The status of the COMPASS experiment

Norihiro DOSHITA
Yamagata University
The COMPASS facility

**Beam:**
- Polarized lepton beam: $\mu^+$, $\mu^-$ 50-280 GeV/c (80% polarization @ 160GeV)
- Hadron beam: $\pi^+$, $\pi^-$, $K^+$, $K^-$, P

**Target:**
- Polarized proton and deuteron target
- Liquid hydrogen target
- Thin nucleus target

**Many combinations of the beam & the target**
**COMPASS programs**

<table>
<thead>
<tr>
<th>Year</th>
<th>Data taking</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Longitudinally, transversally polarized proton target (160 GeV/c muon)</td>
</tr>
<tr>
<td>2008</td>
<td>Hadron beam with LH2 target</td>
</tr>
<tr>
<td>2009</td>
<td>Hadron beam with LH2 target + DVCS test run with muon beam</td>
</tr>
<tr>
<td>2010</td>
<td>Transversally polarized proton target</td>
</tr>
<tr>
<td>2011</td>
<td>Longitudinally polarized proton target (200 GeV/c muon)</td>
</tr>
<tr>
<td>2012</td>
<td>Hadron run, <strong>DVCS run (LH2 with μ+ and μ-) :: COMPASS II started</strong></td>
</tr>
<tr>
<td>2013</td>
<td>No beam</td>
</tr>
<tr>
<td>2014</td>
<td>Drell-Yan run (hadron beam + transversally polarized proton target)</td>
</tr>
<tr>
<td>2015</td>
<td>Drell-Yan run or DVCS</td>
</tr>
<tr>
<td>2016</td>
<td>?</td>
</tr>
</tbody>
</table>

- DVCS run in 2012
- Polarized Drell-Yan preparation
- Recent results from COMPASS

March 18 2013  
N. Doshita
DVCS run in 2012
Kinematic range and feature for GPDs

• Explore uncovered kinematic region between ZEUS/H1 and HERMES+Jlab

• $\mu^+$ and $\mu^-$ beam
• Momentum 100 – 190 GeV
• 80% polarization (at 160 GeV)
• Opposite polarization between $\mu^+$ and $\mu^-$
Deeply Virtual Compton Scattering

GPDs can be accessed from the hard exclusive DVCS processes.

\[ \sigma_{up \rightarrow up\gamma} = \sigma^{BH} + \sigma^{DVCS}_{unpol} + P_\mu \sigma^{DVCS}_{pol} + e_\mu a^{BH} \text{Re}(I) + e_\mu P_\mu \text{Im}(I) \]

\( d\sigma^{BH} : \) well known

\( I : \) interference term
Bethe-Heitler and DVCS cross sections at 160 GeV

\[ d\sigma \propto |T^{DVCS}|^2 + |T^{BH}|^2 + \text{InterferenceTerm} \]

0.005 < \( X_{BJ} \) < 0.01

BH dominates
Reference yield

0.01 < \( X_{BJ} \) < 0.03

Interference
\( \text{Re}T^{DVCS} \) & \( \text{Im}T^{DVCS} \)

\( X_{BJ} > 0.03 \)

DVCS dominates
Transverse Image

**MC:** COMPASS setup with Ecal1+2

March 18 2013

N. Doshita
Access to GPD $H$ and Transverse image

**Beam Charge and Spin Sum**

$$S_{CS,U} = d\sigma^{+\rightarrow} + d\sigma^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \text{Im}(I)\right)$$

**Beam Charge and Spin Difference**

The BH process is independent of beam charge and polarization.

$$D_{CS,U} = d\sigma^{+\rightarrow} - d\sigma^{-\rightarrow} = 2\left(P_\mu d\sigma^{DVCS}_{pol} + e_\mu \text{Re}(I)\right)$$

