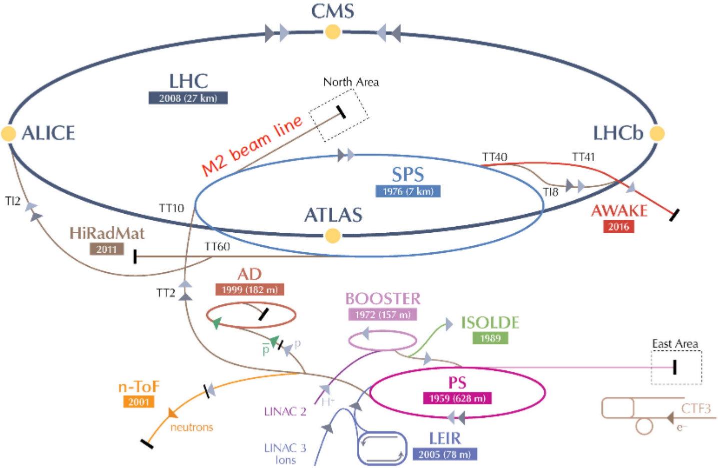
Spectroscopy, gluon structure and polarisability of kaons in the new QCD facility at the M2 beam line at CERN SPS

Barbara Badelek
University of Warsaw

On behalf of COMPASS++/AMBER

CERN acelerators and beam lines

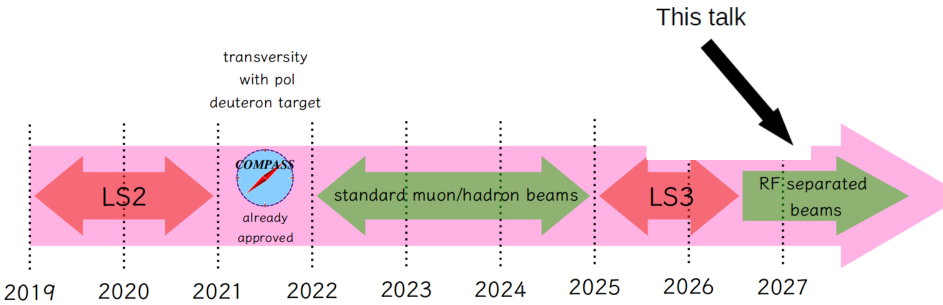


The M2 beam line supplies muons ($\mu^{\pm}$) and hadrons ($\pi^{\pm}$, K$^{\pm}$, p, $\bar{\mathrm{p}}$) to the North Area.

Panorama of COMPASS data taking

COMPASS I	2002 – 2004	nucleon structure μ–d, 160 GeV, L and T polarised target
	2005	CERN accelerator shutdown, increase of acceptance
	2006	nucleon structure μ–d, 160 GeV, L polarised target
	2007	nucleon structure μ–p, 160 GeV, L and T polarised target
	2008 – 2009	hadron spectroscopy; Primakoff reaction
	2010	nucleon structure μ–p, 160 GeV, T polarised target
	2011	nucleon structure μ–p, 200 GeV, L polarised target
	2012	Primakoff reaction; DVCS/SIDIS test
	2013	CERN accelerator shutdown, LS1
COMPASS II	2014	Drell-Yan π–p reaction with T polarised target (test)
	2015	Drell-Yan π–p reaction with T polarised target
	2016 – 2017	DVCS/SIDIS μ–p, 160 GeV, unpolarised target
	2018	Drell-Yan π–p reaction with T polarised target
	2019 – 2020	CERN accelerator shutdown, LS2
	2021	nucleon structure μ–d, 160 GeV, T polarised target (SPSC approved addendum $\Longrightarrow$ A. Martin's talk @ WG6)

Future: CERN accelerator schedule

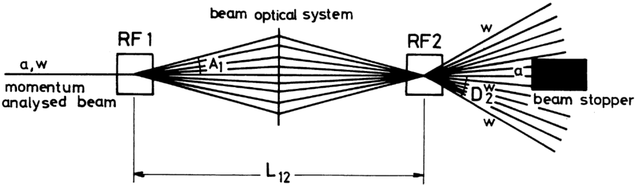


LS = long shutdown of CERN accelerators

Courtesy of Marcia Quaresma, COMPASS

RF-separated hadron beams: an idea

Panofsky-Schnell system with two RF cavities



P. Bernard et al., CERN 68-29

- Particles a,w are momentum-analysed
- Transverse kick by RF1 compensated/amplified by RF2
- Selection of a particle by selecting phase difference, $\Delta\phi$, e.g. $\Delta\phi_{\pi \mathrm{p}}$:

  $\Delta\phi = 2\pi(L_{12}f/c)(\beta_a^{-1} - \beta_w^{-1})$ for large p: $\beta_a^{-1} - \beta_w^{-1} = (m_a^2 - m_w^2)/2p^2$
- L_{12} should increase as p^2 at given f; this limits beam momentum
- Expected: $\mathrm{p_K} \gtrsim$ 80 GeV, $\mathrm{p_{\bar{p}}} \gtrsim$ 110 GeV; sophisticated R&D needed!
- Intensity gains: $\sim$ 80 for K, $\sim$ 50 for $\bar{\mathrm{p}}$ beams (now @ COMPASS: $10^5 \mathrm{s}^{-1}$ of K^-) (standard h^- beam is ~97% pions, ~2.5% kaons, ~0.5% antiprotons).

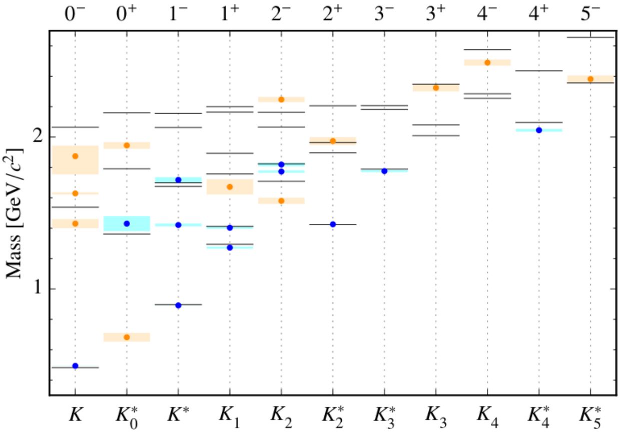
Kaon spectroscopy

COMPASS++/AMBER LoI: hep-ex 1808.00848v6

Kaon spectroscopy with intense kaon beam

Excitation spectrum of strange mesons from PDG:

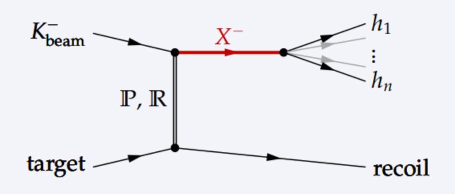
lines – relativistic quark model, blue – PDG summary table, orange – remaining ones

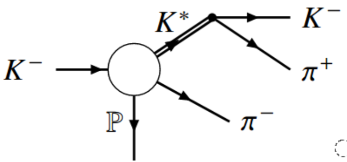


- Most PDG entries more than 30 years old
- Many K–states need confirmation and further studies
- Many QM predicted states are missing
- Hints for supernumerous states
- K spectra needed to analyse decays of heavy mesons (B, D,...)

K. Olive, Review of Particle Physics, Chinese Physics C40 (2016) 100001

Kaon spectroscopy with intense kaon beam... cont'd

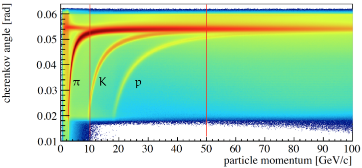




- Kaon beam may produce different final state (excited) kaons via Pomeron (diffractive production) or Regge exchange
- COMPASS collected about a million $K^-p \to K^-\pi^+\pi^-p$ events $\Longrightarrow$ analysis is in progress
- RF separated beam may supply 50 millions events/year (50x world data) $\Longrightarrow$ access to novel, accurate analysis methods

Kaon spectroscopy with intense kaon beam... cont'd

- Experimental requirements: beam ID
  - Upgrade CEDAR detectors (rate capability, thermal stability)
  - Silicon beam telescope (resolution $<40\mu$rad) needed for precise CEDAR PID
- Experimental requirements: spectrometer
  - improved Recoil Particle Detector
  - new vertex detector; improved tracking, acceptance
  - extended K ID in RICH 1 (a new RICH 0 ?): now 50% kaons in $K^-\pi^+\pi^-$ outside acceptance
  - efficient detection of photons for π^0 reconstruction to access $K^-\pi^0\pi^0$ final states



