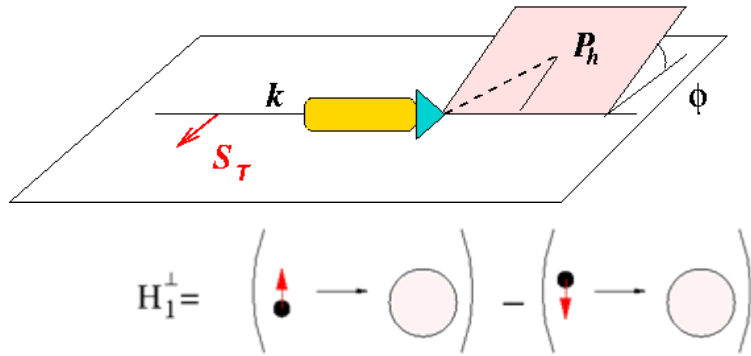


Riassunto della lezione precedente

- importanza del momento trasverso intrinseco dei partoni
 - sezione d'urto più ricca → nuove possibilità per estrarre la trasversità
 - effetto Collins : meccanismo non perturbativo che lega spin del quark a moto orbitale dell'adrone finale

N.B. Funzione di Collins è naïve T-odd
per FSI tra adrone e jet residuo
→ nuova classe di funzioni

effetto Collins in SIDIS $e p^\uparrow \rightarrow e' \pi^\pm X$

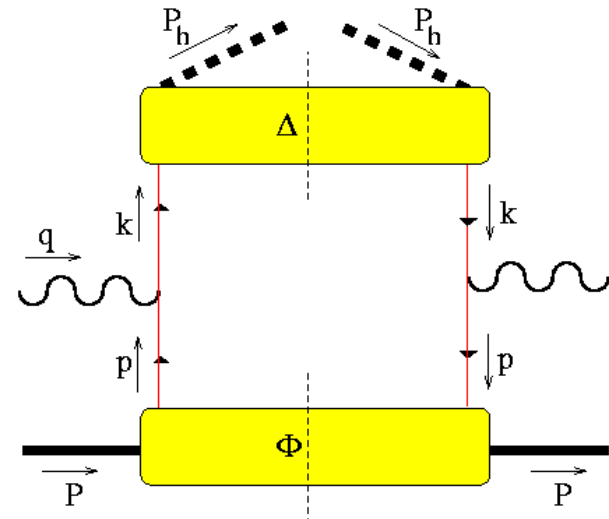


$$H_1^\perp = \left(\begin{array}{c} \uparrow \\ \bullet \end{array} \rightarrow \text{circle} \right) - \left(\begin{array}{c} \bullet \\ \downarrow \end{array} \rightarrow \text{circle} \right)$$

$$h_{1T} = \begin{array}{c} \uparrow \\ \uparrow \end{array} \begin{array}{c} \bullet \\ \bullet \end{array} - \begin{array}{c} \uparrow \\ \downarrow \end{array} \begin{array}{c} \bullet \\ \bullet \end{array}$$

asimmetria in Collins angle

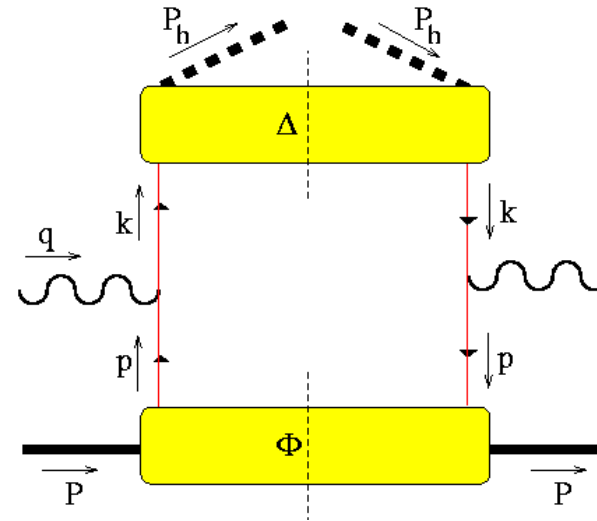
$$\sin \phi_C \propto \mathbf{k} \times \mathbf{P}_h \cdot \mathbf{S}_T$$



effetto Collins in SIDIS $e p^\uparrow \rightarrow e' \pi^\pm X$

Δ	chiral even	chiral-odd
	q	q^\uparrow
π	D_1	H_1^\perp

Φ	chiral even	chiral-odd
	q	q^\uparrow
p	f_1	h_1^\perp
$p^\uparrow = T$	f_{1T}^\perp	g_{1T}, h_{1T}^\perp

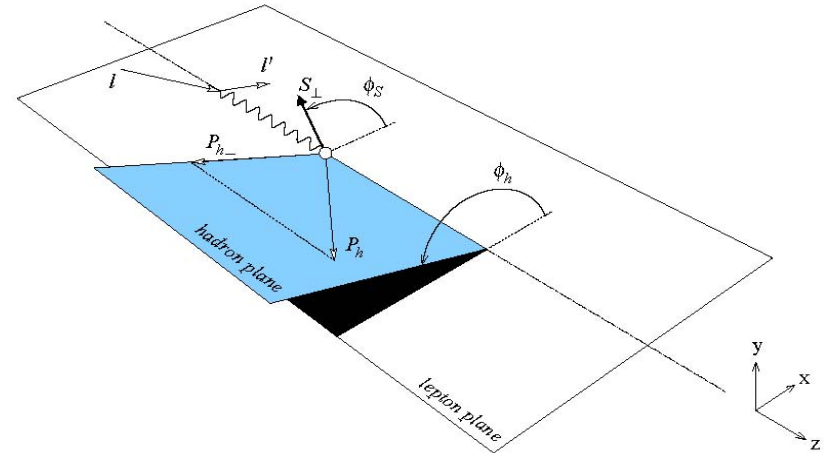
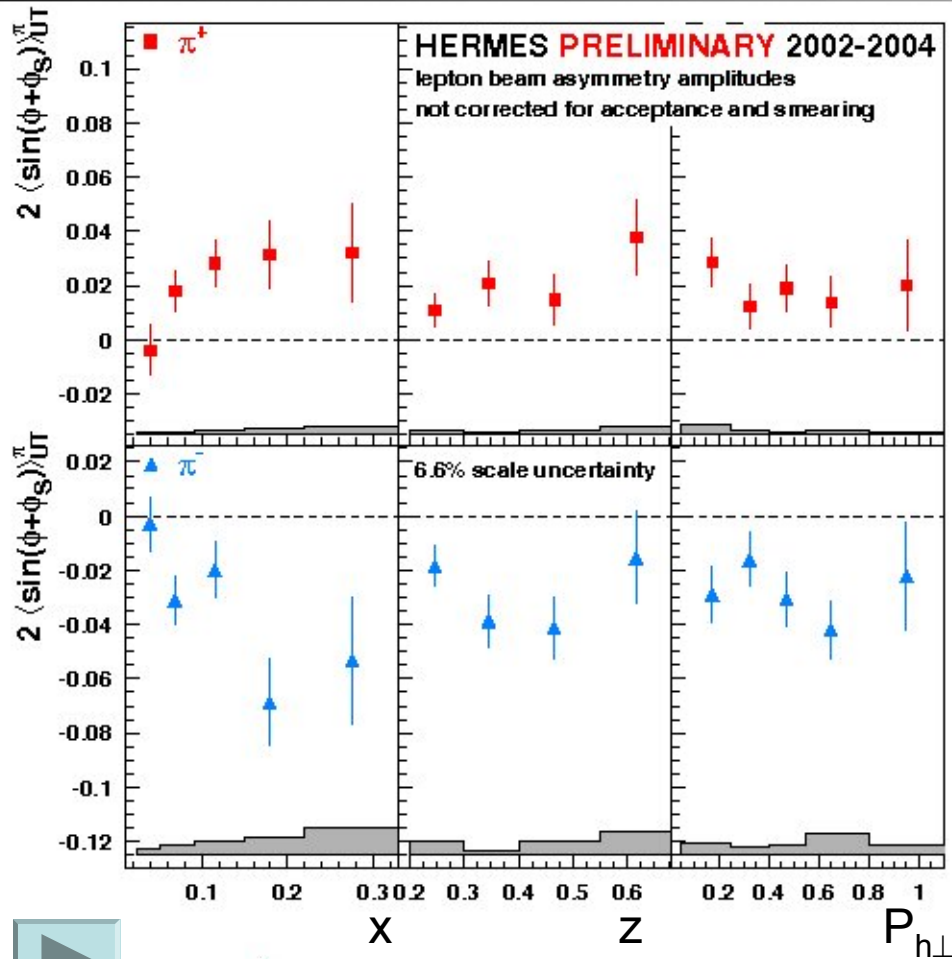


