NLO QCD predictions for gluon polarization from open-charm asymmetries measured at COMPASS
• Part I - *Open-charm results on gluon polarization from COMPASS* - *on behalf of the COMPASS Collaboration*

• Part II - *NLO QCD predictions for gluon polarization from open-charm asymmetries measured at COMPASS*
COMPASS Collaboration at CERN

Common Muon and Proton Apparatus
for Structure and Spectroscopy

Czech Rep., France, Germany, India, Israel, Italy,
Japan, Poland, Portugal, Russia and CERN

Bielefeld, Bochum, Bonn, Burdwan and Calcutta, CERN, Dubna, Erlangen,
Freiburg, Lisbon, Mainz, Moscow, Munich, Prague, Protvino, Saclay,
Tel Aviv, Torino, Trieste, Warsaw, Yamagata

~240 physicists, 30 institutes
Beam: \(2 \cdot 10^8 \mu^+ / \text{spill} \ (4.8s / 16.2s)\)
Luminosity: \(\sim 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\)
Beam polarization: -80%
Beam momentum: 160 GeV/c
Target polarization: \(P_T = 50\% \), \(f \sim 40\%\)
for \(^6\text{LiD} \) (2002 - 2006)
COMPASS in muon run
NIM A 577(2007) 455

- ~ 350 planes
- 180 mrad acceptance
- π, K, p separation (from 2, 9, 17 GeV up to ~ 50 GeV)
The COMPASS polarized target

Target material: $^6\text{LiD}$
Polarisation: $>50\%$
Dilution factor: $\sim0.4$
Dynamic Nuclear Polarization

2006 - new solenoid with acceptance 180 mrad
3 target cells (reduce false asymmetries)

2002 – 2004

RICH 2006 upgrade: better PID

MAPMTs in central region
APV electronics in periphery

$^3\text{He} - ^4\text{He}$ Dilution refrigerator (T~50mK)
Superconducting solenoid (2.5 T)
Two 60 cm long target cells with opposite polarisation

XIII Workshop on High Energy Spin Physics
Krzysztof Kurek

NLO QCD predictions for gluon polarization...
Contents

- COMPASS experiment
- Charmed meson reconstruction at COMPASS
- Signal to background parameterization
- New channels from $D^*$: $\pi^0$ reflection “bump” and “RICH sub-threshold kaons events”
- Neural network approach to signal/background parameterization
- New $\Delta G/G$ result in LO
- Asymmetries from open-charm
- $\Delta G/G$ in LO approximation from COMPASS main $D^0$ and $D^*$ channels
- Summary and plans
Idea: tag $\gamma^* g \rightarrow c\bar{c}$ via open-charm production mechanism

• Clean channel (less MC dependent) under the assumption that production mechanism is PGF only (true in LO pQCD)
• Resolved photon and “intrinsic” charm production mechanism negligible in COMPASS kinematics
• Limited statistics (no vertex detector - long polarized target)
• Huge combinatorial background
• NLO corrections potentially important
Weighted method for open-charm analysis

\[ A^{\text{raw}} = \frac{N^{\uparrow \downarrow} - N^{\uparrow \uparrow}}{N^{\uparrow \downarrow} + N^{\uparrow \uparrow}} = P_B P_T f a_{LL} \sigma_{PGF} \frac{\Delta g}{\sigma_{PGF} + \sigma_{bgd}} + A^{bgd} \]

\( P_B, P_T \) - are beam and target polarizations,
\( f \) - dilution factor (\( \sim 0.4 \) for \(^6\)LiD target)
\( a_{LL} \) is a partonic asymmetry (analyzing power) for subprocess: \( \mu g \rightarrow c\bar{c} \mu' \)

\( \frac{\sigma_{PGF}}{\sigma_{PGF} + \sigma_{bgd}} \) is parameterized in terms of 10 variables, not just as a function of the reconstructed mass.

Each event is weighted with its analyzing power:
\[ f P_B a_{LL} \sigma_{PGF} \frac{\sigma_{PGF}}{\sigma_{PGF} + \sigma_{bgd}} \]

Large gain in statistics (\( a_{LL} \) has positive and negative values)

Events are simultaneously weighted with (\( \cdots \frac{\sigma_{BGD}}{\sigma_{PGF} + \sigma_{bgd}} \))
\( \Rightarrow \) allows simultaneous extraction of signal and background asymmetries,
more efficient than side band subtraction
D⁰ and D∗ meson reconstruction

- **Events considered** (resulting from c quarks fragmentation):
  - D⁰ → Kπ (BR: 4%)
  - D∗ → D⁰π_s → Kππ_s (30% D⁰ tagged with D∗)

- **Selection to reduce the combinatorial background**:
  - Kinematical cuts: Z_D, D⁰ decay angle, K and π momentum
  - RICH identification: K and π ID + electrons rejected from the π_s sample
Thick target - no D⁰ vertex reconstruction