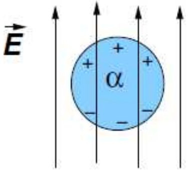
- Competition
  - J-PARC K10 beam: high intensity (10^7 K^- per spill) but low energy (2-10 GeV)
  - GlueX @ JLab: K^0_L beam: low intensity (10^4 s^{-1}), low energy (0.3-10 GeV)
  - Decays of τ and of heavy mesons @ BES III, Belle II, LHCb: low statistics
  - Conclusion: NO COMPETITORS

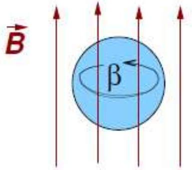
Kaon polarisability

COMPASS++/AMBER LoI: hep-ex 1808.00848v6

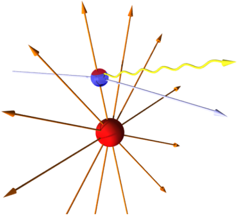
Kaon polarisability via the Primakoff process

- Electric (α) and magnetic (β) polarisabilities (measured in fm^3):





- For an extended object they are related to inner forces determinig the substructure $\longrightarrow$ QCD at low energy (e.g. chiral perturbation theory, χPT)



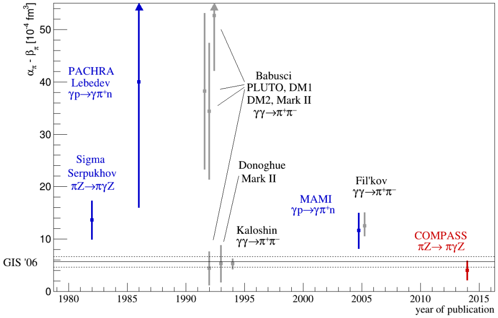
- The most direct method of (exp. and th.) determination given by Primakoff (1951), originally for the $\pi^0 \to \gamma\gamma$ lifetime: using the electric field close to a nucleus as a source of quasi-real γ.

- Polarisabilities measured through modifications of the *bremsstrahlung* (or Primakoff) reaction: K$^-$ Z $\to$K$^-$ γ Z (Z – nuclear charge)

Cartoons courtesy of J. Friedrich, COMPASS

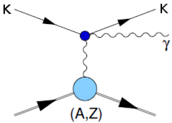
Kaon polarisability via the Primakoff process ...cont'd

- COMPASS result
  for the pion polarisability,
  Primakoff method
  and assuming $\alpha_\pi + \beta_\pi = 0$:
  (C. Adolph, PRL **114** (2015) 062002)
  $\alpha_\pi = (2.0 \pm 0.6 \pm 0.7) \times 10^{-4}$ fm



Plot: T. Nagel, PhD TUM, 2012

- Predictions for kaons:



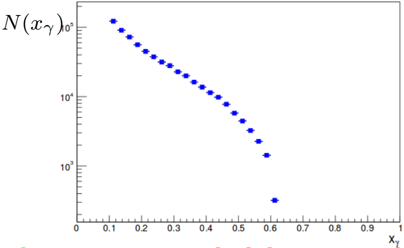
χPT (one-loop approx)
if $\alpha_K + \beta_K = 0$
then $\alpha_K = (0.64 \pm 0.10) \times 10^{-4}$ fm^3

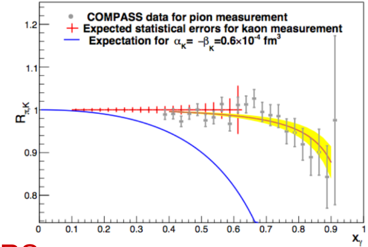
Quark confinement model
if $\alpha_K + \beta_K = 1.0 \times 10^{-4}$ fm^3
then $\alpha_K = 2.3 \times 10^{-4}$ fm^3

Experimental result from kaonic atoms spectra (1973): $\alpha_K < 200 \times 10^{-4}$ fm^3

