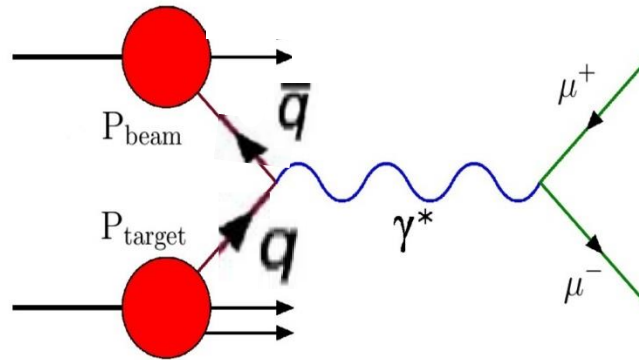


**Accessing GPDs with the exclusive pion-induced  
Drell-Yan process at J-PARC**

**Kazuhiro Tanaka (Juntendo U/KEK)**

# Pion-induced Drell-Yan process

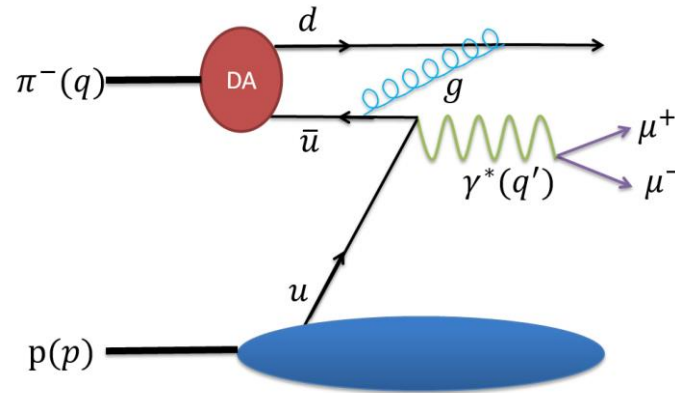
$$\pi N \rightarrow \mu^+ \mu^- X$$



**inclusive**

# Pion-induced Drell-Yan process

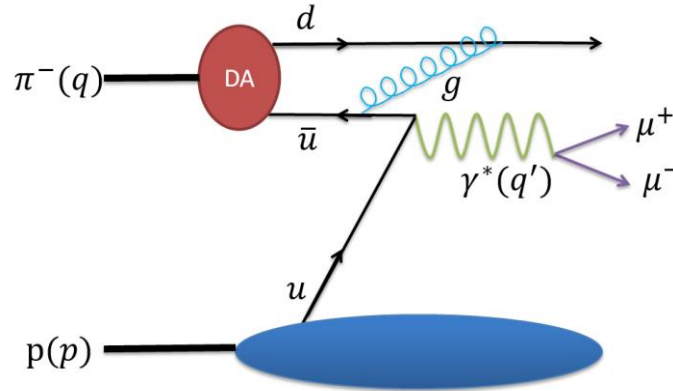
$$\pi N \rightarrow \mu^+ \mu^- X$$



inclusive

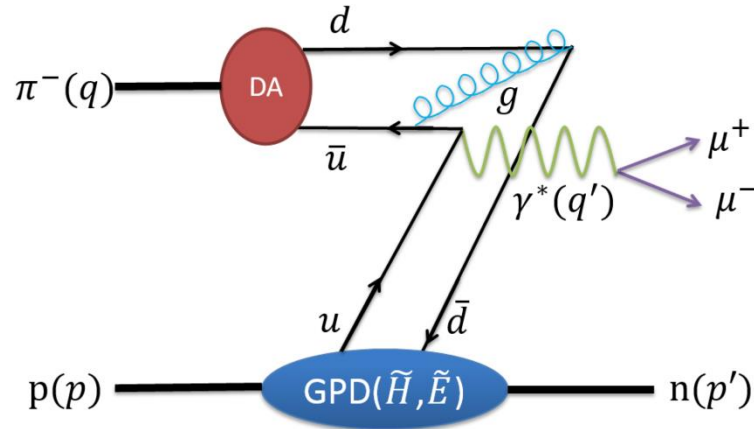
# Pion-induced Drell-Yan process

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



**inclusive**

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



**exclusive**

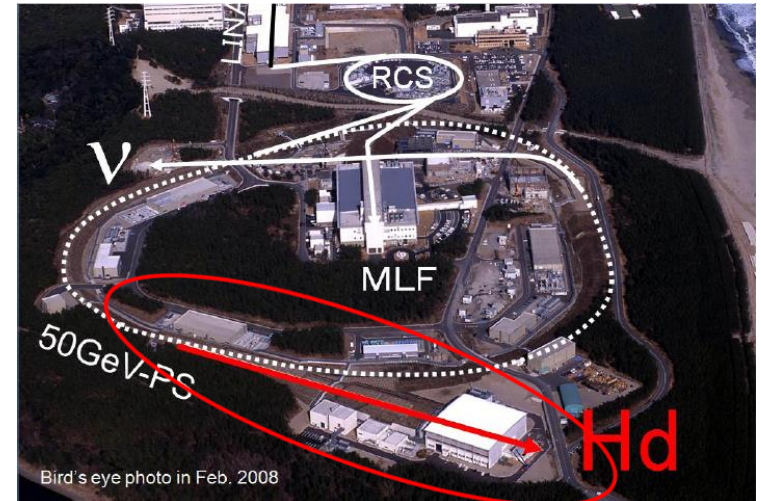
# High momentum beam line at J-PARC

- Primary beam (proton)

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

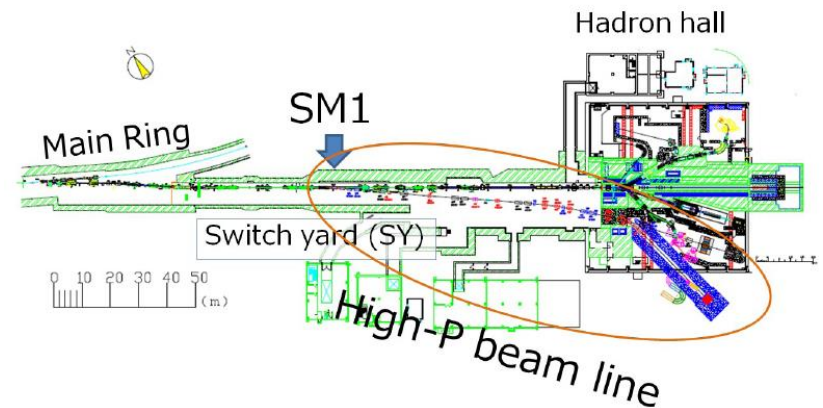
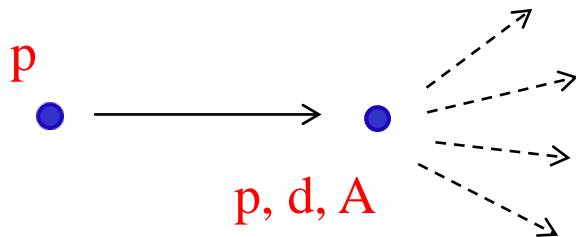
$$L = 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

## Hadron Facility at J-PARC



- Secondary beam (pion)

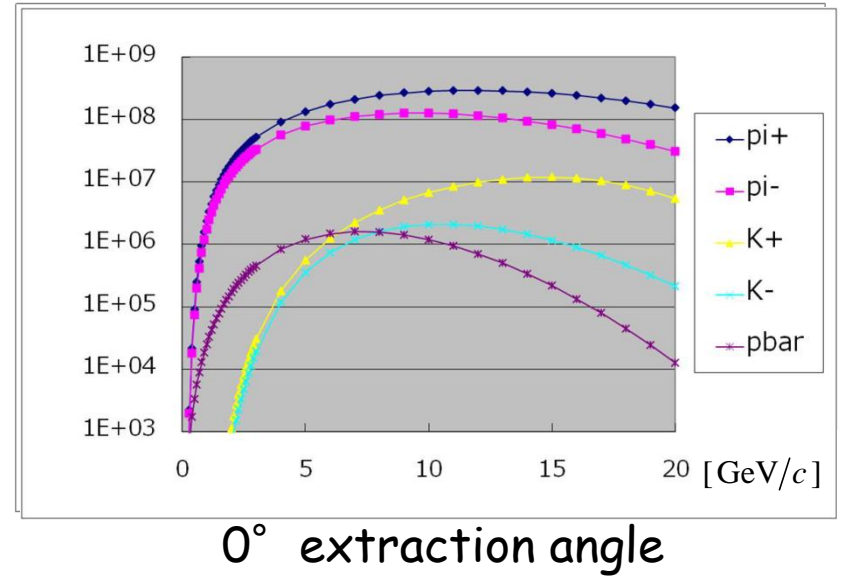
$$E = 15\text{-}20\text{GeV}$$





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

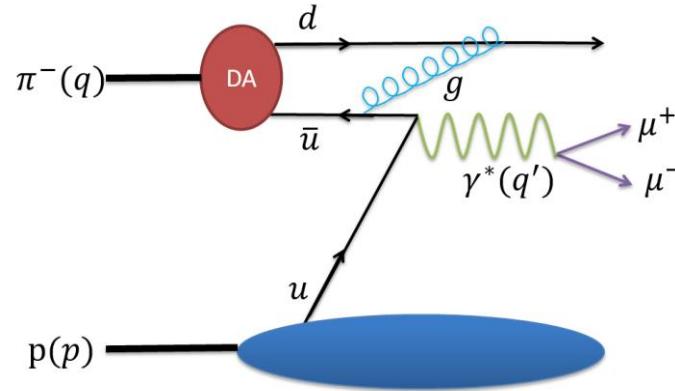
$$d\sigma \sim 1/s^a$$

best suited to study meson-induced  
hard exclusive processes



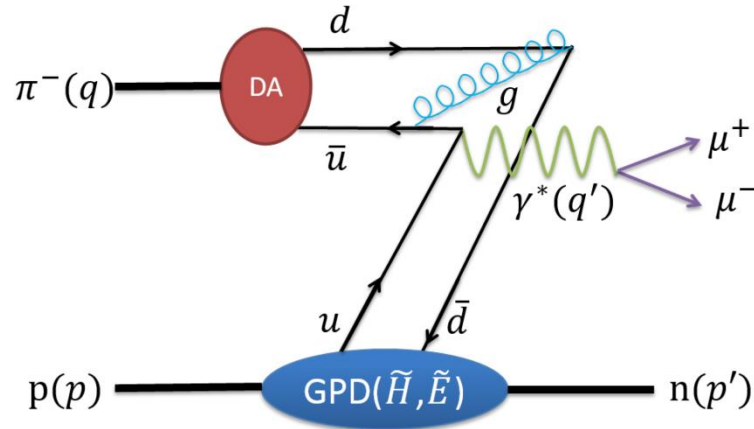
# Pion-induced Drell-Yan process

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



inclusive

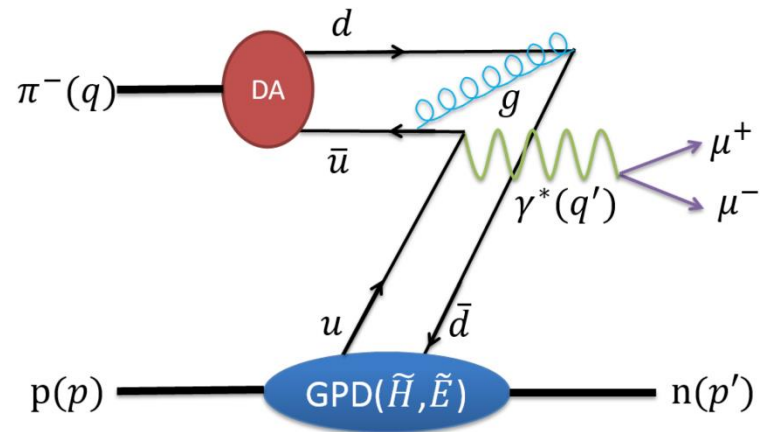
$$\pi N \rightarrow \mu^+ \mu^- N$$



exclusive

# Pion-induced Drell-Yan process

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



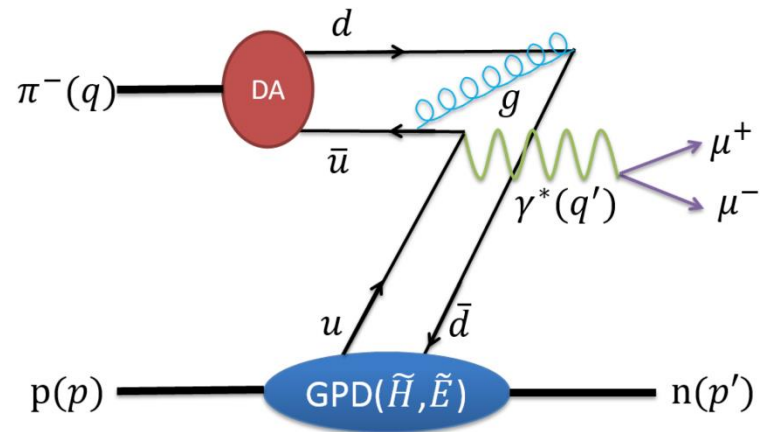
**exclusive**



# Pion-induced Drell-Yan process

QCD factorization formula

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

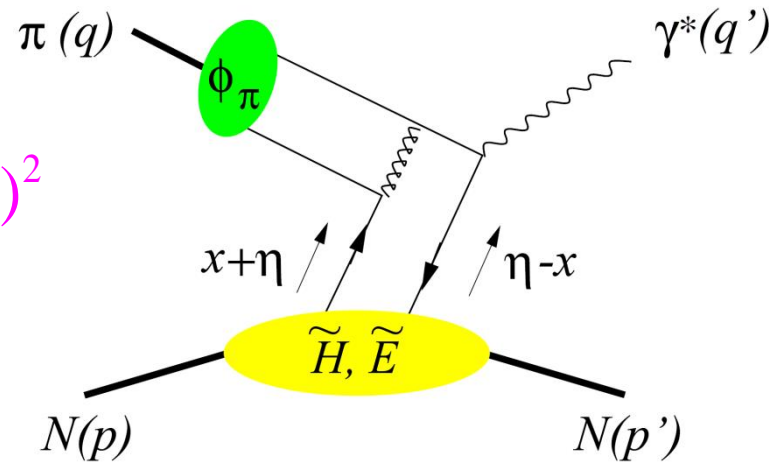


**exclusive**

# Exclusive lepton pair production in $\pi N$ scattering

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

“exclusive DY”

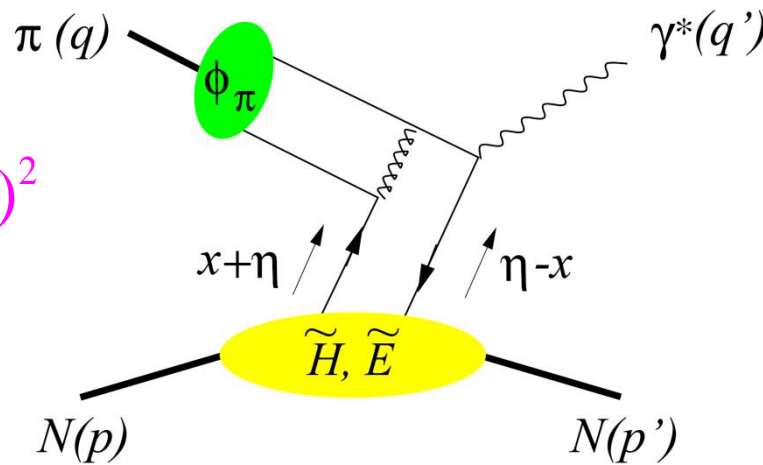


small  $t = \Delta^2 = (q - q')^2$

# Exclusive lepton pair production in $\pi N$ scattering

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

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



"exclusive DY"

LO in QCD  
factorization

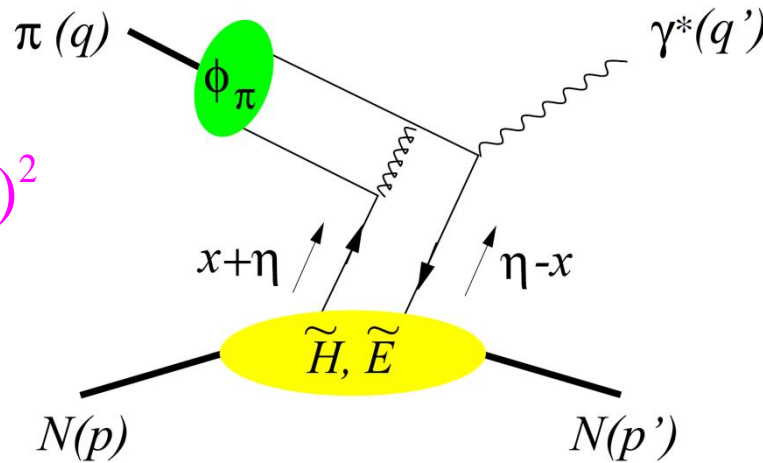
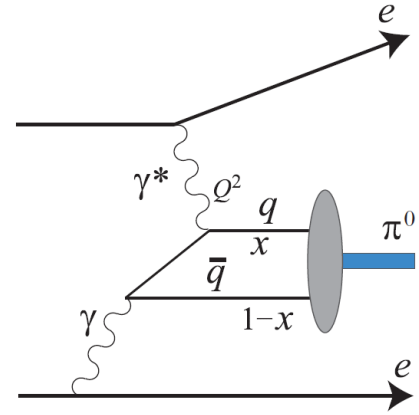
# Exclusive lepton pair production in $\pi N$ scattering

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

@Belle, Babar

"exclusive DY"

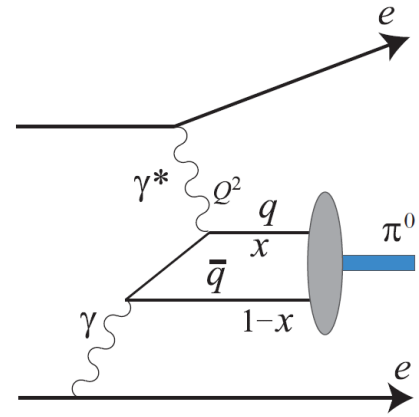
LO in QCD factorization



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

# Exclusive lepton pair production in $\pi N$ scattering

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

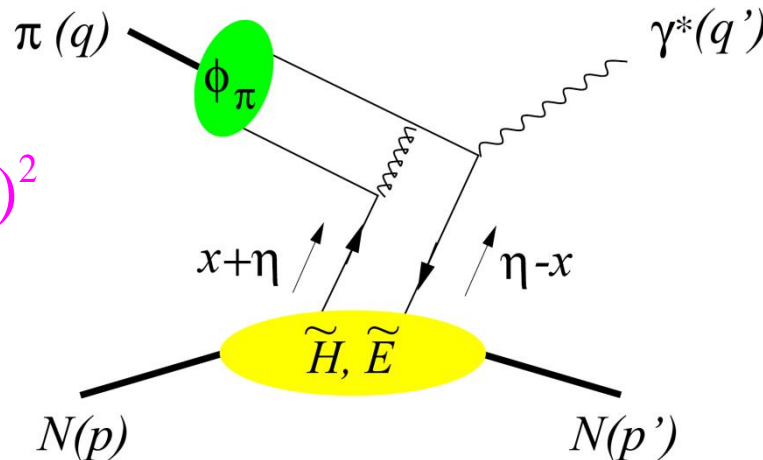


@Belle, Babar

"exclusive DY"

LO in QCD factorization

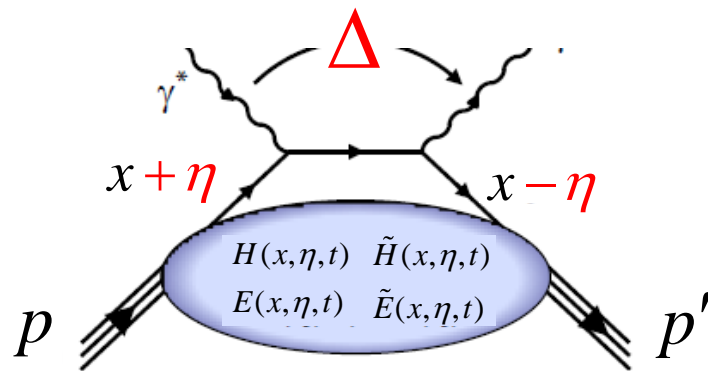
small  $t = \Delta^2 = (q - q')^2$



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

GPD

GPD

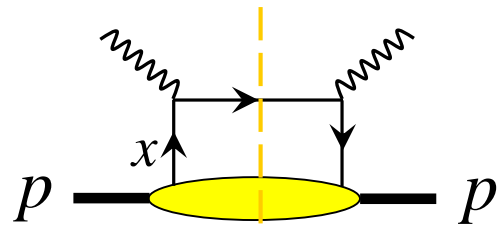
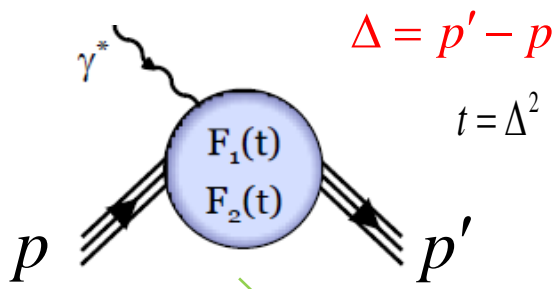


$$-2\eta\bar{P} = \Delta$$

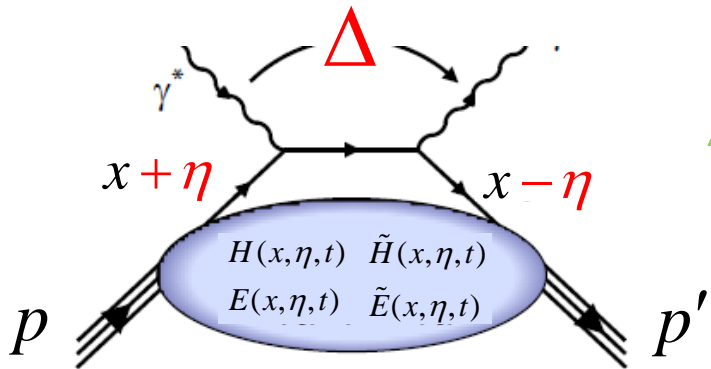
$$\int d\mathbf{z}^- e^{i(x+\eta)pz^-} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$

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

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



**GPD**



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

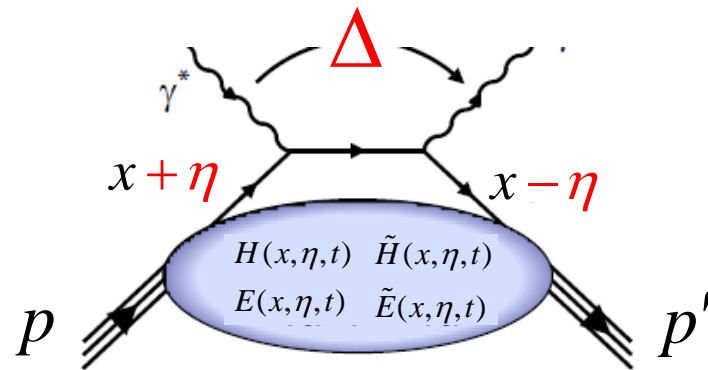
$$\int d\mathbf{z}^- e^{i(x+\eta)\mathbf{p}\mathbf{z}^-} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$

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

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

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

GPD

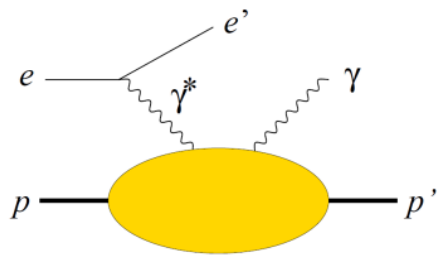


$$-2\eta\bar{P} = \Delta$$

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



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

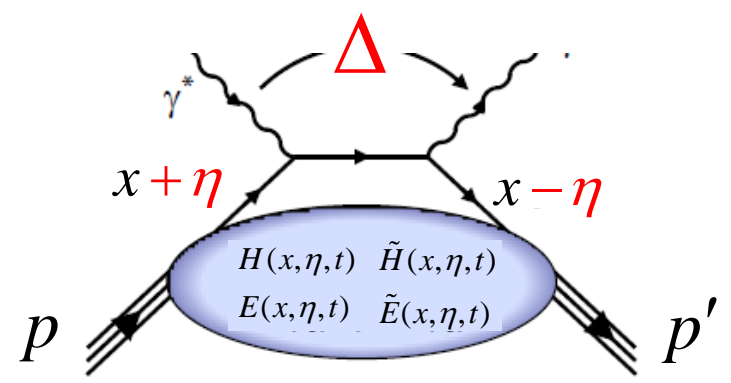


# JLab, HERMES, COMPASS, ...

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

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

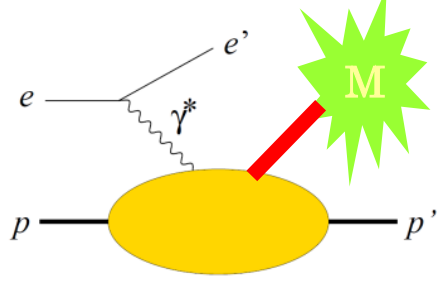
GPD



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

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

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

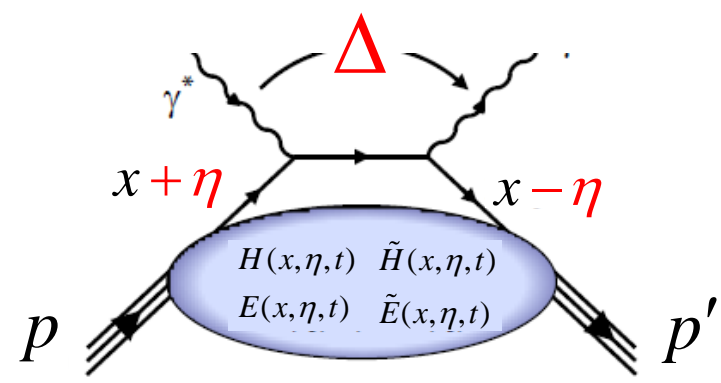


# JLab, HERMES, COMPASS, ...

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

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

GPD

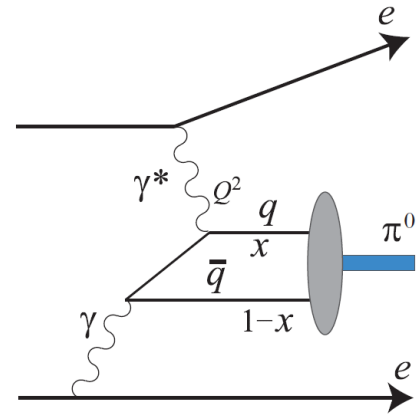


$$-2\eta\bar{P} = \Delta$$

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

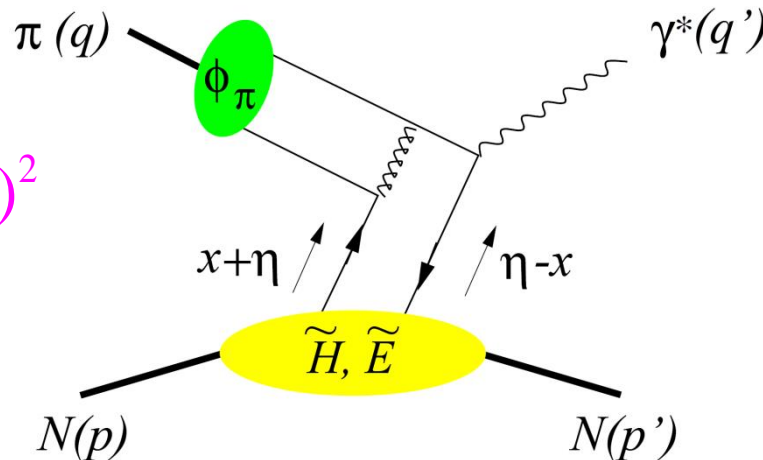
# Exclusive lepton pair production in $\pi N$ scattering

