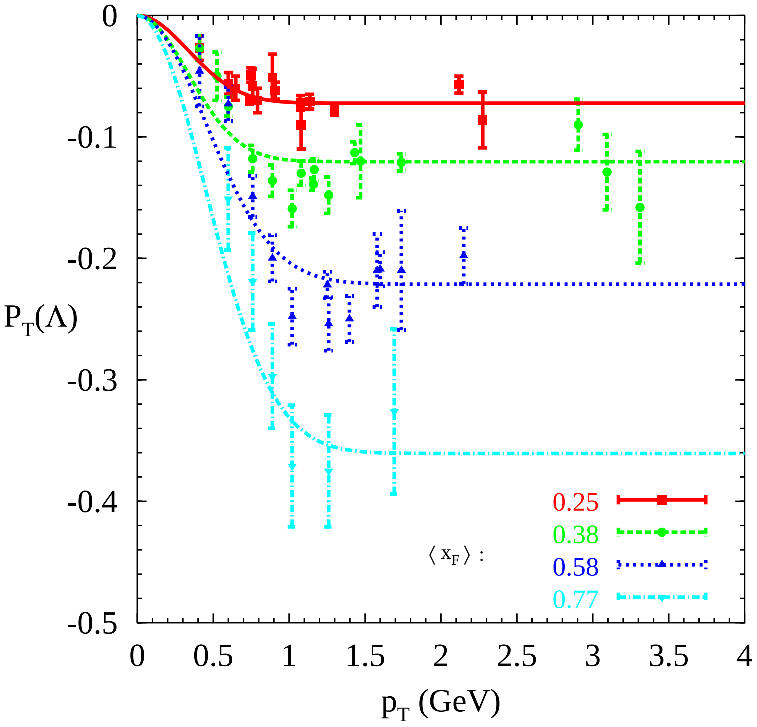
TRANSVERSE Λ POLARIZATION IN INCLUSIVE PROCESSES

Outline:

- Transverse Λ polarization in *unpolarized* hadron collisions, $p\,p(A) \to \Lambda^\uparrow X$:
  The *polarizing fragmentation function* (PFF), a new spin- and $\boldsymbol{k}_\perp$- dependent FF;
- General approach and properties of spin- and $\boldsymbol{k}_\perp$- dependent FF;
- Applications: study of transverse Λ polarization in *unpolarized* (NC, CC) semi-inclusive DIS: $\ell\,p \to \ell'\,\Lambda^\uparrow\,X$ [$\ell \equiv \ell^\pm, \nu$];
- $p^\uparrow\,p \to \Lambda^\uparrow X$ and $\ell\,p^\uparrow \to \ell'\Lambda^\uparrow X$: access to h_1;
- Conclusions and outlook;

Ref.s : M. Anselmino, D. Boer, UD, F. Murgia, PRD63 (2001) 054029; hep-ph/0109186

pA - data: main features



A partial collection of experimental data for $P_T(\Lambda)$ in $p\,p(Be) \to \Lambda^{\uparrow}X$ vs. p_T and for different bins of x_F. The curves are just to guide the eye.

$|P_T(\Lambda)|$:

- is LARGE;
- increases up to $p_T \sim 1$ GeV, where it flattens up to the highest measured p_T;
- in this plateau regime increases linearly with x_F;
- is almost energy-independent;

$P_T(\bar{\Lambda})$ is compatible with zero;

A generalized pQCD approach to Single Spin Asymmetries

1) Extension of usual pQCD formalism (based on factorization theorems) for (semi)inclusive hadronic processes, $A\,B \;\to\; C\,X$, at large energies and (moderately) large p_T

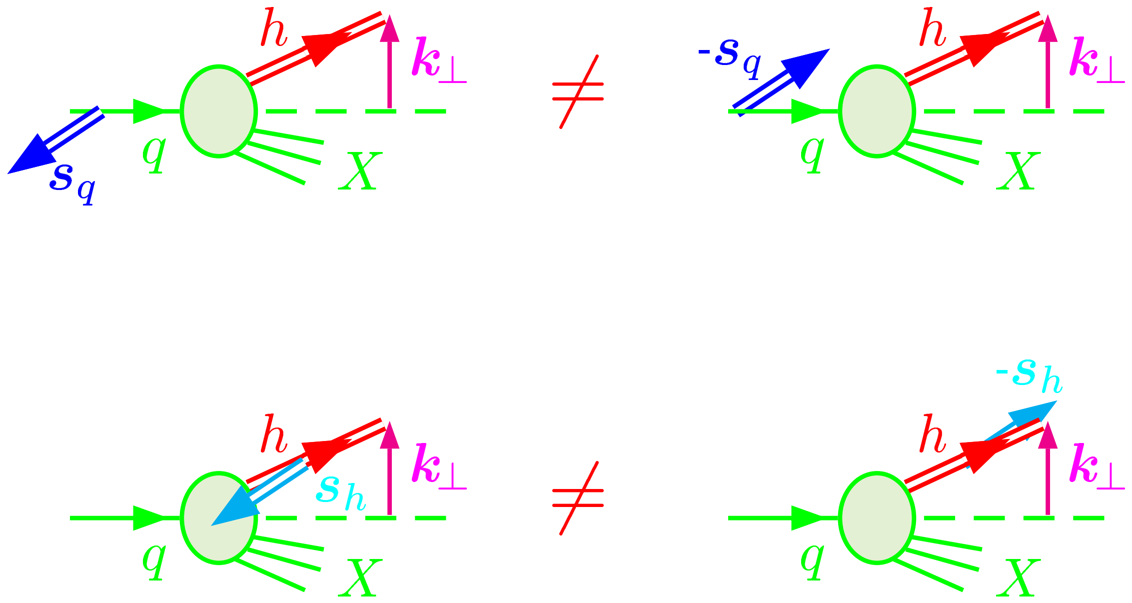
2) Inclusion of spin and intrinsic (partonic) transverse momentum, $\boldsymbol{k}_\perp$, effects

