Transverse Λ polarization at the LHC

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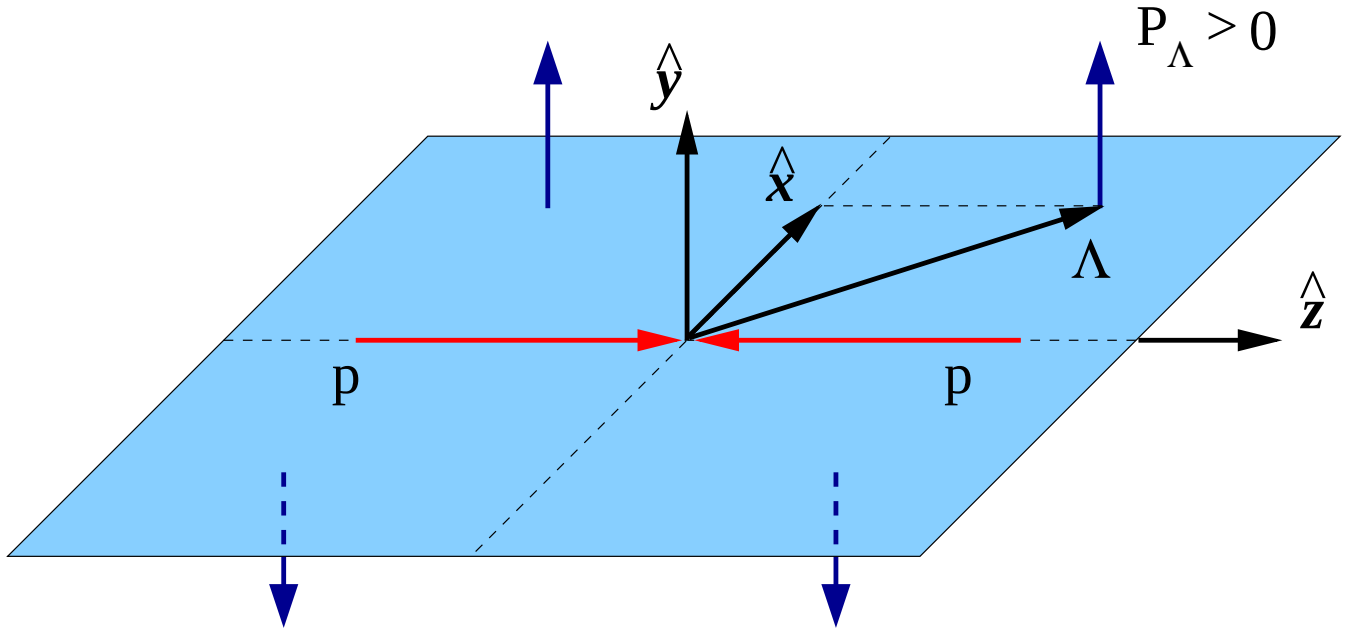
Outline

- Brief review of transverse Λ polarization in $p + p \to \Lambda + X$
- Possible underlying mechanism in the intermediate to high $\boldsymbol{p}_T$ region: transverse momentum and spin dependence in the fragmentation process
- Other consequences and suggestions for investigations at the LHC:
  - $p + p \to \Lambda^\uparrow + \text{jet} + X$ at midrapidity
  - $p + Pb \to \Lambda^\uparrow + X$ in the forward region

