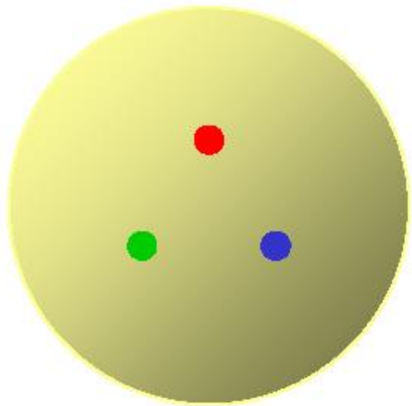
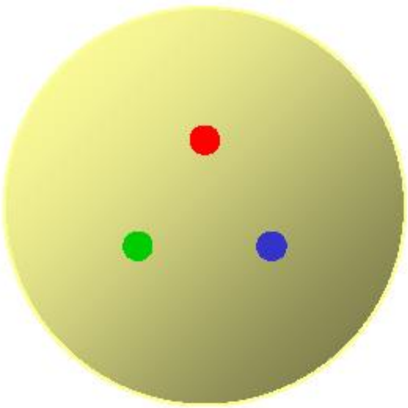
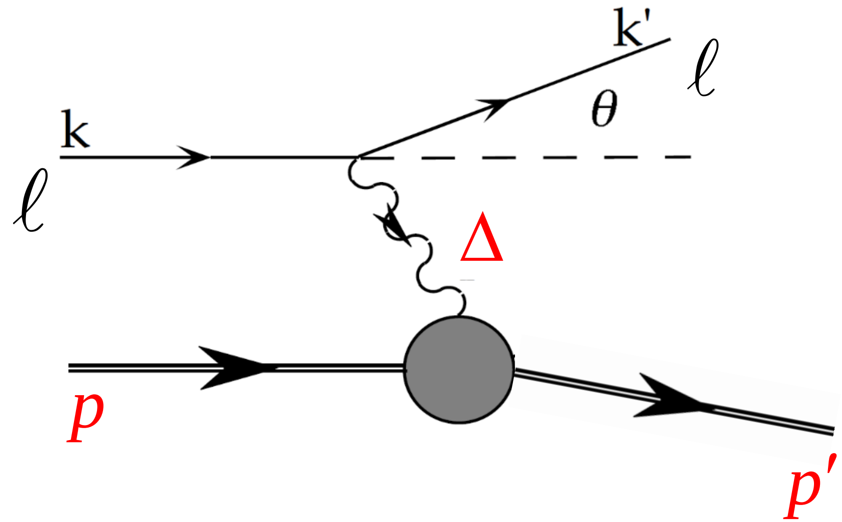
High-energy hadron physics through Drell-Yan-like dilepton productions at J-PARC

Kazuhiro Tanaka (Juntendo U/KEK)



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

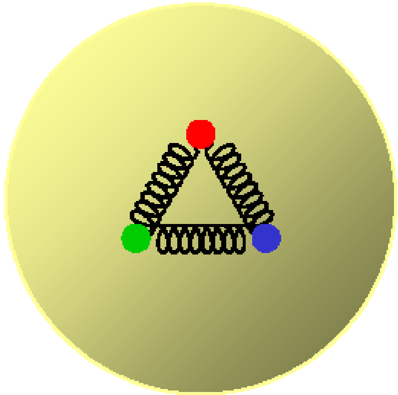




$$\left\langle N(p')\middle|\psi^{\dagger}(0)\psi(0)\middle|N(p)\right\rangle$$

$$\langle N(p')|\bar{\psi}(0)\gamma^{\mu}\psi(0)|N(p)\rangle \sim \bar{u}(p')\left\{\gamma^{\mu}F_1(\Delta^2)+\frac{i\sigma^{\nu\mu}\Delta_{\nu}}{2M_N}F_2(\Delta^2)\right\}u(p)$$

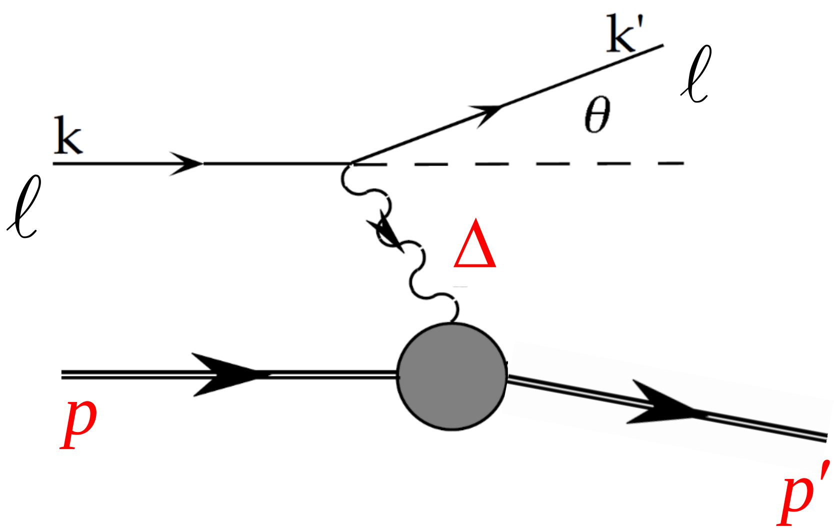
$$\Delta = p' - p$$

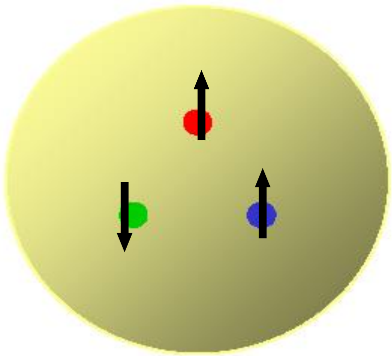


$$\langle N(p')|\psi^\dagger(0)\psi(0)|N(p)\rangle$$

$$\langle N(p')|\bar{\psi}(0)\gamma^\mu\psi(0)|N(p)\rangle \sim \bar{u}(p')\left\{\gamma^\mu F_1(\Delta^2) + \frac{i\sigma^{\nu\mu}\Delta_\nu}{2M_N}F_2(\Delta^2)\right\}u(p)$$

$$\Delta = p' - p$$

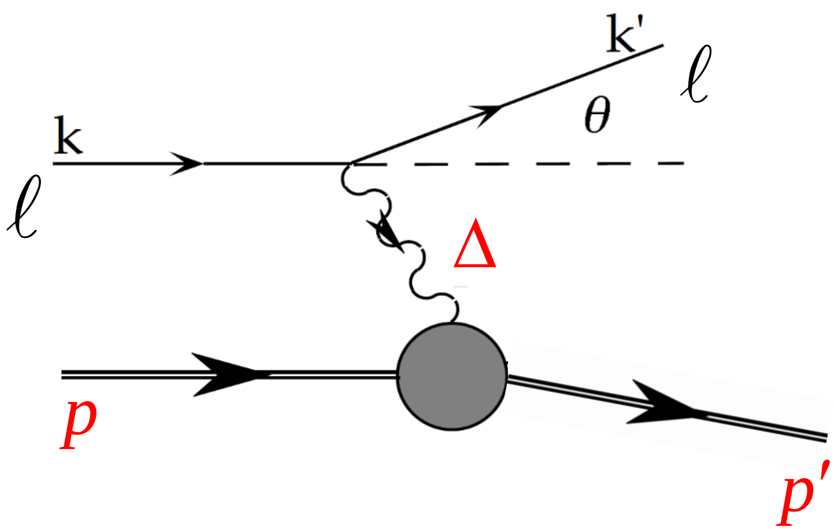


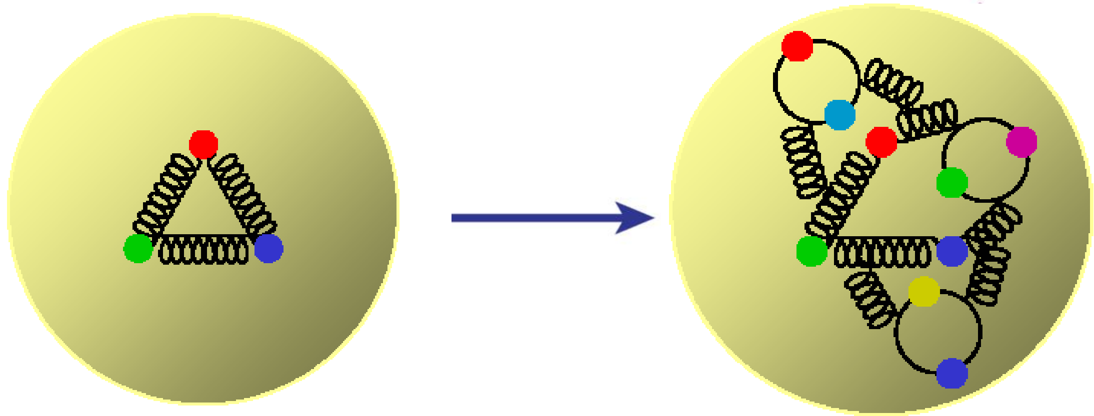


$$\langle N(p')|\psi^{\dagger}(0)\psi(0)|N(p)\rangle$$

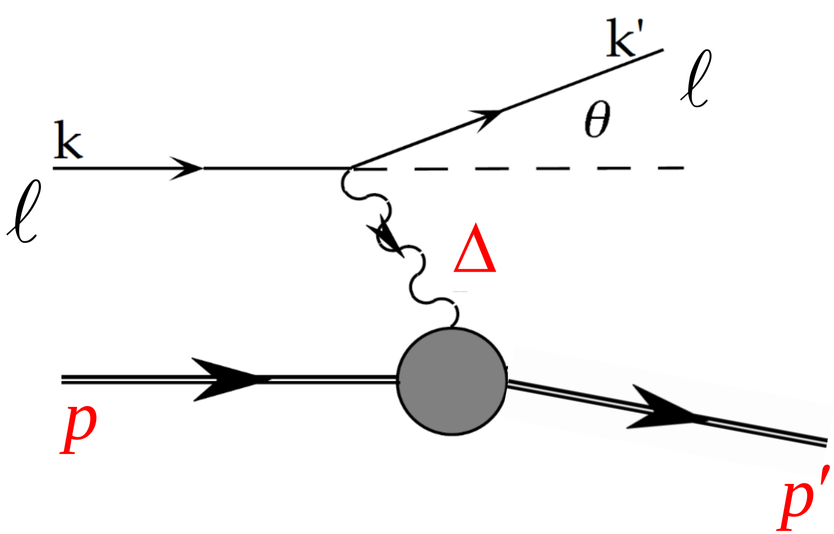
$$\langle N(p')|\bar{\psi}(0)\gamma^{\mu}\psi(0)|N(p)\rangle \sim \bar{u}(p')\left\{\gamma^{\mu}F_1(\Delta^2)+\frac{i\sigma^{\nu\mu}\Delta_{\nu}}{2M_N}F_2(\Delta^2)\right\}u(p)$$

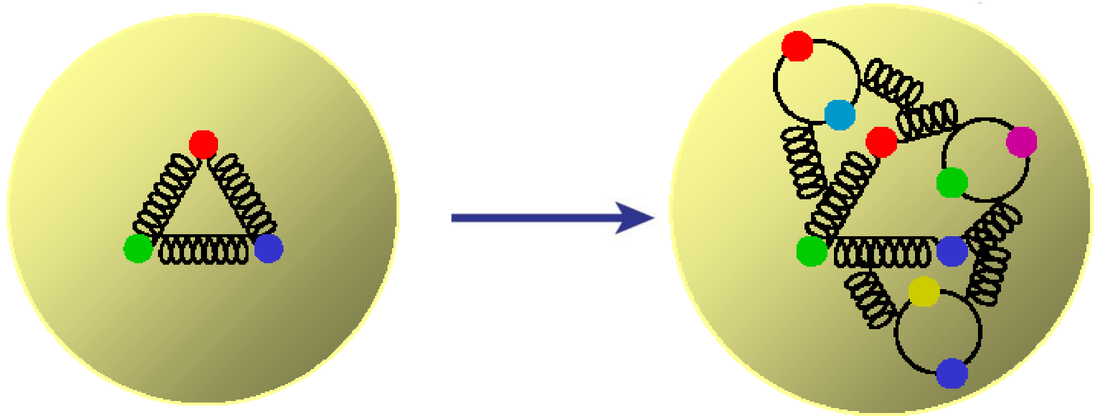
$$\Delta = p' - p$$

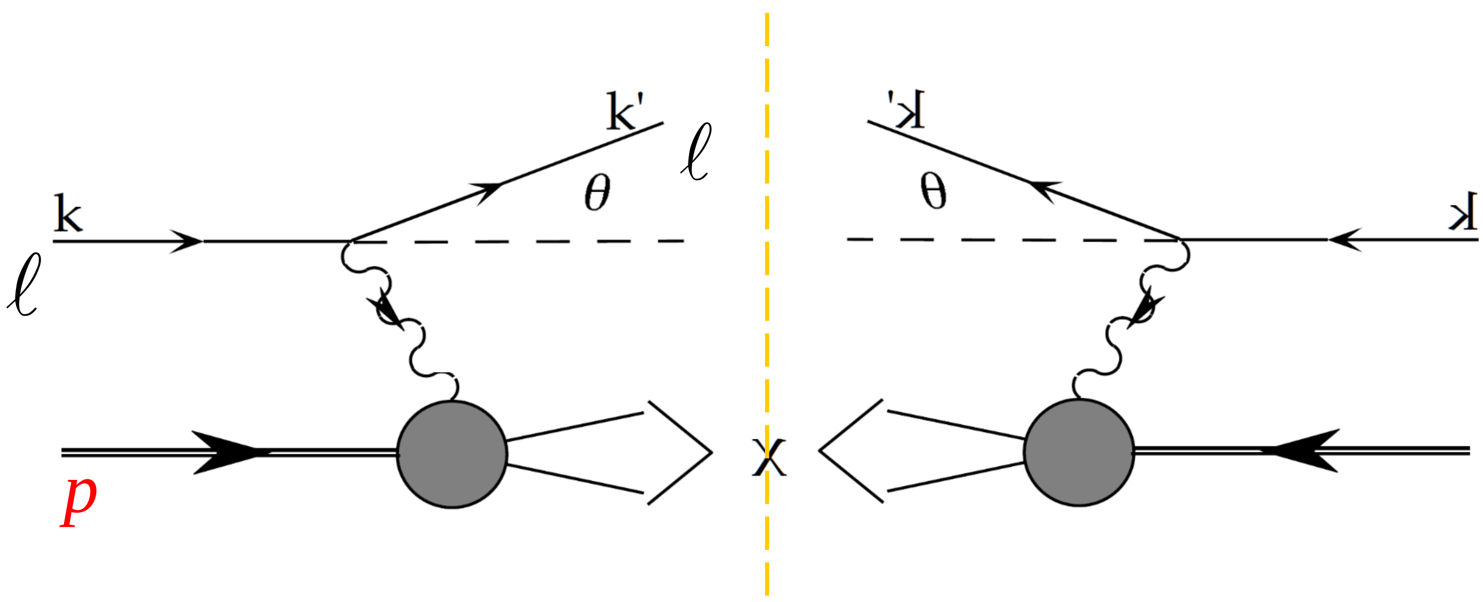




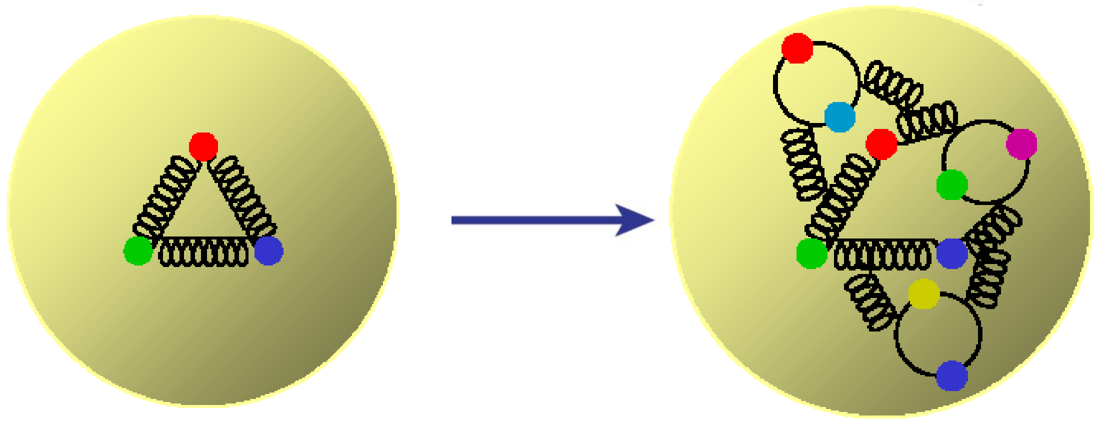
$$\langle N(p')|\psi^{\dagger}(0)\psi(0)|N(p)\rangle$$



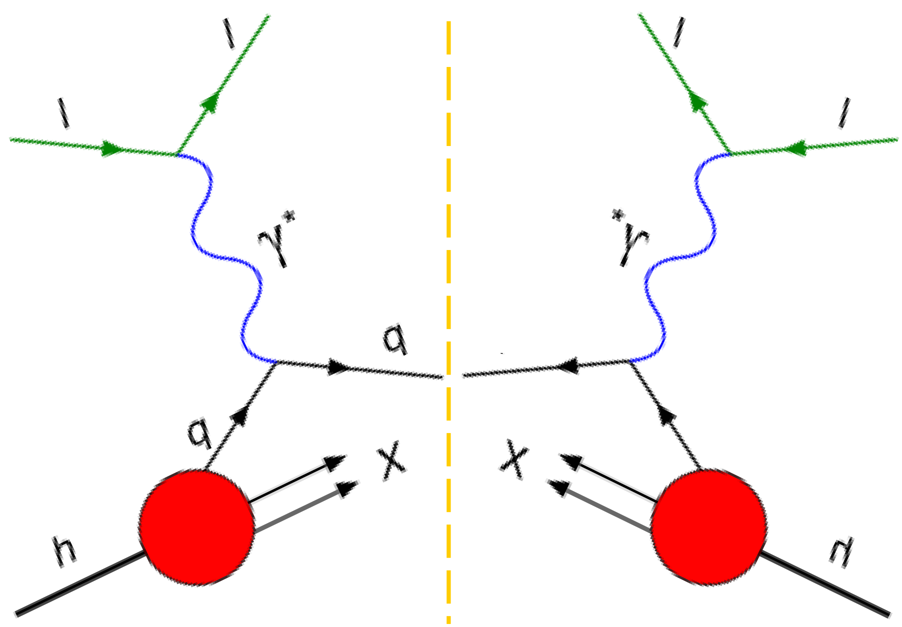


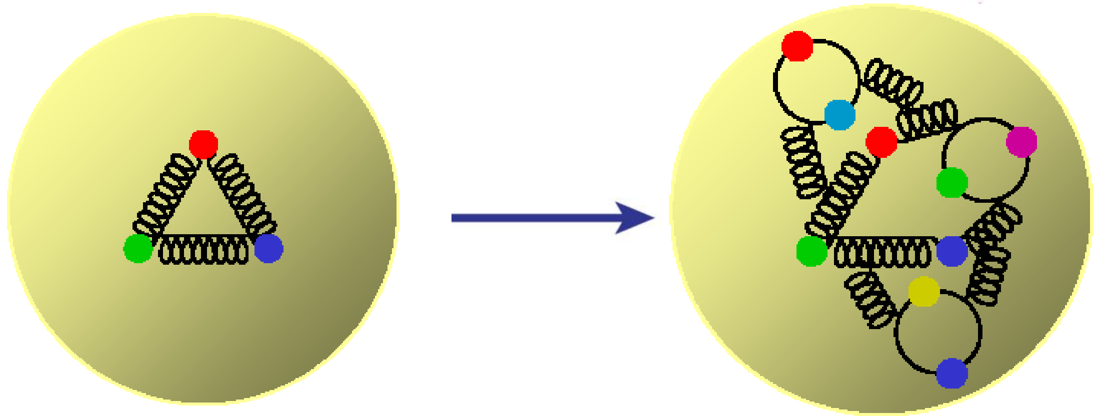


k'
ℓ
θ
k
ℓ
p
X
θ

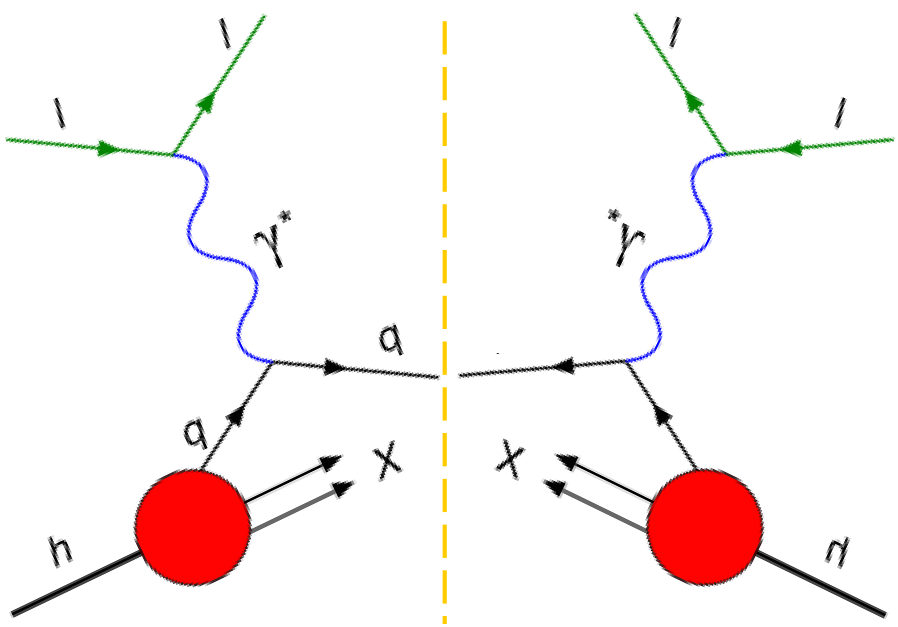


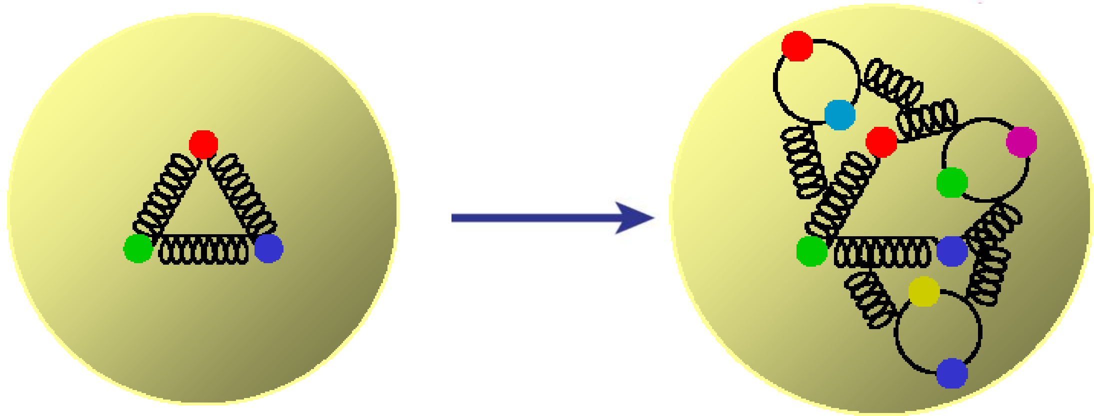
$$\langle N(p)|\psi^{\dagger}(0)\psi(z^{-})|N(p)\rangle$$



