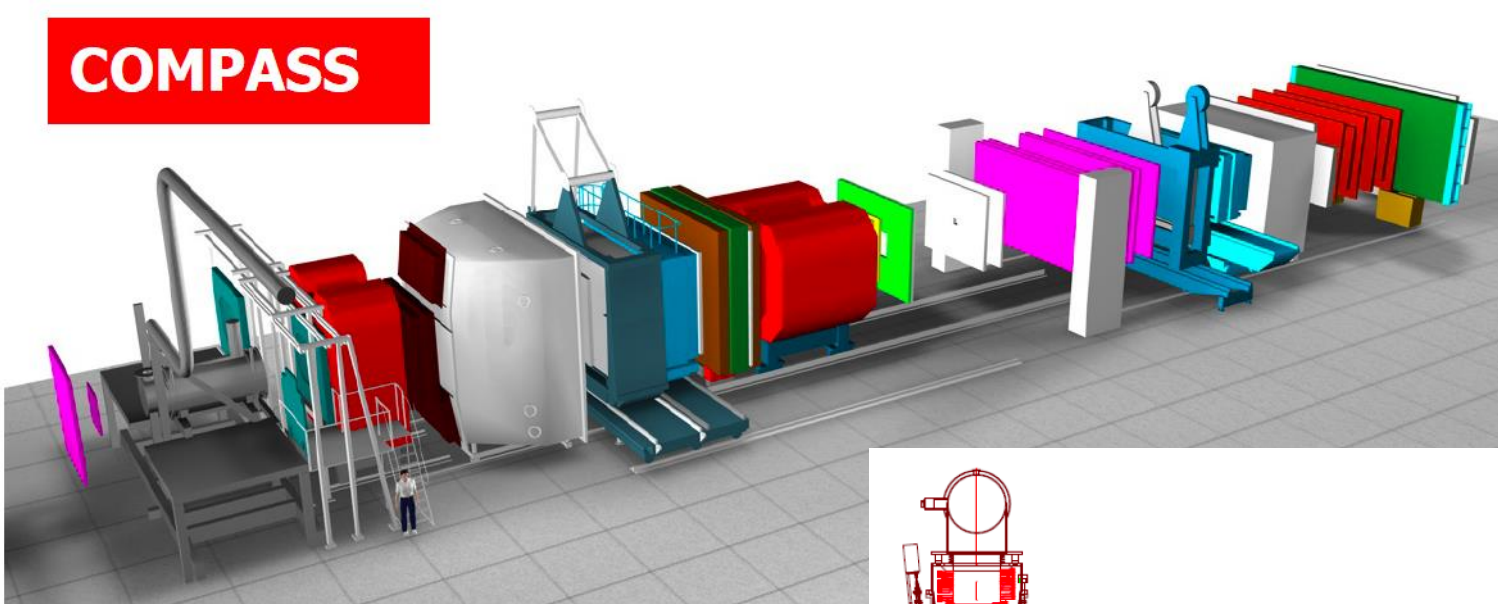
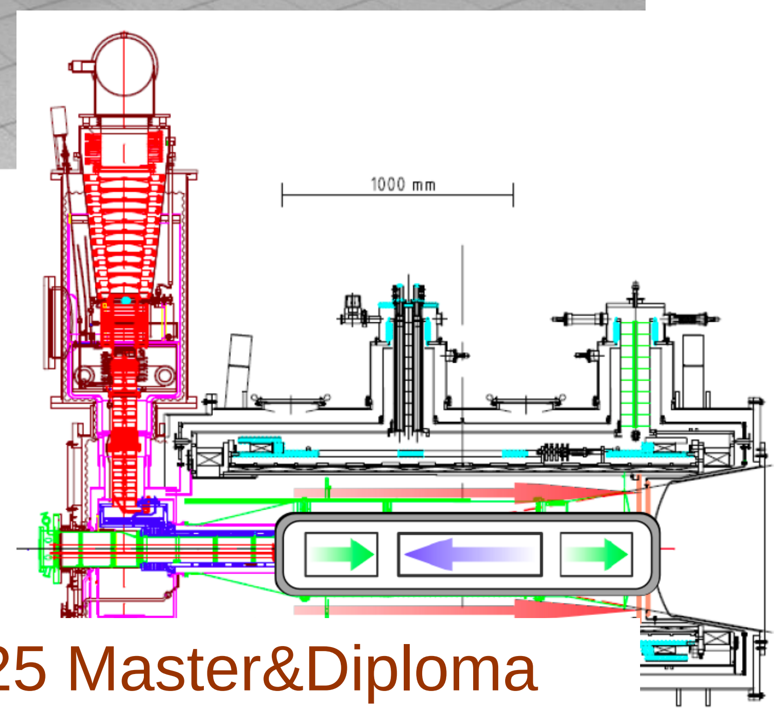
Outline

1. **COMPASS QCD facility**
2. **Beyond 2020 Workshop (March 2016)**
3. **Long term plans**
   - RF separated beam
   - Spectroscopy
   - Drell-Yan
   - Exclusive measurements with muon and hadron beams
4. **Shorter term plans**
   - SIDIS
   - Drell-Yan
   - Astrophysics
5. **Summary**

COMPASS Spectrometer at SPS M2 beam line (CERN)





Universal and flexible apparatus.

