Riassunto della lezione precedente

• evoluzione DGLAP e teoremi di fattorizzazione;
coefficienti di Wilson, scale di fattorizzazione e schemi di calcolo

• e^+e^- inclusivo: $W^{\mu\nu}$ come trasformata di Fourier di operatore bilocale;
contributo dominante a corte distanze: operatore mal definito

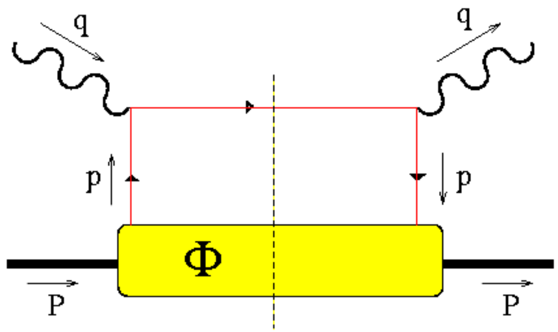
• Operator Product Expansion (OPE): definizione (operativa) di prodotto di due operatori come serie di operatori locali regolari a corte distanze;
dimostrazione rigorosa di fattorizzazione

• e+e- inclusivo: OPE per quark liberi equivalente a QPM
DIS inclusivo: serie OPE organizzabile in serie di potenze $(M/Q)^n$; twist

• OPE dimostrabile solo per processi inclusivi;
approccio diagrammatico per processi semi-inclusivi

• dominanza cinematica Light-Cone (LC) in regime DIS;
definizione variabili LC; equivalenza tra LC e Infinite Momentum Frame (IFM)
algebra di Dirac sul LC: chiralità ed elicità

Riprendiamo risultato OPE per DIS inclusivo



contributo dominante in OPE

$$2MW^{\mu\nu} \quad \sim \quad \sum_f e_f^2 \int d^4p \, \delta((p+q)^2 - m^2) \, \theta(p^0 + q^0 - m)$$

$$\mathrm{Tr}\left[\Phi(p,P)\, \gamma^\mu \, (\not{p} + \not{q} + m)\, \gamma^\nu + \overline{\Phi}(p,P)\, \gamma^\nu \, (\not{p} + \not{q} - m)\, \gamma^\mu\right]$$

$$\Phi(p,P) \;=\; \int \frac{d^4\xi}{(2\pi)^4}\, e^{-ip\cdot\xi}\, \langle P|\bar{\psi}_f(\xi)\, \psi_f(0)|P\rangle$$

$$= \int \frac{d\mathbf{P}_X}{(2\pi)^3 2P_X^0} \langle P|\bar{\psi}_f(0)\,|P_X\rangle\langle P_X|\psi_f(0)|P\rangle\, \delta(P - p - P_X)$$

Φ operatore bilocale, contiene twist ≥ 2

IFM ($Q^2 \rightarrow \infty$) ⇒ isolare contributo leading in 1/Q
equivalentemente calcoliamo Φ sul Light-Cone (LC)

Contributo leading

$$\begin{cases} P^\mu = \frac{1}{\sqrt{2}}\left(A, \frac{M^2}{A}, \mathbf{0}_\perp\right) \xrightarrow{A=Q} P^\mu \sim \left(Q, \frac{1}{Q}, \mathbf{0}_\perp\right) \xrightarrow{Q^2\to\infty} (Q, 0, \mathbf{0}_\perp) \\ p^\mu = \frac{1}{\sqrt{2}}\left(xA, \frac{p^2+\mathbf{p}_\perp^2}{xA}, \mathbf{p}_\perp\right) \xrightarrow{A=Q} \frac{1}{\sqrt{2}}\left(xQ, \frac{p^2+\mathbf{p}_\perp^2}{xQ}, \mathbf{p}_\perp\right) \sim (Q,\, 0,\, \mathbf{0}_\perp) \\ q^\mu = \frac{1}{\sqrt{2}}\left(-x_N A, \frac{Q^2}{x_N A}, \mathbf{0}_\perp\right) \xrightarrow{A=Q} \frac{1}{\sqrt{2}}\left(-x_N Q, \frac{Q}{x_N}, \mathbf{0}_\perp\right) \end{cases}$$

N.B. $p^+ \sim Q \rightarrow (p+q)^- \sim Q$

$$\begin{aligned} 2MW^{\mu\nu} &= \sum_f e_f^2 \int d^4p\, \delta((p+q)^2 - m^2)\, \theta(p^0 + q^0 - m) \\ &\qquad \times \mathrm{Tr}\left[\Phi(p,P)\, \gamma^\mu\, (\gamma\cdot p + \gamma\cdot q + m)\, \gamma^\nu\right] \\ &\sim \frac{1}{2}\sum_f e_f^2 \int dp^- d\mathbf{p}_\perp\, \mathrm{Tr}\left[\Phi(p,P)\, \gamma^\mu\, \gamma^+\, \gamma^\nu\right]\Big|_{p^+ = xP^+} \end{aligned}$$

$$\delta(p^+ + q^+) = \delta(xP^+ - x_N P^+) \rightarrow x \sim x_N \sim x_B$$

(analogamente per antiquark)

(continua)

- decomposizione della matrice di Dirac Φ(p,P,S) sulla base delle strutture di Dirac e dei 4-(pseudo)vettori p,P,S compatibilmente con Hermiticity e invarianza per parità

$$\Phi(p,P,S) = \gamma^0\,\Phi^\dagger(p,P,S)\,\gamma^0$$
$$\Phi(p,P,S) = \gamma^0\,\Phi(\tilde p,\tilde P,-\tilde S)\,\gamma^0$$

base di Dirac $\quad \mathbb{1}\,,\ i\gamma_5\,,\ \gamma^\mu\,,\ \gamma^\mu\gamma_5\,,\ \sigma^{\mu\nu}\,,\ i\sigma^{\mu\nu}\gamma_5$ $\qquad \tilde a^\mu = (a_0, -\mathbf{a})$

$$\begin{aligned}\Phi(p,P,S) &= A_1 M + A_2\,\not{P} + A_3\,\not{p} + A_4\sigma_{\mu\nu}\,P^\mu p^\nu + iA_5\, p\cdot S\gamma_5 + A_6 M\,\not{S}\gamma_5 \\ &+ A_7\frac{p\cdot S}{M}\,\not{P}\gamma_5 + A_8\frac{p\cdot S}{M}\,\not{p}\gamma_5 + iA_9\sigma_{\mu\nu}\gamma_5 S^\mu P^\nu + iA_{10}\sigma_{\mu\nu}\gamma_5 S^\mu p^\nu \\ &+ iA_{11}\frac{p\cdot S}{M^2}\sigma_{\mu\nu}\gamma_5 P^\mu p^\nu + A_{12}\epsilon_{\mu\nu\rho\sigma}\,\frac{\gamma^\mu P^\nu p^\rho S^\sigma}{M}\end{aligned}$$

time-reversal $\to$ 0

$$\Phi^*(p,P,S) = -\mathrm{i}\gamma^1\gamma^3\,\Phi(\tilde p,\tilde P,\tilde S)\,\mathrm{i}\gamma^1\gamma^3$$

$$\mathrm{Tr}\left[\Phi(p,P)\,\gamma^\mu\,\gamma^+\,\gamma^\nu\right]\Big|_{p^+=xP^+} = -4g_\perp^{\mu\nu}\,\underbrace{(A_2 + xA_3)\ P^+}_{\int dp^-\,d\mathbf{p}_\perp \ldots|_{p^+=xP^+}\ \to\ q_f(x)}$$

idem per antiquark

$\Downarrow$

$$2MW^{\mu\nu} \sim -g_\perp^{\mu\nu}\,\frac{1}{2}\sum_f e_f^2\,[q_f(x) + \bar q_f(x)] + o\left(\frac{1}{Q}\right)$$

(continua)

$$2MW^{\mu\nu} \sim -g_\perp^{\mu\nu} \underbrace{\frac{1}{2}\sum_f e_f^2 \left[q_f(x) + \bar{q}_f(x)\right]} + o\left(\frac{1}{Q}\right)$$

x ≈ x_B $\quad$ $F_1(x_B)$ $\rightarrow$ risultato di QPM

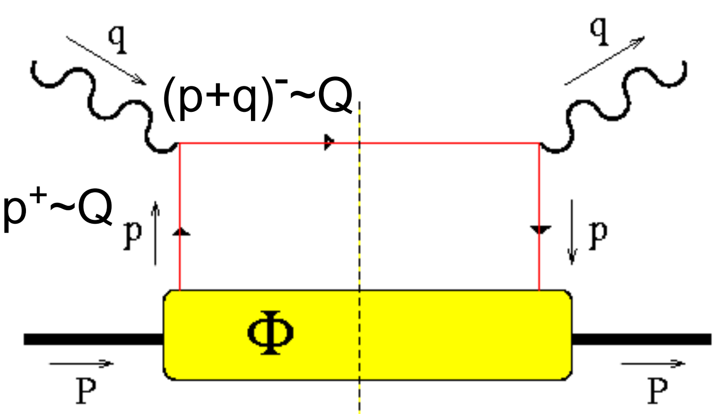
$$W^{\mu\nu} = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) W_1 + \frac{\tilde{P}^\mu \tilde{P}^\nu}{M^2} W_2$$

W_1 risposta a polarizzazione trasversa di γ* $\longrightarrow -g_\perp^{\mu\nu} F_1$

Morale :

operatore bilocale Φ ha twist ≥ 2 ; il contributo a leading twist si ottiene in IFM selezionando il termine dominante in 1/Q ($Q^2 \rightarrow \infty$) ; equivalentemente calcolando Φ sul LC

al leading twist (t=2) si ritrova risultato di QPM per $W^{\mu\nu}$ non polarizzato; ma qual è il risultato generale a t=2 ?



