Hyperon Polarization from Unpolarized pp and ep collisions

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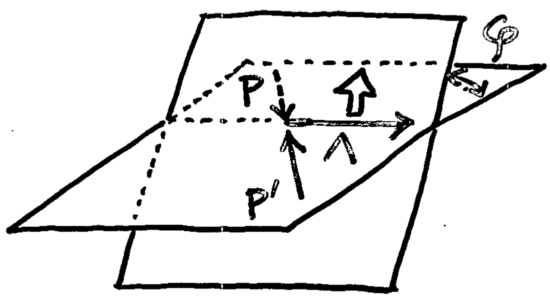
@ SPIN 2002, BNL

Λ production with large transverse momentum in

$$P(p) + \left\{ \begin{matrix} p \\ e \end{matrix} \right\}(p') \to \Lambda^{\uparrow}(\ell, S_\perp) + X$$



$$P_\Lambda \sim \epsilon_{\mu\nu\lambda\sigma} p^\mu p'^\nu \ell^\lambda S_\perp^\sigma \sim \sin\varphi$$

- Study P_Λ in the framework of Collinear factorization
- P_Λ is twist-3 observable
  = Probe of quark-gluon correlation

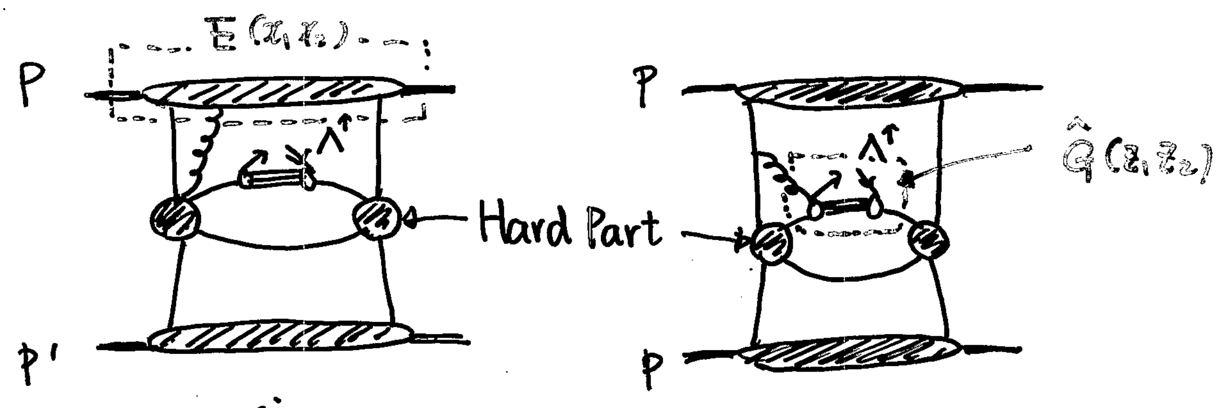
QCD factorization for Twist-3

$P + P \to \Lambda^{\uparrow} + X$

chiral-odd

$$\begin{array}{cccccccc} & P & & P' & & \Lambda^{\uparrow} & & \\ \Delta\sigma \sim & E(x_1\, x_2) & \otimes & \left\{ \begin{array}{c} f_1(x') \\ G(x') \end{array} \right\} & \otimes & \hat{h}_1(z) & \otimes & \hat{\sigma}_1 \quad (i) \\ + & \left\{ \begin{array}{c} f_1(x) \\ G(x) \end{array} \right\} & \otimes & \left\{ \begin{array}{c} f_1(x') \\ G(x') \end{array} \right\} & \otimes & \hat{G}(z_1 z_2) & \otimes & \hat{\sigma}_2 \quad (ii) \end{array}$$

transversity frag. func.



(i) (ii)

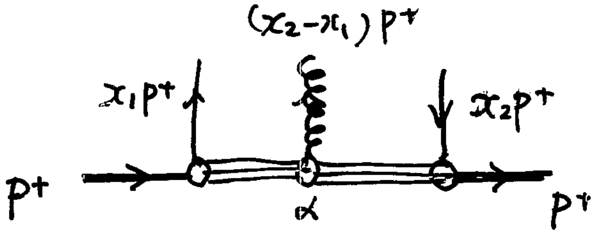
$e + p \to \Lambda^{\uparrow} + X$

$$\begin{array}{cccccc} & P & & \Lambda^{\uparrow} & & \\ \Delta\sigma \sim & E(x_1 x_2) & \otimes & \hat{h}_1(z) & \otimes & \hat{\sigma}_1' \\ + & f_1(x) & \otimes & \hat{G}(z_1, z_2) & \otimes & \hat{\sigma}_2' \end{array}$$

