Power corrections to exclusive Drell-Yan process

Kazuhiro Tanaka (Juntendo U/KEK)

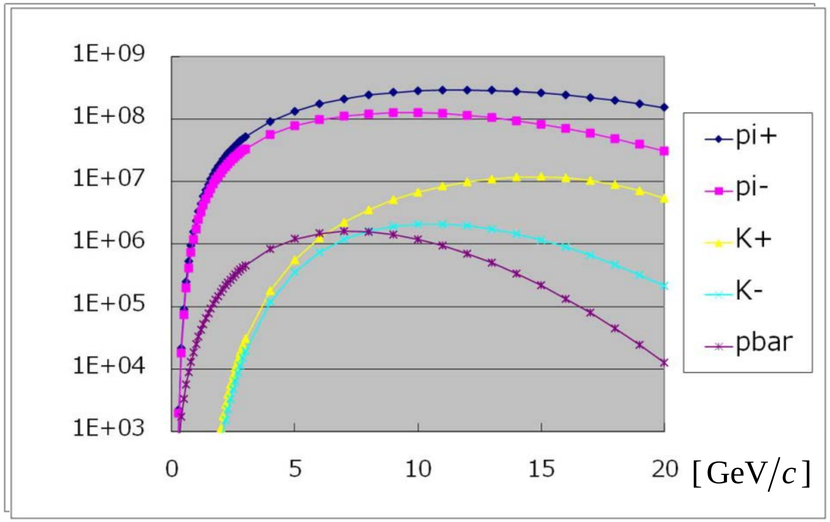
High-momentum beamline

- 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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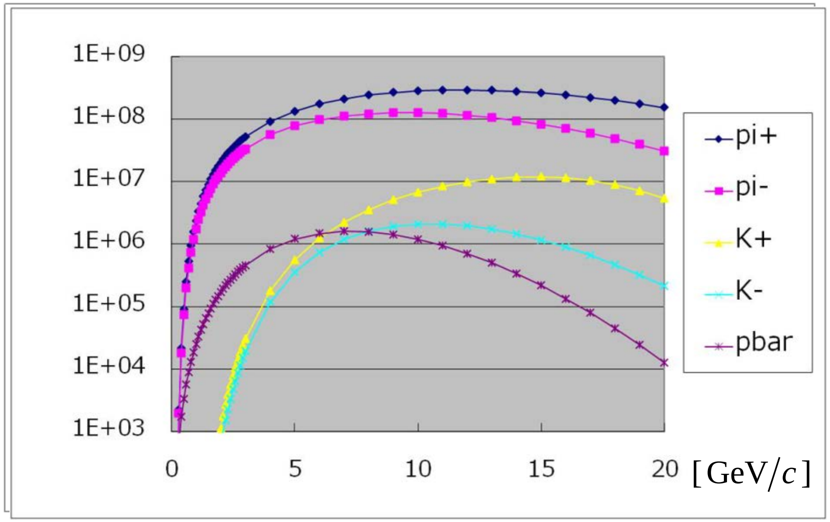


0° extraction angle

high intensity

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

best suited to study meson-induced hard exclusive processes

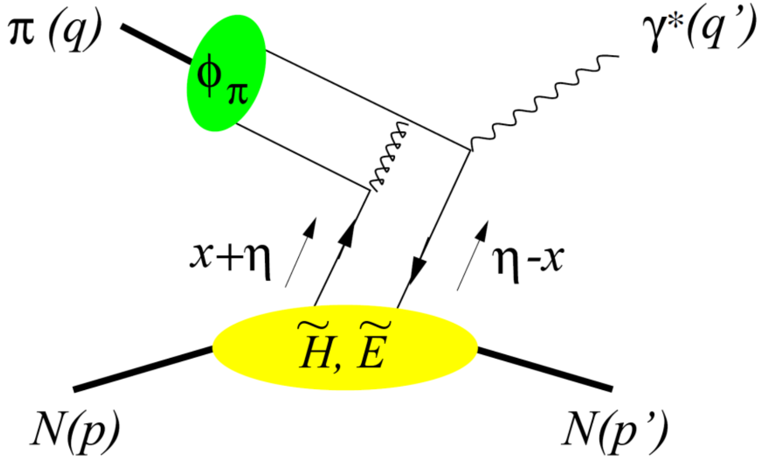
Exclusive lepton pair production in πN scattering

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

Berger, Diehl, Pire, PLB523(2001)265

"exclusive limit of DY"

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



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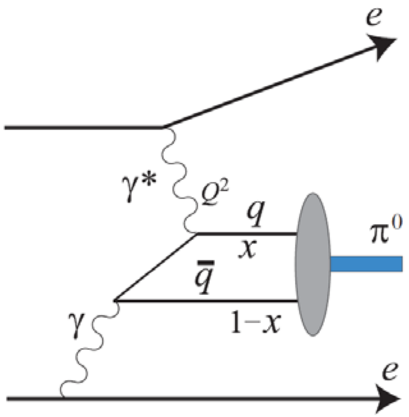

@Belle, Babar

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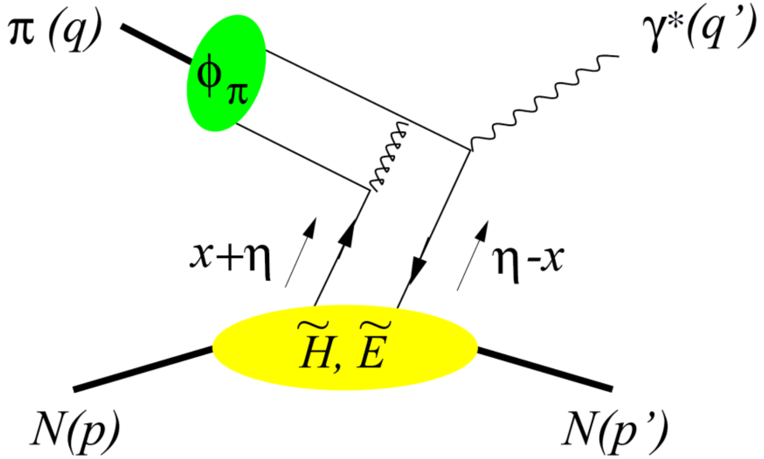

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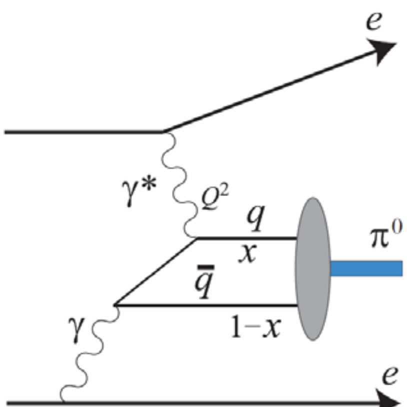

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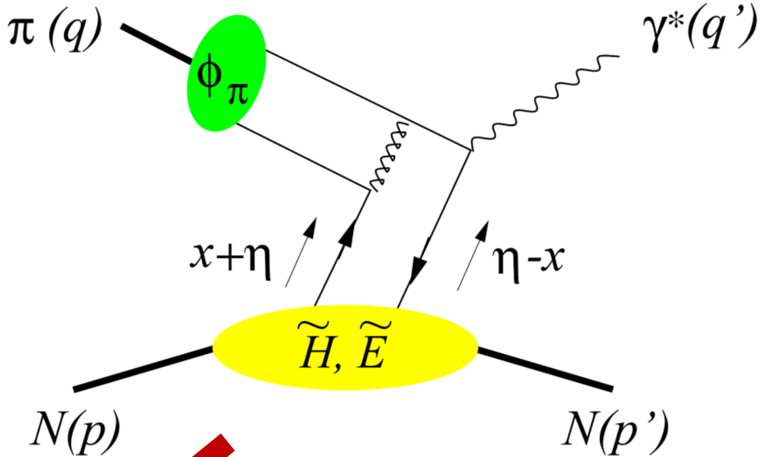

$$t \to 0$$

$$\Delta q(x)$$

Exclusive lepton pair production in πN scattering

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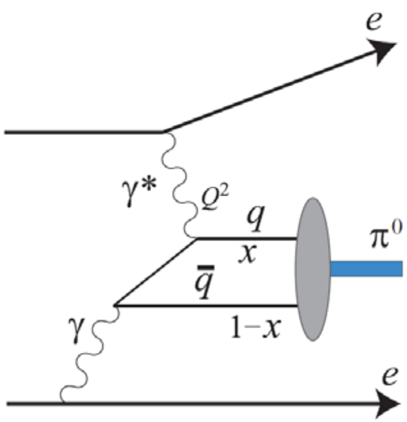
Berger, Diehl, Pire, PLB523(2001)265