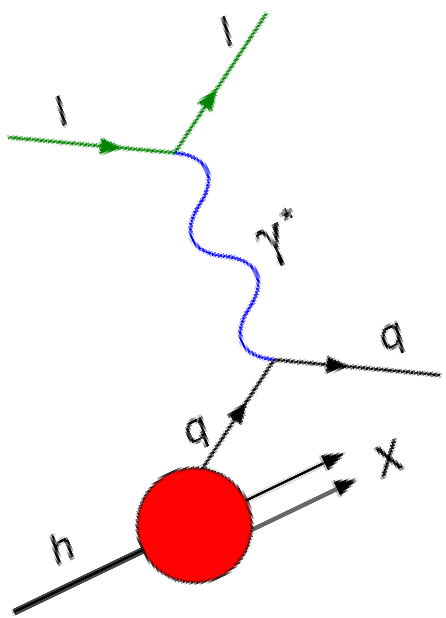


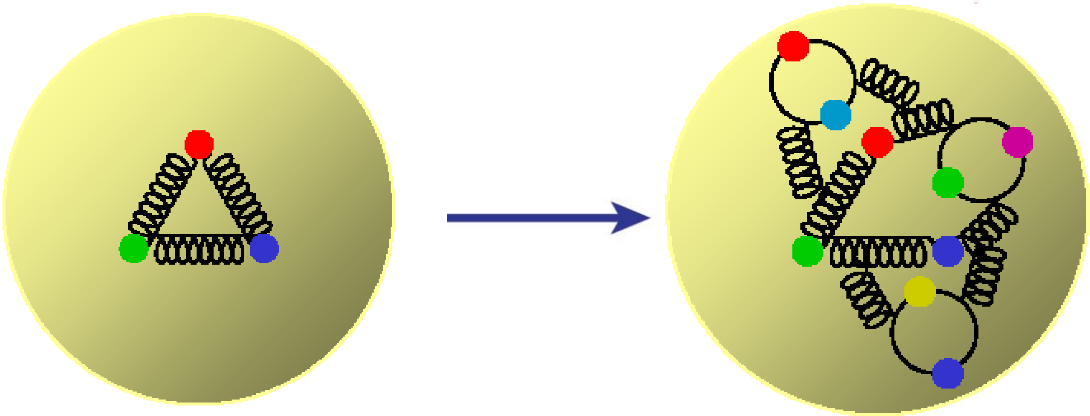
$$\int dz^- e^{ixpz} \langle N(p) | \psi^\dagger(0) \psi(z^-) | N(p) \rangle$$



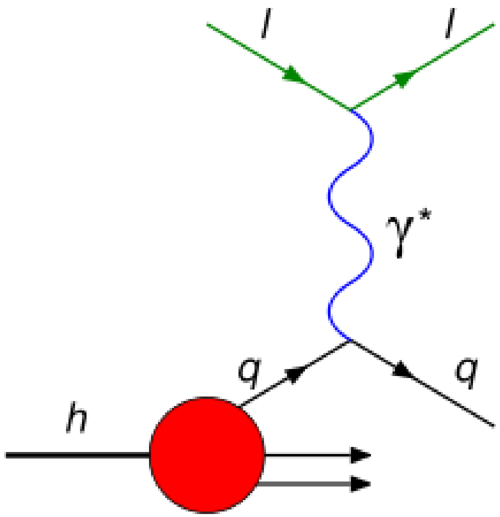


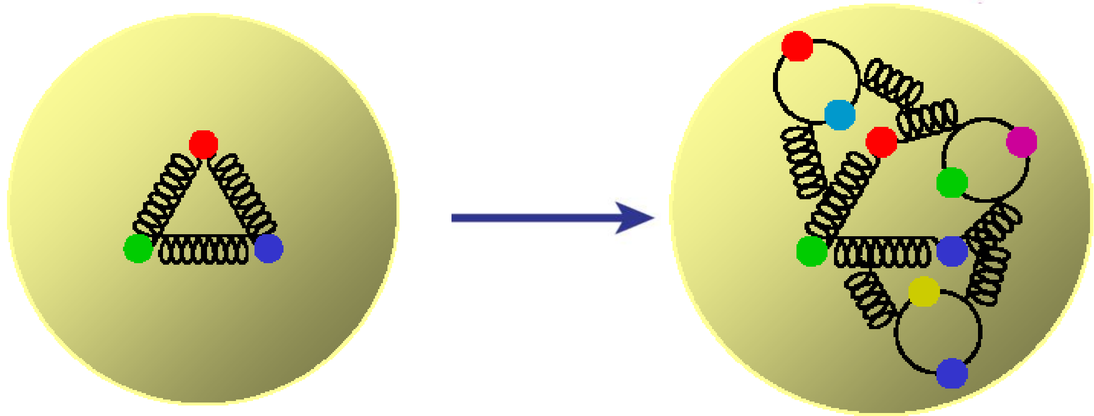
$$\int dz^- e^{ixpz} \langle N(p) | \psi^\dagger(0)\psi(z^-) | N(p) \rangle$$



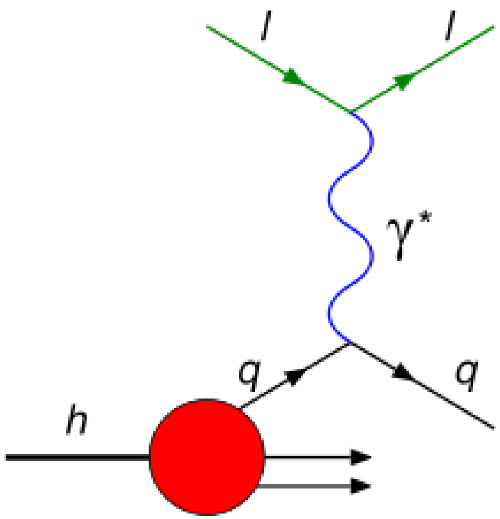


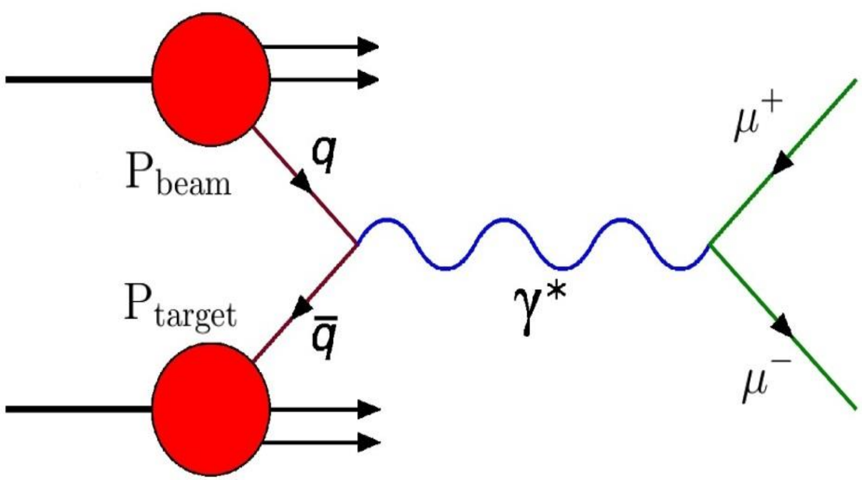
$$\int dz^- e^{ixpz} \langle N(p) | \psi^\dagger(0) \psi(z^-) | N(p) \rangle$$





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





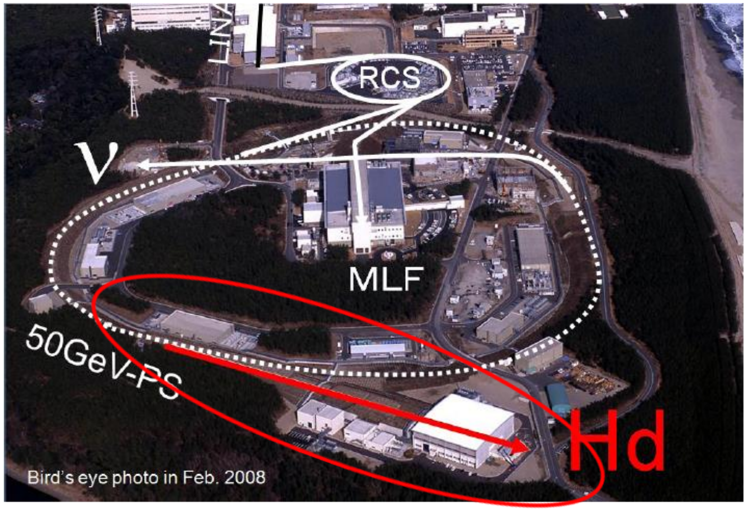
High momentum beam line at J-PARC

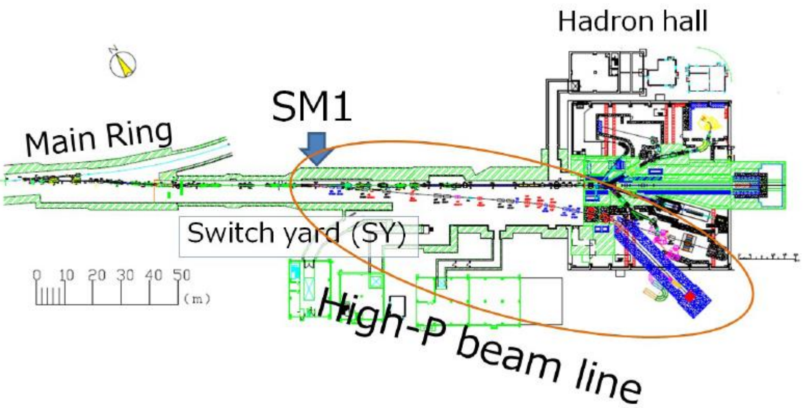
- Primary beam (proton)

$$E = 30\mathrm{GeV}$$

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

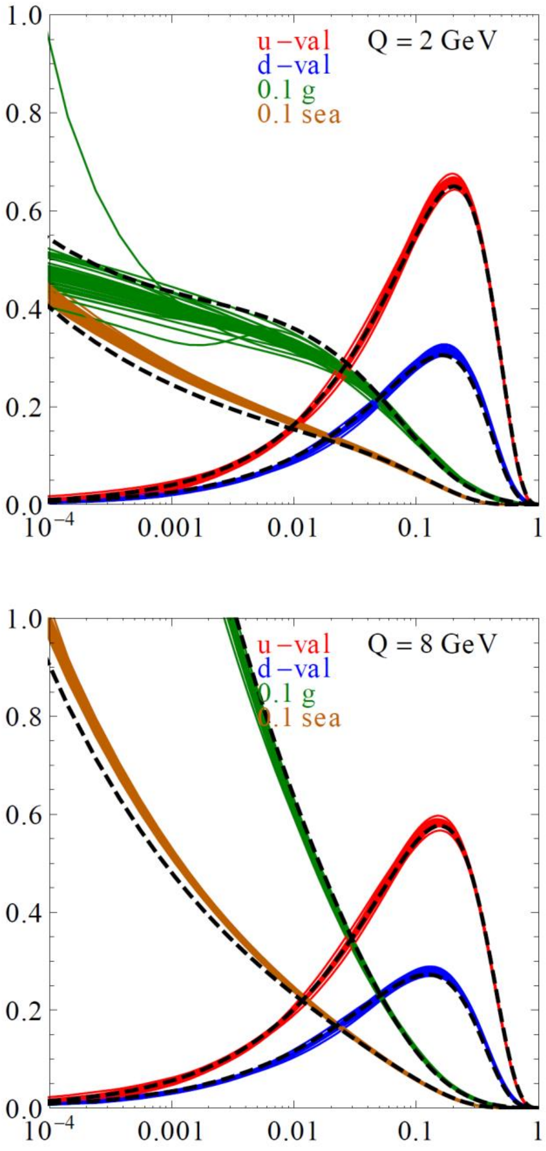
Hadron Facility at J-PARC





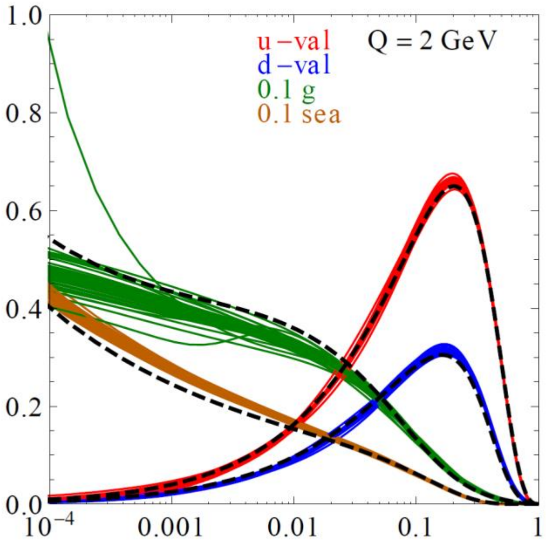
CT10 NNLO, PRD89 ('14) 033009

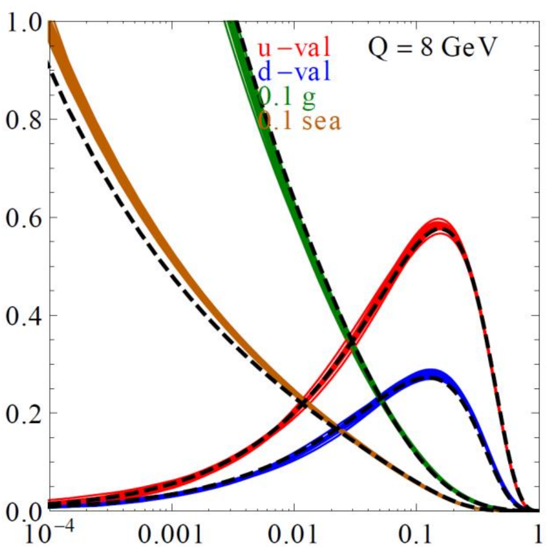
x f(x,Q) versus x



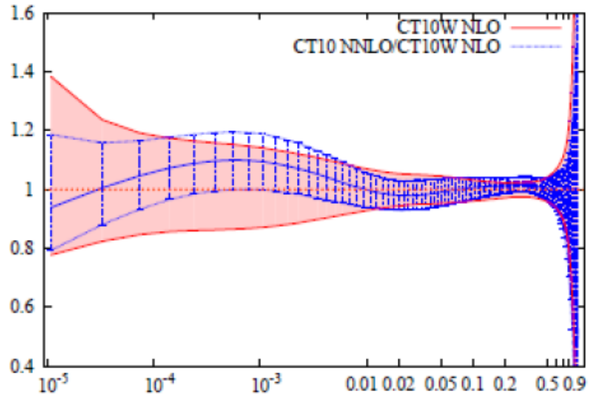
CT10 NNLO, PRD89 ('14) 033009

x f(x,Q) versus x

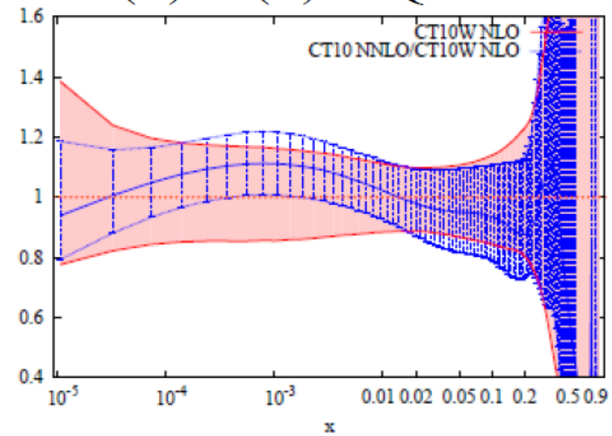


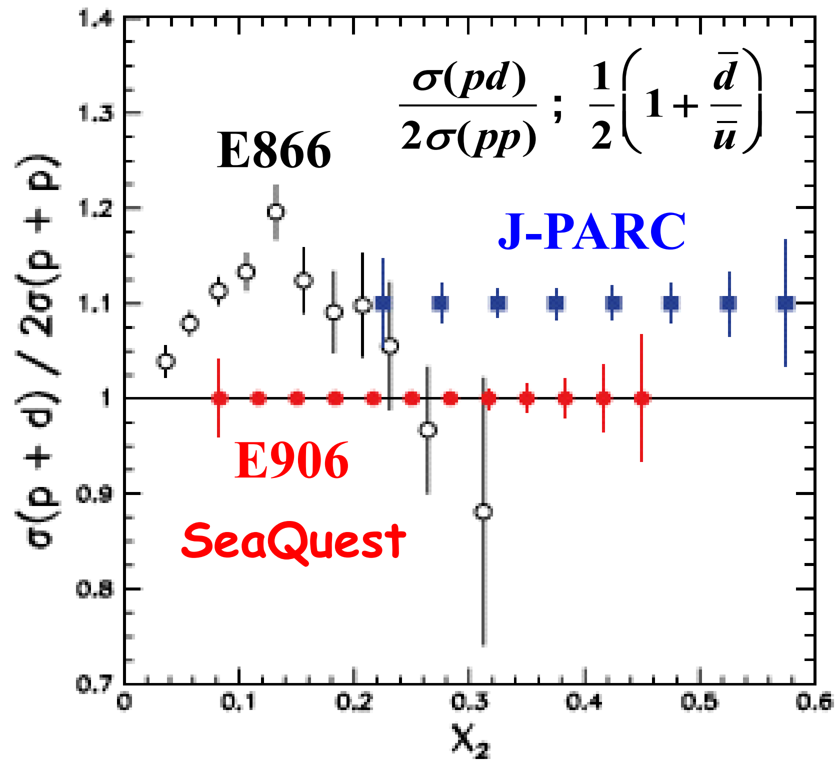


$\delta u(x)/u(x)$ at Q=2GeV



$\delta \bar{u}(x)/\bar{u}(x)$ at Q=2GeV





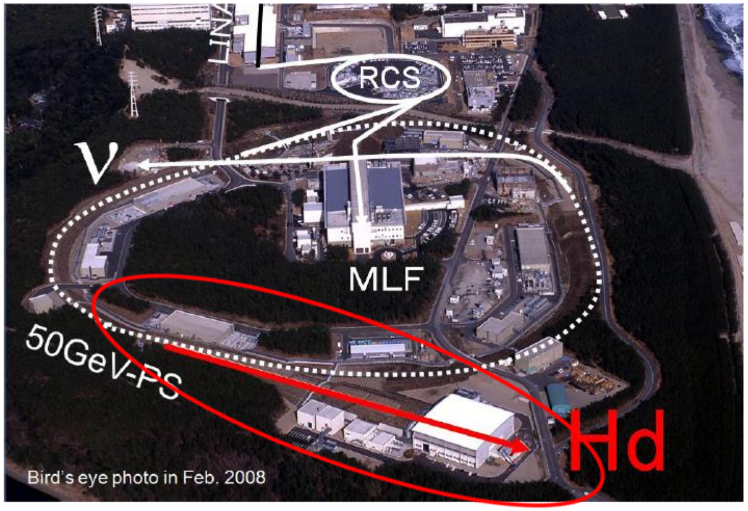
High momentum beam line at J-PARC

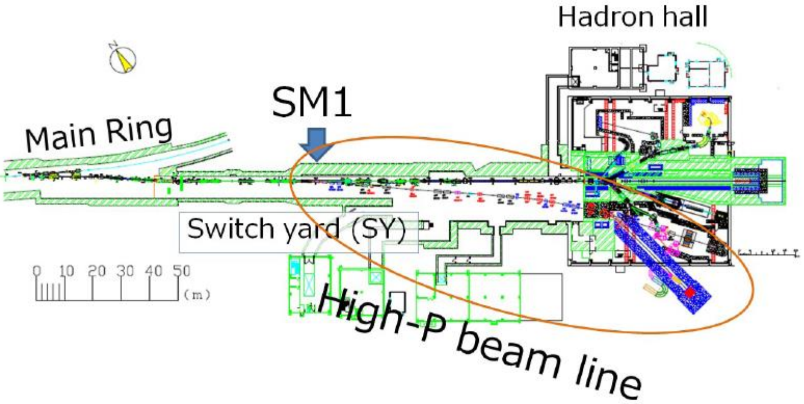
- Primary beam (proton)

$$E = 30\text{GeV}$$

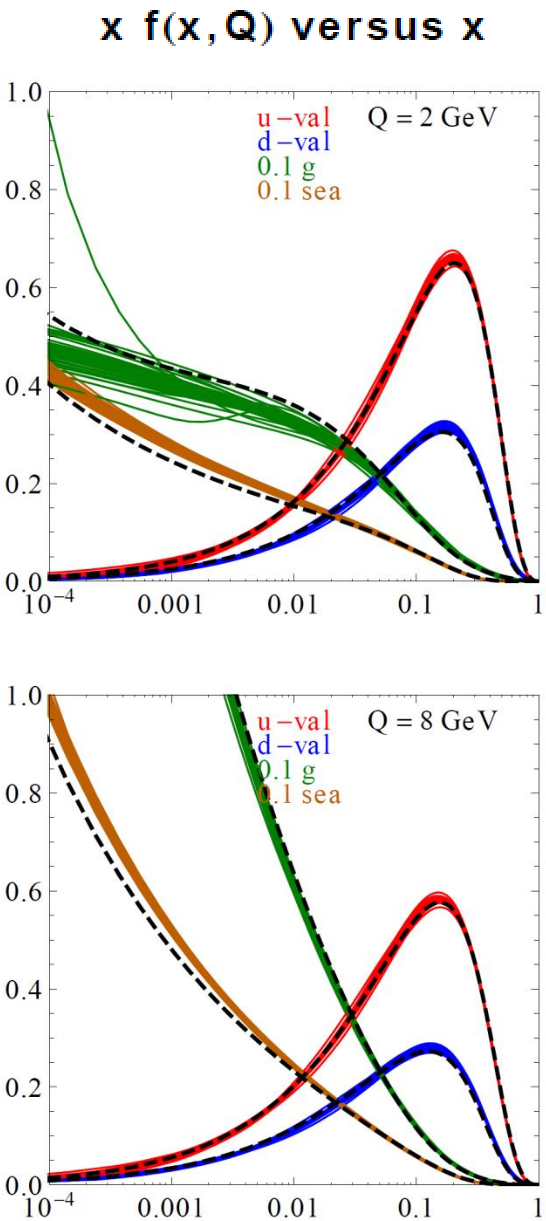
$$L = 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$$