3) New, nonperturbative, twist-two, spin and $\boldsymbol{k}_\perp$-dependent partonic distribution/fragmentation functions are introduced

4) Soft, nonperturbative dynamics generates correlations between the hadron(parton) transverse spin and the parton(hadron) transverse momentum, which imply an azimuthal asymmetry in the $\boldsymbol{k}_\perp$ probability distribution. This in turn originates the asymmetries observed at the hadronic level

Twist-two, spin and $k_\perp$- dependent fragmentation functions

$$\mathbf{q \to h + X}$$



$\Delta^N D_{h/q^\uparrow}(z, \boldsymbol{k}_\perp)$

T-odd,

chiral-odd

$\Delta^N D_{h^\uparrow/q}(z, \boldsymbol{k}_\perp)$

T-odd,

chiral-even

FINAL STATE INTERACTIONS!

- $\Delta^N f_{q/p^\uparrow}(x, \boldsymbol{k}_\perp) \;=\; \hat{f}_{q/p^\uparrow}(x, \boldsymbol{k}_\perp) - \hat{f}_{q/p^\downarrow}(x, \boldsymbol{k}_\perp)$ [Sivers (90)]
- $\Delta^N f_{q^\uparrow/p}(x, \boldsymbol{k}_\perp) \;=\; \hat{f}_{q^\uparrow/p}(x, \boldsymbol{k}_\perp) - \hat{f}_{q^\downarrow/p}(x, \boldsymbol{k}_\perp)$
- $\Delta^N D_{h^\uparrow/q}(z, \boldsymbol{k}_\perp) = \hat{D}_{h^\uparrow/q}(z, \boldsymbol{k}_\perp) - \hat{D}_{h^\downarrow/q}(z, \boldsymbol{k}_\perp)$
- $\Delta^N D_{h/q^\uparrow}(z, \boldsymbol{k}_\perp) = \hat{D}_{h/q^\uparrow}(z, \boldsymbol{k}_\perp) - \hat{D}_{h/q^\downarrow}(z, \boldsymbol{k}_\perp)$ [Collins (93)]

Note: $\hat{f}_{q/p^\downarrow}(x, \boldsymbol{k}_\perp) = \hat{f}_{q/p^\uparrow}(x, -\boldsymbol{k}_\perp)$ and so on

General formalism and applications

P.J. Mulders, R.D. Tangerman, NPB**461** (96); D. Boer, P.J. Mulders, PRD**57** (98); D. Boer, PRD**60** (99), D. Boer *et al.*, NPB**564** (00); M. Anselmino *et al.*, PLB**362** (95); M. Anselmino, F.Murgia, PLB**442** (98); M. Anselmino *et al.*, PRD**60** (99); M. Anselmino *et al.*, EPJC**13** (00); M. Anselmino, F.Murgia, PLB**483** (00);

$$p\,p(A) \to \Lambda^\uparrow\, X \qquad P_{_T}(\Lambda) = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

At leading twist and leading order in $\boldsymbol{k}_\perp$ the numerator in $P_{_T}(\Lambda)$ reads

$$d\sigma^{pp\to\Lambda^\uparrow X} - d\sigma^{pp\to\Lambda^\downarrow X} \sim \sum_{abcd} \int dx_a dx_b$$

$$\times \Big\{ \int d^2\boldsymbol{k}_{\perp c}\, f_{a/p}(x_a)\, f_{b/p}(x_b)\, \frac{d\hat\sigma}{dt}(x_a, x_b; \boldsymbol{k}_{\perp c})\, \Delta^N D_{\Lambda^\uparrow/c}(z, \boldsymbol{k}_{\perp c})$$

$$+ \int d^2\boldsymbol{k}_{\perp a}\, \Delta^N f_{a^\uparrow/p}(x_a, \boldsymbol{k}_{\perp a})\, f_{b/p}(x_b)\, \Delta_{NN}\hat\sigma(x_a, x_b; \boldsymbol{k}_{\perp a})\, \Delta_T D_{\Lambda/c}(z)$$

$$+ \int d^2\boldsymbol{k}_{\perp b}\, f_{a/p}(x_a)\, \Delta^N f_{b^\uparrow/p}(x_b, \boldsymbol{k}_{\perp b})\, \Delta'_{NN}\hat\sigma(x_a, x_b; \boldsymbol{k}_{\perp b})\, \Delta_T D_{\Lambda/c}(z) \Big\}$$