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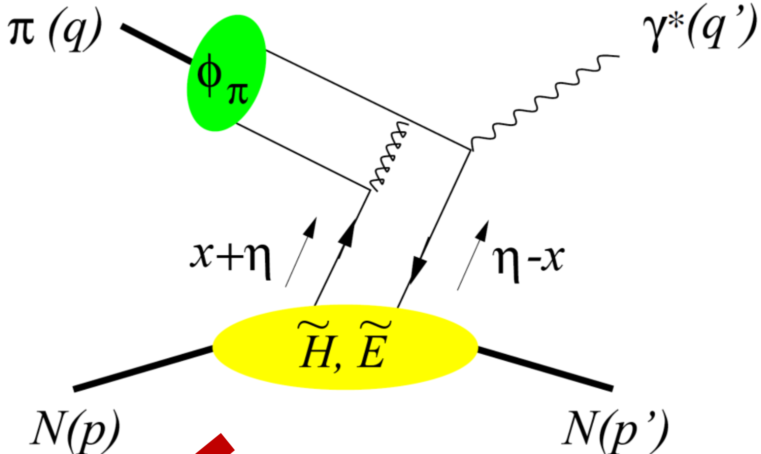

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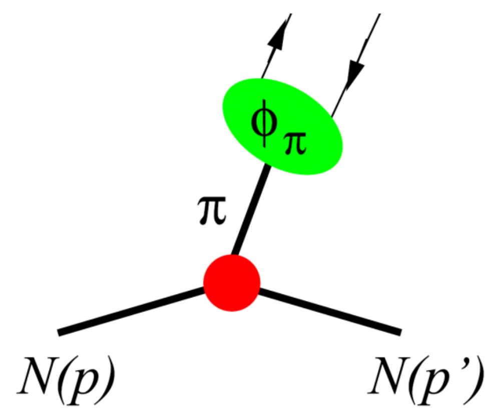
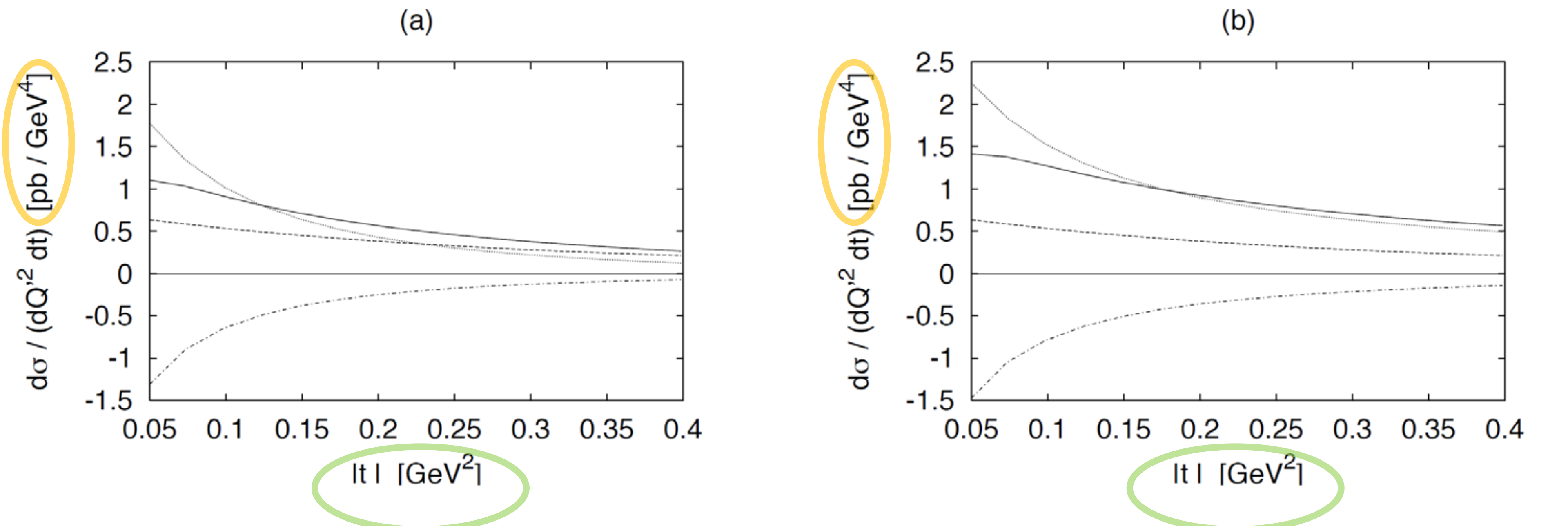


LO Estimates

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

Berger, Diehl, Pire, PLB523(2001)265

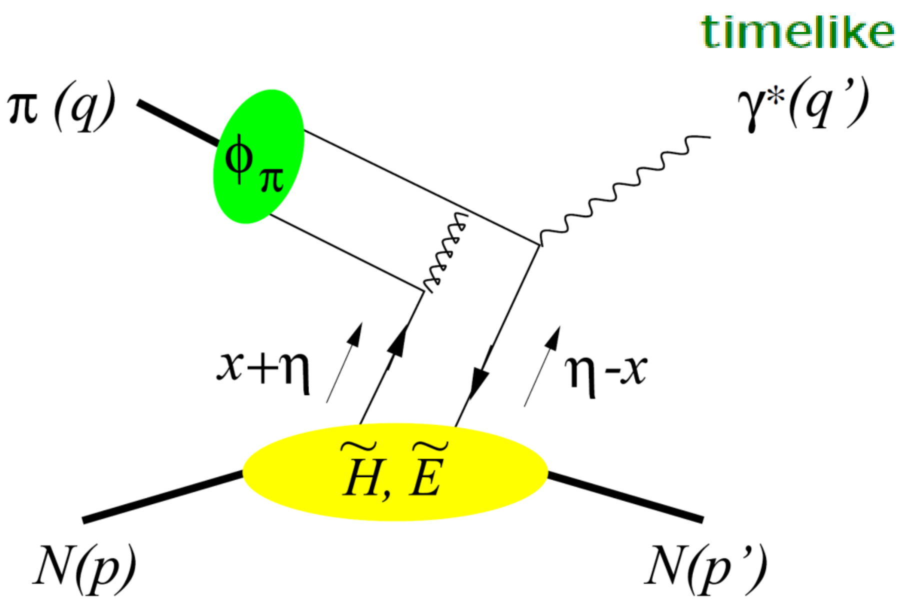
$$Q'^2 = 5 GeV^2 \qquad \tau = 0.2$$



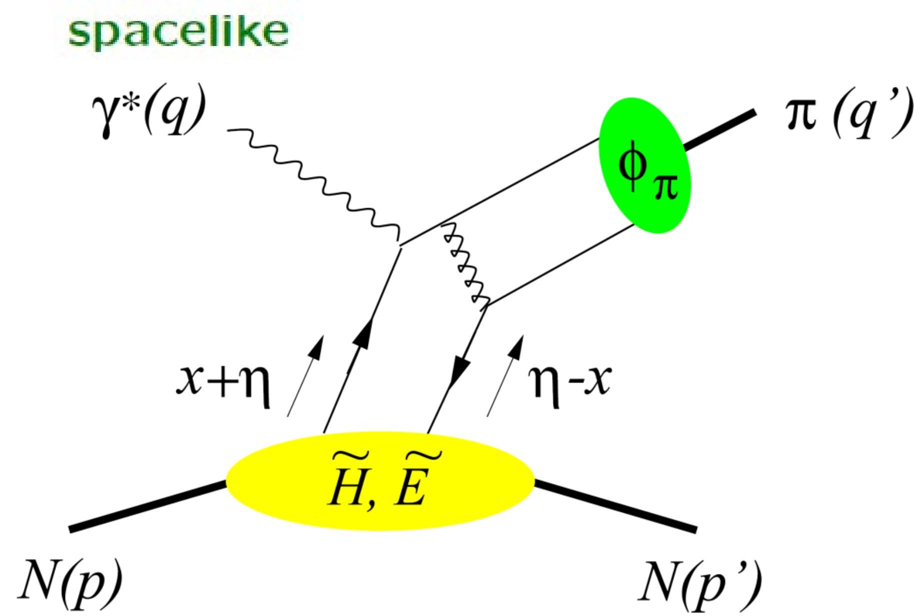
(dashed) $= |\tilde{\mathcal{H}}|^2$; **(dash-dotted)** $=$ **Re**$(\tilde{\mathcal{H}}^* \tilde{\mathcal{E}})$; **(dotted)** $= |\tilde{\mathcal{E}}|^2$

