

# Schema

- riassunto precedente lezione
- situazione sperimentale delle SSA per rivelare l'effetto Collins; polarizzazione trasversa efficace del bersaglio e contaminazione con contributi al subleading twist; analisi dati con bersagli polarizzati puramente trasversi e` attualmente in corso
- difficoltà` teoriche dell'effetto Collins; la rottura della fattorizzazione collineare; l'invarianza di gauge del correlatore quark-quark e l'operatore di "gauge link" → strutture time-reversal-odd anche per le PDF
- nuovi contributi possibili alle SSA: l'effetto Sivers e la funzione di Boer; parallelo con il Drell-Yan (non) polarizzato
- le **I**nterference **F**ragmentation **F**unctions (IFF) come possibile alternativa alla funzione di Collins per estrarre la trasversita`

- proiezioni al leading twist dell'operatore bilocale correlatore quark-quark; PDF e loro interpretazione probabilistica
- necessita` di una PDF chiral-odd al leading twist: la trasversita`; legata a spin trasverso dei quark, non dell'adrone, quindi non soppressa; proprieta` interessanti rispetto all'elicita`; evoluzione svincolata da gluoni e quark del mare di Dirac  $\rightarrow$  PDF di non singoletto
- trasversita` soppressa in DIS inclusivo; chiral-odd partner da DY polarizzato oppure da processi semi-inclusivi come SIDIS
- proiezioni al leading twist dell'operatore bilocale di correlatore quark-quark; FF e loro interpretazione probabilistica
- estrazione di trasversita` al leading twist con DSA; problemi
- importanza di osservare  $p_T$  degli adroni finali  $\rightarrow$  dei partoni; struttura piu` ricca dei correlatori al leading twist  $\rightarrow$  nuove possibilita` di estrazione della trasversita`: l'effetto Collins
- funzione di Collins = partner chiral-odd della trasversita`; si estrae da corrispondente reazione di annichilazione  $e^+e^-$

## SIDIS in dettaglio

DIS inclusivo  $\rightarrow \frac{d\sigma}{dE'd\Omega} = \frac{\alpha^2 E'}{Q^4 E} \frac{1}{2M} L_{\mu\nu} 2MW^{\mu\nu}$

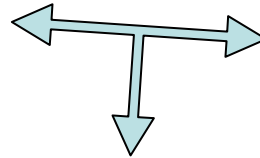
$$\frac{d\sigma}{dx_B dy} = \frac{\pi\alpha^2}{sx_B Q^2} L_{\mu\nu} 2MW^{\mu\nu}$$

$$\left\{ \begin{array}{l} dy = \frac{d\nu}{E} \\ dQ^2 = 2M\nu dx_B = \frac{EE'}{\pi} d\Omega \end{array} \right.$$

SIDIS  $\rightarrow \frac{2E_h d\sigma}{d\mathbf{P}_h dx_B dy d\phi_S} = \frac{\alpha^2}{2sx_B Q^2} L_{\mu\nu} 2MW^{\mu\nu}$

$$\begin{aligned} P_h^\mu &\sim (0, z_h k^-, \mathbf{P}_{h\perp}) \\ \frac{d\mathbf{P}_h}{2E_h} &\sim \frac{dz_h d\mathbf{P}_{h\perp}}{2z_h} \end{aligned}$$

$$\frac{d\sigma}{dx_B dy dz_h d\phi_S d\mathbf{P}_{h\perp}} = \frac{\alpha^2}{4z_h sx_B Q^2} L_{\mu\nu} 2MW^{\mu\nu}$$



$$\Delta^{[\Gamma]}(z, S_h) = \frac{1}{4z} \int dk^+ dk_T \text{Tr} [\Delta(k, P_h, S_h) \Gamma] \Big|_{k^- = P_h^- / z}$$

# Rappresentazione sulla base di elicità

$$\frac{d\sigma}{dx dy dz d\phi_S d\mathbf{P}_{h\perp}} = \frac{\alpha^2}{sx_B Q^2} L_{\mu\nu} \sum_f e_f^2 \int d\mathbf{p}_T d\mathbf{k}_T \delta(\mathbf{p}_T + \mathbf{q}_T - \mathbf{k}_T)$$

$$\text{Tr} \left[ \frac{1}{2} \int dp^- \Phi(p, P, S) \gamma^\mu \frac{1}{4z} \int dk^+ \Delta(k, P_h) \gamma^\nu \right] \Big|_{p^+ = xP^+, k^- = P_h^- / z}$$

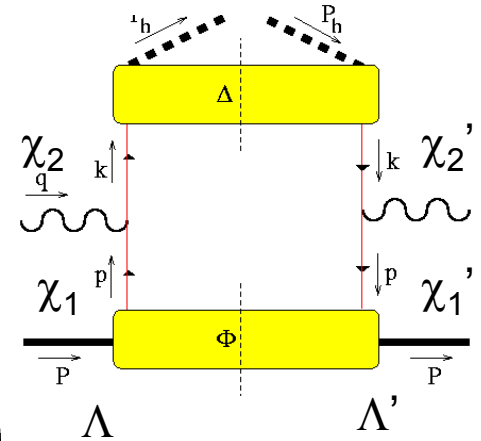
$$\stackrel{twist2}{\sim} \rho_{\Lambda\Lambda'}(S) \left( \frac{d\sigma^{el}}{dy} \right)^{\chi_1\chi'_1; \chi_2\chi'_2} \mathcal{F} \left[ \Phi_{\chi'_1\chi_1}^{\Lambda'\Lambda}(x, \mathbf{p}_T) \Delta_{\chi'_2\chi_2}(z, \mathbf{k}_T) \right]$$

$$\rho(S) = \frac{1}{2} \begin{pmatrix} 1 + \lambda & S_x - iS_y \\ S_x + iS_y & 1 - \lambda \end{pmatrix} \quad \text{matrice densita' del bersaglio}$$

$$\chi_1 = R \quad \chi'_1 = R$$

$$\chi_1 = R \quad \chi'_1 = L$$

$$\Phi(x, \mathbf{p}_T) = \begin{pmatrix} f_1 + g_{1L} & \frac{|\mathbf{p}_T|}{M} e^{-i\phi_p} g_{1T} & \frac{|\mathbf{p}_T|}{M} e^{i\phi_p} h_{1L}^{\perp*} & 2h_1 \\ \frac{|\mathbf{p}_T|}{M} e^{i\phi_p} g_{1T}^* & f_1 - g_{1L} & \frac{|\mathbf{p}_T|^2}{M^2} e^{2i\phi_p} h_{1T}^{\perp} & -\frac{|\mathbf{p}_T|}{M} e^{i\phi_p} h_{1T}^{\perp} \\ \frac{|\mathbf{p}_T|}{M} e^{-i\phi_p} h_{1L}^{\perp} & \frac{|\mathbf{p}_T|^2}{M^2} e^{-2i\phi_p} h_{1T}^{\perp} & f_1 - g_{1L} & -\frac{|\mathbf{p}_T|}{M} e^{-i\phi_p} g_{1T}^* \\ 2h_1 & -\frac{|\mathbf{p}_T|}{M} e^{-i\phi_p} h_{1L}^{\perp*} & -\frac{|\mathbf{p}_T|}{M} e^{i\phi_p} g_{1T} & f_1 + g_{1L} \end{pmatrix}$$



## Sez. d'urto elementare

scatt. elastico e<sup>-</sup>-fermione puntiforme

$$\frac{d\sigma}{dE' d\Omega} = \sigma_{Mott} \left( 1 + \frac{Q^2}{2M^2} \tan^2 \frac{\theta_e}{2} \right) \delta \left( \nu - \frac{Q^2}{2M} \right) \sim \frac{4\alpha^2 E'}{Q^4} \left( 1 + \frac{Q^2}{2M} \frac{Q^2}{4EE'} \right) \delta \left( \nu - \frac{Q^2}{2M} \right)$$

$$\begin{aligned} s &= (P+k)^2 \sim 2ME \\ t &= (k-k')^2 = -Q^2 \\ u &= (P-k')^2 \sim -2ME' \end{aligned} \quad \frac{d\sigma}{dt du} = \frac{\pi}{2MEE'} \frac{d\sigma}{dE' d\Omega}$$

$$\sim \frac{4\pi\alpha^2}{t^2} \frac{1}{2} \frac{2E'}{E} \left( 1 + \frac{Q^2}{2M^2} \frac{Q^2}{4EE'} \right) \delta(2M\nu - Q^2)$$

$$= \frac{4\pi\alpha^2}{t^2} \frac{1}{2} \left( \frac{t^2}{s^2} - \frac{2u}{s} \right) \delta(s+t+u) = \frac{4\pi\alpha^2}{t^2} \frac{1}{2} \left( 1 + \frac{u^2}{s^2} \right) \delta(s+t+u)$$

scatt. elastico elementare e<sup>-</sup>-quark

$s \rightarrow xs$  ;  $u \rightarrow xu$

$$\frac{d\sigma^{el}}{dx_B dy} = \frac{\pi 2M\nu}{E'} \frac{d\sigma^{el}}{dE' d\Omega} = \frac{\pi 2M\nu}{E'} \frac{EE' 2M}{\pi} \frac{d\sigma^{el}}{dt du}$$

$$= 2M\nu s \frac{4\pi\alpha^2 e_f^2}{t^2} \frac{1}{2} \left( 1 + \frac{u^2}{s^2} \right) x \delta(t + x(s+u))$$

$$= sx \frac{4\pi\alpha^2 e_f^2}{Q^4} \left( 1 - y + \frac{y^2}{2} \right) \delta(x - x_B) = \frac{4\pi\alpha^2 e_f^2}{\Omega^2 y} A(y) \delta(x - x_B)$$

$$\frac{d\sigma^{el}}{dy} = \frac{4\pi\alpha^2 e_f^2}{sx_B y^2} A(y)$$

$$y = 1 - \frac{u}{s}; \quad sx_B \sim \frac{Q^2}{y}$$

scatt. elastico elementare e<sup>-</sup>-quark polarizzato

$$\frac{d\sigma^{el}}{dy} = \frac{4\pi\alpha^2 e_f^2}{sx_B y^2} A(y) \rightarrow \frac{2\alpha^2 e_f^2}{sx_B y^2} \left( \begin{array}{cc|cc} A(y) & 0 & 0 & -B(y) \\ 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 \\ -B(y) & 0 & 0 & A(y) \end{array} \right) \quad B(y) = 1-y$$

correlatore quark-quark per la frammentazione

$$\Delta(z, \mathbf{k}_T) = \left( \begin{array}{c|c} \chi_2=R \chi_2'=R & \chi_2=R \chi_2'=L \\ \hline D_1 & ie^{i\phi_k} \frac{|\mathbf{k}_T|}{M_h} H_1^\perp \\ -ie^{-i\phi_k} \frac{|\mathbf{k}_T|}{M_h} H_1^\perp & D_1 \end{array} \right)$$

al twist 2

$$\frac{d\sigma}{dx dy dz d\phi_S d\mathbf{P}_{h\perp}} = \rho(S) \left( \frac{d\sigma^{el}}{dy} \right) \mathcal{F} [\Phi(x, \mathbf{p}_T) \Delta(z, \mathbf{k}_T)] \quad \sum \rightarrow d\sigma_{OO} = A(y) \sum_f \frac{2\alpha^2 e_f^2}{sx_B y^2} \mathcal{F} [f_1^f D_1^f]$$

$$\mathbf{S}_T = 0 \rightarrow d\sigma_{OL} = B(y) \lambda \sin 2\phi_h \sum_f \frac{2\alpha^2 e_f^2}{sx_B y^2} \mathcal{F} \left[ \frac{2\mathbf{p}_T \cdot \hat{\mathbf{P}}_{h\perp} \mathbf{k}_T \cdot \hat{\mathbf{P}}_{h\perp} - \mathbf{p}_T \cdot \mathbf{k}_T}{MM_h} h_{1L}^{\perp f} H_1^{\perp f} \right]$$