Decomposizione di Φ al leading twist

Base di matrici di Dirac $\{\mathbb{1}\,,\ \gamma^\mu\,,\ \gamma^\mu\gamma_5\,,\ i\gamma_5\,,\ i\sigma^{\mu\nu}\gamma_5\}$

$$\Phi(p,P,S) = \frac{1}{2}\left[S\,\mathbb{1} + V_\mu\,\gamma^\mu + A_\mu\,\gamma^\mu\gamma_5 + iP\,\gamma_5 + iT_{\mu\nu}\,\sigma^{\mu\nu}\ \gamma_5\right]$$

$$S = \frac{1}{2}\mathrm{Tr}(\Phi) = C_1(p^2, p\cdot P)$$

$$V^\mu = \frac{1}{2}\mathrm{Tr}(\gamma^\mu\,\Phi) = C_2\,P^\mu + C_3\,p^\mu$$

$$A^\mu = \frac{1}{2}\mathrm{Tr}(\gamma^\mu\gamma_5\,\Phi) = C_4\,S^\mu + C_5\,p\cdot S\,P^\mu + C_6\,P\cdot S\,p^\mu$$

$$P_5 = \frac{1}{2i}\mathrm{Tr}(\gamma_5\,\Phi) = 0$$

$$T^{\mu\nu} = \frac{1}{2i}\mathrm{Tr}(\sigma^{\mu\nu}\,\Phi) = C_7\,P^{[\mu}S^{\nu]} + C_8\,p^{[\mu}S^{\nu]} + C_9\,p\cdot S\,P^{[\mu}p^{\nu]}$$

Tr [$\gamma^+\ldots$] $\rightarrow$ $$q_f(x) = \Phi^{[\gamma^+]} = \int \frac{d\xi^-}{2\pi}\, e^{-ixP^+\xi^-}\,\langle P|\bar\psi_f(\xi^-)\,\gamma^+\,\psi_f(0)|P\rangle$$

Tr [$\gamma^+\gamma_5\ldots$] $\rightarrow$ $$\Delta q_f(x) = \Phi^{[\gamma^+\gamma_5]} = \int \frac{d\xi^-}{2\pi}\, e^{-ixP^+\xi^-}\,\langle P|\bar\psi_f(\xi^-)\,\gamma^+\gamma_5\,\psi_f(0)|P\rangle$$

Tr [$\gamma^+\gamma^i\,\gamma_5\ldots$] $\rightarrow$ $$\delta q_f(x) = \Phi^{[i\sigma^{i+}\gamma_5]} = \int \frac{d\xi^-}{2\pi}\, e^{-ixP^+\xi^-}\,\langle P|\bar\psi_f(\xi^-)\,i\sigma^{i+}\gamma_5\,\psi_f(0)|P\rangle$$

Traccia di operatore bilocale → densità partoniche

$$\begin{aligned}\Phi^{[\gamma^+]}(x) &= \int dp^- d\mathbf{p}_\perp \, \mathrm{Tr}\left[\Phi(p,P)\,\gamma^+\right]\Big|_{p^+=xP^+} \\ &= \sqrt{2}\sum_n |\langle n|\phi_f(0)|P\rangle|^2\,\delta(P^+ - xP^+ - P_n^+) \equiv q_f(x)\end{aligned}$$

componenti light-cone “good”

densità di probabilità
di annichilare in |P>
un quark con momento xP^+

similmente per l’antiquark

$$\begin{aligned}\Phi^{[\gamma^+]}(x) + \bar{\Phi}^{[\gamma^+]}(x) &= \int dp^- d\mathbf{p}_\perp \, \mathrm{Tr}\left[\Phi(p,P,S)\,\gamma^+ - \bar{\Phi}(p,P,S)\,\gamma^+\right]\Big|_{p^+=xP^+} \\ &= q_f(x) + \bar{q}_f(x)\end{aligned}$$

= probabilità di trovare un (anti)quark con flavor f e frazione x del momento longitudinale (light-cone) P^+ dell’adrone

In generale : $\Phi^{[\Gamma]}(x,S) = \int dp^- d\mathbf{p}_\perp \, \mathrm{Tr}\left[\Phi(p,P,S)\,\Gamma\right]\Big|_{p^+=xP^+}$

Proiezioni al leading twist (coinvolgono le componenti "good" ϕ)

$$\begin{aligned}\Phi^{[\gamma^+]}(x,S) &= q(x)\\ \Phi^{[\gamma^+\gamma_5]}(x,S) &= \lambda\,\Delta q(x)\\ \Phi^{[i\sigma^{i+}\gamma_5]}(x,S) &= S_T^i\,\delta q(x)\end{aligned}$$

Proiezioni al twist 3

(coinvolgono le componenti "good" ϕ e "bad" χ)

$$\begin{aligned}\Phi^{[\mathbb{1}]}(x,S) &= \frac{M}{P^+}\,e(x)\\ \Phi^{[\gamma^i\gamma_5]}(x,S) &= \frac{M}{P^+}\,S_T^i\,g_T(x)\\ \Phi^{[i\sigma^{+-}\gamma_5]}(x,S) &= \frac{M}{P^+}\,\lambda\,h_L(x)\end{aligned}$$

Esempio: $\int dp^- d\mathbf{p}_\perp \, \mathrm{Tr}\left[\Phi(p,P,S)\,\mathbb{1}\right]\Big|_{p^+=xP^+} = \frac{M}{P^+}\int \frac{d\xi^-}{2\pi}\, e^{-ixP^+\xi^-}\,\langle P|\underbrace{\bar{\psi}(\xi^-)\,\psi(0)}|P\rangle$

$$\psi^\dagger\gamma^0\psi = \overline{\underline{\phi \quad \chi}}\begin{pmatrix}0 & \sigma_3\\ \sigma_3 & 0\end{pmatrix}\begin{vmatrix}\phi\\ \chi\end{vmatrix} \sim \phi^\dagger\sigma_3\chi \to \phi^\dagger\sigma_3(i\,\not{D}+m)\phi$$

correlatore quark-gluone soppresso

nessuna interpretazione probabilistica

Interpretazione probabilistica al leading twist

proiettori di elicità (chiralità) $P_{R/L} = \dfrac{1 \pm \gamma_5}{2}$ $[P_{R/L},\, P_\pm] = 0$

$$\Phi^{[\gamma^+]} \to \bar{\psi}\,\gamma^+\,\psi \to \psi^\dagger\,P_+\,\psi \to \phi^\dagger\,\phi = \phi^\dagger\,(P_R + P_L)^\dagger\,(P_R + P_L)\,\phi$$
$$= \phi^\dagger(P_R^\dagger P_R + P_L^\dagger P_L)\,\phi = \bar{R}R + \bar{L}L$$

distribuzione di momento

$$\Phi^{[\gamma^+\gamma_5]} \to \bar{\psi}\,\gamma^+\gamma_5\,\psi \to \psi^\dagger\,P_+\,\gamma_5 P_+ \psi \to \phi^\dagger\,(P_R - P_L)\,\phi$$
$$= \phi^\dagger(P_R^\dagger P_R - P_L^\dagger P_L)\,\phi = \bar{R}R - \bar{L}L$$

$[P_\pm, \gamma_5] = 0$

distribuzione di elicità

$$\Phi^{[i\sigma^{i+}\gamma_5]} \to \bar{\psi}\,i\sigma^{i+}\gamma_5\,\psi \ldots \to \phi^\dagger(P_L^\dagger \gamma^i P_R - P_R^\dagger \gamma^i P_L)\,\phi$$

?

(continua)

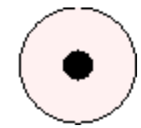
proiettori di polarizzazione trasversa $P_{\uparrow/\downarrow} = \dfrac{1 \pm \gamma^i \gamma_5}{2}$ (da base di elicità a base di trasversità)

$$\Phi^{[i\sigma^{i+}\gamma_5]} \rightarrow \bar{\psi}\, i\sigma^{i+}\gamma_5\, \psi \ldots \rightarrow \phi^\dagger (P_\uparrow P_\uparrow - P_\downarrow P_\downarrow)\, \phi$$

→ δq è distribuzione "netta" di polarizz. trasversa !