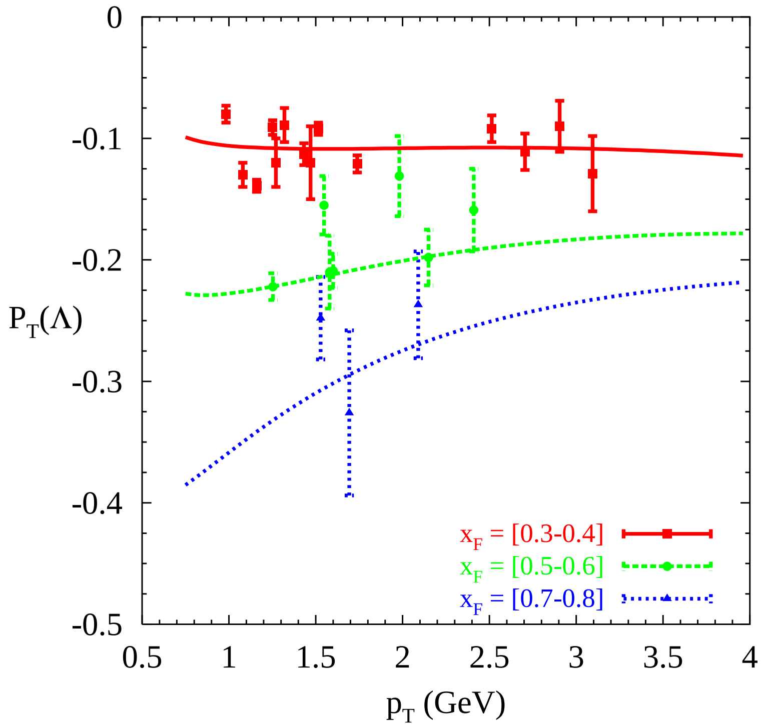
[current fragmentation region, large p_T]

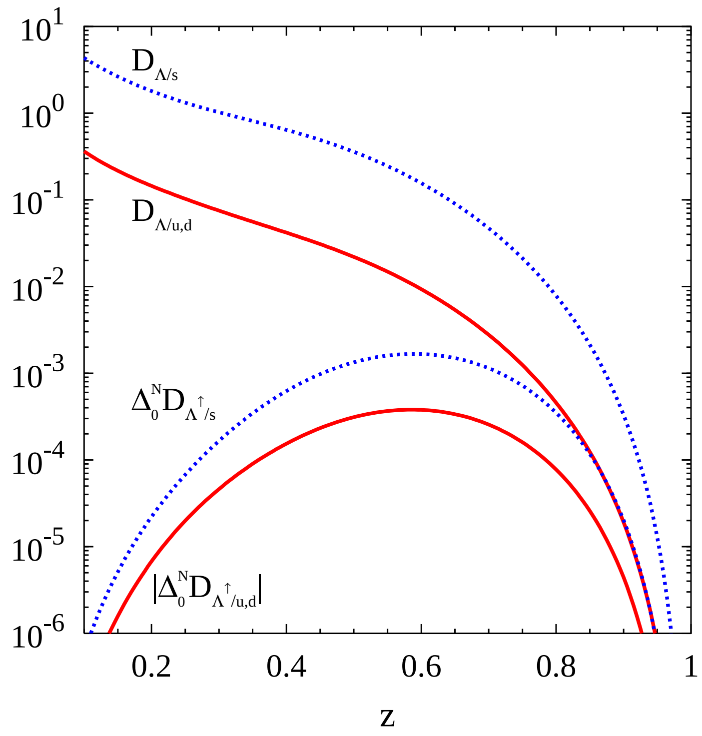
$$P_T^\Lambda(x_F, p_T) = \frac{d\sigma^{p\,p\to\Lambda^\uparrow X} - d\sigma^{p\,p\to\Lambda^\downarrow X}}{d\sigma^{p\,p\to\Lambda^\uparrow X} + d\sigma^{p\,p\to\Lambda^\downarrow X}}$$

$$= \frac{\sum \int dx_a\, dx_b \int d^2\boldsymbol{k}_{\perp c}\, f_{a/p}(x_a)\, f_{b/p}(x_b)\, d\hat\sigma(x_a, x_b; \boldsymbol{k}_{\perp c})\, \Delta^N D_{\Lambda^\uparrow/c}(z, \boldsymbol{k}_{\perp c})}{\sum \int dx_a\, dx_b \int d^2\boldsymbol{k}_{\perp c}\, f_{a/p}(x_a)\, f_{b/p}(x_b)\, d\hat\sigma(x_a, x_b; \boldsymbol{k}_{\perp c})\, D_{\Lambda/c}(z, \boldsymbol{k}_{\perp c})}$$

$$\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp) \equiv D_{\Lambda^\uparrow/q} - D_{\Lambda^\downarrow/q}\ \left[D_{1T}^\perp\right] = \Delta^N D_{\Lambda^\uparrow/q}(z, |\boldsymbol{k}_\perp|)\sin\phi$$

