Particle production in the DIS target fragmentation region

Federico Alberto Ceccopieri

IFPA, Université de Liège, Belgium

federico.alberto.ceccopieri@cern.ch

Jefferson Lab, 6th January 2016
Outline of the talk

• Brief biographical infos
• Research activities and interests
• Target fragmentation in SIDIS : the $\Lambda$ case
Biographical infos

- Graduate in Turin, Italy ’01, advisor G.Passarino (QED)
- Ph.D in Parma, Italy, ’05, advisors S.Forte, M.Cacciari (pQCD)
- Collaborations with L.Trentadue ’06 → present
- 1 year postdoc in Parma, $\pi^+$ target fragmentation at CLAS, M.Osipenko
- TOTEM @ CERN (6 months) Soft and Hard diffraction and MC studies
- ’07 - ’09 : 2 years postdoc in Parma, pQCD at hadron colliders.
- ’09 - ’11 : joint Bruxelles/Liége postdoc, hard diffraction at HERA
- ’11 - today : always active in research while teaching at high school
- Starting next month: Perugia project on MPI
Research Activities Overview

- Target fragmentation in both in DIS and hadronic collisions within the fracture functions formalism. Analyses of leading proton and neutron production in DIS at high energy, $\Lambda$ at intermediate energy (also with NOMAD colleagues in JINR).

- Extraction via global QCD fits of diffractive parton distributions from Diffractive DIS data. Studies of diffractive processes and their factorisation at hadron colliders (analysis in progress for single diffractive DY).

- Study of double parton scattering and double parton distributions in hadronic collisions. Case study: same sign $W^\pm W^\pm$ production at LHC.

- TMD phenomenology. In PLB741 (2015) we have shown that our evolution equations matches Collins and Rogers and Scimemi & al. results in the soft limit. Ongoing collaborations for the analysis of HERMES semi-inclusive data.
The leading particle effect in hadronic collisions

- Consider the following reaction: $\bar{p}p \rightarrow c + X$

- $x_F = \frac{2p_{||}}{\sqrt{s}}$ in hadronic centre of mass

- **Leading particle effect**: privileged quark-flavour quantum number flow from the initial state particle to the final state one

- the more the quark-flavour content is conserved from initial to final state hadron, the more the latter carries a substantial fraction of the energy available in the reaction.

- Pions (Gribov QCD light) don’t show LPE

- However no hard momentum transfer is present in this reaction $\rightarrow$ pQCD can not be applied

Basile & al. '81
The leading particle effect in DIS

- Same effect observed in DIS
- $\mu P \rightarrow \mu + h + X$, DIS@280 GeV
- Same pattern as in hadronic collisions
- LPE for backward proton (uud) and $\Lambda$ (uds)
- No LPE for $\bar{\Lambda}$ ($\bar{u}\bar{d}\bar{s}$), $\bar{p}$ ($\bar{u}\bar{u}\bar{d}$) and mesons
- But here we have hard scale, $Q^2 \gg \Lambda_{QCD}^2$
Consider a Deep Inelastic Scattering event in which a virtual photon of mass $Q^2$ interacts with a parton cascade in the nucleon:

- $t \sim Q^2$ current fragmentation, $t \sim 0$ target fragmentation, with $t = (P - p_h)^2$
- $0 < t < Q^2$ central region: higher order corrections, depends on factorisation scale
Factorisation in SIDIS

- **Factorization theorem** allows the decoupling of short distance (ME) from long distance \((f, D, M)\) physics

- \(f, D, M\) are not calculable from first principles

- The **evolution** of \(f, D, M\) however is known (RGE)

- At lowest order, in the current region \((x_F > 0)\) \(d\sigma \propto f \otimes D\) and in the target region \((x_F < 0)\) \(d\sigma \propto M\)

- **Factorisation** for \(M\) in SIDIS has been proven at collinear and soft level (Grazzini, Trentadue, Veneziano 1998; Collins 1998)

- Collinear factorization confirmed in fixed order pQCD calculation at \(\mathcal{O}(\alpha_s)\) and \(\mathcal{O}(\alpha_s^2)\) (Graudenz, 1994; Daleo & al 2003)
Fracture functions in SIDIS