Unpolarized Twist-3 Distribution : $E_F(x_1 x_2)$, $E_D(x_1 x_2)$

$$\int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi}\, e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle p|\, \psi(0)\, g F^{\alpha\beta}(\mu n) n_\beta\, \bar{\psi}(\lambda n)\, |p\rangle$$

$\uparrow [0\ \mu n]$ $\uparrow [\mu n\ \lambda n]$ gauge link



$P^+ = p^+$

$(\ p^2 = n^2 = 0,\ p\cdot n = 1\ )$

$$= \frac{M_N}{4} \gamma_5 \not{p}\, \gamma_\nu\, \epsilon^{\nu\alpha\sigma\tau} n_\sigma P_\tau\, \underline{E_F(x_1 x_2)} + (\text{others})$$

- $F^{\alpha\beta} n_\beta \rightarrow D^\alpha = \partial^\alpha - igA^\alpha$ defines $\underline{E_D(x_1 x_2)}$.

* Hermiticity & T-inv. gives

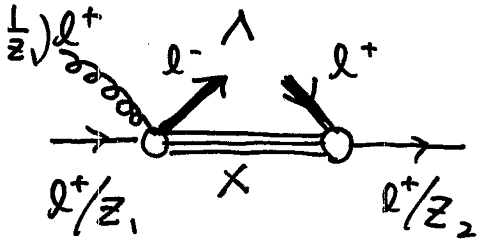
$$\begin{cases} \underline{E_F(x_1\, x_2) = E_F(x_2 x_1)} \\ \underline{E_D(x_1\, x_2) = -E_D(x_2 x_1)} \end{cases}$$

real functions
chiral-odd.

N.B. E_F and E_D are not independent.

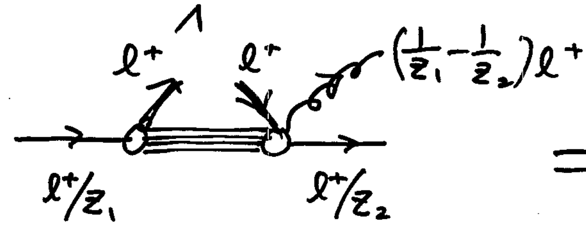
·3 fragmentation function for Λ

$$e^{-i\mu(\frac{1}{z_2}-\frac{1}{z_1})}\langle 0|\psi(0)|\Lambda(\ell)X\rangle\langle\Lambda(\ell)X|\,gF^{\alpha\beta}(\mu w)w_\beta\bar{\psi}(\lambda n)|0\rangle$$



$$\left(\begin{array}{c}\ell^2 = w^2 = 0\\ \ell\cdot w = 1\end{array}\right)$$

$$w S_\perp \underline{\hat{G}_F(z_1 z_2)}/z_2 + i\frac{M}{2}\gamma_5 \not{\ell}\, S_\perp^\alpha \underline{\hat{G}_F^5(z_1 z_2)}/z_2 + \cdots$$

$\sum_X$ 

$$\Rightarrow \left\{\begin{array}{l}\underline{\hat{G}_{FR}(z_1, z_2)}\\ \underline{\hat{G}_{FR}^5(z_1, z_2)}\end{array}\right.$$

& (naive) T-inv. gives

$$\underline{(z_1 z_2) = \hat{G}_{FR}(z_2 z_1)}$$

$$\underline{(z_1 z_2) = -\hat{G}_{FR}^5(z_2 z_1)}$$

$D^\alpha = \partial^\alpha - igA^\alpha$ defines $\hat{G}_F(z_1 z_2)$ $\hat{G}_F^5(z\ z)$

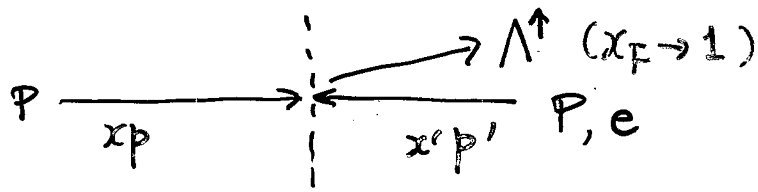
Analysis of twist-3 cross section (c.f. Qiu & Sterman '99 for $p^\uparrow p \to \pi X$)

- $E_F(x,x)$ and $\hat{G}_F(z,z)$ appear as soft-gluon-pole (i.e. $x_1 = x_2$, $z_1 = z_2$), and their derivatives $\frac{d}{dx}E_F(x,x)$ and $\frac{d}{dz}\hat{G}_F(z,z)$ also appear.

