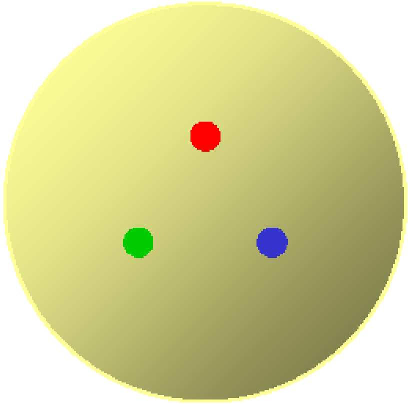
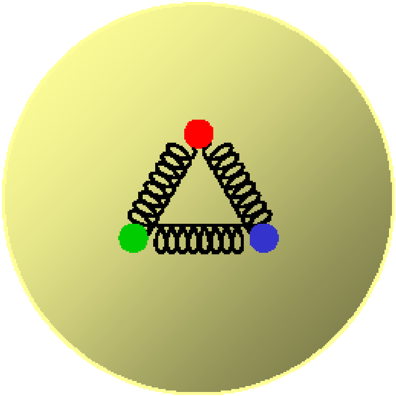
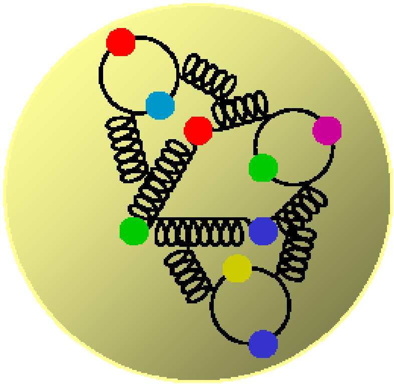
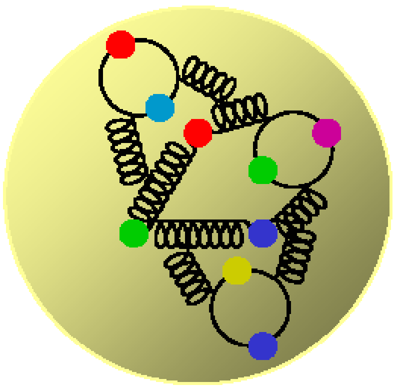
Inclusive and exclusive Drell-Yan at J-PARC

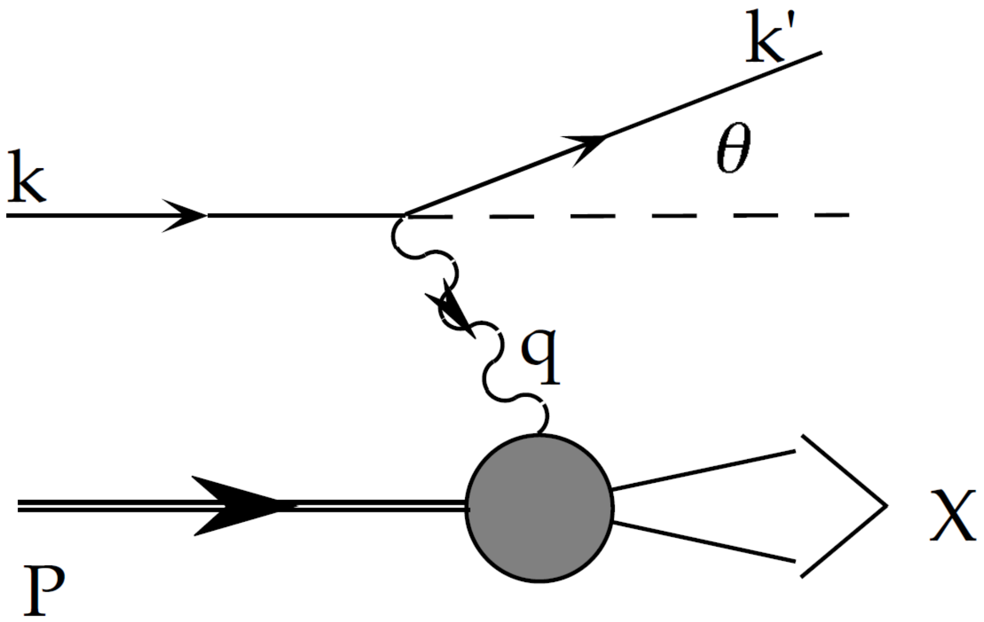
Kazuhiro Tanaka (Juntendo U/KEK)

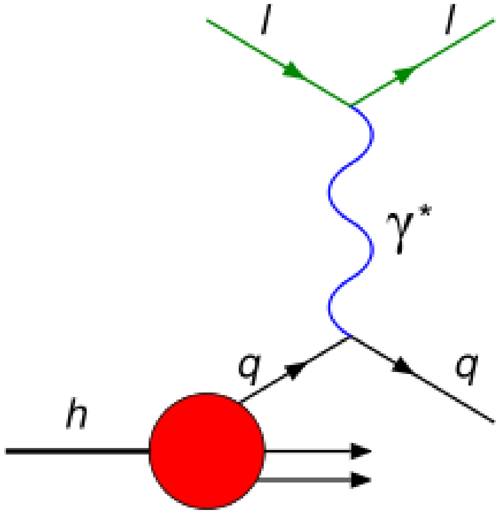






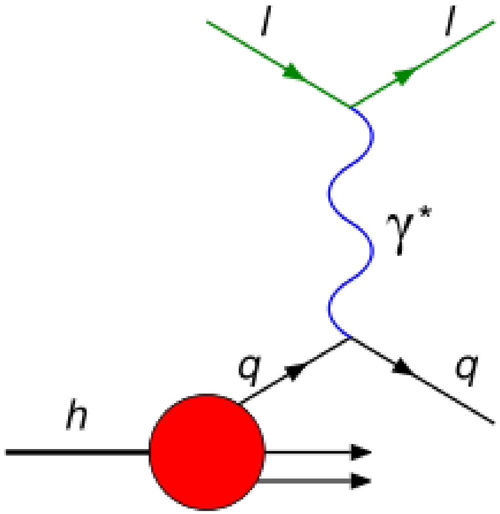



k'
θ
k
q
P
X

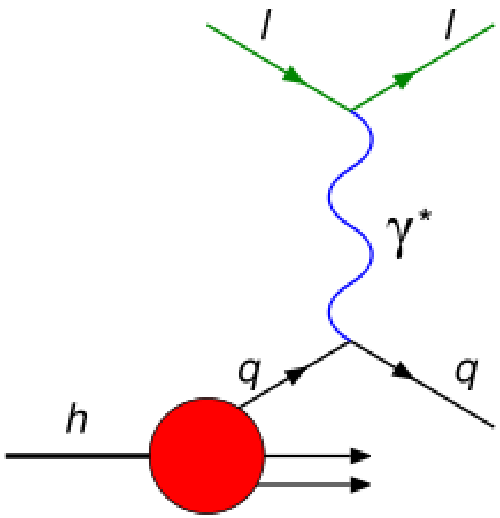


l
l
γ*
q
q
h

DIS

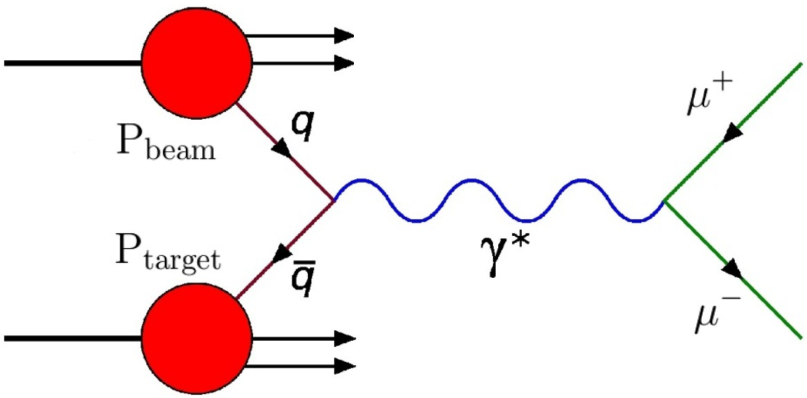


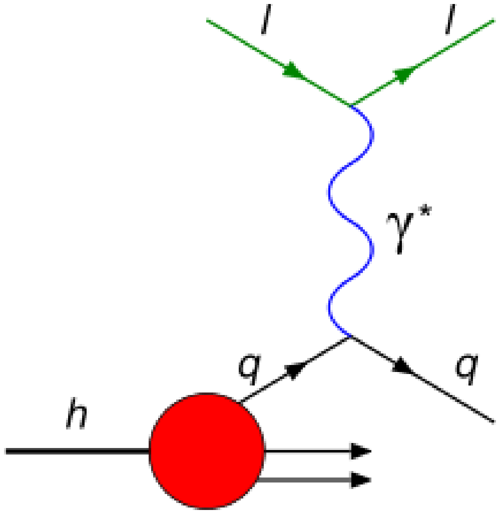
$$\left[q(x)+\bar{q}(x)\right], \qquad G(x)$$



DIS

$$\left[q(x)+\overline{q}(x)\right], \qquad G(x)$$



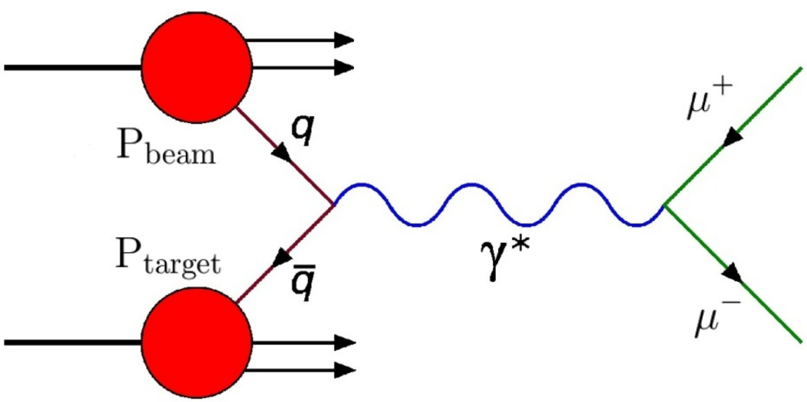


DIS

$$[q(x) + \bar{q}(x)], \quad G(x)$$

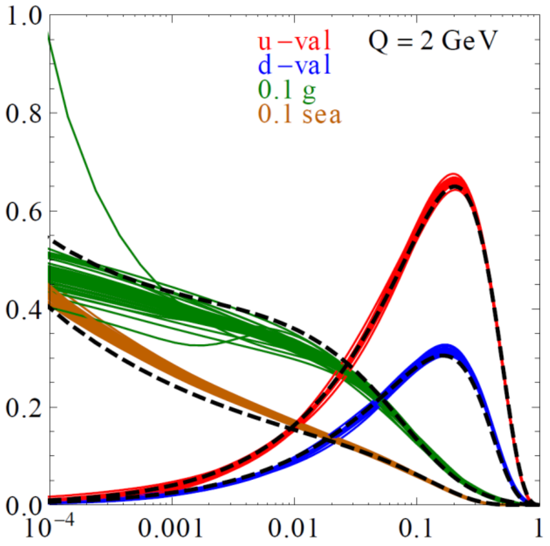
DY

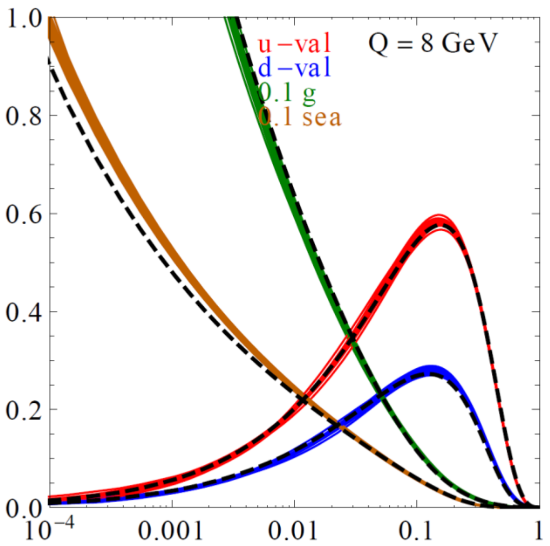
$$q(x), \quad \bar{q}(x), \quad G(x)$$



CT10 NNLO, PRD89 ('14) 033009

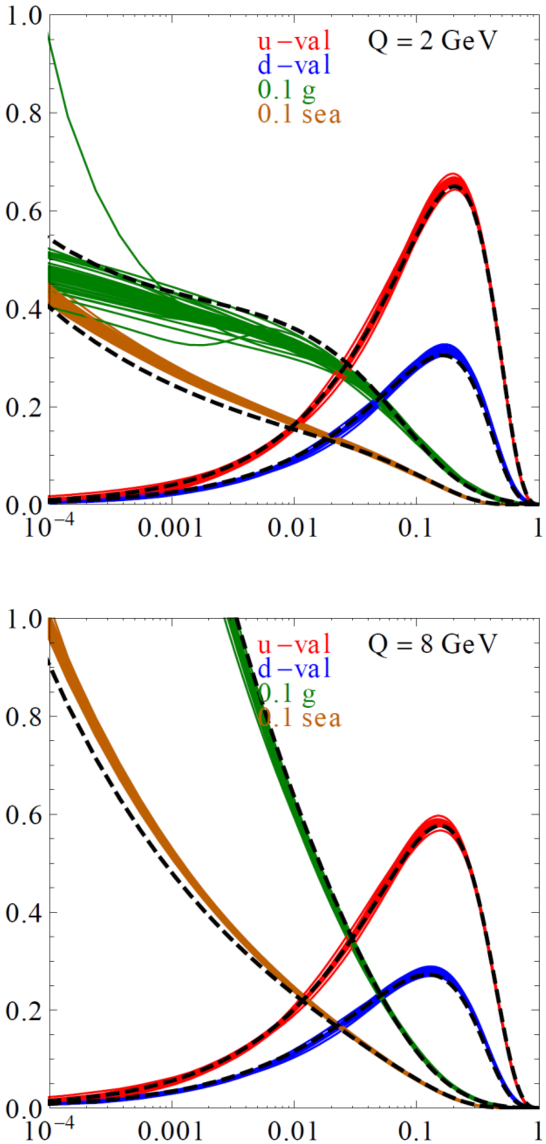
x f(x,Q) versus x

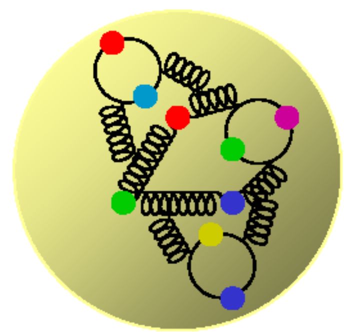




CT10 NNLO, PRD89 ('14) 033009

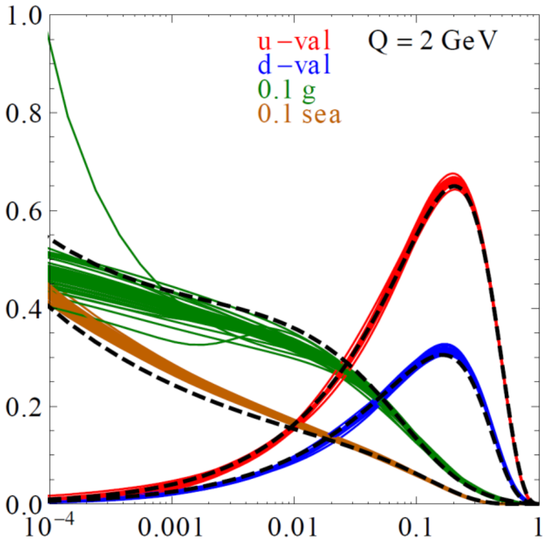
x f(x,Q) versus x

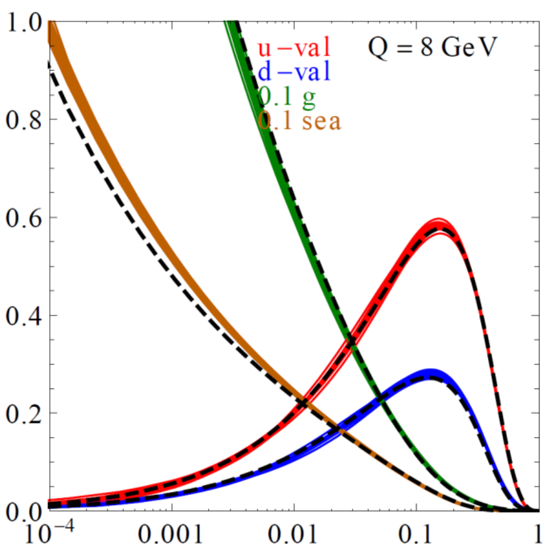




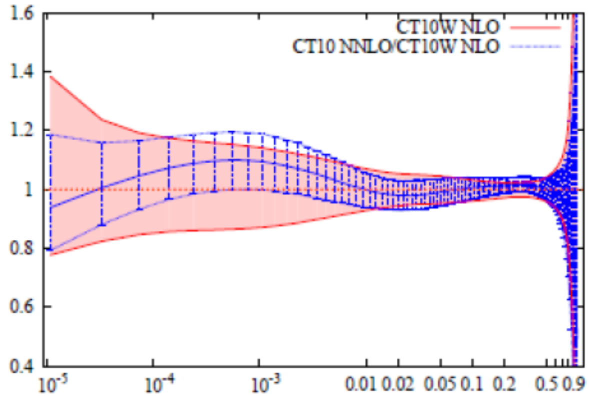
CT10 NNLO, PRD89 ('14) 033009

x f(x,Q) versus x

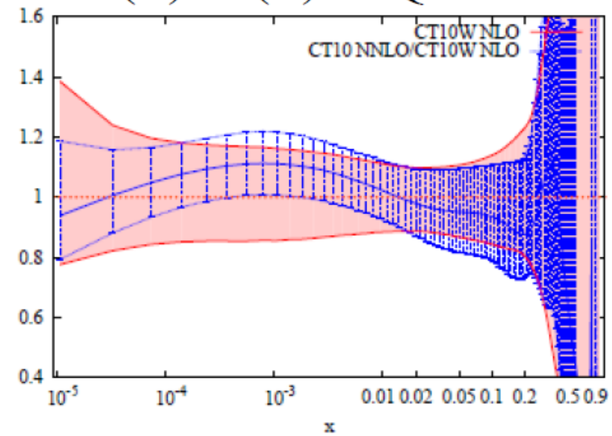


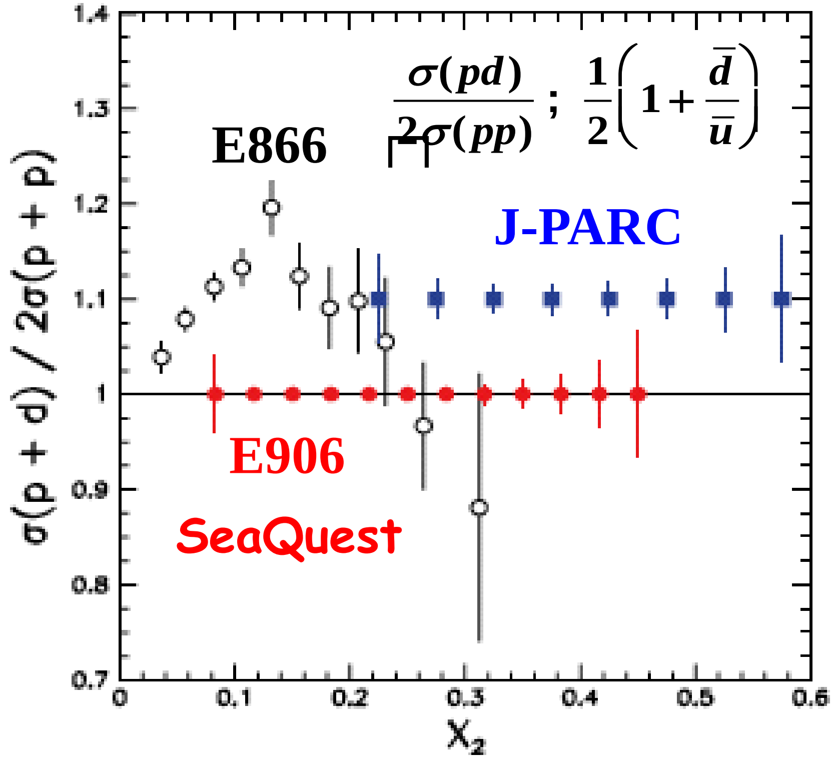


$\delta u(x)/u(x)$ at Q=2GeV



$\delta \bar{u}(x)/\bar{u}(x)$ at Q=2GeV

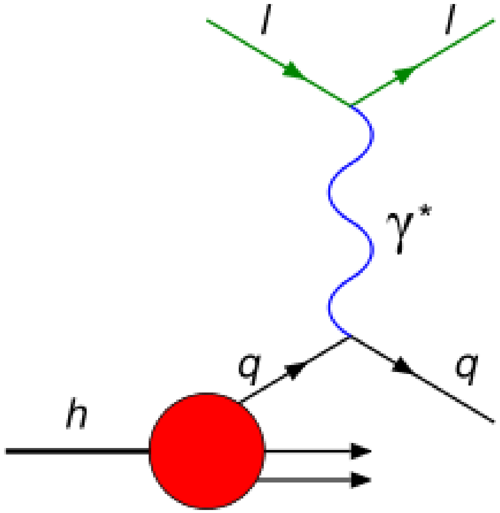




High-momentum beamline

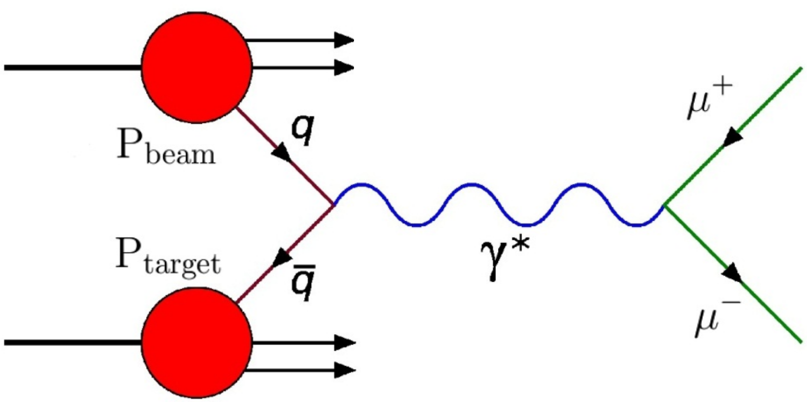
- 30 GeV proton

high intensity



DIS

$$[q(x)+\bar{q}(x)], \quad G(x)$$



DY

$$q(x), \quad \bar{q}(x), \quad G(x)$$

High-momentum beamline

- 30 GeV proton

high intensity

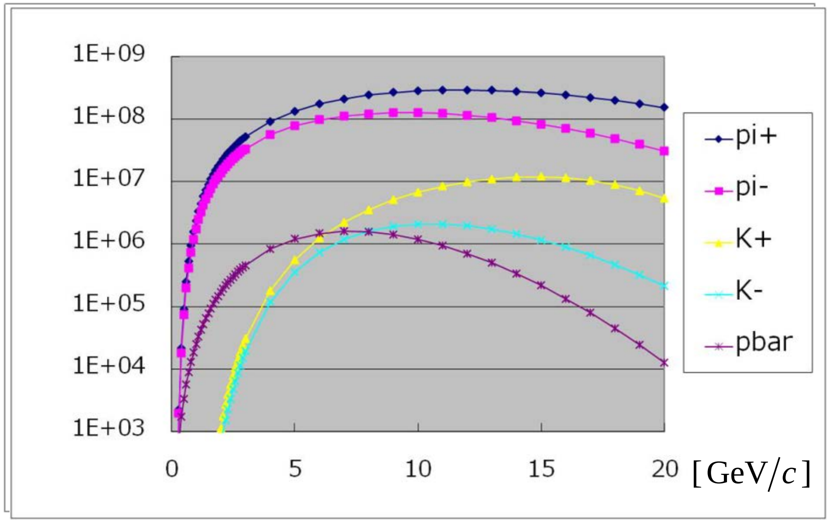
High-momentum beamline

- 30 GeV proton
- ~15-20 GeV unseparated (mainly pions)

