Spin physics at COMPASS: present and future

Gerhard K. Mallot
CERN/PH
On behalf of the COMPASS Collaboration
• COMPASS I
  – Goals
  – Experiment
  – Results
    • Helicity distributions
    • Gluon polarization
    • Transverse spin
    • TMDs

• COMPASS II
  – Drell-Yan
  – DVCS/GPDs
  – Outlook

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Varenna, July 2011
### Global effort: Pol. DIS/pp

<table>
<thead>
<tr>
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<tbody>
<tr>
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<td></td>
<td>HERMES</td>
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<td>JLab</td>
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<td>CLAS/HALL-A</td>
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<td>RHIC</td>
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<td>Phenix/Star</td>
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- A worldwide effort since decades
Laboratories

SLAC
- 49 GeV e^-

CERN
- 160/280 GeV μ^+

DESY
- 27 GeV e^+ PETRA

JLab
- 6 GeV e
- 250+250 GeV pp

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COMPASS I: Goals

• Founded 1996, approved 1998, first data 2002
• Goals of the semi-inclusive measurements
  – Helicity distributions
  – Gluon polarization
  – Transversity PDF
  – Meson and baryon spectroscopy, \( \pi \) polarizability
    (not discussed here)
Experiment: Spectrometer

60m long

E/HCAL1

RICH1

SM1

E/HCAL2

SM2

Hodoscopes

Muon Wall 2, MWPC

MWPC, Gems, Scifi, W45

Muon Wall 1

Straws, Gems

Micromegas, DC, Scifi

Scifi, Silicon

Polarised Target

160/200 GeV μ beam

COMPASS
CERN muon beam

\[ E_\pi = 180 \text{ GeV} \]

Energy: 160 GeV
Intensity: \(2 \cdot 10^8 \mu/\text{Spill}\)
Polarisation: \(\approx 76\%\)
Polarized target system

- **Solenoid**: 2.5T
- **Dipole Magnet**: 0.6T
- **Acceptance**: ± 180 mrad

- **$^3\text{He} - ^4\text{He}$ dilution refrigerator** ($T \sim 50\text{mK}$)
- **$^6\text{LiD}/\text{NH}_3 (d/p)$**
  - 50/90% pol.
  - 40/16% dil. factor

Reconstructed interaction vertices
Polarized target

The coldest place @ CERN:
60mK, 1/30 of LHC magnets temperature
Polarized target installation

- Microwave cavity
- Dilution refrigerator
- New Magnet
Polarized target performance

Polarization of $^6$LiD in 2006

+53.5%  -52.0%  +56.1%
Tracking example: GEMs

Gaseous Electron Multiplier

Gem foil
• 20 triple Gems detectors
• in 10 stations
• 40 coordinates
• size $30 \times 30 \text{ cm}^2$
• 12 ns time resolution
• 50 $\mu$m space resolution
• efficiency $\approx 97\%$
• Ar/CO$_2$ 70/30 %
Particle identification: RICH

• 80 m³ (3 m C₄F₁₀ radiator)
• 116 UV mirrors
• 5.3 m² UV detectors
  – MWPC CsI photo-sensitive cathodes
  – 8×8 mm² pads
• 84k analog r/o channels
• 2006: inner quarter with maPMTs
RICH

- $\pi/K$ separation up to 60 GeV/c
- Large angular acceptance
Results: Data taking

Data taking:

• 2002–2004: polarized deuteron target (\(^6\)LiD), longitudinal & transverse polarization

• 2005: CERN shutdown

• 2006: polarized deuteron target (\(^6\)LiD), long.

• 2007: polarized proton target (NH\(_3\)), longitudinal & transverse polarization

• 2008-2009: spectroscopy

• 2010: polarized proton target (NH\(_3\)), transv.

