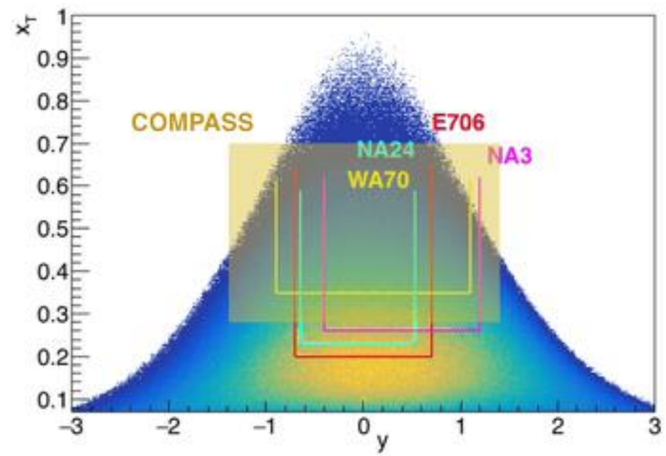
Figure 32: The 3 panels show, for 3 different momenta of the incoming kaon beam, the ratio $R_{s/v}$ as a function of x_K for three hypotheses on the kaon sea-quark content. The projected statistical uncertainties of the experiment are compared to the sensitivity of $R_{s/v}$ to a variation of this content. The three curves representing 10%, 15%, and 20% of kaon momentum carried by sea quarks are derived from SMRS pion PDFs by interchanging *d*-quarks with *s*-quarks.

- First measurement of sea in Kaon
- There is still a room for optimization
- Assumed K^+/K^- beam intensity $2x10^7$ /s
- 280 days of running

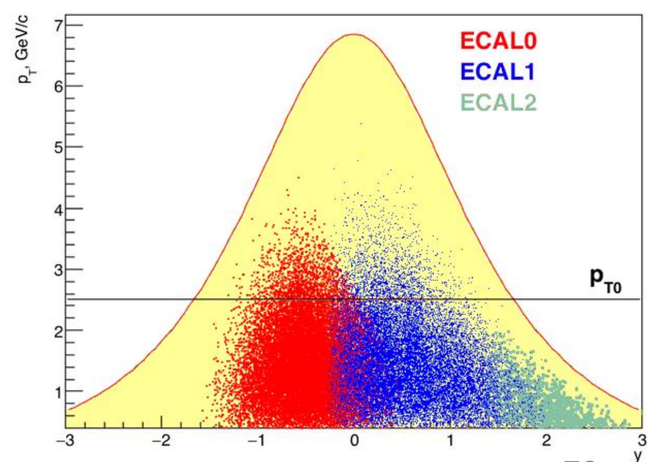
RF separated hadron beam
Meson structure study in DY and PP processes

At the moment there is no experimental information about gluon contribution in kaon. Calculations based on Dyson-Schwinger equations predict 6 times smaller contribution at hadronic scale in respect to pion (Phys. Rev. D93 (7) (2016) 074021)

Pythia-based MC simulation for prompt photons production was used for preliminary estimation of kinematic range accessible at COMPASS. It was compared with corresponding ranges accessible by previous experiments with pion beams.



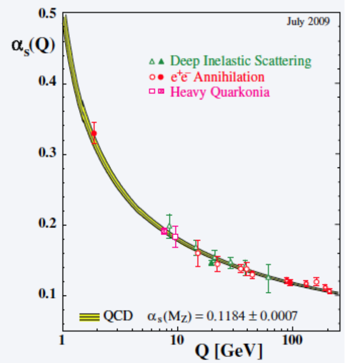
Full MC simulation for prompt photons and minimum bias events was performed for K+ beam of 100 GeV/c and the COMPASS setup configuration of 2017 DVCS run. Possibilities to identify signal and reject background were tested. Some optimization of the setup from point of the material budget was tested.



