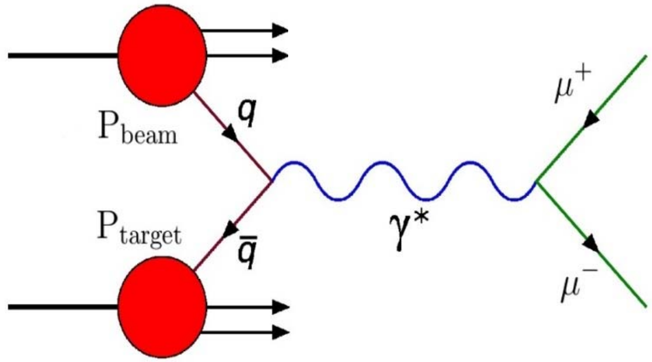
Exclusive pion-induced Drell-Yan process at J-PARC and soft nonfactorizable mechanism

Kazuhiro Tanaka (Juntendo U/KEK)

Pion-induced Drell-Yan process

$$\pi N \to \mu^+ \mu^- X$$



inclusive

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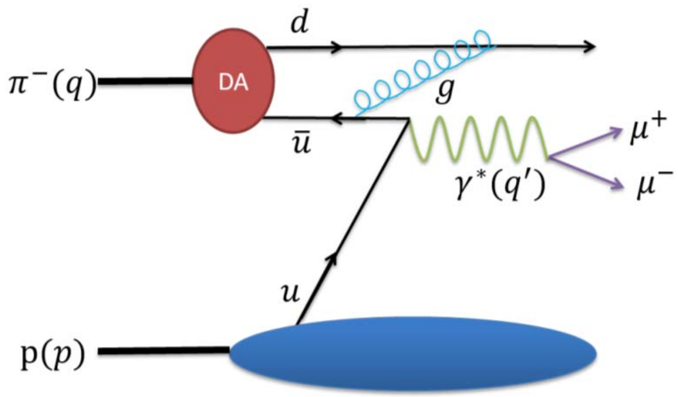

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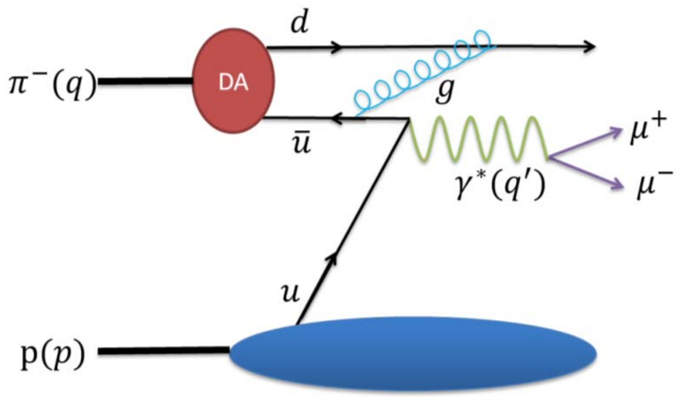

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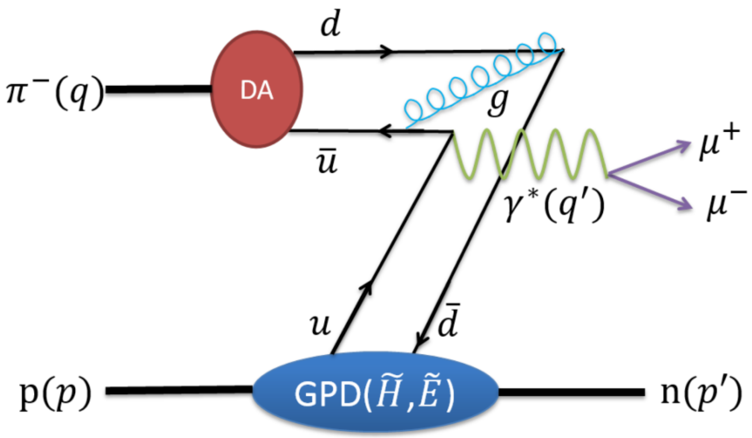


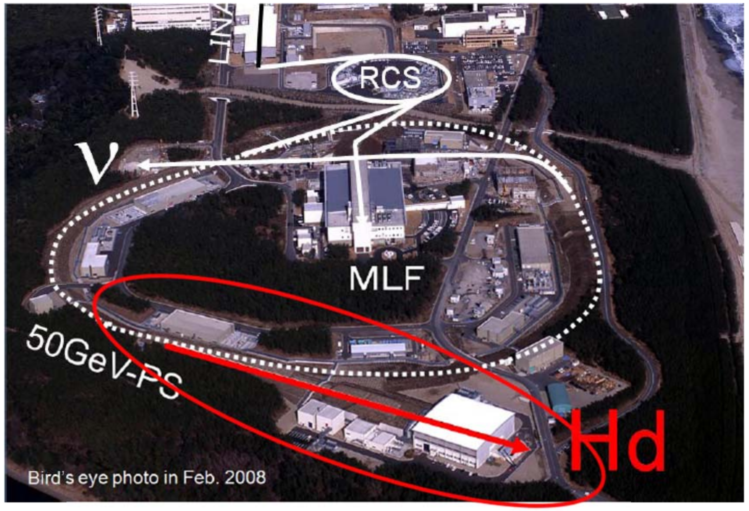
exclusive

High momentum beam line at J-PARC

- Primary beam (proton)

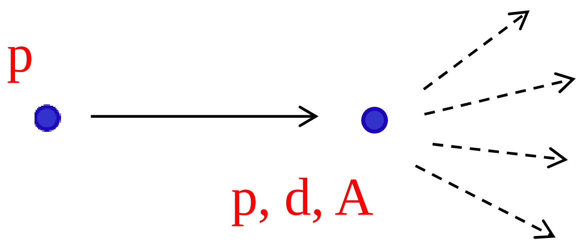
$$E = 30\text{GeV} \; (\rightarrow 50\text{GeV?})$$
$$L = 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

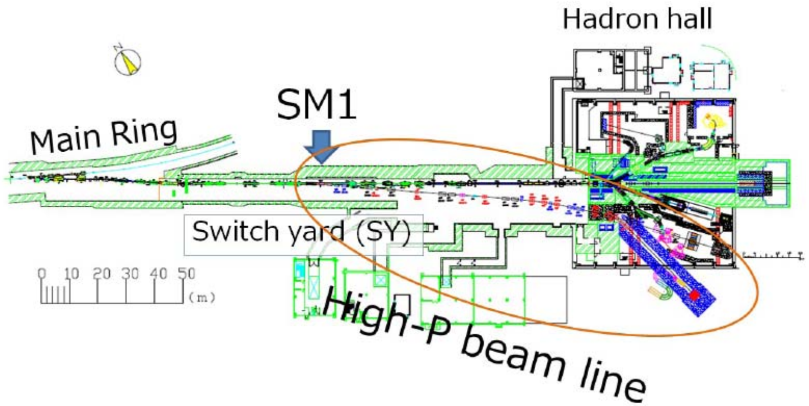
Hadron Facility at J-PARC



- Secondary beam (pion)

E = 15-20GeV





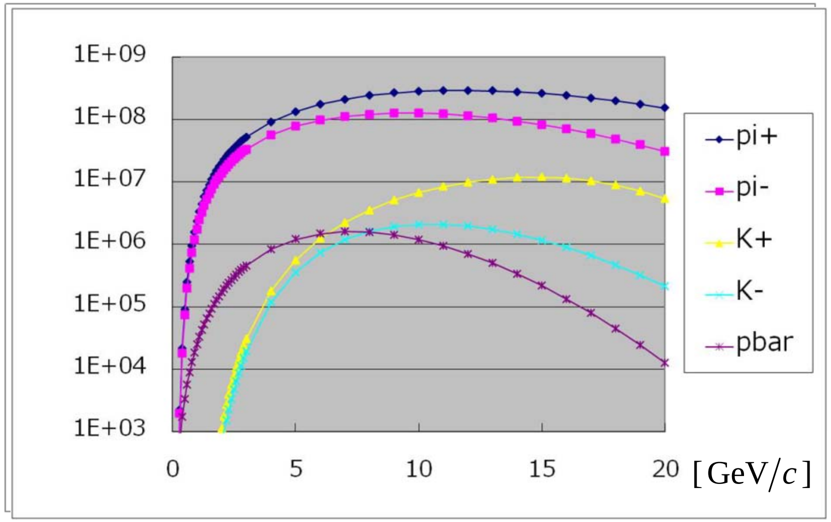
High-momentum beamline

- 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

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

best suited to study meson-induced hard exclusive processes

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

Pion-induced Drell-Yan process

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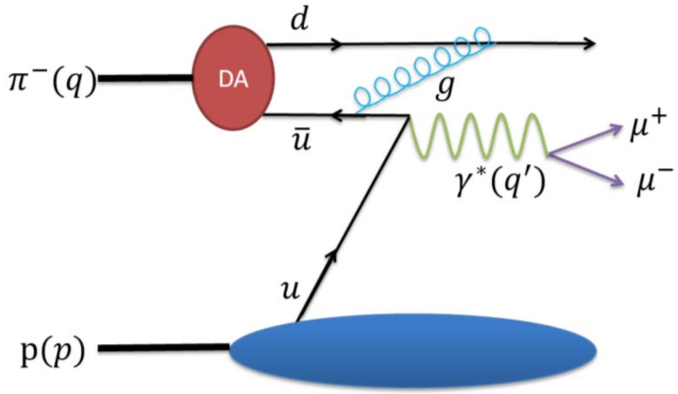

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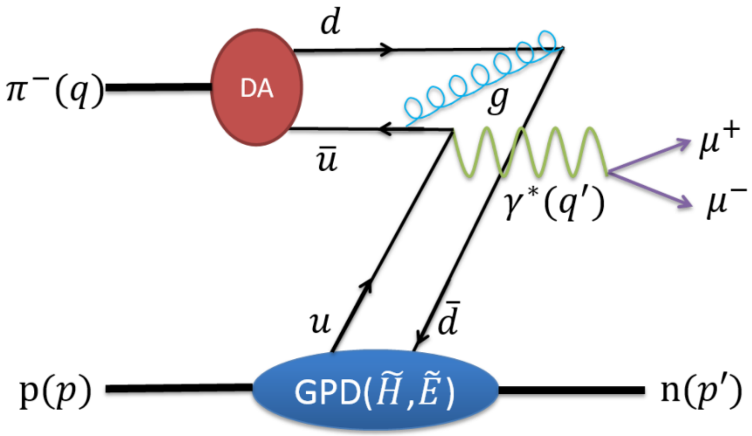

exclusive

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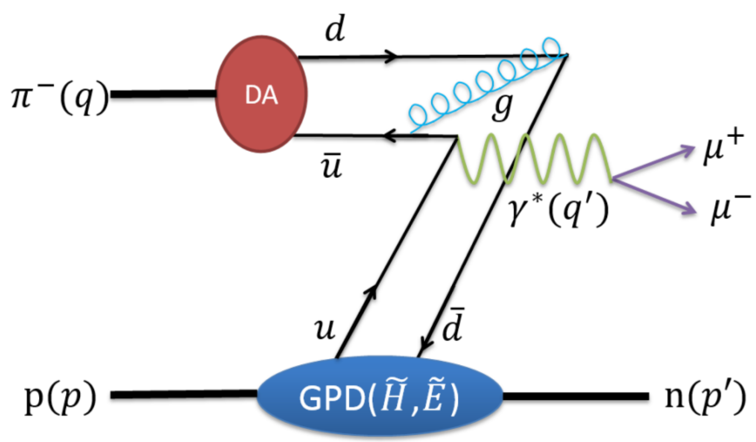
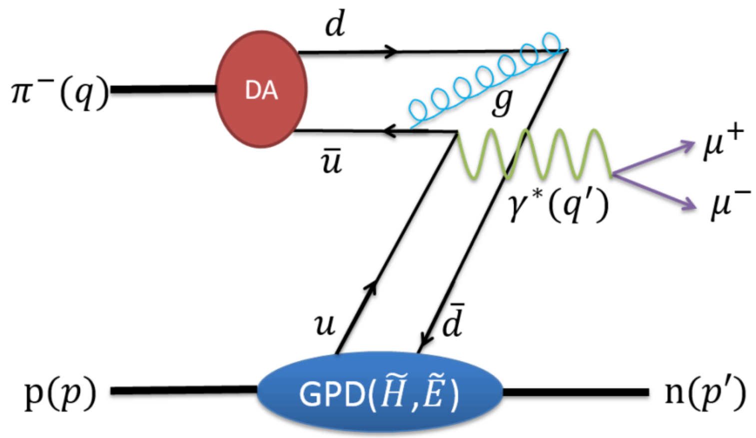


exclusive

Pion-induced Drell-Yan process

QCD factorization formula

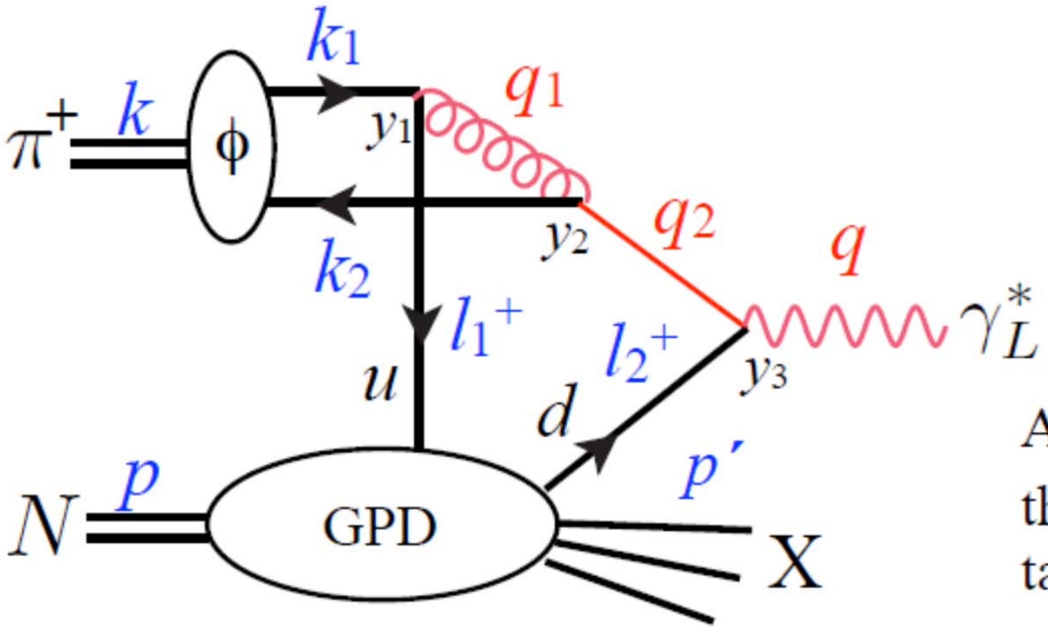
$\pi N \to \mu^+ \mu^- N$



exclusive

Hence the stopped quark should be connected to the target:

$k_1 = (0^+, uk^-, \boldsymbol{k}_\perp)$
$k_2 = (0^+, (1-u)k^-, -\boldsymbol{k}_\perp)$



Since $q_1^2 \approx -uk^- l_1^+ \to \infty$

the pion wave function contributes through its *distribution amplitude* ϕ

Also q_2^2, q_1^-, $q_2^- \to \infty$, hence the space-time separation of the target interaction points y_1, y_3 is

$$|\boldsymbol{y}_{1\perp} - \boldsymbol{y}_{3\perp}| = \mathcal{O}(1/Q) \to 0$$
$$|y_1^+ - y_3^+| = \mathcal{O}(1/Q^2) \to 0$$
$$|y_1^- - y_3^-| = \mathcal{O}(1/\ell_1^+) \text{ finite}$$

For each final state X the target matrix element is given by a GPD with skewness

$$l_2^+ - l_1^+ = q^+ = x_B\, p^+$$

Using perturbative propagators for the gluon q_1 and d-quark q_2 and adding three more diagrams we get

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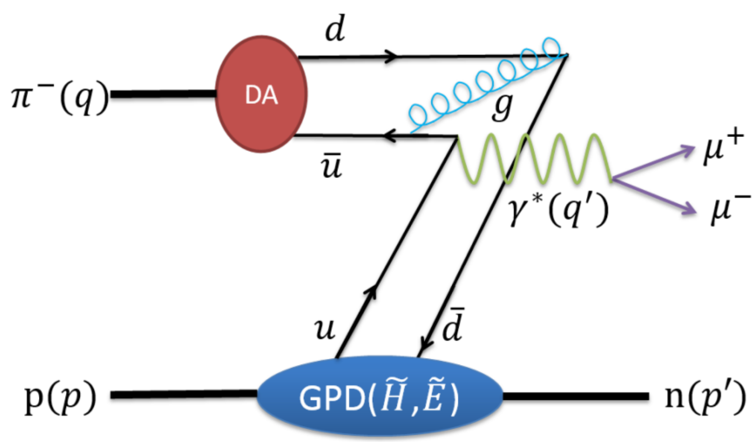


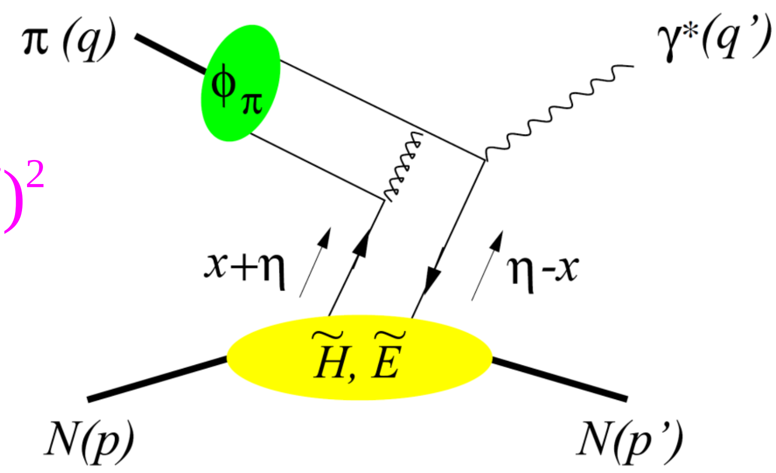
exclusive

Exclusive lepton pair production in πN scattering

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

"exclusive DY"

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



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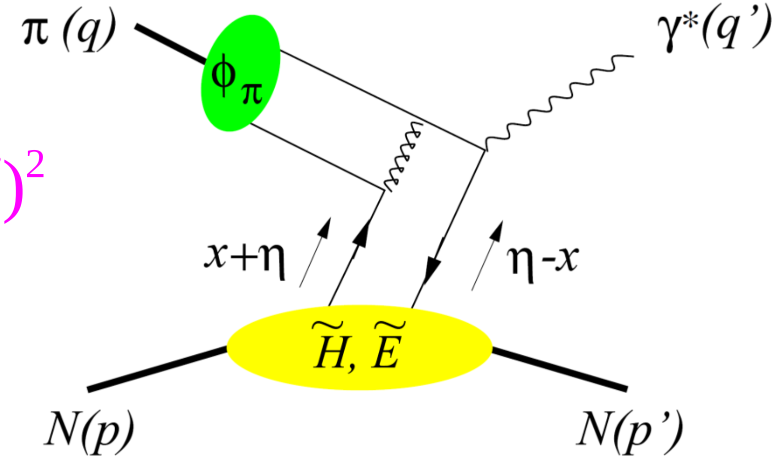

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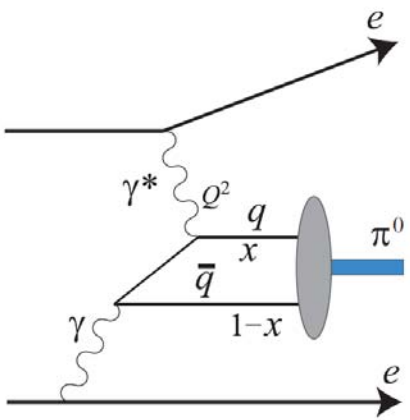

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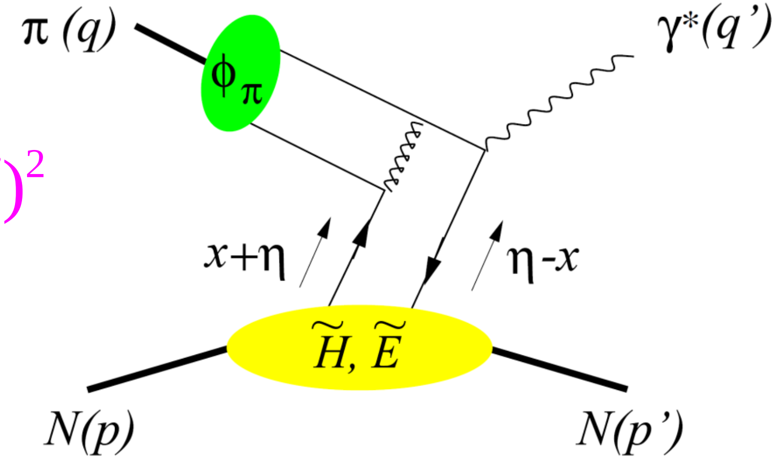

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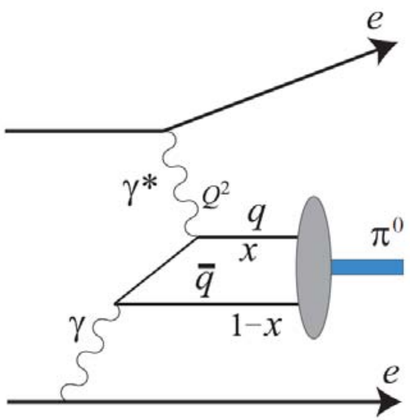

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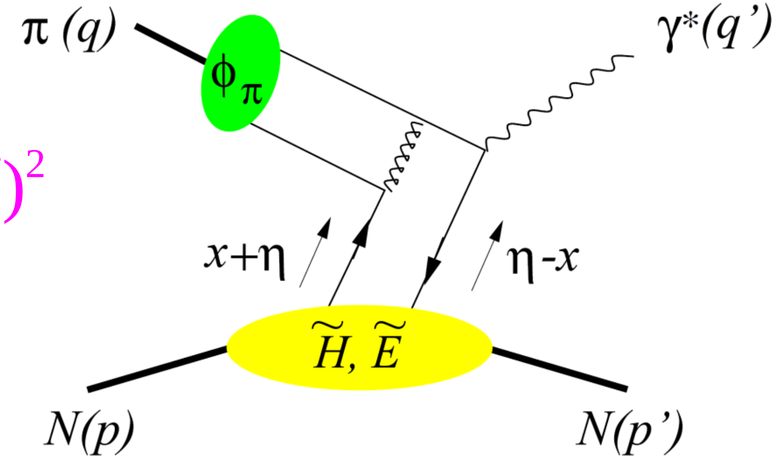
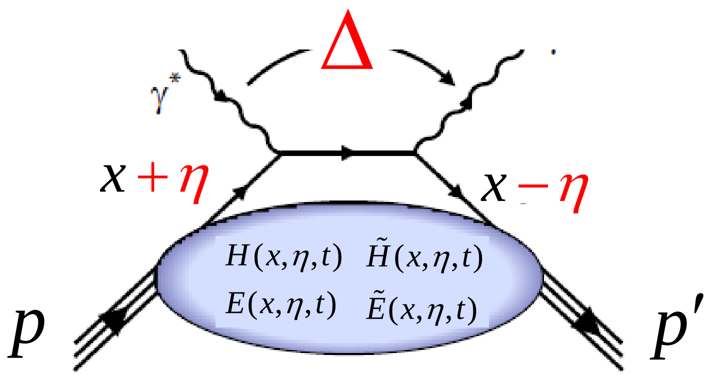


$$\int dz^- e^{i(x+\eta)pz} \langle N(p') | \psi^\dagger(0) \psi(z^-) | N(p) \rangle$$

GPD

GPD



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

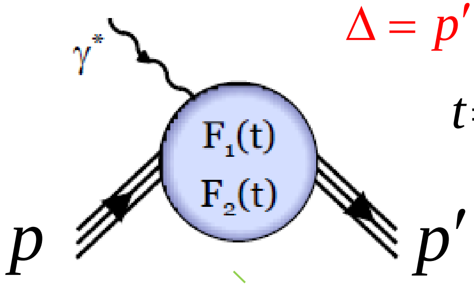
$$\int dz^- e^{i(x+\eta)pz} \langle N(p') | \psi^\dagger(0)\psi(z^-) | N(p) \rangle$$

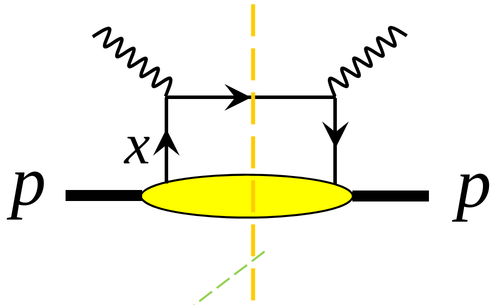
$$\langle N(p')|\psi^\dagger(0)\psi(0)|N(p)\rangle$$

$$\int dz^- e^{ixpz}\langle N(p)|\psi^\dagger(0)\psi(z^-)|N(p)\rangle$$

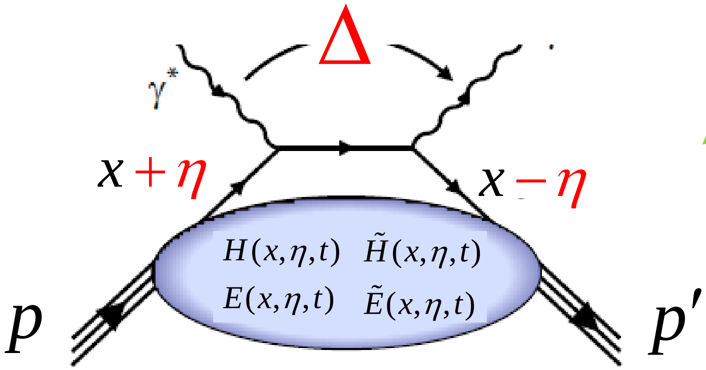
$\Delta = p' - p$

$t = \Delta^2$





GPD



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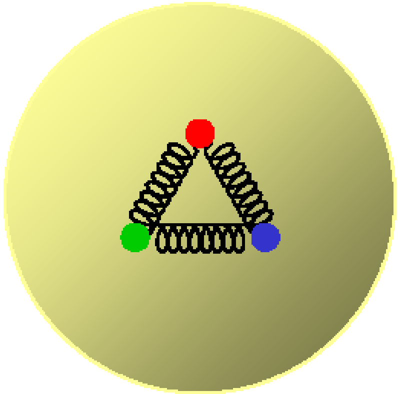

$$\langle N(p')|\psi^{\dagger}(0)\psi(0)|N(p)\rangle$$

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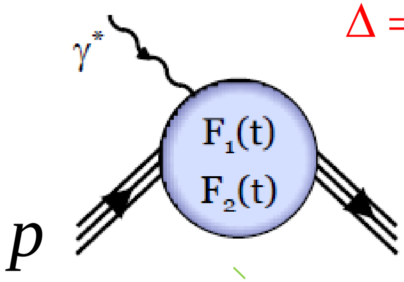

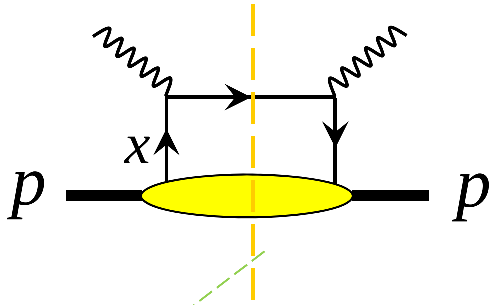

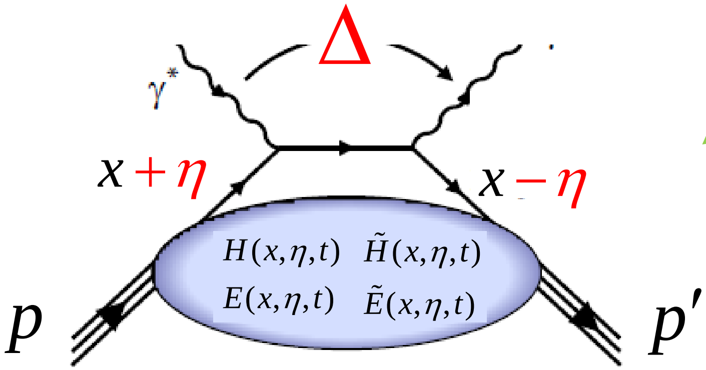

GPD

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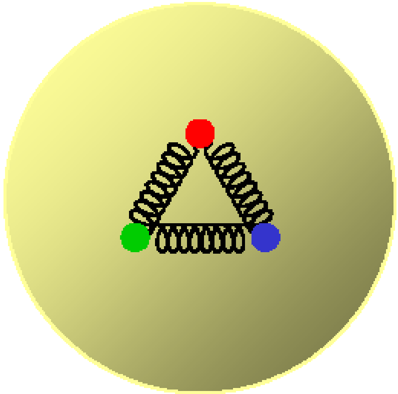

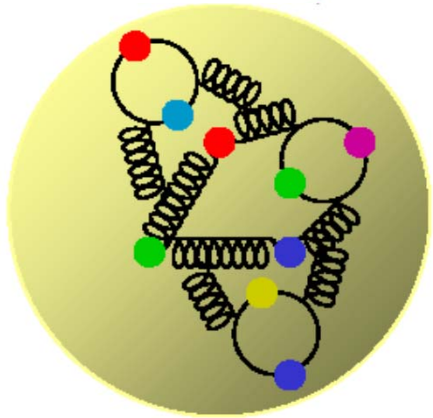

$$\langle N(p')|\psi^\dagger(0)\psi(0)|N(p)\rangle \qquad \int dz^- e^{ixpz}\langle N(p)|\psi^\dagger(0)\psi(z^-)|N(p)\rangle$$

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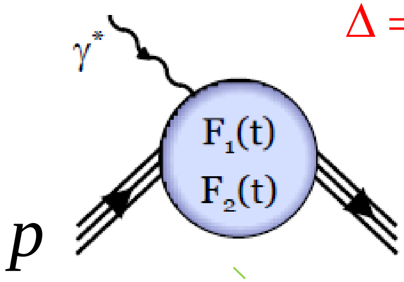

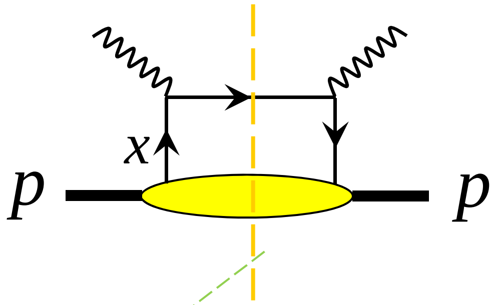

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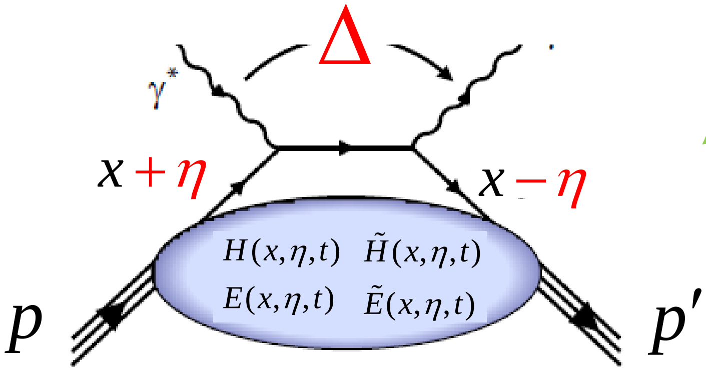

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$$\bar{P} = \frac{p + p'}{2}$$

$$\int \frac{dz^-}{2\pi} e^{i(x+\eta)\bar{P}z} \langle p' | \bar{\psi}(0)\gamma^+\psi(z^-) | p \rangle = \frac{1}{\bar{P}^+}\left[H(x,\eta,t)\bar{u}(p')\gamma^+ u(p) + E(x,\eta,t)\bar{u}(p')\frac{i\sigma^{+\alpha}(p'-p)_\alpha}{2M}u(p) \right]$$

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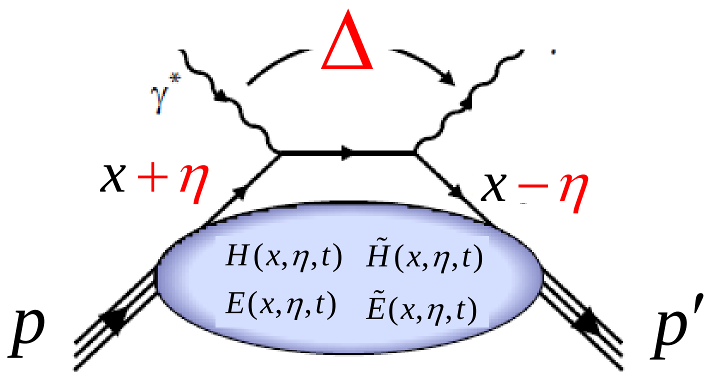

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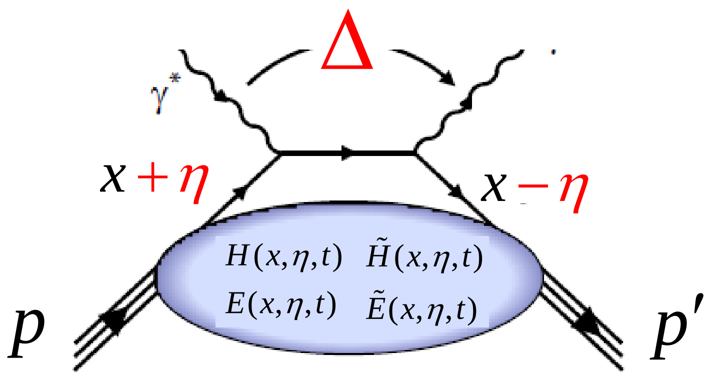
$$J_q = \frac{1}{2}\int_{-1}^{1} dx\, x \left(H(x,\eta,0) + E(x,\eta,0) \right)$$

GPD



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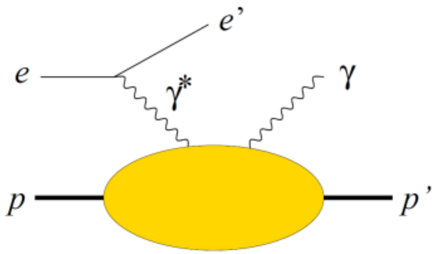

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JLab, HERMES, COMPASS,...