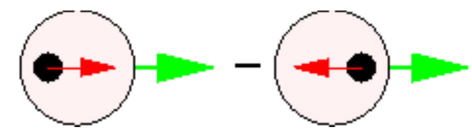
notazioni più usuali e "comode"

$$\Phi^{[\gamma^+]}(x,S) \quad = q(x) \quad \longrightarrow \quad f_1^q(x)$$

$f_1 =$ 

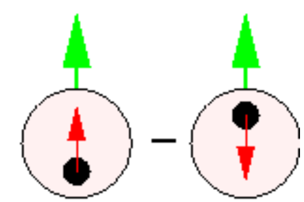
quark non polariz. q **leading twist**

$$\Phi^{[\gamma^+\gamma_5]}(x,S) = \lambda\, \Delta q(x) \longrightarrow \lambda\, g_1^q(x)$$

$g_1 =$ 

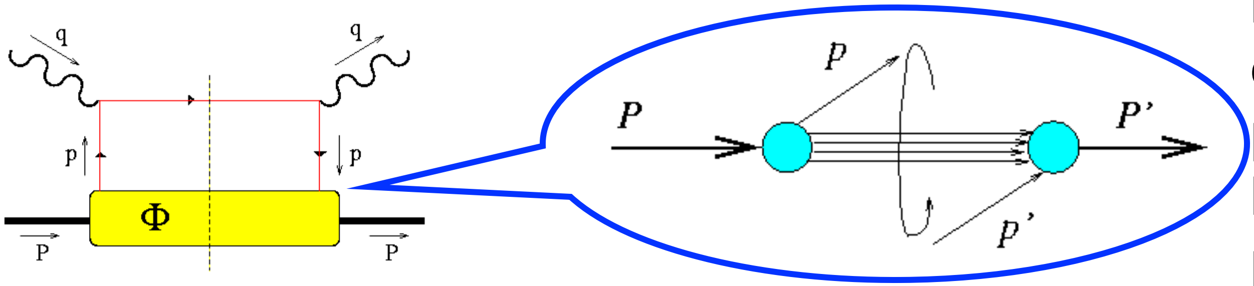
quark long. polariz. $\vec{q}$

$$\Phi^{[i\sigma^{i+}\gamma_5]}(x,S) = S_T^i\, \delta q(x) \longrightarrow S_T^i\, h_1^q(x)$$

$h_1 =$ 

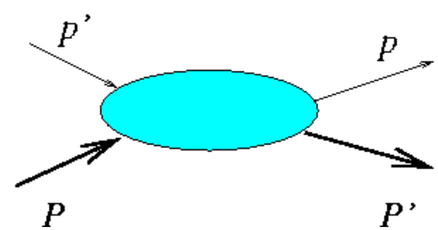
$q\!\uparrow$ **quark trasv. polariz.**

Necessità di 3 PDF's al leading twist



bersaglio con elicità P
emette
partone con elicità p
hard scattering
partone con elicità p'
riassorbito in
adrone con elicità P'

discontinuità nel canale *u* della ampiezza di scattering forward partone-adrone



$\rightarrow A_{Pp,P'p'}$

al leading twist solo componenti "good" $\quad |\psi\rangle \sim \left| \begin{array}{c} \phi_+ \\ \phi_- \\ o(1/Q) \\ o(1/Q) \end{array} \right|$

il processo è collineare modulo *o*(1/Q)

⇒ conservazione dell'elicità P+p' = p+P'

(continua)

invarianza per trasformazioni di parità $\rightarrow A_{Pp,P'p'} = A_{-P-p.-P'-p'}$

invarianza per time-reversal $\rightarrow A_{Pp,P'p'} = A_{P'p',Pp}$

	P	p	$\rightarrow$	P'	p'
1)	+	+		+	+
2)	+	-		+	-
3)	+	+		-	-

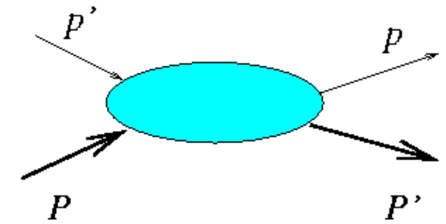
con questi vincoli $\rightarrow$ 3 $A_{Pp,P'p'}$ indipendenti

$$\left\{ \begin{array}{l} (+,+) \rightarrow (+,+) + (+,-) \rightarrow (+,-) \equiv f_1 \; \bar{R}R + \bar{L}L \\ (+,+) \rightarrow (+,+) - (+,-) \rightarrow (+,-) \equiv g_1 \; \bar{R}R - \bar{L}L \end{array} \right.$$

$$(+,+) \rightarrow (-,-) \equiv h_1 \qquad \bar{L}R$$

• relazioni tra PDF's

$A_{Pp,P'p'}$



$(+,+) \rightarrow (+,+) + (+,-) \rightarrow (+,-) \equiv f_1$

$(+,+) \rightarrow (+,+) - (+,-) \rightarrow (+,-) \equiv g_1$

$(+,+) \rightarrow (-,-) \equiv h_1$

per definizione $\rightarrow$ $f_1 \geq |g_1|, |h_1|$, $f_1 \geq 0$

$| (+,+) \pm (-,-) |^2 = A_{++,++} + A_{--,--} \pm 2\, \mathrm{Re} A_{++,--} \geq 0$

invarianza per trasformazioni di parità $\rightarrow A_{Pp,P'p'} = A_{-P-p.-P'-p'}$

$A_{++,++} = ½ (f_1 + g_1) \geq | A_{++,--} | = |h_1|$ $\rightarrow$ diseguaglianza di Soffer valida per ogni x e Q^2 (almeno fino NLO)

Base di elicità $\quad h_1 \sim \phi^\dagger P_L^\dagger \gamma_i P_R \phi$

Base di trasversità $\quad h_1 \sim \phi^\dagger (P_\uparrow^\dagger P_\uparrow - P_\downarrow^\dagger P_\downarrow)\phi$

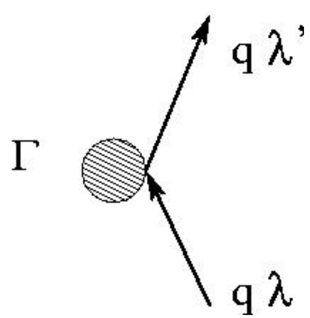
$$\langle \uparrow |...| \uparrow\rangle - \langle \downarrow |...| \downarrow\rangle \propto \langle + |...| -\rangle + \langle - |...| +\rangle$$

$$\begin{cases} |\uparrow\rangle = & \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle) \\ |\downarrow\rangle = & \frac{1}{\sqrt{2}}(|+\rangle - |-\rangle) \end{cases}$$

per componenti "good"
(⇔ twist 2) elicità = chiralità
quindi h_1 non conserva
chiralità (chiral odd)

QCD conserva l'elicità al leading twist

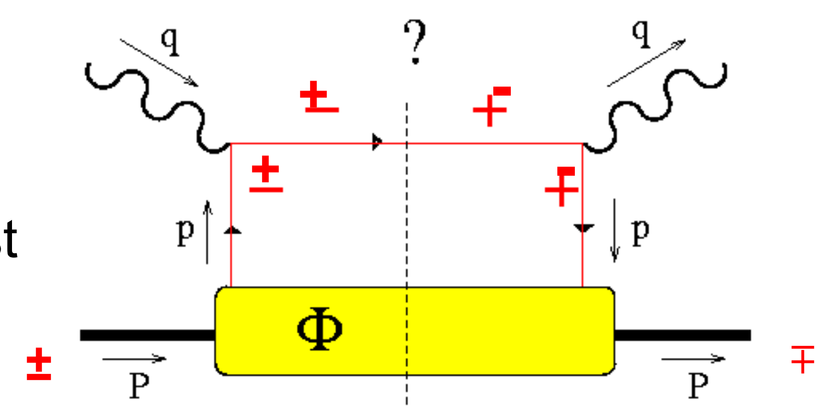
massless quark spinors $\lambda = \pm 1$



$$\begin{aligned} M &\sim \bar{u}_{\lambda'}\,\Gamma\,u_\lambda \\ &\sim \bar{u}_{\lambda'}\,(1-\lambda'\gamma_5)\,(1-\lambda\gamma_5)\,\Gamma\,u_\lambda \\ &\sim \delta_{\lambda\lambda'}\,\bar{u}_{\lambda'}\,\Gamma\,u_\lambda + o\left(\frac{m_q}{E_q}\right) \end{aligned}$$

$$\frac{1+\lambda\gamma_5}{2}u_\lambda = u_\lambda$$

$$\bar{u}_\lambda \frac{1-\lambda\gamma_5}{2} = \bar{u}_\lambda$$



QCD conserva l'elicità al leading twist
→ h_1 soppressa in DIS inclusivo

Differenti proprietà tra f_1, g_1 e h_1

per DIS inclusivo nel QPM c' è parallelo tra PDF's e funzioni di struttura

$$f_1(x) \;\to\; F_1(x_B) = \frac{1}{2}\sum_f e_f^2\,[f_1^f(x_B) + \bar{f}_1^f(x_B)] \longrightarrow \frac{1}{2}\sum_{f\bar{f}} e_f^2\,[q_f^{\uparrow}(x_B) + q_f^{\downarrow}(x_B)]$$

$$g_1(x) \;\to\; G_1(x_B) = \frac{1}{2}\sum_f e_f^2\,[g_1^f(x_B) + \bar{g}_1^f(x_B)] \longrightarrow \frac{1}{2}\sum_{f\bar{f}} e_f^2\,[q_f^{\uparrow}(x_B) - q_f^{\downarrow}(x_B)]$$

ma h_1 non ha controparte a livello di funzioni di struttura, perchè per DIS inclusivo polarizzato, in $W_A^{\mu\nu}$ il contributo di G_2 è soppresso rispetto a quello di G_1 : appare al twist 3

$$W_A^{\mu\nu} \;=\; i\epsilon^{\mu\nu\rho\sigma}\,q_\rho\,S_\sigma\left[M G_1(\nu,Q^2) + \frac{P\cdot q}{M}\,G_2(\nu,Q^2)\right] - i\epsilon^{\mu\nu\rho\sigma}\,q_\rho\,P_\sigma\,\frac{S\cdot q}{M}\,G_2(\nu,Q^2)$$

per tanti anni h_1 è stata ignorata e si è pensato che la polarizzazione trasversa generasse effetti solo al twist 3, confondendola con g_T in G_2

$$\Phi^{[\gamma^i\gamma_5]}(x,S) = \frac{M}{P^+}\,S_T^i\,g_T(x) \;\longrightarrow\; g_1(x) + g_2(x) = \sum_f \frac{e_f^2\,m_f}{2Mx}\,[q_f^{\rightarrow}(x) - q_f^{\leftarrow}(x)]$$

