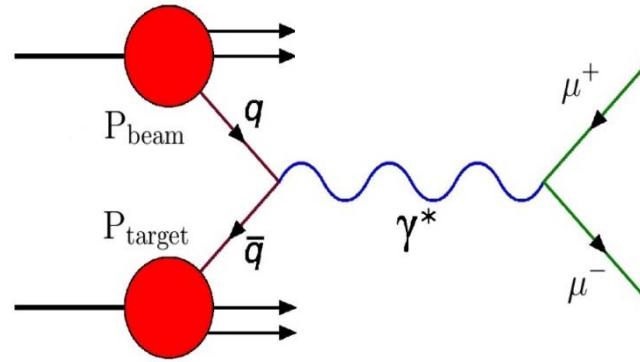


QCD mechanisms  
for accessing the nucleon GPDs  
with the exclusive pion-induced  
Drell-Yan process at J-PARC

Kazuhiro Tanaka (Juntendo U/KEK)

# Pion-induced Drell-Yan process

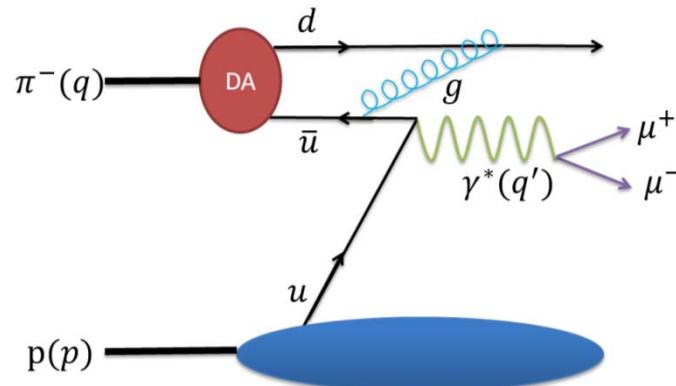
$$\pi N \rightarrow \mu^+ \mu^- X$$



inclusive

# Pion-induced Drell-Yan process

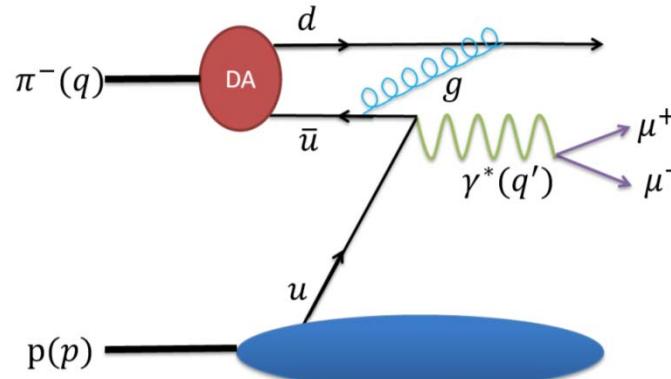
$$\pi N \rightarrow \mu^+ \mu^- X$$



inclusive

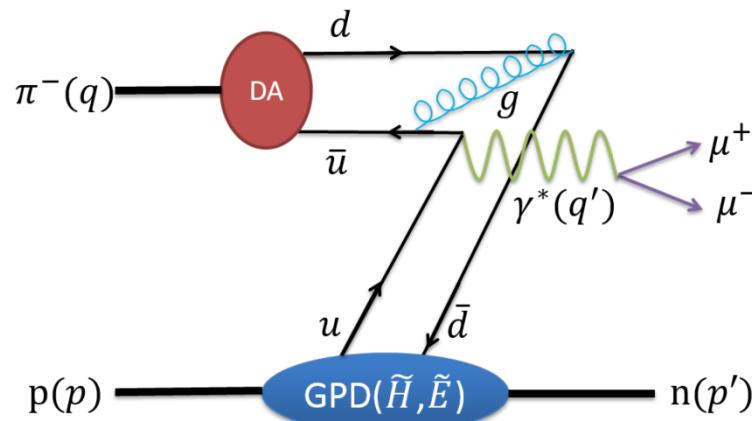
# Pion-induced Drell-Yan process

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



inclusive

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



exclusive

high intensity

not too high energy

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

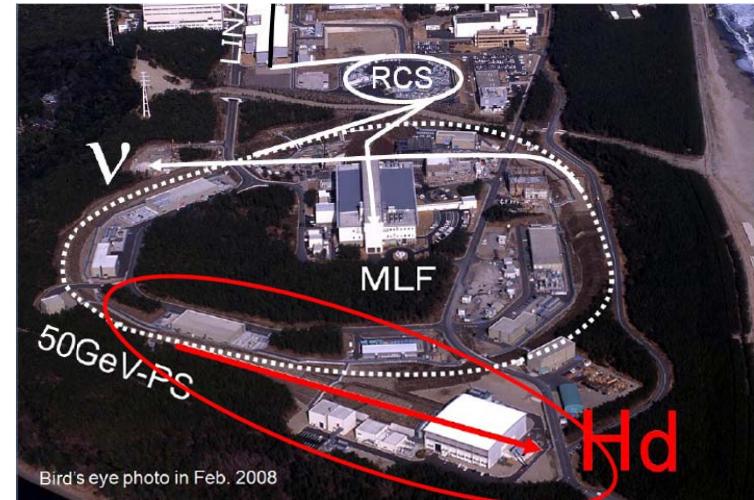
# High momentum beam line at J-PARC

- Primary beam (proton)

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

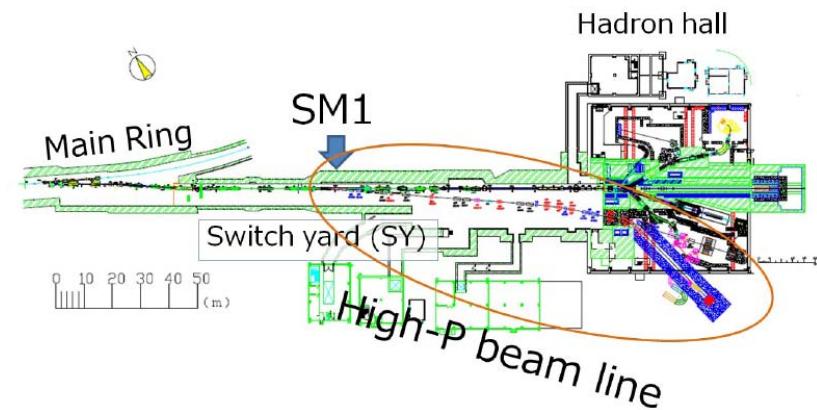
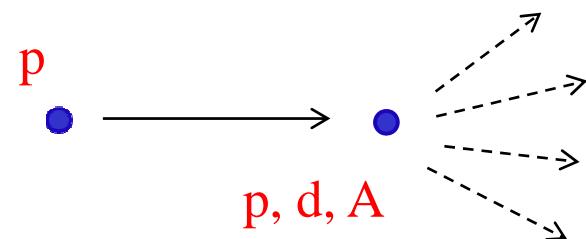
$L = 10^{35} \text{cm}^{-2}\text{s}^{-1}$

Hadron Facility at J-PARC



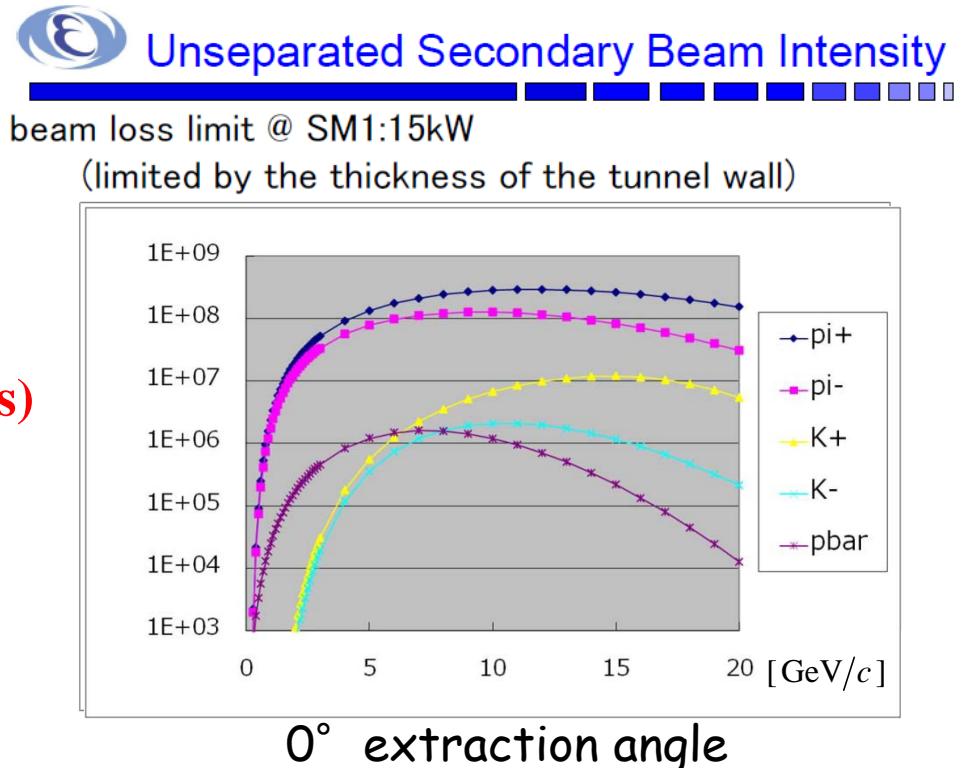
- Secondary beam (pion)

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



## High-momentum beamline

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

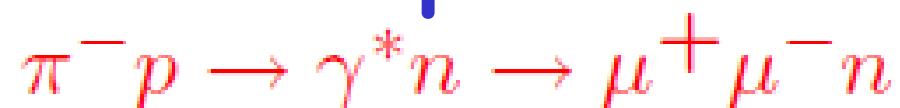


high intensity

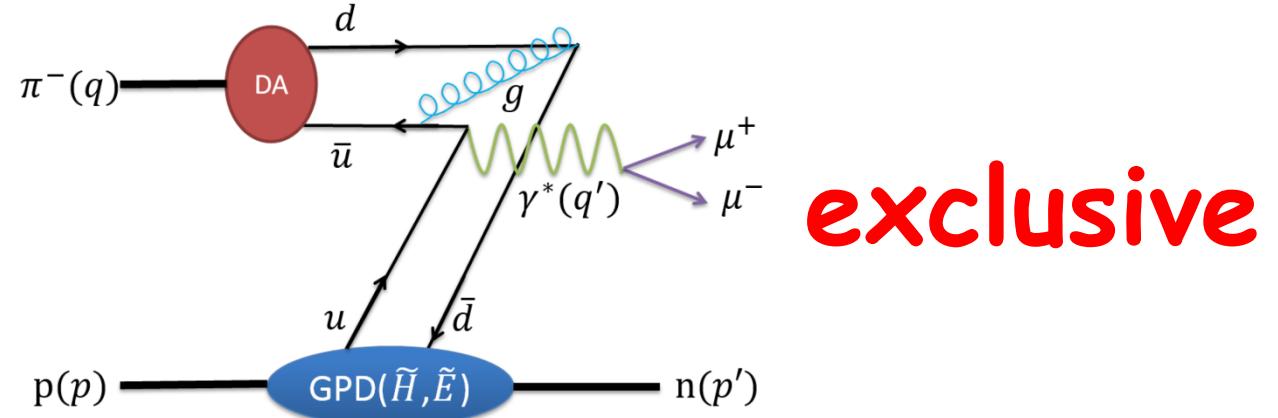
not too high energy

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

best suited to study meson-induced  
hard exclusive processes



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



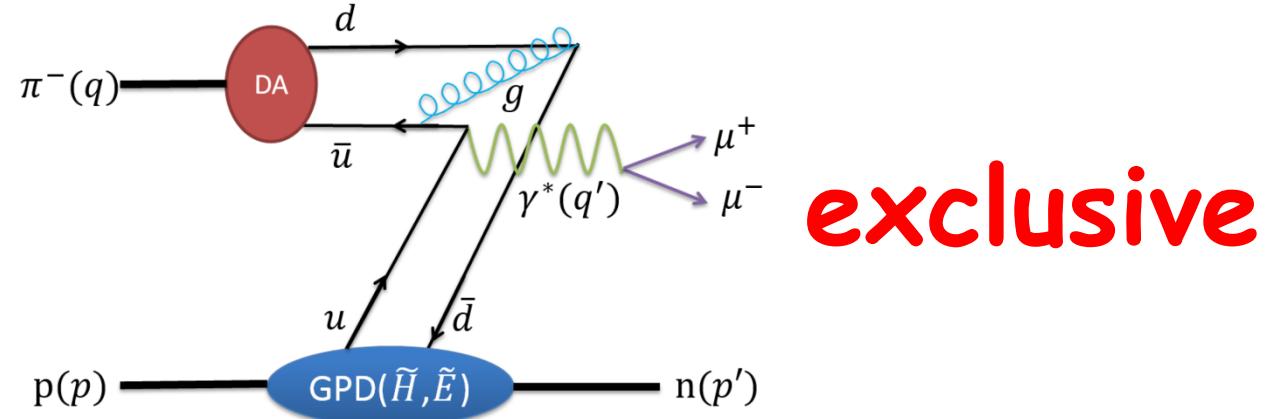
## 1. Cross-section calculation with QCD factorization formula & feasibility study at J-PARC

T. Sawada, W.C. Chang, S. Kumano, J.C. Peng, S. Sawada, KT,  
PRD93 (2016) 114034

## 2. Non-factorizable mechanism and light-cone QCD sum rule estimate

KT, in progress

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



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PRD93 (2016) 114034

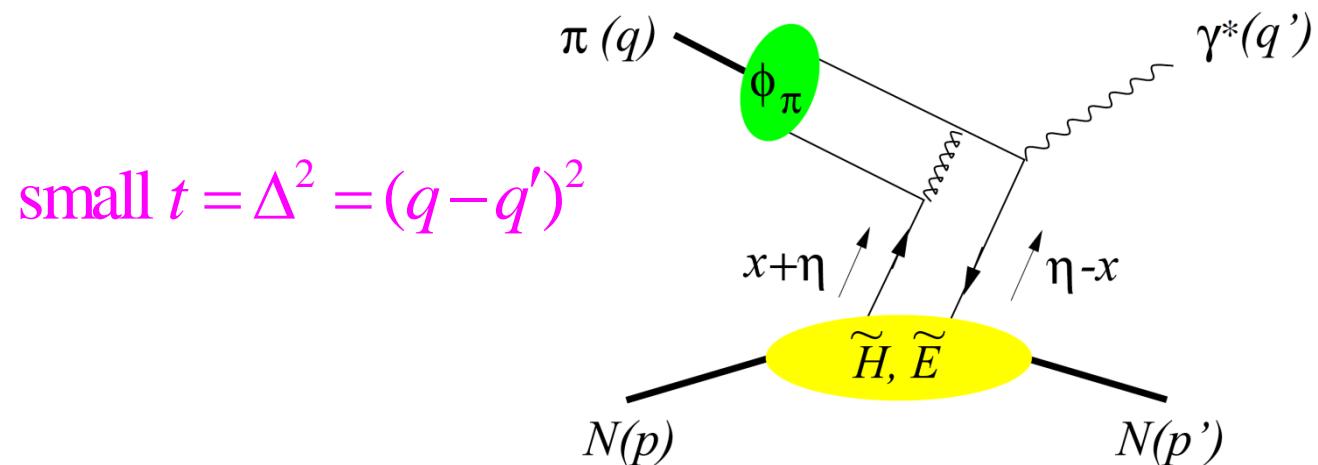
## 2. Non-factorizable mechanism and light-cone QCD sum rule estimate

KT, in progress

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

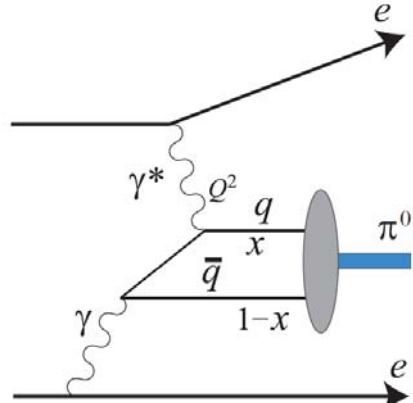
$$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$$

“exclusive limit of DY”



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

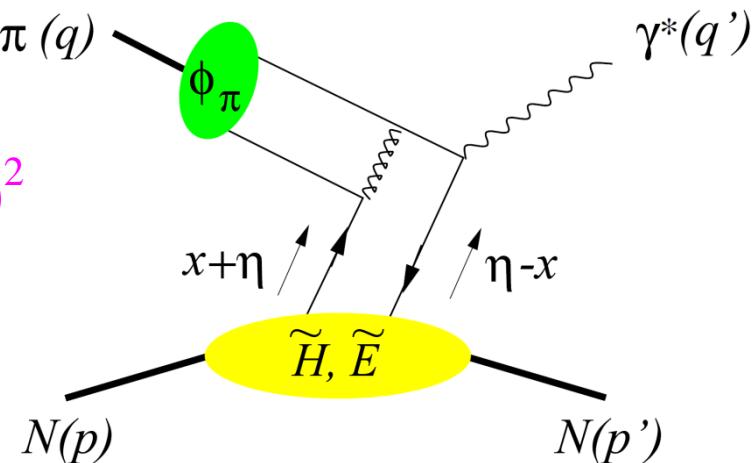
$$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$$



@Belle, Babar

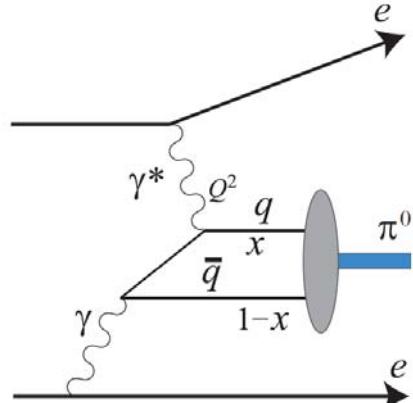
"exclusive limit of DY"

