Overview of COMPASS - Past, Present, and Future

Oleg Denisov (CERN/INFN-Torino)
Outline

1. COMPASS facility at CERN
2. Hadron spectroscopy
   • Light quark spectroscopy
   • Heavy state X(3872)
3. Nucleon structure with muon beam
   • Transversity
   • Sivers
   • Multiplicities
4. GPDs access via DVCS and DVMP
5. Polarised Dell-Yan experiment
6. COMPASS beyond 2020
   • COMPASS short term future
   • COMPASS-like experiment long term future
7. Summary

See as well talks by Franco, Stephane, Alexey, Catarina, Bakur, Boris, Johannes, Vincent, ….
COMPASS QCD facility at CERN (SPS)

Common Muon Proton Apparatus for Structure and Spectroscopy

~240 physicists, 12 countries + CERN, 24 institutions
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 ($\text{NH}_3$ or $^6\text{LiD}$) as well as liquid hydrogen target and nuclear targets
3. Powerful tracking (350 planes) and PiD systems (Muon Walls, Calorimeters, RICH)
COMPASS QCD facility at SPS M2 beam line (CERN) (secondary hadron and lepton beams)

Exotic state, chiral dynamics

COMPASS-I
1997-2011

Hadron Spectroscopy & Polarizability

3D hadron structure,
Proton spin decomposition
(spin crisis)

COMPASS-II
2012-..

Polarised SIDIS

Polarised Drell-Yan

DVCS (GPDs) + unp. SIDIS
Diffractive dissociation I

2008-2009 data taking, 190 GeV/c hadron beam on a hydrogen target.

$3\pi$ data sample $\sim 50 \times 10^6$ exclusive events – factor 10 to 100 to previous experiment

Potential illustration – discovery of a new axial-vector meson $a_1(1420)$ in $1^{++}0^+ f_0(980)\pi$ $P$ wave (PRL).

A lot of work to be invested to develop new methods in order to cope with huge data sample.

Analysis steps:
1. p-w decomposition: 88x88 spin-density matrix for each $t'$ (f.-m. transfer squared) and $m_{3\pi}$ bin (mass-independent fit)
2. For selected wave set (14 waves, 60% of total intensity) fit of the spin-density matrix by a resonance models (B.-W. + coherent non-resonant term)
Statistical uncertainties are negligible compared to systematic ones. Extensive studies were performed to estimate the systematic uncertainties by varying the fit model. For all 14 selected p.w. most of resulting resonance parameters are in agreement with PDG averages, so we are confident in our method.

Left – $a$-like mesons, right – $\pi$-like mesons. Plotted – closed circles – best fit parameters, rectangles – systematic uncertainties for 11 resonant components used in the resonance-model fit to the spin-density matrix of selected 14 waves.
Diffractive dissociation III

Non-resonant contribution – main contributor to systematic. Believed it is caused by pion fluctuation into $\pi^+\pi^-$ isobar ($\rho(770)$) and virtual $\pi$ – Deck amplitude. It projects in many waves.

Deck amplitude was introduced in the mass-independent fit (very promising): blue – no Deck, Red + Green – (resonant + Deck)
- low non-resonant contribution - stays unchanged (a)
- considerable fraction of non-resonant contribution – absorbed into Deck amplitude (b)
- high spin waves – Deck contribution absorbs all intensity (c)
Exotic $X(3872)$ lepto-production update

$X(3872)$ is the first charmonium-like exotic hadron discovered by the Belle collaboration in 2003 and studied than in other experiments. Various interpretations exists: tetra-quark, $DD^*$-molecule, hybrid $ccg$ state, glue-ball or else. Additional information on its width would help to shed light on its nature.