In realtà, questo pregiudizio si basa sulla confusione tra spin trasverso dell'adrone (che appare al twist 3 nel tensore adronico) e distribuzione di polarizzazione trasversa dei partoni in adroni polarizzati trasversalmente, che non necessariamente deve apparire solo al twist 3:

	$\Phi^{[\Gamma]}$	pol. long.	$\Phi^{[\Gamma]}$	pol. trasv.
twist 2	$\gamma^+ \gamma_5$	g_1	$i\, \sigma^{i+}\gamma_5$	h_1
twist 3	$i\, \sigma^{+-}\gamma_5$	h_L	$\gamma^i\, \gamma_5$	g_T

perfetto parallelo "incrociato" tra t=2 e t=3 sia per elicità che polarizzazione trasversa

inoltre h_1 ha stessa importanza di f_1 e g_1 al twist 2. Infatti se sulla base di elicità f_1 e g_1 sono diagonali mentre h_1 no,

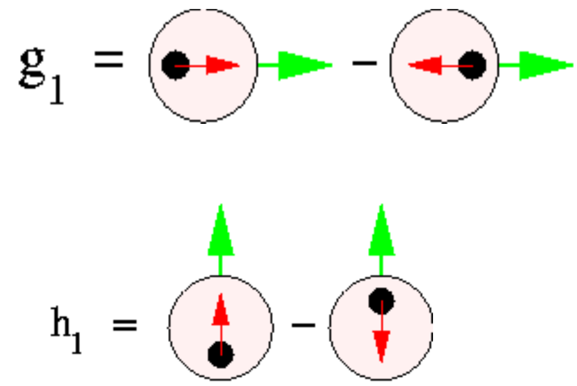
$$f_1 \sim \phi^\dagger (P_R^\dagger P_R + P_L^\dagger P_L)\phi \quad g_1 \sim \phi^\dagger (P_R^\dagger P_R - P_L^\dagger P_L)\phi \quad h_1 \sim \phi^\dagger P_L^\dagger P_R \phi$$

sulla base di trasversità la situazione è opposta:

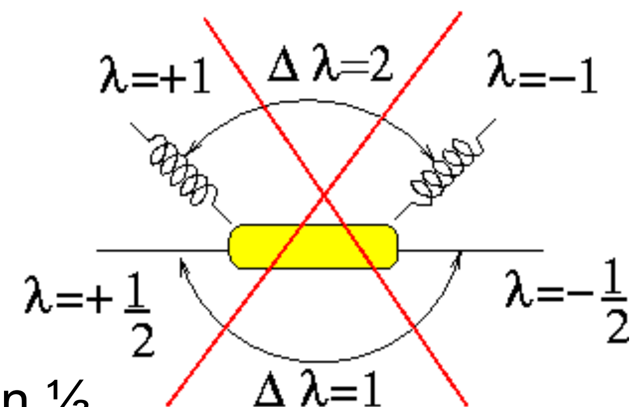
$$f_1 \sim \phi^\dagger (P_\uparrow^\dagger P_\uparrow + P_\downarrow^\dagger P_\downarrow)\phi \quad g_1 \sim \phi^\dagger P_\downarrow^\dagger P_\uparrow \phi \quad h_1 \sim \phi^\dagger (P_\uparrow^\dagger P_\uparrow - P_\downarrow^\dagger P_\downarrow)\phi$$

Chiral-odd h_1 → interessanti proprietà rispetto alle altre distribuzioni

- g_1 e h_1 (e tutte le PDF) sono definite nell'IFM
  cioè boost Q → ∞ lungo l'asse z
  ma boost e rotazioni di Galileo commutano in
  frame nonrelativistico → $g_1 = h_1$
  ogni differenza è data da effetti relativistici
  → info su dinamica relativistica dei quarks



- per gluone si definiscono
  $G(x)$ = la distribuzione di momento
  $\Delta G(x)$ = la distribuzione di elicità
  però non esiste la "trasversità" in adrone a spin ½
  → evoluzione di h_1^q disaccoppiata da gluoni !



(continua)

$$\langle PS|\overline{q}^f \gamma^\mu \gamma_5 q^f |PS\rangle\Big|_{Q^2} = 2\lambda P^\mu \int dx \left[g_1^f(x,Q^2) + g_1^{\overline{f}}(x,Q^2) \right] = 2\lambda P^\mu \, g_A$$

carica assiale

$$\langle PS|\overline{q}^f i\sigma^{\mu\nu} \gamma_5 q^f |PS\rangle\Big|_{Q^2} = 2S^{[\mu}P^{\nu]} \int dx \left[h_1^f(x,Q^2) - h_1^{\overline{f}}(x,Q^2) \right] = 2S^{[\mu}P^{\nu]} \, g_T(Q^2)$$

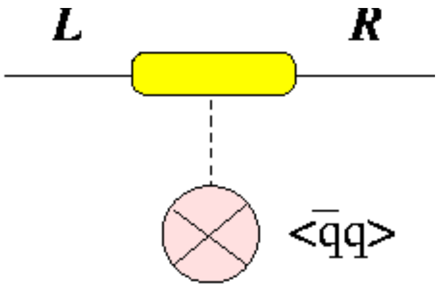
carica tensoriale
(non conservata)

• carica assiale da operatore C(harge)-even
carica tensoriale C-odd → non prende contributi
da coppie quark-antiquark del mare di Dirac

riassumendo: l' evoluzione di $h_1^q(x,Q^2)$ è molto diversa dalle altre PDF perchè non prende contributi dai gluoni → evoluzione tipica di non-singoletto
Inoltre carica tensoriale è struttura di non-singoletto, C-odd e non è conservata
→ h_1 quantità più adatta per studiare contributo di valenza allo spin

(continua)

h_1 non conserva chiralità (chiral odd)
h_1 può quindi essere determinata da processi soft legati alla rottura della simmetria chirale della QCD (ruolo del vuoto nonperturbativo di QCD?)

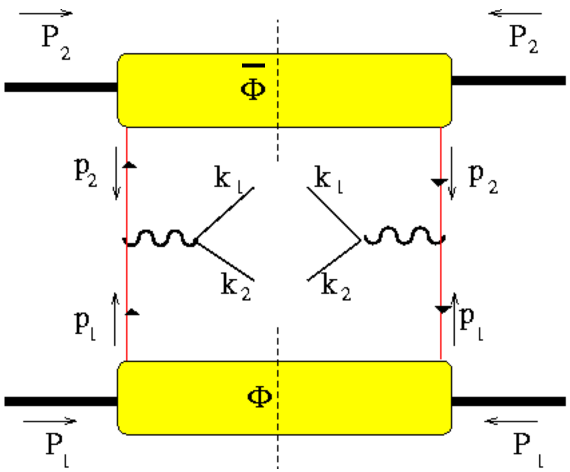


in base di elicità la sezione d'urto deve essere chiral-even
quindi per estrarre h_1 bisogna trovare un processo elementare in cui appaia insieme ad un partner chiral-odd, in modo da "annullare l'effetto"; il vincolo ulteriore è che tale contributo appaia al leading twist.

<u>Come estrarre la trasversità dai dati ?</u>

Come estrarre la trasversità dai dati ?

scelta più ovvia: Drell-Yan polarizzato $\quad p^\uparrow p^\uparrow \to l^+ l^- X$



ma distribuzione di spin trasverso per antiquark in protone polarizzato $\to$ mare di Dirac è soppresso

sarebbe meglio $\quad p^\uparrow \bar{p}^\uparrow \to l^+ l^- X$
ma tecnologia ancora da sviluppare

$$\bar{\Phi}(x,S) = \int dp^- d\mathbf{p}_T \, \bar{\Phi}(p,P,S)\Big|_{p^+ = xP^+} \longrightarrow [\bar{f}_1(x) + \lambda \, \bar{g}_1(x) \, \gamma_5 + \bar{h}_1(x) \, \gamma_5 \, \not{S}_T] \, \not{P}$$