- $E_D(x_1 x_2)$ and $\hat{G}_D(z_1 z_2)$ appear as soft-fermion-pole (i.e. $x_i = 0$ or $z_i = 0$), which is physically expected to be suppressed. $\longrightarrow$ Omit it!

- Focuss on soft-gluon-pole :

At $x_F \to 1$, main contribution is from $x \to 1$, $x' \sim 0$, $z \to 1$



Here $\left|\frac{d}{dx}E_F(x\,x)\right| \gg |E_F(x\,x)|$ $\because$ $E_F(x\,x) \sim (1-x)^\beta$ $(\beta > 0$

$\left|\frac{d}{dz}\hat{G}_F(z\,z)\right| \gg |G_F(z\,z)|$ $\because$ $\hat{G}_F(z,z) \sim (1-z)^{\beta'}$ $(\beta' > 0$

☆ In $pp \to \Lambda^\uparrow X$, keep only $\frac{d}{dx}E_F(x\,x)$ and $\frac{d}{dz}\hat{G}_F(z\,z)$ for valence component (valence-quark soft-gluon approximation.)

☆ In $ep \to \Lambda^\uparrow X$, include all soft-gluon-poles.

$pp \to \Lambda^{\uparrow}(\ell)X$: large x_F

(i) $\displaystyle \frac{d}{dx}E_F(x,x) \otimes \begin{Bmatrix} f_1(x') \\ G(x') \end{Bmatrix} \otimes \hat{h}_1(z) \otimes \hat{\sigma}_1$ (chiral-odd) (Kanazawa & Koike P.R.D64 (2001))

- $\hat{h}_1(z) = \hat{g}_1(z)$: de Florian et al ('98) $(\Lambda+\bar{\Lambda})$

  transversity fragmentation function

- $E_F^a(x,x) \equiv K_a h_1^a(x)$

  same Dirac structure

  $K_u = -K_d = 0.07$ $h_1^a(x) \equiv g_1^a(x)$: GRSV

  (cf. $G_F^a(x,x) \equiv K_a f_1^a(x)$ with $K_u = -K_d = 0.07$ to reproduce A_N (E704) by Qiu & Sterman)

(ii) $\displaystyle f_1(x) \otimes \begin{Bmatrix} f_1(x') \\ G(x') \end{Bmatrix} \otimes \frac{d}{dz}\hat{G}_F(z,z) \otimes \hat{\sigma}_2$ (chiral-even)

- $\hat{G}_F^a(z,z) \equiv \hat{K}_a \hat{f}_1^a(z)$

  Same Dirac structure

  $\hat{K}_u = -\hat{K}_d = 0.07$

  $\hat{f}_1^a$: de Florian et al. ('98) for $\Lambda+\bar{\Lambda}$.

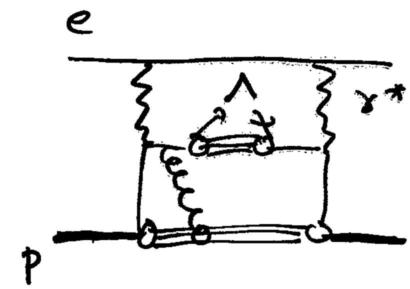
  But for large z, it can be regarded as for Λ.

- N.B. In general $\hat{G}_F(z_1,z_2) \neq \hat{G}_F(z_2,z_1)$.