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



@Belle, Babar

"exclusive DY"



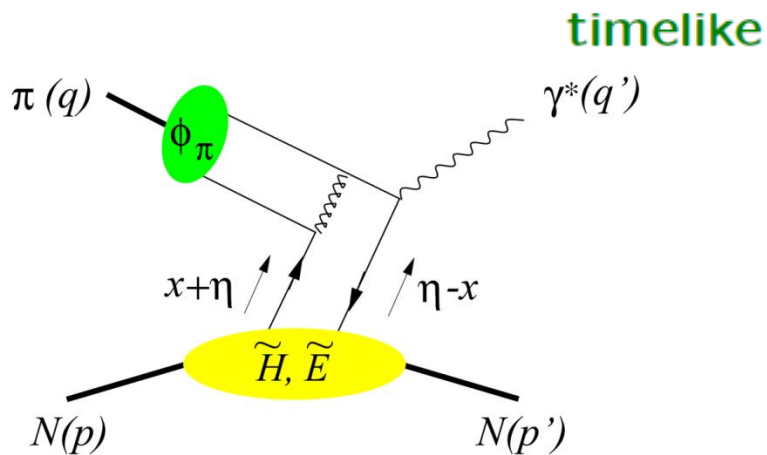
LO in QCD  
factorization

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

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

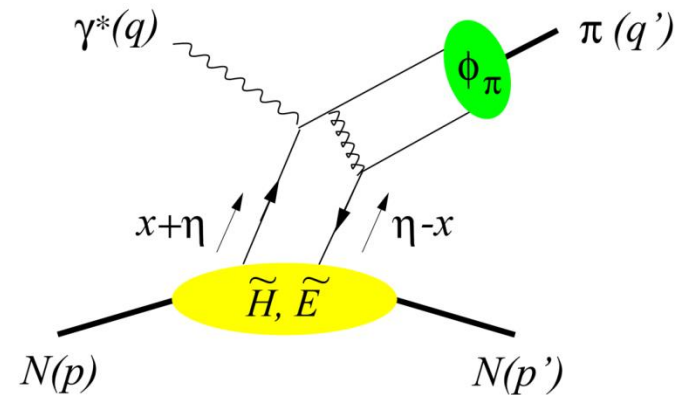
GPD

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



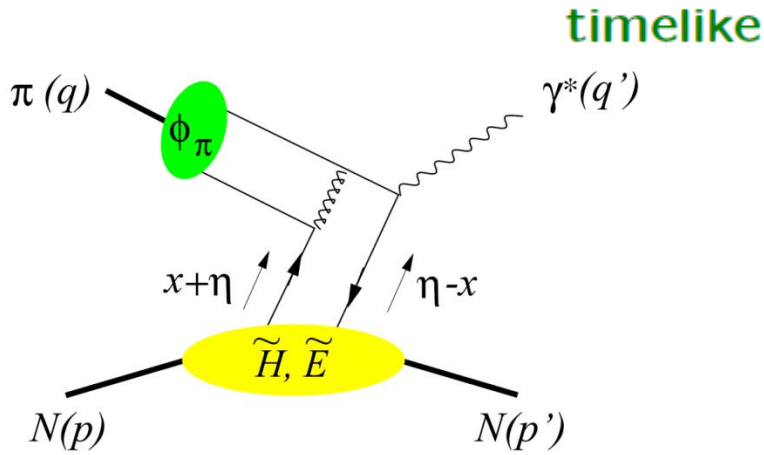
**exDY@J-PARC**

spacelike

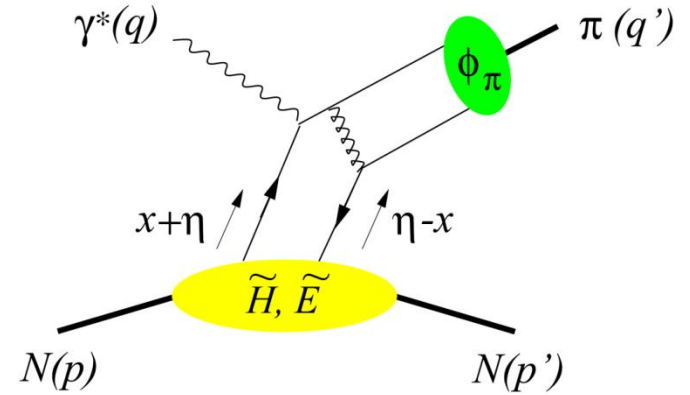


**DVMP@JLab**

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

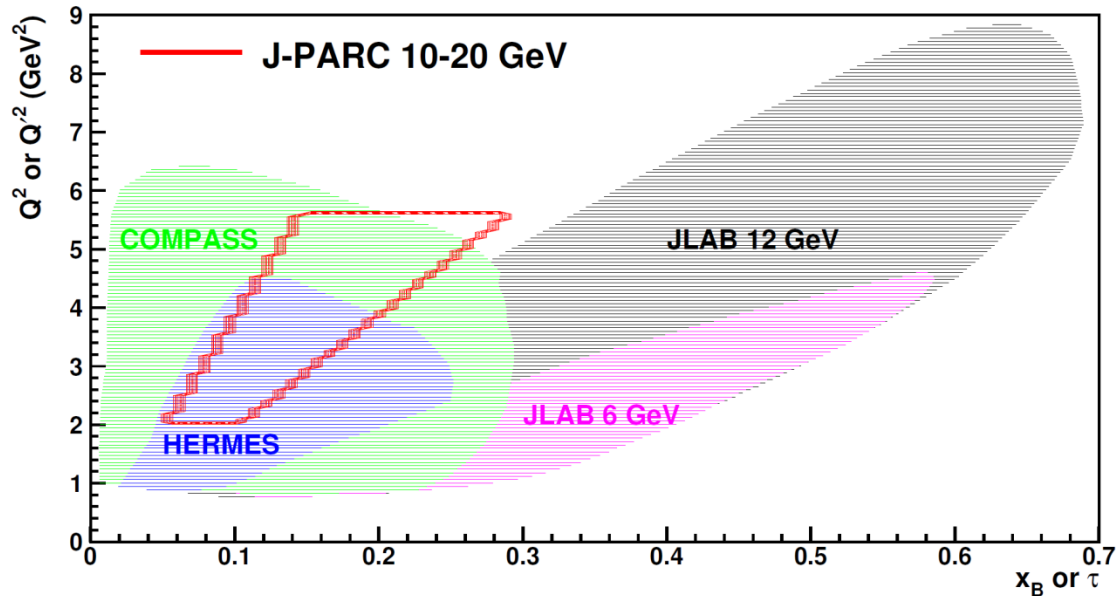


**spacelike**

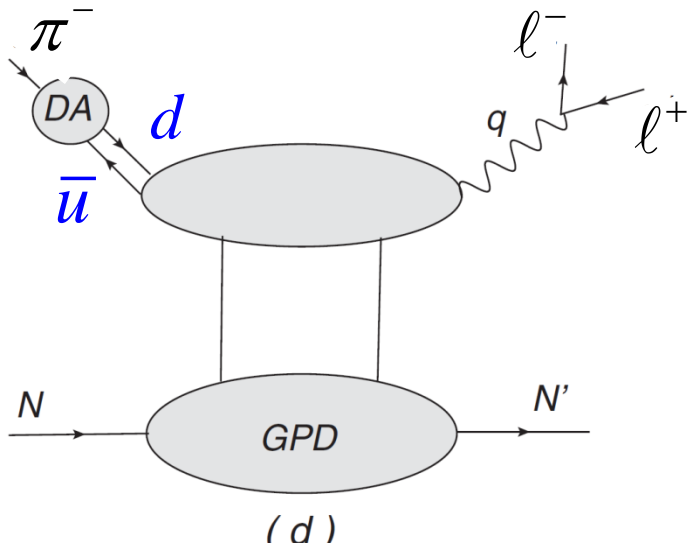


**exDY@J-PARC**

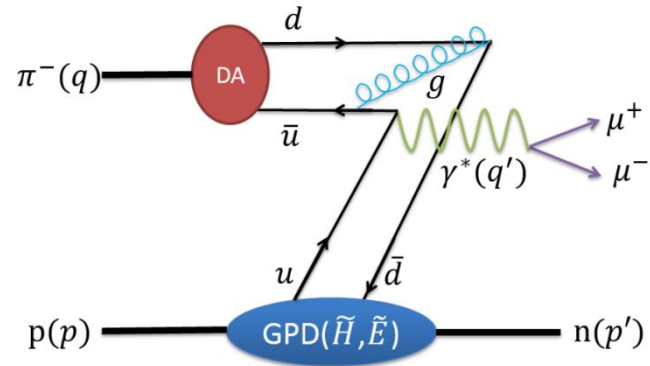
**DVMP@JLab**



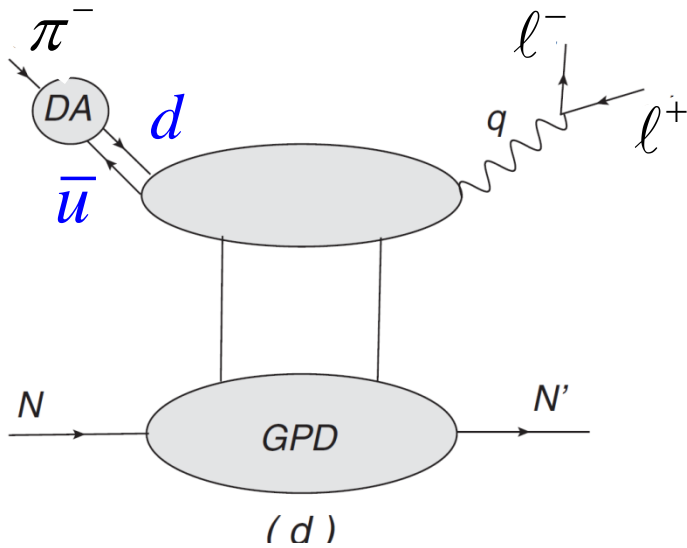
T. Sawada et al.,  
PRD93, 114034



**exDY@J-PARC**



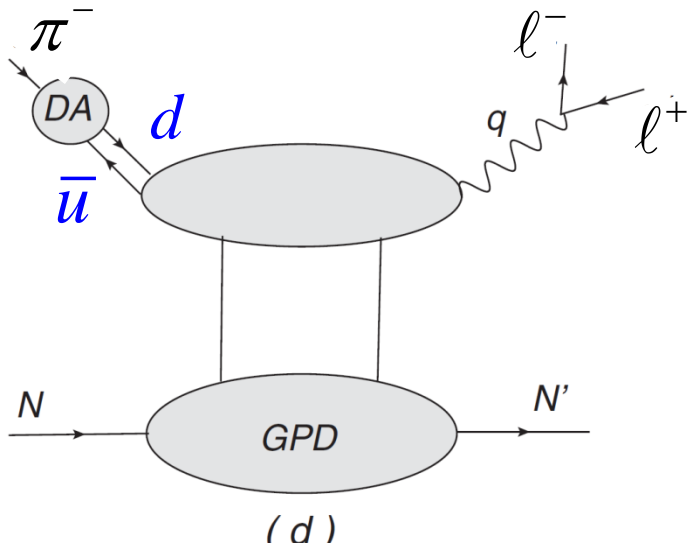
$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z^-} \langle n(p') | \bar{d}(-\frac{z^-}{2}) \gamma^+ \gamma_5 u(\frac{z^-}{2}) | p(p) \rangle = \frac{1}{2P^+} \bar{u}(p') \left[ \tilde{H}^{du}(x, \eta, t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x, \eta, t) \frac{\gamma_5 \Delta^+}{2m_N} \right] u(p)$$



**exDY@J-PARC**

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

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



## exDY@J-PARC

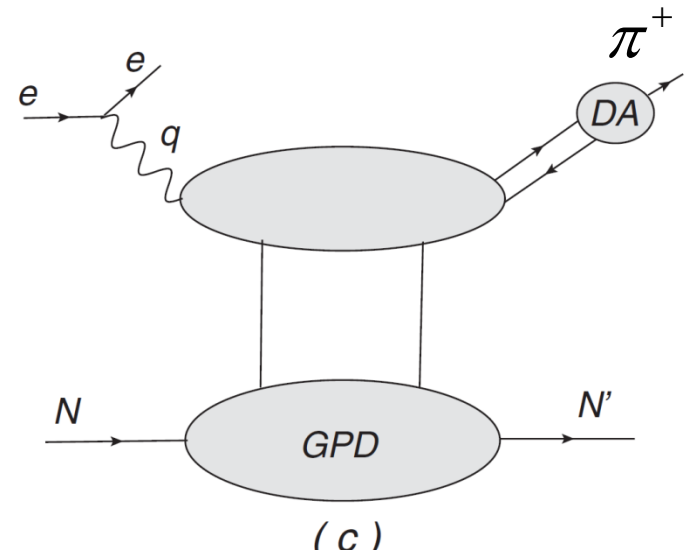
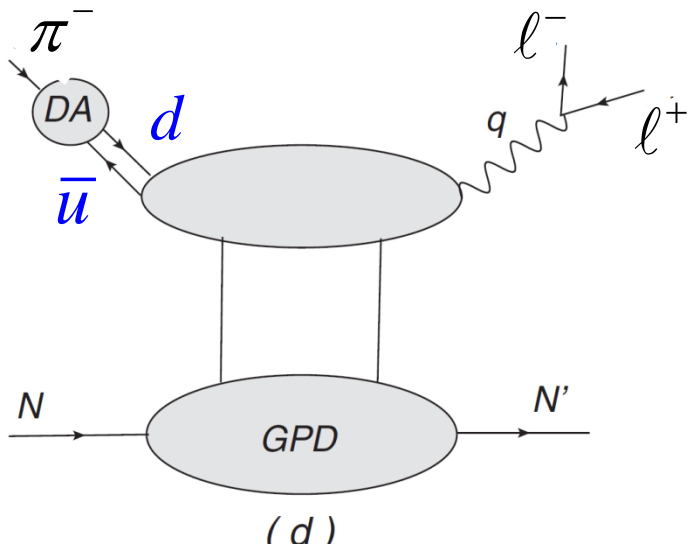
$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z^-} \langle n(p') \left| \bar{d}\left(-\frac{z^-}{2}\right) \gamma^+ \gamma_5 u\left(\frac{z^-}{2}\right) \right| p(p) \rangle = \frac{1}{2P^+} \bar{u}(p') \left[ \tilde{H}^{du}(x, \eta, t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x, \eta, t) \frac{\gamma_5 \Delta^+}{2m_N}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

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

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

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





**exDY@J-PARC**

**DVMP@HERA, JLab**

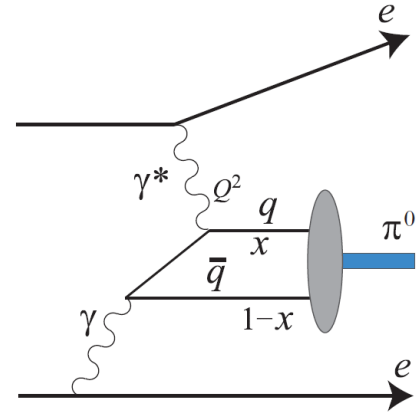
$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}z^-} \langle n(p') \left| \bar{d}\left(-\frac{z^-}{2}\right) \gamma^+ \gamma_5 u\left(\frac{z^-}{2}\right) \right| p(p) \rangle = \frac{1}{2P^+} \bar{u}(p') \left[ \tilde{H}^{du}(x, \eta, t) \gamma^+ \gamma_5 + \tilde{E}^{du}(x, \eta, t) \frac{\gamma_5 \Delta^+}{2m_N}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

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

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

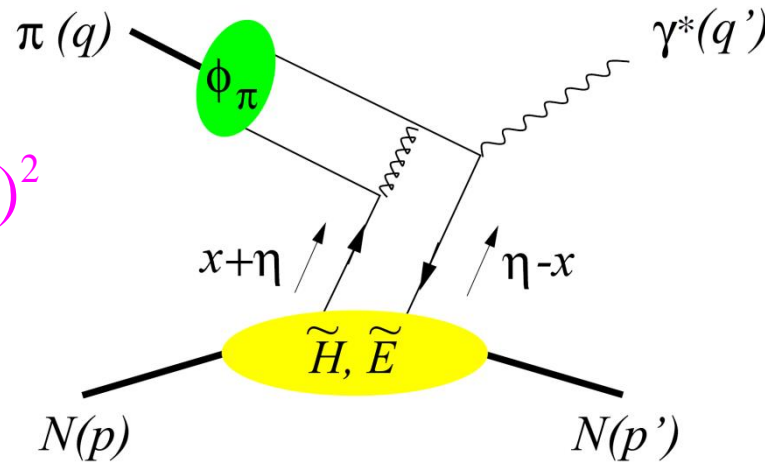
# Exclusive lepton pair production in $\pi N$ scattering

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



@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 $\pi N$ scattering

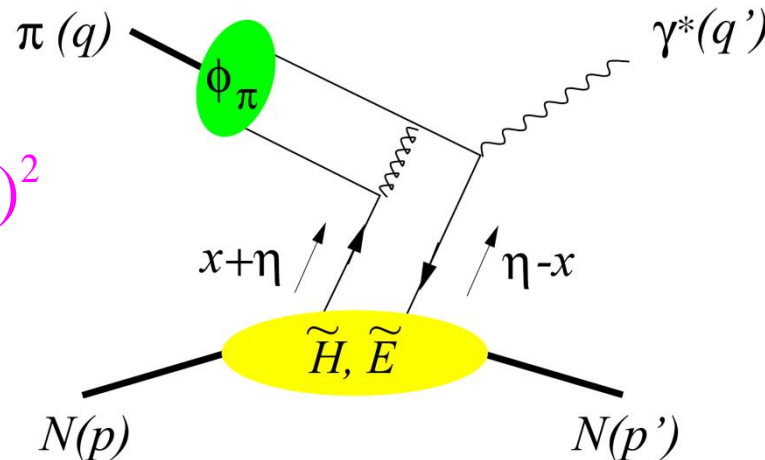
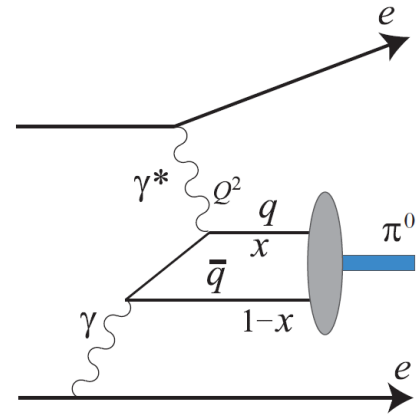
$$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$$

Berger, Diehl, Pire, PLB523(2001)265

@Belle, Babar

"exclusive DY"

LO in QCD factorization



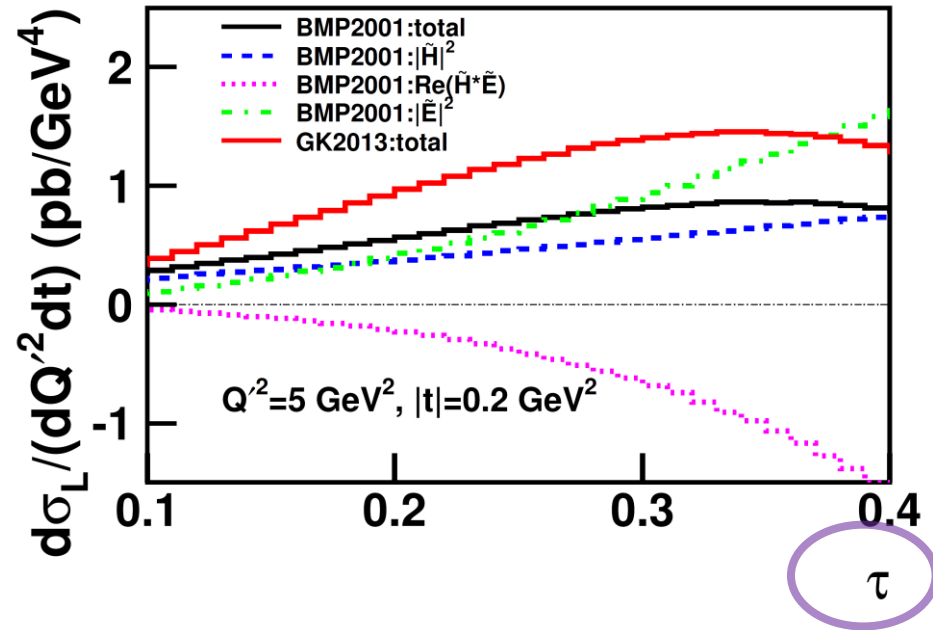
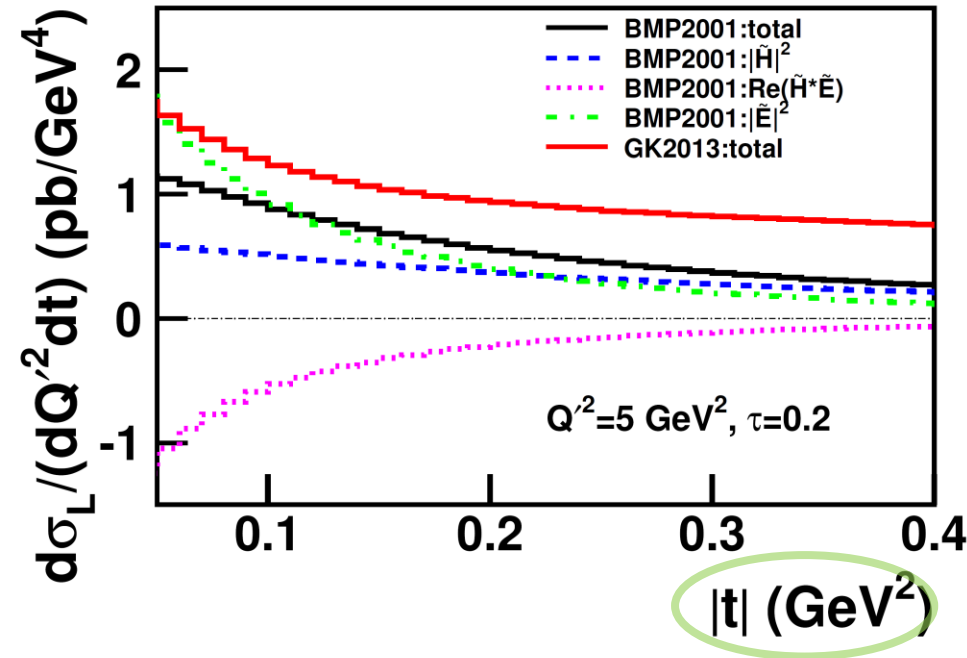
small  $t = \Delta^2 = (q - q')^2$

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

GPD

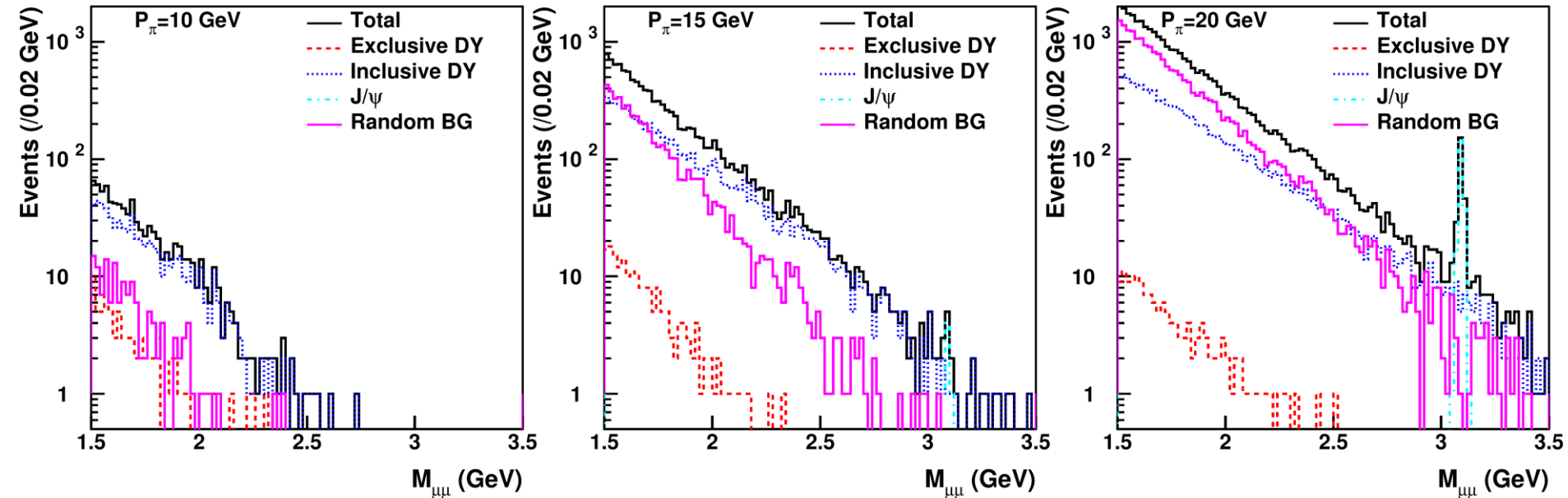
Bjorken variable  $\tau = \frac{Q'^2}{s-M^2}$

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



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

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

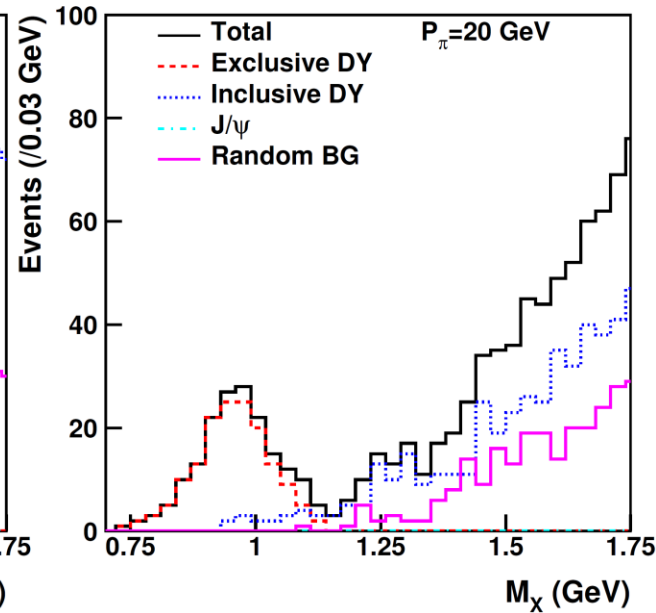
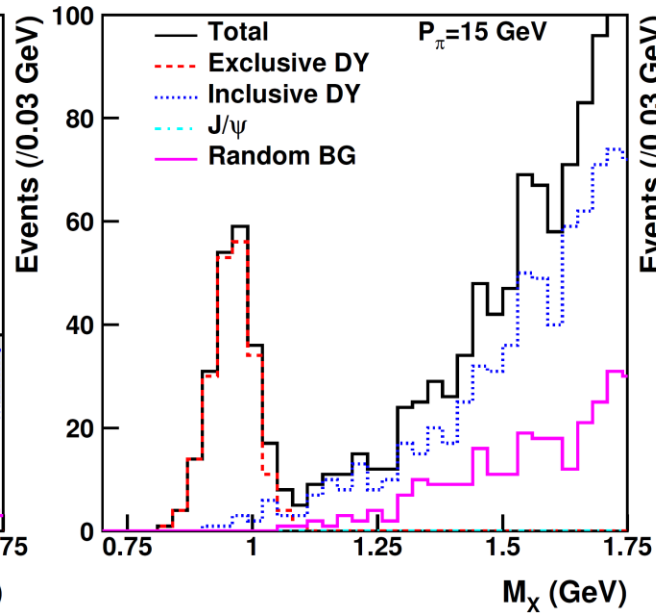
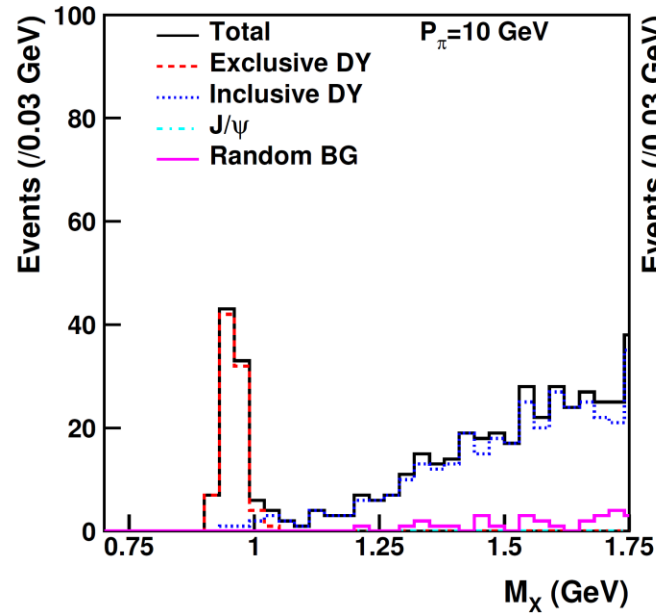