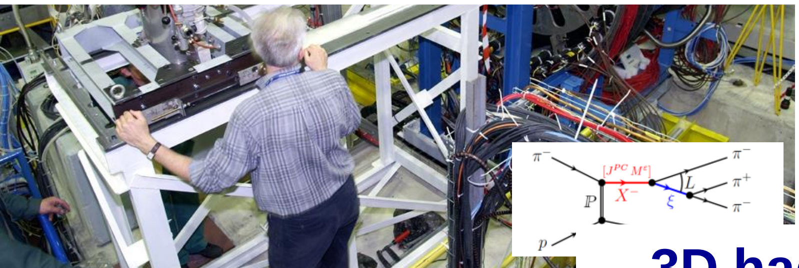
Most important features of the two-stage COMPASS Spectrometer:

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. Ad\
   syst

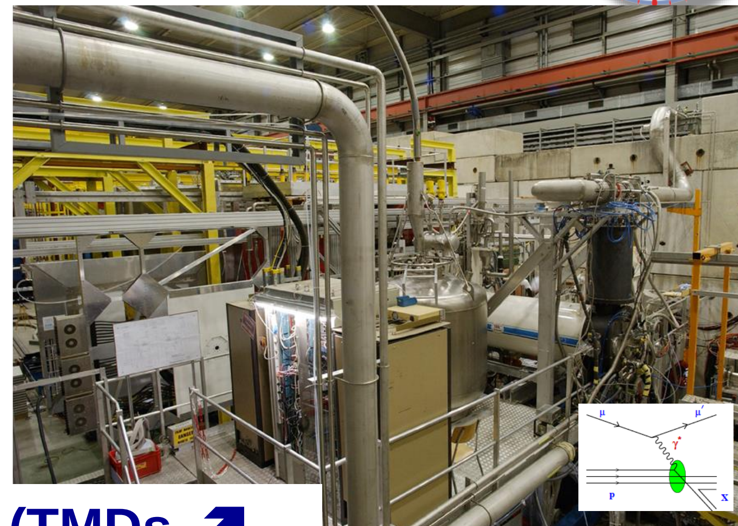
~240 physicists (~60 PhD, ~25 Master&Diploma students), 12 countries + CERN, 24 institutions

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

Exotic state, chiral dynamics



COMPASS-I
1997-2011

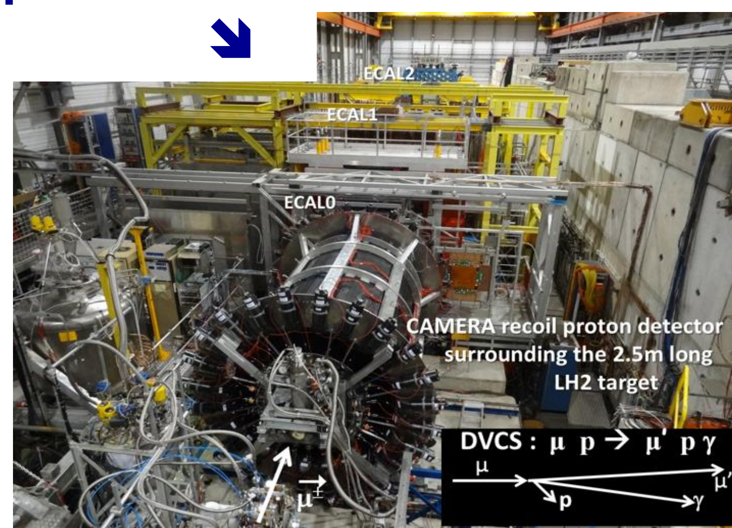


Hadron Spectroscopy &

3D hadron structure (TMDs, GPDs), spin decomposition

sed SIDIS

COMPASS-II
2012-2018



Polarised Drell-Yan

DVCS (GPDs) + unp. SIDIS

Beyond 2020 dedicated Workshop

This week – regular annual COMPASS Workshop (IWHSS'16 Kloster Seeon)

COMPASS beyond 2020 Workshop

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

222-R-001 (CERN)

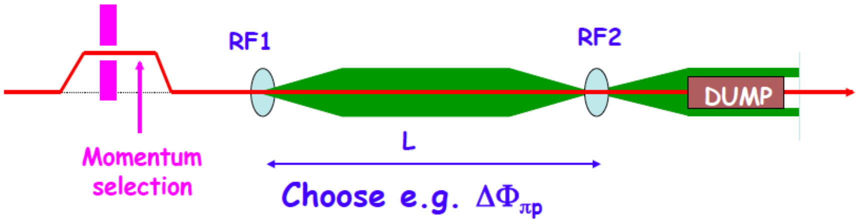
Description The goal of the workshop is to explore hadron physics opportunities for fixed-target COMPASS-like experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). The programme comprises

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

- Reviews of physics results expected in the next 10 years from major labs around the world

- Good attendance (>100 physicists), large interest
- 11 "outside" review talks – Jefferson Lab, RHIC, Fermilab, KEK (Japan) BEPC II (IHEP, Beijing), NICA (JINR, Dubna), CERN (After, LHCb), GSI (Panda), J-PARC (Japan), EIC – China;
- 7 COMPASS talks (chronol.) – SIDIS, GPDs, Chiral Dynamics, astrophysics (dark matter), Drell-Yan, hadron spectroscopy;
- 2 "round-table"-like discussions on possible future with hadron and muon beams;
- Outcome of the Workshop:
    - RF Separated antiproton/kaon beam would provide a unique opportunity for future fixed target COMPASS-like program at CERN
    - Existing muon and hadron beam allows to extend current COMPASS program by doing unique or first class measurements of exclusive processes, SIDIS and Drell-Yan

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

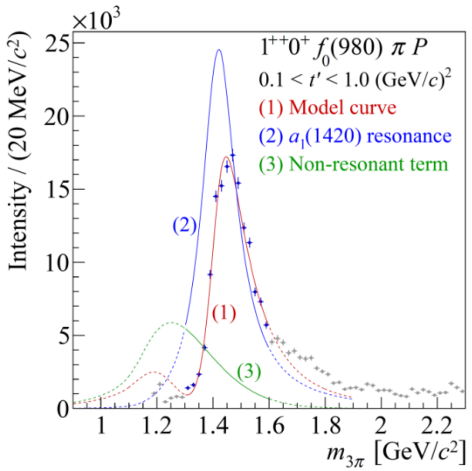
RF separated beam – Hadron spectroscopy (i)

Light Meson Sector & COMPASS contribution

3π data sample ~50×10^6 exclusive events – factor 10 to 100 to previous experiment

Good illustration or our potential is a discovery of a new axial-vector meson $a_1(1420)$ in $1^{++}0^+ f_0(980)\pi$ *P* wave (PRL).