$$\frac{d^6 \sigma_{OT}}{dx dy dz d\phi_S d\mathbf{P}_{h\perp}} = \frac{2\alpha^2}{sxy^2} \sum_{f, \bar{f}} e_f^2 \left\{ A(y) \mathcal{F} \left[f_1^f(x, \mathbf{p}_T^2) D_1^f(z, \mathbf{P}_{hT}^2) \right] \right. \\ \left. + |\mathbf{S}_T| B(y) \underbrace{\sin(\phi_h + \phi_S)}_{\phi_C \text{ angolo di Collins}} \mathcal{F} \left[\frac{\mathbf{k}_T \cdot \hat{\mathbf{P}}_{h\perp}}{M_h} h_1^f(x, \mathbf{p}_T^2) H_1^{\perp f}(z, \mathbf{P}_{hT}^2) \right] \right\}$$

$$A_{UT} = \left[\int d\phi_h d\phi_S \sin(\phi_h + \phi_S) [d\sigma^\uparrow - d\sigma^\downarrow] \right] / \left[\int d\phi_h d\phi_S [d\sigma^\uparrow + d\sigma^\downarrow] \right]$$

$$e p^{\uparrow} \rightarrow e' \pi^{\pm} X$$

Airapetian *et al.*, HERMES
P.R.L. **94** (05) 012002



$$N^{\uparrow} = p^{\uparrow} = \{u^{\uparrow} d^{\downarrow} u^{\uparrow}\}$$

$$\vec{k}(\parallel \hat{z}) \times \vec{P}_h(\parallel \hat{x}) \cdot \vec{S}_T(\parallel \hat{y}) \rightarrow \sin \phi_C > 0$$

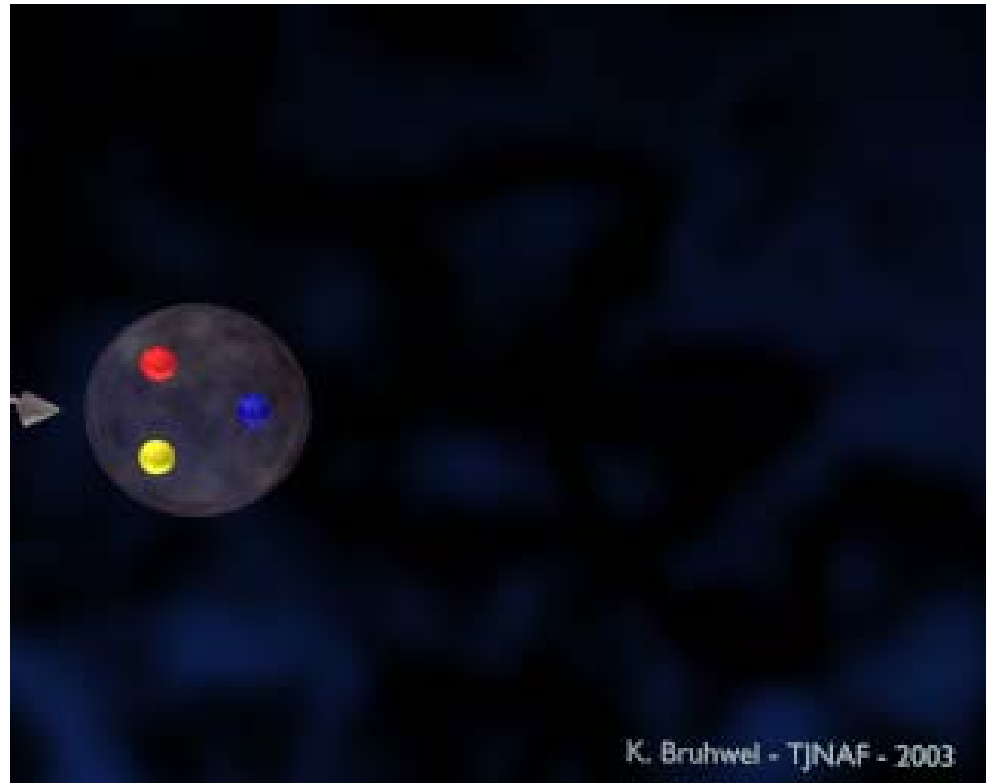
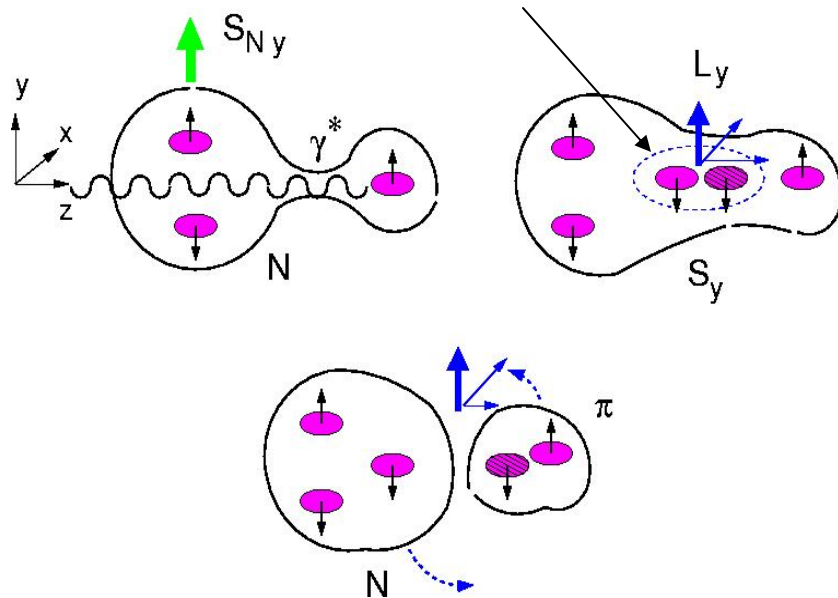
$$\left. \begin{array}{l} \phi_S = \pi/2 \\ \phi = 0 \end{array} \right\} \sin(\phi + \phi_S) > 0$$

$$u \text{ dominance} \rightarrow h_1^u H_1^{\perp(1)u} > 0$$

Congettura semi-classica : poichè γ^* colpisce $q^\uparrow \rightarrow$ la stringa di forza di colore tra q^\uparrow e il diquark (qq) ha un momento angolare orbitale; quando la stringa si rompe, la coppia quark-antiquark porta momento angolare orbitale e determina l'asimmetria azimutale nell'emissione dell'adrone finale osservato (Artru , hep-ph/9310323)