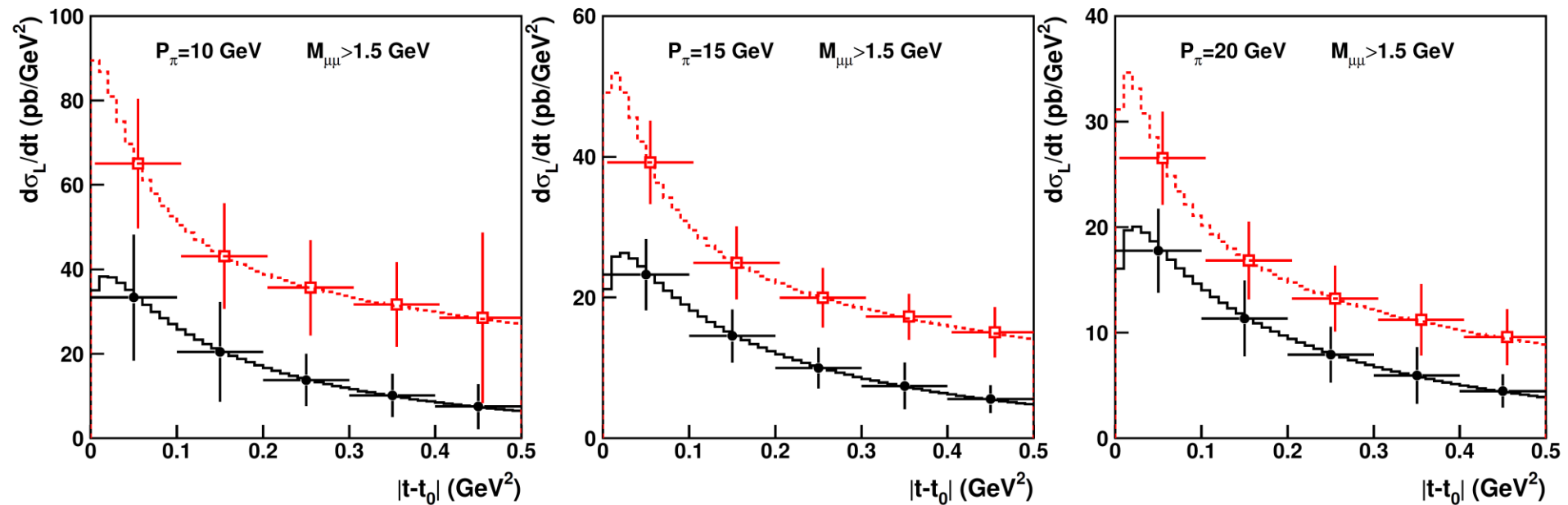
# feasibility with E50 spectrometer at J-PARC

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

# feasibility with E50 spectrometer at J-PARC

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



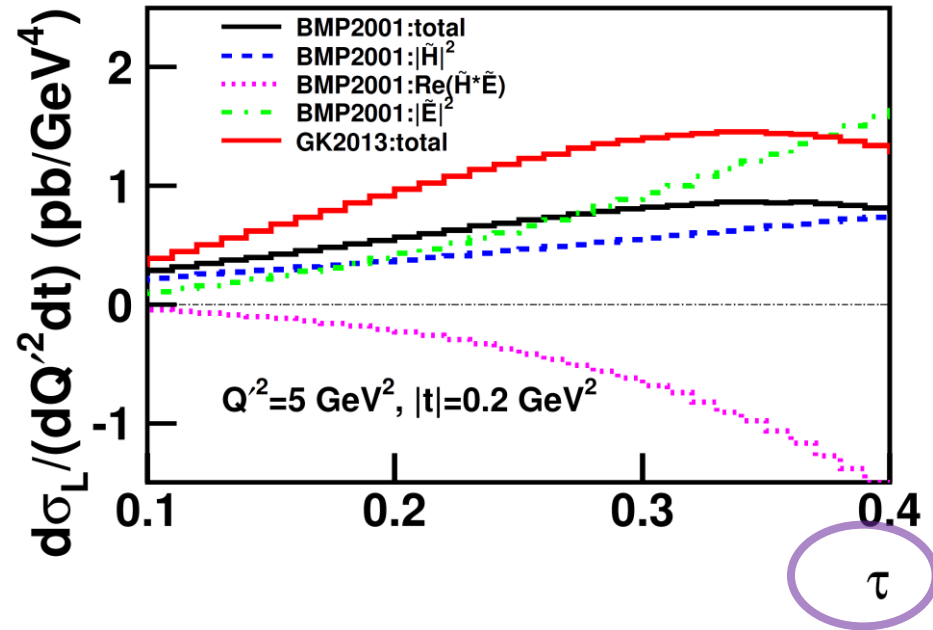
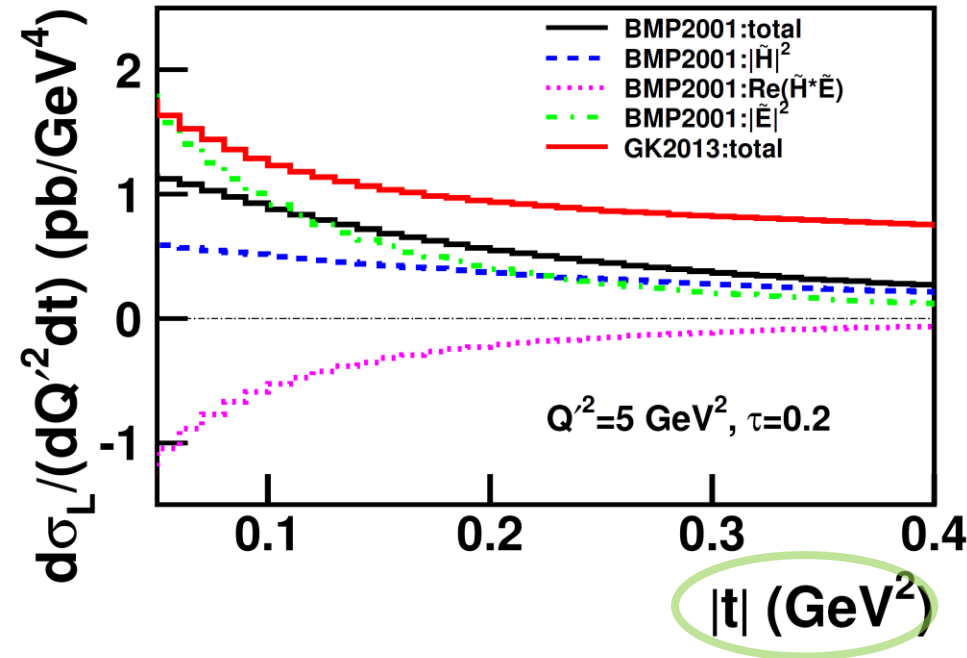


## feasibility with E50 spectrometer at J-PARC

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

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

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



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

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

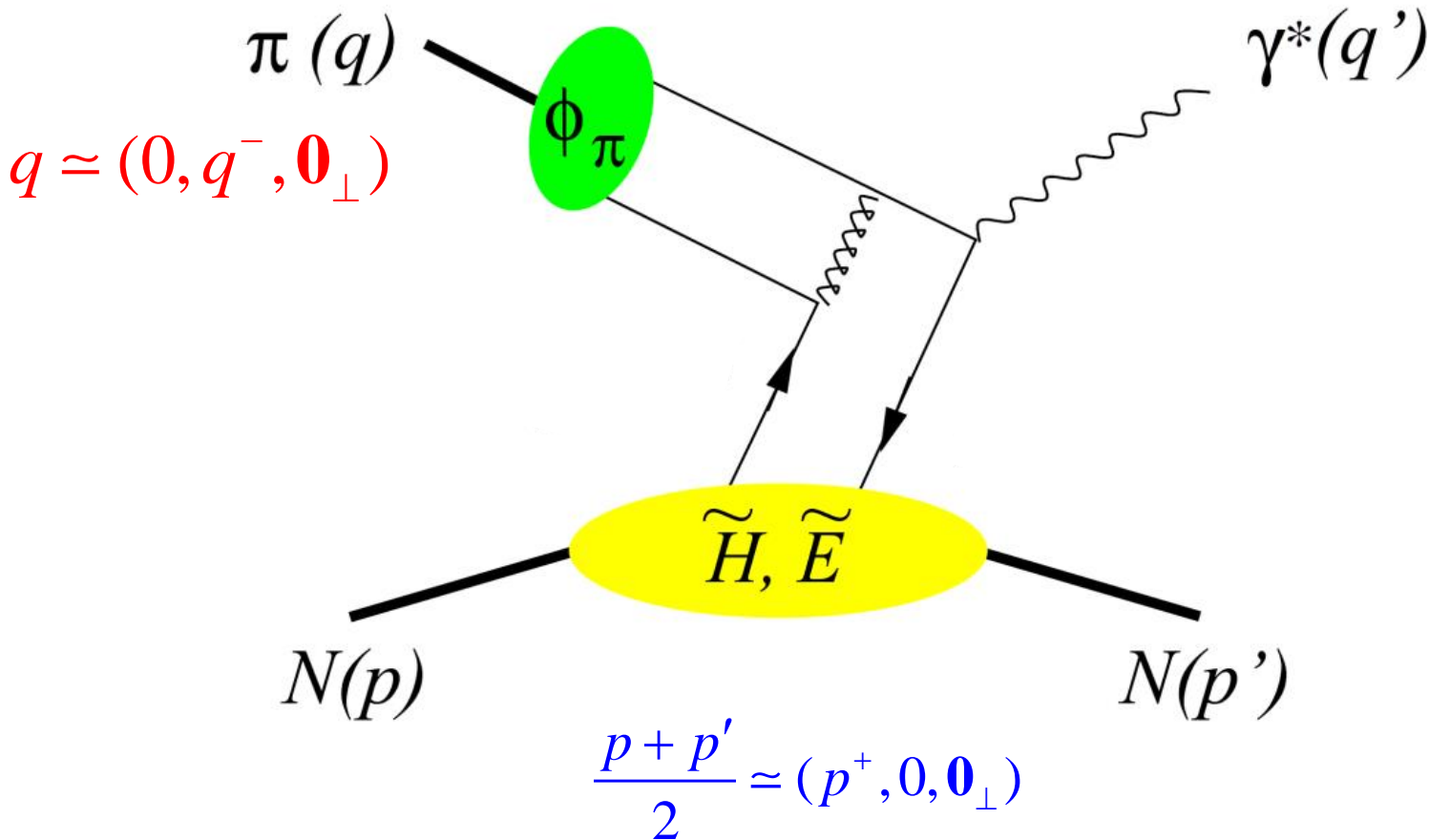


$$\frac{d\sigma}{dQ'^2 dt}(\pi^- p \rightarrow \gamma^* n) = \frac{4\pi\alpha_{\text{em}}^2 \tau^2}{27 Q'^8} f_\pi^2 \left[ (1-\eta^2) |\mathcal{H}^{du}|^2 - 2\eta^2 \text{Re}(\mathcal{H}^{du*} \mathcal{E}^{du}) - \eta^2 \frac{t}{4M^2} |\mathcal{E}^{du}|^2 \right]$$

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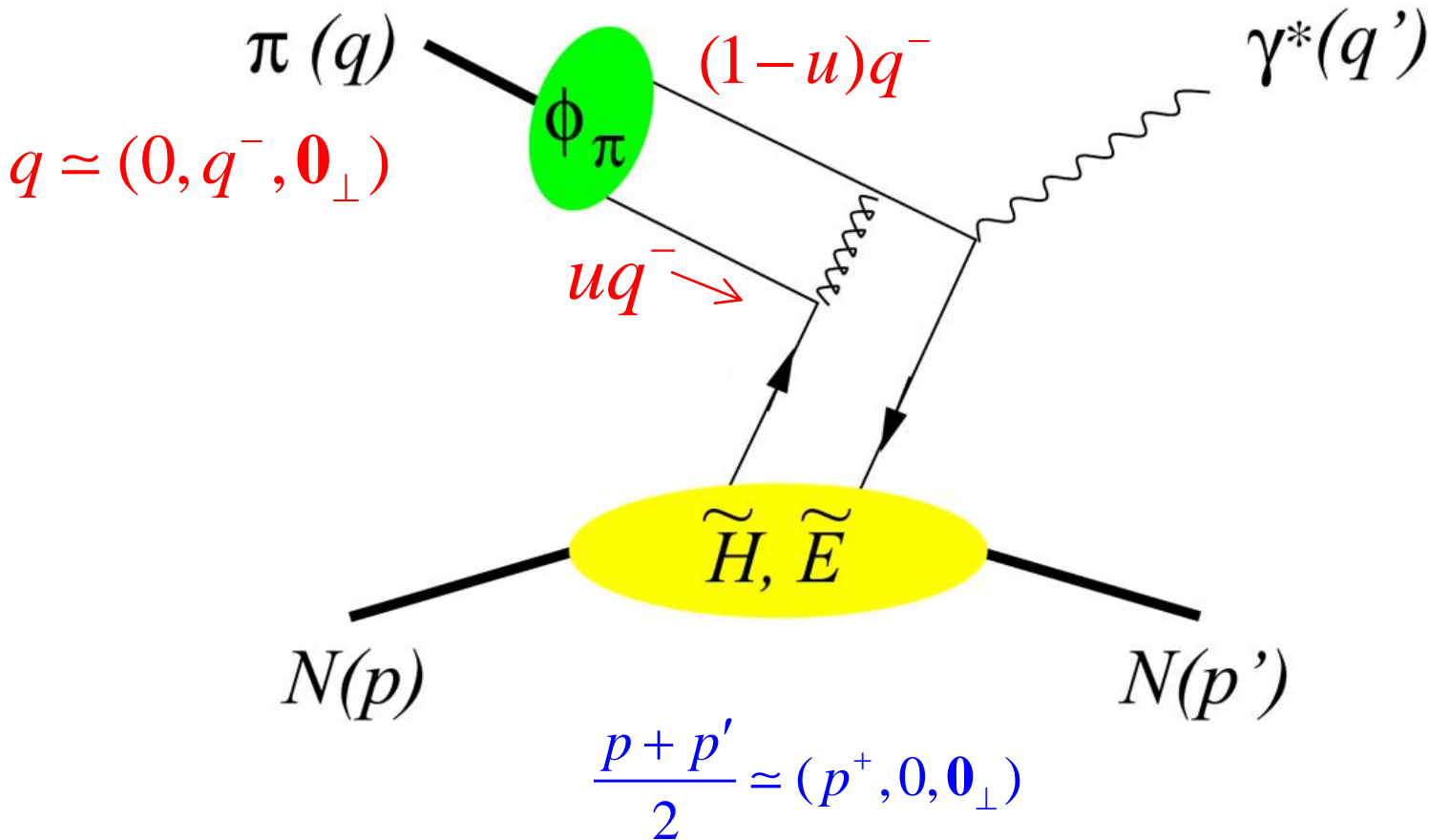
$$\frac{d\sigma}{dQ'^2 dt}(\pi^- p \rightarrow \gamma^* n) = \frac{4\pi\alpha_{\text{em}}^2 \tau^2}{27 Q'^8} f_\pi^2 \left[ (1-\eta^2) |\mathcal{H}^{du}|^2 - 2\eta^2 \text{Re}(\mathcal{H}^{du*} \mathcal{E}^{du}) - \eta^2 \frac{t}{4M^2} |\mathcal{E}^{du}|^2 \right]$$

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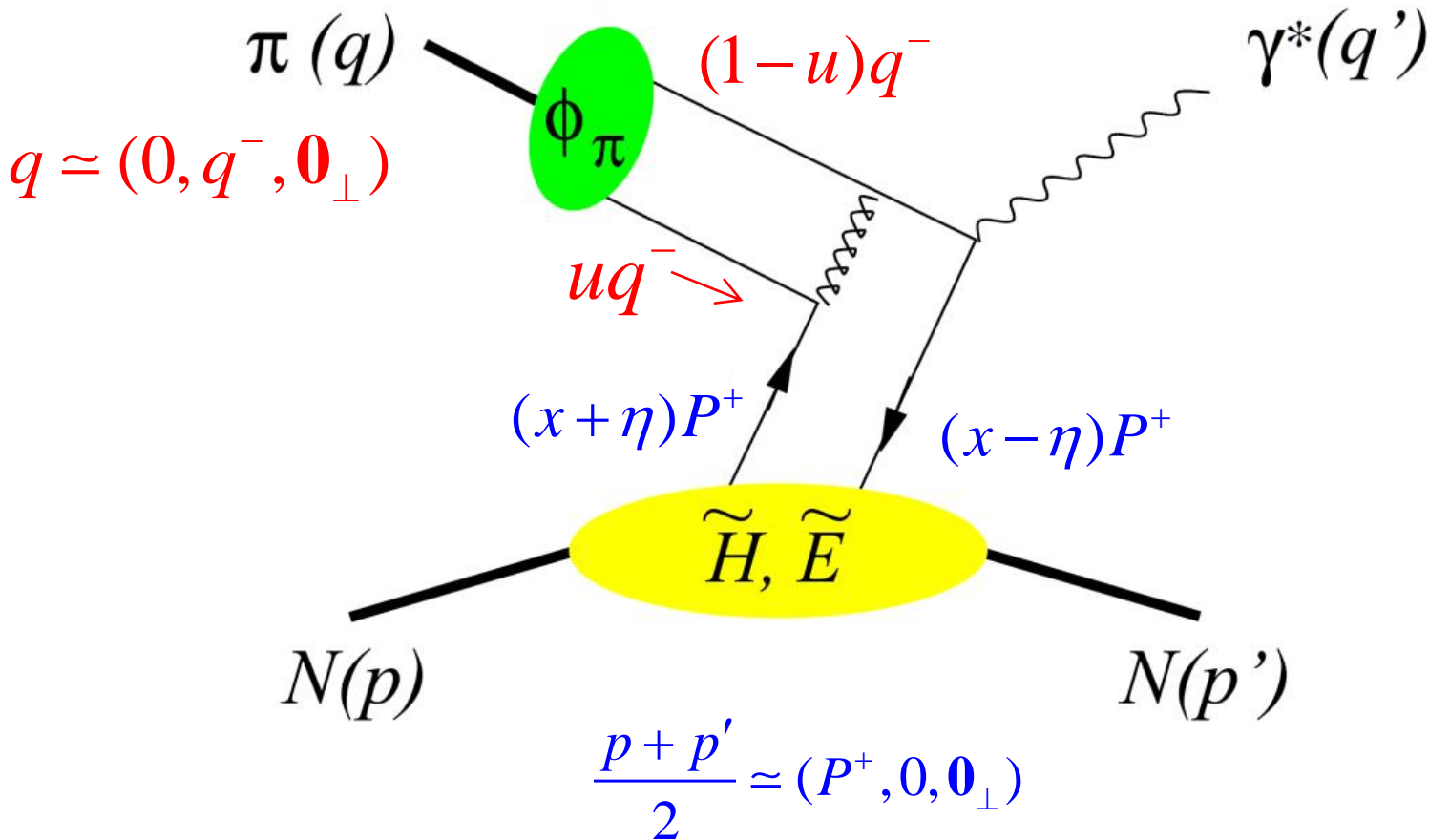
$$\frac{d\sigma}{dQ'^2 dt}(\pi^- p \rightarrow \gamma^* n) = \frac{4\pi\alpha_{\text{em}}^2 \tau^2}{27 Q'^8} f_\pi^2 \left[ (1-\eta^2) |\mathcal{H}^{du}|^2 - 2\eta^2 \text{Re}(\mathcal{H}^{du*} \mathcal{E}^{du}) - \eta^2 \frac{t}{4M^2} |\mathcal{E}^{du}|^2 \right]$$

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



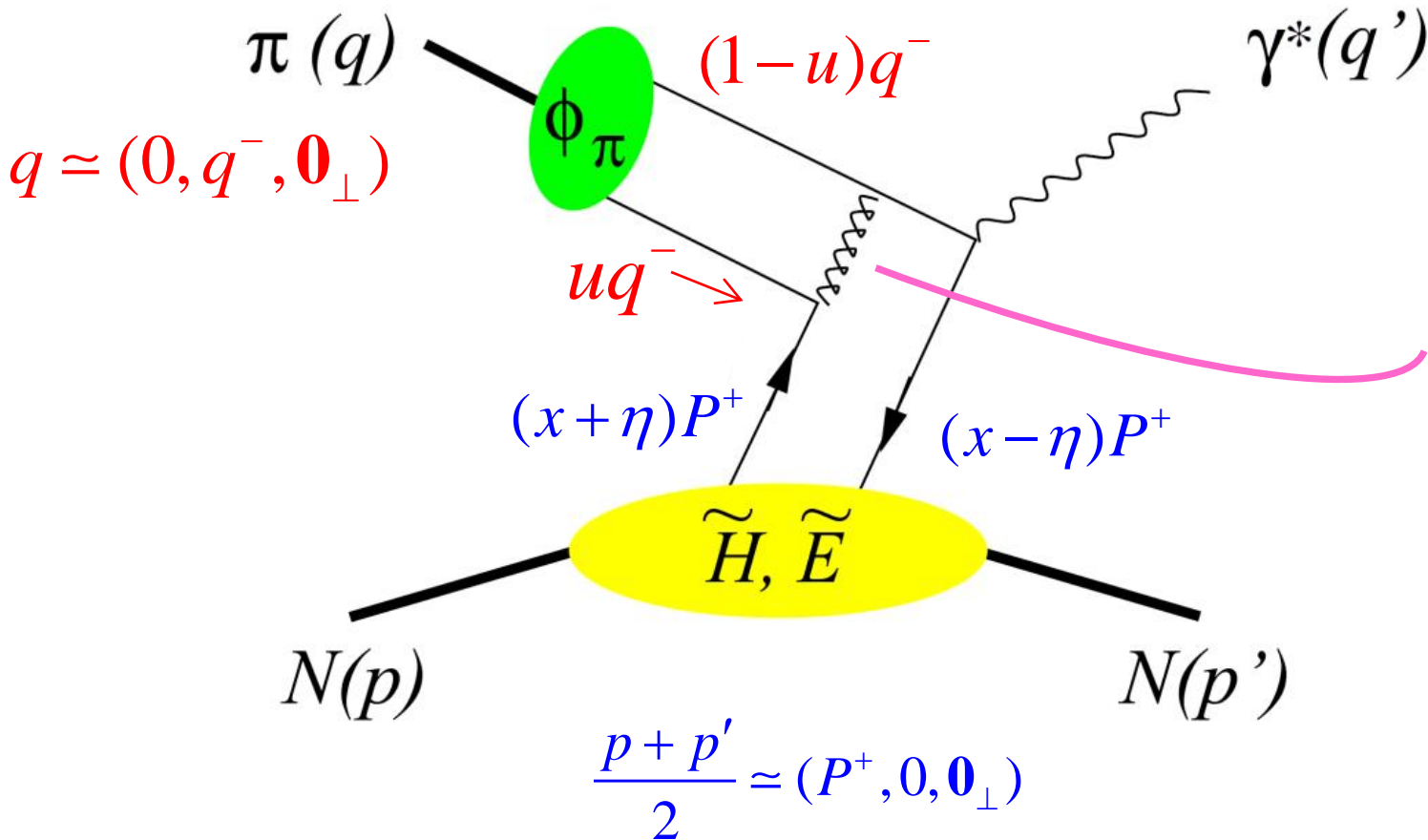
$$\frac{d\sigma}{dQ'^2 dt}(\pi^- p \rightarrow \gamma^* n) = \frac{4\pi\alpha_{\text{em}}^2 \tau^2}{27 Q'^8} f_\pi^2 \left[ (1-\eta^2) |\mathcal{H}^{du}|^2 - 2\eta^2 \text{Re}(\mathcal{H}^{du*} \mathcal{E}^{du}) - \eta^2 \frac{t}{4M^2} |\mathcal{E}^{du}|^2 \right]$$

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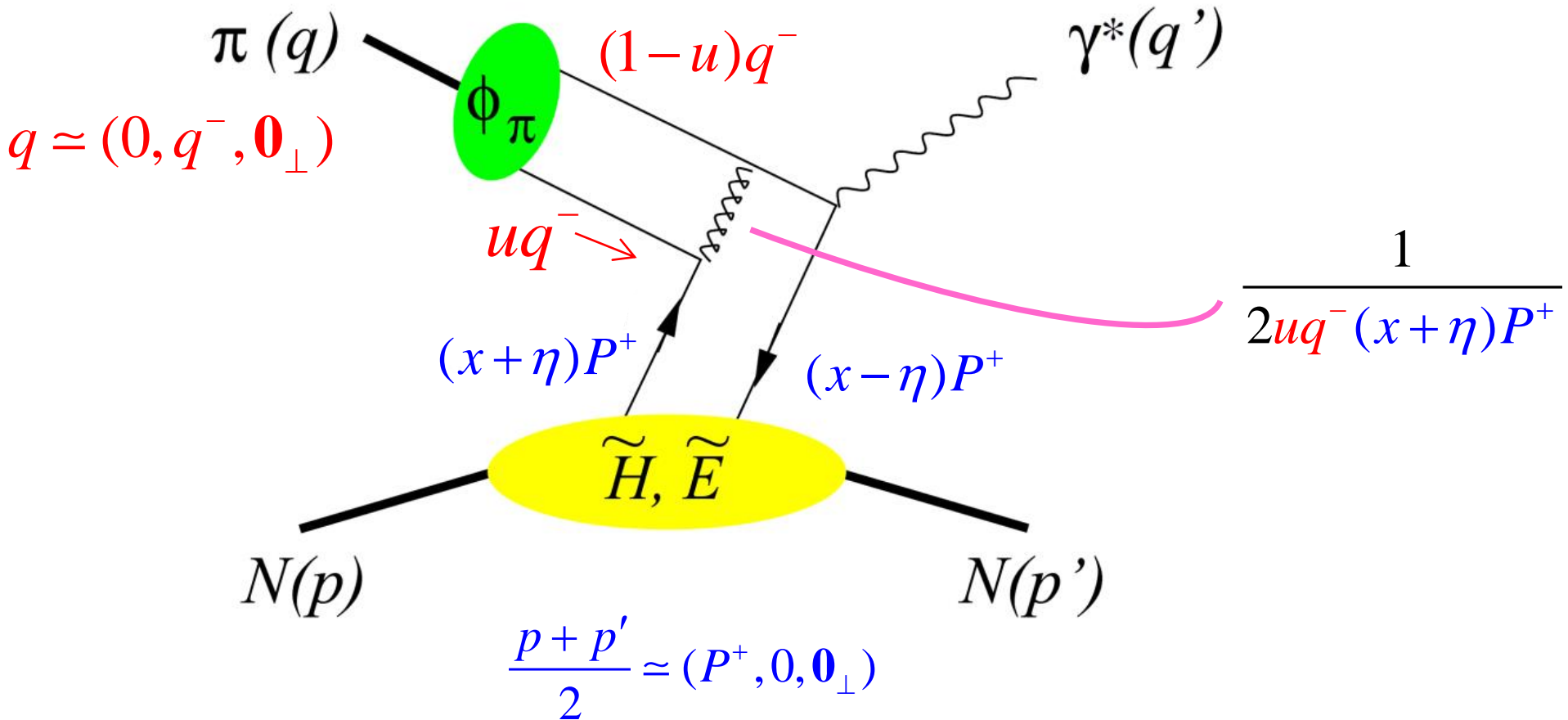
$$\frac{d\sigma}{dQ'^2 dt}(\pi^- p \rightarrow \gamma^* n) = \frac{4\pi\alpha_{\text{em}}^2 \tau^2}{27 Q'^8} f_\pi^2 \left[ (1-\eta^2) |\mathcal{H}^{du}|^2 - 2\eta^2 \text{Re}(\mathcal{H}^{du*} \mathcal{E}^{du}) - \eta^2 \frac{t}{4M^2} |\mathcal{E}^{du}|^2 \right]$$