COMPASS: $a_1(1420)$



It is shown that we have elaborated adequate methods to cope with huge statistics and produced nice results

[C. Adolph et al., COMPASS, PRL 115, 082001 (2015)]

RF separated beam – Hadron spectroscopy (ii)

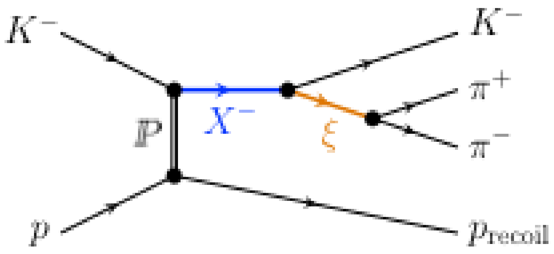
Light and Strange Meson Spectrum

RF separated kaon beam ~ 8 x 10^6 /s, beam momentum ~100 GeV

What can we contribute as COMPASS?

- State-of-the-art high-resolution spectrometer with full PID
- Advanced analysis techniques being developed in the light-quark sector

Method to be used: Kaon beam diffraction scattering on LH_2 and thin nuclear targets



- Goal: ~10 larger data sample than existing worldwide what would make possible to have similar to pion diffraction wave set: 88 waves in 11 t′ bins;
- COMPASS could rewrite PDG tables for strange mesons
- Extend studies of chiral dynamics to strange sector