D⁰ reconstruction: Kπ invariant mass + cuts on D⁰ decay angle + z\textsubscript{D} + RICH particle identification (different likelihoods)

- **D⁰ → K + π**
- +2 more channels:
  - D⁰ → K⁻π⁺ + (π⁰)
  - D*⁺ → D⁰π\textsubscript{soft} → K⁻π⁺π⁺\textsubscript{soft} (with kaons below RICH threshold of 9 GeV)

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**2002 - 2006 D⁰ Mass Spectrum**

nD⁰: 37400

**2002 - 2006 D* Mass Spectrum**

nD*: 8675

New!
Thick target - no $D^0$ vertex reconstruction

$D^0$ reconstruction: $K\pi$ invariant mass + cuts on $D^0$ decay angle + $z_D$ + RICH particle identification (different likelihoods)

- $D^0 \rightarrow K + \pi$

$D^0$ and $D^*$ meson reconstruction

2002 - 2006 $D^0$ Mass Spectrum

$D^0 \rightarrow K + \pi$

$K\pi$ invariant mass + cuts on $D^0$ decay angle + $z_D$ + RICH particle identification (different likelihoods)

$nD^0$: 37400

2002 - 2006 $D^*$ Mass Spectrum

$nD^*: 8675$

$D^* \rightarrow D^0 + \pi_s$

+2 more channels:

$D^0 \rightarrow K^-\pi^+ + (\pi^0)$

$D^{*+} \rightarrow D^0\pi_{soft}^+ \rightarrow K^-\pi^+\pi_{soft}^+$

(with kaons below RICH threshold of 9 GeV)
- a_{LL} parameterization with NN

- a_{LL} is dependent on full knowledge of partonic kinematics:
  \[ a_{LL} = \frac{\Delta \sigma^{\text{PGF}}}{\sigma^{\text{PGF}}} (y, Q^2, x_g, z_C, \phi) \]

- Can't be experimentally obtained! ⇒ only one charmed meson is reconstructed

- a_{LL} is obtained from Monte-Carlo (in LO), to serve as input for a Neural Network parameterization on reconstructed kinematical variables: y, x_{Bj}, Q^2, z_D and p_{T,D}

- 82% correlation NN/MC
- very large dispersion of values, even change of sign: weighting essential
New channels from $D^*$ NN S/(S+B) parameterization method

- Two real data samples (with same cuts) are compared by the Neural Network (giving as input some kinematic variables as a learning vector):
  - Signal model $\rightarrow$ $gcc = K^+\pi^-\pi^- + K^-\pi^+\pi^+$ ($D^*$ spectrum: signal + bg.)
  - Background model $\rightarrow$ $wcc = K^+\pi^+\pi^- + K^-\pi^-\pi^+$

- If the background model is good enough: Net is able to distinguish the signal from the combinatorial background on a event by event basis!

- $\Sigma$ is built in the same way as for main channels, BUT:
  - Only 1 variable is used: Neural Network output
    - Sorts the events according to similar kinematic dependences (thus improving our statistical precision)
    - Results from 2 real data samples comparison, in a mass window around the meson mass
New preliminary result including all channels

\[ \Delta G/G = -0.39 \pm 0.24 \text{ (stat)} \]

published:

\[ \Delta G/G = -0.49 \pm 0.27 \text{ (stat)} \pm 0.11 \text{ (syst)} \]

\[ \langle x_g \rangle = 0.11^{+0.11}_{-0.05} \]

\[ \langle \mu^2 \rangle = 13 \text{ GeV}^2 \]

10% gain in statistical precision!
Summary

- Small value of $\Delta G/G$ is preferred - $\Delta G/G$ compatible with 0 within 2$\sigma$
- Under study:
  - pure NN approach (fit independent)
  - 2007 data (proton)
  - others channels (4 particles from decay)
  - NLO analysis
• Part II - **NLO QCD predictions for gluon polarization from open-charm asymmetries measured at COMPASS**
• Model independent asymmetries were extracted from data only

\[ A_{\text{exp}} = P_B P_T f \left[ R_{PGF} \Delta A^{\gamma N \rightarrow DX} + (1 - R_{PGF}) A_{bkg} \right] \]

\[ \frac{\Delta g}{g} \]

• can be extracted using \( a_{LL}^{PGF} \) calculated at LO:

\[ A_{\text{exp}} = P_B P_T f \left[ R_{PGF} \frac{\Delta g}{g} a_{LL}^{PGF} + (1 - R_{PGF}) A_{bkg} \right] \]

• Similar analysis, but with weight

\[ w = f P_B \frac{S}{S + B} a_{LL} \]

instead of

\[ w = f P_B \frac{S}{S + B} D \]

published: PLB676(2009)31
Contents

• LO and NLO QCD processes for open-charm production
• The role of MC in the COMPASS open-charm analysis
• NLO corrections and the MC approach
• $\Delta G/G$ in the NLO approximation from COMPASS open-charm asymmetries
• Summary
LO subprocesses for charm production – only PGF, No light quarks contribution – means no „physical background”

Simple expression for analysing power even if mass of muon and \( Q^2 \) dependence is taken into account – used in the present COMPASS analysis (published)
NLO calculations for partonic cross sections – much more complicated. Here Feynmann diagrams for „virtual +soft” corrections are presented.