Unseparated Secondary Beam Intensity

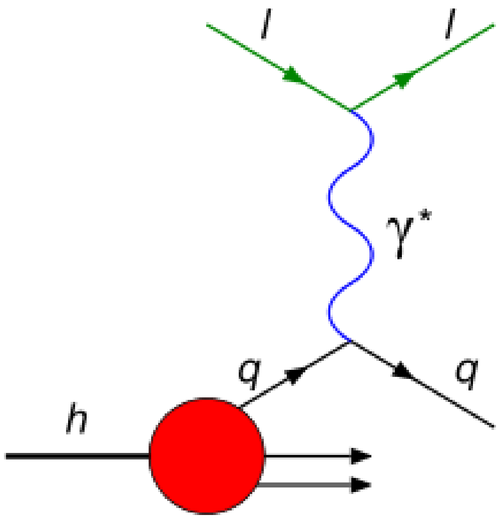
beam loss limit @ SM1:15kW

(limited by the thickness of the tunnel wall)



0° extraction angle

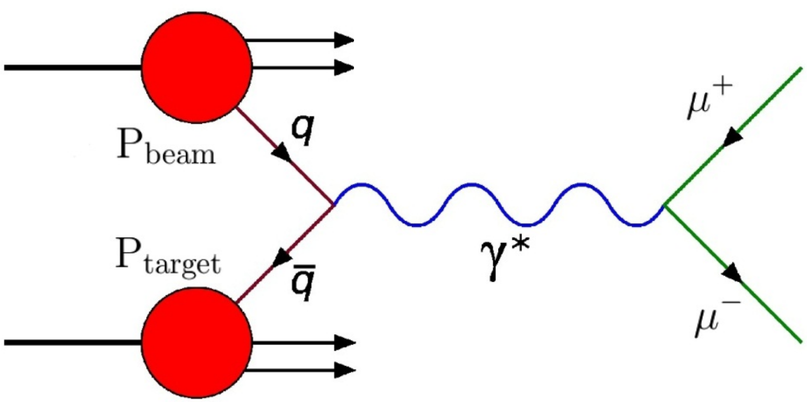
high intensity



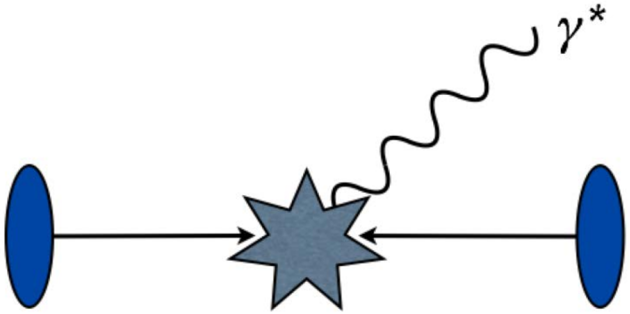
DIS

$$[q(x)+\overline{q}(x)], \qquad G(x)$$

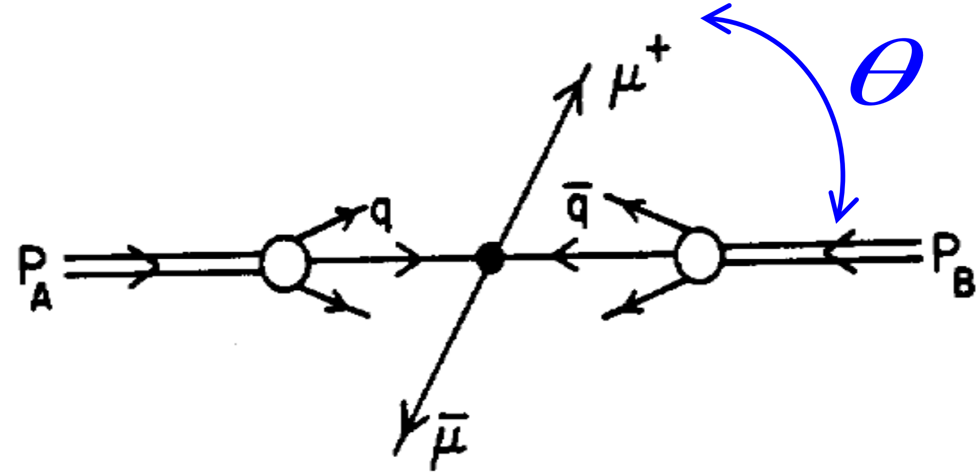
DY



$$q(x), \qquad \overline{q}(x), \qquad G(x)$$



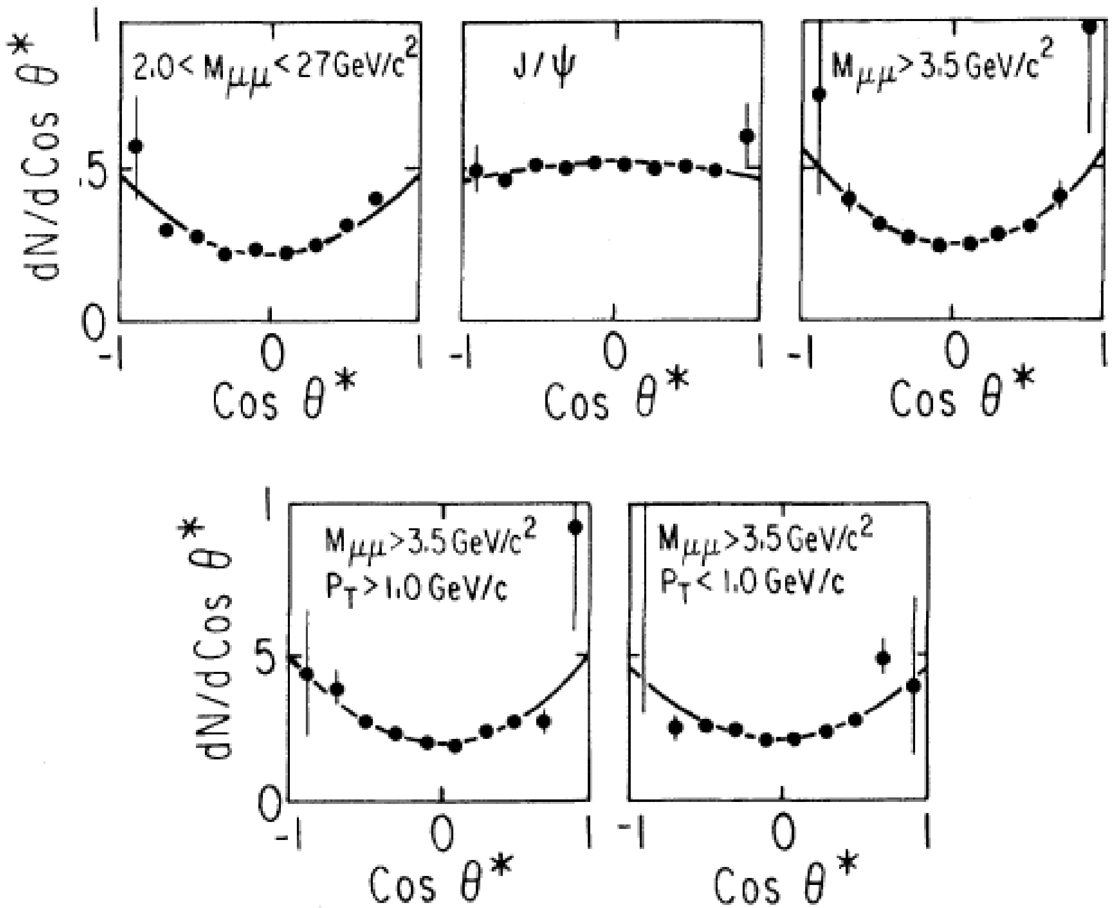
γ^*



μ^+
θ
q
$\bar{q}$
P_A
P_B
$\bar{\mu}$

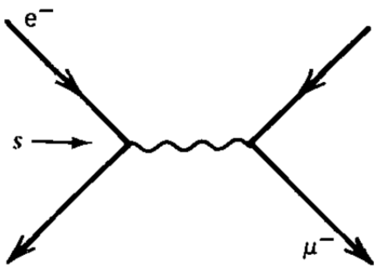
FNAL252-GeV $\pi-$

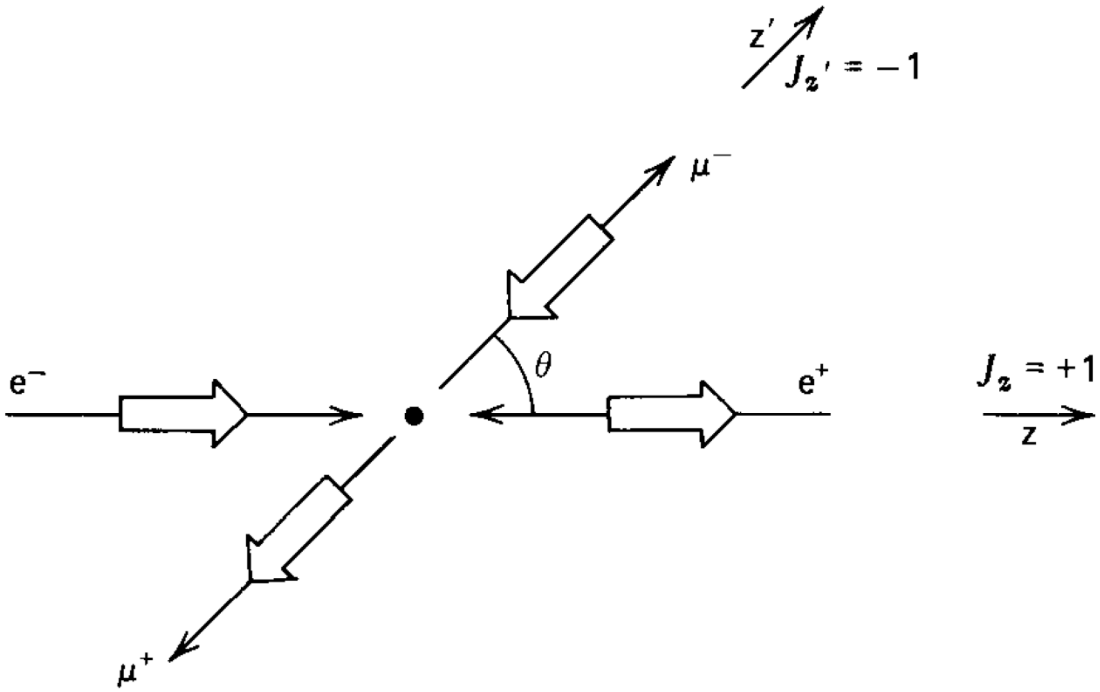
PRL 42, 948, (1979)



$$\frac{d\sigma}{d\Omega} \propto \left(1 + \cos^2 \theta\right)$$

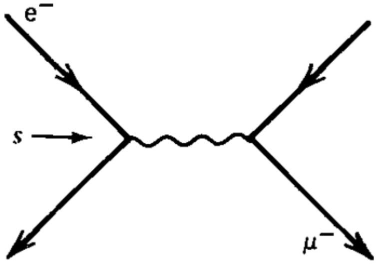
$e^- e^+ \rightarrow \mu^+ \mu^-$

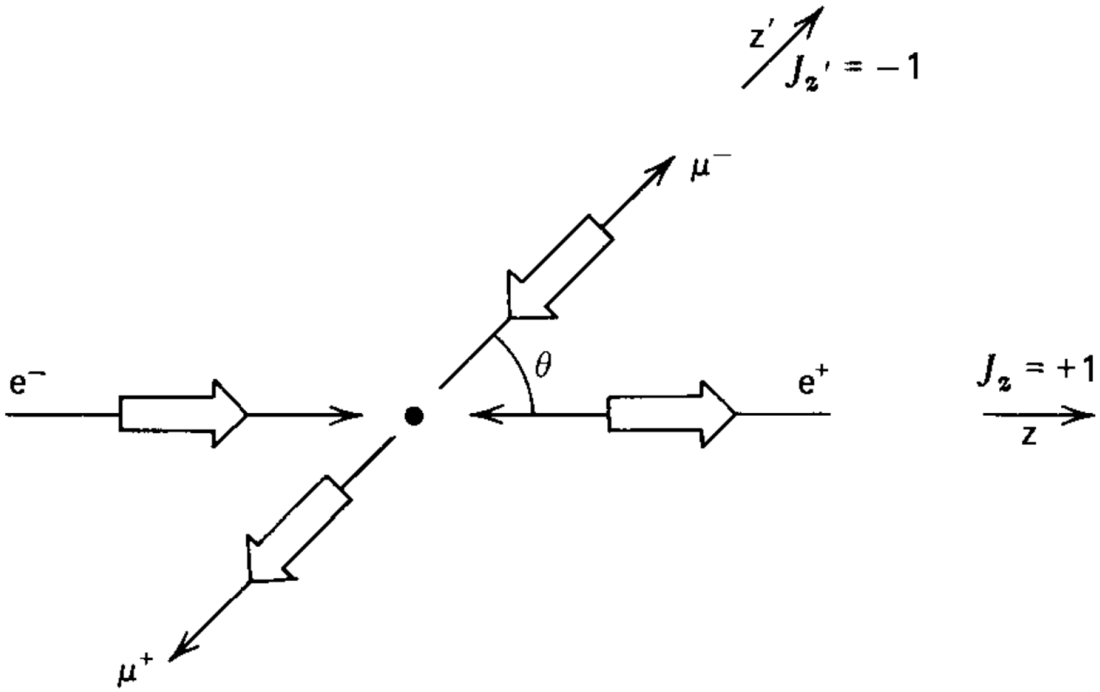




$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left(1 + \cos^2\theta\right)$$

$$e^- e^+ \rightarrow \mu^+ \mu^-$$





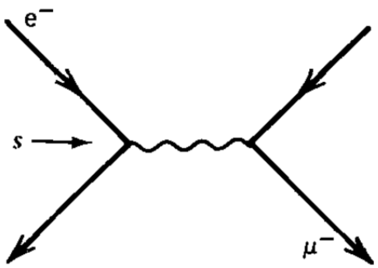
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left(1+\cos^2\theta\right) \propto \left|d^1_{-1\,1}(\theta)\right|^2 + \left|d^1_{1\,1}(\theta)\right|^2$$

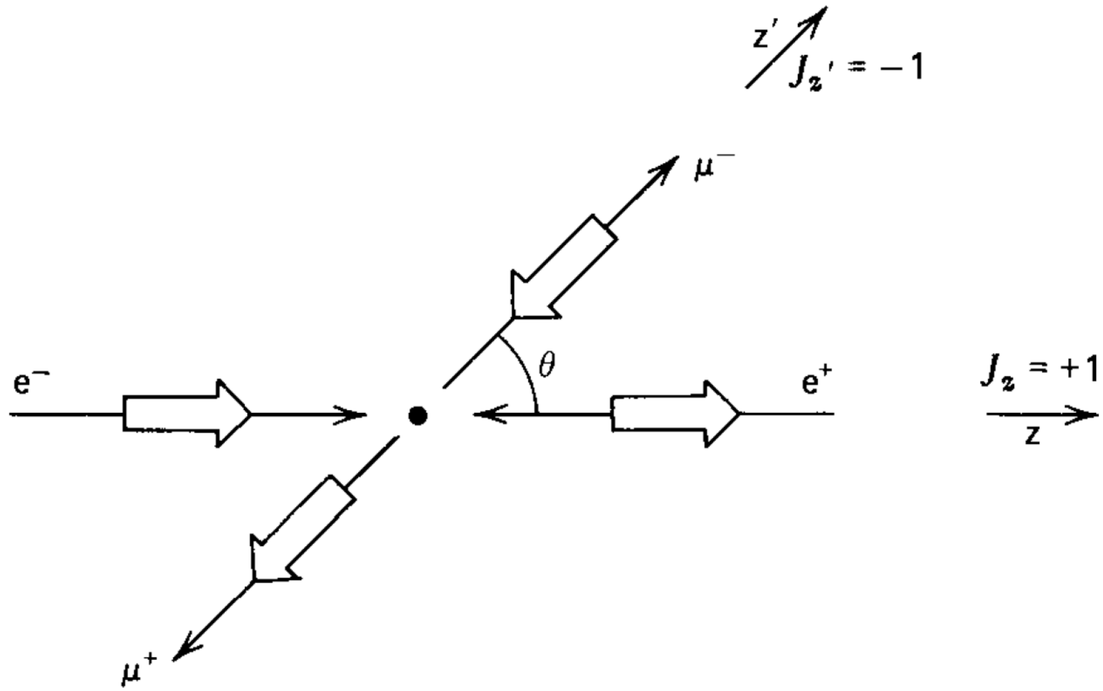
$$d^1_{-1\,1}(\theta) = d^1_{1\,-1}(\theta) = \frac{1-\cos\theta}{2}$$

$$d^j_{\lambda'\lambda}(\theta) = \left\langle j\lambda' \middle| e^{-i\theta \hat{J}_y} \middle| j\lambda \right\rangle$$

$$d^1_{1\,1}(\theta) = d^1_{-1\,-1}(\theta) = \frac{1+\cos\theta}{2}$$

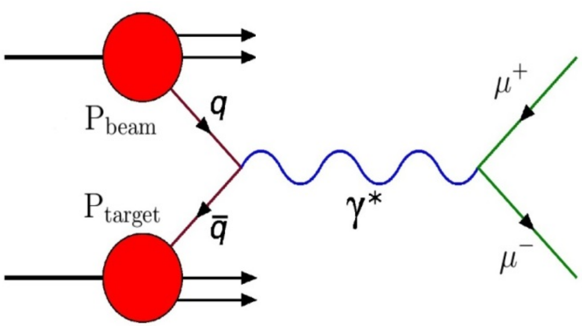
$e^- e^+ \to \mu^+ \mu^-$

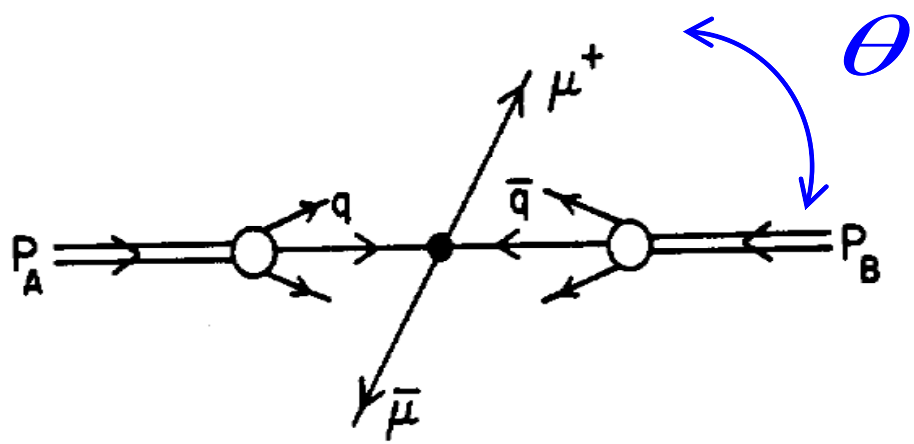




$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left(1+\cos^2\theta\right) \propto \left|d^1_{-1\,1}(\theta)\right|^2 + \left|d^1_{1\,1}(\theta)\right|^2$$

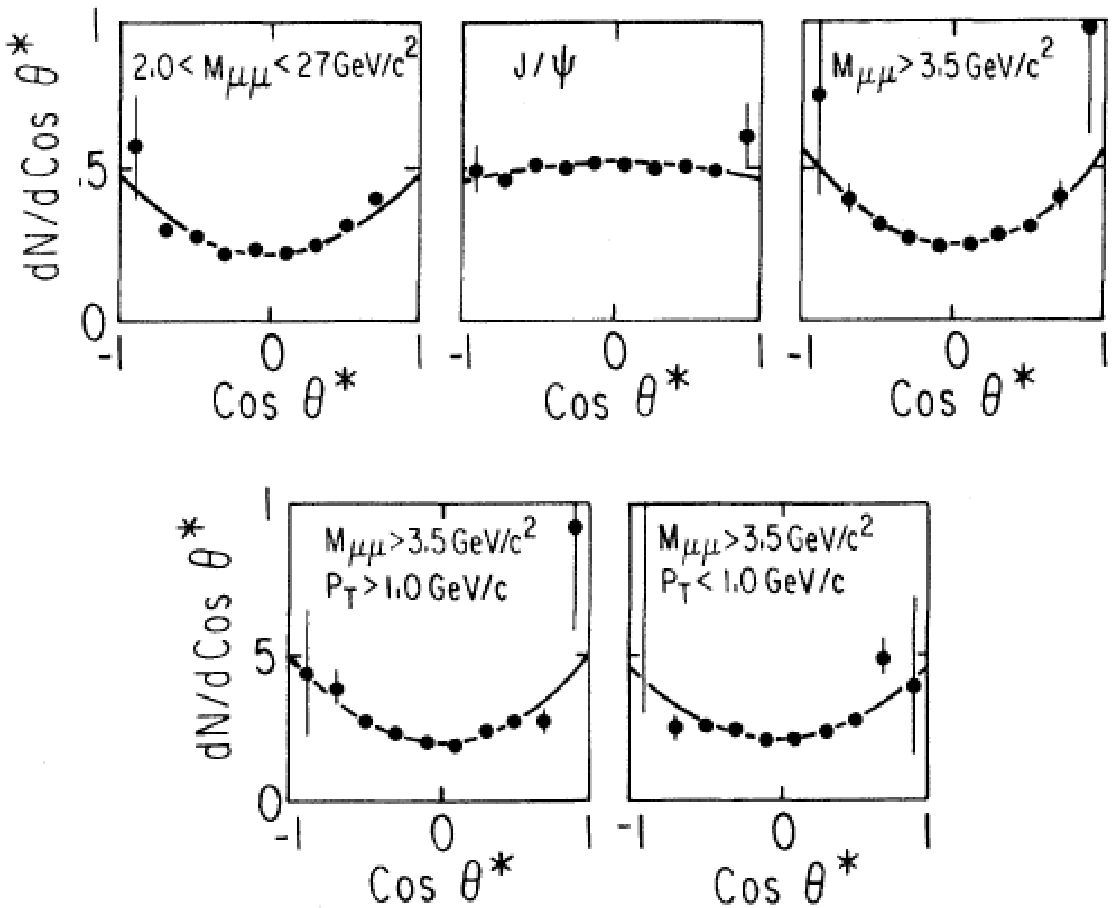
DY





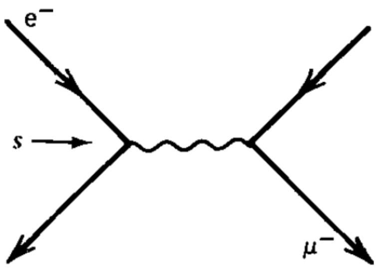
FNAL252-GeV $\pi-$

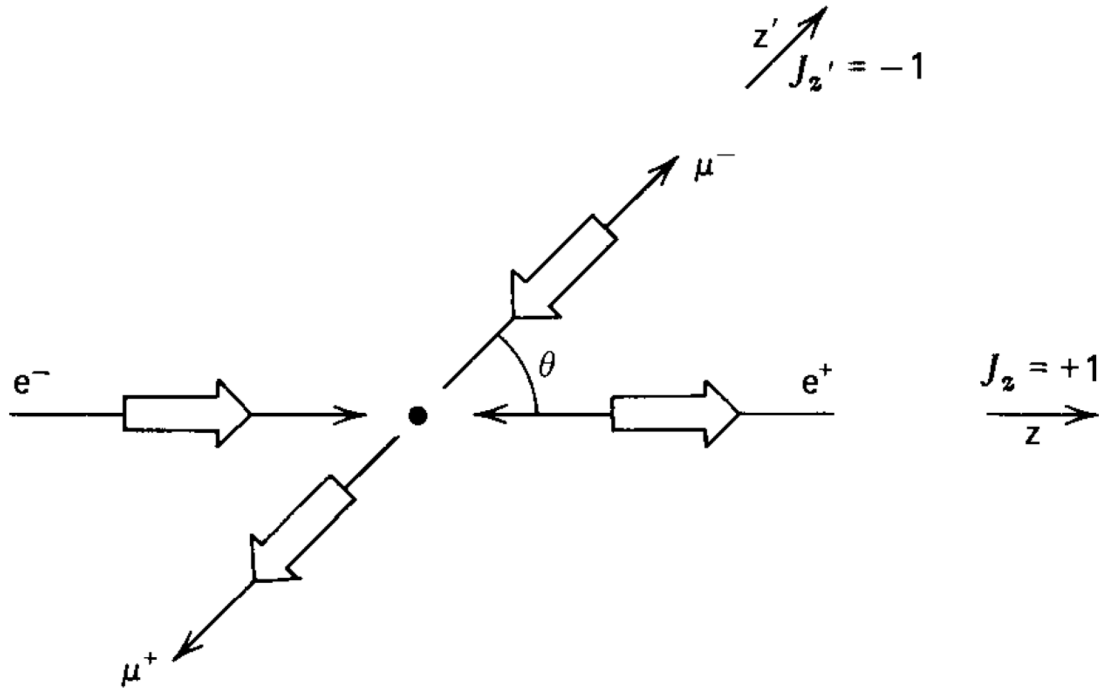
PRL 42, 948, (1979)