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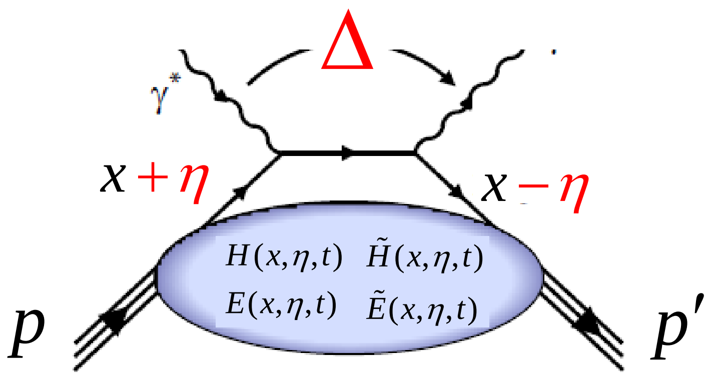

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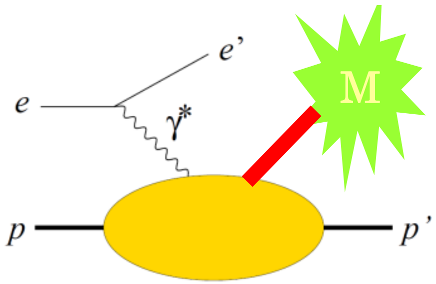

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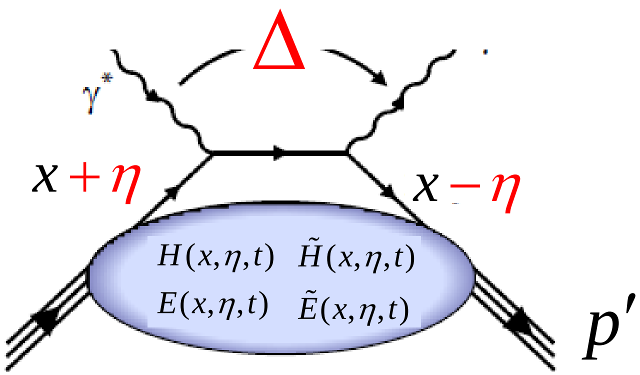

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Exclusive lepton pair production in πN scattering

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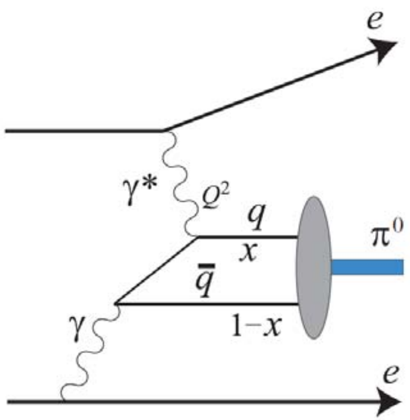

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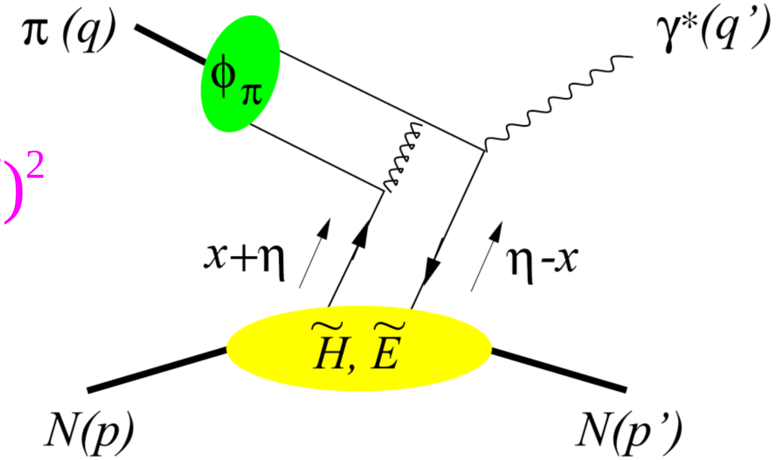

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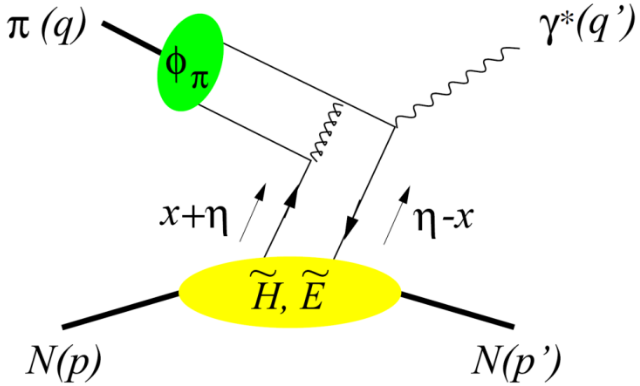
GPD

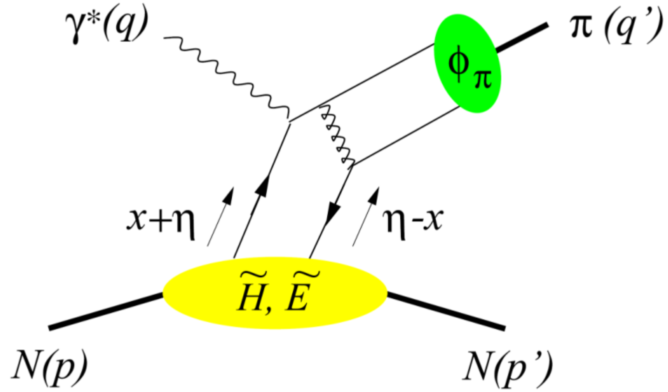
Pion beams reveal $\tilde{H}, \tilde{E}$ Generalized Parton distributions

timelike



exDY@J-PARC

spacelike



DVMP@JLab

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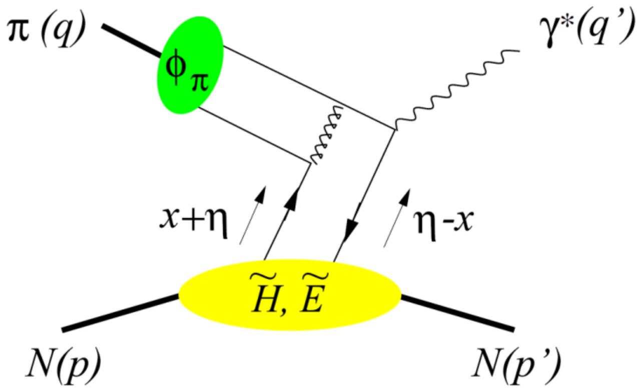

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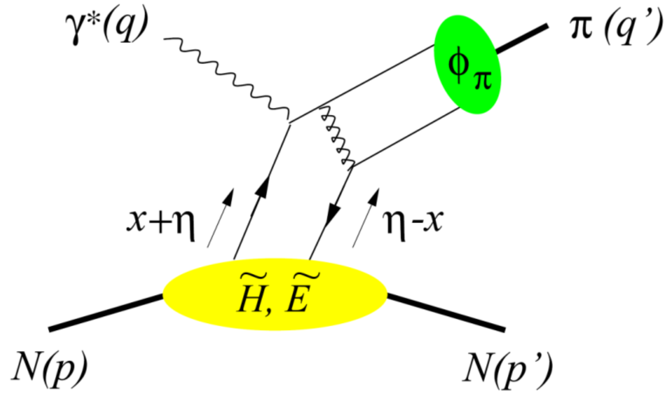

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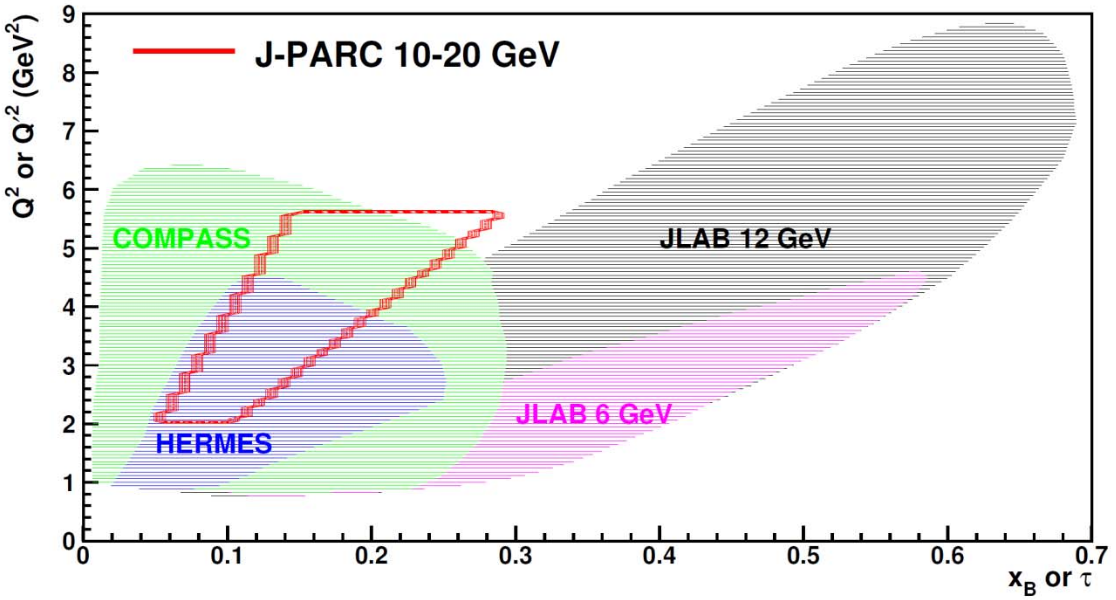
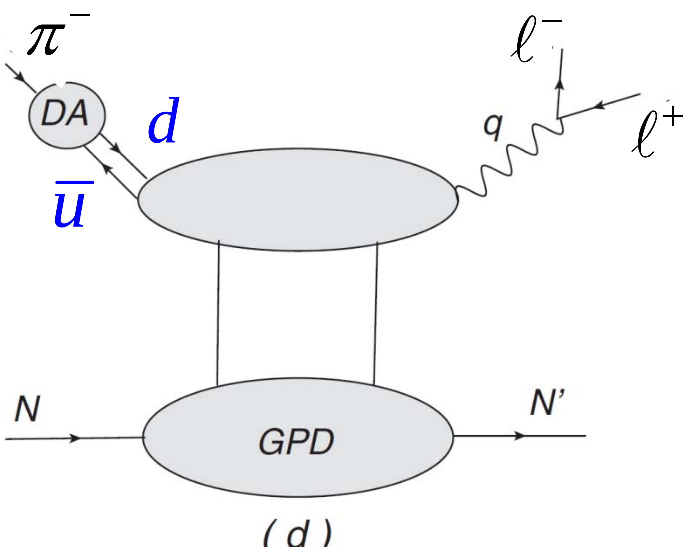
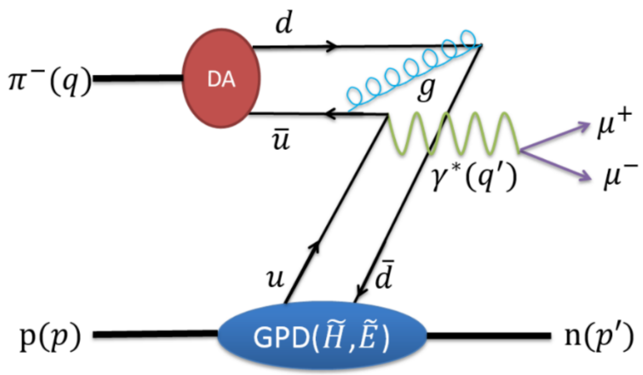


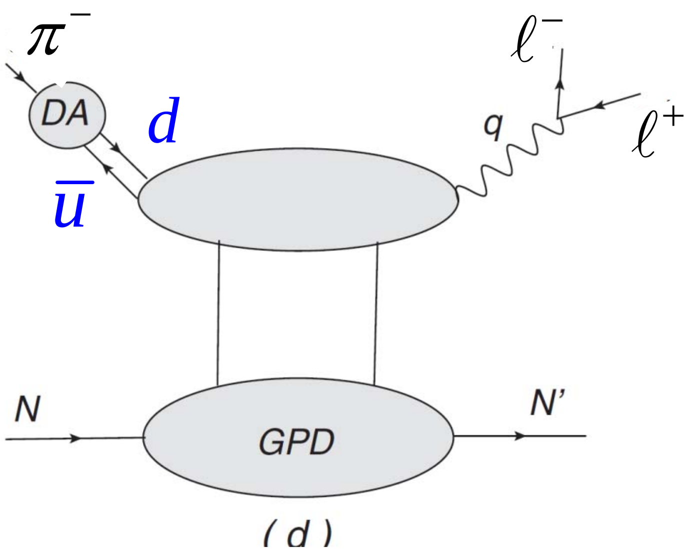
T. Sawada et al., PRD93, 114034



exDY@J-PARC



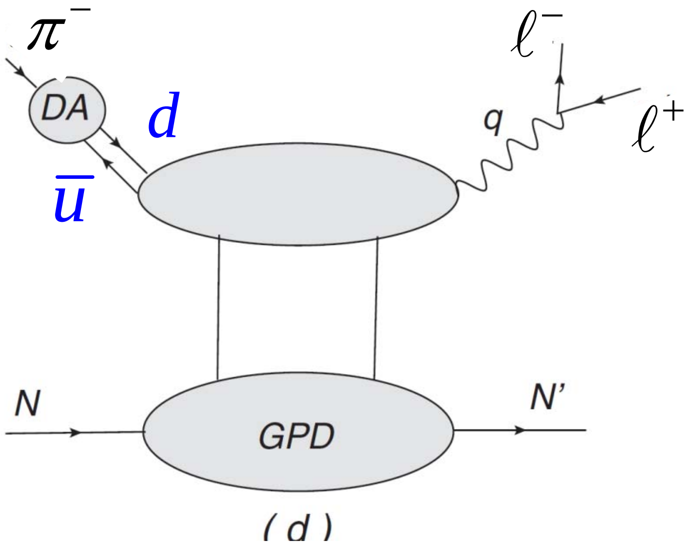
$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) \right| p(p) >= \frac{1}{2P^+} \bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x,\eta,t) \frac{\gamma_5 \Delta^+}{2m_N} \right] u(p)$$



exDY@J-PARC

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) >= \frac{1}{2P^+}\bar{u}(p')\left[\tilde{H}^{du}(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^{du}(x,\eta,t)\frac{\gamma_5\Delta^+}{2m_N} \right] u(p)$$

$$< p(p') \left| \bar{u}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) - \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 d(\frac{z^-}{2}) \right| p(p) >$$



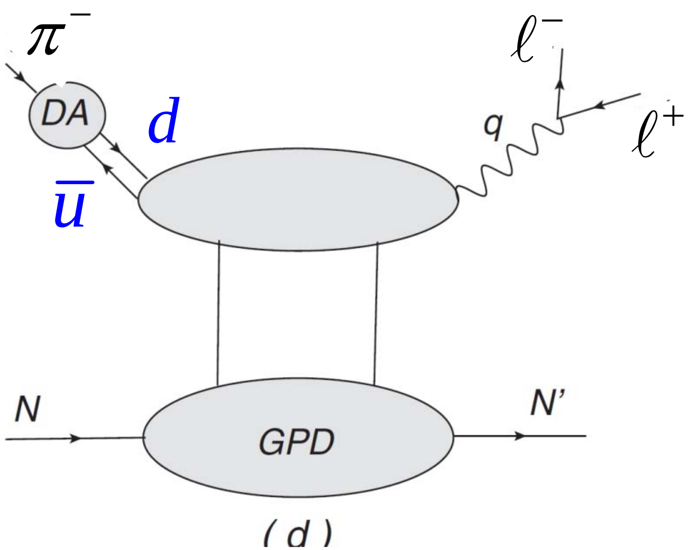
exDY@J-PARC

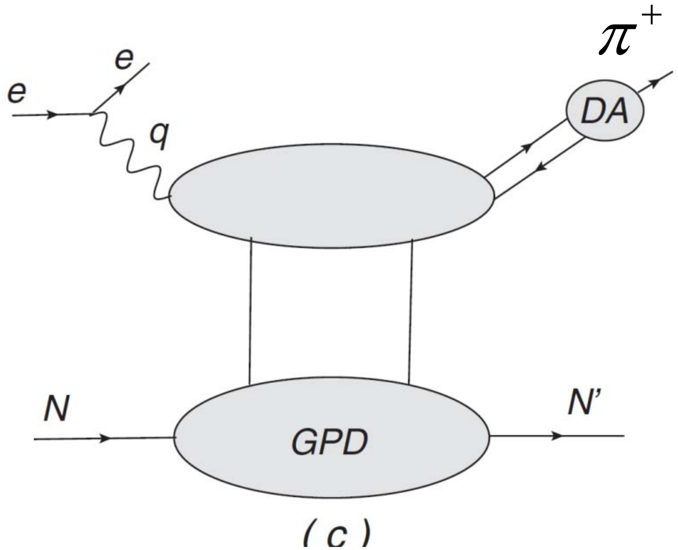
$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) \right| p(p) >= \frac{1}{2P^+} \bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x,\eta,t) \frac{\gamma_5 \Delta^+}{2m_N} \right] u(p)$$

$$< p(p') \left| \bar{u}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) - \bar{d}(-\frac{z^-}{2}) \gamma^+ \gamma_5 d(\frac{z^-}{2}) \right| p(p) >$$

$$\tilde{H}^{du}(x,\eta,t) = \tilde{H}^{u}(x,\eta,t) - \tilde{H}^{d}(x,\eta,t)$$

$$\tilde{E}^{du}(x,\eta,t) = \tilde{E}^{u}(x,\eta,t) - \tilde{E}^{d}(x,\eta,t)$$





exDY@J-PARC **DVMP@HERA,JLab**

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) >= \frac{1}{2P^+}\bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^{du}(x,\eta,t)\frac{\gamma_5\Delta^+}{2m_N} \right] u(p)$$

$$\tilde{H}^{du}(x,\eta,t) = \tilde{H}^{u}(x,\eta,t) - \tilde{H}^{d}(x,\eta,t)$$

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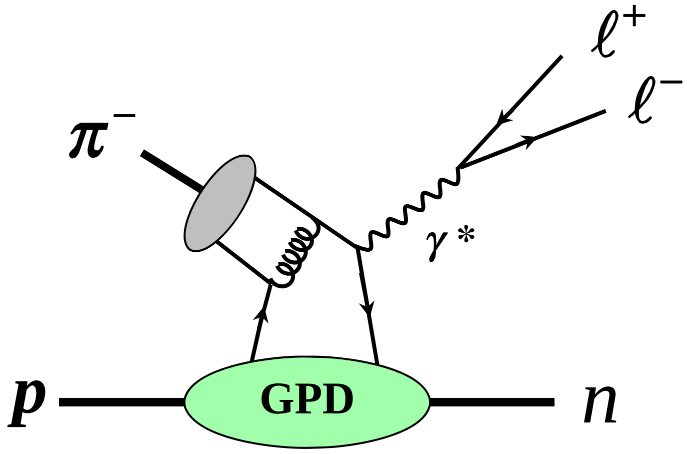

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$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) \right| p(p) >= \frac{1}{2P^+} \bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x,\eta,t) \frac{\gamma_5 \Delta^+}{2m_N} \right] u(p)$$

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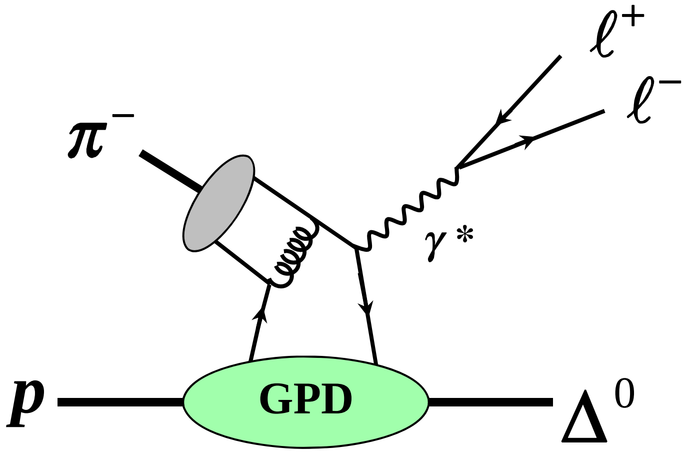
$$\pi^- + p \rightarrow \gamma^* + \Delta^0 \rightarrow \mu^+ + \mu^- + \Delta^0$$



exDY@J-PARC

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) \right| p(p) >= \frac{1}{2P^+} \bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x,\eta,t) \frac{\gamma_5 \Delta^+}{2M} \right] u(p)$$

$$\tilde{H}^{du}(x,\eta,t) = \tilde{H}^{u}(x,\eta,t) - \tilde{H}^{d}(x,\eta,t)$$

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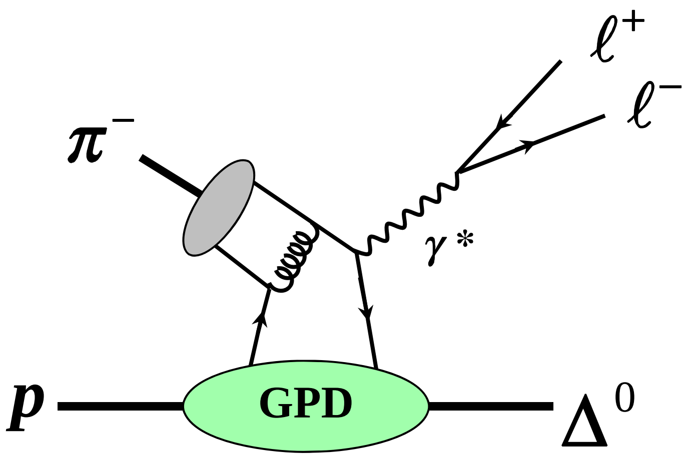
$$\pi^- + p \to \gamma^* + \Delta^0 \to \mu^+ + \mu^- + \Delta^0$$

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < \Delta^0(p') \left| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) >$$



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$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) > = \frac{1}{2P^+}\bar{u}(p')\left[\tilde{H}^{du}(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^{du}(x,\eta,t)\frac{\gamma_5\Delta^+}{2M} \right] u(p)$$

$$\tilde{H}^{du}(x,\eta,t) = \tilde{H}^{u}(x,\eta,t) - \tilde{H}^{d}(x,\eta,t)$$

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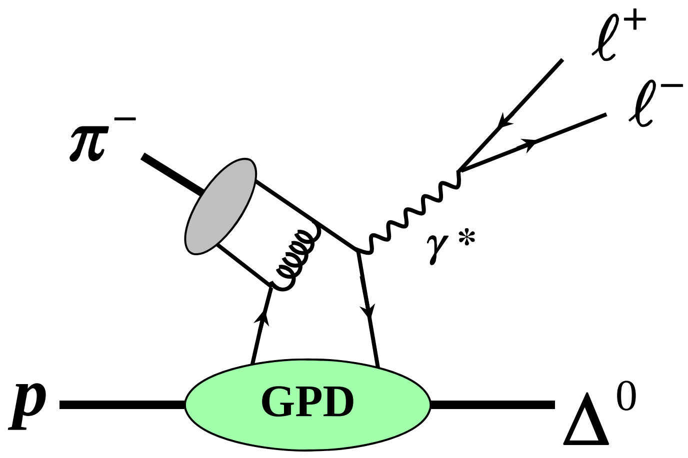

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} \left\langle \Delta^0(p') \middle| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \middle| p(p) \right\rangle$$

$$= \frac{1}{2}\int \frac{dz^-}{4\pi} e^{ix\bar{P}z}$$

$$\times \left\langle \Delta^+(p') \middle| \bar{u}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) - \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 d(\frac{z^-}{2}) \middle| p(p) \right\rangle$$

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} \left\langle n(p') \middle| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \middle| p(p) \right\rangle = \frac{1}{2P^+}\bar{u}(p')\left[\tilde{H}^{du}(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^{du}(x,\eta,t)\frac{\gamma_5\Delta^+}{2M}\right]u(p)$$

$$\tilde{H}^{du}(x,\eta,t) = \tilde{H}^u(x,\eta,t) - \tilde{H}^d(x,\eta,t)$$

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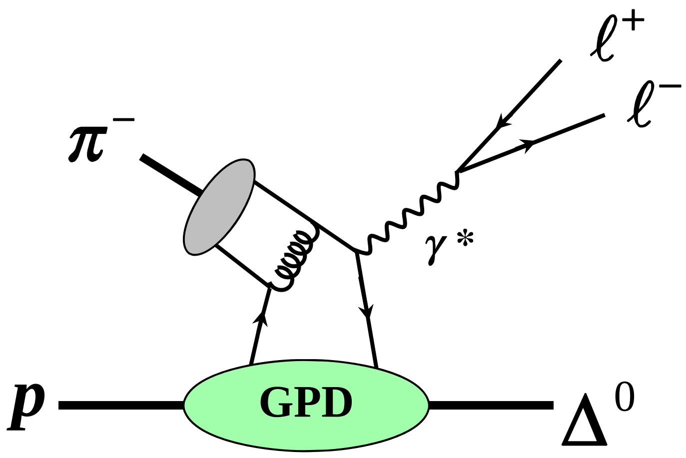
$$\pi^- + p \to \gamma^* + \Delta^0 \to \mu^+ + \mu^- + \Delta^0$$



$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < \Delta^0(p') \left| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) >$$

$$= \frac{1}{2}\int \frac{dz^-}{4\pi} e^{ix\bar{P}z}$$

$$\times < \Delta^+(p') \left| \bar{u}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) - \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 d(\frac{z^-}{2}) \right| p(p) >$$

$$= \frac{1}{\sqrt{2}}\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < p(p') \left| \bar{u}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) - \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 d(\frac{z^-}{2}) \right| p(p) > + O\left(\frac{1}{N_c}\right)$$

$$N_c \to \infty \quad \Delta \Leftrightarrow p$$

Goeke, Polyakov, Vanderhaeghen, Prog. Part. Nucl. Phys.47 ('01) 401

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) > = \frac{1}{2P^+}\bar{u}(p')\left[\tilde{H}^{du}(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^{du}(x,\eta,t)\frac{\gamma_5\Delta^+}{2M} \right] u(p)$$

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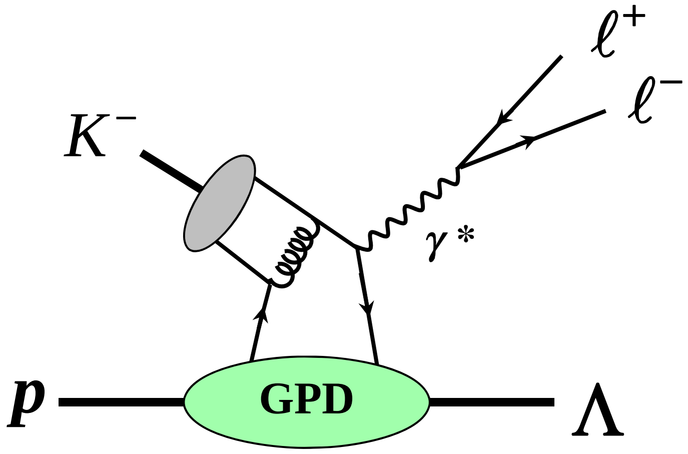
$$K^- + p \to \gamma^* + \Lambda \to \mu^+ + \mu^- + \Lambda$$



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$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) \right| p(p) \; >= \frac{1}{2P^+} \bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x,\eta,t) \frac{\gamma_5 \Delta^+}{2M} \right] u(p)$$

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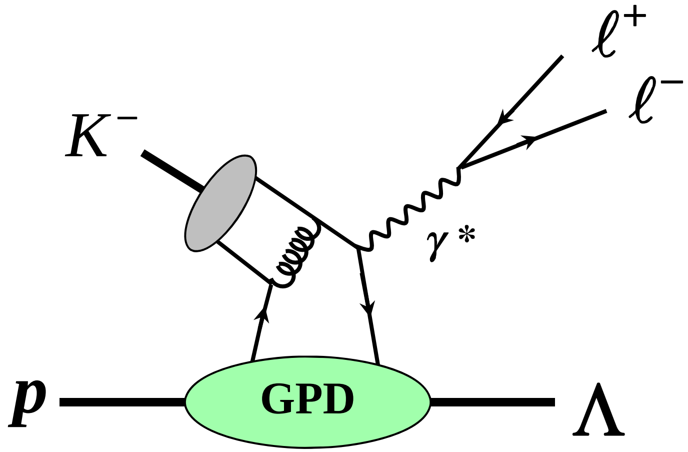
$$K^- + p \to \gamma^* + \Lambda \to \mu^+ + \mu^- + \Lambda$$

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < \Lambda(p') \left| \bar{s}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) >$$



exDY@J-PARC

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) >= \frac{1}{2P^+}\bar{u}(p')\left[\tilde{H}^{du}(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^{du}(x,\eta,t)\frac{\gamma_5\Delta^+}{2M} \right] u(p)$$

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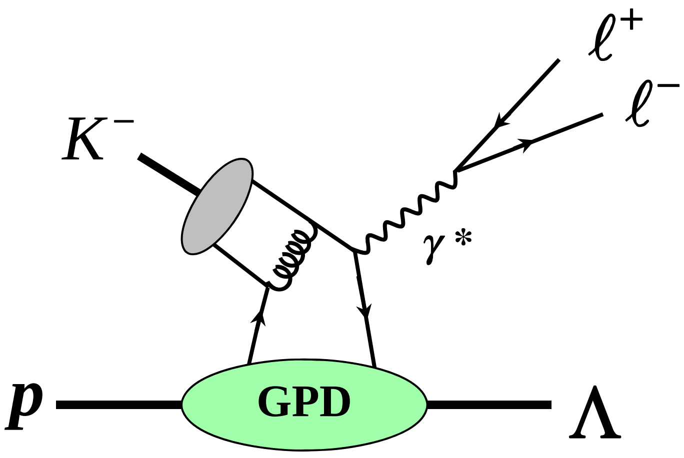
$$K^- + p \to \gamma^* + \Lambda \to \mu^+ + \mu^- + \Lambda$$



$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < \Lambda(p') \left| \bar{s}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) \right| p(p) >$$

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

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) \right| p(p) >= \frac{1}{2P^+} \bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x,\eta,t) \frac{\gamma_5 \Delta^+}{2M} \right] u(p)$$

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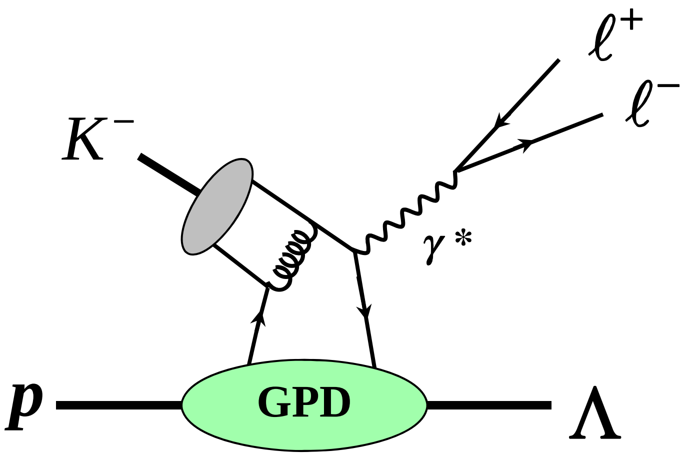
$$K^- + p \to \gamma^* + \Lambda \to \mu^+ + \mu^- + \Lambda$$



$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < \Lambda(p') \left| \bar{s}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) >$$