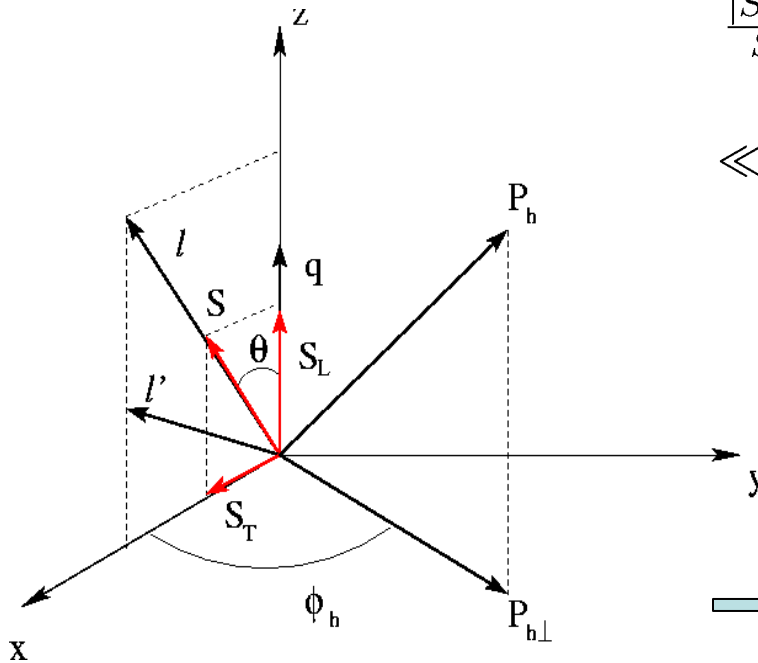
$$\lambda = 0 \rightarrow d\sigma_{OT} = B(y) |\mathbf{S}_T| \sum_f \frac{2\alpha^2 e_f^2}{sx_B y^2} \left\{ \sin(\phi_h + \phi_S) \mathcal{F} \left[ \frac{\mathbf{k}_T \cdot \hat{\mathbf{P}}_{h\perp}}{M_h} h_{1T}^f H_1^{\perp f} \right] \right. \\ \left. + \sin(3\phi_h - \phi_S) \mathcal{F} [\dots h_{1T}^{\perp f} H_1^{\perp f}] \right\}$$

## Situazione sperimentale

solo recentemente si e` ottenuta la disponibilita` di bersagli (protoni) polarizzati trasversalmente rispetto al fascio → dati di prossima pubblicazione

ECT\* Workshop (14-18 giugno, Trento)  
*Transversity: new developments  
 in nucleon spin structure*

dati pubblicati finora ottenuti dal seguente set-up



$$\frac{|\vec{S}_T|}{S} = \sin \theta \sim \sqrt{\frac{4M^2 x}{sy}(1-y)} \sim \frac{1}{Q}$$

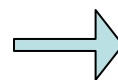
$$\ll \frac{\lambda}{S} = \cos \theta \sim 1 - \frac{2M^2 x}{sy}(1-y) \quad \phi_S = 0, \pi$$

$$d\sigma = d\sigma_{OO} + \lambda d\sigma_{OL}(\text{twist-2+twist-3}) + \mathbf{S}_T d\sigma_{OT}(\text{twist-2})$$

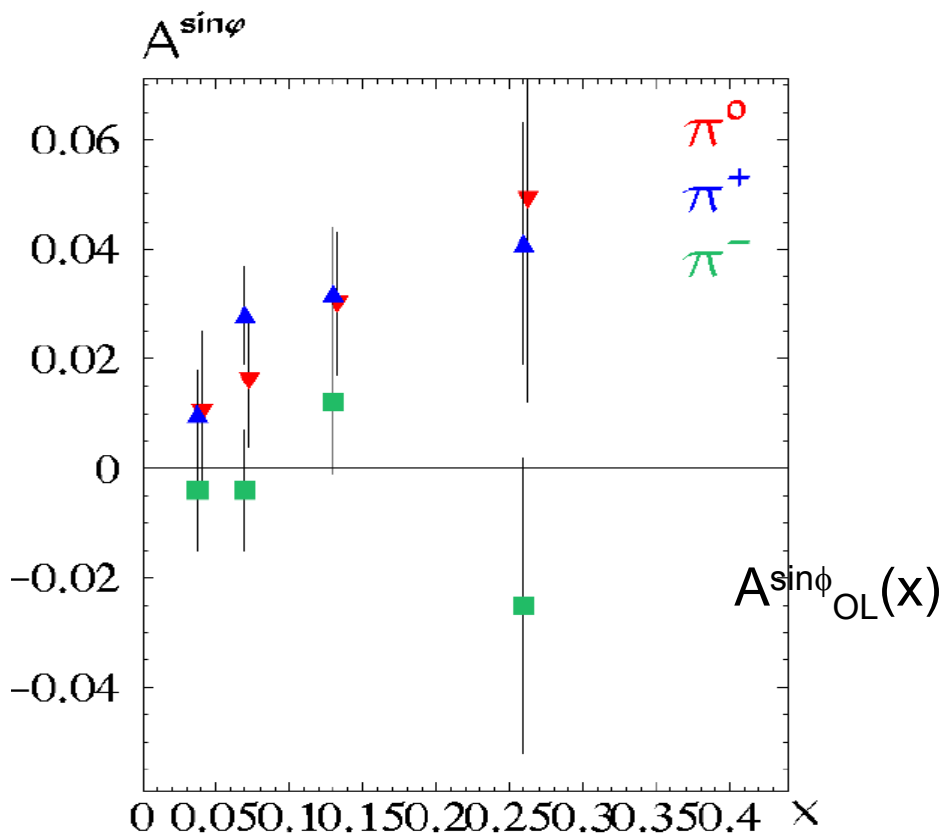
(Airapetian et al., P.R.L. **84**('00)4047

“ “ , P.R. **D64**('01)097101

“ “ , P.L. **B562**('03)182 )



1. SSA  $\neq 0$
2. diversi contributi  $\sim \sin \phi_h$ ; qual e` l'effetto Collins ?



HERMES :  $e^+ + \vec{p} \rightarrow e^{+'} + \pi + X$   
 beam 27.5 GeV ,  $1 < Q^2 < 15 \text{ GeV}^2$   
 $0.023 < x_B < 0.4$  ,  $0.2 < z < 0.7$  ,  $W > 2 \text{ GeV}$   
 $A^{\sin 2\phi}_{OL} \neq 0 \text{ ma} \ll A^{\sin\phi}_{OL}$

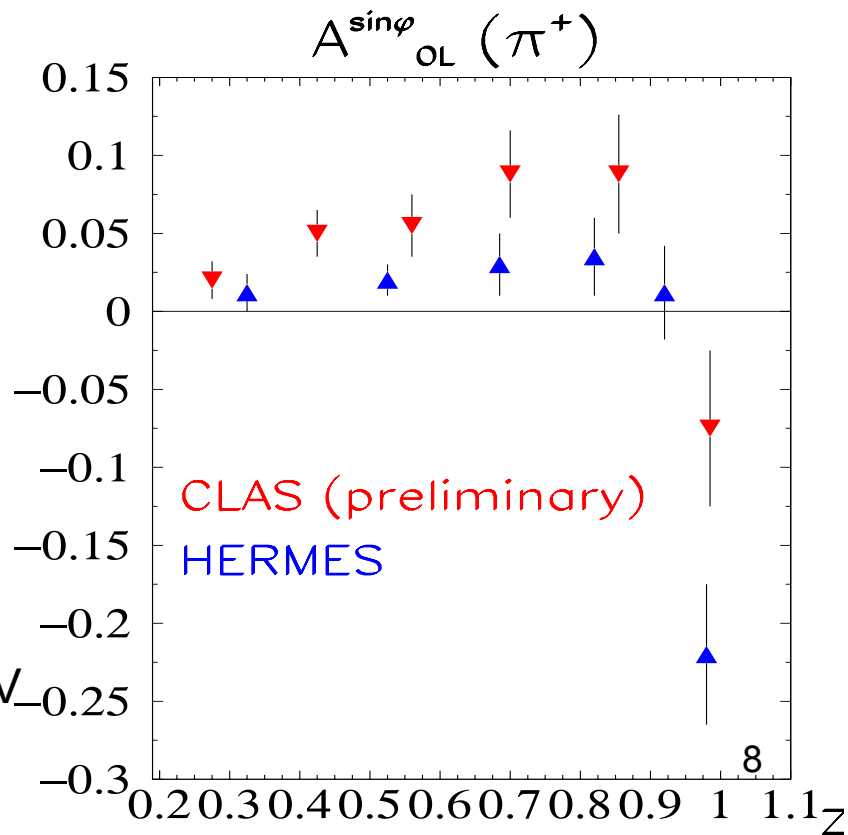
CLAS :  $\vec{e} + \vec{p} \rightarrow e' + \pi^+ + X$   
 Beam 4.3 GeV ,  $1 < Q^2 < 3 \text{ GeV}^2$  ,  $2 < W < 2.6 \text{ GeV}$   
 $0.15 < x_B < 0.4$  ,  $0.5 < z < 0.8$

SMC : SSA in SIDIS on  $p^\uparrow$   
 $A(\pi^+) = 11\% \pm 6\%$      $A(\pi^-) = -2\% \pm 6\%$

E704 : SSA in  $pp^\uparrow \rightarrow \pi X$

DELPHI :  $e^+e^- \rightarrow \pi^+\pi^- X$

asymmetria  $\sim 6.3\%$  del  $\pi^+$   
 intorno all'asse del jet del  $\pi^-$





Problema : invarianza per trasformazioni di  $SU_c(3)$  di  $\Phi$  e  $\Delta$

$$\Phi(x, S) = \int \frac{d^4\xi}{2\pi} e^{-ixP^+\xi^-} \langle P, S | \underbrace{\bar{\psi}(\xi^-) \psi(0)}_{\text{campi di quark a punti 4-dim. diversi}} | P, S \rangle \Big|_{\xi^+, \xi_\perp = 0}$$

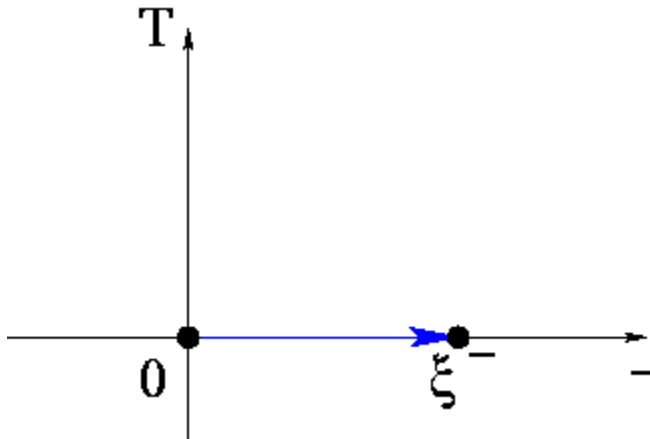
campi di quark a punti 4-dim. diversi  
gauge invarianza per  $SU_c(3)$



gauge-link (tower) operator

$$\bar{\psi}(\xi^-) \psi(0) \longrightarrow \bar{\psi}(\xi^-) U_{[0, \xi^-]} \psi(0) \equiv \bar{\psi}(\xi^-) \mathcal{P} e^{-ig \int_0^{\xi^-} dw \cdot A(w)} \psi(0)$$

$$\bar{\psi}(\xi^-) \sum_{n=0}^{\infty} (-ig)^n \int_0^{\xi^-} dw_1^- A^+(w_1) \dots \int_{w_{n-1}^-}^{\xi^-} dw_n^- A^+(w_n) \Big|_{w_i^+ = \xi^+ = 0, w_{iT} = \xi_T = 0_T} \psi(0)$$



$\mathcal{P}$  = sviluppo dell'esponenziale  
ordinando i cammini di integrazione :  
 $A^+$  ( $\phi, \mathbf{A}_T$ )  $\rightarrow$  twist 2  
 $\mathbf{A}_T$  (indipendente)  $\rightarrow$  twist 3 ....