Transverse Λ polarization in unpolarized scattering

Large asymmetries have been observed in $p + p \to \Lambda^{\uparrow} + X$

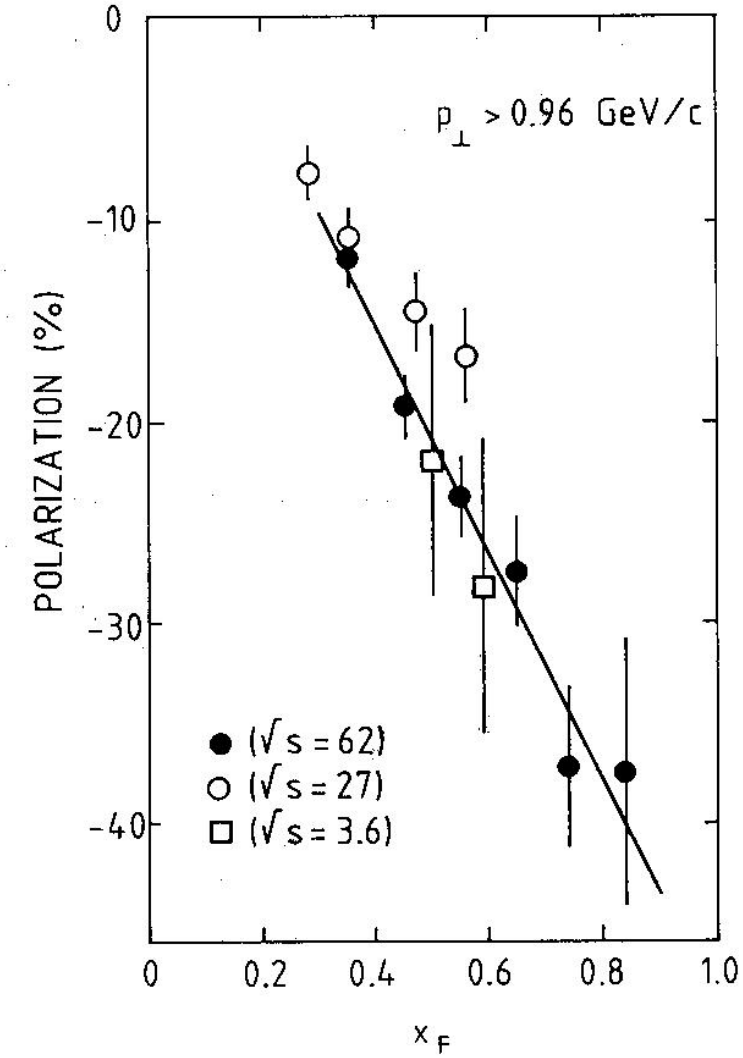
G. Bunce *et al.*, PRL 36 (1976) 1113



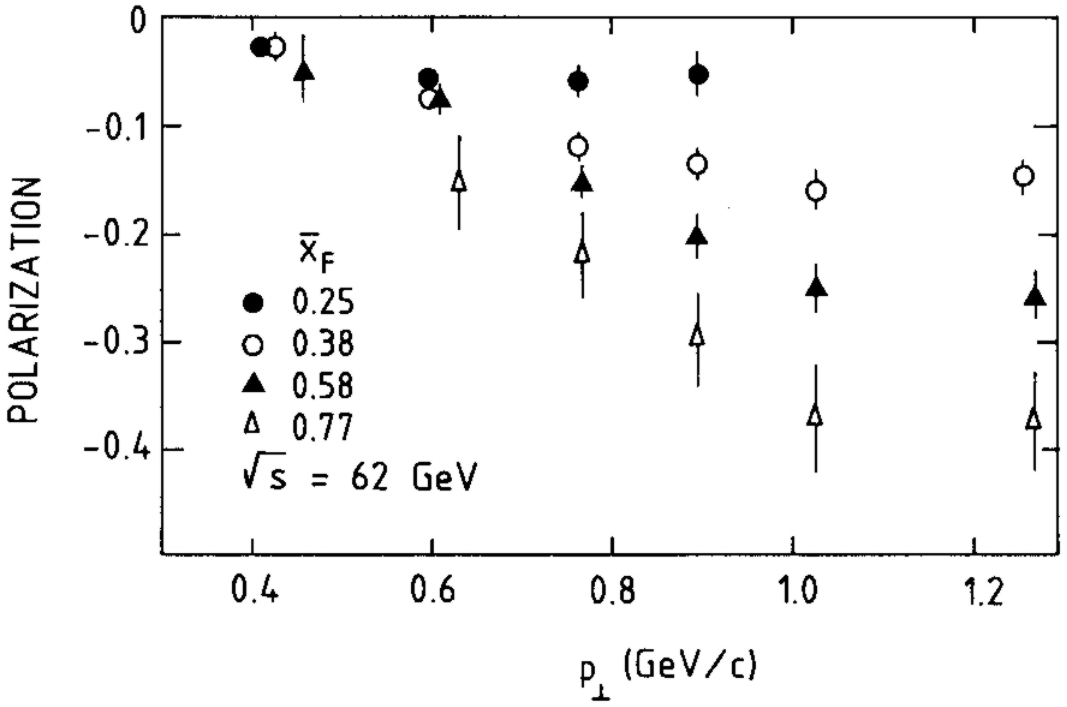
Blue arrows indicate the direction of positive transverse (w.r.t. production plane) polarization P_Λ, in the four quadrants