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



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

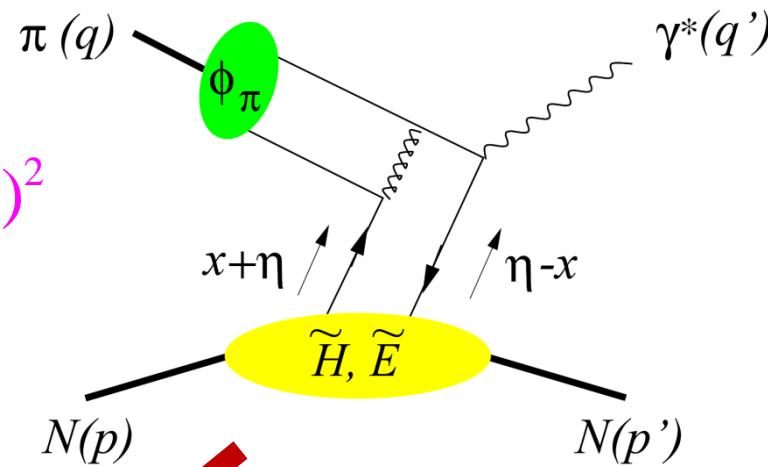
$$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$$



@Belle, Babar

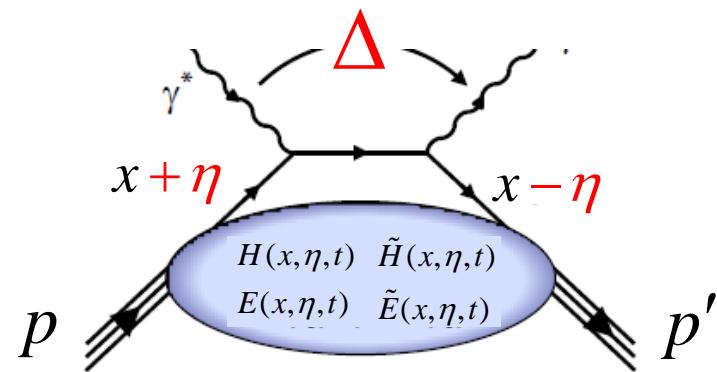
"exclusive limit of DY"

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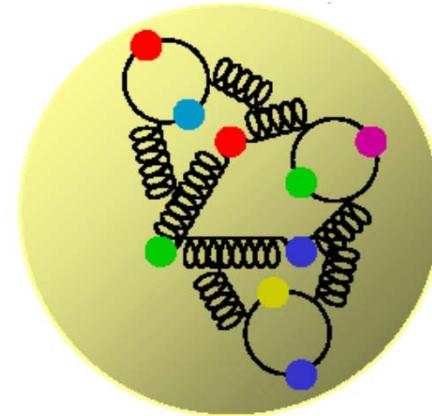
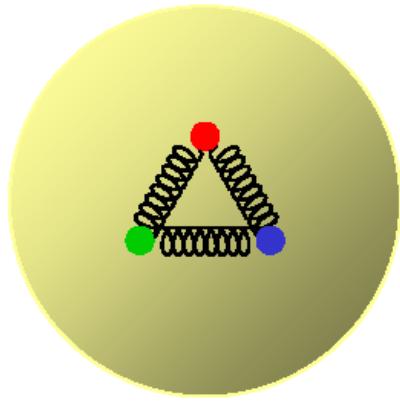
$$\Delta q(x) \quad t \rightarrow 0$$

**GPD**

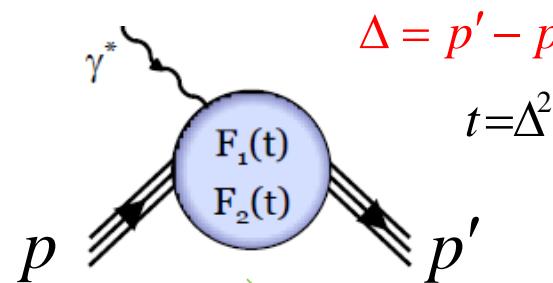


$$-2\eta \bar{P} = \Delta$$

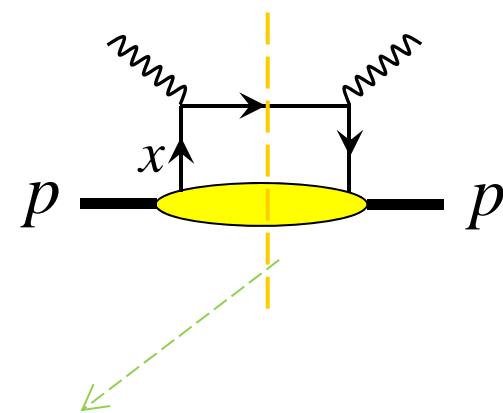
$$\int d\mathbf{z}^- e^{i(\mathbf{x}+\boldsymbol{\eta}) \cdot p \mathbf{z}} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$



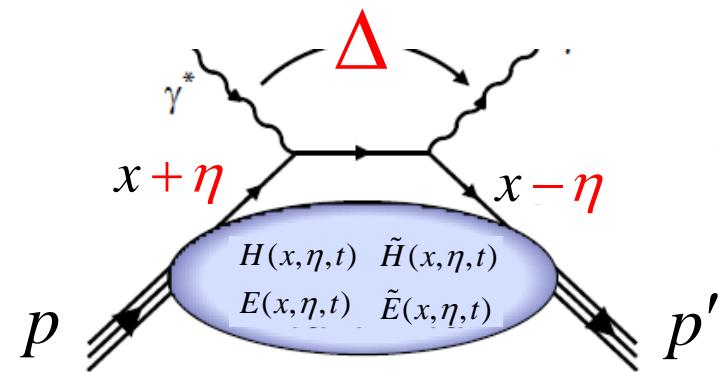
$$\langle N(\mathbf{p}') | \psi^\dagger(0) \psi(0) | N(\mathbf{p}) \rangle$$



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



**GPD**



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

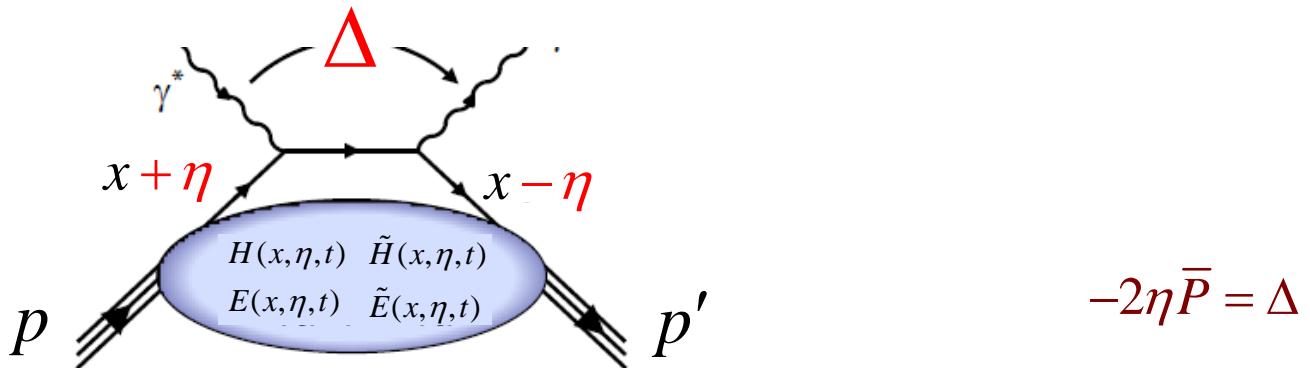
$$\int d\mathbf{z}^- e^{i(\mathbf{x} + \boldsymbol{\eta}) p \mathbf{z}} \langle N(\mathbf{p}') | \psi^\dagger(0) \psi(\mathbf{z}^-) | N(\mathbf{p}) \rangle$$

$$\overline{P}=\frac{\textcolor{blue}{p}+p'}{2}$$

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

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

**GPD**



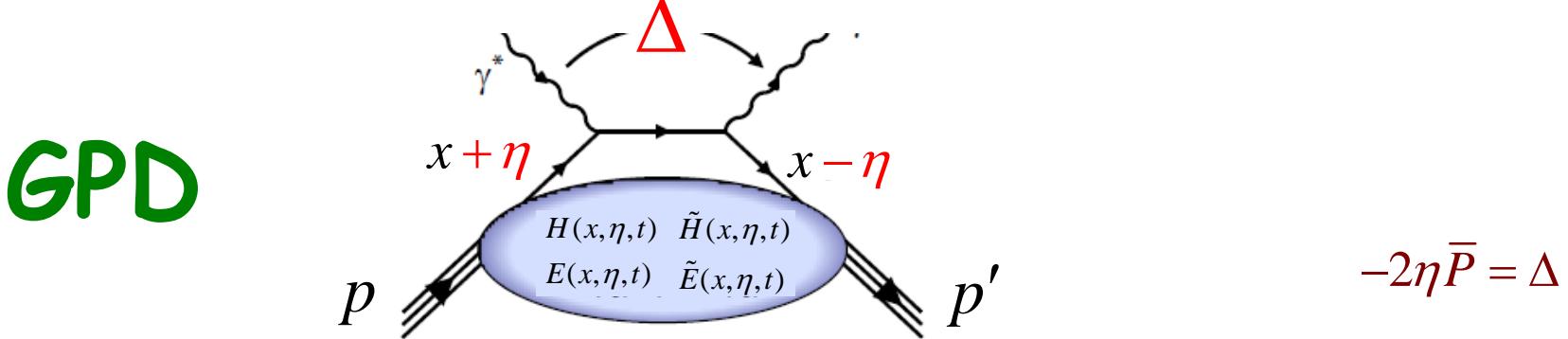
$$\int d\textcolor{red}{z}^- e^{i(\textcolor{blue}{x}+\eta)p\textcolor{red}{z}} \langle N(\textcolor{red}{p}')|\psi^\dagger(0)\psi(\textcolor{red}{z}^-)|N(\textcolor{red}{p})\rangle$$

$$\overline{P}=\frac{\textcolor{blue}{p}+p'}{2}$$

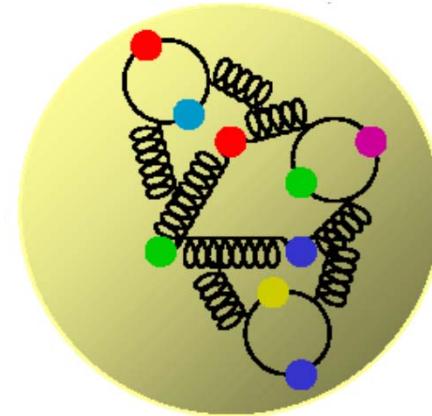
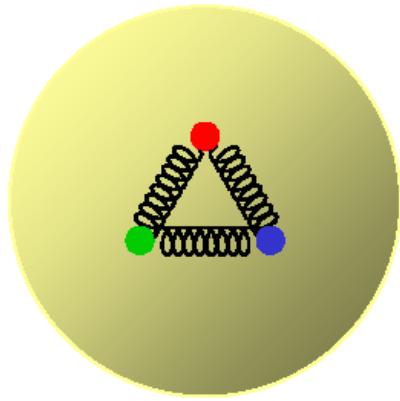
$$\int \frac{d\textcolor{red}{z}^-}{2\pi} e^{i(\textcolor{blue}{x}+\eta)\bar{P}\textcolor{red}{z}} \langle p'|\overline{\psi}(0)\gamma^+\psi(\textcolor{red}{z}^-)|\,p\rangle = \frac{1}{\overline{P}^+}\Bigg[\textcolor{violet}{H}(x,\eta,t)\overline{u}(p')\gamma^+ u(p) + \textcolor{violet}{E}(x,\eta,t)\overline{u}(p')\frac{i\sigma^{+\alpha}(p^{\,\prime}-p)_\alpha}{2M} u(p)\Bigg]$$

$$\int \frac{d\textcolor{red}{z}^-}{2\pi} e^{i(\textcolor{blue}{x}+\eta)\bar{P}\textcolor{red}{z}} \langle p'|\overline{\psi}(0)\gamma^+\gamma_5\psi(\textcolor{red}{z}^-)|\,p\rangle = \frac{1}{\overline{P}^+}\Bigg[\tilde{H}(x,\eta,\textcolor{violet}{t})\overline{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}(x,\eta,\textcolor{violet}{t})\overline{u}(p')\frac{\gamma_5(p^{\,\prime}-p)^+}{2M} u(p)\Bigg]$$

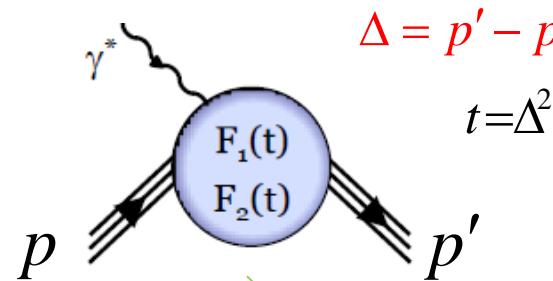
$$J_{\mathfrak{q}}=\frac{1}{2}\int_{-1}^1dx x\big(H(x,\eta,0)+E(x,\eta,0)\big)$$



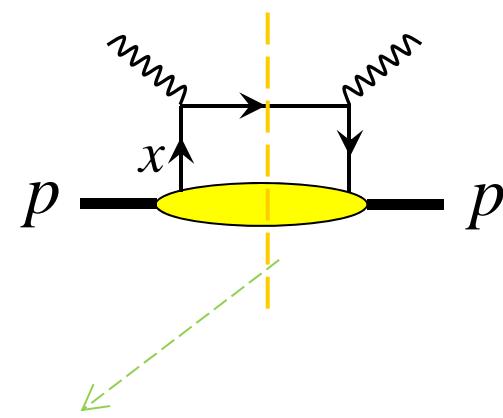
$$\int d\textcolor{red}{z}^- e^{i(\textcolor{blue}{x}+\eta)p\textcolor{red}{z}} \Big\langle N(\textcolor{red}{p}') \Big| \psi^\dagger(0) \psi(\textcolor{red}{z}^-) \Big| N(\textcolor{red}{p}) \Big\rangle$$



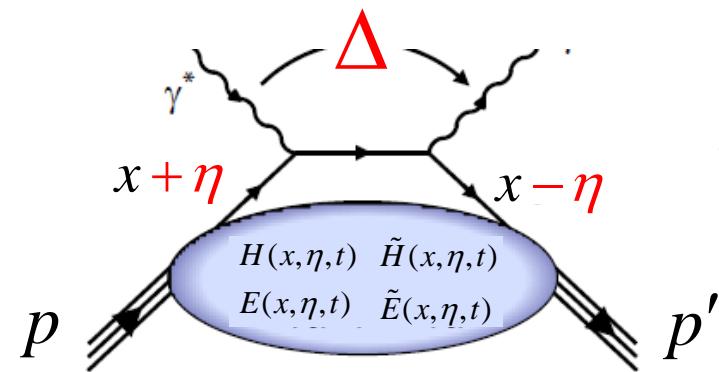
$$\langle N(\mathbf{p}') | \psi^\dagger(0) \psi(0) | N(\mathbf{p}) \rangle$$



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

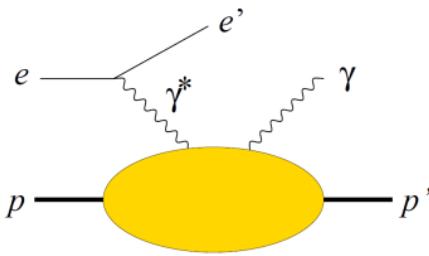


**GPD**



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

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



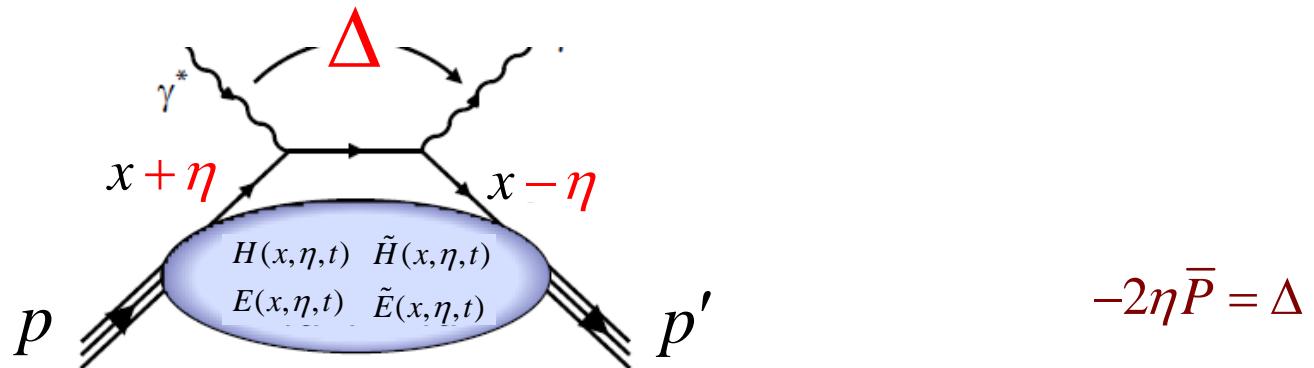
$$\bar{P} = \frac{p + p'}{2}$$

JLab, HERMES, COMPASS, ...

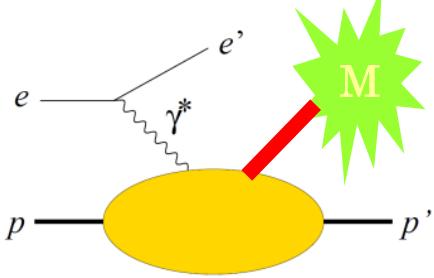
$$\int \frac{d\textcolor{red}{z}^-}{2\pi} e^{i(\textcolor{blue}{x}+\eta)\bar{P}_z} \langle p' | \bar{\psi}(0) \gamma^+ \psi(\textcolor{red}{z}^-) | p \rangle = \frac{1}{\bar{P}^+} \left[ \textcolor{magenta}{H}(x, \eta, t) \bar{u}(p') \gamma^+ u(p) + \textcolor{magenta}{E}(x, \eta, t) \bar{u}(p') \frac{i\sigma^{+\alpha}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

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

**GPD**



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



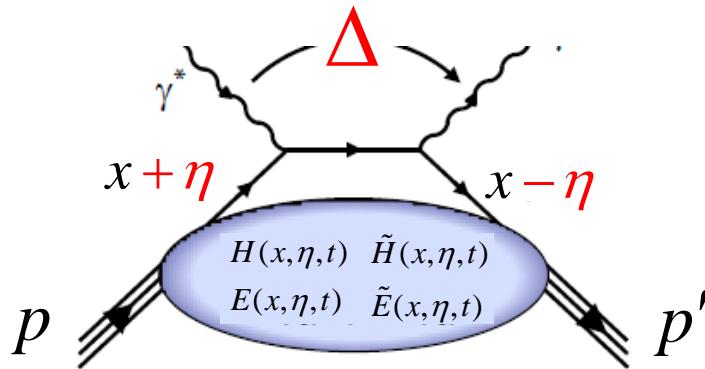
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JLab, HERMES, COMPASS,...

