The structure of the nucleon through DIS hadron muoproduction at the COMPASS experiment

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The birth

HMC

New generation of muon Deep inelastic scattering experiment.

- EMC
- NMC
- SMC

CHEOPS

New generation of meson spectroscopy experient.

- W89
- WA82
- Crystal Barrel

$\sim$ 240 physicists from 28 institutes.

1. The COMPASS experiment
   - The COMPASS spectrometer
   - Muon physics at COMPASS
2. The spin of the nucleon
   - Framework
   - Methods to measure the gluon polarization
   - Results of the gluon contribution to the spin (ΔG)
3. Intrinsic motion of the partons
4. Futur physics

Requirements of the muon program

The spectrometer aims to measure the asymmetry :

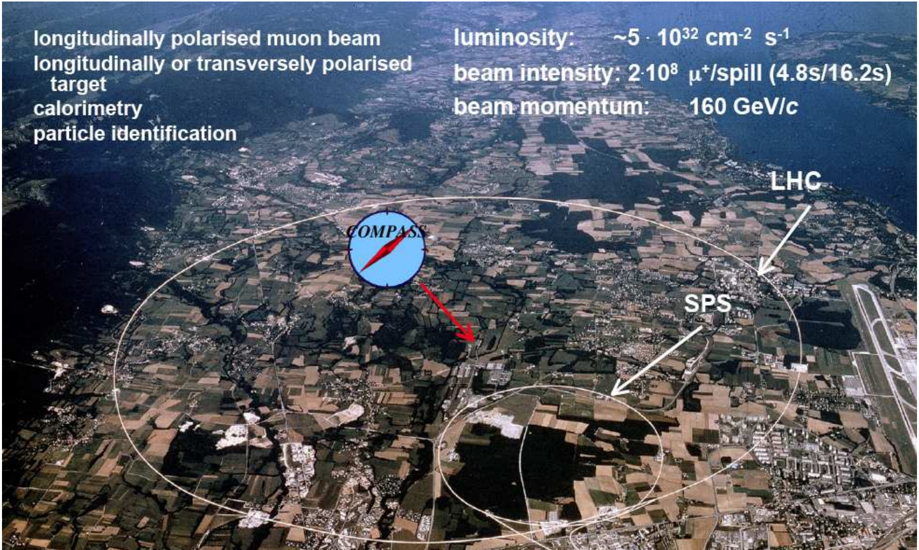
$$A^{\mu N} \equiv \frac{\Delta\sigma}{2\bar{\sigma}}$$

- $\Delta\sigma$: Difference between cross sections for two different spin configurations
- $\bar{\sigma}$: Spin averaged cross section

Both spin configurations are measured simultaneously.

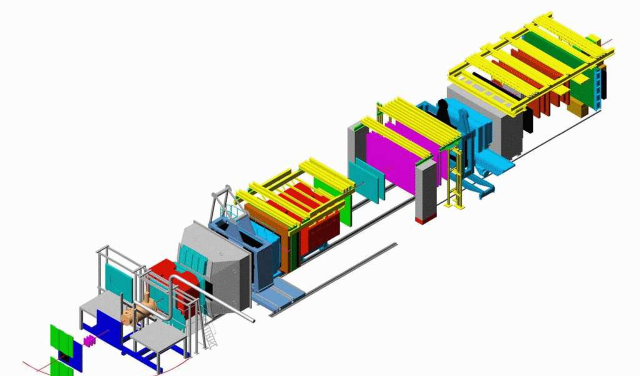
- Polarized beam
- Polarized target
- Hadron identification
- High statistics
- Stability

Beam from the SPS at CERN



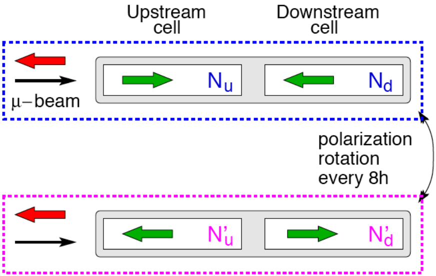
General properties of COMPASS' muon programs

- Beam : μ^+ 160GeV
- cms energy : ≈16GeV
- $2 \cdot 10^8 \mu/cycle$
- Spill cycle every 16.8 seconds (flat top extraction 4.8 sec.)
- Two cells target to measure asymmetries



Target

- Material : $^6LiD \approx$ (spin-0)^4He + Deuteron
- Two cells with opposite polarization