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

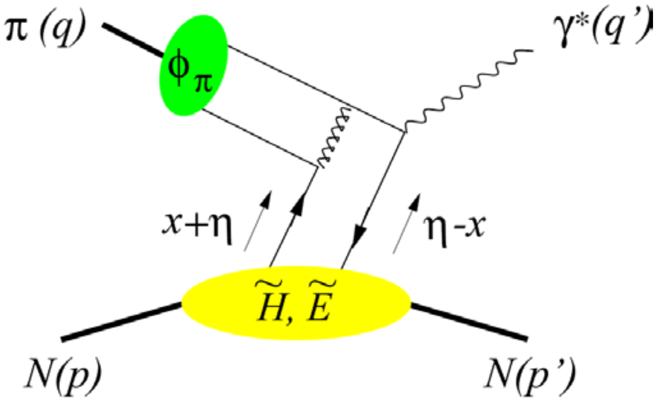
Pion beams reveal $\tilde{H}, \tilde{E}$ Generalized Parton distributions



exDY@J-PARC



DVMP@JLab



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

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

long. photon

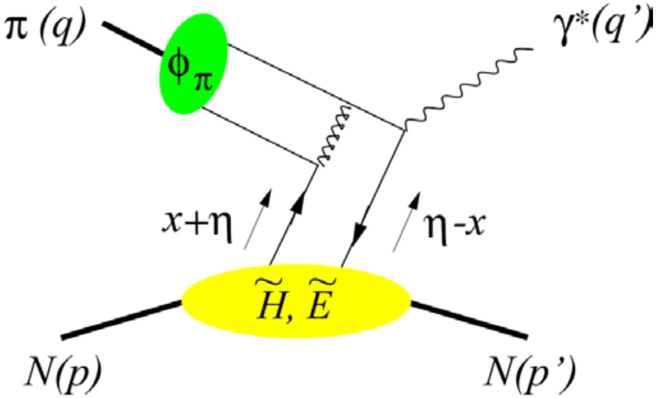
Berger, Diehl, Pire, PLB523(2001)

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

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

$$\tilde{\mathcal{H}}^{du}(\eta,t) = \frac{8\alpha_S}{3}\int_0^1 du\,\frac{\phi_\pi(u)}{4u(1-u)}\int_{-1}^{1} dx\left[\frac{e_d}{-\eta-x-i\epsilon} - \frac{e_u}{-\eta+x-i\epsilon}\right]\left[\tilde{H}^d(x,\eta,t) - \tilde{H}^u(x,\eta,t)\right]$$

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



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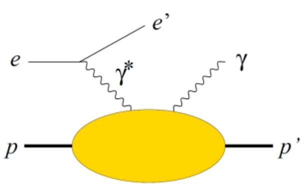

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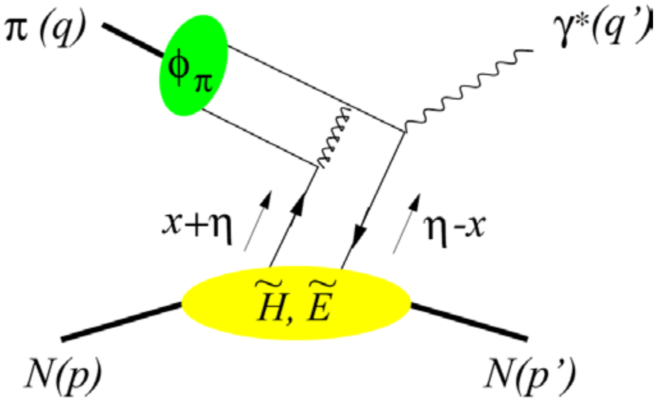
$$J_q = \frac{1}{2}\int_{-1}^{1} dx\, x\left(H^q(x,\eta,0) + E^q(x,\eta,0)\right)$$



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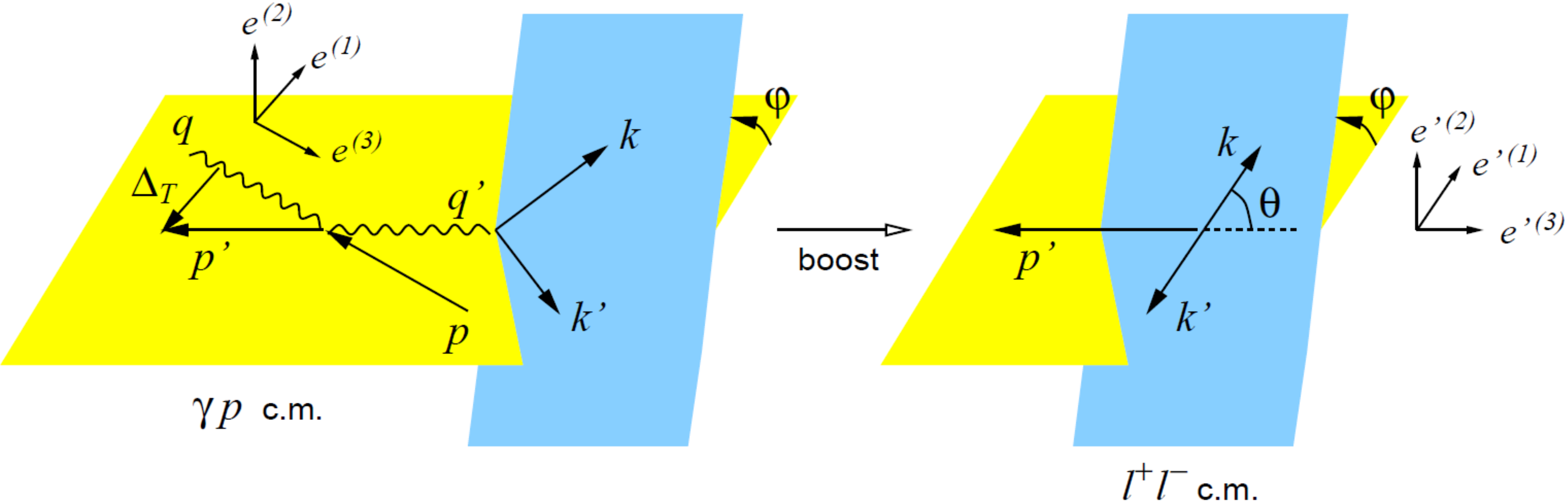