quantici vuoto $J^{PC} = 0^{++}$

quarkonio ha $S=1 \rightarrow 2S+1L_J = 3P_0$



K. Bruhwal - TJNAF - 2003



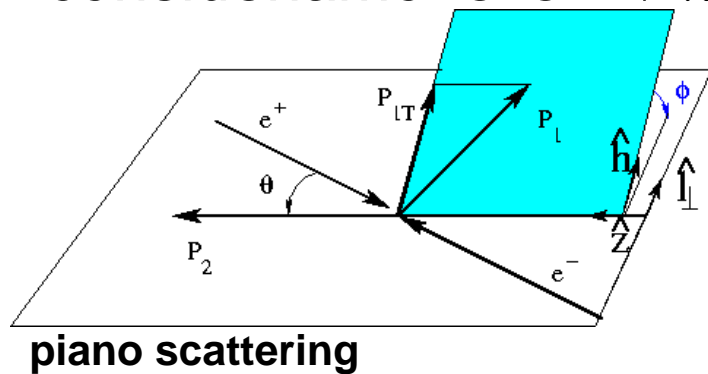
Trasversità e funzione di Collins

incognita h_1 estraibile attraverso nuova incognita H_1^\perp ;
come avere informazioni su H_1^\perp ?

Ji, Ma, Yuan P.R. D71 (04); P.L. **B597** (04)
Collins, Metz P.R.L. **93** (04)

1. dimostrazione di fattorizzazione per SIDIS con funzioni non integrate in \mathbf{p}_T
2. ipotesi di universalità di PDF e PFF (dimostrazione valida solo a twist 2)
3. estrazione di PFF (funzione di Collins H_1^\perp) da $e^+e^- \rightarrow \pi^+\pi^- X$

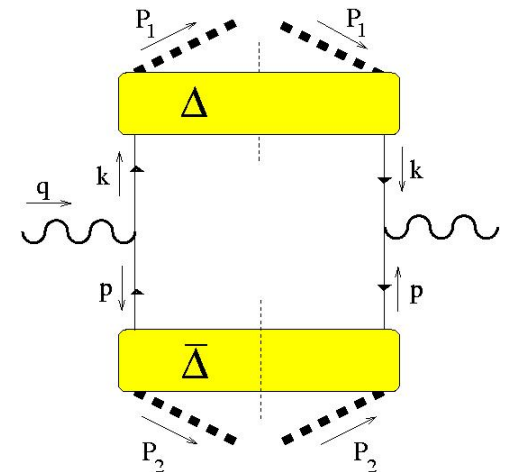
consideriamo $e^+e^- \rightarrow \pi^+\pi^- X$



leading twist

$$z_1 = \frac{P_{h1}^-}{k_1^-}$$

$$z_2 = \frac{P_{h2}^+}{k_2^+}$$

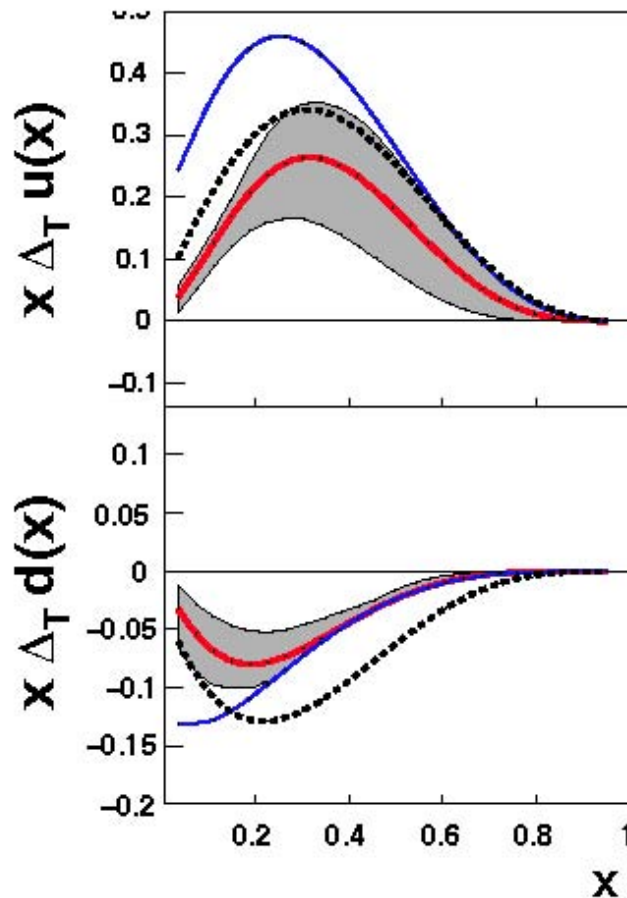


$$\frac{\int d\phi d\mathbf{q}_T \mathbf{q}_T^2 \cos 2\phi \frac{d\sigma}{d\Omega dz_1 dz_2 d\mathbf{q}_T}}{\int d\phi d\mathbf{q}_T \frac{d\sigma}{d\Omega dz_1 dz_2 d\mathbf{q}_T}} = \frac{2 \sin^2 \theta}{1 + \cos^2 \theta} \frac{\sum_{f\bar{f}} e_f^2 H_1^{\perp f(1)}(z_1) \bar{H}_1^{\perp f(1)}(z_2) + (1 \leftrightarrow 2)}{\sum_{f\bar{f}} e_f^2 D_1^f(z_1) \bar{D}_1^f(z_2) + (1 \leftrightarrow 2)}$$

nessuna misura di polarizzazione necessaria !

(continua)

1. fit di dati da esperimento BELLE su e^+e^- a BNL (USA)
2. estrazione di $H_1^{\perp(1)q}(z)$ per $q=u,d$
3. fit di dati HERMES e COMPASS per SSA in SIDIS
4. estrazione di trasversità h_1^q per $q=u,d$
5. $H_1^{\perp(1)u} H_1^{\perp(1)\bar{u}} > 0$; $h_1^u H_1^{\perp(1)u} > 0$
6. si assume $H_1^{\perp(1)u} > 0 \rightarrow h_1^u > 0$



banda grigia = incertezza teorica
linea rossa = valore più probabile
linea blu = Soffer bound
linea tratteggiata = elicità

Anselmino *et al.*
N.P.Proc.Suppl. **191** (09) 98

Difetti della parametrizzazione della trasversità

- per processi dove PDF e PFF dipendono esplicitamente da momento trasverso intrinseco dei partoni, teorema di fattorizzazione dimostrato per:
 - Drell-Yan e e^+e^- (Collins, Soper, Sterman, N.P. **B250** (85) 199)
 - SIDIS solo a twist=2 per $P_{h\perp} \ll Q$ (Ji, Ma, Yuan, P.L. **B597** (04) 299;)
- inoltre nel calcolo delle correzioni radiative \rightarrow cancellazione tra contributi di gluoni soft reali e gluoni virtuali (fattorizzazione collineare) non succede \rightarrow “rottura della fattorizzazione collineare”

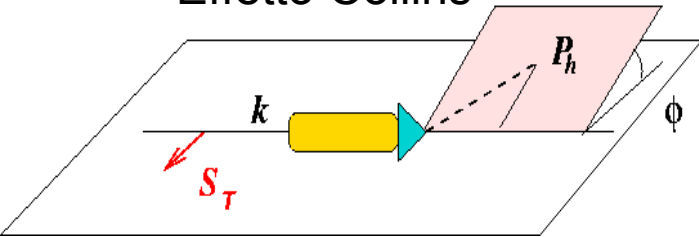
calcolo implica $\propto \int_{|P_{h\perp}|}^{Q^2} \rightarrow$ diluizione della SSA per $|P_{h\perp}| \ll Q^2$

- parametrizzazione attuale di h_1 ottenuta da analisi di dati a diverso Q^2 (SIDIS a $\langle Q^2 \rangle \approx 2.5 \text{ GeV}^2$, e^+e^- a $Q^2 \approx 100 \text{ GeV}^2$) e senza tener conto di evoluzione in $\mathbf{p}_T \rightarrow$ sovrastima di h_1 ?