- Fracture functions $M$ complete the description of SIDIS final state:
- $M$ parametrize soft QCD dynamics in forward semi-inclusive processes.
- $M^h_{i/p}(x, z, Q^2)$ gives the conditional probability that a parton $i$ with a fractional momentum $x$ of the incoming proton enters the hard scattering while an hadron $h$ with fractional momentum $z$ is detected in the TFR of $p$.
- They obey a DGLAP-type inhomogeneous evolution equations:

$$Q^2 \frac{dM^h_{i/p}}{dQ^2} = \frac{\alpha_s}{2\pi} P_{ji} \otimes M^h_{j/p} + \frac{\alpha_s}{2\pi} \hat{P}_{ji} \otimes f_{j/p} D^h_l.$$
$\Lambda$ leptoproduction in DIS

- $\mu P \rightarrow \mu' \Lambda X @ 280$ GeV, DIS regime
- Forward ($x_F > 0$) $\Lambda$ and $\bar{\Lambda}$ production comparable
- No LPE for $\bar{\Lambda}$s, symmetric around $|x_F| \sim 0$
- LPE for $\Lambda$s ($uud \rightarrow uds$)
- Focus on Lambdas in the following
SIDIS variables and cross section

• $z_h$ not good for target: mixes soft and target hadrons for $z_h \to 0$

$$z_h = \frac{P \cdot h}{P \cdot q} = \frac{E^*_h}{E^*_p(1-x_B)} \frac{1 - \cos \theta}{2}$$

• Hadron variables in $\gamma^* N$ c.o.m. frame:

$$z_G = \frac{E^*_h}{E^*_p(1-x_B)}, \quad E^*_p(1-x_B) = W/2, \quad \zeta = \frac{E^*_h}{E^*_p}, \quad x_F = \pm \sqrt{\frac{z_G^2 - 4m_T^2}{W^2}}$$

• The Lambda leptoproduction cross section in term of these variables reads

$$\frac{d\sigma^{\Lambda/N}_{\gamma N}}{dx_B dQ^2 dz_G} \propto \frac{z_G}{|x_F|} \sum_i c_i \left[ f_{i/N}(x_B, Q^2) D^\Lambda_i(z_G, Q^2) + (1-x_B) M^\Lambda_{i/N}(x_B, (1-x_B)z_G, Q^2) \right]$$

• Best strategy to extract $M$: subtract the current from $z_G$ spectra

• But: Large uncertainties on FFs at low $Q$, no $z_G$ spectra available in the literature.

• Resort to kinemtical separation in $x_F$: associate target fragments to $x_F < 0$
Initial conditions for $\Lambda$ fracture functions (1)

- The electroweak current probes the "struck quark" on very short "time scale", $\sim 1/Q_0$

- A parton with flavour $i$ and momentum $x$ is then removed from the proton with probability $f_{i/P}(x_B, Q_0^2)$

- The leftover coloured system reassembles to give colourless $\Lambda$ with fractional momentum $z$ on much longer "time scale", $\sim 1/\Lambda_{QCD}$, with probability $\tilde{D}_i^\Lambda(z)$

- Phenomenological factorisation: $M \propto f \times \tilde{D}$
Initial conditions for $\Lambda$ fracture functions (2)

- Assumption: fracture functions can be factorized, at some low and arbitrary $Q_0^2 \sim 1 \text{ GeV}^2$ scale, in the form

$$(1 - x_B) M_{i/p}^\Lambda(x_B, \zeta, Q_0^2) = M_{i/p}^\Lambda(x_B, z, Q_0^2) = f_{i/p}(x_B, Q_0^2) \tilde{D}^\Lambda_i(z)$$

- $f_{i/p}(x, Q_0^2)$ are standard parton distribution functions (GRV'94)

- $\tilde{D}^\Lambda_i(z)$ are unknown spectator fragmentation functions

- The input distributions are then evolved to arbitrary scales via FF evolution equations.
Initial conditions for $\Lambda$ fracture functions (3)