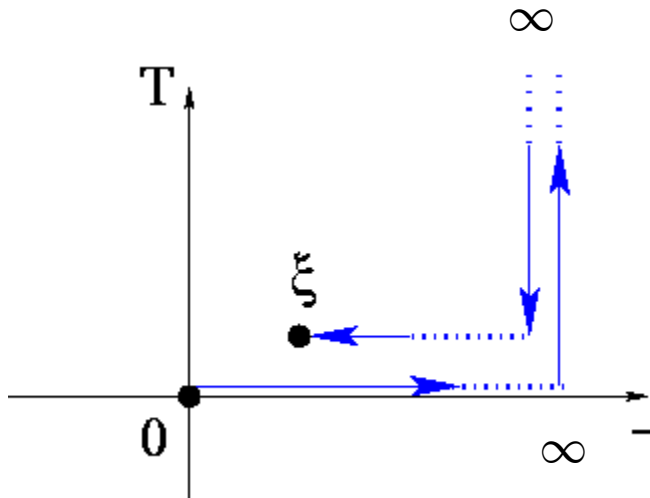
continua

$$\Phi(x, \mathbf{p}_T, S) = \int \frac{d^4 \xi}{(2\pi)^3} e^{-ixP^+ \xi^- + i\mathbf{p}_T \cdot \boldsymbol{\xi}_T} \underbrace{\langle P, S | \bar{\psi}(\xi) \psi(0) | P, S \rangle}_{\xi^+ = 0}$$

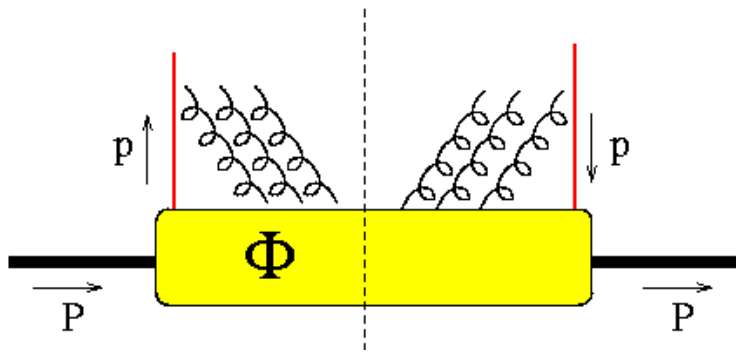


$$\bar{\psi}(\xi) \psi(0) \longrightarrow \bar{\psi}(\xi) U_{[0, \infty^-]} U_{[0, \infty T]} U_{[\infty T, \xi T]} U_{[\infty^-, \xi^-]} \psi(0)$$

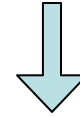
$\equiv \bar{\psi}(\xi) \psi(0)$  interpretazione probabilistica  
al twist 2 preservata



analisi in twist rivela che al twist 2  
contribuiscono sia  $A^+$ , che  $\mathbf{A}_T$  a  
 $n_- = \infty$



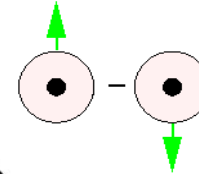
$\Phi$  invariante per trasformazioni di  $SU_c(3)$



“FSI” tra quark e adrone  
 $\Rightarrow$  strutture **T-odd** permesse

(Boer, Mulders, Pijlman, N.P.**B667**(’03)201)

$$\Phi[\gamma^+] (x, \mathbf{p}_T, S) = f_1(x, \mathbf{p}_T^2) - \frac{\mathbf{k}_T \times \mathbf{S}_T}{M} f_{1T}^\perp(x, \mathbf{p}_T)$$

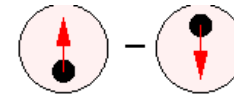


$$\Phi[\gamma^+ \gamma_5] (x, \mathbf{p}_T, S) = \lambda g_{1L}(x, \mathbf{p}_T^2) + \frac{\mathbf{p}_T \cdot \mathbf{S}_T}{M} g_{1T}(x, \mathbf{p}_T^2)$$

$$\Phi[i\sigma^{i+} \gamma_5] (x, \mathbf{p}_T, S) = S_T^i h_{1T}(x, \mathbf{p}_T^2) + \frac{p_T^i}{M} \left[ \lambda h_{1L}^\perp(x, \mathbf{p}_T^2) + \frac{\mathbf{p}_T \cdot \mathbf{S}_T}{M} h_{1T}^\perp(x, \mathbf{p}_T^2) \right]$$

(Boer, P.R.**D60**(’99)014012)

$$- \frac{(\hat{\mathbf{n}}_T \times \mathbf{k}_T)_i}{M} h_{1T}^\perp(x, \mathbf{p}_T)$$



$$\int d\mathbf{p}_T (\mathbf{T}\text{-odd}) = 0$$

analogamente

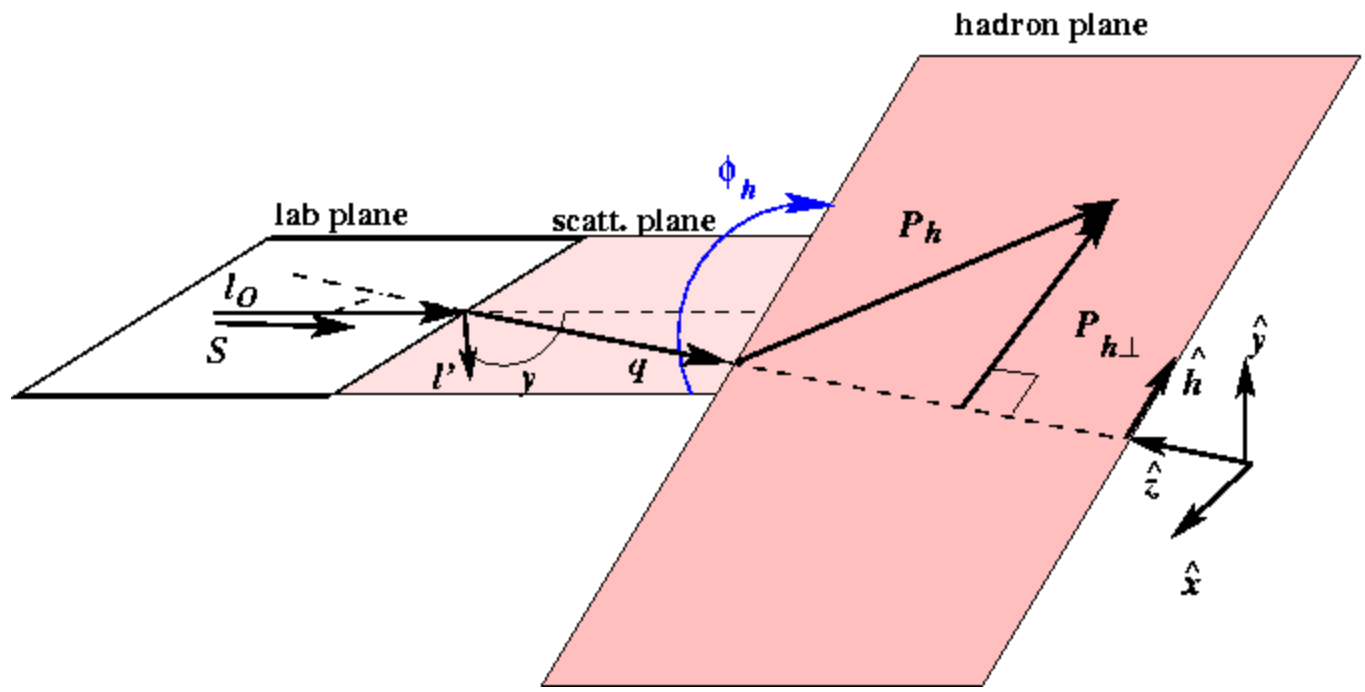
$$\Delta(z, \mathbf{k}_T) \rightarrow \dots \psi(\xi) | \dots \rangle \langle \dots | \bar{\psi}(0) \dots \rightarrow \dots U_{[-\infty^-, \xi^-]} U_{[\infty^T, \xi^T]} \bar{\psi}(\xi) | \dots \rangle \langle \dots | \bar{\psi}(0) \left( U_{[0, -\infty^-]} U_{[0, \infty^T]} \right)^\dagger \dots$$

preserva interpretazione probabilistica al twist 2  
 anche se strutture T-odd sono già presenti

SIDIS con bersaglio polarizzato parallelamente al fascio :  $e + \vec{p}^\uparrow \rightarrow e' + \pi + X$

$$d\sigma = d\sigma_{OO} + \lambda d\sigma_{OL}(\text{twist-2+twist-3}) + \mathbf{S}_T d\sigma_{OT}(\text{twist-2})$$

$$|\mathbf{S}_T| \ll \lambda, \phi_S = 0$$



$$A^{\sin \phi_h} = \frac{\int d\mathbf{P}_{h\perp} \frac{|\mathbf{P}_{h\perp}|}{M_h} \sin \phi_h [d\sigma_{OL} + d\sigma_{OT}]}{\int d\mathbf{P}_{h\perp} d\sigma_{OO}}$$

$$\frac{d\sigma_{OO}}{dx dy dz d\mathbf{P}_{h\perp}} \propto \left\{ \dots \mathcal{F} \left[ x f_1(x, \mathbf{p}_T^2) \quad D_1(z, \mathbf{k}_T^2) \right] + \dots \right\}$$

$$\frac{d\sigma_{OL}}{dx dy dz d\mathbf{P}_{h\perp}} \propto \lambda \left\{ \dots \sin 2\phi_h \mathcal{F} \left[ \frac{2\hat{P}_{h\perp} \cdot \mathbf{k}_T \hat{P}_{h\perp} \cdot \mathbf{p}_T - \mathbf{p}_T \cdot \mathbf{k}_T}{M M_h} \quad x h_{1L}^\perp \quad H_1^\perp \right] \right.$$

$$|\mathbf{S}_T| \ll \lambda$$

$$h_{1L}^\perp \sim x^2 \int_x^1 dy \frac{h_1(y)}{y^2}$$

$$+ o\left(\frac{m_q}{M}\right) + \text{twist-3} + \dots$$

$$\ll x h_1$$

$$A \sin 2\phi < A \sin \phi$$



$$\dots \frac{M}{Q} \sin \phi_h \mathcal{F} \left[ \frac{\hat{P}_{h\perp} \cdot \mathbf{k}_T}{M_h} \quad x \left( x h_L - \frac{m}{M} g_{1L} \right) \quad H_1^\perp \right]$$

$$\sim 2x^2 \int_x^1 dy \frac{h_1(y)}{y^2} + o\left(\frac{m}{M}\right) + \text{twist-3}$$

$$+ \frac{M}{Q} \sin \phi_h \mathcal{F} \left[ \frac{\hat{P}_{h\perp} \cdot \mathbf{p}_T}{M} \quad x h_{1L}^\perp \quad \left( \frac{H}{z} + \frac{\mathbf{k}_T^2}{M_h^2} H_1^\perp \right) \right] \dots \left. \right\}$$

