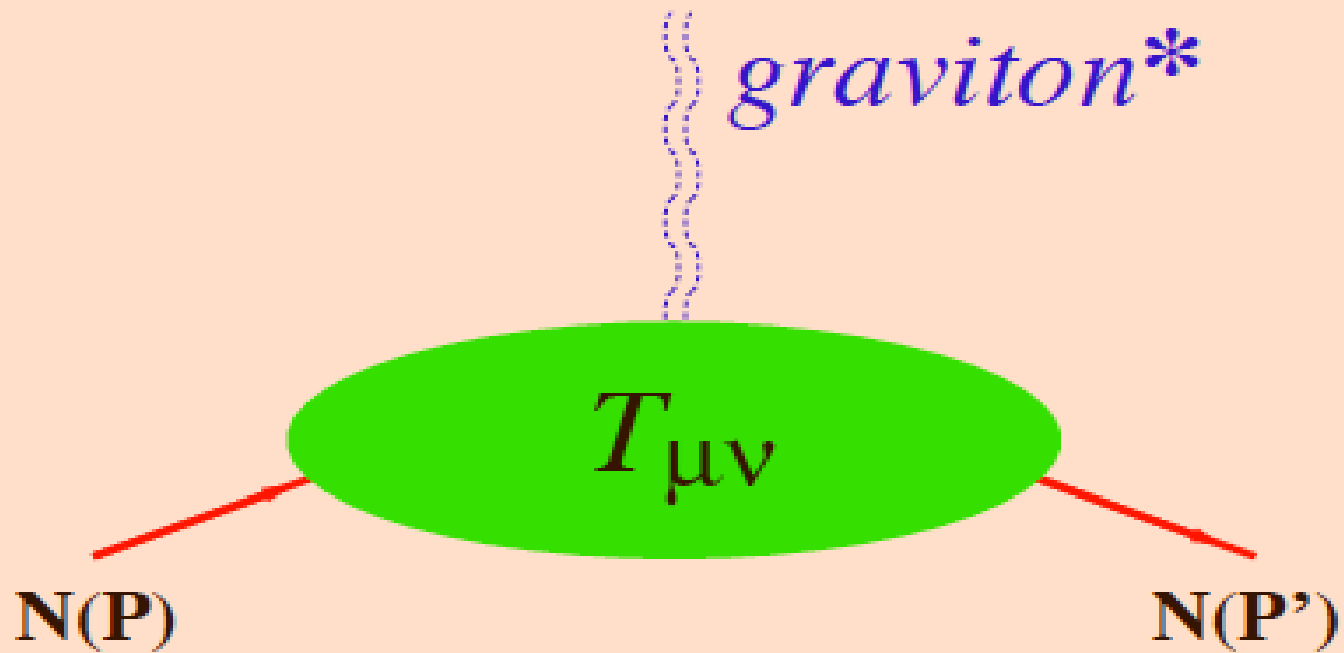


Generalized parton distribution function studies at J-PARC

Kazuhiro Tanaka (Juntendo U/KEK)



$$T^{\mu\nu} = \frac{1}{2} \bar{q} \gamma^{(\mu} i \vec{D}^{\nu)} q + F^{\mu\rho} F_{\rho}{}^{\nu} + \frac{g^{\mu\nu}}{4} F^2$$

$$\equiv T_q^{\mu\nu} + T_g^{\mu\nu}$$

$$T^{\mu\nu} = \frac{1}{2} \bar{q} \gamma^{(\mu} i \vec{D}^{\nu)} q + F^{\mu\rho} F_{\rho}^{\nu} + \frac{g^{\mu\nu}}{4} F^2$$

$$\begin{aligned} \langle p' | T_{q,g}^{\mu\nu} | p \rangle = & \bar{u}(p') \Big[A_{q,g}(t) \gamma^{(\mu} P^{\nu)} + B_{q,g}(t) \frac{P^{(\mu} i \sigma^{\nu)\alpha} \Delta_{\alpha}}{2m_N} \\ & + D_{q,g}(t) \frac{\Delta^{\mu} \Delta^{\nu} - g^{\mu\nu} \Delta^2}{m_N} + \bar{C}_{q,g}(t) m_N g^{\mu\nu} \Big] u(p) \end{aligned}$$

$$P = \frac{p + p'}{2}$$

$$\Delta = p' - p$$

$$t = \Delta^2$$

$$\bar{C}_q(t) + \bar{C}_g(t) = 0$$

$$\partial_{\mu} T^{\mu\nu} = 0$$

$$A_q\left(0\right)+A_g\left(0\right)=1$$

$$\langle p | T^{\mu\nu} | p \rangle = 2 p^{\mu} p^{\nu}$$

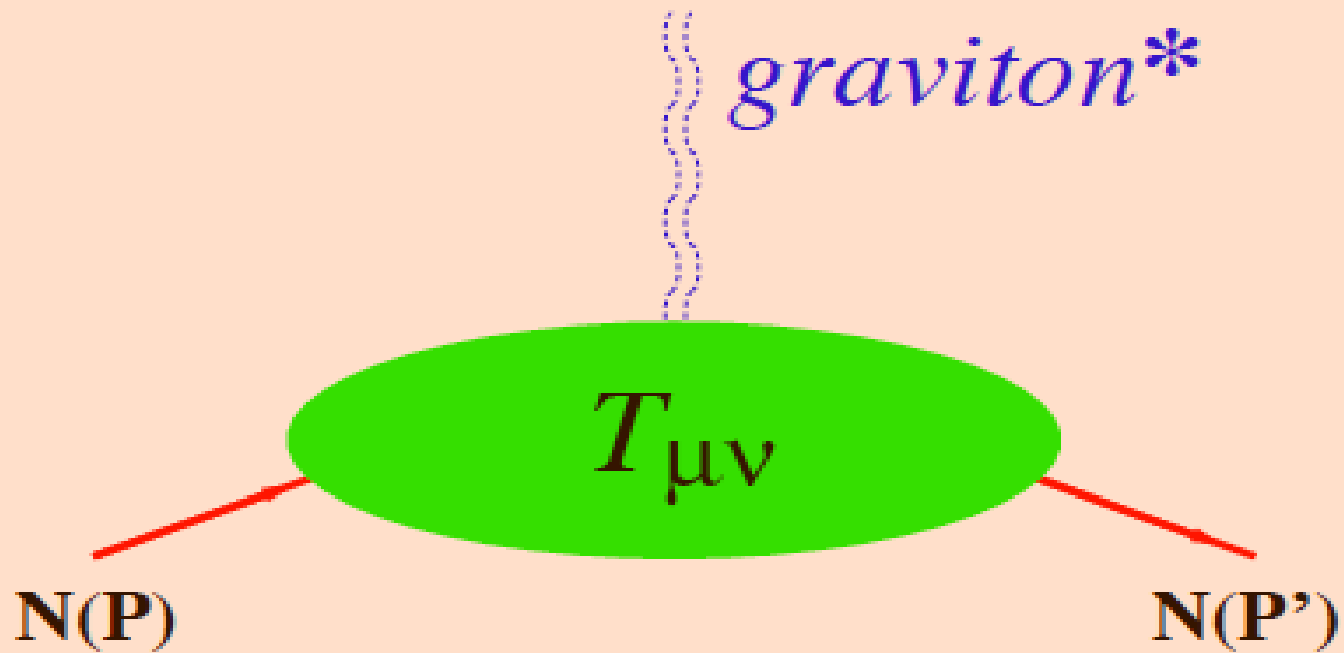
$$\frac{1}{2}\Big(A_q(0)+B_q(0)+A_g(0)+B_g(0)\Big)=\frac{1}{2}$$

$$\frac{\langle pS | J^i | pS \rangle}{\langle pS | pS \rangle} = \frac{1}{2} S^i$$

$$B_q\left(0\right)+B_g\left(0\right)=0$$

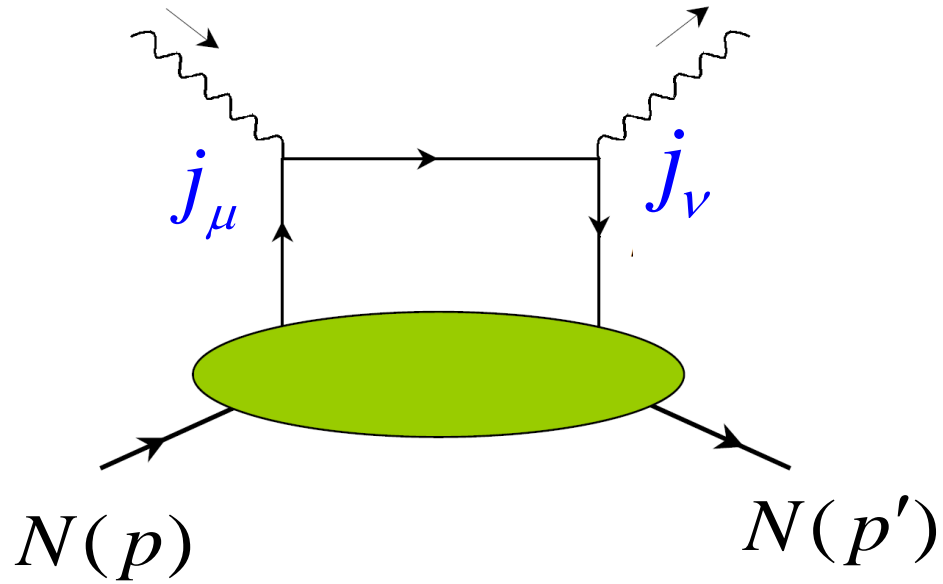
$$J^i = \frac{1}{2} \epsilon^{ijk} \int d^3x M^{+jk}$$

$$M^{\mu\rho\sigma} = x^{\rho} T^{\mu\sigma} - x^{\sigma} T^{\mu\rho}$$



$$T^{\mu\nu} = \frac{1}{2} \bar{q} \gamma^{(\mu} i \vec{D}^{\nu)} q + F^{\mu\rho} F_{\rho}{}^{\nu} + \frac{g^{\mu\nu}}{4} F^2$$

$$\equiv T_q^{\mu\nu} + T_g^{\mu\nu}$$



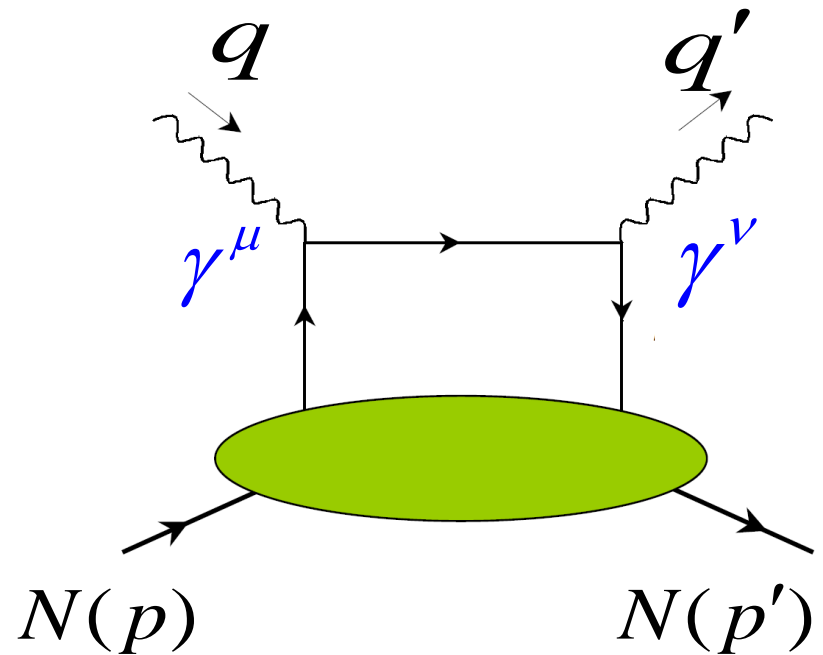
$$j_{\mu}(x) j_{\nu}(0) \sim \sum_i C_i(x) O_i(0)$$

$$C_{\mu\nu;\alpha\beta}^q(x) T_q^{\alpha\beta}$$

$$C_{\mu\nu;\alpha\beta}^g(x) T_g^{\alpha\beta}$$

DVCS

$$\int d^4x e^{iq' \cdot x} \langle p' | T j_\mu^{\text{em}}(0) j_\nu^{\text{em}}(x) | p \rangle$$



$$\bar{P} = \frac{p + p'}{2}, \quad \bar{q} = \frac{q + q'}{2}, \quad \Delta = p' - p = q - q',$$

$$t = \Delta^2, \quad \xi = \frac{-\bar{q}^2}{2\bar{P} \cdot \bar{q}}, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} = \frac{-\Delta \cdot \bar{q}}{2\bar{P} \cdot \bar{q}} + O(\text{twist-4}),$$

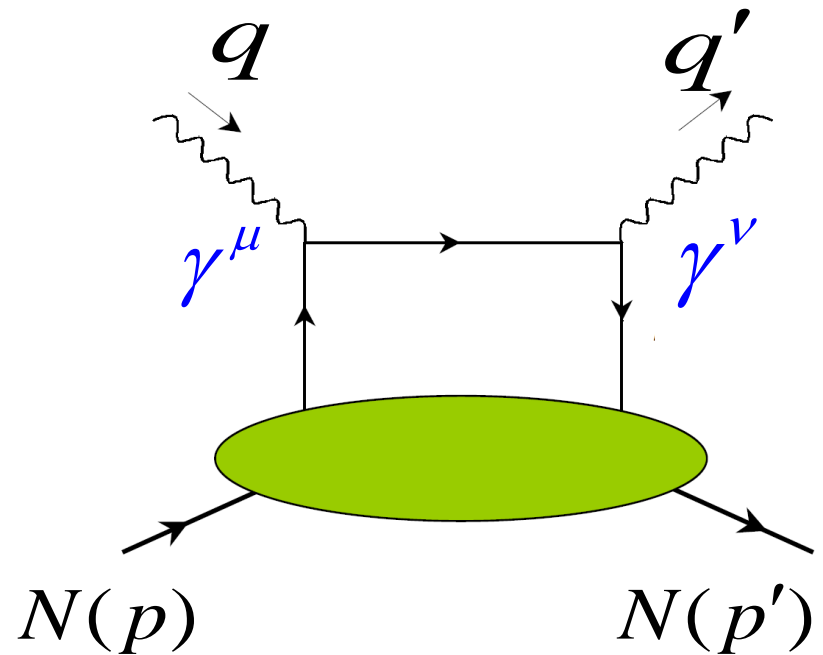
$$n_\mu = -\frac{2\xi}{\bar{q}^2} (\bar{q}_\mu + \xi \bar{P}_\mu), \quad \tilde{n}_\mu = \bar{P}_\mu, \quad (n^2 = \tilde{n}^2 = 0, \quad n \cdot \tilde{n} = 1)$$

generalized Bjorken kinematics:

$$|\bar{q}^2| \rightarrow \infty, \quad |\bar{P} \cdot \bar{q}| \rightarrow \infty, \quad |\Delta \cdot \bar{q}| \rightarrow \infty, \quad \Delta^2 = \text{finite} \quad (\xi \text{ and } \eta \text{ fixed})$$