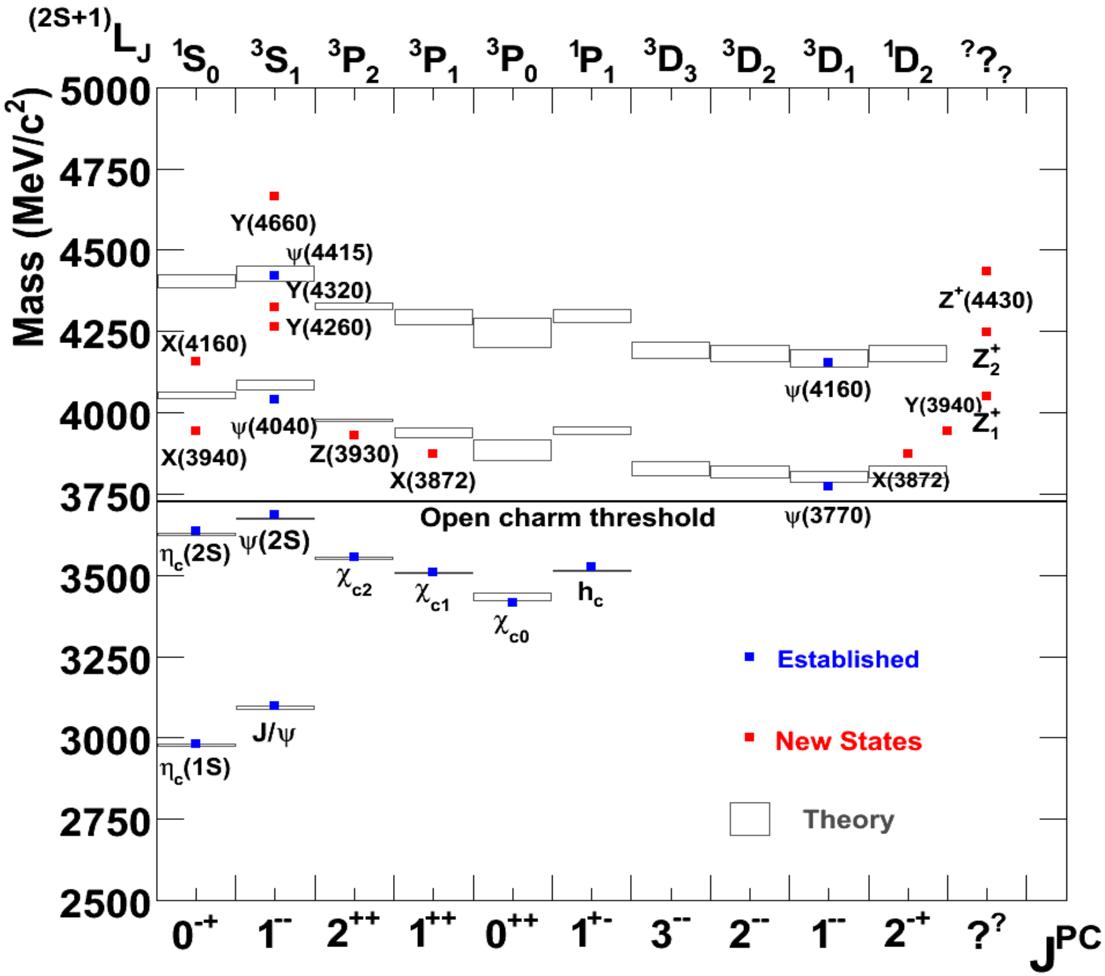
No real competitors

JParc - ~10^5 /s, low momenta kaons

JLab - ~10^4 /s, K^0 long beam, lower momenta

Unique opportunity

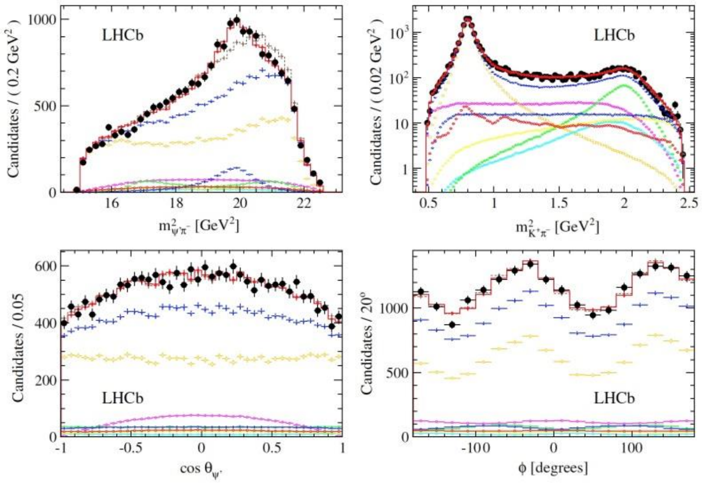
RF separated beam – Hadron spectroscopy (iii)
Charmonium spectra



[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)]

RF separated beam – Hadron spectroscopy (iv)
Charmonium-like mesons

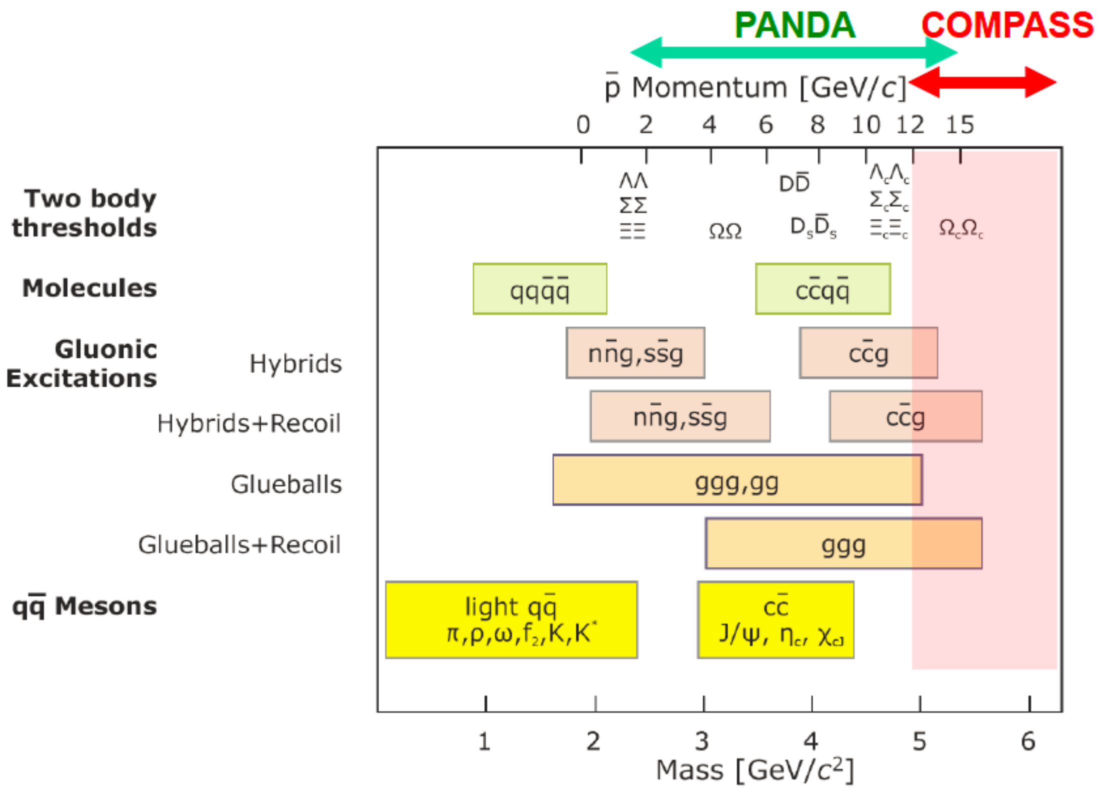
RF separated antiproton beam, beam momentum ~ 20 GeV

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



Running/planed Drell-Yan experiments, COMPASS (π^- beam on $p^\uparrow$) – unique experiment

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\ s^{-1}$)		P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^\pm + p^\uparrow$	190 GeV $\sqrt{s} = 19$	$x_t = 0.1 – 0.3$	2×10^{33}	0.14	$P_t = 80\%$ f = 0.22	1.0×10^{-3}	2014-2015, 2018
PANDA (GSI)	pbar + $p^\uparrow$	15 GeV $\sqrt{s} = 5.5$	$x_t = 0.2 – 0.4$	2×10^{32}	0.07	$P_t = 90\%$ f = 0.22	1.1×10^{-4}	>2025
AFTER	$p^\uparrow + p$	7 TeV $\sqrt{s} = 120$	$x_b = 0.1 – 0.9$	2×10^{32}	0.06	$P_b =$ 100%?	2.3×10^{-5}	>2020
NICA (JINR)	$p^\uparrow + p$	collider $\sqrt{s} = 26$	$x_b = 0.1 – 0.8$	1×10^{32}	0.04	$P_b = 70\%$	6.8×10^{-5}	>2023
PHENIX/STAR (RHIC)	$p^\uparrow + p^\uparrow$	collider $\sqrt{s} = 510$	$x_b = 0.05 – 0.1$	2×10^{32}	0.08	$P_b = 60\%$	1.0×10^{-3}	>2018
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 – 0.5$ $x_b = 0.05 – 0.6$	8×10^{31} 6×10^{32}	0.08	$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	>2021
SeaQuest (FNAL: E-906)	p + p	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$ $x_t = 0.1 – 0.45$	3.4×10^{35}	---	---	---	2012 - 2017
Pol tgt DY‡ (FNAL: E-1039)	p + $p^\uparrow$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 – 0.45$	4.4×10^{35}	0 – 0.2*	$P_t = 85\%$ f = 0.176	0.15	2018-2019
Pol beam DY§ (FNAL: E-1027)	$p^\uparrow$ + p	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$	2×10^{35}	0.04	$P_b = 60\%$	1	2020