$$\frac{d\sigma}{d\Omega} \propto \left(1 + \cos^2\theta\right)$$

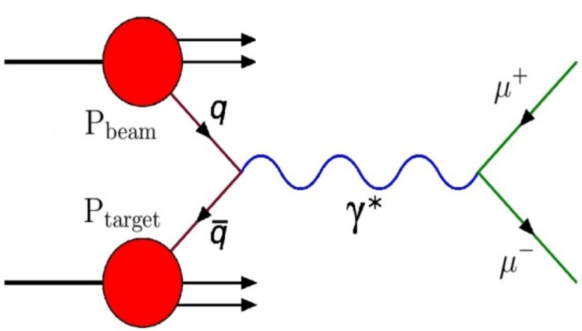
$$e^- e^+ \to \mu^+ \mu^-$$

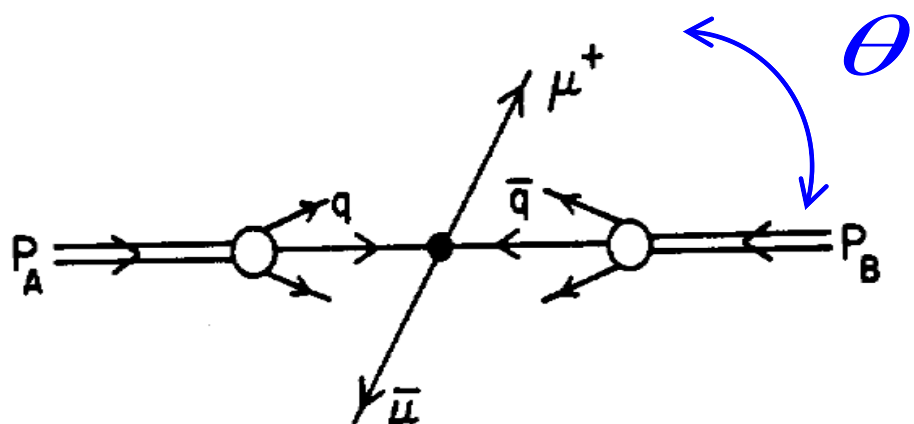




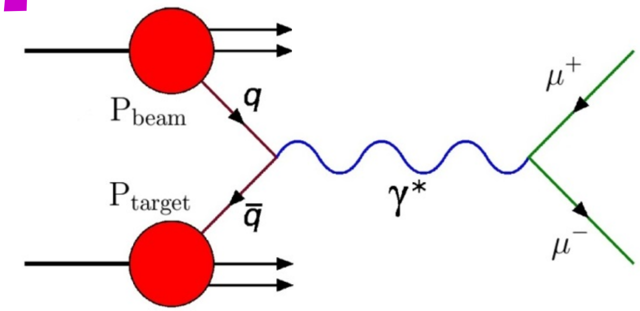
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left(1+\cos^2\theta\right) \propto \left|d^1_{-1\,1}(\theta)\right|^2 + \left|d^1_{1\,1}(\theta)\right|^2$$

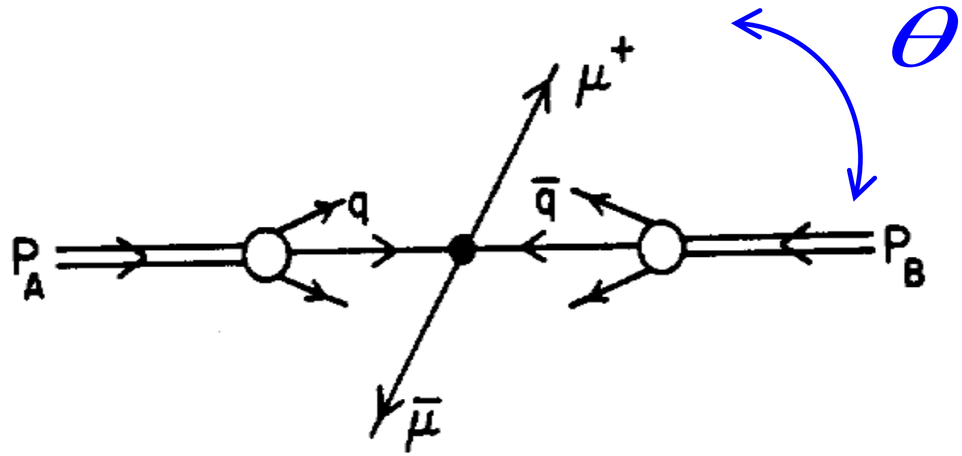
DY





DY

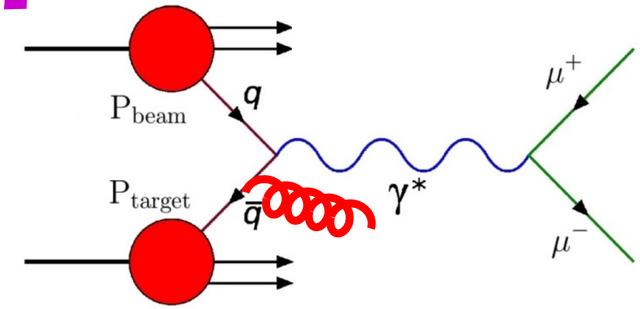


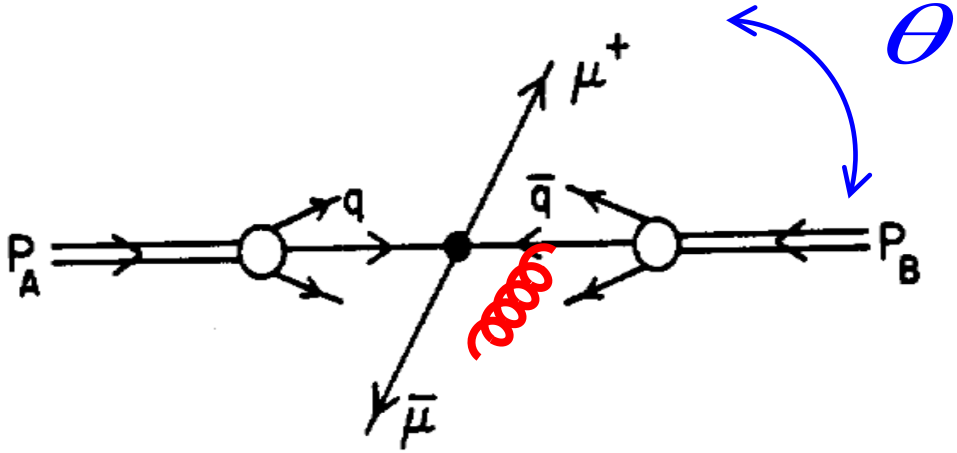


$$\frac{d\sigma}{d\Omega} \propto \left|d^{1}_{-1\,1}(\theta)\right|^2 + \left|d^{1}_{1\,1}(\theta)\right|^2 \propto \left(1+\cos^2\theta\right)$$

spin-$\frac{1}{2}$ quark

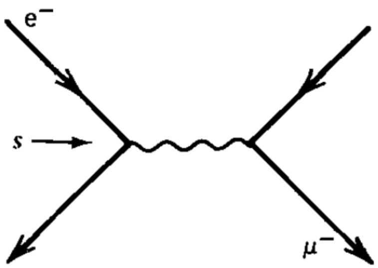
DY

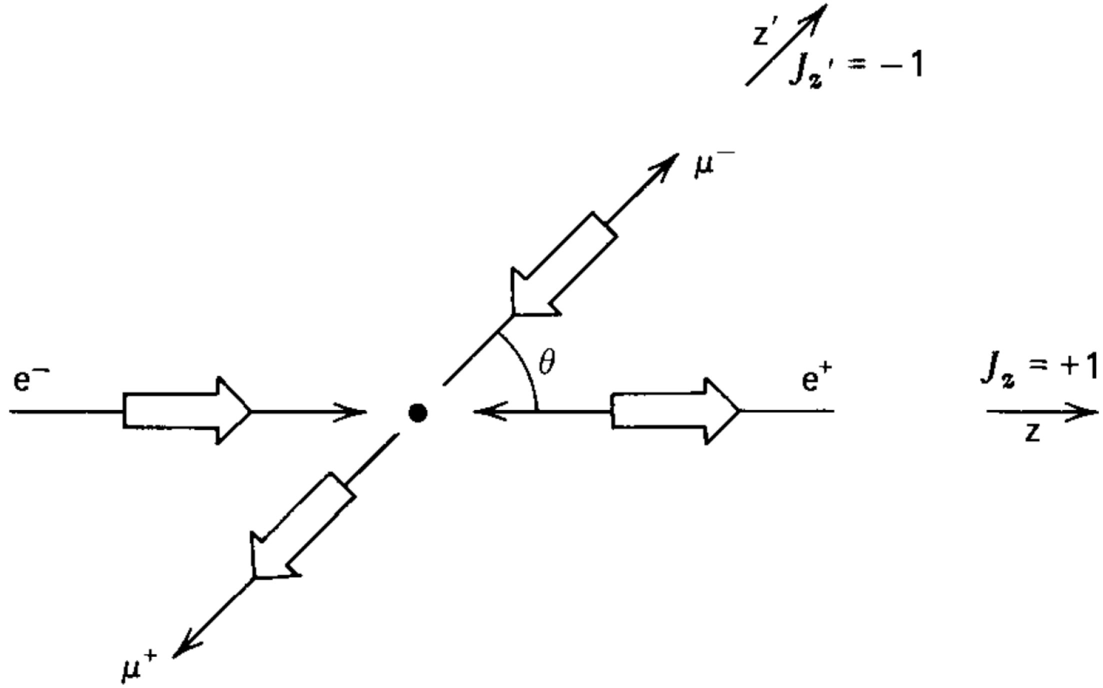




$$\frac{d\sigma}{d\Omega} \propto \left|d^{1}_{-1\,1}(\theta)\right|^{2} + \left|d^{1}_{1\,1}(\theta)\right|^{2} \propto \left(1+\cos^{2}\theta\right)$$

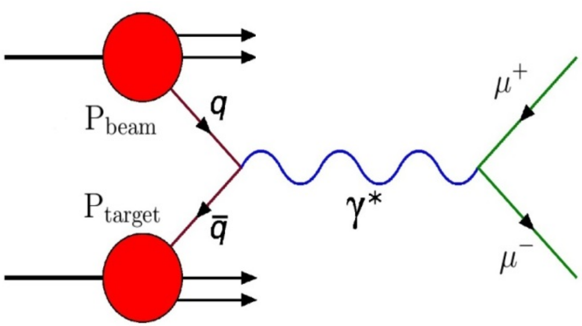
$e^- e^+ \rightarrow \mu^+ \mu^-$

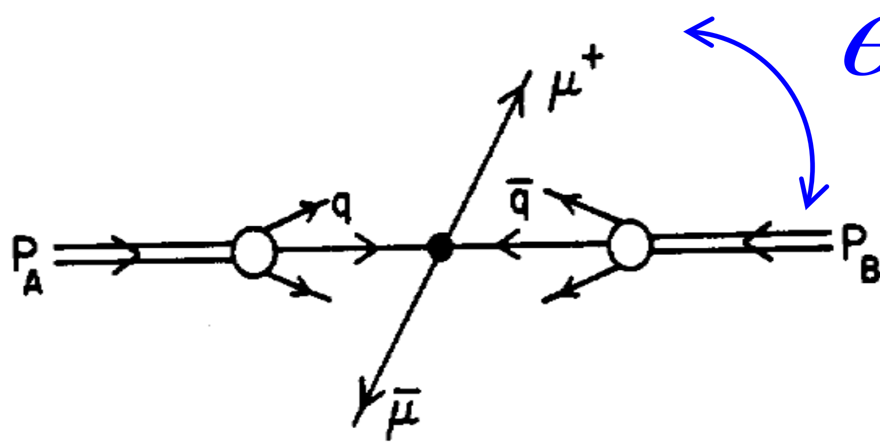


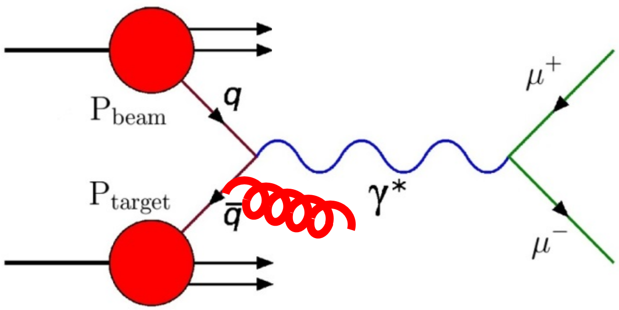


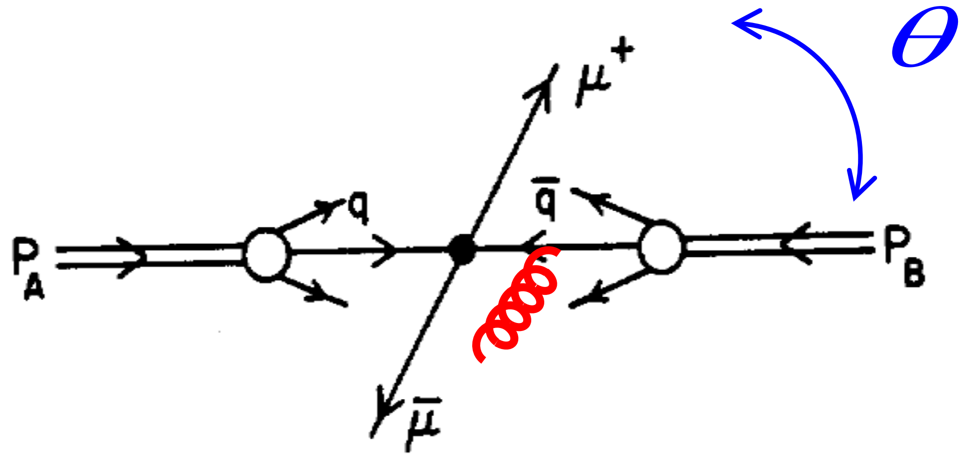
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left(1+\cos^2\theta\right) \propto \left|d^1_{-1\,1}(\theta)\right|^2 + \left|d^1_{1\,1}(\theta)\right|^2$$

DY



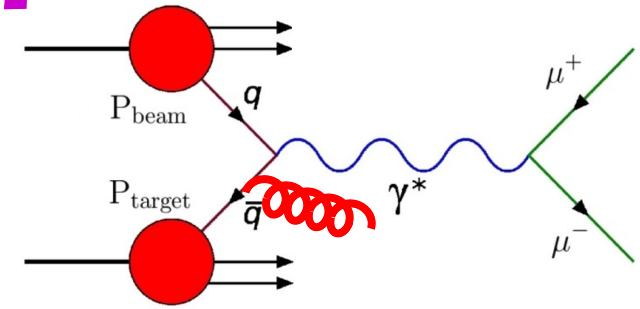


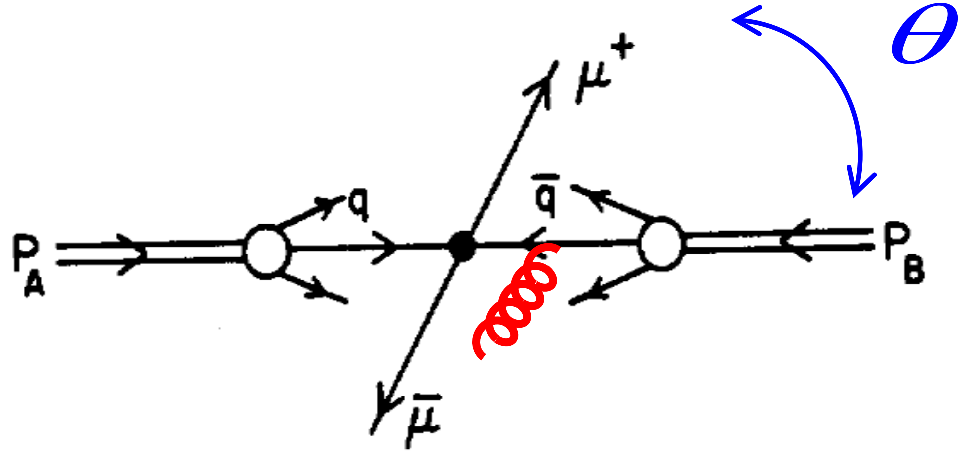




$$\frac{d\sigma}{d\Omega} \propto \left|d^{1}_{-1\,1}(\theta)\right|^{2} + \left|d^{1}_{1\,1}(\theta)\right|^{2} \propto \left(1+\cos^{2}\theta\right)$$

DY





$$\frac{d\sigma}{d\Omega} \propto (1+a)\left(\left|d^1_{-1\,1}(\theta)\right|^2 + \left|d^1_{1\,1}(\theta)\right|^2\right) + b\left(\left|d^1_{-1\,0}(\theta)\right|^2 + \left|d^1_{1\,0}(\theta)\right|^2\right)$$

$$D^j_{\lambda'\lambda}(\alpha,\theta,\phi) = e^{-i\lambda'\alpha} d^j_{\lambda'\lambda}(\theta) e^{-i\lambda\phi}$$

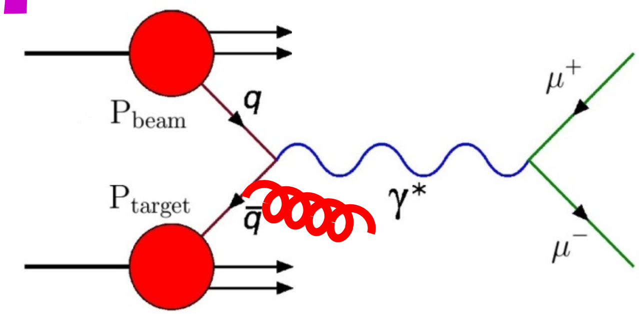
$$d^j_{\lambda'\lambda}(\theta) = \langle j\lambda' | e^{-i\theta \hat{J}_y} | j\lambda \rangle$$

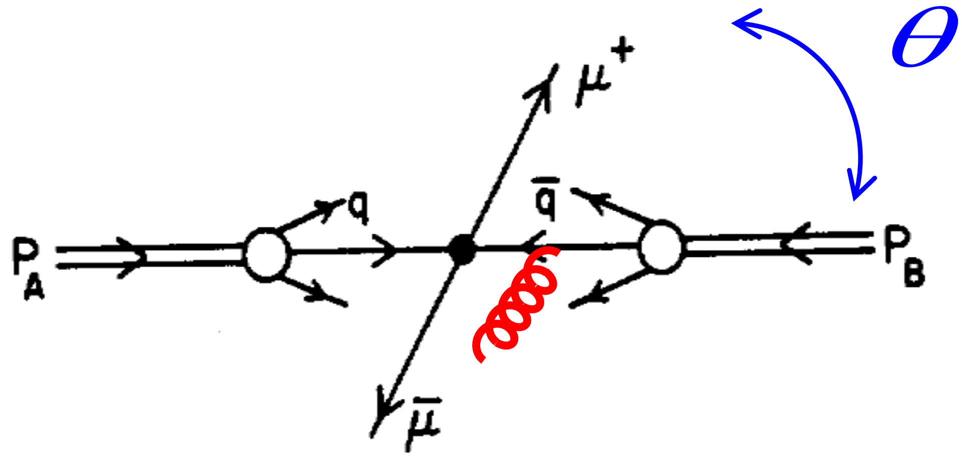
$$d^1_{1\,1}(\theta) = d^1_{-1\,-1}(\theta) = \frac{1+\cos\theta}{2}$$

$$d^1_{-1\,1}(\theta) = d^1_{1\,-1}(\theta) = \frac{1-\cos\theta}{2}$$

$$d^1_{-1\,0}(\theta) = -d^1_{1\,0}(\theta) = \frac{\sin\theta}{\sqrt{2}}$$

DY





$$\frac{d\sigma}{d\Omega} \propto (1+a)\left(\left|d^1_{-1\,1}(\theta)\right|^2 + \left|d^1_{1\,1}(\theta)\right|^2\right) + b\left(\left|d^1_{-1\,0}(\theta)\right|^2 + \left|d^1_{1\,0}(\theta)\right|^2\right)$$

$$+\Re e\left[c_1 d^1_{1\,0}(\theta)\left(d^1_{1\,1}(\theta)e^{-i\phi}\right)^* + c_2 d^1_{1\,-1}(\theta)e^{i\phi}\left(d^1_{1\,1}(\theta)e^{-i\phi}\right)^* + \cdots\right]$$

$$D^j_{\lambda'\lambda}(\alpha,\theta,\phi) = e^{-i\lambda'\alpha} d^j_{\lambda'\lambda}(\theta) e^{-i\lambda\phi}$$

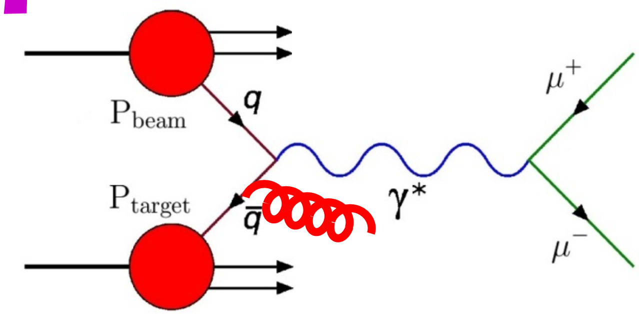
$$d^j_{\lambda'\lambda}(\theta) = \left\langle j\lambda' \right| e^{-i\theta \hat{J}_y} \left| j\lambda \right\rangle$$

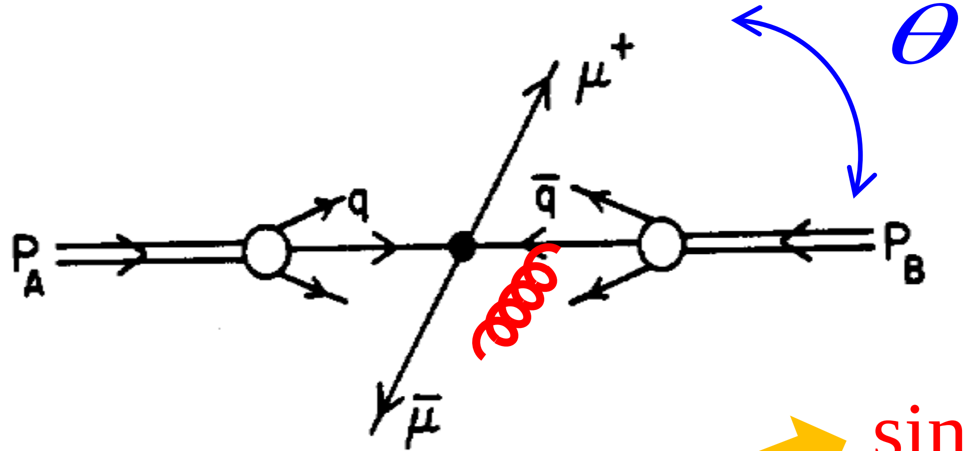
$$d^1_{1\,1}(\theta) = d^1_{-1\,-1}(\theta) = \frac{1+\cos\theta}{2}$$

$$d^1_{-1\,1}(\theta) = d^1_{1\,-1}(\theta) = \frac{1-\cos\theta}{2}$$

$$d^1_{-1\,0}(\theta) = -d^1_{1\,0}(\theta) = \frac{\sin\theta}{\sqrt{2}}$$

DY





$\sin^2\theta$

$$\frac{d\sigma}{d\Omega} \propto (1+a)\left(\left|d^1_{-1\,1}(\theta)\right|^2 + \left|d^1_{1\,1}(\theta)\right|^2\right) + b\left(\left|d^1_{-1\,0}(\theta)\right|^2 + \left|d^1_{1\,0}(\theta)\right|^2\right)$$

$$+\Re e\left[c_1 d^1_{1\,0}(\theta)\left(d^1_{1\,1}(\theta)e^{-i\phi}\right)^* + c_2 d^1_{1\,-1}(\theta)e^{i\phi}\left(d^1_{1\,1}(\theta)e^{-i\phi}\right)^* + \cdots\right]$$