For symmetry reasons $P_\Lambda = 0$ at midrapidity

Generic $p\,p$ data - x_F and p_T dependence



P_Λ turns out to be negative



For p_T above 1 GeV/c P_Λ becomes flat

Theoretical considerations

Most models give qualitative descriptions of the data for $p_T \lesssim 1-2\,\mathrm{GeV}/c$

E.g. the DeGrand-Miettinen model

PRD 23 (1981) 1227 & 24 (1981) 2419

P_Λ stays large at least until the highest measured $p_T \sim 4$ GeV$/c$

For large p_T perturbative QCD and collinear factorization should apply

pQCD conserves helicity, which leads to $P_\Lambda \sim \alpha_s m_q/\sqrt{\hat{s}}$ (= small)

Kane, Pumplin & Repko, PRL 41 (1978) 1689

Collinear factorization

Consider for example the $qg \to qg$ subprocess

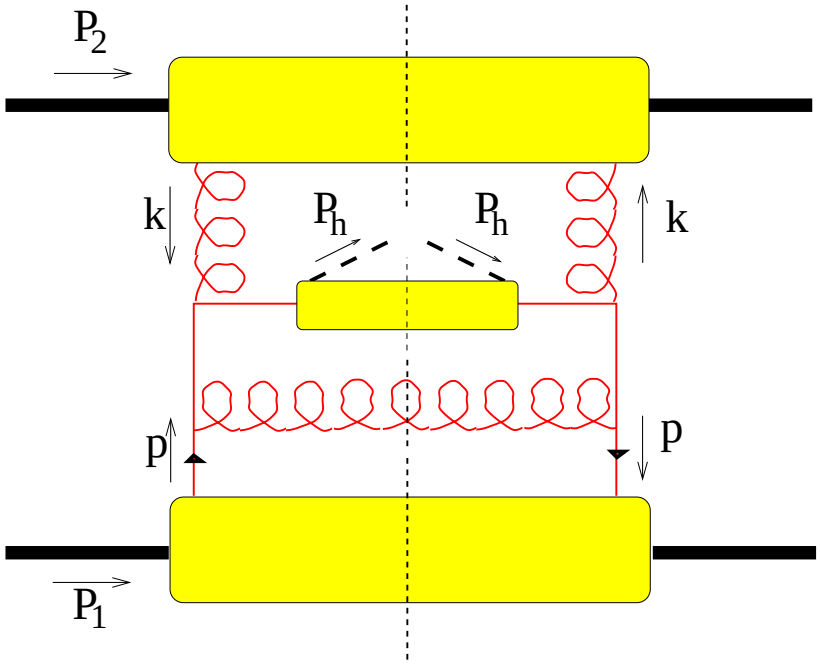
$$\sigma \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}_{qg \to qg} \otimes D_{\Lambda/q}(z)$$

$q(x_1) =$ quark density

$g(x_2) =$ gluon density

$D_{\Lambda/q}(z) = \Lambda$ fragmentation function

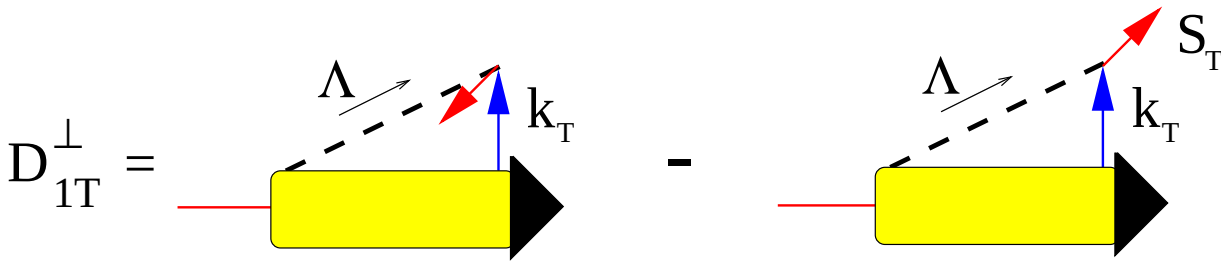
$$P_\Lambda \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}_{qg \to qg} \otimes \, ?$$



No leading twist collinear fragmentation function exists for $q \to \Lambda^\uparrow X$
(due to symmetry reasons)