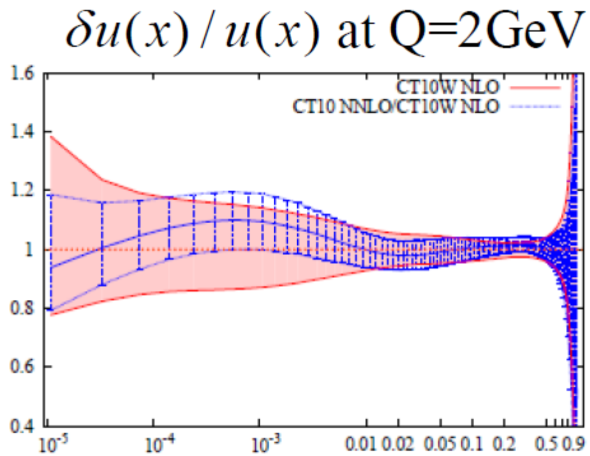
Hadron Facility at J-PARC

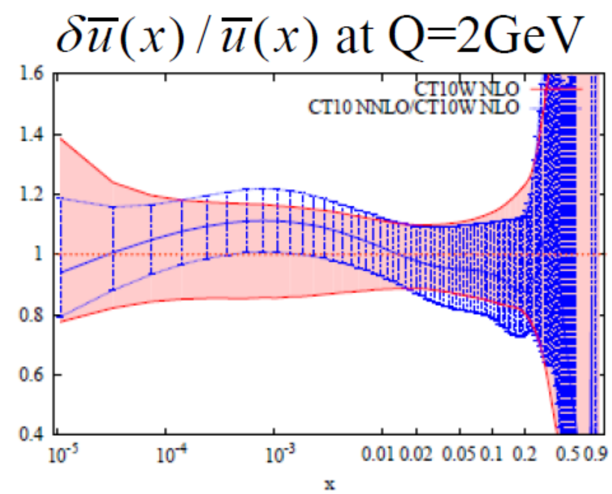


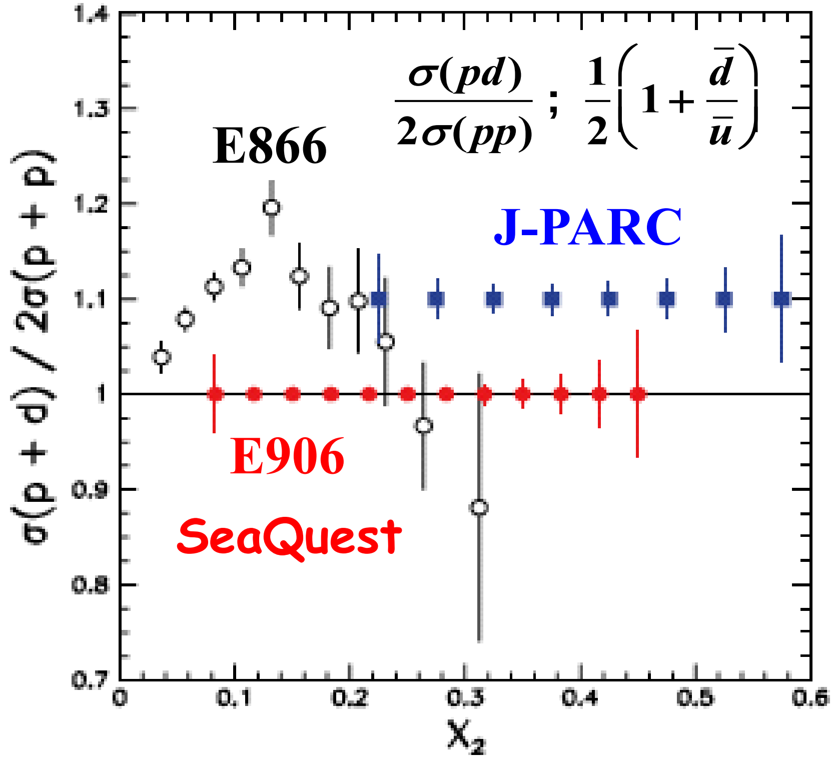


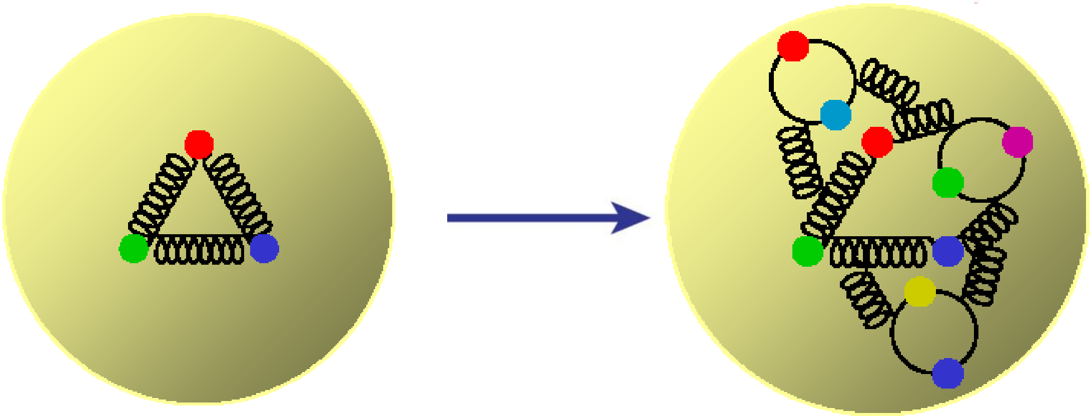
CT10 NNLO, PRD89 ('14) 033009



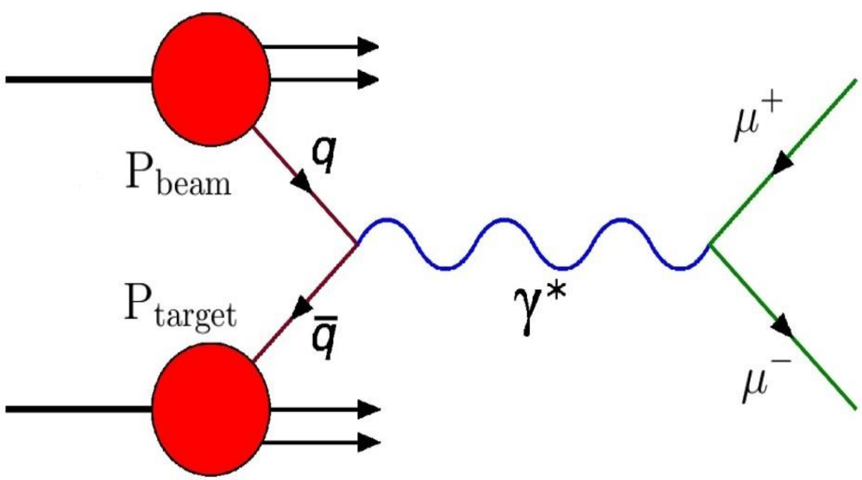


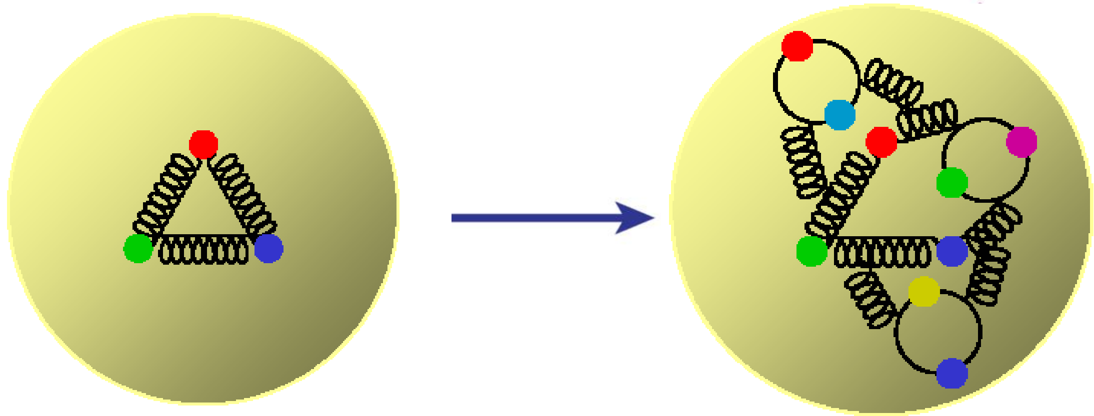






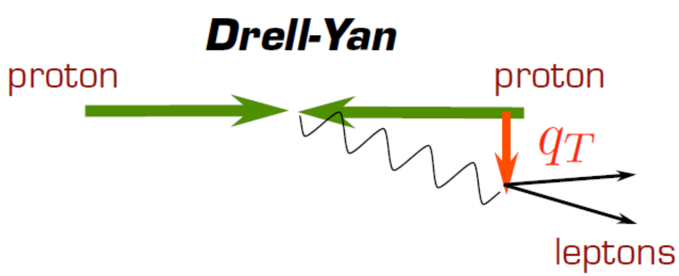
$$\int dz^{-} e^{ixpz} \langle N(p) | \psi^{\dagger}(0) \psi(z^{-}) | N(p) \rangle$$

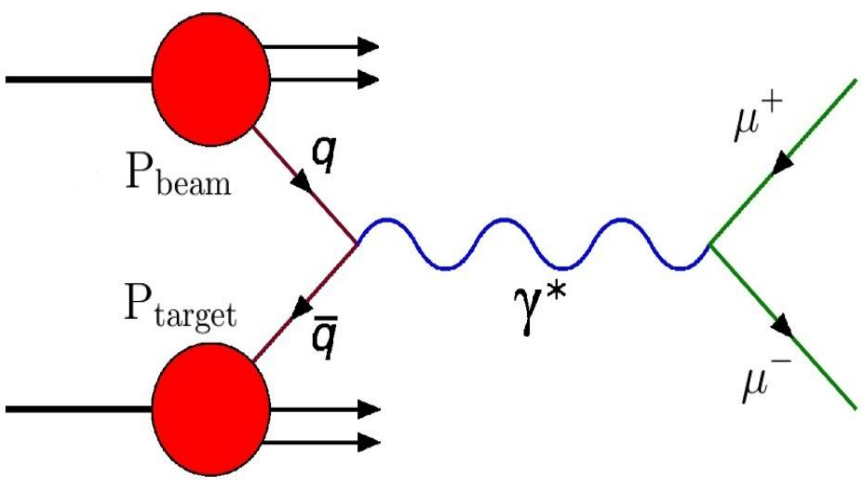


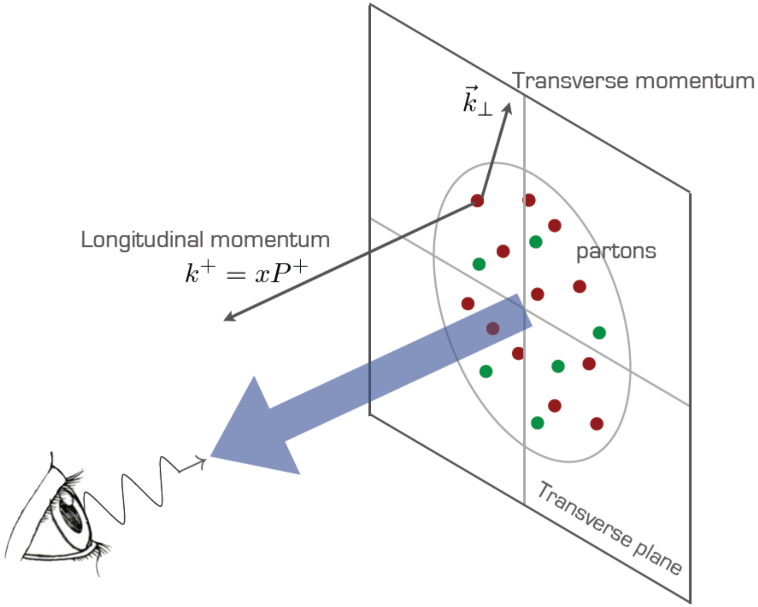


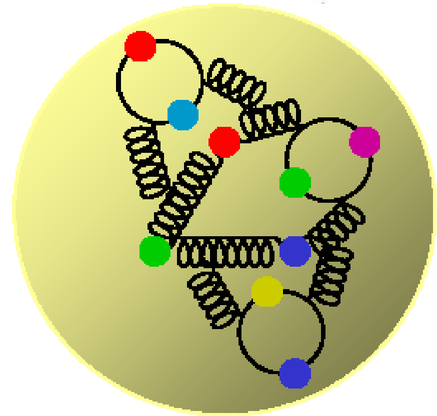
$$\int d^2 z_\perp e^{-i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \int dz^- e^{ixpz} \langle N(p) | \psi^\dagger(0) \psi(z^-, \mathbf{z}_\perp) | N(p) \rangle$$

TMD



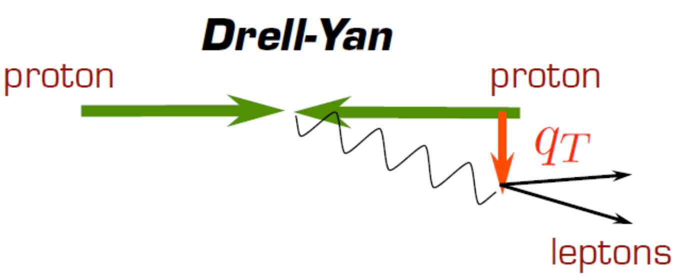


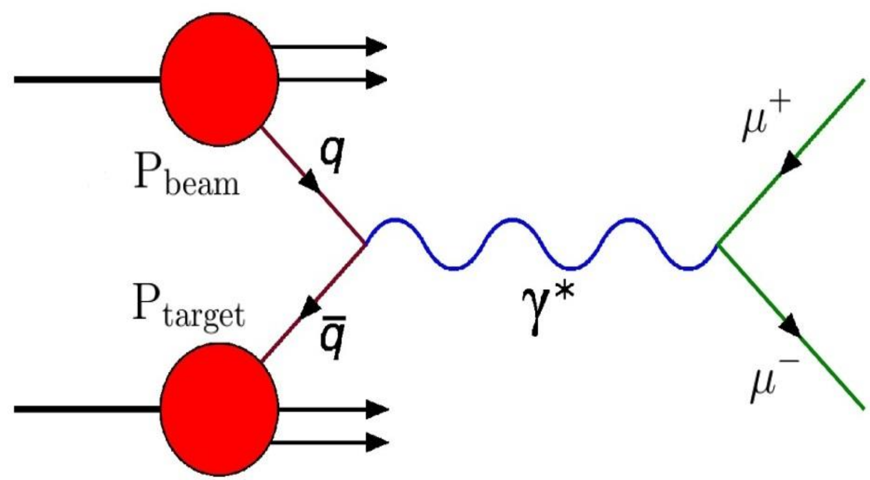


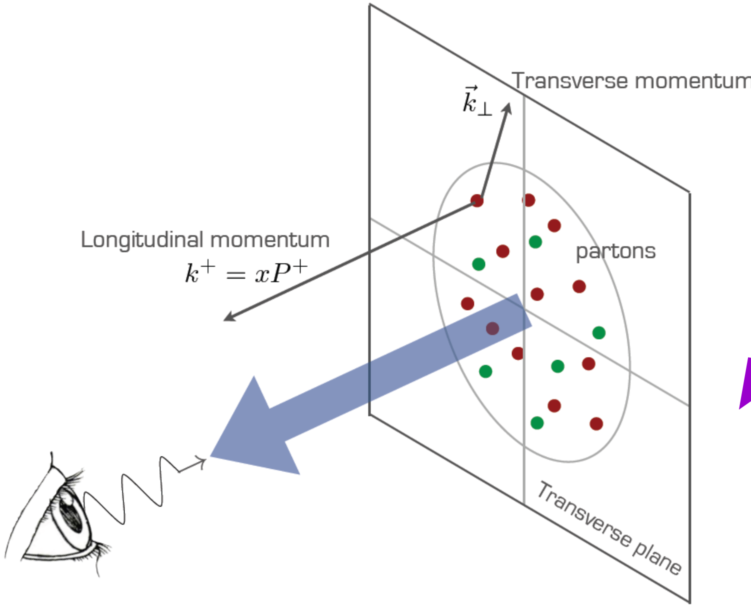


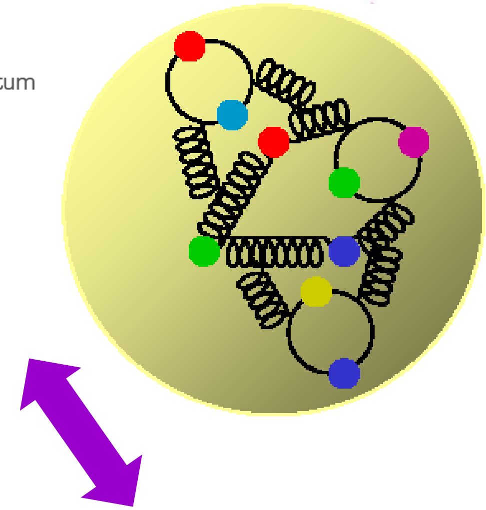
$$\int d^2 z_\perp e^{-i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \int dz^- e^{ixpz} \langle N(p)|\psi^\dagger(0)\psi(z^-,\mathbf{z}_\perp)|N(p)\rangle$$

TMD



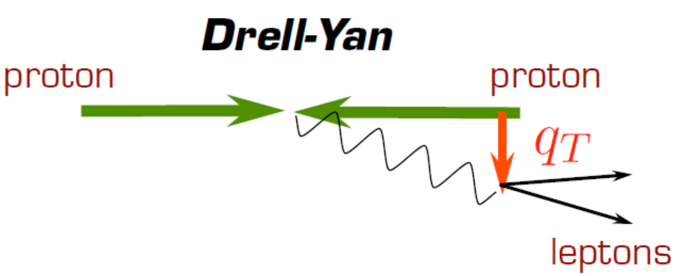


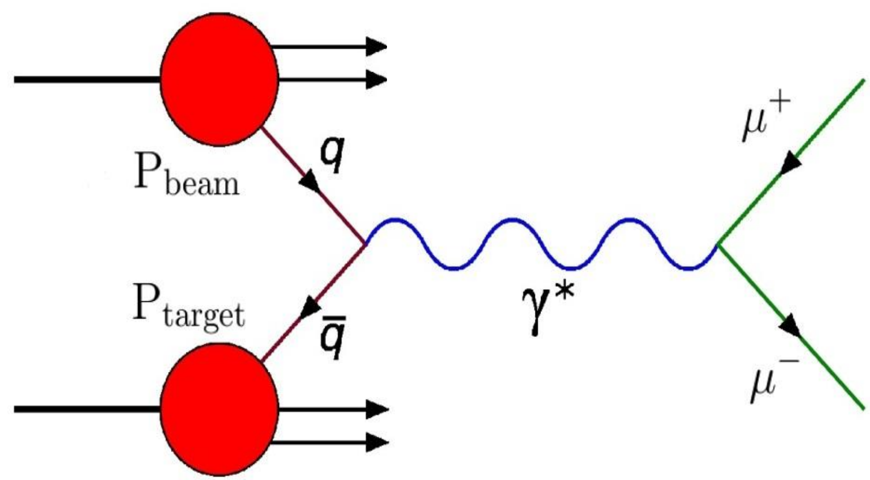


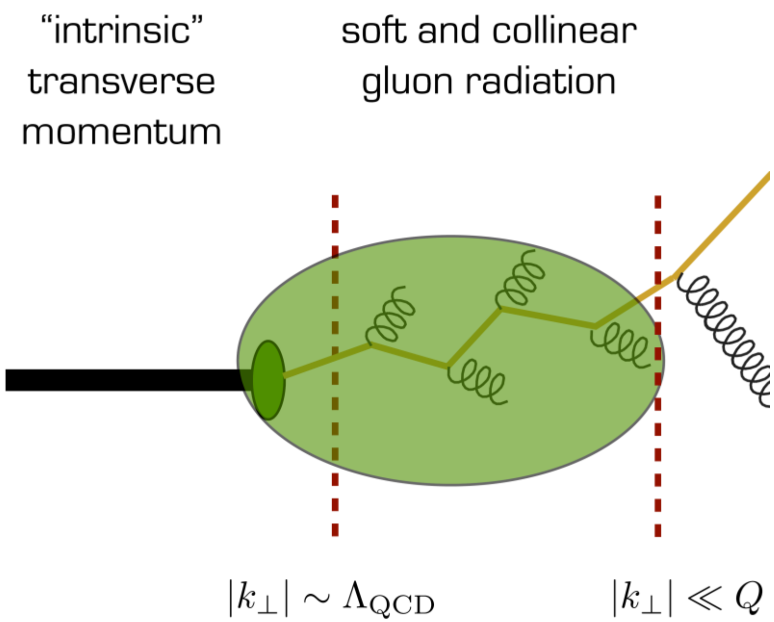


$$\int d^2 z_\perp e^{-i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \int dz^- e^{ixpz} \langle N(p)|\psi^\dagger(0)\psi(z^-,\mathbf{z}_\perp)|N(p)\rangle$$