Loops produce divergences:
- **UV** – removed by renormalization procedure,
- **IR** - related to „zero” momenta of Internal loop particles
NLO calculations for partonic cross sections. Here Feynmamn diagrams for „hard gluon emissions” corrections.

\[ \text{IR} - \text{related to „soft” momenta of gluon emissions. Here there is also colliner divergency for 3-gluons coupling} \]

„VS” and „Hard” parts contain so-called double pole:

\[ \sim \frac{1}{\varepsilon_{UV}} \frac{1}{\varepsilon_{IR}} \]

These terms MUST cancell Factorization.
NLO corrections

NLO calculations for partonic cross sections originated from light quarks. No LO corresponding process!
New channel which produces „physical background”

Not discussed in this talk - only NLO to PGF.
The structure of the cross sections in NLO QCD

\[
\sigma_{NLO}^{NLO} = \frac{\alpha \alpha_s^2 e_q^2}{s^2} \left( \sigma_{\text{non-abelian, Hard}} + \sigma_{\text{QED, Hard}} + \sigma_{\text{non-abelian, SV}}^\text{QED} + \sigma_F^\text{QED} \log\left(\frac{\mu_f^2}{m^2}\right) \right)
\]

\[
\Delta \sigma_{NLO}^{NLO} = \frac{\alpha \alpha_s^2 e_q^2}{s^2} \left( \Delta \sigma_{\text{non-abelian, Hard}} + \Delta \sigma_{\text{QED, Hard}} + \Delta \sigma_{\text{non-abelian, SV}}^\text{QED} + \Delta \sigma_{\text{SV}}^\text{QED} + \Delta \sigma_F^F \log\left(\frac{\mu_f^2}{m^2}\right) \right)
\]

Kinematics:

\[
s + t_1 + u_1 = 0 \quad \text{for LO and "SV" NLO part}
\]

\[
s + t_1 + u_1 = s_4 \quad \text{for "Hard" NLO part (integration over } s_4)\]

\[
t_1 = t - m^2 \quad u_1 = u - m^2
\]
1. NLO corrections available only for photo-production limit. $Q^2 = 0$
2. No big problem for COMPASS: $D$ – depolarization factor

\[ a_{LL}^{LO} = D a_{LL}^{LO,\gamma g} \]
\[ a_{LL}^{NLO} = D a_{LL}^{NLO,\gamma g} \]

Neglecting $Q^2$ in this parts is not a big sin – unimportant effect 😊

Calculated in NLO with the assumptions of photo-production.
Asymmetry and gluon polarization - the procedure

\[ A = \frac{\int \Delta G(x_g) \Delta \hat{\sigma}^{LO} \, du_1 \, dt_1}{\int G(x_g) \hat{\sigma}^{LO} \, du_1 \, dt_1} = \frac{\int \frac{\Delta G}{G} \frac{\Delta \hat{\sigma}}{\hat{\sigma}^{LO}} G(x_g) \hat{\sigma}^{LO} \, du_1 \, dt_1}{\int G(x_g) \hat{\sigma}^{LO} \, du_1 \, dt_1} \]

\[ A = \frac{\Delta G}{G} \frac{\Delta \sigma^{LO}}{\sigma^{LO}} = \frac{\Delta G}{G} \frac{\Delta \hat{\sigma}^{LO}}{\hat{\sigma}^{LO}} = \frac{\Delta G}{G} \frac{\Delta \hat{\sigma}^{LO}}{\hat{\sigma}^{LO}} = \frac{\Delta G}{G} a^{LO} \]

\[ \langle \frac{\Delta G}{G} \rangle = \frac{\int \frac{\Delta G}{G} a^{LO}_{LL} G(x_g) \hat{\sigma}^{LO} \, du_1 \, dt_1}{\int a^{LO}_{LL} G(x_g) \hat{\sigma}^{LO} \, du_1 \, dt_1} = \frac{\Delta G}{G} \langle x_g \rangle \]

\[ \frac{\Delta G}{G} \approx a(x_g - \langle x_g \rangle) + b \quad b = \frac{\Delta G}{G} \langle x_g \rangle \]

\[ \langle x_g \rangle = \frac{\int x_g a^{LO}_{LL} G(x_g) \hat{\sigma}^{LO} \, du_1 \, dt_1}{\int a^{LO}_{LL} G(x_g) \hat{\sigma}^{LO} \, du_1 \, dt_1} \]

\[ \langle a^{LO}_{LL} \rangle = \frac{\int a^{LO}_{LL} G(x_g) \hat{\sigma}^{LO} \, du_1 \, dt_1}{\int G(x_g) \hat{\sigma}^{LO} \, du_1 \, dt_1} \]
The role of MC and theoretical input

