A Collaboration of 240 Physicists of 12 countries

A Facility to study QCD

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY

Future Plans: LoI submitted to CERN/SPSC in January 2009
Proposal in preparation

With the high energy polarised muon beam:

1- Longitudinal Spin Structure
2- Generalized Parton Distributions
3- Transverse Spin Structure (next talk)
SPS beam: protons up to 400 GeV/c, 4.8s/16.2s spills
- Secondary hadron beams ($\pi$, K,...): $2 \times 10^8$ /spill, 150-270 GeV/c
- Tertiary muons: $2 \times 10^8$ /spill, 100-190 GeV/c, 80% polarisation
-> Luminosity $\sim 5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ with polarised targets
Longitudinal Spin Structure Function of the Deuteron

Inclusive measurements on a longitudinally polarised deuteron target in 2002-3-4-6

\[ g_1(x) = \frac{1}{2} \sum_{q=u,d,s} e_q^2 \Delta q(x) \]

\[ \Delta q = \vec{q} - \vec{\bar{q}} \]

- Only place for high energy polarized lepton beams → low x and high Q^2
- Precise measurement + impact at small x → systematics from the extrapolation for the unmeasured low x contribution to \( \int_0^1 g_1(x) \, dx \) considerably reduced

Quark helicity

\[ \Delta \Sigma = \sum_q \int_0^1 \Delta q(x) \, dx \]

\[ Q^2 = 3 \text{ GeV}^2 \]

\[ = 0.30 \pm 0.01 \text{ (stat)} \pm 0.02 \text{ (extrapolation)} \]

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Longitudinal Spin Structure Function of the Proton

Necessity of a balanced statistics between proton and deuteron data

Inclusive measurements on a longitudinally polarised deuteron target in 2002-3-4-6

\[ g_1^d(x) \]

Inclusive measurements on a longitudinally polarised proton target in 2007

\[ g_1^p(x) \]

+ 150 days (1 year) of SPS beam (preferably 200 GeV if same intensity as 160 GeV ?)

At small \( x \) → precise measurement → better extrapolation

COMPASS Projection with 1 additional year of proton
New evaluation of the non-singlet spin structure function $g_1^{NS} \approx 2(g_1^p - g_1^d)$

**COMPASS Projection with 1 additional year of proton**

- Precise shape determination at low $x$
- More reliable extrapolation to $x=0$
- Reduced statistical and systematic errors in the test of the Bjorjen sum rule (fundamental result of QCD)
Flavor asymmetry of the polarised light sea $\Delta\bar{u} - \Delta\bar{d}$

With Semi-Inclusive Hadron Asymmetries

COMPASS Projection with 1 additional year of proton

$\rightarrow$ Separation between extreme models

$\rightarrow$ enters in NLO global fits
“Spin crisis”, possible scenarios

ΔG Gluon helicity: - from production of high p_T pairs, open charm  
- from g_1^p Q^2 evolution

From COMPASS & RHIC, ΔG not large:

- ΔG = |∫ΔG(x_G)| < 0.4
- ΔΣ ≈ a_0 = 0.3

\[
a_0 = \frac{3\alpha_s}{2\pi} \Delta G
\]

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_Z
\]

\[
\frac{1}{2} = \frac{1}{2} \times 0.3 + 0.35 + 0
\]

\[
\frac{1}{2} = \frac{1}{2} \times 0.3 + 0.0 + 0.35
\]

\[
\frac{1}{2} = \frac{1}{2} \times 0.3 - 0.35 + 0.70
\]

Complementary approach for Orbital Angular Momentum:
- Sivers function (next talk)
- Generalized Parton Distributions
Generalised Parton Distribution functions:

- Allow for a unified description of form factors and parton distribution
- Allow for transverse imaging (nucleon tomography) and to access the quark angular momentum

Tomographic parton images of the nucleon:

- Impact parameter $b$
- Longitudinal momentum fraction $x$
- $x < 0.01$
- $x \sim 0.1$
- $x \sim 0.3$
What makes COMPASS a unique case?