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



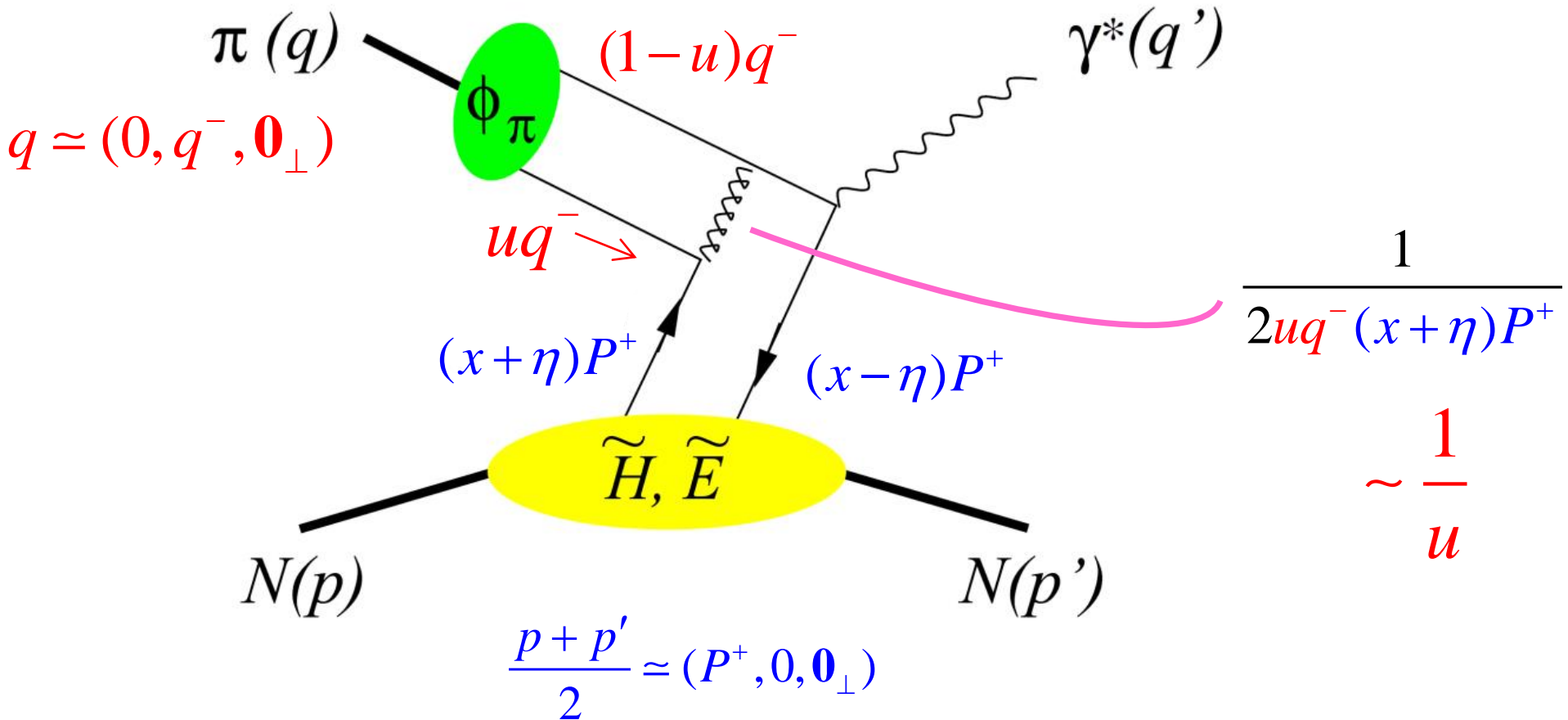
$$\frac{d\sigma}{dQ'^2 dt}(\pi^- p \rightarrow \gamma^* n) = \frac{4\pi\alpha_{\text{em}}^2 \tau^2}{27 Q'^8} f_\pi^2 \left[ (1-\eta^2) |\mathcal{H}^{du}|^2 - 2\eta^2 \text{Re}(\mathcal{H}^{du*} \mathcal{E}^{du}) - \eta^2 \frac{t}{4M^2} |\mathcal{E}^{du}|^2 \right]$$

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

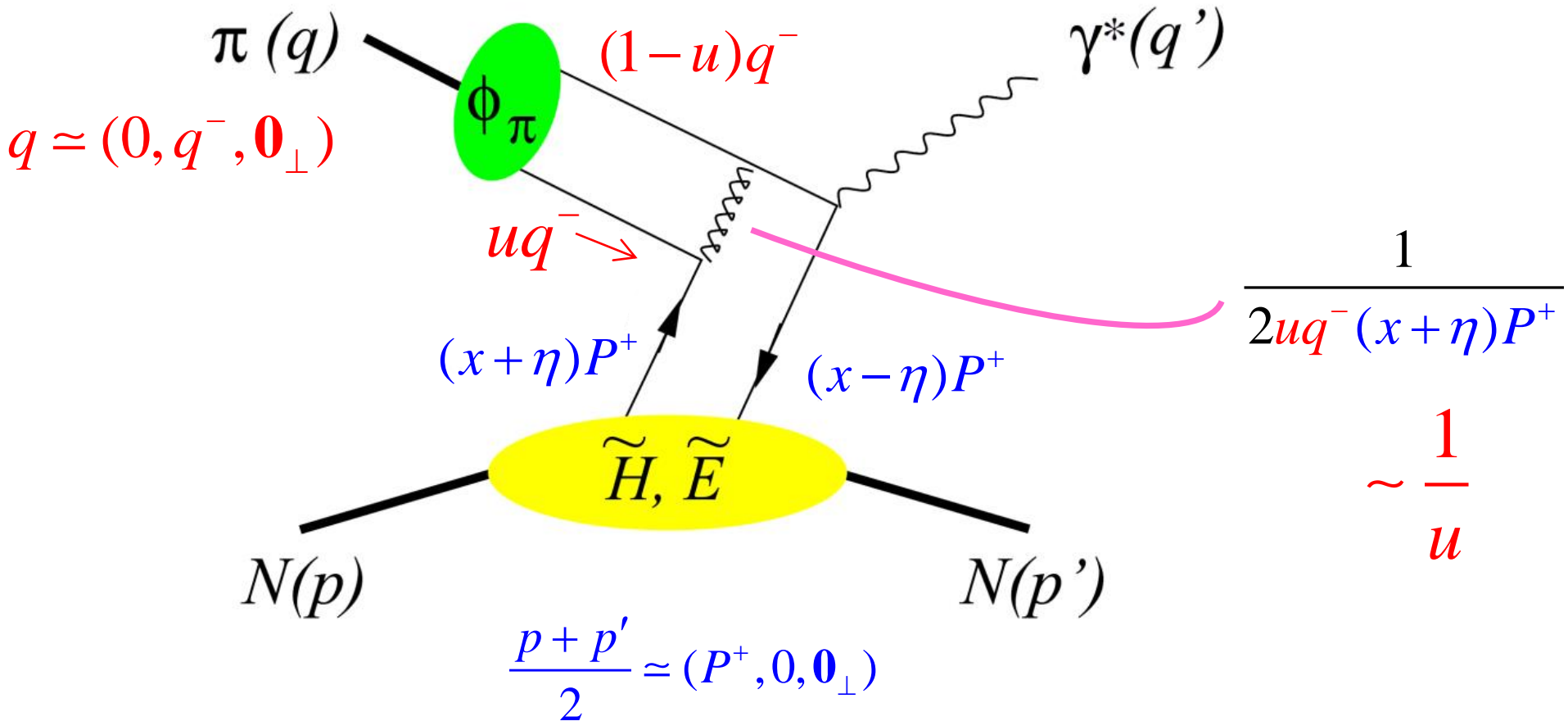
$$\mathcal{H}^{du} = \frac{8\alpha_s}{3} \int_0^1 du \frac{\phi_\pi(u)}{4u(1-u)} \int_{-1}^1 dx \left( \frac{e_d}{-\eta-x-i\epsilon} - \frac{e_u}{-\eta+x-i\epsilon} \right) (\tilde{H}^d(x, \eta, t) - \tilde{H}^u(x, \eta, t))$$



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

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

$$u \rightarrow 0, 1: \quad \phi_\pi(u) \sim u(1-u)$$

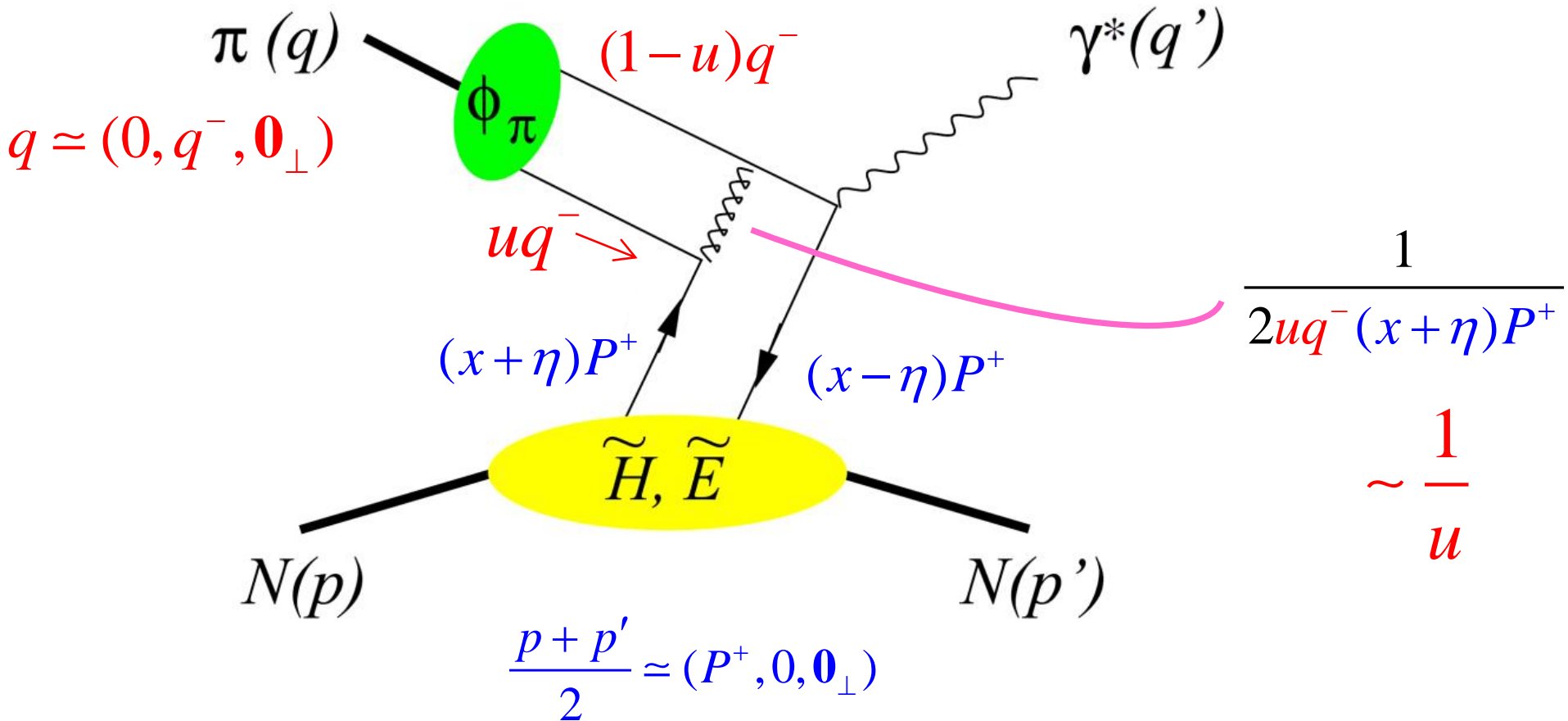


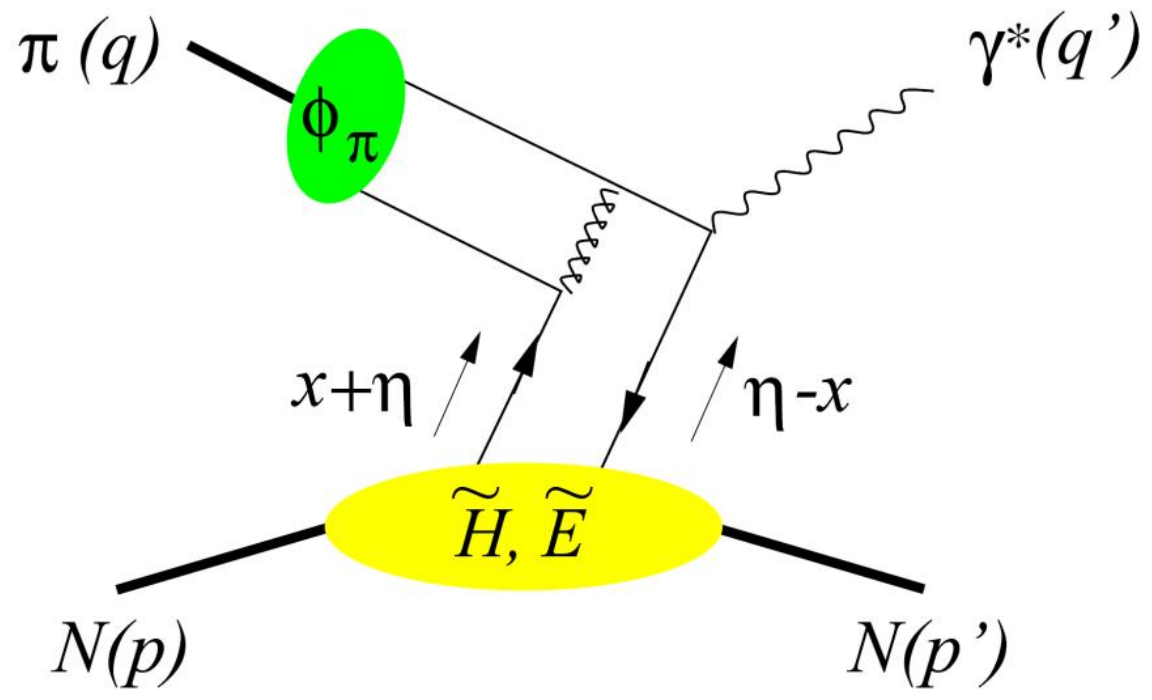


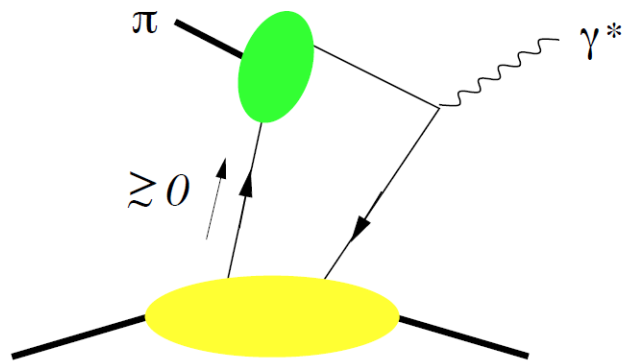
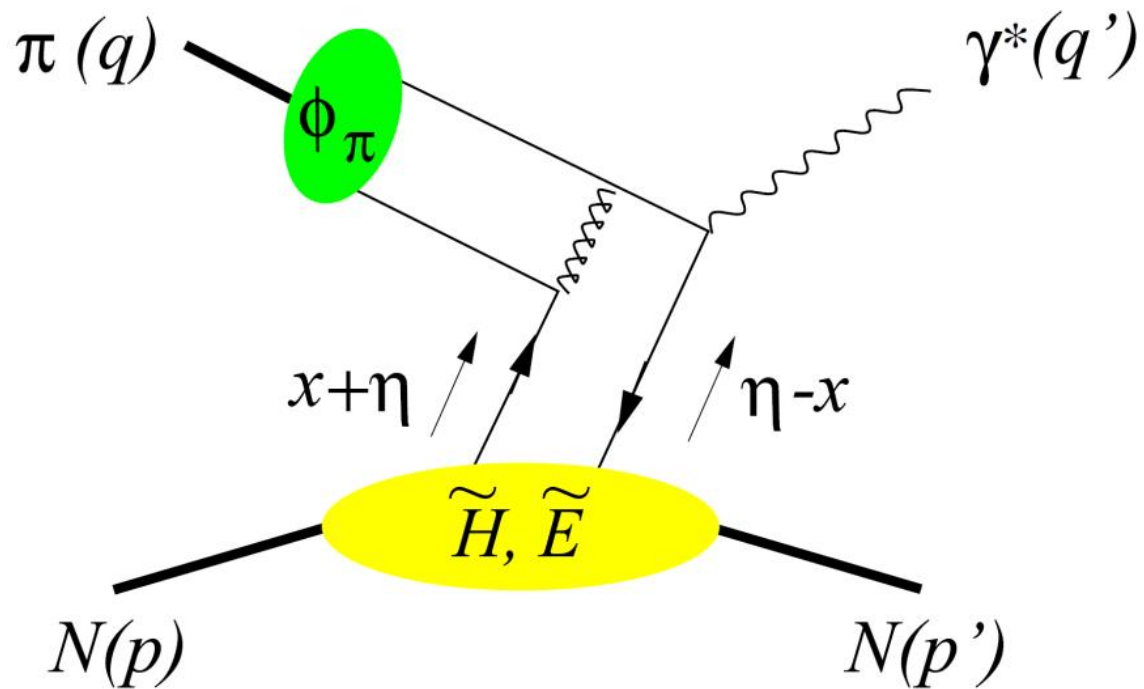
$$\frac{d\sigma}{dQ'^2 dt}(\pi^- p \rightarrow \gamma^* n) = \frac{4\pi\alpha_{\text{em}}^2 \tau^2}{27 Q'^8} f_\pi^2 \left[ (1-\eta^2) |\mathcal{H}^{du}|^2 - 2\eta^2 \text{Re}(\mathcal{H}^{du*} \mathcal{E}^{du}) - \eta^2 \frac{t}{4M^2} |\mathcal{E}^{du}|^2 \right]$$

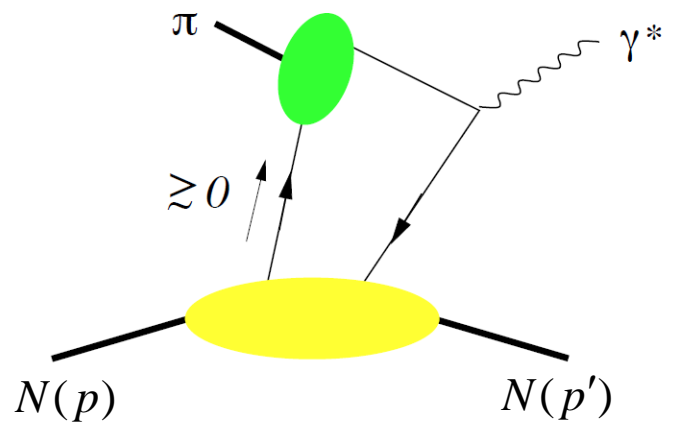
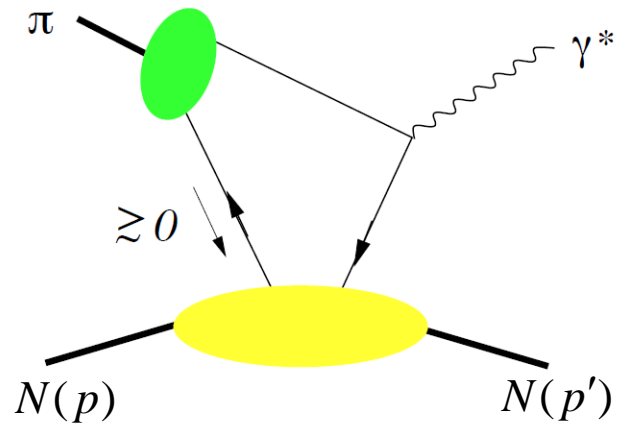
$$\mathcal{H}^{du} = \frac{8\alpha_s}{3} \int_0^1 du \frac{\phi_\pi(u)}{4u(1-u)} \int_{-1}^1 dx \left( \frac{e_d}{-\eta-x-i\epsilon} - \frac{e_u}{-\eta+x-i\epsilon} \right) (\tilde{H}^d(x, \eta, t) - \tilde{H}^u(x, \eta, t))$$

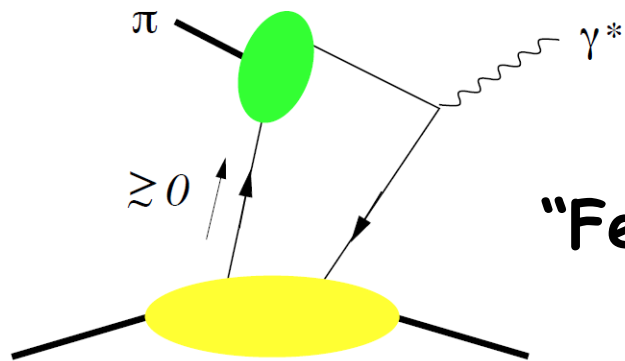
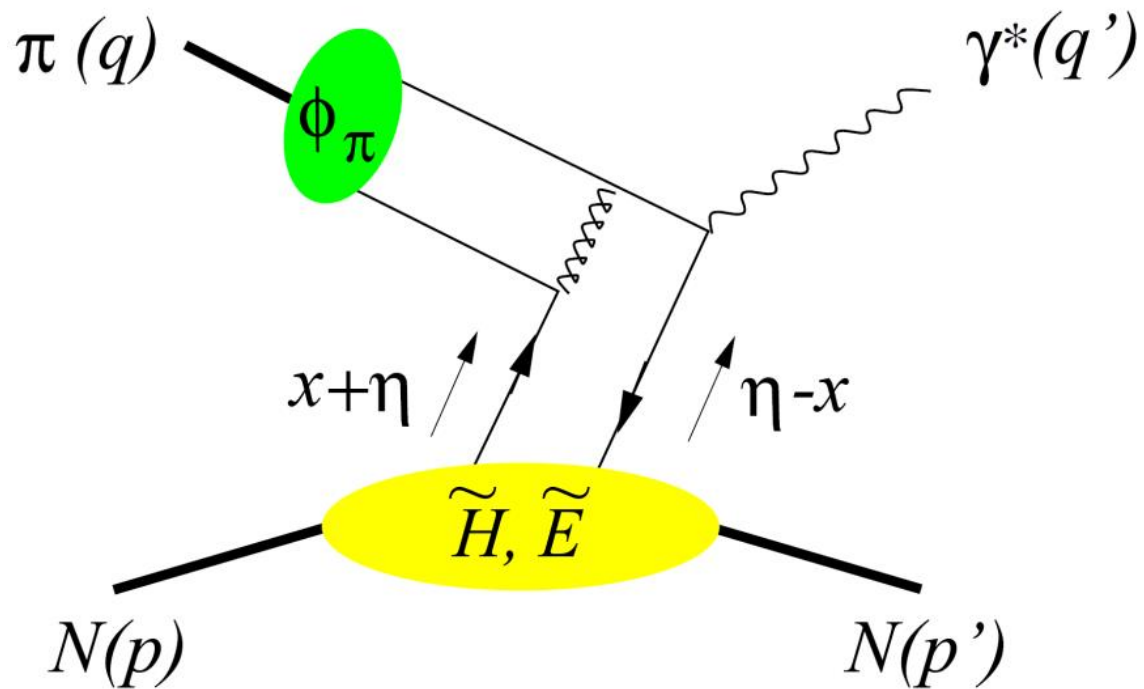
$$u \rightarrow 0, 1: \quad \phi_\pi(u) \sim u(1-u) \quad \phi_{\text{tw.-3}}(u) \sim 1$$