NO competitors

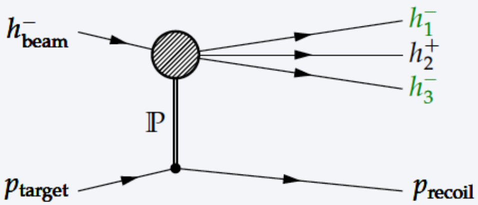
RF separated hadron beam
Strange sector meson spectroscopy with Kaon beam

- Binding of quarks and gluons into hadrons governed by low-energy (long-distance) regime of QCD
- Least understood aspect of QCD
  - Perturbation expansion in α_s not applicable
  - Revert to models or numerical simulation of QCD (lattice QCD)
- Details of binding related to hadron masses
  - Only small fraction of proton mass explained by Higgs mechanism $\Rightarrow$ most generated dynamically



Hadrons reflect workings of QCD at low energies

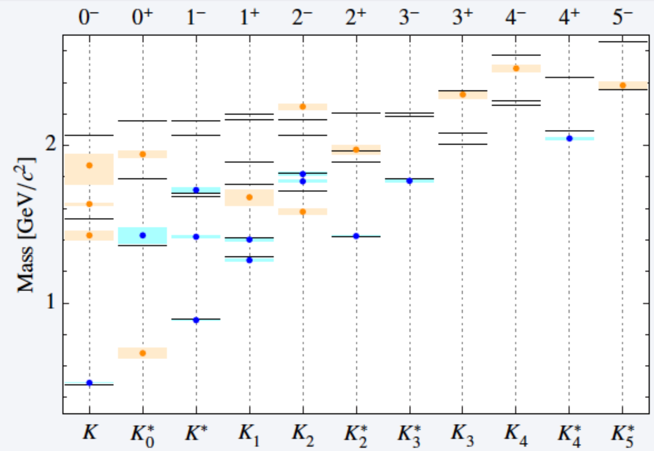
Measurement of **hadron spectra** and **hadron decays** gives valuable input to theory and phenomenology



- Diffractive production of excited kaon states X^- that decay into $K^-\pi^+\pi^-$
- Beam-particle ID via Cherenkov detectors (CEDARs)
  - Ca. $50\times$ more π^- than K^- in beam
- Final-state PID via RICH detector
  - Distinguish K^- from π^- over wide momentum range

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

- Only 12 kaon states in summary table, 13 need confirmation
- Many predicted quark-model states still missing
- Some hints for supernumerous states

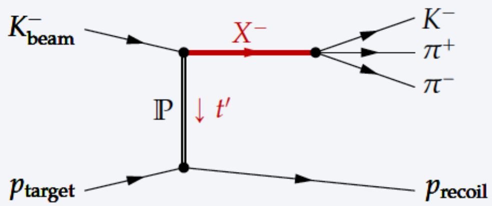


[Courtesy S. Wallner, TUM]

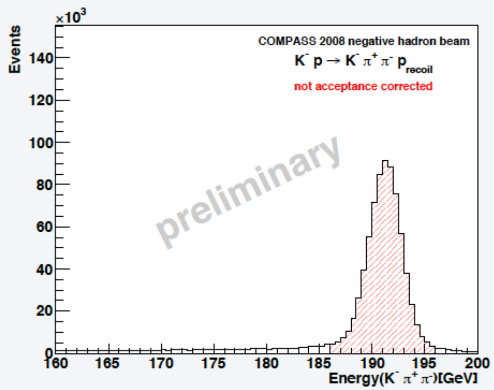
Many kaon states need confirmation

- Little progress in the past
  - Most PDG entries more than 30 years old
  - Since 1990 only 4 kaon states added to PDG (only 1 to summary table)

RF separated hadron beam
Strange sector meson spectroscopy with Kaon beam



- From 2008 data taking campaign
- 270 000 events
- $0.07 < t' < 0.7\,(\mathrm{GeV}/c)^2$
- Exclusivity ensured by measuring recoil proton
  - Also suppresses target excitations



Work in progress: improving analysis

- Improved beam PID + data sample from 2009 run
  $\Rightarrow$ ca. 8×10^5 $K^-\pi^+\pi^-$ events
  $\Rightarrow$ world's largest data set (4× WA03)
- Improved PWA model $\Rightarrow$ clearer resonance signals
- Resonance-model fit $\Rightarrow$ extraction of $K^-\pi^+\pi^-$ resonances and their parameters