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

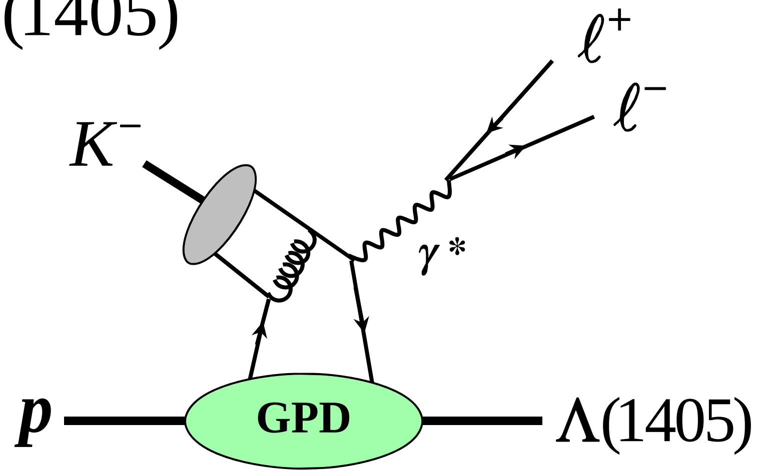
$$\tilde{H}^{su}_{\Lambda p} = \frac{-1}{\sqrt{6}}\left(2\tilde{H}^u - \tilde{H}^d - \tilde{H}^s\right)$$

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) > = \frac{1}{2P^+} \bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^{du}(x,\eta,t)\frac{\gamma_5\Delta^+}{2M} \right] u(p)$$

$$\tilde{H}^{du}(x,\eta,t) = \tilde{H}^u(x,\eta,t) - \tilde{H}^d(x,\eta,t)$$

$$\tilde{E}^{du}(x,\eta,t) = \tilde{E}^u(x,\eta,t) - \tilde{E}^d(x,\eta,t)$$

$$K^- + p \to \gamma^* + \Lambda(1405) \to \mu^+ + \mu^- + \Lambda(1405)$$



$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < \Lambda_{1405}(p') \left| \bar{s}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) \right| p(p) >$$

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) \right| p(p) > = \frac{1}{2P^+} \bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x,\eta,t) \frac{\gamma_5 \Delta^+}{2M} \right] u(p)$$

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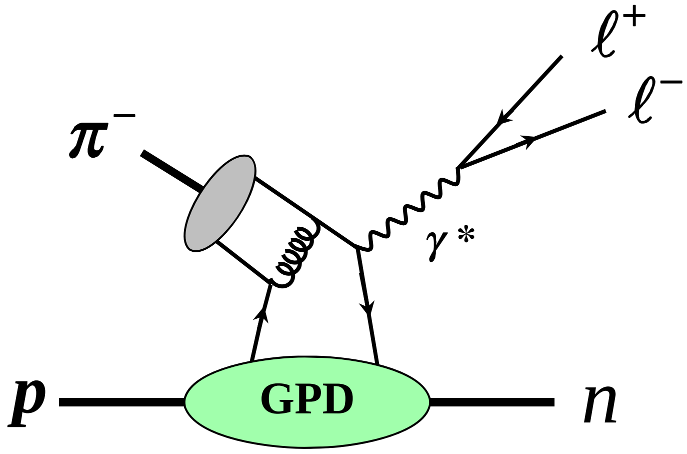

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$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) \right| p(p) >= \frac{1}{2P^+} \bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x,\eta,t) \frac{\gamma_5 \Delta^+}{2m_N} \right] u(p)$$

$$\tilde{H}^{du}(x,\eta,t) = \tilde{H}^{u}(x,\eta,t) - \tilde{H}^{d}(x,\eta,t)$$

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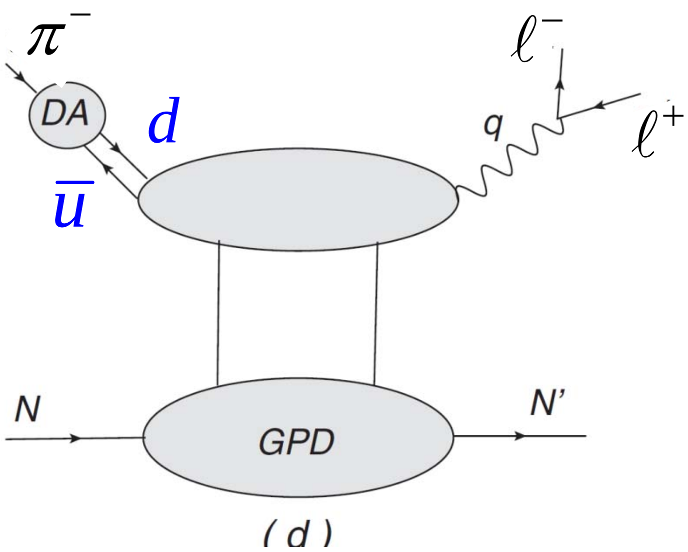


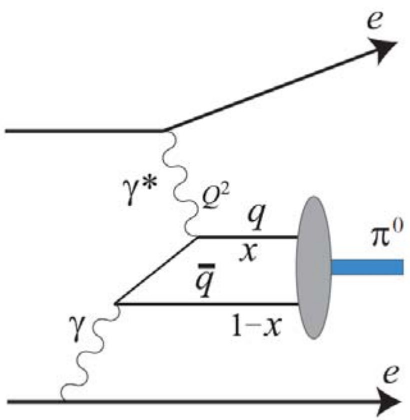
exDY@J-PARC

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z} < n(p') \left| \bar{d}(-\frac{z^-}{2})\gamma^+\gamma_5 u(\frac{z^-}{2}) \right| p(p) >= \frac{1}{2P^+}\bar{u}(p') \left[\tilde{H}^{du}(x,\eta,t)\gamma^+\gamma_5 + \tilde{E}^{du}(x,\eta,t)\frac{\gamma_5\Delta^+}{2m_N} \right] u(p)$$

$$\tilde{H}^{du}(x,\eta,t) = \tilde{H}^u(x,\eta,t) - \tilde{H}^d(x,\eta,t)$$
$$\tilde{E}^{du}(x,\eta,t) = \tilde{E}^u(x,\eta,t) - \tilde{E}^d(x,\eta,t)$$

Exclusive lepton pair production in πN scattering

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

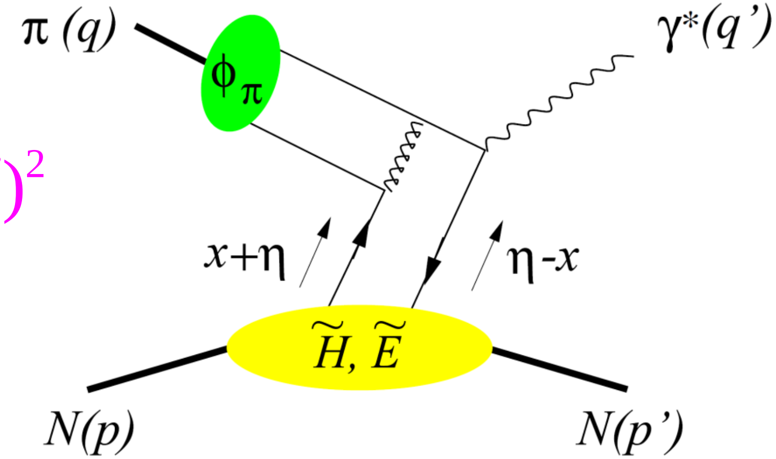


@Belle, Babar

"exclusive DY"

LO in QCD factorization

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



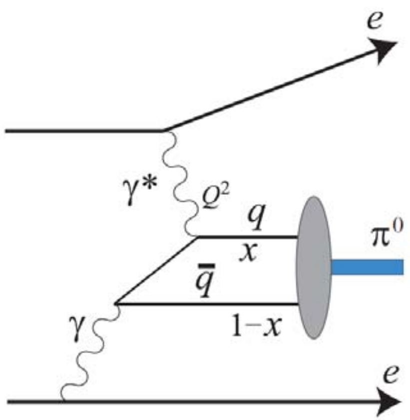
$$\int dz^- e^{i(x+\eta)pz} \langle N(p') | \psi^\dagger(0) \psi(z^-) | N(p) \rangle$$

GPD

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 DY"

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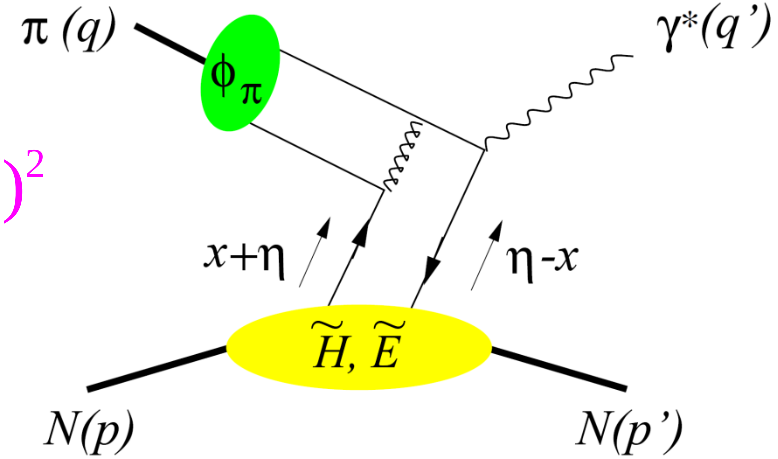


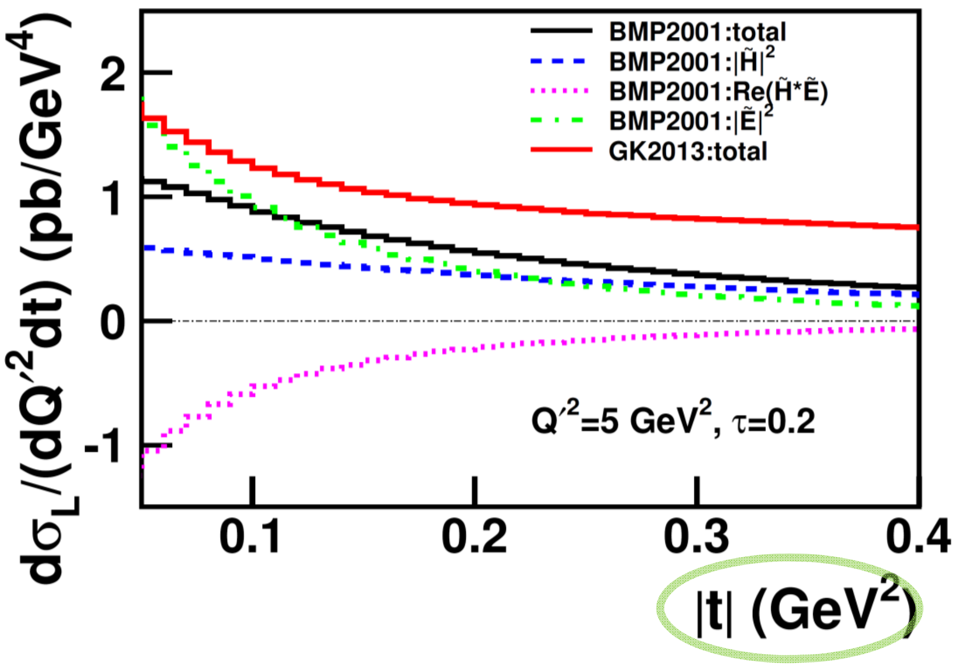
$$\int dz^- e^{i(x+\eta)pz} \langle N(p') | \psi^\dagger(0) \psi(z^-) | N(p) \rangle$$

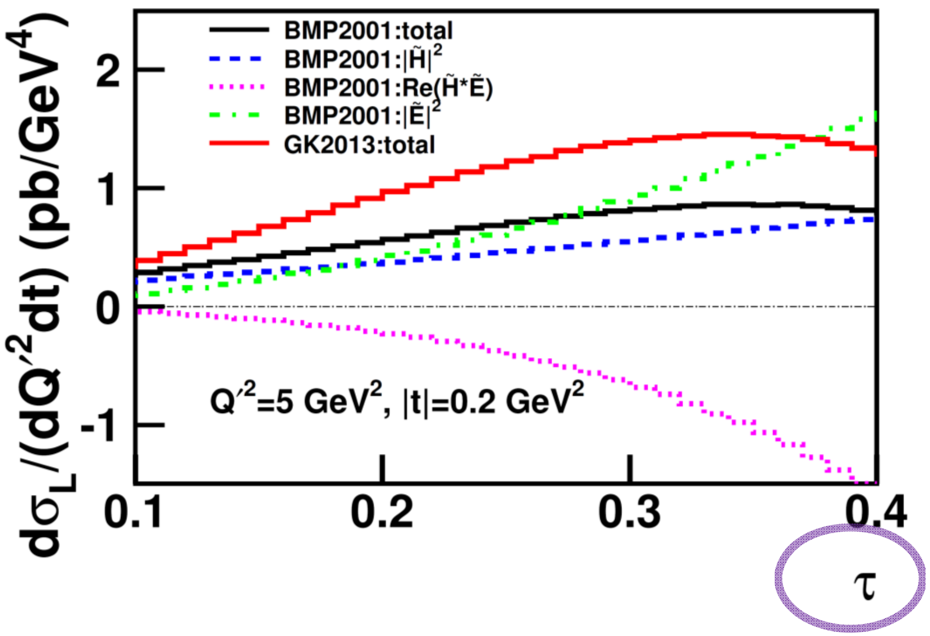
GPD

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

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

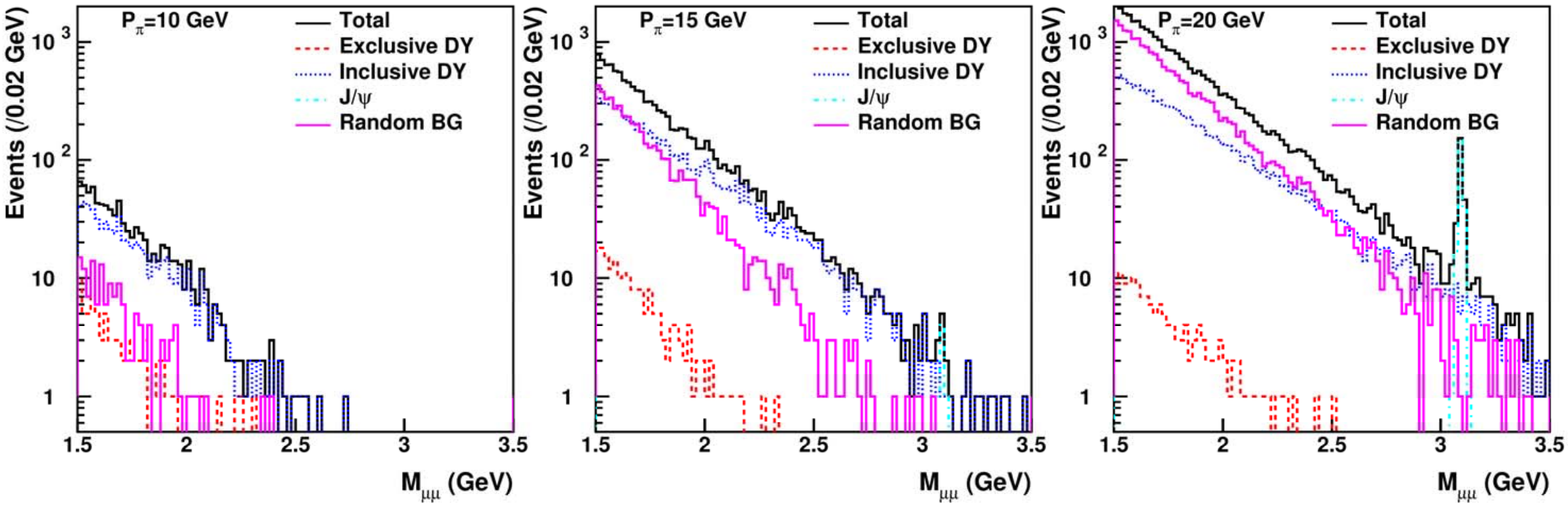
$$Q'^2 = 5\ \mathrm{GeV}^2$$





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

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



feasibility with E50 spectrometer at J-PARC

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

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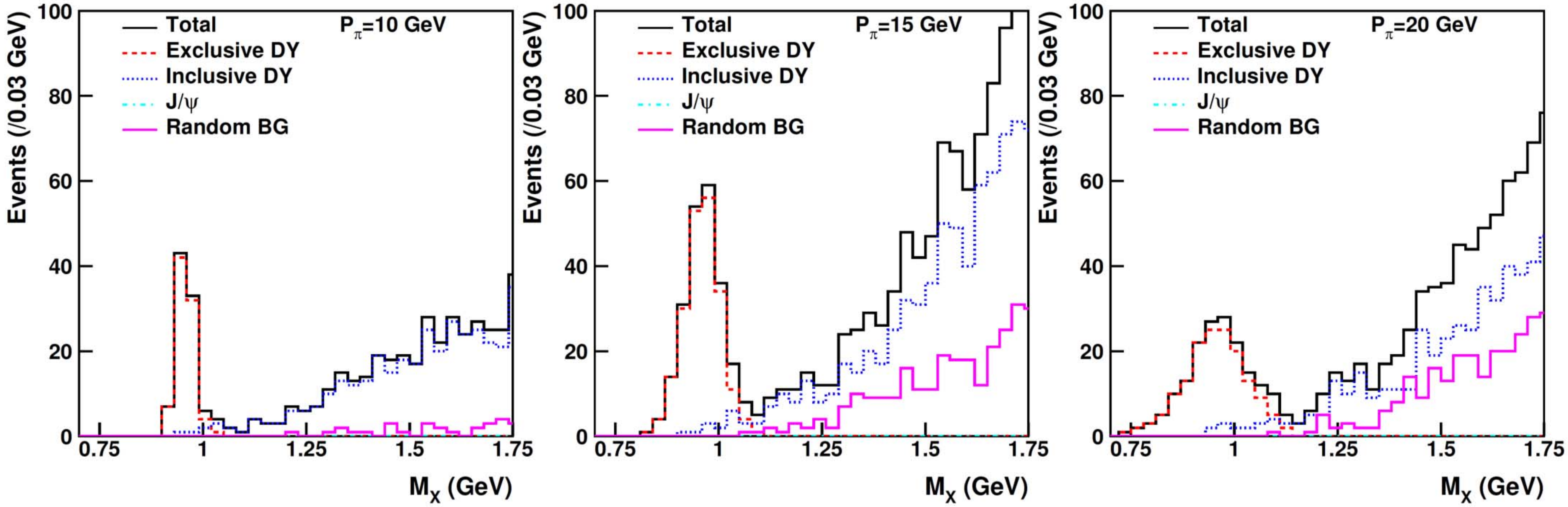

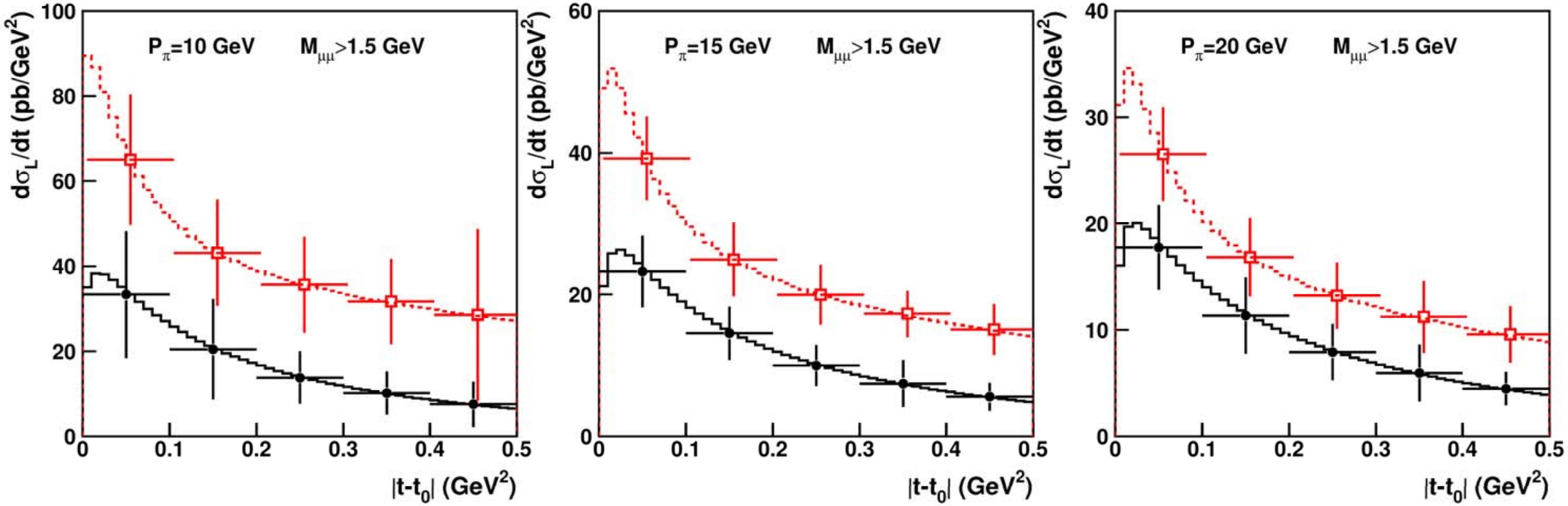

feasibility with E50 spectrometer at J-PARC

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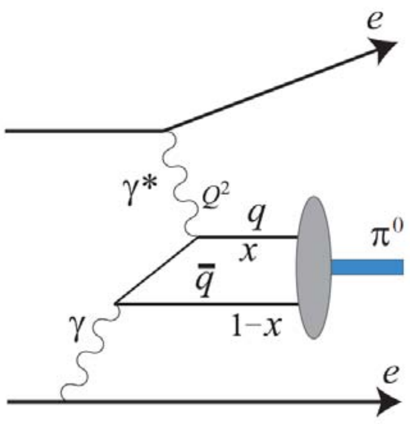
Exclusive lepton pair production in πN scattering

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

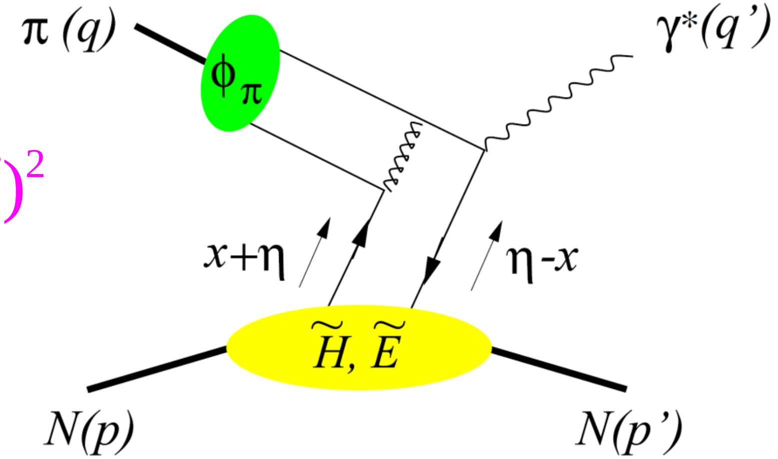


@Belle, Babar

"exclusive DY"

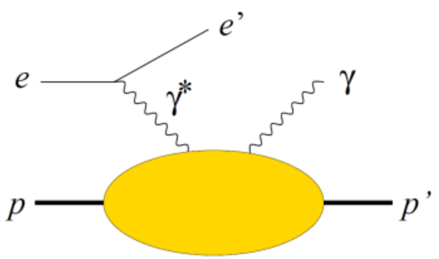
LO in QCD factorization

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



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

GPD



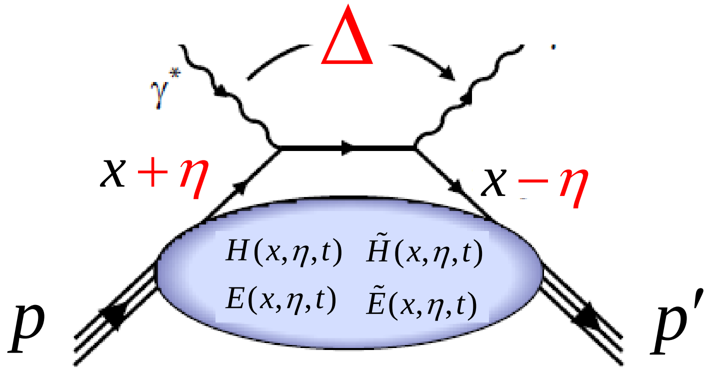
$$\bar{P} = \frac{p+p'}{2}$$

JLab, HERMES, COMPASS,…

$$\int \frac{dz^-}{2\pi} e^{i(x+\eta)\bar{P}z} \langle p' | \bar{\psi}(0)\gamma^+ \psi(z^-) | p \rangle = \frac{1}{\bar{P}^+}\left[H(x,\eta,t)\bar{u}(p')\gamma^+ u(p) + E(x,\eta,t)\bar{u}(p')\frac{i\sigma^{+\alpha}(p'-p)_\alpha}{2M}u(p) \right]$$

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

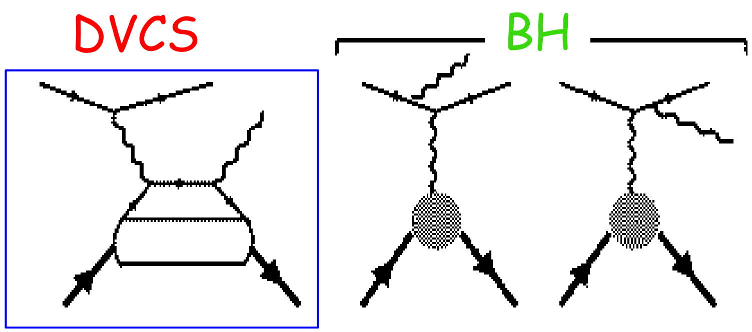
GPD



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

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

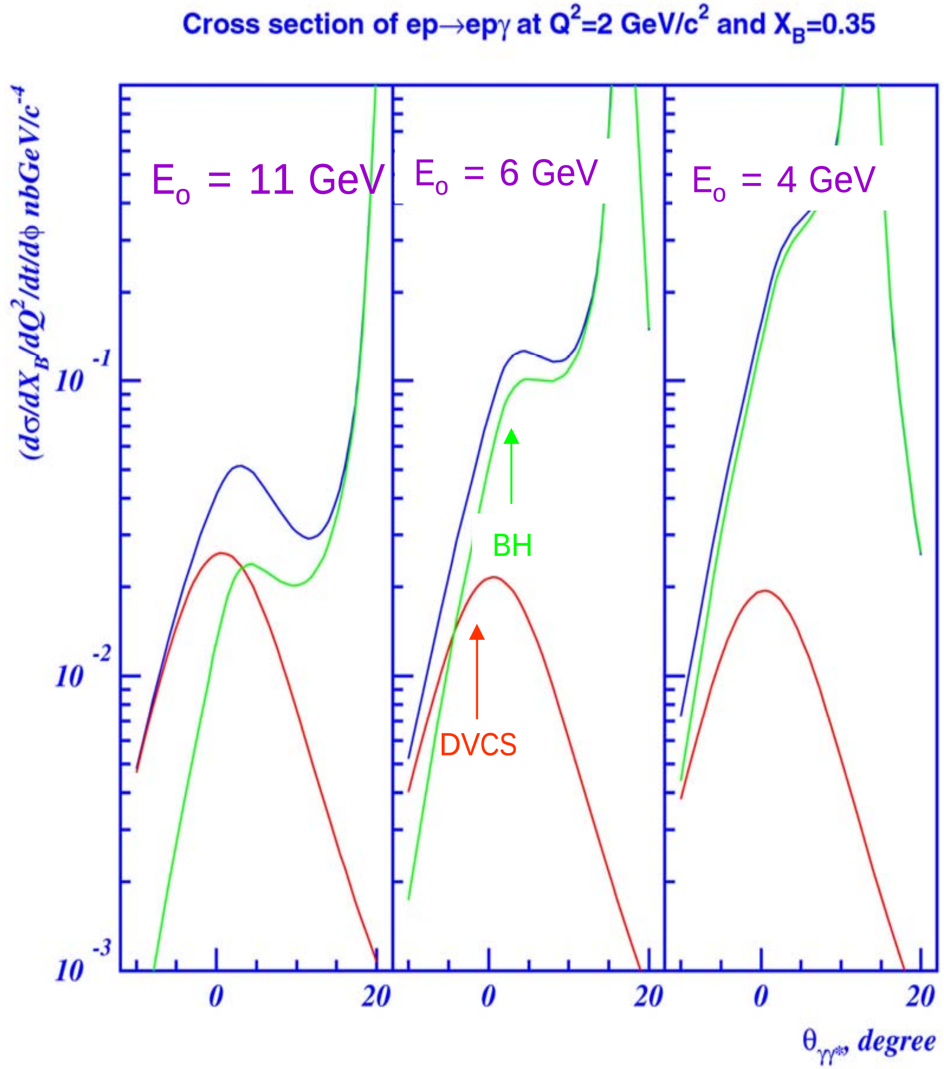
Accessing GPDs through polarized DVCS



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

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

T^{DVCS}: complex, determined by GPDs



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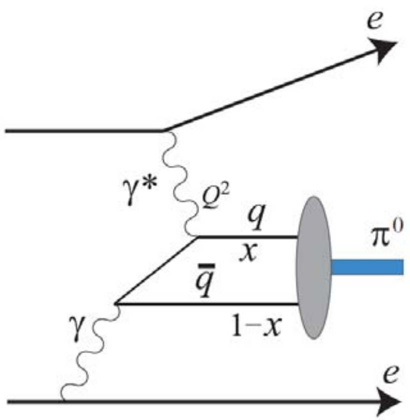

@Belle, Babar

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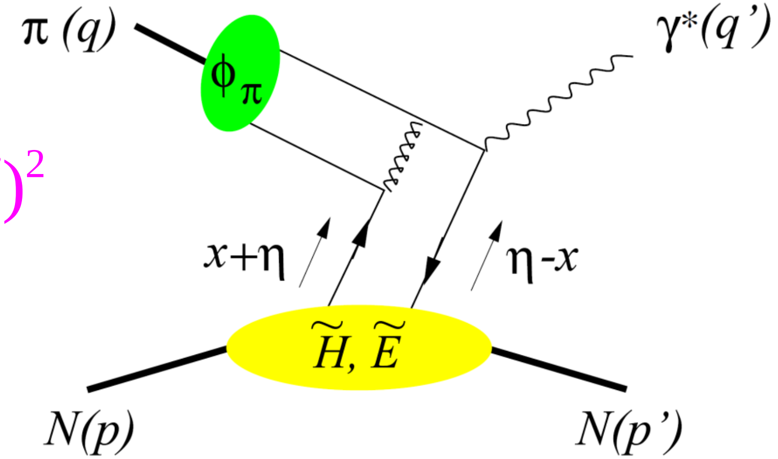

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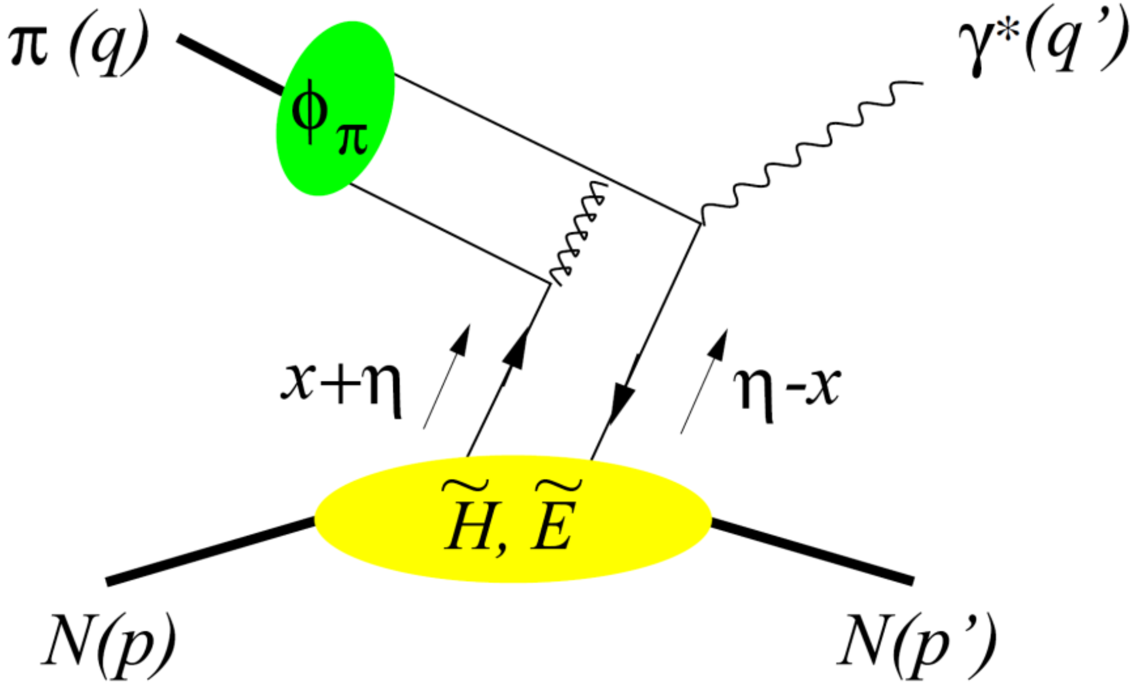
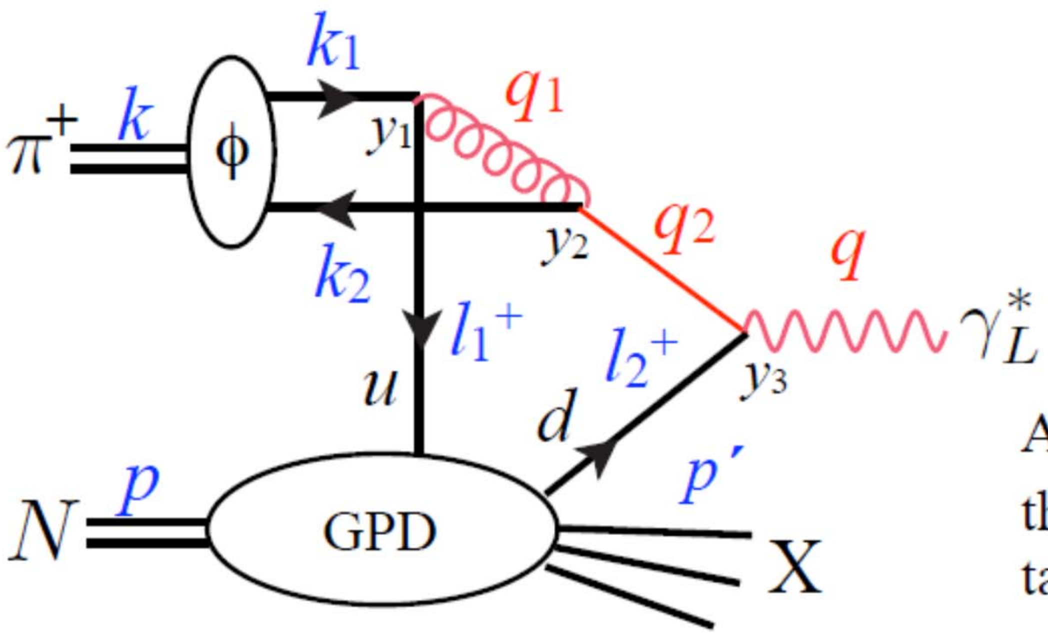
GPD