• 2011: polarized proton target (NH\(_3\)), long.
Results: helicity structure
X-sect. asymmetries

\[ \frac{A_{\text{exp}}}{f \ P_{\mu} \ P_{T} \ D} \sim A_1 \]

- Inclusive scattering

\[ A_1 = \frac{\sum_q e_q^2 g_1^q(x, Q^2)}{\sum_q e_q^2 f_1^q(x, Q^2)} \]

- Semi-inclusive scattering

\[ A^h_1 = \frac{\sum_q e_q^2 g_1^q(x, Q^2) D_{1q}^h(z, Q^2)}{\sum_q e_q^2 f_1^q(x, Q^2) D_{1q}^h(z, Q^2)} \]

\[ z = \frac{E_h}{\nu} \]
Proton $A_1$ asymmetries

incl. & semi-incl. asymmetries for identified $\pi$’s and $K$’s

$A_{1,p}^{\pi^+} \quad \pi^+$

$A_{1,p}^{\pi^-} \quad \pi^-$

$A_{1,p}^{K^+} \quad K^+$

$A_{1,p}^{K^-} \quad K^-$

PLB 693 (2010) 227

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Deuteron $A_1$ asymmetries

Inclusive & semi-inclusive asymmetries for identified $\pi$'s and $K$'s

$A_{1,d}^{\text{incl.}}$, $A_{1,d}^{\pi^+}$, $A_{1,d}^{K^+}$, $A_{1,d}^{\pi^-}$, $A_{1,d}^{K^-}$

COMPASS HERMES

$F_2(x, Q^2) \rightarrow \rightarrow + \rightarrow \rightarrow \quad g_1(x, Q^2) \rightarrow \rightarrow - \rightarrow \rightarrow$
Structure function $g_1(x, Q^2)$

- very precise data
- only COMPASS for $x < 0.01$ ($Q^2 > 1$)

- deuteron data:
  - $\Delta \Sigma = 0.33 \pm 0.03 \pm 0.05$
  - $\Delta s + \Delta s = -0.08 \pm 0.01 \pm 0.02$

- $(\Delta \Sigma = a_0, \text{ evol. to } Q^2 = \infty)$
Bjorken sum rule

\[ \Gamma_{1}^{NS}(Q^2) = \frac{1}{6} \frac{g_{A}}{g_{V}} C_{1}^{NS}(Q^2) \]

\[ g_{1}^{NS}(x, Q^2) = g_{1}^{p}(x, Q^2) - g_{1}^{n}(x, Q^2) \]

\[ |g_{A}/g_{V}| = 1.28 \pm 0.07 \text{(stat.)} \pm 0.10 \text{(syst.)} \]

\[ |g_{A}/g_{V}| = 1.269 \]

from neutron $\beta$ decay

PLB 690 (2010) 466

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Flavour distributions: $\Delta \bar{s} = \Delta s$ ?

LO analysis of 5p+5d asymmetries, DSS FF
6 flavours: u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$

No significant difference! Go on assuming $\Delta s = \Delta \bar{s}$
Flavour distributions

LO analysis of 5p+5d asymmetries, DSS FF
Line: NLO DSSV not including these data

5-flavour fit, assuming Δs = Δs

PLB693 (2010) 227
PRD80 (2009) 034030
Flavour asymmetry?

• Rather small effect, $\Delta \bar{u} > \Delta \bar{d}$
Truncated first moments

\[ \int_{0.004}^{x_{\text{max}}} \Delta q(x) \, dx \]