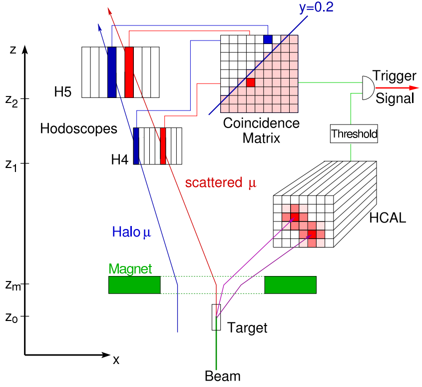
Against systematics, polarization is inversed every $\approx$ 8 hours

Trigger

Requirements

- Large kinematic acceptance $10^{-2} < Q^2 < 100\text{GeV}$
- High rate (decision time < 500ns)
- Minimum deadtime
- Provide an event reference time to all of readout electronics

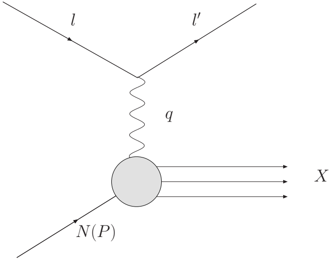
Conceptual quasireal photon trigger



Muon program (2002-2007)

- Polarized muon beam on polarized target
- Gluon polarisation within the nucleon $\frac{\Delta G}{G}$ (longitudinal target polarization)
- Polarized distribution functions
- Polarized fragmentation functions

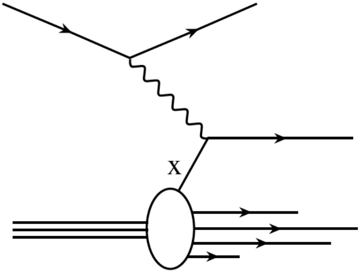
Basic variables of Deep Inelastic Scattering



Basics variables

- l : 4-vector of the incoming muon
- l' : 4-vector of the scattered muon
- q :4-vector of the exchanged virtual photon
- $Q^2 := -q^2$

The quark parton model



- Structureless, colinear, non-interacting partons
- Each parton carries a fraction x of the momentum

Parton distribution functions:

$$q(x) = q^+(x) + q^-(x)$$

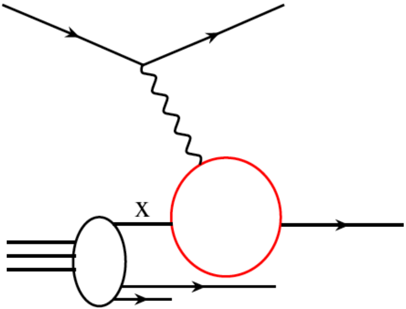
$$\Delta q(x) = q^+(x) - q^-(x)$$

Structure functions :

$$F_1(x) = \frac{1}{2} \sum_{q=u,d,s} e_q^2 q(x)$$

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

QCD improved parton model



Gluon distribution functions:

$$G(x) = G^{+}(x) + G^{-}(x)$$

$$\Delta G(x) = G^{+}(x) - G^{-}(x)$$

QPM valid for $\alpha_s \to 0$ ($Q^2 \to \infty$)

- At finite Q^2, partons interact
- PDF and structure functions depend on Q^2
- Gluons become *involved*

Contributers to the spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^{q+g}$$

- $\Delta\Sigma = q^{+} - q^{-} = \Delta u + \Delta d + \Delta s$ (quarks)
- $\Delta G = G^{+} - G^{-}$ (gluons)
- L^{q+g} (orbital momentum)

The spin **crisis**

Calculation

- Quaks parton model
  $\rightarrow \Delta\Sigma \approx 0.75$
- Ellis-Jaffe ($\Delta s = 0$)
  $\rightarrow \Delta\Sigma \approx 0.6$

Experiment

SLAC/EMC $\rightarrow \Delta\Sigma \approx 0.2$
(Confirmed later by many experiments including COMPASS)

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What else contribute to the spin?