Noncollinear factorization

Dropping the requirement of *collinear* factorization, does allow for a solution



Mulders & Tangerman, NPB 461 (1996) 197

- Transverse momentum dependent: $D_{1T}^{\perp}(z, \boldsymbol{k}_T)$
- A nonperturbative $\boldsymbol{k}_T \times \boldsymbol{S}_T$ dependence in the fragmentation process
- Allowed by the symmetries (parity and time reversal)

Λ polarization arises in the fragmentation of an *unpolarized* quark

Hence, the suggested name "polarizing fragmentation function"

Polarizing fragmentation functions

$D_{1T}^{\perp}$ is thought to be universal, despite its potential color flow dependence

Metz, PLB 549 (2002) 139; Gamberg, Mukherjee, Mulders, PRD 77 (2008) 114026

Meissner, Metz, 0812.3783/hep-ph; Yuan, Zhou, 0903.4680/hep-ph

$D_{1T}^{\perp}$ has been extracted from fixed target $p + p(Be) \to \Lambda^{\uparrow}(\bar{\Lambda}^{\uparrow}) + X$ data

Anselmino, D.B., D'Alesio & Murgia, PRD 63 (2001) 054029

Extraction done under the restriction of $p_T > 1$ GeV$/c$ to exclude the soft regime

Whether this is sufficient to ensure the validity of the description is a matter of concern

Nevertheless, reasonable functions are obtained

$D_{1T}^{\perp}$ has opposite signs for u, d versus s quarks; the latter is larger

This leads to cancellations in order that $P_{\bar{\Lambda}} \approx 0$

Collider data

All data is from fixed target experiments, with $\sqrt{s} \lesssim 60$ GeV, requiring large K factors

Why no data from high energy hadron colliders, such as RHIC or Tevatron?

Problem: capabilities to measure Λ polarization via $\Lambda \to p\,\pi^-$ are usually restricted to the midrapidity region, where the degree of transverse polarization is very small

$P_\Lambda = 0$ at $\eta = 0$ in $p\,p$ collisions in cms

If the origin of the transverse Λ polarization is indeed due to polarizing fragmentation, then another asymmetry could be observed that does not need to vanish at $\eta = 0$

D.B., Bomhof, Hwang, Mulders, PLB 659 (2008) 127

This is an asymmetry in the process $p\,p \to \left(\Lambda^\uparrow \text{jet}\right)\ \text{jet}\,X$

Jet-Λ production

Consider two jets, with momenta K_j and $K_{j'}$, such that $K_j \cdot K_{j'} = \mathcal{O}(\hat{s})$

The Λ is part of one of the two jets, and has momentum K_Λ and polarization S_Λ

An asymmetry can arise that is proportional to:

$$\epsilon_{\mu\nu\alpha\beta} K_j^\mu K_{j'}^\nu K_\Lambda^\alpha S_\Lambda^\beta$$

In principle, it is not power suppressed, nor needs to vanish at $\eta = 0$

In the center of mass frame of the two jets the asymmetry is of the form:

$$\text{SSA} = \frac{d\sigma(+\boldsymbol{S}_\Lambda) - d\sigma(-\boldsymbol{S}_\Lambda)}{d\sigma(+\boldsymbol{S}_\Lambda) + d\sigma(-\boldsymbol{S}_\Lambda)} = \frac{\hat{\boldsymbol{K}}_j \cdot (\boldsymbol{K}_\Lambda \times \boldsymbol{S}_\Lambda)}{z\, M_\Lambda} \frac{d\sigma_T}{d\sigma_U}$$

$d\sigma_T / d\sigma_U$ depends on $D_{1T}^\perp$

Jet-Λ production at the LHC

At LHC this process $p\,p \to \left(\Lambda^{\uparrow}\text{jet}\right)\,\text{jet}\,X$ can be studied

For instance, ALICE can measure Λ's over a wide p_T range,

in a typical yearly run at least up to 16 GeV/c

Rapidity coverage of ALICE: $-0.9 \leq \eta \leq +0.9$

If the jet rapidities ($\eta_{j,j'}$) are in this kinematic region, the cross section is dominated by gluon-gluon ($gg \to gg$) scattering

This leads to

$$\frac{d\sigma_T}{d\sigma_U} \approx \frac{D_{1T}^{\perp\, g}(z, K_{\Lambda\, T}^2)}{D_1^g(z, K_{\Lambda\, T}^2)}$$

No model or fit for $D_{1T}^{\perp\, g}$ is available yet, so no predictions can be made in this case