TMD

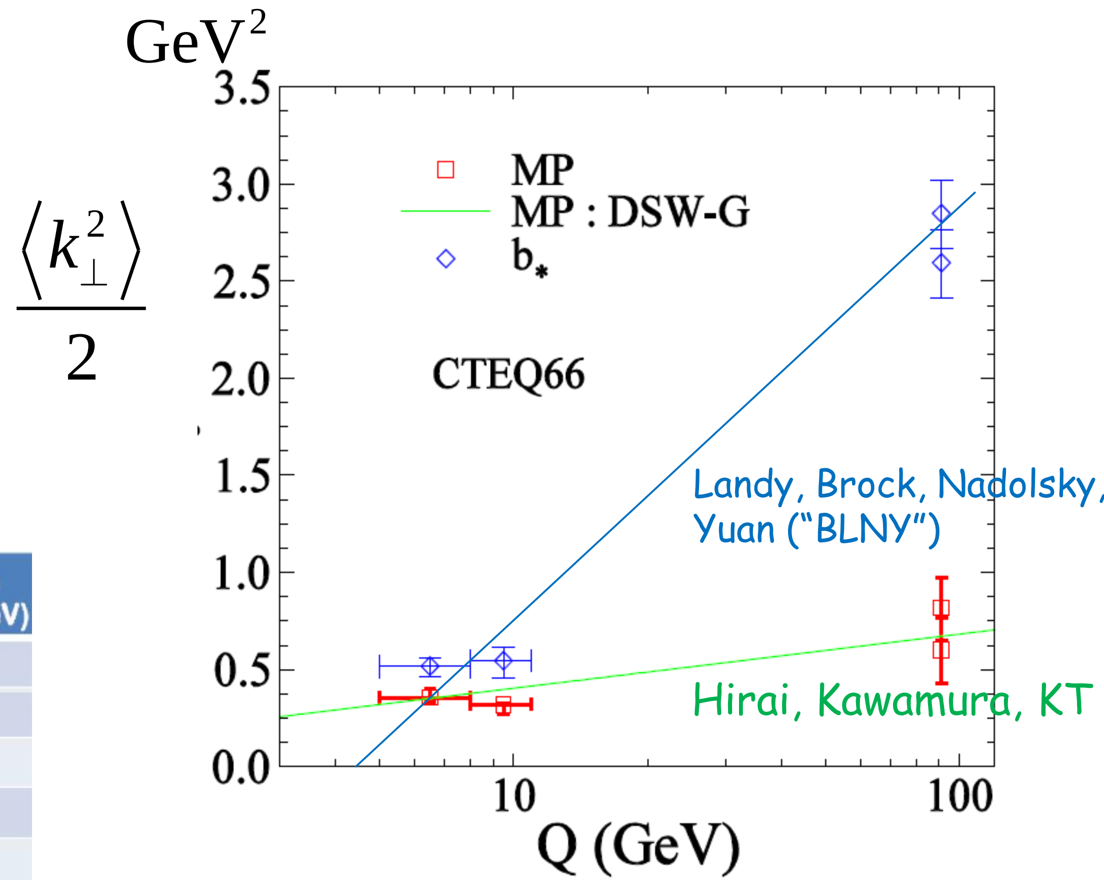






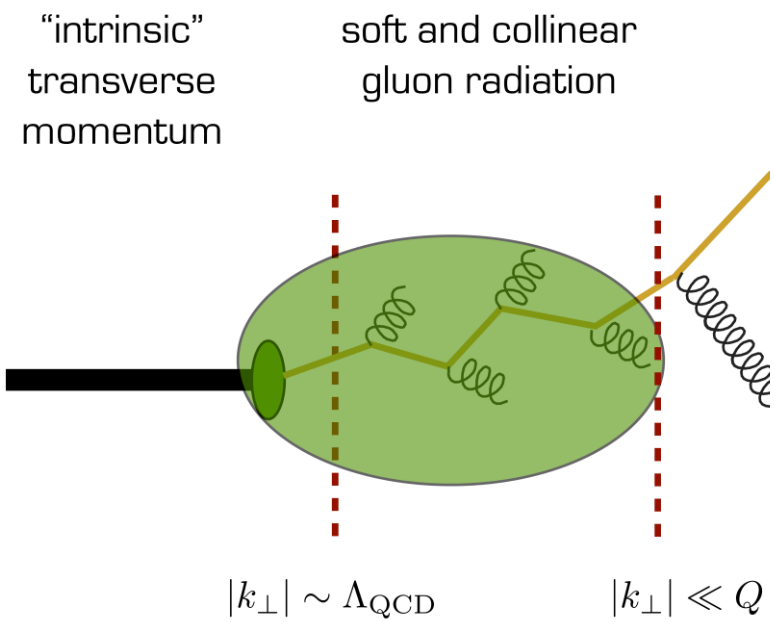
Q: dilepton mass

Global fit



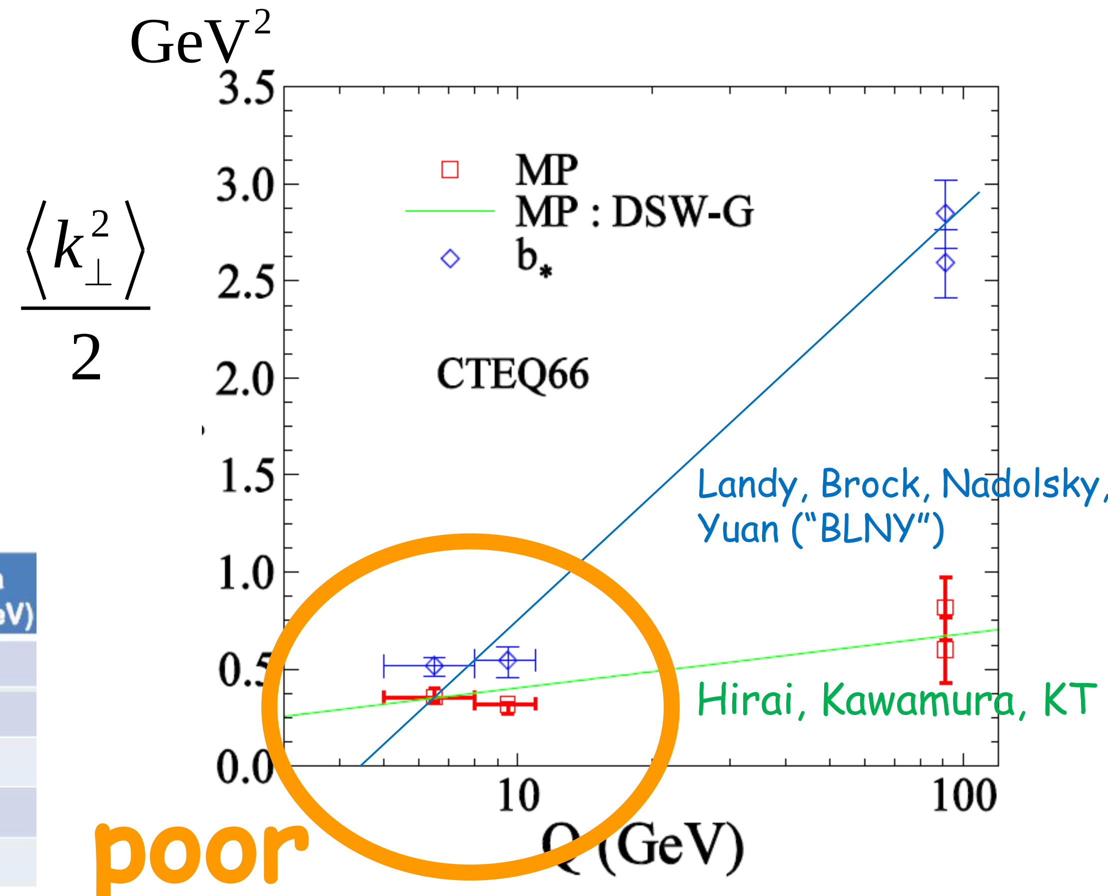
Experimental data sets

	Exp	√s (GeV)	Target	Q range (GeV)	# of data (pT < 22 GeV)
DY	R209	62	P-P	5.0 - 8.0	5
	R209	62	P-P	8.0 - 11.0	5
Z^0	CDF run-0	1800	P-Pbar	75 - 105	7
	CDF run-1	1800	P-Pbar	66 - 116	33
	D0 run-1	1800	P-Pbar	75 - 105	15



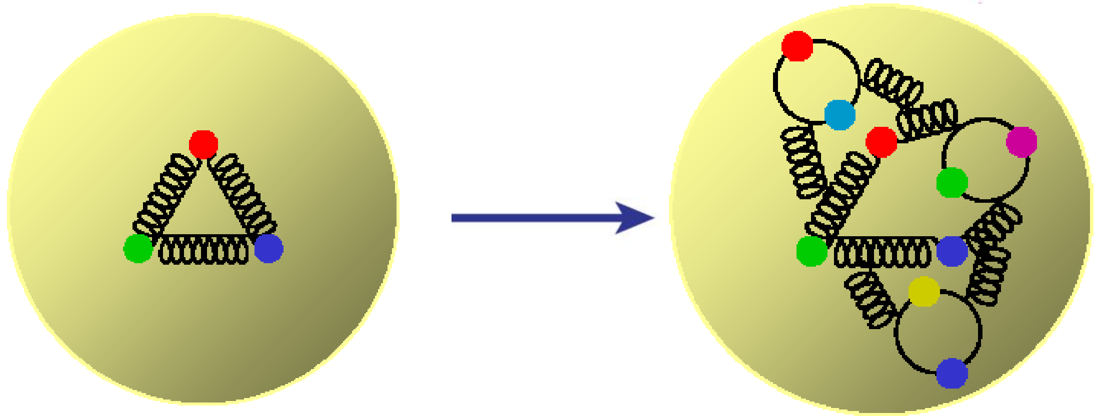
Q : **dilepton mass**

Global fit



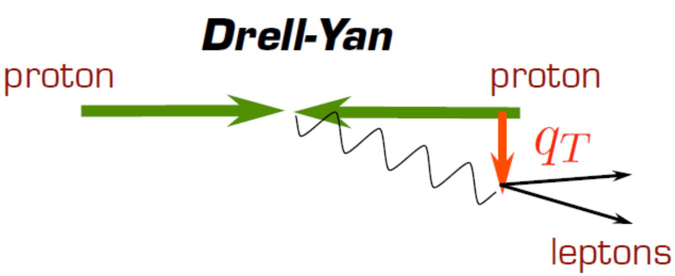
Experimental data sets

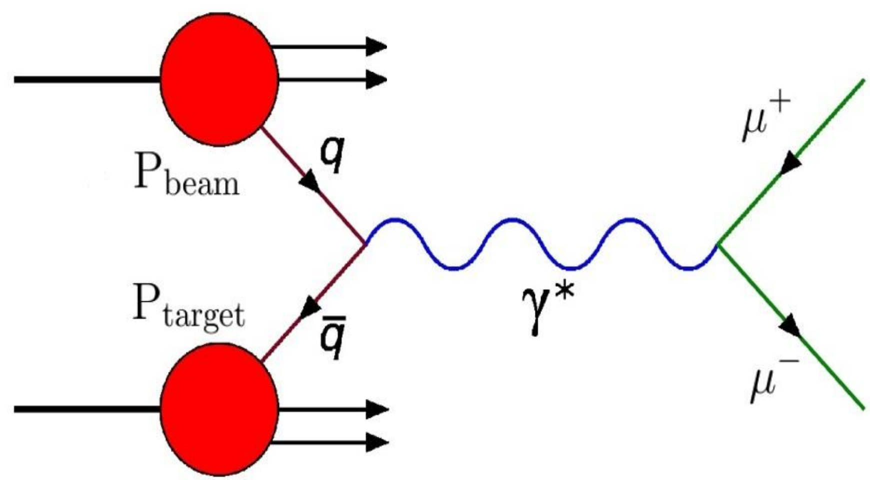
	Exp	√s (GeV)	Target	Q range (GeV)	# of data (pT < 22 GeV)
DY	R209	62	P-P	5.0 - 8.0	5
	R209	62	P-P	8.0 - 11.0	5
Z^0	CDF run-0	1800	P-Pbar	75 - 105	7
	CDF run-1	1800	P-Pbar	66 - 116	33
	D0 run-1	1800	P-Pbar	75 - 105	15

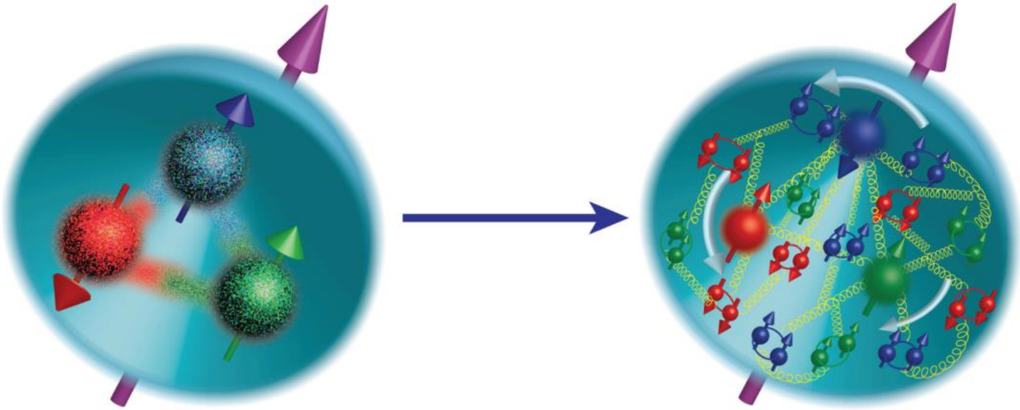


$$\int d^2 z_\perp e^{-i\mathbf{k}_\perp\cdot\mathbf{z}_\perp}\int dz^- e^{ixpz}\,\langle N(p)|\psi^\dagger(0)\psi(z^-,\mathbf{z}_\perp)|N(p)\rangle$$

TMD





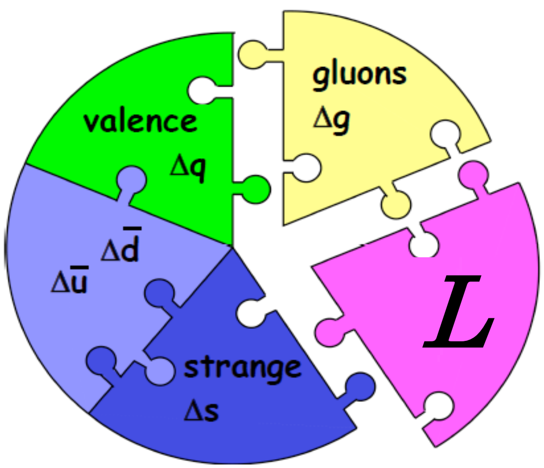


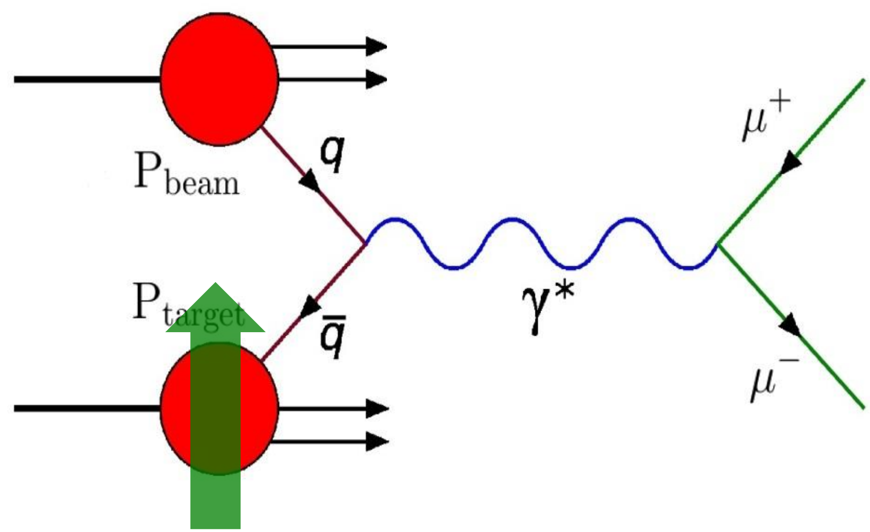
Sivers

$$f_1^{\perp}(x,k_\perp) \sim \int d^2 z_\perp e^{-i\mathbf{k}_\perp\cdot\mathbf{z}_\perp} \int dz^- e^{ixpz} \langle N(p,S_\perp)|\psi^\dagger(0)\psi(z^-,\mathbf{z}_\perp)|N(p,S_\perp)\rangle$$

L_q

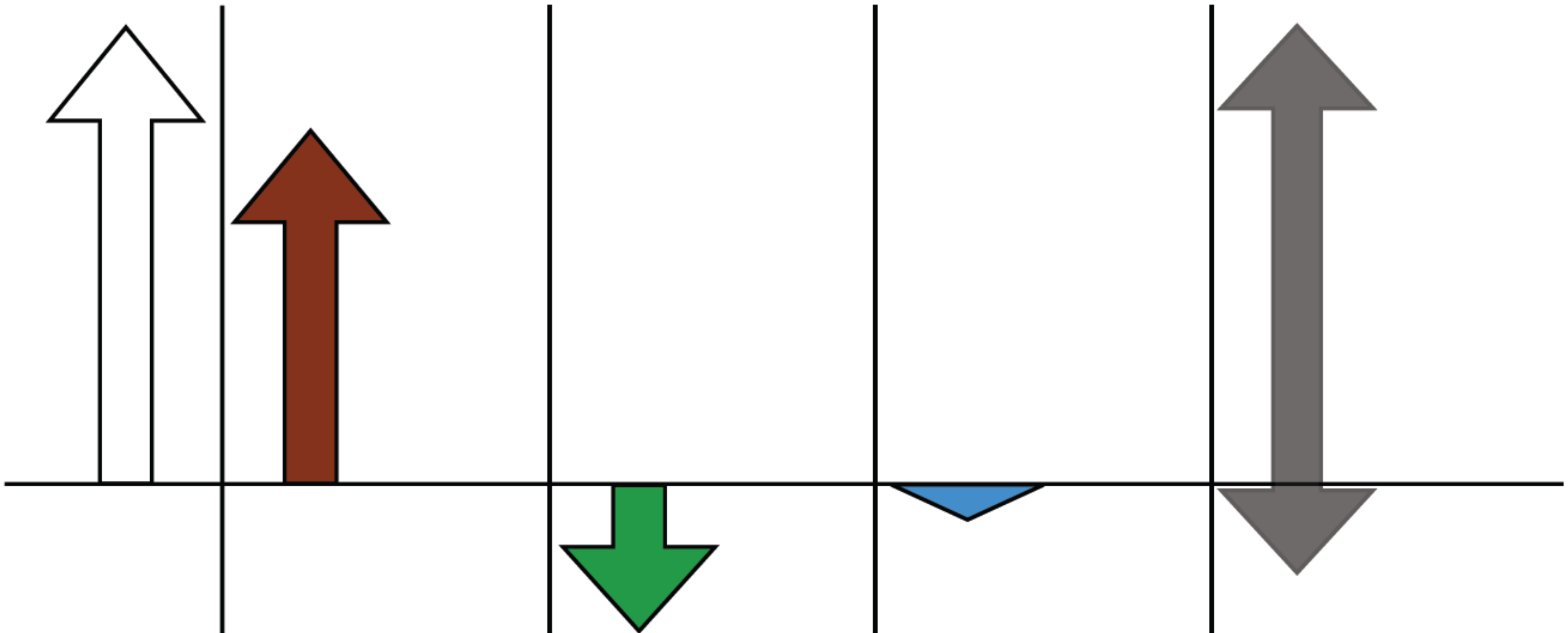
$$S = \frac{1}{2} = L + \frac{1}{2}\Delta\Sigma + \Delta G$$





from A. Bacchetta, HEP2016

Status of spin sum rule



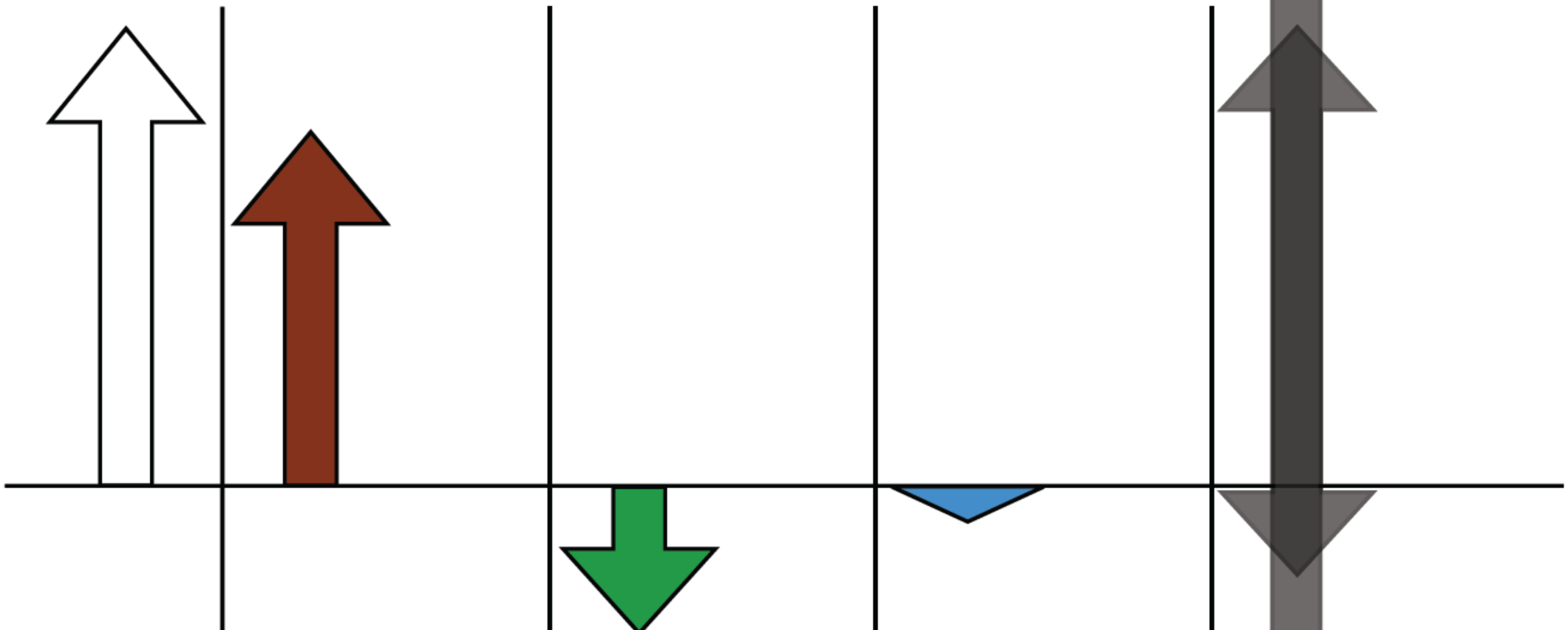
Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)

NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

from A. Bacchetta, HEP2016

Status of spin sum rule

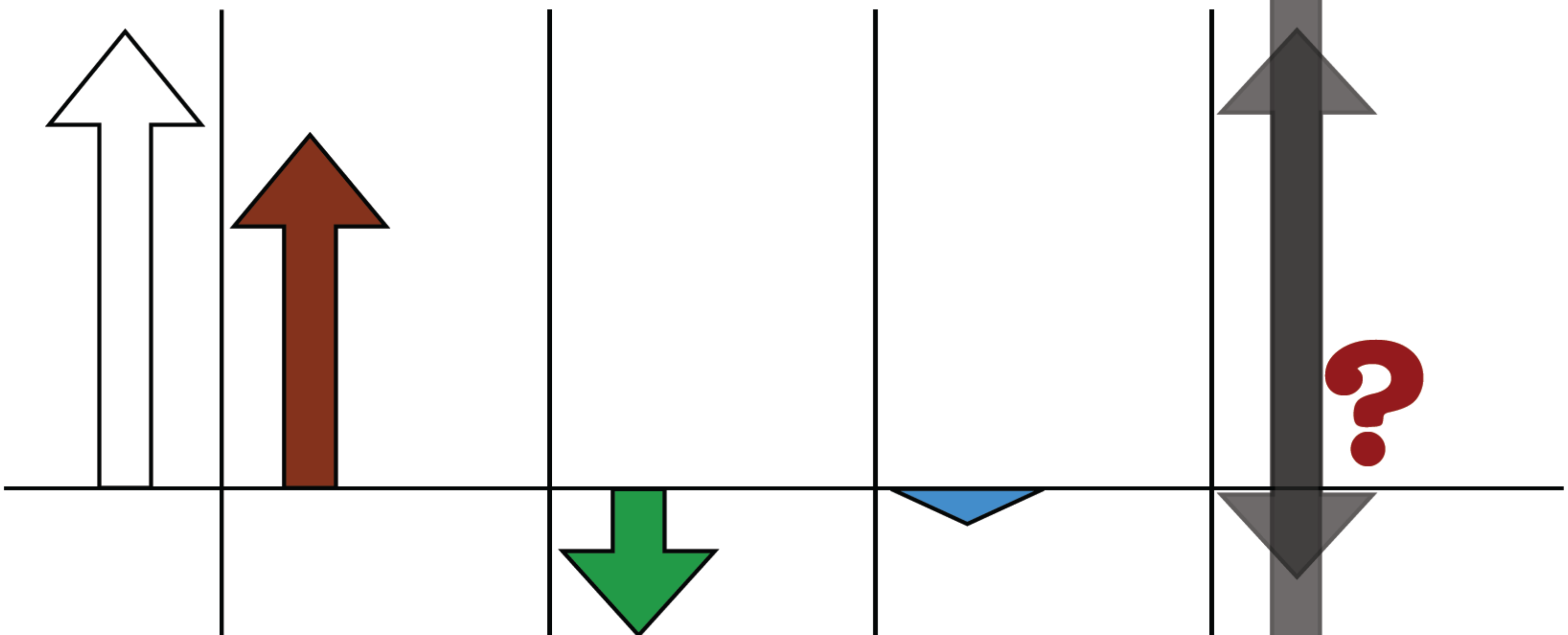


Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
	79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)
NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

from A. Bacchetta, HEP2016

Status of spin sum rule



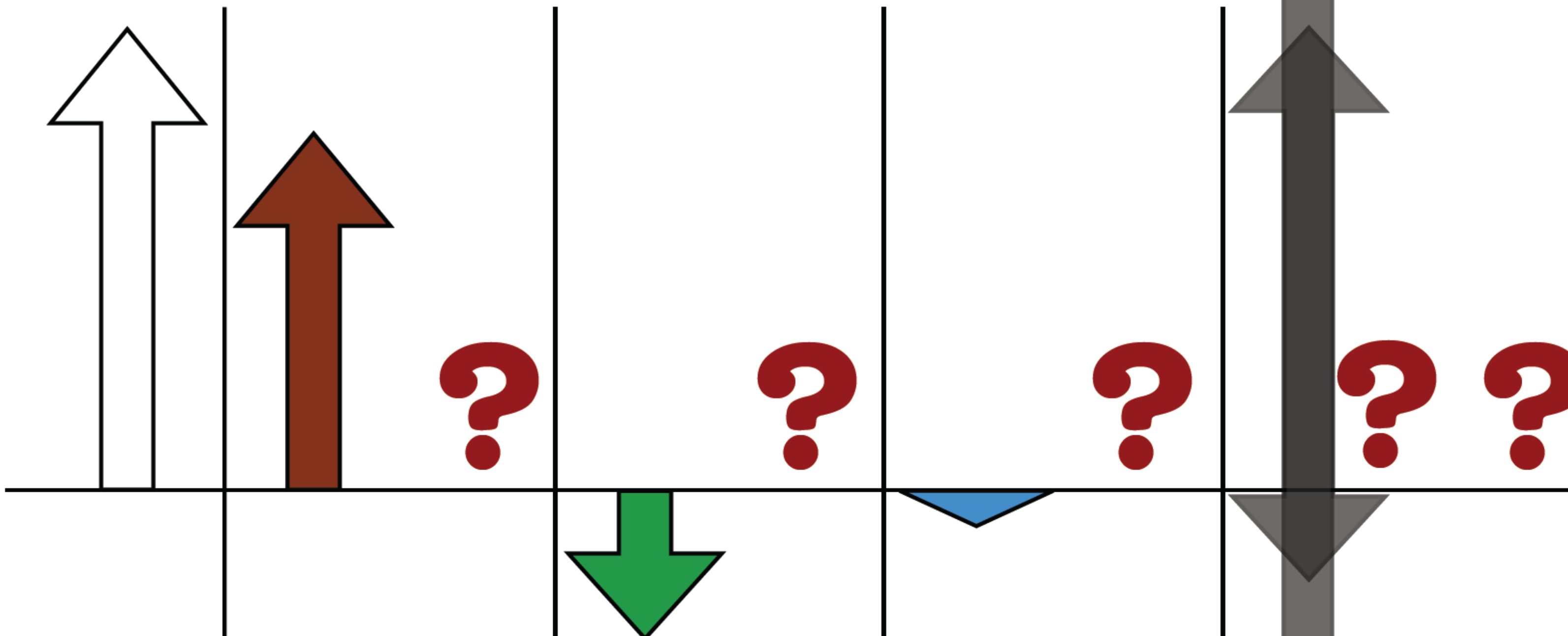
Proton spin

$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)

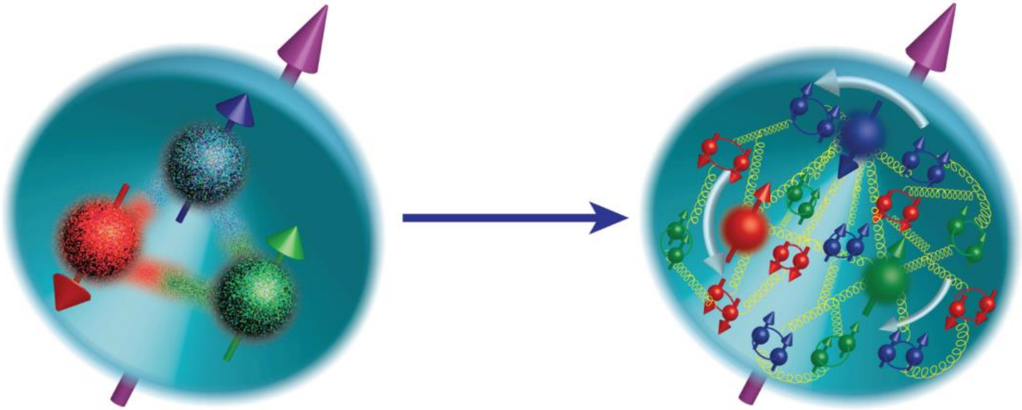
NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

Status of spin sum rule



Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
	79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

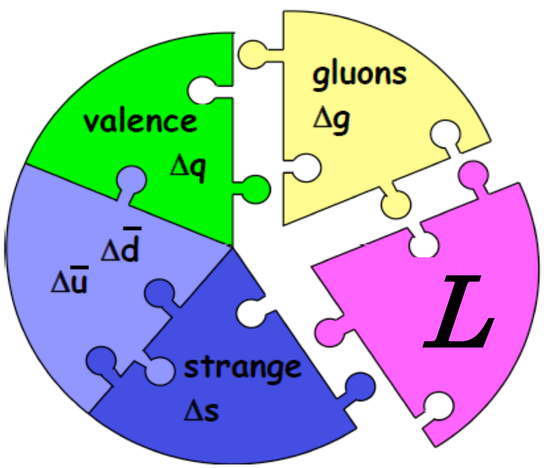
de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)
NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

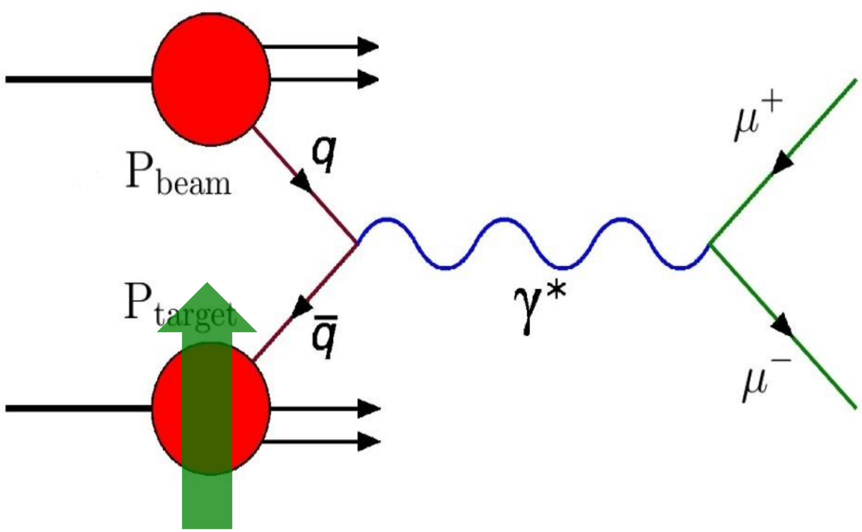


$$f_1^{\perp}(x,k_\perp) \sim \int d^2 z_\perp e^{-i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \int dz^- e^{ixpz} \langle N(p,S_\perp) | \psi^\dagger(0)\psi(z^-,\mathbf{z}_\perp) | N(p,S_\perp) \rangle$$

L_q

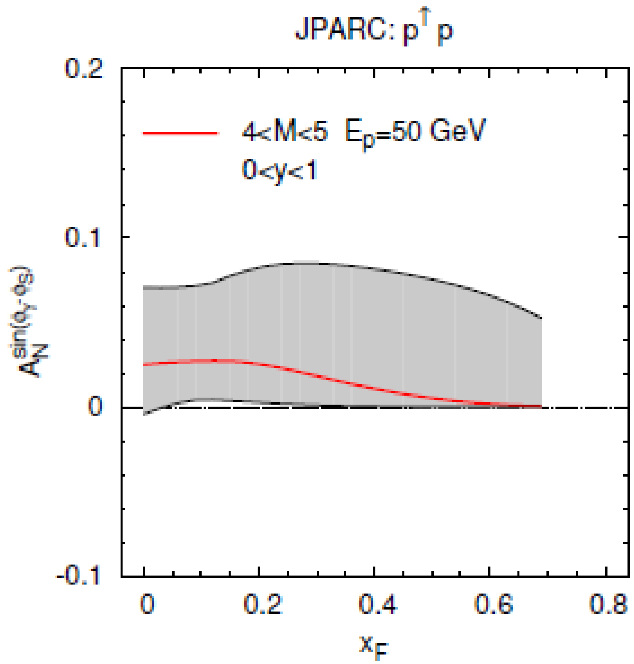
$$S = \frac{1}{2} = L + \frac{1}{2}\Delta\Sigma + \Delta G$$

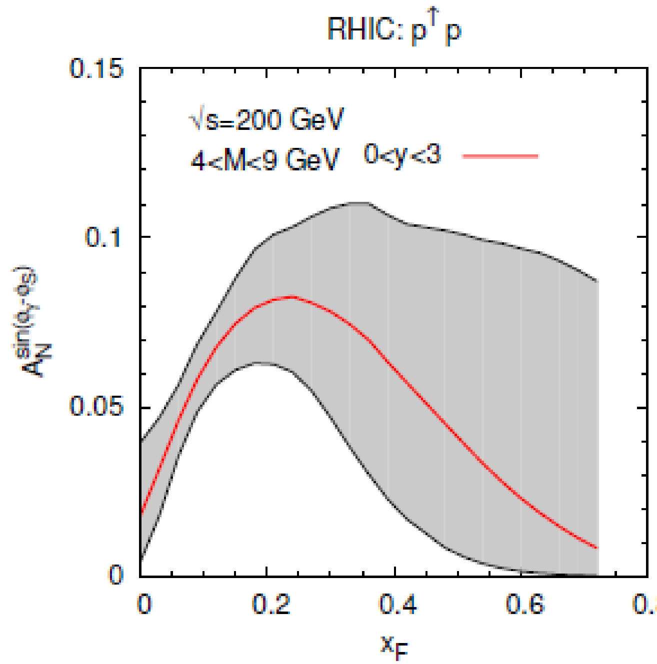




Sivers effect in Drell-Yan

Experimental test of Sivers effect in Drell-Yan is highly desired $(\sin(\phi - \phi_S) f_{1T}^{\perp} \bar{f}_1)$





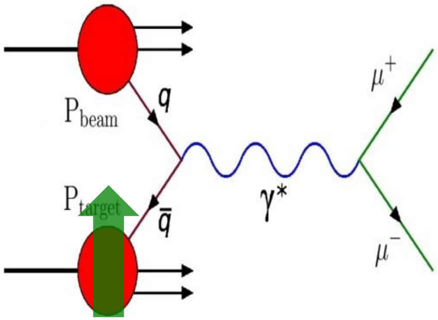
Anselmino *et al.* '09

$p^{\uparrow}p$ DY studies kinematically largely complementary to SIDIS data (careful about nodes)

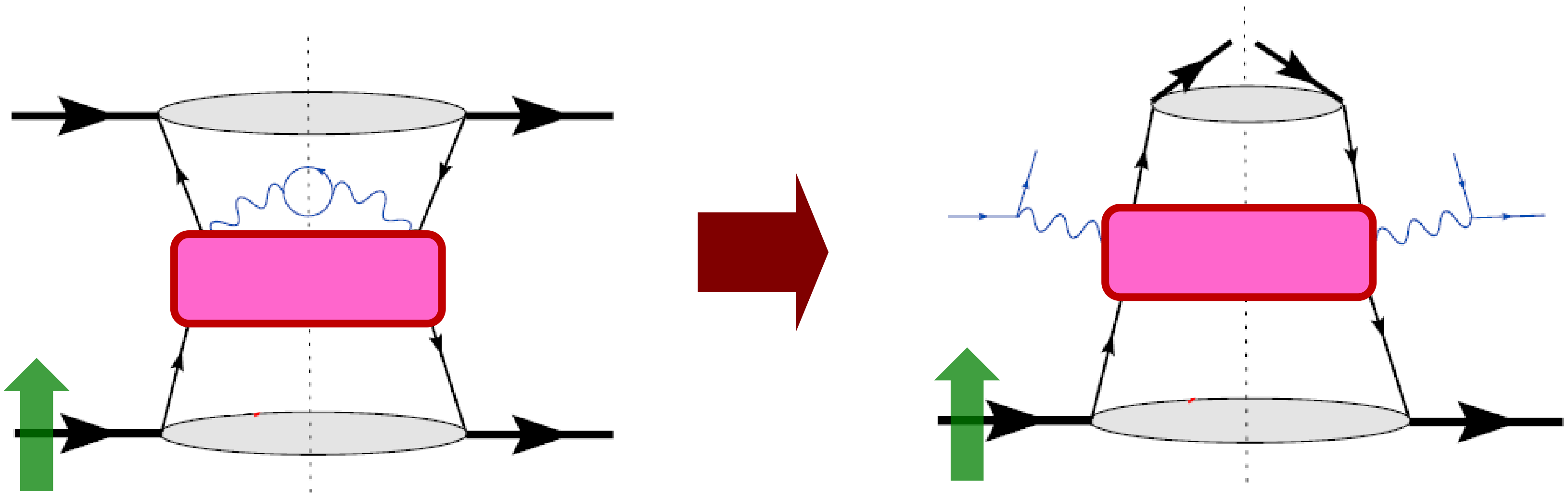
These predictions take into account the *process dependence* of the Sivers function

$$f_1^{\perp}(x,k_\perp) \sim \int d^2 z_\perp e^{-i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \int dz^- e^{ixpz} \langle N(p,S_\perp) | \psi^\dagger(0) \psi(z^-, \mathbf{z}_\perp) | N(p,S_\perp) \rangle$$

Sivers



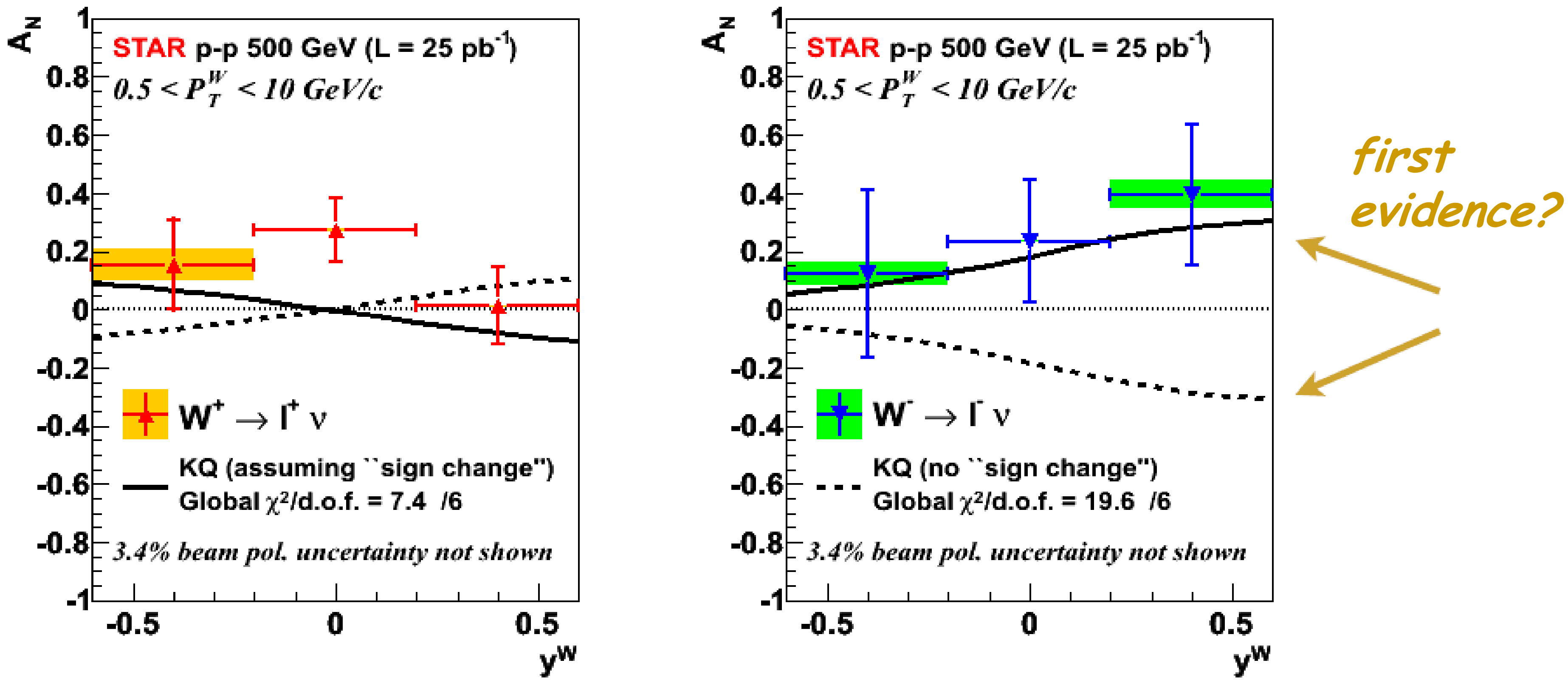
"T-odd"



$$f_1^{\perp}(x,k_\perp)\Big|_{DY} = - f_1^{\perp}(x,k_\perp)\Big|_{SIDIS}$$

W production $p^{\uparrow} + p \to W^{\pm}$ at RHIC

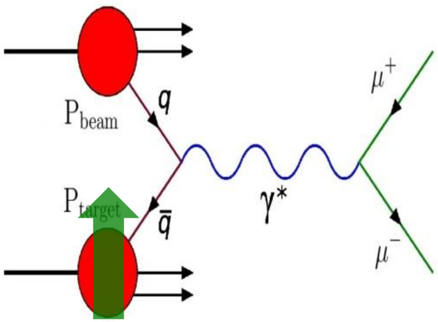
Run-2009
(arXiv:1511.06003)