**Phase II (with polarized target)**

One can access GPD $E$ with a measurement of DVCS using transversely polarized proton target

$$c_0^l + c_1^l \cos \phi + c_2^l \cos 2\phi + c_3^l \cos 3\phi$$

$$s_1^l \sin \phi + s_2^l \sin 2\phi$$

$$s_1^l \propto \text{Im}(F_I, H)$$

$$c_1^l \propto \text{Re}(F_I, H)$$

March 10, 2013  N. Doshita
Transverse imaging

The exclusive cross section is parametrized as:

\[ d\sigma_{DVCS}/dt \propto \exp(-B(x_B)|t|) \]

The t-slope parameter \( B(x_B) \) can be extracted without any models:

\[ \langle r^2_{\perp}(x_B) \rangle \approx 2 \cdot B(x_B) \]

The transverse size of the nucleon

In 2016, 2017
- 2 years of data (280 days)
- 160 GeV polarized muon beam
- \( \mu^+ \) 70 days
- \( \mu^- \) 210 days
- 2.5m LH2 target

COMPASS in 2012
- \( \alpha' = 0.26 \)

COMPASS in 2016+17?
- \( \alpha' = 0.125 \)

ZEUS
- \( \alpha' = 0.26 \)

H1-HERA

\( B(x_B) = B_0 + 2\alpha' \log(x_0/x_B) \)
LH2 and RPD
Recoil proton detector CAMERA

To face the high rates using the high muon beam intensity

Calibration with the pion beam with elastic events (π p → π π)

ToF between 2 rings of scintillators $\sigma(\text{ToF}) < 300\text{ps}$
Ecal0 and larger kinematic range

- 56 modules
- calibrated on October 24
- cover DVCS dominates region
Liquid hydrogen target

Target inside the carbon vacuum chamber

Cooling head and buffer

Side view of Target and CAMERA

BEAM

March 18 2013

N. Doshita
## Differences between in 2008 and in 2012

<table>
<thead>
<tr>
<th></th>
<th>2008 and 2009</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target length</td>
<td>40 cm</td>
<td>255 cm</td>
</tr>
<tr>
<td>Target cell diameter</td>
<td>3.5 cm</td>
<td>4.0 cm</td>
</tr>
<tr>
<td>Vacuum chamber diameter</td>
<td>20 cm</td>
<td>8 cm</td>
</tr>
<tr>
<td>Vacuum chamber material</td>
<td>Aluminum (1.8 mm thickness)</td>
<td>Carbon fiber (1 mm thickness)</td>
</tr>
<tr>
<td>Target cell material</td>
<td>Mylar</td>
<td>Capton</td>
</tr>
<tr>
<td>Cooling power</td>
<td>8 W at 20K</td>
<td>30 W at 20K</td>
</tr>
<tr>
<td>Cooling time</td>
<td>7 hours</td>
<td>15 hours</td>
</tr>
<tr>
<td>H2 Leak rate (cold phase)</td>
<td>0.017 mol/day</td>
<td>0.074 mol/day</td>
</tr>
<tr>
<td>H2 Leak rate (cold phase)</td>
<td>0.040 mmol/day/cm²</td>
<td>0.025 mmol/day/cm²</td>
</tr>
<tr>
<td>Isolation vacuum (warm)</td>
<td>8 \cdot 10^{-6} mbar</td>
<td>1.5 \cdot 10^{-5} mbar</td>
</tr>
<tr>
<td>Isolation vacuum (cold)</td>
<td>1 \cdot 10^{-6} mbar</td>
<td>7 \cdot 10^{-7} mbar</td>
</tr>
</tbody>
</table>

March 18 2013  
N. Doshita
DVCS run in 2012

• Beam : Polarized $\mu^+$ and $\mu^-$ (160 GeV/c)
• Target : Liquid hydrogen target (2.5 m long)
• Data taking : Nov. 1 – Dec. 3
• New detectors : 4m long RPD and ECAL0
• About 6 times larger amount of data of $\mu^+$ than in 2009
• Good data of $\mu^-$ (no data taken in 2009)
Analysis of 2012 data