DVCS

$$\int d^4x e^{iq' \cdot x} \langle p' | T j_\mu^{\text{em}}(0) j_\nu^{\text{em}}(x) | p \rangle$$



$$\bar{P} = \frac{p + p'}{2}, \quad \bar{q} = \frac{q + q'}{2}, \quad \Delta = p' - p = q - q',$$

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$$n_\mu = -\frac{2\xi}{\bar{q}^2}(\bar{q}_\mu + \xi \bar{P}_\mu), \quad \tilde{n}_\mu = \bar{P}_\mu, \quad (n^2 = \tilde{n}^2 = 0, \quad n \cdot \tilde{n} = 1)$$

generalized Bjorken kinematics: **light-cone expansion**

$$|\bar{q}^2| \rightarrow \infty, \quad |\bar{P} \cdot \bar{q}| \rightarrow \infty, \quad |\Delta \cdot \bar{q}| \rightarrow \infty, \quad \Delta^2 = \text{finite} \quad (\xi \text{ and } \eta \text{ fixed})$$

$$\begin{aligned}
& \int d^4x e^{iq' \cdot x} \langle p' | \mathbf{T} j_\mu^{\text{em}}(0) j_\nu^{\text{em}}(x) | p \rangle \\
&= \mathcal{T}_{\mu\nu}^{(1)} \frac{ie_q^2}{\bar{q}^2} \int dx \left(\frac{i}{1 - \frac{x}{\xi} + i\epsilon \bar{q}^2} - \frac{i}{1 + \frac{x}{\xi} + i\epsilon \bar{q}^2} \right) \int \frac{dz^-}{2\pi} e^{ix\bar{P}^+ z^-} \langle N(p') \left| \bar{q}(-\frac{z}{2}) \gamma^+ q(\frac{z}{2}) \right| N(p) \rangle \Big|_{z^+ = \bar{z}_\perp = 0} \\
&+ \mathcal{T}_{\mu\nu}^{(2)} \frac{ie_q^2}{\bar{q}^2} \int dx \left(\frac{i}{1 - \frac{x}{\xi} + i\epsilon \bar{q}^2} + \frac{i}{1 + \frac{x}{\xi} + i\epsilon \bar{q}^2} \right) \int \frac{dz^-}{2\pi} e^{ix\bar{P}^+ z^-} \langle N(p') \left| \bar{q}(-\frac{z}{2}) \gamma^+ \gamma_5 q(\frac{z}{2}) \right| N(p) \rangle \Big|_{z^+ = \bar{z}_\perp = 0} \\
&+ O(\text{twist-3})
\end{aligned}$$

$$\mathcal{T}_{\mu\nu}^{(1)} = \tilde{n}_\mu (\bar{q}_\nu + \xi \tilde{n}_\nu) + \tilde{n}_\nu (\bar{q}_\mu + \xi \tilde{n}_\mu) - g_{\mu\nu} \bar{q} \cdot \tilde{n} = \frac{\bar{q}^2}{2\xi} \left(g_{\mu\nu} - \frac{q'_\mu q_\nu}{q \cdot q'} \right) + 2\xi \left(\bar{P}_\mu - \frac{\bar{P} \cdot q}{q \cdot q'} q'_\mu \right) \left(\bar{P}_\nu - \frac{\bar{P} \cdot q'}{q \cdot q'} q_\nu \right)$$

$$\mathcal{T}_{\mu\nu}^{(2)} = i\varepsilon_{\mu\alpha\nu\rho} \bar{q}^\alpha \tilde{n}^\rho = i\varepsilon^{\lambda\beta\rho\sigma} \bar{P}_\rho \bar{q}_\sigma \left(g_{\mu\lambda} - \frac{\bar{P}_\mu q_\lambda}{\bar{P} \cdot q} \right) \left(g_{\nu\beta} - \frac{\bar{P}_\nu q'_\beta}{\bar{P} \cdot q'} \right)$$

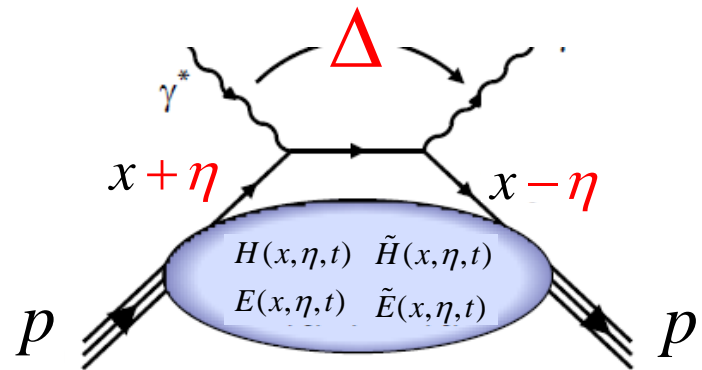
$$q^\mu \mathcal{T}_{\mu\nu}^{(1)} = q'^\nu \mathcal{T}_{\mu\nu}^{(1)} = q^\mu \mathcal{T}_{\mu\nu}^{(2)} = q'^\nu \mathcal{T}_{\mu\nu}^{(2)} = 0,$$

$$\bar{P} = \frac{p + p'}{2}$$

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

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

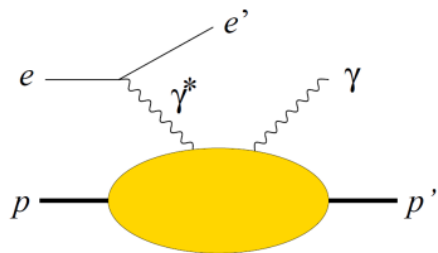
GPD



$$-2\eta\bar{P} = \Delta$$

$$\int d\mathbf{z}^- e^{i(\mathbf{x} + \boldsymbol{\eta}) \cdot \mathbf{p} \mathbf{z}^-} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$

$$\bar{P} = \frac{p + p'}{2}$$

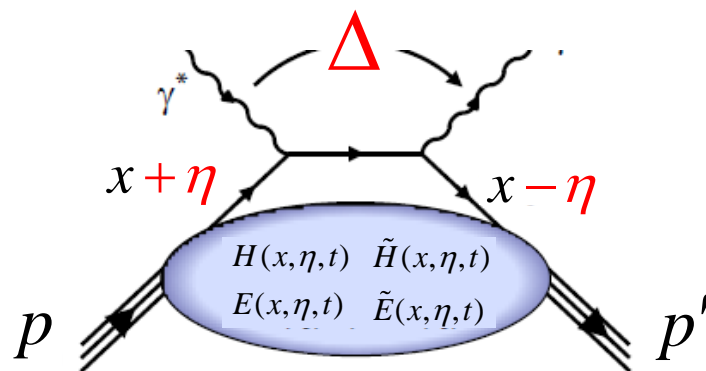


JLab, HERMES, COMPASS, ...

$$\int \frac{d\mathbf{z}^-}{2\pi} e^{i\mathbf{x}\bar{P}\mathbf{z}} \langle p' | \bar{q}(-\frac{\mathbf{z}^-}{2}) \gamma^+ q(\frac{\mathbf{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[H^q(x, \eta, t) \bar{u}(p') \gamma^+ u(p) + E^q(x, \eta, t) \bar{u}(p') \frac{i\sigma^{+\alpha} (p' - p)_\alpha}{2M} u(p) \right]$$

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

GPD

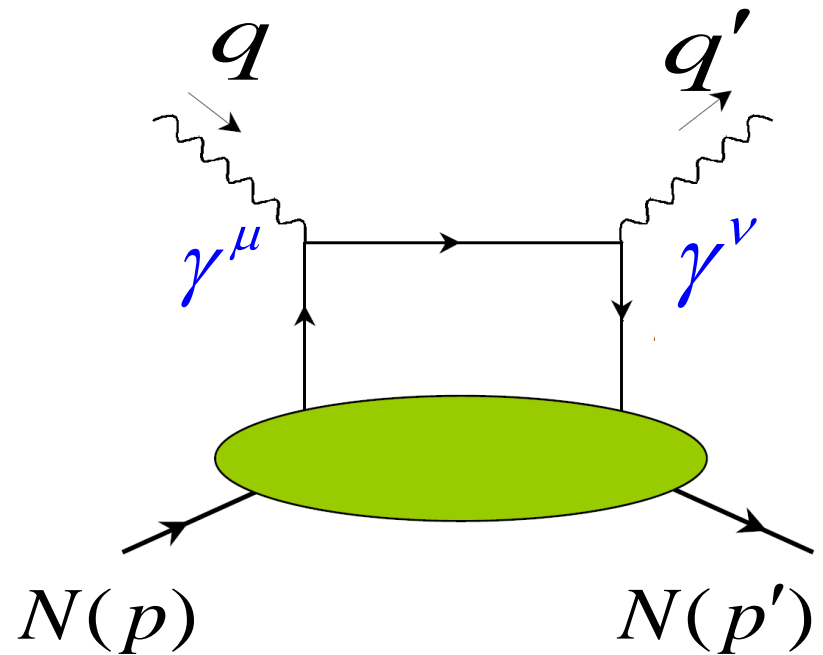


$$-2\eta\bar{P} = \Delta$$

$$\int d\mathbf{z}^- e^{i(\mathbf{x}+\eta)\mathbf{p}\mathbf{z}} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$

DVCS

$$\int d^4x e^{iq' \cdot x} \langle p' | T j_\mu^{\text{em}}(0) j_\nu^{\text{em}}(x) | p \rangle$$



$$\bar{P} = \frac{p + p'}{2}, \quad \bar{q} = \frac{q + q'}{2}, \quad \Delta = p' - p = q - q',$$

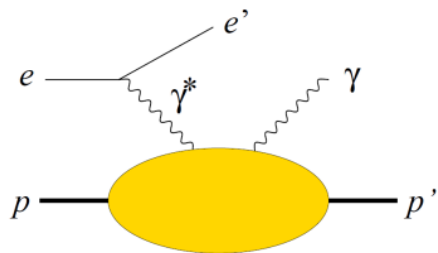
$$t = \Delta^2, \quad \xi = \frac{-\bar{q}^2}{2\bar{P} \cdot \bar{q}}, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} = \frac{-\Delta \cdot \bar{q}}{2\bar{P} \cdot \bar{q}} + O(\text{twist-4}),$$

$$n_\mu = -\frac{2\xi}{\bar{q}^2}(\bar{q}_\mu + \xi \bar{P}_\mu), \quad \tilde{n}_\mu = \bar{P}_\mu, \quad (n^2 = \tilde{n}^2 = 0, \quad n \cdot \tilde{n} = 1)$$

generalized Bjorken kinematics: **light-cone expansion**

$$|\bar{q}^2| \rightarrow \infty, \quad |\bar{P} \cdot \bar{q}| \rightarrow \infty, \quad |\Delta \cdot \bar{q}| \rightarrow \infty, \quad \Delta^2 = \text{finite} \quad (\xi \text{ and } \eta \text{ fixed})$$

$$\bar{P} = \frac{p + p'}{2}$$

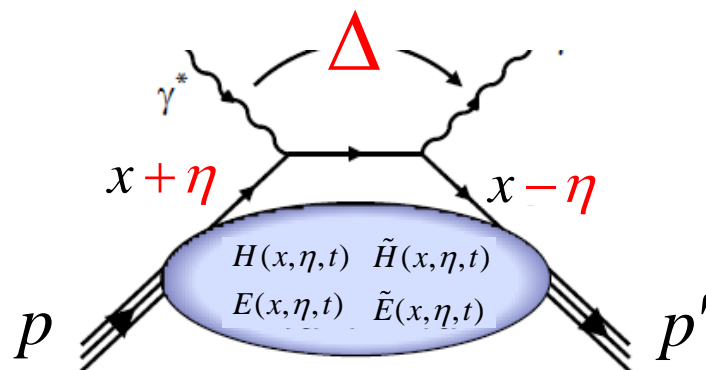


JLab, HERMES, COMPASS, ...

$$\int \frac{d\mathbf{z}^-}{2\pi} e^{i\mathbf{x}\bar{P}\mathbf{z}} \langle p' | \bar{q}(-\frac{\mathbf{z}^-}{2}) \gamma^+ q(\frac{\mathbf{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[H^q(x, \eta, t) \bar{u}(p') \gamma^+ u(p) + E^q(x, \eta, t) \bar{u}(p') \frac{i\sigma^{+\alpha} (p' - p)_\alpha}{2M} u(p) \right]$$

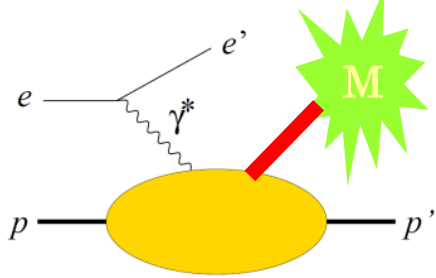
$$\int \frac{d\mathbf{z}^-}{2\pi} e^{i\mathbf{x}\bar{P}\mathbf{z}} \langle p' | \bar{q}(-\frac{\mathbf{z}^-}{2}) \gamma^+ \gamma_5 q(\frac{\mathbf{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[\tilde{H}^q(x, \eta, t) \bar{u}(p') \gamma^+ \gamma_5 u(p) + \tilde{E}^q(x, \eta, t) \bar{u}(p') \frac{\gamma_5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

GPD



$$-2\eta\bar{P} = \Delta$$

$$\int d\mathbf{z}^- e^{i(\mathbf{x}+\eta)\mathbf{p}\mathbf{z}} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$



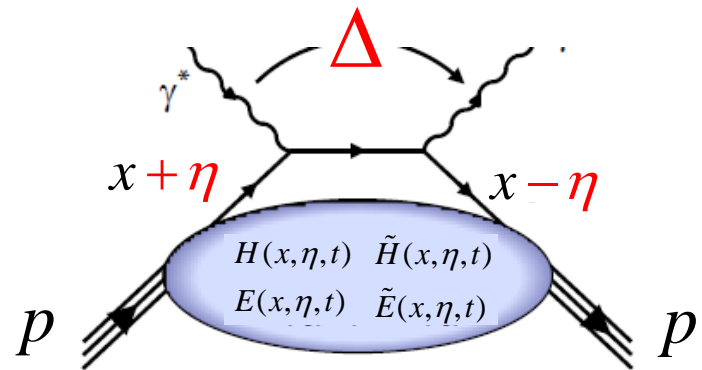
$$\bar{P} = \frac{p + p'}{2}$$

JLab, HERMES, COMPASS, ...

