COMPASS - a facility to study QCD

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– COMPASS experiment
– What we have done
– What we want to do
**What have we done**

**COMPASS** is data taking since 2002 studying

**Nucleon spin puzzle:** \( S_N = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L \)

- muon scattering on polarised \( p(\text{NH}_3) \) and \( d(\text{LiD}) \) with long. and transv. target polarisation
- addendum in 2010 (transv. p) and 2011 (long. p)
- all three leading twist PDFs investigated \( (f_1, g_1, h_1) \)

**Results:** quark spin responsible for 30% of nucleon spin
- gluon contribution small in \( x \) range covered
- hardly any information on orbital angular momentum

**Hadron spectroscopy**

- 190 GeV/\( c \) hadron beams \( (\pi, p, K) \) on unpol. targets \( (\text{liquid } \text{H}_2, \text{Pb}, \text{Ni}, \text{Cu}, \text{W}) \)
- searches for exotics, hybrids and glueballs
- pion polarisabilities
What will we do

Improve the 1-dimensional picture of the nucleon

**Generalized parton distribution (GPD)**
longitudinal momentum structure plus transverse spatial structure accessible in exclusive reaction like DVCS or DVMP

**Flavour separation and fragmentation**
in semi-inclusive deep inelastic scattering (SIDIS)
 improvement of strange quark distribution and fragmentation

**Transverse momentum dependent distributions (TMD)**
dynamic picture using intrinsic transverse momenta of partons accessible in SIDIS and Drell-Yan processes

**QCD at very low momentum transfers**
using Primakoff reactions to access inverse Compton scattering pion/kaon polarisabilities, testing chiral perturbation theory

**COMPASS II proposal:**
submitted in May 2010 for 5 years of data taking in the first phase
approved in December 2010 for initially 3 years of data taking
SPS proton beam:
- Secondary hadron beams ($\pi, K, ...$): $2.10^8$ /spill, 150-270 GeV/c
- Tertiary muon beam (80% pol): $2.10^8$ /spill, 100-200 GeV/c

$\rightarrow$ Luminosity $\sim 5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ with polarised targets
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\[ \text{→ Luminosity } \sim 5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \text{ with polarised targets} \]
Polarised target

target material: $^6$LiD, NH$_3$

polarisation: 50%, 90%

E. Kabuß, Munich, 14.6.2011
Primakoff experiments with $\pi$, $K$

\[ \pi^- Z \rightarrow \pi^- Z \gamma \]

**chiral perturbation theory** predicts low energy behaviour

\[
\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \left[ \frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} \right]_{\text{point}} + C \cdot \frac{s - m_{\pi}^2}{s^2} P(\alpha_{\pi}, \beta_{\pi})
\]

\[ P(\alpha_{\pi}, \beta_{\pi}) = (1 - \cos \theta_{cm})^2 (\alpha_\pi - \beta_\pi) + (1 + \cos \theta_{cm})^2 (\alpha_\pi + \beta_\pi) \frac{s^2}{m_{\pi}^4} 
\]

\[ + (1 - \cos \theta_{cm})^3 (\alpha_2 - \beta_2) \frac{(s - m_{\pi}^2)^2}{24s} \]

- deviation from pointlike due to pion polarisabilities
- measurements: $\alpha_{\pi} - \beta_{\pi}$ (at backward angles), $\alpha_{\pi} + \beta_{\pi}$

**2-loop chiral prediction**

\[ \alpha_{\pi} - \beta_{\pi} = (5.7 \pm 1.0) \times 10^{-4} \text{ fm}^3 \]

**experiments:** $\alpha_{\pi} - \beta_{\pi}$ from 4 to $14 \times 10^{-4}$ 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:
- kaon component in hadron beam: kaon polarisability accessible
- availability of a muon beam (point like) for comparison and systematics
- switching between pion and muon beam within few hours possible
Projections for polarisabilities

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

- expected precision of the new measurement:

<table>
<thead>
<tr>
<th></th>
<th>(\alpha_\pi - \beta_\pi) (10^{-4}) fm(^3)</th>
<th>(\alpha_\pi + \beta_\pi) (10^{-4}) fm(^3)</th>
<th>(\alpha_2 - \beta_2) (10^{-4}) fm(^5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in 120 d</td>
<td>(5.70 \pm 1.0)</td>
<td>(0.16 \pm 0.10)</td>
<td>(16)</td>
</tr>
<tr>
<td>90 d with (\pi), 30 d of (\mu) beam</td>
<td>(\pm 0.66)</td>
<td>(\pm 0.25)</td>
<td>(\pm 1.94)</td>
</tr>
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<td>2-loop ChPT prediction</td>
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<td>COMPASS sensitivity</td>
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</tbody>
</table>
Generalised parton distributions

Factorisation for $Q^2$ large, $t < 1 \text{ GeV}^2$

- generalised parton distributions for quarks $H^f, E^f, \tilde{H}^f, \tilde{E}^f(x, \xi, t)$

- limits:
  $q(x) = H(x, 0, 0)$
  $F(t) = \int dx \ H(x, \xi, t)$

- Ji’s sumrule

$$J^f = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \ x \ [H^f(x, \xi, t) + E^f(x, \xi, t)]$$

$J^f$: total angular momentum contribution of quark $f$
Nucleon tomography

- GPDs allow simultaneous measurement of longitudinal momentum and transverse spatial structure

\[ q^f(x, b_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i \Delta_\perp \cdot b_\perp} H^f(x, 0, -\Delta_\perp^2) \]