Jet-Λ production at the LHC

If it happens that $D_{1T}^{g\perp} \ll D_{1T}^{q\perp}$, then one finds for $\eta_{j'} \approx -\eta_j$ $(x_1 \approx x_2)$

$$\frac{d\sigma_T}{d\sigma_U} \approx [\, b(y)+b(1-y)\,] \frac{\sum_q f_1^q(x_1) D_{1T}^{\perp q}(z, K_{\Lambda T}^2)}{f_1^g(x_1) D_1^g(z, K_{\Lambda T}^2)}, \qquad y = (e^{2\eta_j}+1)^{-1}$$

$$b(y) = \frac{d\hat{\sigma}_{qg\to qg}}{d\hat{\sigma}_{gg\to gg}} = \frac{N^2-1}{2N^2} \frac{(1-y)(1+(1-y)^2)(\,1+(1-y)^2-\frac{1}{N^2}y^2\,)}{(1+y^4+(1-y)^4)(1+y^2+(1-y)^2)}$$

In the considered rapidity interval $b(y)+b(1-y) \approx 0.4$ (almost y independent)

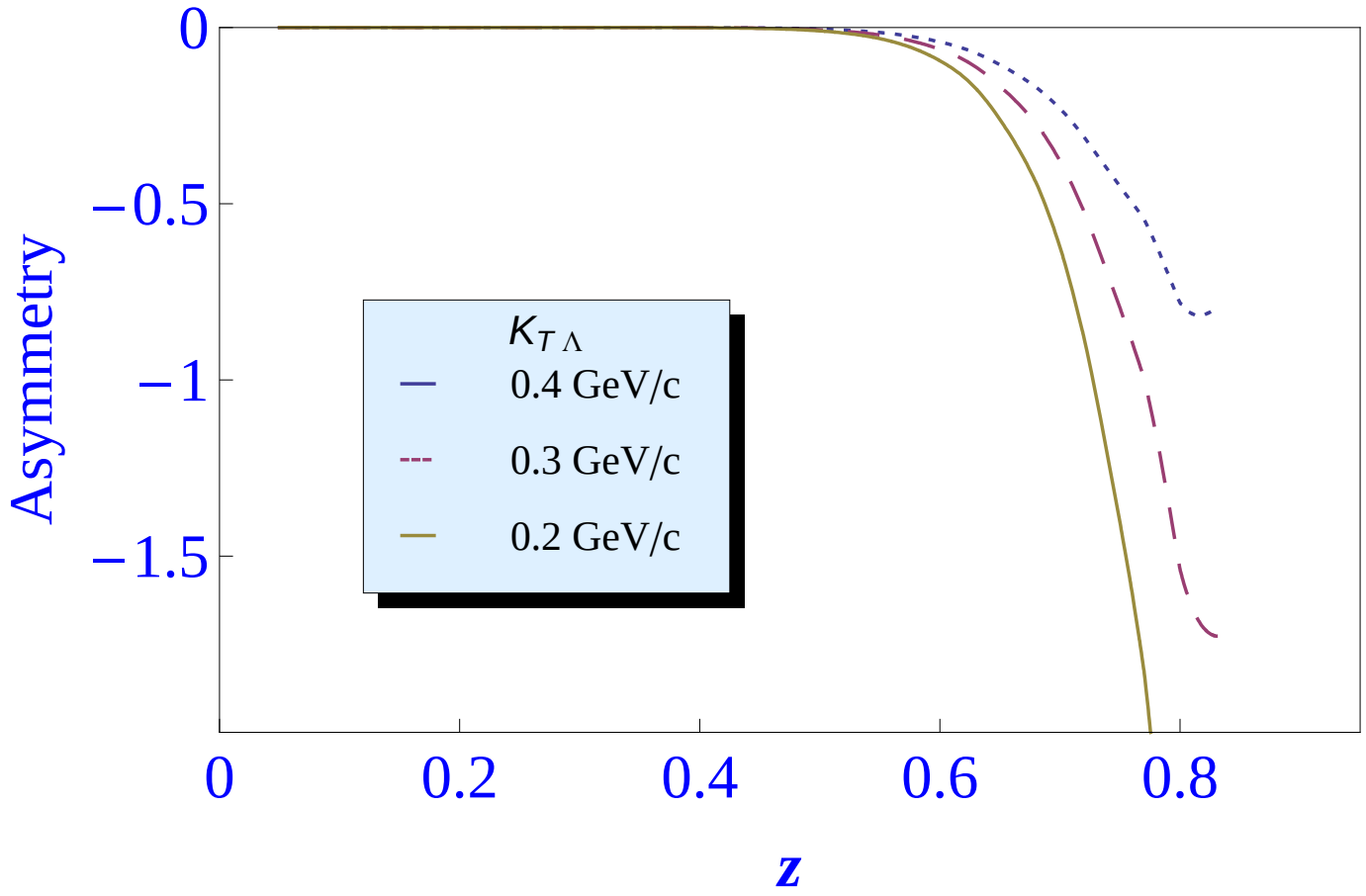
Using extracted ratios for $D_{1T}^{\perp q}/D_1^q$ and $D_1^q/D_1^g (\gg 1)$, yields a negative asymmetry