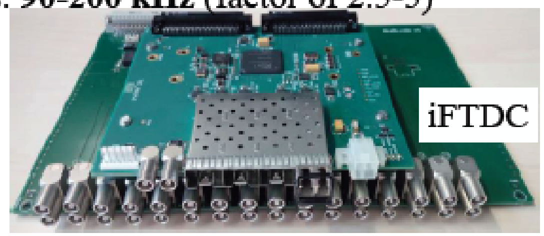
Future program

- *Goal:* collect 10 to 20 × 10^6 $K^-\pi^+\pi^-$ events using high-intensity RF-separated kaon beam
  - Would exceed any existing data sample by at least factor 10
  - *High physics potential:* rewrite PDG for kaon states above 1.5 GeV/c^2 (like LASS and WA03 did 30 year ago)
  - Precision study of $K\pi$ S-wave
- Requires experimental setup with uniform acceptance over wide kinematic range (including PID and calorimeters)
- No direct competitors

Measurement of kaon Compton scattering via the Primakoff effect and an RF separated beam for determination of the kaon polarisability, and kaon-photon induced strange meson production

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



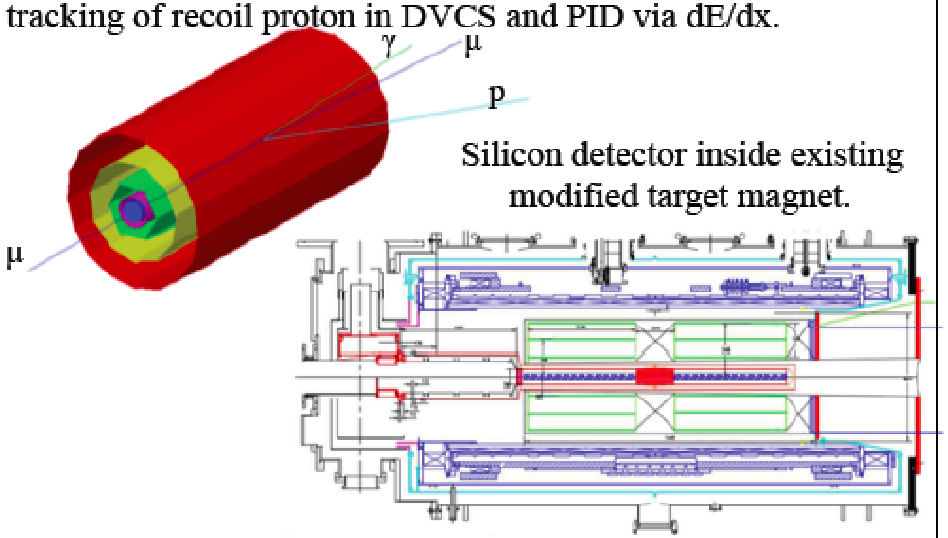
General upgrades of COMPASS-II apparatus:
- New large-size **PixelGEMs**
- **GEMs** or **Micromegas** to replace aging MWPCs
- High-aperture "**RICH0**" for some programs, p < 10-15 GeV?

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.

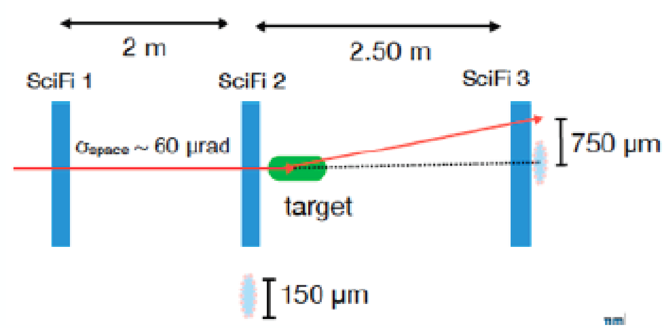
- High-rate-capable **CEDARs** for beam PID for all hadron programs.

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.



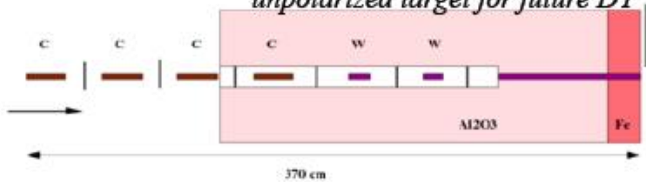
Proton radius:
- **High-pressure active TPC target or hydrogen tube** surrounded by SciFi, 4-8 layers with U/V projections
- **SciFi trigger system** on scattered muon
- Silicon trackers