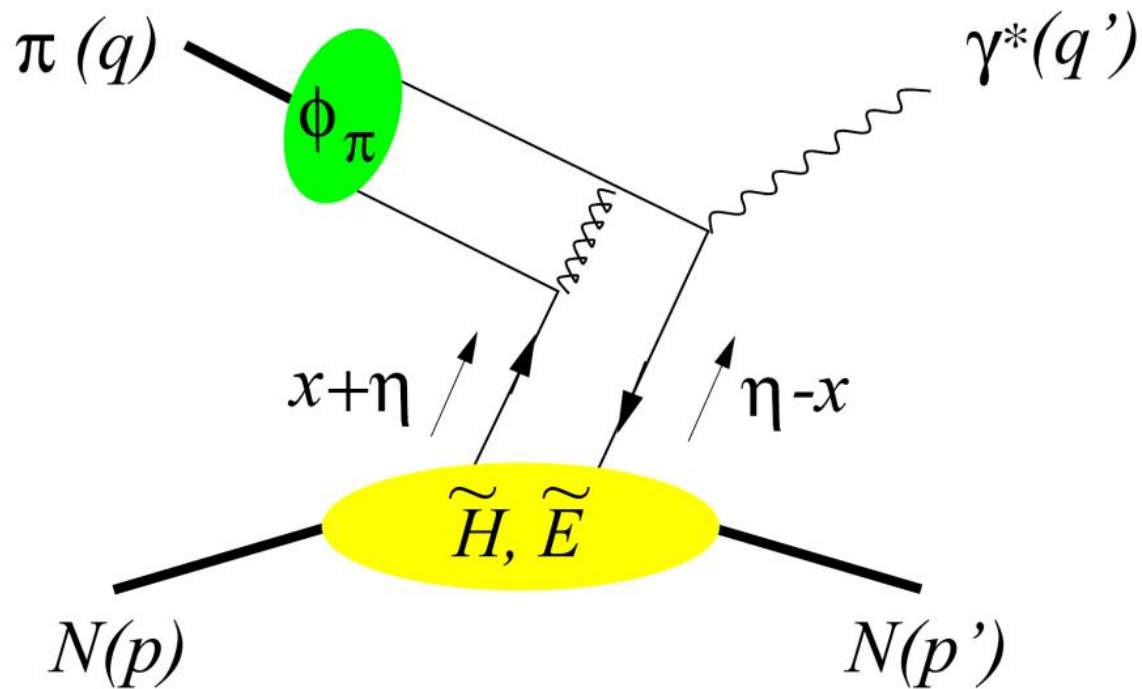




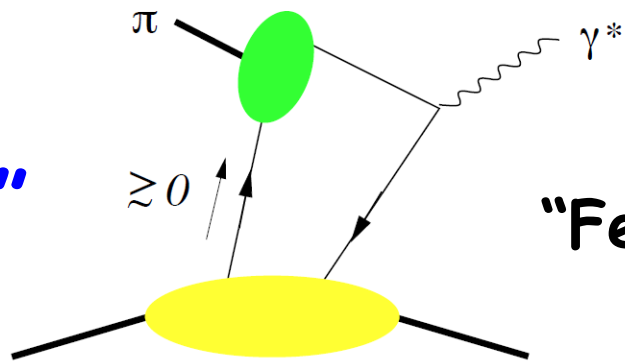




**"Feynman mechanism"**

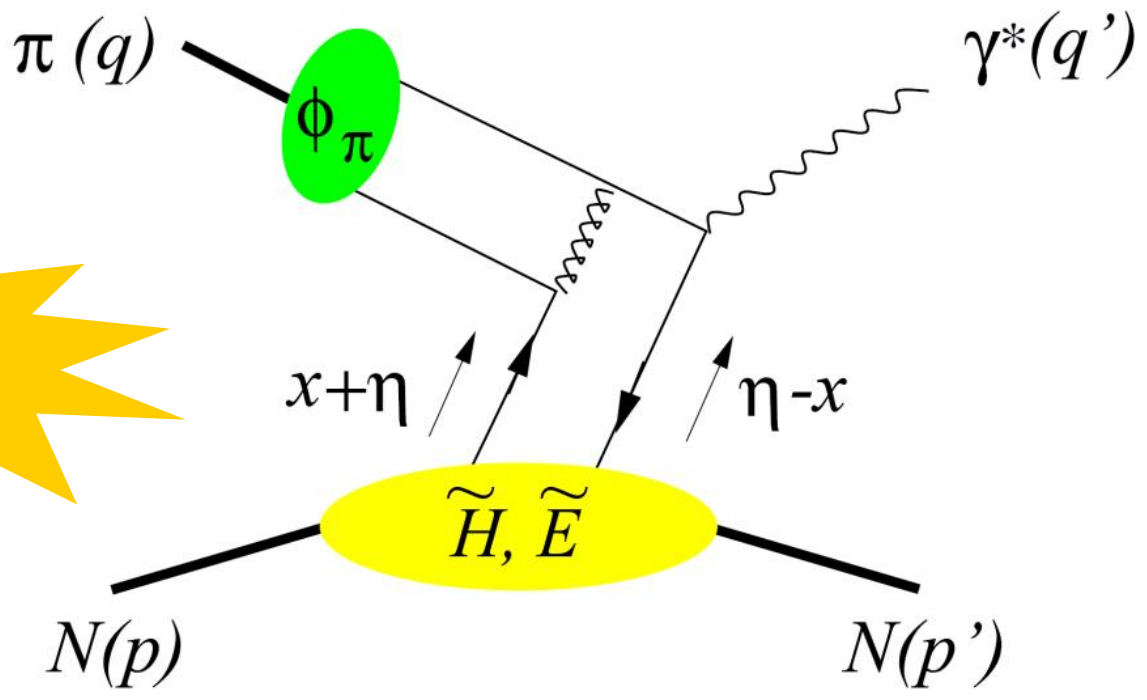


“nonfactorizable”



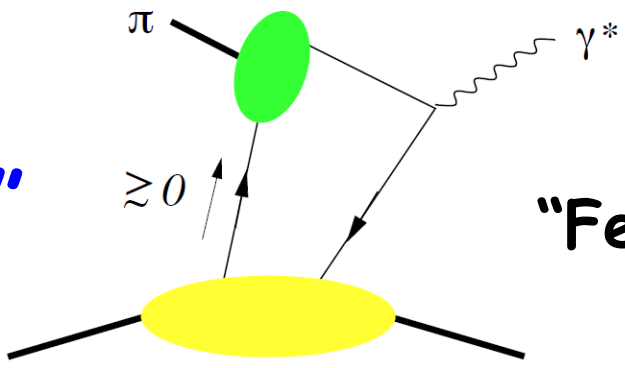
“Feynman mechanism”

**LO in QCD factorization**



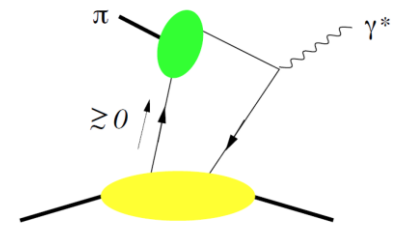
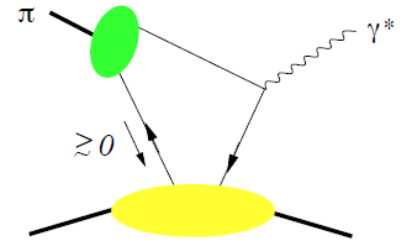
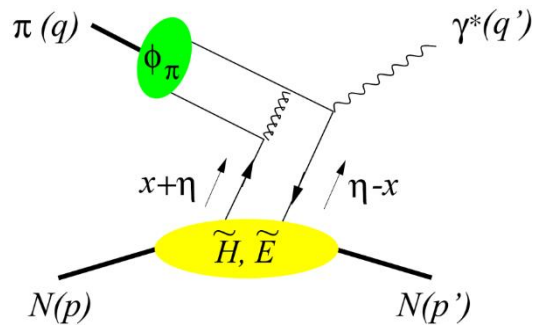
Berger, Diehl, Pire, PLB523(2001)265

**“nonfactorizable”**



**“Feynman mechanism”**

exDY

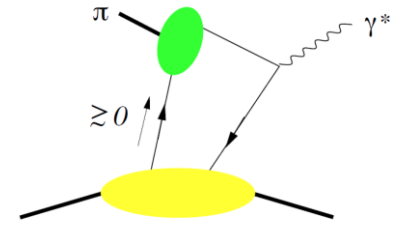
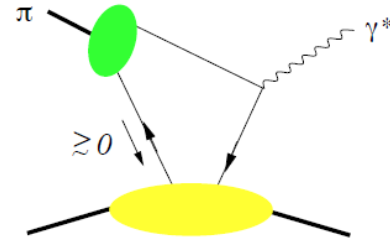
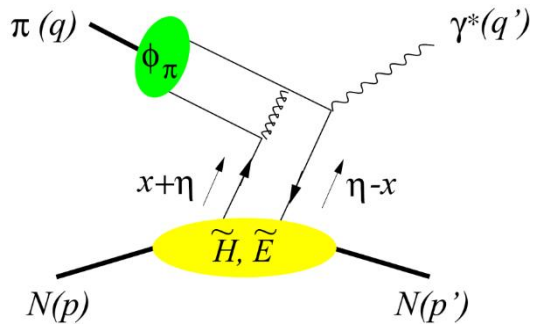


QCD factorization

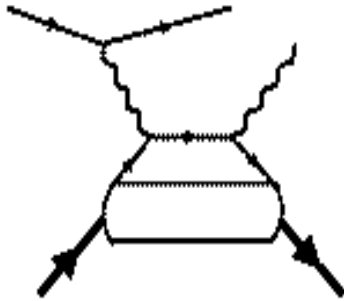
“nonfactorizable”



exDY



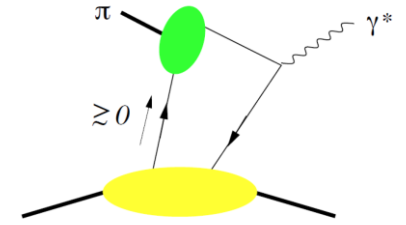
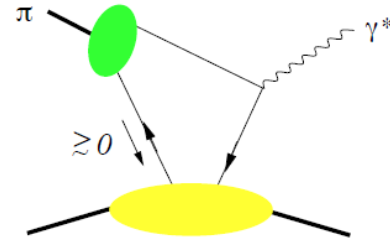
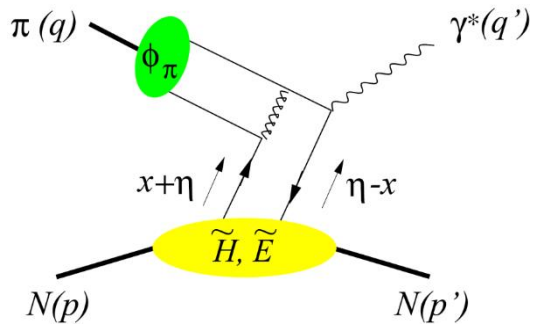
DVCS



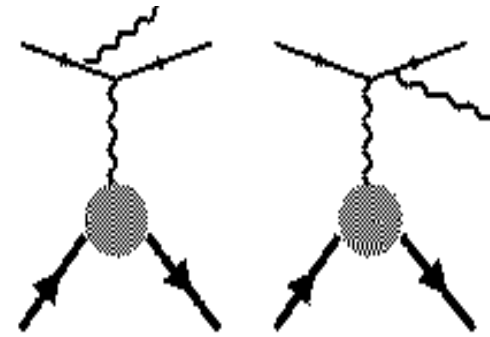
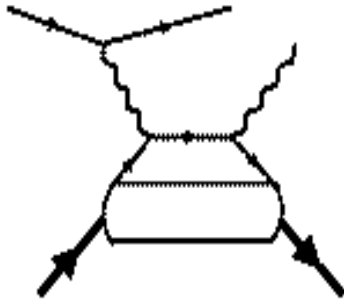
QCD factorization

“nonfactorizable”

exDY



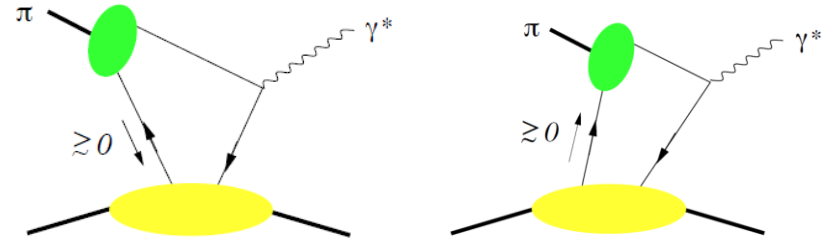
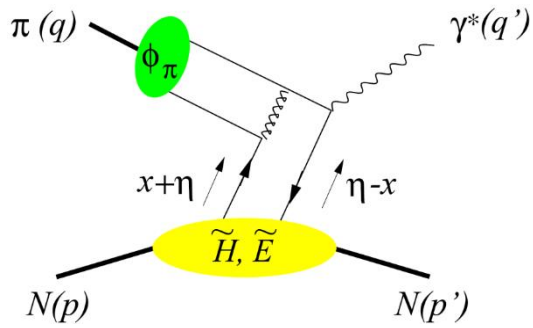
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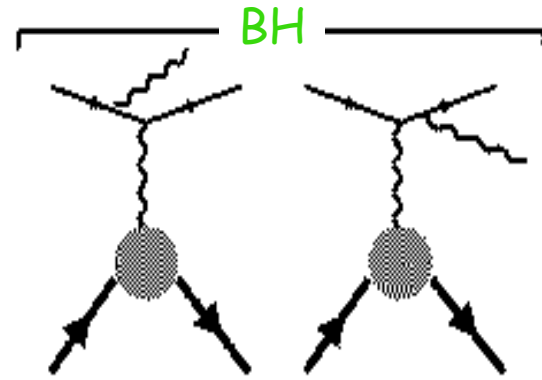
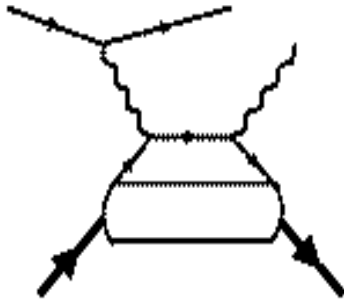
QCD factorization

“nonfactorizable”

exDY



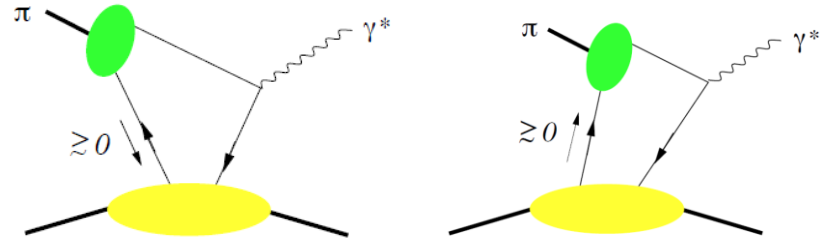
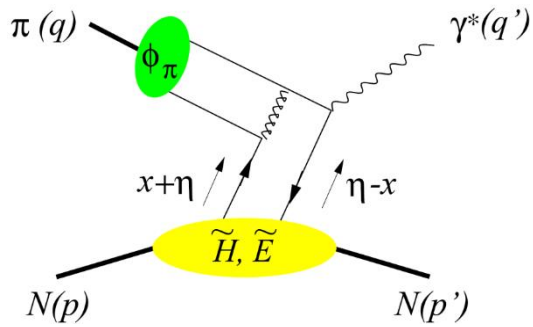
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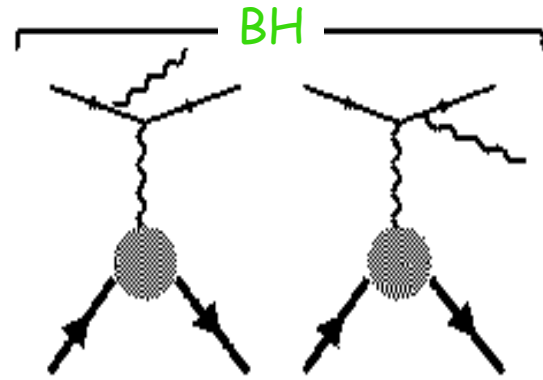
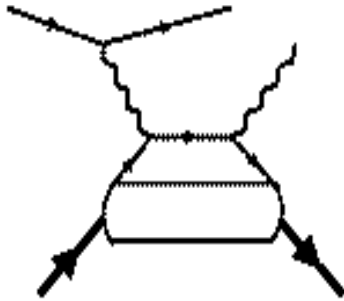
QCD factorization

"nonfactorizable"

exDY



DVCS



QCD factorization

“nonfactorizable”

$$\text{Amp} = A_F \left[ 1 + \frac{\Lambda_{\text{QCD}}}{Q} B_1 + \left( \frac{\Lambda_{\text{QCD}}}{Q} \right)^2 B_2 + \dots \right] + \left( \frac{\Lambda_{\text{QCD}}}{Q} \right)^c D_{\text{non-F}} + \dots$$

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

Brodsky, Lepage, Chernyak, ...  
Collins, Strikman, ...

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

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<sup>(a)</sup> and C. H. Llewellyn Smith

*Department of Theoretical 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.

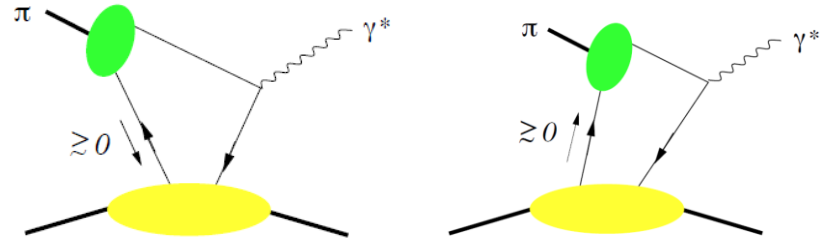
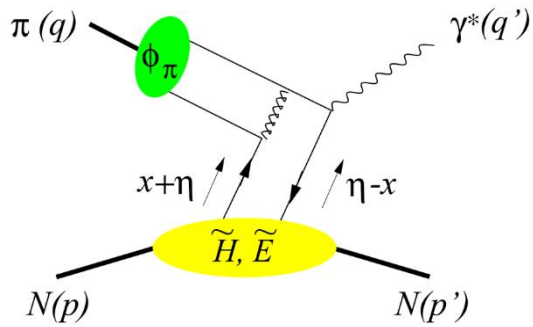
PACS numbers: 12.35.Eq, 13.40.Fn

It has been convincingly argued<sup>1-3</sup> 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<sup>2,3</sup> to explain existing exclusive data by perturbative QCD

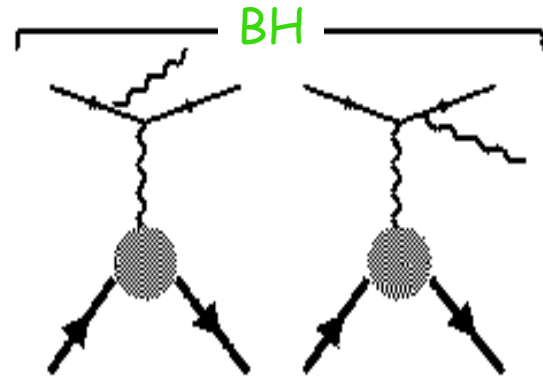
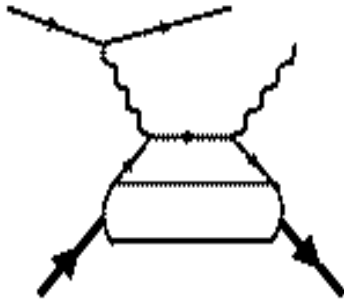
functions with  $\langle p_T^2 \rangle^{1/2} \approx 300$  MeV can naturally generate "soft" nonleading terms which are as large as the data. Similar conclusions hold for the pion.<sup>4</sup> Calculations based on QCD sum rules<sup>5</sup> also generate soft contributions which fit the data for  $F_\pi$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

Our calculations were based on the use of the light-cone quantization formalism<sup>6</sup> adopted by

exDY



DVCS

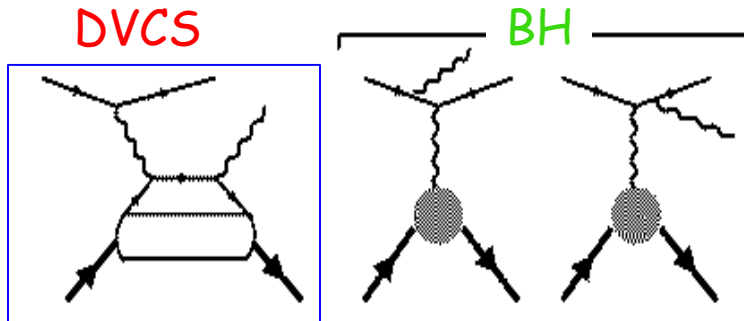


QCD factorization

"nonfactorizable"

$$\text{Amp} = A_F \left[ 1 + \frac{\Lambda_{\text{QCD}}}{Q} B_1 + \left( \frac{\Lambda_{\text{QCD}}}{Q} \right)^2 B_2 + \dots \right] + \left( \frac{\Lambda_{\text{QCD}}}{Q} \right)^c D_{\text{non-F}} + \dots$$

# Accessing GPDs through polarized DVCS

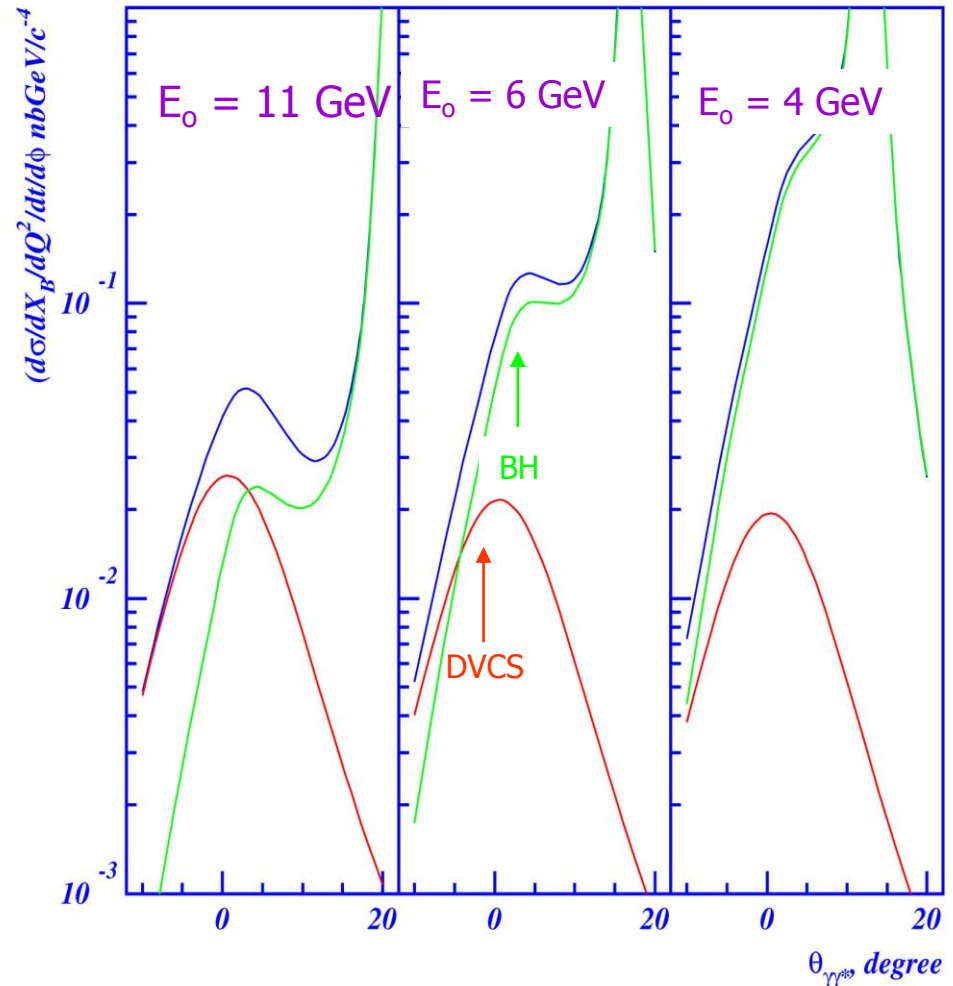


$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$

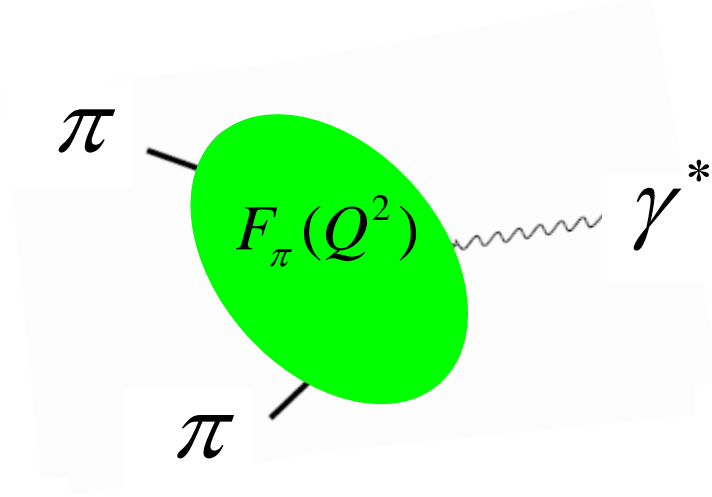
$T^{BH}$ : real, given by elastic form factors

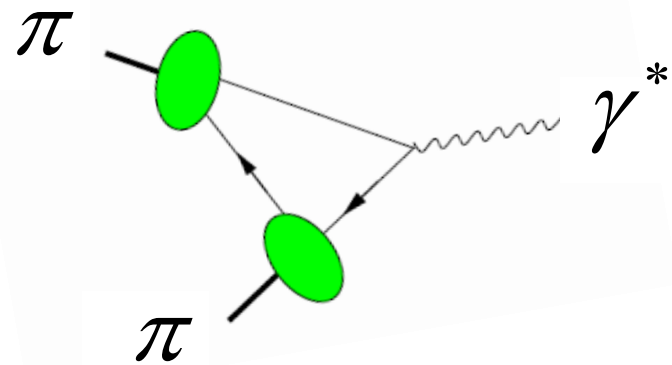
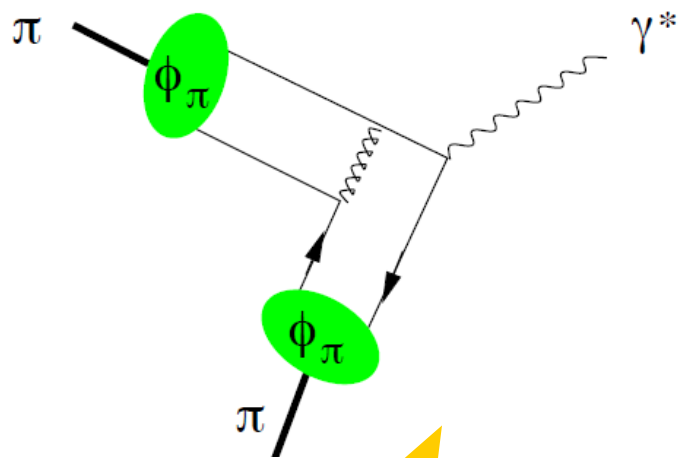
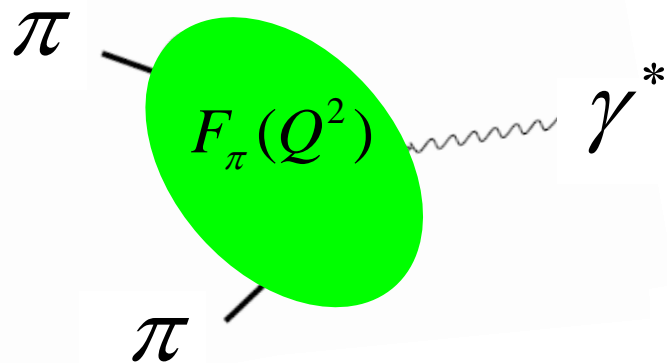
$T^{DVCS}$ : complex, determined by GPDs

Cross section of  $ep \rightarrow e\gamma p$  at  $Q^2=2 \text{ GeV}/c^2$  and  $X_B=0.35$