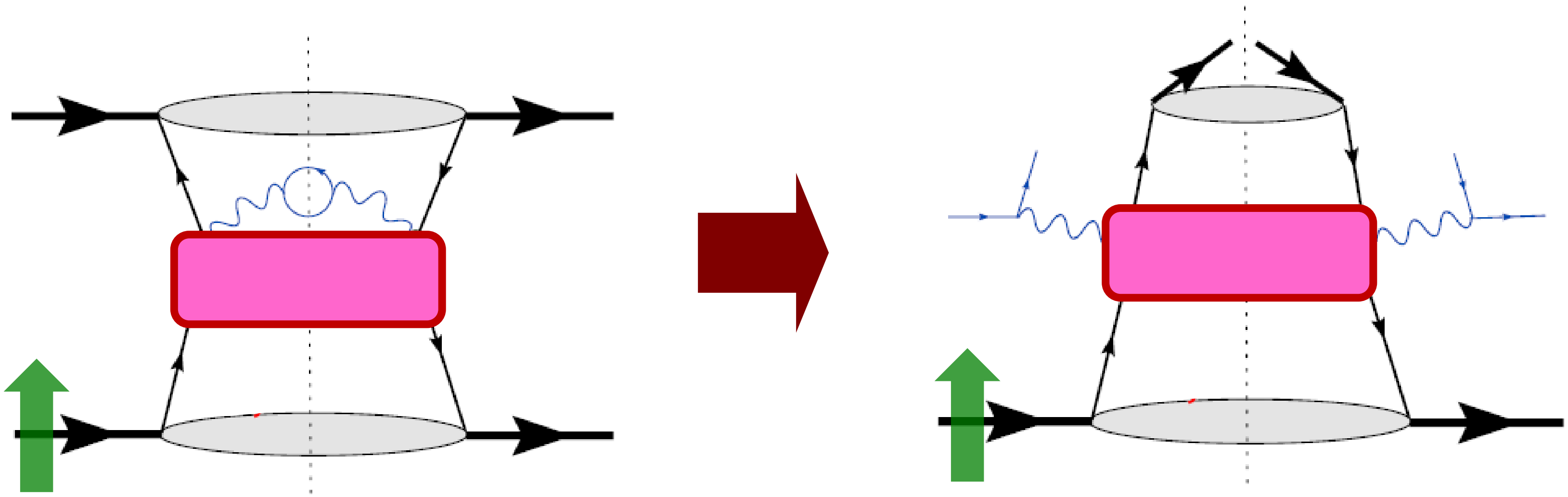
$$f_1^{\perp}(x,k_\perp)\Big|_{DY} = - f_1^{\perp}(x,k_\perp)\Big|_{SIDIS}$$

$$f_1^{\perp}(x,k_\perp) \sim \int d^2 z_\perp e^{-i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \int dz^- e^{ixpz} \langle N(p,S_\perp)|\psi^\dagger(0)\psi(z^-,\mathbf{z}_\perp)|N(p,S_\perp)\rangle$$

Sivers



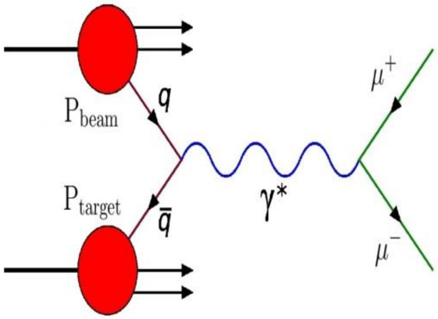
"T-odd"



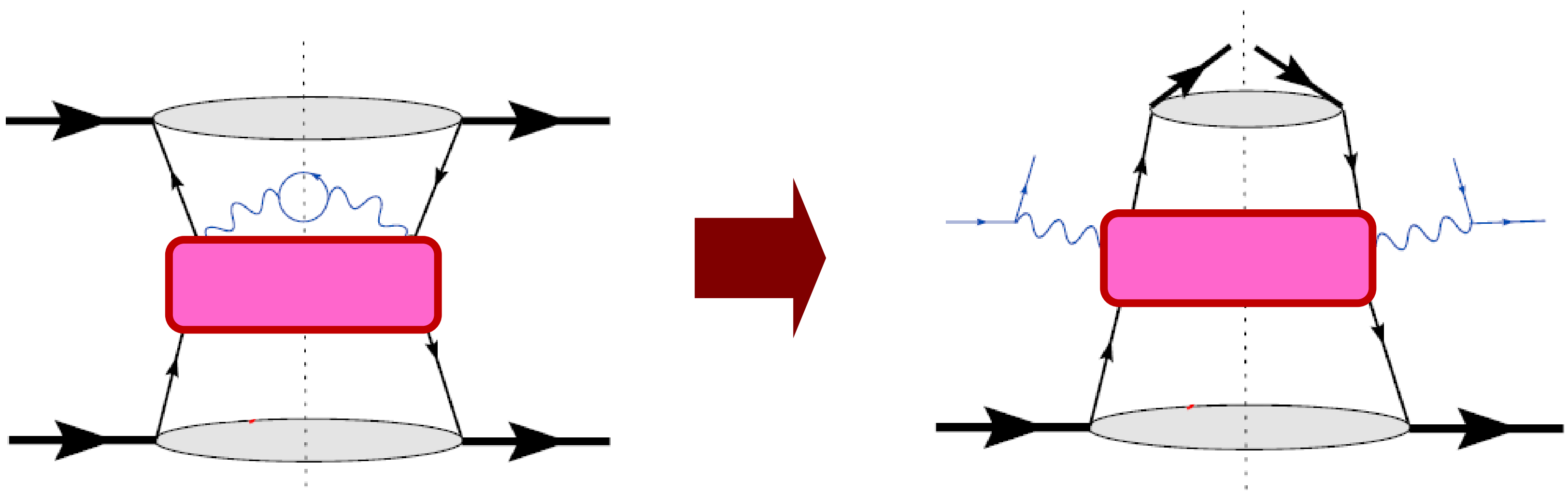
$$f_1^{\perp}(x,k_\perp)\Big|_{DY} = - f_1^{\perp}(x,k_\perp)\Big|_{SIDIS}$$

$$h_1^{\perp}(x,k_{\perp}) \sim \int d^2 z_{\perp} e^{-i\mathbf{k}_{\perp}\cdot\mathbf{z}_{\perp}} \int dz^- e^{ixpz} \langle N(p)|\psi^{\dagger}(0)\gamma^{\perp}\psi(z^-,\mathbf{z}_{\perp})|N(p)\rangle$$

Boer-Mulders



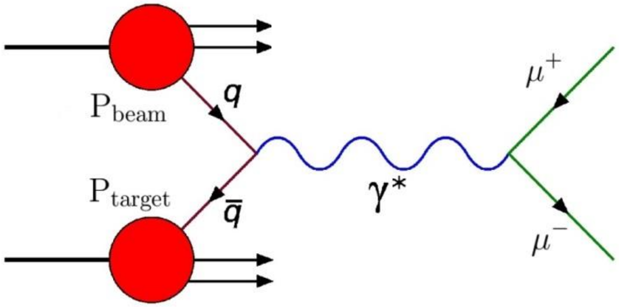
"T-odd"

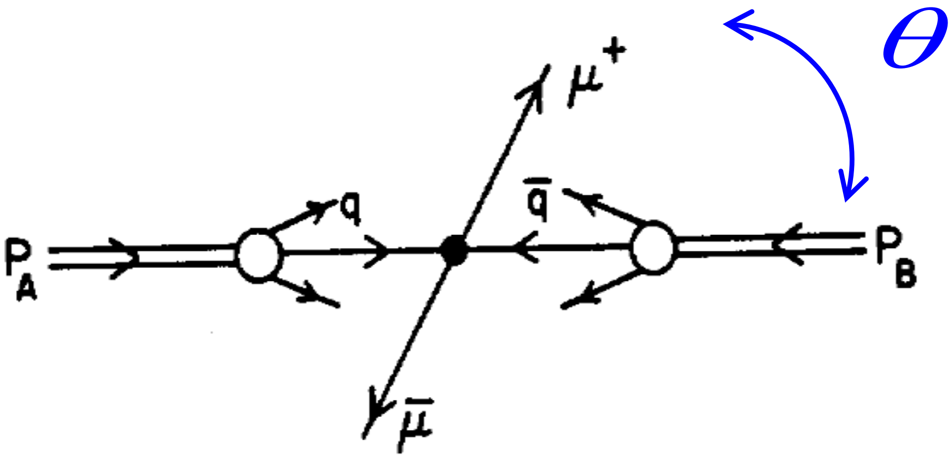


$$h_1^{\perp}(x,k_{\perp})\Big|_{DY} = - \; h_1^{\perp}(x,k_{\perp})\Big|_{SIDIS}$$

$$h_1^{\perp}(x,k_{\perp}) \sim \int d^2 z_{\perp} e^{-i\mathbf{k}_{\perp}\cdot\mathbf{z}_{\perp}} \int dz^- e^{ixpz} \langle N(p) | \psi^{\dagger}(0) \gamma^{\perp} \psi(z^-, \mathbf{z}_{\perp}) | N(p) \rangle$$

Boer-Mulders

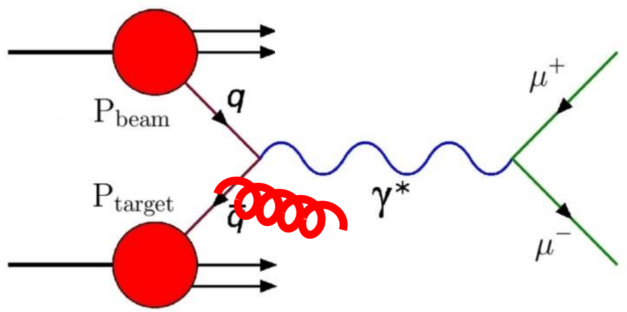


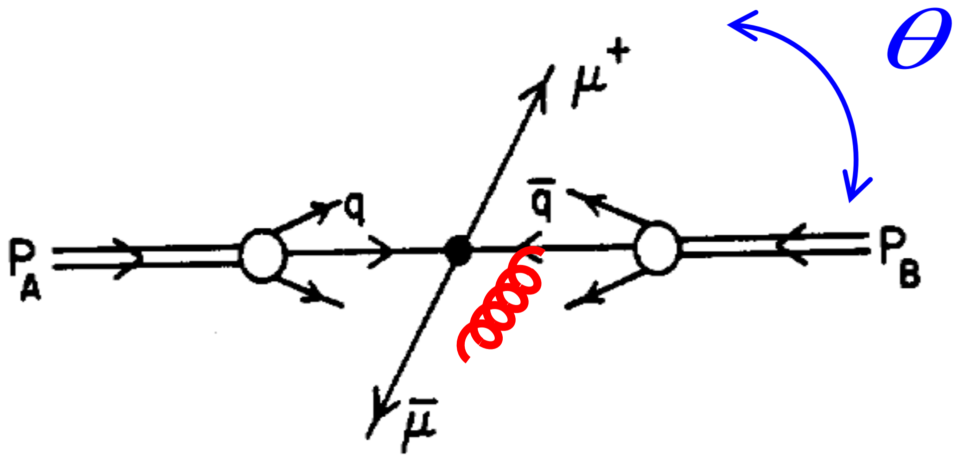


$$\frac{1}{\sigma_0}\frac{d\sigma}{d\Omega} = 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi$$

$$h_1^{\perp}(x,k_\perp) \sim \int d^2 z_\perp e^{-i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \int dz^- e^{ixpz} \langle N(p) | \psi^\dagger(0)\gamma^\perp \psi(z^-, \mathbf{z}_\perp) | N(p) \rangle$$

Boer-Mulders





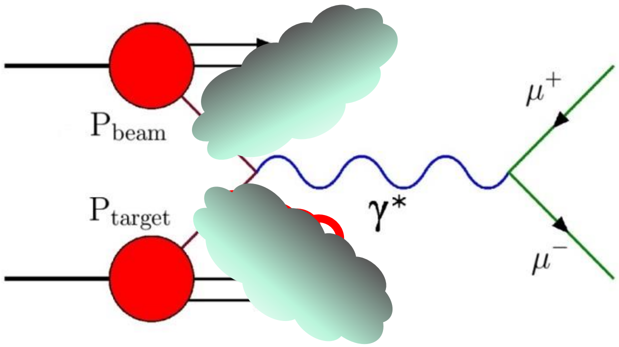
$$\frac{1}{\sigma_0}\frac{d\sigma}{d\Omega} = 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi$$

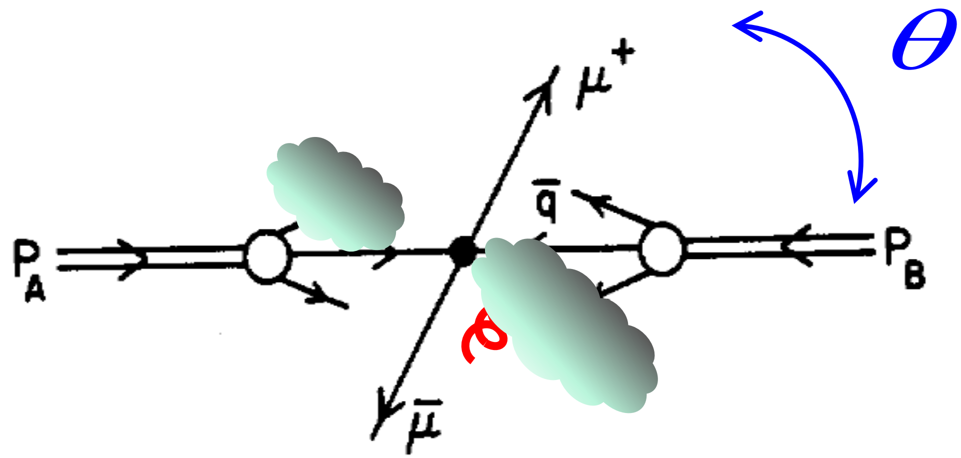
$$1-\lambda, \quad \mu, \quad \nu \quad \propto \alpha_s q_T$$

$$1-\lambda-2\nu = 0$$ **Lam-Tung relation ('78)**

$$h_1^{\perp}(x,k_\perp) \sim \int d^2 z_\perp e^{-i\mathbf{k}_\perp\cdot\mathbf{z}_\perp} \int dz^- e^{ixpz} \langle N(p)|\psi^\dagger(0)\gamma^\perp\psi(z^-,\mathbf{z}_\perp)|N(p)\rangle$$

Boer-Mulders





$$\frac{1}{\sigma_0}\frac{d\sigma}{d\Omega} = 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

$$\nu \gg \alpha_S q_T$$

$$1 - \lambda - 2\nu \neq 0$$ ~~Lam-Tung relation ('78)~~

$h_1^{\perp}(x,k_\perp)$ and/or novel nonpert. mechanisms

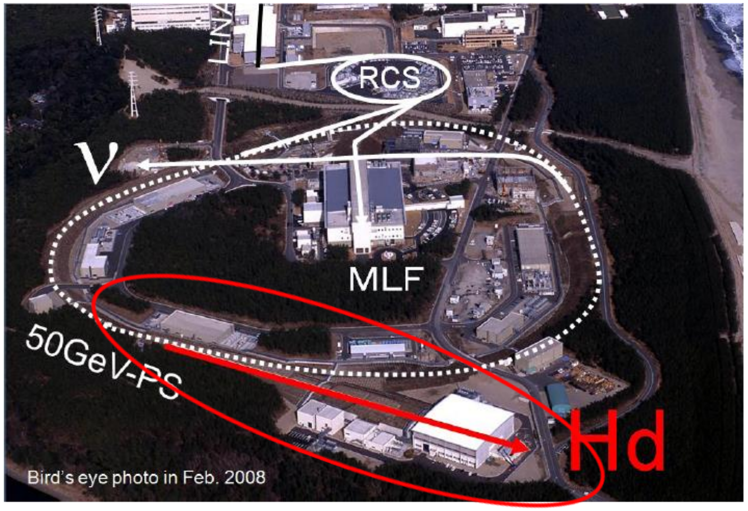
High momentum beam line at J-PARC

- Primary beam (proton)

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

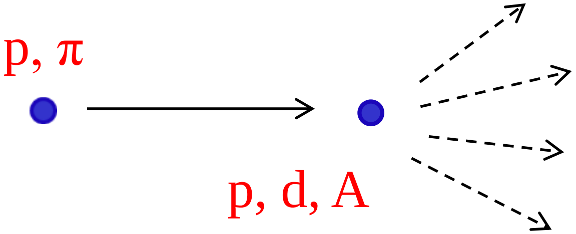
$$L = 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

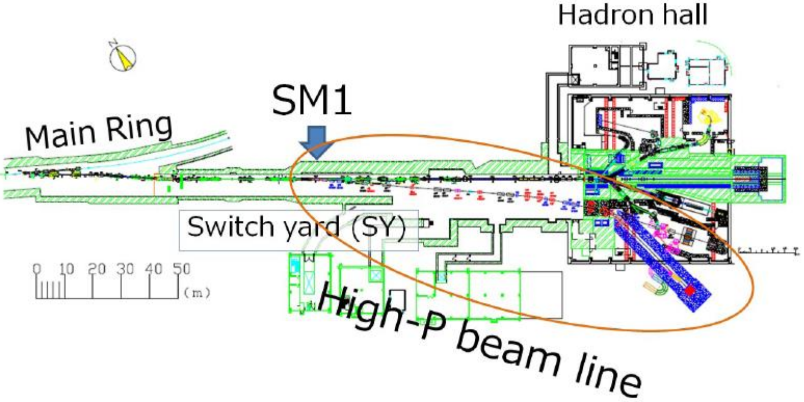
Hadron Facility at J-PARC

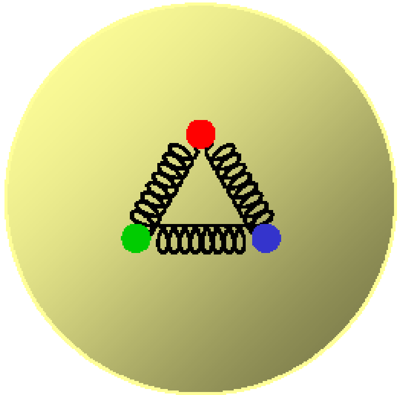


- Secondary beam (pion)

E = 15-20GeV



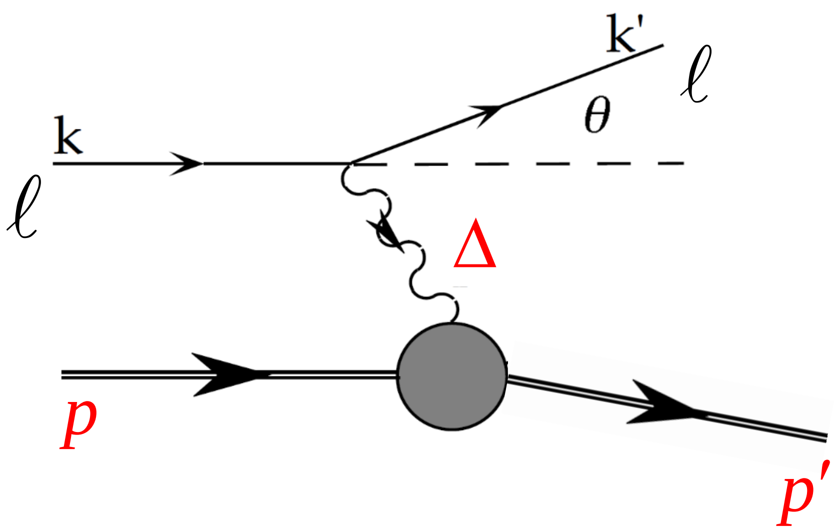


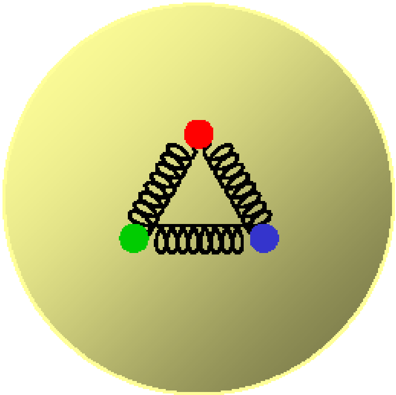


$$\langle N(p')|\psi^{\dagger}(0)\psi(0)|N(p)\rangle$$

$$\langle N(p')|\bar{\psi}(0)\gamma^{\mu}\psi(0)|N(p)\rangle \sim \bar{u}(p')\left\{\gamma^{\mu}F_1(\Delta^2)+\frac{i\sigma^{\nu\mu}\Delta_{\nu}}{2M_N}F_2(\Delta^2)\right\}u(p)$$

$$\Delta = p' - p$$

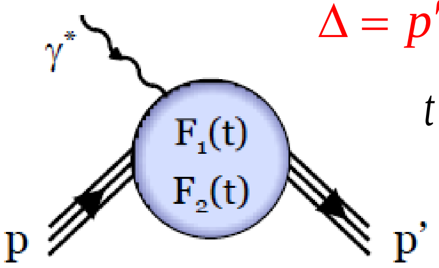


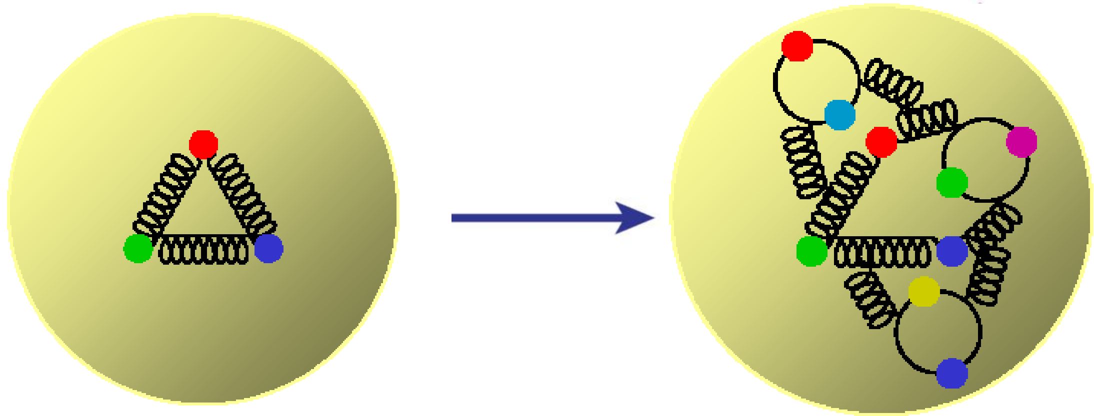


$$\langle N(p')|\psi^\dagger(0)\psi(0)|N(p)\rangle$$

$\Delta = p' - p$

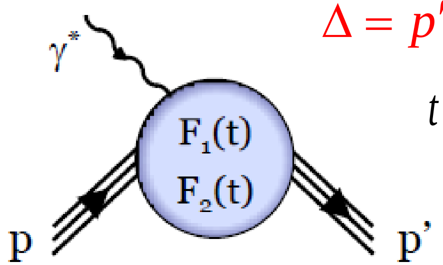
$t = \Delta^2$





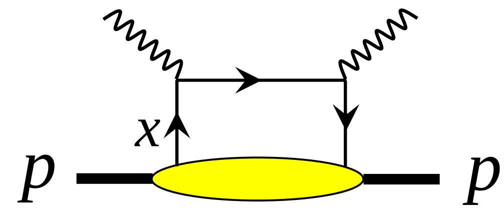
$$\langle N(p') | \psi^\dagger(0)\psi(0) | N(p) \rangle$$

