Fixed target physics at CERN SPS

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- Why fixed targets
- Compass and spin structure of the nucleon
- SHINE - cross sections and energy scan with heavy ions
- Rare K decays - search for New Physics
- Future: GPD and DVCS measurements

Symposium on Physics of Elementary Interactions in the LHC Era
Warsaw, 22.04.2008
Why fixed target?

- Study of the structure of composed object by scattering on it elementary projectiles:
  - Rutherford like experiment
  - charged leptons and neutrinos as projectiles

- Requirements on target
  - polarization
  - material

- Study of decays (particle production)

Present and near future experiments on SPS
What is the CERN - SPS fixed target program?

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- Experiments with strong polish participation
- Experiment without polish participation

from CERN Council 142’th session in 21’st June 2007
Resolution of the "DIS microscope"

This is what we know:
- quarks
- pairs quark-antiquark
- gluons

Deeper we look inside $\Rightarrow$ more quark-antiquark pairs we see ...
Mechanism: quarks emit gluons, gluons produce pairs ...

Emission probability depends on $Q^2$,
splitting functions, $P_{ij}$, describe how the momentum is divided

$$
\frac{d}{d\mu} \left( \frac{\Delta q(x, \mu)}{\Delta g(x, \mu)} \right) = \int_x^1 \frac{dz}{z} \left( \frac{\Delta P_{qq}}{\Delta P_{gq}} \Delta P_{gg} \right)_{(z, \alpha_s(\mu))} \cdot \left( \frac{\Delta q}{\Delta g} \right) \left( \frac{x}{z}, \mu \right)
$$

Scale $\mu$
Replaced by $Q^2$
Determination of quark polarization inside nucleon

Photon spin = 1
Quark spin = 1/2

\[ \Delta \Sigma(MS) = 0.33 \pm 0.03 \text{(stat)} \pm 0.05 \text{(syst)} \]

From naive expectation it should be +1, after relativistic correction about 0.66
So half is missing !!!
Recall: simple quark model

In QCD: proton is not just 3 quarks!

Rich structure of quarks, anti-quarks, gluons
The title "spin crisis" is followed by a discussion on orbital angular momentum. Contributions from quarks and gluons are mentioned, with a note that the missing contribution can be carried by gluons. The equation $S_N = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$ is presented, indicating the quark contribution is not enough for the goal of next generation experiments.
To understand spin structure we have to measure $\Delta G$ and $\Delta L$.

- **First look at $\Delta G$**
  - In lepton nucleon scattering gluon does not couple to virtual photon (or intermediate boson)
  - Selection of Photon Gluon Fusion needed
  - Gluon polarization related to measured asymmetry

- **Competition**
  - Polarized proton-proton collider RHIC
    - Here measured asymmetries compared with expected asymmetries for specific model for the gluon polarization
$\Delta G/G$ at COMPASS

Photon Gluon Fusion

$q = c$  cross section difference in charmed meson production
→ simple theoretical description in LO
→ experiment challenging

$q = u, d, s$  cross section difference in 2+1 jet production
in COMPASS: events with
2 hadrons with high $p_T$
→ experimentally easier
→ theoretical description more complicated

Selection of events where underlying process involved gluon
→ sensitivity to gluon parameters including spin orientation
**D* tagging: D* → D⁰ π**

\[ D^* \rightarrow (K\pi)\pi \quad D^0 \rightarrow K\pi \]

**Cuts:**
\[ z_D > 0.2 \quad |\cos \theta| < 0.85 \quad (\text{Background}) \]
\[ 10 < p_{K} < 35 \text{ GeV} \quad (\text{RICH PID}) \]

**Preliminary**

\[ M_{K\pi} - m_{D^0} \text{ [MeV/c}^2\text{]} \]

\[ M_{K\pi\pi} - M_{K\pi} - m_\pi \text{ [MeV/c}^2\text{]} \]
Improved result for all data on deuteron (2002-2006)

Analysis in two channels:
tagged for $D^*$ production
untagged – only $D^0$ observed

$\Delta G/G = -0.49 \pm 0.27$ (stat) $\pm 0.11$ (syst) $\times g > 0.11$, scale: $\mu^2 = 13$ GeV$^2$
$\Delta G/G$: pairs of high $p_T$ hadrons

Two samples analyzed: $Q^2<1$ GeV$^2$
- Photoproduction region
- $Q^2>1$ GeV$^2$
  - DIS region

Contribution from other processes estimated from MC simulations

\[ \Delta G/G = 0.08 \pm 0.01 \pm 0.05 \] at averaged $x_G = 0.082^{+0.041}_{-0.027}$
results

Best present knowledge from „direct measurements“

Compass → most precise

$\Delta G/G$ small
Hadron beams in Compass: The Primakoff reaction

\[ \pi + Z \rightarrow \pi' + Z + \gamma \]

Electric & Magnetic polarizability

\[ \frac{d\sigma_{\gamma\pi}(\omega, \vartheta)}{d\cos \vartheta} = \frac{2\pi\alpha_f^2}{m_\pi^2} \left( F_{\gamma\pi}^{th} + \frac{m_\pi \omega^2}{\alpha_f} \frac{\alpha_z (1 + \cos^2 \vartheta) + \frac{1}{3} B_{\pi} \cos \vartheta}{1 + \frac{\omega}{m_\pi} (1 - \cos \vartheta)} \right) \]

first data taken in 2004 expected \(~\sim 30k\) events

**nucleon spectroscopy**
- glue balls and hybrids
- charmed mesons and baryons
- semi-leptonic decays
- double-charmed baryons
- Central production