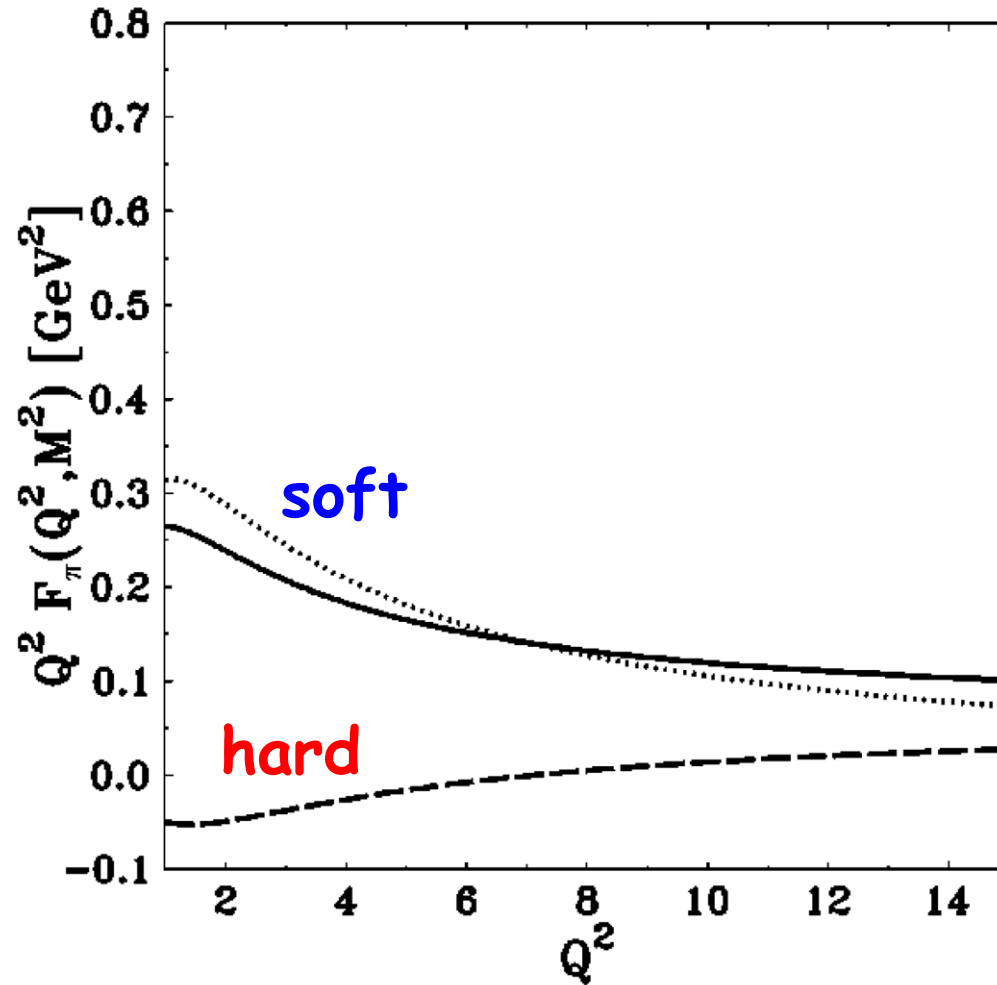


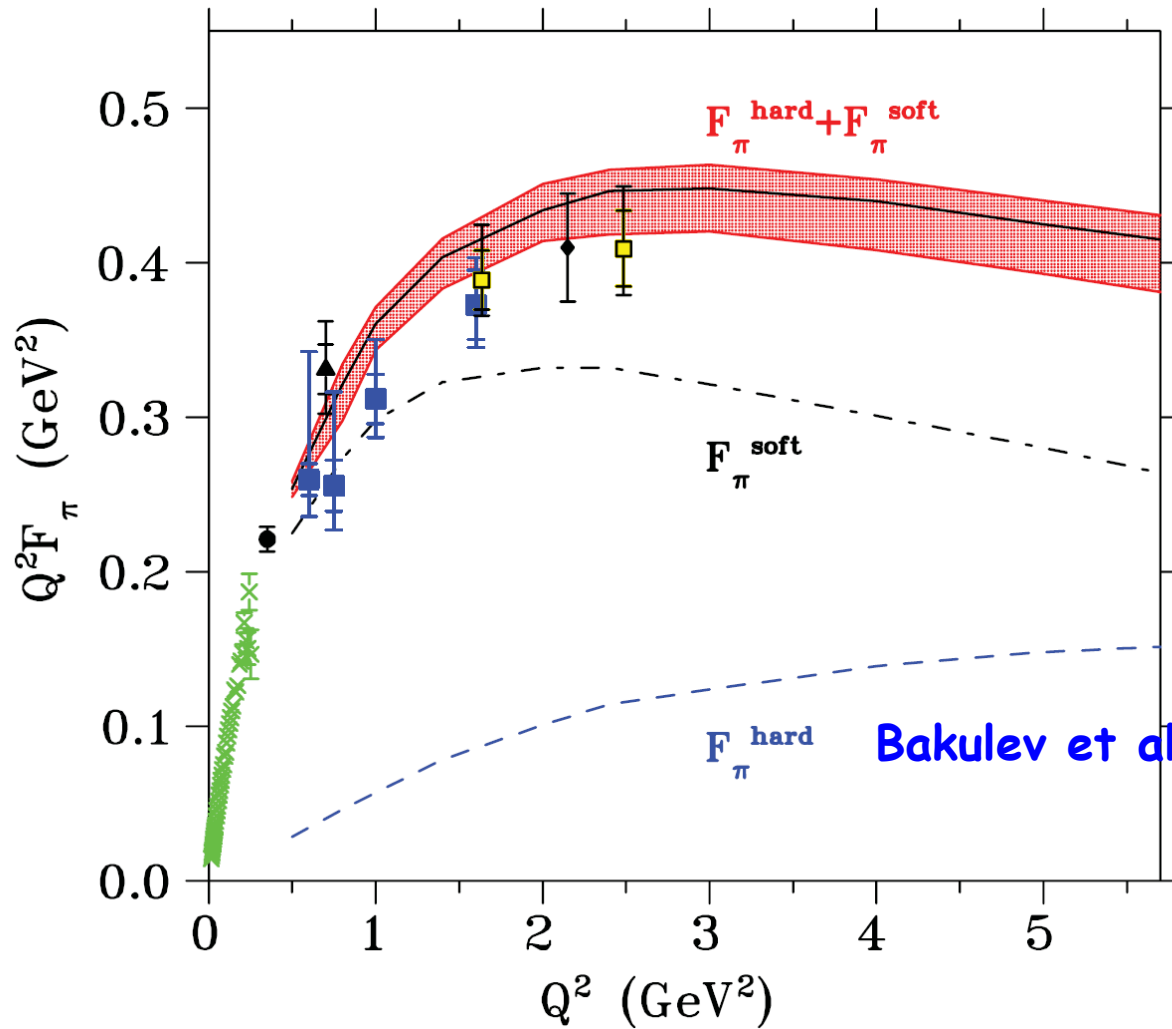


**LO in QCD  
factorization**

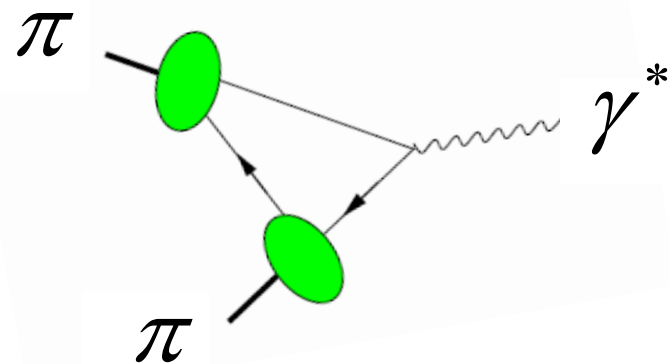
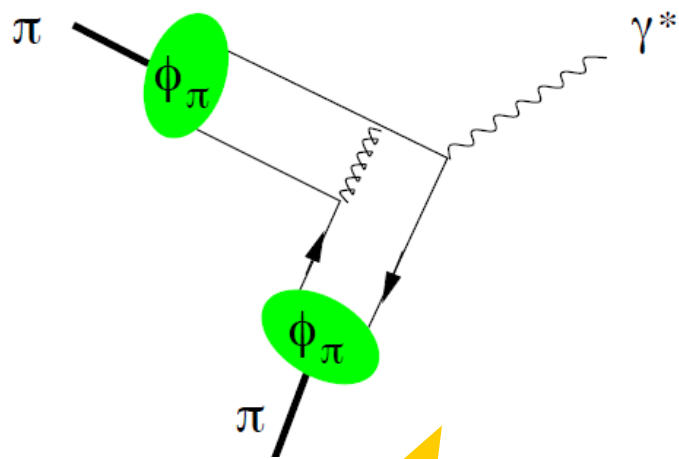
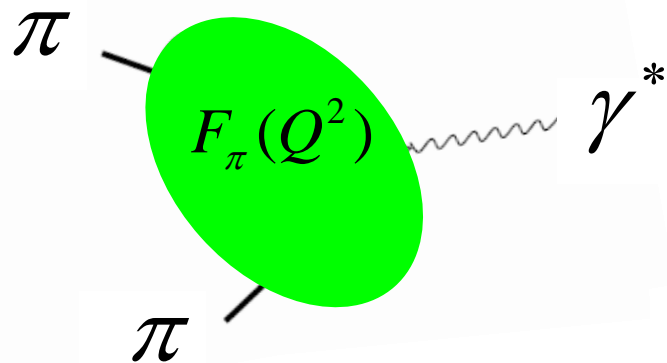
**"nonfactorizable"  
Feynman mechanism**

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





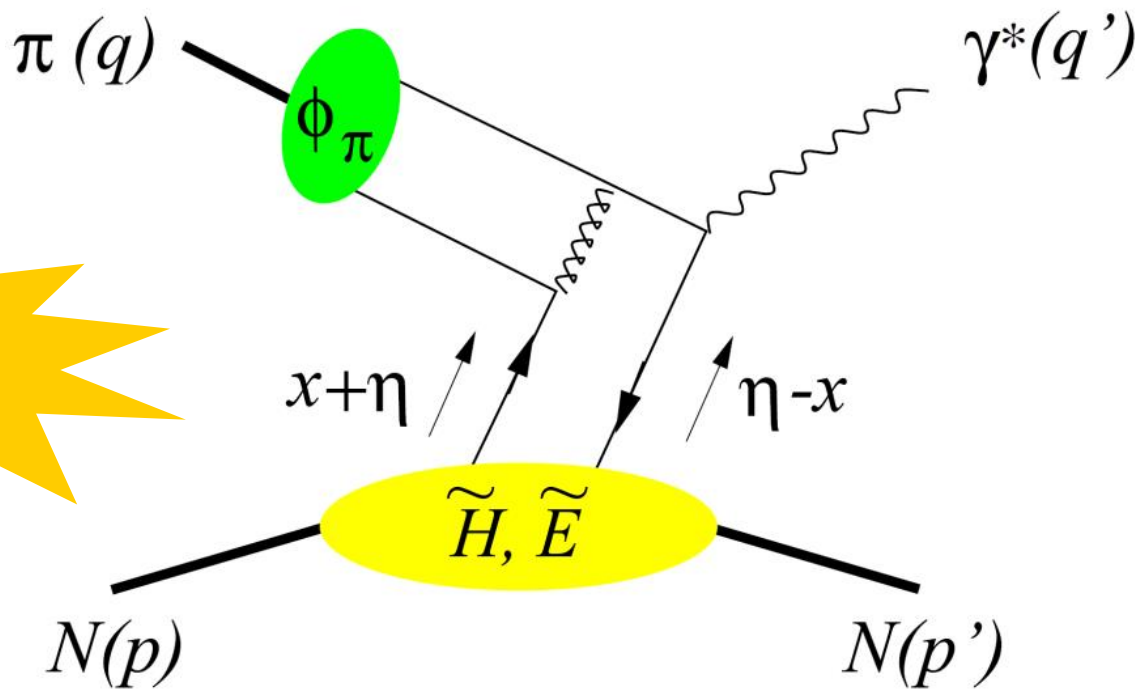
Bakulev et al, PRD70, 033014



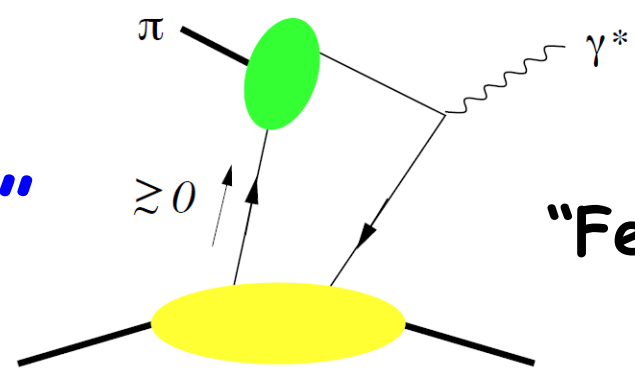
**LO in QCD  
factorization**

**"nonfactorizable"  
Feynman mechanism**

**LO in QCD factorization**

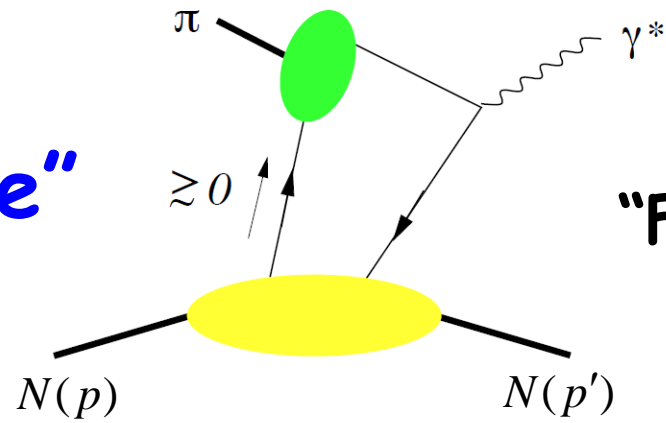


**“nonfactorizable”**

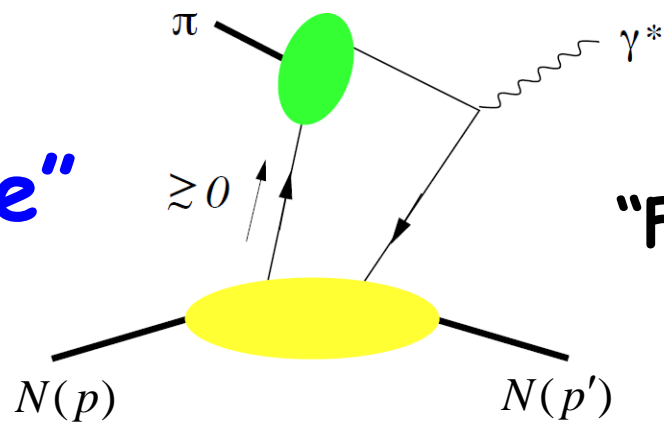
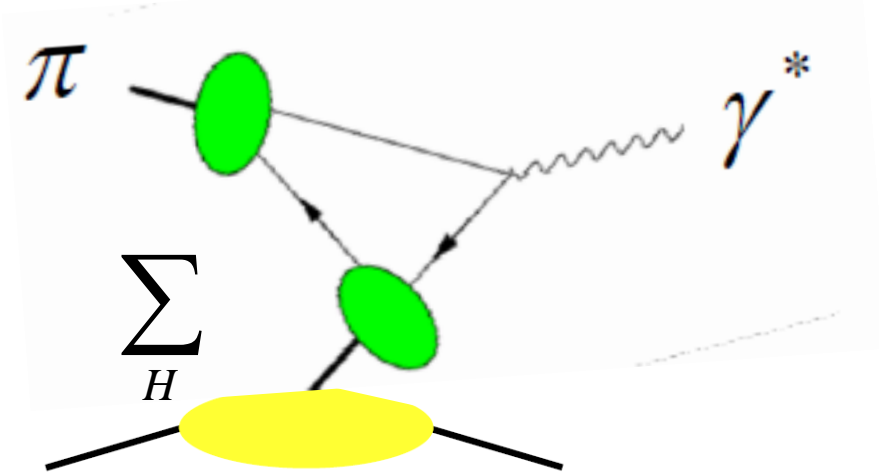


**“Feynman mechanism”**

**“nonfactorizable”**



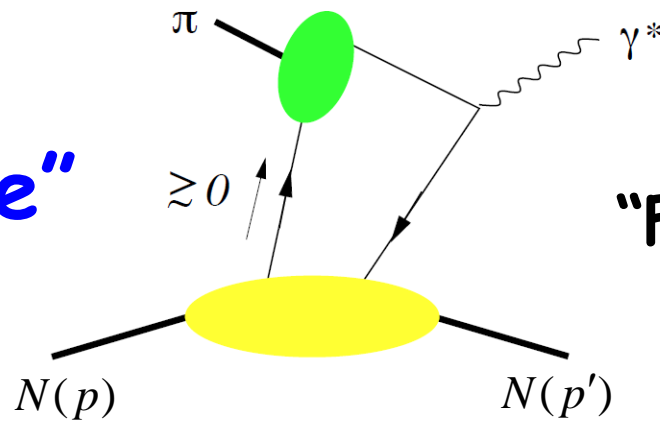
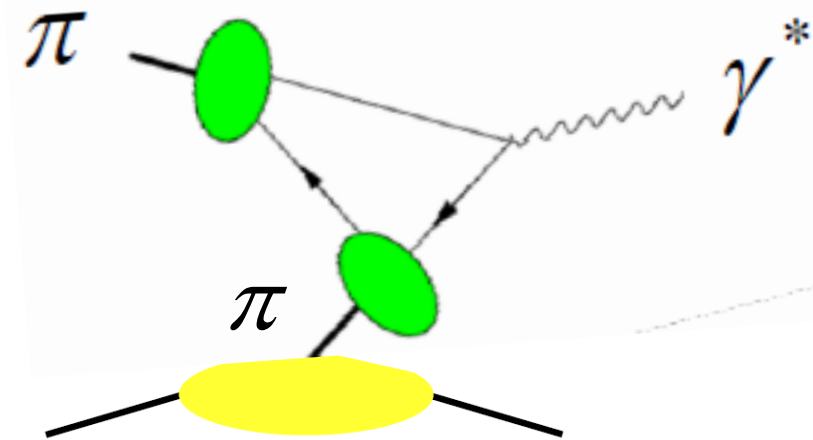
**“Feynman mechanism”**



**“nonfactorizable”**

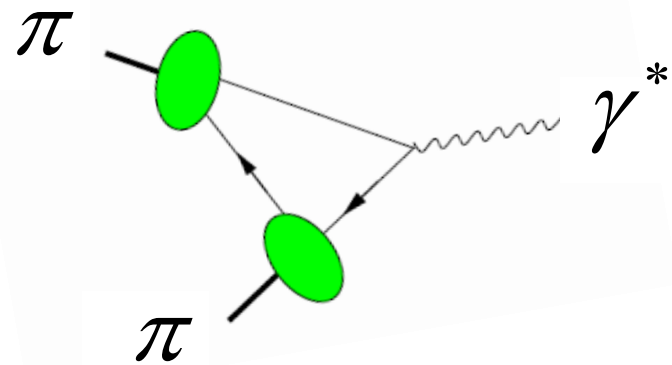
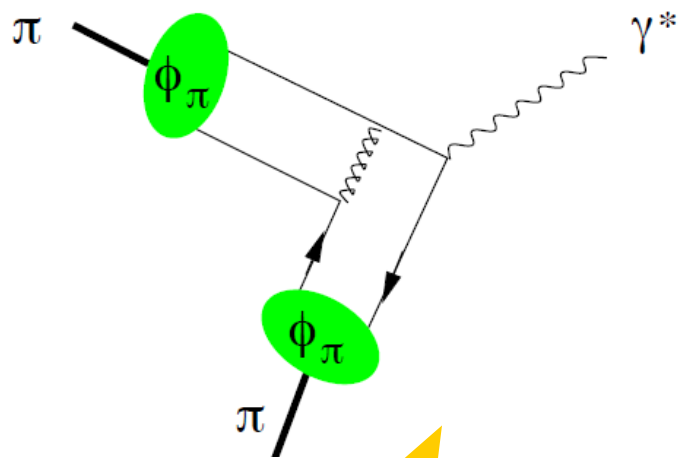
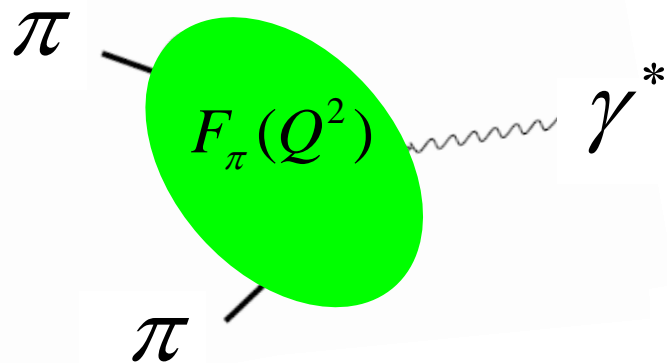
**“Feynman mechanism”**





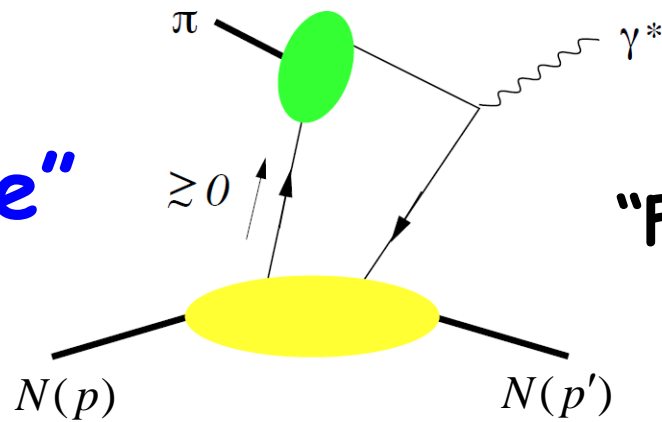
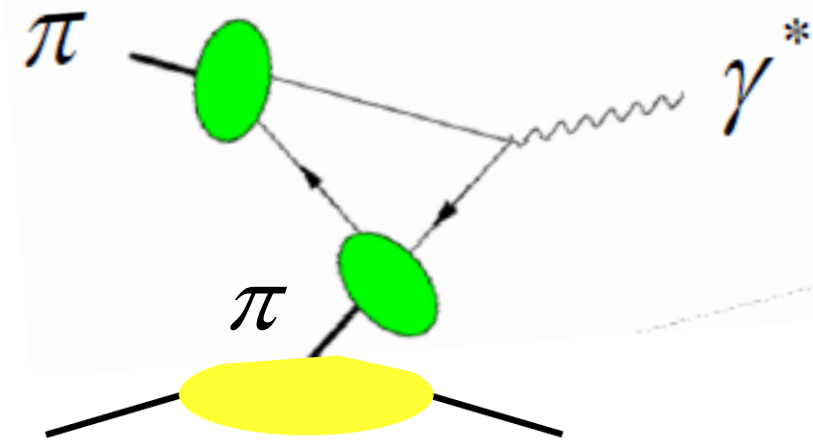
**“nonfactorizable”**

**“Feynman mechanism”**



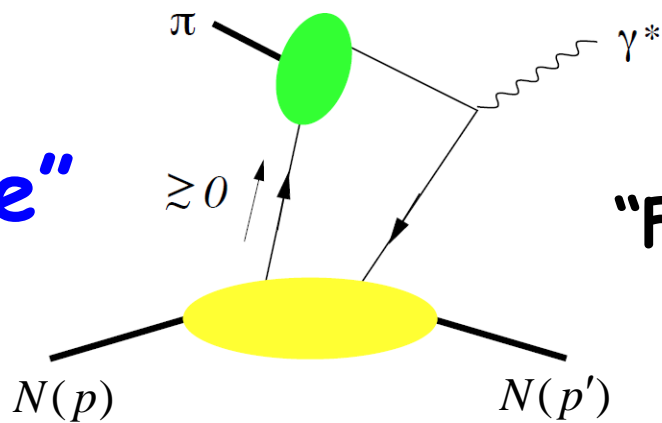
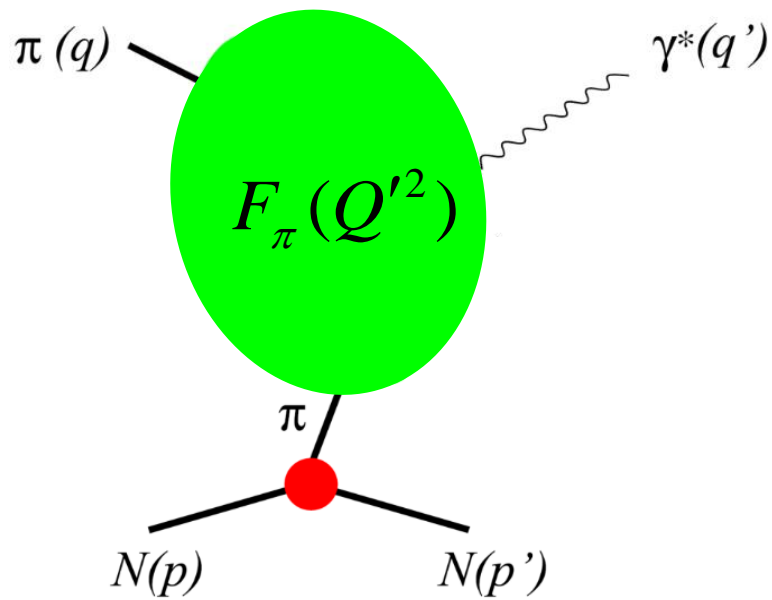
**LO in QCD  
factorization**

**"nonfactorizable"  
Feynman mechanism**



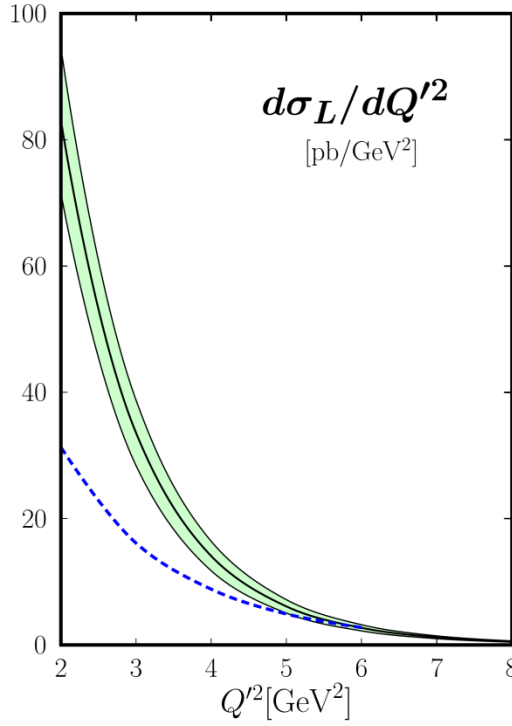
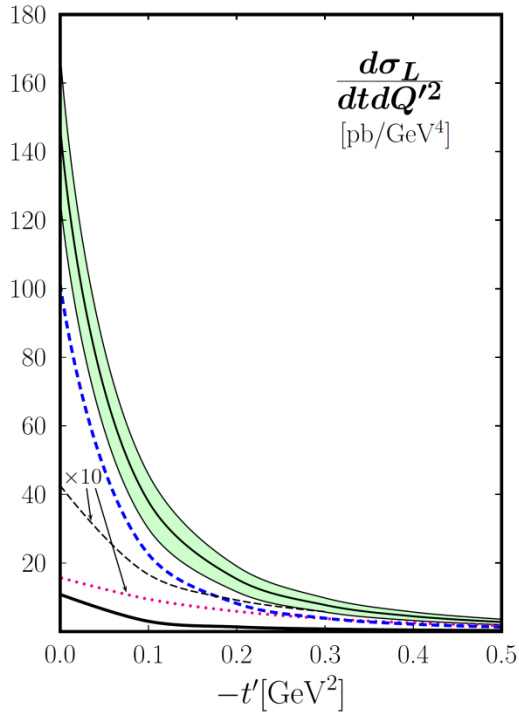
**“nonfactorizable”**