$\equiv \frac{\tilde{H}}{z} \ll H_1^\perp$

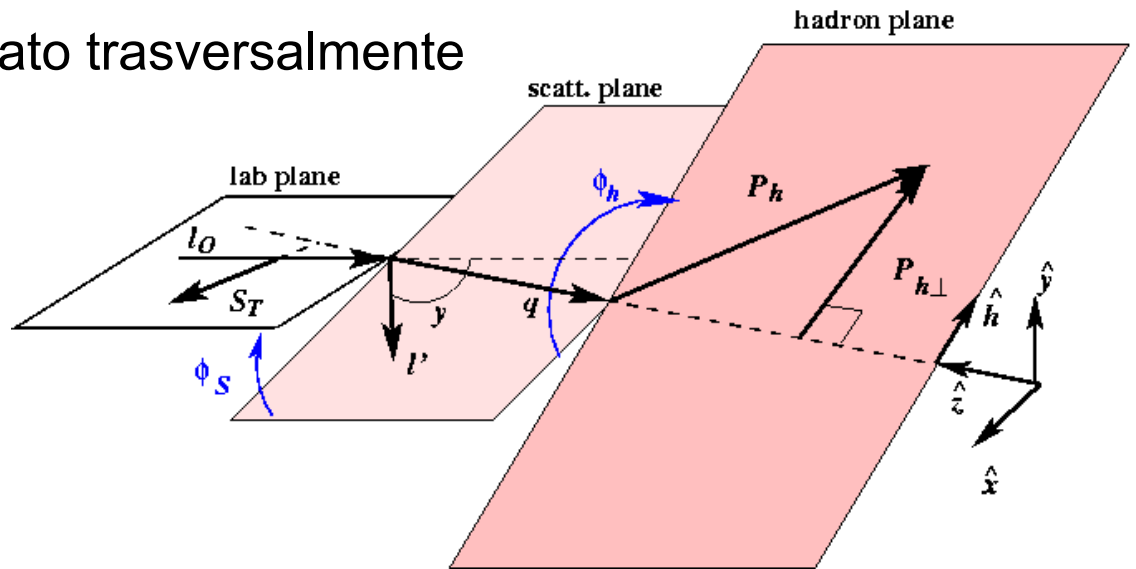
$$\frac{d\sigma_{OT}}{dx dy dz d\mathbf{P}_{h\perp}} \propto |\mathbf{S}_T| \left\{ \dots \sin \phi_h \mathcal{F} \left[ \frac{\hat{P}_{h\perp} \cdot \mathbf{k}_T}{M_h} \quad x h_1 \quad H_1^\perp \right] \leftarrow \text{effetto Collins} \right.$$

$$\text{effetto Sivers} \rightarrow \left. + \sin \phi \mathcal{F} \left[ \frac{\hat{P}_{h\perp} \cdot \mathbf{p}_T}{M} \quad x f_{1T}^\perp \quad D_1 \right] + \dots \right\}$$

# SIDIS su bersaglio polarizzato trasversalmente

$$e + p^\uparrow \rightarrow e' + \pi + X$$

$$\phi_S \neq 0, \pi \quad |\mathbf{S}_T| \text{ non piccola}$$



$$\frac{d^6 \sigma_{OT}}{dx dy dz d\phi_S d\mathbf{P}_{h\perp}} \propto |\mathbf{S}_T| \left\{ \dots \right.$$

$$\sin(\phi_h + \phi_S) \mathcal{F} \left[ \frac{\mathbf{k}_T \cdot \hat{h}}{M_h} x h_1(x, \mathbf{p}_T^2) H_1^\perp(z, \mathbf{k}_T^2) \right] + \dots \quad \leftarrow \text{effetto Collins}$$

$$\sin(\phi_h - \phi_S) \mathcal{F} \left[ \frac{\mathbf{p}_T \cdot \hat{h}}{M} x f_{1T}^\perp(x, \mathbf{p}_T^2) D_1(z, \mathbf{k}_T^2) \right] + \dots \quad \leftarrow \text{effetto Sivers}$$

$$\sin(3\phi_h - \phi_S) \mathcal{F} \left[ \dots h_{1T}^\perp(x, \mathbf{p}_T^2) H_1^\perp(z, \mathbf{k}_T^2) \right] \left. \right\}$$

i due effetti sono separabili in linea di principio ; operativamente, difficoltà legate ai bassi conteggi (per la difficoltà di mantenere una luminosità e una % di polarizzazione trasversa alte)

# SIDIS $e + p^\uparrow \rightarrow e' + \pi + X \rightarrow$ annichilazione $p + p^\uparrow \rightarrow \pi + X$

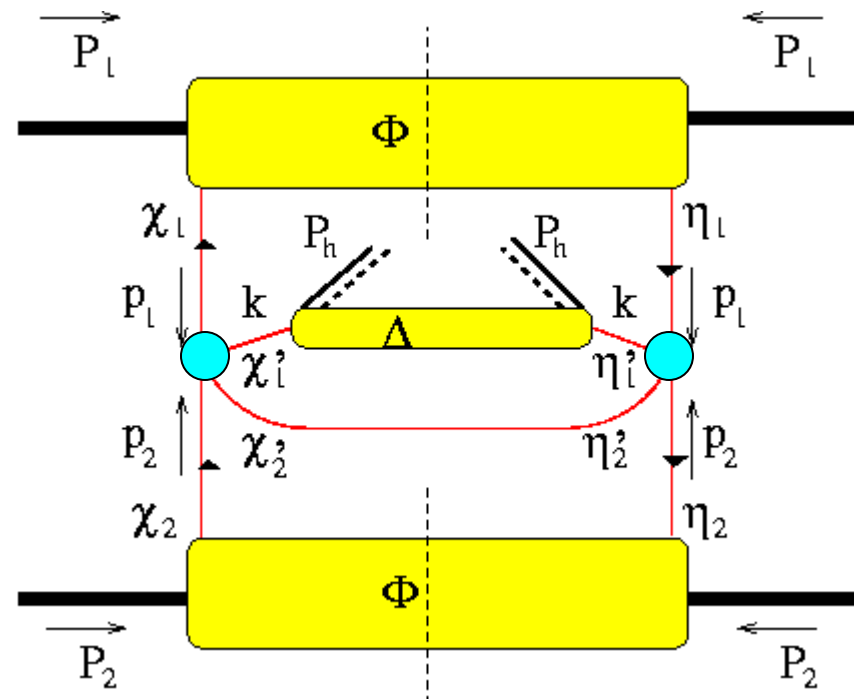
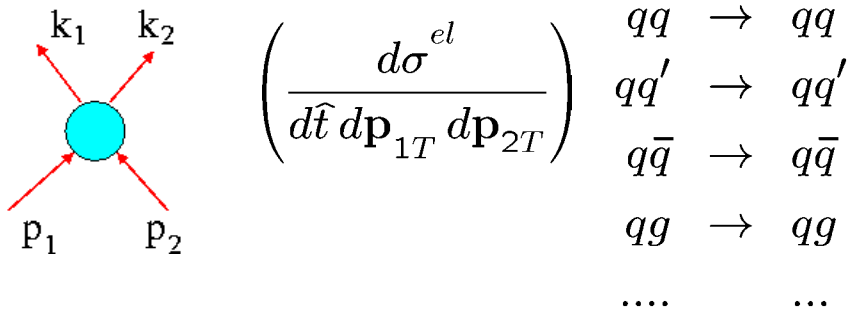
$$\frac{d\sigma}{dt d\phi_S d\mathbf{P}_{h\perp}} \propto \int dx_1 dx_2 dz_1 dz_2 \delta(\hat{s} + \hat{t} + \hat{u}) \delta(z_2 - 1) \delta_{\chi'_2 \eta'_2}$$

$$\mathcal{F} \left[ \Phi(x_1, \mathbf{p}_{1T}, S_1)_{\eta_1 \chi_1} \Phi(x_2, \mathbf{p}_{2T}, S_2)_{\eta_2 \chi_2} \left( \frac{d\sigma^{el}}{d\hat{t} d\mathbf{p}_{1T} d\mathbf{p}_{2T}} \right)_{\chi_1 \chi_2 \rightarrow \chi'_1 \chi'_2} \right] \Delta(z_1, \mathbf{k}_{1T})_{\eta'_1 \chi'_1} \delta(\mathbf{k}_{2T})$$

$$s = (P_1 + P_2)^2 \sim 2P_1 \cdot P_2 \rightarrow \hat{s} = x_1 x_2 s$$

$$t = (P_1 - P_h)^2 \sim -2P_1 \cdot P_h \rightarrow \hat{t} = \frac{x_1}{z} t$$

$$u = (P_2 - P_h)^2 \sim -2P_2 \cdot P_h \rightarrow \hat{u} = \frac{x_2}{z} u$$



dipendenza da  $\mathbf{p}_T$  introduce un fattore  $1/Q$  ( $d\sigma^{el}$  e' per natura T-even!); quindi anche se  $\Phi$  e  $\Delta$  al twist 2  $\rightarrow d\sigma$  soppressa

(Anselmino, D'Alesio, Murgia, in preparazione)

$p + p^\uparrow \rightarrow \pi + X$ : al twist 3 ci sono quattro possibili sorgenti di SSA, tre meccanismi legati a PDF al twist 2, ma soppressi da  $d\sigma^{\text{el}}$ , e uno di twist 3

$\mathbf{k}_T$  stato finale

$$\text{SSA} \sim \frac{\sum_f h_1^f(x_1) \bar{f}_1^f(x_2) H_1^{\perp f(1)}(z)}{\sum_f f_1^f(x_1) \bar{f}_1^f(x_2)}$$

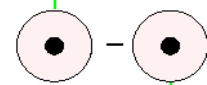
$\mathbf{p}_T$  stato iniziale

$$\left\{ \begin{array}{l} \text{SSA} \sim \frac{\sum_f f_{1T}^{\perp f}(x_1) \bar{f}_1^f(x_2) D_1^f(z)}{\sum_f f_1^f(x_1) \bar{f}_1^f(x_2)} \\ \text{SSA} \sim \frac{\sum_f h_1^{\perp f}(x_1) \bar{h}_1^f(x_2) D_1^f(z)}{\sum_f f_1^f(x_1) \bar{f}_1^f(x_2)} \end{array} \right.$$

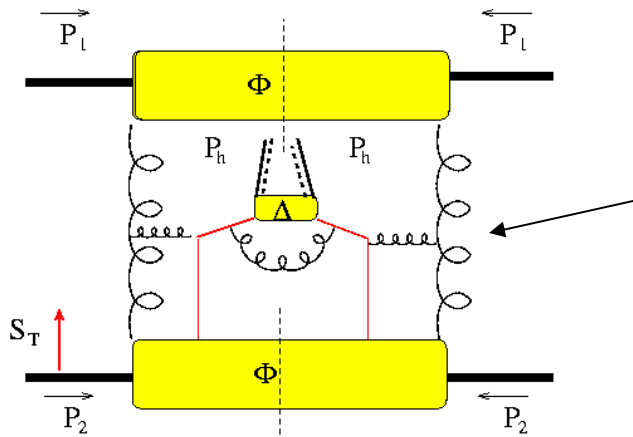
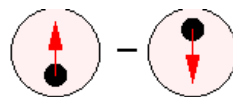
effetto Collins



effetto Sivers



Boer '99



Vertice trilineare

- polo nel propagatore di  $g$
- $\text{Im}(\dots) \rightarrow$  T-odd PDF

effetto Qiu-Sterman

(Qiu & Sterman,  
P.R.L. **67**('91)2264;  
N.P. **B378**('92)52)

qual e' il meccanismo responsabile dell'asimmetria  $\sim 10\%$  osservata a SMC nella reazione  $p+p^\uparrow \rightarrow \pi^+ X$ ?