π (q)
γ*(q')
φπ
x+η
η-x
H̃, Ẽ
N(p)
N(p')

Hence the stopped quark should be connected to the target:

$k_1 = (0^+, uk^-, \boldsymbol{k}_\perp)$
$k_2 = (0^+, (1-u)k^-, -\boldsymbol{k}_\perp)$



Since $q_1^2 \approx -uk^- l_1^+ \to \infty$

the pion wave function contributes through its *distribution amplitude* ϕ

Also q_2^2, q_1^-, $q_2^- \to \infty$, hence the space-time separation of the target interaction points y_1, y_3 is

$$|\boldsymbol{y}_{1\perp} - \boldsymbol{y}_{3\perp}| = \mathcal{O}(1/Q) \to 0$$
$$|y_1^+ - y_3^+| = \mathcal{O}(1/Q^2) \to 0$$
$$|y_1^- - y_3^-| = \mathcal{O}(1/\ell_1^+) \text{ finite}$$

For each final state X the target matrix element is given by a GPD with skewness

$$l_2^+ - l_1^+ = q^+ = x_B\, p^+$$

Using perturbative propagators for the gluon q_1 and d-quark q_2 and adding three more diagrams we get

Hence the stopped quark should be connected to the target:

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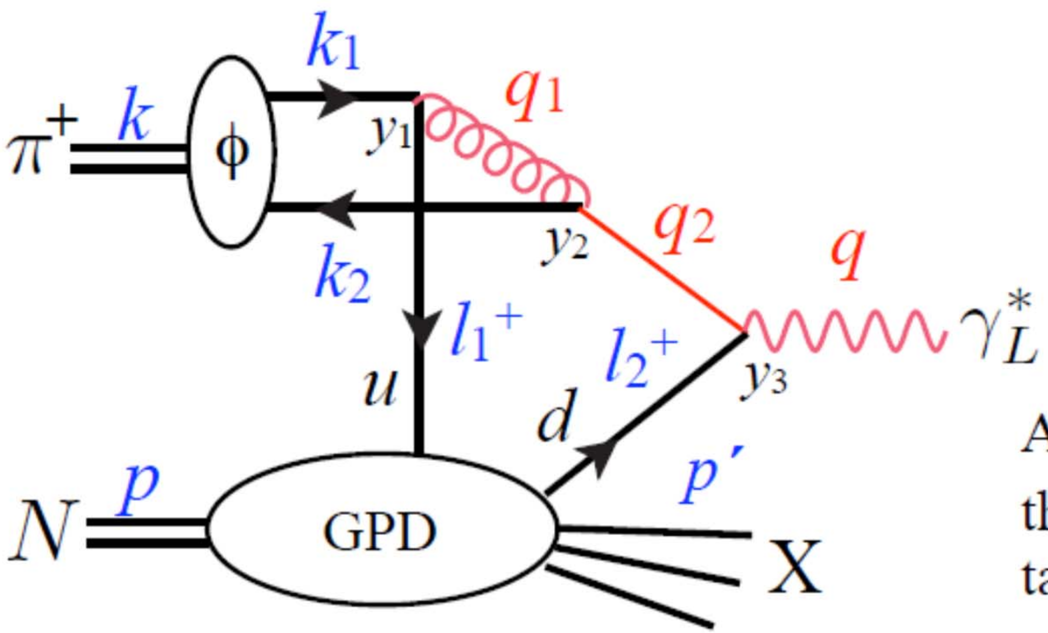

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end-point $(u \to 0,\ 1)$ **behaviors:**

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

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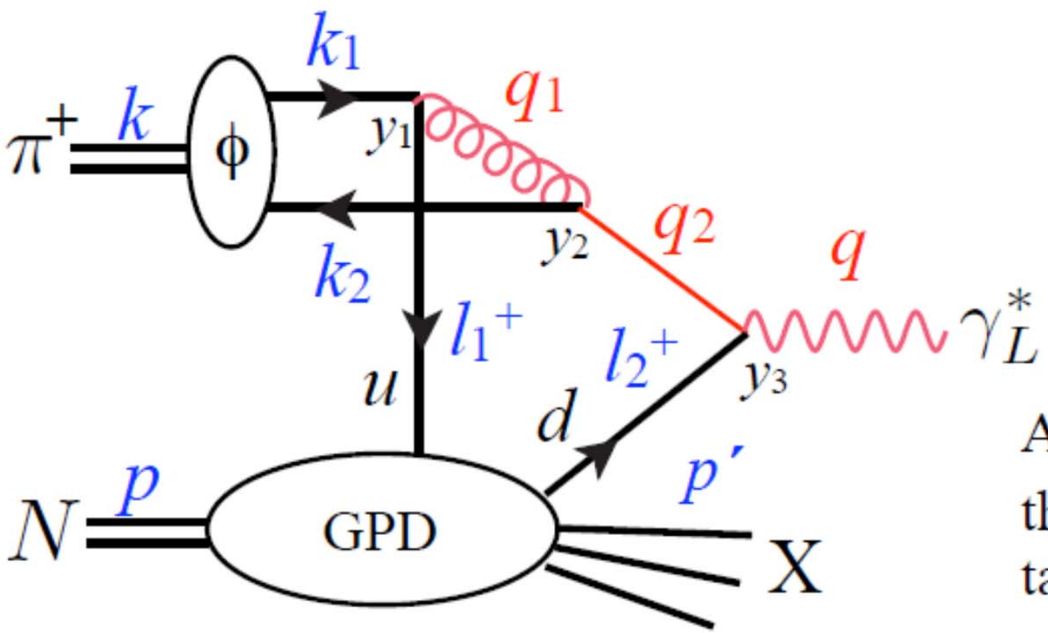

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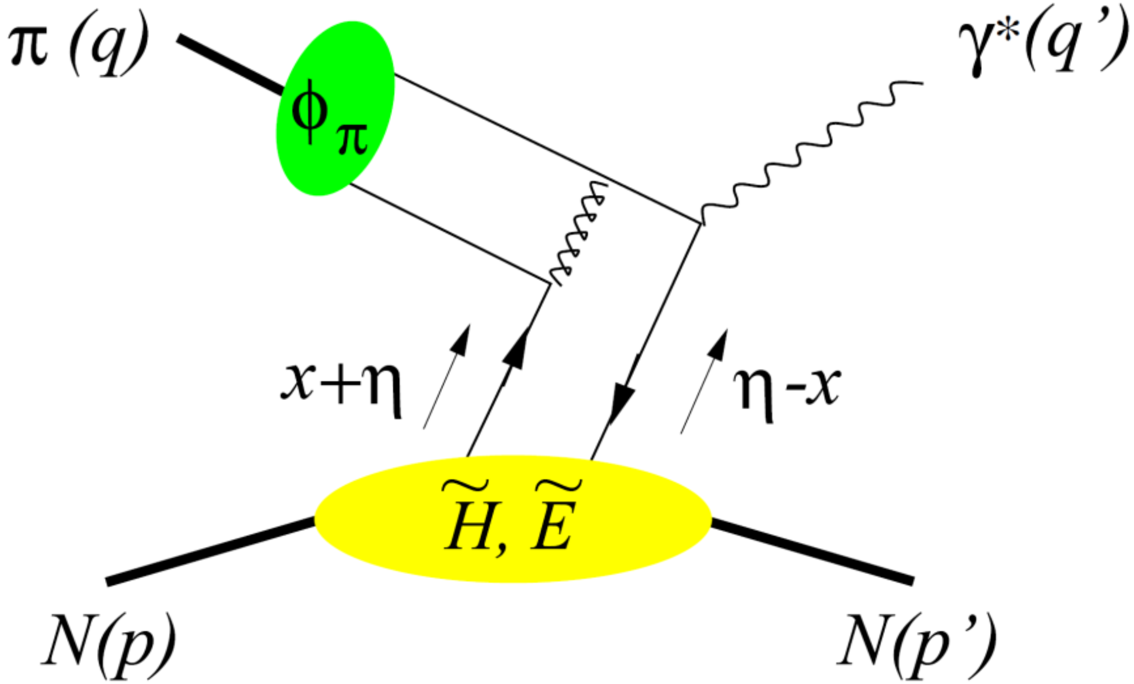
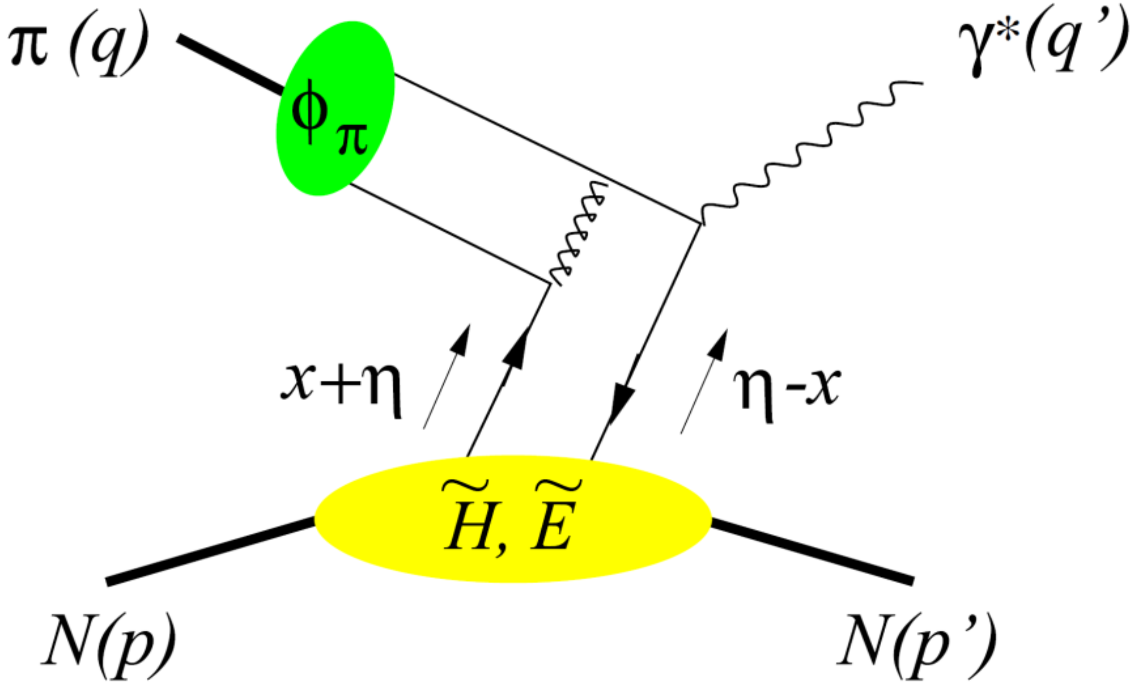
end-point $(u \to 0, 1)$ **behaviors:**

$$\phi_\pi(u) \sim u(1-u) \qquad \phi_{\text{tw.-3}}(u) \sim 1$$



π (q)
γ*(q')
φ_π
x+η
η-x
H̃, Ẽ
N(p)
N(p')



π (q)
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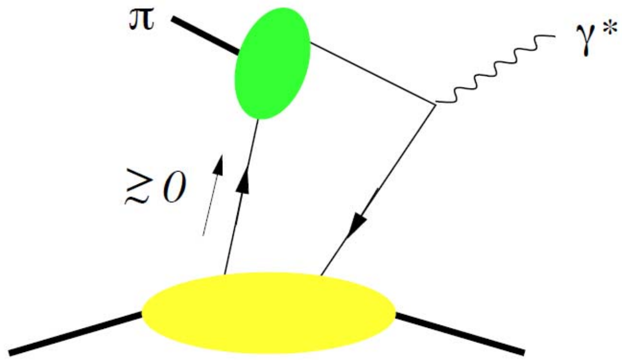
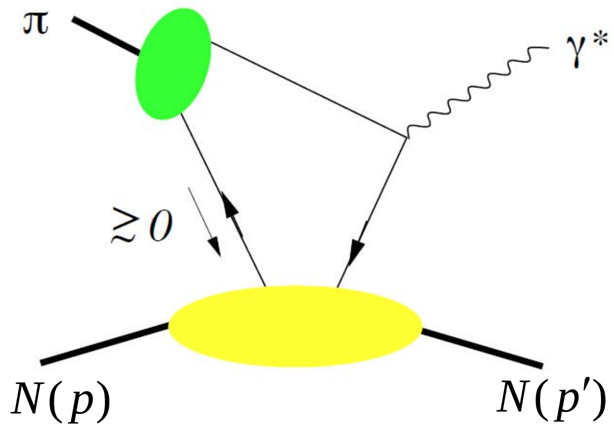
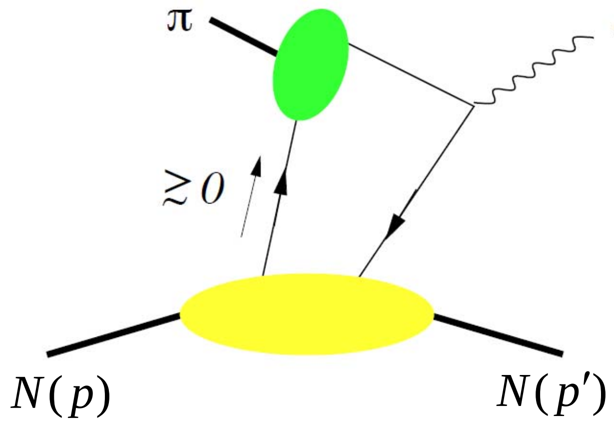
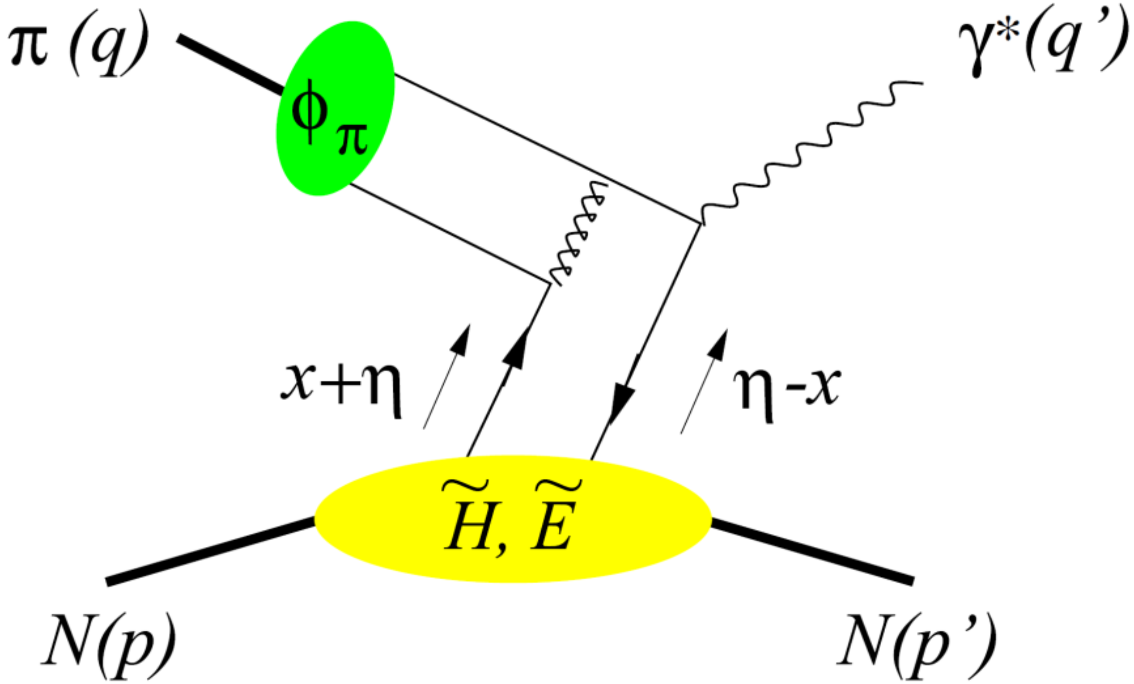
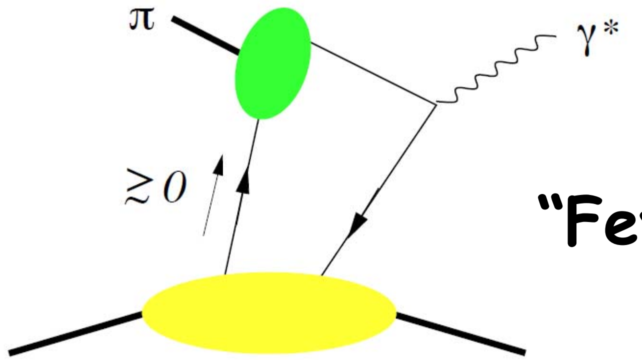


π
γ*
≳ 0

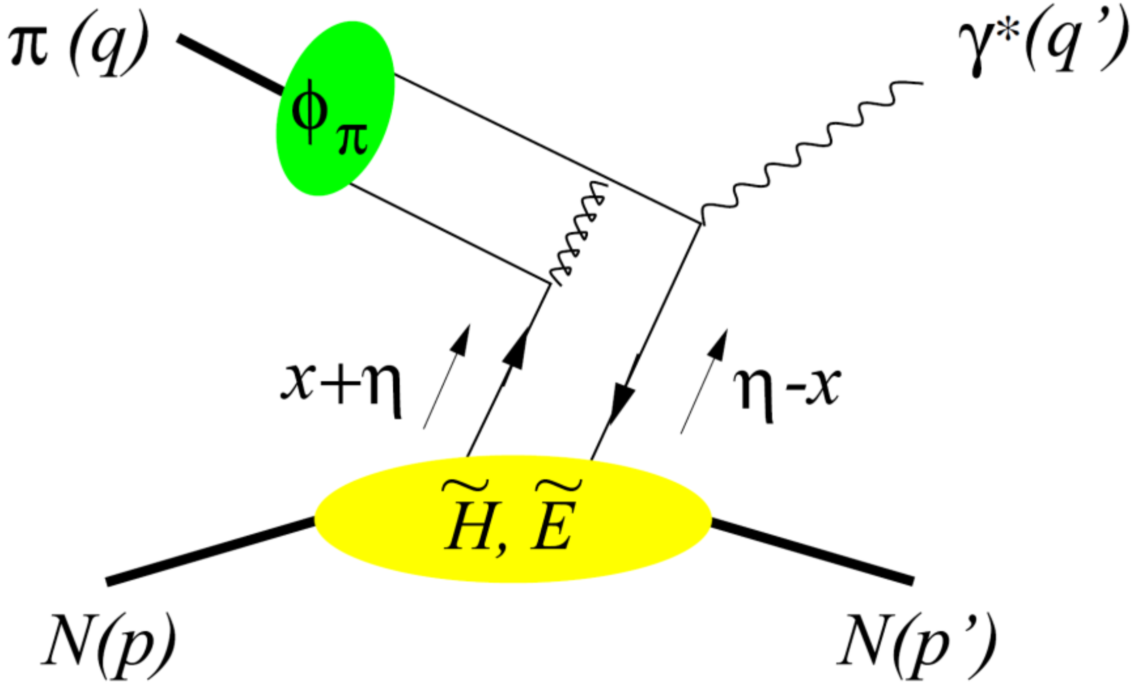

π
γ*
≳0
N(p)
N(p′)

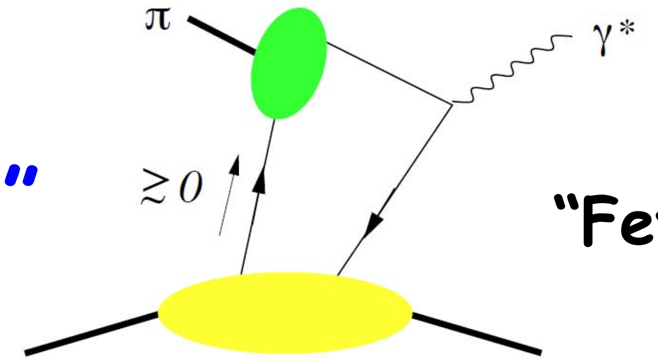

π
γ*
≳0
N(p)
N(p′)





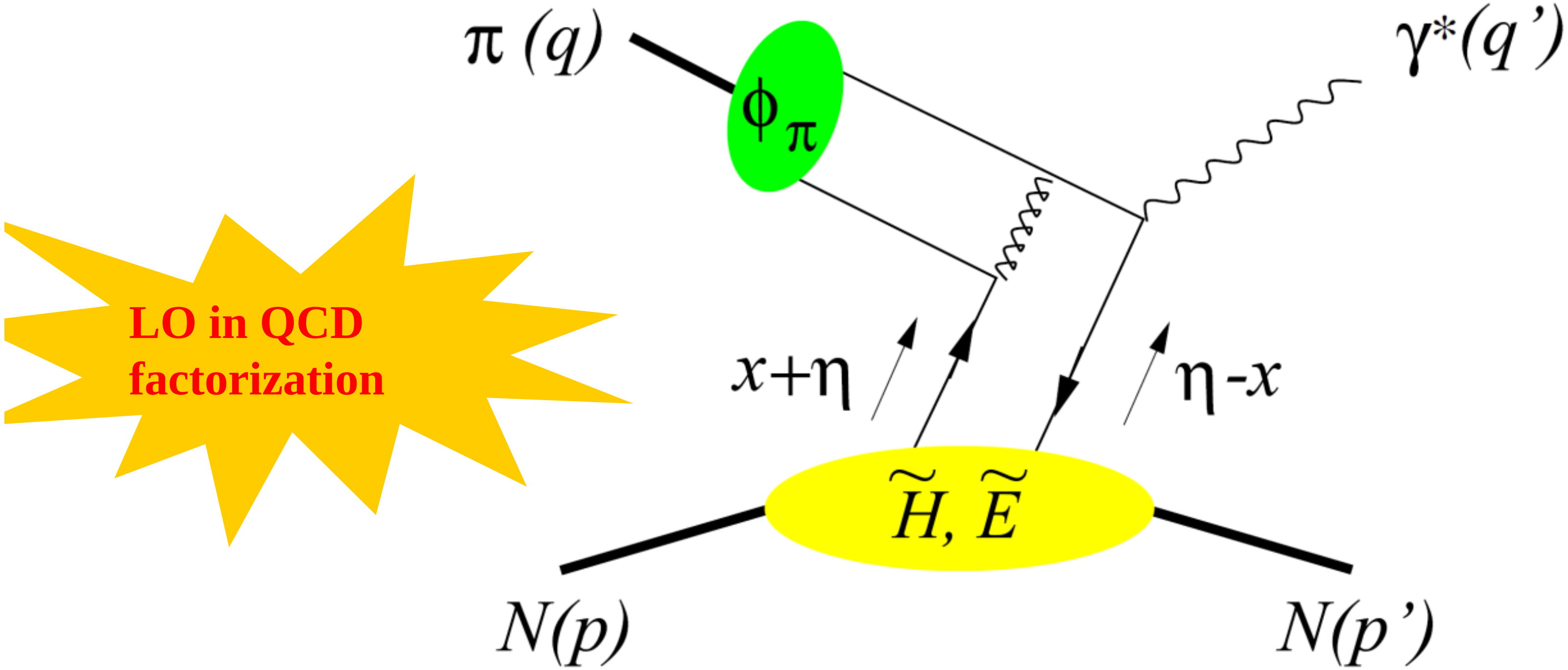
"Feynman mechanism"





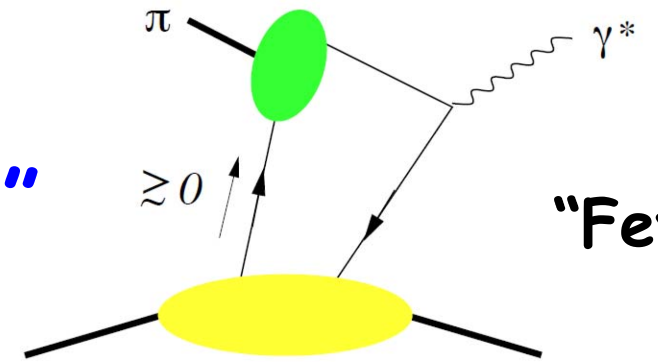
"nonfactorizable"

"Feynman mechanism"



Berger, Diehl, Pire, PLB523(2001)265

"nonfactorizable"



"Feynman mechanism"

Nonfactorizable mechanisms should be suppressed at $Q^2 \to \infty$

Brodsky, Lepage, Chernyak,…
Collins, Strikman, …

Nonfactorizable mechanisms should be suppressed at $Q^2 \to \infty$

Brodsky, Lepage, Chernyak,…
Collins, Strikman, …

VOLUME 52, NUMBER 13 PHYSICAL REVIEW LETTERS 26 MARCH 1984

Asymptotic Q^2 for Exclusive Processes in Quantum Chromodynamics

Nathan Isgur[(a)] and C. H. Llewellyn Smith
Department of Theretical Physics, University of Oxford, Oxford OX1 3NP, England, United Kingdom
(Received 19 October 1983)

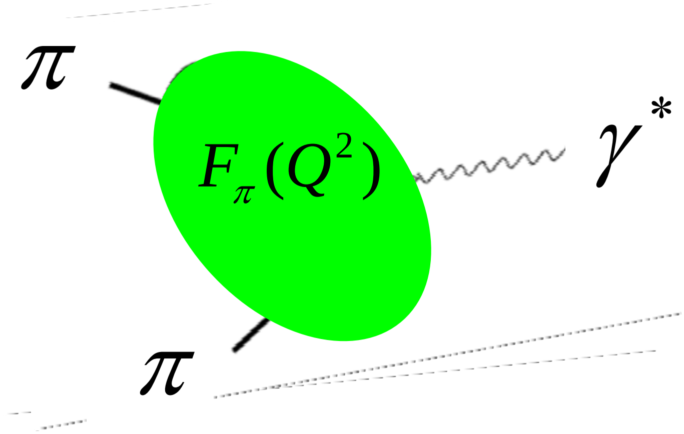
It is found that at available Q^2 the calculable perturbative contributions to the pion electric form factor $F_\pi(Q^2)$ and the nucleon magnetic form factors $G_M^N(Q^2)$ are much smaller than the data, which can probably be explained by soft contributions. Both hard and soft effects are estimated from light-cone/infinite-momentum-frame wave functions suggested by quark models, but the main conclusions have a more general validity.

PACS numbers: 12.35.Eq, 13.40.Fn

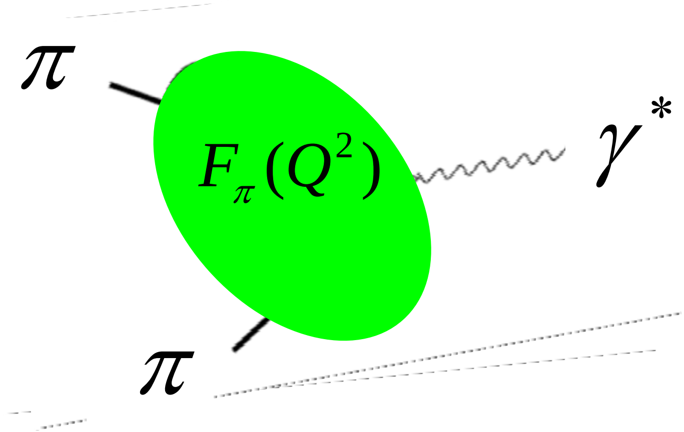
It has been convincingly argued[1-3] that the asymptotic behavior of many exclusive processes is calculable in perturbative QCD. We show here that in the case of elastic form factors these calculable contributions are unlikely to dominate at available momentum transfers. We therefore wish to sound a note of caution about attempts[2,3] to explain existing exclusive data by perturbative QCD.

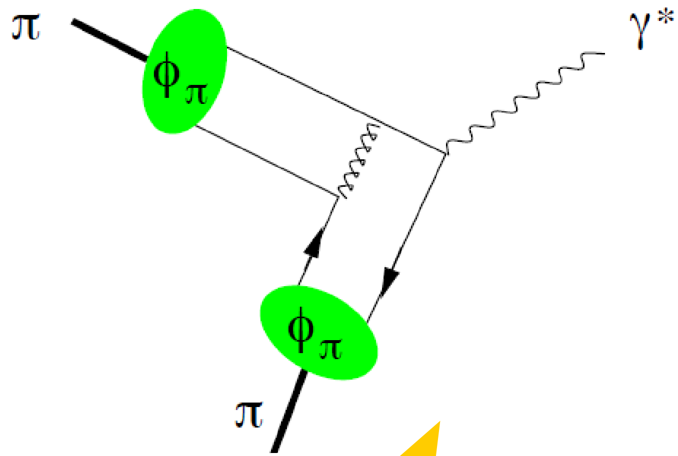
functions with $\langle p_T^2\rangle^{1/2} \simeq 300$ MeV can naturally generate "soft" nonleading terms which are as large as the data. Similar conclusions hold for the pion.[4] Calculations based on QCD sum rules[5] also generate soft contributions which fit the data for F_π and G_M.