Kaon polarisability via the Primakoff process ...cont'd

- Experimental requirements
  - 100 GeV/c RF-separated kaon beam, 5×10^6 s^{-1}
  - spectrometer configuration as for the π beam runs in 2009/2012 (CEDAR in the beam line, 0.3 X_0 Ni target, Si telescopes up- & downstream target)
  - trigger on high energy deposits in ECAL1, ECAL2
  - new DAQ system for trigger rates $\lesssim$ 100 kHz
- Results after 1 year run (5×10^{12} kaons)
  - 6×10^5 K$^-\gamma$ events, $0.1 < x_\gamma < 0.6$, $M_{K\gamma} < 0.8$ GeV/c^2 ($x_\gamma = E\gamma/E_{\rm beam}$)
  - Statistical accuracy under assumption: $\alpha_{\rm K} + \beta_{\rm K} = 0$: $\sigma_{\rm stat} = 0.03 \times 10^{-4}$ fm^3





- Competition: NO COMPETITORS

Figure on the right: courtesy of A. Guskov, COMPASS

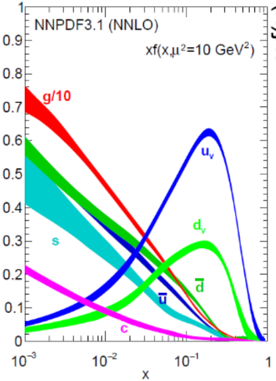
Gluon structure of kaons

via 1) prompt-photon and 2) J/Ψ production

COMPASS++/AMBER   LoI: hep-ex 1808.00848v6

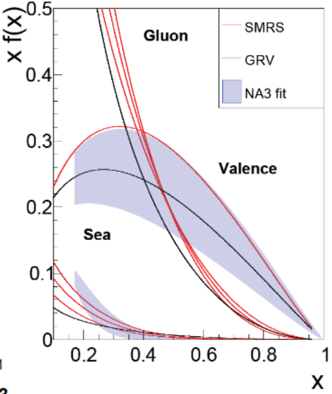
Parton structure of mesons

Proton PDFs

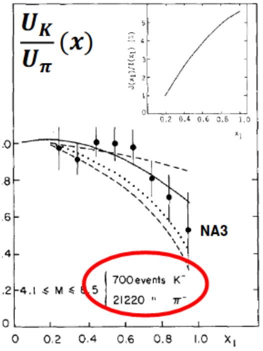


NNPDF3.1: EPJ C77 (2017) 663

Pion PDFs



Kaon PDFs



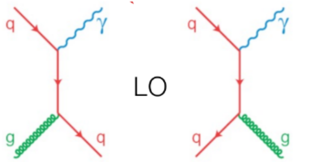
J. Badier et al., Phys. Lett. B 93 (1980) 354

GRV: M. Gluck et al, Z.Phys.C 53 (1992) 651
SMRS: P.J. Sutton et al, Phys.Rev.D 45 (1992) 2349

Courtesy of M.Grosse-Perdekamp, MiniWorkshop on Physics at a Future SPS QCD Facility, 2018

Kaon partonic structure vs π structure

- A source of information on kaon structure (PDFs), presently unknown (the only exp. attempt: NA3 experiment at CERN in the 80-ties)
- Kaons have heavier valence quarks $\Longrightarrow$ expect less glue in K than in π: $\sim$5% (K) vs $\sim$30% (π) vs $\sim$50% (N)
- Two-year run gives PDF precision as in π
- Unknown gluons in K may be accessed via gluon Compton $(\mathrm{qg} \to \gamma \mathrm{q})$ (with annihilation $(\mathrm{q\bar{q}} \to \gamma \mathrm{g})$ as a background) in the prompt-γ production, e.g. Kp$\to \gamma$ X



Courtesy of V. Andrieux, ECT* Workshop 2018

- Factorisation theorem $\Longrightarrow$ cross section:

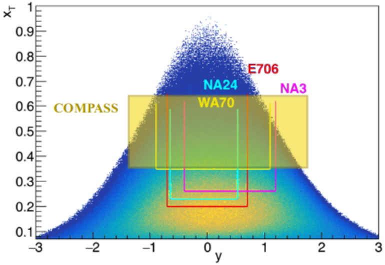
$$\mathrm{d}\sigma_{AB\to\gamma X} = \sum_{a,b=q,\bar{q},g} \int \mathrm{d}x_a \mathrm{d}x_b f_a^A f_b^B \mathrm{d}\sigma_{ab\to\gamma x} + \mathrm{d}\sigma_{fragm.}$$

(a, b = partons in hadrons A, B; $\mathrm{d}\sigma_{fragm.}$ = fragmentation photons, $\lesssim$ 20%)
WA70, E706 expts measured of $\mathrm{d}\sigma_{\pi\mathrm{N}\to\gamma X}$ for gluon determination in π.