\( \Delta s \) small, compatible with zero

<table>
<thead>
<tr>
<th>( x ) range</th>
<th>0.004 &lt; ( x ) &lt; 0.3</th>
<th>0.004 &lt; ( x ) &lt; 0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta u )</td>
<td>0.47 ± 0.02 ± 0.03</td>
<td>0.69 ± 0.02 ± 0.03</td>
</tr>
<tr>
<td>( \Delta d )</td>
<td>−0.27 ± 0.03 ± 0.02</td>
<td>−0.33 ± 0.04 ± 0.03</td>
</tr>
<tr>
<td>( \Delta \bar{u} )</td>
<td>0.02 ± 0.02 ± 0.01</td>
<td>—</td>
</tr>
<tr>
<td>( \Delta \bar{d} )</td>
<td>−0.05 ± 0.03 ± 0.02</td>
<td>—</td>
</tr>
<tr>
<td>( \Delta s (\Delta \bar{s}) )</td>
<td>−0.01 ± 0.01 ± 0.01</td>
<td>—</td>
</tr>
<tr>
<td>( \Delta u_v )</td>
<td>0.46 ± 0.03 ± 0.03</td>
<td>0.67 ± 0.03 ± 0.03</td>
</tr>
<tr>
<td>( \Delta d_v )</td>
<td>−0.23 ± 0.05 ± 0.02</td>
<td>−0.28 ± 0.06 ± 0.03</td>
</tr>
<tr>
<td>( \Delta \bar{u} - \Delta \bar{d} )</td>
<td>0.06 ± 0.04 ± 0.02</td>
<td>—</td>
</tr>
<tr>
<td>( \Delta \bar{u} + \Delta \bar{d} )</td>
<td>−0.03 ± 0.03 ± 0.01</td>
<td>—</td>
</tr>
<tr>
<td>( \Delta \Sigma )</td>
<td>0.15 ± 0.02 ± 0.02</td>
<td>0.31 ± 0.03 ± 0.03</td>
</tr>
</tbody>
</table>
Inclusive data favour $\Delta s < 0$

- Inclusive data only
  $\Delta s \approx -0.08 \pm 0.01$
- Semi-inclusive point to $\Delta s \approx 0$
- Shape of $\Delta s(x)$ at small $x$ unknown
- $\Delta s$ determination crucially depends on the **fragm. functions** used:
  DSS, DNS, HKNS, EMC, ...

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J. Phys.: Conf. Ser. **295** 012054
Strange quark FFs

Measurements of $K$ and $\pi$ multiplicities are mandatory!

$R_{SF} = \frac{\int D_{s}^{K^{+}}(z)dz}{\int D_{u}^{K^{+}}(z)dz}$

DSS: PRD75 (2007)
EMC: NPB321 (1989)
Multiplicities for $K$’s and $\pi$’s

LO:

$$\frac{1}{N^{DIS}(x, Q^2)} \frac{dN^h}{dx \, dz \, dQ^2} = \frac{\sum_q e_q^2 f_q(x, Q^2) \, D_{1,q}^h(z, Q^2)}{\sum_q e_q^2 f_q(x, Q^2)}$$

Unpolarised data

For the $z$ bins:
- $0.20 - 0.30$
- $0.30 - 0.45$
- $0.45 - 0.65$
- $0.65 - 0.85$

Lines: MRST04 PDF
+ DSS FF (LO)
**K** multiplicities, closer look

- $\pi$ multiplicities ± in agreement with LO calc.
- Big deviations for $K$’s $\rightarrow$ **consequences for FF!**
- Data to be included in global analyses
- Only 4 weeks of data, more to come

Same bins as prev. page
Gluon polarization

EMC result 1987/88: quark spins contribute little to nucleon spin!
\[ \Delta \Sigma \text{ compatible with zero} \]

\[ \Delta \Sigma = \sum_q \int g_1^q(x)dx = \sum_q \int \Delta q(x)dx \]

Quark spin hidden by large gluon polarization via axial anomaly?

A crisis in the parton model:
where, oh where is the proton’s spin?

E. Leader\(^1\) and M. Anselmino\(^2\)
Birkbeck College, University of London, London, UK
Dipartimento di Fisica Teorica, Università di Torino, I-10125 Torino, Italy
Received 18 March 1988

THE ANOMALOUS GLUON CONTRIBUTION TO POLARIZED LEPTOPRODUCTION

G. Altarelli and G.G. Ross \(^1\)
CERN, CH-1211 Geneva 23, Switzerland
Received 29 June 1988
To summarise, let us return to the fit of Fig. 7 and 8. At $Q^2=10\text{GeV}^2$ this corresponds to $\Delta g=6.3$ and so the proton helicity is given by