- $a_{LL}$ allows to calculate gluon polarization from measured asymmetries.
- COMPASS is using weighted method - and $a_{LL}$ (theory input) is used in the weight. To calculate $a_{LL}$ MC generator with simulation of the apparatus + reconstruction is used; then $a_{LL}$ is parameterized and run on real data to estimate $a_{LL}$ event by event.
- The weight has impact on value, statistical error and $<x_G>$.
- Changing approximation (from $a_{LL}$ in LO to NLO) can have a serious consequence on importance and precision of the COMPASS result!
Procedure in NLO

- MC with parton shower (MC PS on) to simulate phase space for real emissions
- events have $s_1, u_1$ and $t_1$ and $s_1 + t_1 + u_1 \neq 0$
- Method 1: event is defined by $c\bar{c}$ system: $u_1$ and $t_1$ define event. Integrations over $s_4$ is performed from 0 up to $s_1 + t_1 + u_1$
- Method 2: event is defined by $s_1$ and $t_1(u_1)$ - only one charm observed. Integration over $s_4$ is performed from 0 up to $s_1 + t_1 + u_1$
method 1

- **Advantage**: similar to theoretical calculations in bins - gluons convoluted with hard part in the integration over $s_4$ - good for collinear divergence removal procedure
- **Disadvantage**: shape of gluon distribution is required - model of gluon polarization needed!
- **Assumption done**: MC with PS on reproduces correctly the event distributions produced according to $\sigma^{NLO} \ast G(s_1^{el})/G(s_1)$
method 2

- **Advantage:** model of gluons is not needed. Method is similar to LO approach
- **Disadvantage:** hard part is not convoluted with gluon distribution what is slightly inconsistent. Kinematics of the second charm in the event ignored - not observed as in real data.
- **Assumption done:** MC with PS on reproduces correctly the event distributions produced according to $\sigma^{\text{NLO}}$
method 1 - examples

- Model of the gluon polarization:
  1. $\Delta G/G = \text{const}$,
  COMPASS QCD fits:
  2. positive gluons
  3. negative gluons

- used to illustrate the potential differences between methods based on the same MC events, good for systematic studies
• This part of the talk is not on behalf of COMPASS - pure MC generator (aroma) has been used - no acceptance/reconstruction/apparatus simulation used.
• But - it is not crucial thanks to weighting!
• Tested and compared for LO results
• PDF unpolarized used: MRST2004 LO/NLO, GRV98 LO
• Scale: 2m_c
• No special cuts except cut on energy of the E_D
• MC used only for signal simulation: PSoff/on (LO/NLO)
• s/(s+b) assumed 1 (no background simulation) - therefore statistical error is smaller than in COMPASS analysis
Prediction for $\Delta G/G$ in QCD NLO approximation

based on 2002-2006 COMPASS data and published asymmetries in bins (PLB 676(2009)31)

- LO weighted from PLB: $\Delta G/G = -0.49\pm 0.27$
- LO (from asym. and $a_{LL}$ from PLB): $\Delta G/G = -0.42\pm 0.28$
- LO (MC PSoff, asym. from PLB): $\Delta G/G = -0.47\pm 0.23$

- NLO (MC PSon, asym. from PLB)
  - method 2: $\Delta G/G = +0.032\pm 0.231$
  - $\Delta G/G = \text{const (method 1)}$: $\Delta G/G = -0.051\pm 0.239$
  - $\Delta G/G > 0$, Compass fit (method 1): $\Delta G/G = -0.036\pm 0.239$
  - $\Delta G/G < 0$, Compass fit (method 1): $\Delta G/G = -0.057\pm 0.240$
Comment:

- MC with PS on simulates NLO kinematics of the event in the approximation (Sudakov formfactor approach)
- MC is still in LO approx., PS - depends on MC steering parameters.
- Another approach: simple MC generator weighted by correct NLO cross section
- Belle D*/D⁰ fragmentation function
Peterson set with slightly modified parameters to describe Belle data