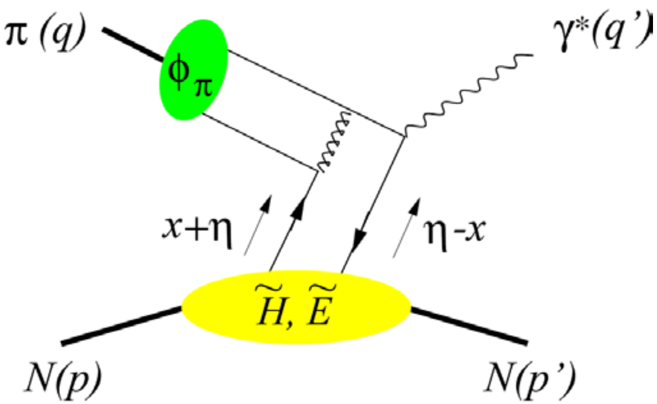

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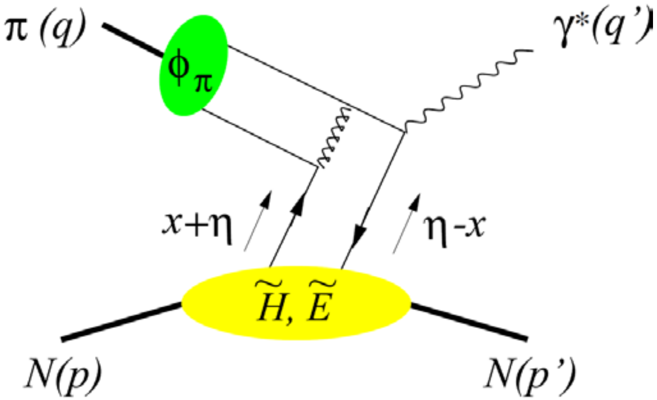

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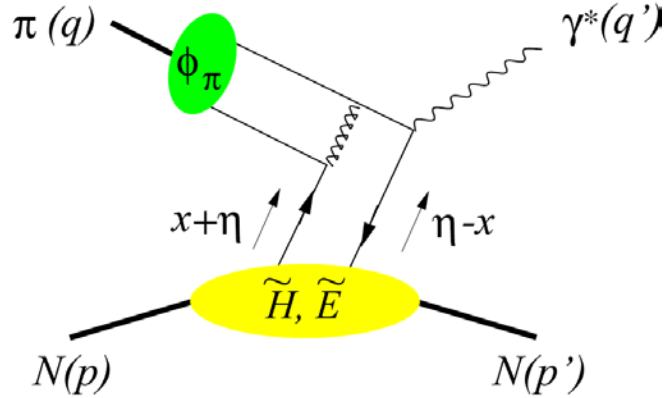
$$M^{\pm1,\lambda;\lambda'}(\pi^- p \to \gamma^* n) \sim \frac{1}{Q'^2}$$

$\dfrac{1}{Q'}$ **correction to** $\dfrac{d\sigma}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi}$

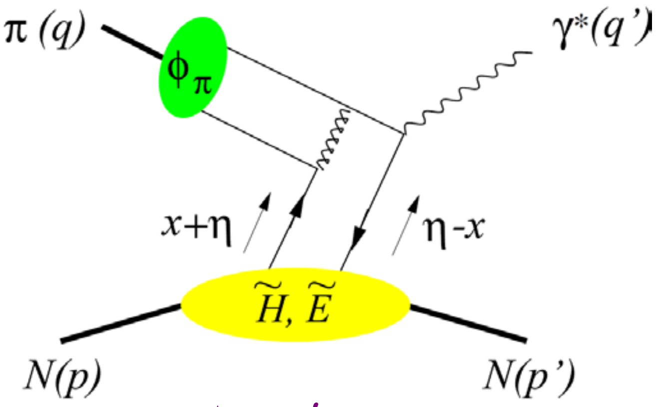
$$\langle 0|\overline{\psi}(0)\gamma^-\gamma_5\psi(y^+)|\pi(q)\rangle = if_\pi q^- \int_0^1 du\, e^{-iuq^-y^+}\,\phi_\pi(u)$$



$$\Delta = p' - p$$

$$\langle p'|\overline{\psi}(0)\gamma^+\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+z^-}\,\overline{u}(p')\left[\tilde{H}^q(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^q(x,\eta,t)\frac{\gamma_5\Delta^+}{2M}\right]u(p)$$

$$\langle 0|\bar{\psi}(0)\gamma^{-}\gamma_{5}\psi(y^{+})|\pi(q)\rangle = if_{\pi}q^{-}\int_{0}^{1}du\, e^{-iuq^{-}y^{+}}\,\phi_{\pi}(u)$$



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$$M^{0,\lambda;\lambda'}(\pi^{-}p\to\gamma^{*}n) \sim \frac{1}{Q'}\frac{1}{u(1-u)\left(\eta\pm x+i\varepsilon\right)}\otimes\phi_{\pi}(u)\otimes\left\{\tilde{H}^{q}(x,\eta,t),\tilde{E}^{q}(x,\eta,t)\right\}$$

$$\langle 0|\bar{\psi}(0)\gamma^-\gamma_5\psi(y^+)|\pi(q)\rangle = if_\pi q^- \int_0^1 du\, e^{-iuq^-y^+}\,\phi_\pi(u)$$

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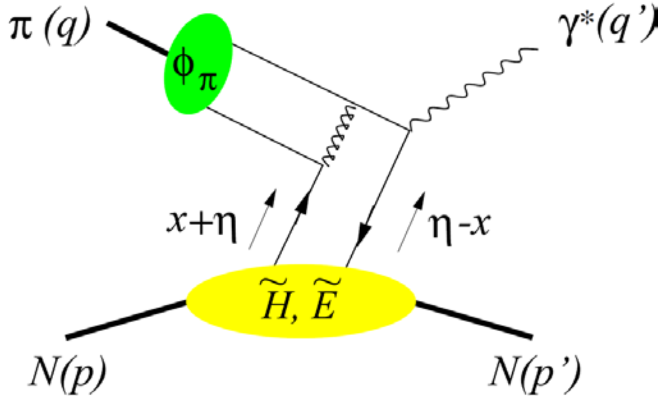
$$\langle 0|\bar{u}(0)\sigma^{-+}\gamma_5 d(y^+)|\pi^-(p)\rangle = -\frac{i}{3}\frac{f_\pi m_\pi^2}{m_u+m_d}q\cdot y\int_0^1 du\, e^{-iuq^-y^+}\,\phi_\sigma(u)$$



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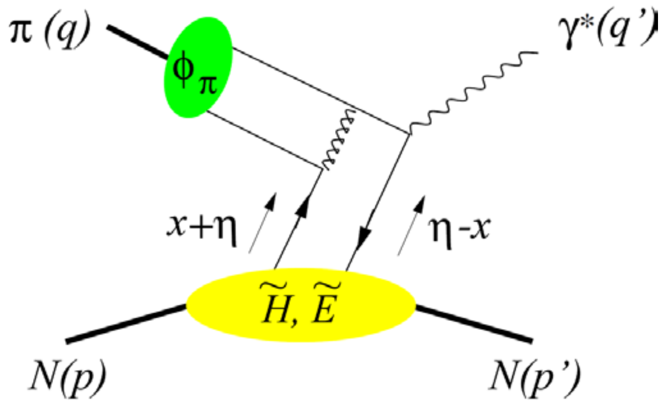

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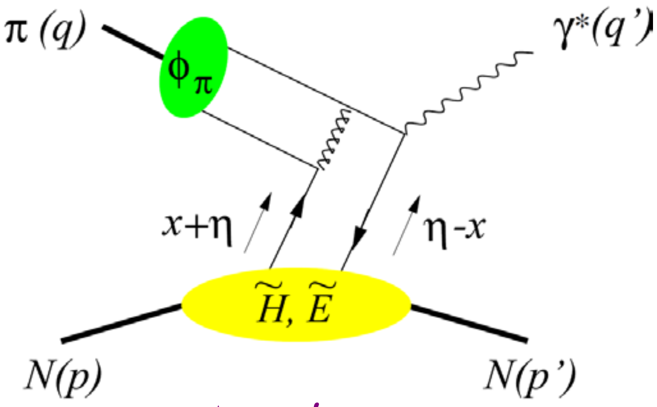