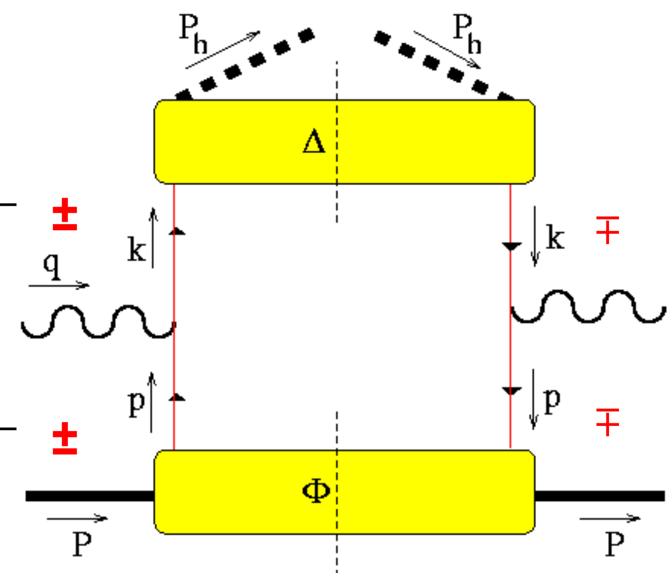
$$\Phi(x,S) = \int dp^- d\mathbf{p}_T \, \Phi(p,P,S)\Big|_{p^+ = xP^+} \longrightarrow [f_1(x) + \lambda \, g_1(x) \, \gamma_5 + h_1(x) \, \gamma_5 \, \not{S}_T] \, \not{P}$$

alternativa: DIS semi-inclusivo (SIDIS)

diagramma
dominante
al leading twist

partner
chiral-odd

chiral-odd



sistema IFM

$$P^\mu = \frac{1}{\sqrt{2}}\left(A,\,\frac{M^2}{A},\,\mathbf{0}_T\right) \to \left(P^+,\,\frac{M^2}{2P^+},\,\mathbf{0}_T\right)$$

$$q^\mu = \frac{1}{\sqrt{2}}\left(-x_N A,\,\frac{Q^2-\mathbf{q}_T^2}{2x_N A},\,\mathbf{q}_T\right) \sim \left(-x_B P^+,\,\frac{P_h^-}{z_h},\,\mathbf{q}_T\right) \to (-Q,\,Q,\,\mathbf{q}_T)$$

$$P_h^\mu \to \left(\frac{M_h^2}{2z_h Q},\,z_h Q,\,\mathbf{0}_T\right)$$

IFM per stato finale:
direzione "-" dominante

$$x_B \sim x_N = -\frac{q^+}{P^+}$$

$$z_h = \frac{P_h^-}{q^-}$$

partoni

$$p^\mu = \left(xP^+,\,\frac{p^2+\mathbf{p}_T^2}{2xP^+},\,\mathbf{p}_T\right)$$

$$k^\mu = \left(\frac{z(k^2+\mathbf{k}_T)}{2P_h^-},\,\frac{P_h^-}{z},\,\mathbf{k}_T\right)$$

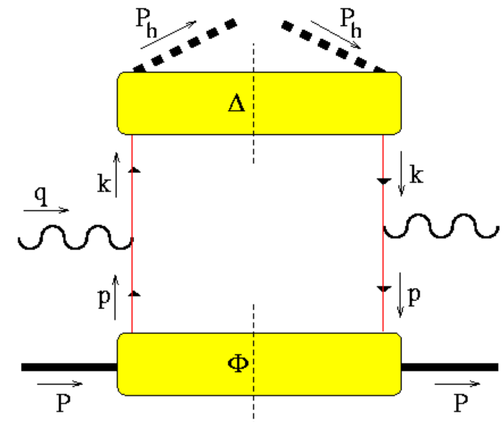
z frazione light-cone
del momento
del quark frammentante

	+	–	
h → q	~ Q	~ 1/Q	$\int dp^-$
hard	~ Q	~ Q	
q → h	~ 1/Q	~ Q	$\int dp^+$

procedura simile a DIS inclusivo

$$2MW^{\mu\nu} = \sum_f e_f^2 \int d^4p\, d^4k\, \delta(p+q-k)$$
$$\mathrm{Tr}\,[\Phi(p,P,S)\,\gamma^\mu\,\Delta(k,P_h,S_h)\,\gamma^\nu] + \left(\begin{array}{c}\mu\leftrightarrow\nu\\ q\leftrightarrow -q\end{array}\right)$$

(antiquark)



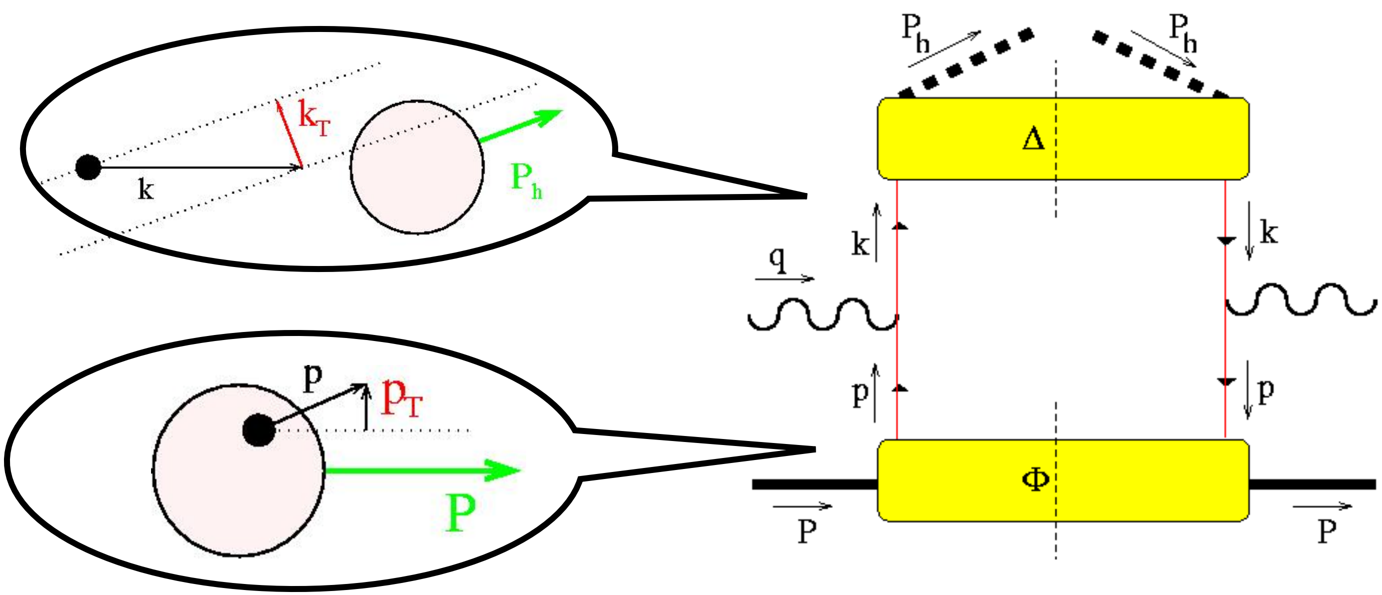
quark "decade" in adrone non colorato
confinamento → neutralizzazione del colore

$$\xrightarrow{Q^2\to\infty} \sum_f e_f^2 \int dp^- d\mathbf{p}_T dk^+ d\mathbf{k}_T\, \delta(\mathbf{p}_T + \mathbf{q}_T - \mathbf{k}_T)$$
$$\mathrm{Tr}\,[\Phi(p,P,S)\,\gamma^\mu\,\Delta(k,P_h,S_h)\,\gamma^\nu]\,\Big|^{p^+=xP^+}_{k^-=P_h^-/z} + \left(\begin{array}{c}\mu\leftrightarrow\nu\\ q\leftrightarrow -q\end{array}\right)$$

$$\Phi(p,P,S) = \int \frac{d^4\xi}{(2\pi)^4}\, e^{-ip\cdot\xi}\, \langle P,S|\bar\psi(\xi)\,\psi(0)|P,S\rangle$$
$$\Delta(k,P_h,S_h) = \sum_X \int \frac{d^4\zeta}{(2\pi)^4}\, e^{ik\cdot\zeta}\, \langle 0|\psi(\zeta)|P_hS_h,X\rangle\,\langle P_hS_h,X|\bar\psi(0)|0\rangle$$

similmente
per antiquark

- in SIDIS {P,q,P_h} non sono tutti collineari;
  comodo scegliere frame dove $\mathbf{q}_T \neq 0$
  → sensibilità ai momenti trasversi dei partoni nel vertice hard
  → struttura più ricca



Decomposizione di Φ al leading twist

Base di matrici di Dirac $\{\mathbb{1}\ ,\ \gamma^\mu\ ,\ \gamma^\mu\gamma_5\ ,\ i\gamma_5\ ,\ i\sigma^{\mu\nu}\gamma_5\}$

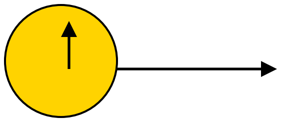
$$\Phi(p,P,S) = \frac{1}{2}\left[S\,\mathbb{1} + V_\mu\,\gamma^\mu + A_\mu\,\gamma^\mu\gamma_5 + iP\,\gamma_5 + iT_{\mu\nu}\,\sigma^{\mu\nu}\ \gamma_5\right]$$

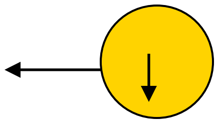
$$\begin{aligned}
S &= \frac{1}{2}\mathrm{Tr}(\Phi) = C_1(p^2, p\cdot P) \\
V^\mu &= \frac{1}{2}\mathrm{Tr}(\gamma^\mu\,\Phi) = C_2\,P^\mu + C_3\,p^\mu + C_{10}\,\varepsilon_{\mu\nu\rho\sigma}S^\nu P^\rho p^\sigma \\
A^\mu &= \frac{1}{2}\mathrm{Tr}(\gamma^\mu\gamma_5\,\Phi) = C_4\,S^\mu + C_5\,p\cdot S\,P^\mu + C_6\,P\cdot S\,p^\mu \\
P_5 &= \frac{1}{2i}\mathrm{Tr}(\gamma_5\,\Phi) = C_{11}\,p\cdot S \\
T^{\mu\nu} &= \frac{1}{2i}\mathrm{Tr}(\sigma^{\mu\nu}\,\Phi) = C_7\,P^{[\mu}S^{\nu]} + C_8\,p^{[\mu}S^{\nu]} + C_9\,p\cdot S\,P^{[\mu}p^{\nu]} + C_{12}\,\varepsilon_{\mu\nu\rho\sigma}P^\rho p^\sigma
\end{aligned}$$

$C_{10}\ \varepsilon_{\mu\nu\rho\sigma}\ S^\nu\ P^\rho\ k^\sigma$: $\mu, \rho = +/-$ $\Rightarrow$ $\nu, \sigma = i\ (=1,2)$

$\Rightarrow$ coinvolge momenti trasversi partonici ($\mathbf{p}_\perp$) ma C_{10} è vincolato da T-reversal
idem per $C_{12}\ \varepsilon_{\mu\nu\rho\sigma}\ P^\rho\ k^\sigma$

Naive T- reversal transformation

|a> =  system with some spin and momentum

|-a> =  flipping spin and momentum

$|i>, |f>$ initial, final states of the system; $\mathcal{T}_{if}$ trans. matrix; T-rev. $\rightarrow |\mathcal{T}_{if}|^2 = |\mathcal{T}_{-f-i}|^2$

naive T- reversal transformation : $\mathcal{T}_{-i-f}$

no FSI $\Rightarrow$ $|i> \leftrightarrow |f>$; $A = 0$; T-rev. = naive T-rev.