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + L_Z$$

$$= 0.35 + 6.3 - 6.15$$

possible scenario:
$\Delta G \approx 6$ \hspace{0.5cm} ($Q^2=10\text{GeV}^2$)
$\Delta g/g(x) = 1$ \hspace{0.5cm} for $x_g > 0.1$

Let’s measure!
Gluon polarization is measurable in PGF

\[ A_\parallel = R_{pgf} \langle \hat{a}_{pgf} \rangle \frac{\Delta G}{G} \]

- measure \( A_\parallel \)
- calculate \( R_{pgf} \) and \( \langle \hat{a}_{pgf} \rangle \) using Monte Carlo
Hadron production

• Analysis of hadron-pair asymmetries:
  – open charm: single $D$ meson
    cleanest process wrt physics background

  – $D^0 \rightarrow K\pi(\pi^0)$
  – high-$p_T$ hadron pairs with $Q^2 > 1 \text{ GeV}^2$
  – high-$p_T$ hadron pairs with $Q^2 < 1 \text{ GeV}^2$
  – Single hadron production $Q^2 < 0.1 \text{ GeV}^2$
Results for $\Delta g$

- All results compatible with zero!
- Confirmed by RHIC results in $pp$

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Single hadron production

- Calculations exist in NLO for small $Q^2$ and large $p_T$ (Vogelsang et al.).
- Theory applicable at COMPASS? YES! Preferred scale $\mu = p_T/2$.
- Next steps: asymmetries, inclusion into global analyses of $\Delta g$.
- Much more data on tape.
Results: transverse spin structure
TMD parton distributions

- 8 intrinsic-transverse-momentum dependent PDFs at LO
- Azimuthal asymmetries with different angular modulations in the hadron and spin azimuthal angles, $\Phi_h$ and $\Phi_s$

### Diagram

<table>
<thead>
<tr>
<th>Quark Polarization</th>
<th>U</th>
<th>L</th>
<th>T</th>
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<tr>
<td>Nucleon Polarization</td>
<td>U</td>
<td>L</td>
<td>T</td>
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<tr>
<td>U</td>
<td>$f_1$</td>
<td>$f_{1T}$</td>
<td>Sivers</td>
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<td>number density</td>
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<td>aka $\Delta^T_0 q$</td>
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<td>L</td>
<td>$g_1$</td>
<td>$g_{1T}$</td>
<td>Transversity</td>
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<tr>
<td>helicity</td>
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<td></td>
<td>aka $\Delta_T q$</td>
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<tr>
<td>T</td>
<td>$h_{1T}$</td>
<td>$h_{1LT}$</td>
<td>$h_{1T}$</td>
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<tr>
<td>Boer–Mulders</td>
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</table>

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Transversity PDF $h_1$

- Couple $h_1$ PDF to chiral-odd Collins FF $H_{1}^{\perp}$

$$A_{Coll}^h \propto \frac{\sum q e_q^2 h_1^q(x) H_{1}^{\perp h/q}(z, P_{hT})}{\sum q e_q^2 f_1^q(x) D^{h/q}(z)}$$

Azimuthal cross-section asymmetry:

$$\frac{\Delta \sigma}{\sigma} \propto A_{Coll} \sin \Phi_C$$

$$\Phi_C = \phi_h - \phi_s - \pi$$
Collins Asymmetries

- large asymmetry for proton ~10%
- zero deuteron result important ⇒ opposite sign of u and d

![Graph showing Collins asymmetries](image)
Collins proton: identified hadrons

$A_C^P$ vs $x$ at different $P_T$ for positive and negative pions ($\pi$) and kaons ($K$). The plots show preliminary results from COMPASS 2007 proton data.
Collins: Comparison to Hermes

- Good agreement
Global Fit

- Fit to COMPASS $d$, HERMES, BELLE (Collins FF, $e^+e^-$)
- in good agreement with new proton data

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Transversity PDF $h_1$ via 2-hadron interference FF $H_1^{\Delta}$

- Alternative: couple $h_1$ to chiral-odd 2-hadron interference FF $H_1^{\Delta}$