$1+\cos^2\theta$

$\sin\theta\cos\theta\cos\phi$

$\sin^2\theta\cos 2\phi$

$$D^j_{\lambda'\lambda}(\alpha,\theta,\phi) = e^{-i\lambda'\alpha} d^j_{\lambda'\lambda}(\theta) e^{-i\lambda\phi}$$

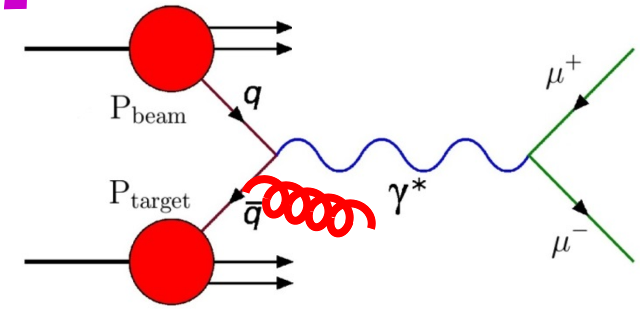
$$d^j_{\lambda'\lambda}(\theta) = \left\langle j\lambda'\right| e^{-i\theta\hat{J}_y} \left| j\lambda\right\rangle$$

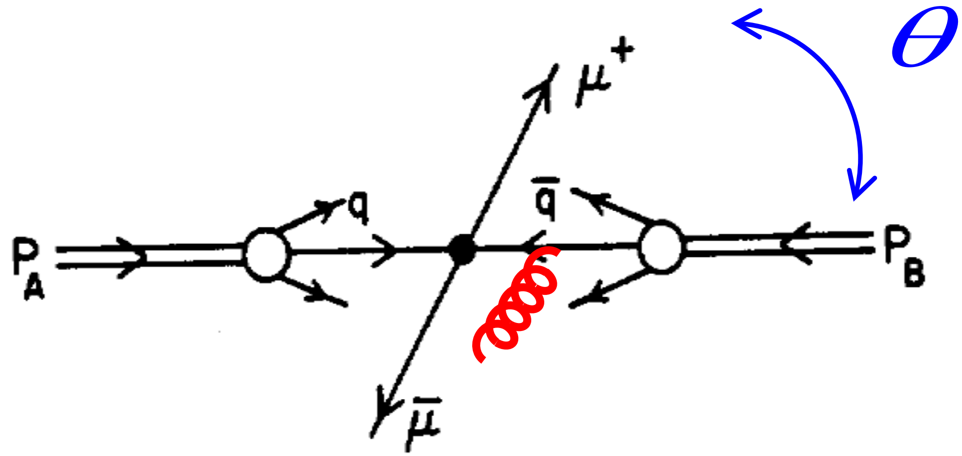
$$d^1_{1\,1}(\theta) = d^1_{-1\,-1}(\theta) = \frac{1+\cos\theta}{2}$$

$$d^1_{-1\,1}(\theta) = d^1_{1\,-1}(\theta) = \frac{1-\cos\theta}{2}$$

$$d^1_{-1\,0}(\theta) = -d^1_{1\,0}(\theta) = \frac{\sin\theta}{\sqrt{2}}$$

DY



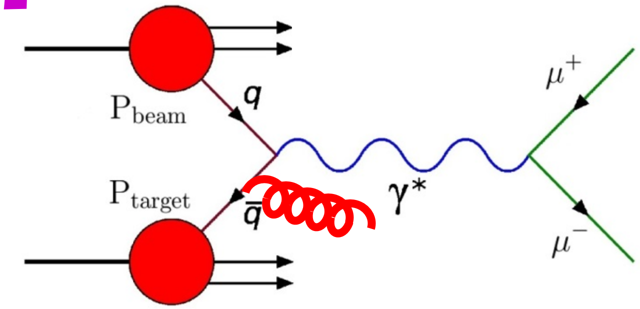


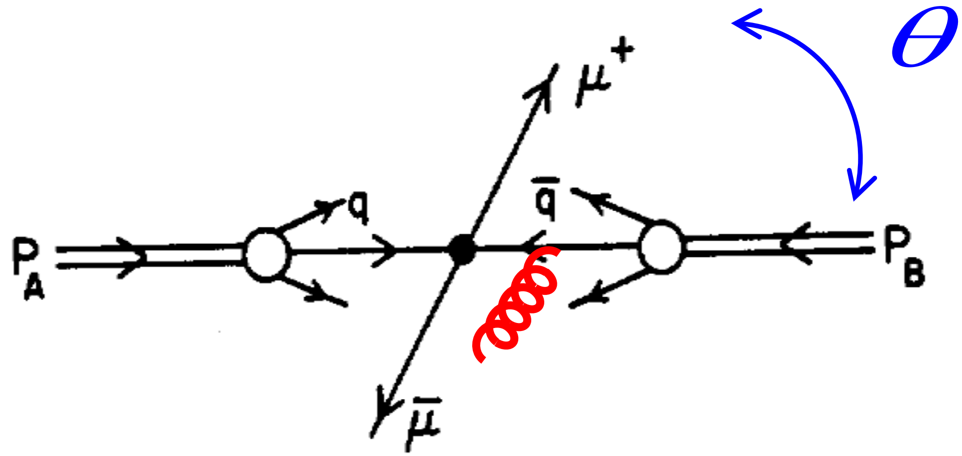
$$\frac{d\sigma}{d\Omega} \propto (1+a)\left(\left|d^1_{-1\,1}(\theta)\right|^2 + \left|d^1_{1\,1}(\theta)\right|^2\right) + b\left(\left|d^1_{-1\,0}(\theta)\right|^2 + \left|d^1_{1\,0}(\theta)\right|^2\right)$$

$$+\Re e\left[c_1 d^1_{1\,0}(\theta)\left(d^1_{1\,1}(\theta)e^{-i\phi}\right)^* + c_2 d^1_{1\,-1}(\theta)e^{i\phi}\left(d^1_{1\,1}(\theta)e^{-i\phi}\right)^* + \cdots\right]$$

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\Omega} = 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

DY





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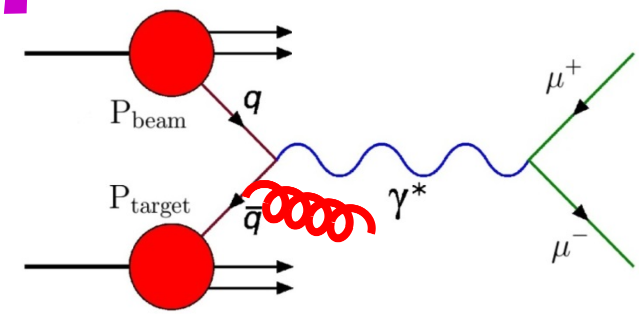
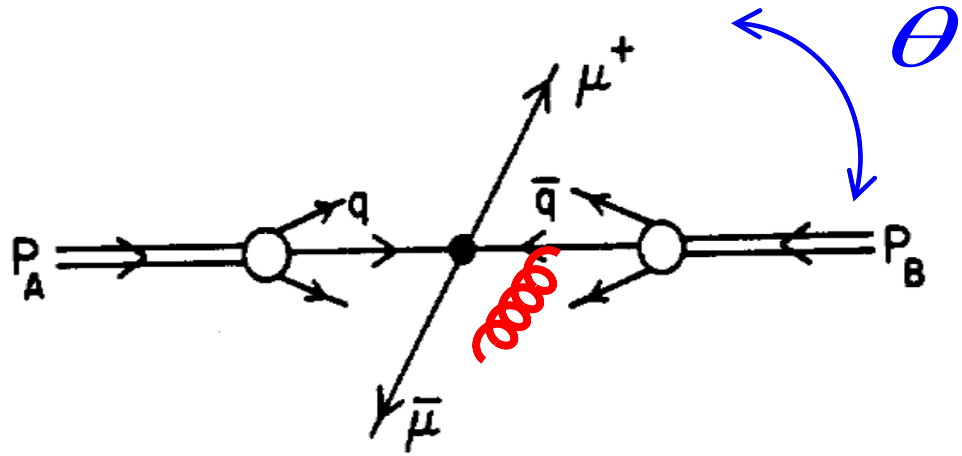
$$1-\lambda,\quad \mu,\quad \nu:\quad \propto Q_T \text{ at } O(\alpha_S)$$

DY





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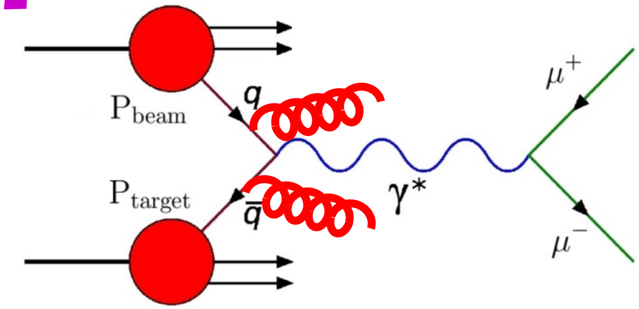
$$1-\lambda,\ \ \mu,\ \ \nu:\ \propto Q_T \text{ at } O(\alpha_S)$$

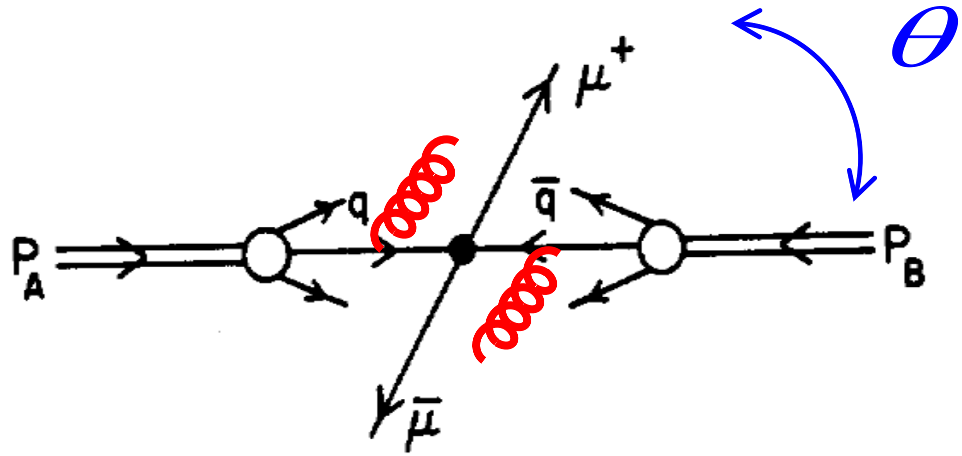
$$1-\lambda-2\nu=0$$

Lam-Tung relation ('78)

spin-1 gluon

DY





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$$1-\lambda-2\nu \simeq 0$$

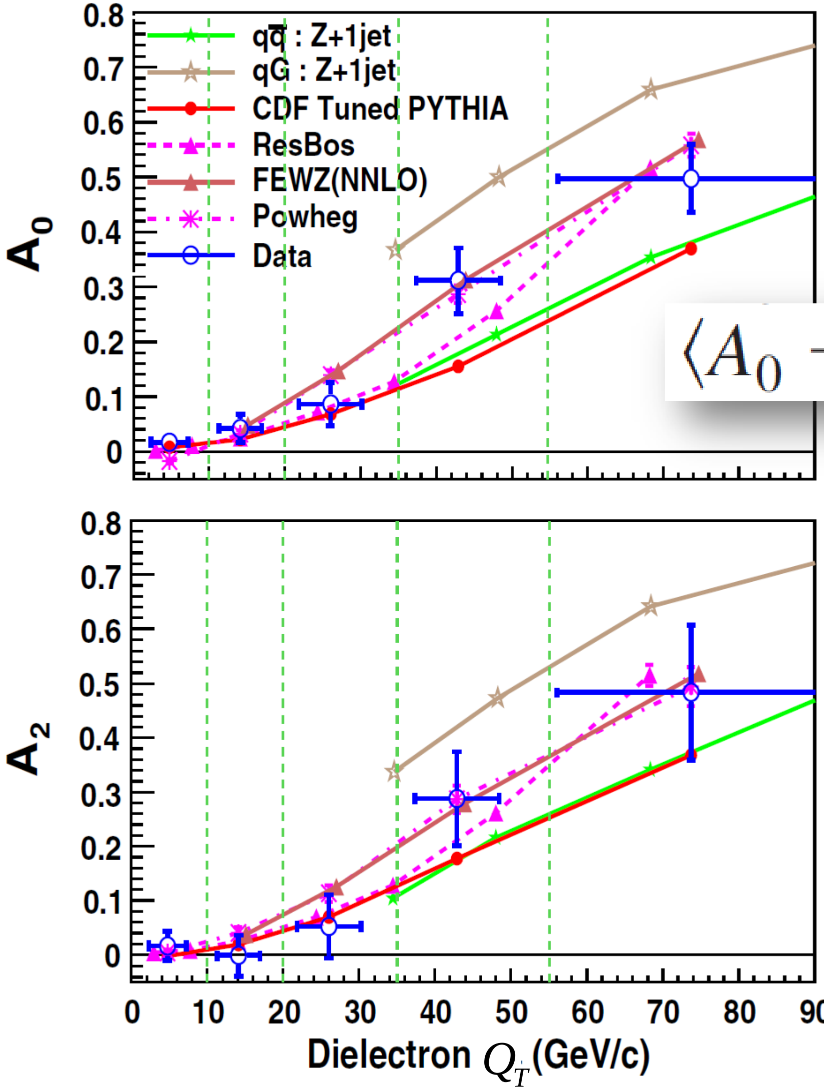
Lam-Tung relation ('78)

spin-1 gluon

CDF (PRL 106, 241801 (2011))
Angular Distribution of p-pbar DY at Z pole

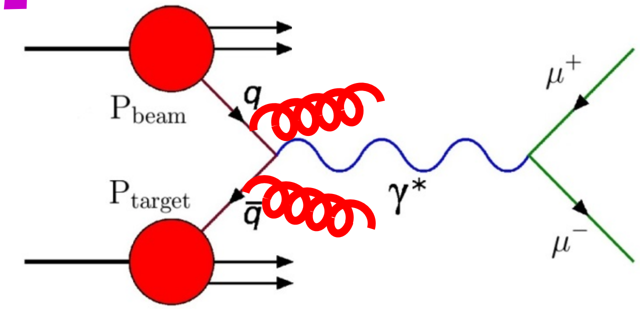
$$A_0 = \frac{2(1-\lambda)}{3+\lambda}$$

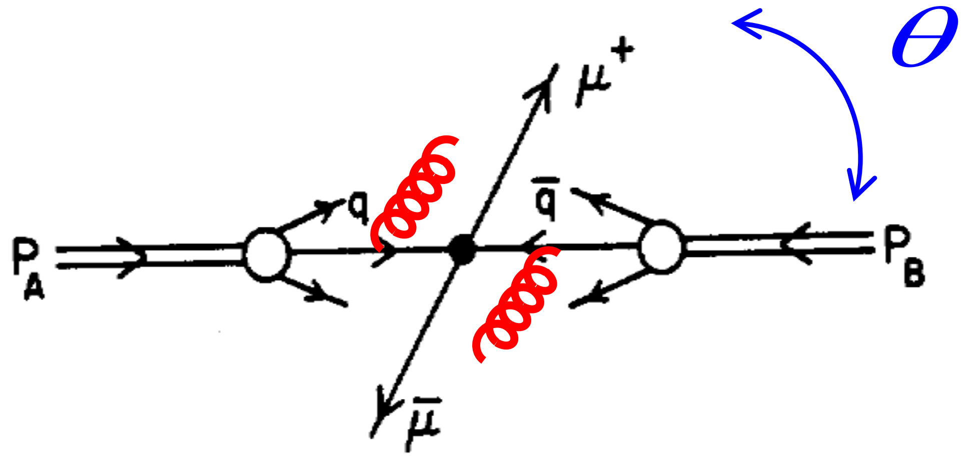
$$A_2 = \frac{4\nu}{3+\lambda}$$



$$\langle A_0 - A_2 \rangle = 0.02 \pm 0.02$$

DY





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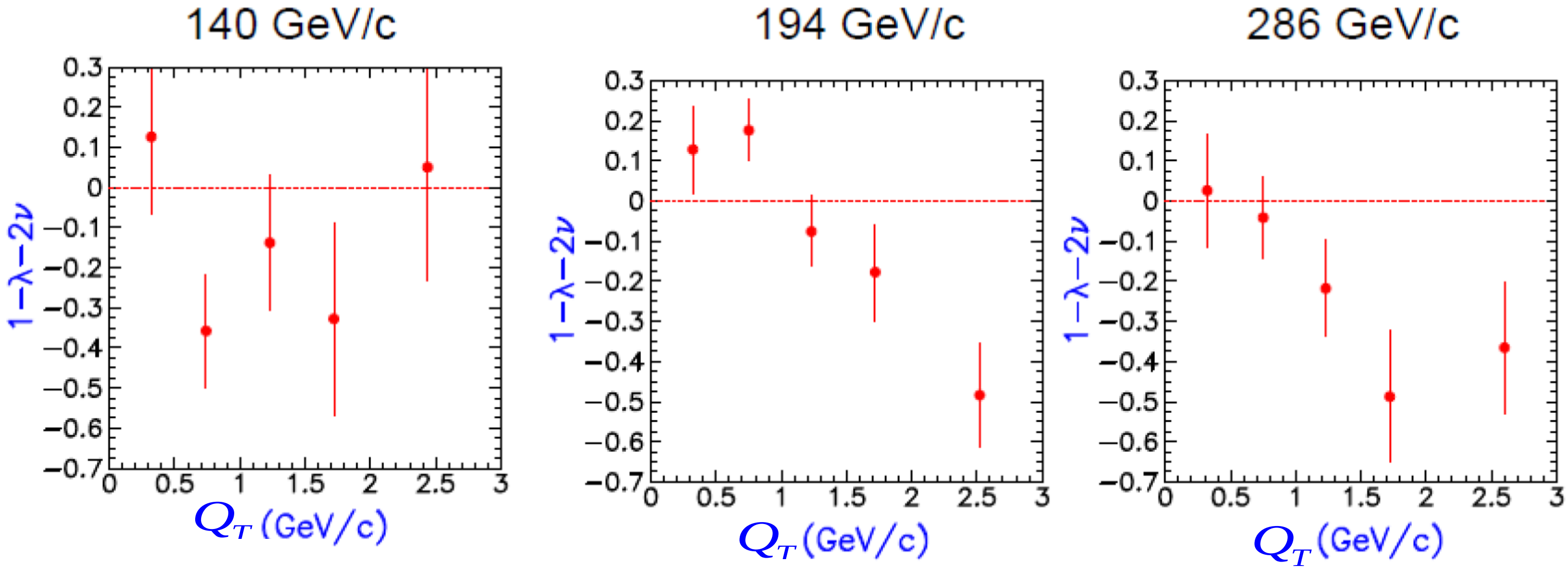
Lam-Tung relation ('78)

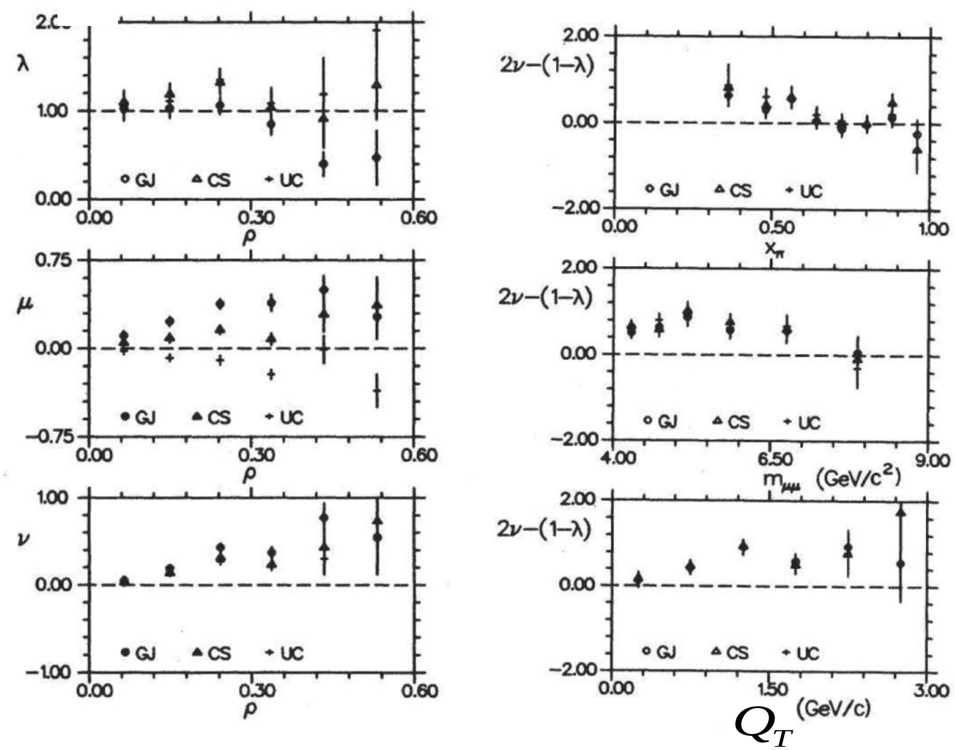
spin-1 gluon

NA10 (Z. Phys. C 37, 545 (1988))



π^--tangsten

π^--deuterium

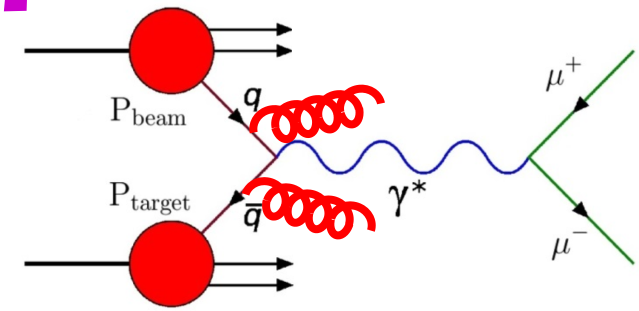


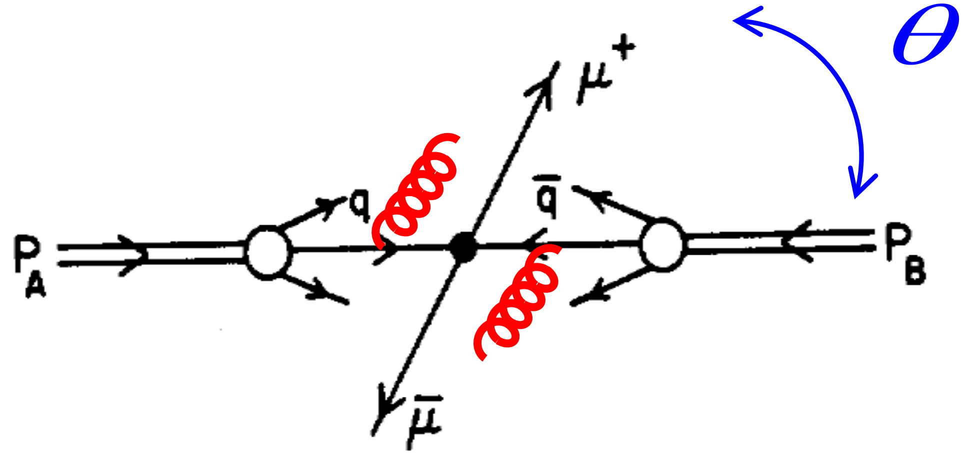
E615 (PRD 39, 92 (1989))

