COMPASS with high intensity muon beams and unpolarized target

Generalized Parton Distributions (GPDs)
sensitivity to the COMPASS kinematics

DVCS with polarized $\mu^+$ and $\mu^-$
Meson production (present $\rho$ studies)

High luminosity and Recoil Detection

Other accurate measurements with the same setup
for Structure Functions Study and Color Transparency

Nicole d'Hose (CEA Saclay) and Horst Fischer (Universität Freiburg)

SPSC meeting at Villars - 25 September 2004
**GPDs** ≡ a 3-dimensional picture of the partonic nucleon structure

**Deep Inelastic Scattering**

\[ e p \rightarrow e X \]

\[ Q^2 \times B_j \]

\[ \gamma^* \rightarrow x \]

\[ p \rightarrow x P \]

\[ x \text{ boost} \]

\[ x P \]

\[ q ( x ) \]

\[ P_x \]

**Hard Exclusive Scattering**

**Deeply Virtual Compton Scattering**

\[ e p \rightarrow e p \gamma \]

\[ \gamma^* \rightarrow Q^2 \]

\[ x^+ \xi \]

\[ x^- \xi \]

\[ p \rightarrow x P \]

\[ r_{\perp} \]

\[ x \text{ boost} \]

\[ x P \]

**Generalized Parton Distribution**

\[ H( x, \xi, t ) \]

\[ ( P_x, r_{y, z} ) \]

*Burkard, Belitsky, Müller, Ralston, Pire*
Why GPDs are promising?

Goal: correlation between the 2 pieces of information:
- distribution of longitudinal momentum carried by the partons $\vec{p}$
- distribution in the transverse plane $\vec{r}$

Implication of orbital angular momentum $\vec{r} \times \vec{p}$ to the total spin of a nucleon

in the context of the COMPASS program

Knowledge of the transverse size of parton distribution in hadron-hadron collisions such as at LHC, RHIC
What do we learn from the 3 dimensional picture $(P_x, r_y, z)$?

   - fast parton close to the N center $\equiv$ small valence quark core
   - slow parton far from the N center $\equiv$ widely sea $q$ and gluons

   
   at large distance, the gluon density
   is generated by the pion cloud
   
   significant increase of
   the N transverse size
   
   if $x_{Bj} < \frac{m_\pi}{m_p}=0.14$

   COMPASS domain
GPDs and relations to the physical observables

The observables are some integrals of GPDs over $x$

Dynamics of partons in the Nucleon Models:
- Parametrization

Elastic Form Factors

$\int H(x,\xi,t)dx = F(t)$

Ji’s sum rule

$2J_q = \int x(H+E)(x,\xi,0)dx$

$1/2 = 1/2 \Delta \Sigma + L_q + \Delta G + L_g$

“ordinary” parton density

$H(x,0,0) = q(x)$

$\tilde{H}(x,0,0) = \Delta q(x)$
Chiral quark-soliton model: Goeke et al., NP47 (2001)

This ansatz reproduces the

**Parametrization of GPDs**

Model 1: \[ H(x,\xi,t) \sim q(x) F(t) \]

Model 2: is more realistic
it considers that fast partons in the small valence core
and slow partons at larger distance (wider meson cloud)
it includes correlation between \( x \) and \( t \)

\[ <b_{\perp}^2> = \alpha' \ln \frac{1}{x} \]
transverse extension of partons in hadronic collisions

\[ H(x,0,t) = q(x) e^{t <b_{\perp}^2>} = q(x) / x^\alpha' \]
\((\alpha'\text{slope of Regge traject.})\)
Necessity of factorization to access GPDs

Deeply Virtual Compton Scattering (DVCS):

Collins et al.

Hard Exclusive Meson Production (HEMP):
Complementarity of the experiments in the world

if \( N_\mu \times 2 \Rightarrow Q^2 < 11 \text{ GeV}^2 \)

for DVCS

Limitation by luminosity

now \( N_\mu = 2 \times 10^8 \mu \) per SPS spill

for DVCS

\( \Rightarrow Q^2 < 7.5 \text{ GeV}^2 \)

At fixed \( x_{\text{Bj}} \), study in \( Q^2 \)

0.0001 < \( x_{\text{Bj}} < 0.01 \)

Valence and sea quarks

And Gluons

Gluons

Valence quarks

H1 and ZEUS


Hermes

PRL87(2001)

COMPASS

JLab

PRL87(2001)
if $N \mu \times 2 \Rightarrow Q^2 < 11 \text{ GeV}^2$
for DVCS

Limitation by luminosity

now $N \mu = 2 \times 10^8 \mu$ per SPS spill
for DVCS $\Rightarrow Q^2 < 7.5 \text{ GeV}^2$

At fixed $x_{Bj}$, study in $Q^2$

$0.0001 \times x_{Bj} < 0.01$
Gluons

Valence and sea quarks
And Gluons

H1 and ZEUS

Hermes

COMPASS

JLab

Valence quarks

Upgraded CEBAF

Hall A

E = 11 GeV

E = 6 GeV

W > 2 GeV

L

A

S
In 2010? sharing CNGS/FT operations
new Linac4 (160GeV, H⁻) as injector for the PSB
improvements on the muon line

what could be the available proton/muon flux?