\Rightarrow cercare SSA generata da partner chiral-odd di h_1 ma indipendente da momento intrinseco dei partoni

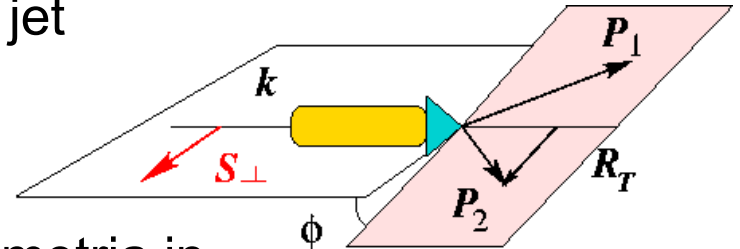
Dihadron Fragmentation Functions

Effetto Collins



$$\int d\mathbf{P}_{hT} \dots \mathbf{k} \times \mathbf{P}_{hT} \cdot \mathbf{S}_q \dots \rightarrow 0$$

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



asimmetria in

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

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

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

poi sviluppato in modo sistematico qui a Pavia)

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

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

$\int d\mathbf{P}_{h\perp} \rightarrow$ SSA in $\phi \equiv \phi_R \rightarrow$ fattorizzazione collineare (non c'è "diluizione" per fattori di forma di Sudakov)

equazioni di evoluzione note [Ceccopieri, Radici, Bacchetta, P.L. **B650** (07) 81]

informazioni su DiFF da sez. d'urto $e^+e^- \rightarrow (\pi^+\pi^-)(\pi^+\pi^-)$ X

esprimibile in forma fattorizzata \rightarrow segnale più "pulito"

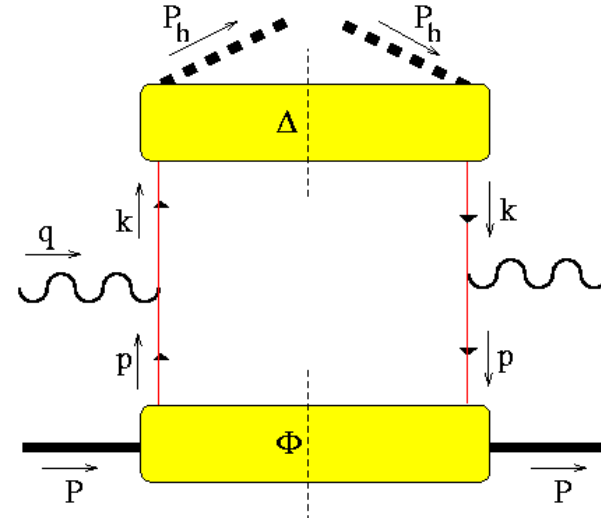
asimmetria generata dalla combinazione $h_1(x) H_1^{\nabla}(z, M_h^2)$



effetto Sivers in SIDIS $e p^\uparrow \rightarrow e' \pi^\pm X$

Δ	chiral even	chiral-odd
	q	q^\uparrow
π	D_1	H_1^\perp

Φ	chiral even	chiral-odd
	q	q^\uparrow
p	f_1	h_1^\perp
$p^\uparrow = T$	f_{1T}^\perp	h_1, h_{1T}^\perp

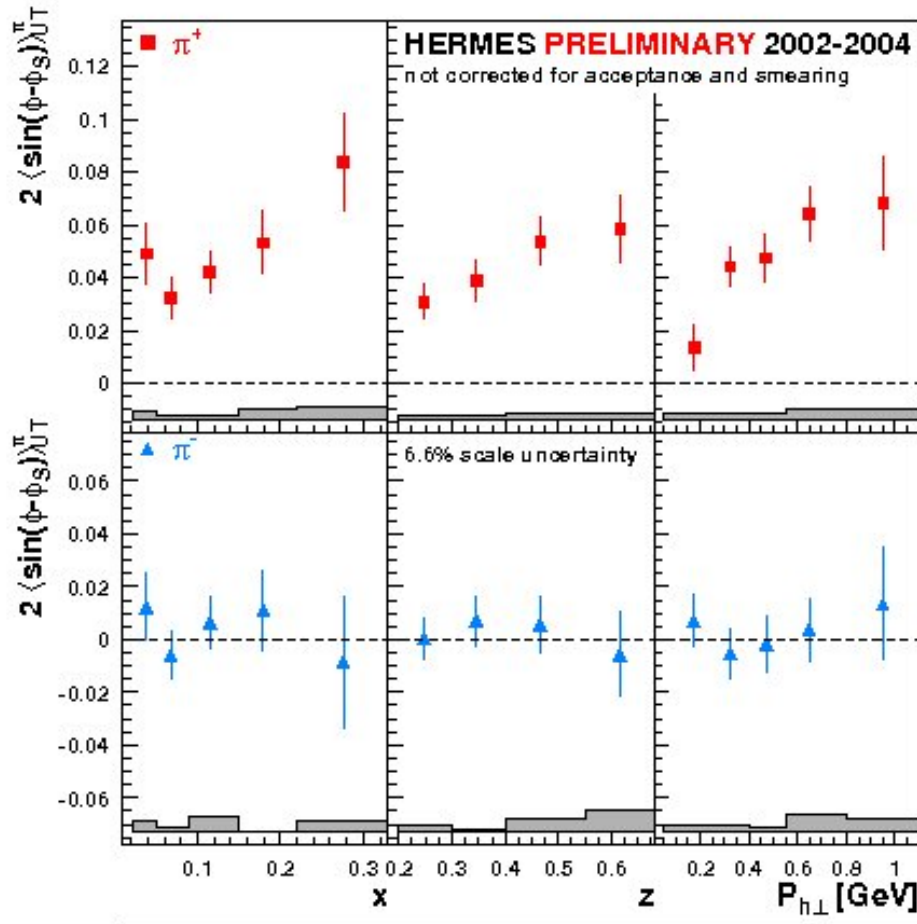


$$\frac{d^6 \sigma_{OT}}{dx dy dz d\phi_S d\mathbf{P}_{h\perp}} = \frac{2\alpha^2}{sxy^2} \sum_{f,\bar{f}} e_f^2 \left\{ A(y) \mathcal{F} \left[f_1^f(x, \mathbf{p}_T^2) D_1^f(z, \mathbf{P}_{hT}^2) \right] - |\mathbf{S}_T| B(y) \sin(\phi_h - \phi_S) \mathcal{F} \left[\frac{\mathbf{p}_T \cdot \hat{\mathbf{P}}_{h\perp}}{M} f_{1T}^\perp(x, \mathbf{p}_T^2) D_1^f(z, \mathbf{P}_{hT}^2) \right] \right\}$$

$$A_{UT} = \left[\int d\phi_h d\phi_S \sin(\phi_h - \phi_S) [d\sigma^\uparrow - d\sigma^\downarrow] \right] / \left[\int d\phi_h d\phi_S [d\sigma^\uparrow + d\sigma^\downarrow] \right]$$