$$\int \frac{d\mathbf{z}^-}{2\pi} e^{i\mathbf{x}\bar{P}\mathbf{z}} \langle p' | \bar{q}(-\frac{\mathbf{z}^-}{2}) \gamma^+ q(\frac{\mathbf{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[H^q(x, \eta, t) \bar{u}(p') \gamma^+ u(p) + E^q(x, \eta, t) \bar{u}(p') \frac{i\sigma^{+\alpha} (p' - p)_\alpha}{2M} u(p) \right]$$

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

GPD



$$-2\eta\bar{P} = \Delta$$

$$\int d\mathbf{z}^- e^{i(\mathbf{x}+\eta)\mathbf{p}\mathbf{z}} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$

$$\int \frac{d\textcolor{red}{z}^-}{2\pi} e^{ix\bar{P}\textcolor{red}{z}} \langle p' | \bar{q}(-\frac{\textcolor{red}{z}^-}{2}) \gamma^+ q(\frac{\textcolor{red}{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[\textcolor{violet}{H}^q(x,\eta,t) \bar{u}(p') \gamma^+ u(p) + \textcolor{violet}{E}^q(x,\eta,t) \bar{u}(p') \frac{i\sigma^{+\alpha}(p'-p)_\alpha}{2M} u(p) \right]$$

$$\int \frac{d\textcolor{red}{z}^-}{2\pi} e^{ix\bar{P}\textcolor{red}{z}} \langle p' | \bar{q}(-\frac{\textcolor{red}{z}^-}{2}) \gamma^+ \textcolor{violet}{\gamma}_5 q(\frac{\textcolor{red}{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[\textcolor{violet}{\tilde{H}}^q(x,\eta,t) \bar{u}(p') \gamma^+ \gamma_5 u(p) + \textcolor{violet}{\tilde{E}}^q(x,\eta,t) \bar{u}(p') \frac{\gamma_5(p'-p)^+}{2M} u(p) \right]$$

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right)$$

$$H^q(x,0,0) = q(x) \, , \qquad \tilde{H}^q(x,0,0) = \Delta q(x).$$

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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right) \quad H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).$$

$$\int_{-1}^1 dx H^q(x, \eta, t) = F_1^q(t), \quad \int_{-1}^1 dx E^q(x, \eta, t) = F_2^q(t),$$

$$\int_{-1}^1 dx \tilde{H}^q(x, \eta, t) = g_A^q(t), \quad \int_{-1}^1 dx \tilde{E}^q(x, \eta, t) = g_P^q(t)$$

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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right) \quad H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).$$

$$\int_{-1}^1 dx H^q(x, \eta, t) = F_1^q(t), \quad \int_{-1}^1 dx E^q(x, \eta, t) = F_2^q(t),$$

$$\int_{-1}^1 dx \tilde{H}^q(x, \eta, t) = g_A^q(t), \quad \int_{-1}^1 dx \tilde{E}^q(x, \eta, t) = g_P^q(t)$$

$$\int_{-1}^1 dx x H^q(x, \eta, t) = \cdots, \quad \int_{-1}^1 dx x E^q(x, \eta, t) = \cdots$$

$$\int \frac{d\textcolor{red}{z}^-}{2\pi} e^{i\textcolor{violet}{x}\bar{P}\textcolor{red}{z}} \langle p' | \bar{q}(-\frac{\textcolor{red}{z}^-}{2}) \gamma^+ q(\frac{\textcolor{red}{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[\textcolor{violet}{H}^q(x,\eta,t) \bar{u}(p') \gamma^+ u(p) + \textcolor{violet}{E}^q(x,\eta,t) \bar{u}(p') \frac{i\sigma^{+\alpha}(p'-p)_\alpha}{2M} u(p) \right]$$

$$\begin{aligned} \frac{1}{2P^+} \left\langle p' \left| \bar{q}(0) \gamma^+ i\vec{D}^+ q(0) \right| p \right\rangle &= \bar{u}(p') \gamma^+ u(p) \int_{-1}^1 dx x H^q(x,\xi,t) + \bar{u}(p') \frac{i\sigma^{+\alpha} \Delta_\alpha}{2m_N} u(p) \int_{-1}^1 dx x E^q(x,\xi,t) \\ &= \frac{1}{P^+} \left\langle p' \left| T_q^{++}(0) \right| p \right\rangle \end{aligned}$$

$$T^{\mu\nu} = \frac{1}{2} \bar{q} \gamma^{(\mu} i \vec{D}^{\nu)} q + F^{\mu\rho} F_{\rho}^{\nu} + \frac{g^{\mu\nu}}{4} F^2$$

$$\begin{aligned} \langle p' | T_{q,g}^{\mu\nu} | p \rangle = & \bar{u}(p') \Big[A_{q,g}(t) \gamma^{(\mu} P^{\nu)} + B_{q,g}(t) \frac{P^{(\mu} i \sigma^{\nu)\alpha} \Delta_{\alpha}}{2m_N} \\ & + D_{q,g}(t) \frac{\Delta^{\mu} \Delta^{\nu} - g^{\mu\nu} \Delta^2}{m_N} + \bar{C}_{q,g}(t) m_N g^{\mu\nu} \Big] u(p) \end{aligned}$$

$$\begin{aligned} P &= \frac{p+p'}{2} \\ \Delta &= p'-p \\ t &= \Delta^2 \end{aligned}$$

$$\bar{C}_q(t)+\bar{C}_g(t)=0$$

$$\partial_{\mu}T^{\mu\nu}=0$$

$$A_q\left(0\right)+A_g\left(0\right)=1$$

$$\langle p|T^{\mu\nu}|p\rangle=2p^{\mu}p^{\nu}$$

$$\frac{1}{2}\Big(A_q(0)+B_q(0)+A_g(0)+B_g(0)\Big)=\frac{1}{2}$$

$$B_q(0)+B_g(0)=0$$

$$\frac{\langle pS|J^i|pS\rangle}{\langle pS|pS\rangle}=\frac{1}{2}S^i$$

$$J^i=\frac{1}{2}\epsilon^{ijk}\int d^3xM^{+jk}$$

$$M^{\mu\rho\sigma}=x^{\rho}T^{\mu\sigma}-x^{\sigma}T^{\mu\rho}$$

$$\int \frac{d\textcolor{red}{z}^-}{2\pi} e^{i\textcolor{violet}{x}\bar{P}\textcolor{red}{z}} \langle p' | \bar{q}(-\frac{\textcolor{red}{z}^-}{2}) \gamma^+ q(\frac{\textcolor{red}{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[\textcolor{violet}{H}^q(x,\eta,t) \bar{u}(p') \gamma^+ u(p) + \textcolor{violet}{E}^q(x,\eta,t) \bar{u}(p') \frac{i\sigma^{+\alpha}(p'-p)_\alpha}{2M} u(p) \right]$$

$$\begin{aligned} \frac{1}{2P^+} \left\langle p' \left| \bar{q}(0) \gamma^+ i\vec{D}^+ q(0) \right| p \right\rangle &= \bar{u}(p') \gamma^+ u(p) \int_{-1}^1 dx x H^q(x,\xi,t) + \bar{u}(p') \frac{i\sigma^{+\alpha} \Delta_\alpha}{2m_N} u(p) \int_{-1}^1 dx x E^q(x,\xi,t) \\ &= \frac{1}{P^+} \left\langle p' \left| T_q^{++}(0) \right| p \right\rangle \end{aligned}$$

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

$$\begin{aligned} \frac{1}{2P^+} \left\langle p' \left| \bar{q}(0) \gamma^+ i\tilde{D}^+ q(0) \right| p \right\rangle &= \bar{u}(p') \gamma^+ u(p) \int_{-1}^1 dx x H^q(x, \xi, t) + \bar{u}(p') \frac{i\sigma^{+\alpha} \Delta_\alpha}{2m_N} u(p) \int_{-1}^1 dx x E^q(x, \xi, t) \\ &= \frac{1}{P^+} \left\langle p' \left| T_q^{++}(0) \right| p \right\rangle = \bar{u}(p') \gamma^+ u(p) \left(A_q(t) + 4\xi^2 D_q(t) \right) + \bar{u}(p') \frac{i\sigma^{+\alpha} \Delta_\alpha}{2m_N} u(p) \left(B_q(t) - 4\xi^2 D_q(t) \right) \end{aligned}$$

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

$$\begin{aligned} \frac{1}{2P^+} \langle p' | \bar{q}(0) \gamma^+ i\tilde{D}^+ q(0) | p \rangle &= \bar{u}(p') \gamma^+ u(p) \int_{-1}^1 dx x H^q(x, \xi, t) + \bar{u}(p') \frac{i\sigma^{+\alpha} \Delta_\alpha}{2m_N} u(p) \int_{-1}^1 dx x E^q(x, \xi, t) \\ &= \frac{1}{P^+} \langle p' | T_q^{++}(0) | p \rangle = \bar{u}(p') \gamma^+ u(p) \left(A_q(t) + 4\xi^2 D_q(t) \right) + \bar{u}(p') \frac{i\sigma^{+\alpha} \Delta_\alpha}{2m_N} u(p) \left(B_q(t) - 4\xi^2 D_q(t) \right) \end{aligned}$$

$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t), \quad \int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right)$$

$$H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).$$

$$\int_{-1}^1 dx H^q(x, \eta, t) = F_1^q(t), \quad \int_{-1}^1 dx E^q(x, \eta, t) = F_2^q(t),$$

$$\int_{-1}^1 dx \tilde{H}^q(x, \eta, t) = g_A^q(t), \quad \int_{-1}^1 dx \tilde{E}^q(x, \eta, t) = g_P^q(t)$$

$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t), \quad \int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right) \quad H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).$$

$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t), \quad \int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

$$\int \frac{d\textcolor{red}{z}^-}{2\pi} e^{ix\bar{P}\textcolor{red}{z}} \langle p' | \bar{q}(-\frac{\textcolor{red}{z}^-}{2}) \gamma^+ q(\frac{\textcolor{red}{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[\textcolor{violet}{H}^q(x,\eta,t) \bar{u}(p') \gamma^+ u(p) + \textcolor{violet}{E}^q(x,\eta,t) \bar{u}(p') \frac{i\sigma^{+\alpha}(p'-p)_\alpha}{2M} u(p) \right]$$

$$\int \frac{d\textcolor{red}{z}^-}{2\pi} e^{ix\bar{P}\textcolor{red}{z}} \langle p' | \bar{q}(-\frac{\textcolor{red}{z}^-}{2}) \gamma^+ \textcolor{violet}{\gamma}_5 q(\frac{\textcolor{red}{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[\textcolor{violet}{\tilde{H}}^q(x,\eta,t) \bar{u}(p') \gamma^+ \gamma_5 u(p) + \textcolor{violet}{\tilde{E}}^q(x,\eta,t) \bar{u}(p') \frac{\gamma_5(p'-p)^+}{2M} u(p) \right]$$

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$\left(\textcolor{blue}{t} = \Delta^2 \rightarrow 0, \quad \textcolor{blue}{\eta} = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right) \qquad H^q(x,0,0) = q(x) \, , \qquad \tilde{H}^q(x,0,0) = \Delta q(x).$$

$$\int_{-1}^1 dx x H^q(x,\eta,t) = A_q(t) + 4\eta^2 D_q(t) \, , \qquad \int_{-1}^1 dx x E^q(x,\eta,t) = B_q(t) - 4\eta^2 D_q(t)$$

$$\textcolor{red}{\int_{-1}^1 dx x q(x) = A_q(0)}$$

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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right) \quad H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).$$

$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t), \quad \int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

$$\int_{-1}^1 dx x q(x) = A_q(0)$$

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

$$T^{\mu\nu} = \frac{1}{2} \bar{q} \gamma^{(\mu} i \vec{D}^{\nu)} q + F^{\mu\rho} F_{\rho}^{\nu} + \frac{g^{\mu\nu}}{4} F^2$$

$$\begin{aligned} \langle p' | T_{q,g}^{\mu\nu} | p \rangle = & \bar{u}(p') \Big[A_{q,g}(t) \gamma^{(\mu} P^{\nu)} + B_{q,g}(t) \frac{P^{(\mu} i \sigma^{\nu)\alpha} \Delta_{\alpha}}{2m_N} \\ & + D_{q,g}(t) \frac{\Delta^{\mu} \Delta^{\nu} - g^{\mu\nu} \Delta^2}{m_N} + \bar{C}_{q,g}(t) m_N g^{\mu\nu} \Big] u(p) \end{aligned}$$

$$P = \frac{p + p'}{2}$$

$$\Delta = p' - p$$

$$t = \Delta^2$$

$$\bar{C}_q(t) + \bar{C}_g(t) = 0$$

$$\partial_{\mu} T^{\mu\nu} = 0$$

$$A_q\left(0\right)+A_g\left(0\right)=1$$

$$\langle p | T^{\mu\nu} | p \rangle = 2 p^{\mu} p^{\nu}$$

$$\frac{1}{2}\Big(A_q(0)+B_q(0)+A_g(0)+B_g(0)\Big)=\frac{1}{2}$$

$$B_q\left(0\right)+B_g\left(0\right)=0$$

$$\frac{\langle pS | J^i | pS \rangle}{\langle pS | pS \rangle} = \frac{1}{2} S^i$$

$$J^i = \frac{1}{2} \epsilon^{ijk} \int d^3x M^{+jk}$$

$$M^{\mu\rho\sigma} = x^{\rho} T^{\mu\sigma} - x^{\sigma} T^{\mu\rho}$$

$$T^{\mu\nu} = \frac{1}{2} \bar{q} \gamma^{(\mu} i \vec{D}^{\nu)} q + F^{\mu\rho} F_{\rho}^{\nu} + \frac{g^{\mu\nu}}{4} F^2$$

$$\begin{aligned} \langle p' | T_{q,g}^{\mu\nu} | p \rangle = & \bar{u}(p') \Big[A_{q,g}(t) \gamma^{(\mu} P^{\nu)} + B_{q,g}(t) \frac{P^{(\mu} i \sigma^{\nu)\alpha} \Delta_{\alpha}}{2m_N} \\ & + D_{q,g}(t) \frac{\Delta^{\mu} \Delta^{\nu} - g^{\mu\nu} \Delta^2}{m_N} + \bar{C}_{q,g}(t) m_N g^{\mu\nu} \Big] u(p) \end{aligned}$$

$$P = \frac{p + p'}{2}$$

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$$\bar{C}_q(t) + \bar{C}_g(t) = 0$$

$$\partial_{\mu} T^{\mu\nu} = 0$$

$$A_q(0) + A_g(0) = 1$$

$$\langle p | T^{\mu\nu} | p \rangle = 2 p^{\mu} p^{\nu}$$

$$\frac{1}{2} \Big(A_q(0) + B_q(0) + A_g(0) + B_g(0) \Big) = \frac{1}{2}$$

$$B_q(0) + B_g(0) = 0$$

$$\frac{\langle pS | J^i | pS \rangle}{\langle pS | pS \rangle} = \frac{1}{2} S^i$$

$$J^i = \frac{1}{2} \epsilon^{ijk} \int d^3x M^{+jk}$$

$$M^{\mu\rho\sigma} = x^{\rho} T^{\mu\sigma} - x^{\sigma} T^{\mu\rho}$$

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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right) \quad H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).$$