COMPASS muon beam data 2003→2010
Study $J/\psi \pi^+\pi^-$ subsystem of exclusive final state $J/\psi \pi^+\pi^-\pi^\pm$

COMPASS di-pion mass spectrum is different compared to the Atlas observation.
\[ \frac{d\sigma}{dx dy d\phi_n d\phi_s} = \frac{\alpha}{2yQ^2} \left( 1 + \frac{y^2}{2(1-x)} \right) \left( F_{UU,I} + \varepsilon F_{UU,L} \right) \]

\[ = 1 + 2\varepsilon (1+\varepsilon) A^{\text{even}}_{UU} \cos \phi_n + \varepsilon A^{\text{even}}_{UU} \cos 2\phi_n + \lambda \sqrt{2\varepsilon (1-\varepsilon)} A^{\text{odd}}_{LL} \sin \phi_n \]

\[ + S_L \left[ \sqrt{2\varepsilon (1+\varepsilon)} A^{\text{odd}}_{UL} \sin \phi_n + \varepsilon A^{\text{even}}_{UL} \sin 2\phi_n \right] \]

\[ + S_T \left[ \sqrt{1-\varepsilon^2} A^{\text{odd}}_{LT} + \sqrt{2\varepsilon (1-\varepsilon)} A^{\text{even}}_{LT} \cos \phi_n \right] \]

\[ \times \left[ A^{\text{even}}_{TT} \sin (\phi_n - \phi_s) + \varepsilon A^{\text{odd}}_{TT} \sin (\phi_n + \phi_s) \right] \]

\[ + S_T \left[ \sqrt{2\varepsilon (1+\varepsilon)} A^{\text{odd}}_{UT} \sin \phi_s + \varepsilon A^{\text{even}}_{UT} \sin 3\phi_s \right] \]

\[ + \sqrt{2\varepsilon (1+\varepsilon)} A^{\text{odd}}_{UT} \sin \phi_s + \sqrt{2\varepsilon (1-\varepsilon)} A^{\text{even}}_{UT} \sin (2\phi_n - \phi_s) \]

\[ + S_T \lambda \left[ \sqrt{1-\varepsilon^2} A^{\text{odd}}_{LT} \cos (\phi_n - \phi_s) + \sqrt{2\varepsilon (1-\varepsilon)} A^{\text{even}}_{LT} \cos \phi_n + \sqrt{2\varepsilon (1-\varepsilon)} A^{\text{odd}}_{LT} \cos (2\phi_n - \phi_s) \right] \]
Collins asymmetry (transversity) zero knowledge ~10 years ago
First seen non zero asymmetry by HERMES on p in 2004

COMPASS:
- Measured on p/D in SIDIS and in di-hadron SIDIS
- Compatible results COMPASS/HERMES
- No (or very slow) QCD evolution? Very intriguing result!

\[ A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^q \otimes H_{1q}^{1h} \]
Collins asymmetry (transversity)
Deuteron data – flavour separation possible

COMPASS:

Flavour dependent

Reasonably well constrained using Belle & Hermes & COMPASS data

fit to HERMES p, COMPASS d, Belle e+e- data
\[ \frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} = \]
\[ \frac{\alpha}{x y Q^2} \left( \frac{y^2}{2(1-\varepsilon)} \right) \left( 1 + \frac{y^2}{2x} \right) (F_{UU,\tau} + \varepsilon F_{UU,L}) \]

\[ + \sqrt{2\varepsilon (1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos \phi_h + \varepsilon A_{UU}^{\cos^2 \phi_h} \cos 2\phi_h \]
\[ + \lambda \sqrt{2\varepsilon (1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin \phi_h \]
\[ + S_L \left[ \sqrt{2\varepsilon (1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin \phi_h + \varepsilon A_{UL}^{\sin^2 \phi_h} \sin 2\phi_h \right] \]
\[ + S_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon (1-\varepsilon)} A_{LL}^{\cos \phi_h} \cos \phi_h \right] \]
\[ \times \left[ \begin{array}{c}
A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\
+ \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\
+ \varepsilon A_{UT}^{\sin^2(\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \\
+ \sqrt{2\varepsilon (1+\varepsilon)} A_{UT}^{\sin \phi_h} \sin \phi_h \\
+ \sqrt{2\varepsilon (1+\varepsilon)} A_{UT}^{\sin^2(2\phi_h - \phi_s)} \sin(2\phi_h - \phi_s) \\
+ \sqrt{2\varepsilon (1-\varepsilon)} A_{UT}^{\cos \phi_h} \cos \phi_s \\
+ \sqrt{2\varepsilon (1-\varepsilon)} A_{UT}^{\cos^2(\phi_h - \phi_s)} \cos(2\phi_h - \phi_s) \\
+ S_T \lambda + \sqrt{2\varepsilon (1-\varepsilon)} A_{UT}^{\cos \phi_s} \cos \phi_s \end{array} \right] \]