• Data production ongoing
  - problems of new detectors
  - Beam/spectro alignment

• Luminosity analysis
  - same method with 2009
  - use test production in 2012 data now

• $\rho^0$ Analysis starts
Polarized Drell-Yan preparation
Drell-Yan process and its angular distribution

\[
\frac{1}{\sigma} \frac{d\sigma}{d\Omega} = \frac{3}{4\pi(\lambda + 3)} \left[ 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \nu \frac{\sin^2 \theta \cos 2\phi}{2} \right]
\]

- The collinearity hypothesis would imply $\lambda = 1$ and $\mu = \nu = 0$.
- NA10 (CERN) and E615 (Fermlab) modulation of $\cos 2\phi$ up to 30%.
- Intrinsic transverse momentum $k_T$ of quarks inside hadron interaction.
- 2 Boer-Mulders PDFs interaction between target and beam quarks.

March 18 2013
N. Doshita
Single polarized Drell-Yan cross section

**COMPASS case::**

The LO expansion of the single polarized Drell-Yan cross section is

\[
\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha^2}{F q^2} \hat{\sigma}_U \left\{ \left( 1 + D_{\sin^2\theta} A_U^{\cos2\phi} \cos 2\phi \right) + \left| \vec{S}_T \right| \left[ A_T^{\sin\phi_S} \sin \phi_S \right. \\
+ D_{\sin^2\theta} \left( A_T^{\sin(2\phi + \phi_S)} \sin(2\phi + \phi_S) + A_T^{\sin(2\phi - \phi_S)} \sin(2\phi - \phi_S) \right) \] \right\}
\]

- \( A_U^{\cos2\phi} : (BM)_\pi \otimes (BM)_P \)
- \( A_T^{\sin\phi_S} : (f_1)_\pi \otimes (Sivers)_P \)
- \( A_T^{\sin(2\phi + \phi_S)} : (BM)_\pi \otimes (Pretz.)_P \)
- \( A_T^{\sin(2\phi - \phi_S)} : (BM)_\pi \otimes (Trans.)_P \)

\( A \): azimuthal asymmetries :: convolution of 2 PDFs
\( D \): depolarization factor
\( S \): target spin component
\( \hat{\sigma}_U \): part of the cross-section surviving integration over \( \phi \) and \( \phi_S \)
\( F \): \( 4\sqrt{(P_a \cdot P_b)^2 - M_a^2 M_b^2} \)

\[ \text{March 18 2013} \]

N. Doshita
Universality of TMD PDFs

Because Sivers and Boer-Mulders PDFs are “Time-reversal odd”, they are expected to change the sign when measured from SIDIS or from DY:

\[ f_{1T}^{\perp} \bigg|_{DY} = - f_{1T}^{\perp} \bigg|_{SIDIS} \]
\[ h_{1}^{\perp} \bigg|_{DY} = - h_{1}^{\perp} \bigg|_{SIDIS} \]

We have the opportunity to test this sign change using the same Spectrometer and the transversely polarized target at COMPASS.
Event rates and statistical accuracy

Luminosity $1.2 \times 10^{32}$ cm$^{-2}$s$^{-1}$  (Beam intensity : $6 \times 10^7$ pions/s)

- 800 DY events per day with $4 < M < 9$ GeV/c$^2$

Assuming 2 years of data taking (280 days)

- 230k events in $4 < M < 9$ GeV/c$^2$ region

This will translate into the statistical errors of the asymmetries.

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>Dimuon mass (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$2 &lt; M_{\mu\mu} &lt; 2.5$</td>
</tr>
<tr>
<td>$\delta A_U^{\cos 2\phi}$</td>
<td>0.0020</td>
</tr>
<tr>
<td>$\delta A_T^{\sin \phi_S}$</td>
<td>0.0062</td>
</tr>
<tr>
<td>$\delta A_T^{\sin(2\phi+\phi_S)}$</td>
<td>0.0123</td>
</tr>
<tr>
<td>$\delta A_T^{\sin(2\phi-\phi_S)}$</td>
<td>0.0123</td>
</tr>
</tbody>
</table>

Possibility to study the asymmetries in the several $x_F$ bins.