Based on 2004 beam characteristics

$N_\mu = 2.10^8$ per SPS cycle  
duration 5.2s repetition each 16.8s

with a new 2.5m liquid hydrogen target \( \Rightarrow \mathcal{L} = 1.3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)

with the 1.2m $^6$LiD target \( \Rightarrow \mathcal{L} = 4.2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)

one year of data taking \( \equiv \) 150 days \( \equiv 7.2 \times 10^5 \) spills/year

the highest luminosity with the Muon Beams
Polarized $\mu^+$ and $\mu^-$ beams

Requirements for DVCS:
- same energy
- maximum intensity
- opposite polarisation to a few %

Solution proposed by Lau Gatignon:
1) To select $P_\pi=110\text{GeV}$ and $P_\mu=100\text{GeV}$ to maximise the muon flux
2) To keep constant the collimator settings which define the $\pi$ and $\mu$ momentum spreads
   $\Rightarrow$ $Pol \ \mu^+ = -0.8 \text{ and } Pol \ \mu^- = +0.8$
3) $N_{\mu^+} \sim 2 \times N_{\mu^-}$
The high energy muon beam at COMPASS allows to play with the relative contributions DVCS-BH which depend on

\[ \frac{1}{y} = 2 m_p E_\ell x_{Bj} / Q^2 \]

Higher energy: DVCS >> BH
⇒ DVCS Cross section

Smaller energy: DVCS ~ BH
⇒ Interference term will provide the DVCS amplitude
Advantage of $\vec{\mu}^+$ and $\vec{\mu}^-$ for Deeply virtual Compton scattering (+Bethe-Heitler)

$$A^{DVCS}_{(\mu p \rightarrow \mu p \gamma)}(t, \xi \sim x_{Bj/2} \text{ fixed}) = \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i \epsilon} = \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} - i \pi H(x = \xi, \xi, t)$$

$$d\sigma(\mu p \rightarrow \mu p \gamma) = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu a^{BH} \Re A^{DVCS} \times \cos n\varphi$$

$$+ P_\mu d\sigma^{DVCS}_{pol} + e_\mu P_\mu a^{BH} \Im A^{DVCS} \times \sin n\varphi$$

$$\sigma^{\vec{\mu}^+} + \sigma^{\vec{\mu}^-} \sim H(x = \xi, \xi, t)$$

$$\sigma^{\vec{\mu}^+} - \sigma^{\vec{\mu}^-} \sim \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi}$$

$P_{\mu^+} = -0.8 \quad P_{\mu^-} = +0.8$

Diehl
DVCS Beam Charge Asymmetry (BCA) measured with the 100 GeV muon beam at COMPASS

\[ \sigma^{\mu^+} - \sigma^{\mu^-} \sim \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} \]

Model 1: \( H(x, \xi, t) \sim q(x) F(t) \)

Model 2: \( H(x, 0, t) = q(x) e^{t \left< b_\perp^2 \right>} \)

\[ = q(x) / x^{\alpha' t} \]

\( \mathcal{L} = 1.3 \times 10^{32} \, \text{cm}^{-2} \, \text{s}^{-1} \)

efficiency=25%

150 days data taking

Only 2/18 data sets

In total 3 bins in \( x_{Bj} = 0.05, 0.1, 0.2 \)

6 bins in \( Q^2 \) from 2 to 7 GeV\(^2\)
Advantage of the kinematical domain of COMPASS

Model 1: \( H(x, \xi, t) \sim q(x) F(t) \)

Model 2: \( H(x, 0, t) = q(x) e^{\frac{t}{\langle b^2 \rangle}} \)
\[ = q(x) / x^{\alpha^* t} \]

sensitivity to the different spatial distribution of partons \( \uparrow \) when \( x_{Bj} \downarrow \)

range of COMPASS
Hard exclusive meson production ($\rho, \omega, \phi, \pi, \eta, \ldots$)

Collins et al. (PRD 56 1997):

1. Factorization applies only for $\gamma^* L$

2. \( \sigma_T \ll \sigma_L \)

$\rho^0$ largest production
$\rho^0 \rightarrow \pi^+ \pi^-$

Scaling predictions:

$1/Q^4$, $1/Q^6$
Selection of $\gamma^*_{L}$

Pseudo-scalar meson (spin 0) as $\pi \Rightarrow$ Rosenbluth separation

$$\sigma_{tot} = \sigma_T + \varepsilon \sigma_L$$

Vector meson (spin 1) as $\rho^0 \Rightarrow$ angular distribution of $\rho^0 \rightarrow \pi^+ \pi^-$

+ s-channel-helicity-conservation in $p(\gamma^*_{L}, \rho^0_L)p$

With COMPASS + $\mu^-$

Complete angular distribution

$\Rightarrow$ Full control of SCHC

COMPASS 2003
50 days $L = 4.2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$

~ Equivalent to predictions 2010
150 days $L = 1.3 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
"Longitudinal" Meson production: filter of GPDs

Cross section:

Vector meson production \((\rho,\omega,\phi...\)) \(\Rightarrow\) \(H\) & \(E\)

Pseudo-scalar production \((\pi,\eta...\)) \(\Rightarrow\) \(\tilde{H}\) & \(\tilde{E}\)

\[ H_{\rho^0} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} H^u + \frac{1}{3} H^d + \frac{3}{8} H^g \right) \]

\[ H_\omega = \frac{1}{\sqrt{2}} \left( \frac{2}{3} H^u - \frac{1}{3} H^d + \frac{1}{8} H^g \right) \]

\[ H_\phi = -\frac{1}{3} H^s - \frac{1}{8} H^g \]

Single spin asymmetry \(\sim E/H\)

for a transverse polarized target
(can be investigated at COMPASS during transversity measurement)
Quark and gluon contributions

\[ \gamma^* + p \rightarrow \rho_0^0 + p \]

- NMC 94
- E665 97
- ZEUS 93+95

- Preliminary errors for COMPASS 2003 (\(^6\)LiD)
  
  COMPASS 2010 (H)

Gluon GPD calculations:
Frankfurt et al. PRD54 (1996)

Quark GPD calculations:
Vanderhaeghen et al. PRD60 (1999)
Meson Production in the future around 2010

With a liquid Hydrogen target and the same muon flux than now

Measurement of hard exclusive meson production

\[ \rho \quad \text{comfortable statistics until } Q^2 = 20 \text{ GeV}^2 \]

\[ \omega \pi \eta \phi \quad \rightarrow \quad Q^2 = 7 \text{ GeV}^2 \]

Benefit of an increase in intensity
for an extension of the range in \( Q^2 \)

NB: for \( \omega \) results from JLab the SCHC was not observed
at \( Q^2 < 4\text{GeV}^2 \) and large \( x_{Bj} \sim 0.4 \)
Necessity to complete at large angle the high resolution COMPASS spectrometer

Deeply Virtual Compton Scattering $\mu p \rightarrow \mu' p' \gamma$

By a recoil detector to insure the exclusivity of the reaction

$\theta_\gamma \leq 12^\circ$

all COMPASS trackers: SciFi, Si, $\mu\Omega$, Gem, DC, Straw, MWPC
Key role of the Calorimetry

ECAL2 from 0.4 to 2° mainly lead glass GAMS
ECAL1 from 2 to 12° good energy and position resolution
   for 2 photons separation
   in a high rate environment

ECAL0 from 12 to 24° to be designed
   for background rejection

Intensive Study of photon and pi0 production
linked to the hadron program
Additional equipment to the COMPASS setup

**A possible solution** (proposed in the Workshop on the Future Physics at COMPASS 26 Sept 2002)

**Challenge:** 200ps ToF Resolution for 4m scintillating system

- an accurate t measurement for 3-dim GPD representation in order to get the spatial information

**Goal of the JRA (Bonn-Mainz-Warsaw-Saclay) in the EU FP6:**

- Realisation of a prototype detector consisting of a 45° sector
Other accurate measurement with the same setup

Parasitic:

- Structure Function $F_2$ on Hydrogen

Dedicated targets:

- Evolution of $F_2$ in the nuclear matter
  Shadowing effect on light nuclei  
  (Smirnov EPJC (1999))

- Color Transparency on C and Pb
**Universal Structure Functions**

\[
\text{DIS } ep \rightarrow eX \quad \frac{d^2 \sigma}{dx dQ^2} = \frac{4\pi \alpha^2}{x Q^2} \left( F_2(x, Q^2)(1 - y - \frac{Q^2}{4E^2}) + xy^2 F_1(x, Q^2) \right)
\]

\[
\frac{d^2 \sigma}{dx dQ^2} = \Gamma(\sigma_T(x, Q^2) + \epsilon \sigma_L(x, Q^2)) \\
R(x, Q^2) = \frac{\sigma_L(x, Q^2)}{\sigma_T(x, Q^2)}
\]

\[
\frac{d^2 \sigma}{dx dQ^2} = \frac{4\pi \alpha^2}{Q^4} \frac{F_2(x, Q^2)}{x} \left( 1 - y - \frac{Q^2}{4E^2} + \frac{y^2 + Q^2 / E^2}{2(1 + R(x, Q^2))} \right)
\]