**“Feynman mechanism”**

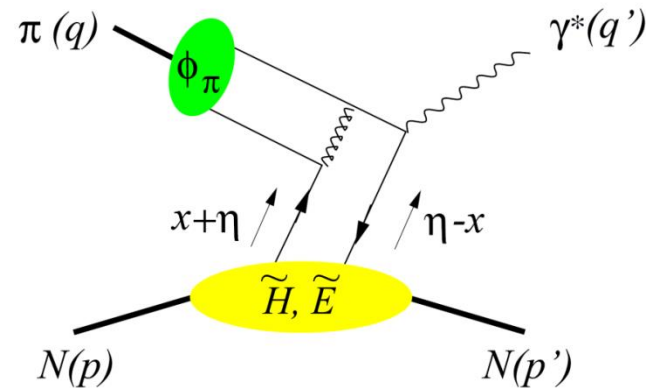
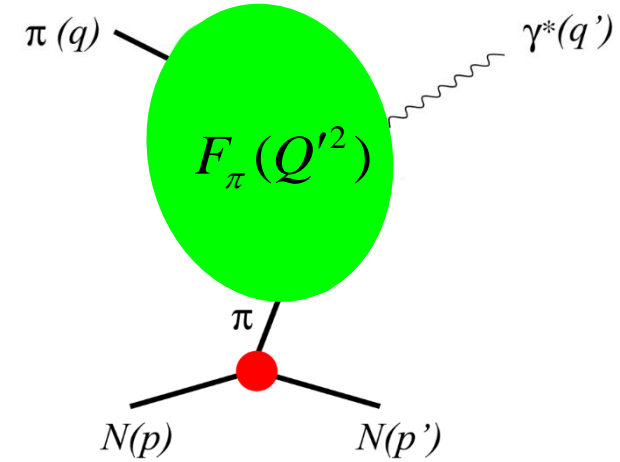


**“nonfactorizable”**

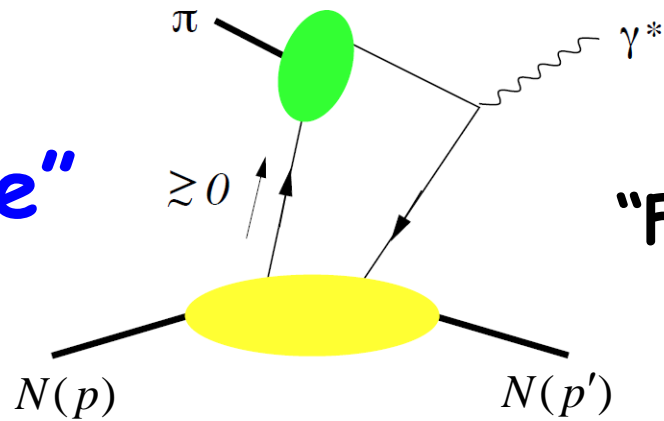
**“Feynman mechanism”**



pion exchange for  $O(\alpha_s^0)$   
empirical  $F_\pi(Q'^2)$

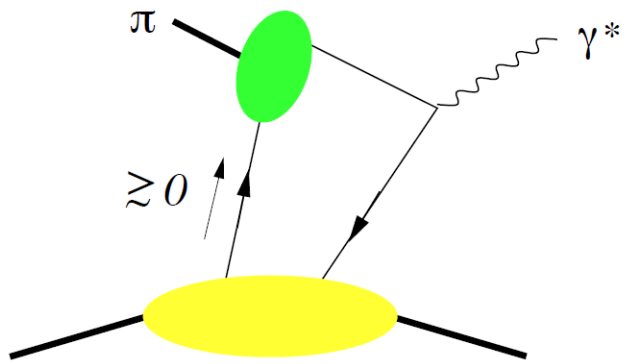


**“nonfactorizable”**

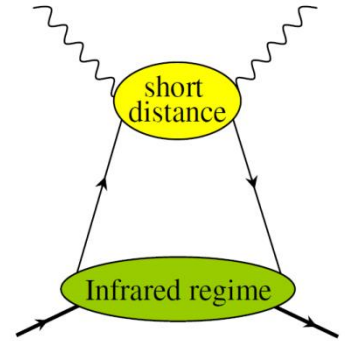
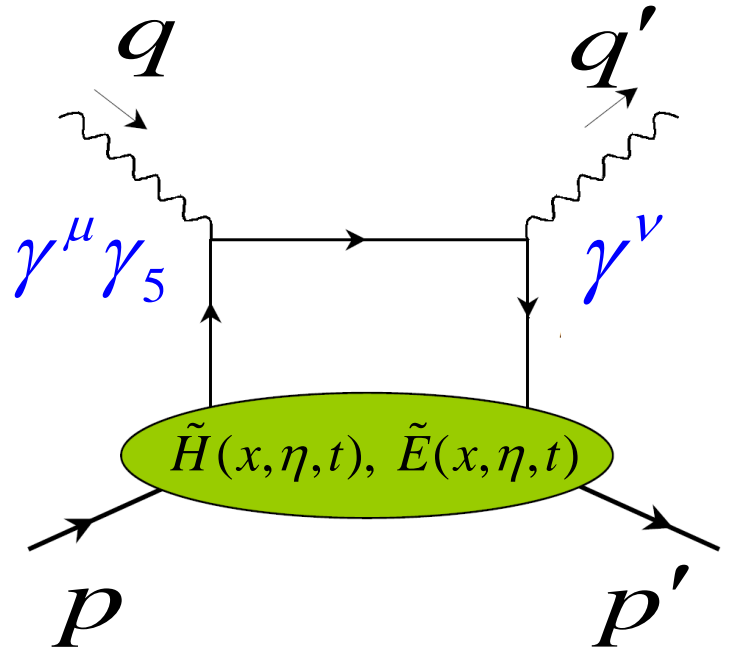


**“Feynman mechanism”**

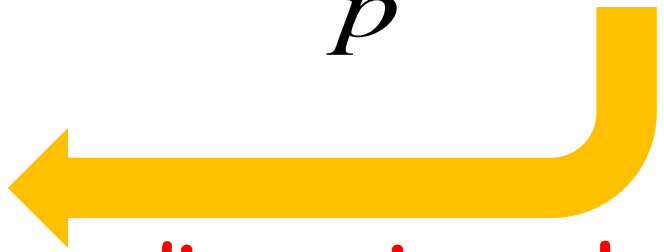
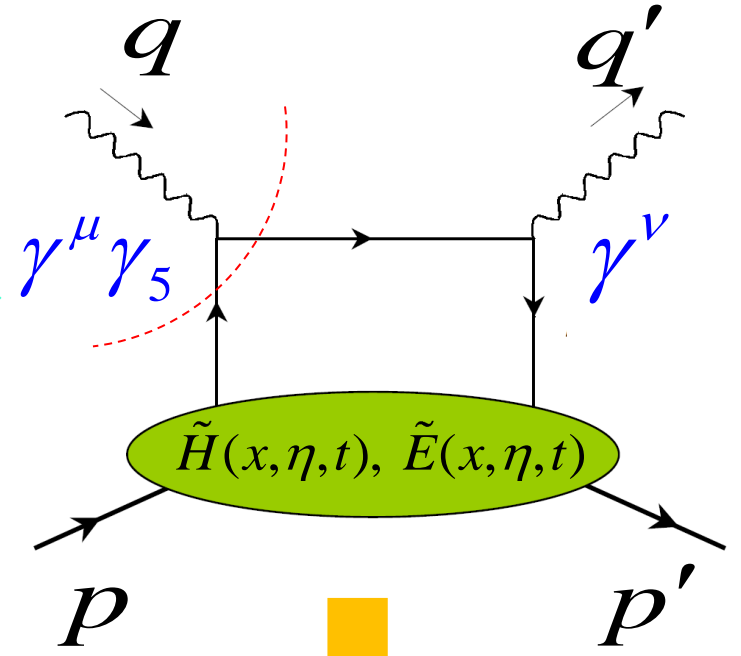
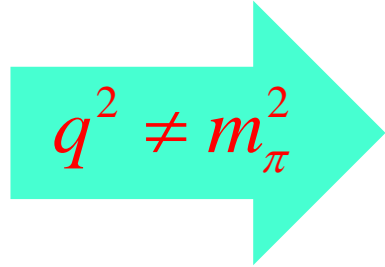
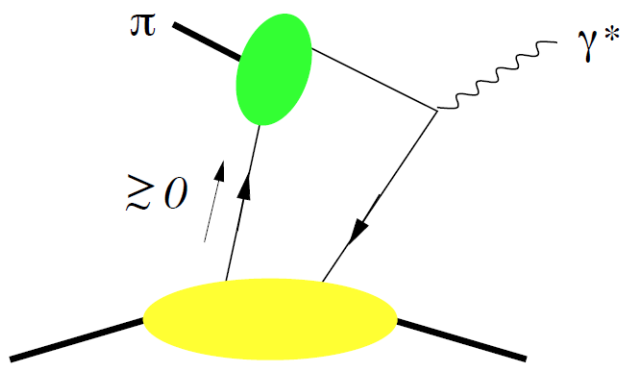
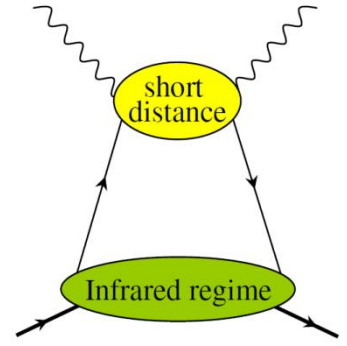
# "nonfactorizable" mechanism



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



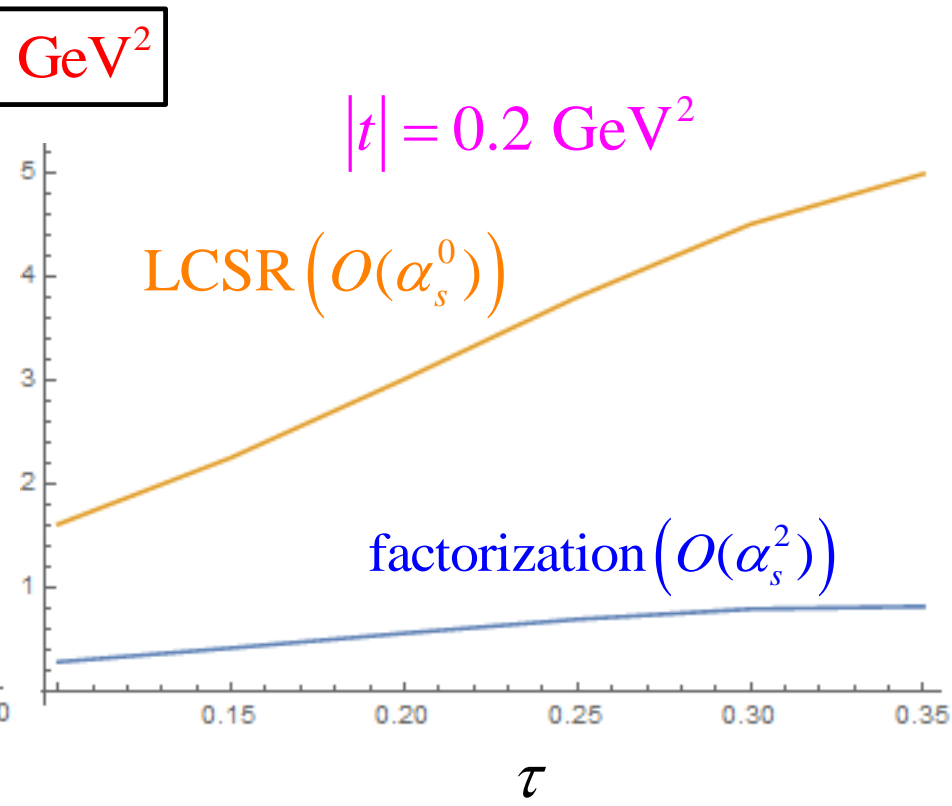
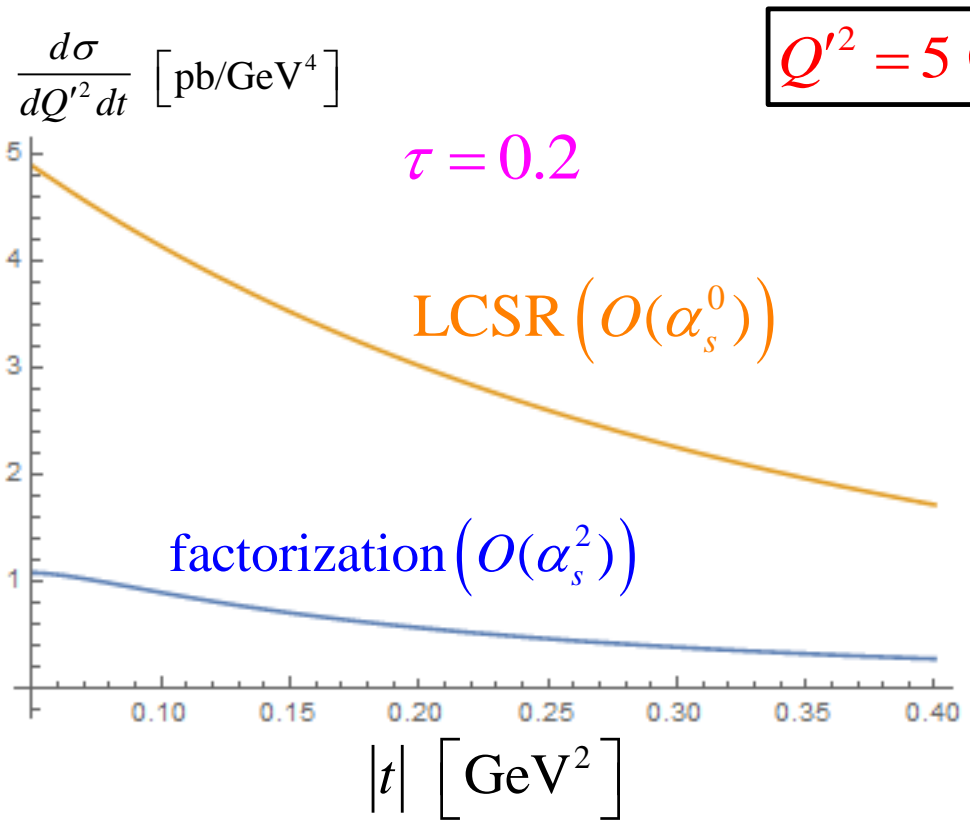
# "nonfactorizable" mechanism



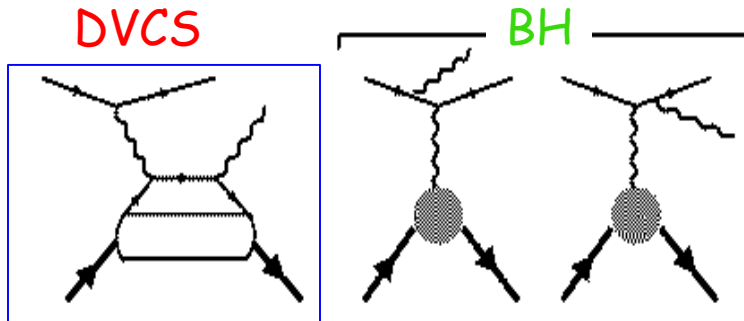
dispersion relation  
quark-hadron duality



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



# Accessing GPDs through polarized DVCS

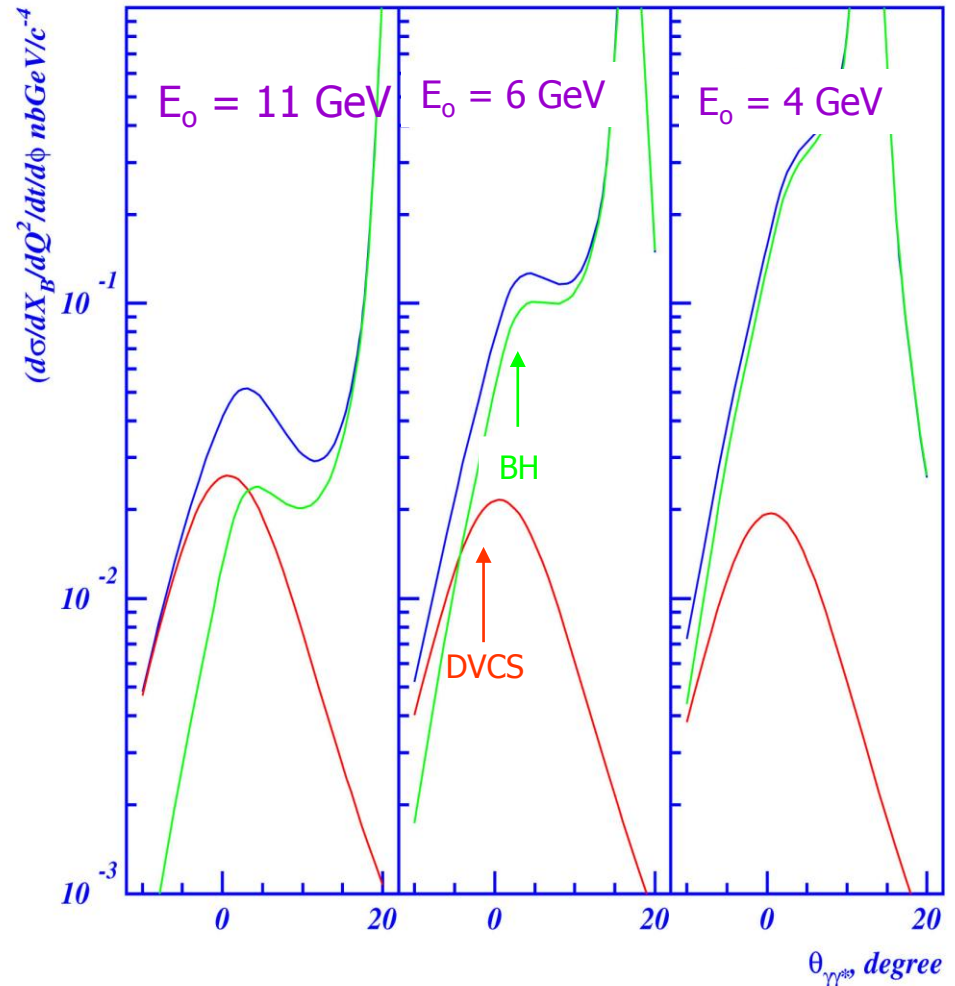


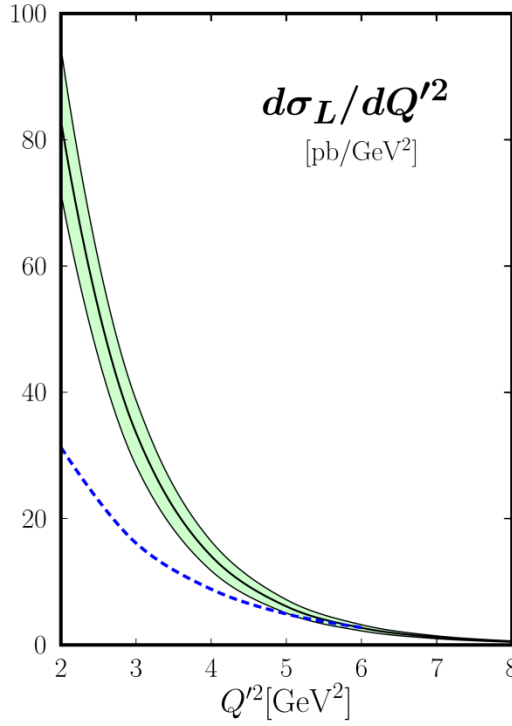
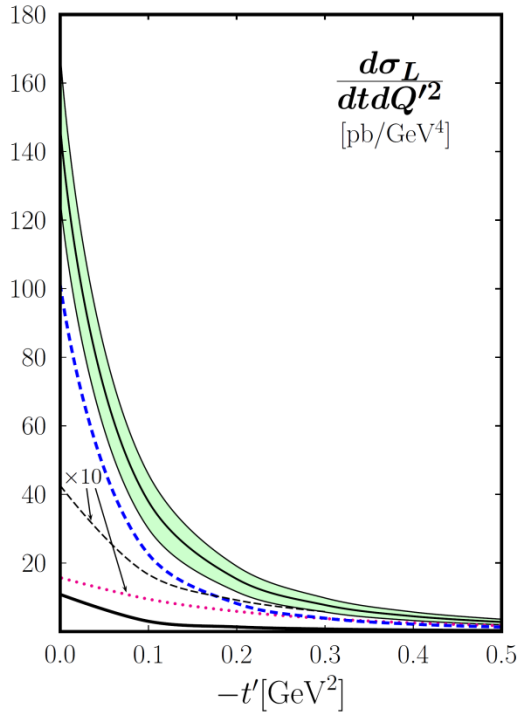
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{\text{DVCS}} + T^{\text{BH}}|^2$$

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

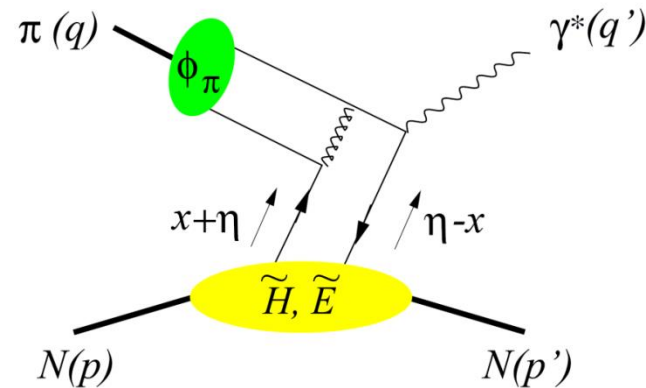
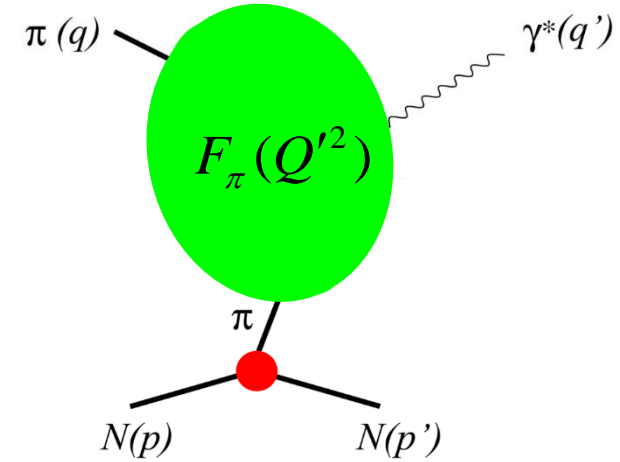
$T^{\text{DVCS}}$ : complex, determined by GPDs

Cross section of  $ep \rightarrow e\gamma p$  at  $Q^2=2 \text{ GeV}/c^2$  and  $X_B=0.35$

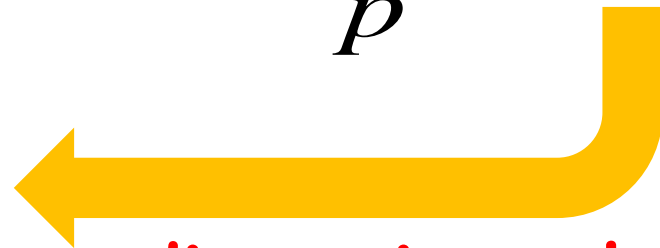
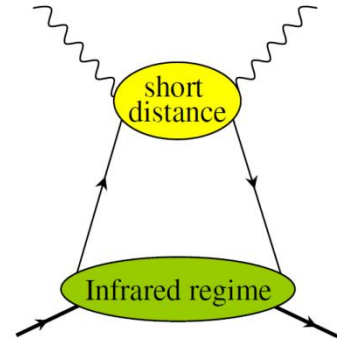
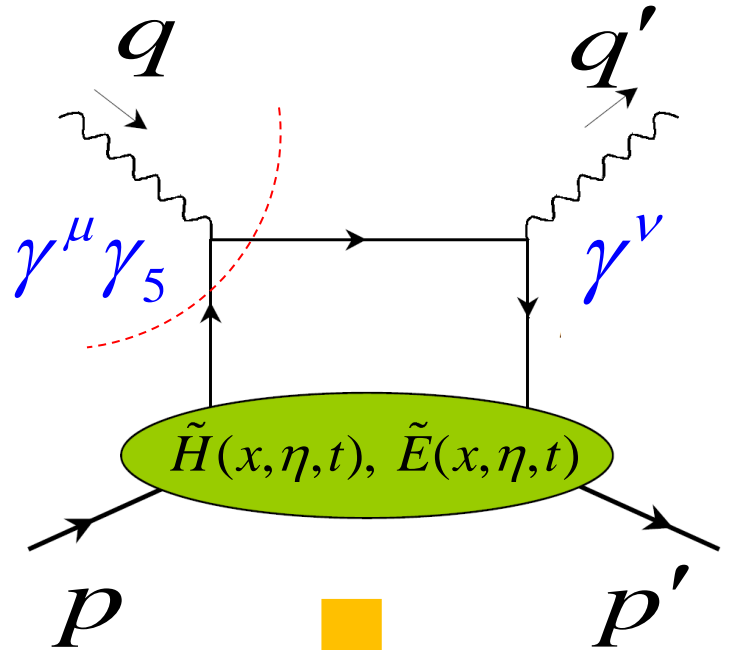
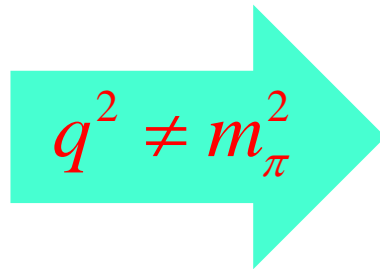
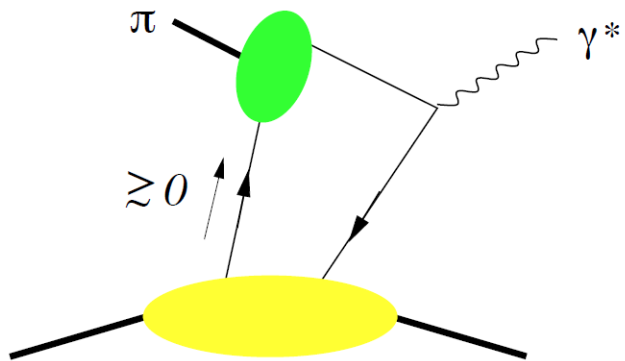




pion exchange for  $O(\alpha_s^0)$   
empirical  $F_\pi(Q'^2)$

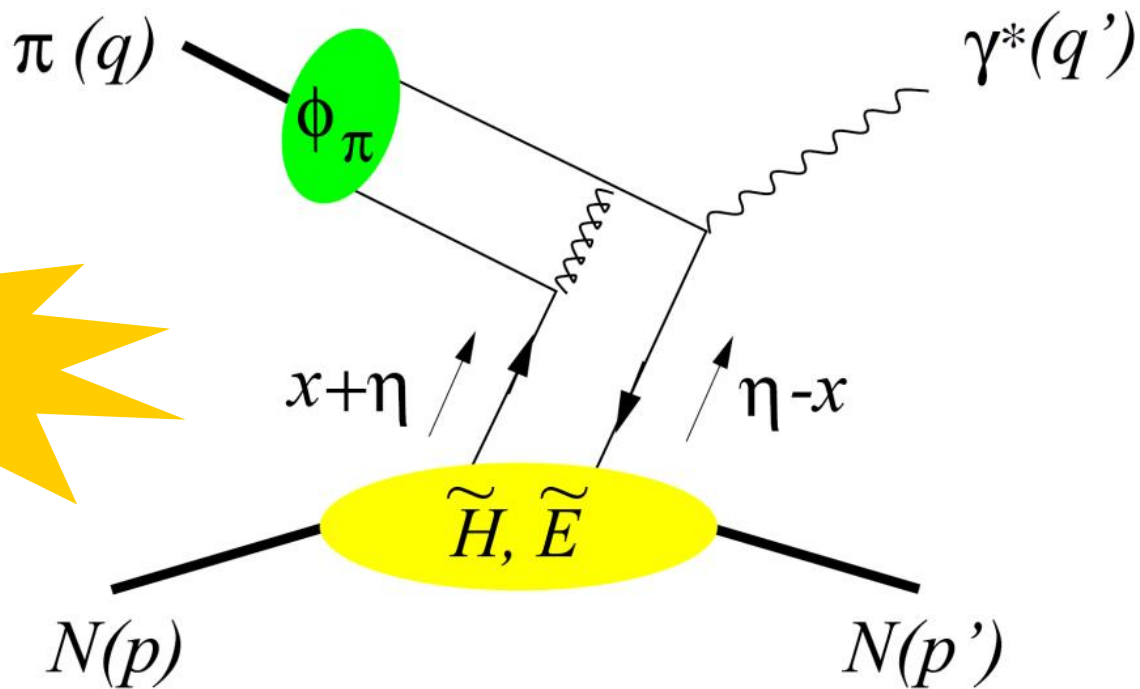


# "nonfactorizable" mechanism

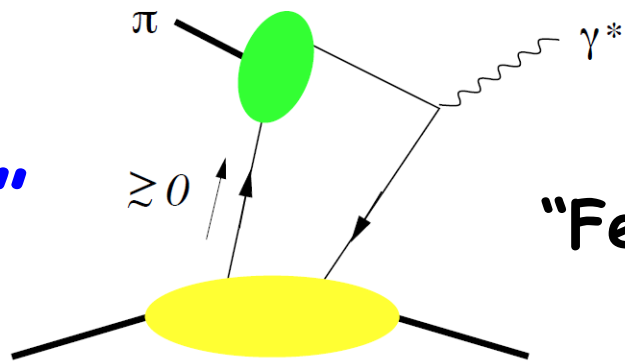


dispersion relation  
quark-hadron duality

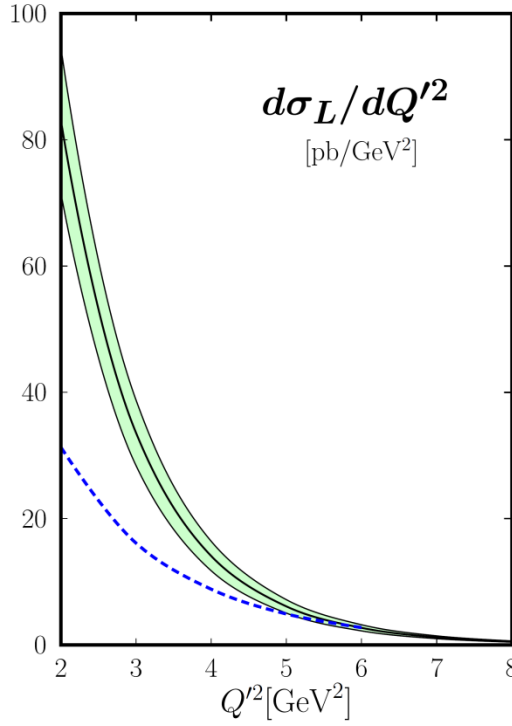
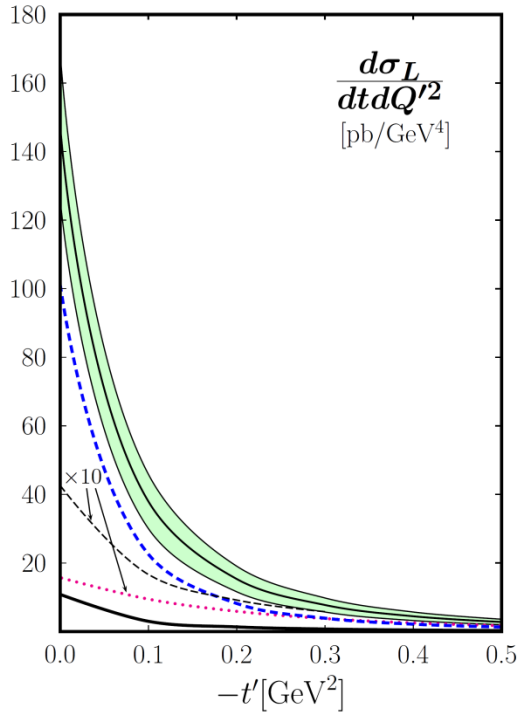
**LO in QCD factorization**