fattorizzazione e universalita' (confronto SIDIS – DY)



per avere piu` informazioni si puo` comparare con il DY (non) polarizzato assumendo la fattorizzazione (teoremi non dimostrati per processi hard dipendenti da momenti trasversi) → universalita` delle PDF

DY polarizzato singolarmente :  $pp^\uparrow \rightarrow l^+l^- X$  (Boer, P.R.D60('99)014012)

$$\frac{d\sigma}{dx_1 dx_2 d\Omega d\mathbf{q}_T} \propto |\mathbf{S}_{T_1}| \sum_f \left\{ \dots \right.$$

SSA per confrontare **funzione di Sivvers**  
con  $ep^\uparrow \rightarrow e'\pi X$  o  $pp^\uparrow \rightarrow \pi X$

$$\left. \begin{aligned} & \sin(\phi - \phi_{S_1}) \mathcal{F} \left[ \hat{\mathbf{h}} \cdot \mathbf{p}_{T_1} \left( f_{1T}^{\perp f} \right) \bar{f}_1^f \right] + \dots \\ & \sin(\phi + \phi_{S_1}) \mathcal{F} \left[ \hat{\mathbf{h}} \cdot \mathbf{p}_{T_2} \left( h_1^f \right) \bar{h}_1^{\perp f} \right] \dots \end{aligned} \right\}$$

SSA per confrontare **trasversita`** con  
 $ep^\uparrow \rightarrow e'\pi X$  o  
 $pp^\uparrow \rightarrow \pi X$

ma serve avere informazioni su  $h_1^\perp$  attraverso  $pp^\uparrow \rightarrow \pi X$  oppure....

DY non polarizzato :  $pp \rightarrow l^+l^- X$

(Boer, P.R.**D60**('99)014012)

$$\frac{d\sigma}{dx_1 dx_2 d\Omega d\mathbf{q}_T} \propto \sum_f \left\{ \mathcal{F} \left[ f_1^f \bar{f}_1^f \right] \dots + \dots \cos 2\phi \mathcal{F} \left[ A(\mathbf{p}_{T_1}, \mathbf{p}_{T_2}) h_1^{\perp f} \bar{h}_1^{\perp f} \right] \dots \right\}$$

storicamente i dati raccolti dalla collaborazione NA10 per  $\pi A \rightarrow \mu^+ \mu^- X$   
sono parametrizzabili come

(Falciano et al., Z.Phys.**C31**('86)513 ;  
Guanzioli et al., Z.Phys.**C37**('88)545)

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin^2 \theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi + o(\alpha_s) \quad \begin{matrix} \lambda \sim 1 \\ \mu \ll \nu \sim 30\% \end{matrix}$$

la QCD perturbativa  $\rightarrow \lambda \sim 1 ; \mu \sim \nu \sim 0 !$

modelli basati su meccanismi a twist > 2 e/o  
sulla rottura della fattorizzazione non spiegano  
asimmetria così evidente:  $\nu \sim 30\%$

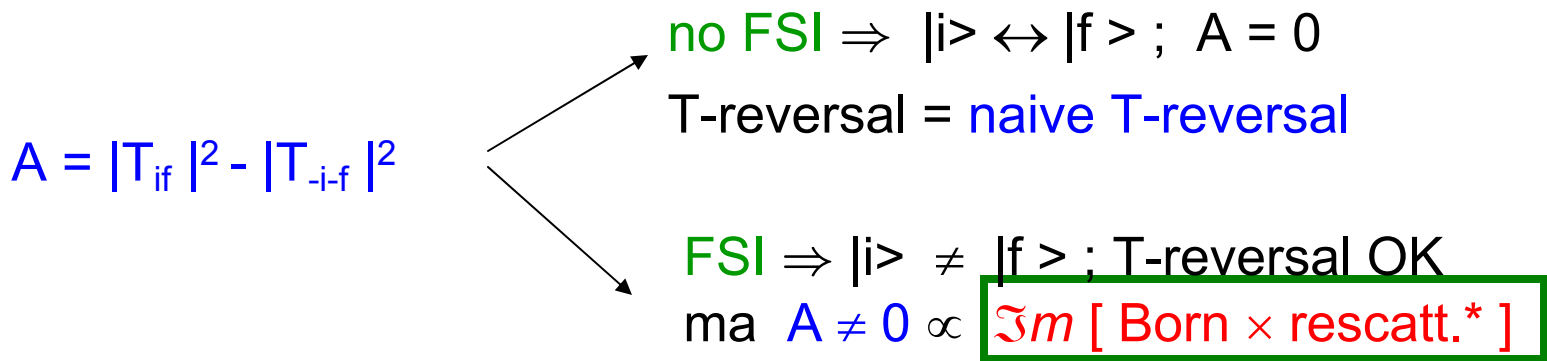
prodotto di **due**  $h_1^\perp$  (PDF al twist 2) ; ciascuna dipende da  $\mathbf{p}_T$  del quark  
polarizzato trasversalmente  $\rightarrow$  coinvolge  $(\Delta L_z = 1) \times 2 \rightarrow \cos 2\phi !$

Funzioni Collins ( $H_1^\perp$ ) di Sivers ( $f_{1T}^\perp$ ) di Boer ( $h_1^\perp$ ) sono esempi di funzioni T-odd  
 → utile classificazione :

$|i\rangle, |f\rangle$  stati iniziale, finale di un sistema con numeri quantici  $i, f$

$T_{if}$  matrice di transizione → invarianza per time-reversal  $|T_{if}|^2 = |T_{f-i}|^2$

definizione di trasformazione naive T-reversal :  $T_{-i-f}$



naive T-odd  $\equiv$  T-odd ma non si viola una legge fondamentale della natura !

$H_1^\perp$  legata a FinalStateInteractions dell'adrone finale con jet residuo  
 (Bacchetta et al., P.R.D65('02)094021)

e per  $f_{1T}^\perp, h_1^\perp$  ?

in reazioni di annichilazione ( $p + p^\uparrow \rightarrow \pi + X$ ) si puo` pensare che strutture T-odd nascano da Initial State Interactions

(Collins, P.L. **B536**('02)43)

ad esempio l'effetto Sivers, visto (ma piccolo) a HERMES

(Makins – HERMES, preliminary ('03))

$$f_{1T}^\perp = \text{diagram with two circles and arrows}$$

The diagram shows the equation  $f_{1T}^\perp =$  followed by two circles. The first circle contains a black dot with a green arrow pointing upwards from its center. The second circle contains a black dot with a green arrow pointing downwards from its center. A minus sign is placed between the two circles.

possibile interpretazione con le Generalized Parton Distributions: se adrone non e` autostato di elicitazione ma e` polarizz.  $\perp$

→ la GPD “E( $\mathbf{p}_T$ ..)” (helicity flip)

e` la trasformata di Fourier di una PDF( $\mathbf{b}_\perp$ ) distorta nel parametro di impatto

→ quark u(d) spostato giu` (su)

→ momento angolare orbitale

→ asimmetria nella deflessione

(Burkardt, P.R. **D66**('02)114005)



K. Bruhwieler - TJNAF - 2003

SIDIS  $e + p^\uparrow \rightarrow e' + \pi + X$

$$H_1^{\perp(1)}(z) = \int dk_T \frac{k_T^2}{2M_h} H_1^\perp(z, \mathbf{k}_T)$$

SSA  $\left\langle \frac{|\mathbf{P}_{h\perp}|}{M_h} \sin \phi_C \right\rangle_{OT} = |\mathbf{S}_T| \frac{B(y)}{A(y)} \frac{\sum_f e_f^2 x h_1^f(x) H_1^{\perp f(1)}(z)}{\sum_f e_f^2 f_1^f(x) D_1^f(z)}$  (Boer & Mulders, Phys. Rev. **D57** ('98) 5780)

Problemi

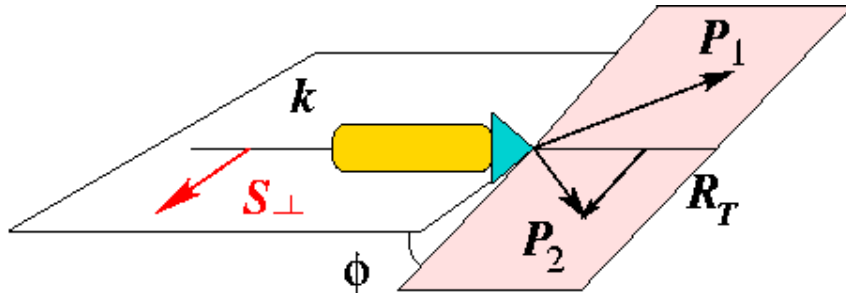
- necessita` di conoscere  $P_{h\perp}$  per ogni bin
- nelle correzioni radiative oltre il prim'ordine, dipendenza da  $P_{h\perp}$  **intrinseco** → cancellazione tra contributi di gluoni soft reali e virtuali (fattorizzazione collineare) non succede → risommazione in fattori di forma di Sudakov

$\propto \int_{|\mathbf{P}_{h\perp}|}^{Q^2}$  diluizione della SSA per  $|\mathbf{P}_{h\perp}| \ll Q^2$  (Boer, N.P. **B603**('01)195)  
 unfavoured  $H_1^{\perp d \rightarrow \pi}$  dominante e piccola (Makins – HERMES preliminary ('03))

- mancanza di teorema di fattorizz. → evoluzione di  $h_1$ ,  $H_1^\perp$  e SSA non legate
- $H_1^\perp$  da  $e^+e^- \rightarrow \pi^+\pi^- X$   $\langle \cos 2\phi \rangle \sim \frac{\sum_f e_f^2 H_1^{\perp f}(z_1) \overline{H}_1^{\perp f}(z_2)}{\sum_f e_f^2 D_1^f(z_1) \overline{D}_1^f(z_2)}$  SSA ~ 6% a DELPHI (Sudakov f.f.?)
- in  $pp^\uparrow \rightarrow \pi X$  le SSA sono sopresse per via della sez. d'urto elementare dipendente da  $\mathbf{p}_T$  intrinseci dei partoni

meccanismo che generi SSA legata ad oggetto chiral-odd (partner di  $h_1$ )  
 senza coinvolgere momento  $\mathbf{p}_T$  intrinseco dei partoni

⇒ SSA con due adroni leading (non polarizzati) nello stesso jet



asimmetria in  
 $\sin \phi \propto \mathbf{P}_1 \times \mathbf{P}_2 \cdot \mathbf{S}_T = \mathbf{P}_h \times \mathbf{R} \cdot \mathbf{S}_T$

$$\mathbf{P}_h = \mathbf{P}_1 + \mathbf{P}_2$$

$$\mathbf{R} = \frac{1}{2} (\mathbf{P}_1 - \mathbf{P}_2)$$

(Collins et al., N.P.**B420**('94)565

Jaffe, Jin, Tang, P.R.L.**80**('98)1166

analisi in twist sistematica

Bianconi et al., P.R.**D62**('00)034008

Bacchetta & Radici, P.R.**D67**('03)094002

Bacchetta & Radici, P.R.**D70**('04)074xxx)

- $\int d\mathbf{P}_{h\perp}$  → SSA in  $\phi \equiv \phi_R$  → fattorizzazione collineare (non c'è "diluizione" per fattori di forma di Sudakov)
- effetto Sivers non c'è → segnale più "pulito"
- possibilità di avere SSA al twist 2 in annichilazione  $pp^\uparrow \rightarrow (\pi\pi)X$