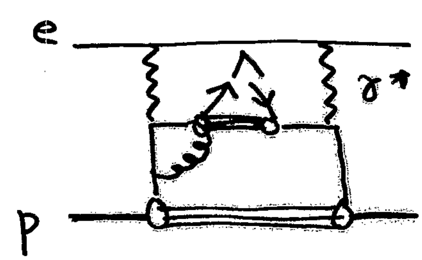
  But assume $\displaystyle \left.\frac{\partial}{\partial z_1}\hat{G}_F(z_1,z)\right|_{z_1=z} = \left.\frac{\partial}{\partial z_2}\hat{G}_F(z,z_2)\right|_{z_2=z}$

$$ep \to \Lambda^{\uparrow}(\ell)X$$

$$\text{(i)} \left\{ \begin{matrix} E_F(x\,x) \\ \frac{d}{dx}E_F(x\,x) \end{matrix} \right\} \otimes \hat{h}_1(x) \otimes \hat{\sigma}_1' \longleftarrow$$



$$\text{(ii)} \quad f_1(x) \otimes \left\{ \begin{matrix} \hat{G}_F(z\,z) \\ \frac{d}{dz}\hat{G}_F(z\,z) \end{matrix} \right\} \otimes \hat{\sigma}_2' \longleftarrow$$

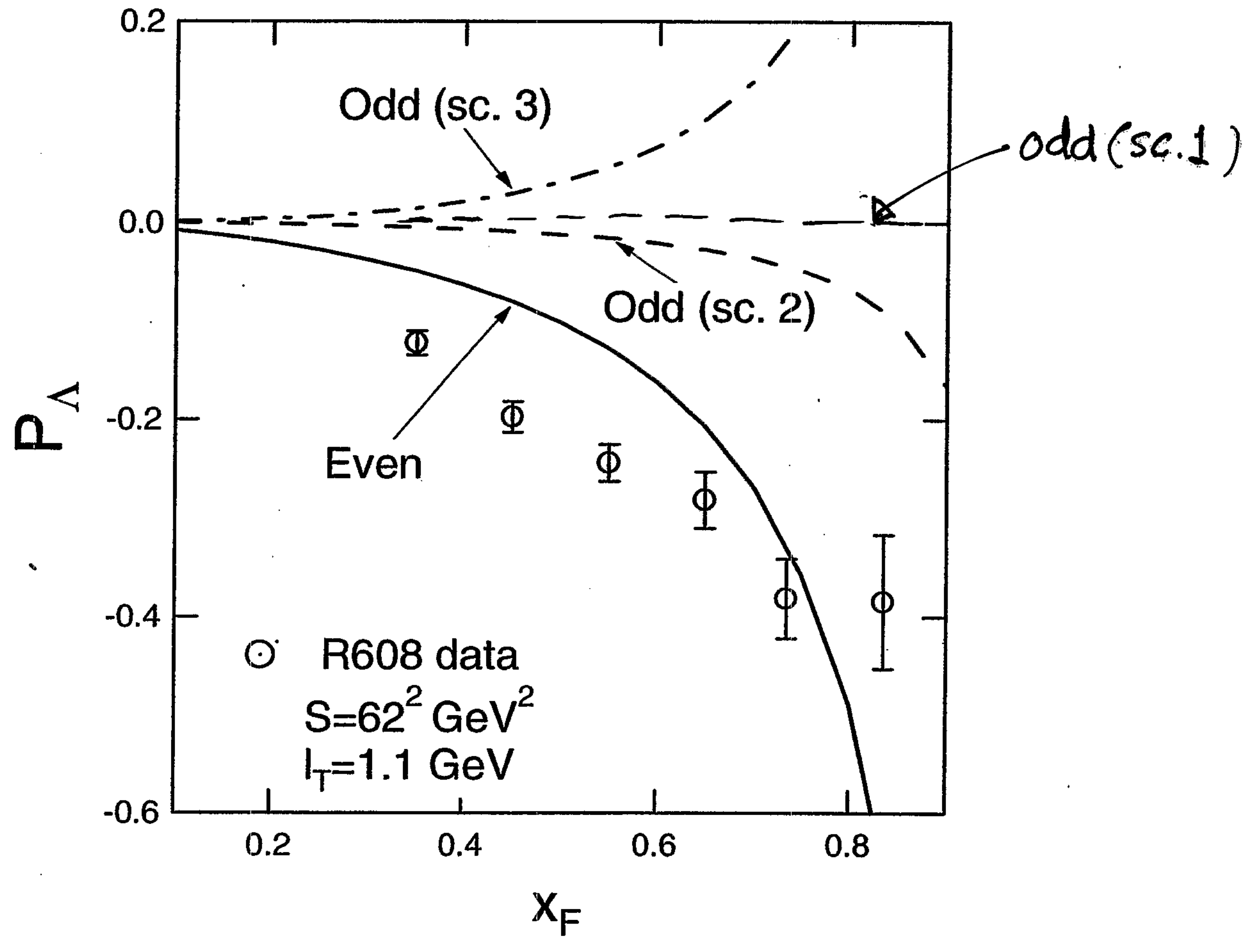


large x_F

$$\sim \quad \frac{K\pi M_N \ell_T}{(-T)} \frac{1}{1-x_F} \sin\varphi \sim \frac{K\pi M_N}{\ell_T} \frac{1}{1-x_F} \sin\varphi$$