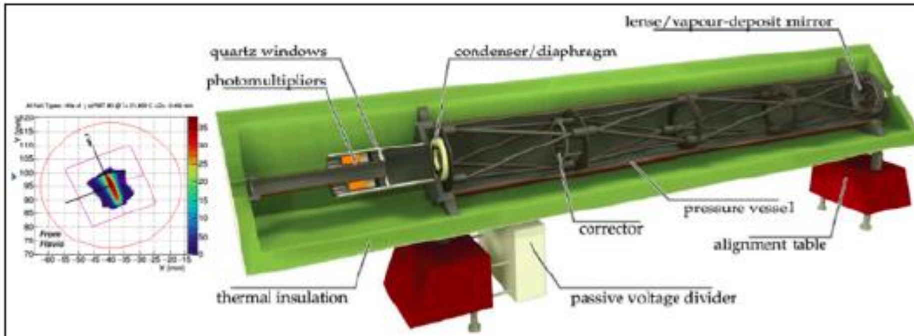
QCD facility – future fixed target experiment at M2
Spectrometer upgrades

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

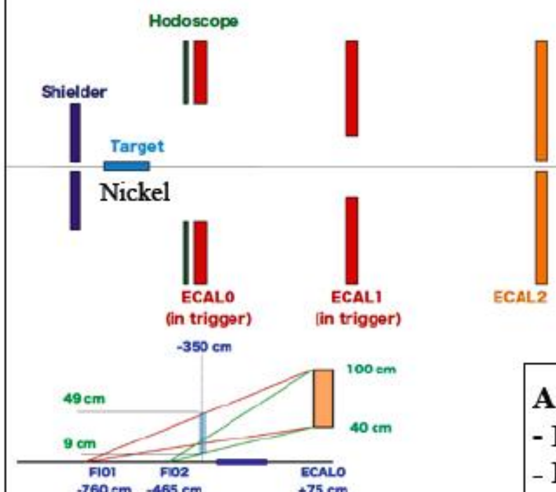
unpolarized target for future DY



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?

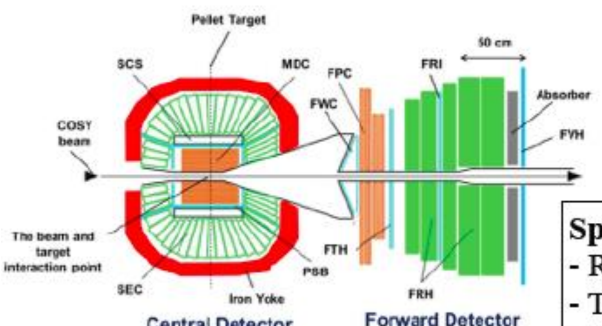


CEDAR upgrade 2018



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?