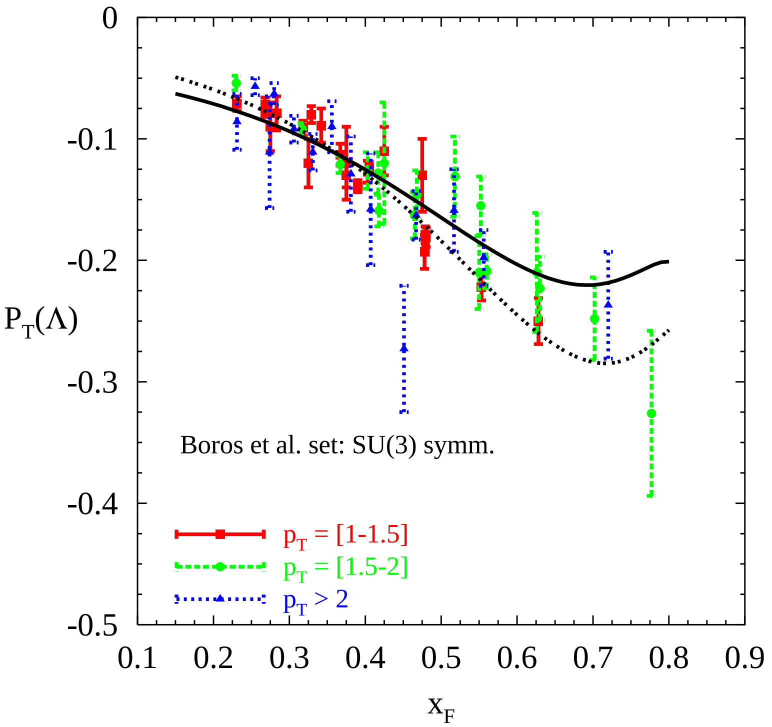
- Λ polarization entirely generated in the fragm. process, $q \to \Lambda^\uparrow + X$;
- Effective, inclusive Λ PFF (consistent with available sets of unpol. FF);
- $\int d^2\boldsymbol{k}_\perp F(\boldsymbol{k}_\perp) \Rightarrow F(k_\perp^0)$, where $k_\perp^0(z) \sim K z^a (1-z)^b$;
- Fit to exp. data $\Rightarrow$ parameterizations for $k_\perp^0(z)$ and $\Delta^N D_{\Lambda^\uparrow/q_v}(z, k_\perp^0)$;
  e.g. $k_\perp^0(z) = 0.66 z^{0.32}(1-z)^{0.5}$
- intrinsic $k_\perp$ in the initial state might give a proper spin-independent enhancing factor (10-100) to explain the large unpolarized cross-sections (as for γ and π)

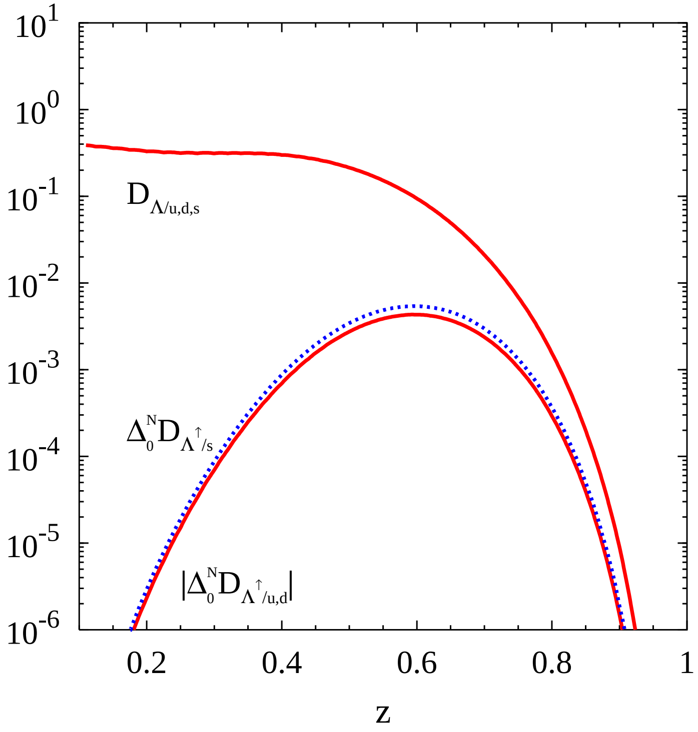




Best fit, obtained with a $SU(3)$ symmetry broken FF set (see plot on the right), to $P_T(\Lambda)$ data from $p-Be$ reactions, vs. p_T and for various x_F bins, at the NN c.m. energy $\sqrt{s} = 30$ GeV.