π^--tangsten

$$\rho = \frac{Q_T}{Q}$$

DY





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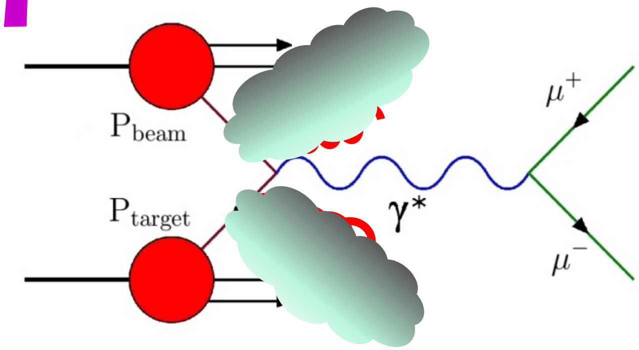

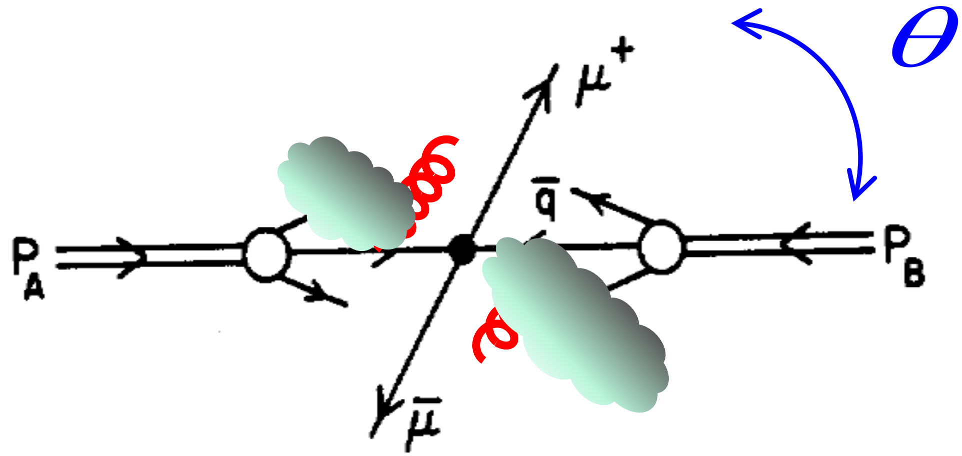

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$$1-\lambda, \quad \mu, \quad \nu: \quad \propto Q_T \text{ at } O(\alpha_S)$$

$$1-\lambda-2\nu \neq 0$$

Lam-Tung relation VIOLATED!

k_T & nonpert. spin flip

H.-n. Li, J-PARC WS ('13)

BM, vacuum effect, and Glauber gluons

	$h_1^\perp \neq 0$	QCD vacuum effect	Glauber gluon
$\rho^{(q,\bar{q})}$	$\rho^{(q)} \otimes \rho^{(\bar{q})}$	possibly entangled	possibly entangled
Q dependence	$\kappa \sim 1/Q$	?	$1/Q^2$
large Q_T limit	$\kappa \to 0$	need not disappear ($\kappa \to \kappa_0$)	need not disappear
flavor dependence	yes	flavor blind	yes
x dependence	yes	if yes, then not hadron blind	yes

D.B., Brandenburg, Nachtmann & Utermann, EPJC 40 (2005) 55

Different experiments ($\pi^\pm, p, \bar{p}, \ldots$ beams) are needed in different kinematical regimes

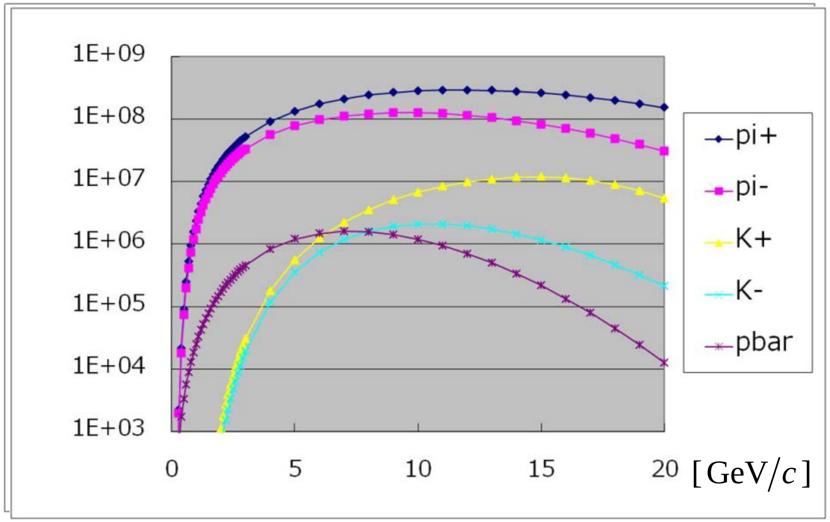
High-momentum beamline

- 30 GeV proton
- ~15-20 GeV unseparated (mainly pions)

Unseparated Secondary Beam Intensity

beam loss limit @ SM1:15kW

(limited by the thickness of the tunnel wall)



0° extraction angle

high intensity

H.-n. Li, J-PARC WS ('13)

BM, vacuum effect, and Glauber gluons

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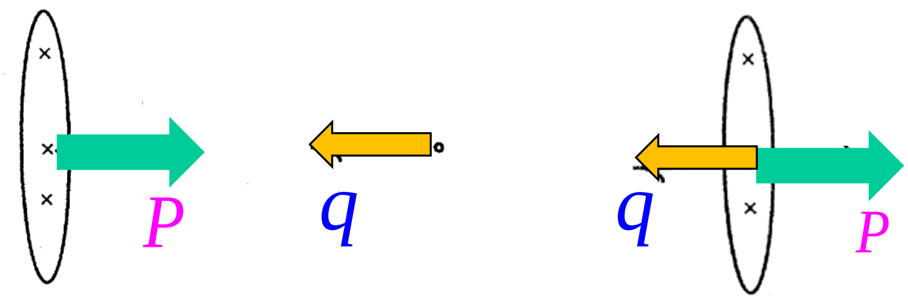
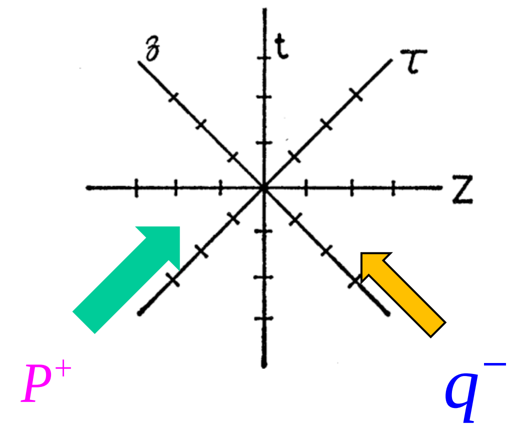
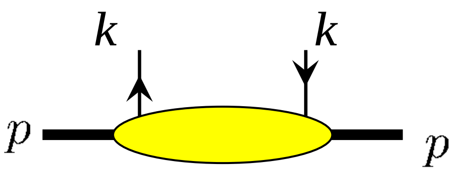


$$z^{\pm} = \frac{z^0 \pm z^3}{\sqrt{2}}$$

$$P^{\pm} = \frac{P^0 \pm P^3}{\sqrt{2}}$$

$$\left(P^- \approx 0\right)$$





$$\int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{ik^+ z^- - i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \langle P | \psi^\dagger(0) \; \psi(z^+ = 0, z^-, \mathbf{z}_\perp) | P \rangle$$

TMD

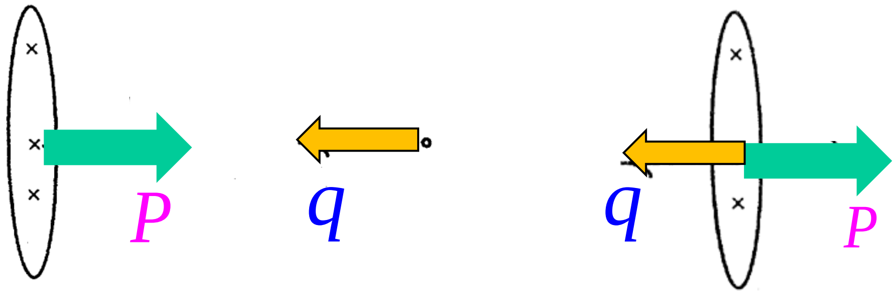
$$U(0; z^-, \mathbf{z}_\perp) = P \exp\left(ig \int_{(z^-, \mathbf{z}_\perp)}^{0} d\xi_\mu A^\mu(\xi) \right)$$

$$f(x) \sim \int \frac{dz^-}{4\pi} e^{i(xP^+)z^-} \langle P | \psi^\dagger(0) \; \psi(z^+ = 0, z^-, \mathbf{z}_\perp = \mathbf{0}_\perp) | P \rangle$$

PDF

$$U(0; z^-, \mathbf{z}_\perp = 0) = P \exp\left(ig \int_{z^-}^{0} d\xi^- A^+(\xi^-) \right)$$

Collins, Soper ('82)



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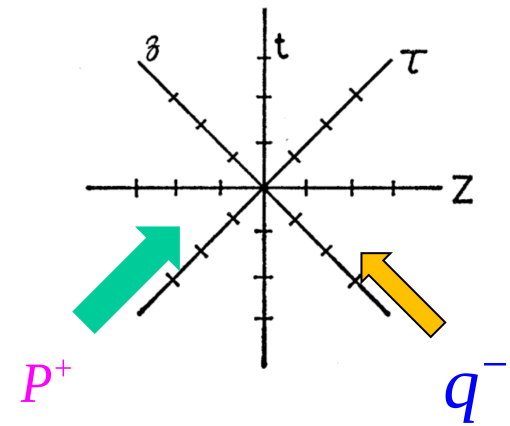
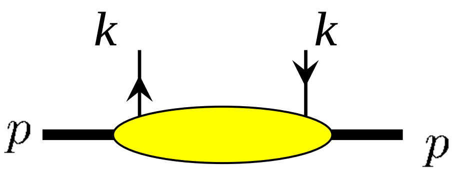
$$\left(P^{-} \approx 0\right)$$





$$\int \frac{dz^{-} d^2 z_{\perp}}{(2\pi)^3} e^{ik^{+}z^{-} - i\mathbf{k}_{\perp}\cdot\mathbf{z}_{\perp}} \langle P | \psi^{\dagger}(0) \;\; \psi(z^{+} = 0, z^{-}, \mathbf{z}_{\perp}) | P \rangle$$

TMD

$$U(0; z^{-}, \mathbf{z}_{\perp}) = P \exp\left(ig \int_{(z^{-}, \mathbf{z}_{\perp})}^{0} d\xi_{\mu} A^{\mu}(\xi) \right)$$

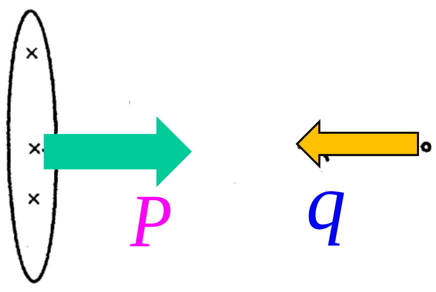
$$h_1^{\perp}(x, k_{\perp}) \sim \int \frac{dz^{-} d^2 z_{\perp}}{(2\pi)^3} e^{i(xP^{+})z^{-} - i\mathbf{k}_{\perp}\cdot\mathbf{z}_{\perp}} \langle P | \bar{\psi}(0) \gamma^{+} \gamma^{\perp} U(0; z^{-}, \mathbf{z}_{\perp}) \psi(z^{-}, \mathbf{z}_{\perp}) | P \rangle$$

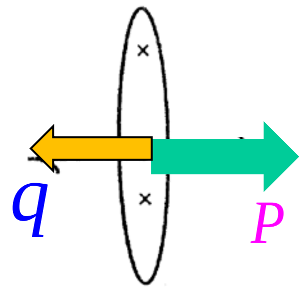
$$f(x) \sim \int \frac{dz^{-}}{4\pi} e^{i(xP^{+})z^{-}} \langle P | \psi^{\dagger}(0) \;\; \psi(z^{+} = 0, z^{-}, \mathbf{z}_{\perp} = \mathbf{0}_{\perp}) | P \rangle$$

PDF

$$U(0; z^{-}, \mathbf{z}_{\perp} = 0) = P \exp\left(ig \int_{z^{-}}^{0} d\xi^{-} A^{+}(\xi^{-}) \right)$$

Collins, Soper ('82)





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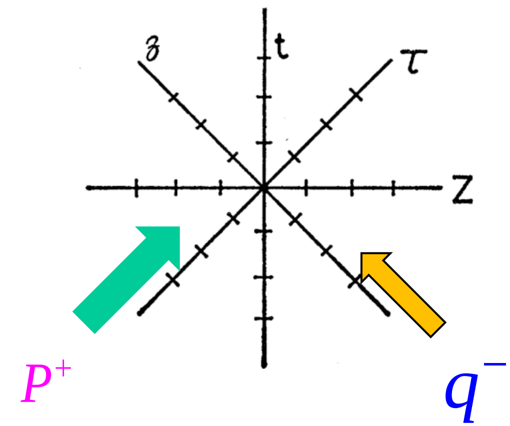
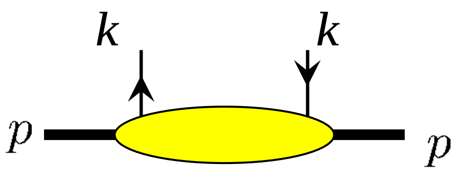




$$\int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{ik^+ z^- - i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \langle P | \psi^\dagger(0) \;\; \psi(z^+ = 0, z^-, \mathbf{z}_\perp) | P \rangle$$

TMD

$$U(0; z^-, \mathbf{z}_\perp) = P \exp\left(ig \int_{(z^-, \mathbf{z}_\perp)}^{0} d\xi_\mu A^\mu(\xi) \right)$$

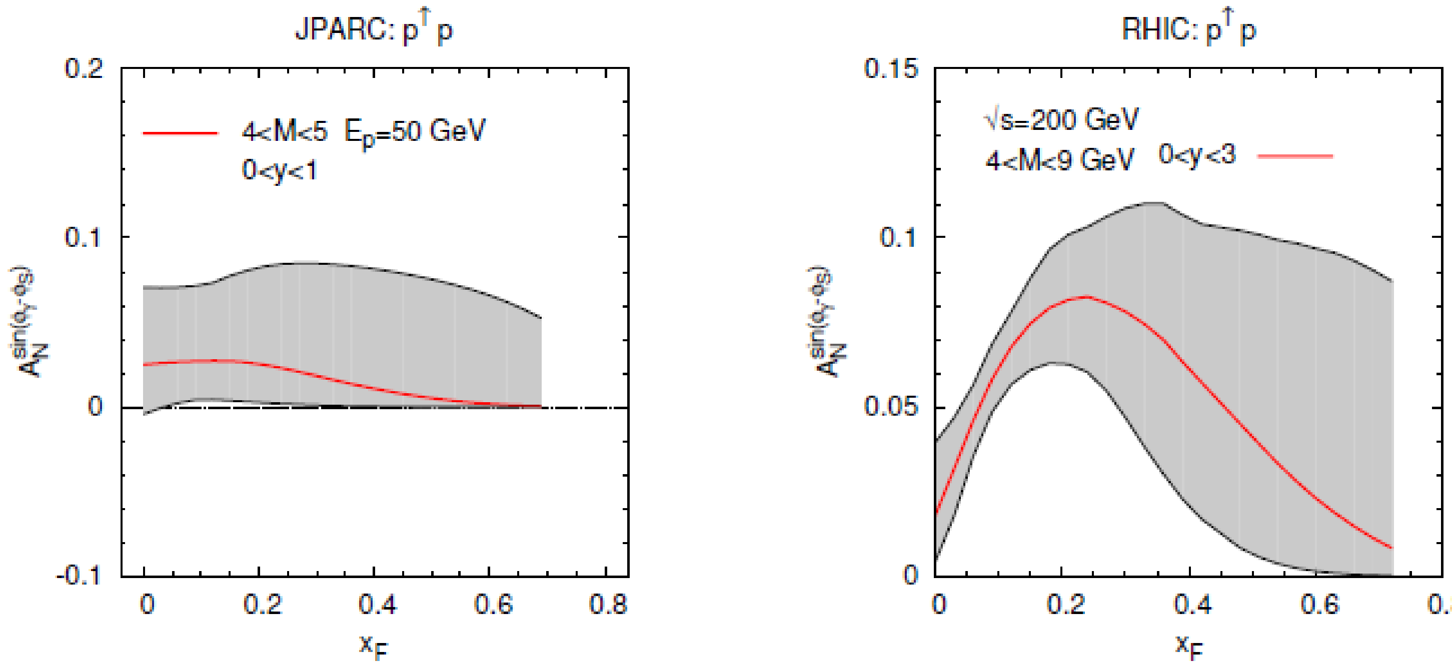
$$h_1^\perp(x, k_\perp) \sim \int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{i(xP^+)z^- - i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \langle P | \bar{\psi}(0) \gamma^+ \gamma^\perp U(0; z^-, \mathbf{z}_\perp) \psi(z^-, \mathbf{z}_\perp) | P \rangle$$

$$f_1^\perp(x, k_\perp) \sim \int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{i(xP^+)z^- - i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \langle PS_\perp | \bar{\psi}(0) \gamma^+ U(0; z^-, \mathbf{z}_\perp) \psi(z^-, \mathbf{z}_\perp) | PS_\perp \rangle$$

$$h_1^\perp(x, k_\perp)\Big|_{DY} = -h_1^\perp(x, k_\perp)\Big|_{DIS} \qquad f_1^\perp(x, k_\perp)\Big|_{DY} = -f_1^\perp(x, k_\perp)\Big|_{DIS}$$

Sivers effect in Drell-Yan

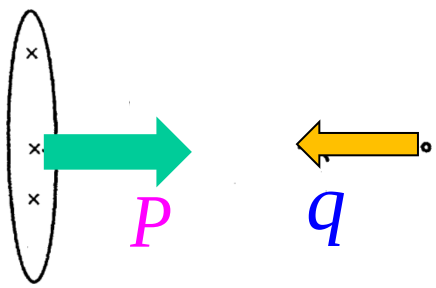
Experimental test of Sivers effect in Drell-Yan is highly desired $(\sin(\phi - \phi_S) f_{1T}^{\perp} \bar{f}_1)$

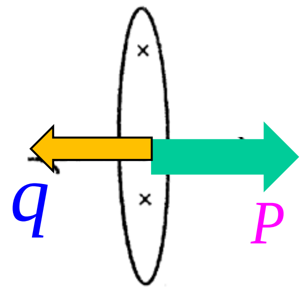


Anselmino *et al.* '09

$p^{\uparrow}p$ DY studies kinematically largely complementary to SIDIS data (careful about nodes)

These predictions take into account the *process dependence* of the Sivers function





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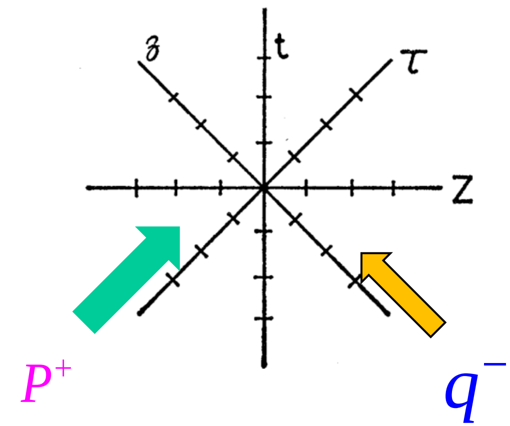
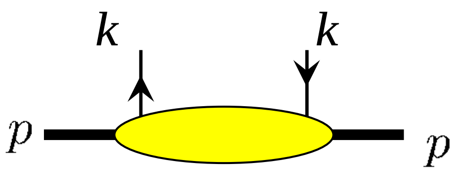




$$\int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{ik^+ z^- - i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \langle P | \psi^\dagger(0) \;\; \psi(z^+ = 0, z^-, \mathbf{z}_\perp) | P \rangle$$

TMD

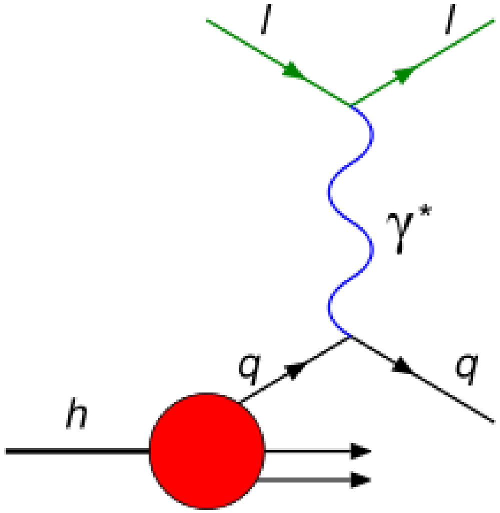
$$U(0; z^-, \mathbf{z}_\perp) = P \exp\left(ig \int_{(z^-, \mathbf{z}_\perp)}^{0} d\xi_\mu A^\mu(\xi) \right)$$

$$f(x) \sim \int \frac{dz^-}{4\pi} e^{i(xP^+)z^-} \langle P | \psi^\dagger(0) \;\; \psi(z^+ = 0, z^-, \mathbf{z}_\perp = \mathbf{0}_\perp) | P \rangle$$

PDF

$$U(0; z^-, \mathbf{z}_\perp = 0) = P \exp\left(ig \int_{z^-}^{0} d\xi^- A^+(\xi^-) \right)$$

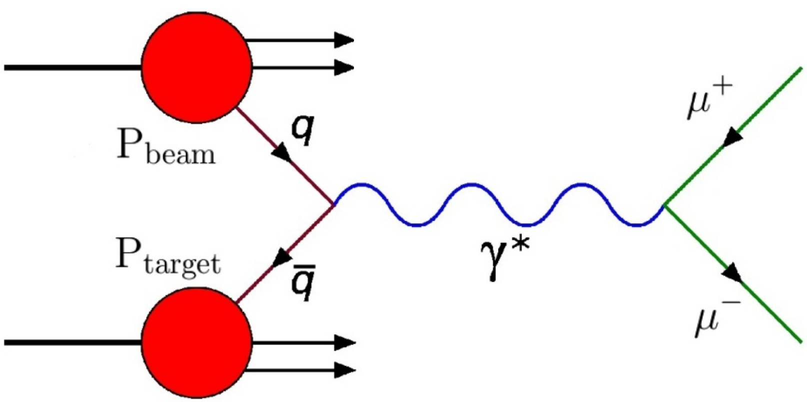
Collins, Soper ('82)