<table>
<thead>
<tr>
<th>Fragmentation function</th>
<th>Functional form</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bowler</td>
<td>$N \frac{1}{z^{1+bm^2}} (1 - z)^a \exp\left(- \frac{bm^2}{z}\right)$</td>
<td>$a, b$ identical for all quarks</td>
</tr>
<tr>
<td>Lund</td>
<td>$N \frac{1}{z} (1 - z)^a \exp\left(- \frac{bm^2}{z}\right)$</td>
<td>$a, b$ identical for all quarks</td>
</tr>
<tr>
<td>Kartvelishvili</td>
<td>$N_2 \alpha_s (1 - z)$</td>
<td></td>
</tr>
<tr>
<td>Collins-Spiller</td>
<td>$N \left(1 - z + \frac{(2-z)e_{1s}^2}{1-z}\right)(1 + z)^2 (1 - \frac{1}{z} - \frac{e_{1s}^2}{1-z})^{-2}$</td>
<td></td>
</tr>
<tr>
<td>Peterson</td>
<td>$N \frac{1}{z} (1 - \frac{1}{z} - \frac{e_{1s}}{1-z})^{-2}$</td>
<td>widely used</td>
</tr>
</tbody>
</table>
• Full NLO cross section weighted MC - with special attention to high $S_4$ - very energetic gluon emission (not generated in PS approach)

• Fragmentation function from Belle, simple independent fragmentation
• $p_T$ generated by hard process from charm quark
• small $p_T$ effect in fragmentation assumed

• method 2 (no gluon shape needed): $\Delta G/G = +0.005 \pm 0.22$
  - in good agreement with MC PS on result
COMPASS, open charm, prel., 02–06
COMPASS, high $p_T$, $Q^2>1$ (GeV/c)$^2$, prel., 02–04
COMPASS, high $p_T$, $Q^2<1$ (GeV/c)$^2$, prel., 02–04
HERMES, high $p_T$, all $Q^2$
HERMES, single high $p_T$ hadrons, all $Q^2$, prel.
SMC, high $p_T$, $Q^2>1$ (GeV/c)$^2$

$\frac{\Delta g}{g}$

$X_g$

fit with $\Delta G>0$, $\mu^2=3$(GeV/c)$^2$

fit with $\Delta G<0$, $\mu^2=3$(GeV/c)$^2$
NLO QCD predictions for gluon polarization...
Conclusions

• NLO corrections for $a_{LL}$ (PGF channel) for COMPASS open-charm asymmetry bins have been computed based on MC PS on and MC weighted by correct NLO cross section

• Preliminary result for gluon polarization has been shown - gluon polarization consistent with 0.

• Missing NLO corrections - quark initiated processes - are under consideration
$\Delta G/G = -0.49 \pm 0.27 \text{ (stat)} \pm 0.11 \text{ (syst)}$

### Systematics:

<table>
<thead>
<tr>
<th>Source</th>
<th>$D^0$</th>
<th>$D^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam polar</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Target polar</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Dil. Fact.</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>False asymmetry</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Signal extraction ($\Sigma$)</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>$a_1$ (charm mass)</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>0.11</td>
<td>0.07</td>
</tr>
</tbody>
</table>

### Published:

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Open-charm signal - per year

Kπ invariant mass weighted spectra

2002 0.43 fb⁻¹
2003 0.58 fb⁻¹
2004 0.92 fb⁻¹
2006 0.85 fb⁻¹

D^*

D^0
Considering $A_B = 0$

\[
\frac{\Delta G}{G} = \frac{1}{2P_T P^\mu f a_{LL}} \frac{S}{S+B} \times \left( \frac{N^u - N^d}{N^u + N^d} + \frac{N^{u'} - N^{d'}}{N^{u'} + N^{d'}} \right)
\]

**Event weight**

**Partonic asymmetry**

**Signal strength of Open-Charm events**

**Using**

\[ A_1 = \langle a_{LL} \rangle \frac{\Delta G}{G} \text{ with } a_{LL} = \frac{\Delta \sigma_{PGF}}{\sigma_{PGF}} \]

Asymmetries are less sensitive to experimental changes than cross section differences.

**Events with small** \((P_\mu \cdot P_T^\tau f \cdot a_{LL} (S/S+B))\) **factors contain less information about the asymmetry:**

- Weighting the events with the option chosen minimizes de statistical error

\[
\frac{\Delta G}{G} = \frac{1}{2P_T} \times \left( \frac{\omega_u - \omega_d}{\omega_u^2 + \omega_d^2} + \frac{\omega_{u'} - \omega_{d'}}{\omega_{u'}^2 + \omega_{d'}^2} \right) \text{ with a statistical gain: } \frac{\langle \omega^2 \rangle}{\langle \omega \rangle^2}
\]
How to parameterize $\Sigma$?