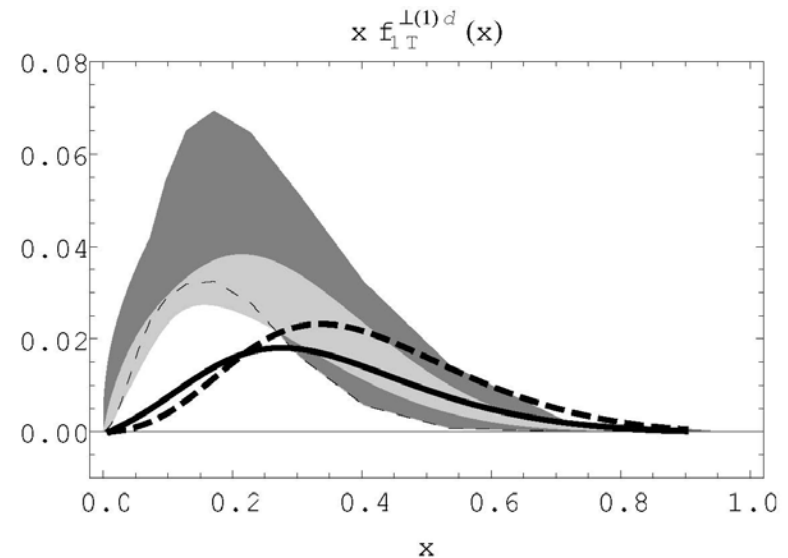
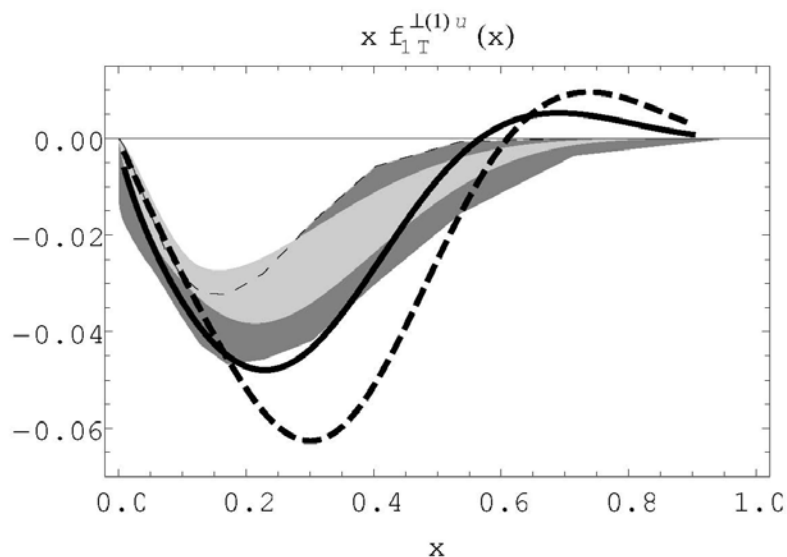
effetto Sivers e relativa **Single Spin Asymmetry**

$$\frac{\int d\phi_h \sin(\phi_h - \phi_S) (d\sigma^\uparrow - d\sigma^\downarrow)}{\int d\phi_h (d\sigma^\uparrow + d\sigma^\downarrow)} \propto -|S_T| \frac{B(y)}{A(y)} \frac{\sum_{f\bar{f}} e_f^2 f_{1T}^{\perp f(1)}(x) D_1^f(z)}{\sum_{f\bar{f}} e_f^2 f_1^f(x) D_1^f(z)}$$



π^+ positivo $\rightarrow f_{1T}^{\perp u}$ negativa
 $f_{1T}^{\perp d}$ positiva
 (piccola)

Diversi modelli per calcolare la funzione di Sivers, ma soprattutto nuove parametrizzazioni da analisi di dati di HERMES (dipendenti dal flavor), di BNL e di COMPASS



Anselmino *et al.*, E.P.J. **A39** (09) 89

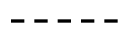
Collins *et al.*, P.R. **D73** (06) 014021

$Q^2 = 2.5$

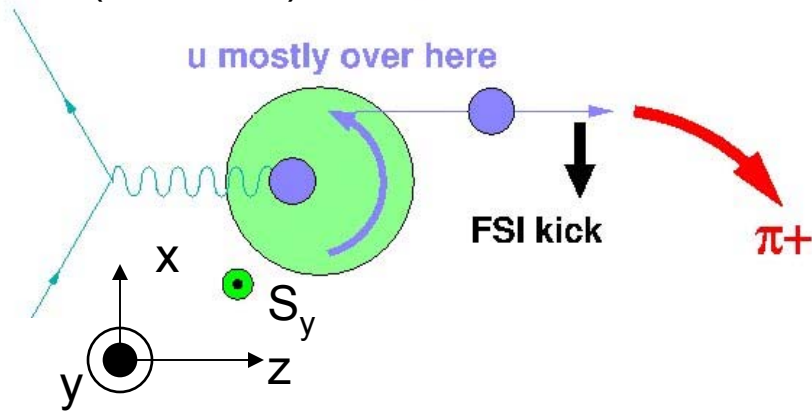


Bacchetta, Radici, Conti, Guagnelli, EPJ. **A45** (10) 373

$Q_0^2 = 0.3$



(continua)



$$\left. \begin{array}{l} \phi_S = \pi/2 \\ \phi = \pi \end{array} \right\} \sin(\phi - \phi_S) > 0$$

deflessione quark d a $x > 0$

possibile interpretazione:

$N^\uparrow \rightarrow$ distribuzione asimmetrica
nel piano trasverso: u va
a $x > 0$ e d va a $x < 0$

perché $S_y \neq 0 \rightarrow L_q \neq 0$

γ colpisce u che viene deflesso
a $x < 0$ per confinamento (forza
colore attrattiva); opposto per d
(Burkardt, Phys. Rev. D **66** ('02) 114005)

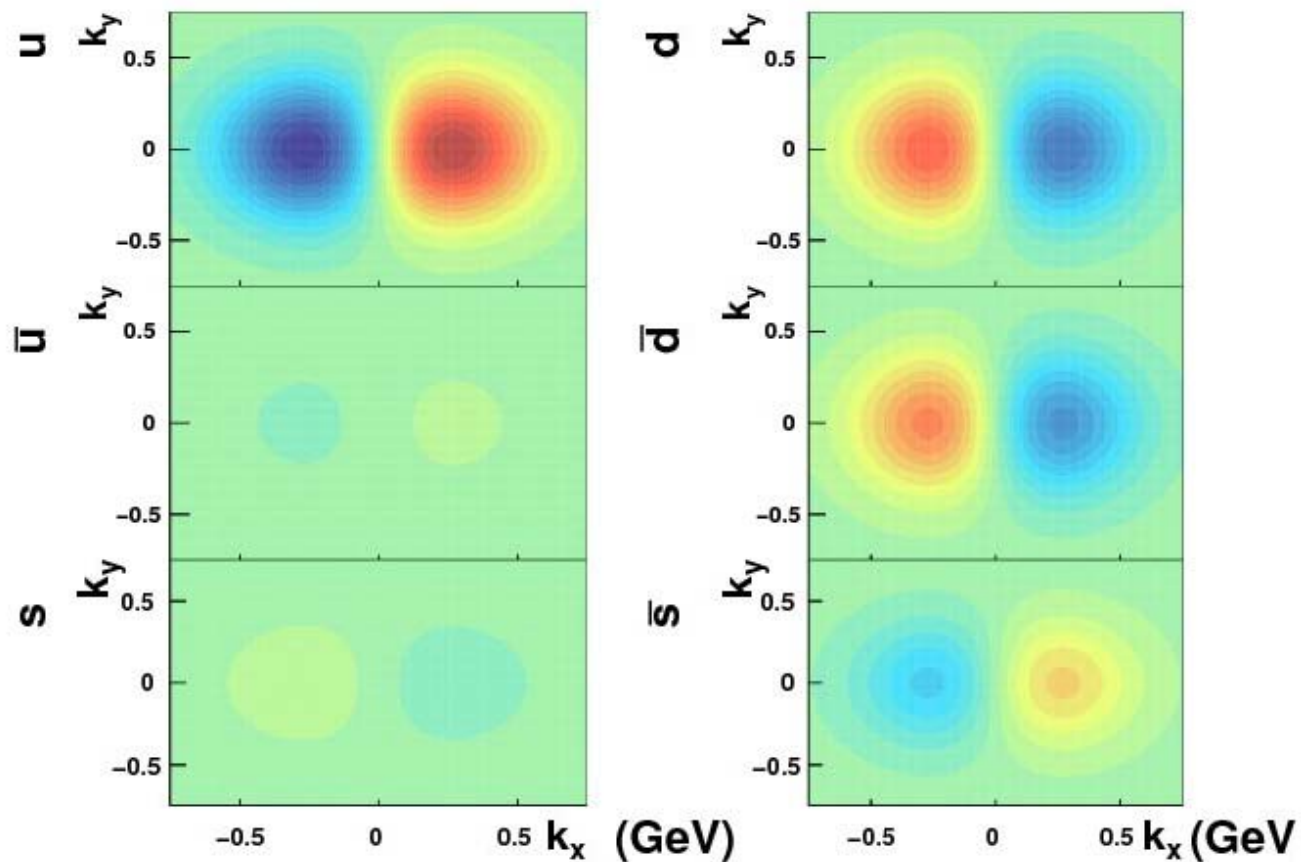
effetto diretto del momento
angolare orbitale dei quark