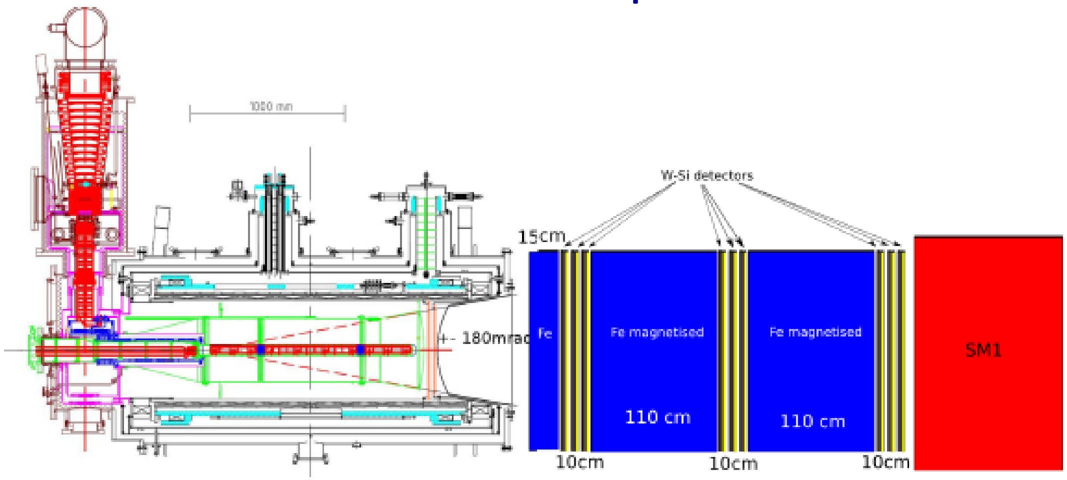


WASA detector with target spectrometer

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

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

<u>Initial detector consideration:</u>

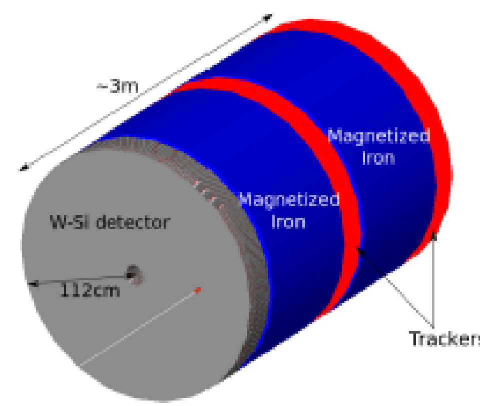
Combination of

- Baby-Mind detector

  M. Antonova *et al.* arXiv:1704.08079

- W-Si detectors, a la BNL

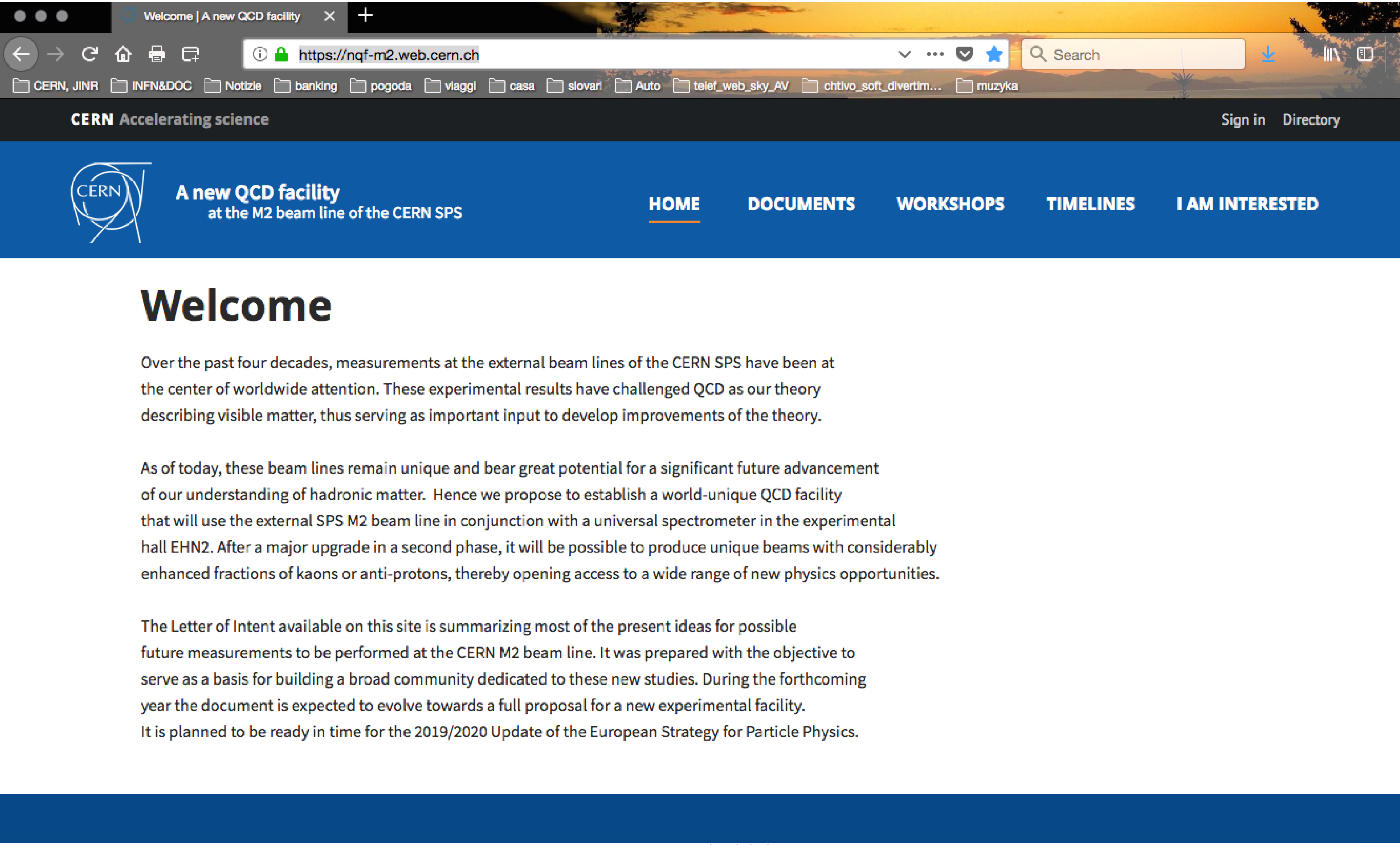
  AnDY | Phenix MPCEX | Phenix NCC



Current status of NQF initiative

A New QCD facility at the M2 beam line

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



Welcome | A new QCD facility

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

CERN Accelerating science

Sign in Directory

A new QCD facility
at the M2 beam line of the CERN SPS

HOME DOCUMENTS WORKSHOPS TIMELINES I AM INTERESTED

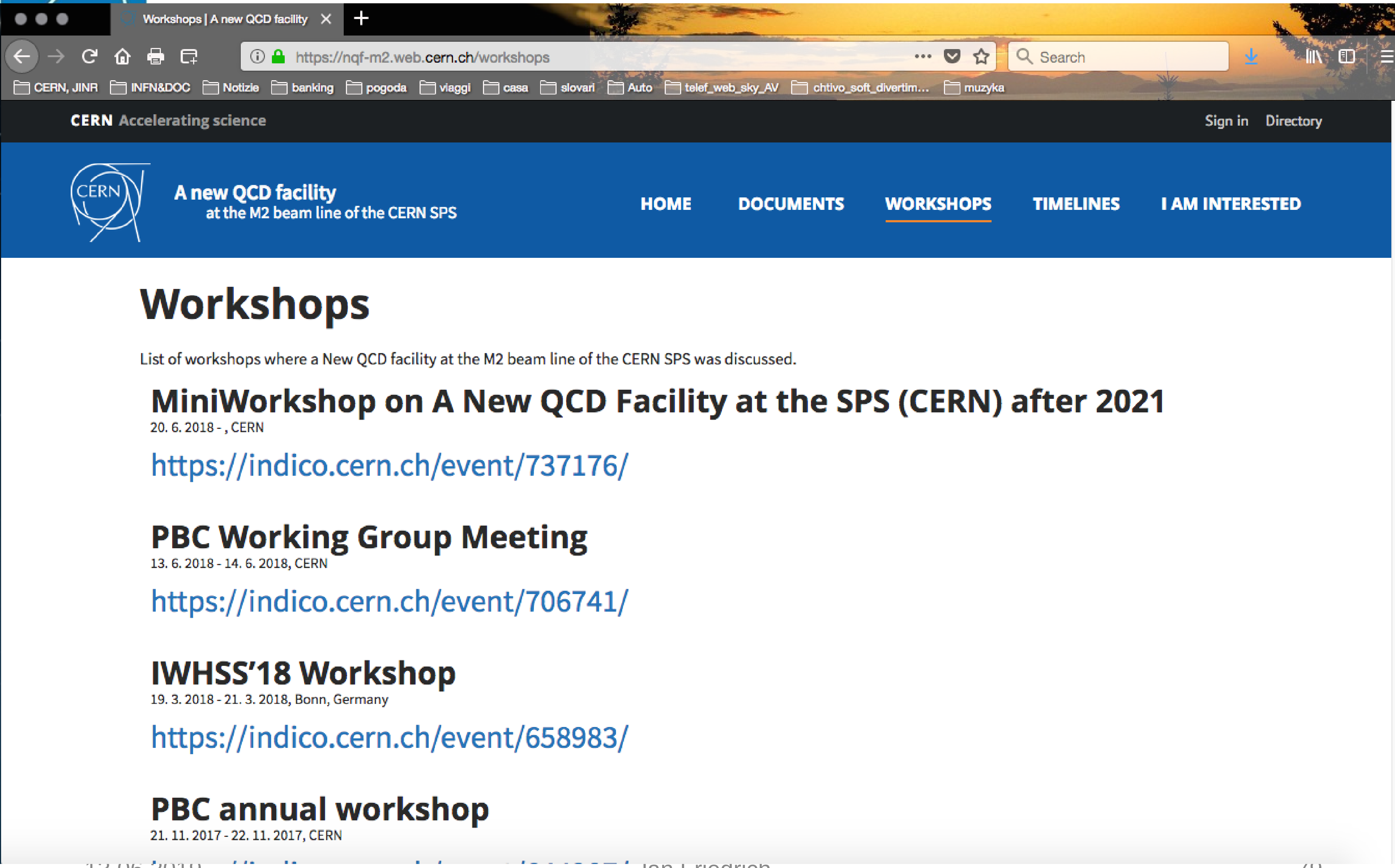
Welcome

Over the past four decades, measurements at the external beam lines of the CERN SPS have been at the center of worldwide attention. These experimental results have challenged QCD as our theory describing visible matter, thus serving as important input to develop improvements of the theory.