$|\Delta_0^N D_{\Lambda^\uparrow/u,d}|$ and $\Delta_0^N D_{\Lambda^\uparrow/s}$, as given by our best fit parameters, compared to the Indumathi *et al.* unpolarized FF, $D_{\Lambda/u,d}$ and $D_{\Lambda/s}$. Notice that $\Delta_0^N D_{\Lambda^\uparrow/u,d}$ is negative.





Best fit, obtained with a $SU(3)$ symmetric FF set (see plot on the right), to $P_T(\Lambda)$ data from $p-Be$ reactions, vs. x_F and for various p_T bins, at $\sqrt{s} = 30$ GeV. The two theoretical curves correspond to $p_T = 1.5$ GeV (dotted) and $p_T = 3$ GeV (solid).

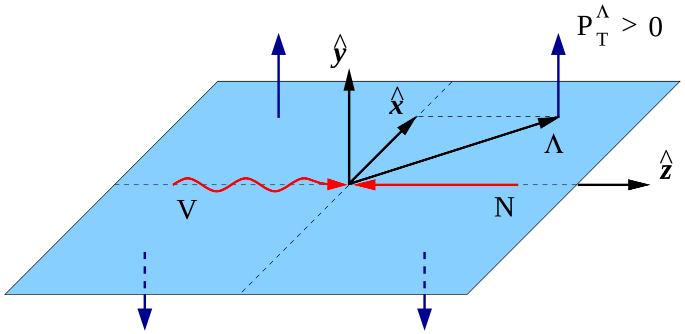
$|\Delta_0^N D_{\Lambda^\uparrow/u,d}|$ and $\Delta_0^N D_{\Lambda^\uparrow/s}$, as given by our best fit parameters, compared to the Boros *et al.* unpolarized FF, $D_{\Lambda/u,d} = D_{\Lambda/s}$. Notice that $\Delta_0^N D_{\Lambda^\uparrow/u,d}$ is negative.

$P_T^\Lambda(x, y, z_h, \boldsymbol{p}_T)$ in unpolarized semi-inclusive DIS $(x_F > 0)$

$$P_T = \frac{d\sigma^{\Lambda^\uparrow} - d\sigma^{\Lambda^\downarrow}}{d\sigma^{\Lambda^\uparrow} + d\sigma^{\Lambda^\downarrow}}\,, \qquad d\sigma^{\Lambda^{\uparrow(\downarrow)}} = \sum f_{q/p}(x)\,\frac{d\hat\sigma^{\ell q}}{dy} D_{\Lambda^{\uparrow(\downarrow)}/q}(z_h, \boldsymbol{p}_T)$$

$$z_h = p \cdot p_h / p \cdot q$$

$$D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp) = \frac{1}{2} D_{\Lambda/q}(z, k_\perp) + \frac{1}{2}\Delta^N D_{\Lambda^\uparrow/q}(z, k_\perp)\sin\phi$$



SIDIS kinematical representation in the virtual boson - proton c.m. reference frame: $\hat{z}$-axis along the virt. boson direction; $\hat{x}$-axis along the hadron $\boldsymbol{p}_T \equiv \boldsymbol{k}_\perp$; $\hat{y} = \hat{z} \times \hat{x}$ and $\phi = \pi/2$.

The arrows show positive P_T^Λ.

$D_{\Lambda/q}(z, k_\perp)$ and $\Delta^N D_{\Lambda^\uparrow/q}(z, k_\perp)$: gaussian parameterizations

- Define: $D_{\Lambda/q}(z, k_\perp) = \frac{d(z)}{M^2}\, \exp\left[-\frac{k_\perp^{\,2}}{M^2 f(z)}\right]$;

  $\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp) = \frac{\delta(z)}{M^2}\, \frac{k_\perp}{M}\, \exp\left[-\frac{k_\perp^{\,2}}{M^2 \varphi(z)}\right]\, \sin\phi;$

  where ϕ is the angle between the spin and $\boldsymbol{k}_\perp$ of Λ

- Require:

▶ $\int d^2k_\perp \left[k_\perp^{\,2}\right] D_{\Lambda/q}(z, k_\perp) = \left[\langle k_\perp^{\,2}(z)\rangle\right] D_{\Lambda/q}(z) \quad \Rightarrow \quad$ fix $d(z), f(z)$;

▶ $|\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp)| \,/\, D_{\Lambda/q}(z, k_\perp) \le 1, \;\forall\, z$ and $\boldsymbol{k}_\perp$; $\quad \varphi(z) = r\, f(z)$

$$\Rightarrow \quad r < 1 \qquad \frac{|\delta(z)|}{d(z)} \le \left[\frac{2e}{f(z)}\, \frac{1-r}{r}\right]^{1/2}$$

To obey the positivity constraint in a most natural and simple way:

$$\frac{\delta(z)}{M^3} = \left[N_q \, \frac{z^\alpha(1-z)^\beta}{\alpha^\alpha\beta^\beta/(\alpha+\beta)^{(\alpha+\beta)}}\right] \frac{D_{\Lambda/q}(z)}{\pi[\langle k_\perp^2(z)\rangle]^{3/2}} \, [2e(1-r)/r]^{1/2} \qquad (1)$$

with $\alpha, \beta > 0$, $|N_q| \leq 1$.