Quark

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>( f_1^u(x, k_T^2) ) number density</td>
<td>( h_1^{1u}(x, k_T^2) ) Boer-Mulders</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>( g_1^u(x, k_T^2) ) helicity</td>
<td>( h_1^{1L}(x, k_T^2) ) worm-gear L</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>( f_{1T}^{1L}(x, k_T^2) ) Sivers</td>
<td>( g_{1T}^{1u}(x, k_T^2) ) Kotzinian-Mulders worm-gear T</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>( h_{1T}^{1T}(x, k_T^2) ) transversity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>( h_{1T}^{1L}(x, k_T^2) ) pretzelosity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

+ two FFs: \( D_{1a}(z, P_T^2) \) and \( H_{1a}^{1h}(z, P_T^2) \)...
Sivers asymmetry: first round (earlier 2000):
Sivers 2004 – first Hermes data at proton – non zero asymmetry, COMPASS at deuteron - zero

COMPASS Results of 2005
Hep-ex/0503002
Solid state $^6$LD polarised target

Hermes Results of 2004
hep-ph/0408013
Gaseous H$_2$ polarized target

Doubts…..
Joint data analysis form Hermes and COMPASS – no contradictions

As it was shown by Mauro Anselmino and Colleagues (second half of 2005) when first extraction of Sivers function has been performed from Hermes and COMPASS data (Transversity’2005, hep-ph/051101)) that the contributions from u- and d-quarks are opposite.
Sivers 2009 – final results Hermes&COMPASS data perfectly fits together

COMPASS Final results on deuteron (data 2002-2004) PLB 673 (2009)

Hermes Final results on proton PRL 103 (2009)

Flavour separation is essential
COMPASS ↔ Hermes proton data
COMPASS Sivers is smaller – QCD evolution eff.?

Even if exist evolution has to be rather slow
Unpolarised SIDIS
NEW!! Access to TMD-FFs via hadron multiplicities

TMD multiplicity – ratio of hadron yields and the number of DIS events in multi-dimensional space is the most relevant experimental observable to investigate spin-averaged TMD-PDFs and TMD-FFs

$^6\text{LiD}$ (deuteron) isoscalar target

$$\frac{d\mathcal{N}_h^h}{d\mathcal{N}_{\text{DIS}}} \propto \sum q e_q^2 q D_q^h$$

the cross-section dependence on $p_{T_h}$ comes from:

- intrinsic $k_T$ of the quarks
- $p_\perp$ generated in the quark fragmentation

$\langle p_{T_h}^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_T^2 \rangle$

The small $P_{hT}^2$ region ($< 1 \text{ (GeV/c)}^2$) - hadron transverse momenta are expected to arise from non-perturbative effects
Larger $P_{hT}^2$, - contributions from higher-order perturbative QCD are expected to dominate.
NEW!! TMD hadron multiplicities in SIDIS (multidimensional)

Fig. 5: Multiplicities of positively (full squares) and negatively (full circles) charged hadrons as a function of $P_{H}^{2}$ in $(x, Q^2)$ bins for $0.2 < z < 0.3$. Error bars on the points correspond to the statistical uncertainties. The systematic uncertainties ($\sigma_{sys}/M^{h}$) are shown as bands at the bottom.
NEW!! TMD hadron multiplicities in SIDIS (multidimensional)

Fig. 7: Same as Fig. 5 for $0.4 < z < 0.6$.  

total: 4918 data points
SIDIS (kaon) multiplicities


The 3-dimensional data set (x, y and z) ➔ an important input for future NLO pQCD analyses of world data in terms of FFs.

Important message – HERMES and COMPASS data are in tension. Can not be explained only by different $Q^2$ range, the discussion is going on.