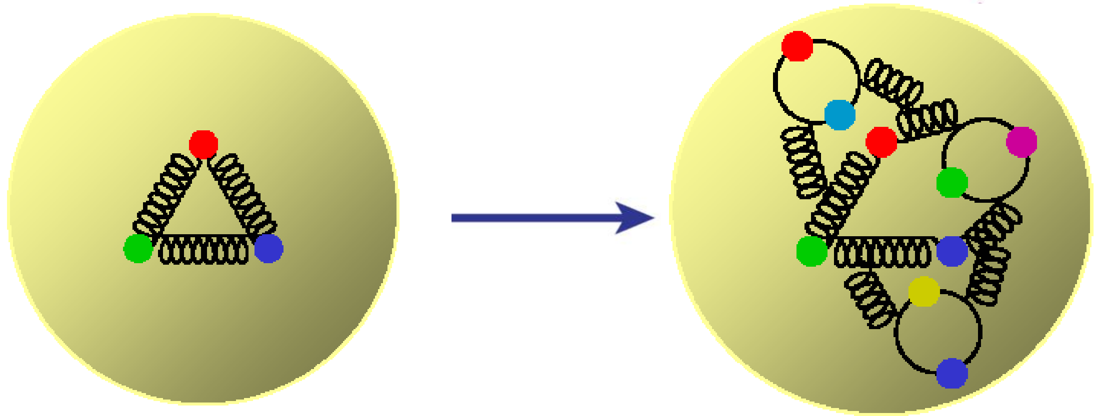
$$\int dz^- e^{ixpz} \langle N(p) | \psi^\dagger(0)\psi(z^-) | N(p) \rangle$$



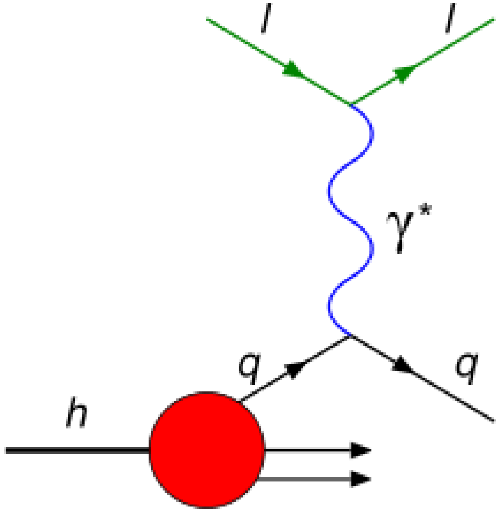
$$\Delta = p' - p$$

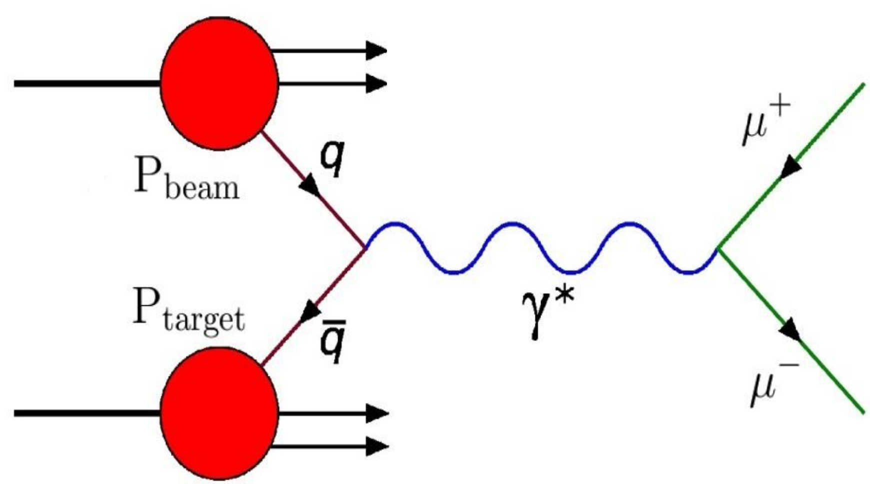
$$t = \Delta^2$$

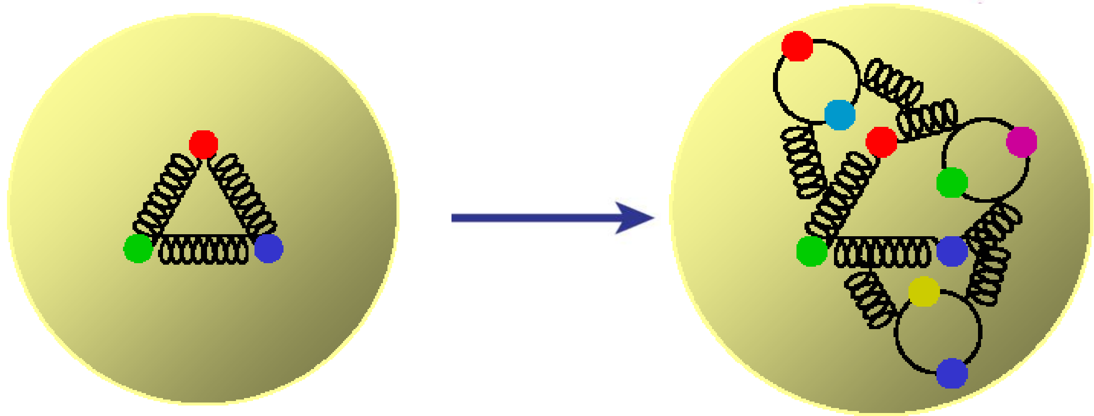




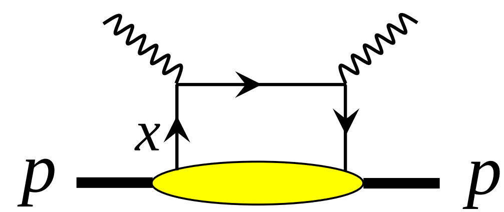
$$\int dz^{-} e^{ixpz} \langle N(p) | \psi^{\dagger}(0) \psi(z^{-}) | N(p) \rangle$$

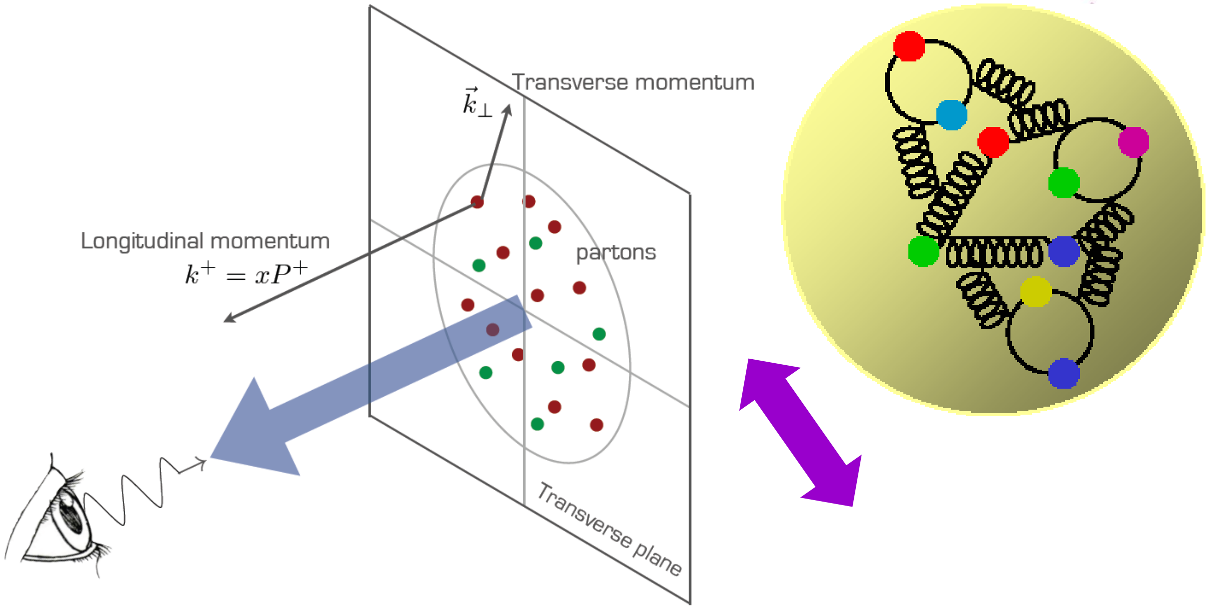






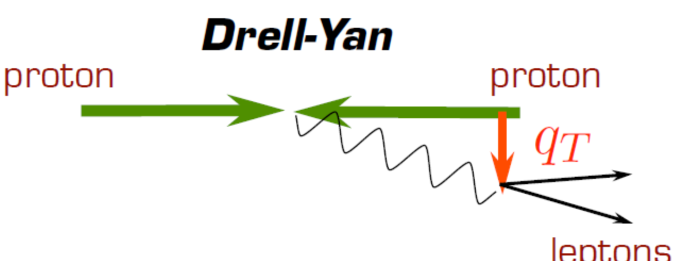
$$\int dz^- e^{ixpz} \langle N(p) | \psi^\dagger(0) \psi(z^-) | N(p) \rangle$$

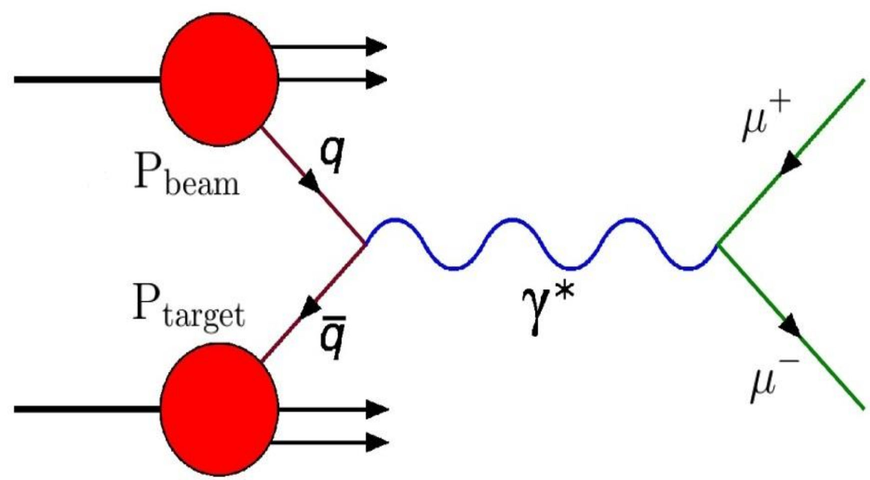


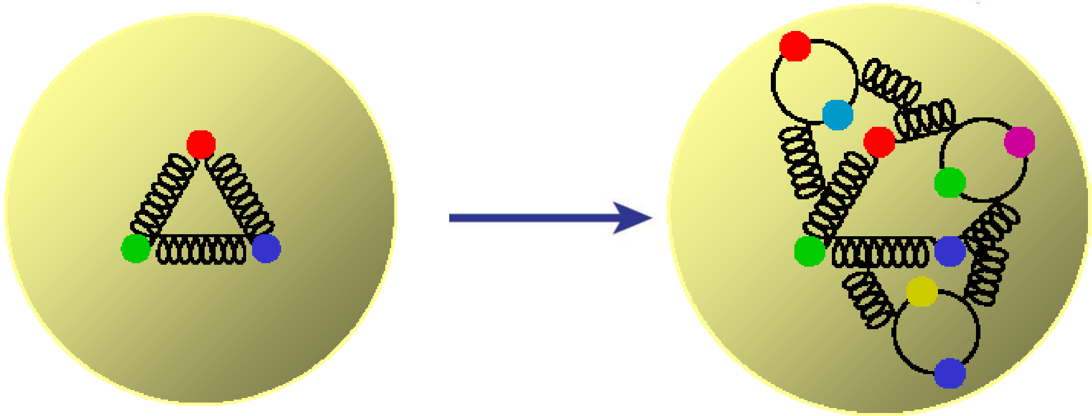


$$\int d^2 z_\perp e^{-i\mathbf{k}_\perp \cdot \mathbf{z}_\perp} \int dz^- e^{ixpz} \langle N(p) | \psi^\dagger(0) \psi(z^-, \mathbf{z}_\perp) | N(p) \rangle$$

TMD





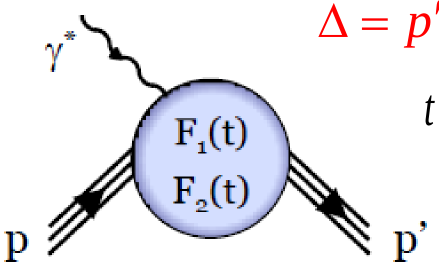


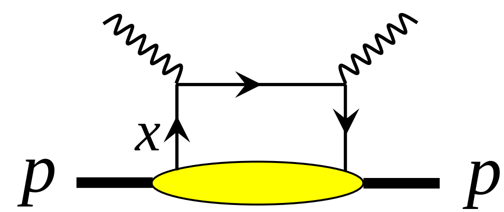
$$\langle N(p') | \psi^\dagger(0)\psi(0) | N(p) \rangle$$

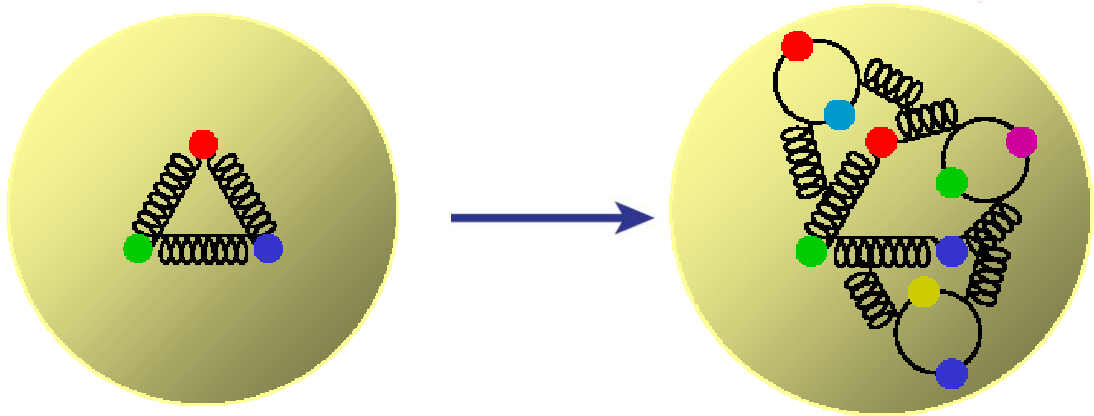
$$\int dz^- e^{ixpz} \langle N(p) | \psi^\dagger(0)\psi(z^-) | N(p) \rangle$$

$\Delta = p' - p$

$t = \Delta^2$

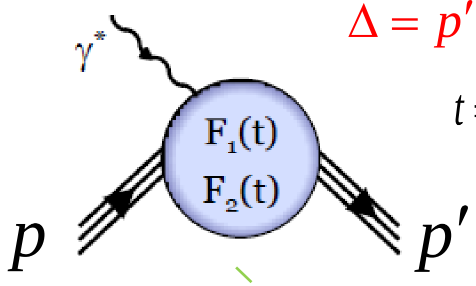






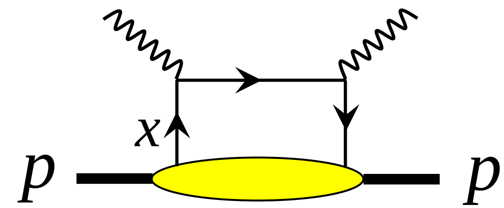
$$\langle N(p')|\psi^{\dagger}(0)\psi(0)|N(p)\rangle$$

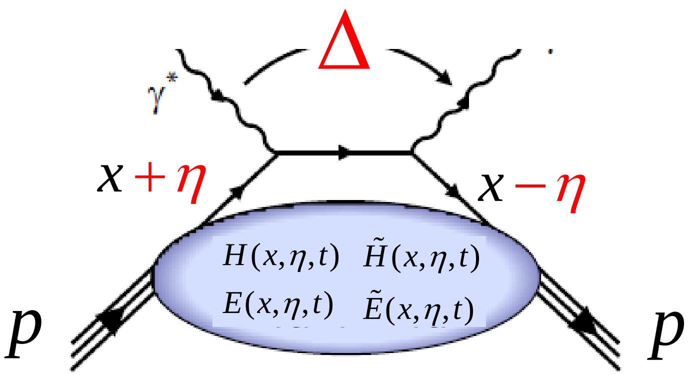
$$\int dz^{-} e^{ixpz}\langle N(p)|\psi^{\dagger}(0)\psi(z^{-})|N(p)\rangle$$



$\Delta = p' - p$

$t = \Delta^2$

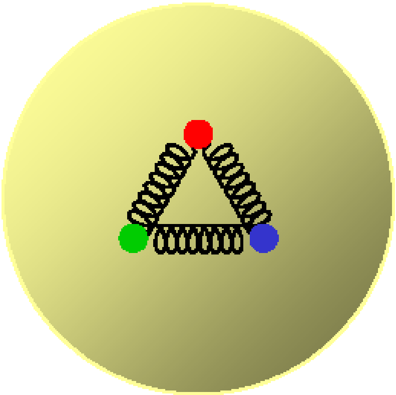




GPD

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

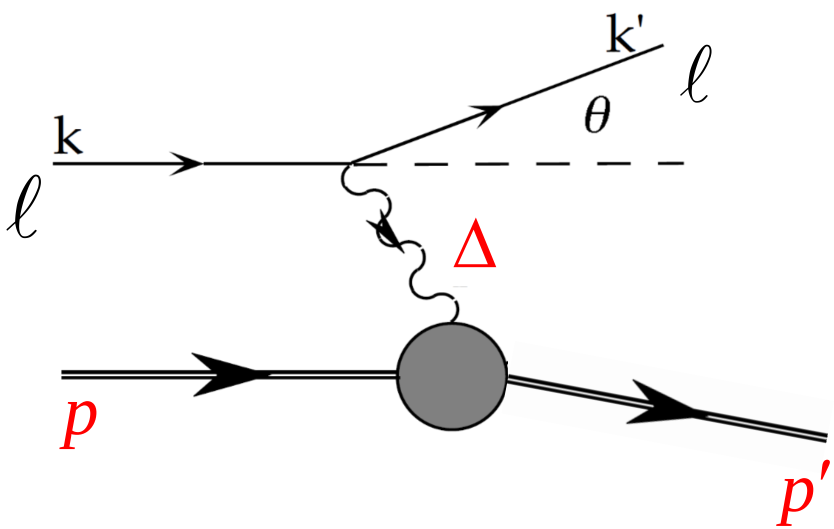
$$\int dz^{-} e^{i(x+\eta)pz}\langle N(p')|\psi^{\dagger}(0)\psi(z^{-})|N(p)\rangle$$