Qualitative analysis of pp data:

- $P^\Lambda < 0$ AND $P^{\bar\Lambda} \simeq 0$ $\Rightarrow$ $N_{u,d} < 0, \; N_s > 0$
- increasing of $|P^\Lambda|$ with x_F $\Rightarrow$ large $\alpha, \beta \simeq O(1)$
- large values of $|P^\Lambda|$ $\Rightarrow$ $r \simeq O(1)$ (similar Gaussian shapes)

$\alpha = 6, \;\beta = 1, \; r = 0.7, \; \sqrt{\langle k_\perp^2(z)\rangle} = 0.61 z^{0.27}(1-z)^{0.2}$ (from pions)

Scenarios:

1. $N_{u,d} = -0.8$, $N_s = 1$ (same weight for up and strange quarks)
2. $N_{u,d} = -0.3$, $N_s = 1$ (à la Burkardt and Jaffe)

Analytical results

- $\nu\, p \to \ell^-\, \Lambda^\uparrow\, X \quad P_T^\Lambda = \dfrac{(d+R\,s)\,\Delta^N D_{\Lambda^\uparrow/u} + \bar{u}\,(\Delta^N D_{\Lambda^\uparrow/\bar{d}} + R\,\Delta^N D_{\Lambda^\uparrow/\bar{s}})\,(1-y)^2}{(d+R\,s)\,D_{\Lambda/u} + \bar{u}\,(D_{\Lambda/\bar{d}} + R\,D_{\Lambda/\bar{s}})\,(1-y)^2}$

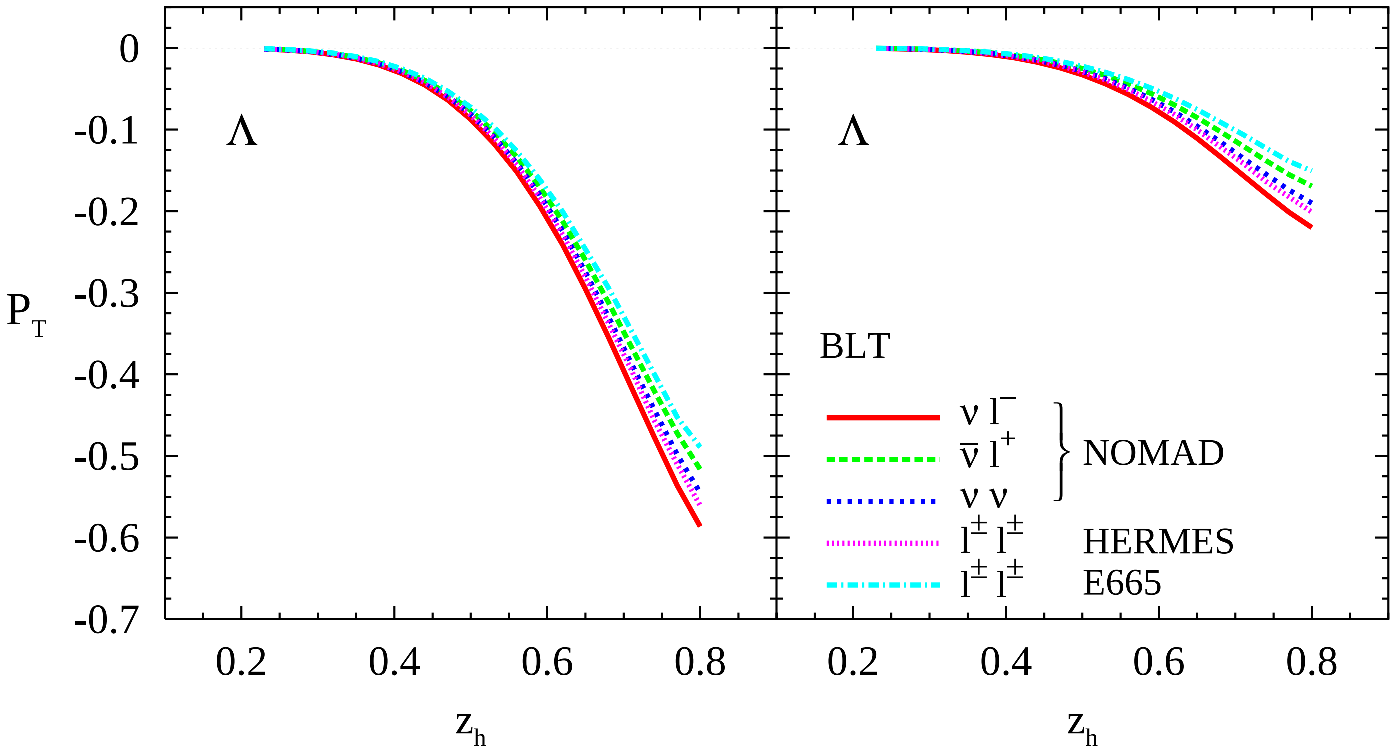
- $\bar{\nu}\, p \to \ell^+\, \Lambda^\uparrow\, X \quad P_T^\Lambda = \dfrac{(1-y)^2 u\,(\Delta^N D_{\Lambda^\uparrow/u} + R\,\Delta^N D_{\Lambda^\uparrow/s}) + (\bar{d}+R\,\bar{s})\,\Delta^N D_{\Lambda^\uparrow/\bar{u}}}{(1-y)^2 u\,(D_{\Lambda/u} + R\,D_{\Lambda/s}) + (\bar{d}+R\,\bar{s})\,D_{\Lambda/\bar{u}}}$