1- CERN SPS high energy muon beam 100/190 GeV
   Kinematic domain
   \(10^{-2} < x < 10^{-1}\)

2- availability of \(\mu^+\) and \(\mu^-\) with opposite polarisation
   polarisation=80%

3- with a 2.5m long LH2 target
   Lumi= \(10^{32}\) cm\(^{-2}\) s\(^{-1}\)
   (limit for a collider without R&D)
   \(\rightarrow\) \(Q^2\) up to 8 GeV\(^2\)

\(\rightarrow\) Any lumi upgrade extents the reach of the proposed measurements

if Lumi \(\times 4\) \(\rightarrow\) more comfortable statistics for \(Q^2\) up to 12 GeV\(^2\)

Note: ENC@FAIR \(E_p=15\)GeV \(E_e=3\)GeV
   equivalent to \(E_\mu @\) CERN=100GeV
2 channels studied:
- exclusive meson production
- exclusive single-photon production

\[ \mu p \rightarrow \mu \gamma p \]

\[ d\sigma \propto |T_{\text{DVCS}}|^2 + |T_{\text{BH}}|^2 + \text{Interference Term} \]

at COMPASS we can deal with
✓ either BH
✓ either DVCS
✓ or the interference
Comparison BH and DVCS at 160 GeV

At $Q^2 = 2 \text{ GeV}^2$, $|t| = 0.1 \text{ GeV}^2$

- $x = 0.01$: BH dominates, DVCS boosted by interference
  - DVCS reference yield
  - $\text{Re } T^{\text{DVCS}}$ or $\text{Im } T^{\text{DVCS}}$
  - study of $d\sigma^{\text{DVCS}}/dt$
  - (not possible at JLab)

- $x = 0.04$: BH and DVCS at the same level

- $x = 0.1$: DVCS dominates

BH dominates
excellent
reference yield
$$d\sigma_{(\mu p\rightarrow\mu p\gamma)} = d\sigma^{\text{BH}} + d\sigma^{\text{DVCS unpol}} + P_{\mu} d\sigma^{\text{DVCS pol}}$$
$$+ e_{\mu} a^{\text{BH}} \Re T^{\text{DVCS}} + e_{\mu} P_{\mu} a^{\text{BH}} \Im T^{\text{DVCS}}$$

**Beam Charge & Spin Difference**

$$D_{u,cs} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) = 2(e_{\mu} a^{\text{BH}} \Re T^{\text{DVCS}} + P_{\mu} d\sigma^{\text{DVCS pol}})$$

$$C_0^{\text{Int}} + C_1^{\text{Int}} \cos \phi + C_2^{\text{Int}} \cos 2\phi + C_3^{\text{Int}} \cos 3\phi$$

$$S_1^{\text{DVCS}} \sin \phi$$

**Beam Charge & Spin Sum**

$$S_{u,cs} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) = 2(d\sigma^{\text{BH}} + d\sigma^{\text{DVCS unpol}} + e_{\mu} P_{\mu} a^{\text{BH}} \Im T^{\text{DVCS}})$$

$$C_0^{\text{DVCS}} + C_1^{\text{DVCS}} \cos \phi + C_2^{\text{DVCS}} \cos 2\phi$$

$$S_1^{\text{Int}} \sin \phi + S_2^{\text{Int}} \sin 2\phi$$
Transverse imaging at COMPASS

Using $S_{U,CS}$ and integration over $\phi$ and BH subtraction

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

\[ B(x) = b_0 + 2 \alpha' \ln(x_0/x) \]

\[ \alpha' = 0.125 \text{ GeV}^{-2} \]

FFS model

for valence quark $\alpha' \sim 1 \text{ GeV}^{-2}$ to reproduce FF

for gluon $\alpha' \sim 0.164 \text{ GeV}^{-2}$ ($J/\Psi$ at $Q^2=0$)