De Florian, Stratmann & Vogelsang, PRD 57 (1998) 5811

Anselmino, D.B., D'Alesio & Murgia, PRD 63 (2001) 054029

Expected to yield a qualitative estimate only

Jet-Λ production at the LHC



The asymmetry exceeds -1 for smaller $K_{T\Lambda}$ at large z, hence is overestimated

Asymmetry is quite sensitive to the cancellation between u, d and s contributions

Forward rapidity data

Λ polarization is especially interesting in $p\,A$ reactions at very high $\sqrt{s}$, large A and η

In this kinematic regime of small x, saturation of the gluon density is expected

However, in the forward direction often protons cannot be identified, which hampers the measurement of Λ polarization

None of the existing data is in the saturation regime

Suggestion: use neutral decays $\Lambda \to n\,\pi^0$ to measure Λ polarization at forward rapidities

Offers a direct probe of gluon saturation in both $p\,p$ and $p\,Pb$ collisions at the LHC

The saturation scale Q_s and even its evolution with x could be probed in this way

D.B. & Dumitru, PLB 556 (2003) 33; D.B., Utermann, Wessels, PLB 671 (2009) 91

Hadron production in the saturation regime

The cross section of forward hadron production in the (near-)saturation regime:

$$\text{pdf} \otimes \text{dipole cross section} \otimes \text{FF}$$

Dumitru, Jalilian-Marian, PRL 89 (2002) 022301

Since $D_{1T}^{\perp}$ is $\boldsymbol{k}_T$-odd, it essentially probes the derivative of the dipole cross section

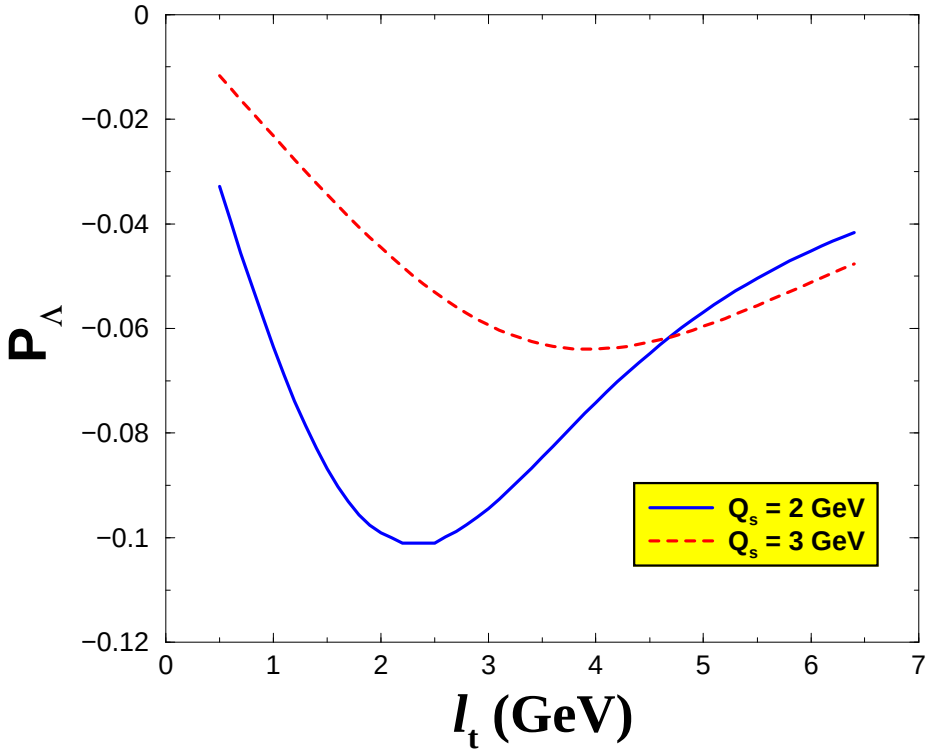
At transverse momenta of $\mathcal{O}(Q_s)$ the dipole cross section changes much