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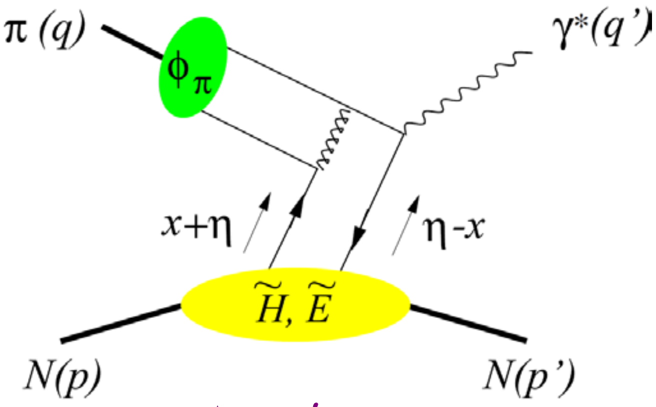
$$M^{0,\lambda;\lambda'}(\pi^-p\to\gamma^*n) \sim \frac{1}{Q'}\frac{1}{u(1-u)\left(\eta\pm x+i\varepsilon\right)}\otimes\phi_\pi(u)\otimes\left\{\tilde{H}^q(x,\eta,t),\tilde{E}^q(x,\eta,t)\right\}$$

$$M^{\pm1,\lambda;\lambda'}(\pi^-p\to\gamma^*n) \sim \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)\left(\eta\pm x+i\varepsilon\right)}\otimes\phi_\pi(u)\otimes\left\{\tilde{H}^q(x,\eta,t),\tilde{E}^q(x,\eta,t)\right\}$$
$$+\frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)\left(\eta\pm x+i\varepsilon\right)^2}\otimes\phi_p(u)\otimes\left\{H_T^q(x,\eta,t),\tilde{H}_T^q(x,\eta,t),E_T^q(x,\eta,t),\tilde{E}_T^q(x,\eta,t)\right\}$$

$$\langle 0|\bar{\psi}(0)\gamma^{-}\gamma_5\psi(y^{+})|\pi(q)\rangle = i f_\pi q^{-}\int_0^1 du\, e^{-iuq^{-}y^{+}}\,\phi_\pi(u)$$

$$\langle 0|\bar{\psi}(0)i\gamma_5\psi(y^{+})|\pi^{-}(p)\rangle = \frac{f_\pi m_\pi^2}{m_u+m_d}\int_0^1 du\, e^{-iuq^{-}y^{+}}\,\phi_p(u)$$

$$\langle 0|\bar{u}(0)\sigma^{-+}\gamma_5 d(y^{+})|\pi^{-}(p)\rangle = \frac{i}{3}\frac{f_\pi m_\pi^2}{m_u+m_d}\,q\cdot y\int_0^1 du\, e^{-iuq^{-}y^{+}}\,\phi_\sigma(u)$$



$$\Delta = p' - p$$

$$\langle p'|\bar{\psi}(0)\gamma^{+}\gamma_5\psi(z^{-})|p\rangle = \int_{-1}^{1} dx\, e^{-i(x+\eta)\bar{P}^{+}z^{-}}\,\bar{u}(p')\left[\tilde{H}^q(x,\eta,t)\gamma^{+}\gamma_5 + \tilde{E}^q(x,\eta,t)\frac{\gamma_5\Delta^{+}}{2M}\right]u(p)$$

$$\langle p'|\bar{\psi}(0)\sigma^{+\perp}\gamma_5\psi(z^{-})|p\rangle = \int_{-1}^{1} dx\, e^{-i(x+\eta)\bar{P}^{+}z^{-}}\,\bar{u}(p')\left[H_T^q(x,\eta,t)\sigma^{+\perp}\gamma_5 + \tilde{H}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\bar{P}}}{M^2} + E_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\alpha}\gamma_\alpha}{2M} + \tilde{E}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\bar{P}\alpha}\gamma_\alpha}{M}\right]u(p)$$

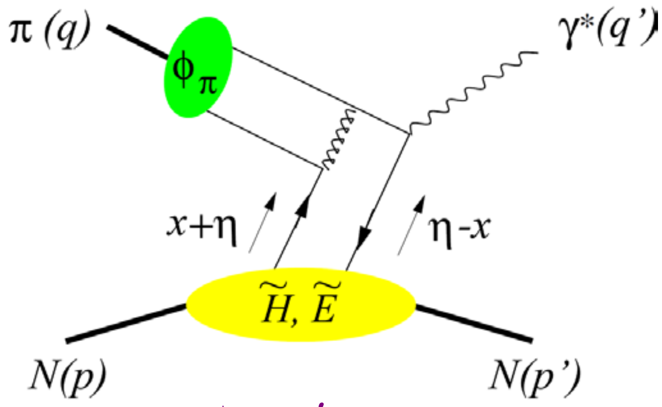
$$M^{0,\lambda;\lambda'}(\pi^{-}p\to\gamma^{*}n) \sim \frac{1}{Q'}\frac{1}{u(1-u)\left(\eta\pm x+i\varepsilon\right)}\otimes\phi_\pi(u)\otimes\left\{\tilde{H}^q(x,\eta,t),\tilde{E}^q(x,\eta,t)\right\}$$

$$M^{\pm1,\lambda;\lambda'}(\pi^{-}p\to\gamma^{*}n) \sim \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)\left(\eta\pm x+i\varepsilon\right)}\otimes\phi_\pi(u)\otimes\left\{\tilde{H}^q(x,\eta,t),\tilde{E}^q(x,\eta,t)\right\}$$
$$+\frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)\left(\eta\pm x+i\varepsilon\right)^2}\otimes\phi_p(u)\otimes\left\{H_T^q(x,\eta,t),\tilde{H}_T^q(x,\eta,t),E_T^q(x,\eta,t),\tilde{E}_T^q(x,\eta,t)\right\}$$

$$\langle 0|\bar{\psi}(0)\gamma^-\gamma_5\psi(y^+)|\pi(q)\rangle = if_\pi q^-\int_0^1 du\, e^{-iuq^-y^+}\,\phi_\pi(u)$$

$$\langle 0|\bar{\psi}(0)i\gamma_5\psi(y^+)|\pi^-(p)\rangle = \frac{f_\pi m_\pi^2}{m_u+m_d}\int_0^1 du\, e^{-iuq^-y^+}\,\phi_p(u)$$

$$\langle 0|\bar{u}(0)\sigma^{-+}\gamma_5 d(y^+)|\pi^-(p)\rangle = \frac{i}{3}\frac{f_\pi m_\pi^2}{m_u+m_d}q\cdot y\int_0^1 du\, e^{-iuq^-y^+}\,\phi_\sigma(u)$$



$$\Delta = p' - p$$

$$\langle p'|\bar{\psi}(0)\gamma^+\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+z^-}\,\bar{u}(p')\left[\tilde{H}^q(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^q(x,\eta,t)\frac{\gamma_5\Delta^+}{2M}\right]u(p)$$

$$\langle p'|\bar{\psi}(0)\sigma^{+\perp}\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+z^-}\,\bar{u}(p')\left[H_T^q(x,\eta,t)\sigma^{+\perp}\gamma_5 + \tilde{H}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\bar{P}}}{M^2} + E_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\alpha}\gamma_\alpha}{2M} + \tilde{E}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\bar{P}\alpha}\gamma_\alpha}{M}\right]u(p)$$

$$M^{0,\lambda;\lambda'}(\pi^-p\to\gamma^*n) \sim \frac{1}{Q'}\frac{1}{u(1-u)\left(\eta\pm x+i\varepsilon\right)}\otimes\phi_\pi(u)\otimes\left\{\tilde{H}^q(x,\eta,t),\tilde{E}^q(x,\eta,t)\right\}$$