Our calculations were based on the use of the light-cone quantization formalism[6] adopted by

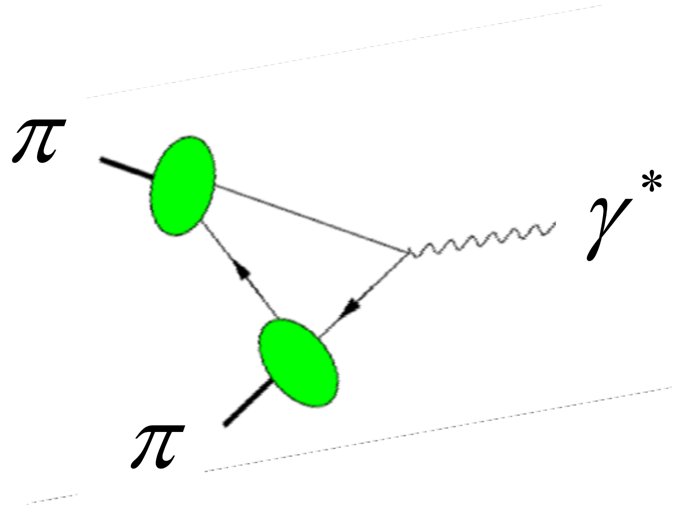


π
$F_\pi(Q^2)$
γ^*
π



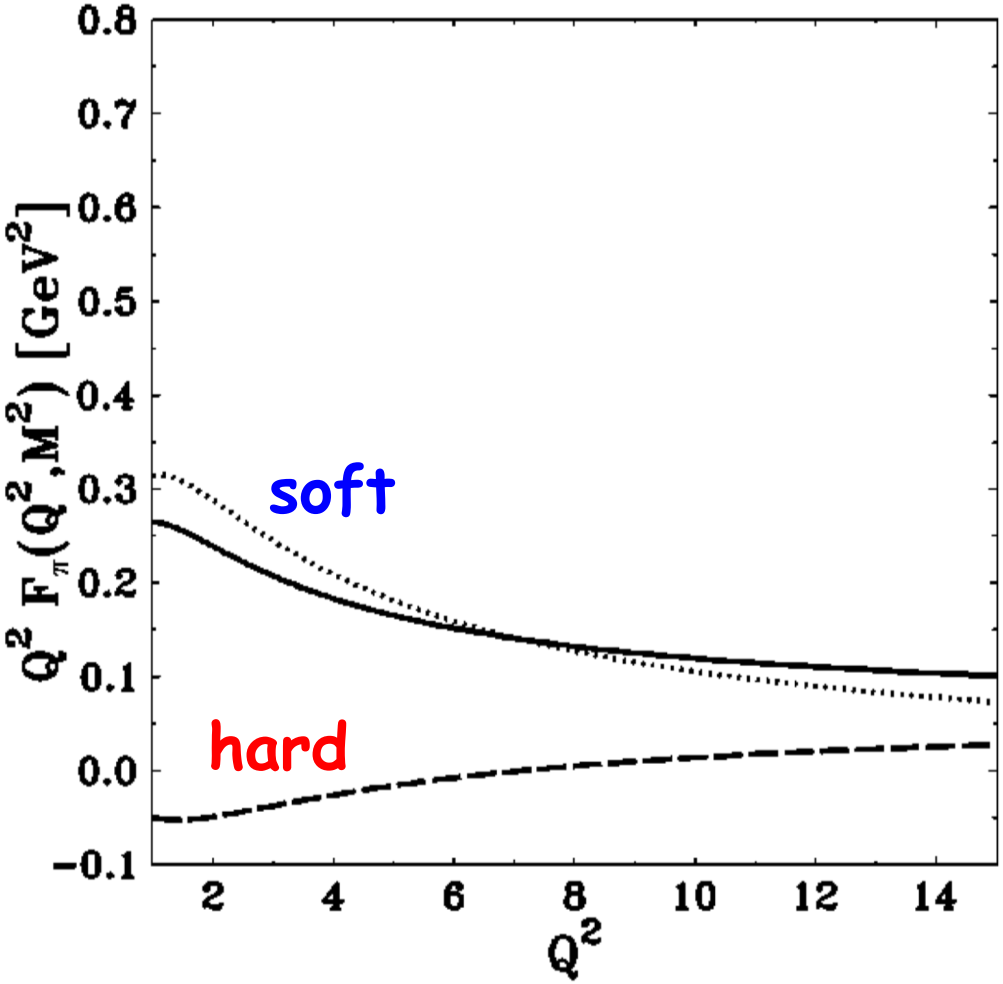


LO in QCD factorization



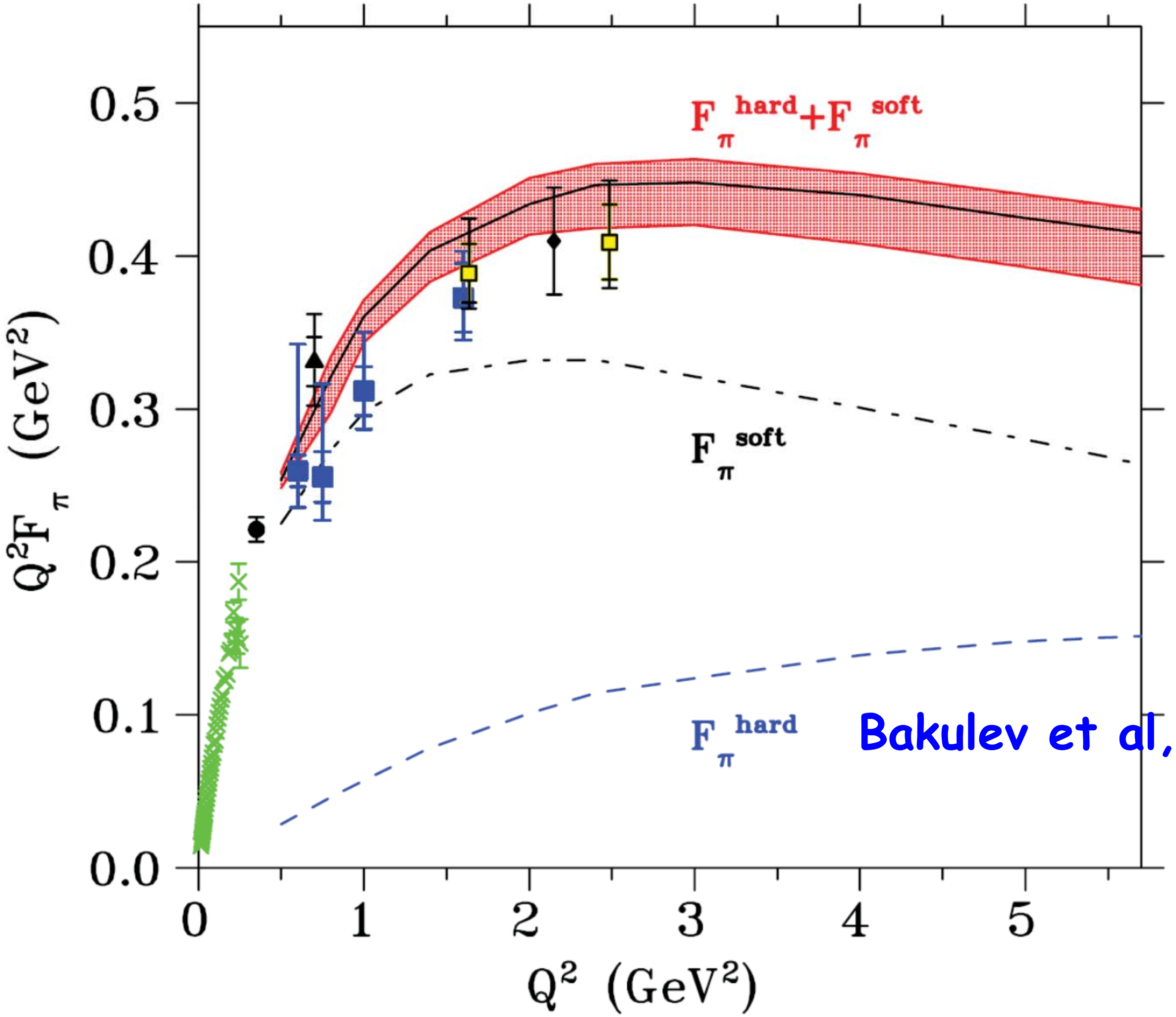
"nonfactorizable" Feynman mechanism

hard & soft contributions in "light-cone QCD SR (LCSR)"

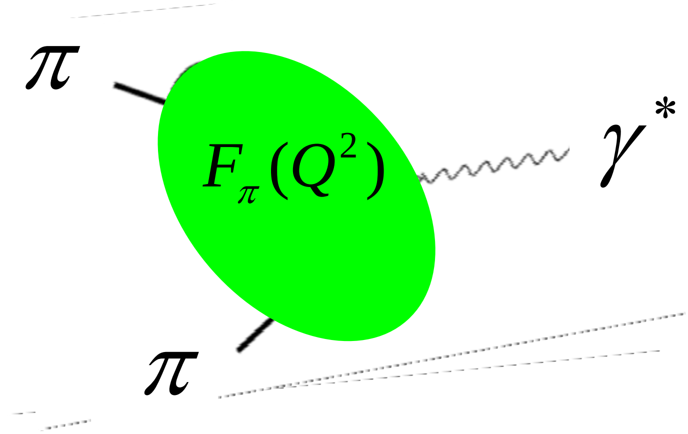


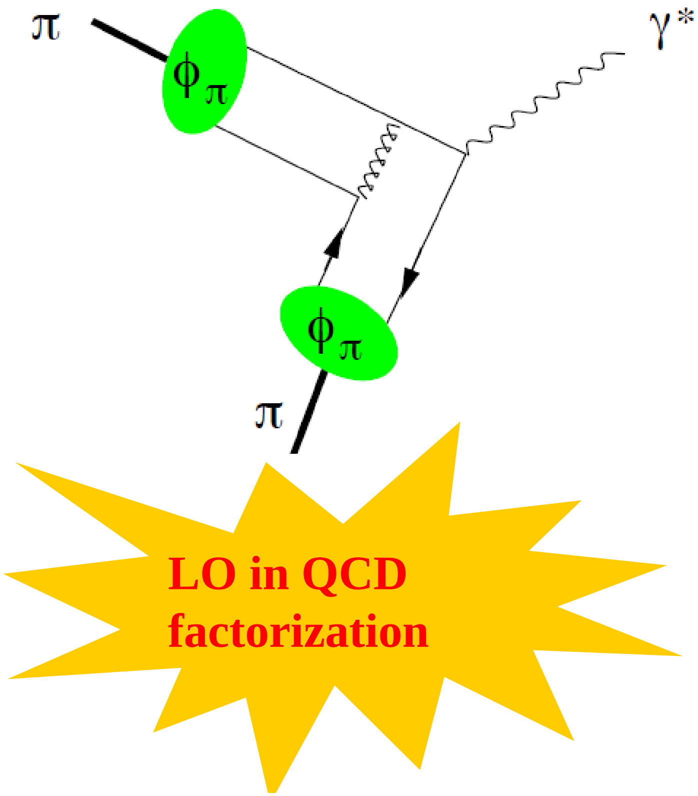
Braun, Khodjamirian, Maul, PRD61 ('00) 073004

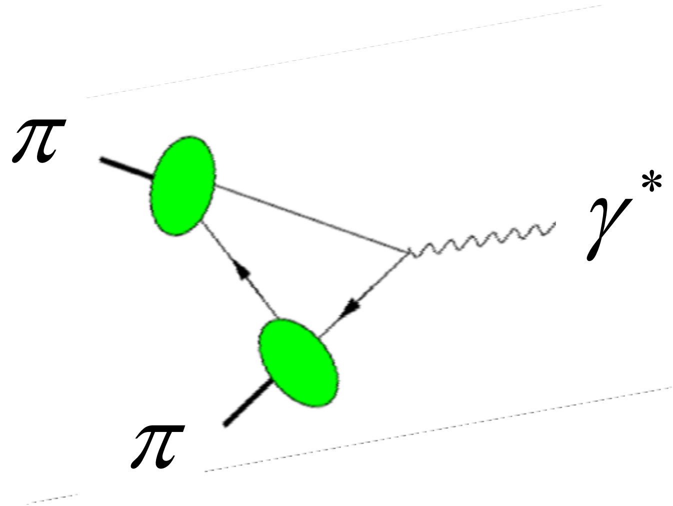
JLab data, PRC78 ('08) 045023



Bakulev et al, PRD70, 033014

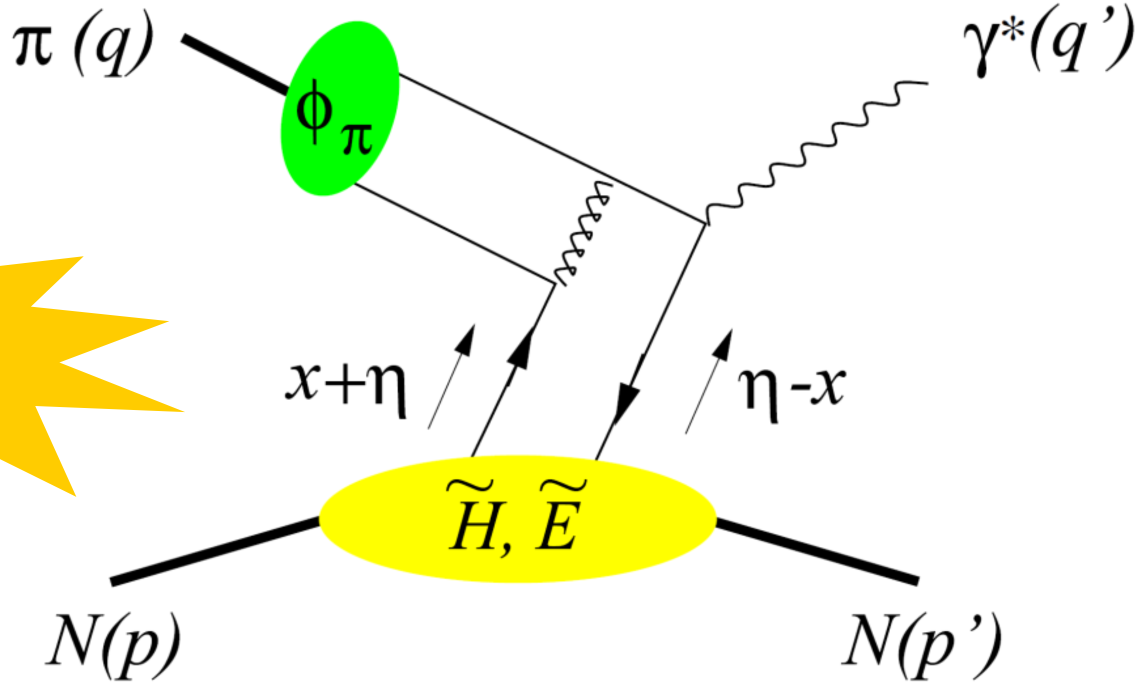


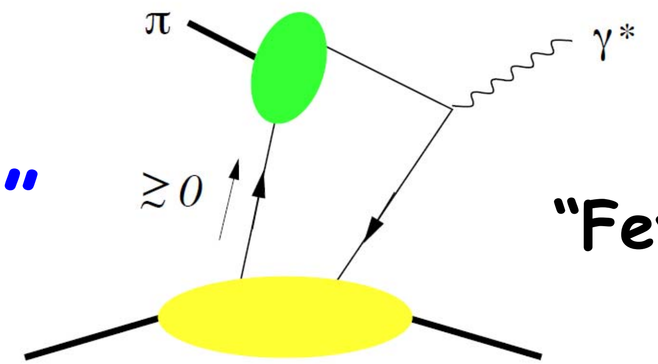




"nonfactorizable"
Feynman mechanism

LO in QCD factorization

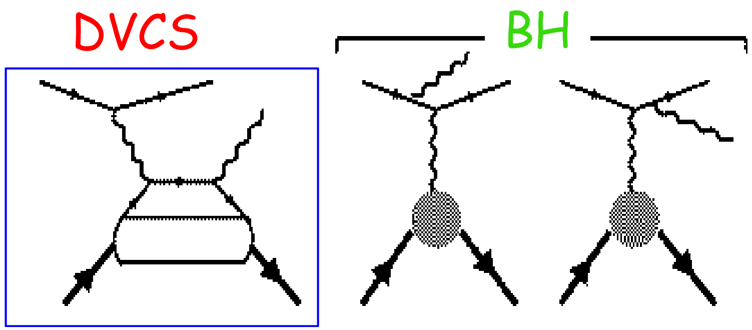




"nonfactorizable"

"Feynman mechanism"

Accessing GPDs through polarized DVCS



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

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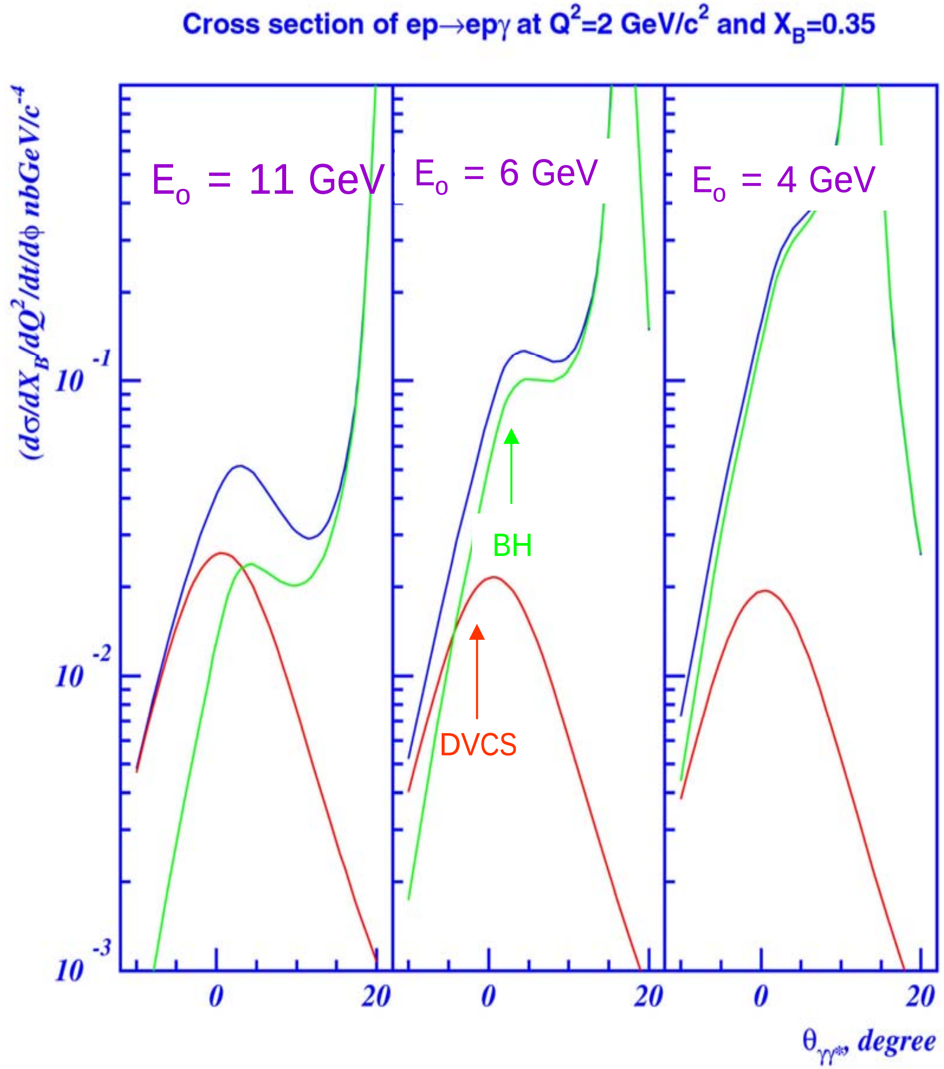
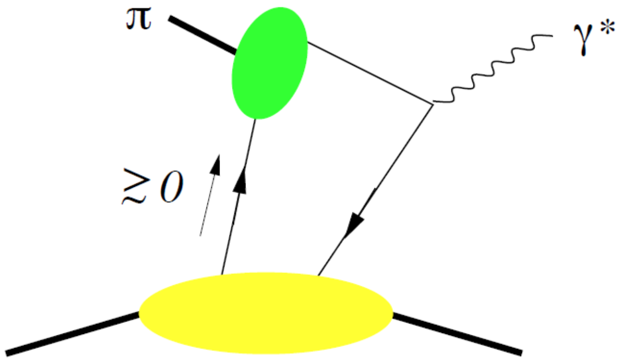


“nonfactorizable” mechanism



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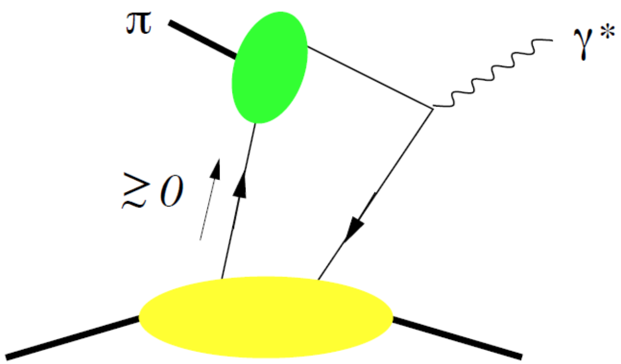
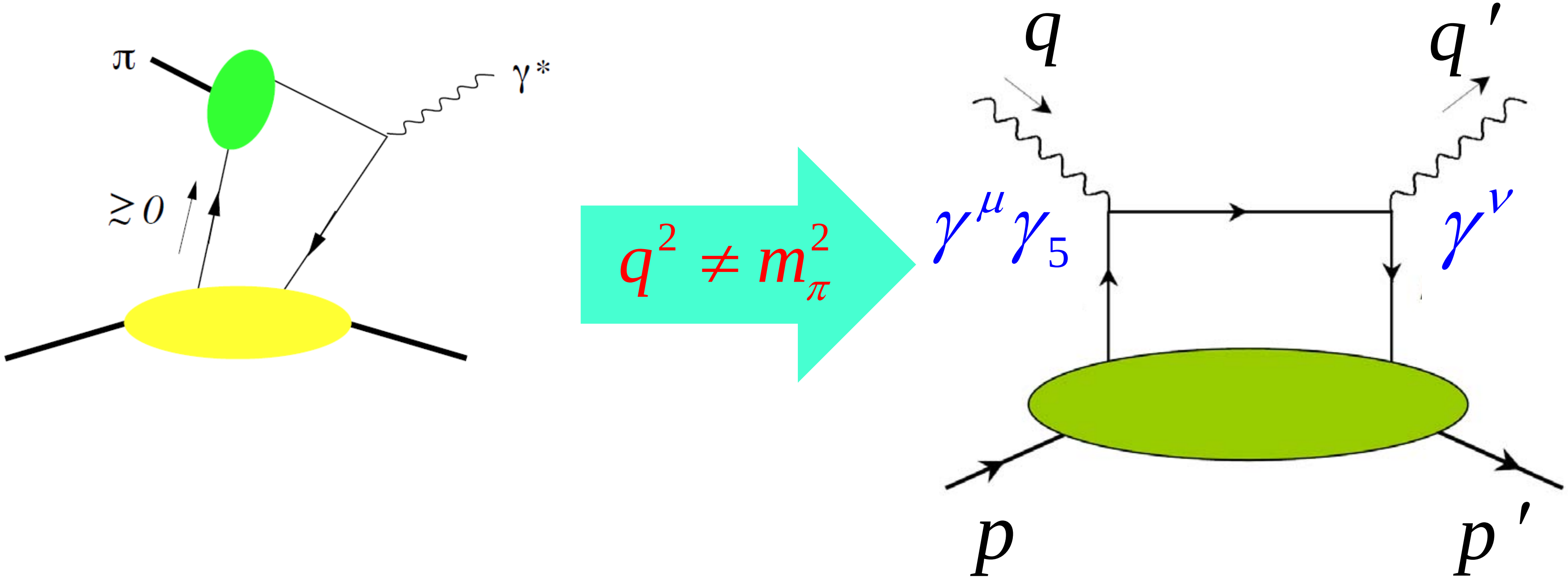
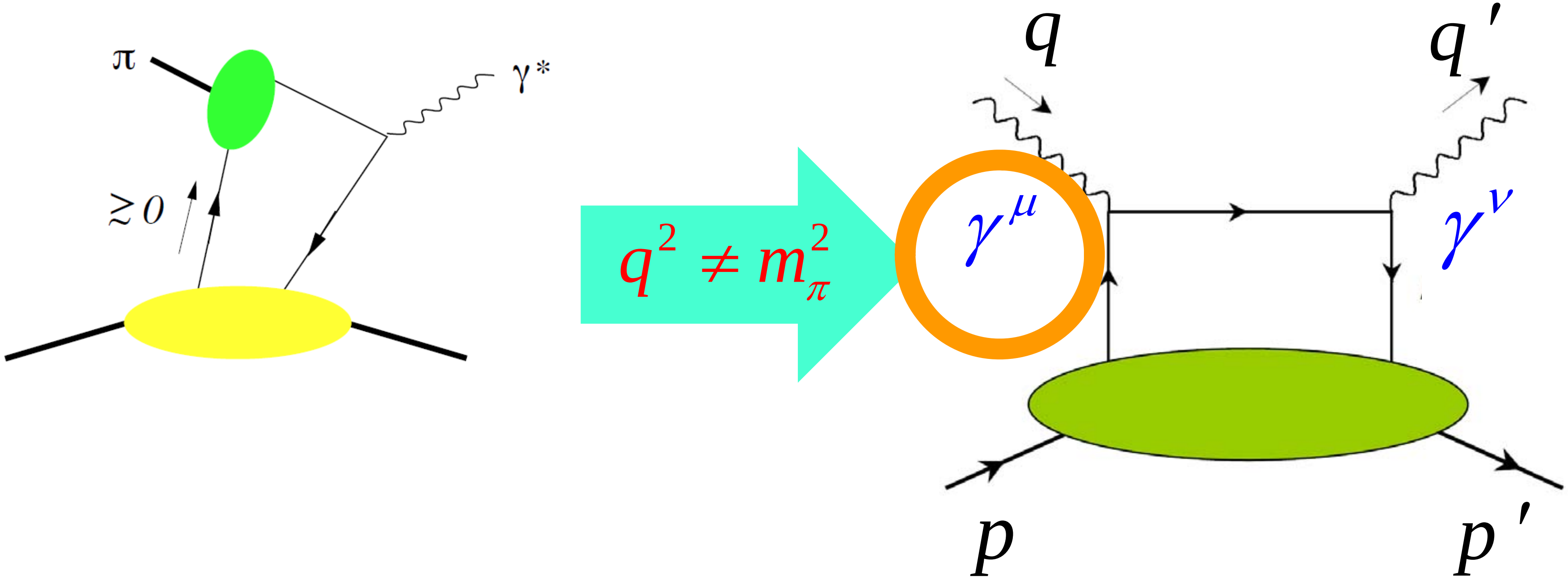


“LCSR”

"nonfactorizable" mechanism



“nonfactorizable” mechanism



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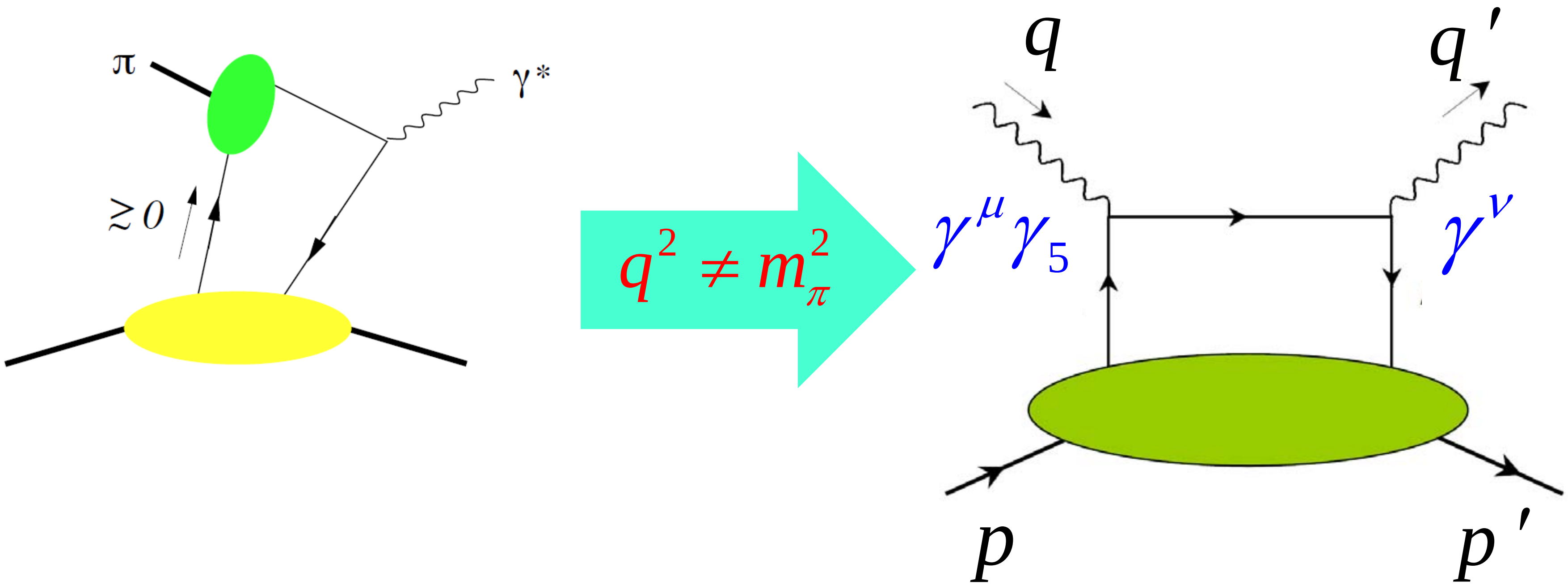

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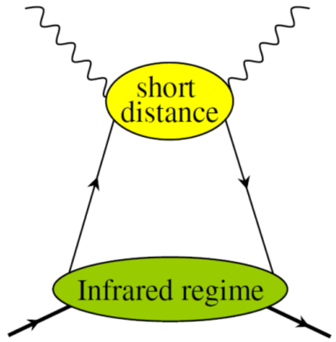

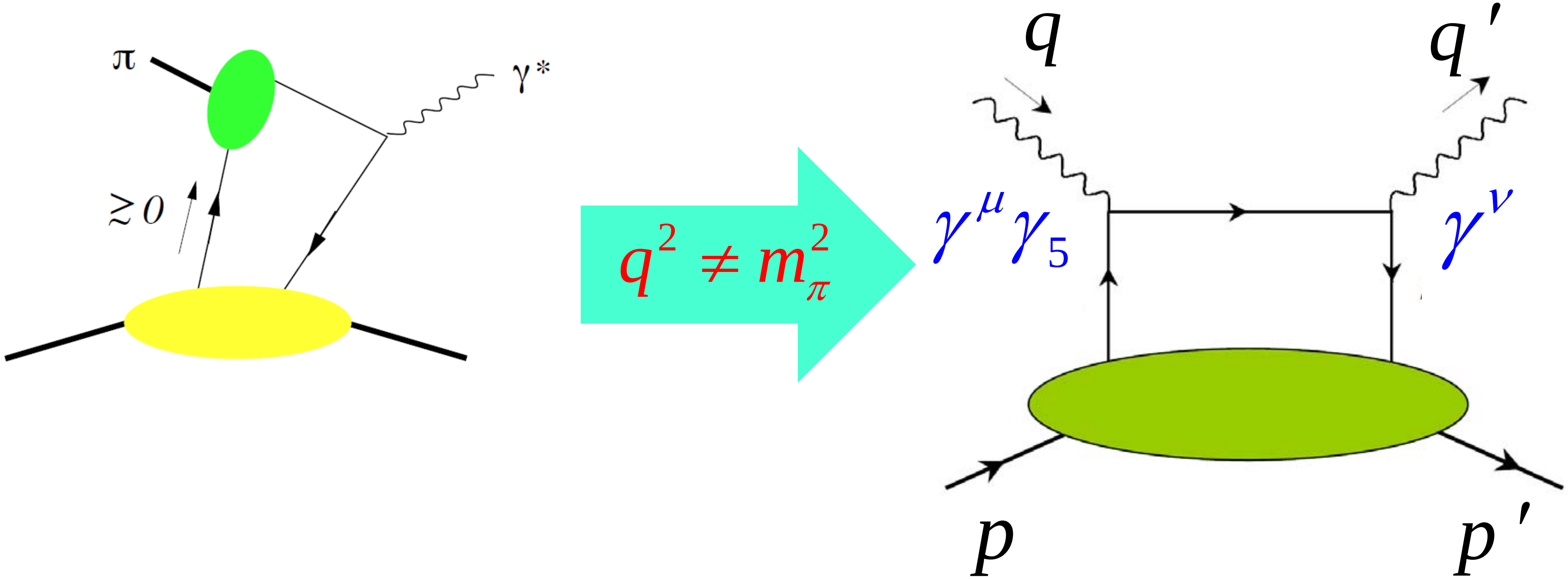

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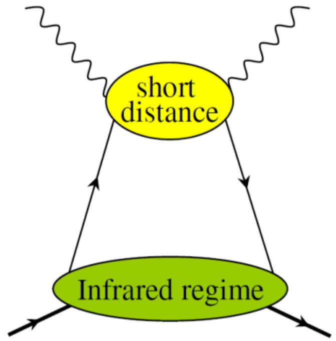
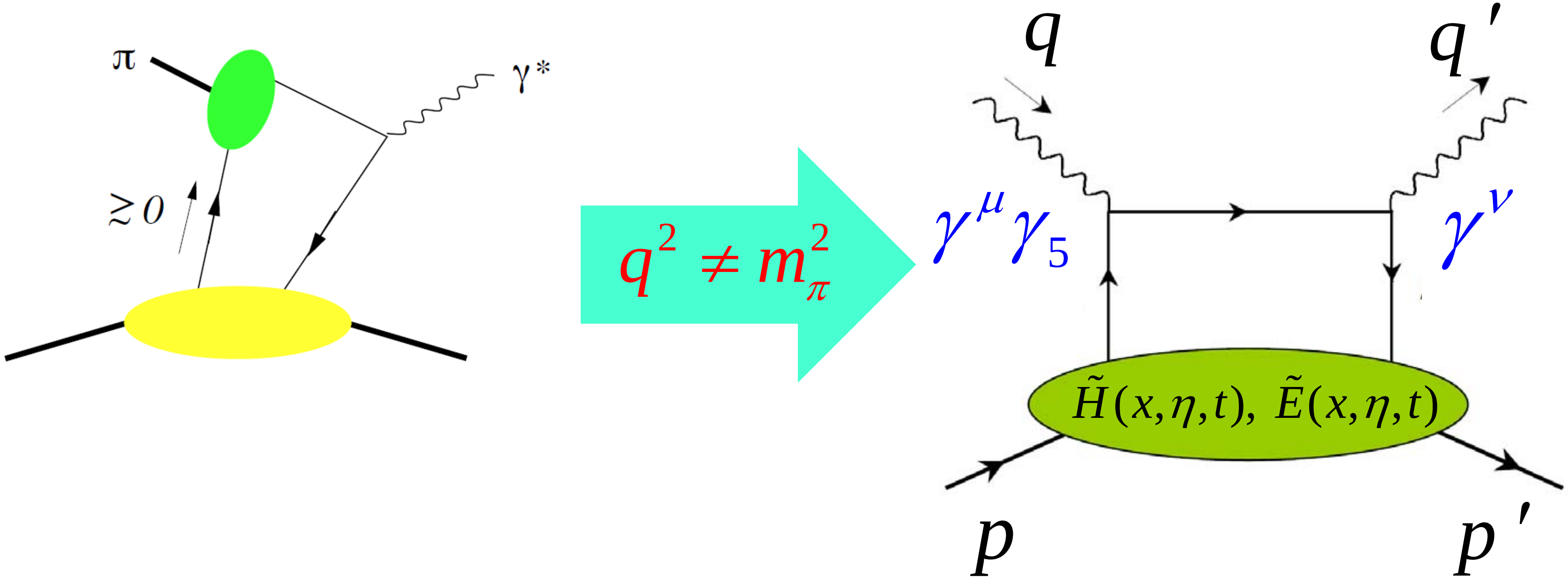
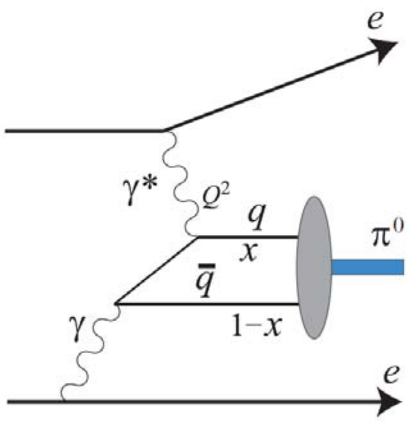