## Correlatore quark-quark per 2 hadron - SIDIS

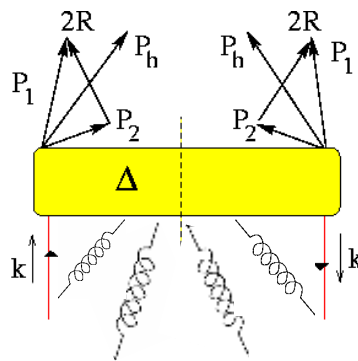
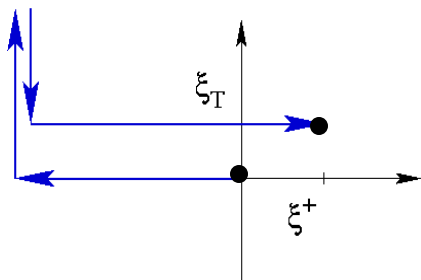
decomposizione della matrice di Dirac  $\Delta(k, P_h, R)$  sulla base delle strutture di Dirac e dei 4-vettori  $k, P_h, R$  compatibilmente con Hermiticity e invarianza per parita` e time-reversal

$$\Delta(k, P_h, R) = \sum_X \int \frac{d^4\xi}{(2\pi)^4} e^{ik \cdot \xi} \langle 0 | \psi(\xi) | P_1, P_2, X \rangle \langle P_1, P_2, X | \bar{\psi}(0) | 0 \rangle$$

invarianza per  $SU_c(3)$  di gauge

$$\Delta(\vec{k}_T, P_h, R) = \int dk^+ \Delta(k, P_h, R) \Big|_{k^- = P_h^- / z}$$

$$= \sum_X \int \frac{d\xi^+ d\vec{\xi}_T}{(2\pi)^3} e^{ik \cdot \xi} \langle 0 | U_{[\infty, \xi]}^T U_{[-\infty, \xi]}^+ \psi(\xi) | P_1, P_2, X \rangle \langle P_1, P_2, X | \bar{\psi}(0) U_{[0, -\infty]}^+ U_{[0, \infty]}^T | 0 \rangle \Big|_{\xi^- = 0}$$



gauge link riassorbito in  $\psi$   
 $\rightarrow$  interpretazione probabilistica  
 al twist 2 ancora possibile

analogamente per antiquark

proiezioni al leading twist :  $\Delta^{(\Gamma)} = \frac{1}{4z} \int dk^+ \text{Tr} [\Gamma \Delta(k, P_h, R)] \Big|_{k^- = P_h^- / z}$

$$\Delta^{(\gamma^-)} = D_1 = \bullet \longrightarrow \begin{array}{c} \circ \\ \circ \end{array}$$

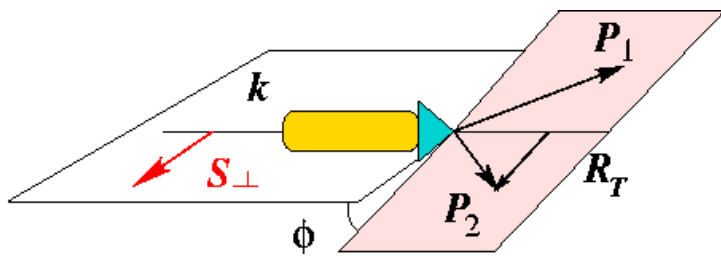
$$\Delta^{(\gamma^- \gamma_5)} = \frac{(\mathbf{R}_T \times \mathbf{k}_T)}{M_h^2} G_1^\perp$$

$$G_1^\perp = \left( \bullet \xrightarrow{\text{red arrow}} \begin{array}{c} \circ \\ \circ \end{array} \right) - \left( \xrightarrow{\text{red arrow}} \bullet \begin{array}{c} \circ \\ \circ \end{array} \right)$$

$$\Delta^{(i\sigma^{i-} \gamma_5)} = \frac{(\hat{\mathbf{n}}_T \times \mathbf{k}_T)_i}{M_h} H_1^\perp + \frac{(\hat{\mathbf{n}}_T \times \mathbf{R}_T)_i}{M_h} H_1^\triangleleft$$

$$\begin{array}{l} \longrightarrow \\ \longrightarrow \end{array} \left( \begin{array}{c} \uparrow \text{red arrow} \\ \bullet \end{array} \longrightarrow \begin{array}{c} \circ \\ \circ \end{array} \right) - \left( \begin{array}{c} \bullet \\ \downarrow \text{red arrow} \end{array} \longrightarrow \begin{array}{c} \circ \\ \circ \end{array} \right)$$

$D_1, G_1^\perp$  chiral-even ; le H chiral odd ;  $D_1$  T-even ; le altre T-odd



$$\left\{ \begin{array}{l} \mathbf{R}_T^2 = \xi (1-\xi) M_h^2 - (1-\xi) M_1^2 - \xi M_2^2 \\ \Delta^{(\Gamma)} \propto \int dk^+ dk^- \delta(k^- - P_h^- / z) \dots \\ \mathbf{P}_{hT} = 0 \\ P_1^2 = M_1^2 \\ P_2^2 = M_2^2 \end{array} \right. \quad \xi = P_1^- / P_h^-$$

$\Rightarrow$  5 variabili indipendenti

$$\Delta^{(\Gamma)}(z, \xi, \mathbf{k}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T, \mathbf{R}_T^2)$$

$\swarrow \quad \searrow$   
 $P_1 \quad P_2$

orientazione di  $\mathbf{k}$  rispetto a  $(P_1, P_2)$

orientazione relativa di  $(P_1, P_2)$



$$\Delta(z, \xi, M_h^2, \phi_R) = \frac{1}{4z} \int dk^+ d\mathbf{k}_T \Delta(k, P_h, R) \Big|_{k^- = P_h^- / z} = \frac{1}{2} \left\{ D_1 + i \frac{\mathcal{R}_T}{M_h} H_1^\triangleleft \right\} \frac{1}{2} \gamma^+$$

$$\text{Tr} [\Delta \gamma^-] \equiv \Delta_{\chi\chi'}$$

T-odd, chiral-odd

$$\Delta_{\chi\chi'} = \left( \begin{array}{c|c} \chi=R, \chi'=R & \chi=R, \chi'=L \\ \hline D_1(z, \xi, M_h^2) & ie^{i\phi_R} \frac{|\mathbf{R}_T|}{M_h} H_1^\triangleleft(z, \xi, M_h^2) \\ \hline -ie^{-i\phi_R} \frac{|\mathbf{R}_T|}{M_h} H_1^\triangleleft(z, \xi, M_h^2) & D_1(z, \xi, M_h^2) \end{array} \right)$$

$$\|\Delta\| \geq 0 \rightarrow$$

$$D_1 \geq 0; D_1 \geq \frac{|\mathbf{R}_T|}{M_h} |H_1^\triangleleft|$$

proiezioni  
al twist 3 :

$$\Delta^{[\mathbf{1}]} = E \quad \Delta^{[\gamma^i]} = \frac{\epsilon_T^{ij} R_T^j}{M_h} D^{\triangleleft'} + \frac{\epsilon_T^{ij} k_T^j}{M_h} D^\perp$$

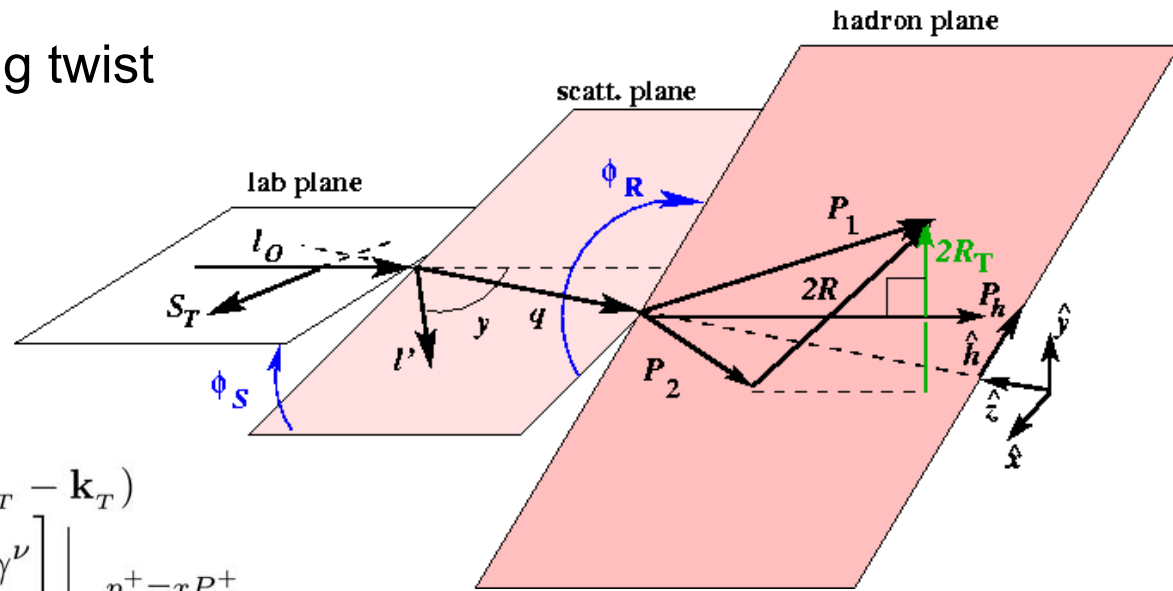
$$\Delta^{[\gamma_5]} = 0 \quad \Delta^{[\gamma^i \gamma_5]} = \gamma_5 \frac{\epsilon_T^{ij} \gamma^i R_T^j}{M_h} G^{\triangleleft'} + \gamma_5 \frac{\epsilon_T^{ij} \gamma^i k_T^j}{M_h} G^\perp$$

$$\Delta^{[\sigma^{ij}]} = H^{\triangleleft} \quad \Delta^{[\sigma^{-+}]} = H \quad \Delta^{[\sigma^{i+}]} = 0$$

$$\int d\vec{k}_T \Delta^{[\Gamma]} = \Delta(z, \xi, M_h^2, \phi_R) = \frac{M_h \sqrt{2}}{4zQ} \left\{ E + \frac{\mathcal{R}_T}{M_h} D^{\triangleleft} + \sigma^{+-} H + \gamma_5 \frac{\epsilon_T^{ij} \gamma^i R_T^j}{M_h} G^{\triangleleft} \right\}$$

$e p^\uparrow \rightarrow e' (H_1 H_2) X$  al leading twist

(Radici et al., P.R.**D65**('02)074031)



$$2MW^{\mu\nu} = \int d\mathbf{q}_T \int d\mathbf{k}_T d\mathbf{p}_T \delta(\mathbf{p}_T + \mathbf{q}_T - \mathbf{k}_T) \text{Tr} \left[ \int dp^- \Phi \gamma^\mu \int dk^+ \Delta \gamma^\nu \right] \Big|_{\substack{p^+ = xP^+ \\ k^- = P_h^- / z}}$$

$$\frac{d\sigma}{dx dy dz d\xi dM_h^2 d\phi_S d\phi_R} = \Phi_{\chi'_1 \chi_1}(x, S) \left( \frac{d\sigma^{el}}{dy} \right)_{\chi_1 \chi'_1} \Delta_{\chi'_2 \chi_2}(z, \xi, M_h^2, \phi_R)$$

$$= d\sigma_{OO} \rightarrow \dots f_1(x) D_1(z, \xi, M_h^2)$$

$$+ d\sigma_{OL} \rightarrow 0$$

$$+ d\sigma_{OT} \rightarrow \dots \frac{|\mathbf{S}_T| |\mathbf{R}_T|}{M_h} \sin(\phi_S + \phi_R) h_1(x) H_1^\chi(z, \xi, M_h^2)$$

non c'è effetto Sivers ; non c'è dipendenza esplicita da  $\mathbf{P}_{h\perp}$   
 $\rightarrow$  fattorizzazione collineare