They provide the parton distributions:

\[
F_2(x, Q^2) = x \sum_q e_q^2 (q(x, Q^2) + \bar{q}(x, Q^2))
\]

New measurements of \( F_2 \) and \( R \) are beneficial if they have improved statistics and systematical errors or if they are in new kinematical domains.
Success of QCD

The NLO DGLAP equations describe the $Q^2$ evolution of $F_2$

Possible New Accurate Measurement At COMPASS
Projection for COMPASS
75 days with $N_\mu=2.10^8$/spill and 2.5m Hydrogen target
Kinematical domains for colliders and fixed target experiments

until $Q^2 = 10^{-3}$

$\times = 3.10^{-5}$

COMPASS
Understanding of low $x$ physics

New phenomena
Coherent interaction of partons
Log $1/x$ in the QCD evolution

Transition from high to low $Q^2$
to understand confinement

Saturation model

New data at low $x$ low $Q^2$
with COMPASS

**Color Transparency CT via exclusive vector meson production**

QCD prediction

\[ \exists \text{ small color singlet object for which interactions with nuclear medium vanish at large } Q^2 \]

\[ r_\perp = k/Q \] k varies with quark mass

\[ r_\perp(u\bar{u}) \approx r_\perp(d\bar{d}) \approx 0.3 \text{fm} \quad \text{at } Q^2 = 10 \text{ GeV}^2 \]

Small size configuration SSC

\[ r_\perp \approx 0.3 \text{fm} \]

SSC interaction in pQCD

\[ \sigma_{q\bar{q}N}(r_\perp, x_{Bj}) \approx 3 \text{mb at } x_{Bj} = 10^{-2} \]

on quasi-free nucleons in nuclei

\[ \sigma_{\rho N} \approx 25 \text{mb} \]

CT: \[ T = \frac{\sigma_A/A}{\sigma_N} \rightarrow 1 \quad \text{when } Q^2 \rightarrow \]

Coherence length

\[ l_c = \frac{2\nu}{Q^2 + M_{q\bar{q}}^2} \]

Coherence effects can mimic CT

\[ l_c = 1-6 \text{fm at HERMES} \]

\[ 1-20 \text{fm at COMPASS} \]

\[ 1-200 \text{fm at E665} \]

\[ r_{pb} = 11 \text{fm} \]
Color Transparency CT via exclusive vector meson production

complete programme for CT at COMPASS

- $A$, $Q^2$, and $x_{Bj}$ dependence of cross sections for $\rho$ (or $\phi, J/\Psi$...) production
- Study at fixed coherence length
- Measure both coherent $\mu A \rightarrow \mu \rho A$ and incoherent $\mu A \rightarrow \mu \rho N(A-1)$
- Measure $\sigma_L$ and $\sigma_T$

On C and Pb of 70g/cm2
2.10$^8$ $\mu$/spill
38 days equally distributed
$\varepsilon_{SPS+COMPASS}=25\%$

Large number of events in the COMPASS acceptance

$E_\mu=190$ GeV

$2 < Q^2 < 20$ GeV$^2$
$0.006 < x_{Bj} < 0.1$
$1 < l_c < 20$fm  $r_{Pb}=11$fm
Competition to COMPASS

measurements at COMPASS in 2010
in the $x_{Bj}$ intermediate range
compared to:

HERMES 2 data years until 2007
  equivalent integrated luminosity/year
  with a new recoil detector
  reduced kinematical domain in $Q^2$

e-RHIC in the far future around 2015?
  high energy in the collider mode
  high luminosity

Rq: H1 and ZEUS until 2007 ($x_{Bj} < 10^{-2}$)
  JLab 11 GeV in 2010 (large $x_{Bj}$)
Roadmap for GPDs at COMPASS

2004-2009
Present COMPASS experiment with a polarized target
Complete analysis of $\rho$ production
→ SCHC study in a large range in $Q^2$ 0.02-25 GeV$^2$
→ E/H investigation with the transverse polarized target

2004-2006
Realization of the recoil detector prototype within the JRA
JRA/FP6: Bonn, Mainz and Warsaw and CEA Saclay

We are considering to submit a proposal in 2006

2007-2009: construction of the recoil detector cryogenic target, ECAL0

2010-2015: GPDs and related physics at COMPASS