NLO QCD predictions for gluon polarization from the open-charm $D^0$ meson production at COMPASS

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• QCD NLO corrections to open-charm production
• Asymmetry decomposition for open-charm channel
• Role of MC, PS concept and application to QCD NLO approach
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• Predictions for gluon polarization in QCD NLO approximation at COMPASS (based on published asymmetries)
Open-charm production@COMPASS - Photon-Gluon Fusion (PGF) - the only process in LO QCD.

\[
\sigma^{PGF} = G \otimes \hat{\sigma}^{PGF} \otimes H \\
\Delta\sigma^{PGF} = \Delta G \otimes \Delta \hat{\sigma}^{PGF} \otimes H \\
\text{assumption: } \frac{\Delta G}{G} (x) \approx a(x - \bar{x}) + b \\
A \approx \frac{\Delta G}{G} (\bar{x}_G) < \hat{a}^{PGF}_{LL} >
\]
Open-charm production at COMPASS - Photon-Gluon Fusion (PGF) - the only process in LO QCD.

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\[ \Delta \sigma^{PGF} = \Delta G \otimes \Delta \hat{\sigma}^{PGF} \otimes H \]

assumption: \[ \frac{\Delta G}{G} (x) \approx a(x - \bar{x}) + b \]

from data \[ A \approx \frac{\Delta G}{G} (\bar{x}_G) \langle \hat{a}^{PGF}_{LL} \rangle \]

from MC
Open-charm production@COMPASS - Photon-Gluon Fusion (PGF) - the only process in LO QCD.

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assumption: \[ \frac{\Delta G}{G}(x) \approx a(x - \bar{x}) + b \]

from data

from MC

COMPASS LO analysis in details: see presentation of Celso Franco
Open-charm production@COMPASS - Photon-Gluon Fusion (PGF) - the only process in LO QCD.

charm channel:
1. in LO QCD approach pure PGF events
   but
1. Low statistics
2. Huge combinatorial background to fight


Notice: here A is a signal asymmetry only;

\[ A^{\text{meas}} = \frac{s}{s+b}A^D + \frac{b}{s+b}A^B \]

\( a_{LL} \) parameterized (with neural network) using only observed quantities \((x,y,Q^2, z_D, p_T^D)\) and calculated from real data

COMPASS LO analysis in details: see presentation of Celso Franco
NLO QCD corrections for open-charm

(a) 

(b) 

(c) 

(d) 

(e) 

(f) 

(g) 

(h) 

(i) 

(k_1 \rightarrow p_1 \quad k_1 \rightarrow p_1 \quad k_2 \rightarrow p_2 \quad k_2 \rightarrow p_2 

(a) 

(b) 

(c) 

(d)
NLO QCD approximation - kinematics

\[ 2 \rightarrow 2 \quad \Rightarrow \quad g(k_1) + \gamma(k_2) \rightarrow c(p_1) + \bar{c}(p_2) \]

\[ 2 \rightarrow 3 \quad \Rightarrow \quad g(k_1) + \gamma(k_2) \rightarrow c(p_1) + \bar{c}(p_2) + g(k_3) \]

\[ s_1 = (k_1 + k_2)^2 + Q^2 = 2k_1k_2 \]

\[ t_1 = (k_2 - p_2)^2 - m^2 = -2p_2k_2 \quad \text{\( k_1 \) - photon} \]

\[ u_1 = (k_1 - p_2)^2 - m^2 = -2p_2k_1 \quad \text{\( k_2 \) - gluon/quark} \]

\[ s_4 = (k_3 + p_1)^2 - m^2 = 2k_3p_1 \quad \text{\( p_1, p_2 \) - charm quarks} \]

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

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

\[ 2 \rightarrow 3 \quad \Rightarrow \quad s_1 + t_1 + u_1 = s_4 \]
1. **NLO corrections available only for photo-production limit.** $Q^2 = 0$

2. **No problem for COMPASS:** $D$ – depolarization factor

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

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

$Q^2$ neglected in this parts - very good approximation
1. MC events used for establish parton kinematics event-by-event basis
2. PS-on allows to have “room” for integration over $s_4$

MC is used for simulating Phase Space for NLO/LO calculations

3. Including light quark channel new background (hidden in signal events) is present. At the first look the situation is similar to high-$p_T$: unwanted processes which should be subtracted. There is however a big difference: The quark channel cross section is a “reduced” cross section (NLO) and mostly negative in the COMPASS kinematical range

Also gluon NLO xs can be negative - the physical meaning has total xs: LO+NLO
NLO QCD predictions for gluon polarization from the open-charm D0 meson production at COMPASS

COMPASS

quark integrated partonic xs
Stratmann&Bojak
NLO QCD cross sections - gluon part

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COMPASS

NLO QCD predictions for gluon polarization from the open-charm D0 meson production at COMPASS