(continua)

distorsione nel piano trasverso della distribuzione di partoni provocata da polarizzazione trasversa del protone

rosso = + carica
blu = - carica



Invarianza per trasformazioni di $SU_c(3)$ di Φ e Δ

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

campi di quark a punti 4-dim. diversi

per $\psi(\xi) \rightarrow \exp[i\alpha(\xi)] \psi(\xi)$ si perde gauge invarianza

serve un operatore tale che $U(\xi_1, \xi_2) \rightarrow \exp[i\alpha(\xi_1)] U(\xi_1, \xi_2) \exp[-i\alpha(\xi_2)]$

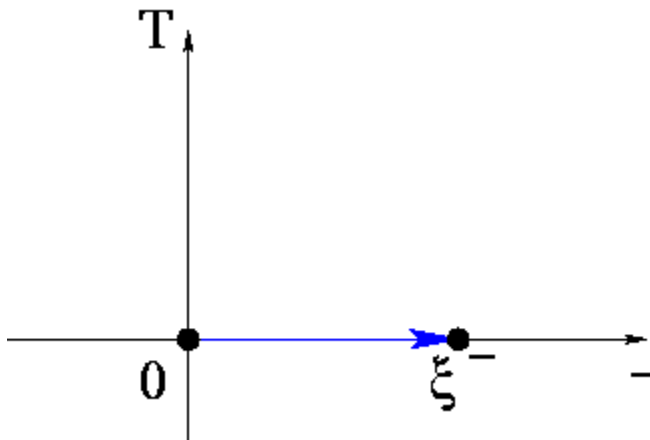
gauge-link (tower) operator



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



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



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

$A^+ = 0$ gauge \rightarrow def. precedente

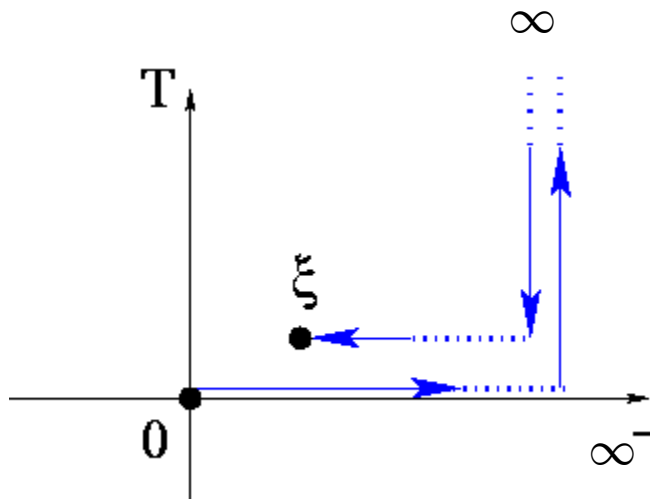
(continua)

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



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

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

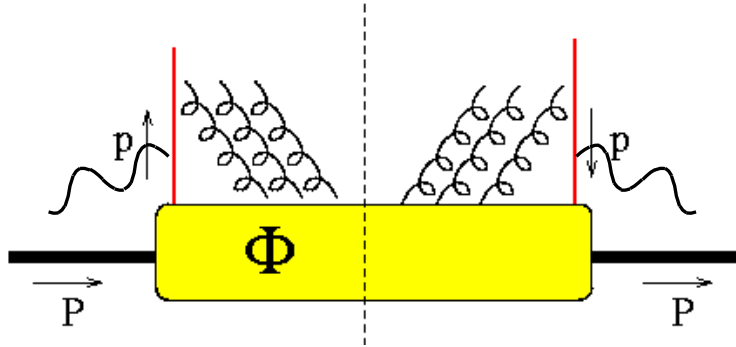
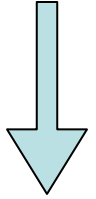


analisi in twist rivela che al twist 2
contribuiscono sia A^+ ,
che \mathbf{A}_T a $n_- = \infty$ eliminaibile in
axial gauge $A^+ = 0$
non eliminaibile nei gauge standard!

Φ invariante per trasformazioni di $SU_c(3)$

$$U_{[0,\xi^-]} = \mathcal{P} e^{-ig \int_0^{\xi^-} dw^- A^+(w^-)}$$

$$\approx 1 + (-ig) \int_0^{\xi^-} dw^- A^+(w^-) \Big|_{\dots} + (-ig)^2 \int_0^{\xi^-} dw_1^- A^+(w_1^-) \int_{w_1^-}^{\xi^-} dw_2^- A^+(w_2^-) \Big|_{\dots} + \dots$$



“FSI” tra quark e adrone via gluoni soffici
lungo direzione “+” e “T” a $n_+ = \infty$
 \Rightarrow strutture **naïve T-odd** permesse

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

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

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

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

$$+ \frac{(\mathbf{p}_T \times \hat{\mathbf{P}})_i}{M} h_1^\perp(x, \mathbf{p}_T^2)$$

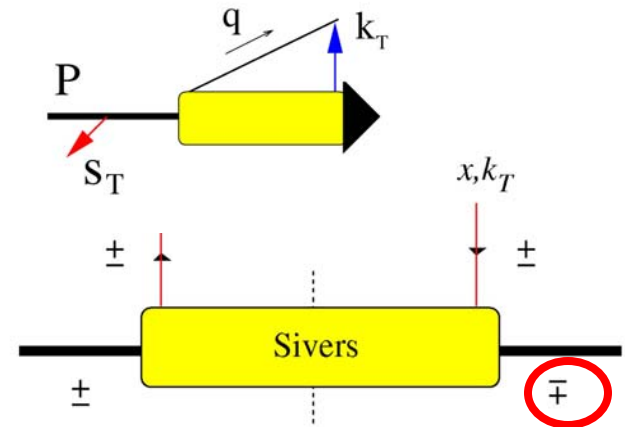
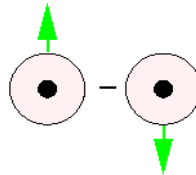
$$\int d\mathbf{p}_T \text{ (T-odd) } = 0$$