‡ *8 cm NH_3 target* / § *$L = 1 \times 10^{36}\ cm^{-2}\ s^{-1}$ (LH_2 tgt limited) / $L = 2 \times 10^{35}\ cm^{-2}\ s^{-1}$ (10% of MI beam limited)*

**not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams, f=0.22 for π^- beam on NH_3)

RF separated beam – Drell-Yan (i)

RF separated antiproton/kaon beam, the maximal possible beam intensity (very rough estimate) of ~3-4x10^7 /s can be reached (antiprotons) and ~8x10^6 /s (kaons)

Assuming flux of 1x10^7 /s for kaon/antiproton,
background free high mass range $4 < M_{\mu\mu} < 9\ GeV/c^2$ and
140 days of data taking with the efficiency of 2015 Drell-Yan Run.

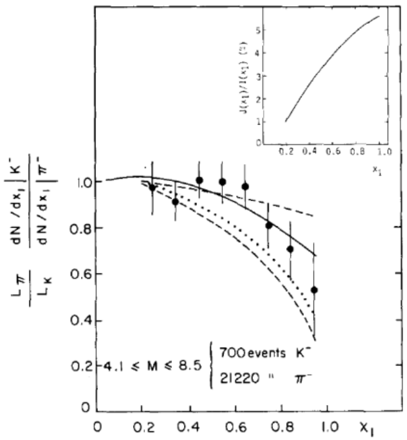
	NH_3	Al (7cm)	W	NA3	NA10	E537	E615
K^- beam	14,000	2,800	29,600	700			
$\bar{p}$ beam	15,750	2,750	22,500			387	

The overall gain for RF separated beam compare to previous experiments is factor 50 to 100

RF separated beam – Drell-Yan (ii)
kaon-induced DY

- Kaon-induced DY is the only source of information on **kaon structure which is unknown**
- Together with pion induced DY will represent the unique data set for unstable particle structure study
- Unpolarised case, possibility to use different nuclear targets targets (like LH_2, Al, W, Cu):
    1. Kaon structure function (PDFs)
    2. Nucleon strange quark structure
    3. Fundamental Lam-Tung relation for kaon
    4. Boer-Mulders TMDs (quark-spin – quark-k_T correl.) for kaons
    5. EMC effects & flavour dependent EMC effects (kaons)
    6. Kaon Distribution Amplitude, *J/Ψ* production mechanism

$$\frac{d\sigma^{K-}/dx_1}{d\sigma^{\pi-}/dx_1} = \frac{\bar{u}_K}{\bar{u}_\pi}(x_1)$$



Collaboration, PLB 93, 354 (1980

NA10 π^-W

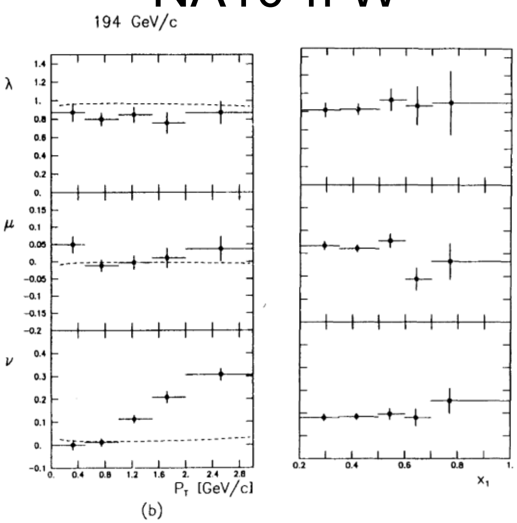
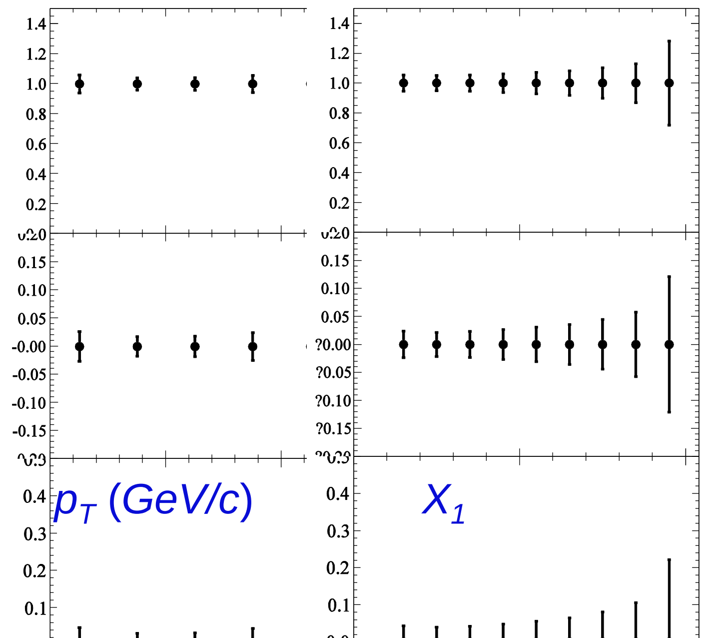


