COMPASS - a facility to study QCD

Eva-Maria Kabuß,
Institut für Kernphysik,
Mainz University
for the COMPASS collaboration

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– COMPASS experiment
– What we have done
– What we want to do
Bielefeld, Bochum, Bonn, Burdwan/Calcutta, CERN, Dubna, Erlangen, Freiburg, Lissabon, Mainz, Moscow, Munich, Prague, Protvino, Saclay, Tel Aviv, Turino, Trieste, Warsaw, Yamagata
(30 institutes, 240 physicists)

COMMON MUON AND PROTON APPARATUS
FOR STRUCTURE AND SPECTROSCOPY

Muon beam
Spin dependent structure functions
Gluon polarisation
Polarised quark distributions
Transversity
Lambda polarisation
Vector meson production

Hadron beam
Primakoff scattering
Mesonspectroscopy
– Glueballs
– Hybrids
– Multi-quark states
Charmed baryons
SPS proton beam: $1.4 \times 10^{13}$/spill of 4.8s, 400 GeV/c

- Secondary hadron beams ($\pi, K, \ldots$): $2 \times 10^8$/spill, 150-270 GeV/c
- Tertiary muon beam (80% pol): $2 \times 10^9$/spill, 100-200 GeV/c

$\rightarrow$ Luminosity $\sim 5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ with polarised targets
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SPS
CNGS
Gran Sasso 732 kms
COMPASS

LHC

high energy beam(s), broad kinematic range, large angular acceptance
Polarised target

- Polarised target: $^6$LiD, NH$_3$
- Polarisation: 50%, 90%

COMPASS 2002-03 data
Spin structure results

Asymmetries and PDFs from longitudinal and transverse data (p and d)

PLB 676 (2009) 31

PLB 690 (2010) 466

EPJC 64 (2009) 171

PRL 94 (2005) 202002

E. Kabuß, Bad Honnef, 3.12.2010
Spin structure

Data

- polarised $^6$LiD (L,T) data taking 2002-2006
- polarised NH$_3$ (L,T) data taking 2007

Analysis

- most results published or released for conferences
- analysis of single high $p_T$ hadrons still going on
- focus on unpolarised physics from $^6$LiD (isoscalar)

Addendum

- 2010 NH$_3$ transversely polarised → transversity, Sivers DF
- 2011 NH$_3$ longitudinally polarised → low $x$ $g_1^p$, strange quark polarisation
Spectroscopy results

- diffractive, central and Primakoff production
- $\pi$ beam on Pb in 2004
- $\pi$ and p beam in 2008/9
- $\text{IH}_2$, Pb, Ni, W targets
Exploring the 3-dim. phase-space structure of the nucleon

up to now: main focus on $\Delta q$ quark helicity distributions
$\Delta q_{\perp}$ transverse quark distributions
(from DIS and SIDS)
→ longitudinal momentum structure of the nucleon

next step:
**Generalised Parton Distributions**
→ accessible in exclusive reactions like DVCS and DVMP

**Transverse Momentum Dependent Distributions**
→ accessible in SIDIS and Drell Yan processes

in addition:
**QCD at very low $Q^2$: Pion Polarisability**
→ Primakoff processes

**COMPASS II proposal:**
submitted in May for 5 years of data taking in the first step
recommended by SPSC in September for initially 3 years of data taking
Primakoff experiments with $\pi, K$

$$\pi^- Z \rightarrow \pi^- Z \gamma$$

- Low energy behaviour predicted by chiral perturbation theory

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \left[ \frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} \right]_{\text{point}} + C \cdot \frac{s - m^2_{\pi}}{s^2} \left[ (1 - \cos\theta_{cm})^2(\alpha_{\pi} - \beta_{\pi}) + (1 + \cos\theta_{cm})^2(\alpha_{\pi} + \beta_{\pi}) \right] \frac{s^2}{m^4_{\pi}} + \text{h.o.}$$

- deviation from pointlike due to pion polarisabilities

- $\alpha_{\pi} - \beta_{\pi}$ measured at backward angles, $\alpha_{\pi} + \beta_{\pi}$

2-loop chiral predictions

$$\alpha_{\pi} + \beta_{\pi} = (0.2 \pm 0.1) \cdot 10^{-4} \text{ fm}^3$$

$$\alpha_{\pi} - \beta_{\pi} = (5.7 \pm 1.0) \cdot 10^{-4} \text{ fm}^3$$

experiments: $\alpha_{\pi} - \beta_{\pi}$ from 4 to $14 \cdot 10^{-4} \text{ fm}^3$
Pion polarisability measurement

- effect increases with $s^2$
- effects due to $\alpha_\pi - \beta_\pi$ much larger than for $\alpha_\pi + \beta_\pi$

unique at COMPASS:

- availability of a muon beam (point like) for comparison and systematics
Summary for Primakoff

- already two (test)measurements performed, clear signal from Primakoff events

![Graph showing number of events vs. Q^2 for different materials and beams.]