Recently new results were produced on the kaon multiplicity ratio $K^+/K^-$, at high $z$, $0.75 < z < 1$. Surprisingly our data go far beyond the LO upper boundary value of $(u+d)/(\bar{u}+\bar{d})$ calculated at $x=0.03$ using MSTW08L as well as beyond the actual predictions of the $K^+/K^-$ multiplicity ratio using Lund model or LO DSS fit.
2012, 20 days long data taking, 160 GeV pion beam for calibration, $\mu^+$ and $\mu^-$ for physics, 2.5 meters long $LH_2$ target
Two competing processes (Bethe-Heitler and DVCS) Contribute differently in the different $x(\nu)$-ranges
COMPASS acceptance for DVCS: rather smooth and symmetric in $\phi_{\gamma^*\gamma}$
Using: \((d\sigma^{\leftrightarrow} + d\sigma^{\rightarrow\rightarrow})\)

Integrate over \(\phi\)

Subtract Bethe-Heitler (BH)

\[
\frac{d\sigma}{d|t|} \propto e^{-B|t|}; \quad <r_\perp^2 > \sim 2B(x_{Bj}) \quad \text{at small } x_{Bj}
\]
\[ B = 4.31 \pm 0.62 \pm 0.09 (\text{GeV}/c)^{-2} \]
The final statistics penalised by late start (08/07/2015) because of the PT magnet and spectrometer commissioning.

9 periods are collected (~2 weeks long each, polarisation is inverted after first week)

Good machine performance: on average 84%
Good spectrometer availability: ~80%
First ever polarised Drell-Yan paper ([CERN-EP/2017-003, hep-ex/1701.02453](https://arxiv.org/abs/1701.02453)) has been submitted to PRL – very positive comments by referees, being published soon.

Total number of $J/\psi$ (NH$_3$) is $\sim 1,500.00$

Total number of HM DY ($4.3 \text{ GeV/c}^2 < M_{\mu\mu} < 8.5 \text{ GeV/c}^2$) (NH$_3$) is $\sim 35,000$
The measured mean Sivers asymmetry and the theoretical predictions for different $Q^2$ evolution schemes from Anselmino (DGLAP), Echevarria (TMD1) and Sun (TMD2). The dark-shaded (light-shaded) predictions are evaluated with (without) the sign-change hypothesis.

Mean TSAs. Systematic uncertainties are shown as error bands next to the vertical axis.
NEW!! TSAs in Drell-Yan compared to SIDIS

\[
\frac{d\sigma}{dx dy dz d\phi_T d\phi_z} \propto \left( F_{UU,1} + \varepsilon F_{UU,1} \right) \left\{ 1 + \ldots \right\}
\]

\[
+ S_T \left\{ \begin{array}{l}
A_{UT}^{\text{sin}(\phi_T - \phi_z)} \sin(\phi_T - \phi_z) \\
+ \varepsilon A_{UT}^{\text{sin}(\phi_T + \phi_z)} \sin(\phi_T + \phi_z) \\
+ \varepsilon A_{UT}^{\text{sin}(3\phi_T - \phi_z)} \sin(3\phi_T - \phi_z) \\
+ \sqrt{2}\varepsilon(1+\varepsilon)A_{UT}^{\text{sin}\phi_T} \sin(\phi_T) \\
+ \sqrt{2}\varepsilon(1+\varepsilon)A_{UT}^{\text{sin}(2\phi_T - \phi_z)} \sin(2\phi_T - \phi_z) \end{array} \right\}
\]

COMPASS PLB 770 (2017) 138

\[
\frac{d\sigma^{10}}{d\Omega} \propto F_U^1 \left\{ 1 + \cos^2 \theta_{CS} \right\} \left\{ 1 + \ldots \right\}
\]

\[
+ S_T \left\{ \begin{array}{l}
A_T^{\text{sin}\phi_T} \sin\phi_T \\
+ D_{[\varepsilon^2\phi_T]} \left\{ \begin{array}{l}
A_T^{\text{sin}(2\phi_T - \phi_S)} \sin(2\phi_T - \phi_S) \\
+ \varepsilon A_T^{\text{sin}(2\phi_T + \phi_S)} \sin(2\phi_T + \phi_S) \end{array} \right\} \\
+ D_{[\varepsilon^2\phi_S]} \left\{ \begin{array}{l}
A_T^{\text{sin}(\phi_T - \phi_S)} \sin(\phi_T - \phi_S) \\
+ \varepsilon A_T^{\text{sin}(\phi_T + \phi_S)} \sin(\phi_T + \phi_S) \end{array} \right\} \end{array} \right\}
\]