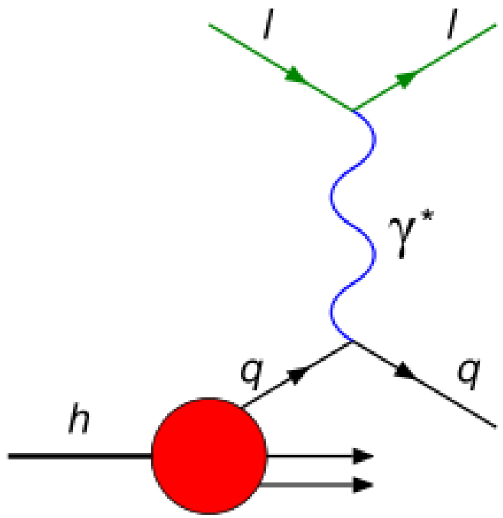
DIS

$$[q(x)+\bar{q}(x)], \quad G(x)$$

DY



$$q(x), \quad \bar{q}(x), \quad G(x)$$



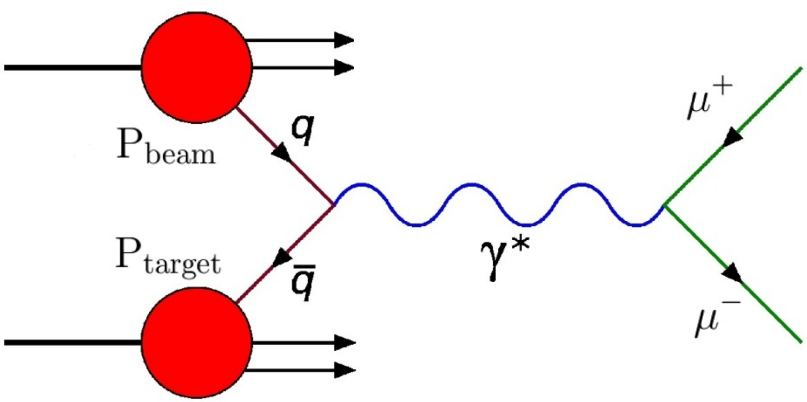
DIS

$$\left[q(x)+\bar{q}(x)\right], \qquad G(x)$$

$$\left[\Delta q(x)+\Delta\bar{q}(x)\right], \qquad \Delta G(x)$$

$$\left[g_T(x)+\bar{g}_T(x)\right]$$

DY



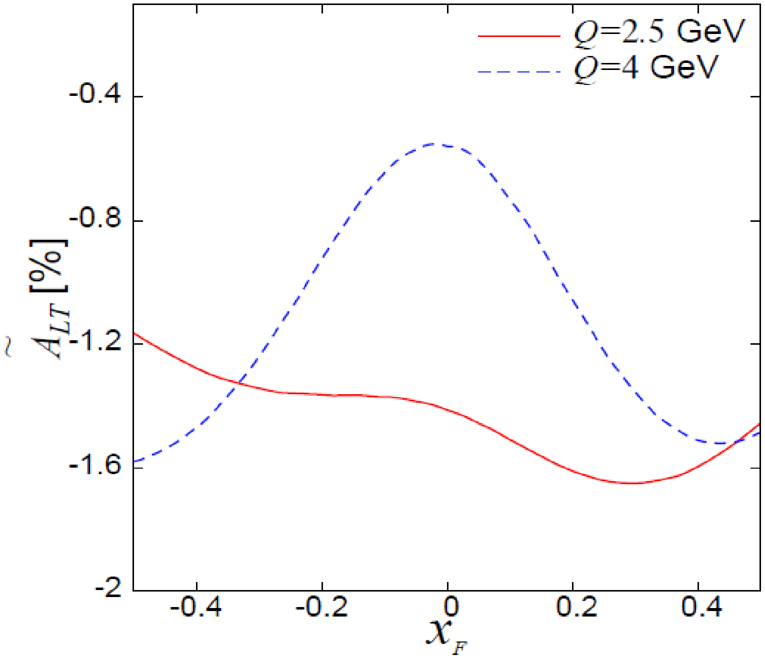
$$q(x), \qquad \bar{q}(x), \qquad G(x)$$

$$\Delta q(x), \qquad \Delta\bar{q}(x), \qquad \Delta G(x)$$

$$g_T(x), \qquad \bar{g}_T(x)$$

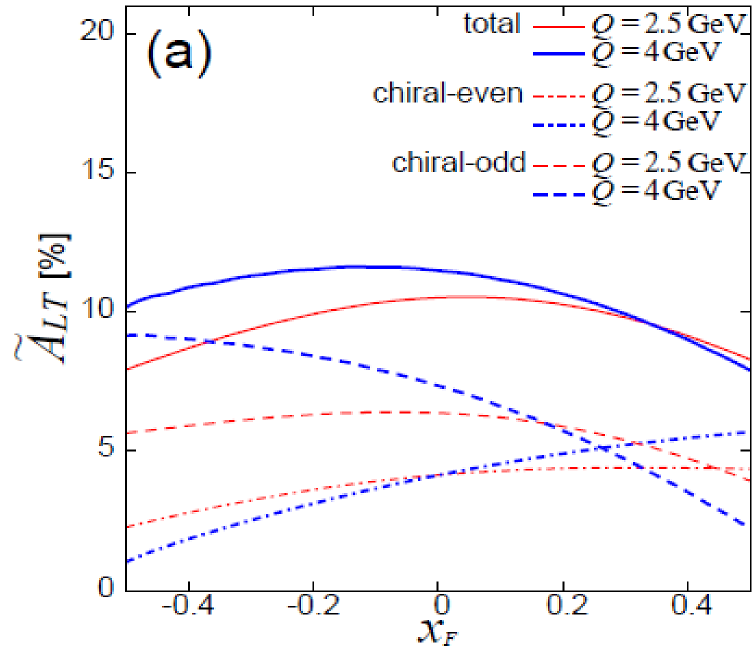
$$\delta q(x), \quad \delta\bar{q}(x), \quad h_L(x), \quad \bar{h}_L(x)$$

@J-PARC $\sqrt{S} = 10$ GeV



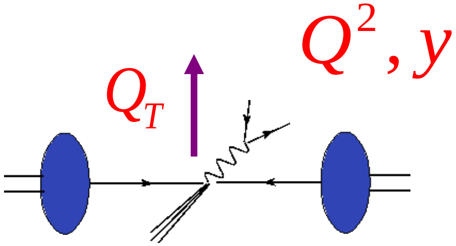
S. Yoshida

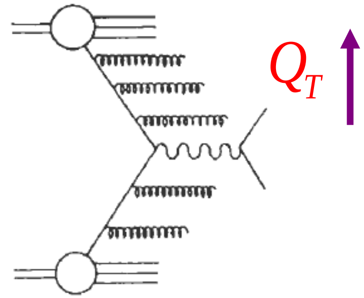
@GSI $\sqrt{S} = 6.7$ GeV



Y. Koike, KT, S. Yoshida, PLB668('08)286

$$x_F = x_1 - x_2$$





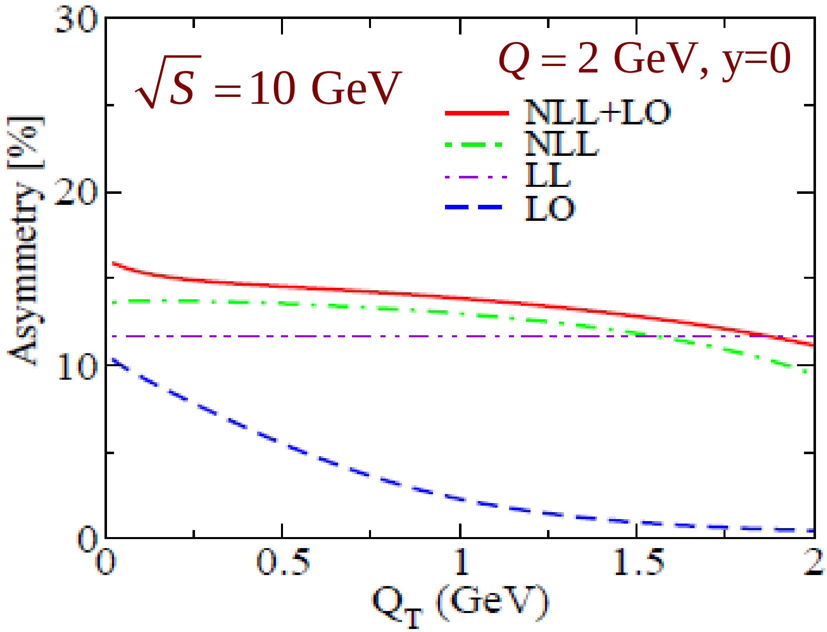
$\alpha_s \ln^2\left(Q^2/Q_T^2\right)$

$\alpha_s \ln\left(Q^2/Q_T^2\right)$

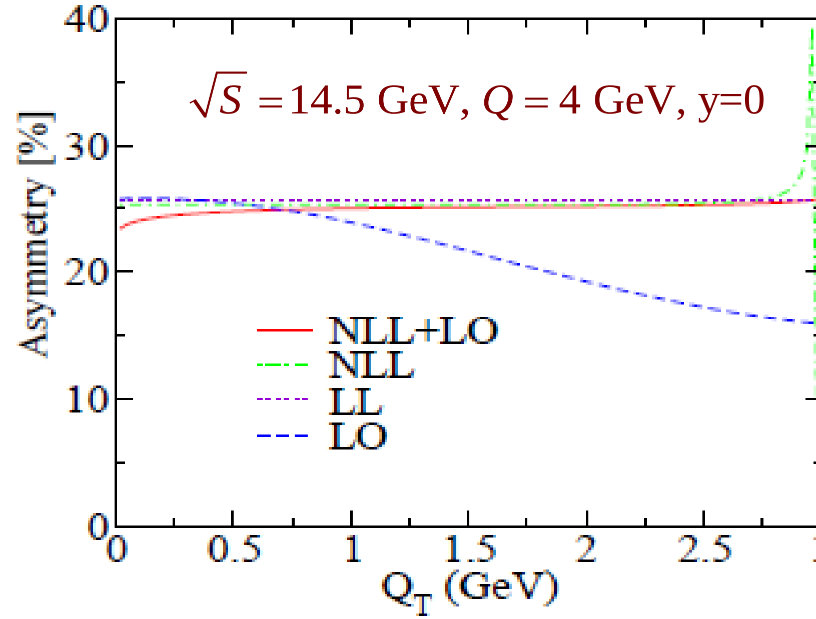
resummation

H. Kawamura, J. Kodaira, KT, NPB777 ('07) 203, PTP 118 ('07) 581
PLB662 ('08) 139

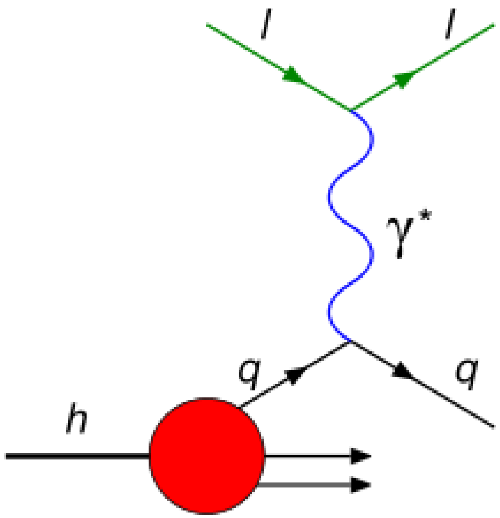
@ J-PARC



@ GSI



DIS

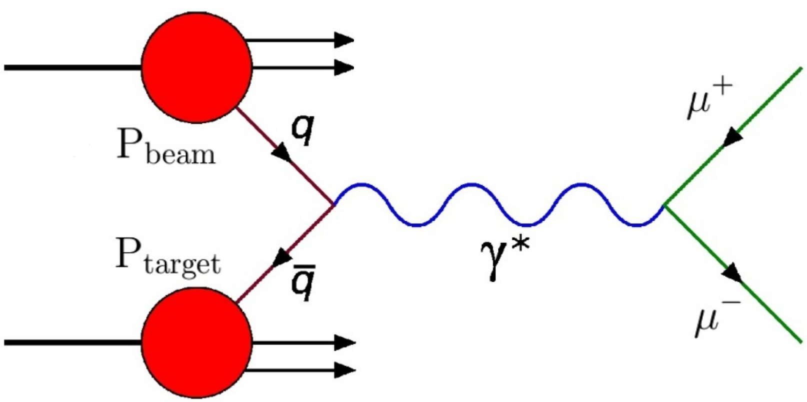


$$\left[q(x)+\bar{q}(x)\right], \qquad G(x)$$

$$\left[\Delta q(x)+\Delta\bar{q}(x)\right], \qquad \Delta G(x)$$

$$\left[g_T(x)+\bar{g}_T(x)\right]$$

DY



$$q(x), \qquad \bar{q}(x), \qquad G(x)$$

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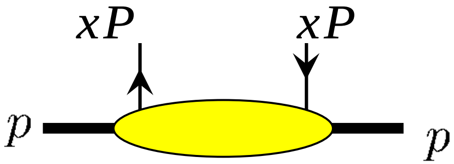
$$g_T(x), \qquad \bar{g}_T(x)$$

$$\delta q(x), \quad \delta\bar{q}(x), \quad h_L(x), \quad \bar{h}_L(x)$$



PDF

$$f(x) \sim \int \frac{dz^-}{4\pi} e^{i(xP^+)z^-} \langle P | \psi^\dagger(0) \quad \psi(z^-) | P \rangle$$

$$z^- = \lambda n^- \qquad P \cdot n = P^+ n^- = 1$$

Jaffe, Ji ('92)

$$\int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S | \bar{\psi}(0) \gamma^\sigma \psi(\lambda n) | P\ S \rangle = q(x) P^\sigma$$

$$\int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S | \bar{\psi}(0) \gamma^\sigma \gamma_5 \psi(\lambda n) | P\ S \rangle = \Delta q(x) (S \cdot n) P^\sigma + g_T(x) S_\perp^\sigma$$

$$\int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S | \bar{\psi}(0) \sigma^{\mu\nu} i\gamma_5 \psi(\lambda n) | P\ S \rangle = \delta q(x) \frac{S_\perp^\mu P^\nu - S_\perp^\nu P^\mu}{M_N} + h_L(x) \left(P^\mu n^\nu - P^\nu n^\mu \right) M_N (S \cdot n)$$

$$\int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S | \bar{\psi}(0) \psi(\lambda n) | P\ S \rangle = M_N e(x)$$

Ji, PLB289 ('92) 137

$$-\frac{(n^-)^2}{x} \int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S | F^{+\nu}(0) F^{+\sigma}(\lambda n) | P\ S \rangle$$

$$= \frac{1}{4} \left[G(x) g_\perp^{\nu\sigma} + \Delta G(x) i\epsilon^{\nu\sigma P n} (S \cdot n) + 2 G_{3E}(x) i\epsilon^{\nu\sigma\alpha n} S_{\perp\alpha} \right]$$

$$M^{\mu\nu} \qquad M^{03} \qquad M^{12} = J^3$$

$$\left[M^{\mu\nu}, \psi(x) \right] = -\left(i\left(x^\mu \partial^\nu - x^\nu \partial^\mu \right) + \frac{1}{2}\sigma^{\mu\nu} \right)\psi(x)$$

$$\int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S \,|\, \psi^\dagger(0) \mathbf{1} \psi(\lambda n) \,|\, P\ S \rangle = \int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S \,|\, \bar{\psi}(0) \frac{1}{\sqrt{2}} \gamma^+ \psi(\lambda n) \,|\, P\ S \rangle \sim q(x)$$

$$\hat{s}^i = \frac{1}{2}\varepsilon^{ijk} \frac{\sigma^{jk}}{2} \qquad \left[\hat{s}^1, \hat{s}^2 \right] = i\hat{s}^3$$

$$2\int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S \,|\, \psi^\dagger(0) \hat{s}^3 \psi(\lambda n) \,|\, P\ S \rangle = \int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S \,|\, \bar{\psi}(0) \frac{1}{\sqrt{2}} \gamma^+ \gamma_5 \psi(\lambda n) \,|\, P\ S \rangle \sim \Delta q(x)$$

$$2\int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S \,|\, \psi^\dagger(0) \hat{s}^\perp \psi(\lambda n) \,|\, P\ S \rangle = \int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\ S \,|\, \bar{\psi}(0) \gamma^\perp \gamma_5 \psi(\lambda n) \,|\, P\ S \rangle \sim g_T(x)$$

KT (2014)

$$\left[M^{\mu\nu}, F^{\alpha\beta}(x)\right] = -\left(i\left(x^{\mu}\partial^{\nu} - x^{\nu}\partial^{\mu}\right) + \Sigma^{\mu\nu}\right)F^{\alpha\beta}(x)$$

$$\Sigma^{\mu\nu}F^{\alpha\beta} = i\left(g^{\mu\alpha}F^{\nu\beta} - g^{\nu\alpha}F^{\mu\beta} - (\alpha \leftrightarrow \beta)\right)$$

$$\int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\, S \,|\, F^{\alpha\beta}(0)^{\dagger} \mathbf{1} F^{\alpha\beta}(\lambda n) \,|\, P\, S\rangle = -\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P\, S \,|\, F^{+\beta}(0) F^{+}{}_{\beta}(\lambda n) \,|\, P\, S\rangle \sim xG(x)$$

$$\hat{s}^{i} = \frac{1}{2}\varepsilon^{ijk}\Sigma^{jk} \qquad \left[\hat{s}^{1}, \hat{s}^{2}\right] = i\hat{s}^{3}$$

$$\int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\, S \,|\, F^{\alpha\beta}(0)^{\dagger} \hat{s}^{3} F^{\alpha\beta}(\lambda n) \,|\, P\, S\rangle = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P\, S \,|\, iF^{+\beta}(0) \widetilde{F}^{+}{}_{\beta}(\lambda n) \,|\, P\, S\rangle \sim x\Delta G(x)$$

$$\int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P\, S \,|\, F^{\alpha\beta}(0)^{\dagger} \hat{s}^{\perp} F^{\alpha\beta}(\lambda n) \,|\, P\, S\rangle = \frac{-i}{\sqrt{2}} \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P\, S \,|\, \widetilde{F}^{+\perp}(0) F^{+-}(\lambda n) + F^{+\perp}(0) F^{12}(\lambda n) + \cdots \,|\, P\, S\rangle$$

$$\sim x\left(G_{3E}(x) + G_{3H}(x)\right) \equiv xG_{T}(x)$$

KT (2014)

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P\, S \,|\, \Phi^{\dagger}(0) \begin{Bmatrix} \mathbf{1} \\ \hat{s}^{i} \end{Bmatrix} \Phi(\lambda n) \,|\, P\, S\rangle$$

$$\Phi = \psi, F^{\mu\nu}$$

$q(x)$	$\Delta q(x)$	$g_T(x)$
$G(x)$	$\Delta G(x)$	$G_T(x)$
density	**helicity**	**flip**

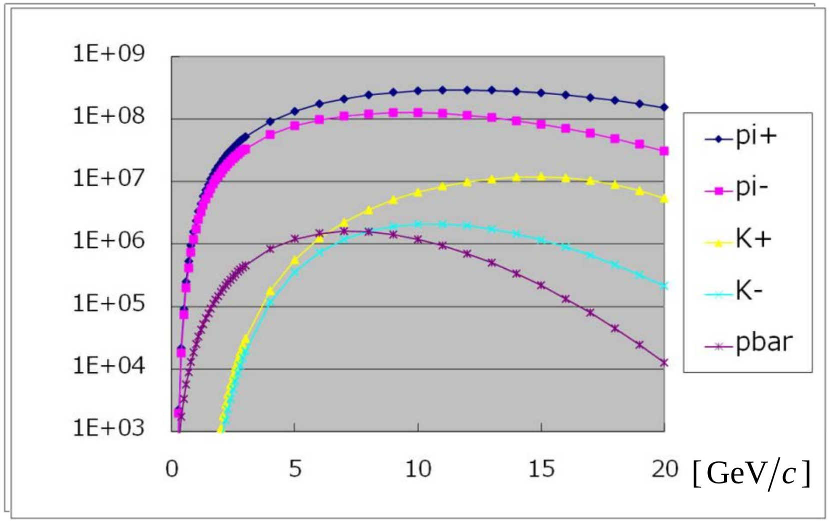
High-momentum beamline

- 30 GeV proton
- ~15-20 GeV unseparated (mainly pions)

Unseparated Secondary Beam Intensity

beam loss limit @ SM1:15kW

(limited by the thickness of the tunnel wall)



0° extraction angle

high intensity

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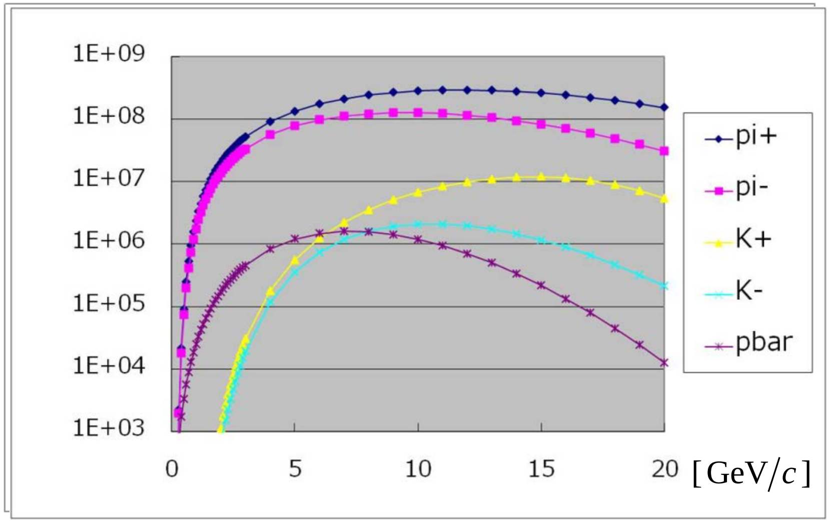


0° extraction angle

high intensity

not too high energy $d\sigma \sim 1/s^a$

best suited to study meson-induced hard exclusive processes

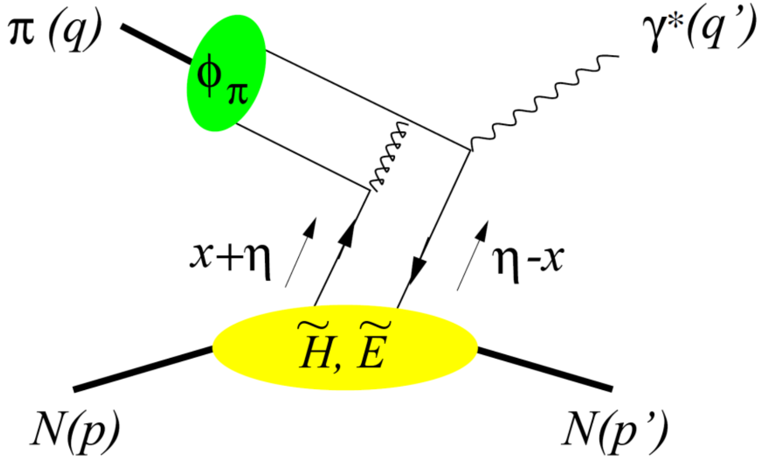
Exclusive lepton pair production in πN scattering

$$\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$$

Berger, Diehl, Pire, PLB523(2001)265

"exclusive limit of DY"

small $t = (q - q')^2$



Exclusive lepton pair production in πN scattering

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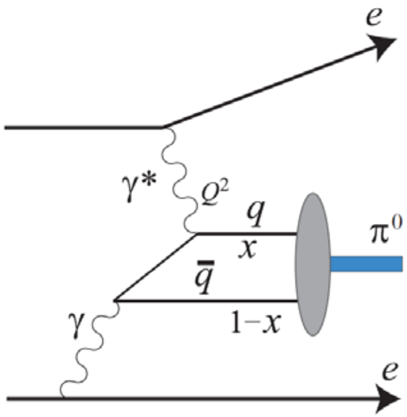
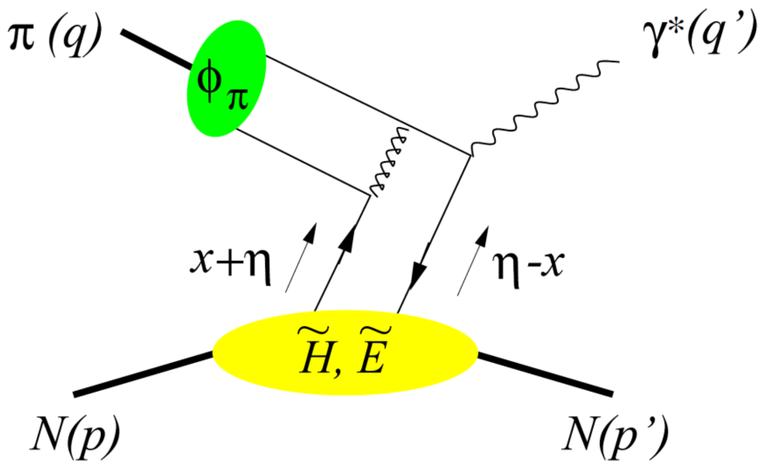
Berger, Diehl, Pire, PLB523(2001)265