Fig. 3

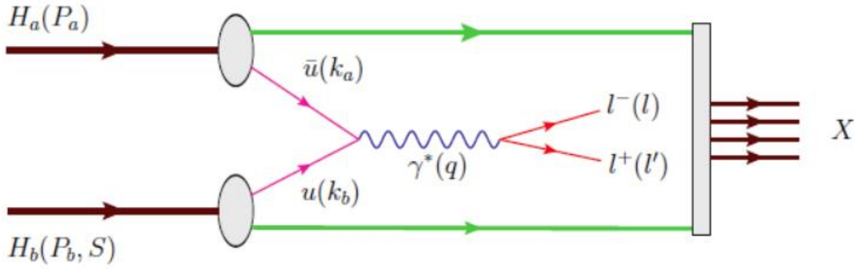
COMPASS K^-W

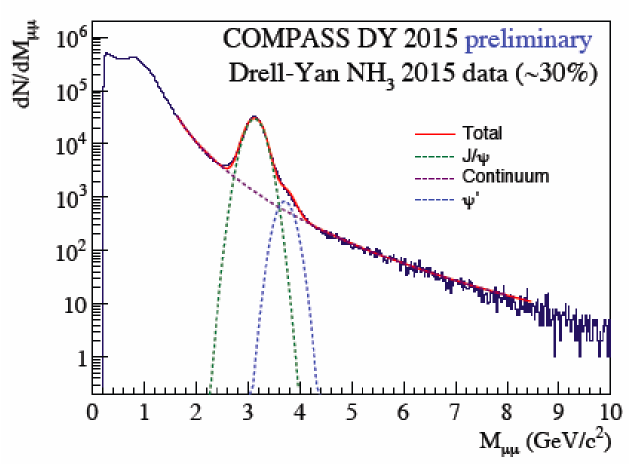


No competitors, unique data

RF separated beam - Drell-Yan (iii)
antiproton-induced Drell-Yan

- Antiproton-induced polarised DY makes **TMD's extraction model independent**
- Allows to profit from good knowledge of proton PDFs (from SIDIS) and as alternative probe permits to test TMDs universality
- New data on all TMDs induced asymmetries in both High Mass and *J/Ψ* regions:
  1. Model independent Boer-Mulders (quark-spin – quark-k_T correl.) extraction (CPT equiv.)
  2. Model independent Transversity extraction
  3. Lam-Tung relation for antiprotons (QCD effects)
  4. Sivers asymmetry (nucleon-spin – quark-k_T correlations) with no uncertainty from pion PDFs
  5. Sivers function for gluons (*J/Ψ* regions)
  6. Flavour separated TMDs extraction
  7. EMC effects & flavour dependent EMC effects





No competitors, unique data

Exclusive measurements using COMPASS Polarised Target

Generalised Parton Distributions (GPD) *E* and access to Orbital Angular Momentum

Recoil detector to be inserted in the COMPASS PT magnet

- Muon beam, access to GPD *E* processes to be measured:

  ✓ DVCS (μ p↑ ➔ μ p γ)
  ✓ DVMP (μ p↑ ➔ μ ρ (ω) γ)

  Projections: ➔

  Competitors: No competitors in COMPASS kinematic range (small x_{Bj})

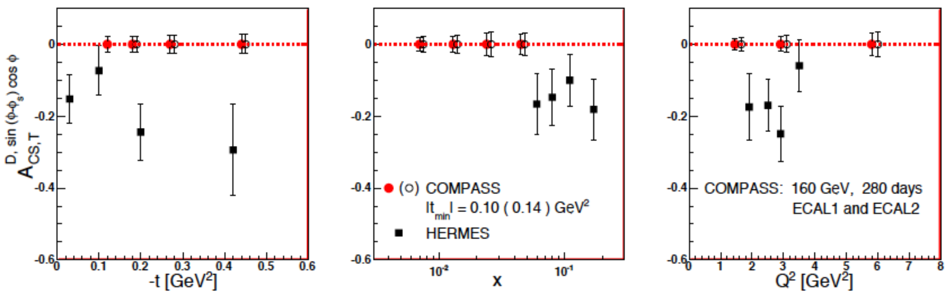


Figure 13: Expected statistical accuracy of $A_{CS,T}^{D,\sin(\phi-\phi_s)\cos\phi}$ as a function of $-t$, x_B and Q^2 from a measurement in 280 days, using a 160 GeV muon beam and ECAL1+ECAL2. Solid and open circles correspond to the simulations for the two hypothetical configurations of the target region (see text). Also shown is the asymmetry $A_{U,T}^{\sin(\phi-\phi_s)\cos\phi}$ measured at HERMES [41] with its statistical errors.