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

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**GPD**

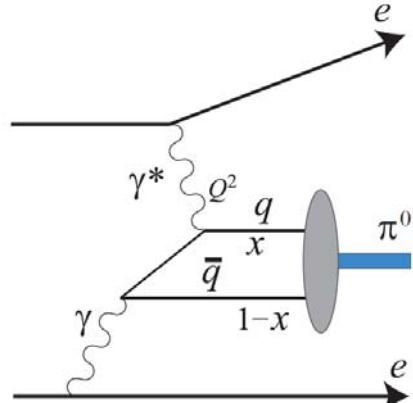


$$-2\eta \bar{P} = \Delta$$

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

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

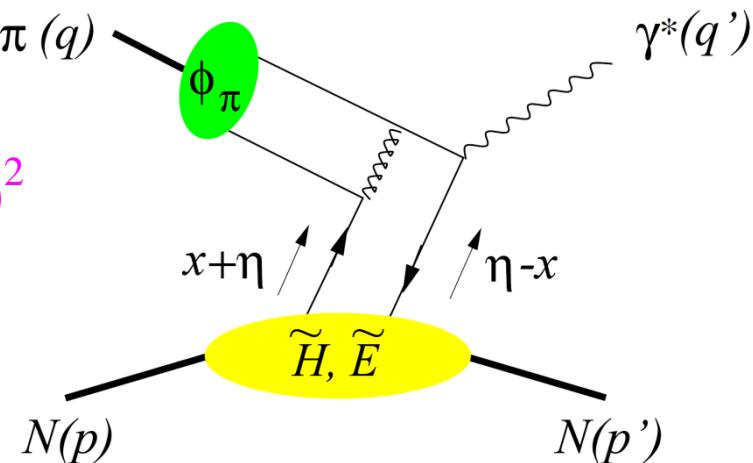
$$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$$



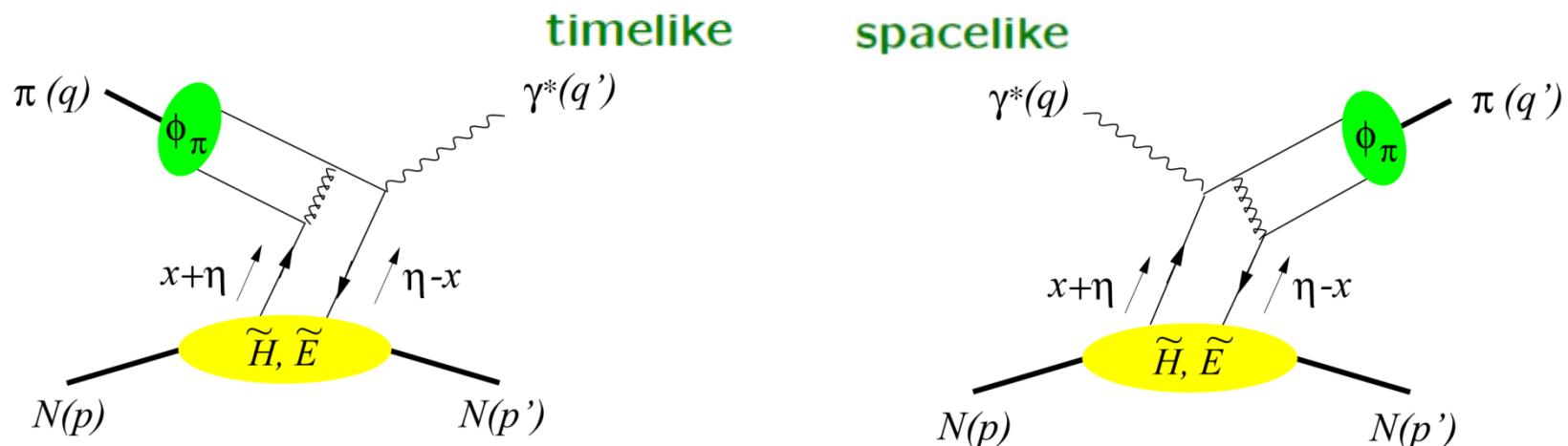
@Belle, Babar

"exclusive limit of DY"

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

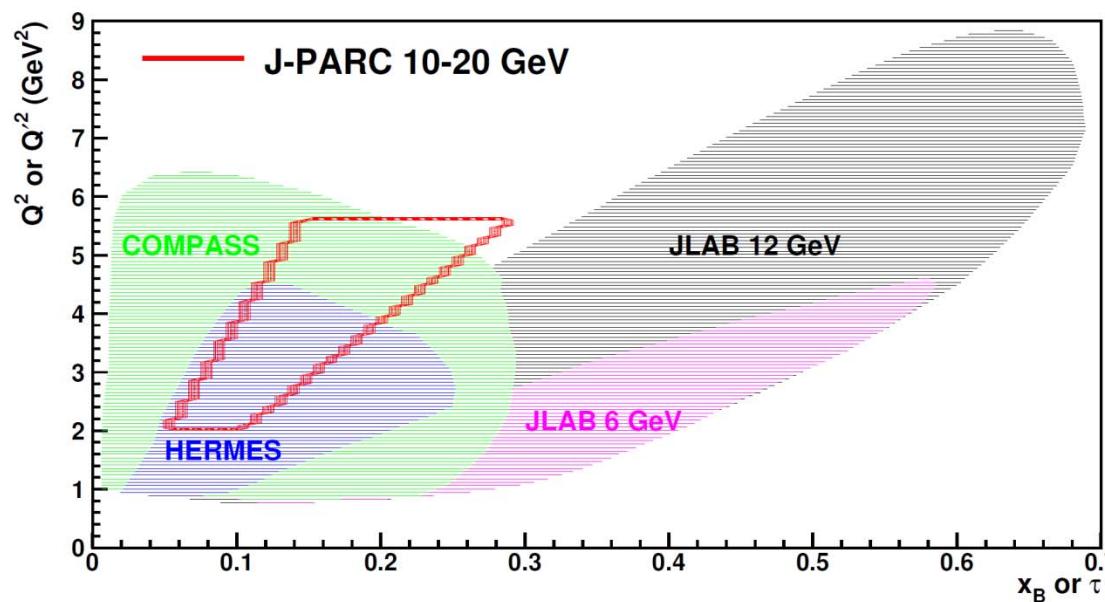


# Pion beams reveal $\tilde{H}, \tilde{E}$ Generalized Parton distributions



**exDY@J-PARC**

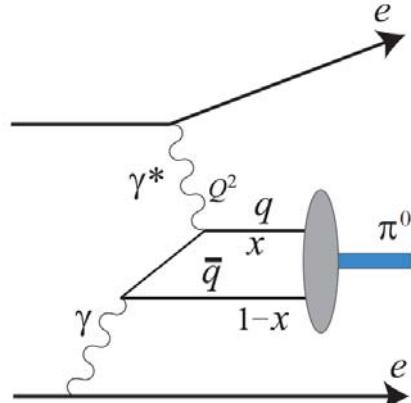
**DVMP@JLab**



T. Sawada et al.,  
PRD93, 114034

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

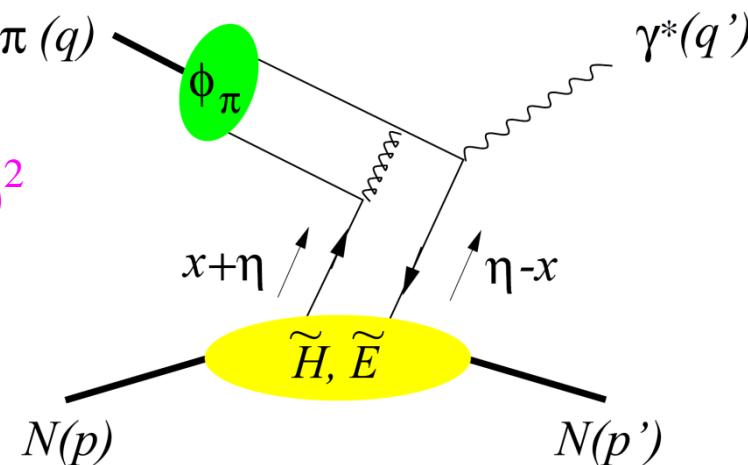
$$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$$



@Belle, Babar

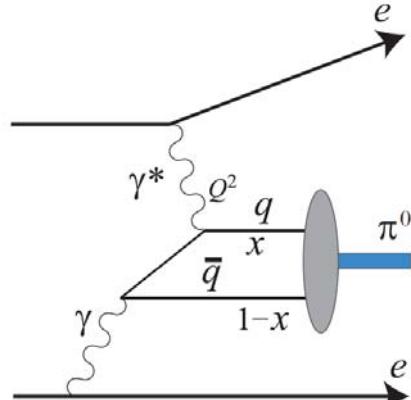
"exclusive DY"

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



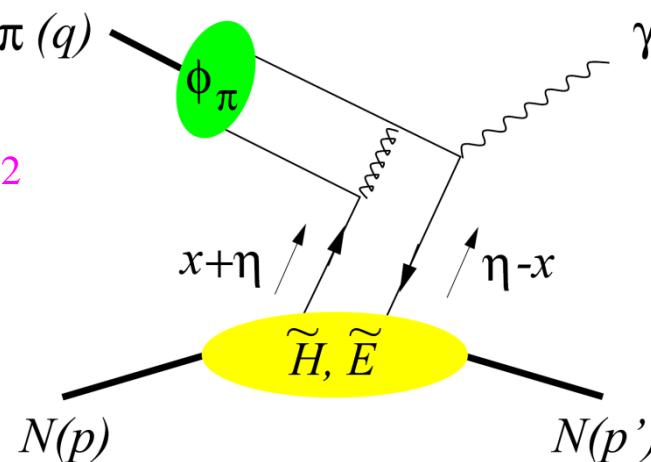
## Exclusive lepton pair production in $\pi N$ scattering

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

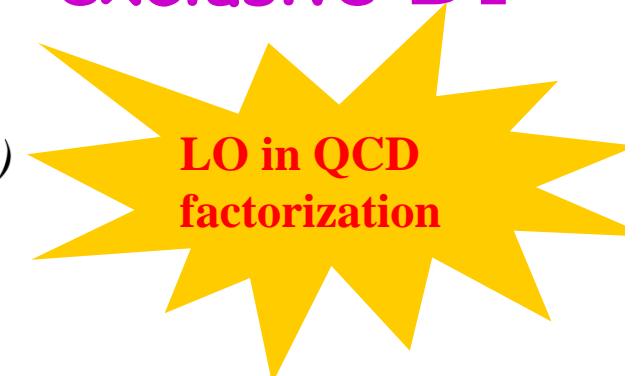


@Belle, Babar

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



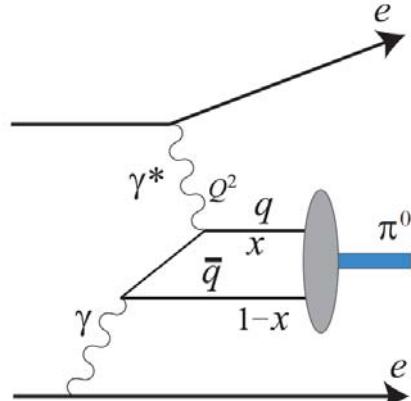
"exclusive DY"



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

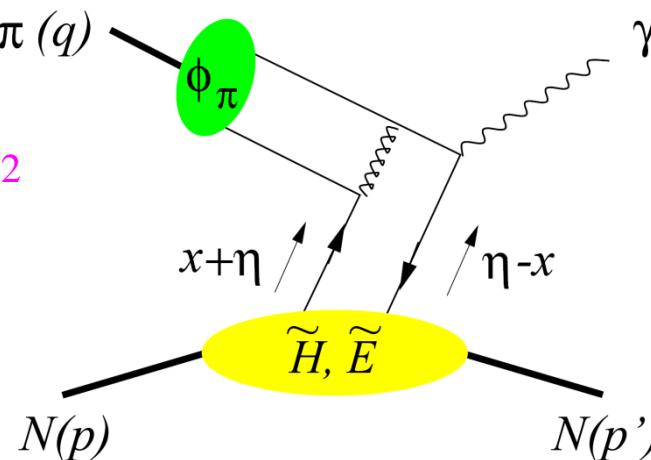
$$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$$

Berger, Diehl, Pire, PLB523(2001)265

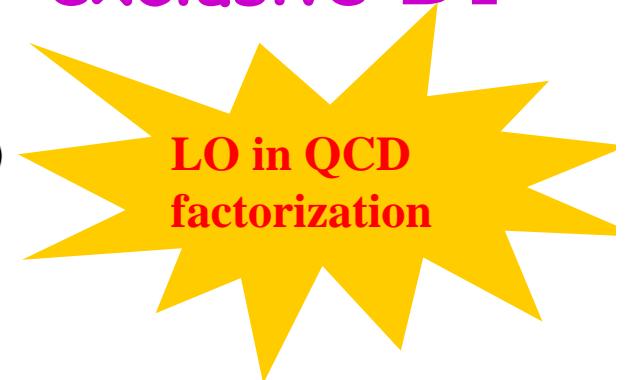


@Belle, Babar

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



"exclusive DY"