March 18 2013

N. Doshita
Comparing with theory predictions

$4 < M_{\mu\mu} < 9 \, \text{GeV} / c^2$

\[ f_1^\pi \otimes \text{Sivers}^p \]
Anselmino et al,
PRD79(2009)054010

\[ BM^\pi \otimes BM^p \]
B. Zhang et al,
PRD77(2008)054011

\[ BM^\pi \otimes \text{pretzel}^p \]
Zhun Lu et al,
arXiv:1101.2702v2

\[ BM^\pi \otimes \text{transv}^p \]
A.N. Sissakian et al,
Phys.Part.Nucl.41:64-100,2010

March 18 2013
N. Doshita
Target position and absorber

Concrete wall
Dilution refrigerator
Polarizing magnet
Hadron absorber
Cavity
Beam
Target working space

2.3 m

March 18 2013
N. Doshita
New set up of the experiment
Polarized target

• **Move target position to 2.3 m upstream**
  - piping, cabling, μ-waveguide, space in front of target

• **Magnet repair**
  - correction coils, isolation, precooling system
  - dipole magnet field rotation function
  - cooling test is foreseen in September

• **Radiation issue**
  - limited access to target area
  - magnet control system, NMR system
  - remote control system

• **3 target cells -> 2 cells**
  - 30-60-30 cm(2 x 5cm gap) -> 55-55cm(20cm gap)
  - microwave cavity modification
Acceptance of COMPASS

The acceptance for $4 \leq M_{\mu\mu} \leq 9 \text{ GeV}/c^2$: $38.38 \pm 1.05 \%$

- 22.17% with both muons in LAS
- 1.46% with both muons in SAS
- 14.75% with one muon in LAS and the other in SAS
New trackers

• Scintillation fiber detector
  - install in the space of hadron absorber
  - What size will be fit?
  - Radiation damage

• Drift chambers (DC5/DC6)
  - Large angle tracker
  - size 2.2m x 2.0m?
Recent results
• **$A_1^p$ and $g_1^p$ from the 2011 run**
  - Access to lower $x$ region

• **LO flavor separation results**
  - The results agree with DSSV NLO parametrization
  - on the way to extract FF ratios : needed to understand better $\Delta S$ puzzle

• **Updated results for $\Delta G/G$ obtained in various analysis**
  - Updated high-$P_T$ hadron pairs, $Q^2 > 1$ (GeV/c)$^2$ analysis:
    - $\Delta G/G = 0.125 \pm 0.060 \pm 0.063$, subm. To PLB
  - Updated LO open charm analysis: $\Delta G/G = -0.08 \pm 0.21 \pm 0.11$
  - New NLO open charm analysis: $\Delta G/G = -0.20 \pm 0.21 \pm 0.08$
  - All world results agree with each other.
  - $\Delta G$ is small, but the sign of it is still not determined.

• **Exclusive $\rho^0$ muoproduction on transversely polarized $p$ and $d$**
  - without recoil proton detector

• **Two-hadron asymmetries on transversely polarized $p$ and $d$**
  - identified : 2002-2004 and 2010 data released, 2007 data will be released.
$A_1^p$ and $g_1^p$ (2007 vs 2011)

160 GeV/c muon beam in 2007
200 GeV/c muon beam in 2011

To access lower $x$ region

March 18 2013
N. Doshita
World data of $g_1^{p,d}$

$g_1^p$

- COMPASS

$g_1^d$

- SMC
- E143
- E155
- HERMES
- COMPASS'07
- COMPASS'11 prel.
- CLAS W>2.5
- LSS 05

March 18 2013

N. Doshita
LO Flavor Separation

The curves are DSSV NLO parametrization PRL 101(2008)072001; PRD80(2009)034030
Good agreement between COMPASS data and DSSV parametrization