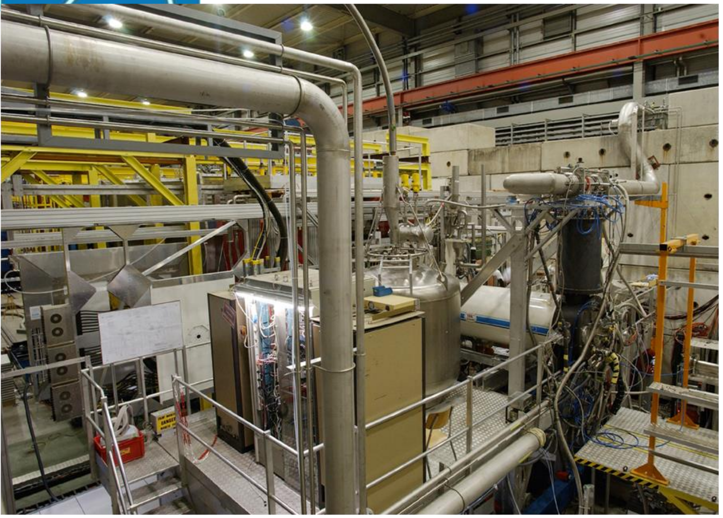
- Hadron beam (π^- dominated), processes to be studied:

  ✓ π p↑ ➔ $\mu^+ \mu^-$ p
  ✓ π p↑ ➔ $\mu^+ \mu^-$ π p

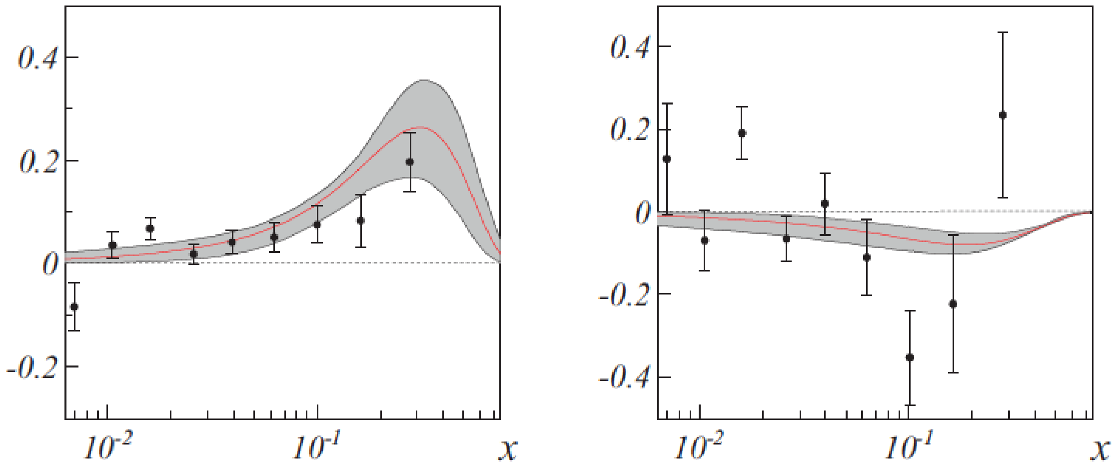
  Projections & feasibility: under investigation

  Competitors: No competitors in our kinematical domain

SIDIS – transversely polarised Deuteron Target (^6LiD) Transversity/Sivers PDF extraction



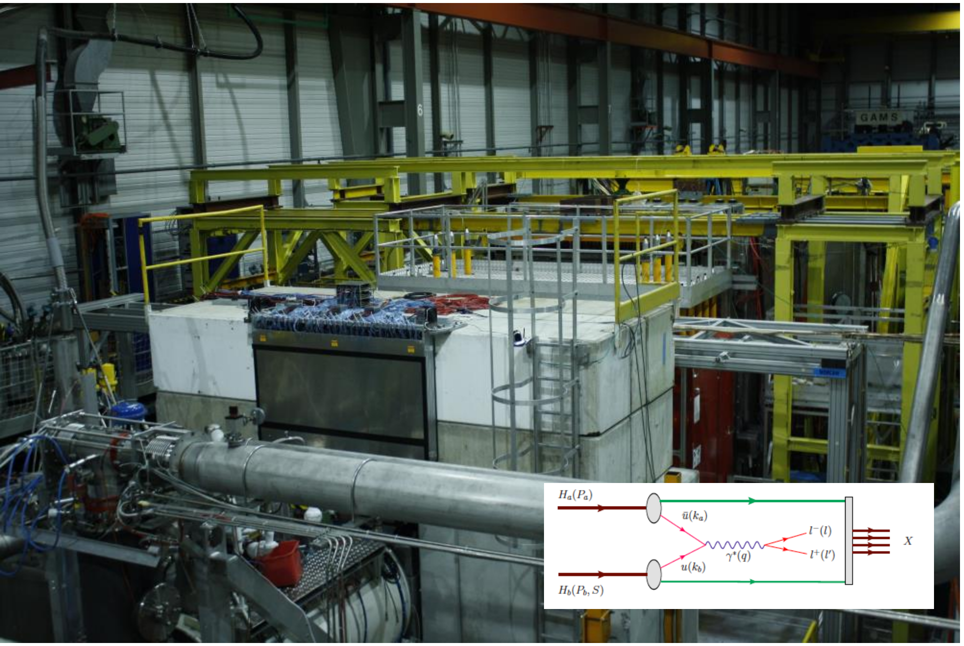
- TMD PDFs and Transversity $h_1(x)$ are flavour dependent.
- Flavour separation ➔ data on both proton (NH_3) and deuteron (^6LiD) transversely polarised targets.
- Proton data set is factor of 4 compare to deuteron (see error bars for transversity $h_1(x)$ in the plot below)
-It is logical to increase the deuteron data set (so far the only data sets available are COMPASS (^6LiD) and CLAS (^3He) targets).