Chiral-odd : $\frac{d}{dx} E_F(x,x) \otimes \begin{Bmatrix} f_1(x') \\ G(x') \end{Bmatrix} \otimes \hat{h}_1(z) \otimes \hat{\sigma}$

Chiral-even : $f_1(x) \otimes \begin{Bmatrix} f_1(x') \\ G(x') \end{Bmatrix} \otimes \frac{d}{dz} \hat{G}_F(z,z) \otimes \hat{\sigma}'$



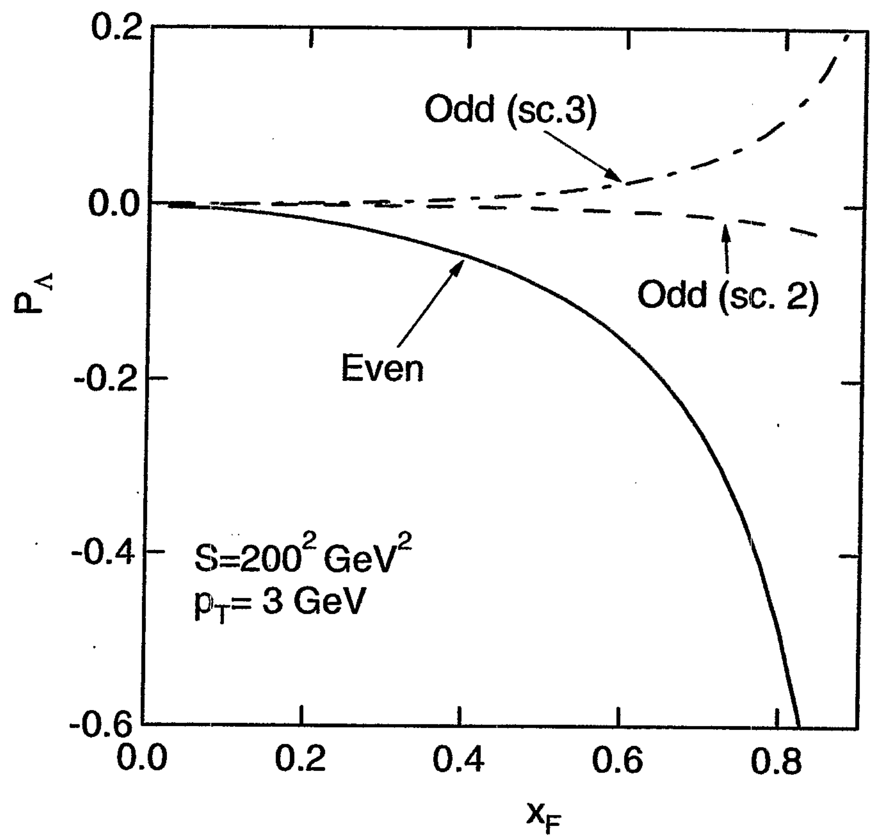
For chiral-odd contribution, $\hat{h}_1(z) = \hat{g}_1(z)$.

from e^+e^- data
de Florian et.al. ('98)

sc.1 : Non rela. quark model.

sc.2 : Burkardt-Jaffe ($\hat{h}_1^u = \hat{h}_1^d = -0.2\,\hat{h}_1^s$)