$A = |\mathcal{T}_{if}|^2 - |\mathcal{T}_{-i-f}|^2$

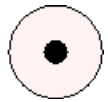
FSI) $|i> \neq |f>$; T- rev. OK

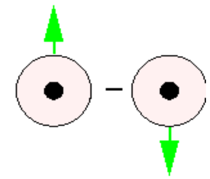
but $A \neq 0 \propto \Im m$ [Born $\times$ rescatt.*]

PDF dipendenti da momento trasverso intrinseco

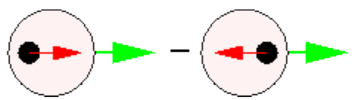
Proiezioni al leading twist

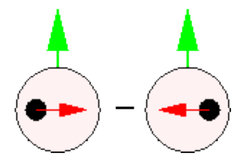
$$\Phi^{[\Gamma]}(x,\mathbf{p}_T,S)=\int dp^-\,\mathrm{Tr}\left[\Phi(p,P,S)\,\Gamma\right]\Big|_{p^+=xP^+}$$

$\mathrm{f}_1 =$ 

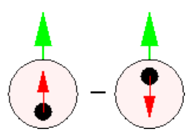


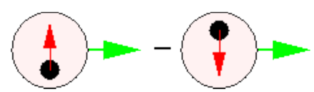
$$\Phi^{[\gamma^+]}(x,\mathbf{p}_T,S) \;=\; f_1(x,\mathbf{p}_T^2) - \frac{\mathbf{p}_T\times\mathbf{S}_T\cdot\hat{\mathbf{P}}}{M}\,f_{1T}^{\perp}(x,\mathbf{p}_T^2)$$

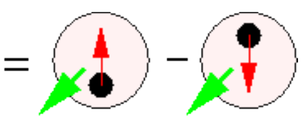
$\mathrm{g}_{1L} =$ 

$\mathrm{g}_{1T} =$ 

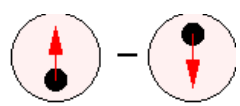
$$\Phi^{[\gamma^+\gamma_5]}(x,\mathbf{p}_T,S) \;=\; \lambda\,g_{1L}(x,\mathbf{p}_T^2) + \frac{\mathbf{p}_T\cdot\mathbf{S}_T}{M}\,g_{1T}(x,\mathbf{p}_T^2)$$

$\mathrm{h}_{1T} =$ 

$\mathrm{h}_{1L}^{\perp} =$ 

$\mathrm{h}_{1T}^{\perp} =$ 

$$\Phi^{[i\sigma^{i+}\gamma_5]}(x,\mathbf{p}_T,S) \;=\; S_T^i\,h_1 + \frac{p_T^i}{M}\,\lambda\,h_{1L}^{\perp} + \frac{S_T^i}{M^2}\left(p_T^i p_T^j - \frac{1}{2}\,\mathbf{p}_T^2\,\delta_{ij}\right)h_{1T}^{\perp} + \frac{\left(\mathbf{p}_T\times\hat{\mathbf{P}}\right)_i}{M}\,h_1^{\perp}$$

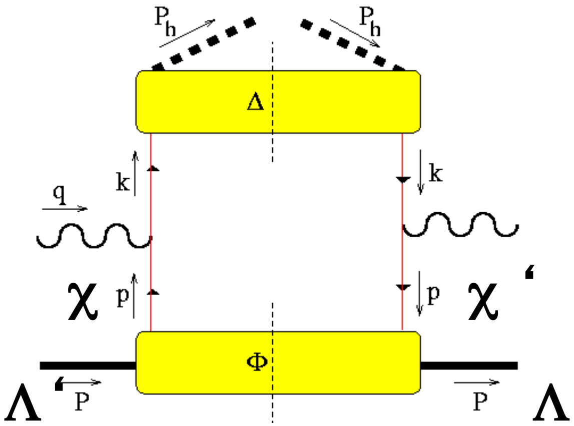


$q^{\uparrow}$

twist 2 $\quad N^{\uparrow}$

pesata con $\mathbf{p}_T$

Rappresentazione di elicità di Φ $(x,\mathbf{p}_T,S)$



PDF	chiral even		chiral-odd
	q non pol.	$q^{\rightarrow}$	$q^{\uparrow}$
H non pol.	f_1		$h_1^{\perp}$
$H^{\rightarrow}$ =L		g_{1L}	$h_{1L}^{\perp}$
$H^{\uparrow}$ = T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

$$h_1 = h_{1T} + h_{1T}^{\perp}\,\frac{\vec{p}_T^{\,2}}{M^2}$$

Decomposizione di Δ al leading twist

Base di matrici di Dirac $\{\mathbb{1}\ ,\ \gamma^\mu\ ,\ \gamma^\mu\gamma_5\ ,\ i\gamma_5\ ,\ i\sigma^{\mu\nu}\gamma_5\}$

$$\Delta(k, P_h, S_h) = \frac{1}{2}\,[S\,\mathbb{1} + V_\mu\,\gamma^\mu + A_\mu\,\gamma^\mu\gamma_5 + iP\,\gamma_5 + iT_{\mu\nu}\,\sigma^{\mu\nu}\ \gamma_5]$$

$$\begin{aligned}
S &= \frac{1}{2}\,\mathrm{Tr}(\Delta) = C_1(k^2, k\cdot P_h) \\
V^\mu &= \frac{1}{2}\,\mathrm{Tr}(\gamma^\mu\,\Delta) = C_2\,P_h^\mu + C_3\,k^\mu + C_{10}\,\varepsilon_{\mu\nu\rho\sigma}S_h^\nu P_h^\rho k^\sigma \\
A^\mu &= \frac{1}{2}\,\mathrm{Tr}(\gamma^\mu\gamma_5\,\Delta) = C_4\,S_h^\mu + C_5\,p\cdot S_h\,P_h^\mu + C_6\,P_h\cdot S_h\,k^\mu \\
P_5 &= \frac{1}{2i}\,\mathrm{Tr}(\gamma_5\,\Delta) = C_{11}\,k\cdot S_h \\
T^{\mu\nu} &= \frac{1}{2i}\,\mathrm{Tr}(\sigma^{\mu\nu}\,\Delta) = C_7\,P_h^{[\mu}S_h^{\nu]} + C_8\,k^{[\mu}S_h^{\nu]} + C_9\,k\cdot S_h\,P_h^{[\mu}k^{\nu]} + C_{12}\,\varepsilon_{\mu\nu\rho\sigma}P_h^\rho k^\sigma
\end{aligned}$$

Tr [… γ⁻] →

$$\Delta^{[\gamma^-]} = \sum_X\!\!\!\!\!\!\int \frac{d\zeta^+}{2\pi}\, e^{iP_h^-\zeta^+/z}\,\langle 0|\psi_f(\zeta^+)|P_hS_h,X\rangle\langle P_hS_h,X|\bar\psi_f(0)\,\gamma^-|0\rangle$$

Tr [… γ⁻ γ₅] →

$$\Delta^{[\gamma^-\gamma_5]} = \sum_X\!\!\!\!\!\!\int \frac{d\zeta^+}{2\pi}\, e^{iP_h^-\zeta^+/z}\,\langle 0|\psi_f(\zeta^+)|P_hS_h,X\rangle\langle P_hS_h,X|\bar\psi_f(0)\,\gamma^-\gamma_5|0\rangle$$

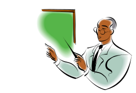
Tr [… γ⁻ γⁱ γ₅] →

$$\Delta^{[i\sigma^{i-}\gamma_5]} = \sum_X\!\!\!\!\!\!\int \frac{d\zeta^+}{2\pi}\, e^{iP_h^-\zeta^+/z}\,\langle 0|\psi_f(\zeta^+)|P_hS_h,X\rangle$$

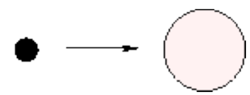
$$\langle P_hS_h,X|\bar\psi_f(0)\,i\sigma^{i-}\gamma_5|0\rangle$$

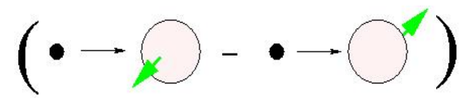
Correlatore con momento trasverso intrinseco

$$\Delta^{[\Gamma]}(z, \mathbf{P}_{hT}, S_h) = \frac{1}{4z} \int dk^+ \, \mathrm{Tr}\left[\Delta(k, P_h, S_h)\,\Gamma\right]\Big|_{k^- = P_h^-/z}$$