(continua)

$$f(q/p^\uparrow) = f_1^q(x, \mathbf{k}_T^2) - f_{1T}^{\perp q}(x, \mathbf{k}_T^2) \frac{\hat{\mathbf{P}} \times \mathbf{k}_T \cdot \mathbf{S}}{M}$$

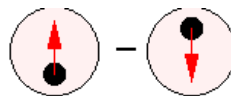
$$-f_{1T}^{\perp q}(x, \mathbf{k}_T^2) 2 \frac{\hat{\mathbf{P}} \times \mathbf{k}_T \cdot \mathbf{S}}{M} = f(q/p^\uparrow) - f(q/p^\downarrow)$$

funzione di Sivers

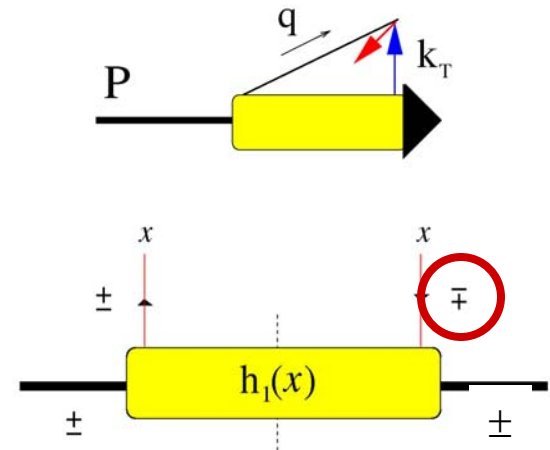


$$f(q^\uparrow/p) = \frac{1}{2} \left(f_1^q(x, \mathbf{k}_T^2) - h_1^{\perp q}(x, \mathbf{k}_T^2) \frac{\hat{\mathbf{P}} \times \mathbf{k}_T \cdot \mathbf{S}_q}{M} \right)$$

$$-h_1^{\perp q}(x, \mathbf{k}_T^2) \frac{\hat{\mathbf{P}} \times \mathbf{k}_T \cdot \mathbf{S}_q}{M} = f(q^\uparrow/p) - f(q^\downarrow/p)$$



funzione di Boer-Mulders



Teorema di universalità per funzione di Sivers

Teorema di fattorizzazione

(Ji, Ma, Yuan, P.R. D71 (05) 034005;
Collins, Metz, P.R.L. **93** (04) 252001)

$$\frac{d^6\sigma_{OT}}{dx dy dz d\phi_S d\mathbf{P}_{h\perp}} = \frac{2\alpha^2}{sxy^2} \sum_{f\bar{f}} e_f^2 \left\{ \right.$$

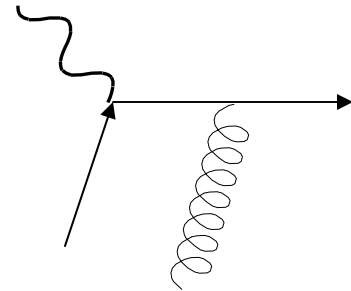
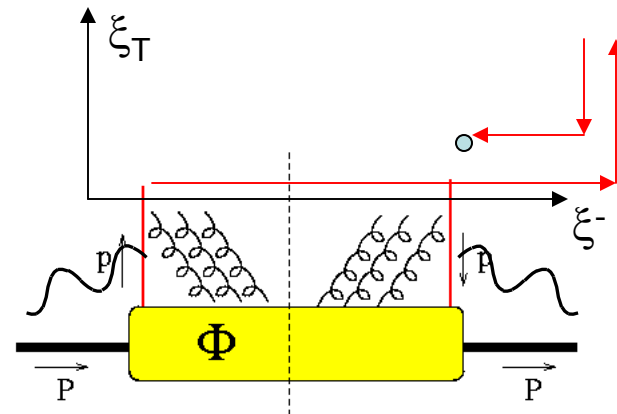
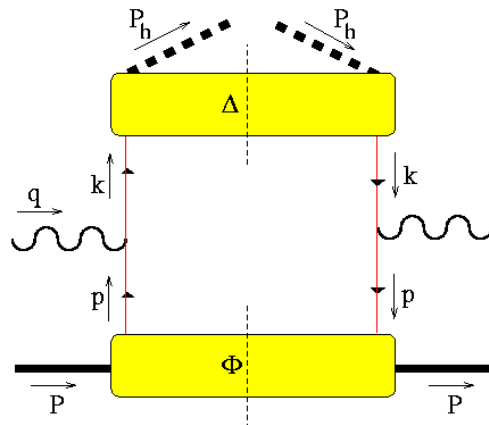
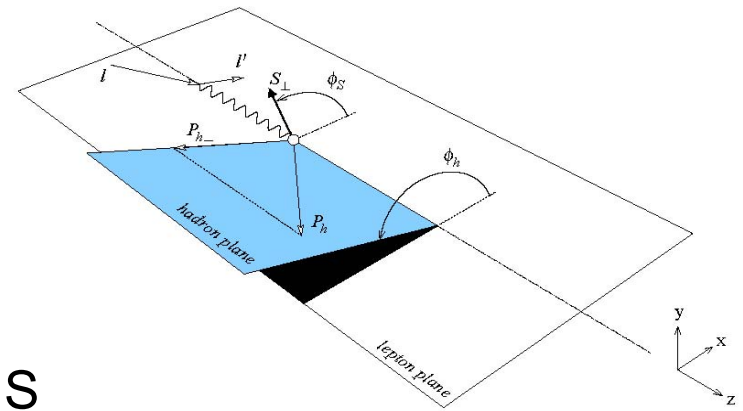
$$A(y) \mathcal{F} \left[f_1^f(x, \mathbf{p}_T^2) D_1^f(z, \mathbf{k}_T^2) \right]$$

$$+ \dots$$

$$- |\mathbf{S}_T| B(y) \sin(\phi_h - \phi_S) \mathcal{F} \left[\frac{\mathbf{p}_T \cdot \hat{\mathbf{P}}_{h\perp}}{M} f_{1T}^\perp(x, \mathbf{p}_T^2) D_1^f(z, \mathbf{k}_T^2) \right] + \dots \left. \right\}$$

SIDIS

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

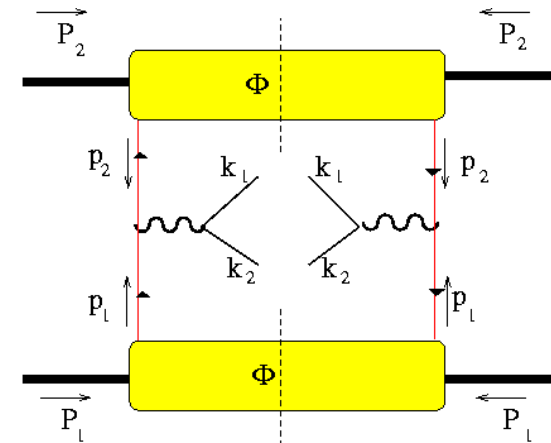


effetto Sivers in Drell-Yan

$$p p^\uparrow \rightarrow e^+ e^- X$$

Φ_2	chiral	even	chiral-odd
	q	q^\rightarrow	q^\uparrow
P_2	f_1		h_1^\perp

Φ_1	chiral	even	chiral-odd
	q	q^\rightarrow	q^\uparrow
P_1	f_1		h_1^\perp
$P_1^\uparrow = T$	f_{1T}^\perp	g_{1T}	h_1, h_{1T}^\perp