Exclusive lepton pair production in πN scattering

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



@Belle, Babar

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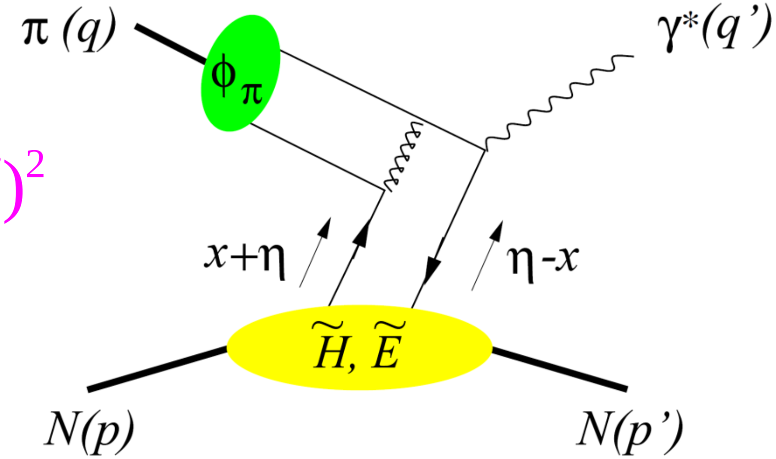


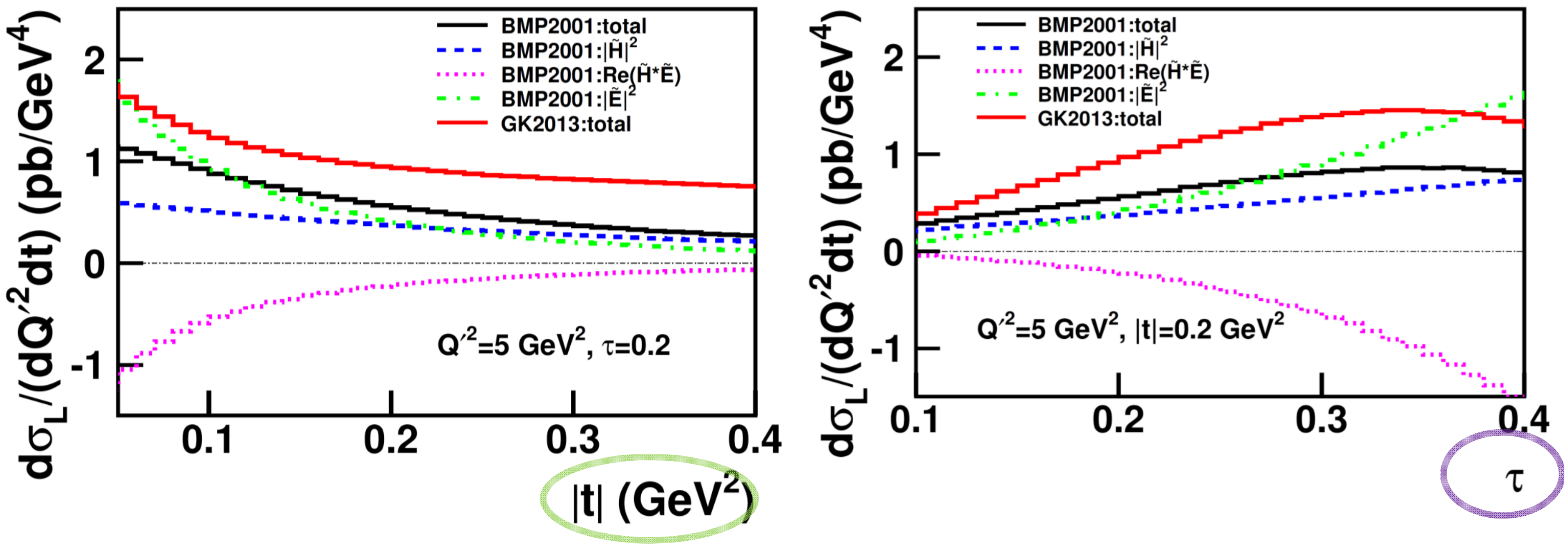
$$\int dz^- e^{i(x+\eta)pz} \langle N(p') | \psi^\dagger(0) \psi(z^-) | N(p) \rangle$$

GPD

T. Sawada, W.C. Chang, S. Kumano, J.C. Peng, S. Sawada, KT, PRD93, 114034 ('16)

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

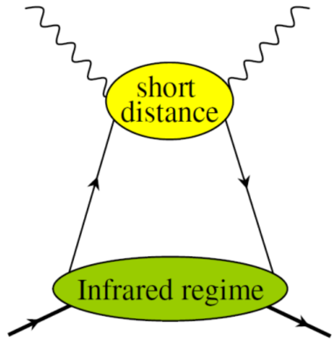
$Q'^2 = 5\ \mathrm{GeV}^2$

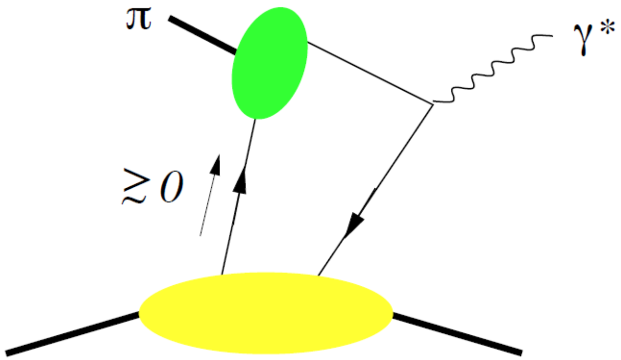


$$\frac{d\sigma}{dQ'^2\,dt}(\pi^- p \to \gamma^* n) = \frac{4\pi\alpha_{em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \left[(1-\eta^2)|\tilde{\mathscr{H}}^{du}|^2 - 2\eta^2 \mathrm{Re}\left(\tilde{\mathscr{H}}^{du*}\tilde{\mathscr{E}}^{du}\right) - \eta^2 \frac{t}{4M^2}|\tilde{\mathscr{E}}^{du}|^2 \right]$$

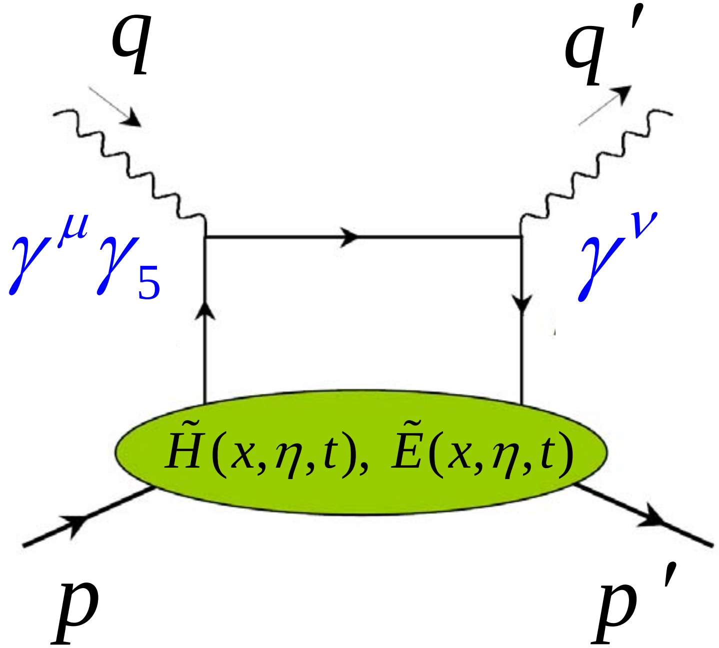
$$\tilde{\mathscr{H}}^{du} = \frac{8\alpha_s}{3}\int_0^1 du \frac{\phi_\pi(u)}{4u(1-u)}\int_{-1}^1 dx \left(\frac{e_d}{-\eta - x - i\epsilon} - \frac{e_u}{-\eta + x - i\epsilon} \right)\left(\tilde{H}^d(x,\eta,t) - \tilde{H}^u(x,\eta,t) \right)$$

“nonfactorizable” mechanism

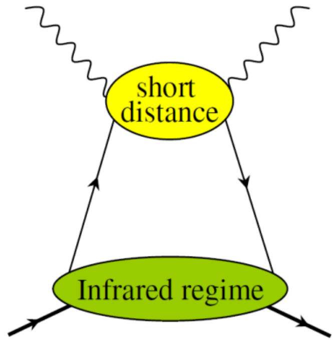


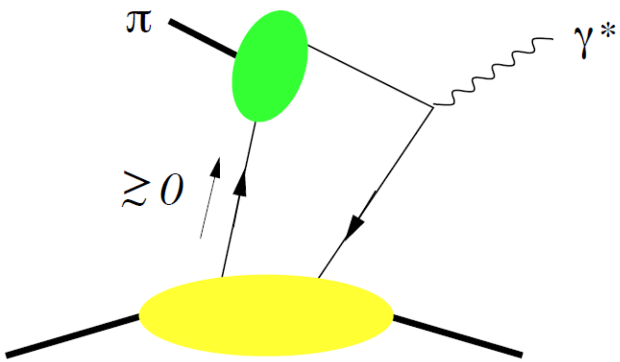


$q^2 \neq m_\pi^2$



"nonfactorizable" mechanism





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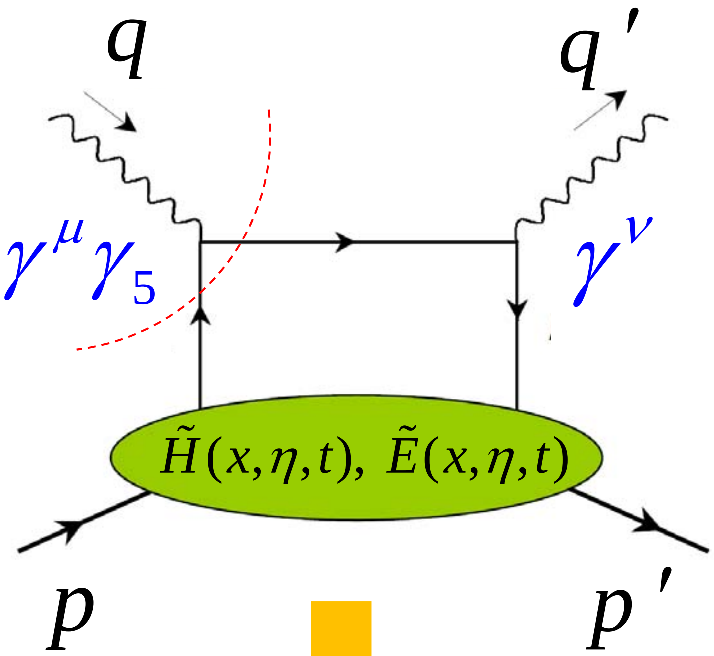
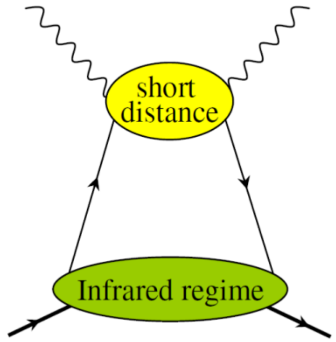
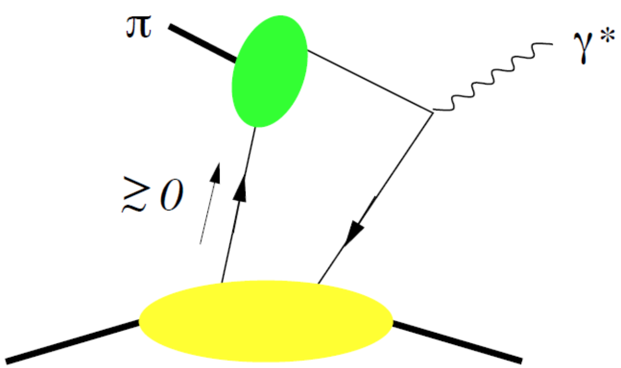


dispersion relation

"nonfactorizable" mechanism





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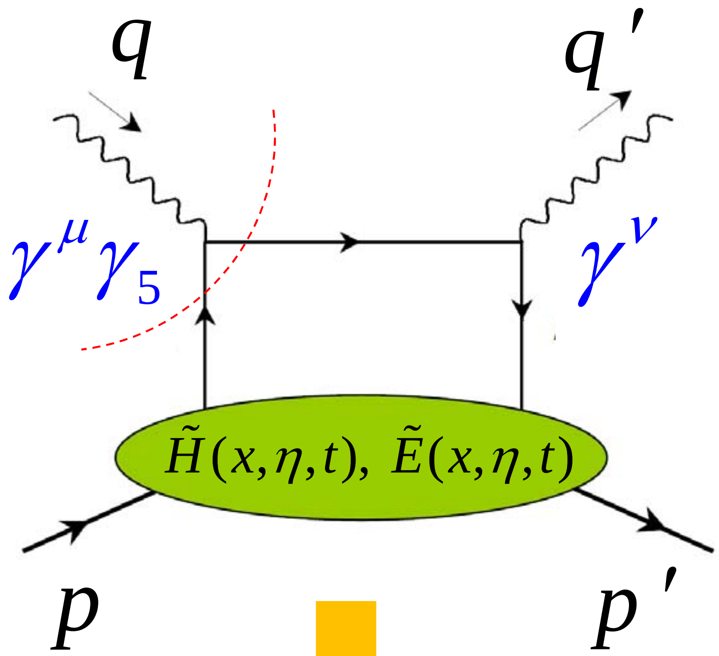


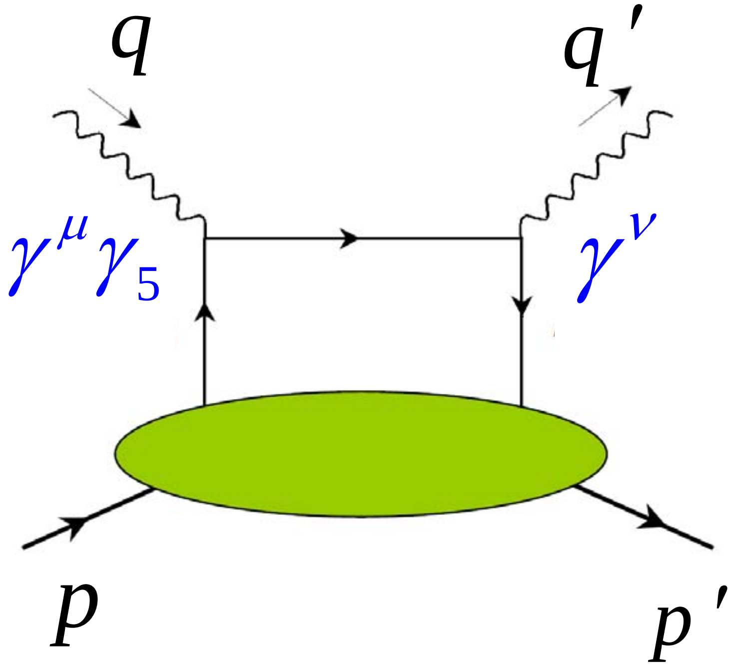
dispersion relation

quark-hadron duality

KT, arXiv:1703.02190, 1709.01063

$$\int d^4x e^{iq'\cdot x}\langle p'|\mathrm{T}\, j_\mu^5(0)\, j_\nu^{\mathrm{em}}(x)|p\rangle$$

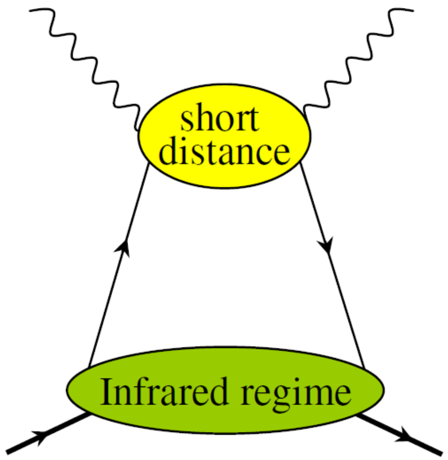
$$\equiv -iT_{\mu\nu}$$



$$j_\mu^5 = \bar{d}\gamma_\mu\gamma_5 u$$

$$j_\nu^{\mathrm{em}} = e_u \bar{u}\gamma_\nu u + e_d \bar{d}\gamma_\nu d$$

$$|q^2|, |q'^2| \gg \Lambda^2_{\mathrm{QCD}}$$



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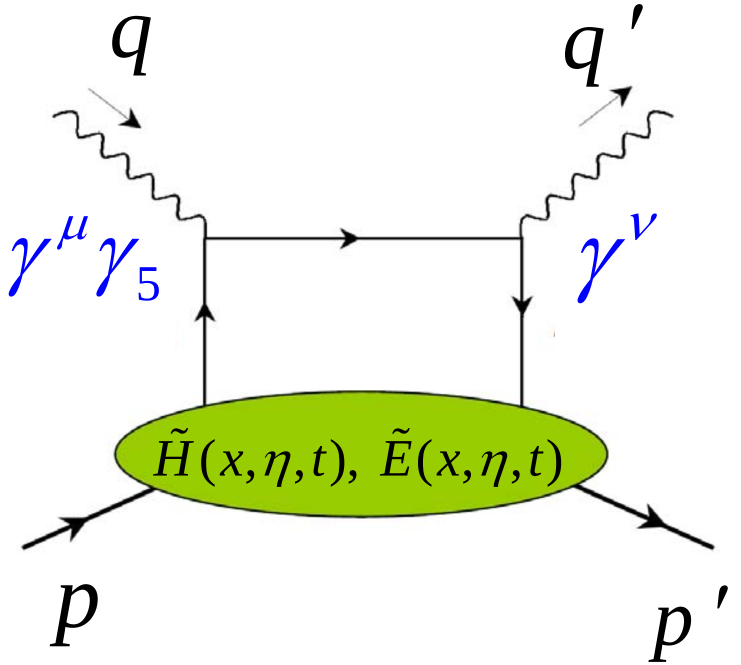


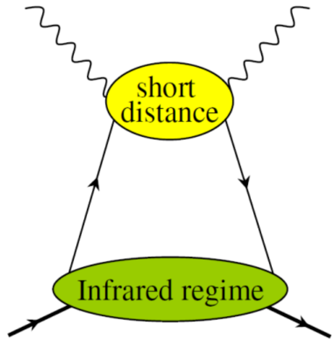
$$|q^2|, |q'^2| \gg \Lambda_{\mathrm{QCD}}^2$$

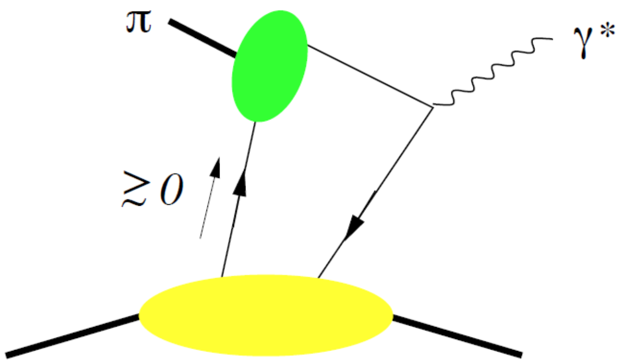
$$T_{\mu\nu}$$

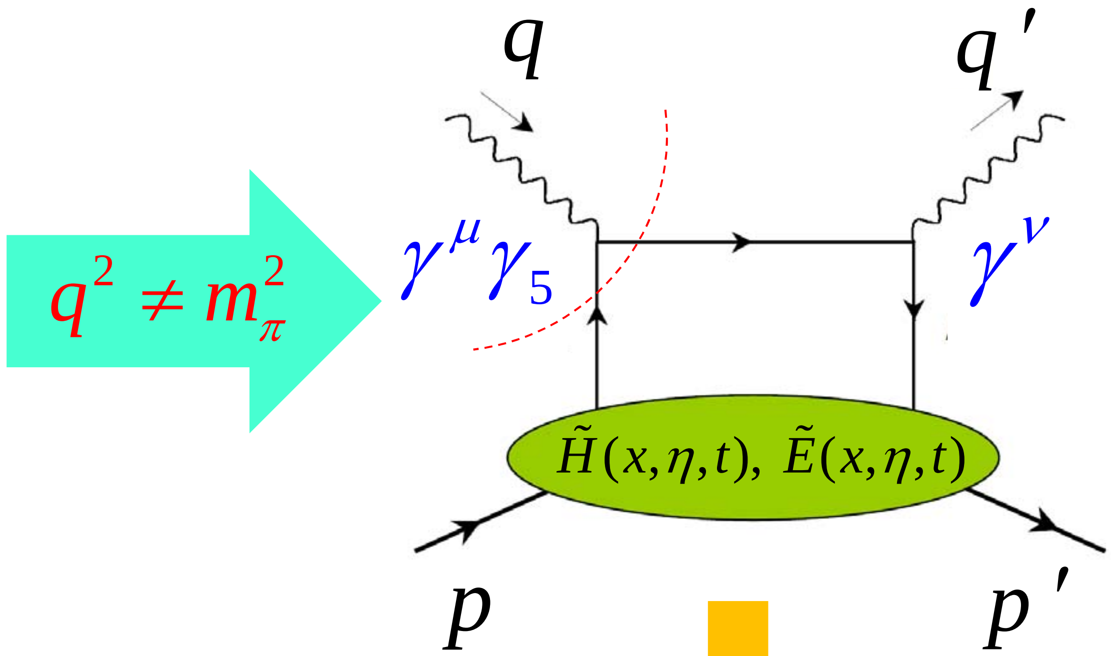
$$= -q_\mu g_\nu^- \int dx \Big\{ C_H(x,\eta,Q'^2,q^2)\left[e_u \tilde{H}^{du}(x,\eta,t) - e_d \tilde{H}^{du}(-x,\eta,t)\right]\bar{u}(p')\gamma^+\gamma_5 u(p)$$

$$+ C_E(x,\eta,Q'^2,q^2)\left[e_u \tilde{E}^{du}(x,\eta,t) - e_d \tilde{E}^{du}(-x,\eta,t)\right]\bar{u}(p')\frac{\gamma_5(p'-p)^+}{2M}u(p)\Big\} + \cdots$$

"nonfactorizable" mechanism







dispersion relation

quark-hadron duality

KT, arXiv:1703.02190, 1709.01063

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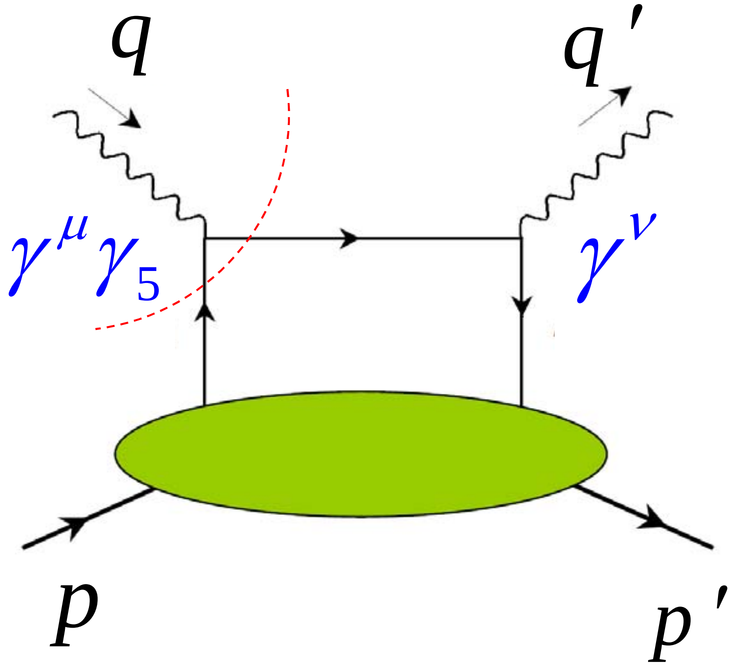
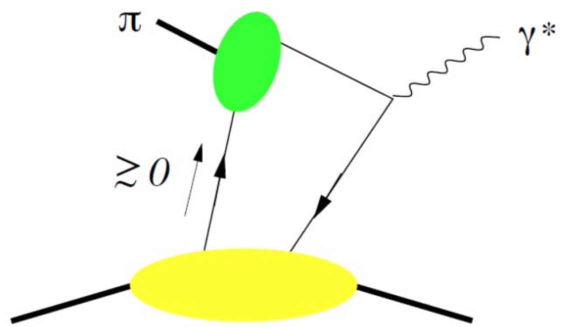


$$\langle 0|\, j^5_\mu\, |\pi^-(k)\rangle = ik_\mu f_\pi$$

$$T_{\mu\nu} = iq_\mu\left[f_\pi \frac{1}{q^2 - m_\pi^2}\left(\quad \right) + \int_{q^2_{\mathrm{th}}}^{\infty} dm^2 \frac{\tilde{a}_\nu(m^2)}{q^2 - m^2}\right] + \cdots$$



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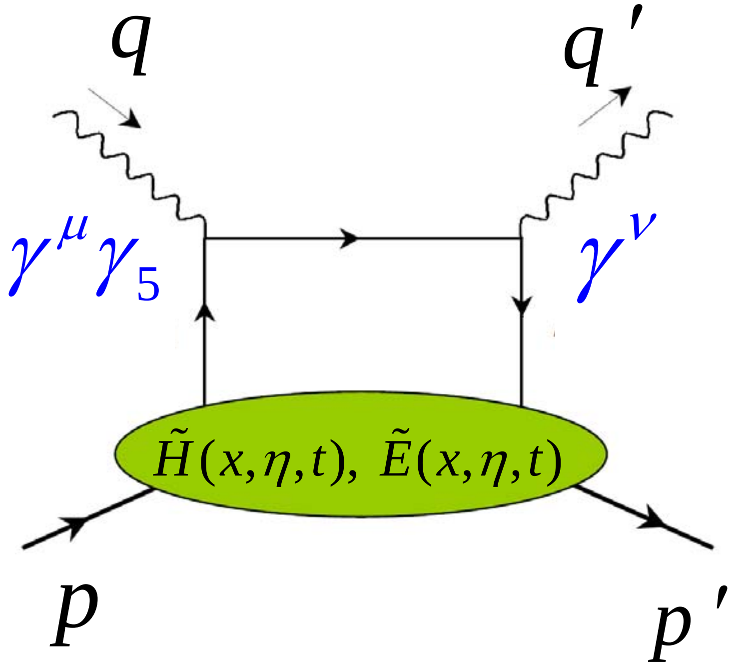
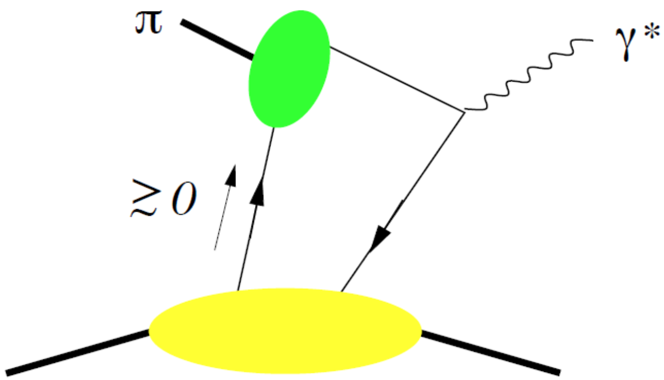


$$|q^2|,|q'^2| \gg \Lambda^2_{\mathrm{QCD}}$$

$$T_{\mu\nu}$$
$$= -q_\mu g^-_\nu \int dx \Big\{ C_H(x,\eta,Q'^2,q^2)\left[e_u\tilde{H}^{du}(x,\eta,t) - e_d\tilde{H}^{du}(-x,\eta,t)\right]\bar{u}(p')\gamma^+\gamma_5 u(p)$$
$$+C_E(x,\eta,Q'^2,q^2)\left[e_u\tilde{E}^{du}(x,\eta,t) - e_d\tilde{E}^{du}(-x,\eta,t)\right]\bar{u}(p')\frac{\gamma_5(p'-p)^+}{2M}u(p)\Big\} + \cdots$$

Light-cone QCD SR (LCSR)



$x_0 : \frac{q_{\rm th}^2}{Q'^2}$ **quark-hadron duality**

$$\hat{L}_{M_B}\left(\frac{1}{m^2-q^2}\right)=\frac{1}{M_B^2}e^{-\frac{m^2}{M_B^2}}$$

$$\sim g_\nu^- \frac{1}{f_\pi}\int_\eta^{x_0} dx\, e^{-\frac{x-\eta}{x+\eta}\frac{Q'^2}{M_B^2}}\tilde{C}_H(x,\eta,Q'^2)$$

$$\times\left[e_u \tilde{H}^{du}(x,\eta,t)-e_d \tilde{H}^{du}(-x,\eta,t)\right]$$

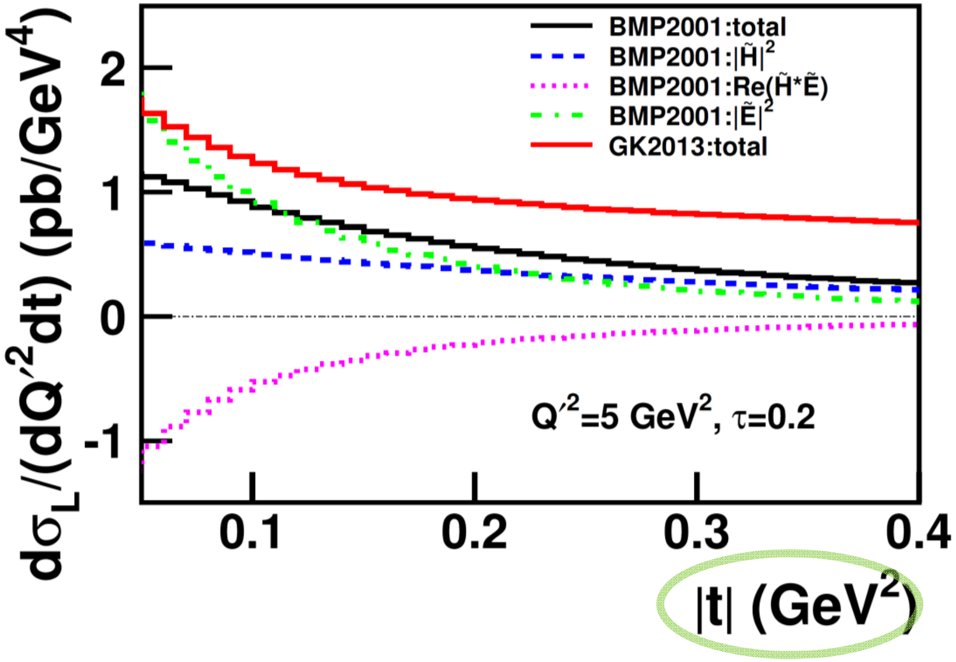
$$\times\bar{u}(p')\gamma^+\gamma_5 u(p)+\cdots$$

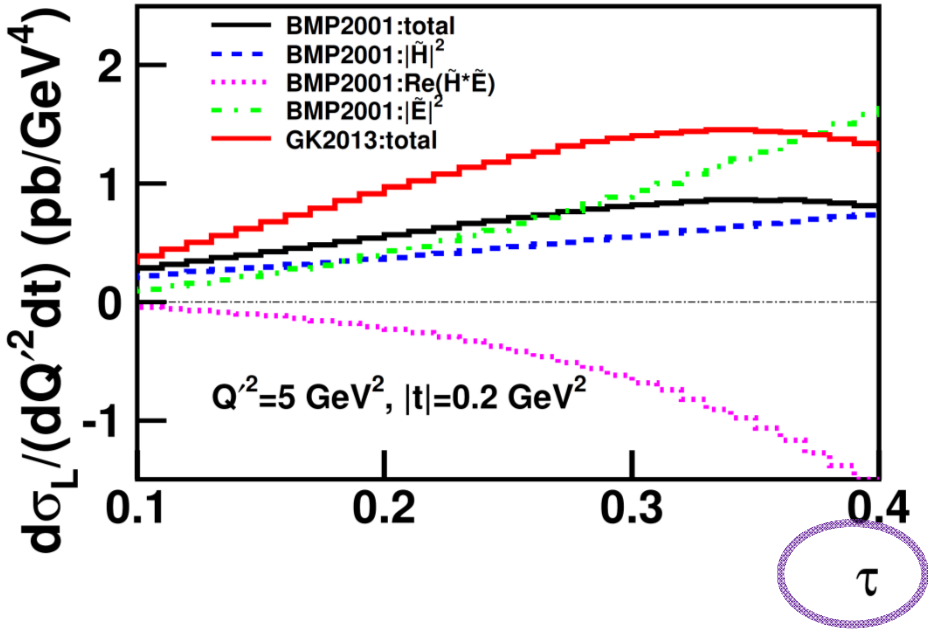
$$\tilde{H}^{du}(x,\eta,t)=\tilde{H}^u(x,\eta,t)-\tilde{H}^d(x,\eta,t)$$