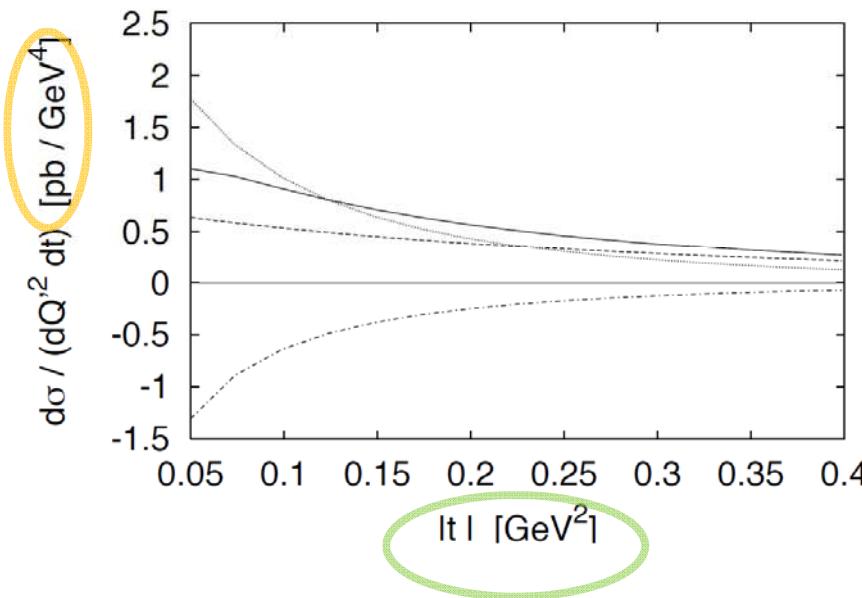
Bjorken variable

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

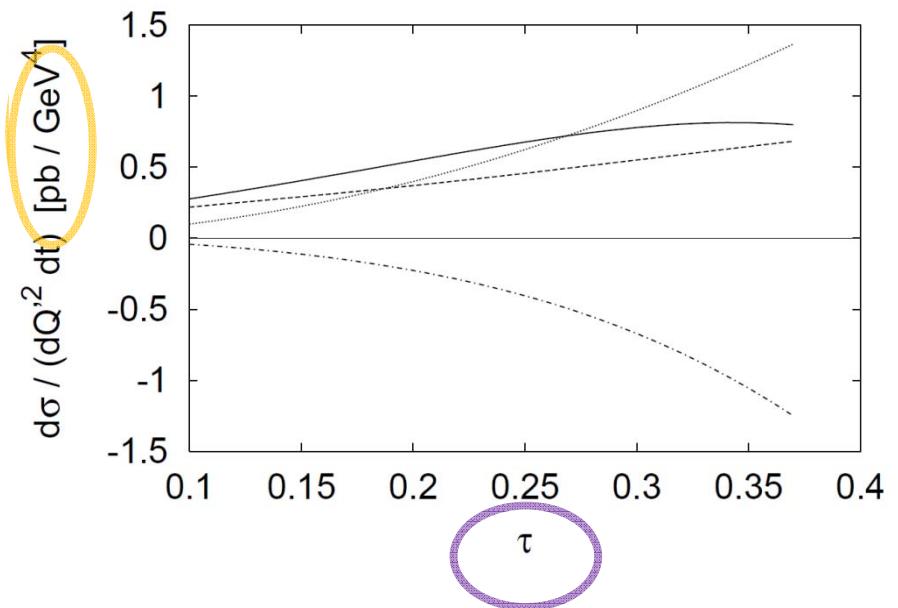
Berger, Diehl, Pire, PLB523(2001)265

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

$$\tau = 0.2$$



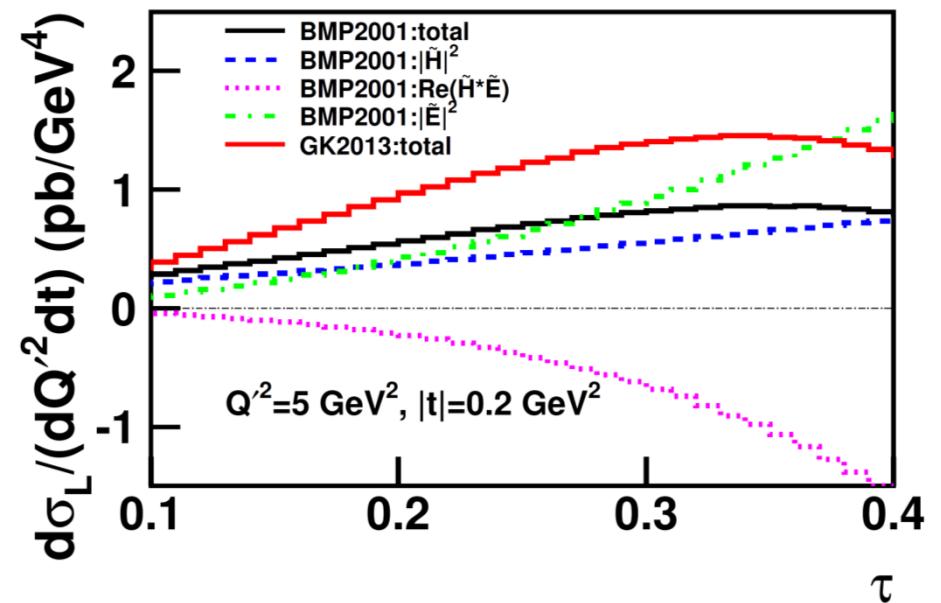
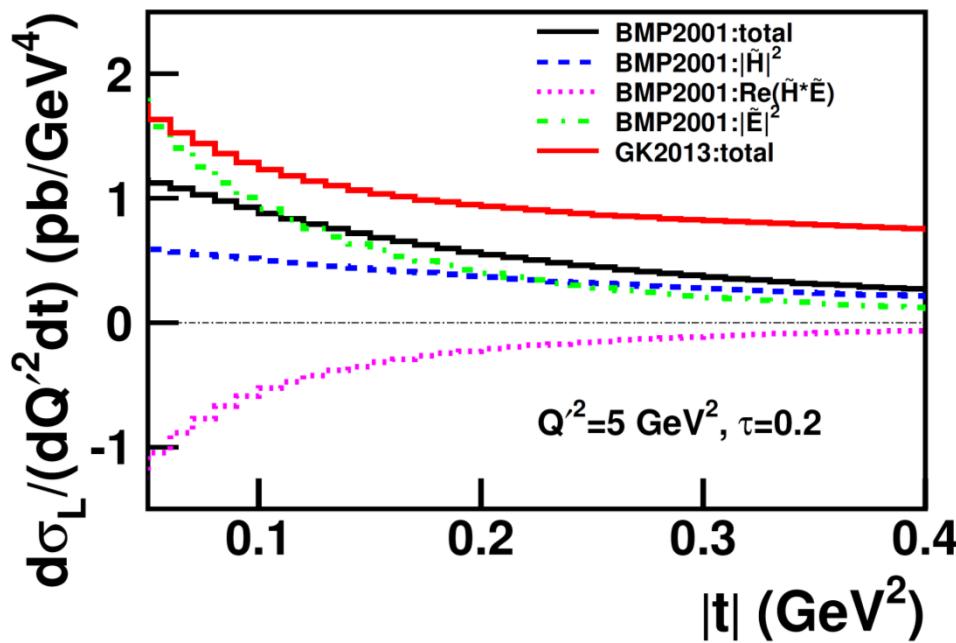
$$|t| = 0.2 \text{ GeV}^2$$

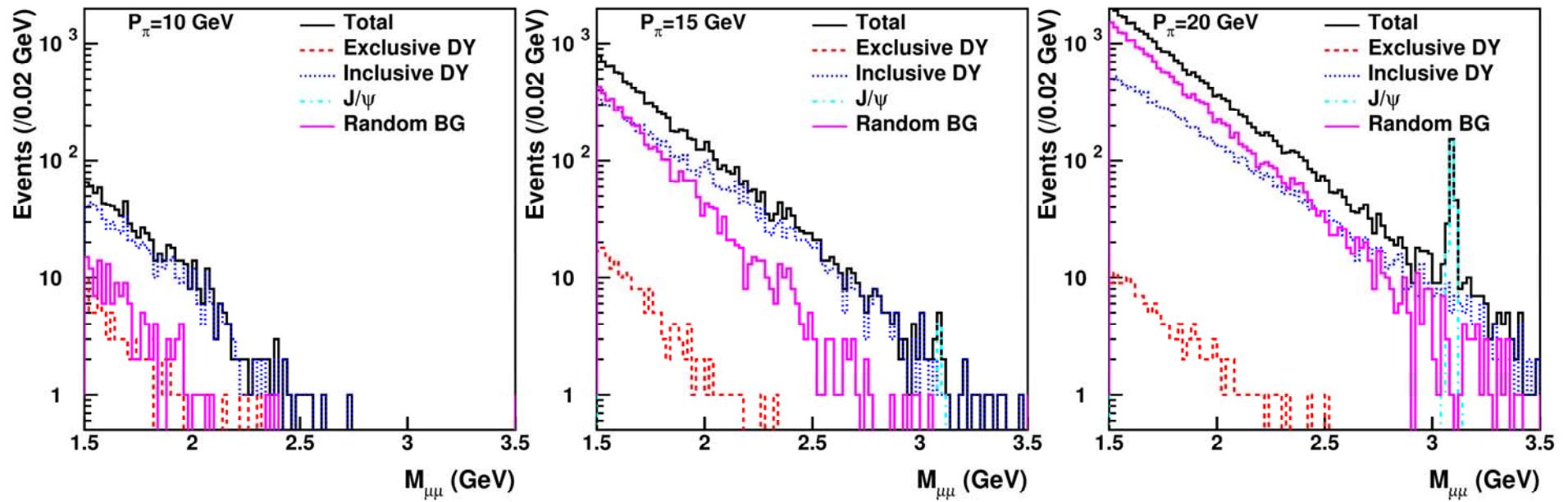


**(dashed)** =  $|\tilde{\mathcal{H}}|^2$  ; **(dash-dotted)** =  $\text{Re}(\tilde{\mathcal{H}}^* \tilde{\mathcal{E}})$  ; **(dotted)** =  $|\tilde{\mathcal{E}}|^2$

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

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





# feasibility with E50 spectrometer at J-PARC

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

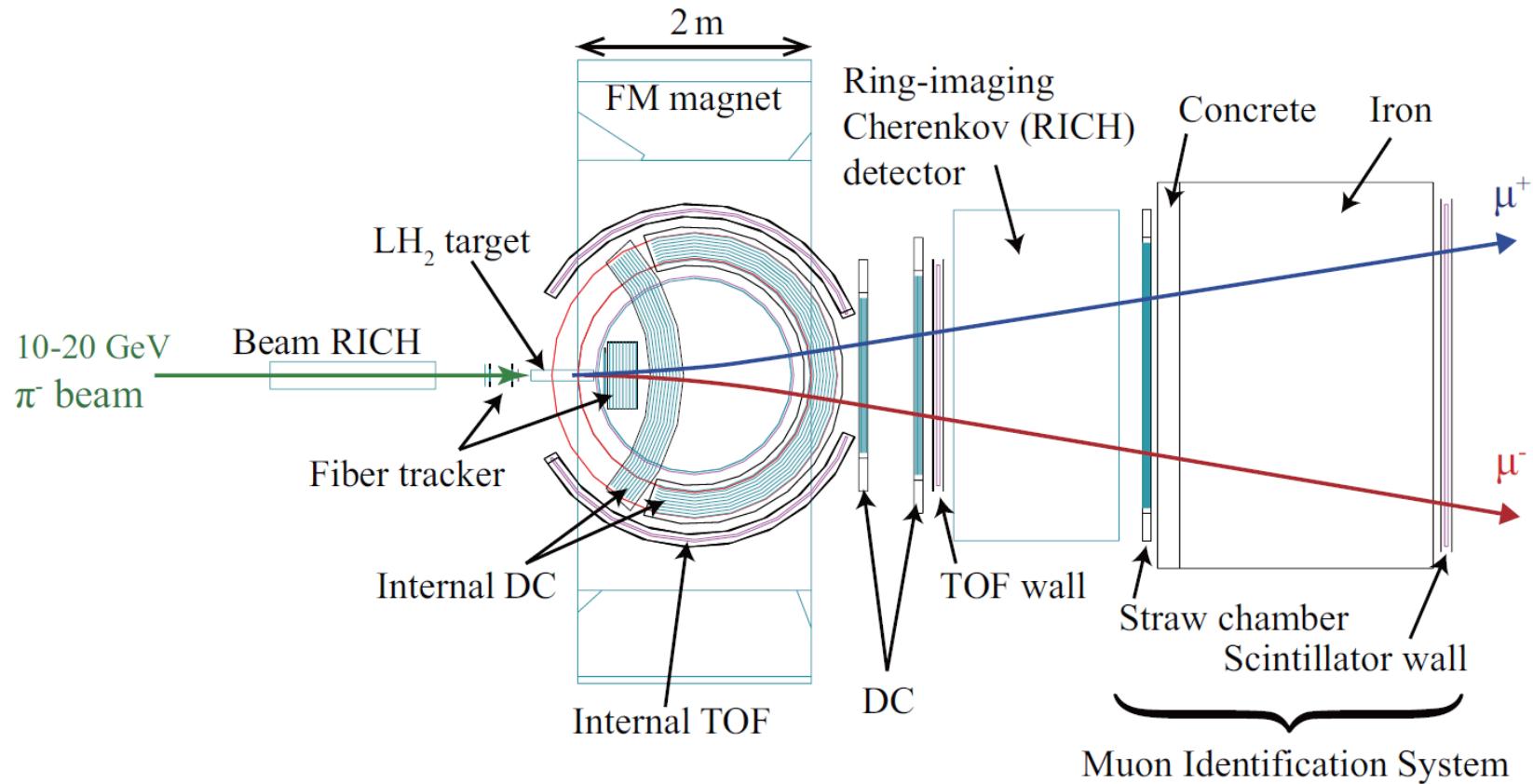
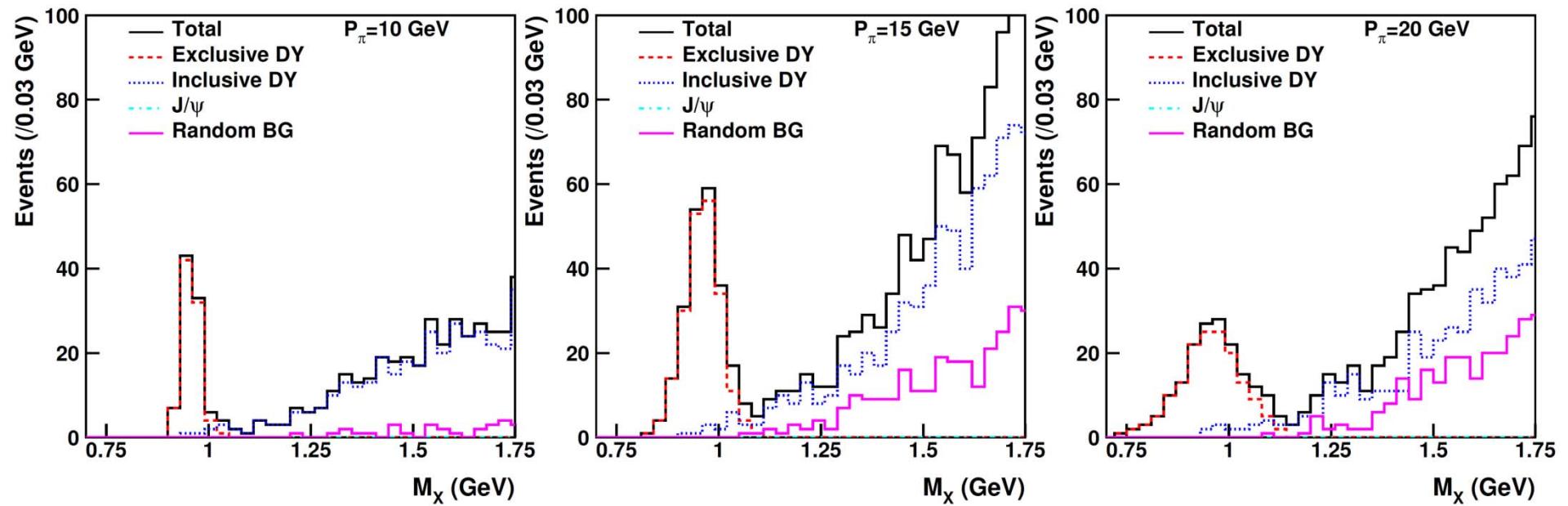


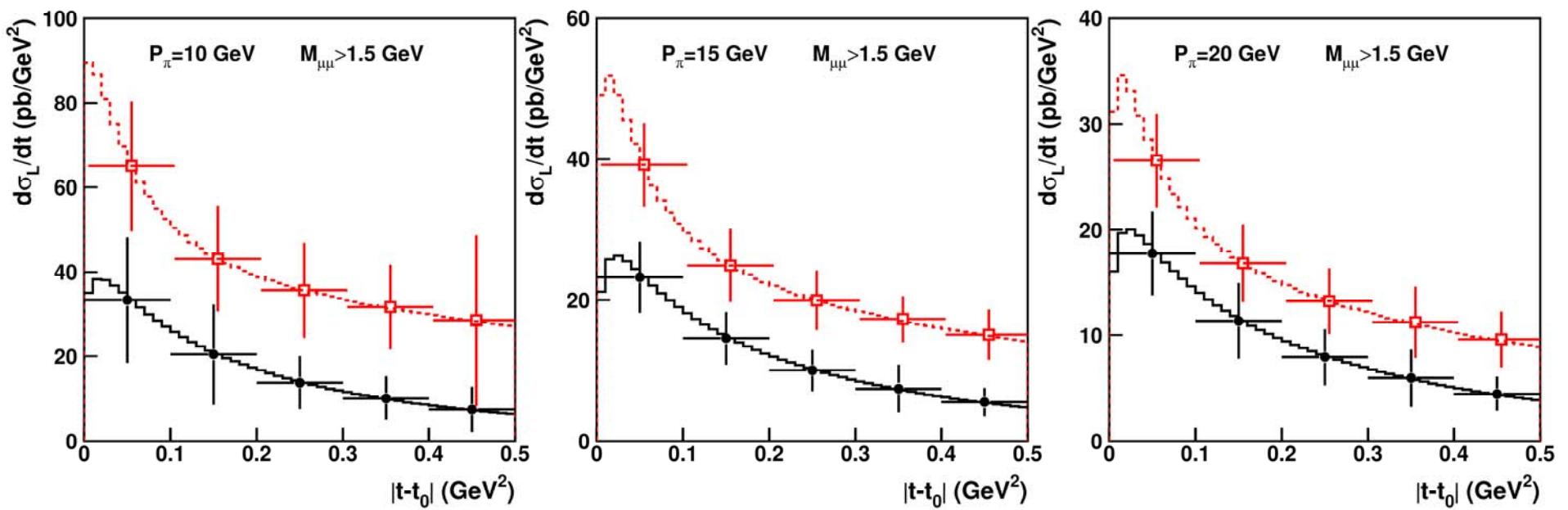
FIG. 9: Conceptual design of J-PARC E50 spectrometer with muon identification system.

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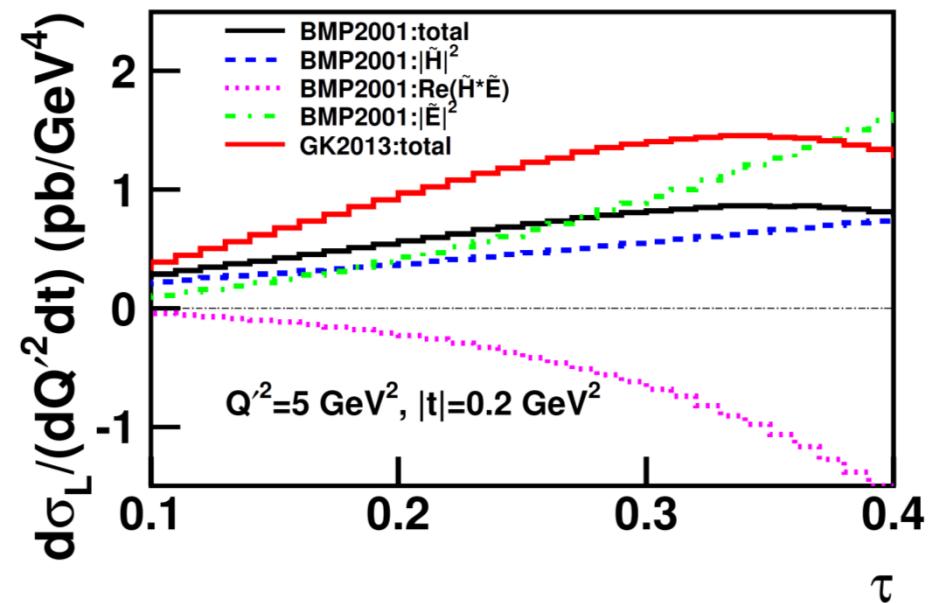
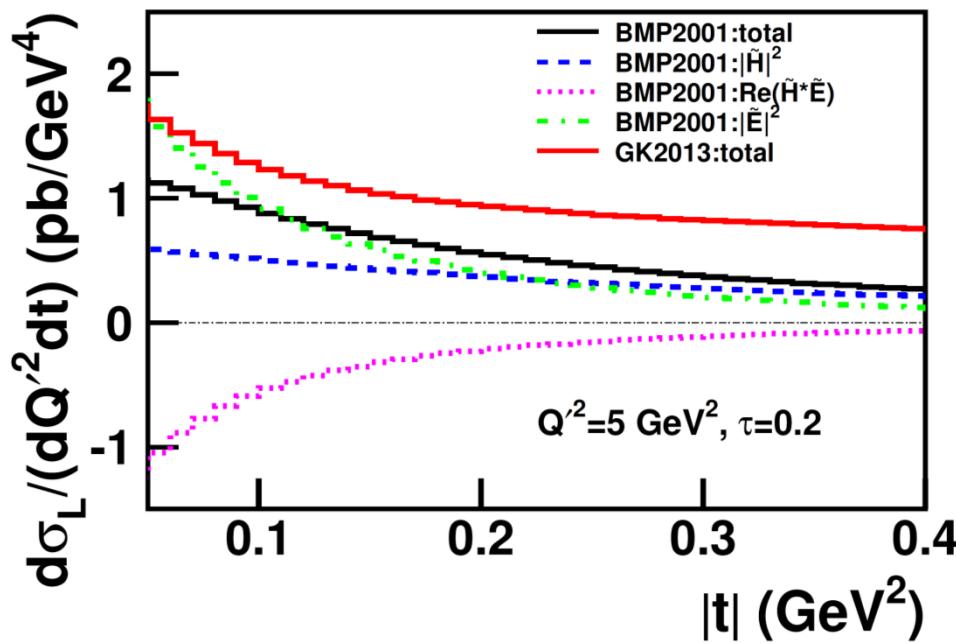
# feasibility with E50 spectrometer at J-PARC