Gluon distribution in K$^+$ via prompt γ production

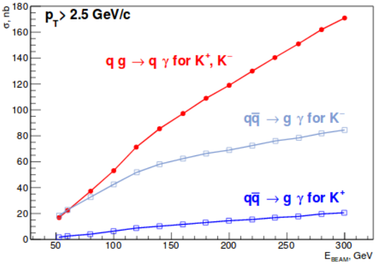
- Measurement of $E\mathrm{d}^3\sigma_{\mathrm{K}^+\mathrm{p}\to\gamma X}/\mathrm{d}p^3$ for the following conditions: $p_T >$ 2.5 GeV/c, –1.4 $< y <$1.8, E_{K^+} = 100 GeV $\Longrightarrow x_g^{\mathrm{K}}$ >0.05, $Q^2 \sim p_T^2$.

$x_T = 2p_T/\sqrt{s}$ vs y



(using Vogelsang & Whalley, J. Phys. G23 (1997) A1)

σ vs E_{beam} @ $g_\pi(x,Q^2) = g_K(x,Q^2)$



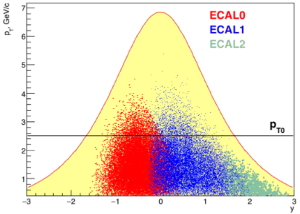
- K$^-$ beam also planned to be used
- Main contribution to systematics (dominating over statistics): photons from decays of secondary π^0 and η, especially at low p_T.

Gluon distribution in K^+ via prompt γ production... cont'd

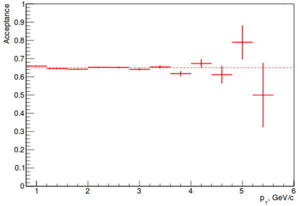
Experimental requirements:

- Beam: K^+ of 100 GeV/c or higher and intensity 5×10^6 K^+/s
- CEDAR to remove non-K particles in the beam
- target: 2m long, liquid H_2, $\sim 0.2X_0$ or a solid, low-Z material
- Present electromagnetic calorimeters ECAL0, ECAL1, ECAL2 suffice for detecting prompt photons and supress π^0 background.

p_T vs y, COMPASS 2017 setup



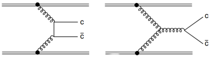
2017 COMPASS acceptance vs p_T



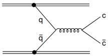
- Other: shielding upstream the target, tracking detector in front of ECAL0,...
- 140 days of running, p_T >2.5 GeV/c, $-1.4 < y < 1.8 \Longrightarrow 0.85\times10^6$ qg $\rightarrow \gamma$q evts
- Competition: NO COMPETITORS

Gluon distribution in K via J/Ψ production

- A complementary method to infer gluon distribution in K: KN$\rightarrow$ J/Ψ X$\rightarrow$ $\mu\mu$ X;
  $q\bar{q}$ annihilation and gg fusion contributions to the cross section
- Large cross section $\sim$100 nb/nucleon at low x_F at 'COMPASS' energies
- ...but J/Ψ production mechanism strongly model-dependent
- however using both K$^{\pm}$ beams, K^{+} = ($u\bar{s}$), K^{-} = ($\bar{u}s$), greatly helps:

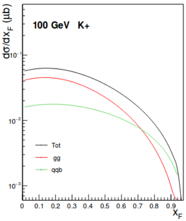


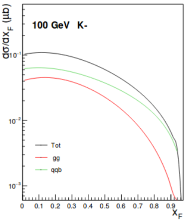
$$\bar{u}^{K^-}_{val}\ u^{N}_{val} \propto \sigma^{K^-}_{J/\Psi} - \sigma^{K^+}_{J/\Psi} \Longrightarrow \bar{u}^{K^-}_{val}$$



all other terms cancel

- The remaining gg part (and thus gluons in K) can therefore be inferred in a model dependent way, e.g. Colour Evaporation Model (here K$^{\pm}$ ^{12}C).