$\sin\theta$

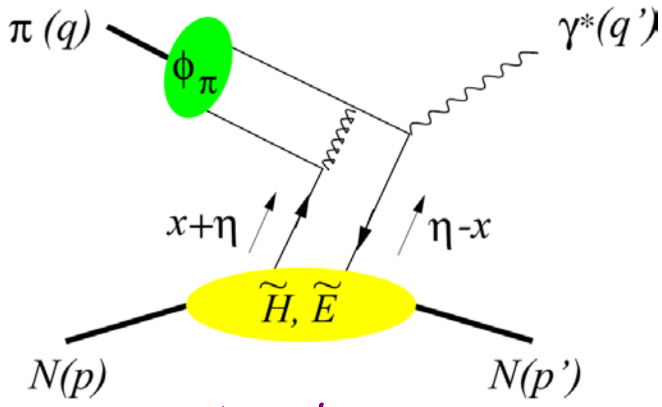
$$M^{\pm1,\lambda;\lambda'}(\pi^-p\to\gamma^*n) \sim \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)\left(\eta\pm x+i\varepsilon\right)}\otimes\phi_\pi(u)\otimes\left\{\tilde{H}^q(x,\eta,t),\tilde{E}^q(x,\eta,t)\right\}$$
$$+\frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)\left(\eta\pm x+i\varepsilon\right)^2}\otimes\phi_p(u)\otimes\left\{H_T^q(x,\eta,t),\tilde{H}_T^q(x,\eta,t),E_T^q(x,\eta,t),\tilde{E}_T^q(x,\eta,t)\right\}$$

$e^{\pm i\varphi}\cos\theta$

$$\langle 0|\bar{\psi}(0)\gamma^- \gamma_5 \psi(y^+)|\pi(q)\rangle = i f_\pi q^- \int_0^1 du\, e^{-iuq^- y^+}\, \phi_\pi(u)$$

$$\langle 0|\bar{\psi}(0) i\gamma_5 \psi(y^+)|\pi^-(p)\rangle = \frac{f_\pi m_\pi^2}{m_u + m_d} \int_0^1 du\, e^{-iuq^- y^+}\, \phi_p(u)$$

$$\langle 0|\bar{u}(0)\sigma^{-+}\gamma_5 d(y^+)|\pi^-(p)\rangle = \frac{i}{3}\frac{f_\pi m_\pi^2}{m_u + m_d} q\cdot y \int_0^1 du\, e^{-iuq^- y^+}\, \phi_\sigma(u)$$



$$\Delta = p' - p$$

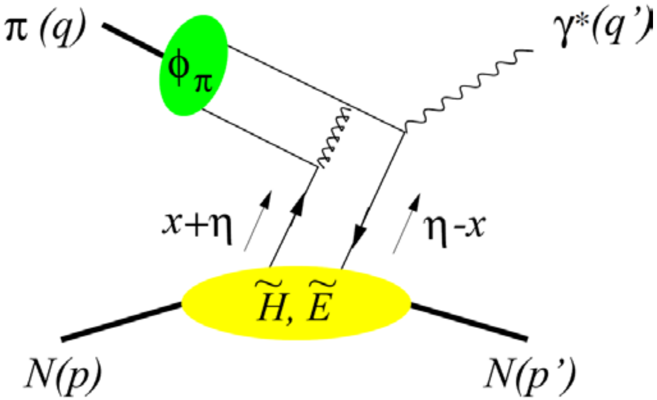
$$\langle p'|\bar{\psi}(0)\gamma^+\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+ z^-}\, \bar{u}(p')\left[\tilde{H}^q(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^q(x,\eta,t)\frac{\gamma_5\Delta^+}{2M}\right]u(p)$$

$$\langle p'|\bar{\psi}(0)\sigma^{+\perp}\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+ z^-}\, \bar{u}(p')\left[H_T^q(x,\eta,t)\sigma^{+\perp}\gamma_5 + \tilde{H}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\bar{P}}}{M^2} + E_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\alpha}\gamma_\alpha}{2M} + \tilde{E}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\bar{P}\alpha}\gamma_\alpha}{M}\right]u(p)$$

$$M^{0,\lambda;\lambda'}(\pi^- p \to \gamma^* n) \sim \frac{1}{Q'}\frac{1}{u(1-u)(\eta \pm x + i\varepsilon)} \otimes \phi_\pi(u) \otimes \left\{\tilde{H}^q(x,\eta,t), \tilde{E}^q(x,\eta,t)\right\} \qquad \sin\theta$$

$$M^{\pm 1,\lambda;\lambda'}(\pi^- p \to \gamma^* n) \sim \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)(\eta \pm x + i\varepsilon)} \otimes \phi_\pi(u) \otimes \left\{\tilde{H}^q(x,\eta,t), \tilde{E}^q(x,\eta,t)\right\}$$
$$+ \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)(\eta \pm x + i\varepsilon)^2} \otimes \phi_p(u) \otimes \left\{H_T^q(x,\eta,t), \tilde{H}_T^q(x,\eta,t), E_T^q(x,\eta,t), \tilde{E}_T^q(x,\eta,t)\right\} \qquad e^{\pm i\varphi}\cos\theta$$

$$\frac{d\sigma}{dQ'^2 dt d(\cos\theta) d\phi} \sim \frac{f_\pi^2}{Q'^8}\left\{a_{\text{tw.2}}\sin^2\theta + \frac{\Delta_\perp}{Q'}\left[\left(b_{\text{tw.2}} + b_{\text{tw.3}}\right)\sin 2\theta\cos\varphi + c_{\text{tw.3}}\sin 2\theta \sin\varphi\right]\right\}$$



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

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

long. photon

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

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

$$\tilde{\mathcal{H}}^{du}(\eta,t) = \frac{8\alpha_S}{3}\int_0^1 du\,\frac{\phi_\pi(u)}{4u(1-u)}\int_{-1}^{1}dx\left[\frac{e_d}{-\eta-x-i\epsilon} - \frac{e_u}{-\eta+x-i\epsilon}\right]\left[\tilde{H}^d(x,\eta,t) - \tilde{H}^u(x,\eta,t)\right]$$

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

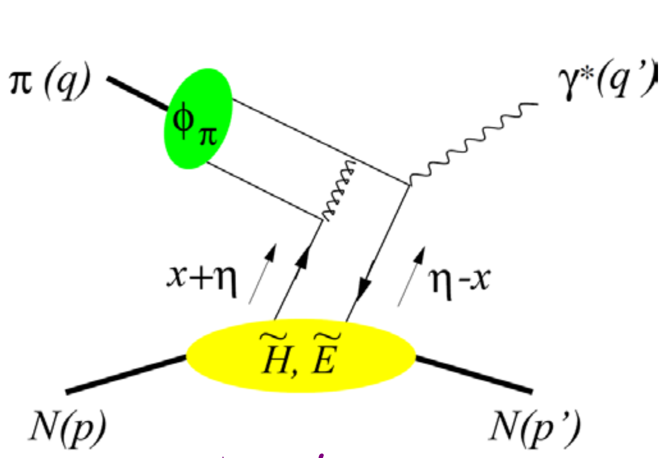
$M^{\pm1,\lambda;\lambda'}(\pi^- p\to\gamma^* n)\sim\frac{1}{Q'^2}$

$\frac{1}{Q'}$ **correction to** $\frac{d\sigma}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi}$

$$\langle 0|\bar{\psi}(0)\gamma^-\gamma_5\psi(y^+)|\pi(q)\rangle = if_\pi q^- \int_0^1 du\, e^{-iuq^-y^+}\,\phi_\pi(u)$$

$$\langle 0|\bar{\psi}(0)i\gamma_5\psi(y^+)|\pi^-(p)\rangle = \frac{f_\pi m_\pi^2}{m_u+m_d}\int_0^1 du\, e^{-iuq^-y^+}\,\phi_p(u)$$

$$\langle 0|\bar{u}(0)\sigma^{-+}\gamma_5 d(y^+)|\pi^-(p)\rangle = \frac{i}{3}\frac{f_\pi m_\pi^2}{m_u+m_d} q\cdot y\int_0^1 du\, e^{-iuq^-y^+}\,\phi_\sigma(u)$$



$$\Delta = p' - p$$

$$\langle p'|\bar{\psi}(0)\gamma^+\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+z^-}\,\bar{u}(p')\left[\tilde{H}^q(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^q(x,\eta,t)\frac{\gamma_5\Delta^+}{2M}\right]u(p)$$

$$\langle p'|\bar{\psi}(0)\sigma^{+\perp}\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+z^-}\,\bar{u}(p')\left[H_T^q(x,\eta,t)\sigma^{+\perp}\gamma_5 + \tilde{H}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\bar{P}}}{M^2} + E_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\alpha}\gamma_\alpha}{2M} + \tilde{E}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\bar{P}\alpha}\gamma_\alpha}{M}\right]u(p)$$

$$M^{0,\lambda;\lambda'}(\pi^- p \to \gamma^* n) \sim \frac{1}{Q'}\frac{1}{u(1-u)(\eta\pm x+i\varepsilon)}\otimes\phi_\pi(u)\otimes\left\{\tilde{H}^q(x,\eta,t),\tilde{E}^q(x,\eta,t)\right\}$$