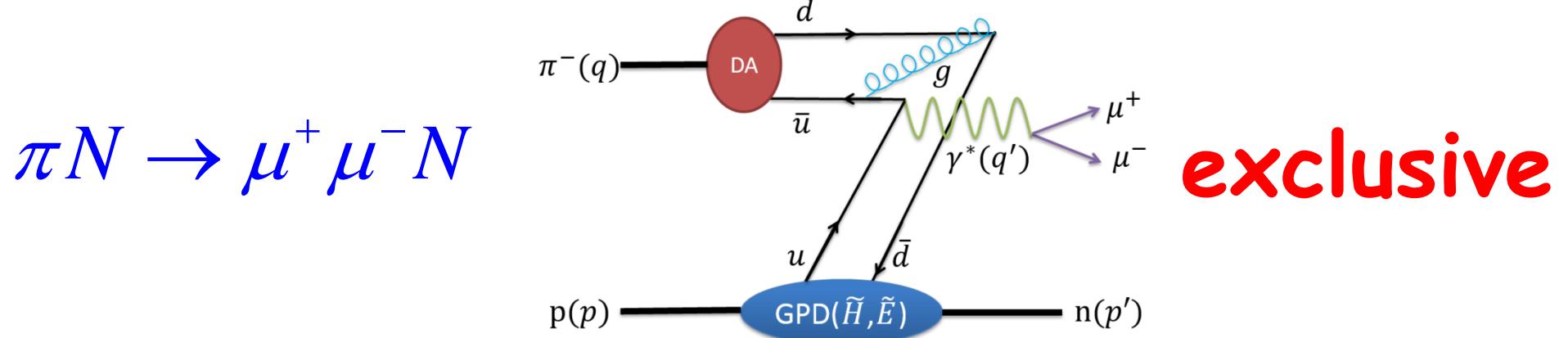
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# feasibility with E50 spectrometer at J-PARC

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## 1. Cross-section calculation with QCD factorization formula & feasibility study at J-PARC

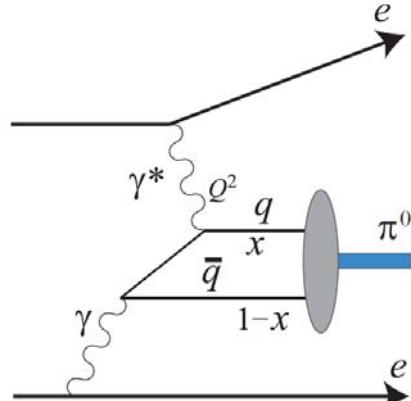
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 PRD93 (2016) 114034

## 2. Non-factorizable mechanism and light-cone QCD sum rule estimate

KT, in progress

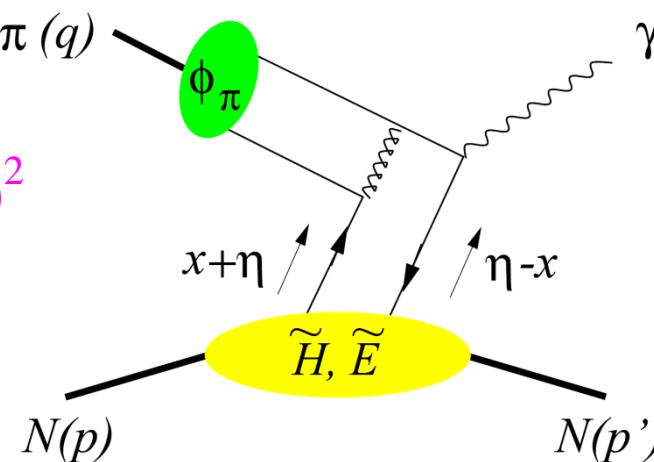
## Exclusive lepton pair production in $\pi N$ scattering

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



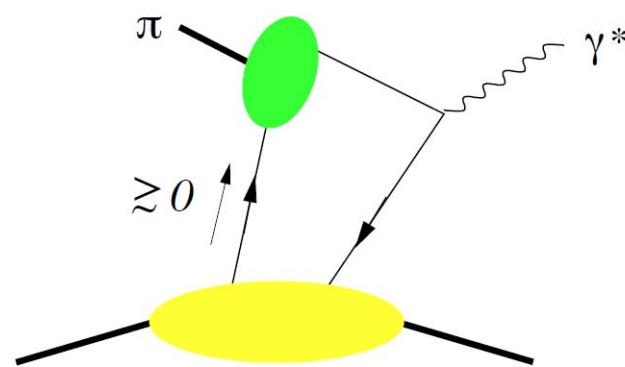
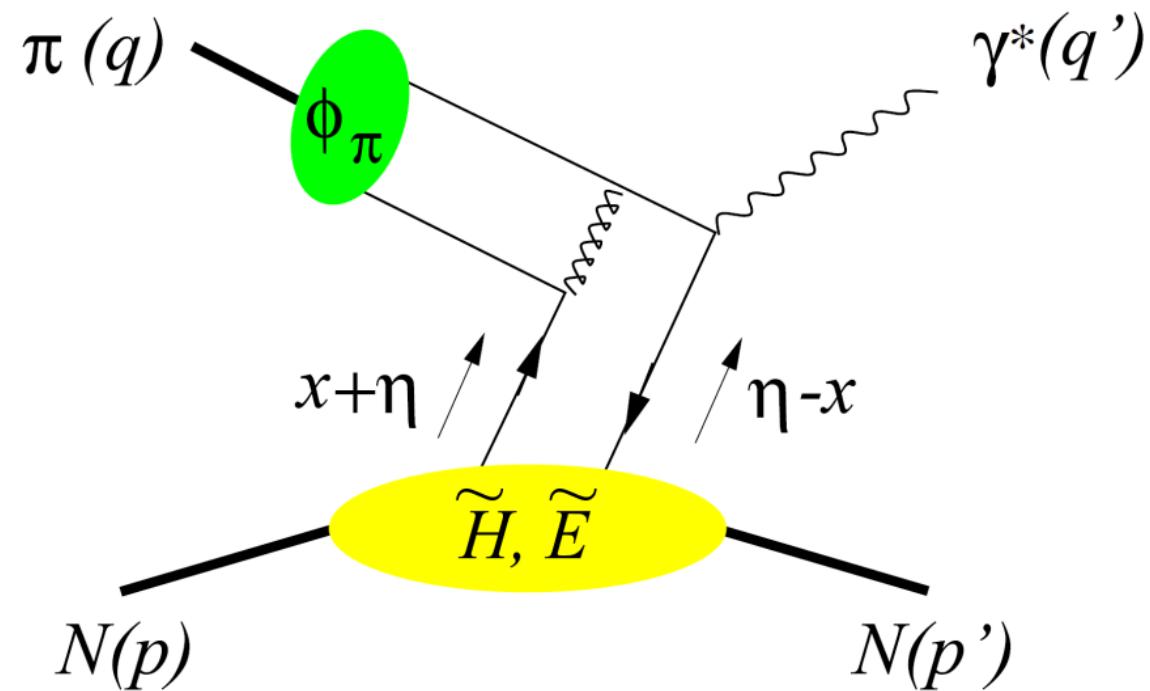
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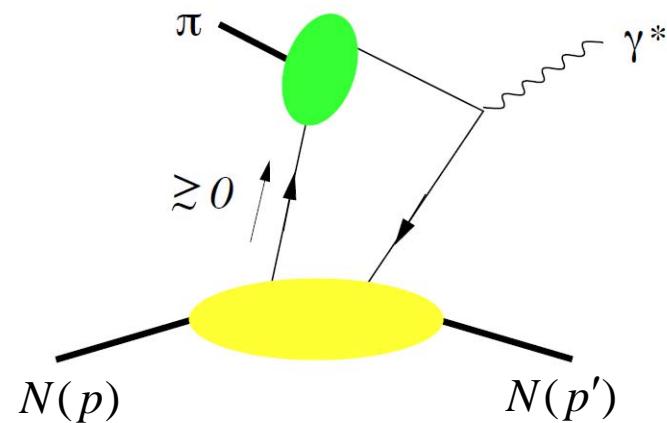
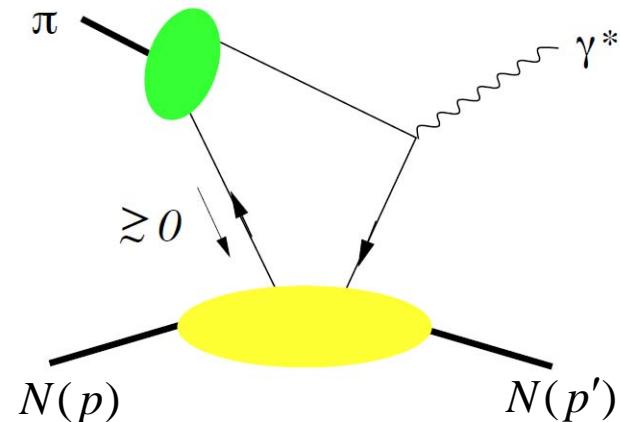
small  $t = \Delta^2 = (q - q')^2$



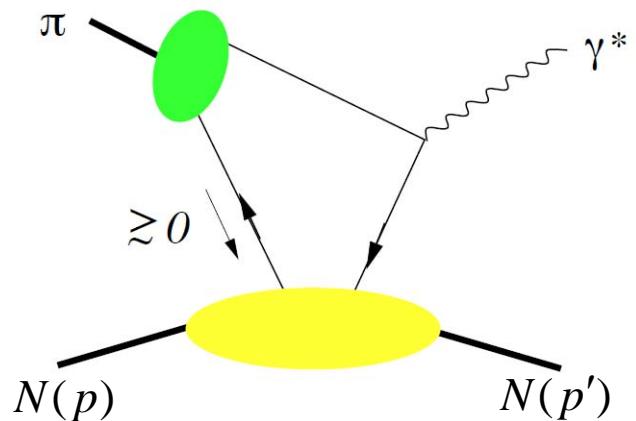
"exclusive DY"



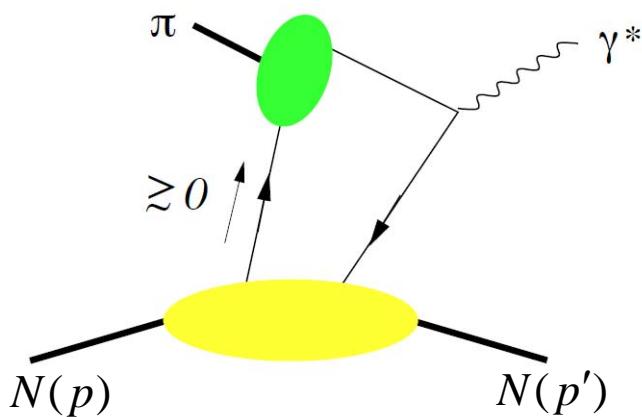




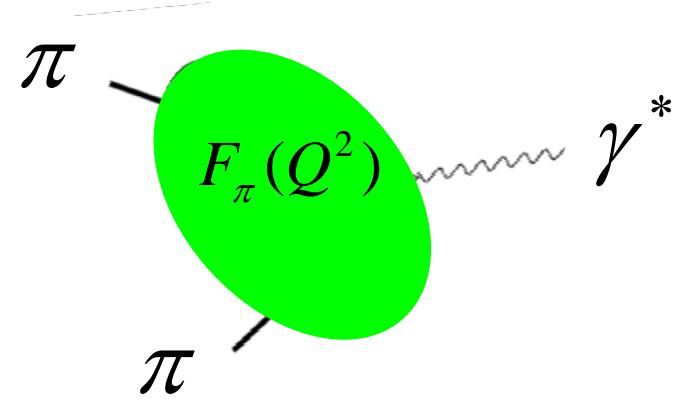
## “nonfactorizable” mechanism

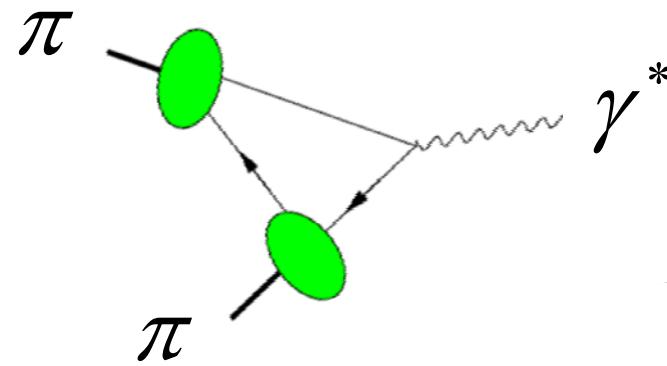
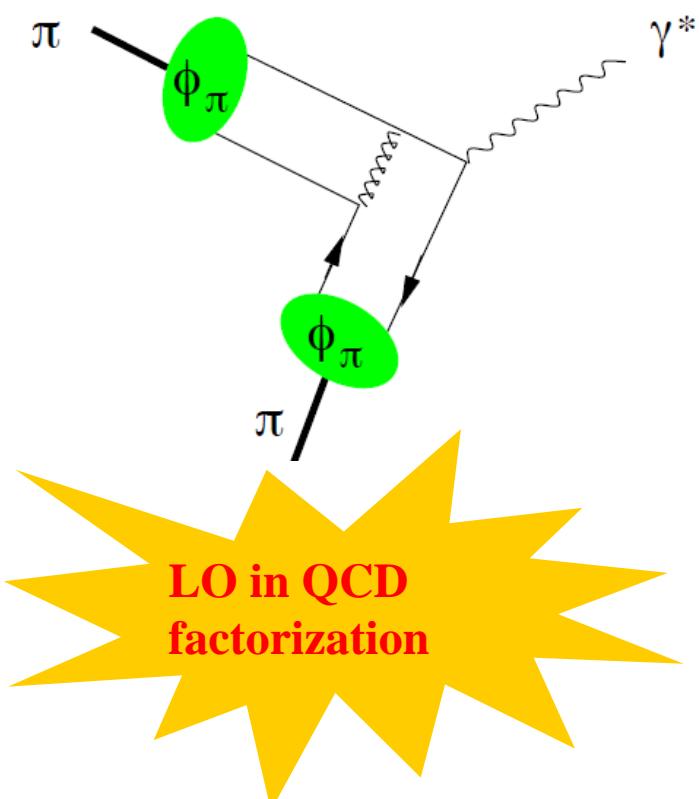
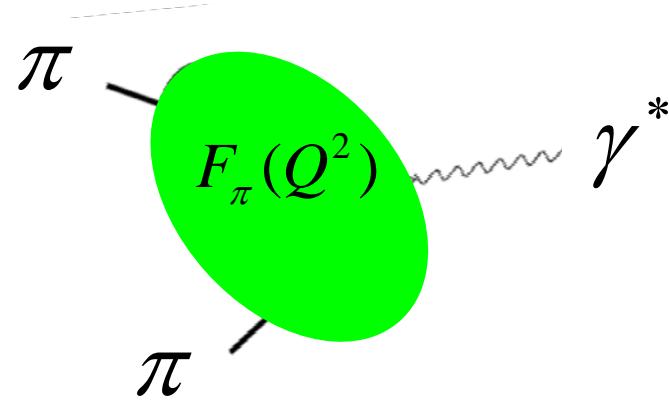


lower order in  $\alpha_s$



“Feynman mechanism”

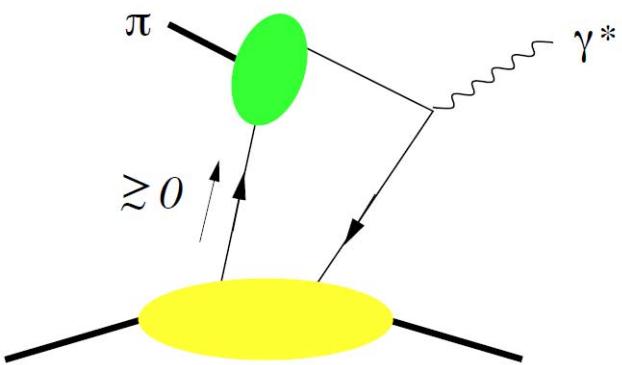
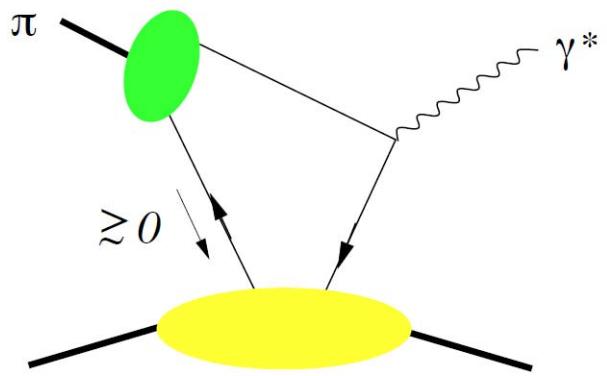