T. Sawada, W.C. Chang, S. Kumano, J.C. Peng, S. Sawada, KT,
PRD93, 114034 ('16)

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

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





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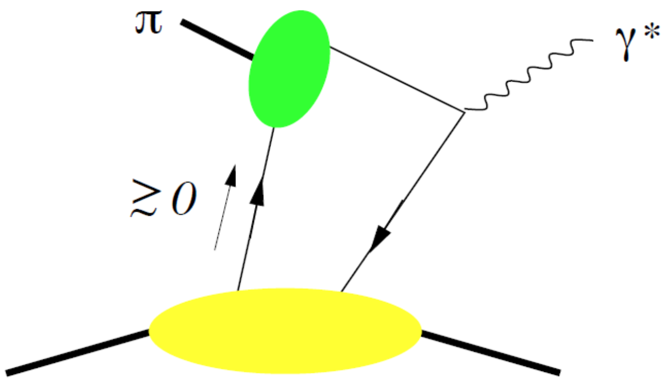
Light-cone QCD SR (LCSR)



$x_0 \sim \frac{q_{\rm th}^2}{Q'^2}$ **quark-hadron duality**

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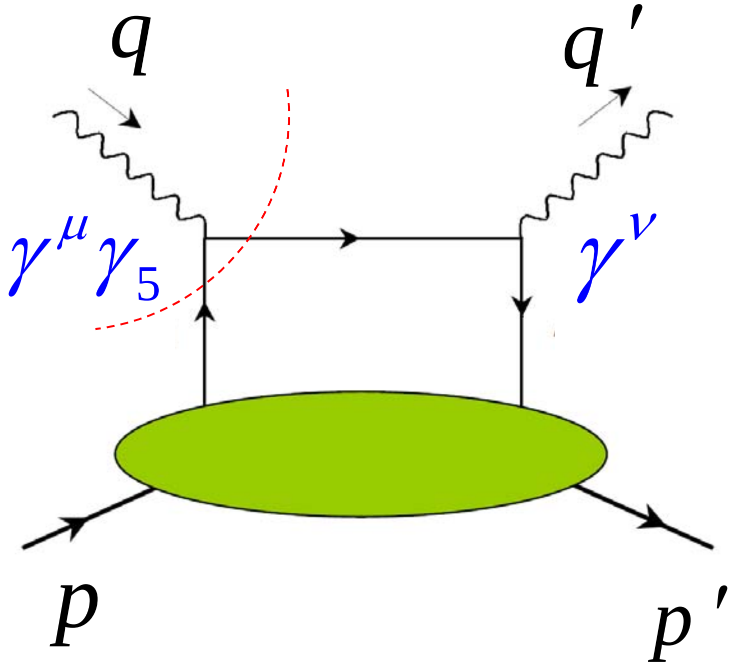
$$\equiv -iT_{\mu\nu}$$



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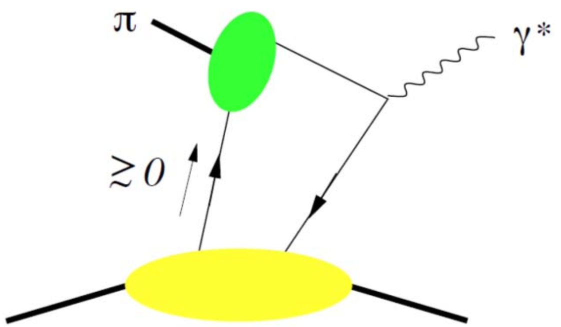
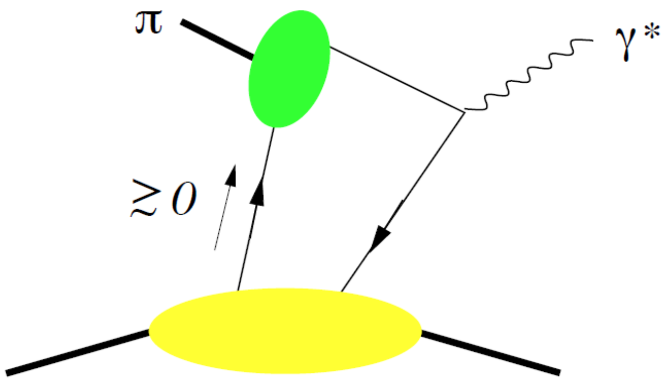


$$\left. + \int_{q^2_{\mathrm{th}}}^{\infty} dm^2 \frac{\tilde{a}_\nu(m^2)}{q^2-m^2} \right] + \cdots$$

Light-cone QCD SR (LCSR)



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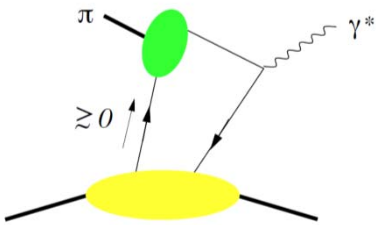
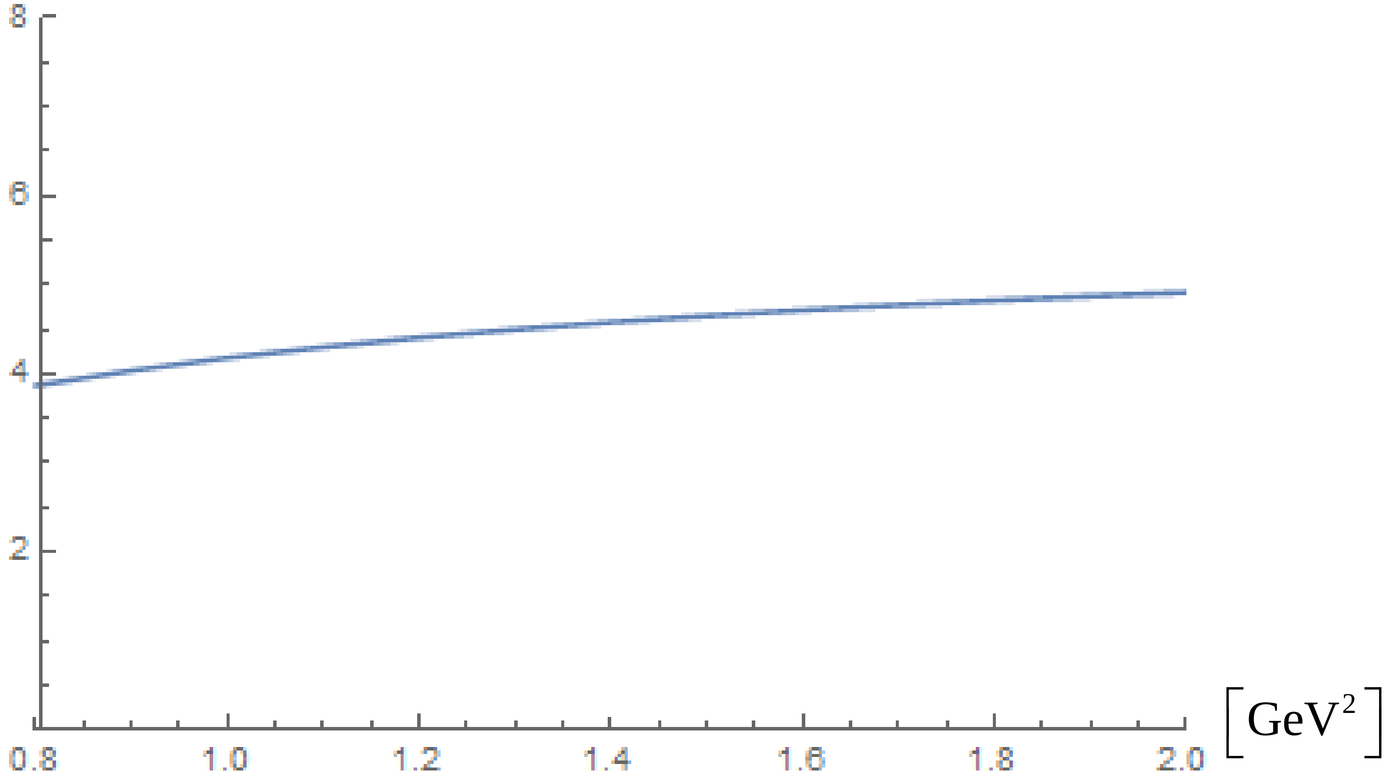
$$\tilde{H}^{du}(x,\eta,t)=\tilde{H}^{u}(x,\eta,t)-\tilde{H}^{d}(x,\eta,t)$$

KT, arXiv:1703.02190, 1709.01063

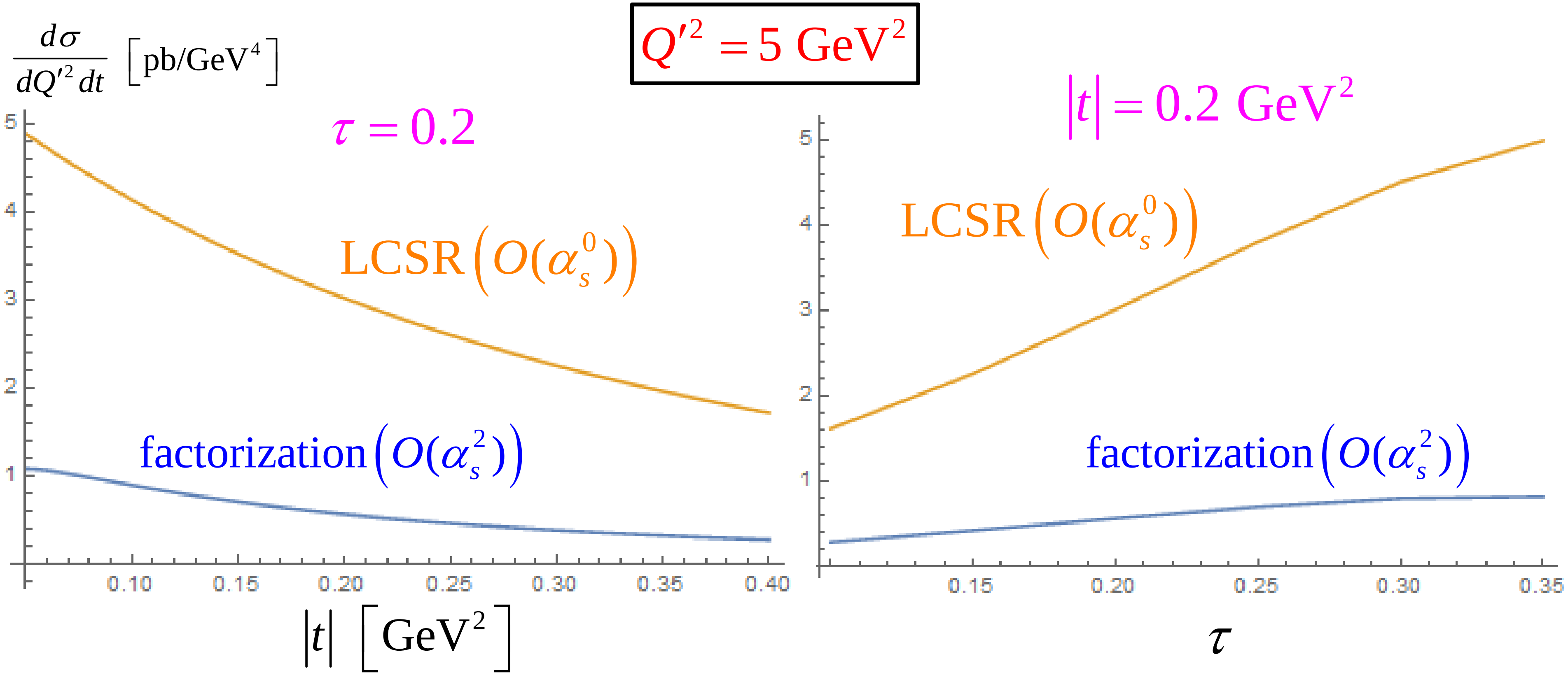


from LCSR



M_B^2 (Borel parameter)

KT, arXiv:1703.02190, 1709.01063

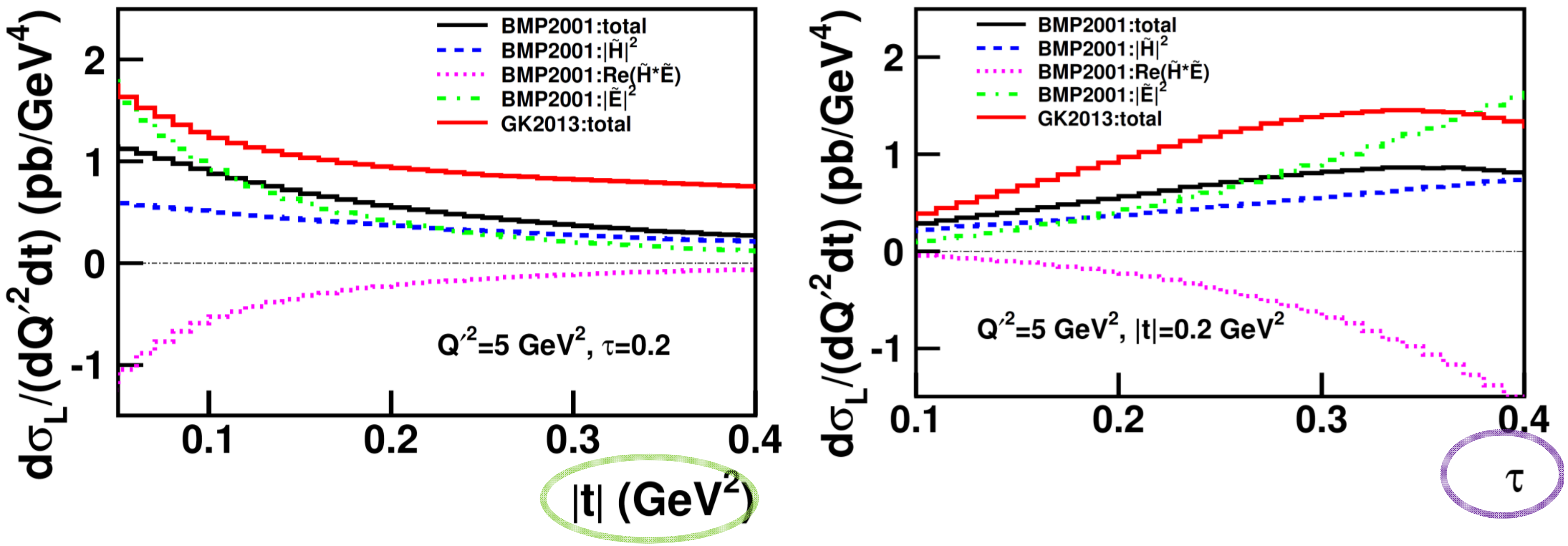


$$\frac{d\sigma}{dQ'^2 dt}(\pi^- p \to \gamma^* n) = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \left[(1-\eta^2)|\widetilde{\mathscr{H}}^{du}|^2 - 2\eta^2 \,\mathrm{Re}\left(\widetilde{\mathscr{H}}^{du*}\widetilde{\mathscr{E}}^{du}\right) - \eta^2 \frac{t}{4M^2}|\widetilde{\mathscr{E}}^{du}|^2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

T. Sawada, W.C. Chang, S. Kumano, J.C. Peng, S. Sawada, KT, PRD93, 114034 ('16)

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

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



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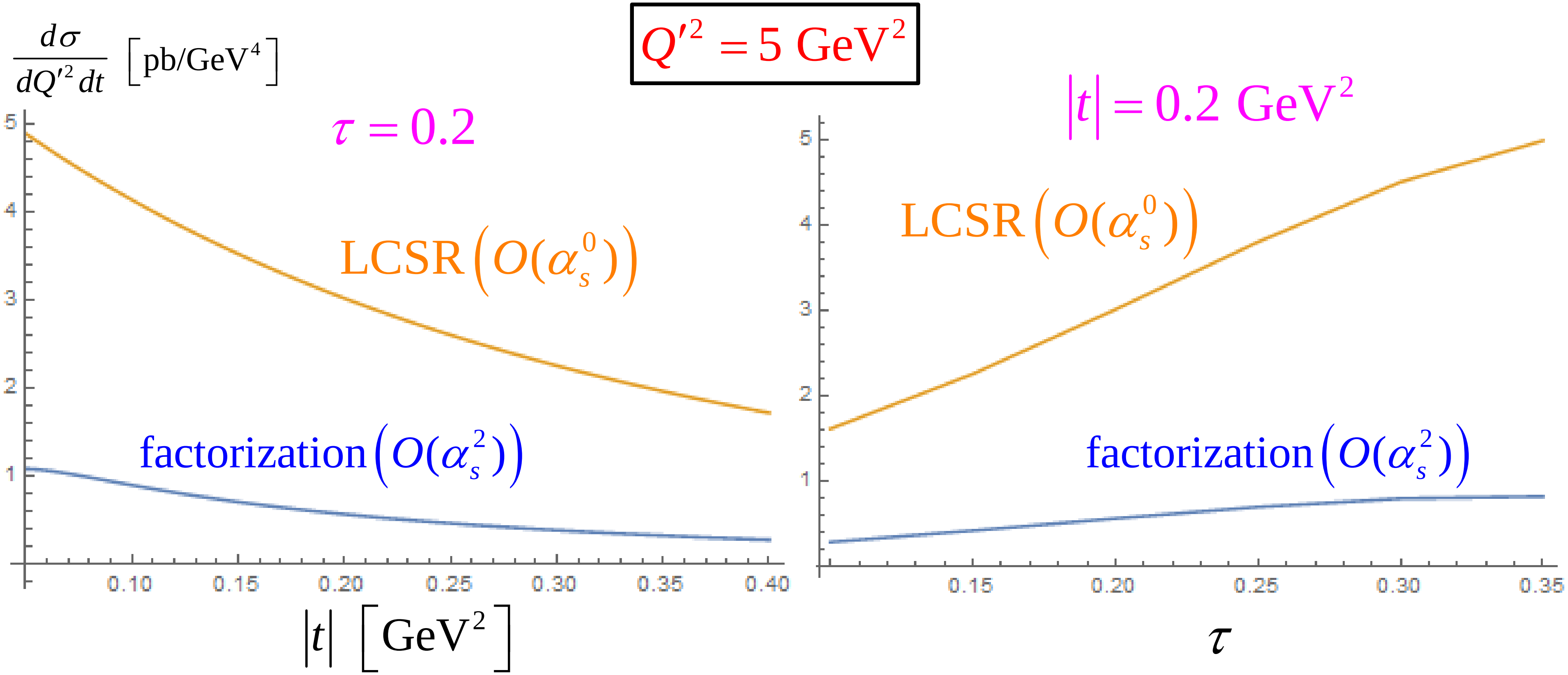
$$\tilde{\mathscr{H}}^{du} = \frac{8\alpha_s}{3}\int_0^1 du \frac{\phi_\pi(u)}{4u(1-u)}\int_{-1}^1 dx \left(\frac{e_d}{-\eta - x - i\epsilon} - \frac{e_u}{-\eta + x - i\epsilon} \right)\left(\tilde{H}^d(x,\eta,t) - \tilde{H}^u(x,\eta,t) \right)$$

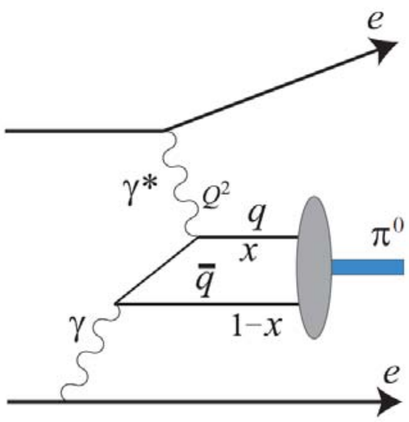
KT, arXiv:1703.02190, 1709.01063



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

Exclusive lepton pair production in πN scattering

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

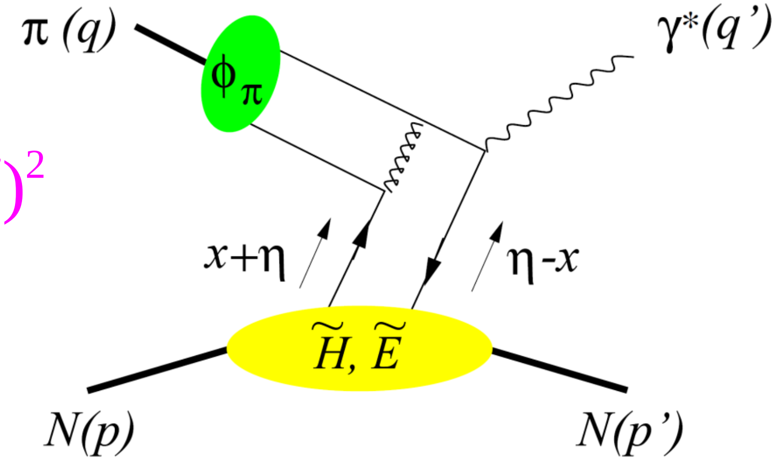


@Belle, Babar

"exclusive DY"

LO in QCD factorization

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



KT, arXiv:1703.02190, 1709.01063

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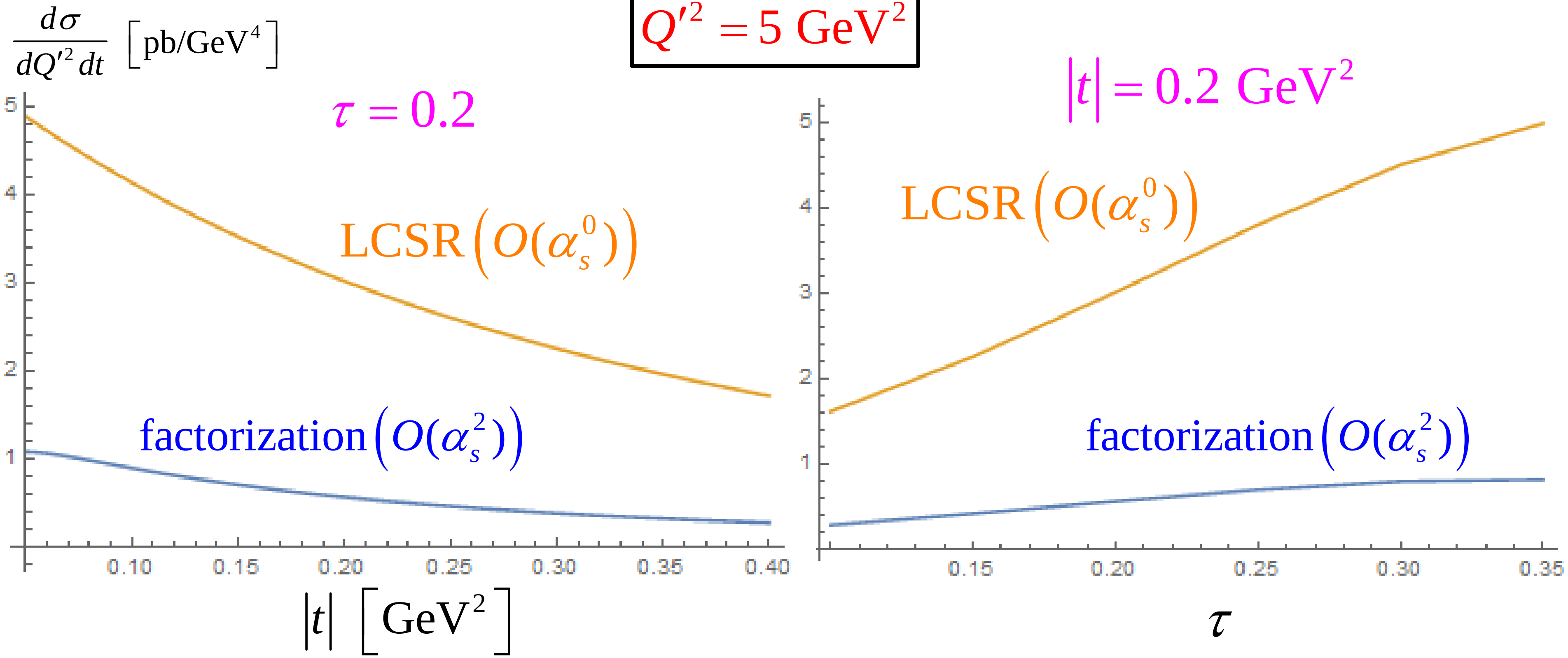

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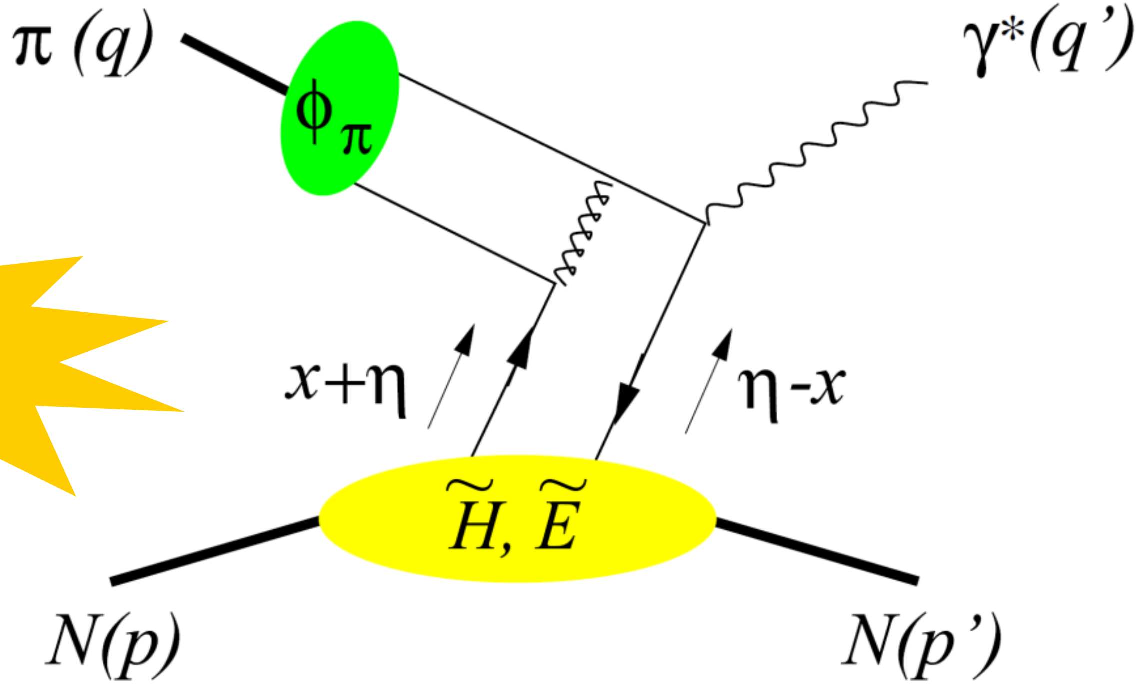
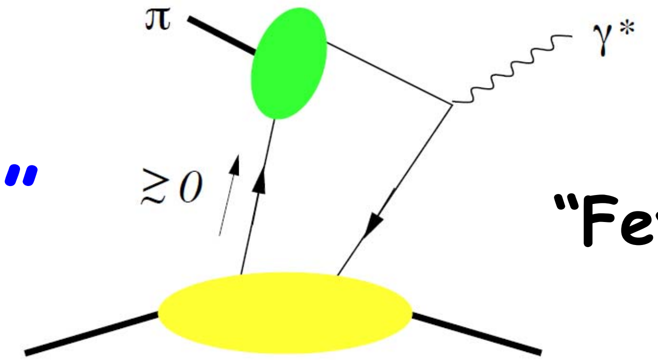


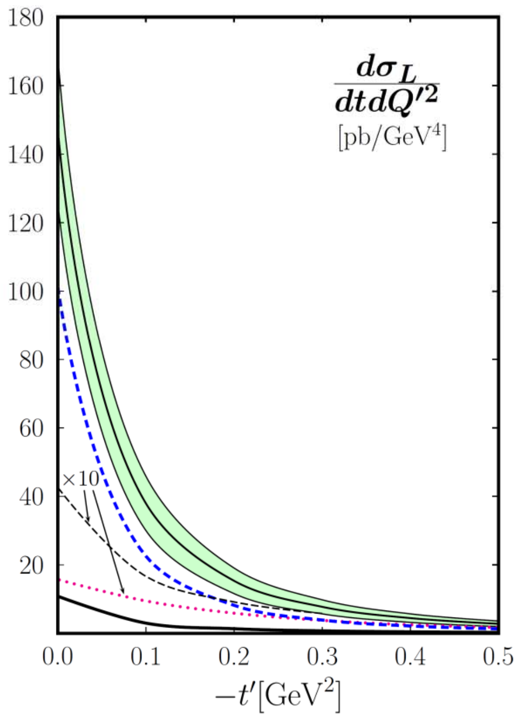
LO in QCD factorization

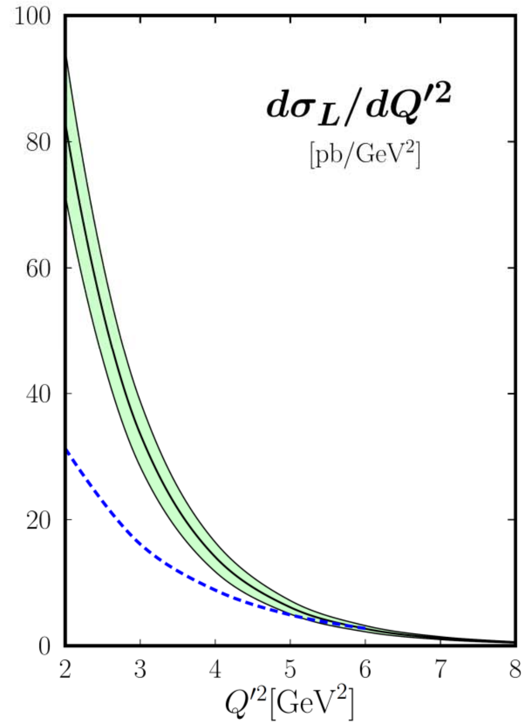
“nonfactorizable”

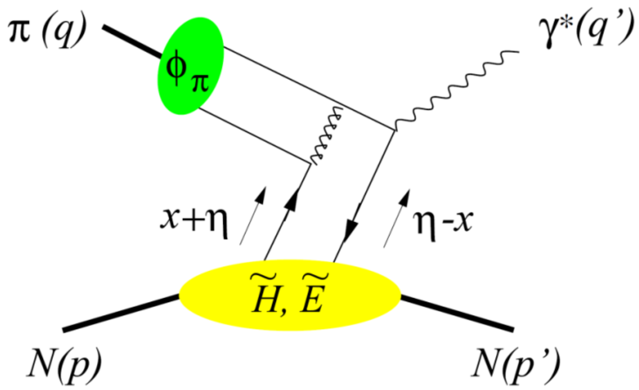


“Feynman mechanism”