- $\nu\, p \to \nu\, \Lambda^\uparrow\, X \quad P_T^\Lambda \simeq \dfrac{(K u+d)\,\Delta^N D_{\Lambda^\uparrow/u} + s\,\Delta^N D_{\Lambda^\uparrow/s}}{(K u+d)\,D_{\Lambda/u} + s\,D_{\Lambda/s}}$

- $\ell\, p \to \ell'\, \Lambda^\uparrow\, X \quad P_T^\Lambda \simeq \dfrac{(4u+d)\,\Delta^N D_{\Lambda^\uparrow/u} + s\,\Delta^N D_{\Lambda^\uparrow/s}}{(4u+d)\,D_{\Lambda/u} + s\,D_{\Lambda/s}}$

where $R = \tan^2\theta_c \simeq 0.056$ and $K \simeq 0.555$.

For $z_h > 0.2$ we have $D_{\Lambda/\bar{q}} \ll D_{\Lambda/q}$ and $\Delta^N D_{\Lambda^\uparrow/\bar{q}} \simeq 0$ (= 0 in our model)

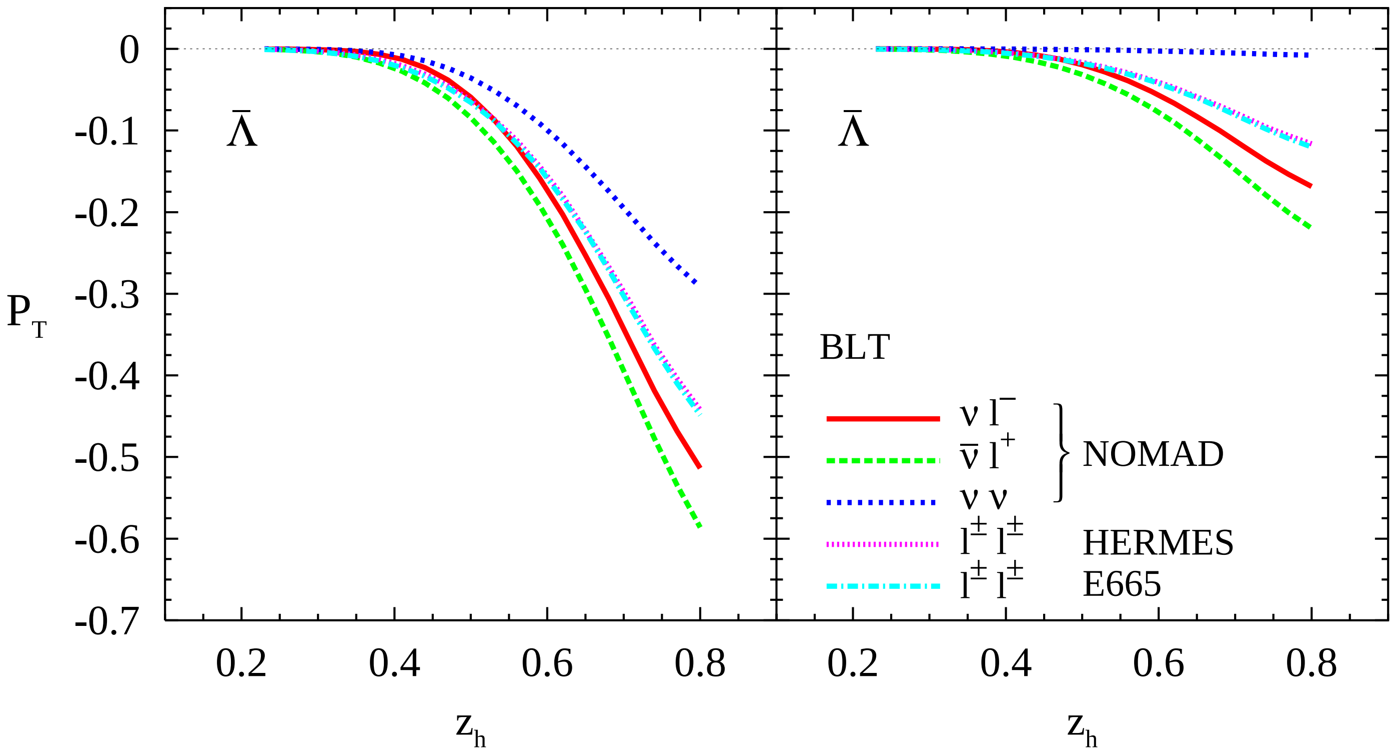


$P_T(\Lambda)$ vs. z_h, integrated over p_T, with a $SU(3)$ symmetric set for the unpolarized FF and with scenario 1 (on the left) and scenario 2 (on the right) for the polarizing FF, for different semi-inclusive DIS processes.