$\alpha' \sim 0.02 \text{ GeV}^{-2}$ ($J/\Psi$ at $Q^2=2-80 \text{ GeV}^2$)

\[ \approx \text{ meson Regge traj.} \]

\[ \ll \alpha' \sim 0.25 \text{ GeV}^{-2} \]

for soft Pomeron
Using $D_{u,cs} / S_{u,cs}$: Beam Charge and Spin Asymmetry

Comparison to different models

$E_\mu = 160$ GeV, $1 \leq Q^2 \leq 4$ GeV$^2$, $0.03 \leq x \leq 0.07$
statistical errors only (in 140 days)

- VGG Reggeized $(x,t)$-correlation ($\alpha' = 0.8$)
- VGG Factorized $(x,t)$-dependence ($\alpha' \sim 0.1$)

160 GeV muon beam
2.5m LH$_2$ target
$\varepsilon_{\text{global}} = 10\%$, 140 days
Lumi = 1222 pb$^{-1}$

fit on world data

LOI CERN-SPSC-2009-003
Beam Charge and Spin Asymmetry over the kinematic domain

Prediction with VGG

160 GeV muon beam
2.5m LH₂ target
\( \varepsilon_{\text{global}} = 10\% \), 140 days
Lumi=1222pb⁻¹

\( Q^2 = 12 \text{ GeV}^2 \)

\( x = 0.15 \)

If Lumi \( \times 4 \) \( \rightarrow \) statistics errors divided by 2
more bins up to \( Q^2 = 12 \text{ GeV}^2 \)
Proposal to study “GPDs @ COMPASS” in 2 phases

Phase 1: DVCS experiment in ~2012 to constrain GPD H
with $\mu^+\downarrow, \mu^-\uparrow$ beam + unpolarized long LH2 (proton) target

\[ \frac{d\sigma}{dt} \rightarrow \text{transverse imaging} \]

\[ \mathcal{D}_{U,CS} \equiv d\sigma(\mu^+\downarrow) - d\sigma(\mu^-\uparrow) \propto c_0^{\text{Int}} + c_1^{\text{Int}} \cos \phi \quad \text{and} \quad c_{0,1}^{\text{Int}} \sim \Re(F_1 H) \]

\[ \mathcal{S}_{U,CS} \equiv d\sigma(\mu^+\downarrow) + d\sigma(\mu^-\uparrow) \propto s_1^{\text{Int}} \sin \phi \quad \text{and} \quad s_1^{\text{Int}} \sim \Im(F_1 H) \]

Phase 2: DVCS experiment in ~2014 to constrain GPD E
with $\mu^+$ and transversely polarized NH3 (proton) target

\[ d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S+\pi) \]

\[ \propto \Im(F_2 H - F_1 E) \sin(\phi-\phi_S) \cos \phi \]
Experimental setup upgrade (for DVCS)

To be designed and built

**Phase 1**
- ~ 2.5 m Liquid Hydrogen Target
- ~ 4 m Recoil Proton Detector

**Phase 2**
- Polarised Transverse Target
- Associated RPD

Small Recoil Proton Detector and a 40cm LH2 target available in 2008
Already DVCS test in 1 day in 2008
with 1/3 nominal $\mu$ intensity, 1/6 target length
(using the present recoil proton detector)

Angular distribution in $\phi$

- Clear signature of BH events
- DVCS events are expected with a flat distribution

Looks encouraging, 2 weeks measurements in 2009
Conclusions

the unique **high energy polarised muon** beam at COMPASS allows very precise measurements in Longitudinal Spin Structure at low $x$

- test of Bjorken sum rule
- flavor asymmetry of the polarised light sea
- impact on QCD fits

the availability of both $\mu^+\downarrow$ and $\mu^-\uparrow$ beams is the decisive assets for the GPD program @ COMPASS

- unique and large domain $10^{-2} < x < 10^{-1}$
- BH, DVCS and Re $T_{DVCS}^D$ or Im $T_{DVCS}^D$

could be nicely completed by a substantial increase of
- luminosity (to increase the GPD domain in $Q^2$)
- energy (to still increase the domain at small $x$)

*(Possible upgrade of the M2 beam line discussed today)*