$\sin\theta$

$$M^{\pm1,\lambda;\lambda'}(\pi^- p \to \gamma^* n) \sim \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)(\eta\pm x+i\varepsilon)}\otimes\phi_\pi(u)\otimes\left\{\tilde{H}^q(x,\eta,t),\tilde{E}^q(x,\eta,t)\right\}$$
$$+\frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)(\eta\pm x+i\varepsilon)^2}\otimes\phi_p(u)\otimes\left\{H_T^q(x,\eta,t),\tilde{H}_T^q(x,\eta,t),E_T^q(x,\eta,t),\tilde{E}_T^q(x,\eta,t)\right\}$$

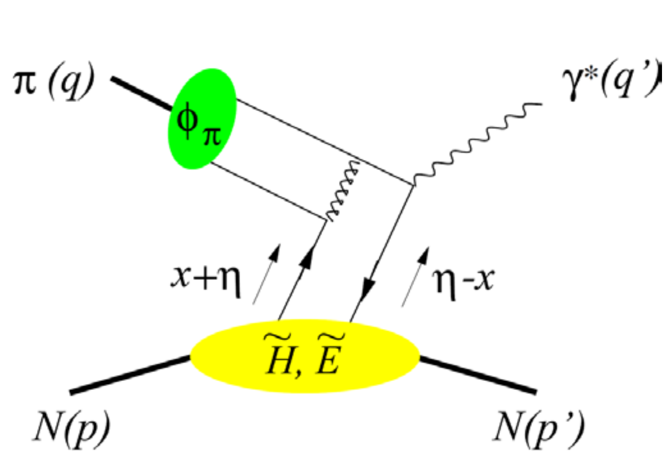
$e^{\pm i\varphi}\cos\theta$

$$\frac{d\sigma}{dQ'^2 dt d(\cos\theta)d\phi} \sim \frac{f_\pi^2}{Q'^8}\left\{a_{\text{tw.2}}\sin^2\theta + \frac{\Delta_\perp}{Q'}\left[\left(b_{\text{tw.2}}+b_{\text{tw.3}}\right)\sin 2\theta\cos\varphi + c_{\text{tw.3}}\sin 2\theta\sin\varphi\right]\right\}$$

$$\langle 0|\bar{\psi}(0)\gamma^-\gamma_5\psi(y^+)|\pi(q)\rangle = if_\pi q^- \int_0^1 du\, e^{-iuq^-y^+}\ \phi_\pi(u)$$

$$\langle 0|\bar{\psi}(0)i\gamma_5\psi(y^+)|\pi^-(p)\rangle = \frac{f_\pi m_\pi^2}{m_u + m_d}\int_0^1 du\, e^{-iuq^-y^+}\ \phi_p(u)$$

$$\langle 0|\bar{u}(0)\sigma^{-+}\gamma_5 d(y^+)|\pi^-(p)\rangle = \frac{i}{3}\frac{f_\pi m_\pi^2}{m_u + m_d}\, q\cdot y\int_0^1 du\, e^{-iuq^-y^+}\ \phi_\sigma(u)$$



$$\Delta = p' - p$$

$$\langle p'|\bar{\psi}(0)\gamma^+\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+z^-}\,\bar{u}(p')\left[\tilde{H}^q(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^q(x,\eta,t)\frac{\gamma_5\Delta^+}{2M}\right]u(p)$$

$$\langle p'|\bar{\psi}(0)\sigma^{+\perp}\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+z^-}\,\bar{u}(p')\left[H_T^q(x,\eta,t)\sigma^{+\perp}\gamma_5 + \tilde{H}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\bar{P}}}{M^2} + E_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\alpha}\gamma_\alpha}{2M} + \tilde{E}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\bar{P}\alpha}\gamma_\alpha}{M}\right]u(p)$$

$$M^{0,\lambda;\lambda'}(\pi^- p \to \gamma^* n) \sim \frac{1}{Q'}\frac{1}{u(1-u)(\eta \pm x + i\varepsilon)} \otimes \phi_\pi(u) \otimes \left\{\tilde{H}^q(x,\eta,t), \tilde{E}^q(x,\eta,t)\right\}$$

$$\sin\theta$$

$$M^{\pm 1,\lambda;\lambda'}(\pi^- p \to \gamma^* n) \sim \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)(\eta \pm x + i\varepsilon)} \otimes \phi_\pi(u) \otimes \left\{\tilde{H}^q(x,\eta,t), \tilde{E}^q(x,\eta,t)\right\}$$
$$+ \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)(\eta \pm x + i\varepsilon)^2} \otimes \phi_p(u) \otimes \left\{H_T^q(x,\eta,t), \tilde{H}_T^q(x,\eta,t), E_T^q(x,\eta,t), \tilde{E}_T^q(x,\eta,t)\right\}$$

$$e^{\pm i\varphi}\cos\theta$$

$$\frac{d\sigma}{dQ'^2 dt\, d(\cos\theta)\, d\phi} \sim \frac{f_\pi^2}{Q'^8}\left\{a_{\rm tw.2}\sin^2\theta + \frac{\Delta_\perp}{Q'}\left[\left(b_{\rm tw.2} + b_{\rm tw.3}\right)\sin 2\theta\cos\varphi + c_{\rm tw.3}\sin 2\theta\sin\varphi\right]\right\}$$

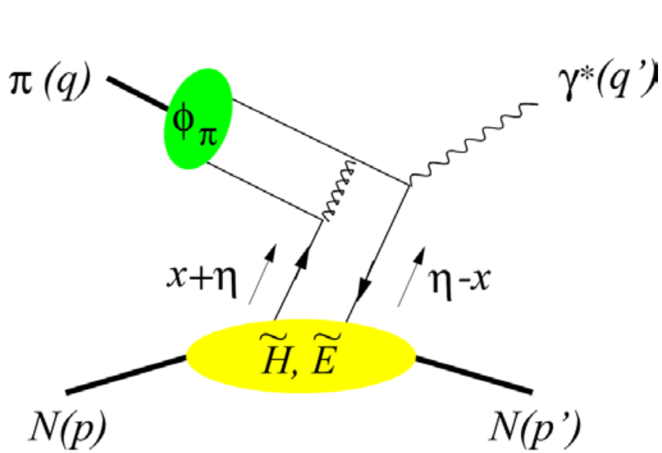
$$b_{\rm tw.2} \sim a_{\rm tw.2} \qquad b_{\rm tw.3}, c_{\rm tw.3} \propto \int_0^1 \frac{du}{u}$$

$$\langle 0|\bar{\psi}(0)\gamma^-\gamma_5\psi(y^+)|\pi(q)\rangle = if_\pi q^- \int_0^1 du\, e^{-iuq^-y^+}\,\phi_\pi(u)$$

$$\langle 0|\bar{\psi}(0)i\gamma_5\psi(y^+)|\pi^-(p)\rangle = \frac{f_\pi m_\pi^2}{m_u+m_d}\int_0^1 du\, e^{-iuq^-y^+}\,\phi_p(u)$$

$$\langle 0|\bar{u}(0)\sigma^{-+}\gamma_5 d(y^+)|\pi^-(p)\rangle = \frac{i}{3}\frac{f_\pi m_\pi^2}{m_u+m_d}q\cdot y\int_0^1 du\, e^{-iuq^-y^+}\,\phi_\sigma(u)$$