Factorization schemes : ambiguity on the definition of $\Delta\Sigma \rightarrow \Delta\Sigma - \frac{2\alpha_s}{2\pi}\Delta G$
Hence the importance to know ΔG

How to find out about ΔG

By calculation photon-gluon fusion cross section asymmetry :

$$A_{pgf}^{\mu N} \equiv \frac{\sigma^{\leftarrow\Rightarrow} - \sigma^{\leftarrow\Leftarrow}}{\sigma^{\leftarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}} \propto \frac{\Delta G}{G}$$

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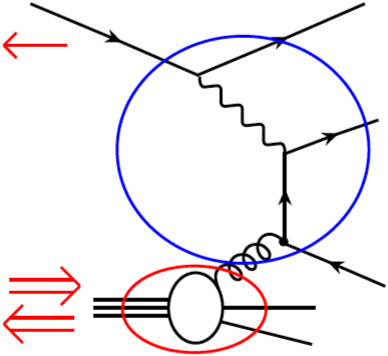
Two ways to have a sample of photon-gluon fusion :

- Open charm process
- Hadron with high transverse momentum

The photon-gluon fusion (pgf)

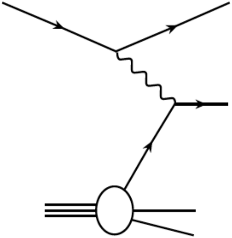


pgf asymmetry is factorized into hard and soft asymmetries.

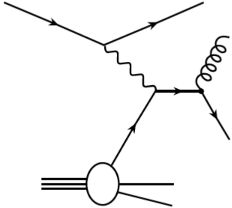
$$A^{\mu N}_{pgf} \equiv \frac{\sigma^{\leftarrow\Rightarrow} - \sigma^{\leftarrow\Leftarrow}}{\sigma^{\leftarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}} = \hat{a}_{pgf}\frac{\Delta G}{G}$$

Background processes

Leading order



QCD Compton



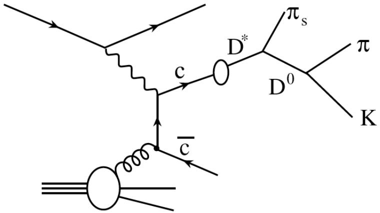
Soft process

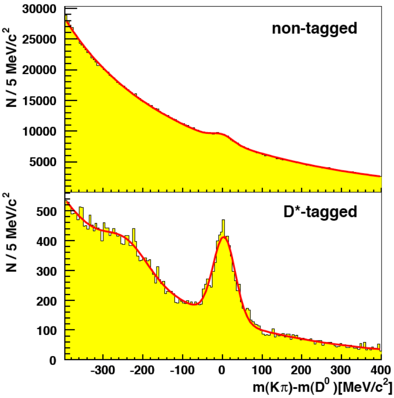
Asymmetry with background

$$A_{\parallel}^{\mu^* N} \approx \hat{a}_{pgf} \frac{\Delta G}{G} R_{pgf} + A_1^{QCDC} R_{QCDC} + A_1^{LO} R_{LO} + \cdots$$

Open charm

Clean signal, but low statistics





Hadron with high tranverse momentum

High statistics, background description, low/high Q2

$$A_{\parallel}^{\mu N} = R_{pgf}\,\hat{a}_{pgf}\,\frac{\Delta G}{G} + A_{Bgd}$$

- No need to select a particular decay channel $\rightarrow$ high statistics
- No peak $\rightarrow$ no way to measure R_{pgf} and A_{Bgd}
- Monte Carlo dependence (R_{pgf}, A_{Bgd})
- $\Rightarrow$ Good statiscal accuracy, but large systematic errors.

Different high p_T samples

Hadron pairs $Q^2 < 1$

- $p_T^h > 0.6(GeV/c)$
- $(p_T^{h1})^2 + (p_T^{h2})^2 > 2.5(GeV/c)^2$
- $R_{pgf} \approx 0.3$
- $R_{QCDC} \approx 0.1$
- $R_{Soft} \approx 0.5$
- $R_{LO} + R_{lowp_T} < 0.07$

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Hadron pairs $Q^2 > 1$

- $p_T^h > 0.7 (GeV/c)$
- Inv. mass of the two hadron $> 1.5 (GeV/c)$
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- $R_{QCDC} \approx 0.3$
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Single hadron $Q^2 < 0.5$

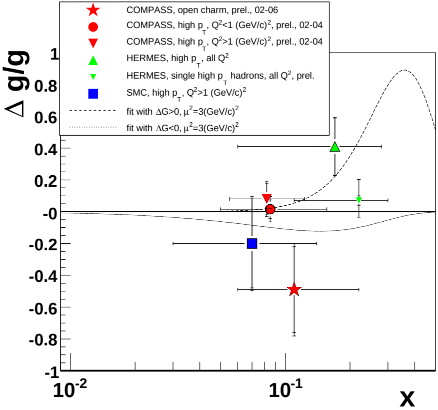
- Different analysis (comparison with theoretical predictions)
- $p_T^h > 1.5, 2, 2.5(GeV/c)$

Single hadron analysis

Theorists make asymmetry prediction for different ΔG.