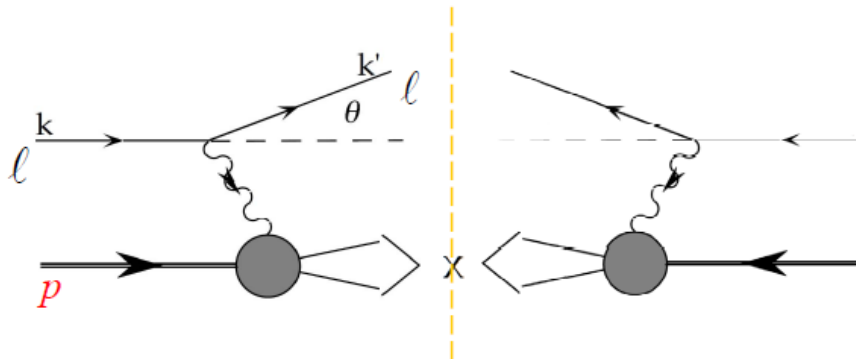
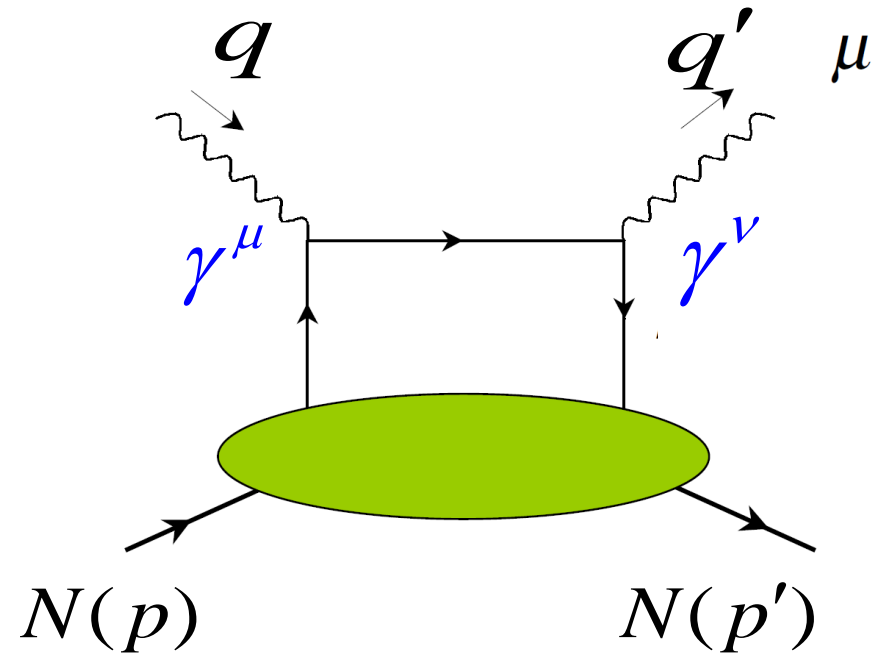
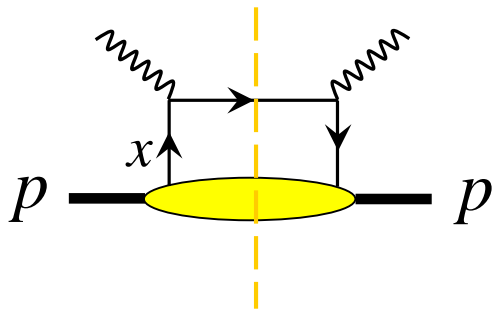
$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t), \quad \int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

$$\int_{-1}^1 dx x q(x) = A_q(0)$$

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$H^q(x, 0, 0) = q(x)$$



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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right) \quad H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).$$

$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t), \quad \int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

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$$T^{\mu\nu} = \frac{1}{2} \bar{q} \gamma^{(\mu} i \vec{D}^{\nu)} q + F^{\mu\rho} F_{\rho}{}^{\nu} + \frac{g^{\mu\nu}}{4} F^2$$

$$\begin{aligned} \langle p' | T_{q,g}^{\mu\nu} | p \rangle = & \bar{u}(p') \left[A_{q,g}(t) \gamma^{(\mu} P^{\nu)} + B_{q,g}(t) \frac{P^{(\mu} i \sigma^{\nu)\alpha} \Delta_{\alpha}}{2m_N} \right. \\ & \left. + D_{q,g}(t) \frac{\Delta^{\mu} \Delta^{\nu} - g^{\mu\nu} \Delta^2}{m_N} + \bar{C}_{q,g}(t) m_N g^{\mu\nu} \right] u(p) \end{aligned}$$

$$P = \frac{p + p'}{2}$$

$$\Delta = p' - p$$

$$t = \Delta^2$$

$$\bar{C}_q(t) + \bar{C}_g(t) = 0$$

$$\partial_{\mu} T^{\mu\nu} = 0$$

$$\boxed{A_q(0)} + A_g(0) = 1$$

$$\simeq 1/2$$

$$\frac{1}{2} \left(A_q(0) + B_q(0) + A_g(0) + B_g(0) \right) = \frac{1}{2}$$

$$B_q(0) + B_g(0) = 0$$

$$\langle p | T^{\mu\nu} | p \rangle = 2 p^{\mu} p^{\nu}$$

$$\frac{\langle pS | J^i | pS \rangle}{\langle pS | pS \rangle} = \frac{1}{2} S^i$$

$$J^i = \frac{1}{2} \epsilon^{ijk} \int d^3x M^{+jk}$$

$$M^{\mu\rho\sigma} = x^{\rho} T^{\mu\sigma} - x^{\sigma} T^{\mu\rho}$$

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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

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$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t), \quad \int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

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

$$T^{\mu\nu} = \frac{1}{2} \bar{q} \gamma^{(\mu} i \vec{D}^{\nu)} q + F^{\mu\rho} F_{\rho}{}^{\nu} + \frac{g^{\mu\nu}}{4} F^2$$

$$\begin{aligned} \langle p' | T_{q,g}^{\mu\nu} | p \rangle = & \bar{u}(p') \left[A_{q,g}(t) \gamma^{(\mu} P^{\nu)} + B_{q,g}(t) \frac{P^{(\mu} i \sigma^{\nu)\alpha} \Delta_{\alpha}}{2m_N} \right. \\ & \left. + D_{q,g}(t) \frac{\Delta^{\mu} \Delta^{\nu} - g^{\mu\nu} \Delta^2}{m_N} + \bar{C}_{q,g}(t) m_N g^{\mu\nu} \right] u(p) \end{aligned}$$

$$P = \frac{p + p'}{2}$$

$$\Delta = p' - p$$

$$t = \Delta^2$$

$$\bar{C}_q(t) + \bar{C}_g(t) = 0$$

$$\partial_{\mu} T^{\mu\nu} = 0$$

$$A_q(0) + A_g(0) = 1$$

$$\langle p | T^{\mu\nu} | p \rangle = 2 p^{\mu} p^{\nu}$$

$$\simeq 1/2$$

$$\frac{1}{2} (A_q(0) + B_q(0) - A_g(0) + B_g(0)) = \frac{1}{2}$$

$$\frac{\langle pS | J^i | pS \rangle}{\langle pS | pS \rangle} = \frac{1}{2} S^i$$

$$B_q(0) + B_g(0) = 0$$

$$J^i = \frac{1}{2} \epsilon^{ijk} \int d^3x M^{+jk}$$

$$M^{\mu\rho\sigma} = x^{\rho} T^{\mu\sigma} - x^{\sigma} T^{\mu\rho}$$

$$T^{\mu\nu} = \frac{1}{2} \bar{q} \gamma^{(\mu} i \vec{D}^{\nu)} q + F^{\mu\rho} F_{\rho}^{\nu} + \frac{g^{\mu\nu}}{4} F^2$$

$$\begin{aligned} \langle p' | T_{q,g}^{\mu\nu} | p \rangle = & \bar{u}(p') \Big[A_{q,g}(t) \gamma^{(\mu} P^{\nu)} + B_{q,g}(t) \frac{P^{(\mu} i \sigma^{\nu)\alpha} \Delta_{\alpha}}{2m_N} \\ & + D_{q,g}(t) \frac{\Delta^{\mu} \Delta^{\nu} - g^{\mu\nu} \Delta^2}{m_N} + \bar{C}_{q,g}(t) m_N g^{\mu\nu} \Big] u(p) \end{aligned}$$

$$\begin{aligned} P &= \frac{p + p'}{2} \\ \Delta &= p' - p \\ t &= \Delta^2 \end{aligned}$$

$$\bar{C}_q(t) + \bar{C}_g(t) = 0$$

$$\partial_{\mu} T^{\mu\nu} = 0$$

$$\boxed{A_q(0)} + A_g(0) = 1$$

$\simeq 1/2$

$$\langle p | T^{\mu\nu} | p \rangle = 2 p^{\mu} p^{\nu}$$

$$\frac{1}{2} \left(\boxed{A_q(0) + B_q(0)} + A_g(0) + B_g(0) \right) = \frac{1}{2}$$

$B_q(0) + B_g(0) = 0$

$$\frac{\langle pS | J^i | pS \rangle}{\langle pS | pS \rangle} = \frac{1}{2} S^i$$

$$J^i = \frac{1}{2} \epsilon^{ijk} \int d^3x M^{+jk}$$

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

$$M^{\mu\rho\sigma} = x^{\rho} T^{\mu\sigma} - x^{\sigma} T^{\mu\rho}$$

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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

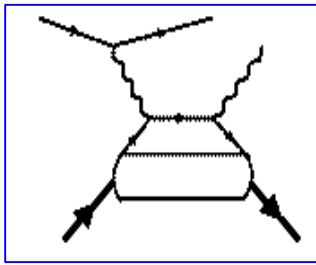
$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right) \quad H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).$$

$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t), \quad \int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

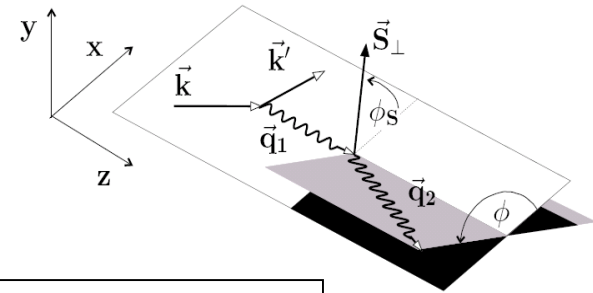
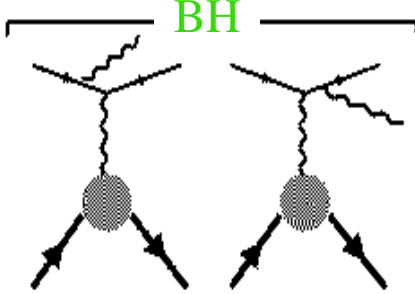
$$\int_{-1}^1 dx x q(x) = A_q(0)$$

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

DVCS



BH



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |\mathbf{T}^{\text{DVCS}} + \mathbf{T}^{\text{BH}}|^2$$

\mathbf{T}^{BH} : real, given by elastic form factors

\mathbf{T}^{DVCS} : complex, determined by GPDs

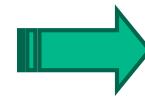
$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$$\eta \sim x_B / (2 - x_B)$$

$$k = t / 4M^2$$

Polarized beam, unpolarized target:

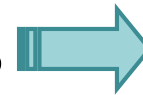
$$\Delta\sigma_{LU} \sim \sin\phi \{F_1 \# + \eta(F_1 + F_2) \tilde{\#} + k F_2 \mathcal{E}\} d\phi$$



$$H(x, \eta, t)$$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi \{F_1 \tilde{\#} + \eta(F_1 + F_2) (\# + \eta / (1 + \eta) \mathcal{E})\} d\phi$$



$$\tilde{H}(x, \eta, t)$$

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi) \{k(F_2 \# - F_1 \mathcal{E})\} d\phi$$



$$E(x, \eta, t)$$

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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right) \quad H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).$$

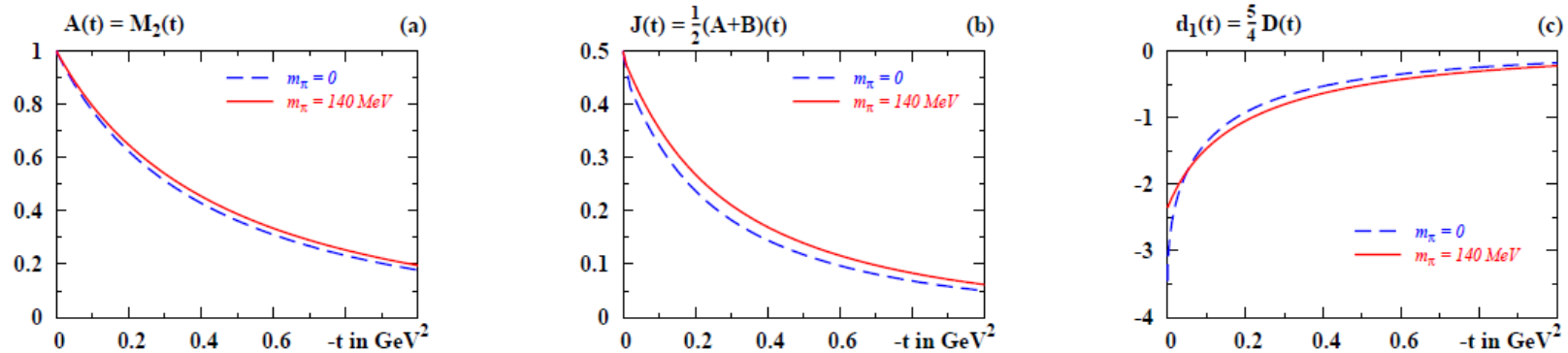
$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t), \quad \int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

$$\int_{-1}^1 dx x q(x) = A_q(0)$$

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

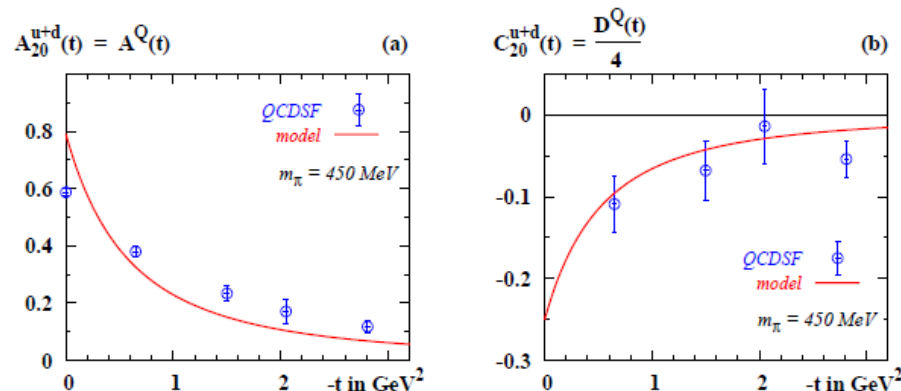
EMT form factors & D -term of nucleon:

- nature: **unknown!**
- model: e.g. chiral quark soliton model, Goeke et al, PRD75 (2007) 094021



well-tested model, many nucleon properties vs data within 30% ✓

- lattice: QCDSF Collaboration, Gökeler et al, PRL92 (2004) 042002 & hep-ph/0312104 → test models



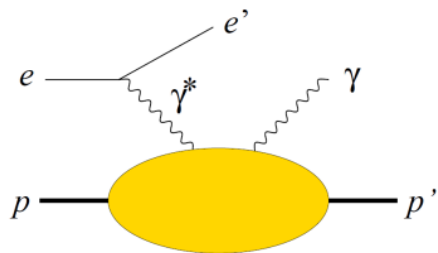
lattice QCD, bag model, Skyrme model,
chiral quark soliton model: $D_{\text{nucleon}} < 0$

other particles:
nuclei, pions, photons, Q -balls, Q -cloud, Higgs(!)
have also negative D -terms! (in theory!)