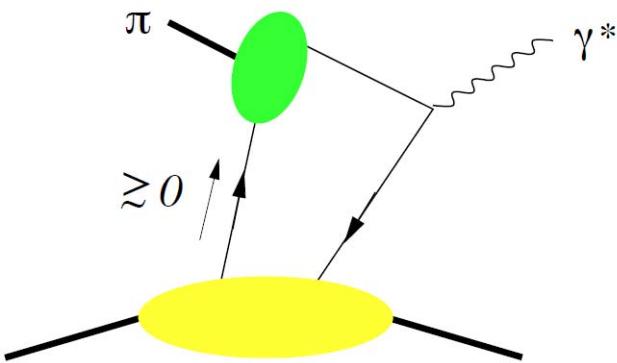
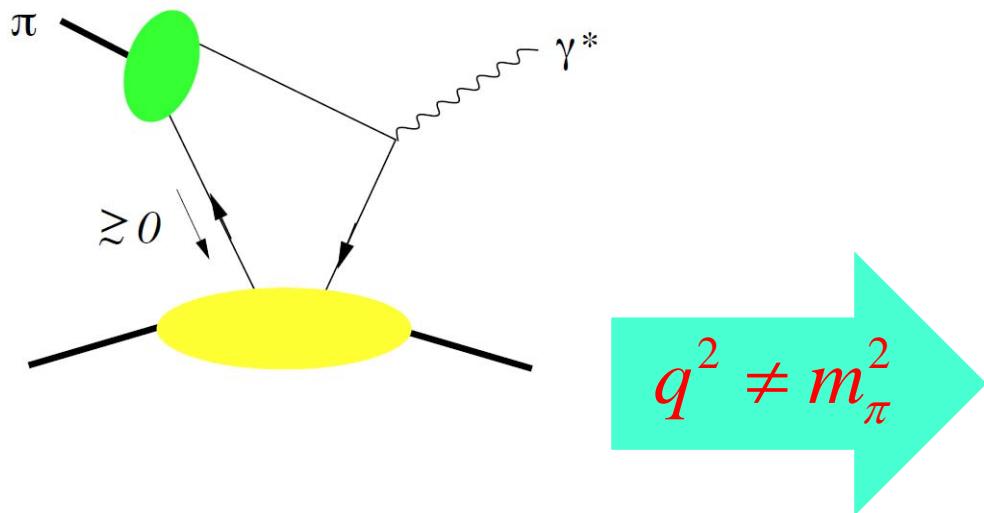
**“nonfactorizable”  
Feynman mechanism**

LO in QCD  
factorization

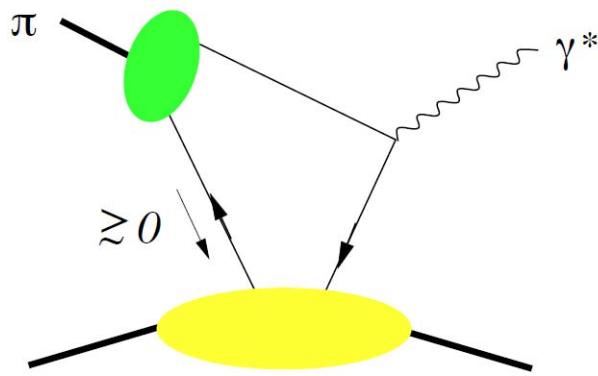
# “nonfactorizable” mechanism



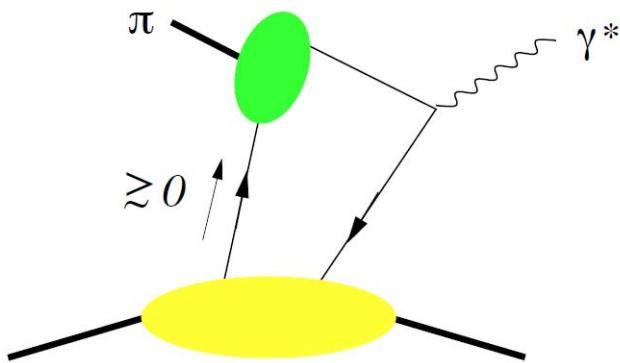
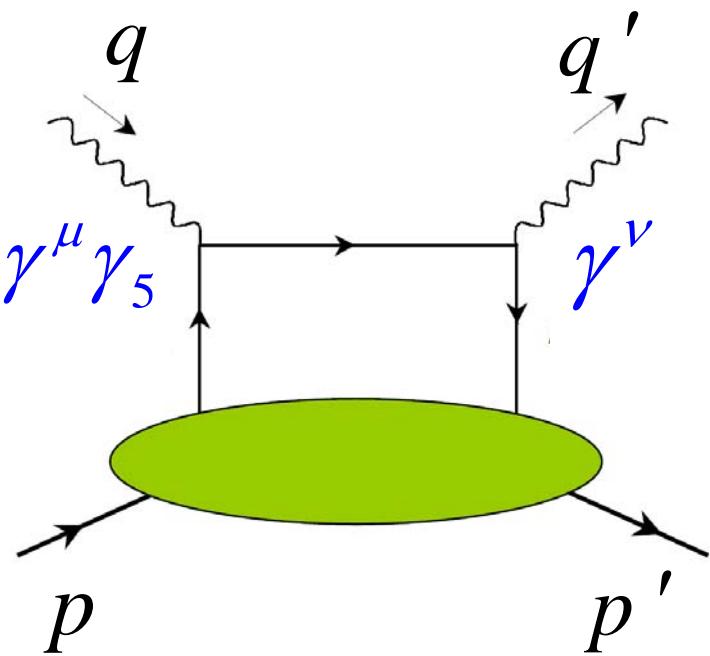
# “nonfactorizable” mechanism



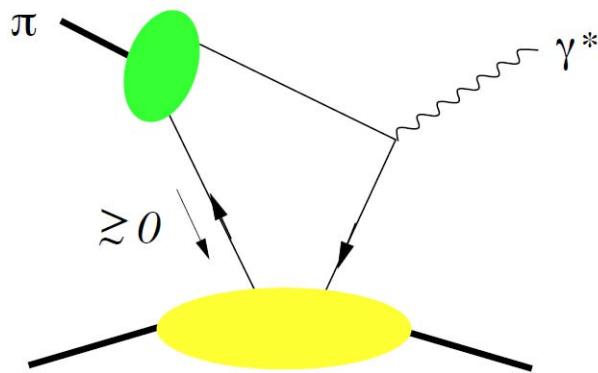
# “nonfactorizable” mechanism



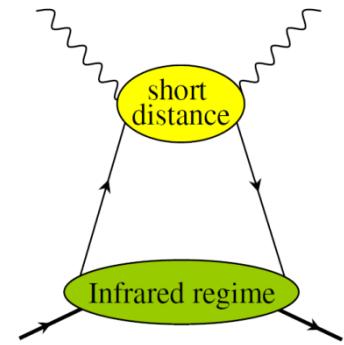
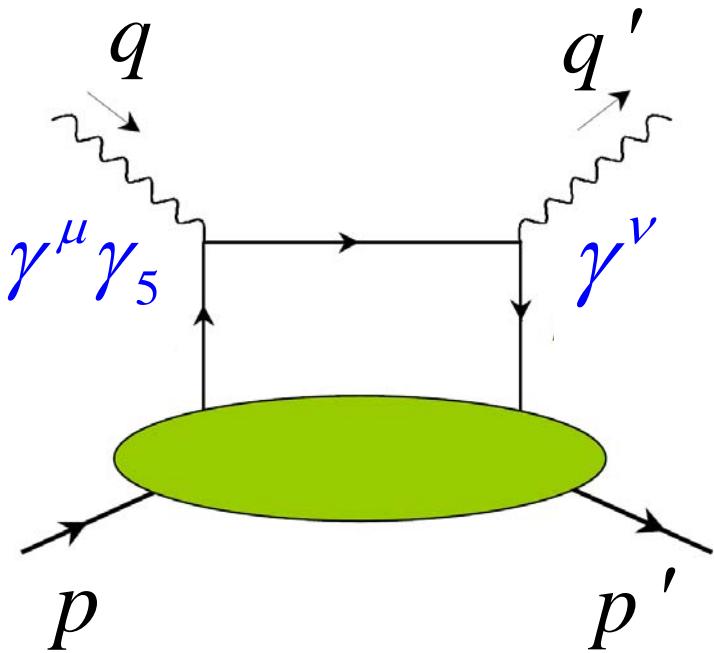
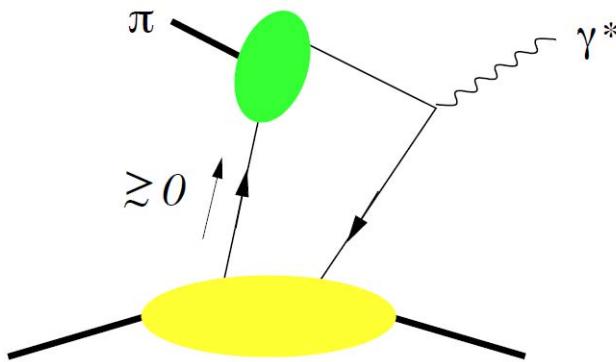
$q^2 \neq m_\pi^2$



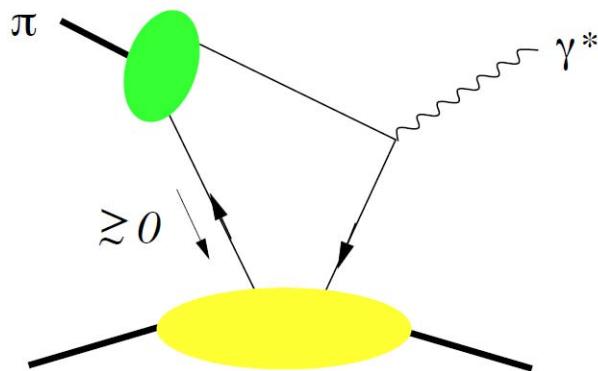
# “nonfactorizable” mechanism



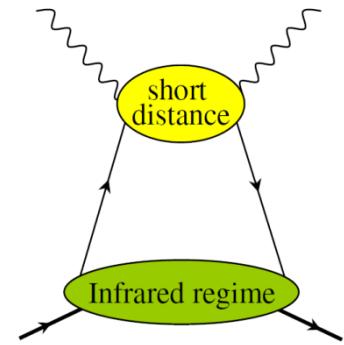
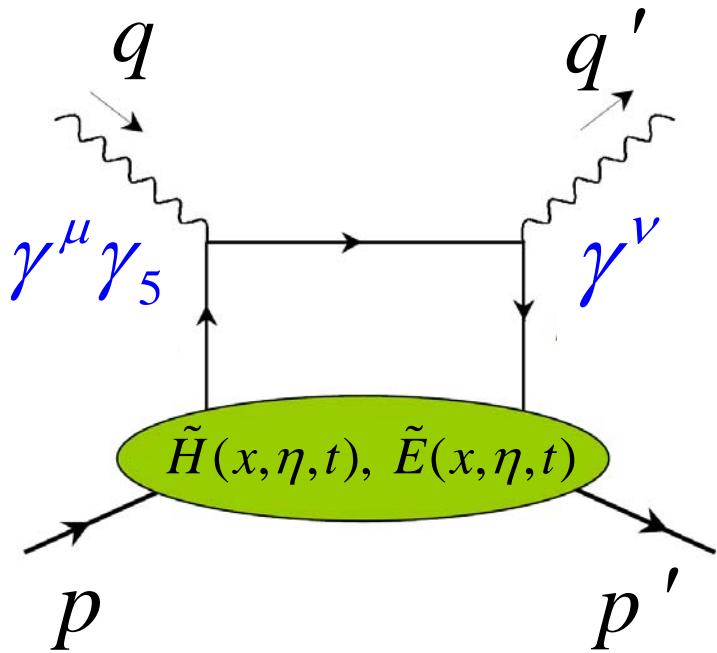
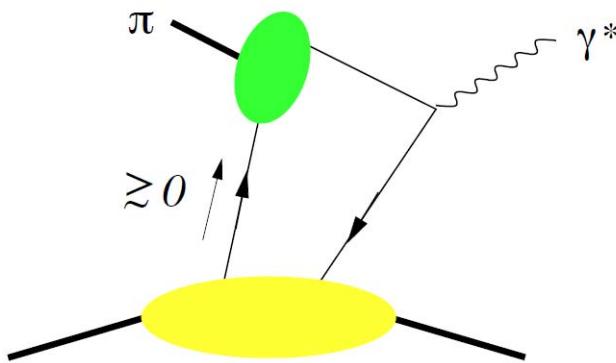
$q^2 \neq m_\pi^2$



# “nonfactorizable” mechanism



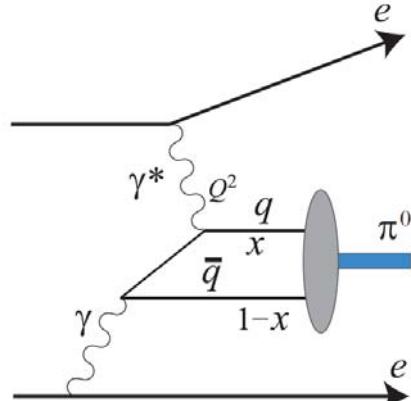
$q^2 \neq m_\pi^2$



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

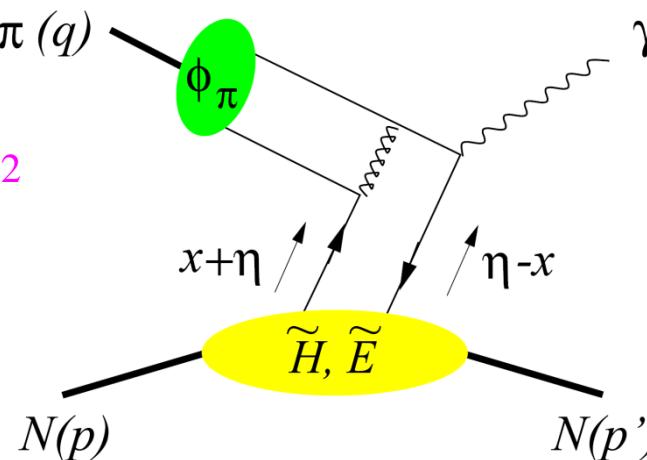
$$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$$

Berger, Diehl, Pire, PLB523(2001)265

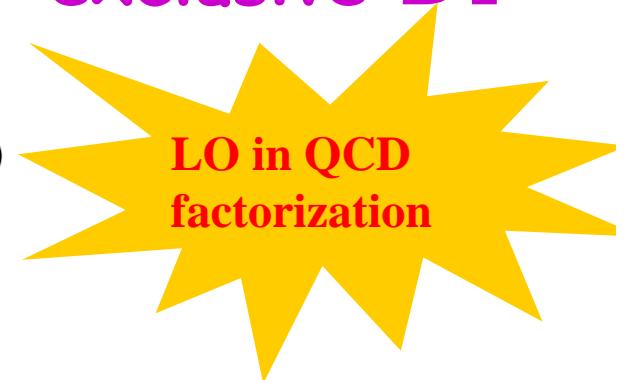


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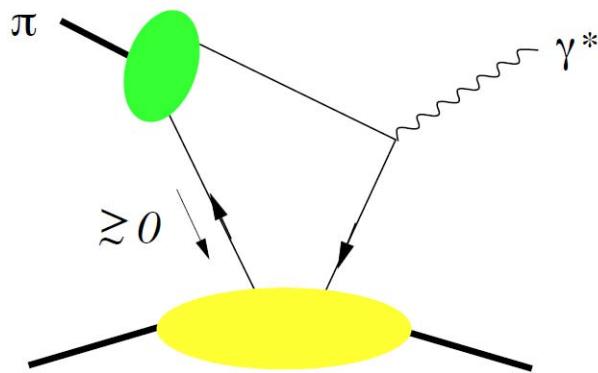
small  $t = \Delta^2 = (q - q')^2$



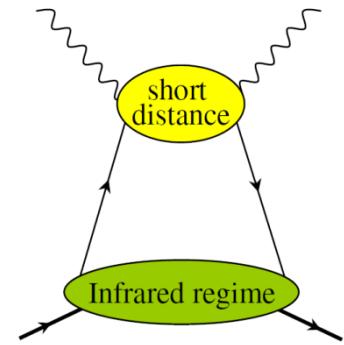
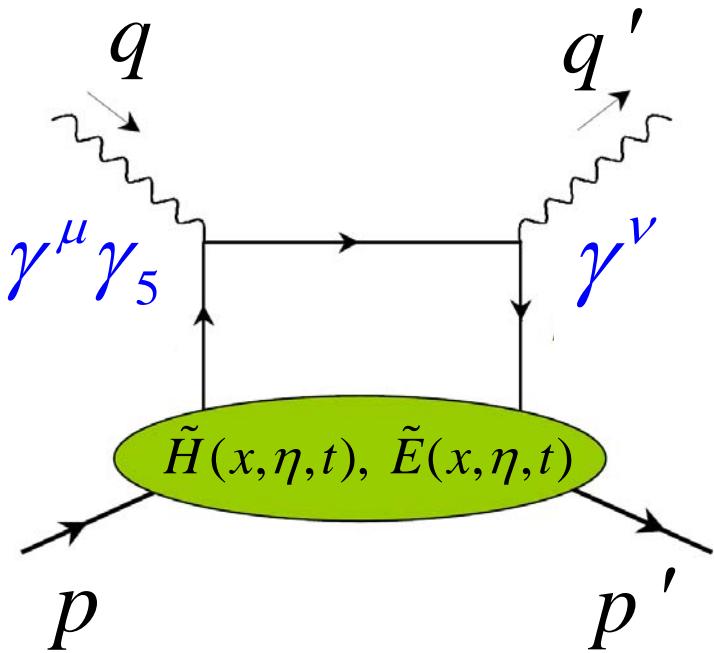
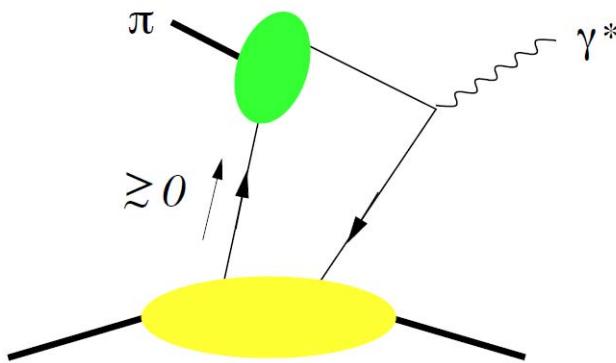
"exclusive DY"