@Belle, Babar

"exclusive limit of DY"



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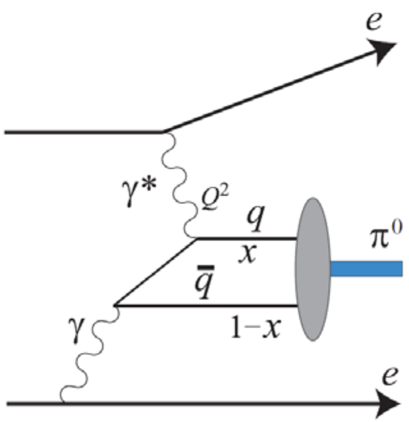

@Belle, Babar

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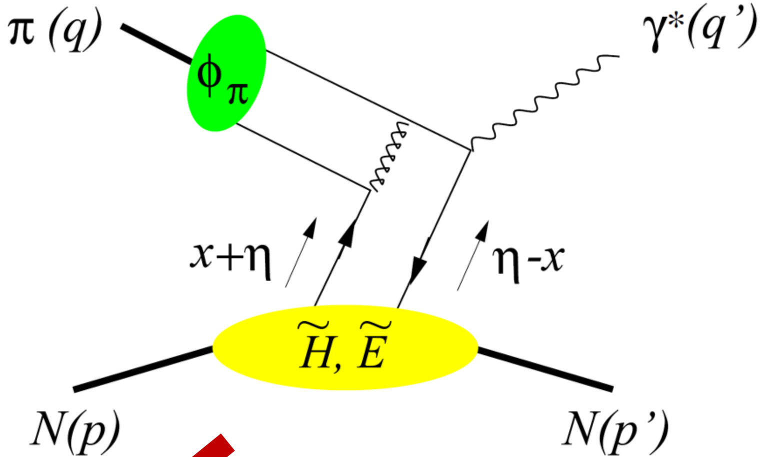


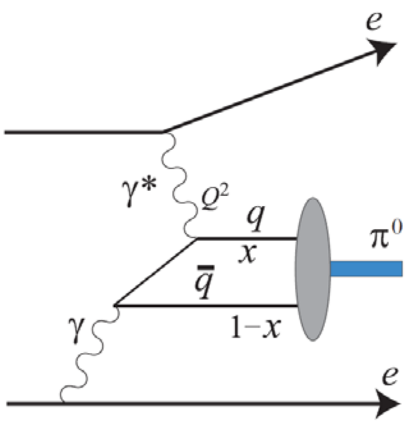
$t \to 0$

$\Delta q(x)$

Exclusive lepton pair production in πN scattering

$\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$

Berger, Diehl, Pire, PLB523(2001)265



@Belle, Babar

"exclusive limit of DY"

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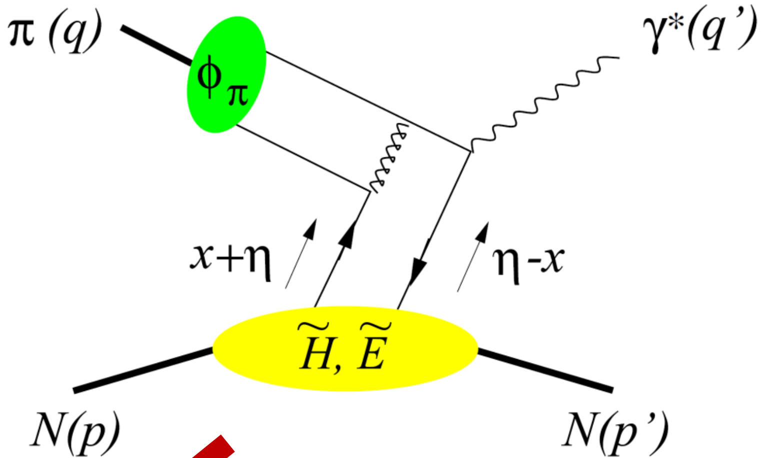
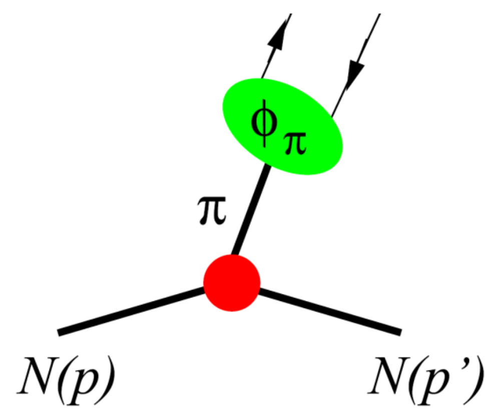


$t \to 0$

$\Delta q(x)$

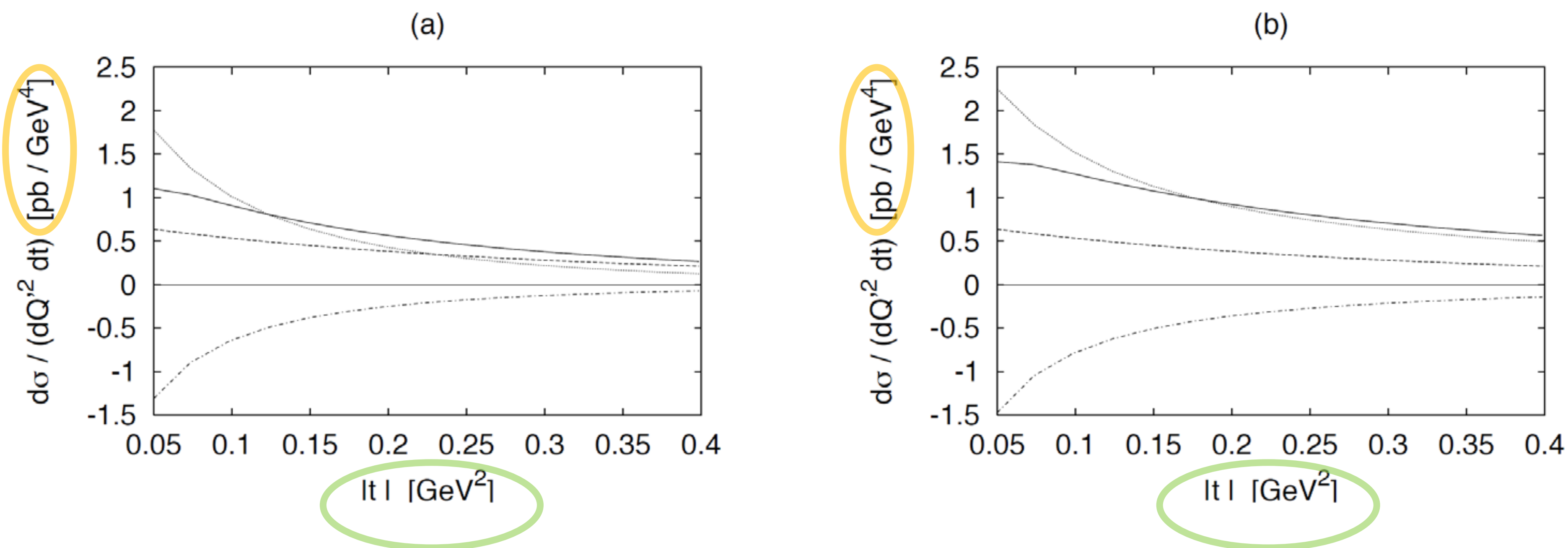


LO Estimates

Bjorken variable $\tau = \frac{Q'^2}{s - M^2}$

Berger, Diehl, Pire, PLB523(2001)265

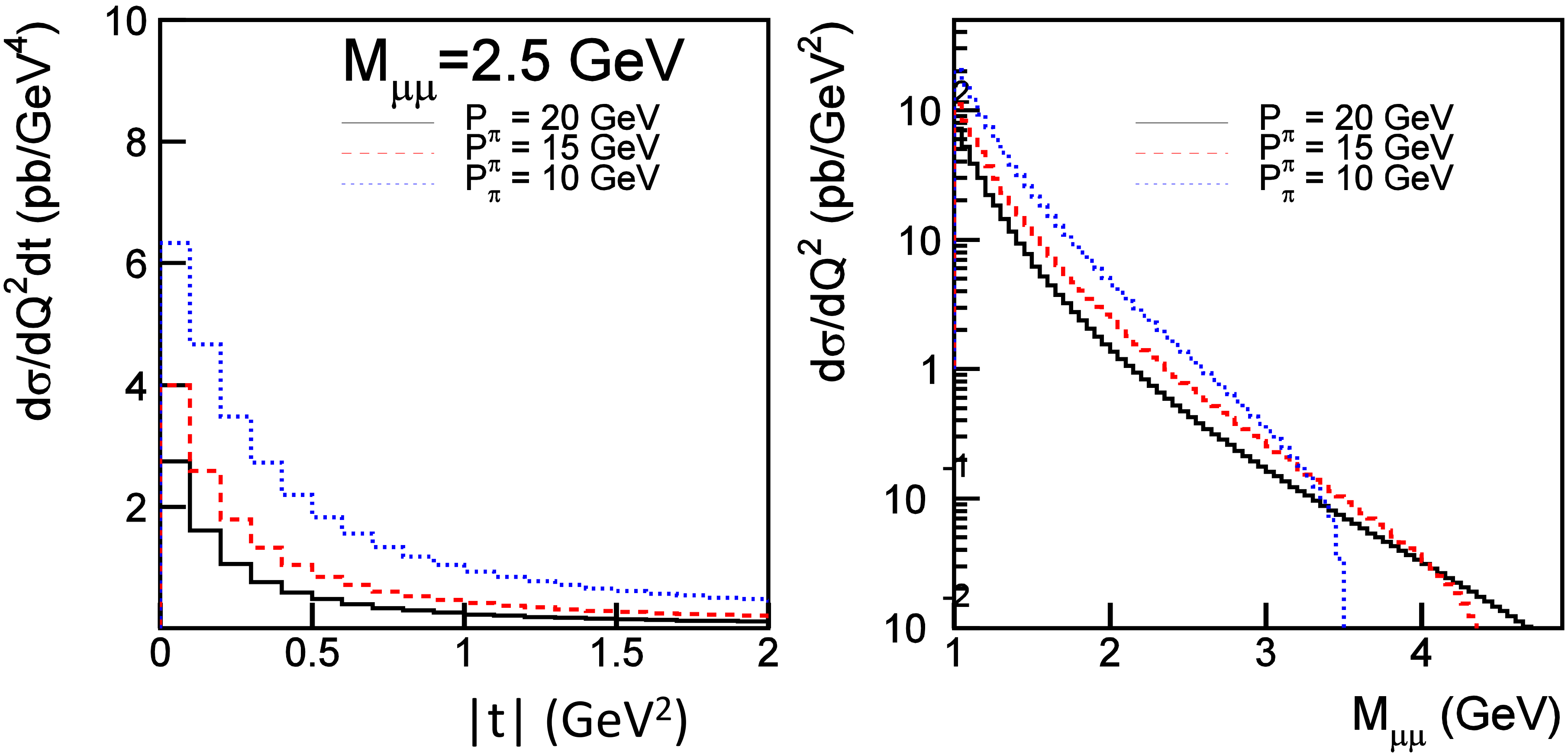
$Q'^2 = 5 GeV^2 \qquad \tau = 0.2$



(dashed) $= |\tilde{\mathcal{H}}|^2$; **(dash-dotted)** $=$ **Re**$(\tilde{\mathcal{H}}^* \tilde{\mathcal{E}})$; **(dotted)** $= |\tilde{\mathcal{E}}|^2$

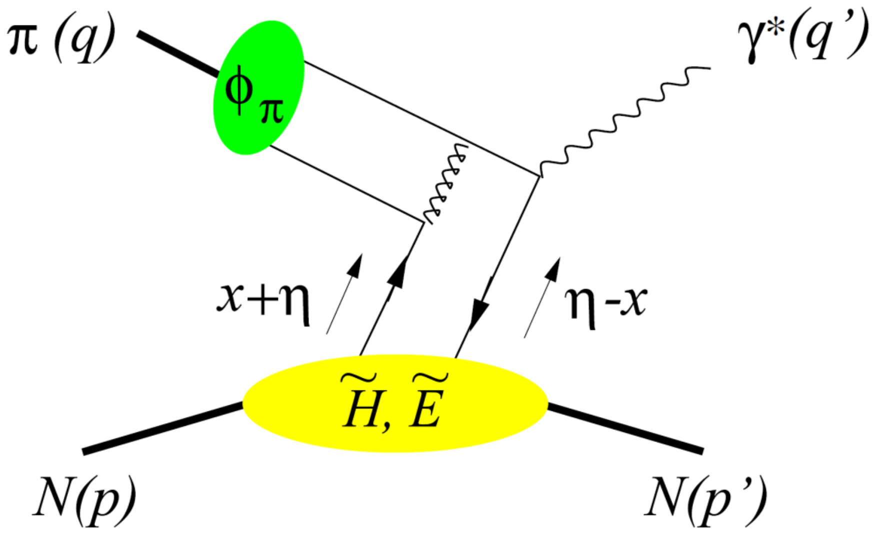
$$\frac{d\sigma}{dQ'^2\, dt}(\pi^- p \to \gamma^* n) = \frac{4\pi\alpha_{em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \left[(1-\eta^2)\,|\widetilde{H}^{du}|^2 - 2\eta^2 \mathrm{Re}\left(\widetilde{H}^{du*} \widetilde{E}^{du}\right) - \eta^2 \frac{t}{4M^2} |\widetilde{E}^{du}|^2 \right]$$

$\pi N \to \mu^+ \mu^- N$: |t| and Q ($M_{\mu\mu}$) dependence



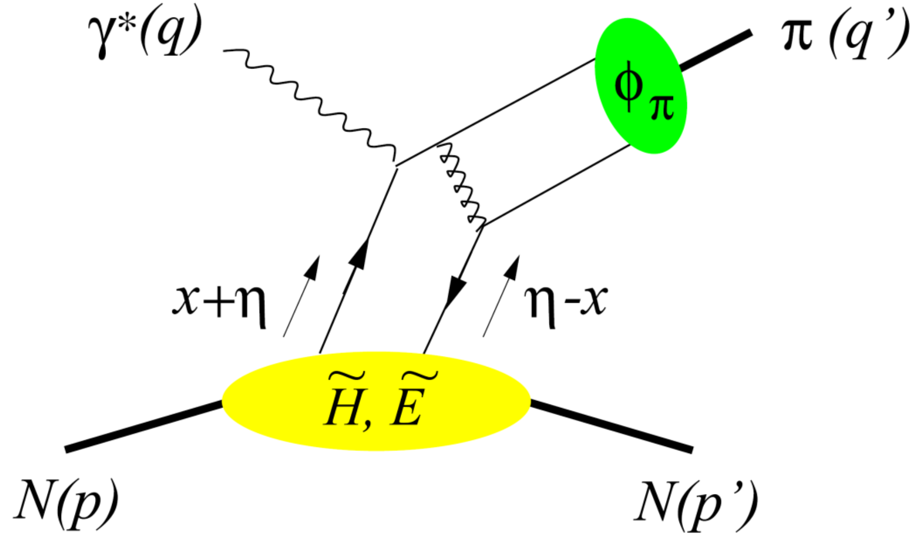
Pion beams reveal $\tilde{H}, \tilde{E}$ Generalized Parton distributions

timelike



exDY@J-PARC

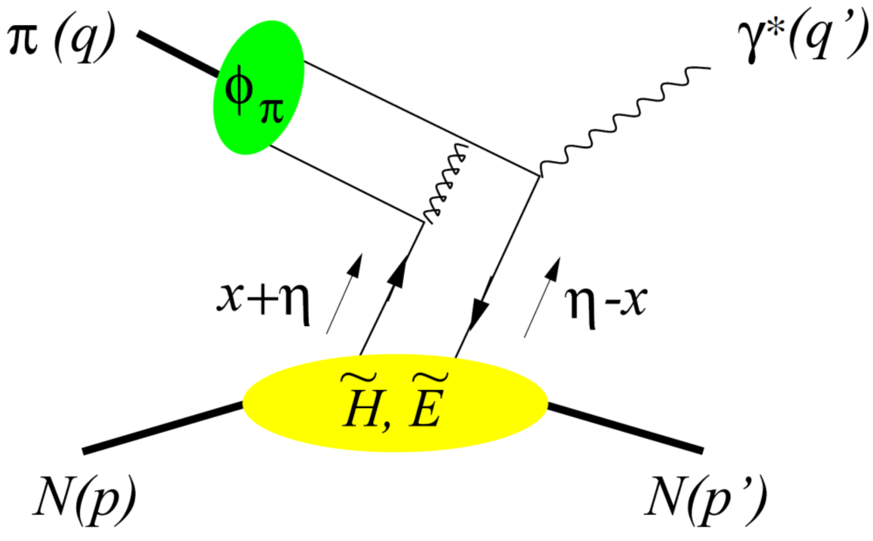
spacelike



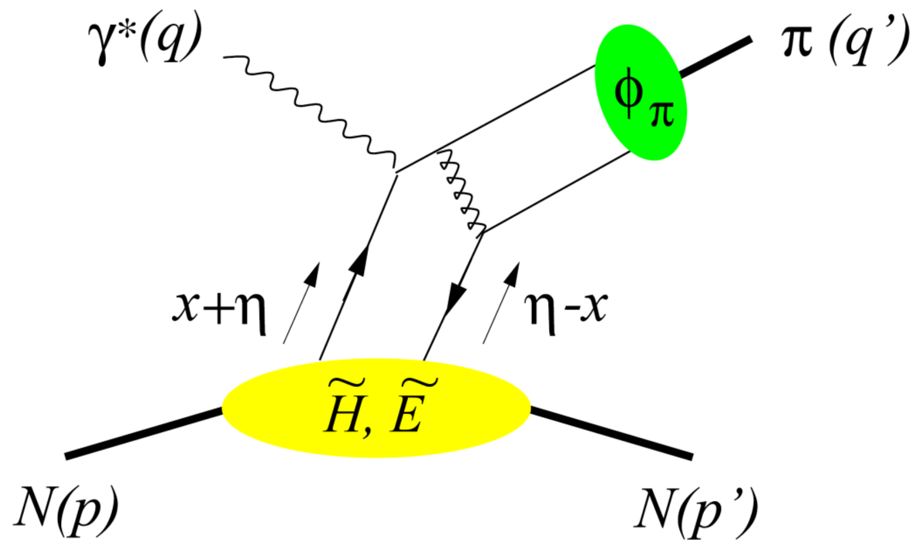
DVMP@JLab

Pion beams reveal $\tilde{H}, \tilde{E}$ Generalized Parton distributions

timelike

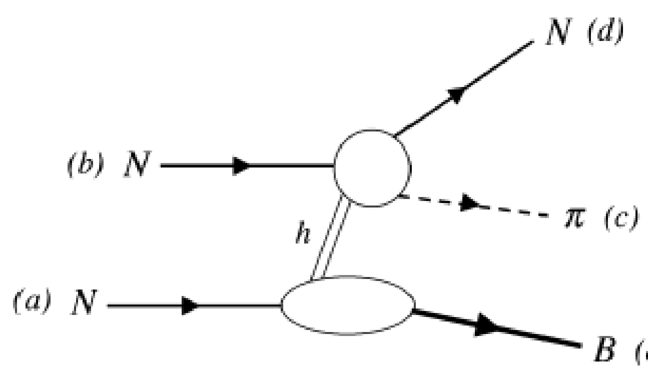


spacelike

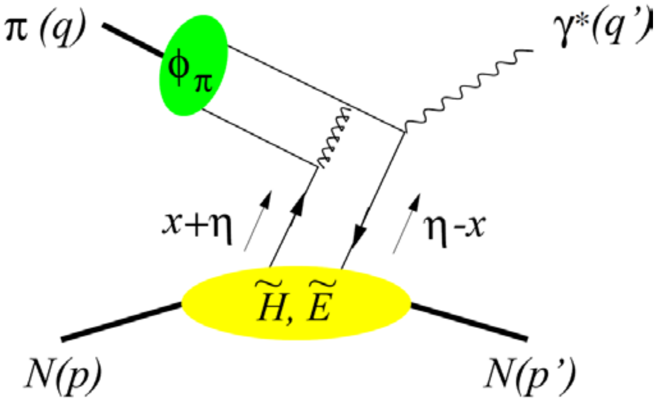


exDY@J-PARC

DVMP@JLab



Kumano,Sudoh,Strikman, PRD80(2000)074003.