Teorema di fattorizzazione
(Collins, Soper, Sterman, N.P. **B250** (85) 199)

(continua)

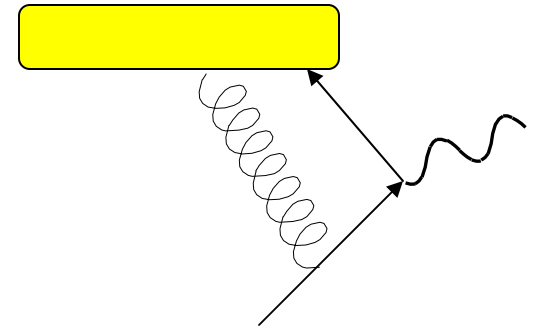
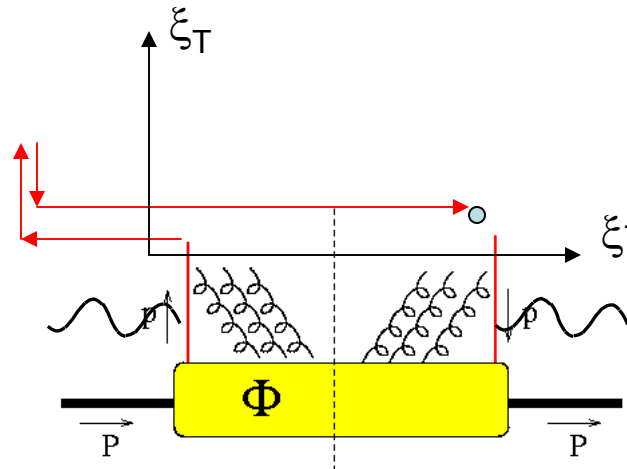
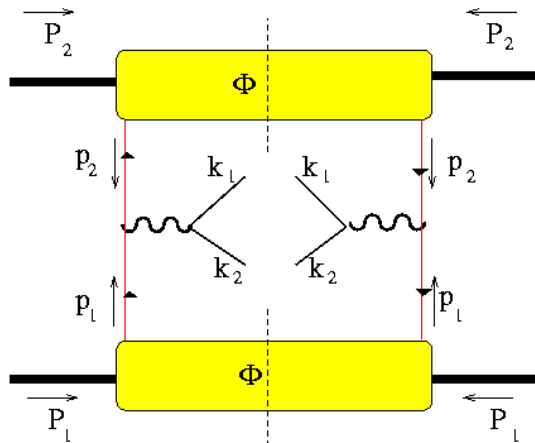
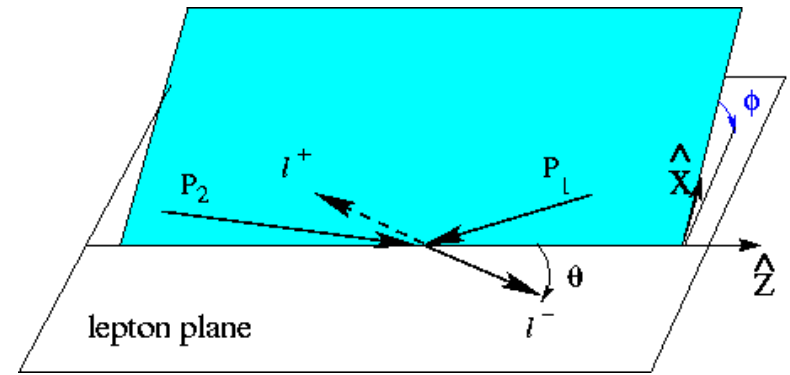
Drell-Yan
 $p p^\uparrow \rightarrow e^+ e^- X$

$$\frac{d\sigma}{dx_1 dx_2 d\Omega d\mathbf{q}_T} = \frac{\alpha^2}{3Q^2} \sum_{f\bar{f}} e_f^2 \left\{ \right.$$

$$A(y) \mathcal{F} \left[f_1^f(x_1, \mathbf{p}_{1T}^2) \bar{f}_1^{\bar{f}}(x_2, \mathbf{p}_{2T}^2) \right]$$

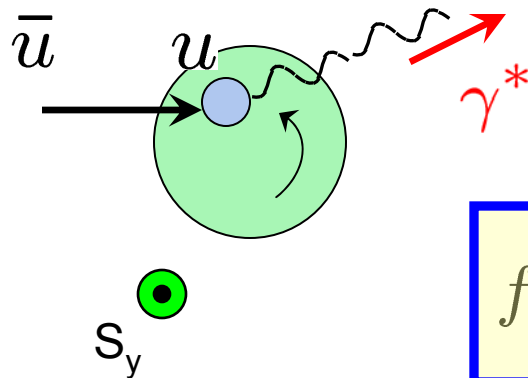
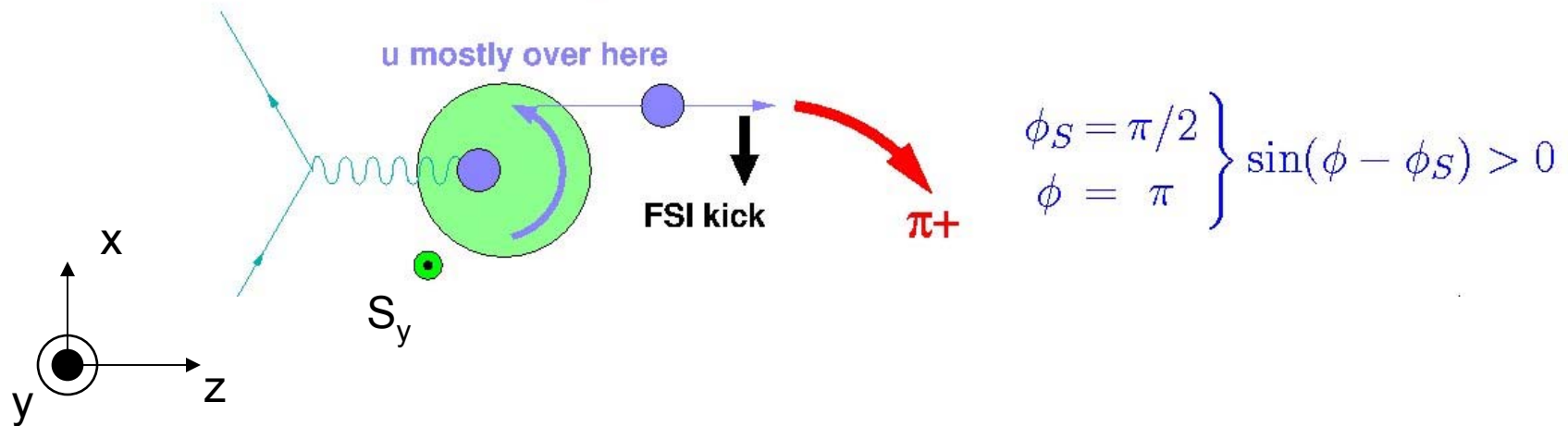
+.....

$$+ |\mathbf{S}_{1T}| A(y) \sin(\phi - \phi_{S1}) \mathcal{F} \left[\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_{1T}}{M_1} f_{1T}^{\perp f}(x_1, \mathbf{p}_{1T}^2) \bar{f}_1^{\bar{f}}(x_2, \mathbf{p}_{2T}^2) \right] + \dots \left. \right\}$$



cambio di segno !

(continua)



$$f_{1T}^{\perp q} \big|_{SIDIS} = -f_{1T}^{\perp q} \big|_{Drell-Yan}$$

STAR & PHENIX @ RHIC
 PAX @ GSI

conferma sperimentale ? Collins P.L. **B536** (02) 43