# SSA nell'angolo azimutale $\phi_R$

$$A_{OT}^{\sin \phi} = \frac{\int d\phi_S d\phi_R d\xi \sin(\phi_S + \phi_R) [d\sigma(p^\uparrow) - d\sigma(p^\downarrow)]}{\int d\phi_S d\phi_R d\xi [d\sigma(p^\uparrow) + d\sigma(p^\downarrow)]} H_{1(R)}^{\triangleleft f}(z, M_h^2)$$

$$\propto |S_T| \frac{\sum_f e_f^2 h_1^f(x) \int d\xi d\phi_R \frac{|\mathbf{R}_T|}{2M_h} H_1^{\triangleleft f}(z, \xi, M_h^2)}{\sum_f e_f^2 f_1^f(x) D_1^f(z, M_h^2)}$$

chiral-odd e T-odd

teorema di fattorizzazione non ancora dimostrato

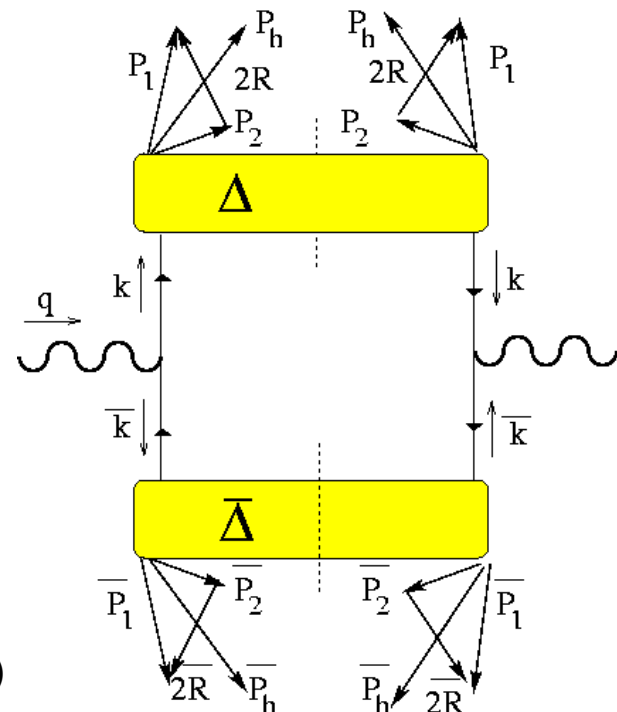
→ check empirico al twist 2

$$W^{\mu\nu} \sim 3 \int d\mathbf{k}_T d\bar{\mathbf{k}}_T \delta(\mathbf{k}_T + \bar{\mathbf{k}}_T - \mathbf{q}_T)$$

$$\times \text{Tr} \left[ \int d\bar{k}^- \bar{\Delta}(\bar{k}, \bar{P}_h, \bar{R}) \Big|_{\bar{k}^+ = \bar{P}_h^+ / \bar{z}} \gamma^\mu \right.$$

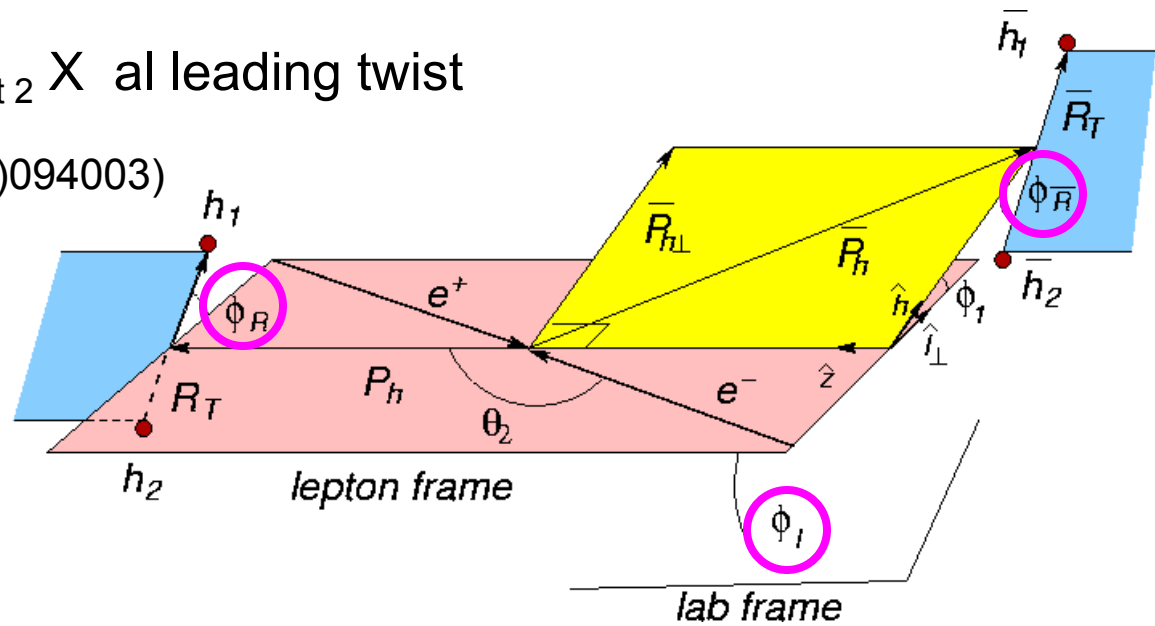
$$\left. \times \int dk^+ \Delta(k, P_h, R) \Big|_{k^- = P_h^- / z} \gamma^\nu \right]$$

(Artru & Collins, Z.Phys. **C69**('96)277)



$e^+e^- \rightarrow (\pi^+ \pi^-)_{\text{jet } 1} (\pi^+ \pi^-)_{\text{jet } 2} X$  al leading twist

(Boer, Jakob & Radici, P.R.D67('03)094003)



$$\frac{d\sigma}{dzd\xi dM_h^2 d\phi_R d\bar{z} d\bar{\xi} d\bar{M}_h^2 d\bar{\phi}_R d\mathbf{q}_T dy d\phi_l} = \frac{6\alpha^2}{Q^2} z^2 \bar{z}^2 \left\{ \dots + \cos(\phi_R + \bar{\phi}_R - 2\phi_l) \right. \\ \left. \times B(y) |\mathbf{R}_T| |\bar{\mathbf{R}}_T| \mathcal{F} \left[ \frac{H_1^\Delta \bar{H}_1^\Delta}{M_h \bar{M}_h} \right] + \dots \right\}$$

asimmetria azimutale di "Artru-Collins"

$$A_H(y, z, M_h^2, \bar{z}, \bar{M}_h^2) = \frac{\int \frac{d\phi_l}{2\pi} d\phi_R d\xi d\bar{\phi}_R d\bar{\xi} d\mathbf{q}_T \cos(\phi_R + \bar{\phi}_R - 2\phi_l) d\sigma}{\int \frac{d\phi_l}{2\pi} d\phi_R d\xi d\bar{\phi}_R d\bar{\xi} d\mathbf{q}_T d\sigma} = \\ = \frac{\langle \cos(\phi_R + \bar{\phi}_R - 2\phi_l) \rangle}{\langle 1 \rangle} \propto \frac{\sum_f e_f^2 H_{1(R)}^{\Delta f} \bar{H}_{1(R)}^{\Delta f}}{\sum_f e_f^2 D_1^f \bar{D}_1^f}$$

la stessa che in SIDIS

$H_1^{\rightarrow}$  T-odd  $\rightarrow$  legata a **FSI**; ma quali meccanismi? Poiche' il correlatore  $\Delta$  coinvolge  $\sum_X \dots |P_1 P_2 X\rangle \langle P_1 P_2 X| \dots$  sugli stati intermedi del jet residuo  $\rightarrow$  le FSI  $H_i \leftrightarrow \text{jet}$ ,  $i=1,2$ , sono "mediate via", mentre rimane la **FSI**  $H_1 \leftrightarrow H_2$

FSI richiede due canali comparabili, A e B, che portino allo stesso stato finale quindi  $|T|^2 \sim \text{Im}\{A B^*\}$   $\leftarrow$  interferenza dipende dalla differenza di fase

da qui il nome di **I**nterference **F**ragmentation **F**unctions

$(H_1, H_2) = (\pi, \pi), (\pi, K), (K, K) \dots$

$|\pi_1 \pi_2, X\rangle \sim |(\pi_1 \pi_2)_{L=0}\rangle + |(\pi_1 \pi_2)_{L=1}\rangle + \dots$

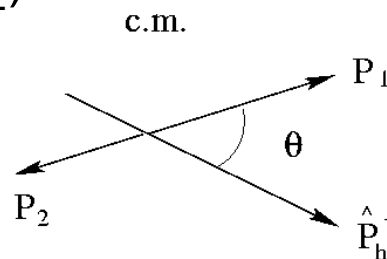
interferenza tra " $\sigma$ "  $\rightarrow (\pi \pi)_{L=0}$  e " $\rho$ "  $\rightarrow (\pi \pi)_{L=1}$

nel c.m. del sistema  $(\pi_1 \pi_2)$

$$P_1^2 = M_1^2, P_2^2 = M_2^2$$

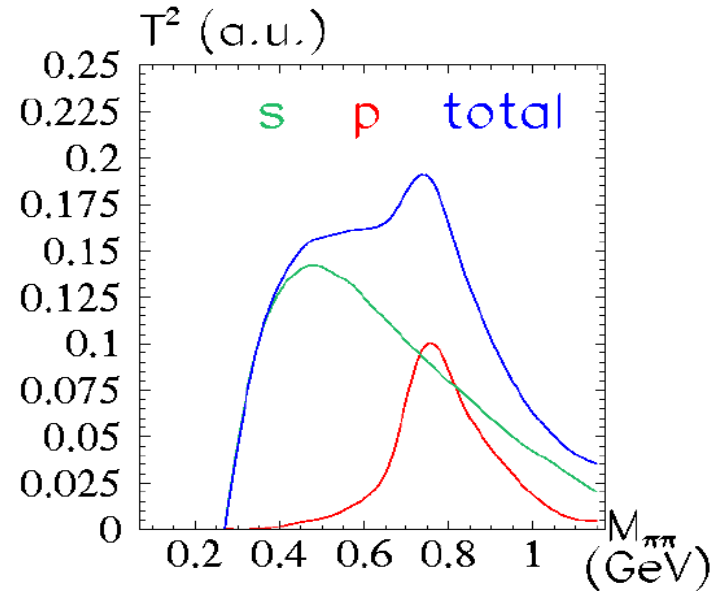
$$P_1 + P_2 = P_h = (M_h, \mathbf{0})$$

$$P_1 = -P_2 = \mathbf{R}$$



$$\rightarrow \xi = a(M_1, M_2, M_h) + b(M_1, M_2, M_h) \cos \theta$$

$$\rightarrow \Delta_{\chi\chi'}(z, \xi(\cos \theta), M_h^2) = \sum_n \Delta_{\chi\chi', n}(z, M_h^2) P_n(\cos \theta)$$



$$\Delta_{\chi\chi'}(z, \xi(\cos \theta), M_h^2) = \sum_n \Delta_{\chi\chi',n}(z, M_h^2) P_n(\cos \theta)$$