- Single hadron because (sizable) NLO pQCD is at hand (not the case for hadron pairs)
- pQCD framwork has been applied and checked for collider data
- Applicability not clear at fix target energies
- First need to compare unpolarized "benchmark" cross sections

Summary of $\Delta G/G$ results



From $\Delta G/G$ to G

Model dependent, ambiguous relation with $\Delta\Sigma$.
EX : AB renormalization schemes :

$$\Delta\Sigma = a_0 + C\Delta G$$

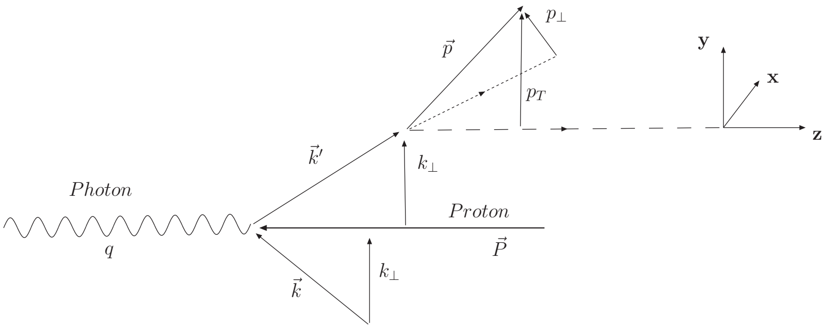
- Experiment results (small a_0) imply ΔG about 3
- Small $\frac{\Delta G}{G}$ at $x \approx 0.1$ is not enough to say $\Delta G \neq 3$, but makes large value unlikely.

Where else can we look for the spin?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^{q+g}$$

Only thing left is the angular momentum.
A non-zero angular momentum means there is internal motion.
It was shown more than 20 years ago that the intrinsic momentum could have an effect on the azymuthal dependence of the cross section (Cahn effect).

Intrinsic motion of the partons



- $k_\perp$: Intrinsic transverse momentum of the interacting parton w.r.t. nucleon direction ($\vec{P}$)
- p_T : Hadron's transverse momentum w.r.t. γ^*
- $p_\perp$: Hadron's transverse momentum w.r.t. scattered parton direction ($\vec{k}'$)
- z : Fraction of the virtual photon's energy carried by the quark

Cross section with intrinsic transverse momentum

At $\mathcal{O}\left(\frac{k_\perp}{Q}\right)$, the SIDIS cross section looks like :

$$\frac{d^5\sigma^{\mu P \to \mu' + h + X}}{dx_{Bj}\, dQ^2\, dz\, d^2\vec{p}_T} \approx \sum_q e_q^2 \int d^2\vec{k}_\perp\, f_q(x_{Bj}, k_\perp) \frac{d\hat{\sigma}^{\mu q \to \mu q}}{dQ^2} D_q^h(z, \vec{p}_\perp)$$

where $\frac{d\hat{\sigma}^{\mu q \to \mu q}}{dQ^2}$ is the QED point-like interaction μ + quark.

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Assumptions

- QCD Parton model 1st order
- $k_\perp$ fully taken into account in parton distribution functions.

The gaussian ansatz

The $p_\perp$ and $k_\perp$ dependance are assumed to be gaussian :

$$f_q(x, k_\perp) = f_q(x) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2 / \langle k_\perp^2 \rangle}$$

$$D_q^h(z, \vec{p}_\perp) = D_q^h(z) \frac{1}{\pi \langle p_\perp^2 \rangle} e^{-p_\perp^2 / \langle p_\perp^2 \rangle}$$

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The cross section then becomes proportional to :

$$\frac{d^5 \sigma^{\mu P \to \mu + h + X}}{dx_{Bj} dQ^2 dz dp_T} \propto \sum_q e_q^2 f_q(x_{Bj}) D_q^h(z) \frac{p_T}{\pi \langle p_T^2 \rangle} e^{-p_T^2 / \langle p_T^2 \rangle}$$