Long run with hadron beam this year
II. Very rare decays - possible signal of new physics

- Very rare decays: possible signal of new physics
- CP, CPT measurements (well-known decays)
  - \( K^\pm \to \pi^\pm \pi^\mp \pi^\mp \)
  - \( K_S^0 \to 3\pi^0 \)
  - \( K^\pm \to \pi^\pm \pi^0 \pi^0 \)
  - \( K_S^0 \to \pi l\nu \)
  - \( K^\pm \to \pi^\pm \pi^0 \gamma \)
  - \( \phi^\pm, \phi^{00} \)

- Short-distance modes (SM = precise)
  - \( K_L \to \pi^0 l^+ l^- \), \( K_L \to \pi^0 \nu \bar{\nu} \), \( K^\pm \to \pi^\pm \nu \bar{\nu} \)

- Long-distance modes (tests of low-energy effective theory)
  - \( K^\pm \to \pi^\pm l^+ l^- \), \( K_L \to l^+ l^- \)

“New physics” decays (SM = 0):
- LFV: \( K_L^0 \to \mu e, K_L^0, K^\pm \to \pi \mu e \)

Precision measurements (SM/NP window):
- Transverse \( \mu \) polar.
  - \( K^+ \to \pi \mu \nu, K^+ \to \mu \nu \gamma \)

A measurement of the 4 decay modes:
- \( K^+ \to \pi^+ \nu \nu \), \( K^0_L \to \pi^0 \nu \bar{\nu} \)
- \( K^0_L \to \pi^0 e^+ e^- \), \( K^0_L \to \pi^0 \mu^+ \mu^- \)

New frontier: very rare decays, \( \mathcal{O}(10^{-10^{\pm 11}}) \)

More: \( \epsilon'/\epsilon \), CKM parameters, CPT tests (m(K) vs m(Kbar)), etc.

NA62 – P326

is a crucial element in the exploration of the new physics discovered at the LHC.
Physics motivation

Acurate determination of the universality triangle

Probes short distance behaviour of the Standard Model

Extremely sensitive to possible new degrees of freedom beyond the Standard Model

Independent of the B-system
Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Branching ratio measured by E787/E949

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10} s$$

SM prediction to be tested:

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.8 \pm 0.1) \times 10^{-10}$$

Significant improvement needed

Kinematical rejection

+ veto on photons to remove background
III. Hadron-hadron, hadron-ion, ion-ion (SHINE – SPS Heavy Ion and Neutrino Experiment)

Experiment running, (after first year of data taking)

Three subjects combined around detector with high acceptance and good particle identification: NA49 detector

Phase transition study in ion-ion scattering

Precise measurement of hadron production in pC scattering → input for neutrino beam simulations (T2K)

Proton nucleus scattering at high energy, data for cosmic ray studies
Information for neutrino beam in T2K experiment

data with 30 GeV protons on two targets:

- 2 different carbon targets (isotropic graphite, \( \rho = 1.84 \text{ g/cm}^3 \)):
  - Thin Carbon Target: 2.5 x 2.5 x 2cm\(^3\), int. length \( \sim 0.04 \)
  - T2K Replica Target: \( \theta = 2.6 \text{cm} \times 90 \text{cm} \), int. length \( \sim 1.9 \)
Why production of $\pi$ and $K$ have to be known better?

To define quantitatively the region of interest the particle yield has been increased by 30% independently in each momentum and angle bin.

Region of interest: $0.5 < p < 5$ GeV/c; $0 < \theta < 250$ mrad

Needed statistics to improve knowledge about beam:

$\sim 200k \, \pi^+$ reconstructed tracks
ion-ion scattering

New data to be register by NA61/SHINE

may lead to discovery of the critical point of strongly interacting matter by an observation of a hill of fluctuations in two dimensional plane (energy)-(system size) or equivalently (temperature)-(baryo-chemical potential)

In particular the critical point should lead to an increase of multiplicity and transverse momentum fluctuations
Longer scale future (>2011)

General Parton Distributions

Next step – study 3D structure of the nucleon
  ➔ additional transverse information
  ➔ present structure functions – limit of 3D case
NEW: 3-dimensional picture of the partonic nucleon structure

Deep Inelastic Scattering

\[ e p \rightarrow e X \]

\[ Q^2 x_{Bj} \]

\[ \gamma^* x \]

\[ p \]

\[ x \text{ boost} \]

Parton Density \[ q(x) \]

\[ P_x \]

Hard Exclusive Scattering

Deeply Virtual Compton Scattering

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

\[ Q^2 \]

\[ \gamma^* \]

\[ x + \xi \]

\[ x - \xi \]

\[ \gamma \]

\[ p \]

\[ \text{GPDs} \]

Generalized Parton Distribution \[ H(x, \xi, t) \]

\[ (P_x, r_{\perp y, z}) \]
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
- Ji's sum rule

Elastic Form Factors:

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

Ji's sum rule:

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

\[
\frac{1}{2} = \frac{1}{\Delta} \left( \Sigma + L_q + \Delta G + L_g \right)
\]

Fit of Parameters to the data

parton density

$H(x, 0, 0) = q(x)$
$\tilde{H}(x, 0, 0) = \Delta q(x)$
Still many fields for fixed target experiments

Study of nucleon structure concentrated on spin puzzle, important role of \( \mu N \) data

In future GPD is a very likely goal

Rare decays of kaon can bring important information for flavour structure understanding

Here there is also space for longer term plans

Precise data with particle identification can contribute to other fields (neutrino physics, cosmic ray physics)

Measurements with heavy ion beams can give input to critical point searches and deconfinement understanding