- Exploit GRV'94 valence/sea decomposition $\oplus$ simplified flavour and energy dependence

$$
(1 - x_B)M_{u/p}^\Lambda(x_B, z, Q_0^2) = u_v(x_B, Q_0^2)N_u z^{\alpha_u} (1 - z)^{\beta_u} + u_s(x, Q_0^2)N_s z^{\alpha_s} (1 - z)^{\beta_s} \\
(1 - x_B)M_{d/p}^\Lambda(x_B, z, Q_0^2) = d_v(x_B, Q_0^2)N_d z^{\alpha_d} (1 - z)^{\beta_d} + d_s(x, Q_0^2)N_s z^{\alpha_s} (1 - z)^{\beta_s} \\
(1 - x_B)M_{g/p}^\Lambda(x_B, z, Q_0^2) = g(x, Q_0^2)N_s z^{\alpha_s} (1 - z)^{\beta_s} \\
(1 - x_B)q_{s/p}^\Lambda(x_B, z, Q_0^2) = q_s(x_B, Q_0^2)N_s z^{\alpha_s} (1 - z)^{\beta_s}
$$

- In case of scattering on a sea quark, the spectator fragments independently of the flavour of the latter: $N_s z^{\alpha_s} (1 - z)^{\beta_s}$

- $x_B$ dependence driven by pdfs. 12 free pars

- Gluon spectator fragmentation unconstrained, set $\tilde{D}_g^\Lambda = \tilde{D}_{qs}^\Lambda$, $\rightarrow$ 9 free pars
Data set used in the fit

- \( lN \rightarrow l'\Lambda X, l = \mu, \nu, \bar{\nu} \)
- \( E_l = \) from 38 to 490 GeV + neutrino fluxes
- SKAT collaboration reported sizeable 
  A-dependence of backward \( \Lambda \) production,
  \( \langle n_\Lambda \rangle \propto A^\delta \)
- Temptative explanation : secondary interactions,
  \( \pi N \rightarrow \Lambda X \), inside nuclear medium
- fit data only light targets : \( N = p, D, n \)
  \( \rightarrow \) quark-flavour separation
- observable : \( d\sigma^\Lambda / dx_F \)
- Inclusive \( \Lambda \) sample : \( \Lambda \) coming from higher mass resonance decays included in the sample

Figure 1: The A-dependence of the total yields of \( N^0, \Lambda, \Lambda^* \) and \( \pi^- \). The curves are the result of the exponential fit.
Fit results and error propagation

- Study of the eigenvalues of the Hessian matrix $\rightarrow$ parameter reduction: 7 free pars

- $\tilde{D}_i^\Lambda = N_i z^{\alpha_i} (1 - z)^{\beta_i}$

- 3 normalizations $N_i$ well determined

- $\beta_i$ determined with acceptable errors

- $\alpha_i$ mostly unconstrained: $\alpha_u = \alpha_d$ and $\alpha_{qs} = 0$

- $\chi^2/d.o.f. = 44.14/(46 - 7) = 1.13$

- propagation experimental uncertainties: 14 additional $\Lambda$FF set corresponding to $\Delta \chi^2 = 1$

Federico A. Ceccopieri
Predictions for CLAS@12GeV

SIDIS selection:

- $0.2 < y < 0.8$, $Q^2 > 1 \text{ GeV}^2$, $W^2 > 5 \text{ GeV}^2$
- target $\Lambda : x_F < 0$

<table>
<thead>
<tr>
<th>Target/Observable</th>
<th>$\langle n(\Lambda) \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>$0.038 \pm 0.003 (exp)<em>{+0.004}^{+0.004 (mass)}</em>{-0.004} (scale)$</td>
</tr>
<tr>
<td>deuteron</td>
<td>$0.032 \pm 0.002 (exp)<em>{+0.003}^{+0.003 (mass)}</em>{-0.004} (scale)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Target/Observable</th>
<th>$\sigma^\Lambda$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>$2382 \pm 170 (exp)<em>{+247}^{+247 (mass)}</em>{-269} (scale)$</td>
</tr>
<tr>
<td>deuteron</td>
<td>$1758 \pm 102 (exp)<em>{+196}^{+196 (mass)}</em>{-206} (scale)$</td>
</tr>
</tbody>
</table>

Ceccopieri arXiv:1508.07459
Propagation of exp uncertainties from the $\Lambda$FF fit

- Best fit + 14 additional $\Lambda$FF set corresponding to $\Delta\chi^2 = 1$ built from eigenvectors of the Hessian matrix
- $\delta\langle n(\Lambda) \rangle = \pm 0.003$
Sensitivity to mass corrections

- Mass corrections: $x_F = \pm \sqrt{z_G^2 - \frac{4\epsilon m_T^2}{W^2}}$, $m_T \simeq m_\Lambda$ since $p_t^\Lambda \ll m_\Lambda$ (exp)