Bjorken variable: $\tau = \dfrac{Q'^2}{2p\cdot q}$

Skewness: $\eta = \dfrac{p^+ - p'^+}{p^+ + p'^+}$

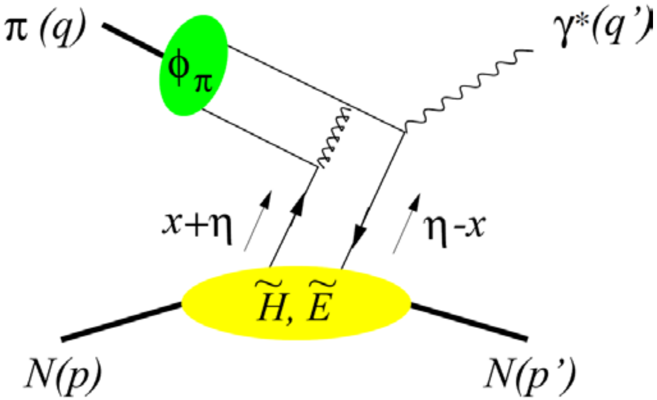
long. photon ↘

$$\frac{d\sigma}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi} = \frac{\alpha\text{em}}{256\,\pi^3}\frac{\tau^2}{Q'^6}\sum_{\lambda',\lambda}|M^{0\lambda',\lambda}|^2 \sin^2\theta$$

$$M^{0\lambda',\lambda}(\pi^- p \to \gamma^* n) = -ie\,\frac{4\pi}{3}\,\frac{f_\pi}{Q'}\,\frac{1}{(p+p')^+}\,\bar{u}(p',\lambda')\left[\gamma^+\gamma_5\,\tilde{\mathcal{H}}^{du}(\eta,t) + \gamma_5\frac{(p'-p)^+}{2M}\,\tilde{\mathcal{E}}^{du}(\eta,t)\right]u(p,\lambda)$$

$$\tilde{\mathcal{H}}^{du}(\eta,t) = \frac{8\alpha_S}{3}\int_{-1}^{1} dz\,\frac{\phi_\pi(z)}{1-z^2}\int_{-1}^{1} dx\left[\frac{e_d}{-\eta-x-i\epsilon} - \frac{e_u}{-\eta+x-i\epsilon}\right]\left[\tilde{H}^d(x,\eta,t) - \tilde{H}^u(x,\eta,t)\right]$$

$$\int\frac{dz^-}{2\pi}e^{ixP^+z^-}\langle p'|\bar{q}(-\frac{z^-}{2})\gamma^+\gamma_5 q(\frac{z^-}{2})|p\rangle = \frac{1}{P^+}\left[\tilde{H}^q(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}^q(x,\xi,t)\bar{u}(p')\frac{\gamma_5(p'-p)^+}{2m}u(p)\right]$$



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long. photon

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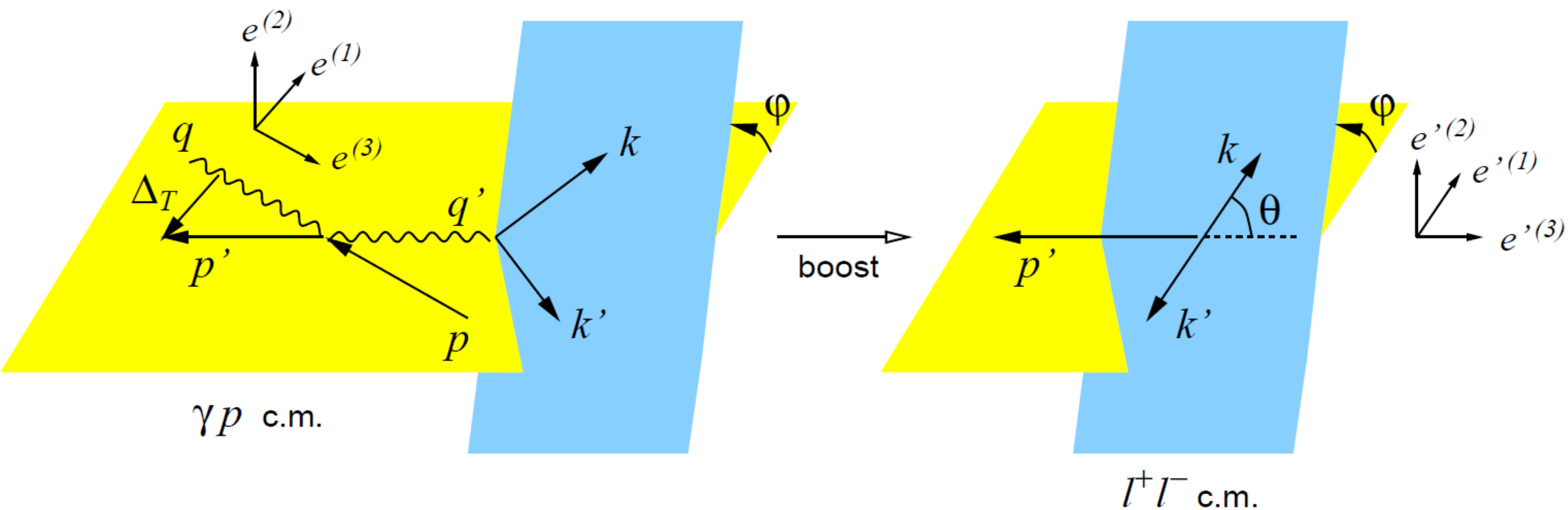

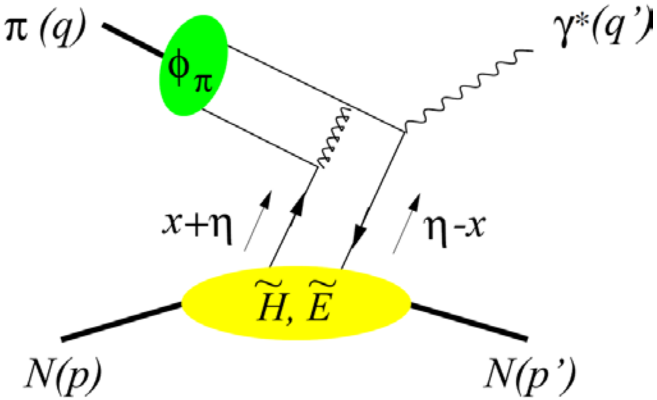

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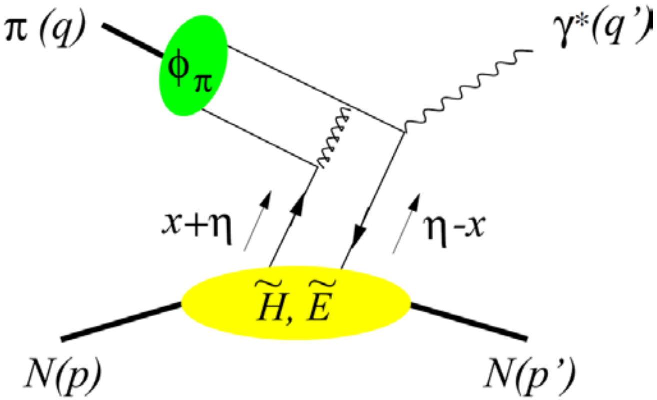

Bjorken variable: $\tau = \dfrac{Q'^2}{2p\cdot q}$

Skewness: $\eta = \dfrac{p^+ - p'^+}{p^+ + p'^+}$

long. photon

$\left|d^1_{-1\,0}(\theta)\right|^2 + \left|d^1_{1\,0}(\theta)\right|^2$

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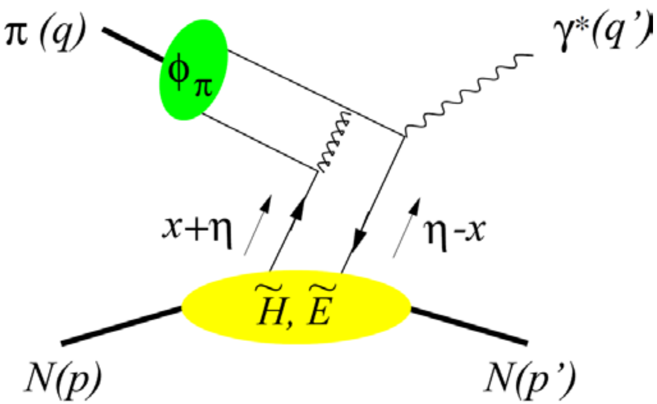

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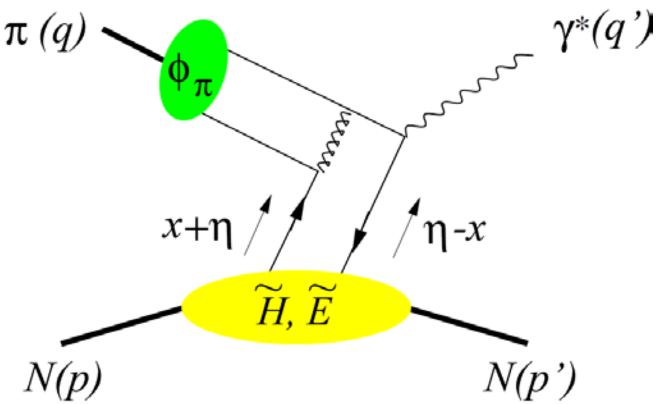

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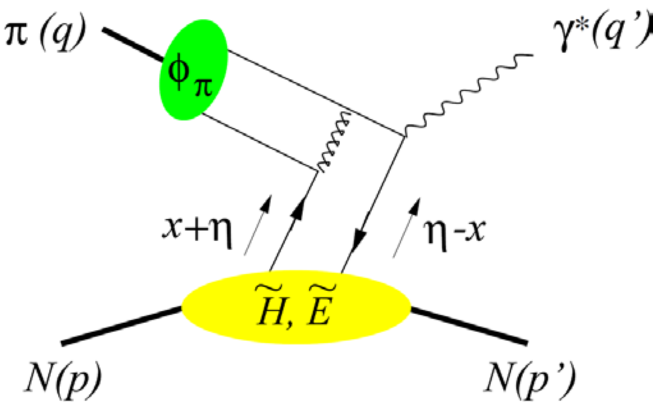
angular distribution $\propto \sin 2\theta\cos\varphi$

$$\sim \Re e\left[d^1_{1\,0}(\theta)\left(d^1_{1\,1}(\theta)e^{-i\phi}\right)^*\right]$$



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angular distribution $\propto \sin 2\theta \cos\varphi$

need quantitative estimate!

$$\sim \Re e\left[d^1_{10}(\theta)\left(d^1_{11}(\theta)e^{-i\phi}\right)^*\right]$$

Polarized target:

Target Transverse Spin asymmetry

At the twist 2 level : $$\frac{d^{\uparrow}\sigma - d^{\downarrow}\sigma}{d^{\uparrow}\sigma + d^{\downarrow}\sigma} = A_{\rm UT}^{\sin(\phi-\phi_S)} \sin(\phi-\phi_S) + \text{other harmonics}$$

$$A_{UT} = \frac{-2\sqrt{\frac{t-t_{min}}{t_{min}}}\,\eta^2\,\mathcal{I}m\,(\,\tilde{\mathcal{H}}\,\tilde{\mathcal{E}}^*\,)}{(1-\eta^2)|\tilde{\mathcal{H}}|^2-\frac{t}{4M^2}|\eta\tilde{\mathcal{E}}|^2-2\eta^2\mathcal{R}e(\tilde{\mathcal{H}}\tilde{\mathcal{E}}^*)}$$

⇨ New information on GPDs.

e.g. if $\tilde{E}$ is well modelized by pion pole, $\tilde{\mathcal{E}}$ is real $\rightarrow A_{UT} \sim \tilde{H}(x, \xi = x, t)$

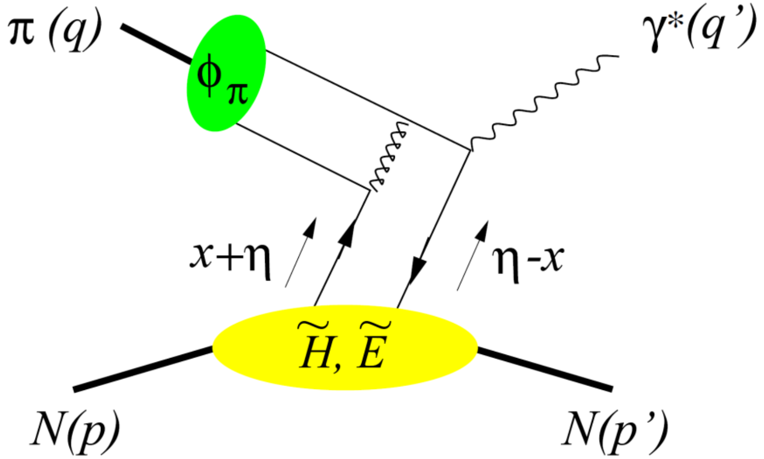
Exclusive lepton pair production in πN scattering

$$\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$$

Berger, Diehl, Pire, PLB523(2001)265

"exclusive limit of DY"

small $t = (q - q')^2$



$$\pi^- p \to \rho^- p \qquad \rho^- \to \pi^- \pi^0$$

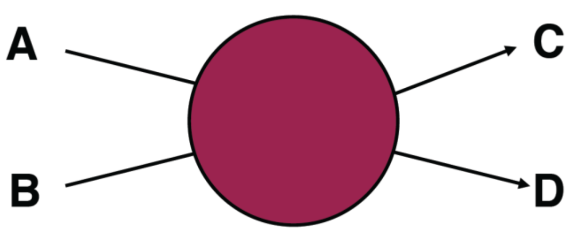
$$(4\pi/3)\, W(\theta,\phi) = r_{0,0}\cos^2(\theta) + r_{1,1}\sin^2(\theta) - r_{1,-1}\sin^2(\theta)\cos(2\phi) - \sqrt{2}\,\mathrm{Re}(r_{1,0})\sin(2\theta)\cos(\phi),$$

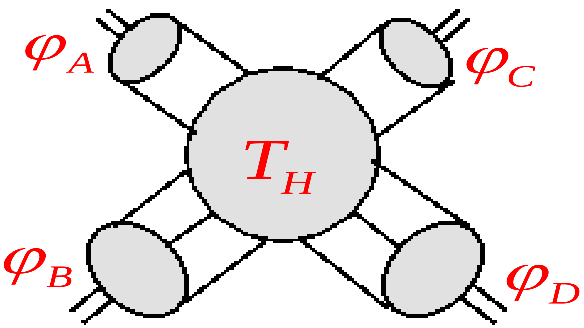
$$r_{i,i'} = \sum_{m,n} A^{i}_{m,n} A^{i'*}_{m,n}. \qquad m = i + n = i' + n$$

BNL AGS E755('88) 9.9 GeV

$$r_{0,0} = 0.12 \pm 0.30, \qquad r_{1,1} = 0.44 \pm 0.15,$$

$$r_{1,-1} = 0.32 \pm 0.10, \qquad \mathrm{Re}(r_{1,0}) = -0.01 \pm 0.05.$$





Hadron helicity conservation

$$\sum_i \lambda_{H^i} = \sum_f \lambda_{H^f}$$

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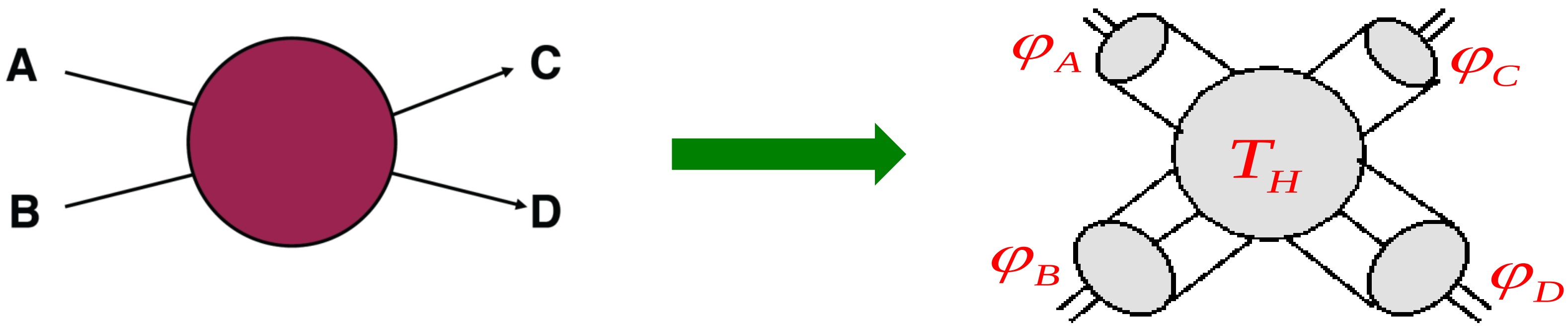

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violated!

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Higher twist effect?

VOLUME 56, NUMBER 16 PHYSICAL REVIEW LETTERS 21 APRIL 1986

Polarization Effects in Exclusive Hadron Scattering

Glennys R. Farrar

Department of Physics, Rutgers University, Piscataway, New Jersey 08854

(Received 5 March 1986)

Measured helicity nonconservation in $\pi^- p \to \rho^- p$ and in pp elastic scattering indicates that higher-twist contributions are $\frac{1}{10}-\frac{1}{3}$ the size of the leading-twist amplitudes, and that the relative phase between certain pp amplitudes is at least 16°. The reported levels of helicity nonconservation are therefore consistent with leading-twist perturbative QCD.

PACS numbers: 13.85.Dz, 12.38.Bx, 12.38.Qk, 13.85.Fb

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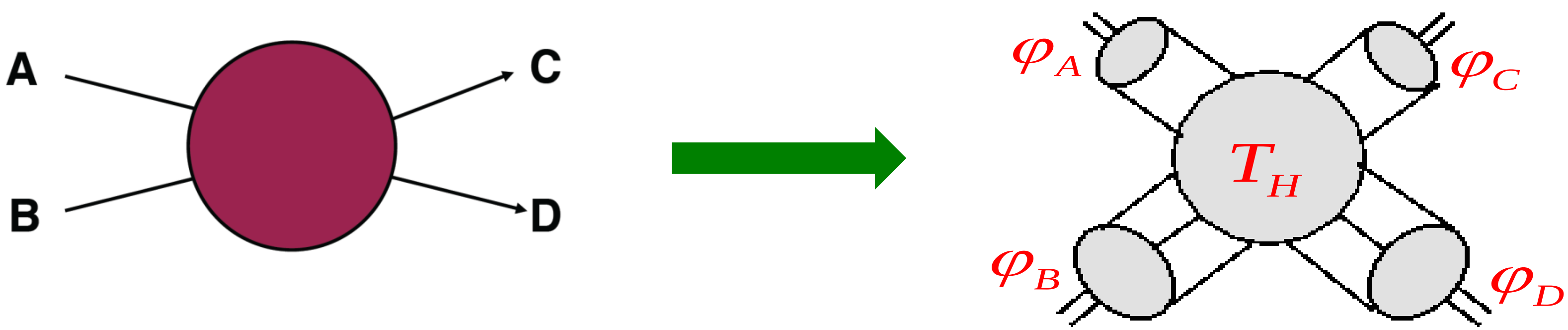


Hadron helicity conservation

$$\sum_i \lambda_{H^i} = \sum_f \lambda_{H^f}$$

violated!

persist at J-PARC?

15-20 GeV

Systematic study of hard exclusive meson-nucleon reactions

$\pi^{\pm} p \rightarrow p \pi^{\pm}$,

$K^{\pm} p \rightarrow p K^{\pm}$,

$\pi^{\pm} p \rightarrow p \rho^{\pm}$,

$\pi^{\pm} p \rightarrow \pi^{+} \Delta^{\pm}$,

$\pi^{\pm} p \rightarrow K^{+} \Sigma^{\pm}$,

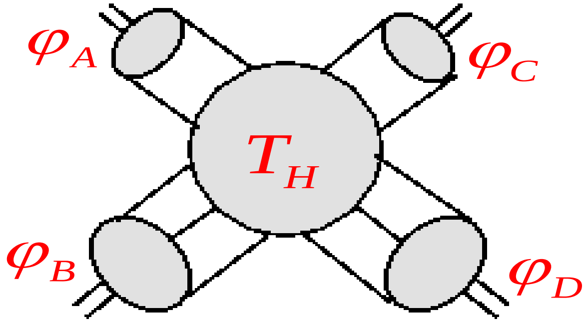
$\pi^{-} p \rightarrow \Lambda^{0} K^{0}, \Sigma^{0} K^{0}$,

$p^{\pm} p \rightarrow p p^{\pm}$.

BNL AGS E755('88) 9.9 GeV

E838('94) 5.9 GeV

J-PARC 15-20 GeV



$$= \int dx_a dx_b dx_c dx_d \times \varphi_D^*(x_d)\varphi_C^*(x_c)T_H(x_i, s, \theta_{CM})\varphi_B(x_b)\varphi_A(x_a)$$

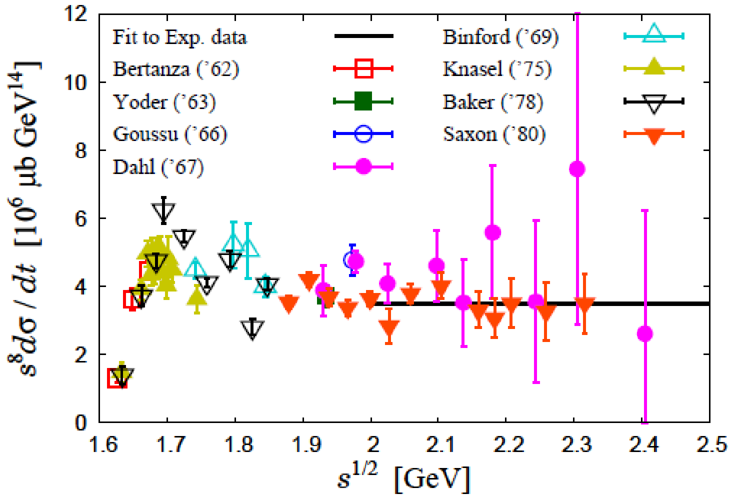
$$\frac{d\sigma}{dt} \sim \frac{1}{s^{n-2}}$$

$$n = n_A + n_B + n_C + n_D$$

Lambda & Lambda(1405)

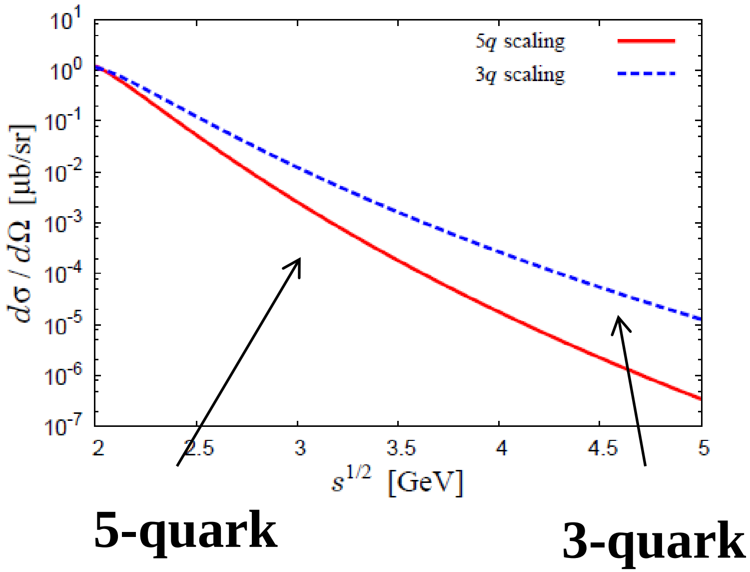
Kawamura, Kumano, Sekihara, PRD88 ('13) 034010

$\pi^- + p \to K + \Lambda$



$n = 10$

$\pi^- + p \to K + \Lambda,\ K + \Lambda(1405)$



$n = 10$ or 12?

Summary

unpol. beam $p, \pi^{\pm}, K^{\pm}, \cdots$

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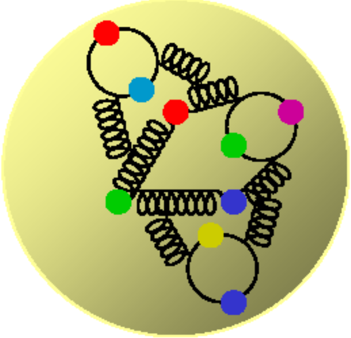

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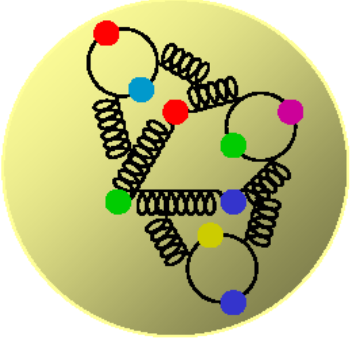

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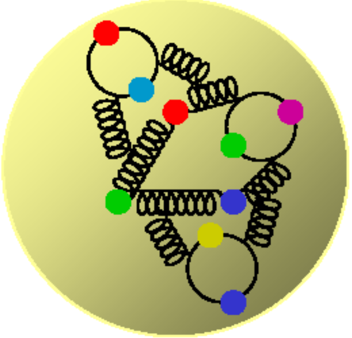

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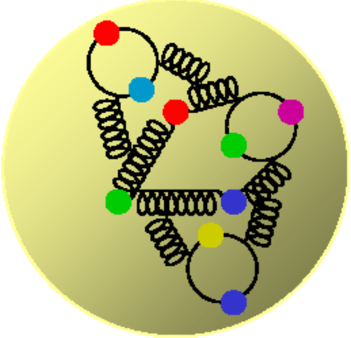

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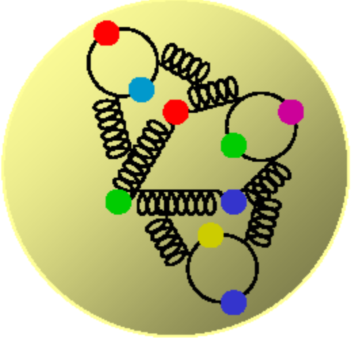

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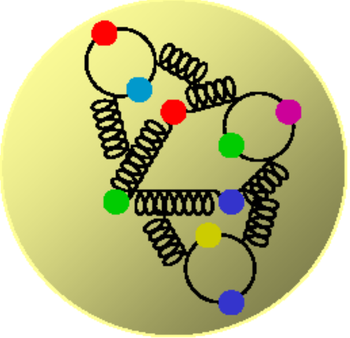

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~~**helicity conserv.**~~

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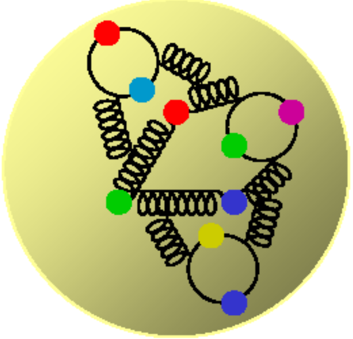

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interplay of soft/hard QCD mechanism

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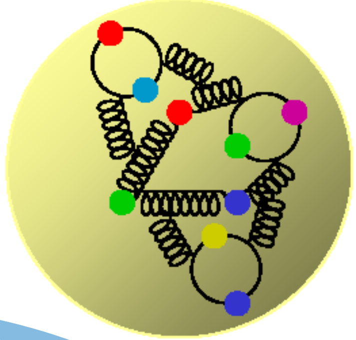

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~~helicity conserv.~~

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