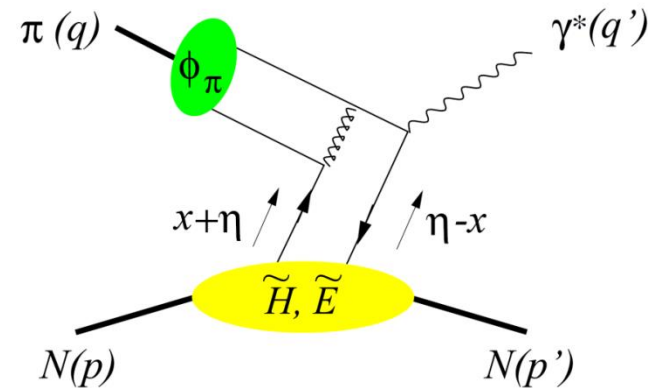
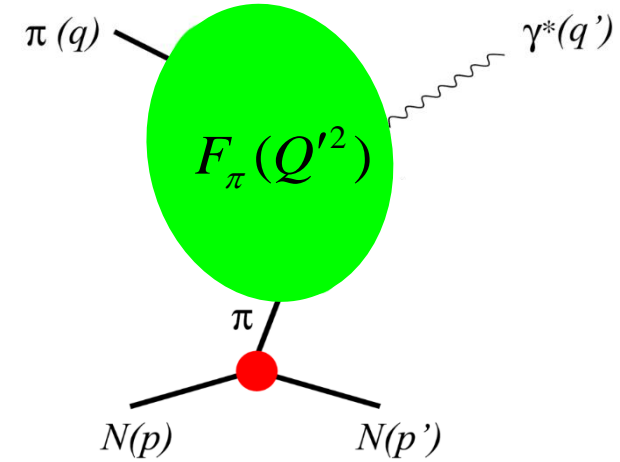
**“nonfactorizable”**

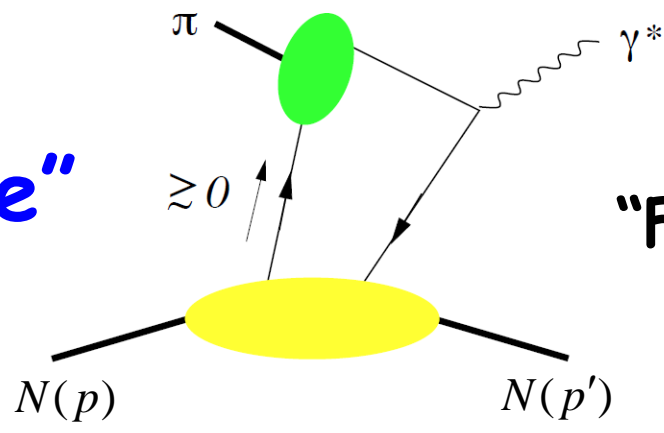
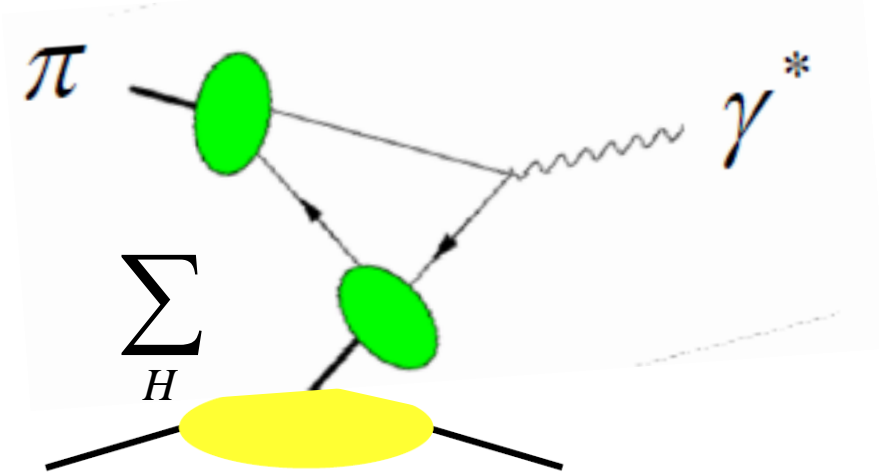


**“Feynman mechanism”**



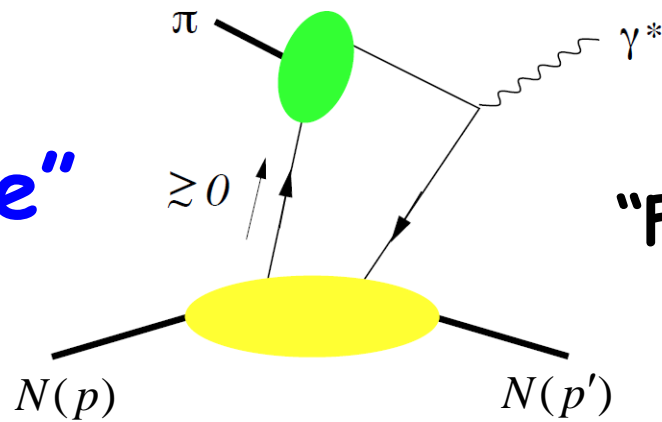
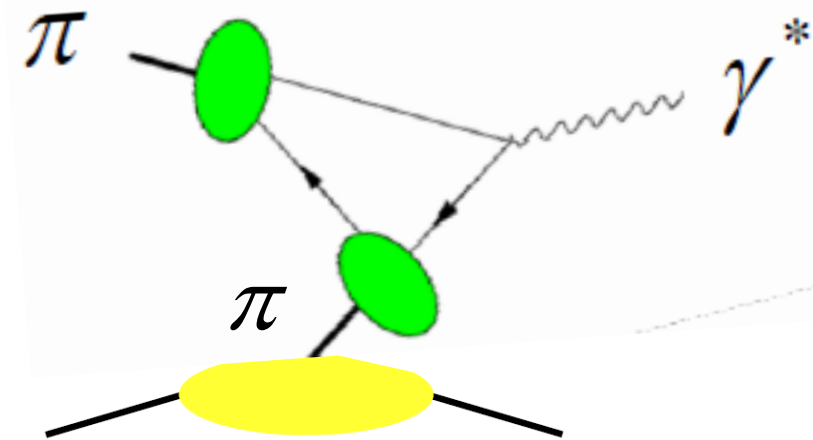
pion exchange for  $O(\alpha_s^0)$   
empirical  $F_\pi(Q'^2)$





**“nonfactorizable”**

**“Feynman mechanism”**

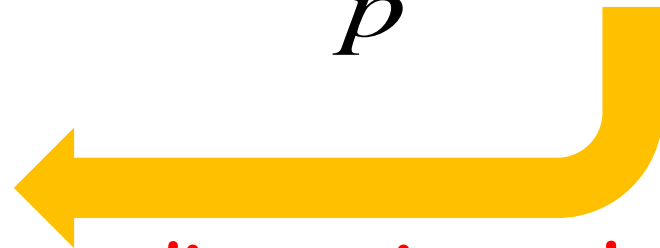
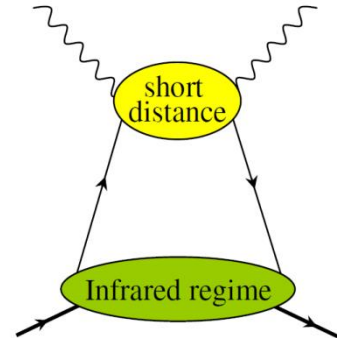
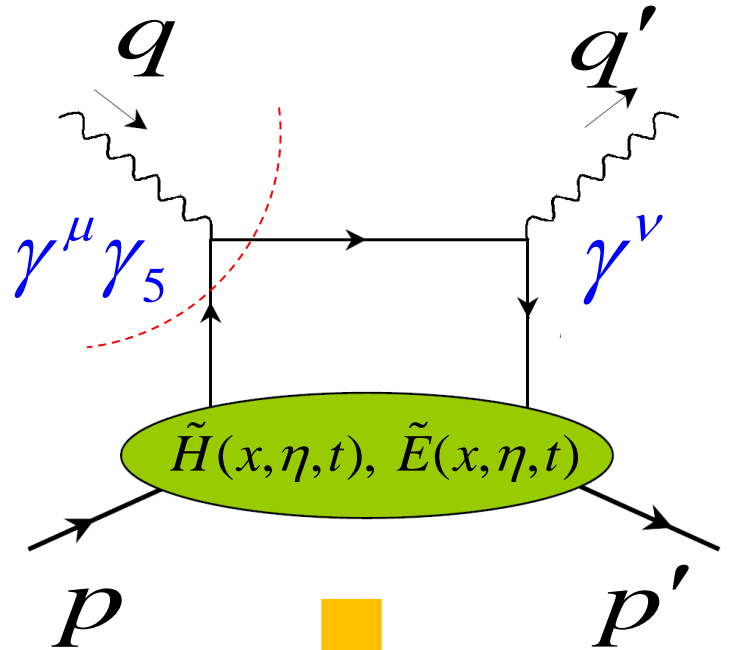
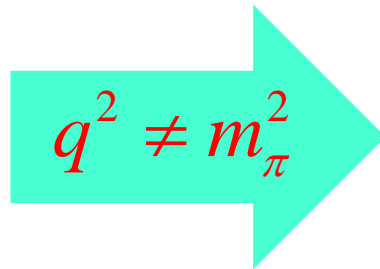
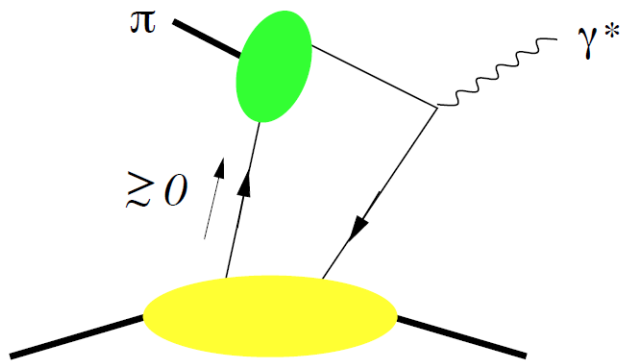


**“nonfactorizable”**

**“Feynman mechanism”**

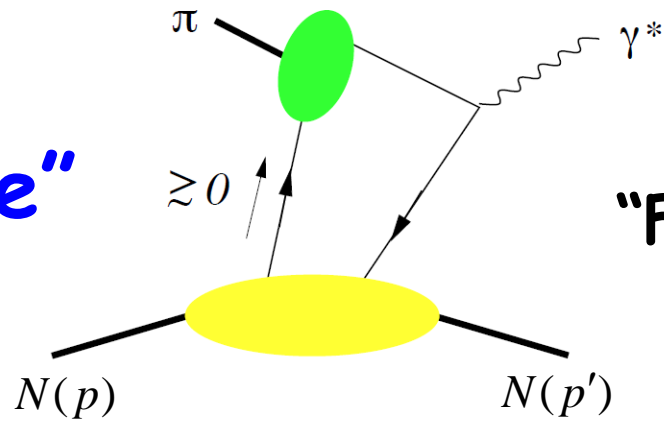


# "nonfactorizable" mechanism



dispersion relation  
quark-hadron duality

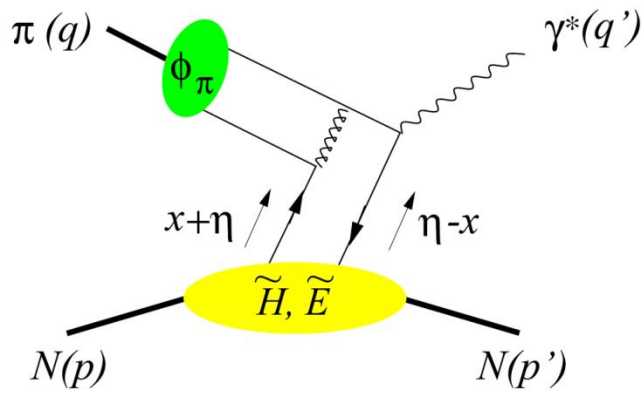
**“nonfactorizable”**



**“Feynman mechanism”**

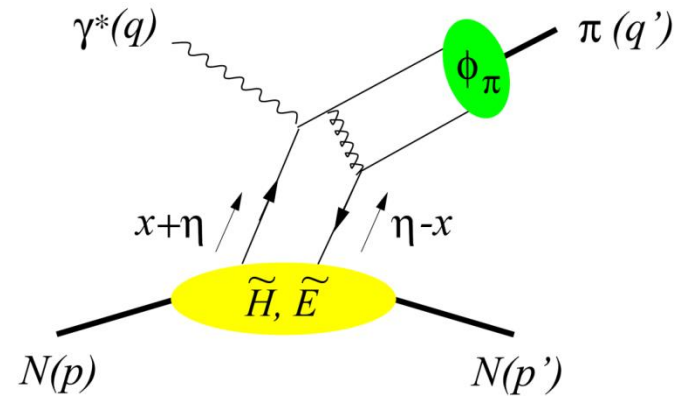
# exDY

timelike



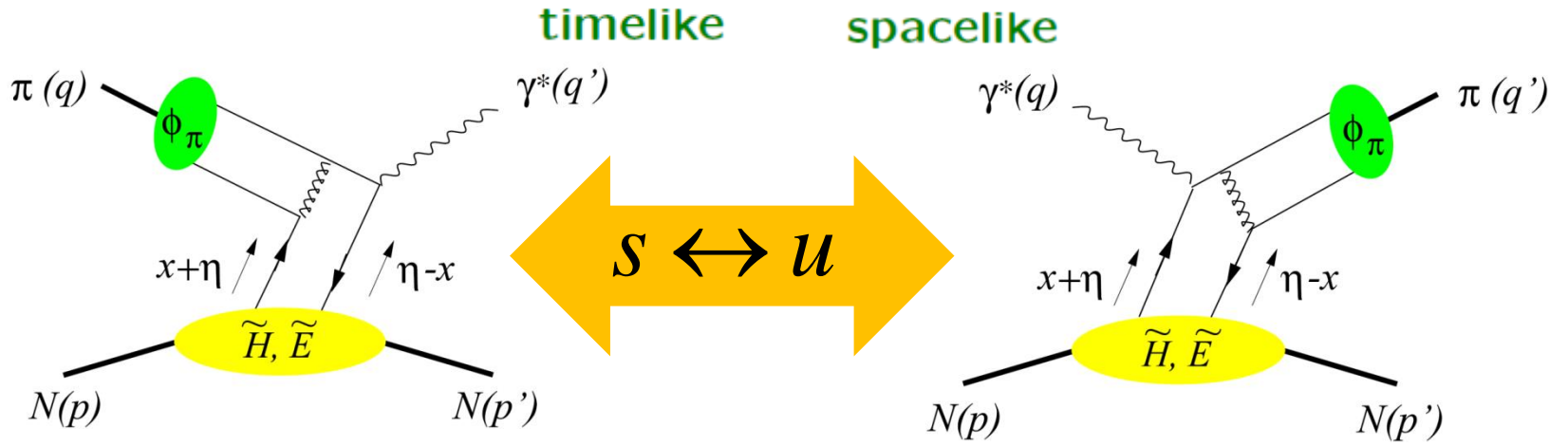
# DVMP

spacelike



# exDY

# DVMP

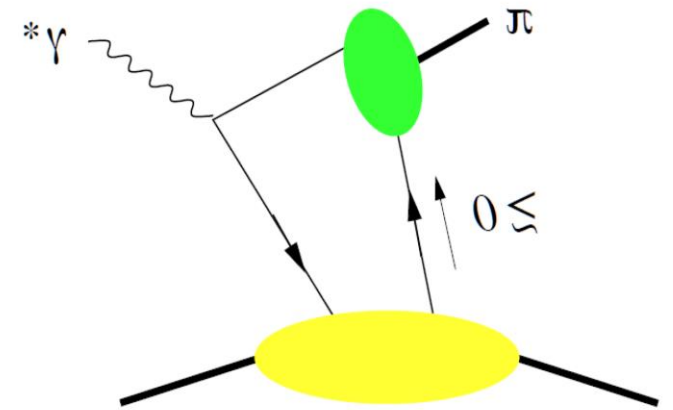
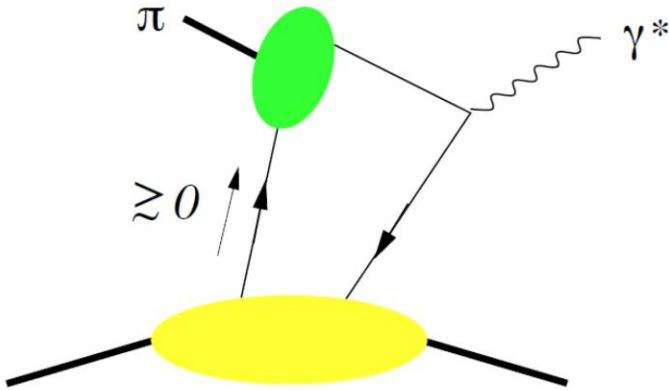
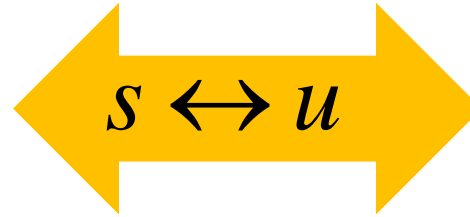


# exDY

# DVMP

timelike

spacelike

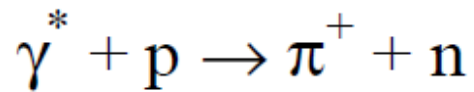
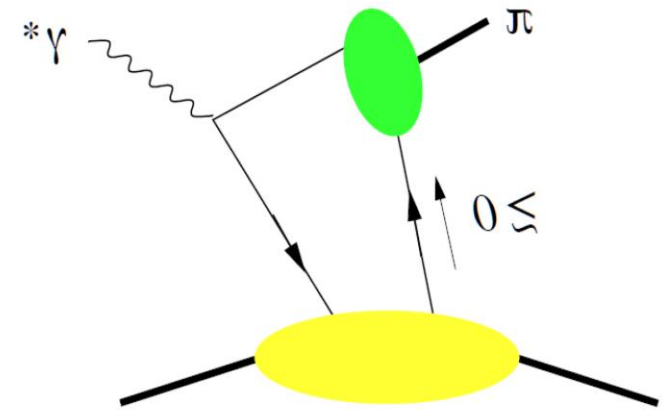
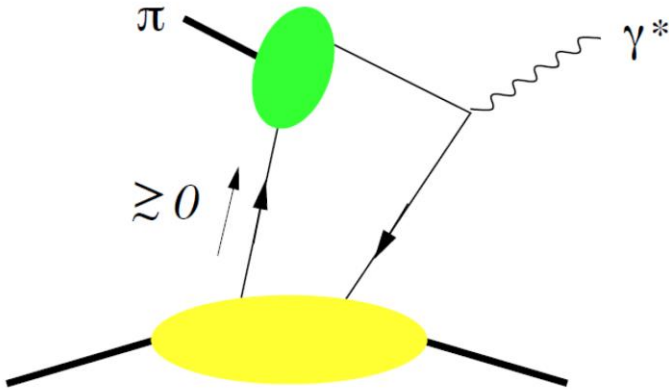
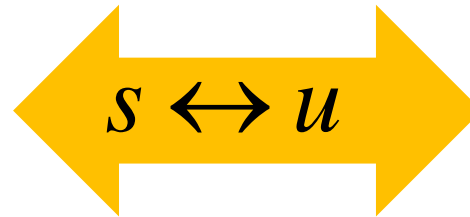


# exDY

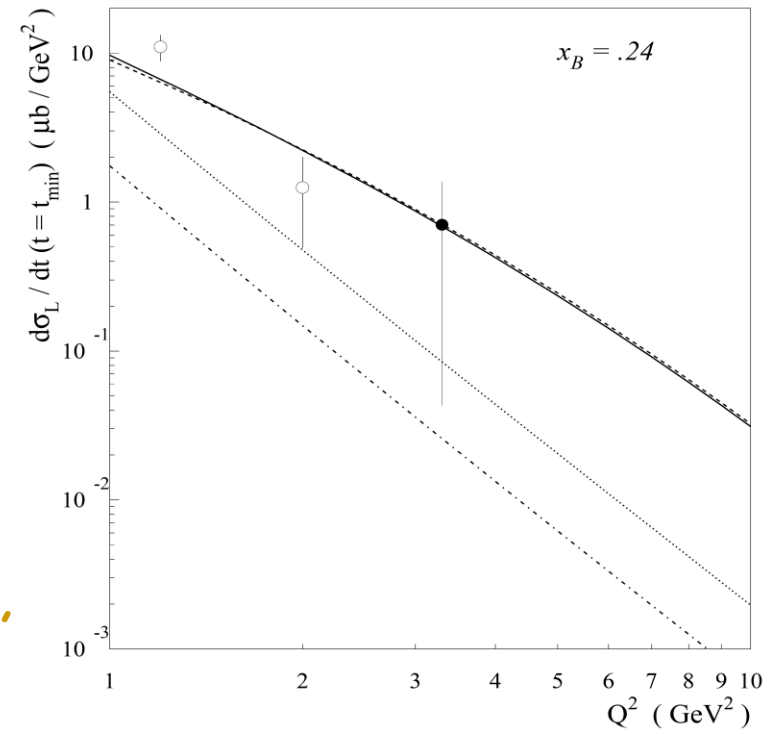
# DVMP

timelike

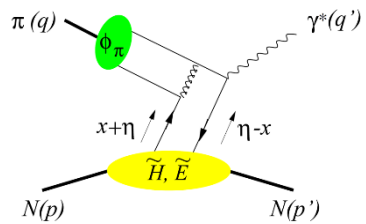
spacelike



Vanderhaeghen, Guichon, Guidal,  
PRD60 ('99) 094017



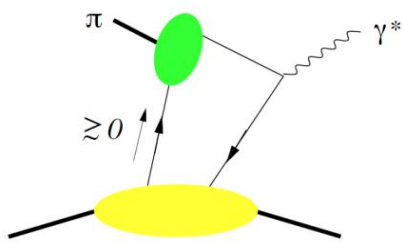
# Summary exDY ( $\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$ ) GPDs



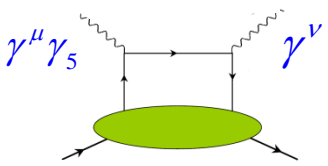
**QCD factorization: measurement at J-PARC is feasible**

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

soft nonfactorizable mechanism

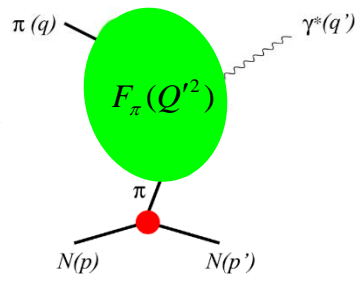


**LCSR**



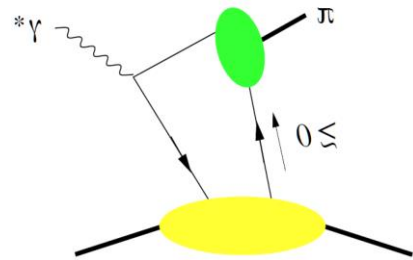
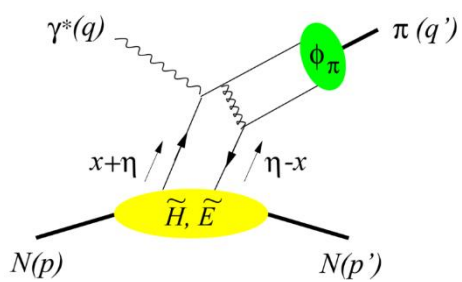
$\tilde{H}, \tilde{E}$

Goloskokov, Kroll, PLB748 ('15) 323



$F_\pi(Q'^2)$

**S ↔ U**



**cross section for  $lp \rightarrow l' \pi^+ n$**