One day we will have this from experiment!

what will we learn?

$$\bar{P} = \frac{p + p'}{2}$$

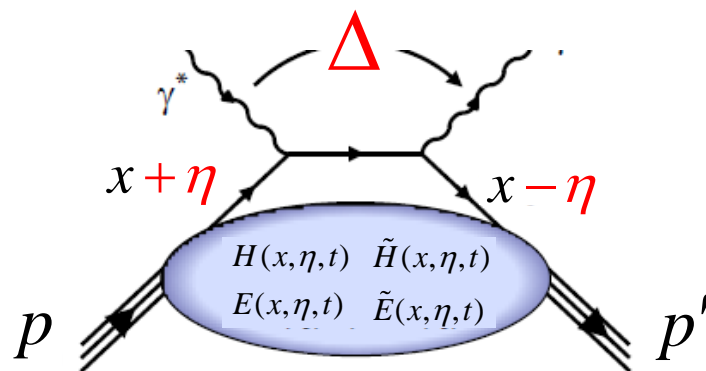


JLab, HERMES, COMPASS, ...

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

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

GPD



$$-2\eta\bar{P} = \Delta$$

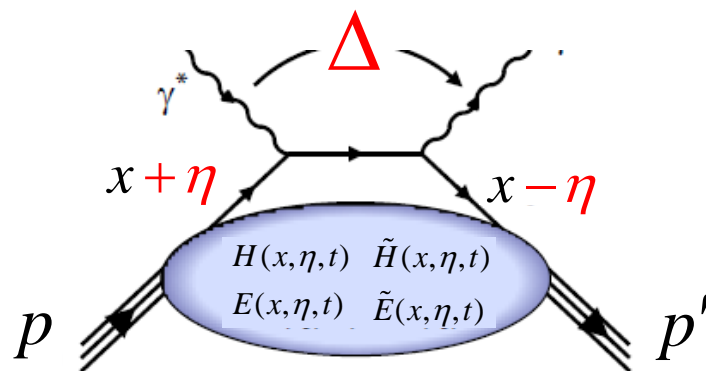
$$\int d\mathbf{z}^- e^{i(x+\eta)pz^-} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$

A diagram illustrating a virtual photon exchange. A yellow oval represents a proton, with two horizontal black lines labeled p entering and exiting it. A wavy line labeled γ^* connects the proton to an electron. The electron is represented by a horizontal black line labeled e entering from the left and a horizontal black line labeled e' exiting to the upper right. A red arrow points from the wavy line to a green starburst labeled M .

$$\int \frac{d\bar{z}^-}{2\pi} e^{i x \bar{P} z^-} \langle p' | \bar{q}(-\frac{\bar{z}^-}{2}) \gamma^+ q(\frac{\bar{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[H(x, \eta, t) \bar{u}(p') \gamma^+ u(p) + E(x, \eta, t) \bar{u}(p') \frac{i \sigma^{+\alpha} (p' - p)_\alpha}{2M} u(p) \right]$$

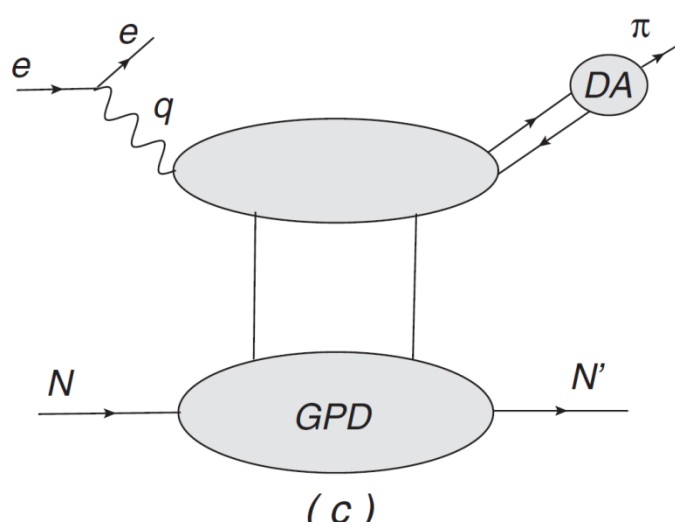
$$\int \frac{d\bar{z}^-}{2\pi} e^{ix\bar{P}z^-} \langle p' | \bar{q}(-\frac{\bar{z}^-}{2}) \gamma^+ \gamma_5 q(\frac{\bar{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[\tilde{H}(x, \eta, t) \bar{u}(p') \gamma^+ \gamma_5 u(p) + \tilde{E}(x, \eta, t) \bar{u}(p') \frac{\gamma_5 (p' - p)^+}{2M} u(p)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

GPD

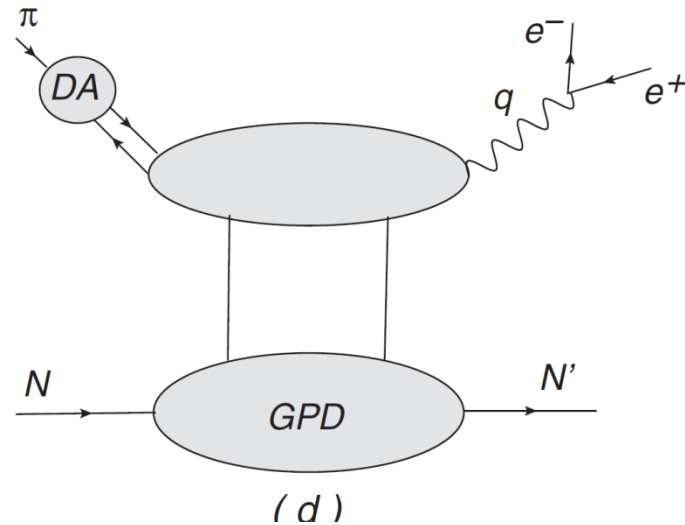


$$-2\eta\bar{P} = \Delta$$

$$\int d\mathbf{z}^- e^{i(\mathbf{x}+\boldsymbol{\eta})\mathbf{p}\mathbf{z}^-} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$



DVMP@HERA, JLab



exDY@J-PARC

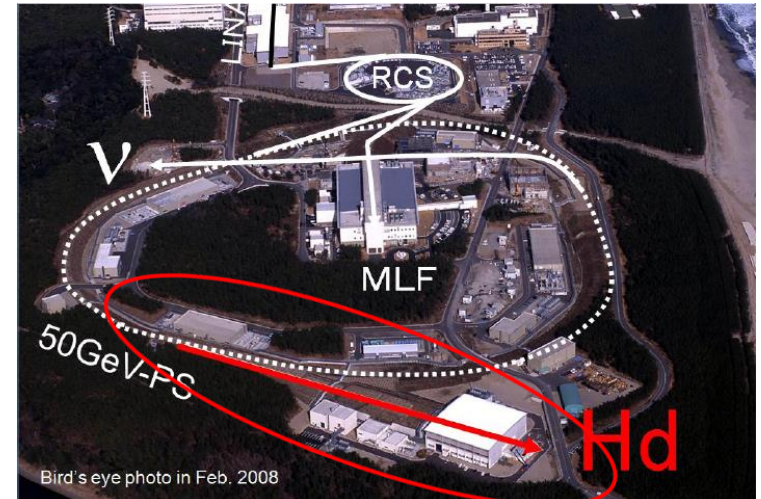
High momentum beam line at J-PARC

- Primary beam (proton)

$$E = 30\text{GeV} \ (\rightarrow 50\text{GeV?})$$

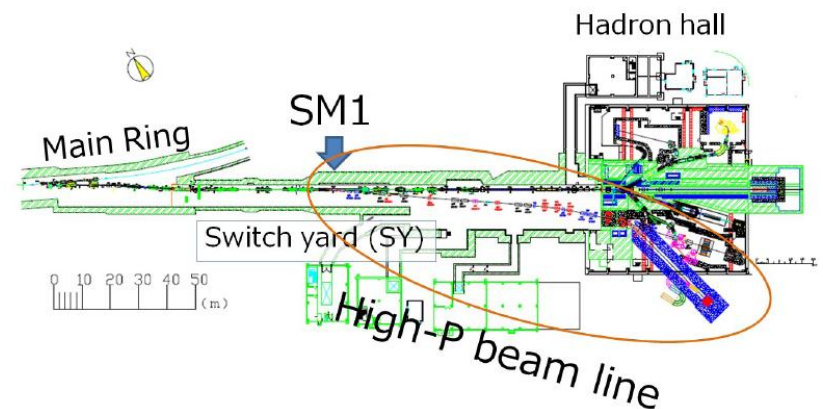
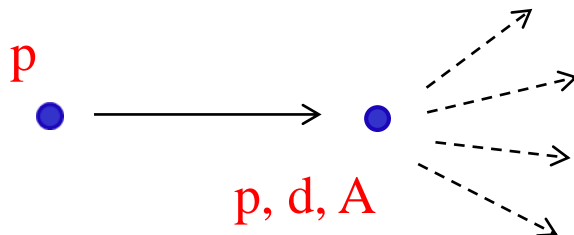
$$L = 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

Hadron Facility at J-PARC



- Secondary beam (pion)

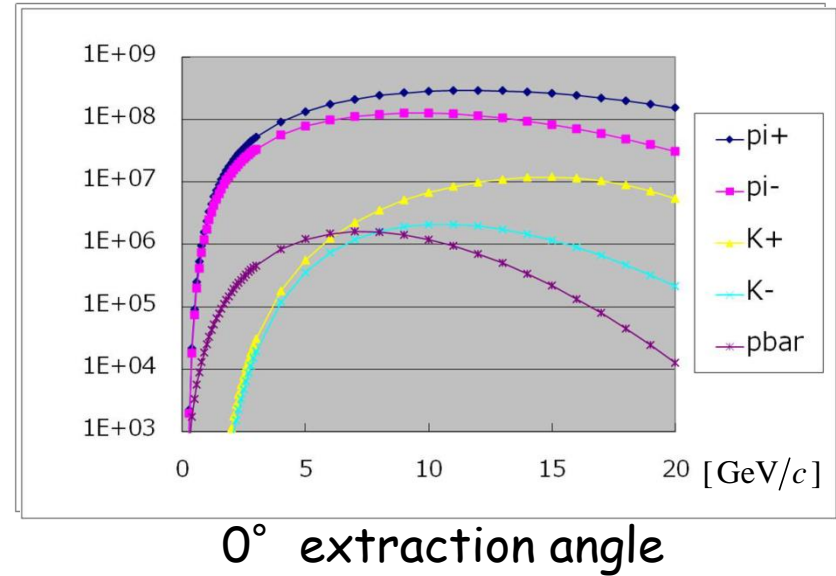
$$E = 15\text{-}20\text{GeV}$$





beam loss limit @ SM1:15kW

(limited by the thickness of the tunnel wall)



High-momentum beamline

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

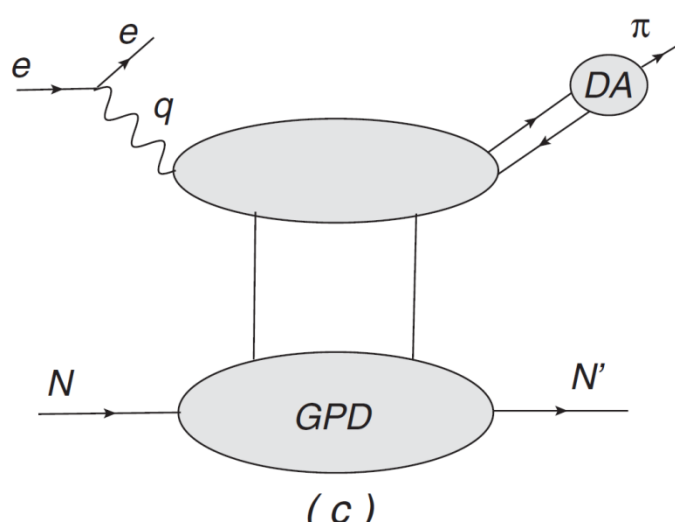
high intensity

not too high energy

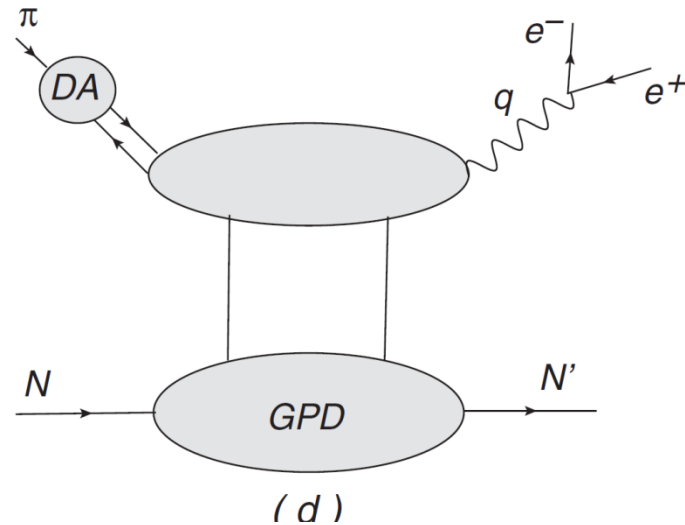
$$d\sigma \sim 1/s^a$$

best suited to study meson-induced
hard exclusive processes

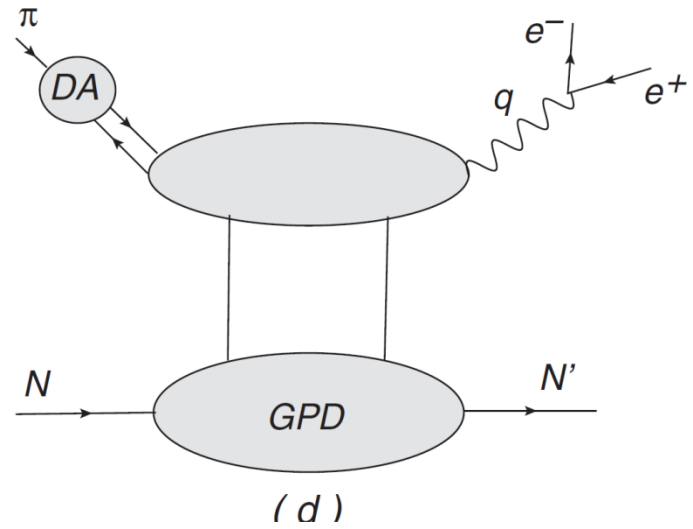
$$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$$