COMPASS arXiv:1704.00488 [hep-ex]

<table>
<thead>
<tr>
<th>h^+</th>
<th>16 &lt; Q^2/(GeV/c)^2 &lt; 81</th>
<th>\langle y \rangle \sim 0.238</th>
</tr>
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<tr>
<td>A_{UT}^{\text{sin}(\phi_T - \phi_z)}</td>
<td>\text{h^+}</td>
<td>16 &lt; Q^2/(GeV/c)^2 &lt; 81</td>
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<tr>
<td>A_{UT}^{\text{sin}(3\phi_T - \phi_z)}</td>
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</tr>
</tbody>
</table>

COMPASS 2015 data
4.3 < M_{\mu\mu}/(GeV/c)^2 < 8.5

-0.05 0 0.05

-0.2 0 0.2

7-11-2017

Oleg Denisov
Further improvements for 2018 Drell-Yan Run
CEDARs system

One of the main goals of the polarised Drell-Yan program at COMPASS is unambiguous verification of the Sivers asymmetry sign change.

First year of DY data taking (2015) was very successful, the validity of the experimental approach was proven and significant statistics were collected. The statistical uncertainty of Sivers asymmetry was found to be equal to 0.057.
In order to unambiguously verify the Sivers sign change our goal is to reduce the statistical error for total DY data sample (2015+2018) by factor ~2 down to ~0.03.

The number of improvements are planned for 2018 data taking compared to 2015:
- Shorter commissioning time and longer data taking period (factor ~1.3 gain);
- New beam telescope as we were suffering in 2015 from insufficient redundancy (at least 3 more SciFi planes) (gain in incoming track reconstruction efficiency of at least 10%);
- Better spectrometer protection against high radiation in the area (factor 1.1)
- Improvements on trigger system (purity and efficiency), reduced DAQ and Veto system dead time (hard to quantify right now, factor of ~1.2)
- Further optimisation of the Polarised target polarization procedure, higher average PT polarisation (potentially factor ~1.1-1.2)
- Neural network techniques will be applied to subtract resonant background (factor ~ 1.4)

IMPORTANT: In order to carry out the DY program with kaons and antiprotons the CEDARs system will be upgraded: new photomultipliers, read/out, thermal insulation.
Beyond 2020 dedicated Workshop
This week – regular annual COMPASS Workshop (IWHSS’16 Kloster Seeon)

- 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 – essential for the future of the COMPASS-like experiment at SPS

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

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

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

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

“Normal” $h^-$ beam composition:
$\sim 97\%$ ($\pi$) $\sim 2.5\%$ (K) $\sim 0.5\%$ (pbar)
Short term future COMPASS Proposal (extension of the COMPASS-II experiment) was submitted to the SPSC ~1 month ago. The goal is to ensure COMPASS running after Long Shutdown II (2019-2020) for at least one year to keep collaboration going on and to provide an access to fresh funds. Decision by the SPSC (recommendation) is expected in January 2018.
Short term COMPASS future I:
SIDIS – transversely polarised Deuteron Target ($^6$LiD)

- TMD PDFs and Transversity $h_1(x)$ are flavour dependent.
- Flavour separation $\Rightarrow$ data on both proton ($\text{NH}_3$) and deuteron ($^6$LiD) 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 ($^6$LiD) and CLAS ($^3$He) targets).