Stratmann & Bojak
\[
\sigma^{\text{signal}} = \left( G \otimes \left( \hat{\sigma}^{\text{PGF,LO}} + \hat{\sigma}^{\text{PGF,NLO}} \right) + \sum_{q} e_{q}^{2} q \otimes \hat{\sigma}^{\text{quark,light}} + \sum_{q} q \otimes \hat{\sigma}^{\text{quark,charm}} \right) \otimes H
\]

\[
\sigma^{\text{signal}} = \left( G \otimes \hat{\sigma}^{\text{Gluon}} + \sum_{q} q \otimes \hat{\sigma}^{\text{quark}} \right) \otimes H
\]

\[
\hat{\sigma}^{\text{Gluon}} = \hat{\sigma}^{\text{PGF,LO}} + \hat{\sigma}^{\text{PGF,NLO}} \quad \hat{\sigma}^{\text{quark}} = \hat{\sigma}^{\text{quark,charm}} + \frac{5}{18} \hat{\sigma}^{\text{quark,light}}
\]

\[
\Delta \sigma^{\text{signal}} = \left( \Delta G \otimes \Delta \hat{\sigma}^{\text{Gluon}} + \sum_{q} \Delta q \otimes \Delta \hat{\sigma}^{\text{quark}} \right) \otimes H
\]

\[
A^{\text{signal}} = \frac{\Delta \sigma^{\text{signal}}}{\sigma} = \left( \frac{\Delta G}{G} \otimes \Delta \hat{\sigma}^{\text{Gluon}} + A_{1}^{d,c} \sum_{q} q \otimes \Delta \hat{\sigma}^{\text{quark}} \right) \otimes H
\]

\[
A^{\text{measured}} = f P_{T} P_{b} \left( \frac{S}{S + B} A^{\text{signal}} + \frac{B}{S + B} A^{B} \right) \quad A_{1}^{d,c} = \frac{A_{1}^{d}}{1 - \frac{3}{2} \omega_{D}}
\]

Asymmetry decomposition

\[
\text{\textit{H - fragmentation,}} \quad \otimes - \text{convolution integral}
\]

\textit{thanks to deuteron target}
\[ \sigma^{\text{signal}} = \left( G \otimes (\hat{\sigma}^{\text{PGF, LO}} + \hat{\sigma}^{\text{PGF, NLO}}) + \sum_q e_q^2 q \otimes \hat{\sigma}^{\text{quark, light}} + \sum_q q \otimes \hat{\sigma}^{\text{quark, charm}} \right) \otimes H \]

\[ \sigma^{\text{signal}} = \left( G \otimes \hat{\sigma}^{\text{Gluon}} + \sum_q q \otimes \hat{\sigma}^{\text{quark}} \right) \otimes H \]

\[ \hat{\sigma}^{\text{Gluon}} = \hat{\sigma}^{\text{PGF, LO}} + \hat{\sigma}^{\text{PGF, NLO}} \quad \hat{\sigma}^{\text{quark}} = \hat{\sigma}^{\text{quark, charm}} + \frac{5}{18} \hat{\sigma}^{\text{quark, light}} \]

\[ \Delta \sigma^{\text{signal}} = \left( \Delta G \otimes \Delta \hat{\sigma}^{\text{Gluon}} + \sum_q \Delta q \otimes \Delta \hat{\sigma}^{\text{quark}} \right) \otimes H \]

\[ A^{\text{signal}} = \frac{\Delta \sigma^{\text{signal}}}{\sigma} = \left( \frac{\Delta G}{G} \otimes \Delta \hat{\sigma}^{\text{Gluon}} + A_{1}^{d,c} \sum_q q \otimes \Delta \hat{\sigma}^{\text{quark}} \right) \otimes H \]

\[ A^{\text{measured}} = f_P T P_b \left( \frac{S}{S + B} A^{\text{signal}} + \frac{B}{S + B} A^B \right) \]

\[ A_{1}^{d,c} = \frac{A_1^d}{1 - \frac{3}{2} \omega_D} \]

Asymmetry decomposition

thanks to deuteron target

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NLO QCD predictions for gluon polarization from the open-charm D0 meson production at COMPASS
Asymmetry decomposition

\[ A_{\text{signal}} = - \left( \frac{\Delta G}{G} + A_1^{d.c} \sum_q q \hat{\Delta}^{\text{quark}} \right) \left( \frac{G \hat{\Delta}^{\text{Gluon}}}{G \hat{\Delta}^{\text{Gluon}} + \sum_q q \hat{\Delta}^{\text{quark}}} \right) \left( G \hat{\Delta}^{\text{Gluon}} + \sum_q q \hat{\Delta}^{\text{quark}} \right) H \]

\[ = \left( \langle \frac{\Delta G}{G} a_{LL} + A_1^{d.c} a_{LL}^q \rangle \right) \left( \frac{\Delta G}{G} \right) a_{LL} + \langle A_1^{d.c} a_{LL}^q \rangle = \left( \langle \frac{\Delta G}{G} \rangle a_{LL} \right) + \langle A_1^{d.c} a_{LL}^q \rangle \left( \frac{\Delta G}{G} + A_1^{d.c} \frac{a_{LL}^q}{a_{LL}} \right) \langle a_{LL} \rangle \]

\[ a_{LL} = \frac{G \hat{\Delta}^{\text{Gluon}}}{G \hat{\Delta}^{\text{Gluon}} + \sum_q q \hat{\Delta}^{\text{quark}}} \]

\[ a_{LL}^q = \frac{\sum_q q \hat{\Delta}^{\text{quark}}}{G \hat{\Delta}^{\text{Gluon}} + \sum_q q \hat{\Delta}^{\text{quark}}} \]
1. Aroma with PS-on describes COMPASS data very well

2. every event from MC has s.t.u variables fixed what allows to calculate xs in LO (unique) and in NLO: partially integrated over one charm quark.