As of today, these beam lines remain unique and bear great potential for a significant future advancement of our understanding of hadronic matter. Hence we propose to establish a world-unique QCD facility that will use the external SPS M2 beam line in conjunction with a universal spectrometer in the experimental hall EHN2. After a major upgrade in a second phase, it will be possible to produce unique beams with considerably enhanced fractions of kaons or anti-protons, thereby opening access to a wide range of new physics opportunities.

The Letter of Intent available on this site is summarizing most of the present ideas for possible future measurements to be performed at the CERN M2 beam line. It was prepared with the objective to serve as a basis for building a broad community dedicated to these new studies. During the forthcoming year the document is expected to evolve towards a full proposal for a new experimental facility.
It is planned to be ready in time for the 2019/2020 Update of the European Strategy for Particle Physics.

A New QCD facility at the M2 beam line
WEB Page: https://nqf-m2.web.cern.ch/



A New QCD facility at the M2 beam line
WEB Page: https://nqf-m2.web.cern.ch/

Timelines | A new QCD facility

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

CERN Accelerating science

Sign in Directory

A new QCD facility
at the M2 beam line of the CERN SPS

HOME DOCUMENTS WORKSHOPS TIMELINES I AM INTERESTED

Timelines

Timelines for LoI submission to the SPSC and timelines for Proposal preparation

- End of July 2018: LoI available world wide, start of the promotion campaign. The goal is threefold:
  - to advertise the project and to win new collaborators
  - to collect new ideas
  - to establish the priority list of all possible experiments
- October 2018 (tentatively): LoI submission to SPSC (prioritized list of experiments, running plan)
- In parallel start of the Proposal preparation and New Collaboration formation
- End of 2019 (tentatively): Proposal submission to the SPSC

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

12/12/2018

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 nearly unknown quark-gluon structure of pion and kaon. Studying this process with an antiproton beam will allow for a complementary study of transverse-momentum-dependent parton distribution functions in the nucleon, and operating with pions new data on exclusive vector-meson production will emerge.