- Arbitrary variations: $\epsilon = \{0.9, 1, 1.1\}$

- $\delta \langle n(\Lambda) \rangle = \pm 0.004$, slight shape change
Sensitivity to higher orders

- factorisation scale: $\mu_F^2 = \{1/2Q^2, Q^2, 2Q^2\}$
- moderate scale dependence for differential yield $\rightarrow$ compensation with scale dependence iDIS
- $\delta\langle n(\Lambda) \rangle = \pm 0.001$

Federico A. Ceccopieri

Jlab, 6 Jan 2016, p.19/25
Predictions for CLAS@12GeV

- comparison with inclusive DIS: correlation between hard scattering and target $\Lambda$ production

<table>
<thead>
<tr>
<th>Variable</th>
<th>iDIS</th>
<th>$\Lambda$DIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle x_B \rangle$</td>
<td>0.18</td>
<td>0.17</td>
</tr>
<tr>
<td>$\langle y \rangle$</td>
<td>0.45</td>
<td>0.48</td>
</tr>
<tr>
<td>$\langle Q^2 \rangle$ [GeV$^2$]</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>$\langle W^2 \rangle$ [GeV$^2$]</td>
<td>10.3</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Federico A. Ceccopieri

Jlab, 6 Jan 2016, p.20/25
• **Left**: test leading twist hypothesis, assumed by fracture functions formalism

• **Right**: mild rise of $\Lambda$ multiplicity with $Q^2$: test pQCD evolution of fracture functions

• compare spectra in DIS and PHP regime: how the transition to the non-perturbative regime in $Q^2$ affects the Lambda spectrum in the target region.
Predictions for CLAS@12GeV

- The $Q^2$-differential cross section deserve special attention
- it may provide crucial test for the predicted evolution of FFs
- BUT : low values of $W^2$ accessed by the experiment
- the $Q^2$ spectrum receives significant hadron mass corrections
- They suppress the cross section as $x_B$ increases.
- to spot $Q^2$ scaling violations from FF evolution use reduced cross section (all $Q^2$-dep. from $M$):

$$\frac{1}{\sigma_0} \frac{d\sigma^{\Lambda/N}}{dx_B \, dy \, dz} = \frac{z}{|x_F|} \sum_i e_i^2 M_i^{\Lambda/N}$$
Predictions for CLAS@12GeV

- $\frac{1}{\sigma_{DIS}} \frac{d\sigma^\Lambda}{dx_F}$ in $(x_B, Q^2)$ ranges for both proton and deuteron targets

- This way of presenting the data is probably the more exhaustive and it might be valuable for the determination of Lambda fracture functions in forthcoming global fit analyses:

- maximal sensitivity to $\tilde{D}$'s parameters
Strange correlation in SIDIS final state

- Consider double inclusive cross section:
  \[ lN \rightarrow \Lambda K^+ X \], in DIS regime

- Trigger on very backward Lambdas (uds),
  \[-1 < x_F < -0.5 \] and \( K^+ (u\bar{s}) \) for all \( x_F \)

- Measure cross section (or related distributions)
  as a function of the rapidity difference \( \Delta y = y_{K^+} - y_{\Lambda} \)

- for forward \( K^+ \) (say \( x_F > 0.5 \)), the cross section can predicted:
  it has the form : \( d\sigma / d\Delta y \propto M_{i/N}^\Lambda \otimes D_{i}^{K^+} \)

- Observable sensitive to strangeness propagation across final state:
  - small \( \Delta y \), \( \Lambda K^+ \) close in PS, measure strange short-range correlation
  - large \( \Delta y \), \( \Lambda K^+ \) distant in PS, measure strange long-range correlation
  - dependence on final state multiplicity or \( W^2 \)?
Conclusions

• For a complete description of SIDIS one has to deal with target fragmentation: its description in terms fracture functions is slowly improving (Relevant for EIC)

• Phenomenology at all energy and for different particles ($p, n, \Lambda, \pi, \bar{p}$) is required

• A model for the description of backward $\Lambda$ production has been constructed in the fracture functions framework (CM12)

• Predictions for a number of observables for CLAS@12GeV have been presented: potential to test underlying theory and to sharpen the model

• ... strange correlations in DIS final state

• ... low energy diffractive DIS program with forward protons at CLAS?

• ... factorisation test in hadronic collisions