- expected precision of the new measurement:

  
  \[
  \begin{array}{c|ccc}
  & \alpha_\pi - \beta_\pi & \alpha_\pi + \beta_\pi & \alpha_2 - \beta_2 \\
  \text{in 120 days} & 5.70 \pm 1.0 & 0.016 \pm 0.10 & 16 \\
  \text{90 days with } \pi \text{ beam} & \pm 0.66 & \pm 0.25 & \pm 1.94 \\
  \text{30 days of } \mu \text{ beam} & & & \\
  \end{array}
  \]

2-loop ChPT prediction
exp. accuracy
Generalised parton distributions

- **novel concept**: $H^f, E^f, \tilde{H}^f, \tilde{E}^f(x, \xi, t)$
- **limits**: $q(x) = H(x, 0, 0)$ normal PDF
  $F(t) = \int dx \ H(x, \xi, t)$ elastic form factor
- **Ji’s sumrule** for quark total angular momentum
  \[
  J^f = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \ x \left[ H^f(x, \xi, t) + E^f(x, \xi, t) \right]
  \]
- **Nucleon tomography**: $q^f(x, b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\Delta_\perp \cdot b_\perp} H^f(x, 0, -\Delta_\perp^2)$

simultaneous measurement of longitudinal momentum and transverse spatial structure
Why GPDs at **COMPASS**?

- **CERN high energy muon beam:**
  - 100–160 GeV, 80% polarisation
  - $\mu^+$ and $\mu^-$ with opposite polarisation

- **unique kinematic range**
  between HERA and HERMES/JLab
  - intermediate $x_{Bj}$:
    $\implies$ sea and valence quarks
  - high $x_{Bj}$ limit from acceptance
  - $Q^2$ up to 8GeV$^2$
    $\implies$ limit from cross section with $L = 10^{32}$ cm$^{-2}$s$^{-1}$

- **planned measurements:**
  - deeply virtual Compton scattering
  - deeply virtual meson production
Experimental requirements

Method

- same final state for BH and DVCS
- BH used a reference yield
- measurement with $\mu^+$ and $\mu^-$ with opposite pol.
- yields Re and Im part of GPD H

Experimental set-up

- long liquid hydrogen target surrounded by recoil detector (2 layers)
- hermetic coverage with electromagn, calorimeter
- already a few test measurements
Projected results

- **Transverse imaging:**
  \[ B(x) \sim 1/2 \langle r_\perp^2(x) \rangle \]
  no model dependence

- **Azimuthal dependence:**
  comparison to different models
  \[ \implies c_1^I \propto \text{Re}(F_1 \mathcal{H}) \]

projections with 2 years of data
\[ \varepsilon_{\text{global}} = 10\% \]
\[ L = 1222 \text{ pb}^{-1} \]
Transverse Momentum Dependent Distributions

- access to the transverse momentum in the nucleon
- at leading twist 8 TMDs (3 survive integration over $k_T$: $q$, $\Delta q$ and $\Delta q_T$)

- examples of TMDs:
  - **Boer-Mulders function** $h_1^\perp$:
    correlation of quark $k_T$ and quark transverse spin in unpol. nucleons
  - **Sivers function** $f_{1T}^\perp$:
    correlation of quark $k_T$ and nucleon transverse spin

- Boer-Mulders and Sivers function are T-odd $\rightarrow$ process dependent

\[
\begin{align*}
  h_1^\perp(SIDIS) &= -h_1^\perp(DY) \\
  f_{1T}^\perp(SIDIS) &= -f_{1T}^\perp(DY)
\end{align*}
\]

- needs experimental verification, Sivers measurement needs polarised target
Drell-Yan at COMPASS

\[ \pi^- p^\uparrow \rightarrow \mu^+ \mu^- X \]

- **DY**: convolution of two TMDs measured,
- **SIDIS**: TMD convoluted with fragmentation function
- complementary information
- ideal DY measurement: antiproton on proton
- good compromise \( \pi^- \) on protons
- DY dominated by annihilation of valence anti-quark from \( \pi^- \) and valence quark from polarised proton
- large acceptance of COMPASS in the valence region of \( p \) and \( \pi \) where large SSA are expected
Experimental requirements

- high intensity pion beam (up to $10^9$/spill)
- transversely polarised NH$_3$ target
- hadron absorber mandatory
- results from 2009 beam test

COMPASS DY test run 2009

COMPASS DY beam test 2009

$J/\psi$

3170$\pm$70 events
$M=3.092\pm0.005$ GeV
$\sigma_M=0.227\pm0.004$ GeV

Preliminary
Predictions for Sivers asymmetry

- 3 ranges of study: above $J/\psi$ $4 < M_{\mu^+\mu^-} < 9$ GeV (clean signal), $J/\psi$, below $J/\psi$ $2 < M_{\mu^+\mu^-} < 2.5$ GeV (large background) prediction are given for high mass range

- [Graph showing $\sin \phi_s$ vs. $x_F = x_{\pi} - x_{\pi^+}$]

- key measurements:
  - TMD universality, change of sign from SIDIS to DY, study of $J/\psi$ production mechanism

- projections with 2 years of data
  - $6 \cdot 10^8 \pi$ spill (9.6 s)
  - 1.1 m pol. NH$_3$
Conclusions and Outlook

COMPASS

• rich harvest in results on spin structure and spectoscopy
• PWA of hadron data just starting
• very sucessfull data taking in 2010 for transversity and Sivers DF
• next year will be mainly devoted to longitudinally spin physics

New proposal (COMPASS II)

• for 5 years GPDs, DY and Primakoff processes, already recommended by SPSC
• in parallel with GPD a rich programme in unpolarised DIS and SIDIS

On the long term

• more hadron beam running depending on the results
• DVCS with polarised target discussed
• DY with antiproton beam

COMPASS has a great potential in new fields and work is started to get the spectrometer upgraded for the new programmes