- spectrometer acceptance to be increased e.g. an active hadron absorber with tracking magnetic field, large acceptance for $\mu\mu$ pairs
- light isoscalar target, ^{12}C ?
- 1+1 year running with K^{+} & K^{-}; $\sim 10^6$ J/ψ evts
- no high-energy, high-intensity K beams planned in the world
- Competition: NO COMPETITORS

Requirements for future programmes @ the M2 beam line after 2021

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
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	~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	~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
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

LoI, hep-ex 1808.00848v6

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Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	[illegible]	[illegible] years	recoil silicon, modified polarised target magnet
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Prim[illegible]	[illegible] pion [illegible]life time	~100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
[illegible]s (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
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Listen to other COMPASS++/AMBER talks in this WG7

LoI, hep-ex 1808.00848v6

Outlook

- COMPASS facility is very successful in studies of nucleon structure and spectroscopy.
- "COMPASS Beyond 2020" (March 2016) and
"Physics Beyond Colliders" (ongoing from Sept. 2016) workshops at CERN reveal a strong and active interest of the community in this physics.
- COMPASS++/AMBER presented
a Letter-of-Intent concerning the long-term future, hep-ex 1808.00848v6, with a rich programme, chiefly on the μ-p elastic scattering, Drell-Yan physics and hadron structure. Proposal coming in 2019
(see also talks by V. Andrieux, S. Gevorkyan, Ch. Dreisbach at this WG7 and A. Martin at WG6).

  Apart of existing muon and hadron, new RF-separated K and $\bar{\mathrm{p}}$ beams open new possibilities in hadron structure studies.
- New groups are welcome to join and contribute!

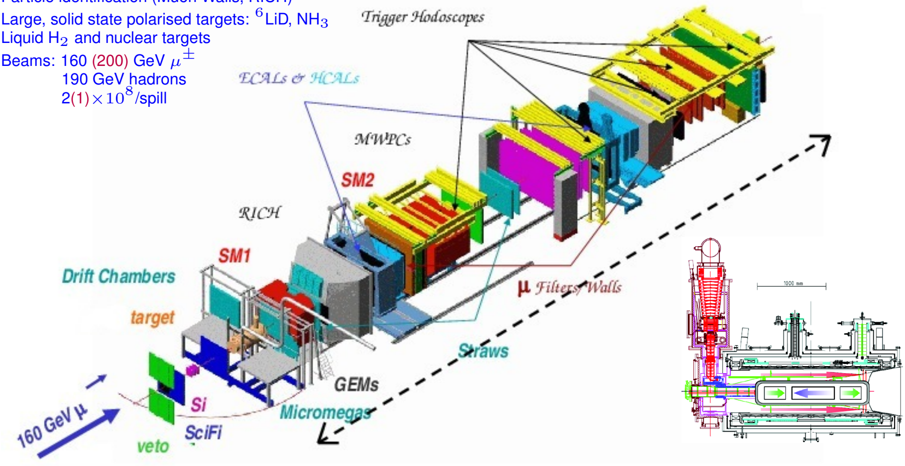
SPARES

Versatile COMPASS facility at the M2 beam line at CERN

COMPASS Spectrometer (muon run)

Nucl. Instr. Meth. A577 (2007) 455

Two stages
Calorimetry
Particle identification (Muon Walls, RICH)
Large, solid state polarised targets: ^{6}LiD, NH_3
Liquid H_2 and nuclear targets
Beams: 160 (200) GeV $\mu^{\pm}$
190 GeV hadrons
2(1)$\times 10^{8}$/spill



COMPASS++/AMBER: new QCD facility

at the M2 beam line of the CERN SPS

- Long term plans for future ($>$ 2021) experiment
  in the new QCD facility at the M2 beam line at CERN SPS
  $\Longrightarrow$ LoI: hep-ex 1808.00848v6;   PBC (QCD WG report): hep-ex 1901.04482v1
  (see also talks by V. Andrieux, S. Gevorkyan and Ch. Dreisbach at this WG7).
    - renewed collaboration (COMPASS++/AMBER)
    - proton radius measurement in μp$\rightarrow$ μp
    - muon and hadron (π, K, $\bar{\mathrm{p}}$) beams
    - conventional- and newly designed RF-separated K and $\bar{\mathrm{p}}$ beams
    - 7–8 year endeavour

- Planning began in March 2016: “Beyond 2020” workshop at CERN.
- Intertwined with “Physics Beyond Colliders” initiative at CERN ($>$Sept. 2016).
- Assessment by the European Strategy Group expected in 2020.
- Proposal to appear in 2019