PLB 693 (2010) 227
Strange Sea Polarization

**DIS data**: \[ \int \Delta s + \Delta \bar{s} = -0.08 \pm 0.01 \pm 0.02 \]

**SIDIS data**: \[ \Delta s(x) \approx 0 \text{?} \]

\[ R_{SF} = \frac{D_s^{K^-}}{D_u^{K^-}} = \frac{D_s^{K^+}}{D_u^{K^+}} \]

If \( R_{SF} \) is small, inclusive and semi-inclusive results for \( \Delta S \) agree with each other

COMPASS: 2011 data at 200 GeV

- More data on quark fragmentation functions
- More data at low \( x \)
- Extraction of \( R_{SF} \) from COMPASS data only

March 18 2013

N. Doshita
Summary of $\Delta G/G$ from COMPASS

- COMPASS, high $p_T$, $Q^2 > 1$ (GeV/c)$^2$, [02, 06] data, $\langle \mu^2 \rangle = 3$ (GeV/c)$^2$, preliminary
- COMPASS, high $p_T$, $Q^2 < 1$ (GeV/c)$^2$, [02, 04] data, $\langle \mu^2 \rangle = 3$ (GeV/c)$^2$, preliminary
- COMPASS, Open Charm, LO, all $Q^2$, [02, 07] data, $\langle \mu^2 \rangle = 3$ (GeV/c)$^2$, preliminary
- SMC, high $p_T$, $Q^2 > 1$ (GeV/c)$^2$, $\langle \mu^2 \rangle = 3$ (GeV/c)$^2$
- HERMES, high $p_T$, all $Q^2$, $\langle \mu^2 \rangle = 3$ (GeV/c)$^2$

The all results agree with each other.
GPD : Deeply virtual exclusive $\rho$ without recoil detection

Cross section measurements:
- Pseudo – scalar : $\pi, \eta \rightarrow \tilde{H}, \tilde{E}$
- Vector meson : $\rho, \omega, \phi \rightarrow H, E$

$\rho : \omega : \phi \sim 9 : 1 : 2$ at large $Q^2$

Vector meson production from transversely polarized target asymmetry

$$A_{UT}^{\sin(\phi-S)} \propto \sqrt{-t''} \frac{\text{Im}(E^*H)}{|H|^2}$$

- $E, H$ : weighted sums of GPD $E^{f}$ and $H^{f}$
- Give access to GPD $E$

No recoil detection :: high background, mainly from non-exclusive SIDIS
- Subtracted based on LEPTO, rescaled by like-sign $h$ pairs

March 18 2013
N. Doshita
Transversity via two hadrons

Comparison COMPASS/HERMES:

- deuteron
- proton

March 18 2013
Identified two-hadron asymmetry in the 2010 run

\[ \sin \phi_{\text{as}} \sin \theta_{UT,p} \]

\( x > 0.032 \)
\( x < 0.032 \)
HERMES

COMPASS 2010 proton data

\[ \sin \phi_{\text{as}} \sin \theta_{UT,p} \]

\( x > 0.032 \)
\( x < 0.032 \)
HERMES

\[ \sin \phi_{\text{as}} \sin \theta_{UT,p} \]

\( x > 0.032 \)
\( x < 0.032 \)
HERMES

HERMES

COMPASS \( x > 0.032 \)
COMPASS \( x < 0.032 \)

March 18 2013

N. Doshita
Summary

• The 2012 DVCS run
  - data taking: successfully done with $\mu^+$ and $\mu^-$
  - data production on going

• Polarized Drell-Yan preparation
  - a lot of things to prepare: target, trackers, absorber
  - already started: magnet repair, experimental hall arrangement

• Recent analysis
  - $A_1$, $g_1$, $\Delta s$, $\Delta G/G$, Transversity, exclusive $\rho$