Cross-section asymmetry:

$$\frac{\Delta \sigma}{\sigma} \propto A_{RS} \sin \phi_{RS} \sin \theta$$

$$\phi_{RS} = \phi_R + \phi_S - \pi; \sin \theta \simeq 1$$
two-hadron asymmetry

- Large asymmetries
- Interference FF and transversity sizable

COMPASS 2007 transverse proton data

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Comparison to a recent Fit

- Recent fit (dominated by HERMES, COMPASS $p$ not yet in)

Sivers Asymmetry:

• proposed (1990, Sivers)
• thought to vanish (1993, Collins)
• resurrected (2002, Brodsky, Hwang, Schmitt)
• different sign in DY and SIDIS
Proton Sivers Asymmetry

- compatible with zero for the deuteron
- non-zero asymmetry for pos. hadrons
• Hermes data show somewhat larger asymmetry for positive π’s
Sivers as function of $W$

- Tendency for asymmetries to increase towards small $W$, however some correlation with other kinematic variables
Spin-averaged asymmetries

- Unpolarized target $^6$LiD (deuteron)
- Kinematic factor divided out
- $\sin \phi$ modulation is small
COMPASS is more!

- Proton, pion and kaon beams
- Pion/kaon polarizability
- Meson and baryon spectroscopy, PWA

\[ \pi^- p \rightarrow \pi^- \pi^+ \pi^- p \]

\[ \pi^- p \rightarrow \pi^- \pi^0 \pi^0 p \]
What’s next?

• Focus on transverse structure of the nucleon

• Transverse size and orbital angular momentum (GPDs)
• Restricted universality of T-odd TMDs (Sivers, Boer-Mulders), sign change from SIDIS to DY, additional TMDs (pretzelocity, worm-gear)

• COMPASS-II Proposal
  wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf

• Other new facilitites/experiments
  • JLAB, RHIC, JLAB 11 GeV, JPARC,
  • ENC, eRHIC/ELIC, NICA/SPD
• Generalized Parton Distributions (GPD)
• Drell-Yan
• Pion (and kaon) Polarizabilities

COMPASS-II Proposal

Approved December 2010

The COMPASS Collaboration
Novel concept, universal, $H, \tilde{H}, E, \tilde{E}$

$H (E)$ nucleon helicity (non)conservation

Nucleon form factors and PDFs as limiting cases

Correlating transverse spatial and longitudinal momentum degrees of freedom (‘tomography’)

**Total orbital momentum:**

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

X.-D. Ji, PRL 78 (1997) 610

$x$ is not $x$-Bjorken
Orbital angular momentum

A model-dependent case-study

COMPASS

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• DVCS is the cleanest process to determine GPDs
• Need a world-wide effort
• Global analysis over large kinematic range mandatory
• COMPASS-II: from HERA to JLAB 12 GeV kinematics
• DVCS can be separated from BH and the GPD $H$ can constrained the cross section using different charge & spin ($e_\mu$ & $P_\mu$) combinations of the $\mu$ beam.

• Note: $\mu^\pm$ have opposite polarization at COMPASS.

\[
d\sigma_{\mu p \to \mu p \gamma} = d\sigma^{BH} + d\sigma_0^{DVCS} + P_\mu d\Delta \sigma^{DVCS} + e_\mu \text{Re } l + P_\mu e_\mu \text{Im } l
\]

Charge & Spin difference and sum:
\[
D = d\sigma^\pm - d\sigma^- = 2(d\sigma_0^{DVCS} + \text{Re } l)
\]
\[
S = d\sigma^\pm + d\sigma^- = 2(d\sigma^{BH} + d\sigma_0^{DVCS} + \text{Im } l)
\]

Related to:
\[
H(x=\xi,\xi, t)
\]
\[
\mathcal{P} \int dx \; H(x,\xi, t) / (x-\xi)
\]
`Tomography’

- Subtract BH from $S$, integrate over $\phi \rightarrow$ unpol. DVCS x-sect
- $\xi=0 \rightarrow t = -\Delta_T^2$, no long. transfer

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

- Transverse size as function of longitudinal momentum fraction

Independent of a GPD parametrisation!