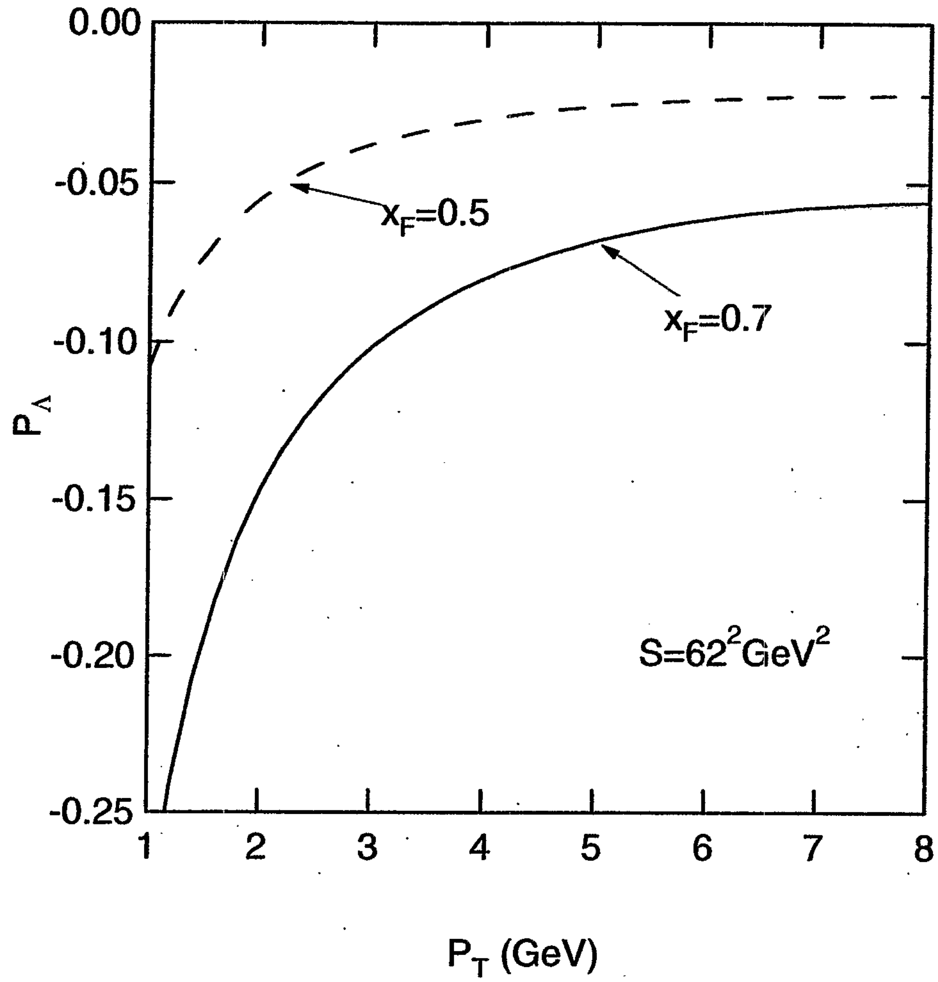
sc.3 : $\hat{h}_1^u = \hat{h}_1^d = \hat{h}_1^s$

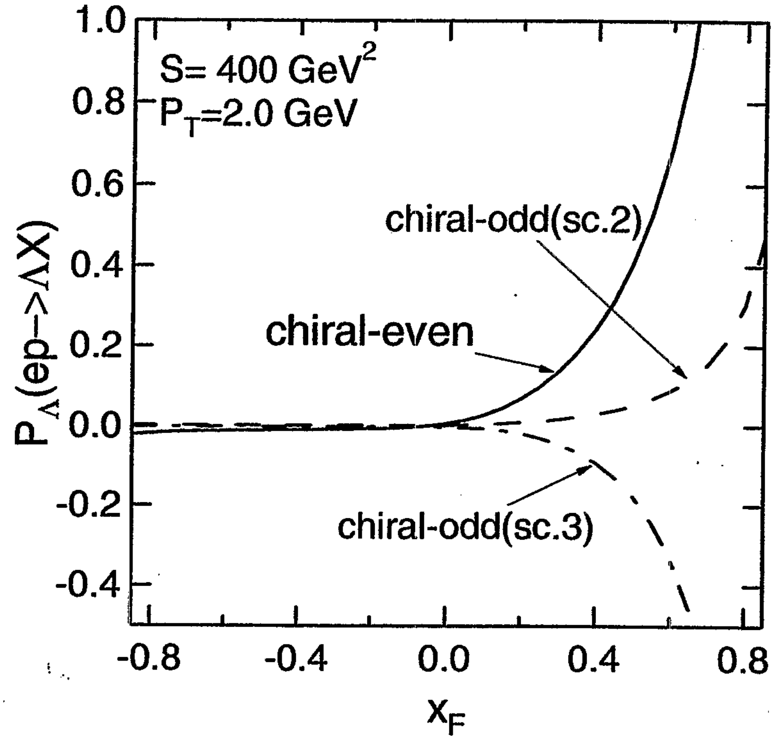


0.2
0.0
-0.2
-0.4
-0.6
0.0
0.2
0.4
0.6
0.8
P_Λ
x_F
Odd (sc.3)
Odd (sc. 2)
Even
$S=200^2$ GeV^2
p_T= 3 GeV