- A function to build $\Sigma_p = S/B$ is defined, and parameterized for every event:
  - $\Sigma_p$ is built (iteratively) over some kinematic variables and RICH response:
    - $(\Sigma_p)_{\text{initial}} = 1$
    - Mass spectra is divided in bins of each variable (binning needed for statistical gain)
    - Fit all $D^0$ and $D^*$ mass spectra inside each bin of each variable
  - $\Sigma_p$ is adjusted (for every event inside each bin) to $(S/B)_{\text{fit}}$
  - After convergence, parameterization is checked:
    - No artificial peak produced in wrong charge mass spectra
  - Mass dependence $\Rightarrow$ Included in $\Sigma$ after convergence of $\Sigma_p$

[Box]

- $(\Sigma = \Sigma_p / \Sigma_p + 1)$ in the weight $\rightarrow$ probability for a given event to be background or Open-Charm
Polarised target

- Target material: $^6\text{LiD}$
- Polarisation: $P_T > 50\%$
- Solenoid field: $2.5 \, \text{T}$
- $^3\text{He}/^4\text{He}$: $T_{\text{min}} \sim 50 \, \text{mK}$
- Dilution factor: $f \sim 0.4$

Dynamic nuclear polarisation:

- High electron polarisation (high magnetic moment)
- Microwave irradiation of material, for simultaneous flip of electron and nucleon spin
- After spin flip, electron relaxates to lower energy state
- Nucleon has long relaxation time (low magnetic moment)
Why measure gluon spin from Open-Charm?

- $\bar{c}c$ production is dominated by the PGF process, and free from physical background (ideal for probing gluon polarisation)
  - In our center of mass energy, the contribution from intrinsic charm ($c$ quarks not coming from hard gluons) in the nucleon is negligible
  - Perturbative scale set by charm mass $4m_c^2$
  - Nonperturbative sea models predict at most 0.7\% for intrinsic charm contribution
    - Expected at high $x_{Bj}$ (compass $x_{Bj} < 0.1$)
  - $\bar{c}c$ suppressed during fragmentation (at our energies)

Intrinsic charm predictions: CTEQ6.5c

- In the COMPASS kinematic domain:
  - No intrinsic charm contamination is predicted by the theory driven results
  - Only the more phenomenological “See-like” scenario should be taken into account (under study)

![Graph comparing models](image)
GRSV, $\Delta G$

max, 2.5
std, 0.6
min, 0.2
Method for $\Delta G/G$ and polarised $A_B$ extraction

- The number of events comes from asymmetries in the following way:

$$N_{u,d} = a \phi n (S + B) (1 + P_T P_\mu f (a_{LL} \frac{S}{S+B} \frac{\Delta G}{G} + a_{LL}^B \frac{B}{S+B} A_B))$$

$a =$ acceptance, $\phi =$ muon flux, $n =$ number of target nucleons

- We have 4 cell configurations ($2$ cells oppositely polarised + field reversal for acceptance normalization):

  - Weight the 4 $N_{u,d}$ equations by $\omega_s$ and by $\omega_B = P_\mu f \cdot D(y) (B/S+B)$

$$\langle \sum_{k=1}^{N_{cell}} \omega_i^k \rangle = \hat{a}_{[cell, i]} (1 + (\langle \beta_{cell, s} \rangle \omega_i) A_s + (\langle \beta_{cell, b} \rangle \omega_i) A_B) = f_{cell, i}$$

(cell = u, d, u', d')

$$\Delta G/G$$

(i = S, B)

- 8 eq. with 10 unknowns

$$\hat{a} = a \phi n \sigma = a \phi n (\sigma_{PGF} + \sigma_B) = a \phi n (S + B)$$

$$\beta_s = P_B P_T f a_{LL} \frac{S}{S+B} \beta_s = P_B P_T f D \frac{B}{S+B}$$
How to solve equations for simultaneous $\Delta G/G$ and $A_B$ extraction?

- **Possible acceptance changes with time are the same for both cells** *(also the muon flux is the same for both cells):*

  \[ \frac{\hat{a}_{u,s} \hat{a}_{d',s}}{\hat{a}_{u',s} \hat{a}_{d,s}} = 1, \quad \frac{\hat{a}_{u,B} \hat{a}_{d',B}}{\hat{a}_{u',B} \hat{a}_{d,B}} = 1 \]

- **Signal and background events are affected in same way before and after a field reversal:**

  \[ \frac{\hat{a}_{u,s}}{\hat{a}_{u,B}} = \frac{\hat{a}_{u',s}}{\hat{a}_{u',B}}, \quad \frac{\hat{a}_{d,s}}{\hat{a}_{d,B}} = \frac{\hat{a}_{d',s}}{\hat{a}_{d',B}} \]

- **Unknowns are obtained by a $\chi^2$ minimization:**

  \[ x^2 = (\mathbf{N} - \mathbf{f})^T \mathbf{Cov}^{-1} (\mathbf{N} - \mathbf{f}) \]
Validation of parameterization *(2006 example)*

\[ S/(S+B) \text{ from a fit on the data} \]