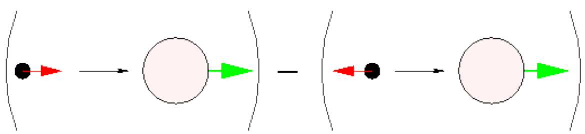


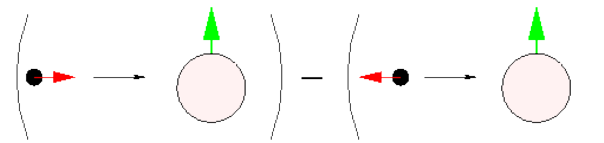
Proiezioni al leading twist

$D_1 =$ 

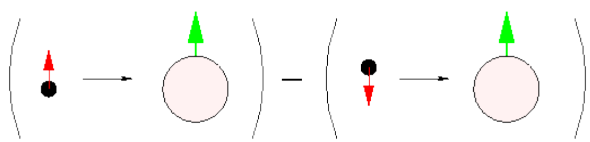
$D_{1T}^{\perp} =$ 

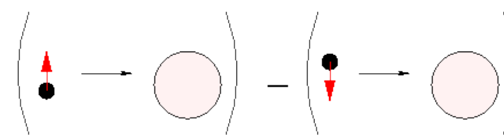
$$\Delta^{[\gamma^-]}(z, \mathbf{P}_{hT}, S_h) = D_1(z, \mathbf{P}_{hT}^2) + \frac{(\mathbf{k}_T \times \mathbf{S}_{hT})_i}{M_h} D_{1T}^{\perp}(z, \mathbf{P}_{hT}^2)$$

$G_{1L} =$ 

$G_{1T} =$ 

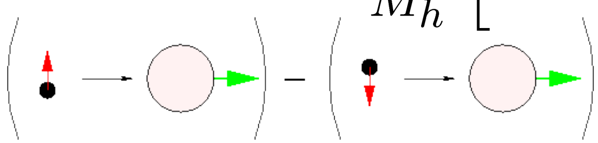
$$\Delta^{[\gamma^- \gamma_5]}(z, \mathbf{P}_{hT}, S_h) = \lambda_h \, G_{1L}(z, \mathbf{P}_{hT}^2) + \frac{\mathbf{k}_T \cdot \mathbf{S}_{hT}}{M_h} G_{1T}^{\perp}(z, \mathbf{P}_{hT}^2)$$

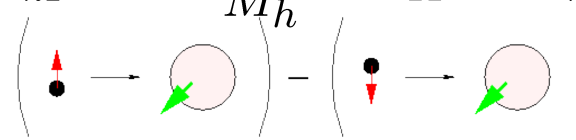
$H_{1T} =$ 

$H_1^{\perp} =$ 

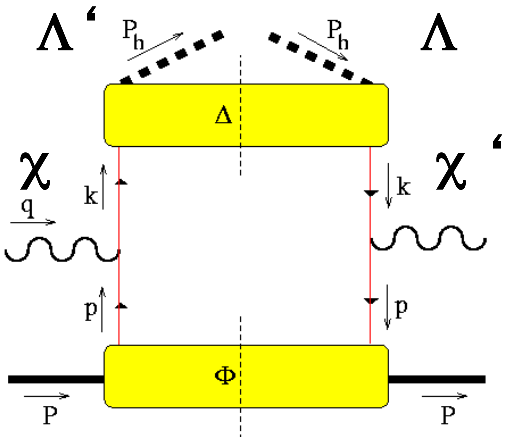
$$\Delta^{[i\sigma^{i-}\gamma_5]}(z, \mathbf{P}_{hT}, S_h) = S_{hT}^i \, H_{1T}(z, \mathbf{P}_{hT}^2) + \frac{(\hat{\mathbf{n}}_F \times \mathbf{k}_T)_i}{M_h} H_1^{\perp}(z, \mathbf{P}_{hT}^2)$$

$$+ \frac{k_T^i}{M_h}\left[\lambda_h \, H_{1L}^{\perp}(z, \mathbf{P}_{hT}^2) + \frac{\mathbf{k}_T \cdot \mathbf{S}_{hT}}{M_h} H_{1T}^{\perp}(z, \mathbf{P}_{hT}^2)\right]$$

$H_{1L}^{\perp} =$ 

$H_{1T}^{\perp} =$ 

Rappresentazione di elicità di $\Delta\,(z,\mathbf{P}_{hT},S_h)$

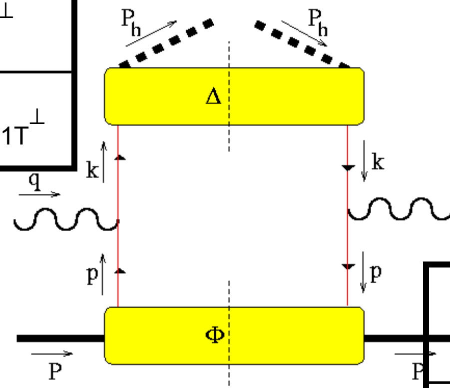


PFF	chiral even		chiral-odd
	q non pol.	$q^{\rightarrow}$	$q^{\uparrow}$
H non pol.	D_1		$H_1^{\perp}$
$H^{\rightarrow}$ =L		G_{1L}	$H_{1L}^{\perp}$
$H^{\uparrow}$ = T	$D_{1T}^{\perp}$	G_{1T}	H_1, $H_{1T}^{\perp}$

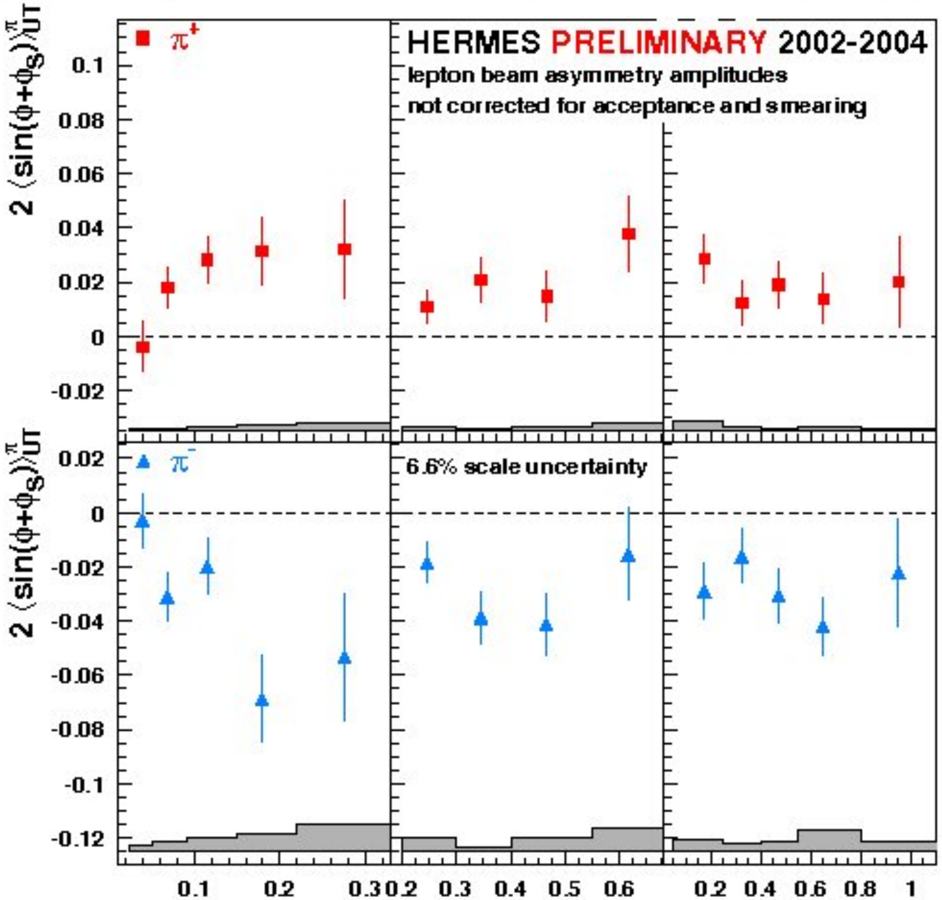
naïve T-even

naïve T-odd

PFF	chiral even		chiral-odd
	q non pol.	$q^{\rightarrow}$	$q^{\uparrow}$
H non pol.	D_1		$H_1^{\perp}$
$H^{\rightarrow}$ =L		G_{1L}	$H_{1L}^{\perp}$
$H^{\uparrow}$ = T	$D_{1T}^{\perp}$	G_{1T}	H_1, $H_{1T}^{\perp}$

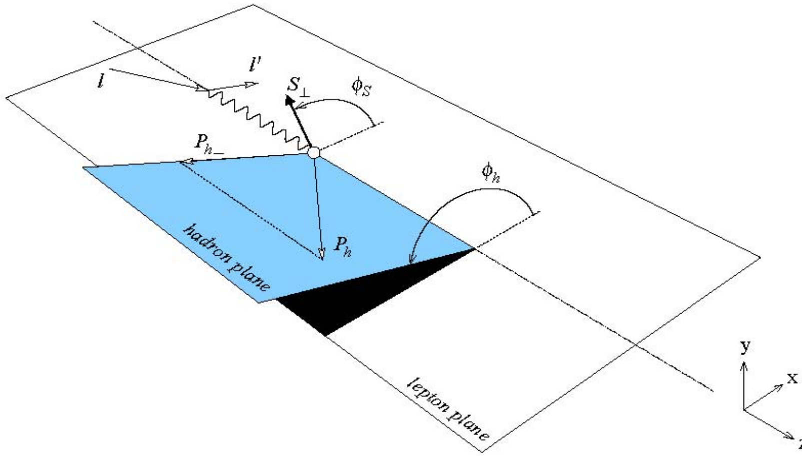


PDF	chiral even		chiral-odd
	q non pol.	$q^{\rightarrow}$	$q^{\uparrow}$
H non pol.	f_1		$h_1^{\perp}$
$H^{\rightarrow}$ =L		g_{1L}	$h_{1L}^{\perp}$
$H^{\uparrow}$ = T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$