- for \( \xi \to 0 \): \( t = -\Delta_\perp^2 \) purely transverse and

- \( b_\perp \) distance to center of momentum (\( b \) in figure is \( b_\perp \))
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 $x$: $\Rightarrow$ sea and valence quarks
  - high $x$ limit from acceptance
  - $Q^2$ up to $8\text{GeV}^2$
    $\Rightarrow$ limit from cross section
    with $L = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

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

Phase 1: 2.5 m long unpolarised liquid H$_2$ target $\Rightarrow$ GPD H
Phase 2: transversely polarised liquid NH$_3$ target $\Rightarrow$ GPD E

E. Kabuš, Munich, 14.6.2011
Experimental requirements

- two competing processes: DVCS and BH
- Bethe-Heitler dominates at low $x$
- used a reference yield
- measurement with $\mu^+$ and $\mu^-$ with opposite polarisation
  
  $$S_{CS,U} \equiv d\sigma_{+\downarrow} + d\sigma_{-\uparrow}$$
  
  $$D_{CS,U} \equiv d\sigma_{+\downarrow} - d\sigma_{-\uparrow}$$

- yield Re(H) and Im(H)
- additionally deeply virtual meson production

Experimental set-up

- 2.5 m long liquid hydrogen target
- 4 m long recoil proton detector (2 layers)
- ’hermetic’ coverage with electromagnetic calorimetry
Test measurement 2009

- data taking with $\mu^+$ (8 times more stat.) and $\mu^-$ at about nominal intensity
- 40 cm liquid H$_2$ target and small recoil proton detector
- measure BH events plus relative DVCS and DVMP contributions
- comparison of $\mu^+$ and $\mu^-$ data: $\mu^-$ flux is factor of 3 lower at 160 GeV $\implies$ limitation on overall luminosity

$\implies$ clear DVCS signal observed at $Q^2 > 1 \text{ GeV}^2$, $x > 0.03$
Projected results

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

- **Azimuthal dependence:**
  comparison to different models
  \[ \Rightarrow c^I_1 \propto \text{Re}(F_1 \mathcal{H}) \]

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

- dynamic picture of the nucleon using intrinsic transverse momentum $k_T$ of partons
- sensitivity to quark orbital angular momentum
- at leading twist: full description with 8 TMDs
- 3 survive integration over $k_T$: $f_1$, $g_1$ and $h_1$

- TMDs are accessed by azimuthal asymmetries
- studied in SIDIS using unpolarised and transversely polarised target
- in SIDIS convolution with fragmentation function
**Boer-Mulders and Sivers DF in SIDIS**

**BM function** $h_{1}^{⊥}$: correlation of quark $k_{T}$ and transverse spin in unpol. nucleons

- 2004 data on deuteron target: non-zero Boer-Mulders asymmetry ($A_{LU}^{\cos 2\phi}$)
- Boer-Mulders on proton will be measured in parallel with DVCS

**Sivers function** $f_{1T}^{⊥}$: correlation of quark $k_{T}$ and nucleon transverse spin

- Sivers asymmetry ($A_{LT}^{\sin \phi S}$) measured at COMPASS with pol. deuteron and proton target
- positive asymmetry for $h_{+}$ on proton, but smaller than seen by HERMES

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

\[ h_{1}^{⊥}(\text{SIDIS}) = -h_{1}^{⊥}(\text{DY}) \]
\[ f_{1T}^{⊥}(\text{SIDIS}) = -f_{1T}^{⊥}(\text{DY}) \]

$\rightarrow$ Crucial test of non-perturbative QCD and of TMD approach
**Drell-Yan at COMPASS**

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

- **DY**: convolution of two TMDs measured
- Access to 4 azimuthal modulations: Boer-Mulders, Sivers, pretzelosity and transversity PDFs
- Ideal DY measurement: \( \bar{p}p \)
- Good compromise \( \pi^- p \)
- 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 190 GeV/c pion beam (up to $10^9$/spill)
- transversely polarised NH$_3$ target
- hadron absorber downstream of target
- dimuon trigger system

Results from 2009 beam test

COMPASS DY test run 2009

- $J/\psi$ events: $3170 \pm 70$
- $M = 3.092 \pm 0.005$ GeV
- $\sigma_M = 0.227 \pm 0.004$ GeV

Preliminary
Projections for azimuthal asymmetries

\[ 4 \text{ GeV}/c^2 < M_{\mu^+\mu^-} < 9 \text{ GeV}/c^2 \]

- Sivers
- Boer-Mulders
- BM \otimes \text{pretzelosity}
- BM \otimes \text{transversity}

projections with 2 years of data
6 \cdot 10^8 \pi \text{ spill (9.6 s)}
1.1 \text{ m pol. NH}_3

- **key measurements**: TMD universality, change of sign from SIDIS to DY, study of \( J/\psi \) production mechanism
Conclusions and Outlook

New proposal (**COMPASS II**) with

- DVCS and DVMP for the study of GPDs in a kinematic region not yet covered by experiments
- in parallel with GPD measurement rich programme in unpolarised DIS and SIDIS
- first polarised Drell-Yan experiment to study TMDs
- measurement of pion (kaon) polarsabilities

⇒ at least 5 years of data taking, can start from 2012

Program accepted in December 2010 for a first period of 3 years

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