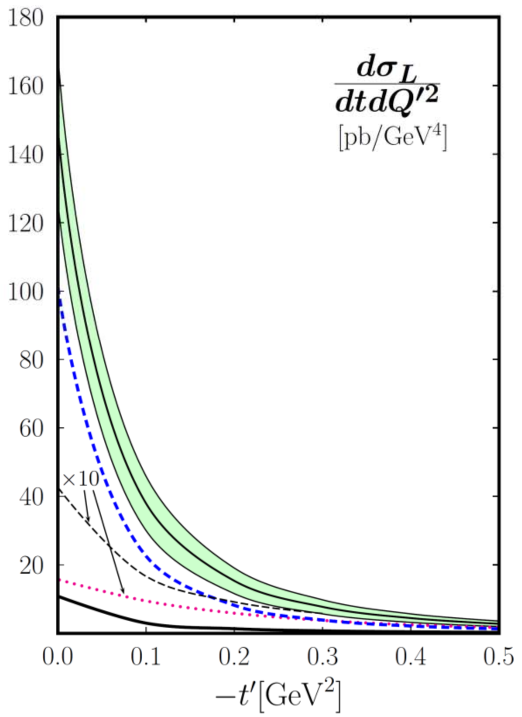
Goloskokov, Kroll, PLB748 ('15) 323

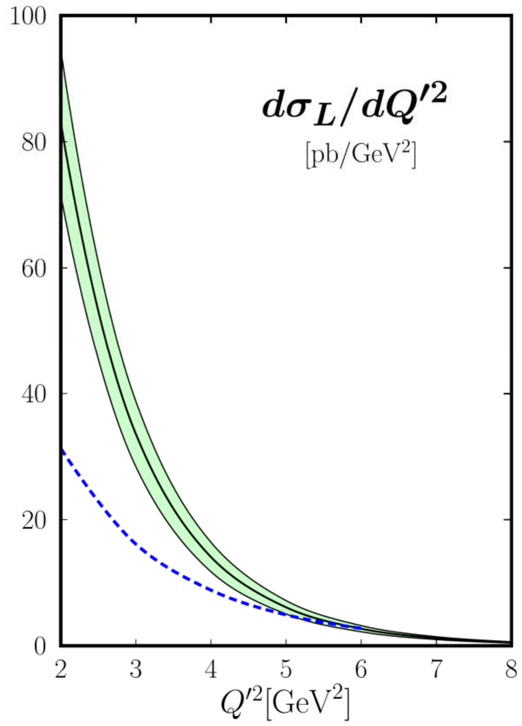




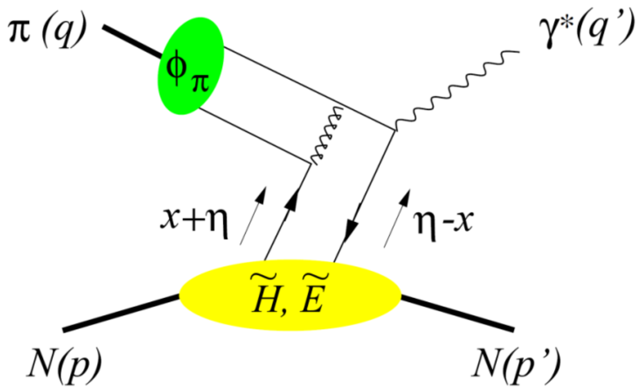


Goloskokov, Kroll, PLB748 ('15) 323



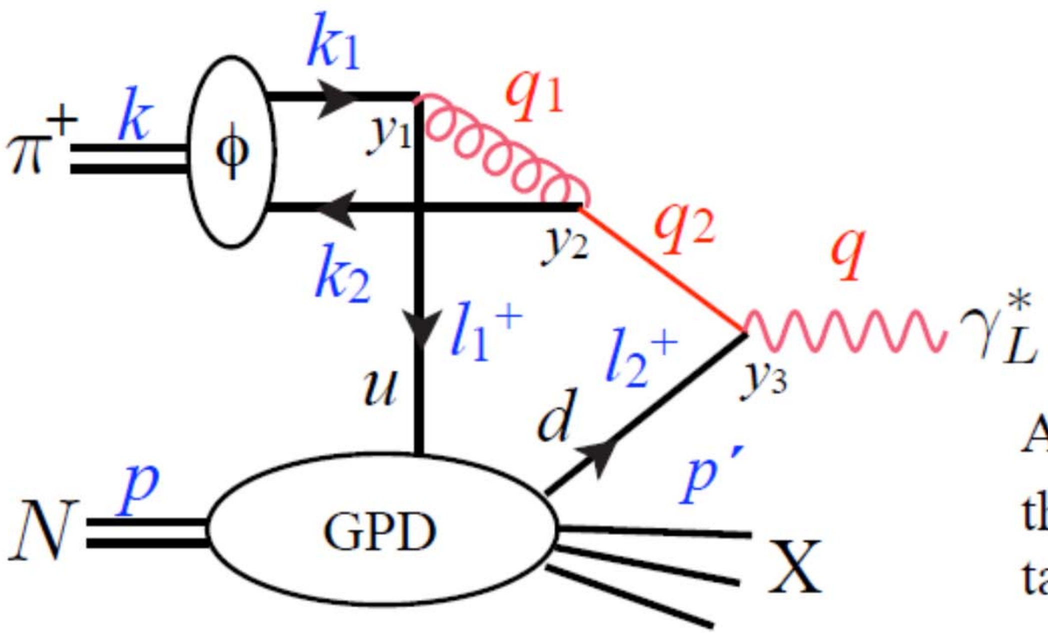


k_T factorization for $O(\alpha_s)$



Hence the stopped quark should be connected to the target:

$$k_1 = (0^+, uk^-, \boldsymbol{k}_\perp)$$
$$k_2 = (0^+, (1-u)k^-, -\boldsymbol{k}_\perp)$$



Since $q_1^2 \approx -uk^- l_1^+ \to \infty$

the pion wave function contributes through its *distribution amplitude* ϕ

Also q_2^2, q_1^-, $q_2^- \to \infty$, hence the space-time separation of the target interaction points y_1, y_3 is

For each final state X the target matrix element is given by a GPD with skewness

$$|y_{1\perp} - y_{3\perp}| = \mathcal{O}(1/Q) \to 0$$
$$|y_1^+ - y_3^+| = \mathcal{O}(1/Q^2) \to 0$$

end-point $(u \to 0, 1)$ **behaviors:**

$$\phi_\pi(u) \sim u(1-u) \qquad \phi_{\text{tw.-3}}(u) \sim 1$$

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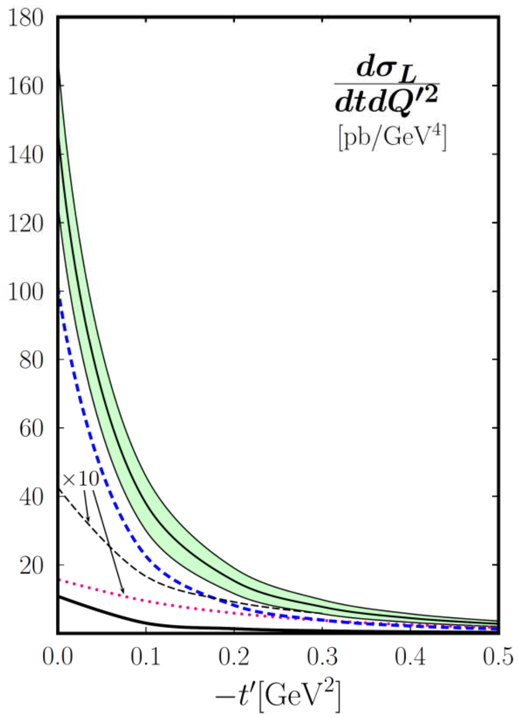
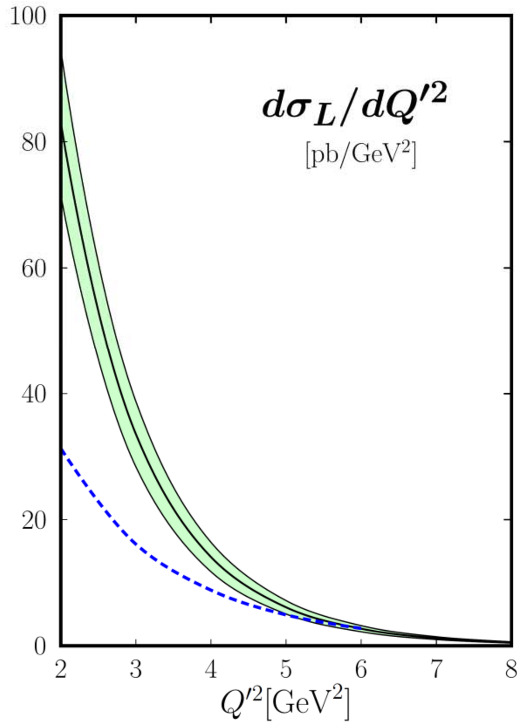
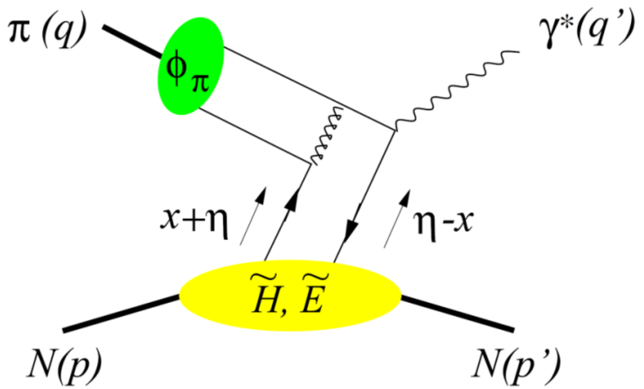
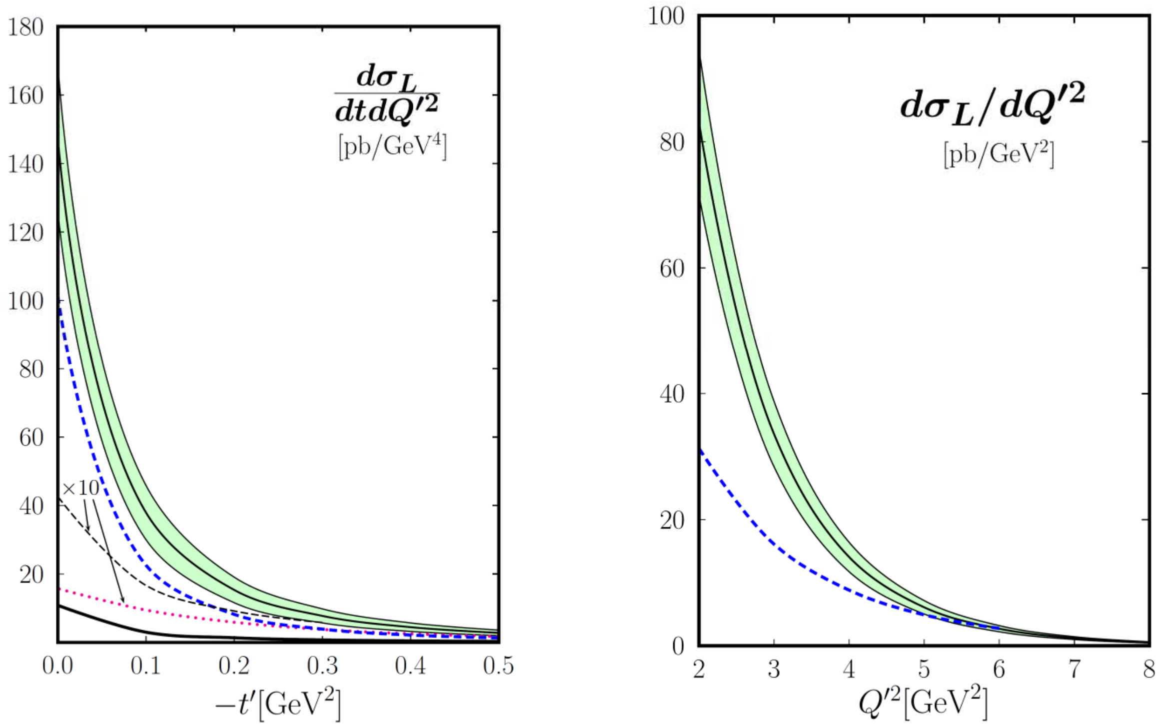


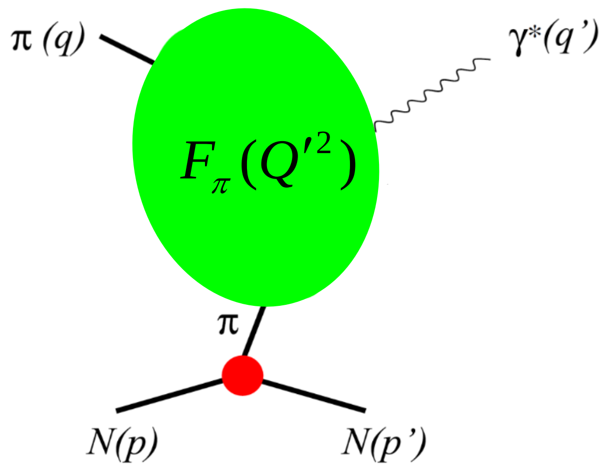


k_T factorization for $O(\alpha_s)$



Goloskokov, Kroll, PLB748 ('15) 323

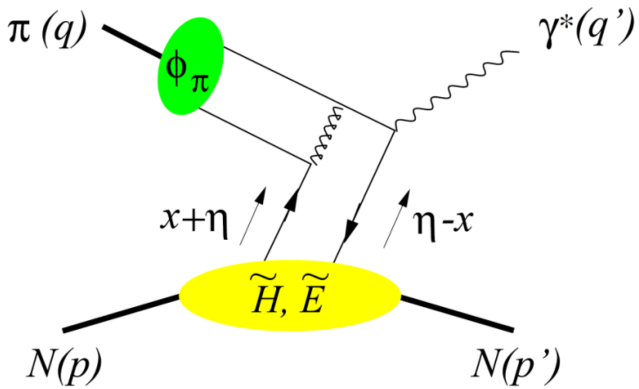


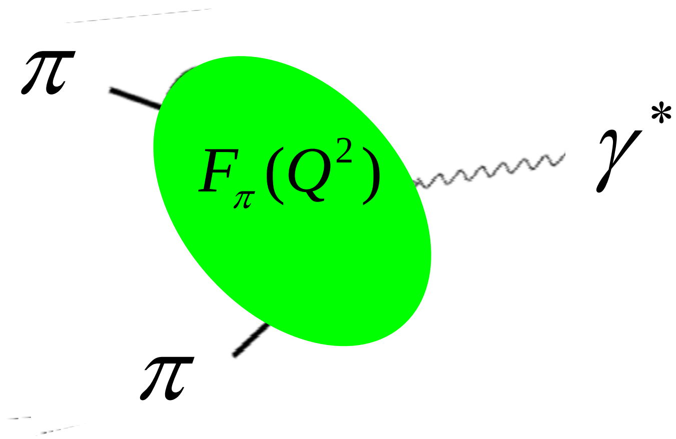


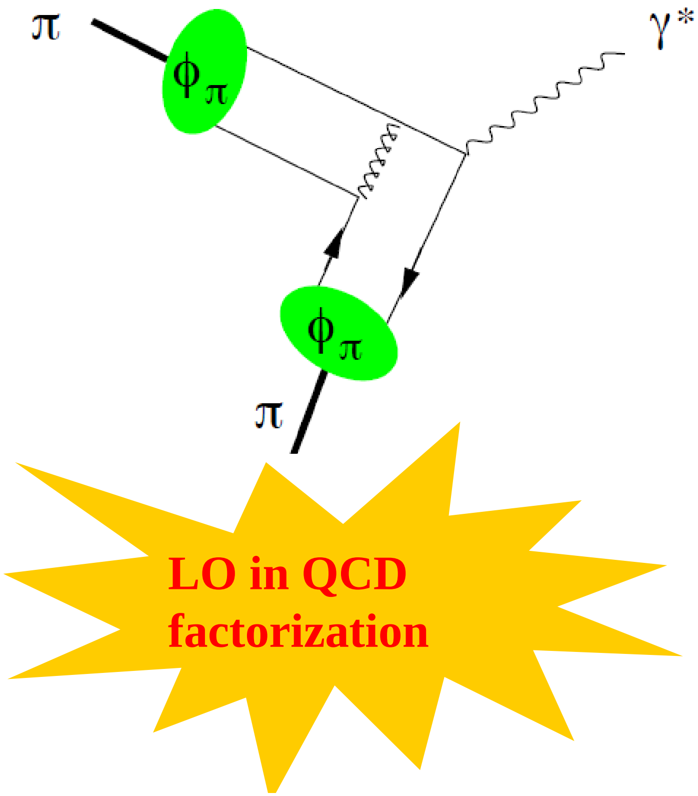
pion exchange for $O(\alpha_s^0)$

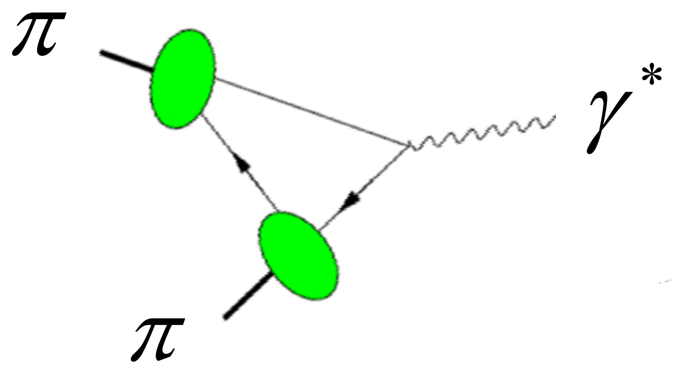
empirical $F_\pi(Q'^2)$

k_T factorization for $O(\alpha_s)$









"nonfactorizable" Feynman mechanism

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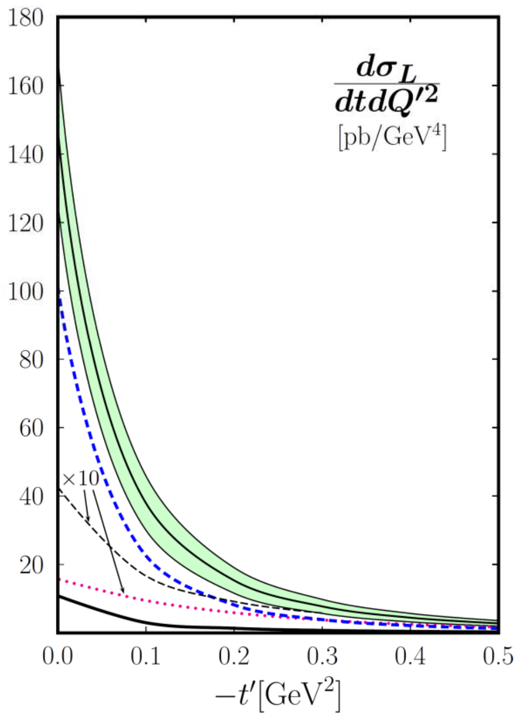
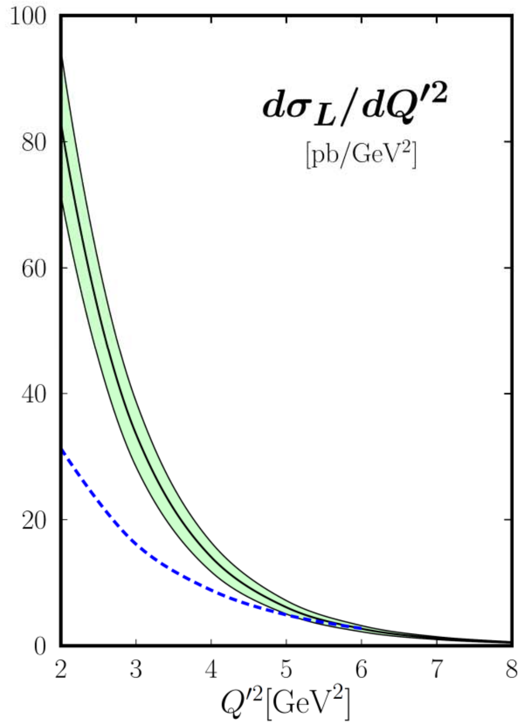
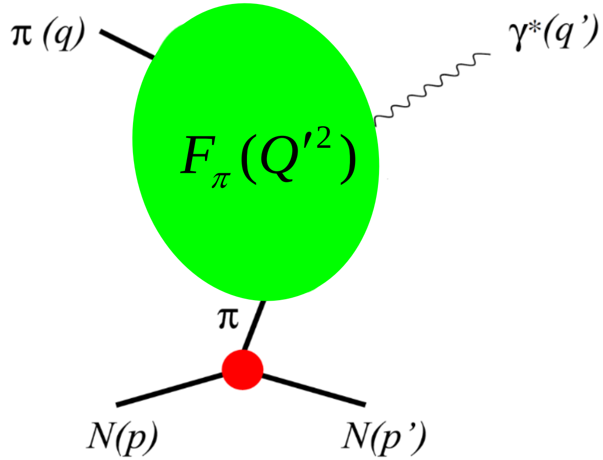
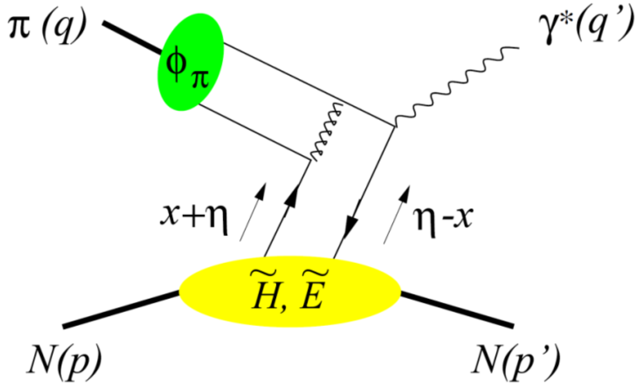






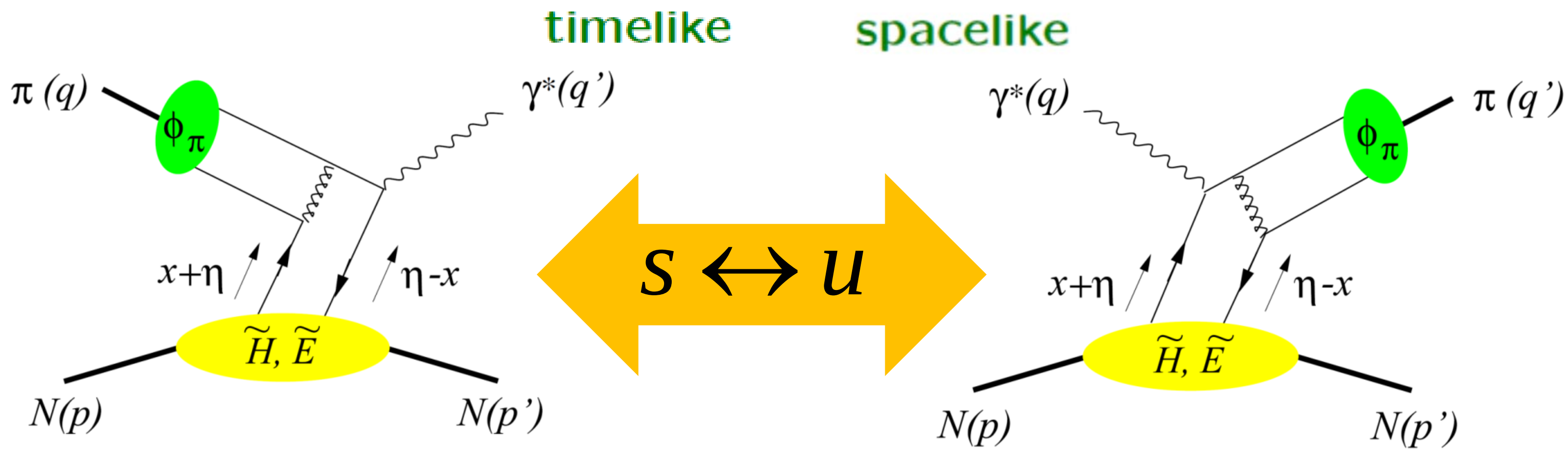
pion exchange for $O(\alpha_s^0)$

empirical $F_\pi(Q'^2)$



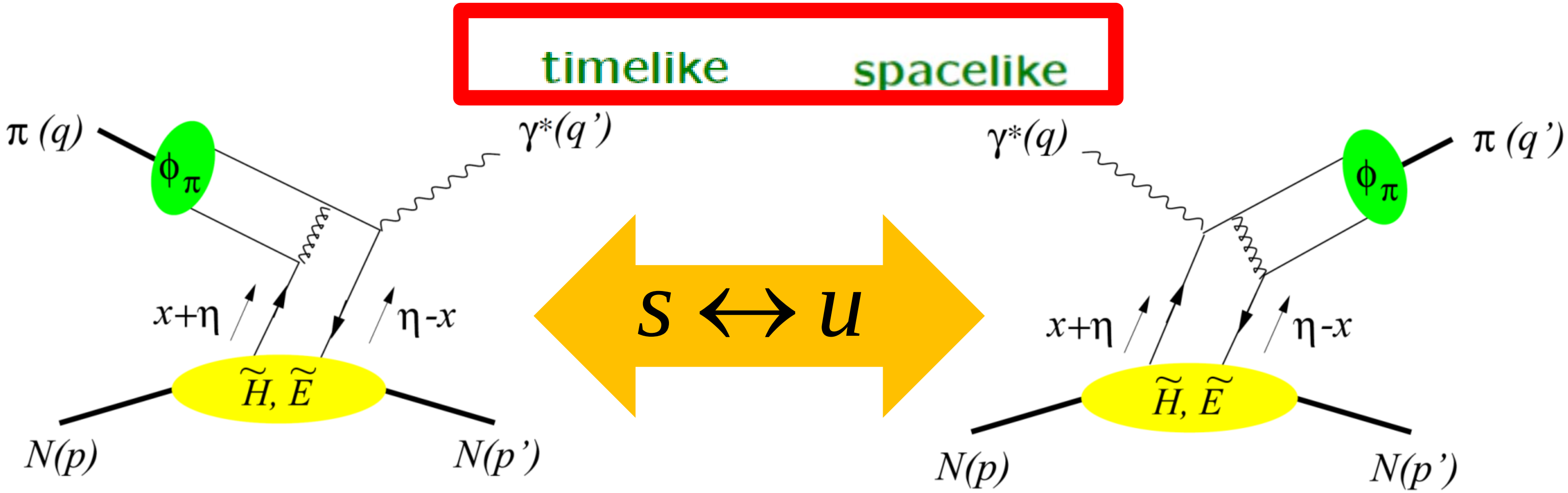
k_T factorization for $O(\alpha_s)$

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



exDY@J-PARC **DVMP@JLab**

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

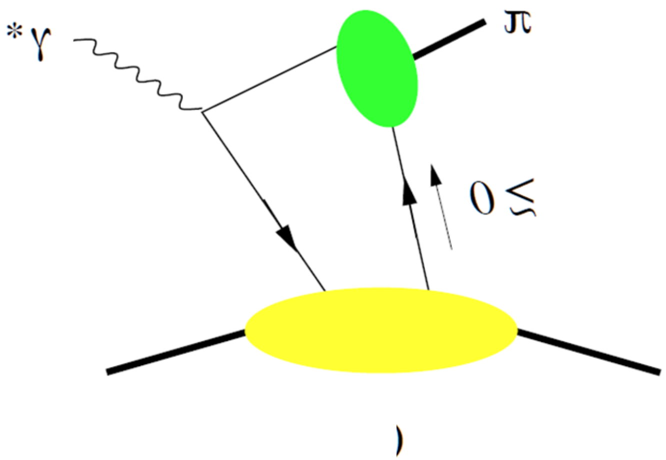


exDY@J-PARC **DVMP@JLab**

$$q \leftrightarrow -q'$$

$s \leftrightarrow u \qquad q \leftrightarrow -q'$

LCSR



$\tilde{x}_0 : \frac{q_{th}^2}{(-Q^2)}$ **quark-hadron duality**

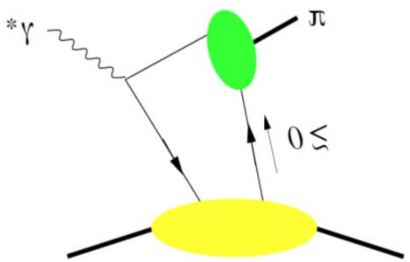
$$\hat{L}_{M_B}\left(\frac{1}{m^2-q^2}\right)=\frac{1}{M_B^2}e^{-\frac{m^2}{M_B^2}}$$

$$\sim g_v^- \frac{1}{f_\pi}\int_{\tilde{x}_0}^{\eta} dx\, e^{-\frac{x-\eta}{x+\eta}\frac{(-Q^2)}{M_B^2}} \tilde{C}_H(x,\eta,Q'^2)$$

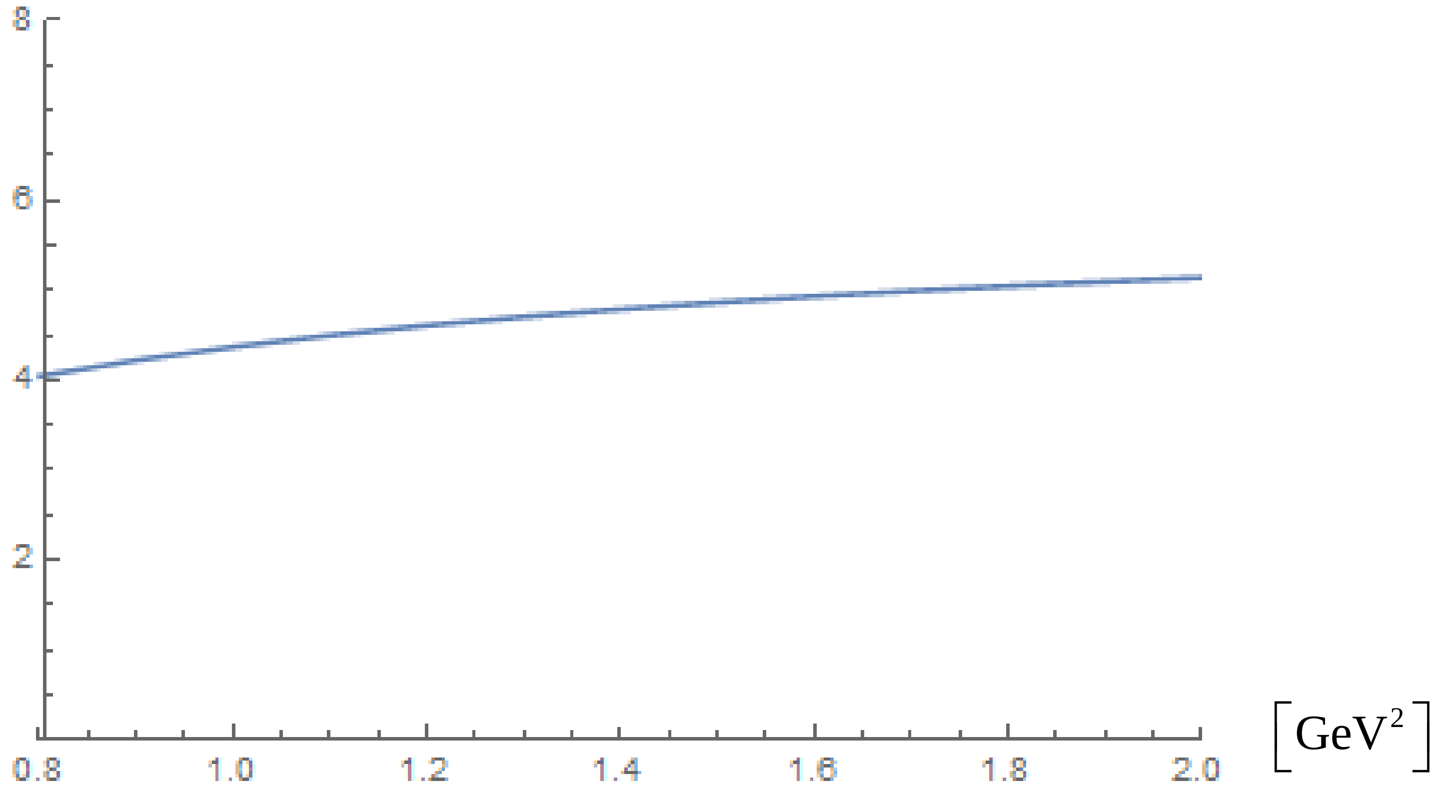
$$\times\left[e_u \tilde{H}^{du}(x,\eta,t)-e_d\tilde{H}^{du}(-x,\eta,t)\right]$$

$$\times\bar{u}(p')\gamma^+\gamma_5 u(p)+\cdots$$

$$\tilde{H}^{du}(x,\eta,t)=\tilde{H}^{u}(x,\eta,t)-\tilde{H}^{d}(x,\eta,t)$$

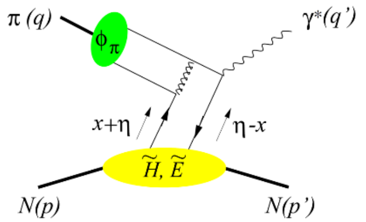


for $\ell p \to \ell' \pi^+ n$ from LCSR



M_B^2 (Borel parameter)

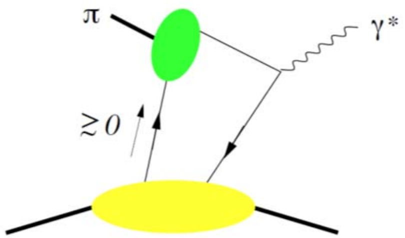
Summary exDY ($\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$) GPDs



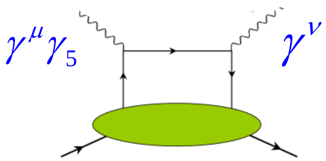
QCD factorization: measurement at J-PARC is feasible

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

soft nonfactorizable mechanism (SNM)



LCSR

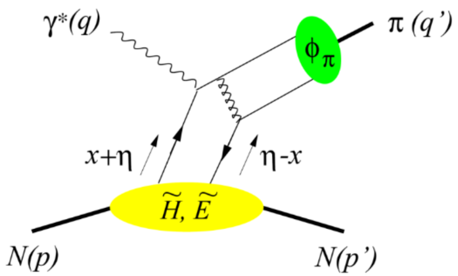


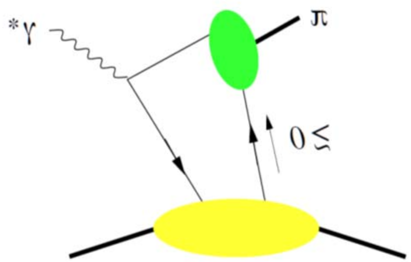
$\tilde{H},\ \tilde{E},\ q_{\rm th}^2 (\sim 0.7\ \mathrm{GeV}^2)$

SNM > QCD factorization

α_s^0 α_s^2

$s \leftrightarrow u$





cross section for $\ell p \to \ell' \pi^+ n$