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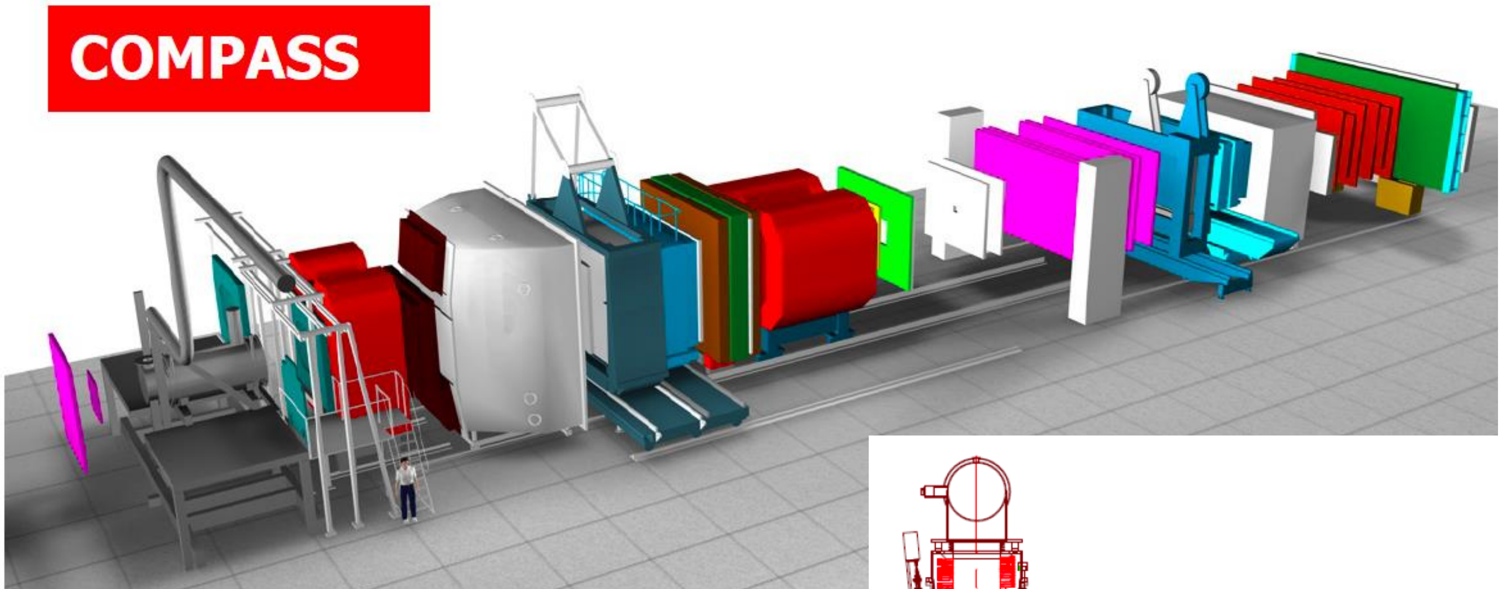
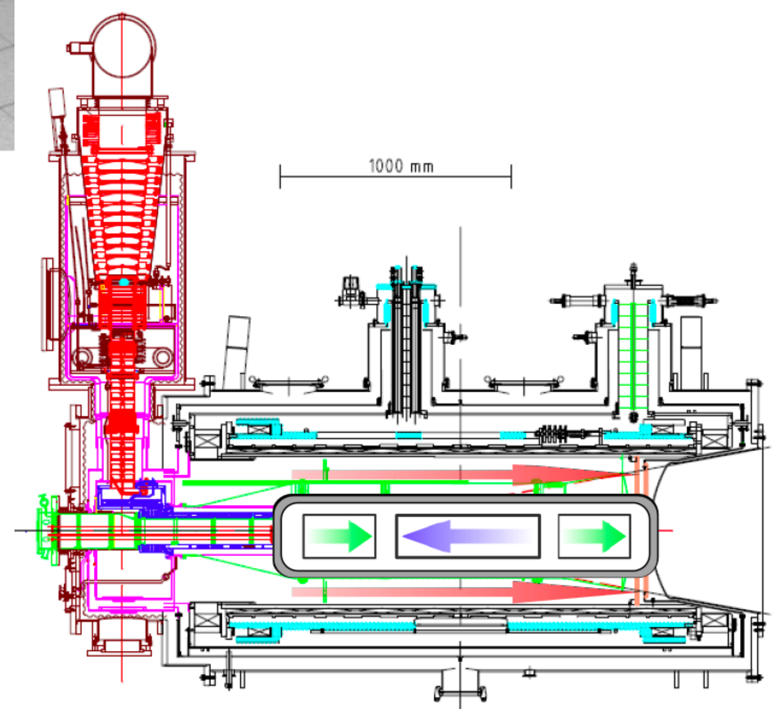
Will serve as an input for ESPP among other documents, for example summary document by Physics Beyond Colliders (PBC) committee at CERN (we are participating in the work of this committee)

Summary

- Long Term QCD program at CERN SPS ➔ strong interest in the hadron physics community
- RF separated antiproton/kaon beam will provide unique opportunity for meson spectroscopy and meson structure study
- Existing muon and hadron beams allows to enrich current COMPASS program
- New Collaboration should be founded in the next 1-2 years – JOIN!

COMPASS Spectrometer at SPS M2 beam line (CERN)





Universal and flexible apparatus.
Most important features of the two-stage COMPASS Spectrometer:

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

Short term COMPASS-II future (2021)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–SPSC–2017–XXX
SPSC-X-XXX
October 2, 2017

d-Quark Transversity

Transverse Deuteron Run (2021) was approved by CERN Research Board in June 2018

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The COMPASS Collaboration
and
PNPI

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