DVMP@HERA, JLab



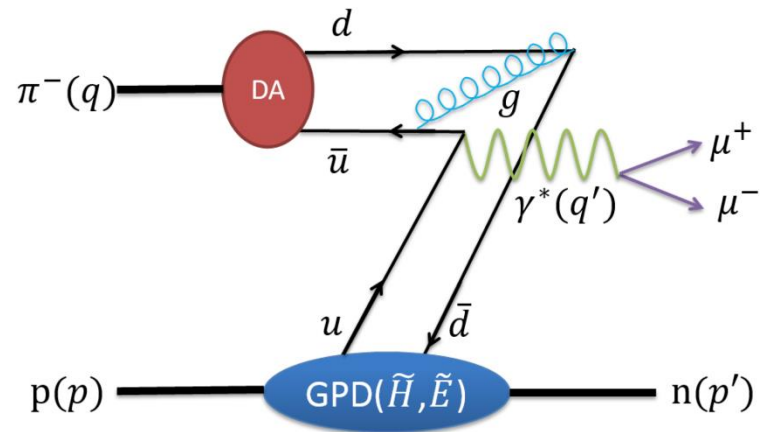
exDY@J-PARC



exDY@J-PARC

Pion-induced Drell-Yan process

$$\pi N \rightarrow \mu^+ \mu^- N$$

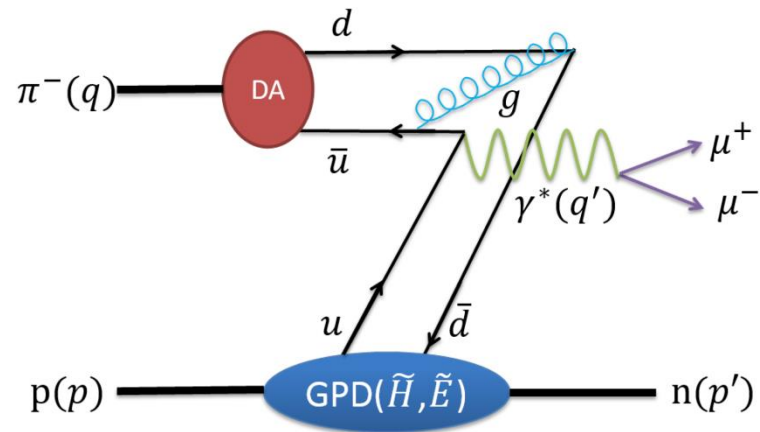


exclusive

Pion-induced Drell-Yan process

QCD factorization formula

$$\pi N \rightarrow \mu^+ \mu^- N$$



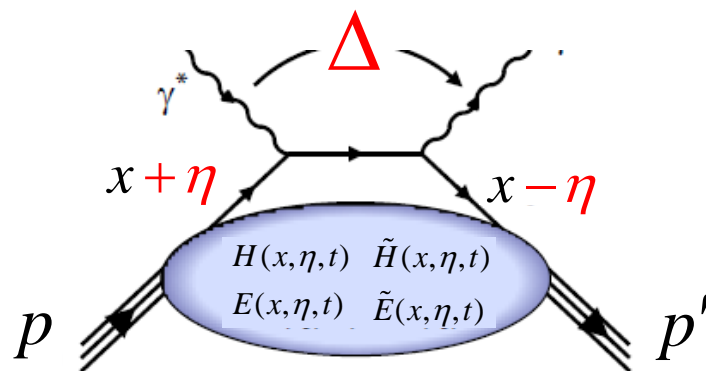
exclusive

A diagram illustrating a virtual photon exchange. A yellow oval represents a proton, with two horizontal black lines labeled p entering and exiting it. A green starburst labeled M represents a muon. A red line connects the proton to the muon. A wavy line labeled γ^* connects the proton to an electron e , which then becomes a muon e' .

$$\int \frac{d\bar{z}^-}{2\pi} e^{i x \bar{P} z^-} \langle p' | \bar{q}(-\frac{\bar{z}^-}{2}) \gamma^+ q(\frac{\bar{z}^-}{2}) | p \rangle = \frac{1}{\bar{P}^+} \left[H(x, \eta, t) \bar{u}(p') \gamma^+ u(p) + E(x, \eta, t) \bar{u}(p') \frac{i \sigma^{+\alpha} (p' - p)_\alpha}{2M} u(p) \right]$$

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

GPD

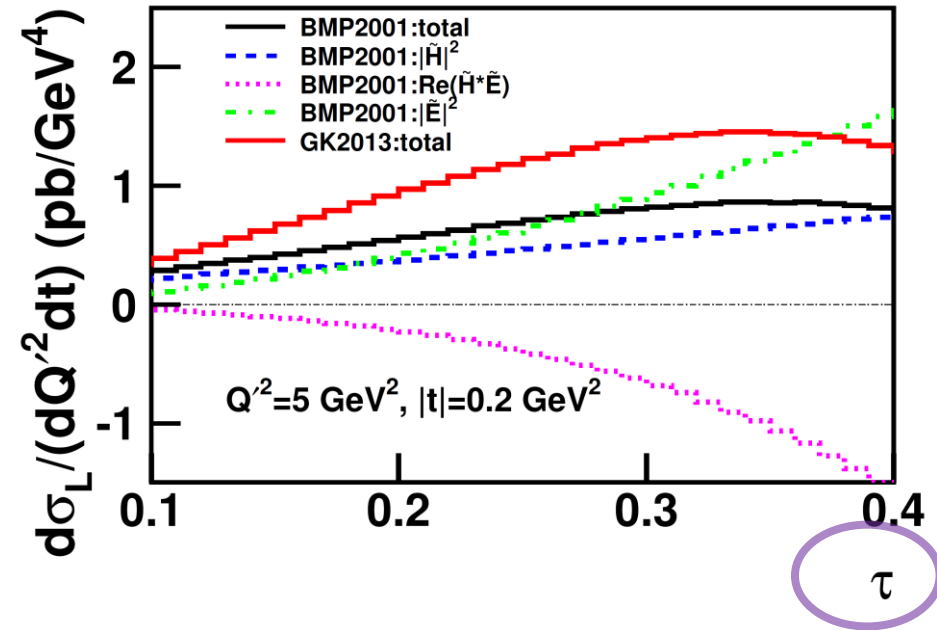
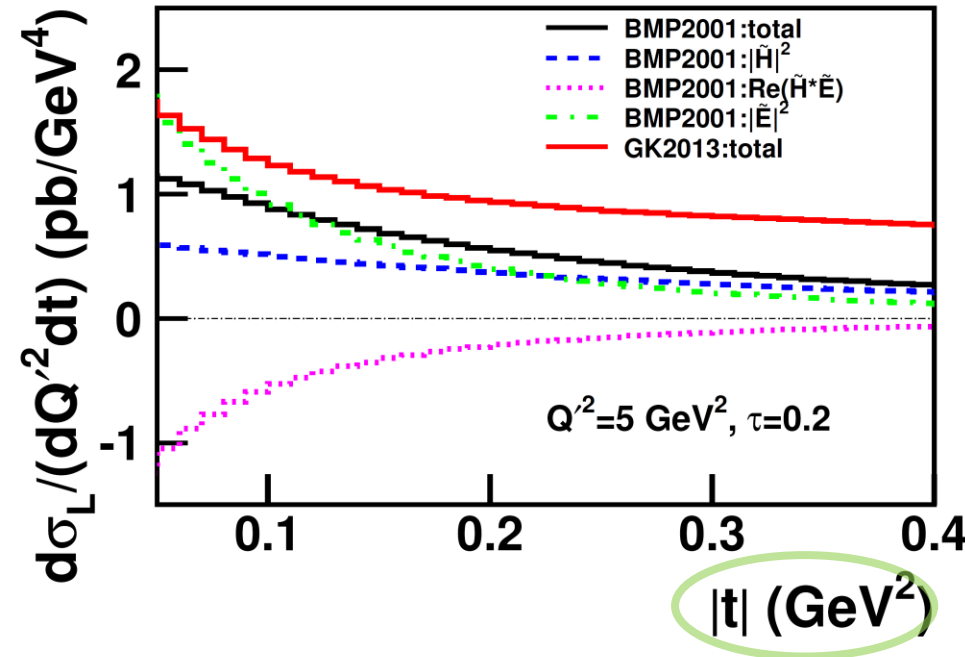


$$-2\eta\bar{P} = \Delta$$

$$\int d\mathbf{z}^- e^{i(\mathbf{x}+\boldsymbol{\eta})\mathbf{p}\mathbf{z}} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$

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

$$Q'^2 = 5 \text{ GeV}^2$$



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

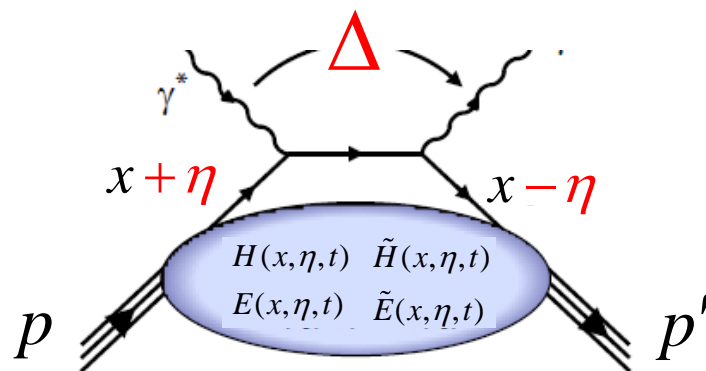
$$\mathcal{H}^{du} = \frac{8\alpha_s}{3} \int_0^1 du \frac{\phi_\pi(u)}{4u(1-u)} \int_{-1}^1 dx \left(\frac{e_d}{-\eta - x - i\epsilon} - \frac{e_u}{-\eta + x - i\epsilon} \right) (\tilde{H}^d(x, \eta, t) - \tilde{H}^u(x, \eta, t))$$

A diagram illustrating the interaction between a proton and a nucleus. A proton line, labeled p on the left and p' on the right, enters a yellow oval representing the nucleus. A wavy line representing a virtual photon, labeled γ^* , connects the proton to a green starburst labeled M . An electron line, labeled e on the left and e' on the right, also interacts with the M vertex. A red line connects the nucleus to the M vertex.

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

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

GPD



$$-2\eta\bar{P} = \Delta$$

$$\int d\mathbf{z}^- e^{i(\mathbf{x}+\boldsymbol{\eta})\mathbf{p}\mathbf{z}^-} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$

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

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

$$\Delta^\mu = p'^\mu - p^\mu \rightarrow 0$$

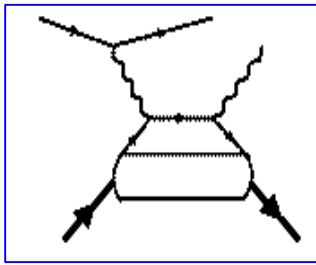
$$\left(t = \Delta^2 \rightarrow 0, \quad \eta = \frac{-\Delta \cdot n}{2\bar{P} \cdot n} \rightarrow 0 \right) \quad H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).$$

$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t), \quad \int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

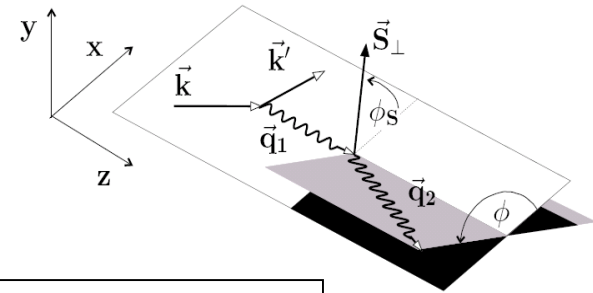
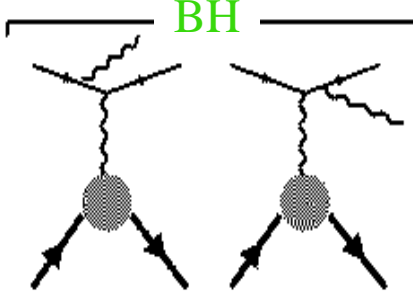
$$\int_{-1}^1 dx x q(x) = A_q(0)$$

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

DVCS



BH



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |\mathbf{T}^{\text{DVCS}} + \mathbf{T}^{\text{BH}}|^2$$

\mathbf{T}^{BH} : real, given by elastic form factors

\mathbf{T}^{DVCS} : complex, determined by GPDs

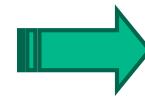
$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$$\eta \sim x_B / (2 - x_B)$$

$$k = t / 4M^2$$

Polarized beam, unpolarized target:

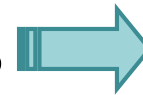
$$\Delta\sigma_{LU} \sim \sin\phi \{F_1 \# + \eta(F_1 + F_2) \tilde{\#} + k F_2 \mathcal{E}\} d\phi$$



$$H(x, \eta, t)$$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi \{F_1 \tilde{\#} + \eta(F_1 + F_2) (\# + \eta / (1 + \eta) \mathcal{E})\} d\phi$$



$$\tilde{H}(x, \eta, t)$$

Unpolarized beam, transverse target:

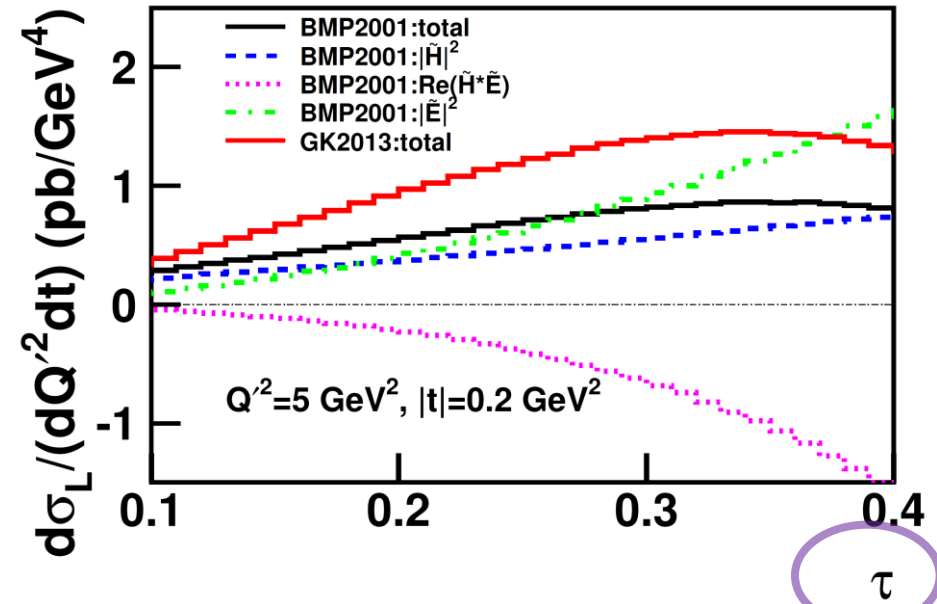
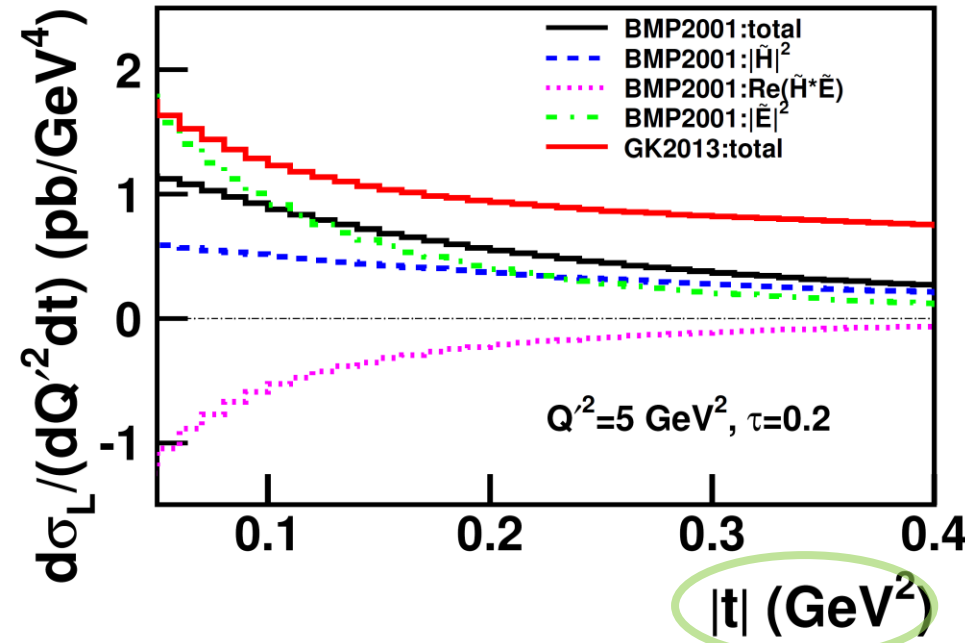
$$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi) \{k(F_2 \# - F_1 \mathcal{E})\} d\phi$$



$$E(x, \eta, t)$$

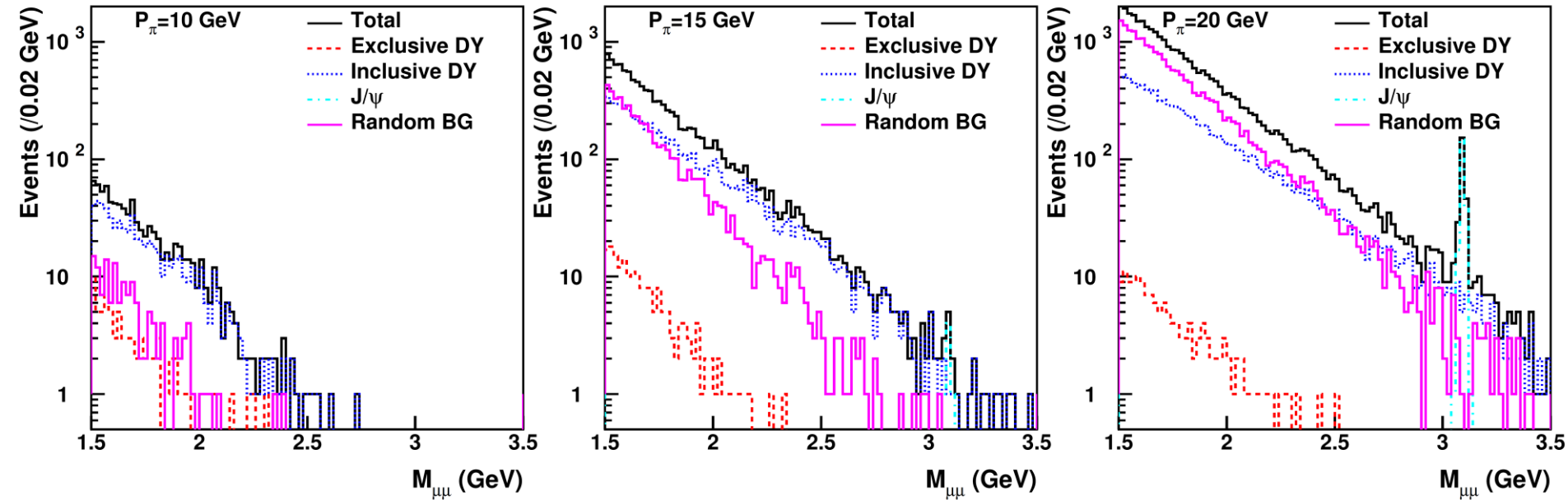
Bjorken variable $\tau = \frac{Q'^2}{s-M^2}$

$$Q'^2 = 5 \text{ GeV}^2$$



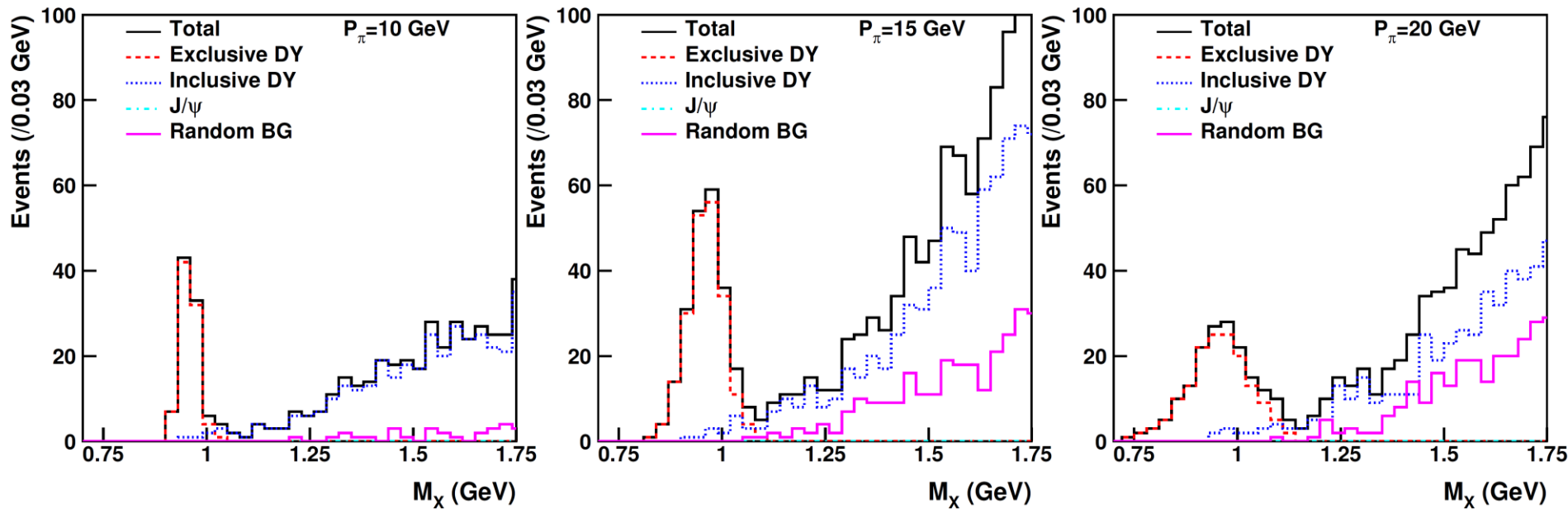
$$\frac{d\sigma}{dQ'^2 dt}(\pi^- p \rightarrow \gamma^* n) = \frac{4\pi\alpha_{\text{em}}^2}{27} \frac{\tau^2}{Q'^8} f_\pi^2 \left[(1-\eta^2) |\mathcal{H}^{du}|^2 - 2\eta^2 \text{Re}(\mathcal{H}^{du*} \mathcal{E}^{du}) - \eta^2 \frac{t}{4M^2} |\mathcal{E}^{du}|^2 \right]$$

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



feasibility with E50 spectrometer at J-PARC

T. Sawada, W.C. Chang, S. Kumano, J.C. Peng, S. Sawada, KT,
PRD93, 114034



feasibility with E50 spectrometer at J-PARC

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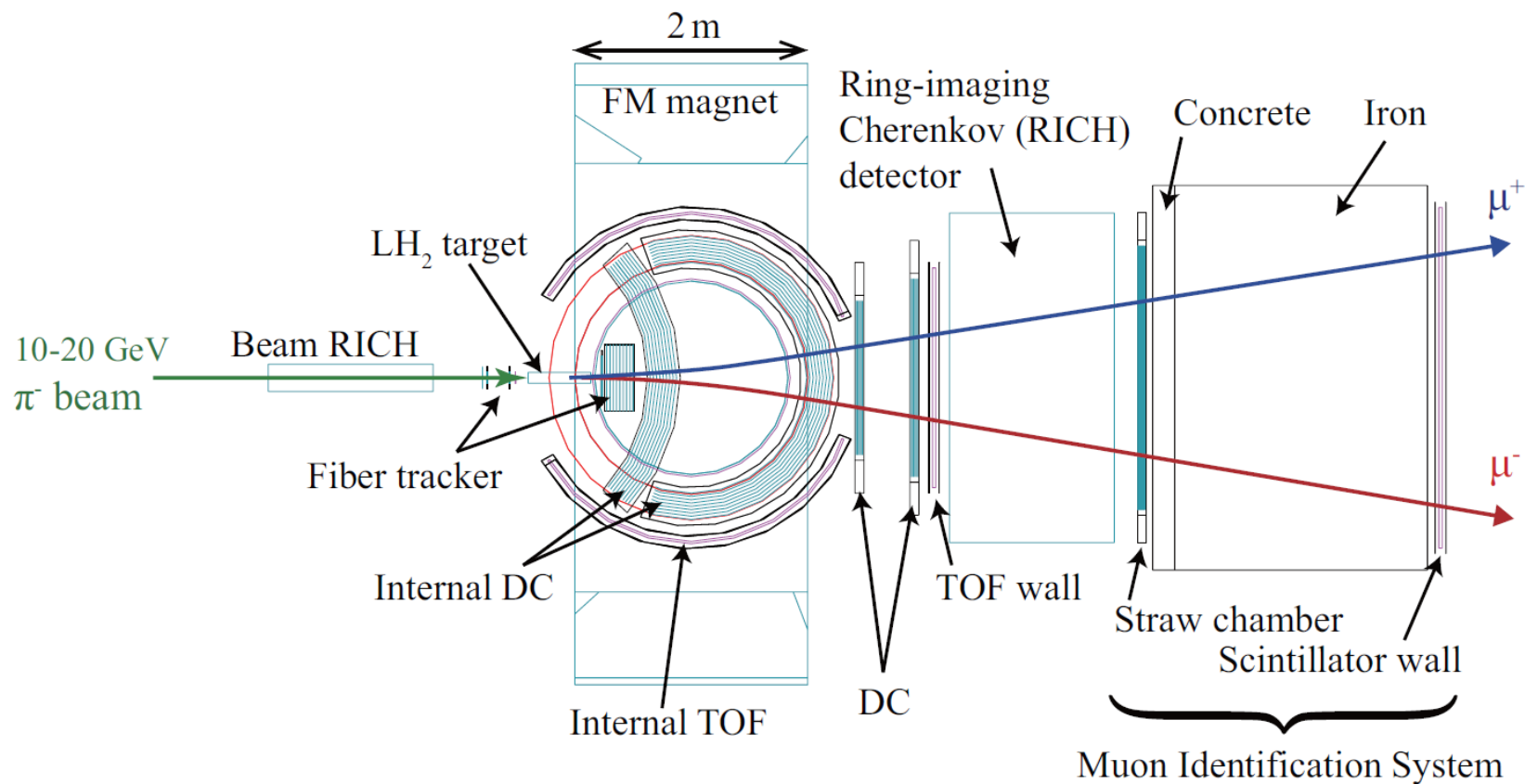


FIG. 9: Conceptual design of J-PARC E50 spectrometer with muon identification system.