(b) $x \sim 0.003$ 

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COMPASS-II projection

- COMPASS-II projection, 2 years of data taking
- Pilot run 2012
- $x_B$ region unique to COMPASS

\[ \frac{d\sigma_0^{DVCS}}{dt} \propto \exp(-B(x_B)|t|) \]

\[ \langle r_\perp^2(x_B) \rangle \approx 2B(x_B) \]

\[ B(x_B) = B_0 + 2\alpha' \log \frac{x_0}{x_B} \]
• Rapid variation of relative contributions with $x_B$
• Normalisation of BH contribution at small $x_B$
BH vs DVCS data

- Test runs in 2008/2009 – 40 cm long $H_2$ target
- Clear DVCS signal, BH can be subtracted
• Charge & spin asymmetry
• Sensitive to GPD $H$ models
• Cancelation of several experimental uncertainties
• Easier to measure than absolute cross-sections
• Asymmetries, sums and differences in $6x_B \times 4$ $Q^2$ bins as function of $\phi$
• Simulation for 2 years data taking, 160 GeV/c and a 2.5 m long liquid $H_2$ target
• Not shown: Deeply virtual vector meson production

\[
\mathcal{A} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{D}{S}
\]
Proj. charge & spin difference

$E_{\mu} = 160$ GeV  \quad 1 \leq Q^2 \leq 4$ GeV$^2$  \quad $0.03 \leq x_B \leq 0.07$

- VGG Reggeized $(x,t)$-correlation $\alpha' = 0.8$
- VGG Factorized $(x,t)$-dependence $\alpha' = 0.05$

Mueller fit on world data
- (with JLab Hall A)
- (without JLab Hall A)
Proj. charge & spin asymmetry

$E_\mu = 160$ GeV  \quad 1 \leq Q^2 \leq 4$ GeV$^2$  \quad 0.03 \leq x_B \leq 0.07

- VGG Reggeized (x,t)-correlation
- VGG Factorized (x,t)-dependence

Mueller fit on world data
- (with JLab Hall A)
- (without JLab Hall A)
Semi-inclusive DIS

- COMPASS I had $^6$LiD and NH$_3$ (i.e. deuterons for unpol.)
- COMPASS II pure hydrogen target in parallel with DVCS
  - $A^{\cos \phi}, A^{\cos 2\phi}, A^{\sin \phi}$ for proton
  - Hadron multiplicities for FF, strange quark PDF

Proj. for 1 week
DVCS – main new equipment

New electromagnetic calorimeter, ECAL0
Liquid hydrogen target, 2.5 m long
Proton Time-Of-Flight detector, 4.0 m long
Experimental setup: Camera

- 2 barrels 4m long long scintillators
- ~ 300ps timing resolution
- 2.5 m long LH2 target

Gandalf Readout Project:
1 GHz digitalisation of the PMT signal to cope for high rate
Geometry target region

PMT

4.2 m
3.6 m

Ring B

PMT

30 cm

Ring A

beam

LH2 target

11 m

25 cm

2.5 m

Long light guide

30 cm

ECAL 0

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ECAL0

- new **ECAL0** large angle calorimeter
- Multipixel Avalanche Photodiode readout

**ECAL0** 248 modules (12 × 12 cm²) of 9 cells read by 9 MAPDs
Drell–Yan Process

- No fragmentation function involved
- Convolution of two PDFs
- Best: pol. antiproton–proton (long-term)
- Simpler: negative pion on pol. proton (short-term)
- Pion valence anti-u annihilates with proton u
Restricted universality in SIDIS and DY

SIDIS: FSI

DY: ISI

T-odd TMD

`gauge link changes sign for T-odd TMD’, restricted universality of T-odd TMDs

\[ f_{1T}^{\perp} \bigg|_{D} = \overline{f_{1T}^{\perp}} \bigg|_{D} \quad \text{and} \quad h_{1}^{\perp} \bigg|_{D} = \overline{h_{1}^{\perp}} \bigg|_{D} \]