Strong P_T dependence at $1 \leq P_T \lesssim 3$ GeV

$\Longleftrightarrow$ DATA





S= 400 GeV^2
P_T=2.0 GeV
chiral-odd(sc.2)
chiral-even
chiral-odd(sc.3)
P_Λ(ep->ΛX)
x_F
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.8
-0.4
0.0
0.4
0.8

Comparison between PP and eP collisions

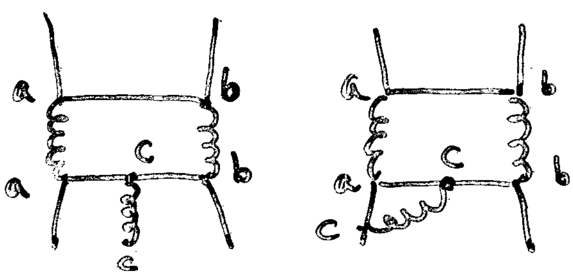
★ Signs of P_Λ^{ep} are opposite to P_Λ^{pp}.

At large x_F, $|P_\Lambda^{ep}| \gg |P_\Lambda^{pp}|$.

This is due to the color factor in <u>polarized</u> cross sections.

Main diagrams at large x_F:

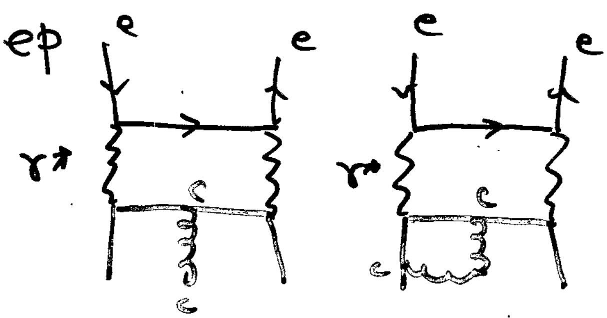
PP



$$\mathrm{Tr}[t^b t^c t^a t^c] = \underline{\frac{-1}{2N_c}}\,\mathrm{Tr}[t^b t^a]$$

Suppression & Sign change!

ep



no difference from unpol. case.

★ If we determine $E_F(x\,x)$ and $\hat{G}_F(z\,z)$ to reproduce R608 (pp) data by brute force, it gives $|P_\Lambda^{ep}| > 1$.

⇒ ① Applied kinematic region is not good. (ℓ_T too small)

② Our model for the twist-3 functions is not good.

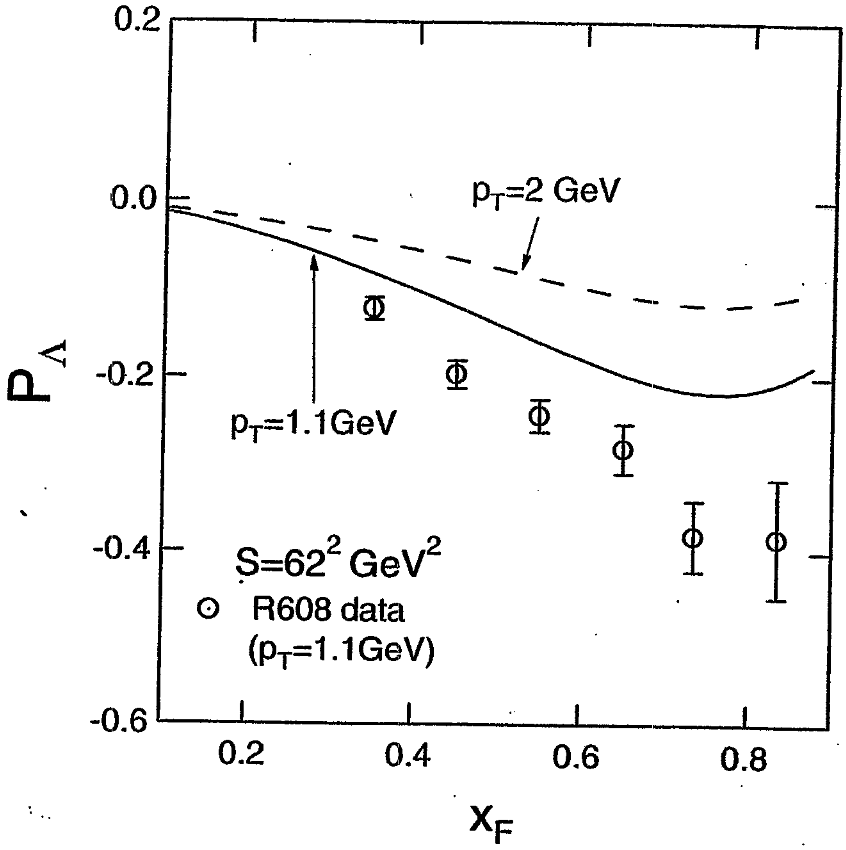
In particular, $\frac{1}{1-x_F}$ ($x_F \to 1$) behavior has to be fixed.