Letter of Intent on an experiment for generalized parton distributions and pion distribution amplitudes with exclusive pion-induced Drell-Yan process at J-PARC

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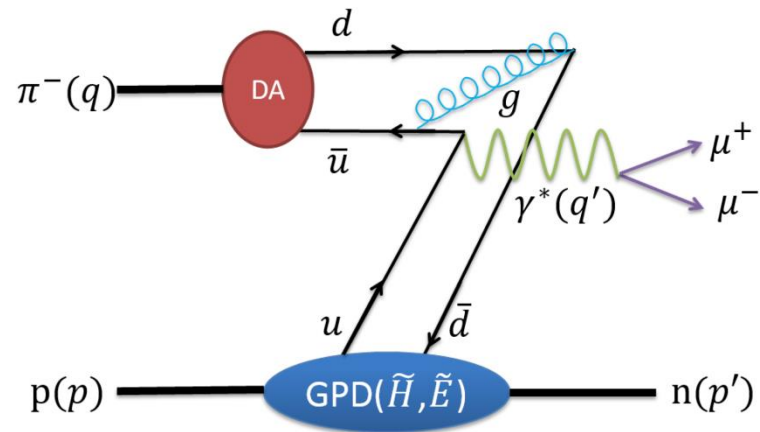
^f*High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

^g*Department of Physics, Juntendo University, Inzai, Chiba 270-1695, Japan*

Pion-induced Drell-Yan process

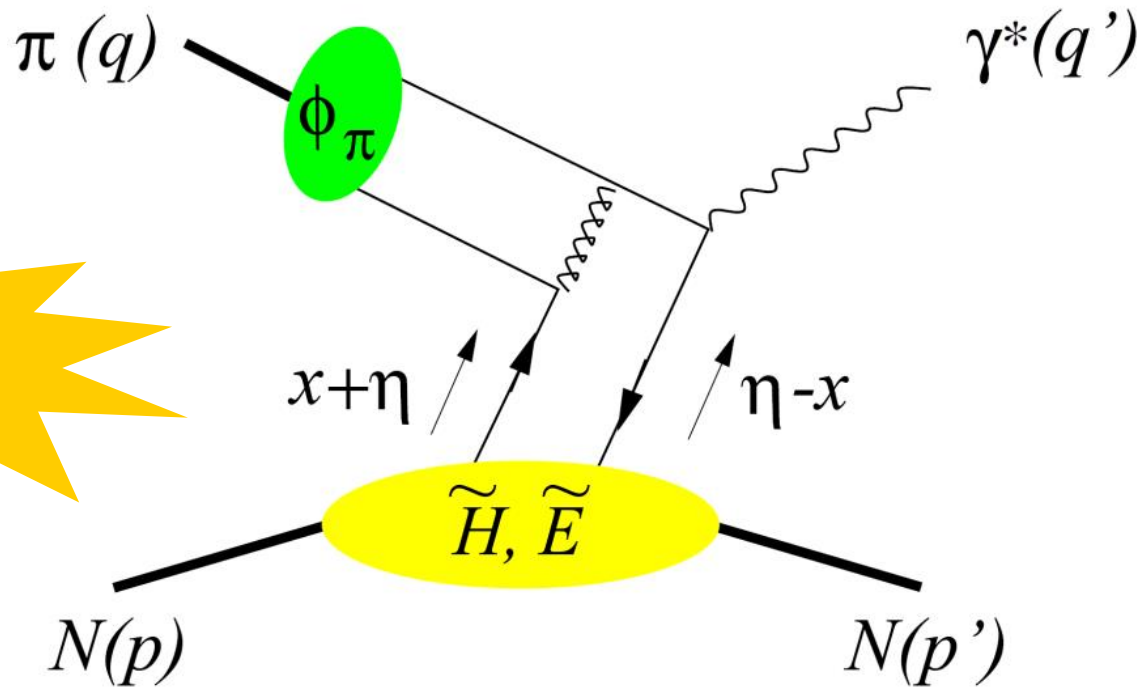
QCD factorization formula

$$\pi N \rightarrow \mu^+ \mu^- N$$

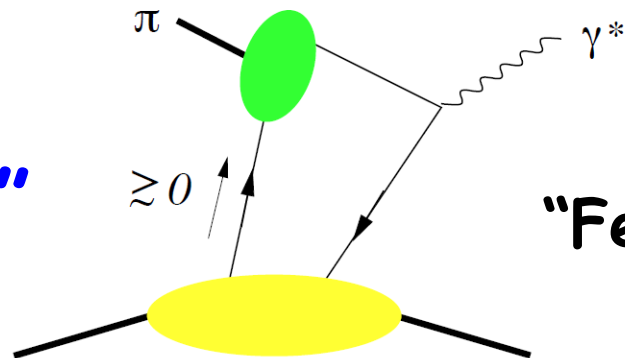


exclusive

**LO in QCD
factorization**

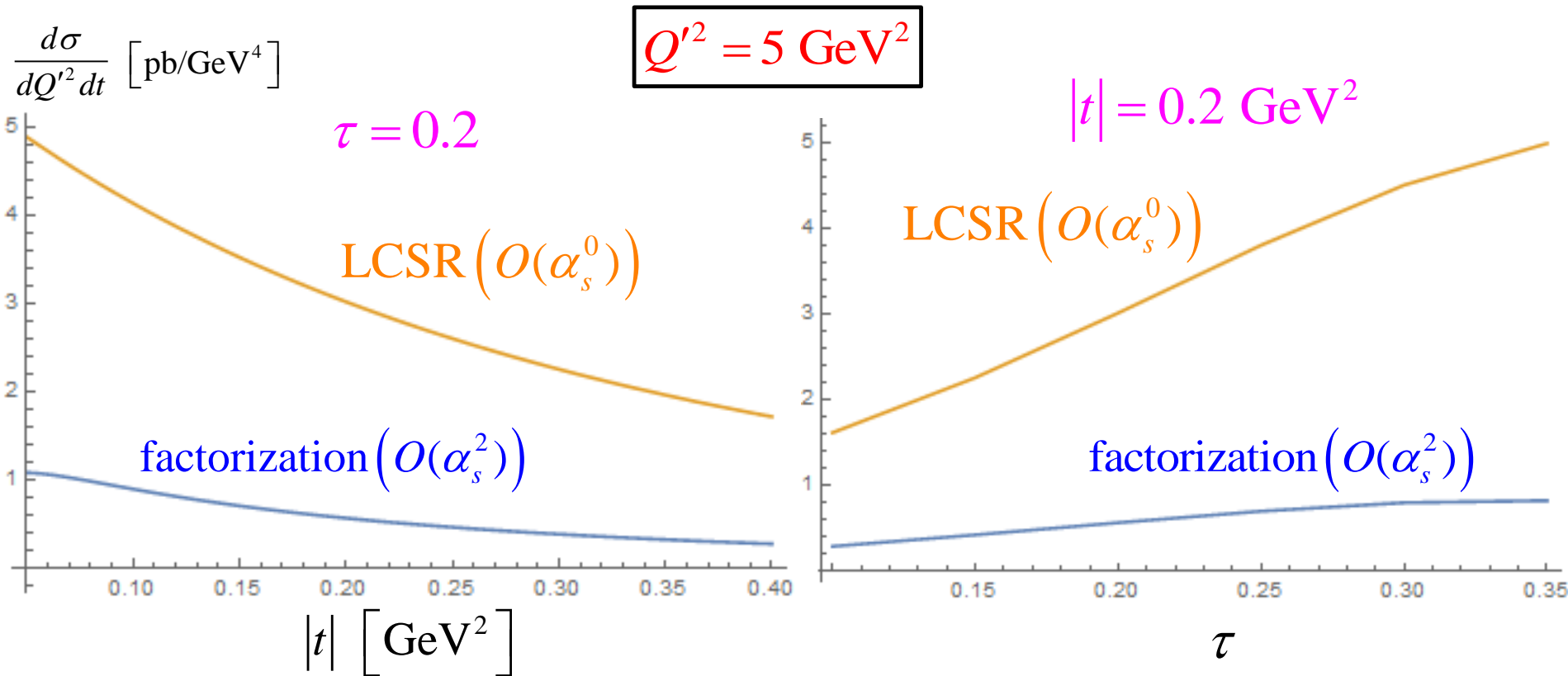


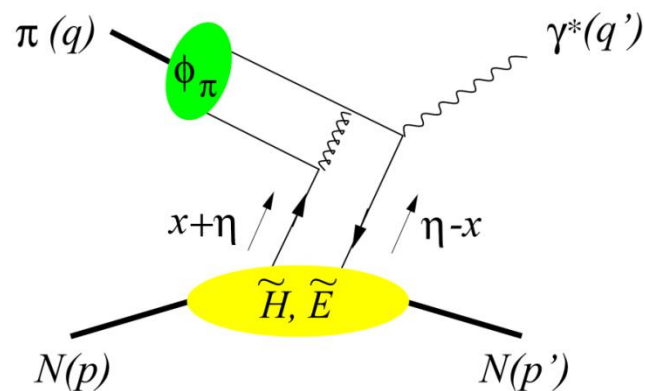
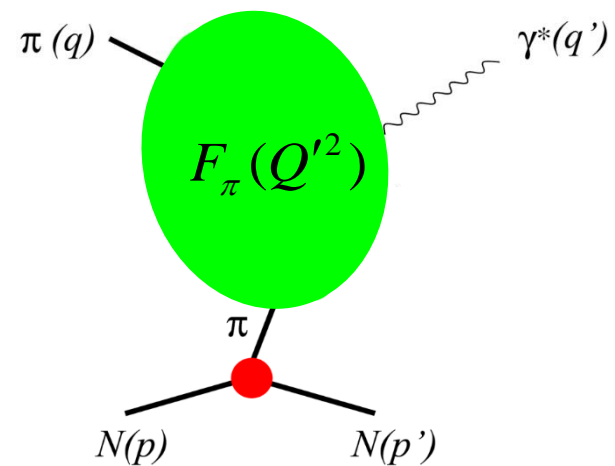
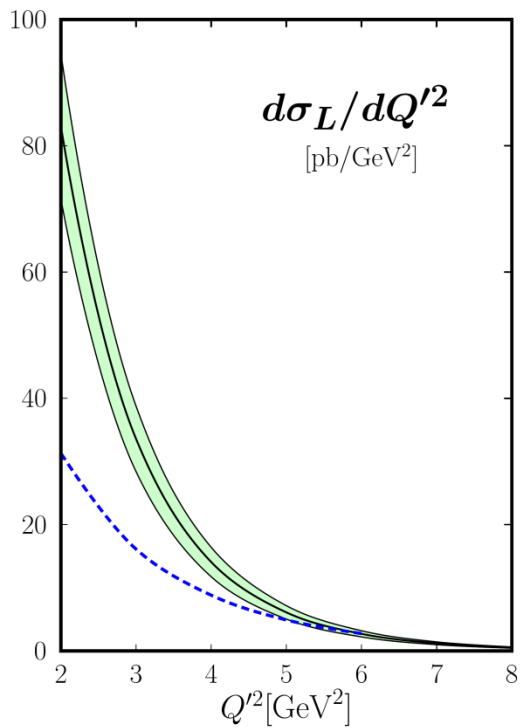
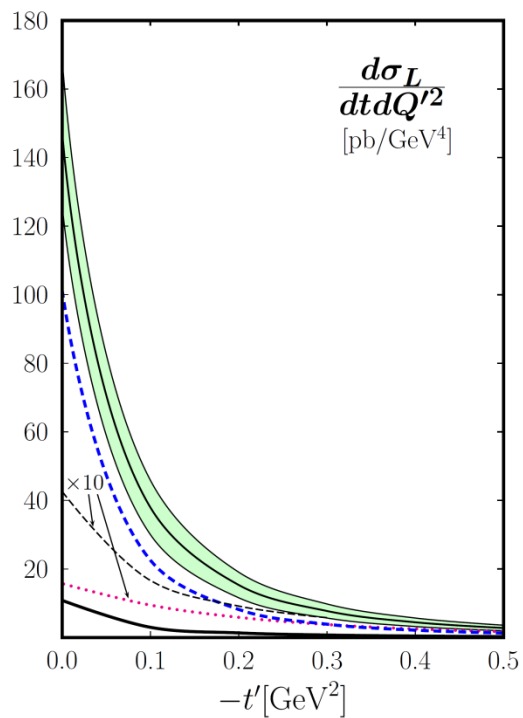
“nonfactorizable”



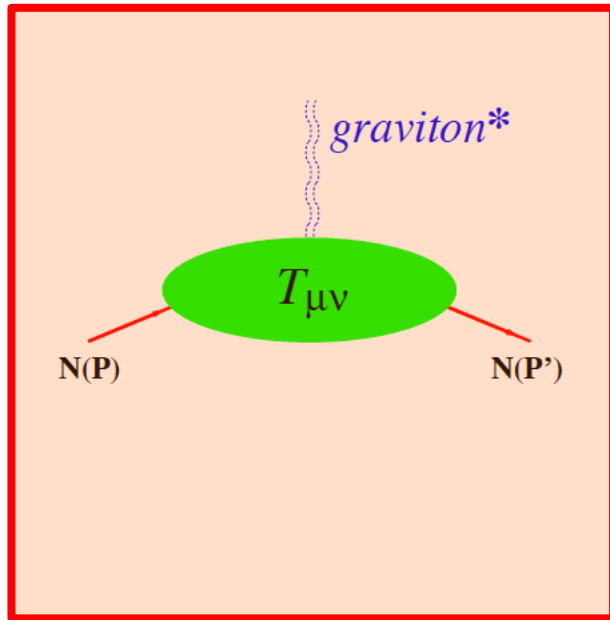
“Feynman mechanism”

$$\frac{d\sigma}{dQ'^2 dt} (\pi^- p \rightarrow \gamma^* n)$$





Summary



mass & energy
distribution

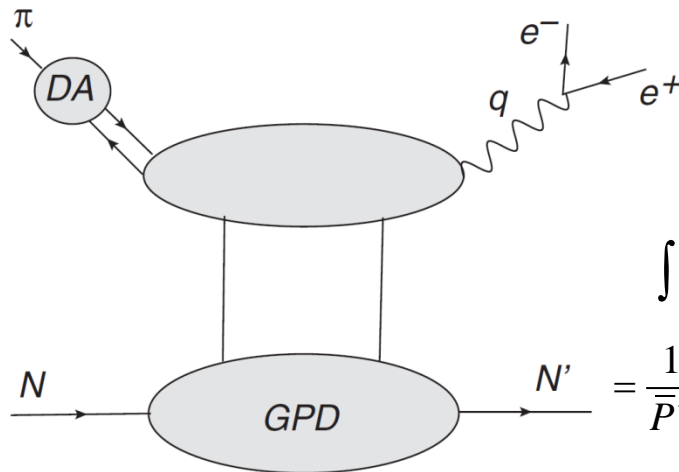
$$\int_{-1}^1 dx x H^q(x, \eta, t) = A_q(t) + 4\eta^2 D_q(t)$$

$$\int_{-1}^1 dx x E^q(x, \eta, t) = B_q(t) - 4\eta^2 D_q(t)$$

angular
momentum
distribution

force &
pressure
distribution

Gravitational form factors can be accessed through GPDs



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$$\int \frac{dz^-}{2\pi} e^{ix\bar{P}z^-} \langle p' | \bar{q}(-\frac{z^-}{2}) \gamma^+ \gamma_5 q(\frac{z^-}{2}) | p \rangle$$

$$= \frac{1}{P^+} \left[\tilde{H}^q(x, \eta, t) \bar{u}(p') \gamma^+ \gamma_5 u(p) + \tilde{E}^q(x, \eta, t) \bar{u}(p') \frac{\gamma_5 (p' - p)^+}{2M} u(p) \right]$$