Competitors:
- No competitors in our kinematic range,
Jlab will start by 2020
Short term COMPASS future I:
Proton radius measurement in elastic mu-p scattering

- 100 GeV SPS muon beam (M2)
- Hydrogen high-pressure active TPC target cell (PNPI development)
- Measure the cross-section (shape) over broad $Q^2$ range $10^{-4}$ ... $10^{-1}$
- From $10^{-3}$ ... $2 \times 10^{-2}$ fit the proton radius (slope of electric form factor)
- Precision 0.03 fm with conservative beam trigger (0.5% beam intensity)
- Goal: 0.01 fm (from 180 days) trigger concept to be solved

unique because...
- muon beam requires a factor 10 smaller radiative corrections than e- beams (vs. Mainz, Jlab)
- high-energy muon beam, very small scattering angles: practically no Coulomb correction (vs. MUSE)
- best systematics control

IKAR active target cell
A. Vorobyev, St. Petersburg

Oleg Denisov
Long term future COMPASS-like experiment LoI (new physics) is under preparation now. The goal is to bring together strongly renewed COMPASS-based Collaboration (will have a different name) enthusiastic about opportunities of doing physics at CERN with conventional and newly designed RF separated kaon and antiproton beams. The total duration of the program might reach 7-8 years of running with hadron and muon beams.

Indications by European Strategy Group is expected at the beginning of 2020 (May?).
RF separated beam – Hadron spectroscopy (i) 
Light Meson Sector & COMPASS contribution

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

3π data sample \( \sim 50 \times 10^6 \) 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).

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

[Oleg Denisov]
RF separated beam – Hadron spectroscopy (ii)
Light and Strange Meson Spectrum

RF separated kaon beam $\sim 8 \times 10^6$/s, beam momentum $\sim 100$ 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: $\sim 10$ 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 - $\sim 10^5$/s, low momenta kaons
JLab - $\sim 10^4$/s, $K^0$ long beam, lower momenta

Unique opportunity

7-11-2017
Oleg Denisov
### Running/planed Drell-Yan experiments, COMPASS (π⁻ beam on p↑) – unique experiment

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Particles</th>
<th>Energy (GeV)</th>
<th>x_b or x_t</th>
<th>Luminosity (cm⁻² s⁻¹)</th>
<th>P_b or P_t (f)</th>
<th>rFOM#</th>
<th>Timeline</th>
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<tbody>
<tr>
<td>COMPASS (CERN)</td>
<td>π⁺⁻ + p↑</td>
<td>190 GeV</td>
<td>x_t = 0.1 – 0.3</td>
<td>2 x 10³³</td>
<td>0.14</td>
<td>P_t = 80% f = 0.22</td>
<td>1.0 x 10⁻³</td>
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<tr>
<td>PANDA (GSI)</td>
<td>pbar + p↑</td>
<td>15 GeV</td>
<td>x_t = 0.2 – 0.4</td>
<td>2 x 10³²</td>
<td>0.07</td>
<td>P_t = 90% f = 0.22</td>
<td>1.1 x 10⁻⁴</td>
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<tr>
<td>AFTER</td>
<td>p↑ + p</td>
<td>7 TeV</td>
<td>x_b = 0.1 – 0.9</td>
<td>2 x 10³²</td>
<td>0.06</td>
<td>P_b = 100%?</td>
<td>2.3 x 10⁻⁵</td>
</tr>
<tr>
<td>NICA (JINR)</td>
<td>p↑ + p</td>
<td>collider</td>
<td>x_b = 0.1 – 0.8</td>
<td>1 x 10³²</td>
<td>0.04</td>
<td>P_b = 70%</td>
<td>6.8 x 10⁻⁵</td>
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<td>PHENIX/STAR (RHIC)</td>
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<td>collider</td>
<td>x_b = 0.05 – 0.1</td>
<td>2 x 10³²</td>
<td>0.08</td>
<td>P_b = 60%</td>
<td>1.0 x 10⁻³</td>
</tr>
<tr>
<td>fsPHENIX (RHIC)</td>
<td>p↑ + p</td>
<td>√s = 510</td>
<td>x_b = 0.1 – 0.5</td>
<td>8 x 10³¹ 6 x 10³²</td>
<td>0.08</td>
<td>P_b = 60% P_b = 50%</td>
<td>4.0 x 10⁻⁴</td>
</tr>
<tr>
<td>SeaQuest (FNAL: E-906)</td>
<td>p + p</td>
<td>120 GeV</td>
<td>x_b = 0.35 – 0.9</td>
<td>3.4 x 10³⁵</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Pol tgt DY‡ (FNAL: E-1039)</td>
<td>p + p↑</td>
<td>120 GeV</td>
<td>x_t = 0.1 – 0.45</td>
<td>4.4 x 10³⁵</td>
<td>0 – 0.2*</td>
<td>P_t = 85% f = 0.176</td>
<td>0.15</td>
</tr>
<tr>
<td>Pol beam DY§ (FNAL: E-1027)</td>
<td>p↑ + p</td>
<td>120 GeV</td>
<td>x_b = 0.35 – 0.9</td>
<td>2 x 10³⁵</td>
<td>0.04</td>
<td>P_b = 60%</td>
<td>1</td>
</tr>
</tbody>
</table>