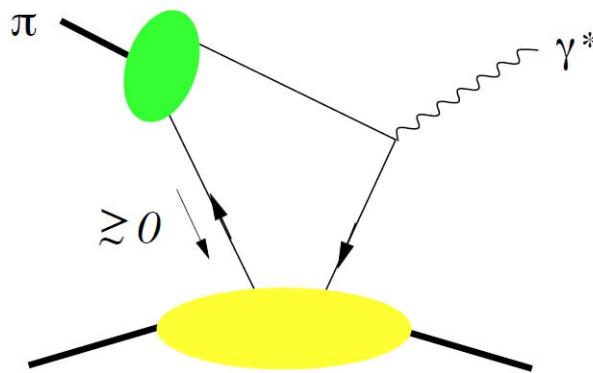
# “nonfactorizable” mechanism



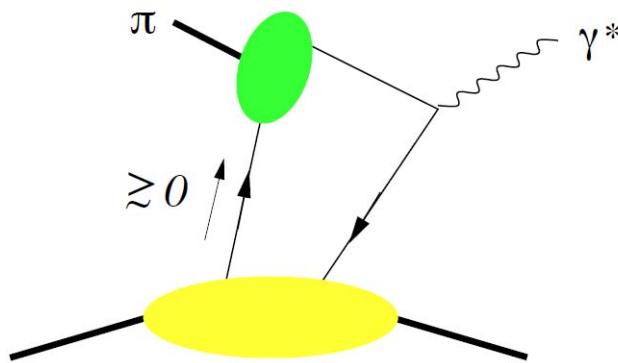
$q^2 \neq m_\pi^2$



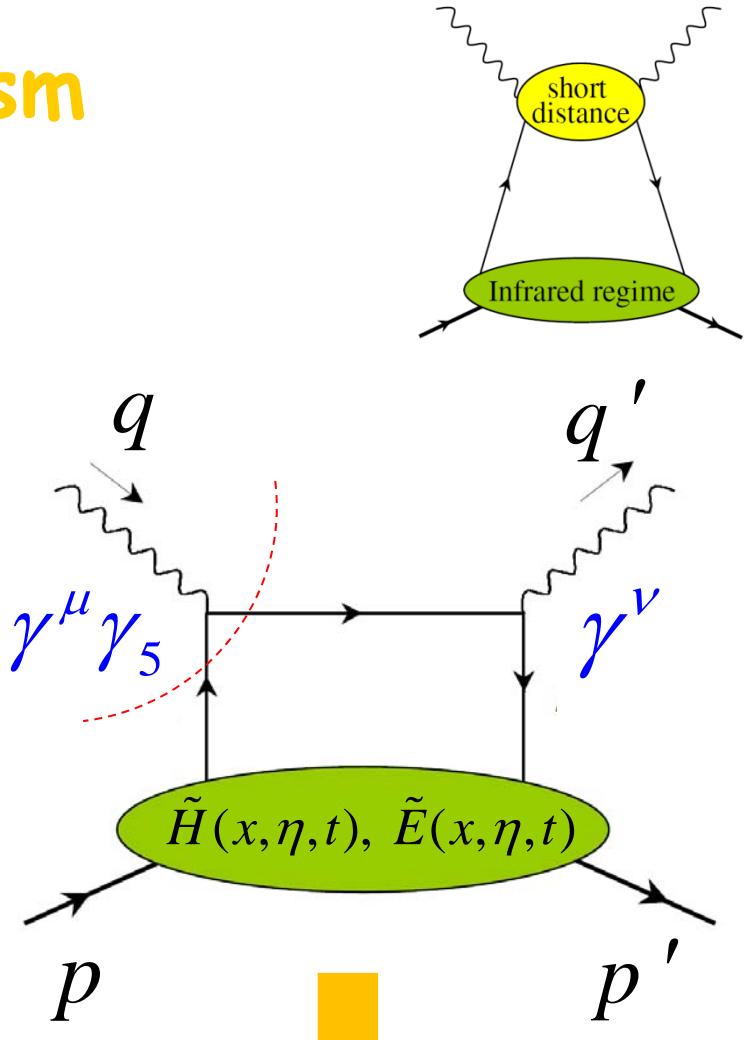
# “nonfactorizable” mechanism



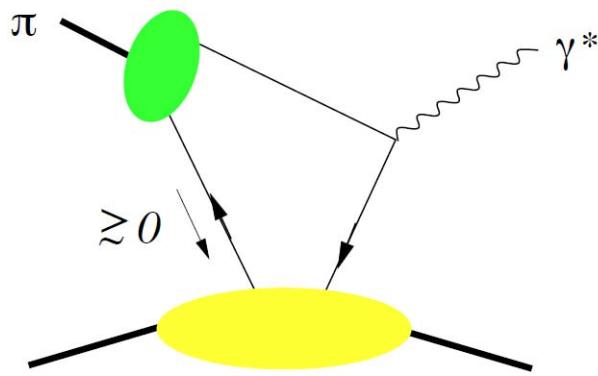
$q^2 \neq m_\pi^2$



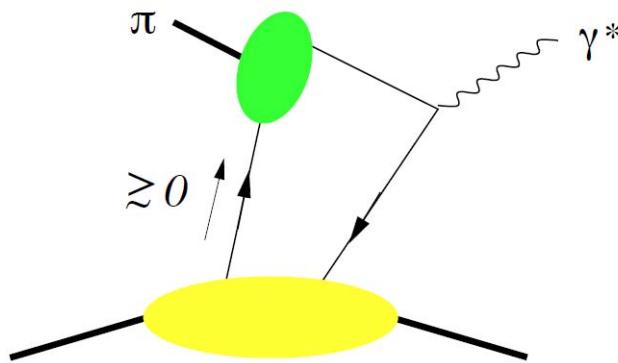
dispersion relation



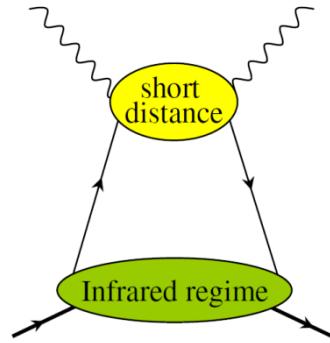
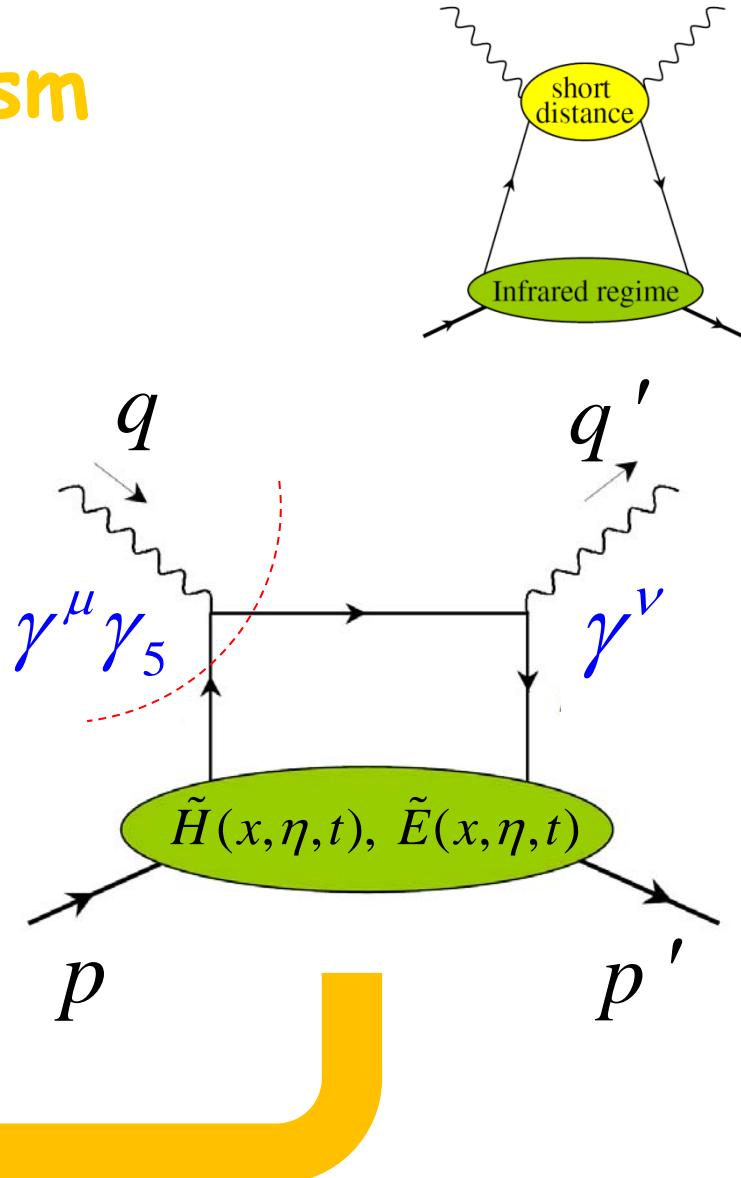
# “nonfactorizable” mechanism



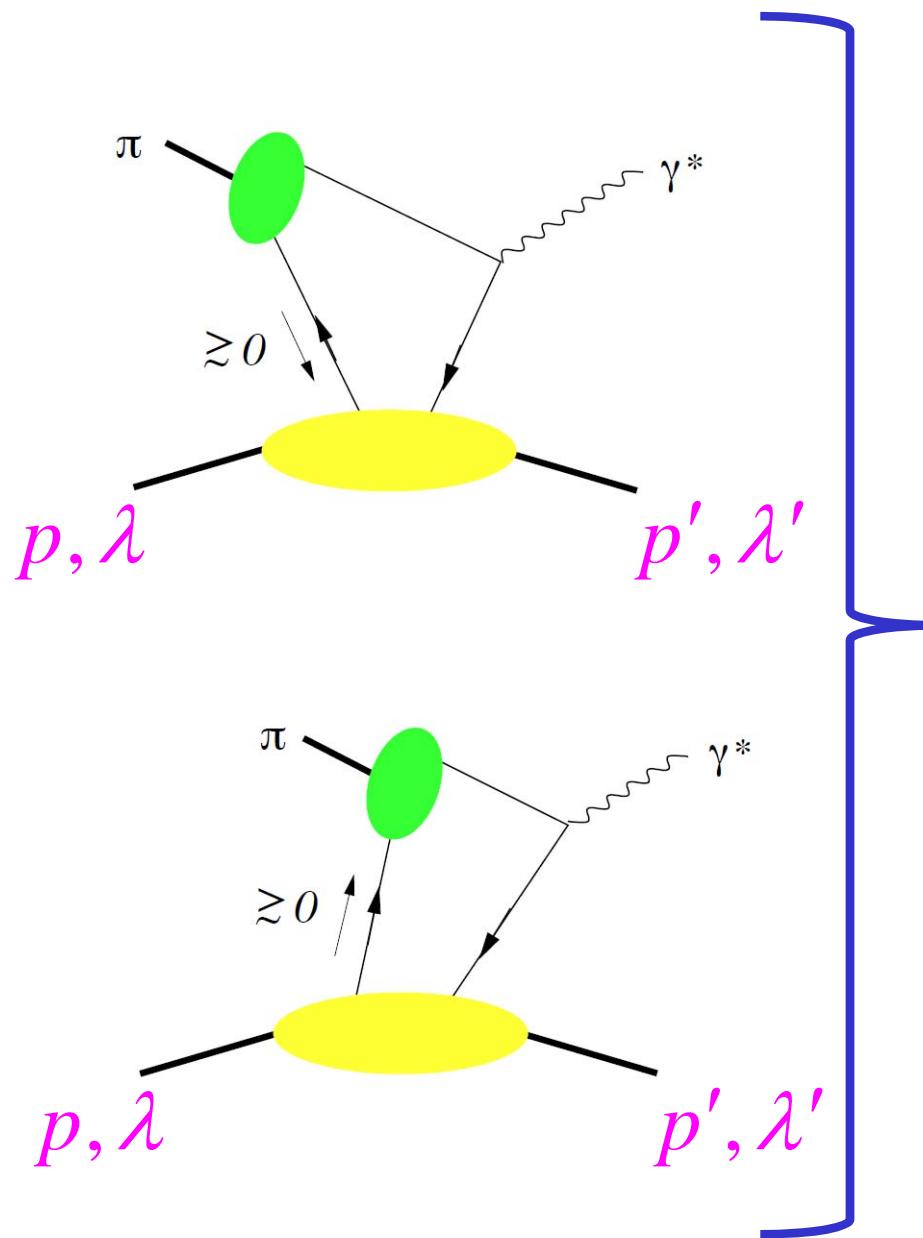
$q^2 \neq m_\pi^2$



dispersion relation  
quark-hadron duality



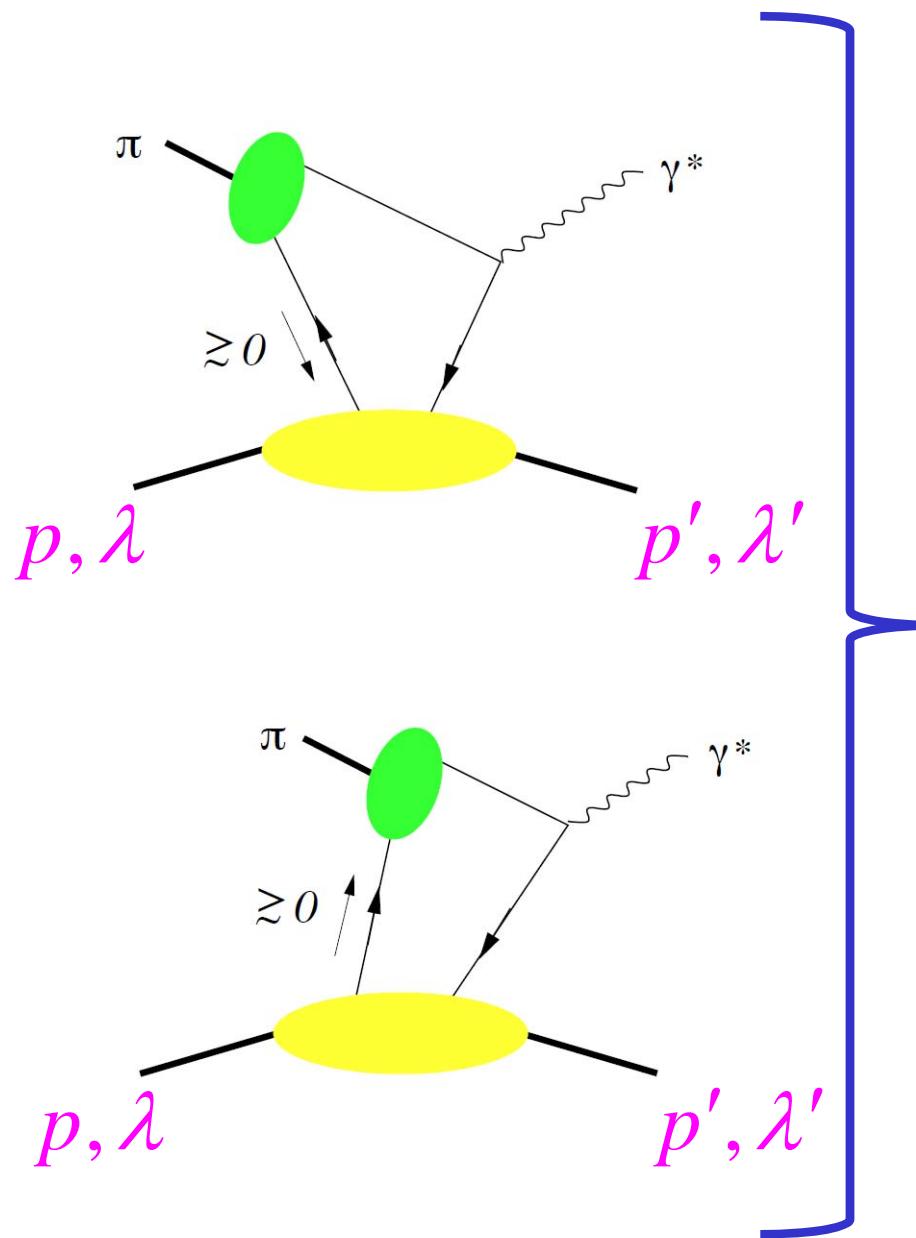
# “nonfactorizable” mechanism



$$\begin{aligned}
 &= g_\nu^{-1} \int_{\eta}^{x_0} dx \ e^{-\frac{x-\eta}{x+\eta} \frac{Q'^2}{M_B^2}} \tilde{C}_H(x, \eta, Q'^2) \\
 &\times \left[ e_u \tilde{H}^{du}(x, \eta, t) - e_d \tilde{H}^{du}(-x, \eta, t) \right] \\
 &\times \bar{u}(p' \lambda') \gamma^+ \gamma_5 u(p \lambda) + \dots
 \end{aligned}$$

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

## “nonfactorizable” mechanism

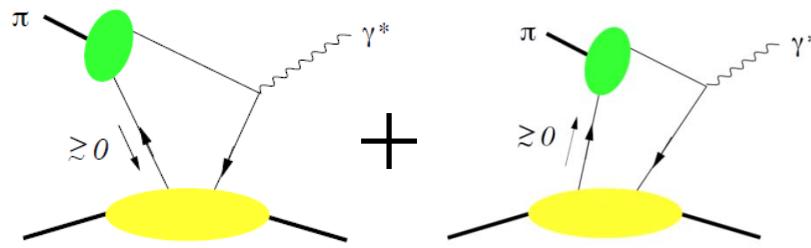


“Light-cone QCD SR (LCSR)”