**Data vs. Σ-Parameterization in Σ bins (2006 D^0-tagged)**

**Data vs. Σ-Parameterization in weight bins (2006 D^0-tagged)**

**COMPASS Preliminary**
Invariant mass of $K\pi$ pairs - $S/(S+B)$ weighting

Raw Histograms

Σ-weighted Histograms

Preliminary

COMPASS 2002 - 2006 $D^0$-tagged Weighted Mass Spectrum

Preliminary

COMPASS 2002 - 2006 $D^0$-tagged Weighted Mass Spectrum

COMPASS 2002 - 2006 $D^0$-untagged Weighted Mass Spectrum

COMPASS 2002 - 2006 $D^0$-untagged Weighted Mass Spectrum

NLO QCD predictions for gluon polarization...
\[ A = \frac{\int \Delta G(x_g)(\Delta \hat{\sigma}^{LO} + \Delta \hat{\sigma}^{NLO})ds_1dt_1}{\int G(x_g)(\hat{\sigma}^{LO} + \hat{\sigma}^{NLO})ds_1dt_1} + \frac{\int \Delta G(x'_g)\Delta \hat{\sigma}^{NLO}ds_4ds_1dt_1}{\int G(x'_g)\hat{\sigma}^{NLO}ds_4ds_1dt_1} \]

\[ \hat{\sigma}^{NLO}(t_1,s_1) = \hat{\sigma}^{LO} + \hat{\sigma}^{NLO} + \int \hat{\sigma}^{NLO}_{\text{hard}}ds_4 \]

\[ \Delta \hat{\sigma}^{NLO}(t_1,s_1) = \Delta \hat{\sigma}^{LO} + \Delta \hat{\sigma}^{NLO} + \int \Delta \hat{\sigma}^{NLO}_{\text{hard}}ds_4 \]

\[ \int \frac{\Delta G}{G} \frac{\Delta \hat{\sigma}^{NLO}(t_1,s_1)}{\hat{\sigma}^{NLO}(t_1,s_1)} G(x_g)\hat{\sigma}^{NLO}(t_1,s_1)dt_1ds_1 \]

\[ A = \frac{\int \Delta G}{G} a^{NLO}_{LL} G(x_g)\hat{\sigma}^{NLO}(t_1,s_1)dt_1ds_1 \]

NLO - method 2 event is defined by \( s_1 \) and \( t_1(u_1) \)

\( s_1 \) define \( x_g \)
\[
A = \frac{\int \Delta G(x_g) (\Delta \hat{\sigma}^{LO} + \Delta \hat{\sigma}^{NLO}) du_1 dt_1 + \int \Delta G(x_g') \Delta \hat{\sigma}_{hard}^{NLO} ds_4 du_1 dt_1}{\int G(x_g) (\hat{\sigma}^{LO} + \hat{\sigma}^{NLO}_{SV}) du_1 dt_1 + \int G(x_g') \hat{\sigma}_{hard}^{NLO} ds_4 du_1 dt_1}
\]

\[
\int \Delta G(x_g) \left[ \hat{\sigma}^{LO} + \hat{\sigma}^{NLO}_{SV} + \int \frac{\Delta G(x_g')}{\Delta G(x_g)} \Delta \hat{\sigma}_{hard}^{NLO} ds_4 \right] du_1 dt_1
\]

\[
\hat{\sigma}_{NLO}^{NLO}(t_1, u_1) = \hat{\sigma}^{LO} + \hat{\sigma}^{NLO}_{SV} + \int \frac{G(x_g')}{G(x_g)} \hat{\sigma}_{hard}^{NLO} ds_4
\]

\[
\Delta \hat{\sigma}_{NLO}^{NLO}(t_1, u_1) = \Delta \hat{\sigma}^{LO} + \Delta \hat{\sigma}^{NLO}_{SV} + \int \frac{\Delta G(x_g')}{\Delta G(x_g)} \Delta \hat{\sigma}_{hard}^{NLO} ds_4
\]

\[
A = \frac{\int \frac{\Delta G}{G} \frac{\Delta \hat{\sigma}_{NLO}^{NLO}(t_1, u_1)}{\hat{\sigma}_{NLO}^{NLO}(t_1, u_1)} G(x_g) \hat{\sigma}_{NLO}^{NLO}(t_1, u_1) du_1 dt_1}{\int G(x_g) \hat{\sigma}_{NLO}^{NLO}(t_1, u_1) du_1 dt_1}
\]

\[
A = \frac{\int \frac{\Delta G}{G} a^{NLO}_{LL} G(x_g) \hat{\sigma}_{NLO}^{NLO}(t_1, u_1) du_1 dt_1}{\int G(x_g) \hat{\sigma}_{NLO}^{NLO}(t_1, u_1) du_1 dt_1}
\]
2 → 2 \quad \Rightarrow \quad g(k_1) + \gamma(k_2) \rightarrow c(p_1) + \overline{c}(p_2)