$$\phi_\pi(u) \sim u(1-u) \qquad \phi_p(u) \sim 1$$



$$\Delta = p' - p$$

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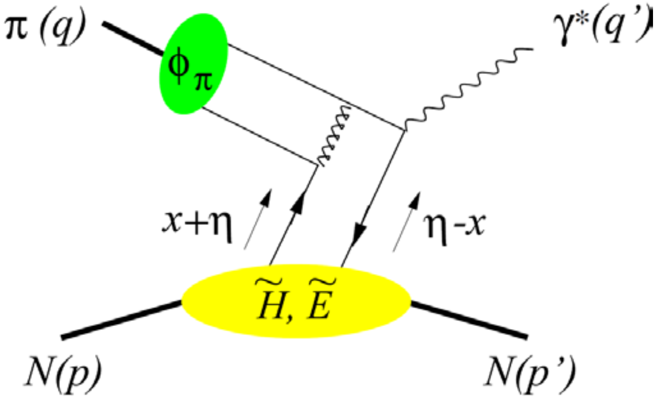
$$M^{0,\lambda;\lambda'}(\pi^-p\to\gamma^*n) \sim \frac{1}{Q'}\frac{1}{u(1-u)(\eta\pm x+i\varepsilon)}\otimes\phi_\pi(u)\otimes\left\{\tilde{H}^q(x,\eta,t),\tilde{E}^q(x,\eta,t)\right\} \qquad \sin\theta$$

$$M^{\pm1,\lambda;\lambda'}(\pi^-p\to\gamma^*n) \sim \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)(\eta\pm x+i\varepsilon)}\otimes\phi_\pi(u)\otimes\left\{\tilde{H}^q(x,\eta,t),\tilde{E}^q(x,\eta,t)\right\}$$
$$+\frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)(\eta\pm x+i\varepsilon)^2}\otimes\phi_p(u)\otimes\left\{H_T^q(x,\eta,t),\tilde{H}_T^q(x,\eta,t),E_T^q(x,\eta,t),\tilde{E}_T^q(x,\eta,t)\right\} \qquad e^{\pm i\varphi}\cos\theta$$

$$\frac{d\sigma}{dQ'^2dtd(\cos\theta)d\phi} \sim \frac{f_\pi^2}{Q'^8}\left\{a_{\text{tw.2}}\sin^2\theta + \frac{\Delta_\perp}{Q'}\left[(b_{\text{tw.2}}+b_{\text{tw.3}})\sin 2\theta\cos\varphi + c_{\text{tw.3}}\sin 2\theta\sin\varphi\right]\right\}$$

$$b_{\text{tw.2}} \sim a_{\text{tw.2}} \qquad b_{\text{tw.3}}, c_{\text{tw.3}} \propto \int_0^1 \frac{du}{u}$$



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

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

long. photon

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

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

$$\tilde{\mathcal{H}}^{du}(\eta,t) = \frac{8\alpha_S}{3}\int_0^1 du\,\frac{\phi_\pi(u)}{4u(1-u)}\int_{-1}^1 dx\left[\frac{e_d}{-\eta-x-i\epsilon} - \frac{e_u}{-\eta+x-i\epsilon}\right]\left[\tilde{H}^d(x,\eta,t) - \tilde{H}^u(x,\eta,t)\right]$$

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

$$M^{\pm1,\lambda;\lambda'}(\pi^- p \to \gamma^* n) \sim \frac{1}{Q'^2}$$

$\frac{1}{Q'}$ **correction to** $\frac{d\sigma}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi}$

angular distribution:

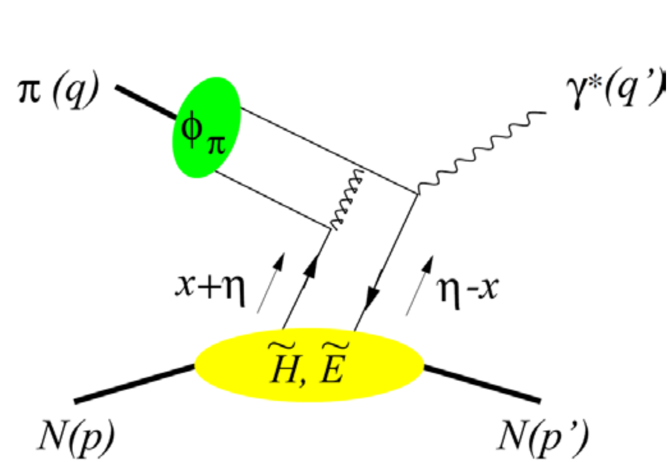
$$\sin 2\theta \cos\varphi$$

$$\langle 0|\bar{\psi}(0)\gamma^-\gamma_5\psi(y^+)|\pi(q)\rangle = i f_\pi q^- \int_0^1 du\, e^{-iuq^-y^+}\,\phi_\pi(u)$$

$$\langle 0|\bar{\psi}(0)i\gamma_5\psi(y^+)|\pi^-(p)\rangle = \frac{f_\pi m_\pi^2}{m_u+m_d}\int_0^1 du\, e^{-iuq^-y^+}\,\phi_p(u)$$

$$\langle 0|\bar{u}(0)\sigma^{-+}\gamma_5 d(y^+)|\pi^-(p)\rangle = \frac{i}{3}\frac{f_\pi m_\pi^2}{m_u+m_d}\,q\cdot y\int_0^1 du\, e^{-iuq^-y^+}\,\phi_\sigma(u)$$

$$\phi_\pi(u) \sim u(1-u) \qquad \phi_p(u) \sim 1$$



$$\Delta = p' - p$$

$$\langle p'|\bar{\psi}(0)\gamma^+\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+z^-}\,\bar{u}(p')\left[\tilde{H}^q(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^q(x,\eta,t)\frac{\gamma_5\Delta^+}{2M}\right]u(p)$$

$$\langle p'|\bar{\psi}(0)\sigma^{+\perp}\gamma_5\psi(z^-)|p\rangle = \int_{-1}^1 dx e^{-i(x+\eta)\bar{P}^+z^-}\,\bar{u}(p')\left[H_T^q(x,\eta,t)\sigma^{+\perp}\gamma_5 + \tilde{H}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\bar{P}}}{M^2} + E_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\Delta\alpha}\gamma_\alpha}{2M} + \tilde{E}_T^q(x,\eta,t)\frac{\varepsilon^{+\perp\bar{P}\alpha}\gamma_\alpha}{M}\right]u(p)$$

$$M^{0,\lambda;\lambda'}(\pi^- p \to \gamma^* n) \sim \frac{1}{Q'}\frac{1}{u(1-u)(\eta \pm x + i\varepsilon)} \otimes \phi_\pi(u) \otimes \left\{\tilde{H}^q(x,\eta,t), \tilde{E}^q(x,\eta,t)\right\}$$

$$\sin\theta$$

$$M^{\pm 1,\lambda;\lambda'}(\pi^- p \to \gamma^* n) \sim \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)(\eta \pm x + i\varepsilon)} \otimes \phi_\pi(u) \otimes \left\{\tilde{H}^q(x,\eta,t), \tilde{E}^q(x,\eta,t)\right\}$$
$$+ \frac{\Delta_\perp}{Q'^2}\frac{1}{u(1-u)(\eta \pm x + i\varepsilon)^2} \otimes \phi_p(u) \otimes \left\{H_T^q(x,\eta,t), \tilde{H}_T^q(x,\eta,t), E_T^q(x,\eta,t), \tilde{E}_T^q(x,\eta,t)\right\}$$

$$e^{\pm i\varphi}\cos\theta$$

$$\frac{d\sigma}{dQ'^2\,dt\,d(\cos\theta)\,d\phi} \sim \frac{f_\pi^2}{Q'^8}\left\{a_{\text{tw.2}}\sin^2\theta + \frac{\Delta_\perp}{Q'}\left[\left(b_{\text{tw.2}} + b_{\text{tw.3}}\right)\sin 2\theta\cos\varphi + c_{\text{tw.3}}\sin 2\theta\sin\varphi\right]\right\}$$

$$b_{\text{tw.2}} \sim a_{\text{tw.2}} \qquad b_{\text{tw.3}}, c_{\text{tw.3}} \propto \int_0^1 \frac{du}{u}$$

nonfactorizable mechanism??