*8 cm NH₃ target / ⁵L = 1 x 10³⁶ cm⁻² s⁻¹ (LH₂ tgt limited) / L = 2 x 10³⁵ cm⁻² s⁻¹ (10% of MI beam limited) / *not constrained by SIDIS data / ⁶rFOM = relative lumi * P² f² wrt E-1027 (f=1 for pol p beams, f=0.22 for π⁻ beam on NH₃)
COMPASS pion-induced Drell-Yan \((\text{LH}_2, \text{}^6\text{LiD, Ni...})\)

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 \(\text{NH}_3\) (first ever polarised data)
- In order to perform f.s. – must to have data on \(^6\text{LiD},\) will be first ever data sample (projections are shown)
- Pion PDFs flavour separation
- Shorter exposition on unpolarised \(\text{LH}_2\) 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**
RF separated antiproton/kaon beam, the maximal possible beam intensity (very rough estimate) of $\sim3\times10^7$ /s can be reached (antiprotons) and $\sim8\times10^6$ /s (kaons)

Assuming flux of $1\times10^7$ /s for kaon/antiproton, background free high mass range $4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$ and 140 days of data taking with the efficiency of 2015 Drell-Yan Run.

<table>
<thead>
<tr>
<th></th>
<th>NH$_3$</th>
<th>Al (7cm)</th>
<th>W</th>
<th>NA3</th>
<th>NA10</th>
<th>E537</th>
<th>E615</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-$ beam</td>
<td>14,000</td>
<td>2,800</td>
<td>29,600</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{p}$ beam</td>
<td>15,750</td>
<td>2,750</td>
<td>22,500</td>
<td></td>
<td>387</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 LH₂, 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-kₚ correl.) for kaons
  5. EMC effects & flavour dependent EMC effects (kaons)
  6. Kaon Distribution Amplitude, J/Ψ production mechanism

\[
\frac{d\sigma^K}{dx_1} = \frac{d\sigma^\pi}{dx_1} = \frac{\bar{u}_K(x_1)}{\bar{u}_\pi(x_1)}
\]

NA10 π⁻W

COMPASS K⁻W

Fig. 3

NA3 Collaboration, PLB 93, 354 (1980)

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 \( \Psi \) 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 (\( \Psi \) regions)
  6. Flavour separated TMDs extraction
  7. EMC effects & flavour dependent EMC effects

No competitors, unique data
Gluon structure of the kaon in completely unknown while gluon contribution to its mass is especially important for understanding of the nature of the kaon. Some models conclude about much smaller gluon contribution in the kaon rather than in the pion while opposite arguments based on the experimental results have been also expressed. Prompt photon production in the hard process of the gluon Compton scattering in kaon-nucleon interaction provides access to the gluon PDFs of the kaon.

The data taking with the kaon beam has to be preceded by data taking with a pion beam at similar conditions for detailed study of systematic effects.
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)
Summary

• COMPASS: from glorious past to bright future

• “Beyond 2020” workshop at CERN (March 20-22 2016) ➔ success, strong interest in the hadron physics community, anticipate PBC activity initiated by CERN

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

• Existing muon and hadron beams offer unique possibilities to extend current COMPASS program by adding new measurement

• Short term future proposal (SIDIS + Proton Radius) has been already submitted to SPSC, Long term future LoI is in preparation, will be made public at the beginning of 2018
Thank you!