Sivers
Boer-Mulders

J.C. Collins, PLB536 (2002) 43

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## Future DY experiments

<table>
<thead>
<tr>
<th>Facility</th>
<th>Type</th>
<th>$s$ (GeV$^2$)</th>
<th>Time-line</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RHIC (STAR, PHENIX)</strong> [147]</td>
<td>collider, $p^\uparrow p^\uparrow$</td>
<td>$200^2$, $500^2$</td>
<td>$&gt; 2014$</td>
</tr>
<tr>
<td><strong>RHIC (internal target)</strong> [148]</td>
<td>fixed target, $p^\uparrow p^\uparrow$</td>
<td>$500$</td>
<td>$&gt; 2015$</td>
</tr>
<tr>
<td><strong>E906 (Fermilab)</strong> [149]</td>
<td>fixed target, $pp$</td>
<td>$226$</td>
<td>$&gt; 2010$</td>
</tr>
<tr>
<td><strong>J-PARC</strong> [150]</td>
<td>fixed target, $pp^\uparrow$</td>
<td>$60 \div 100$</td>
<td>$&gt; 2015$</td>
</tr>
<tr>
<td><strong>GSI (PAX)</strong> [151]</td>
<td>collider, $\bar{p}^\uparrow p^\uparrow$</td>
<td>$200$</td>
<td>$&gt; 2017$</td>
</tr>
<tr>
<td><strong>GSI (Panda)</strong> [152]</td>
<td>fixed target, $\bar{p}p$</td>
<td>$30$</td>
<td>$&gt; 2016$</td>
</tr>
<tr>
<td><strong>NICA</strong> [153]</td>
<td>collider, $p^\uparrow p^\uparrow$, $d^\uparrow d^\uparrow$</td>
<td>$676$</td>
<td>$&gt; 2014$</td>
</tr>
<tr>
<td><strong>COMPASS</strong> (this Paper)</td>
<td>fixed target, $\pi^- p^\uparrow$</td>
<td>$300 \div 400$</td>
<td>2014</td>
</tr>
</tbody>
</table>

**RHIC AnDY**

- collider
- pp pol.
- $500^2$
- $> 2013$
Drell–Yan muon pair mass regions

2 < \(M_{\mu^+\mu^-}\) < 2.5 GeV possible region
Combinatorial background < 1:1

J/\(\psi\) region

4 < \(M_{\mu^+\mu^-}\) < 9 GeV Safe region
• COMPASS-II: 190 GeV/c $\pi^-$ beam on transversely pol. proton target

• $\pi^-$ valence u-antiquark picks nucleon’s u quark in valence region (u-quark dominance)

• Access to transversity, the T-odd Sivers and Boer-Mulders TMDs
Major rearrangement of target region

- Quench and Exhaust Lines
- Cable trays
- Transfer Line
- Control Racks
- Absorber
- He-pipes
- Micro Wave guides
- Pol. target

G.K. Mallot/CERN
Varenna, July 2011
COMPASS polarized DY

\[ x_F = x_{\pi} - x_p \]
More projections

\[ 2.0 \leq M_{\mu\mu} \leq 2.5 \text{ GeV/c}^2 \]

\[ 4.0 \leq M_{\mu\mu} \leq 9.0 \text{ GeV/c}^2 \]
COMPASS-II schedule

2012 Primakoff scattering: DVCS pilot run: Polarizabilities of $\pi$ and K $t$-slope, transverse size

2013 Accelerator shutdown

2014 Drell-Yan: Universality of TMDs

2015–2016 DVCS and DVMP: Study GPDs, “nucleon tomography”

Unpolarized SIDIS: FF, strangeness PDF, TMDs

Caveat: CERN Accelerator schedule not fixed beyond Nov 2012
Summary

• Wealth of data from COMPASS, more to come, e.g
  – Single hadron production asymmetries ($\Delta G$)
  – Hadron spectroscopy
• Focus shifting to 3D structure of the nucleon
• COMPASS II will make major contributions
• Exciting times ahead (also off-LHC)
(Nucleon) Spin is fun