2 → 3 \quad \Rightarrow \quad g(k_1) + \gamma(k_2) \rightarrow c(p_1) + \overline{c}(p_2) + g(k_3)

s_1 = (k_1 + k_2)^2 + Q^2 = 2k_1k_2

t_1 = (k_2 - p_2)^2 - m^2 = -2p_2k_2

u_1 = (k_1 - p_2)^2 - m^2 = -2p_2k_1

s_4 = (k_3 + p_1)^2 - m^2 = 2k_3p_1

x_g = \frac{s_1}{2Pq} = \frac{s_4 - t_1 - u_1}{2MEy}

2 \rightarrow 2 \quad \Rightarrow \quad s_1 + t_1 + u_1 = 0

2 \rightarrow 3 \quad \Rightarrow \quad s_1 + t_1 + u_1 = s_4
Asymmetries in bins in $p_T$ and $E$ of $D^0$

Table 2

<table>
<thead>
<tr>
<th>Bin limits</th>
<th>$A_{\gamma N \rightarrow D^0 X}$</th>
<th>$(y)$</th>
<th>$(Q^2)$ (GeV/c)$^2$</th>
<th>$(p_T^D)$ (GeV/c)</th>
<th>$(E_D)$ (GeV)</th>
<th>$D((X))$</th>
<th>$c_{UL}(X))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–0.3</td>
<td>–1.34 ± 0.85</td>
<td>0.47</td>
<td>0.50</td>
<td>0.19</td>
<td>24.8</td>
<td>0.57</td>
<td>0.37</td>
</tr>
<tr>
<td>0–0.3</td>
<td>–0.27 ± 0.52</td>
<td>0.58</td>
<td>0.75</td>
<td>0.20</td>
<td>39.2</td>
<td>0.70</td>
<td>0.48</td>
</tr>
<tr>
<td>0–0.3</td>
<td>–0.07 ± 0.66</td>
<td>0.67</td>
<td>1.06</td>
<td>0.20</td>
<td>60.0</td>
<td>0.80</td>
<td>0.61</td>
</tr>
<tr>
<td>0.3–0.7</td>
<td>–0.85 ± 0.51</td>
<td>0.47</td>
<td>0.47</td>
<td>0.50</td>
<td>25.1</td>
<td>0.56</td>
<td>0.26</td>
</tr>
<tr>
<td>0.3–0.7</td>
<td>0.09 ± 0.29</td>
<td>0.58</td>
<td>0.65</td>
<td>0.51</td>
<td>39.4</td>
<td>0.71</td>
<td>0.34</td>
</tr>
<tr>
<td>0.3–0.7</td>
<td>–0.20 ± 0.37</td>
<td>0.67</td>
<td>0.68</td>
<td>0.50</td>
<td>59.6</td>
<td>0.80</td>
<td>0.46</td>
</tr>
<tr>
<td>0.7–1</td>
<td>–0.47 ± 0.56</td>
<td>0.48</td>
<td>0.53</td>
<td>0.85</td>
<td>25.2</td>
<td>0.58</td>
<td>0.13</td>
</tr>
<tr>
<td>0.7–1</td>
<td>–0.49 ± 0.32</td>
<td>0.58</td>
<td>0.66</td>
<td>0.85</td>
<td>39.1</td>
<td>0.70</td>
<td>0.17</td>
</tr>
<tr>
<td>0.7–1</td>
<td>1.23 ± 0.43</td>
<td>0.68</td>
<td>0.73</td>
<td>0.84</td>
<td>59.4</td>
<td>0.81</td>
<td>0.26</td>
</tr>
<tr>
<td>1–1.5</td>
<td>–0.87 ± 0.48</td>
<td>0.50</td>
<td>0.49</td>
<td>1.21</td>
<td>25.7</td>
<td>0.60</td>
<td>0.01</td>
</tr>
<tr>
<td>1–1.5</td>
<td>–0.24 ± 0.25</td>
<td>0.60</td>
<td>0.62</td>
<td>1.22</td>
<td>39.5</td>
<td>0.73</td>
<td>0.00</td>
</tr>
<tr>
<td>1–1.5</td>
<td>–0.18 ± 0.34</td>
<td>0.69</td>
<td>0.77</td>
<td>1.22</td>
<td>59.3</td>
<td>0.83</td>
<td>0.04</td>
</tr>
<tr>
<td>&gt; 1.5</td>
<td>0.83 ± 0.71</td>
<td>0.52</td>
<td>0.51</td>
<td>1.77</td>
<td>26.2</td>
<td>0.63</td>
<td>–0.13</td>
</tr>
<tr>
<td>&gt; 1.5</td>
<td>0.18 ± 0.28</td>
<td>0.61</td>
<td>0.68</td>
<td>1.87</td>
<td>40.0</td>
<td>0.74</td>
<td>–0.20</td>
</tr>
<tr>
<td>&gt; 1.5</td>
<td>0.44 ± 0.33</td>
<td>0.71</td>
<td>0.86</td>
<td>1.94</td>
<td>59.9</td>
<td>0.84</td>
<td>–0.24</td>
</tr>
</tbody>
</table>

weighted!

$$w = \int P_B \frac{S}{S + B} D$$

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