3. Integration over energy of emitted gluon ($s_4$) is performed event-by-event from 0 to $s_1+t_1+u_1$. After integration over $s_4$ xs depends only on two variables as in LO and can be combined with LO result.

4. All reduced NLO xs should be added together to avoid numerical instabilities.

**Used sample:** PS-on/off (Aroma) 
2004/2006 setups, of COMPASS used in MC
MC calculations: quark unpolarized $xs$

quark channel reduced $xs$ NLO as a function of $s_1$
MC calculations: LO gluon vs quark xs

quark channel reduced xs NLO versus LO PGF
The correction for gluon polarization - $a_{LL}$ for quark is convoluted with unpolarized quark pdf and deuteron asymmetry.

**Gluon valence quarks**

**Deuteron asymmetry parameterization as a function of $x$**
MC calculations: $a_{LL}$

NLO gluon

A*$a_{LL}$ quark ch.

LO (PGF)
• **Model independent asymmetries were extracted from data only**

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

\[ \frac{\Delta g}{g} \text{ can be extracted using } a_{LL}^{\text{PGF}} \text{ calculated at } \text{LO} : \]

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

• **Similar analysis, but with weight**

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

instead of

\[ w = f P_B \frac{S}{S + B} D \]
LO published: $\Delta G/G = -0.49 \pm 0.27$

NLO: based on asymmetries in bins
- $\Delta G/G = +0.008 \pm 0.25$
- $\Delta G/G = \text{const} : \quad \Delta G/G = -0.018 \pm 0.31$
- $\Delta G/G > 0$, Compass NLO QCD fit: $\Delta G/G = -0.083 \pm 0.4$
- $\Delta G/G < 0$, Compass NLO QCD fit: $\Delta G/G = -0.18 \pm 0.31$

NLO: simple MC weighted NLO xs
$\Delta G/G = +0.005 \pm 0.22$
Gluon polarization results: tests

shift in $s_1$ ~17 GeV!

$u_1$ centered at ~6 GeV

t$_1$ centered at 0.4 GeV

events from MC with PS-on and PS-off “paired” to have a pair of events with the same observed quantities ($x,y,Q^2,z_D,p_T^D$). Differences in $s,t,u$ are shown
Gluon polarization results: tests

NLO effect slightly overestimated

shift in $s_1$
~17 GeV!

$u_1$ centered
at ~6 GeV

$t_1$ centered
at 0.4 GeV

It is better to use $t_1$ and $u_1$
instead of $s_1$ and $t_1$
but it costs: polarized gluons model
needed to perform integration over $s_4$
to test the effect 3 models have been used
(see previous slide)

events from MC with PS-on and PS-off “paired” to have a pair of events with the
same observed quantities ($x, y, Q^2, z_D, p_T^D$). Differences in $s, t, u$ are shown
Conclusions

- 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)$^2$

$\Delta g/g$

$X_g$

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

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

\[ \begin{array}{c}
\star \text{COMPASS, open charm, prel., 02–06} \\
\text{-} \text{COMPASS, high } p_T, Q^2 > 1 \text{ (GeV/c)}^2, \text{ prel., 02–04} \\
\bullet \text{COMPASS, high } p_T, Q^2 < 1 \text{ (GeV/c)}^2, \text{ prel., 02–04} \\
\triangle \text{HERMES, high } p_T, \text{ all } Q^2 \\
\text{–} \text{HERMES, single high } p_T \text{ hadrons, all } Q^2, \text{ prel.} \\
\blacksquare \text{SMC, high } p_T, Q^2 > 1 \text{ (GeV/c)}^2
\end{array} \]

\[ \begin{array}{c}
\text{fit with } \Delta G > 0, \mu^2 = 3(\text{GeV/c})^2 \\
\text{fit with } \Delta G < 0, \mu^2 = 3(\text{GeV/c})^2
\end{array} \]

NLO QCD predictions for gluon polarization from the open-charm D0 meson production at COMPASS
Conclusions

NLO corrections - significant also on asymmetries. Should be considered as a upper limit of the effect.
Final COMPASS LO result - closer to zero (see Celso Franco talk)
- new asymmetries soon - NLO analysis ongoing
Why measure gluon spin from Open-Charm?

- $c\bar{c}$ 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 $x_{Bj} < 0.1$)
  - $c\bar{c}$ suppressed during fragmentation (at our energies)

NLO QCD predictions for gluon polarization from the open-charm D0 meson production at COMPASS

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)

![Comparison of models graph]