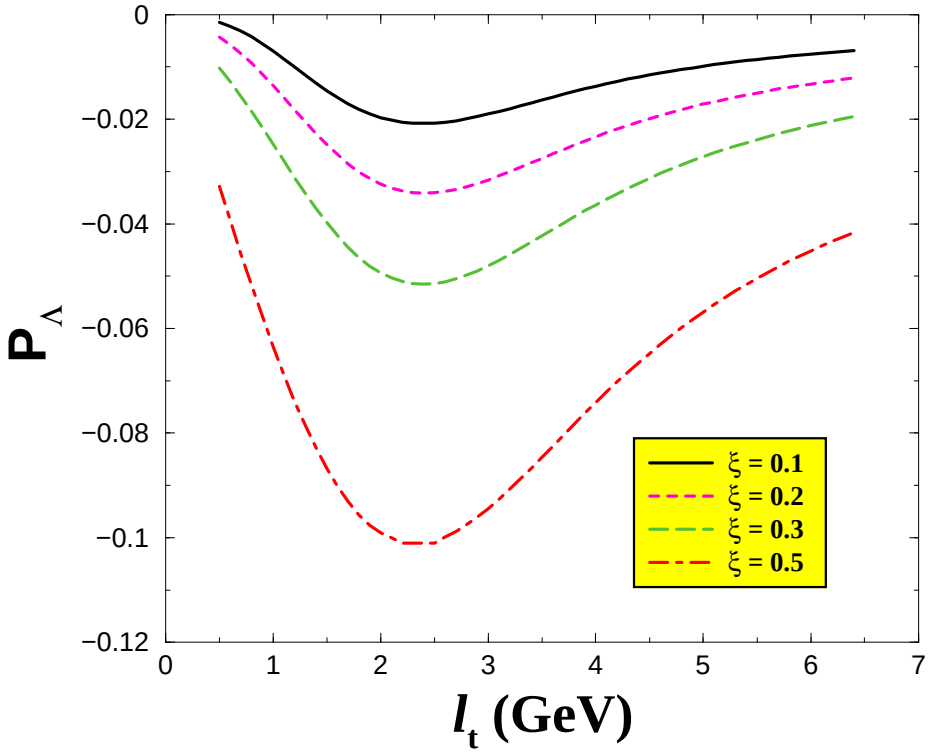
This leads to a Q_s-dependent peak in the Λ polarization

First demonstrated for the McLerran-Venugopalan model, which has constant Q_s

McLerran, Venugopalan, PRD 49 (1994) 2233 & 3352

Λ polarization in $p + A \to \Lambda^{\uparrow} + X$





D.B. & Dumitru, PLB 556 (2003) 33

In the MV model, where Q_s is a constant, the peak is $x_F(=\xi)$ independent

Λ polarization in the saturation regime

The saturation scale actually changes with the small-x values probed:

$$Q_s^2(x) \propto \left(\frac{1}{x}\right)^{\lambda}$$

Models that incorporate this are for instance:

- GBW model, describes well small-x DIS data

  Golec-Biernat, Wüsthoff, PRD 59 (1999) 014017

- DHJ model, describes well forward $d\,Au \to \pi X$ RHIC data

  Dumitru, Hayashigaki, Jalilian-Marian, NPA 765 (2006) 464

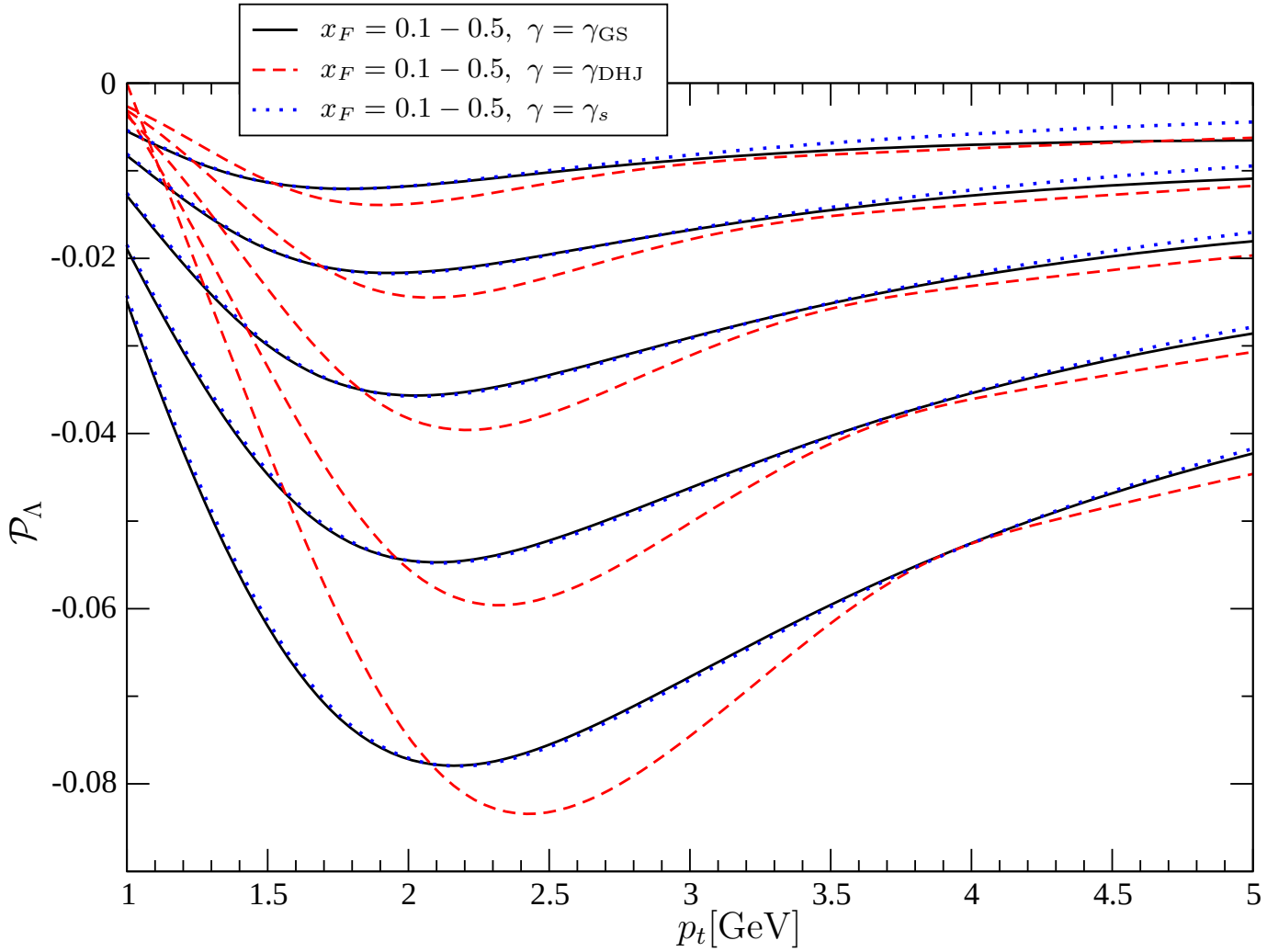
- GS model, describes well $d\,Au \to \pi X$ and DIS small-x data

  D.B., Utermann, Wessels, PRD 77 (2008) 054014

DHJ and GS models lead to same conclusion about peak of Λ polarization:

Its x_F dependence is to very good approximation the x dependence of Q_s!

Λ polarization in $p + Pb \to \Lambda^{\uparrow} + X$ at $\sqrt{s} = 8.8$ TeV



D.B., Utermann, Wessels, PLB 671 (2009) 91

Conclusions

If indeed Λ polarization in $p + p(Be) \to \Lambda^{\uparrow} + X$ at intermediate p_T arises in the fragmentation of unpolarized quarks, at LHC other consequences could be observable:

- An unsuppressed $\boldsymbol{K}_j \cdot (\boldsymbol{K}_\Lambda \times \boldsymbol{S}_\Lambda)$ asymmetry in $p\,p \to \left(\Lambda^{\uparrow}\text{jet}\right)\,\text{jet}\,X$ at midrapidity

- The x dependence of Q_s via the x_F dependence of the peak of the Λ polarization in forward $p + Pb \to \Lambda^{\uparrow} + X$

Λ polarization studies at colliders could prove very interesting!