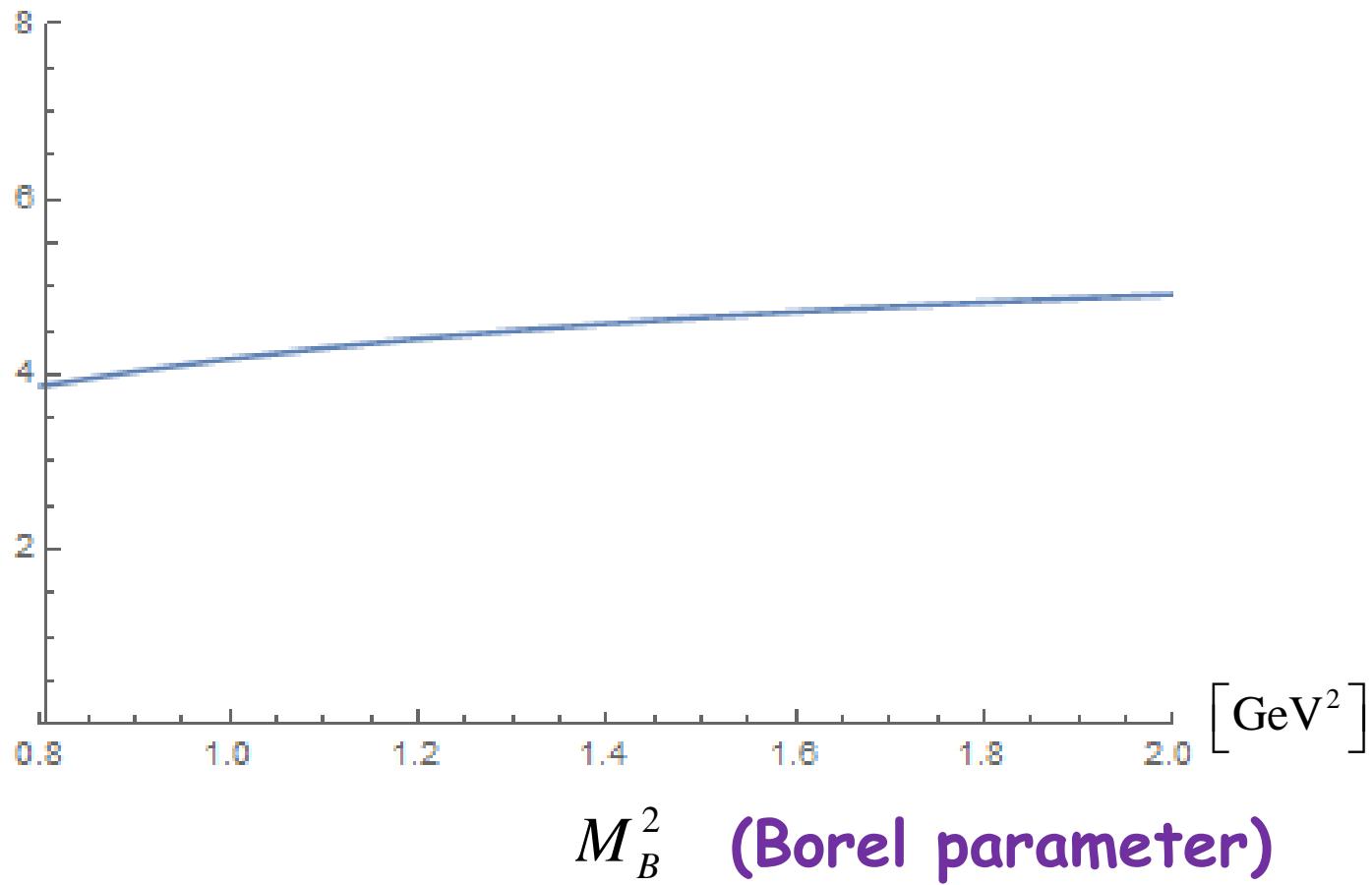
$$\begin{aligned}
 &= g_\nu^- \int_{\eta}^{x_0} dx e^{-\frac{x-\eta}{x+\eta} \frac{Q'^2}{M_B^2}} \tilde{C}_H(x, \eta, Q'^2) \\
 &\times \left[ e_u \tilde{H}^{du}(x, \eta, t) - e_d \tilde{H}^{du}(-x, \eta, t) \right] \\
 &\times \bar{u}(p' \lambda') \gamma^+ \gamma_5 u(p \lambda) + \dots
 \end{aligned}$$

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

KT



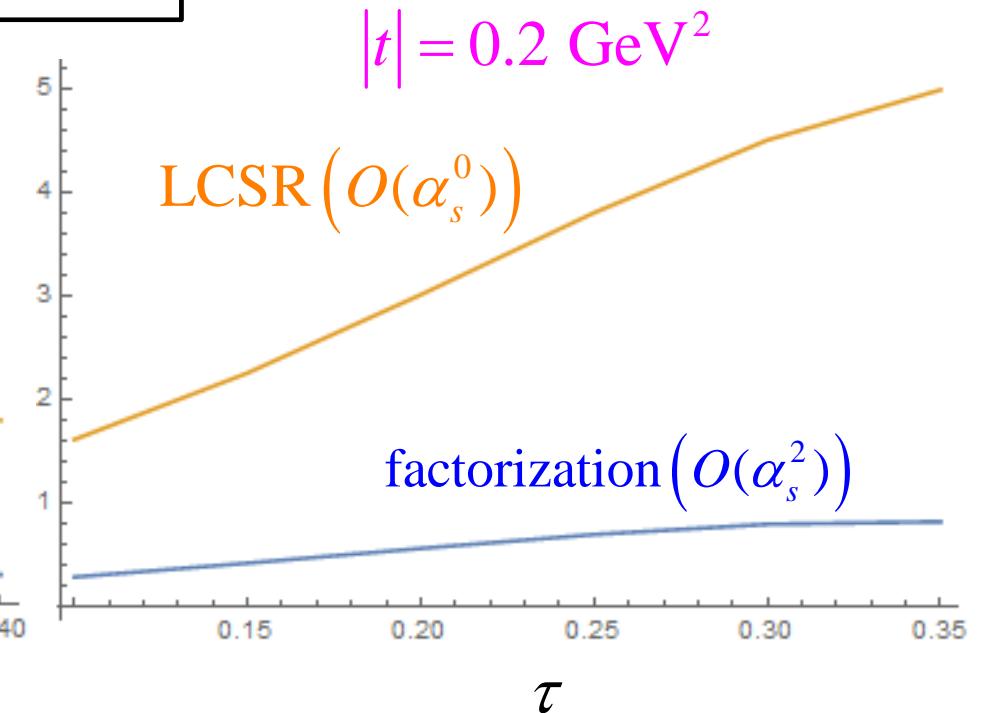
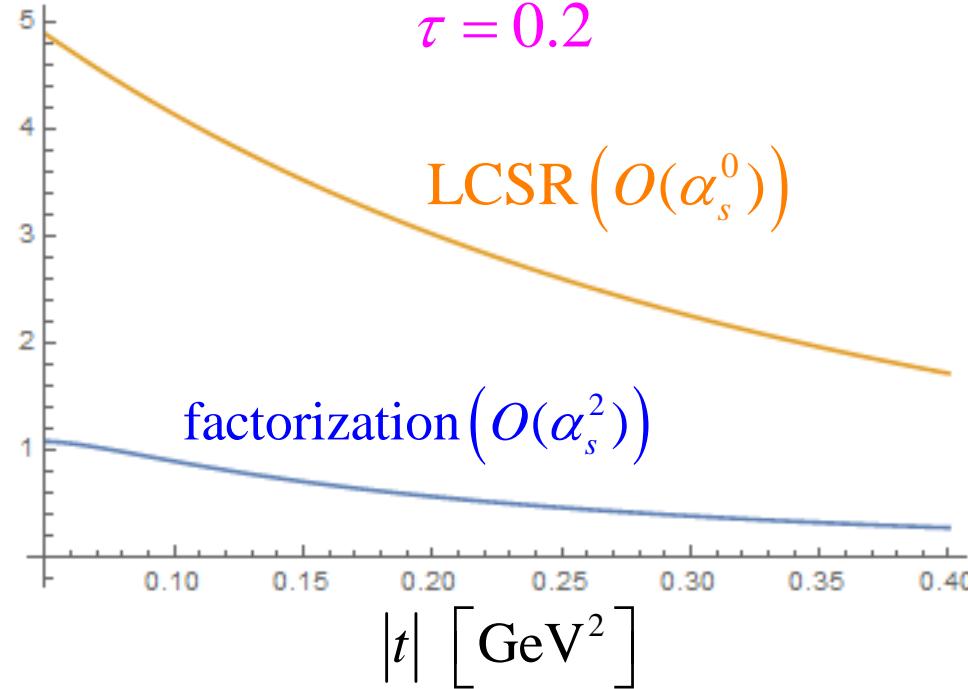
from LCSR



$$\frac{d\sigma}{dQ'^2 dt} \left[ \text{pb}/\text{GeV}^4 \right]$$

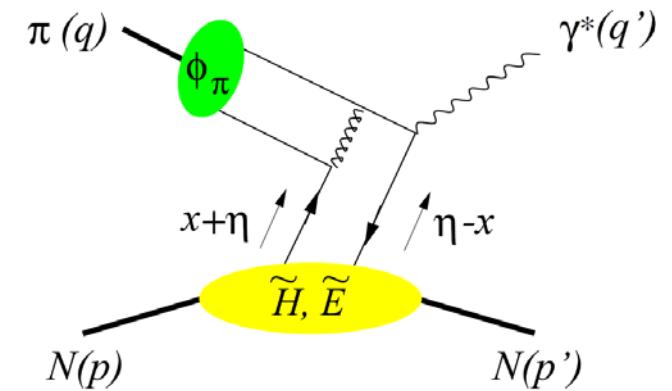
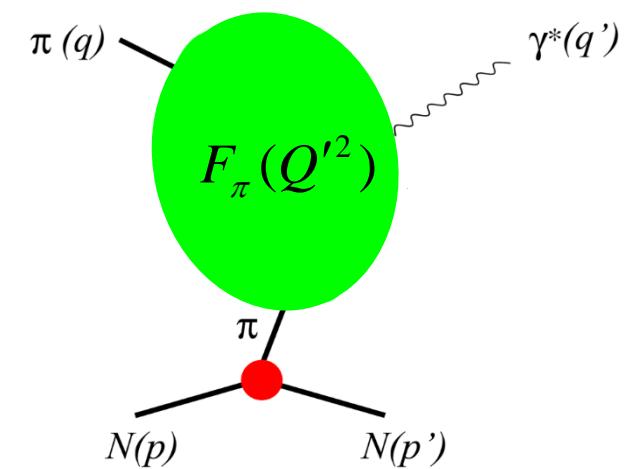
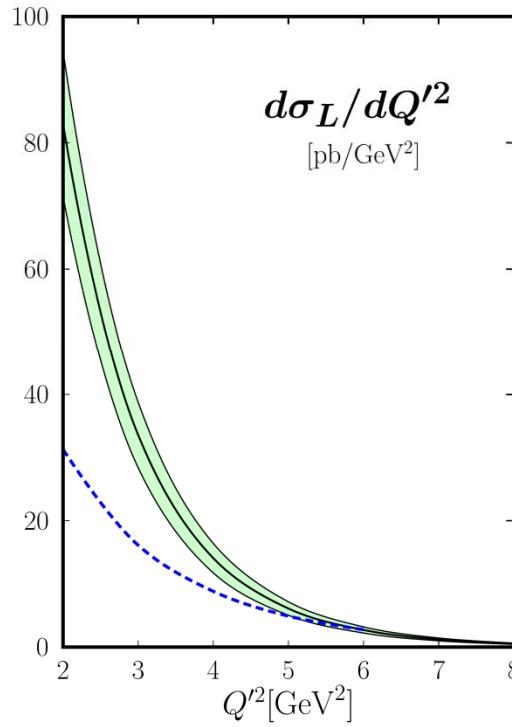
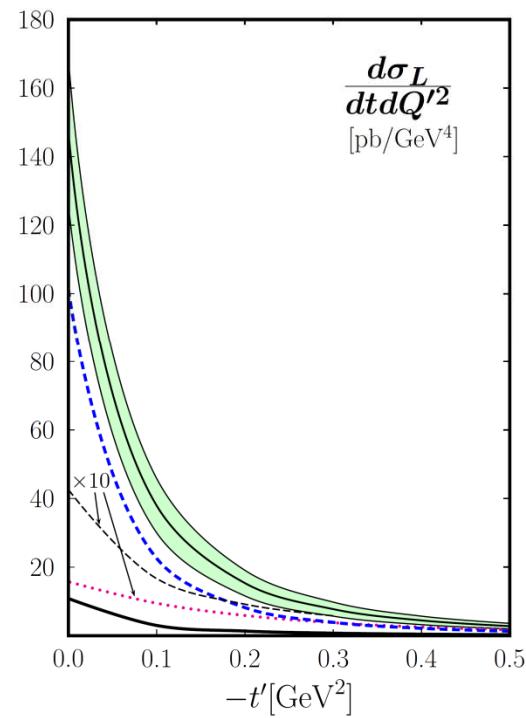
$$\tau = 0.2$$

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

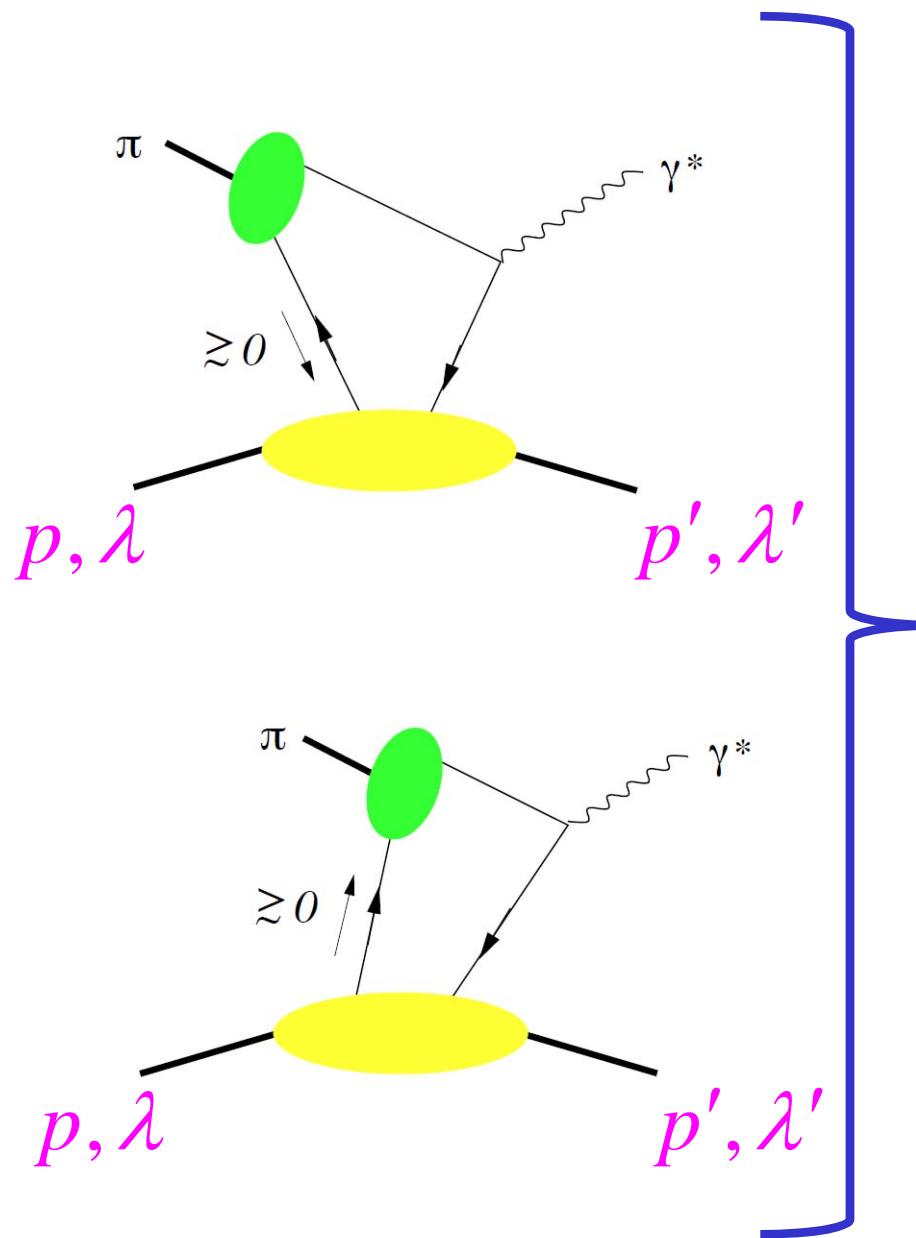


$$\frac{d\sigma}{dQ'^2 dt} (\pi^- p \rightarrow \gamma^* n)$$

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



## “nonfactorizable” mechanism



“Light-cone QCD SR (LCSR)”

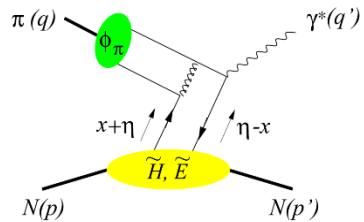
$$\begin{aligned}
 &= g_\nu^- \int_{\eta}^{x_0} dx e^{-\frac{x-\eta}{x+\eta} \frac{Q'^2}{M_B^2}} \tilde{C}_H(x, \eta, Q'^2) \\
 &\times \left[ e_u \tilde{H}^{du}(x, \eta, t) - e_d \tilde{H}^{du}(-x, \eta, t) \right] \\
 &\times \bar{u}(p' \lambda') \gamma^+ \gamma_5 u(p \lambda) + \dots
 \end{aligned}$$

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

# Summary

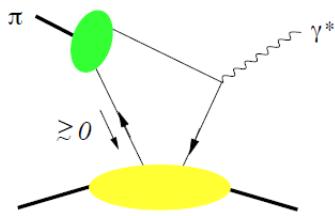
exDY (  $\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$  ) @J-PARC

GPDs

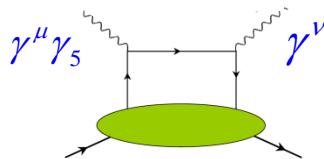


estimate with QCD factorization & feasibility study

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PRD93, 114034



LCSR



$\tilde{H}, \tilde{E}, q^2_{\text{th}} (\sim 0.7 \text{ GeV}^2)$

SNM > QCD factorization

$\alpha_s^0$

$\alpha_s^2$

*interplay of soft/hard QCD mechanism*



TABLE II: Expected cross sections for the exclusive and inclusive Drell-Yan processes.

	Exclusive Drell-Yan $\begin{pmatrix} M_{\mu^+\mu^-} > 1.5 \text{ GeV}, \\  t - t_0  < 0.5 \text{ GeV}^2 \end{pmatrix}$		Inclusive Drell-Yan $(M_{\mu^+\mu^-} > 1.5 \text{ GeV})$
	BMP2001	GK2013	
$P_\pi = 10 \text{ GeV}$	6.29 pb	17.53 pb	2.11 nb
$P_\pi = 15 \text{ GeV}$	4.67 pb	10.65 pb	2.71 nb
$P_\pi = 20 \text{ GeV}$	3.70 pb	7.25 pb	3.08 nb

**feasibility with E50 spectrometer at J-PARC**

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 PRD93, 114034