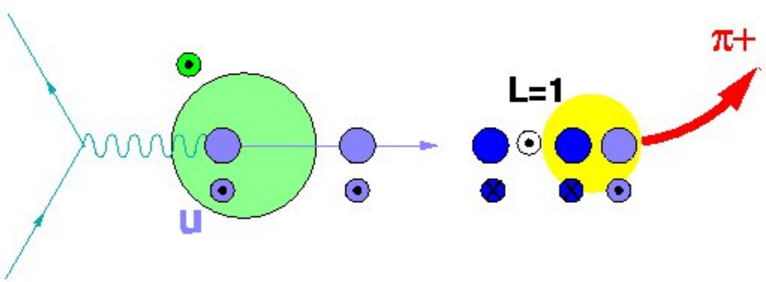
$$e\,p^{\uparrow} \to e'\,\pi^{\pm}\,X$$

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



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

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

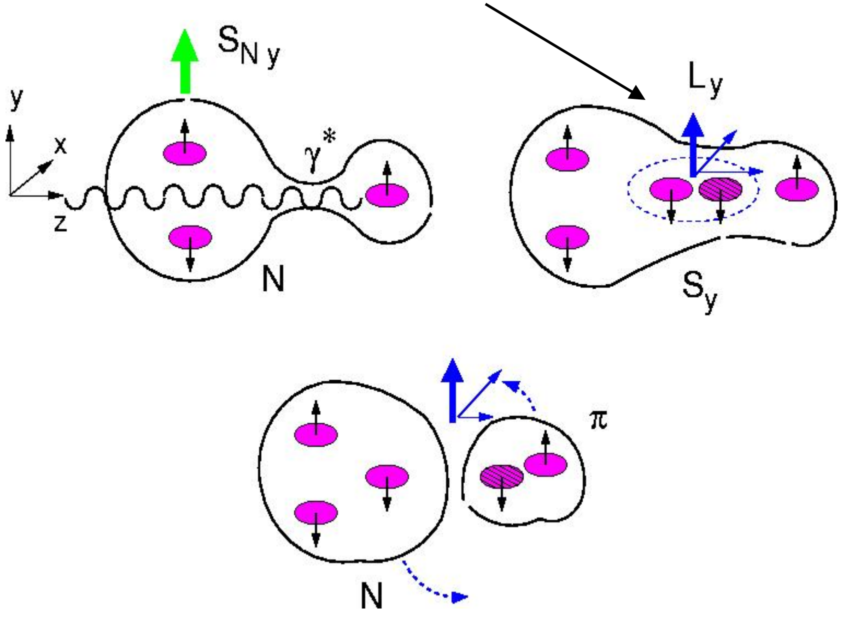


$$\left.\begin{array}{l}\phi_S = \pi/2 \\ \phi \;=\; 0\end{array}\right\} \sin(\phi + \phi_S) > 0$$

Congettura semi-classica : poichè γ^* colpisce $q^\uparrow$ si forma una stringa di forza di colore; quando la stringa si rompe, si forma un quarkonio con spin 1 e momento angolare orbitale opposto; tale momento angolare orbitale e determina l'asimmetria azimutale nell'emissione dell'adrone finale

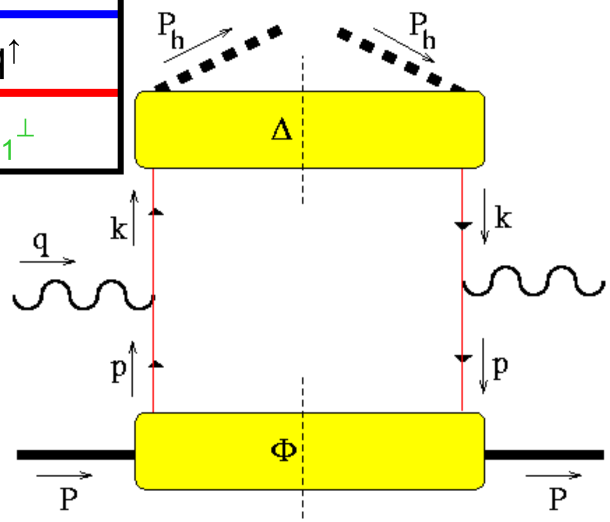
(Artru , hep-ph/9310323)

quantici vuoto $J^{PC} = 0^{++}$
quarkonio ha S=1 $\rightarrow$ $^{2S+1}L_J = {}^3P_0$



effetto Sivers in SIDIS $e\,p^{\uparrow} \to e'\,\pi^{\pm}\,X$

Δ	chiral even		chiral-odd
	q	q$^{\rightarrow}$	q$^{\uparrow}$
π	D_1		$H_1^{\perp}$



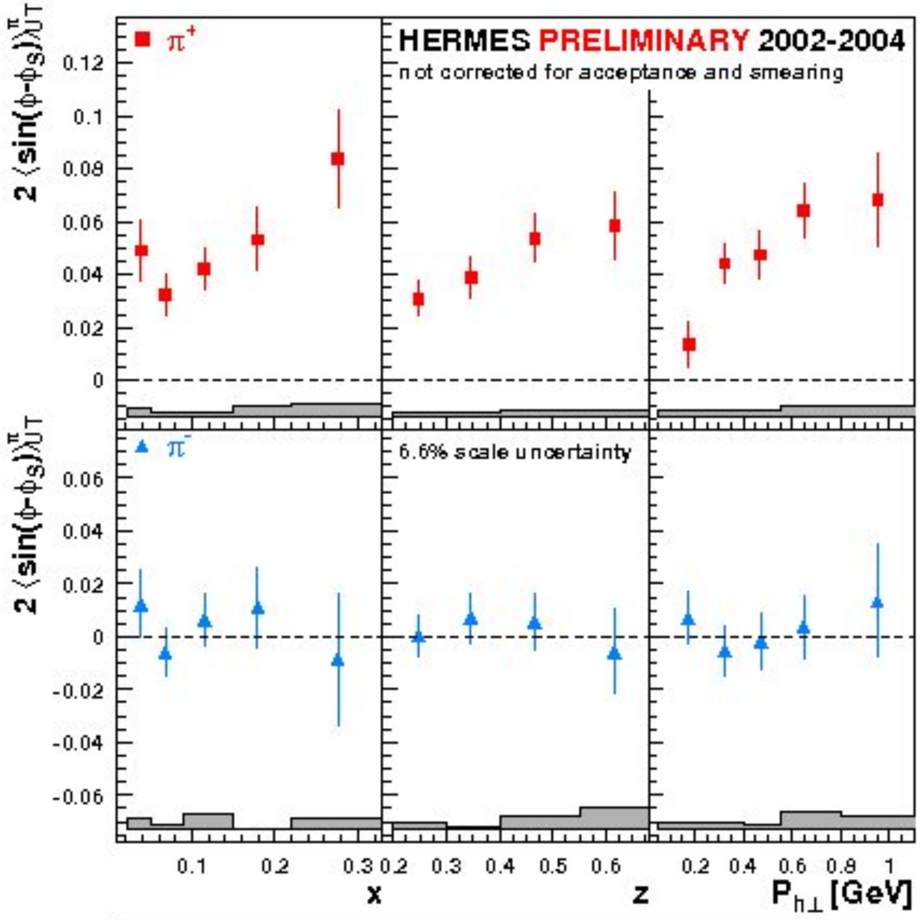
Φ	chiral even		chiral-odd
	q	q$^{\rightarrow}$	q$^{\uparrow}$
p	f_1		$h_1^{\perp}$
p$^{\uparrow}$ = T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

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

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

effetto Sivers e relativa Single Spin Asymmetry

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

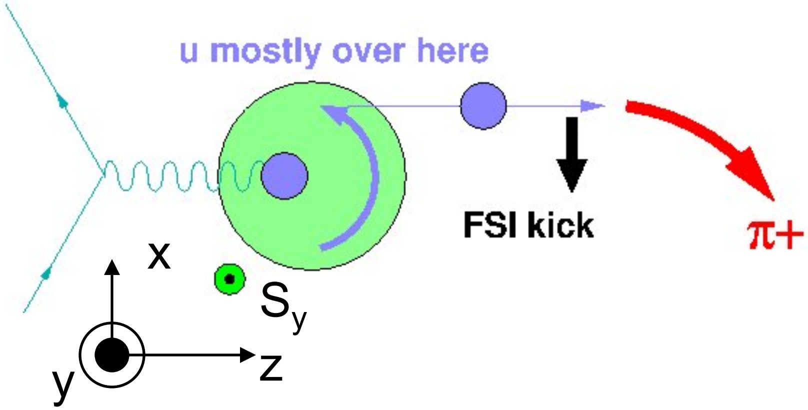


π^+ positivo $\rightarrow f_{1T}^{\perp\,u}$ negativa

$f_{1T}^{\perp\,d}$ positiva

(piccola)

(continua)



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

possibile interpretazione:
N↑ → 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

esempio di deflessione
per quark *d* a x>0