HERMES: $0.023 \leq x \leq 0.4$, $y \leq 0.85$, $1 \leq Q^2 \leq 10$ GeV^2, $E_\Lambda \geq 4.5$ GeV

NOMAD: $\langle x \rangle = 0.22$, $\langle y \rangle = 0.48$, $\langle Q^2 \rangle \simeq 9$ GeV^2

E665: $10^{-3} \leq x \leq 10^{-1}$, $0.1 \leq y \leq 0.8$, $1 \leq Q^2 \leq 2.5$ GeV^2



$P_T(\bar{\Lambda})$ vs. z_h, integrated over p_T, with a $SU(3)$ symmetric set for the unpolarized FF and with scenario 1 (on the left) and scenario 2 (on the right) for the polarizing FF, for different semi-inclusive DIS processes.

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Transversity: h_1 from $p^{\uparrow} p \to \Lambda^{\uparrow} X$

$$D_{NN} \equiv \frac{d\sigma^{p^{\uparrow} p \to \Lambda^{\uparrow} X} - d\sigma^{p^{\uparrow} p \to \Lambda^{\downarrow} X}}{d\sigma^{p^{\uparrow} p \to \Lambda^{\uparrow} X} + d\sigma^{p^{\uparrow} p \to \Lambda^{\downarrow} X}} = \frac{\Delta_{NN}\sigma}{2\sigma_{\rm unp}} \qquad (2)$$

In collinear partonic configuration, at LO

$$\Delta_{NN}\sigma \sim \sum_{abcd} \int dx_a dx_b\, h_{1a/p}(x_a)\, f_{b/p}(x_b)\, \Delta_{NN}\hat{\sigma}(x_a, x_b)\, \Delta_T D_{\Lambda/c}(z)$$

$$\Delta_{NN}\hat{\sigma} \equiv \frac{d\hat{\sigma}^{a^{\uparrow} b \to c^{\uparrow} d}}{d\hat{t}} - \frac{d\hat{\sigma}^{a^{\uparrow} b \to c^{\downarrow} d}}{d\hat{t}}$$

$$h_{1a/p} \equiv \Delta_T f_{a/p} \equiv f_{a^{\uparrow}/p^{\uparrow}} - f_{a^{\downarrow}/p^{\uparrow}} \qquad \Delta_T D_{\Lambda/c} \equiv D_{\Lambda^{\uparrow}/c^{\uparrow}} - D_{\Lambda^{\downarrow}/c^{\uparrow}}$$

[D. de Florian, J. Soffer, M. Stratmann, W. Vogelsang, PLB(1998)]

Transversity: h_1 from $\ell\, p^\uparrow \to \ell' \Lambda^\uparrow X \quad (x_F > 0)$

$$P_T = \frac{\sum_q e_q^2\, h_{1q/p}(x)\, \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 f_{q/p}(x) D_{\Lambda/q}(z)}\, \frac{2(1-y)}{1+(1-y)^2} \tag{3}$$

Factorization in variables (test)

$x = Q^2/2p\cdot q \quad y = p\cdot q/p\cdot \ell \quad z = p\cdot p_h/p\cdot q$

$h_{1q/p}$ QCD dynamics $\Delta_T D_{\Lambda/q}$

[M. Anselmino, M. Boglione, F. Murgia, PLB(2000)]

Conclusions and outlook

- $\Uparrow$ PFF $\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp)$ + $\boldsymbol{k}_\perp$- extended pQCD factorization scheme: good description of transverse Λ, $\bar{\Lambda}$ polarization in $p\,A \to \Lambda^\uparrow\,X$;
- $\Downarrow$ Unpolarized cross-sections underestimated (data sub-set): $\boldsymbol{k}_\perp$ in the pdf's may give the enhancing (10-100) spin-independent factor (γ, π)
- $\Uparrow$ Study of P_T^Λ in unpolarized semi-inclusive DIS ($x_F > 0$): importance of a comparison of different processes (CC vs. NC) to test $\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp)$;
- $\Uparrow$ More data from semi-inclusive DIS to test the z and $\boldsymbol{k}_\perp$ dependence of PFF and from pp reactions at large p_T (RICH);
- $\Uparrow$ Importance of $p^\uparrow p \to \Lambda^\uparrow X$ (and $\ell p^\uparrow \to \ell' \Lambda^\uparrow X$) to shed light on h_1.
- $\Uparrow$ Similar approach (spin- and $\boldsymbol{k}_\perp$- dependent functions) applied to other Transverse Single Spin Asymmetries: a whole new phenomenology.