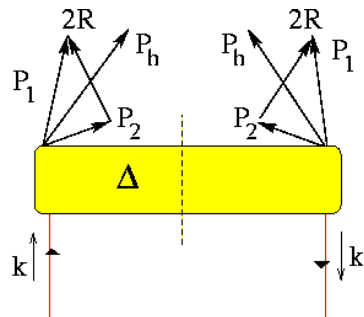
$$n=0 \quad P_0 = 1 \quad 1 \quad 1 \quad \rightarrow \quad \Delta_{\chi\chi',0} \equiv \Delta_{\chi\chi',OO}$$

$$n=1 \quad P_1 = \cos \theta \quad 1 \quad \cos \theta \quad \rightarrow \quad \Delta_{\chi\chi',1} \equiv \Delta_{\chi\chi',OL}$$

$$\sin \theta \quad 1 \quad \sin \theta \quad \rightarrow \quad \equiv \Delta_{\chi\chi',OT}$$

$$n=2 \quad 1 \quad P_2 \quad \rightarrow \quad \Delta_{\chi\chi',2} \equiv \Delta_{\chi\chi',LL}$$

$$P_2 = \frac{1}{4}(3 \cos^2 \theta - 1)$$



$$\Delta_{\chi\chi'}(z, \xi(\cos \theta), M_h^2) = \sum_{LM, L'M'} (\Delta_{\chi\chi'})_{LM}^{L'M'} 4\pi Y_{LM} Y_{L'M'}^*$$

$$\equiv \sum_{LM, L'M'} (\Delta_{\chi\chi'})_{LM}^{L'M'}(z, M_h^2) D_{LM}^{L'M'}(\theta, \phi_R)$$

$$\Delta = \left( \begin{array}{c|c} \Delta_{RR} & \Delta_{RL} \\ \hline \Delta_{RL}^* & \Delta_{RR} \end{array} \right)$$

$$\Delta_{\chi\chi'} = \left( \begin{array}{c|ccc} \mathbf{s} & \mathbf{p,1} & \mathbf{p,0} & \mathbf{p,-1} \\ \hline (\Delta_{\chi\chi'})_{00}^{00} & (\Delta_{\chi\chi'})_{00}^{11} & (\Delta_{\chi\chi'})_{00}^{10} & (\Delta_{\chi\chi'})_{00}^{1-1} \\ (\Delta_{\chi\chi'})_{11}^{00} & (\Delta_{\chi\chi'})_{11}^{11} & (\Delta_{\chi\chi'})_{11}^{10} & (\Delta_{\chi\chi'})_{11}^{1-1} \\ (\Delta_{\chi\chi'})_{10}^{00} & (\Delta_{\chi\chi'})_{10}^{11} & (\Delta_{\chi\chi'})_{10}^{10} & (\Delta_{\chi\chi'})_{10}^{1-1} \\ (\Delta_{\chi\chi'})_{1-1}^{00} & (\Delta_{\chi\chi'})_{1-1}^{11} & (\Delta_{\chi\chi'})_{1-1}^{10} & (\Delta_{\chi\chi'})_{1-1}^{1-1} \end{array} \right) \begin{array}{l} \mathbf{s} \\ \mathbf{---} \\ \mathbf{p,1} \\ \mathbf{p,0} \\ \mathbf{p,-1} \end{array}$$

quindi IFF T-odd da interferenza onde s-p oppure p-p

e  $p^\uparrow \rightarrow e' (H_1 H_2) X$  al leading twist

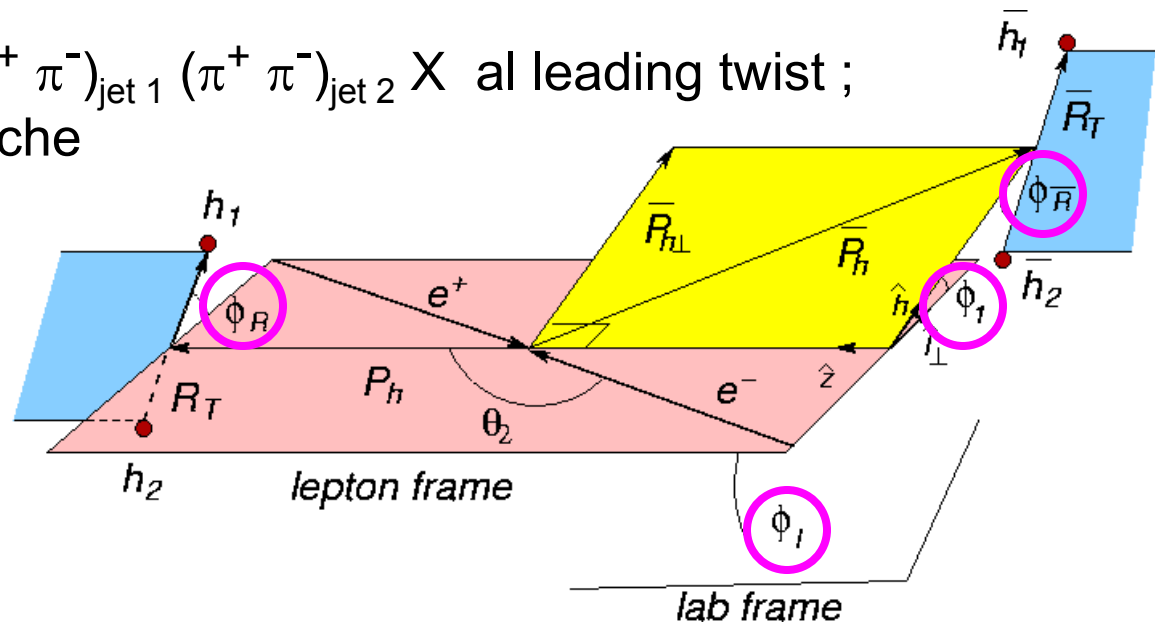
$$\begin{aligned} \frac{d\sigma_{OT}}{dx dy dz d\xi dM_h^2 d\phi_R d\phi_S} &= \\ &= \Phi_{\chi'_1\chi_1}(x, S) \left( \frac{d\sigma^{el}}{dy} \right)_{\chi_1\chi'_1}^{\chi_2\chi'_2} \left( \Delta_{\chi'_2\chi_2} \right)_{LM}^{L'M'}(z, M_h^2) D_{LM}^{L'M'}(\theta, \phi_R) \\ &\propto \frac{|\mathbf{S}_T| |\mathbf{R}| \sin \theta}{M_h} \sin(\phi_R + \phi_S) h_1(x) \left( H_{1,OT}^\chi + H_{1,LT}^\chi \cos \theta \right) \end{aligned}$$

2 modi diversi di isolare  $h_1$  !

legato a frammentazione di spin 1 ( $\rho$ )

riconsideriamo  $e^+e^- \rightarrow (\pi^+ \pi^-)_{\text{jet } 1} (\pi^+ \pi^-)_{\text{jet } 2} X$  al leading twist ;  
 la sez. d'urto contiene anche

(Boer, Jakob & Radici,  
 P.R. **D67**('03)094003)



$$\frac{d\sigma}{dz d\xi dM_h^2 d\phi_R d\bar{z} d\bar{\xi} d\bar{M}_h^2 d\bar{\phi}_R d\mathbf{q}_T dy d\phi_l} = \frac{6\alpha^2}{Q^2} z^2 \bar{z}^2 \left\{ \dots + A(y) |\mathbf{R}_T| |\bar{\mathbf{R}}_T| \right.$$

$$\times \left[ \sum_i A_i(\phi_1, \phi_R, \phi_l) \mathcal{F} \left[ B_i(\hat{h}, \hat{g}, \mathbf{k}_T, \bar{\mathbf{k}}_T) \frac{G_1^\perp}{M_h^2} \frac{\bar{G}_1^\perp}{\bar{M}_h^2} \right] \right] \dots \left. \right\}$$

asimmetria azimutale di “jet handedness”

$$A_G(y, z, M_h^2, \bar{z}, \bar{M}_h^2) = \frac{\int \frac{d\phi_l}{2\pi} d\phi_R d\xi d\bar{\phi}_R d\bar{\xi} d\mathbf{q}_T \cos 2(\phi_R - \bar{\phi}_R) d\sigma}{\int \frac{d\phi_l}{2\pi} d\phi_R d\xi d\bar{\phi}_R d\bar{\xi} d\mathbf{q}_T d\sigma} = \frac{\langle \cos 2(\phi_R - \bar{\phi}_R) \rangle}{\langle 1 \rangle}$$

$$\propto \frac{\sum_f e_f^2 G_{1\ominus}^{\perp f} \bar{G}_{1\ominus}^{\perp f}}{\sum_f e_f^2 D_1^f \bar{D}_1^f}$$

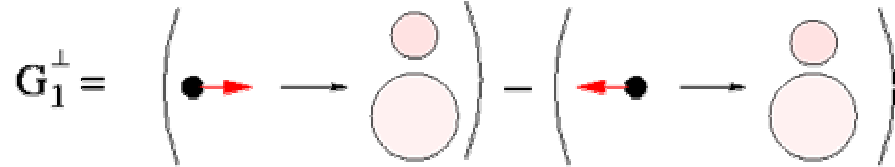


asimmetria dipende da

$$G_{1\circlearrowleft}^\perp(z, M_h^2) \equiv \int d\xi d\phi_R d\vec{k}_T \quad \vec{k}_T \cdot \vec{R}_T \quad G_1^\perp(z, \xi, \vec{k}_T^2, \vec{R}_T^2, \vec{k}_T \cdot \vec{R}_T)$$

N.B. : caso unico di IFF chiral-even con quark long. polarizzato ; infatti

$$\int d\xi d\phi_R d\vec{k}_T G_1^\perp(z, \xi, \vec{k}_T^2, \vec{R}_T^2, \vec{k}_T \cdot \vec{R}_T) = 0 \quad \text{per conservazione di parita'}$$

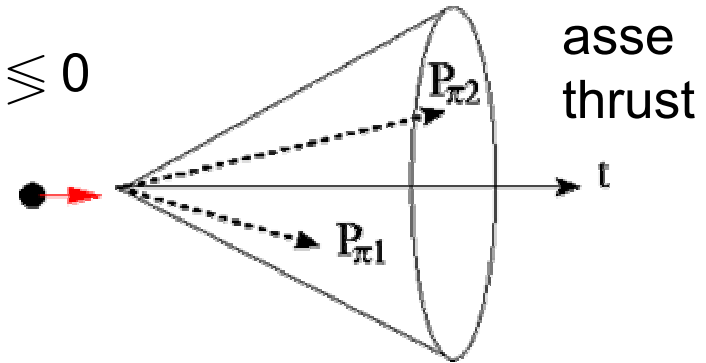


“jet handedness” D :  $N_{R/L} \leftrightarrow \vec{P}_{\pi_1} \times \vec{P}_{\pi_2} \cdot \vec{t} \leq 0$

analogia

$$D \leftrightarrow (\mathbf{k}_T \times \mathbf{R}_T) G_1^\perp$$

$$D = \frac{N_R - N_L}{N_R + N_L} \propto P_q$$



$$e^+e^- \rightarrow (\pi^+\pi^-)_{\text{jet } 1} (\pi^+\pi^-)_{\text{jet } 2} X$$

$N_{R/L}$

$N_{R/L}$

$\rightarrow$  correlazione di handedness

$$C = \frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}$$

$$A_G \propto \frac{\sum_f e_f^2 G_{1\circlearrowleft}^\perp G_{1\circlearrowright}^\perp}{\sum_f e_f^2 D_1^f \bar{D}_1^f}$$

estraendo  $G_1^\perp$  da

$$e + \vec{p} \rightarrow (\pi\pi)X$$

$$d\sigma \sim \{ \dots \mathcal{F} [ \dots g_1 G_1^\perp ] \dots \}$$

pQCD :  $C < 0$     dati :  $C > 0 !$

$\rightarrow$  violazione di CP

ruolo del vuoto di QCD ?