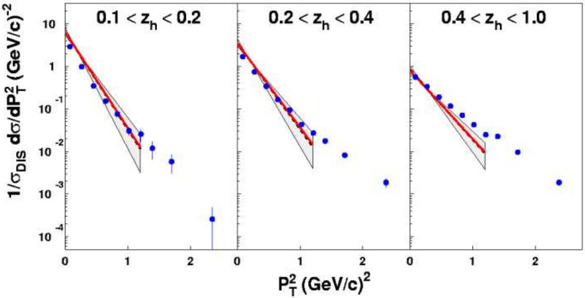
where $\langle p_T^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$

Remarks :

- Flavor independent
- Describes (integrated) data well up to $p_T \approx 1\text{GeV}/c$

Fit results for $\langle p_\perp^2 \rangle$ and $\langle k_\perp^2 \rangle$

Constant values of $\langle p_\perp^2 \rangle$ and $\langle k_\perp^2 \rangle$ are used by fitting the cross section of several experiments.



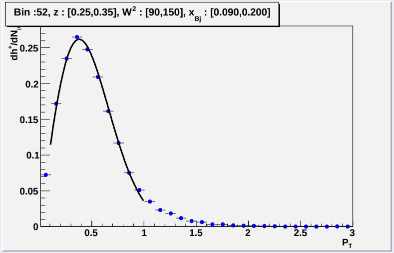
The results are :

- $\langle p_\perp^2 \rangle = 0.20\ (\mathrm{GeV}/c)^2$ (0.25 with Higher order pQCD)
- $\langle k_\perp^2 \rangle = 0.25\ (\mathrm{GeV}/c)^2$ (0.28 with Higher order pQCD)

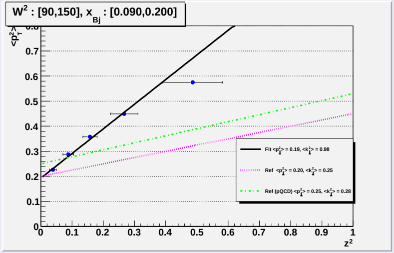
Fitting $\langle k_\perp^2 \rangle$ for different kinematical intervals

Using the $p_T \cdot e^{-p_T^2/\langle p_T^2 \rangle}$ dependence of the cross section and the relation $\langle p_T^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$, it is possible to extract $\langle k_\perp^2 \rangle$ for different kinematical ranges.

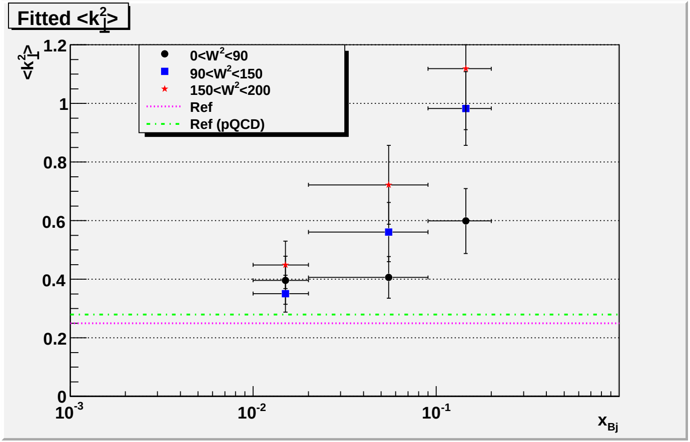
Cross section fit



$\langle p_T^2 \rangle$ vs z^2 fit



Is the gaussian ansatz too simple?



Drell-Yan process at COMPASS

$$\pi + P \rightarrow l\bar{l} + X$$

Drell-Yan is complementary to DIS studies to nucleon (spin) structure. Good tool to access the intrinsic motion of quarks.

GPDs program for COMPASS future

$$\mu + P \rightarrow \mu' + \gamma + P_{slow}$$

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

Study of the nucleon structure via Generalised Parton Distributions by measuring Deeply virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP).
A pilot run at COMPASS is planed by the end of the year.

Conclusion

- COMPASS has contributed significantly to the knowledge of the nucleon spin structure.
- We still do not know the whole story about the spin budget of the nucleon.
- A large amount of data has been cumulated for the precise measurement of the gluon contribution to the spin.
- There is still a lot to do with the already taken data.
- There is still a lot of data to take both for the previous analysis (improving precision) and on new analysis.