Competitors:
- No competitors in our kinematic range, Jlab will start by 2020

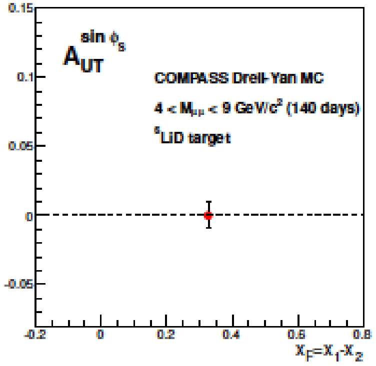
Fig. 6: $xh_1^u(x)$ (left) and $xh_1^d(x)$ (right) from the 'two hadron' asymmetries of 2010 proton and of 2002-2004 deuteron data (from[30]). The curves show the transversity PDFs obtained from a fit of Collins asymmetries [29]

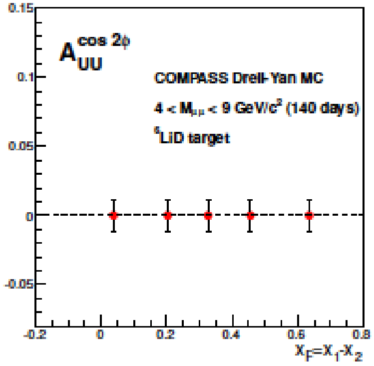
COMPASS pion-induced Drell-Yan (LH_2, ^{6}LiD)

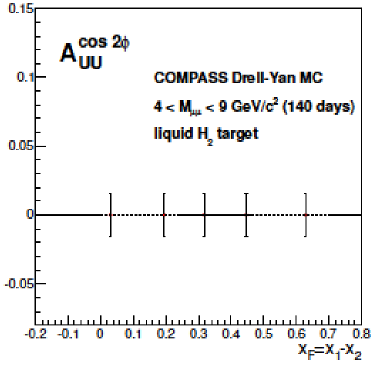


The same arguments as for SIDIS TMDs flavour separated extraction valid as well for our Drell-Yan data, both TMDs and “normal” pion PDFs.

- World largest Drell-Yan data set on NH_3 (first ever polarised data)
- In order to perform f.s. – must to have data on ^{6}LiD, will be first ever data sample (projections are shown)
- Pion PDFs flavour separation
- Shorter exposition on unpolarised LH_2 target is required to test fundamental Lam-Tung relation and to extract Boer-Mulders TMD using “clean” (no nuclear effects) LH target – complementary to SIDIS.

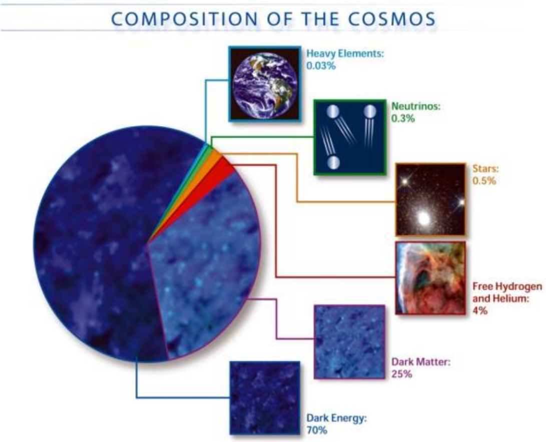






Unique, no competitors

Astrophysics – search for dark matter,
contribution from COMPASS



- New AMS(2) data – the antiparticle flux is well known now (few % pres.);
- 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%.

Thus the primary goal is to measure inclusive antiproton (positron, gamma) production cross section in a wide kinematical range with the precision <10%. **Compared to NA49 COMPASS have factor ~1000** as luminosity. COMPASS:

- Proton beam energy range 50-250 GeV
- Secondary particles identification:
  - Antiprotons (RICH)
  - Positrons and Gamma (ECals)

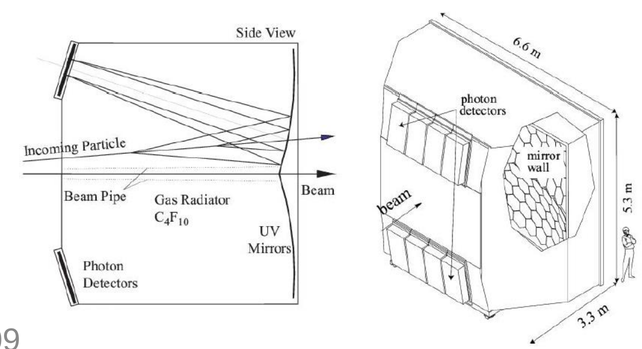
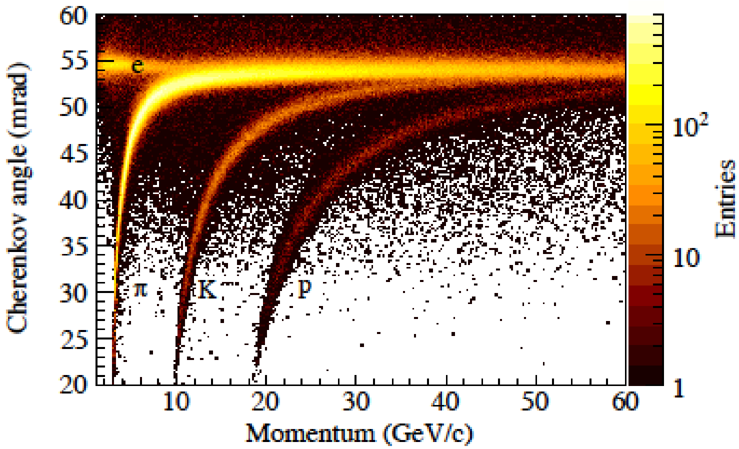


Figure 34. COMPASS RICH-1: principle and artistic view.



Summary

- "Beyond 2020" workshop at CERN (March 20-22) ➔ success, strong interest in the hadron physics community

- RF separated antiproton/kaon beam will provide unique opportunity for hadron spectroscopy and Drell-Yan physics

- Existing muon and hadron beams allows to extend current COMPASS program

Thank you!