Ex. We have $\hat{G}_F(z\,z) \underset{z\to 1}{\sim} (1-z)^\beta$ ($\beta = 1.83$)

Tentatively $\beta \to \beta(z) = \beta + z^8$

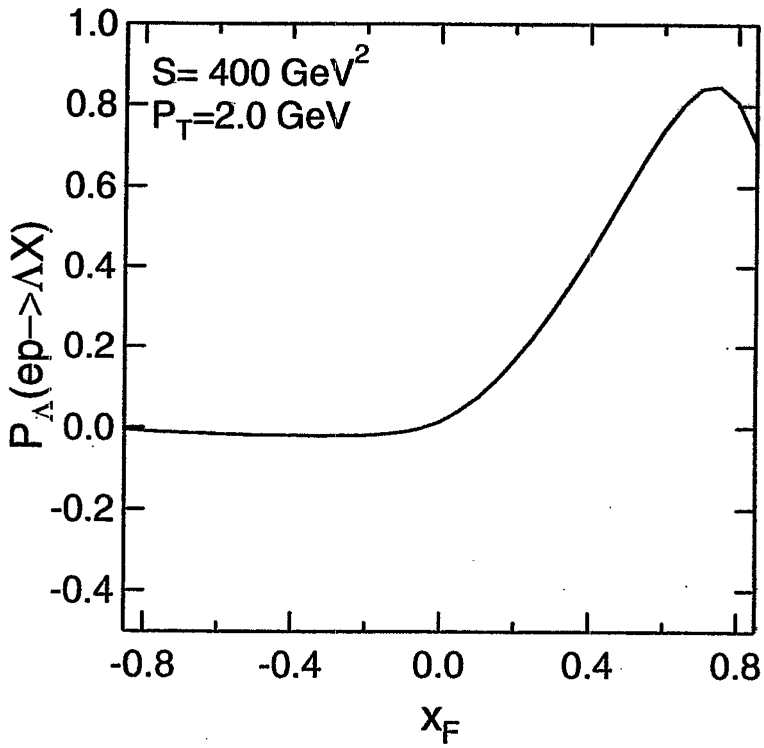
$pp \to \Lambda^{\uparrow} X$

(chiral-even)



$ep \to \Lambda^{\uparrow} X$

(chiral-even)



Summary

(1) Λ polarization P_Λ in $pp \to \Lambda^\uparrow X$ and $ep \to \Lambda^\uparrow X$ is studied within QCD factorization theorem. All twist-3 contributions are identified and formula given.

(2) $pp \to \Lambda^\uparrow X$: Valence-quark soft-gluon approximation keeping only derivatives of the twist-3 functions is adopted. A model

$$E_F(x\,x) \sim h_1(x)\,,\quad \hat{\hat{G}}_F(z\,z) \sim \hat{\hat{f}}_1(z)$$ is used to see qualitative behavior of P_Λ.

→ Growth of P_Λ at large x_F.

(3) $ep \to \Lambda^\uparrow X$: The formula include all the soft-gluon poles. A model determined by $pp \to \Lambda^\uparrow X$ is tested.

→ Signs of P_Λ^{ep} is opposite to P_Λ^{pp}, and $|P_\Lambda^{ep}| \gg |P_\Lambda^{pp}|$ at large x_F.

→ $|P_\Lambda^{ep}| > 1$ at large x_F

→ Applied kinematic region and the model should be reconsidered.

- Global analysis of pp and ep data (large l_T) and nonperturbative calculation of $\hat{G}_F$, E_F etc