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

$$\langle N(p')|\bar{\psi}(0)\gamma^{\mu}\psi(0)|N(p)\rangle \sim \bar{u}(p')\left\{\gamma^{\mu}F_1(\Delta^2)+\frac{i\sigma^{\nu\mu}\Delta_{\nu}}{2M_N}F_2(\Delta^2)\right\}u(p)$$

$$\Delta = p' - p$$

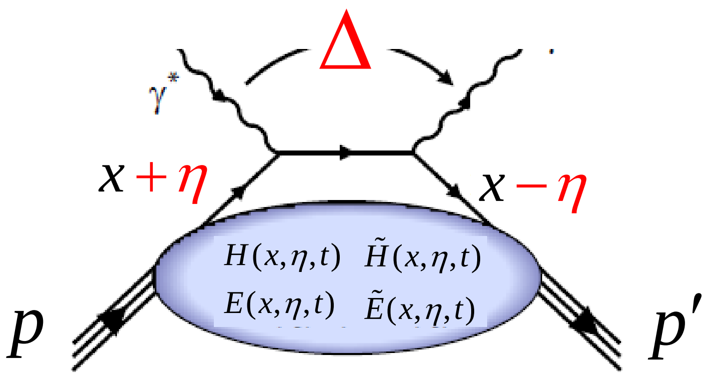


$$\bar{P} = \frac{p + p'}{2}$$

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

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

GPD



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

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

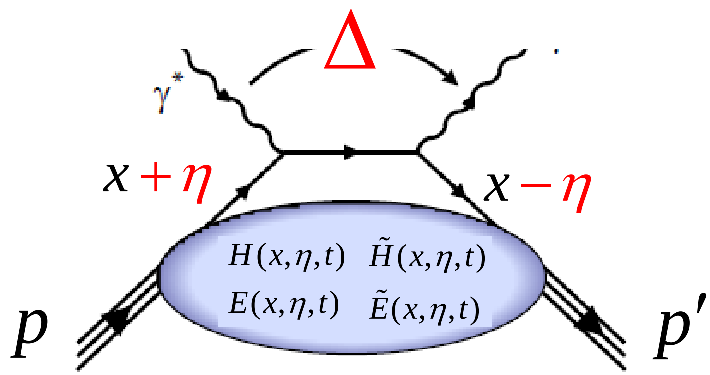
$$\bar{P} = \frac{p+p'}{2}$$

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

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

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

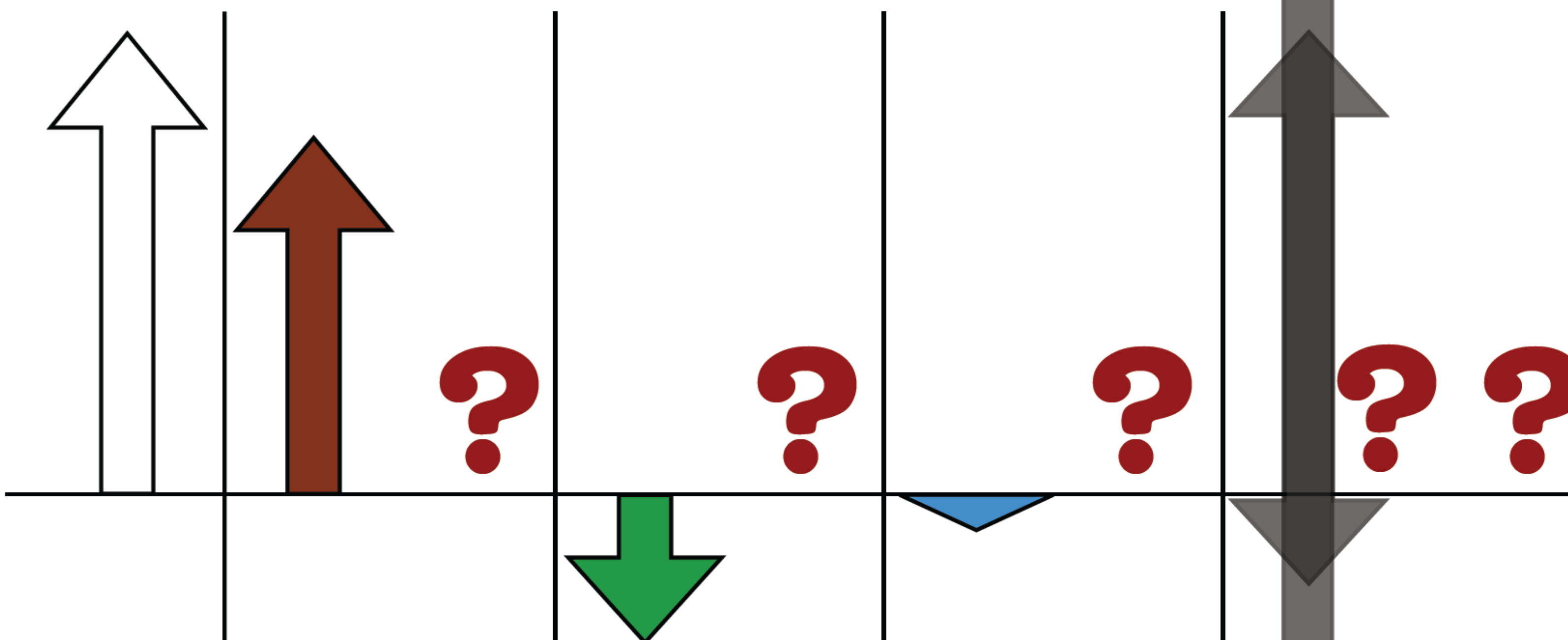
GPD



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

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

Status of spin sum rule



Proton spin

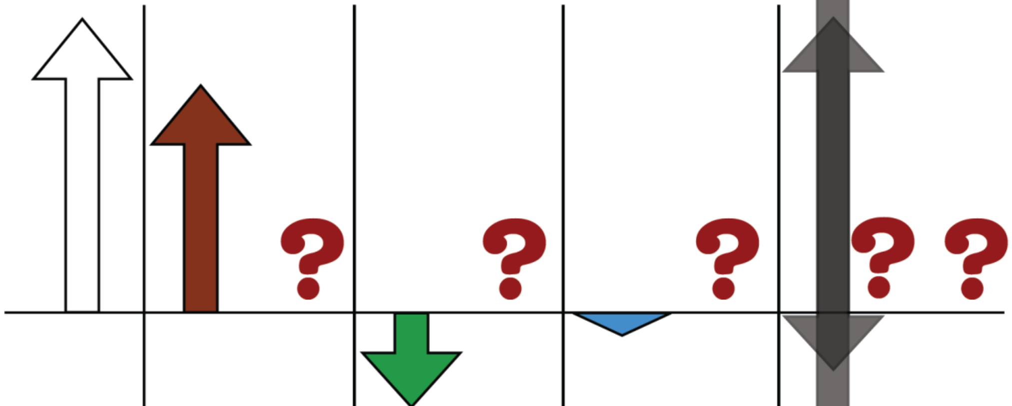
$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)

NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

from A. Bacchetta, HEP2016

Status of spin sum rule

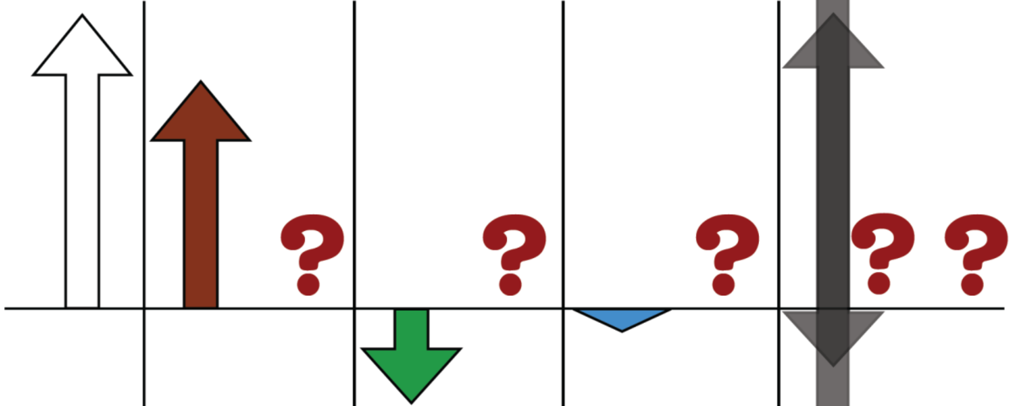


Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
	79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)
NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

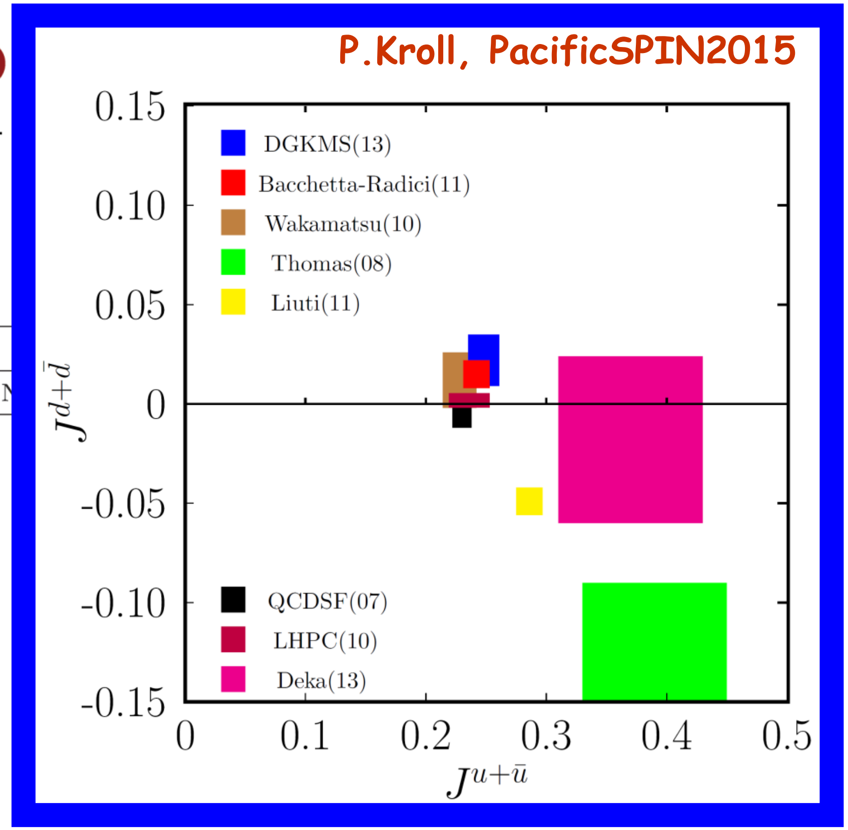
from A. Bacchetta, HEP2016

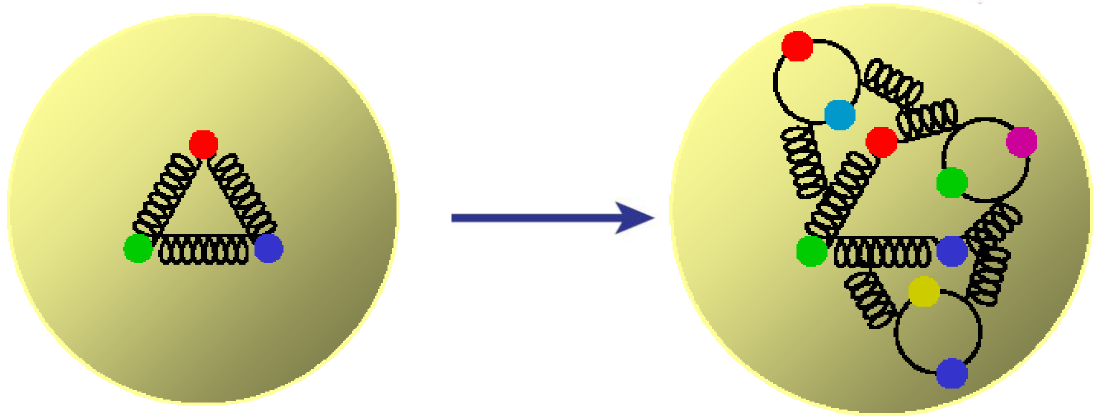
Status of spin sum rule



Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		
	79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		N

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)
NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13



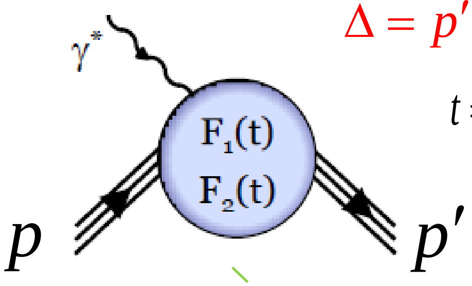


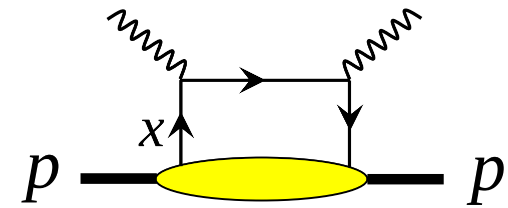
$$\langle N(p')|\psi^\dagger(0)\psi(0)|N(p)\rangle$$

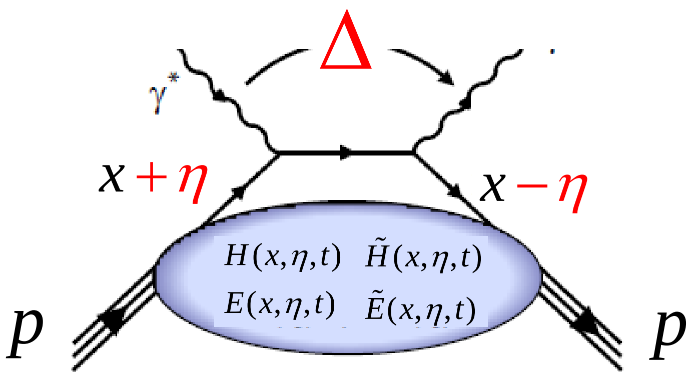
$$\int dz^- e^{ixpz}\langle N(p)|\psi^\dagger(0)\psi(z^-)|N(p)\rangle$$

$\Delta = p' - p$

$t = \Delta^2$



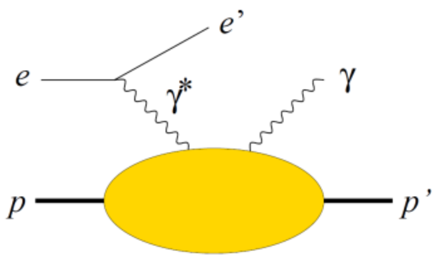




GPD

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

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



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

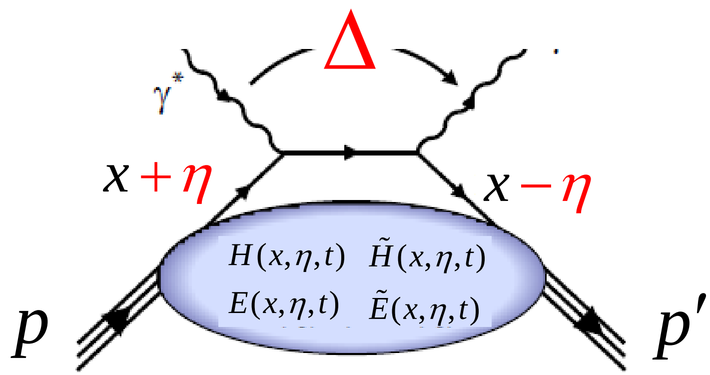
JLab, HERMES, COMPASS,…

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

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

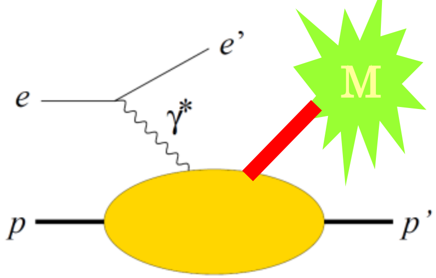
$$J_q = \frac{1}{2}\int_{-1}^{1} dx x\left(H(x,\eta,0)+E(x,\eta,0)\right)$$

GPD



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

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



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

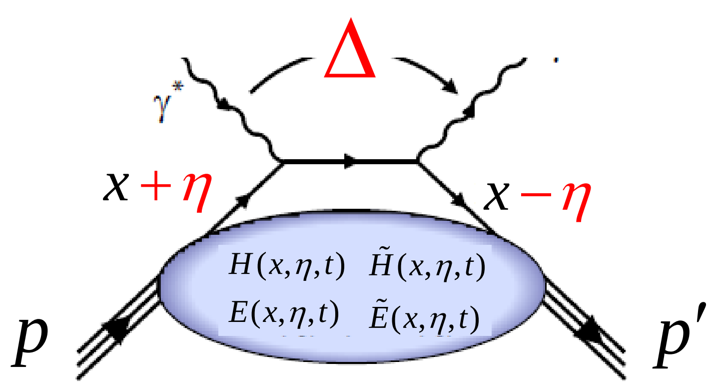
JLab, HERMES, COMPASS,...

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

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

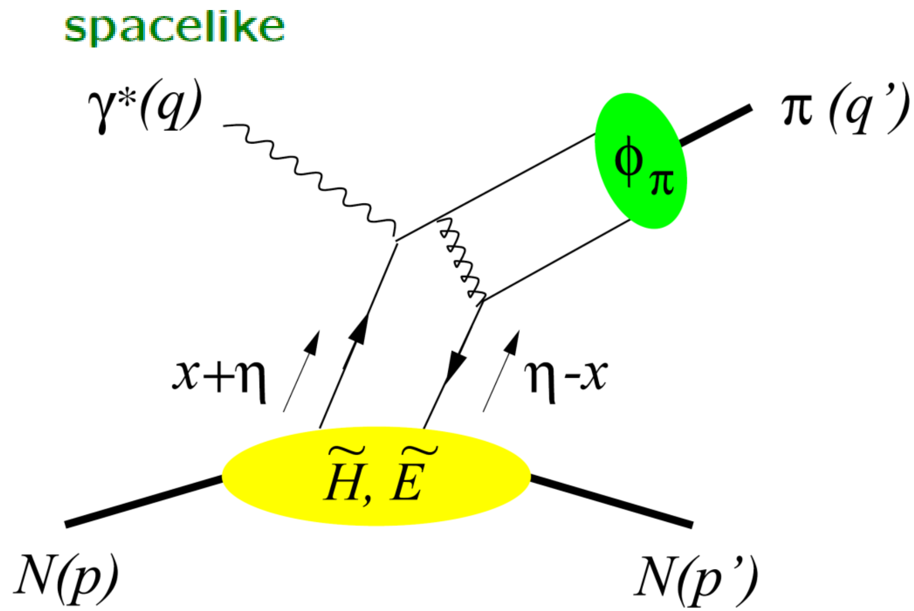
$$J_q = \frac{1}{2}\int_{-1}^{1} dx x \left(H(x,\eta,0) + E(x,\eta,0) \right)$$

GPD



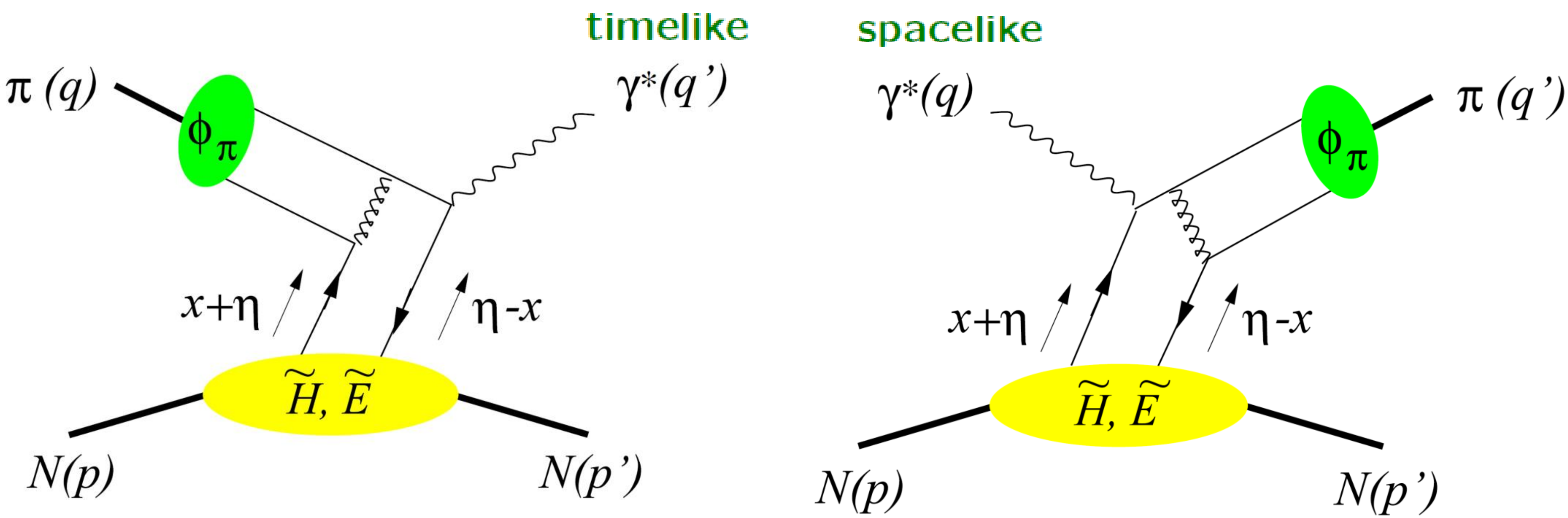
$$-2\eta\bar{P} = \Delta$$

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



DVMP@JLab

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



DVMP@JLab

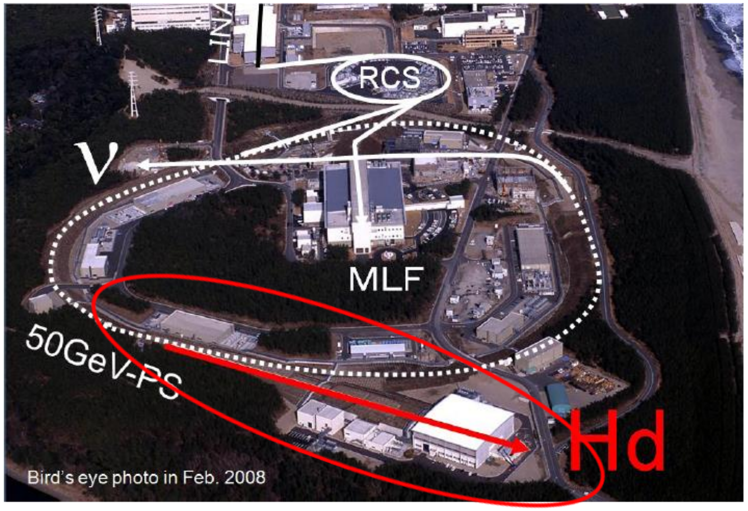
High momentum beam line at J-PARC

- Primary beam (proton)

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

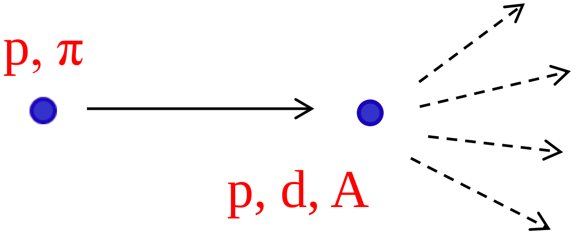
$$L = 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

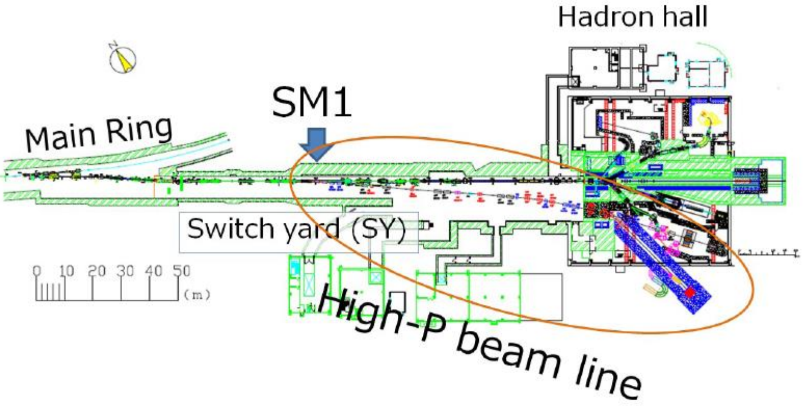
Hadron Facility at J-PARC



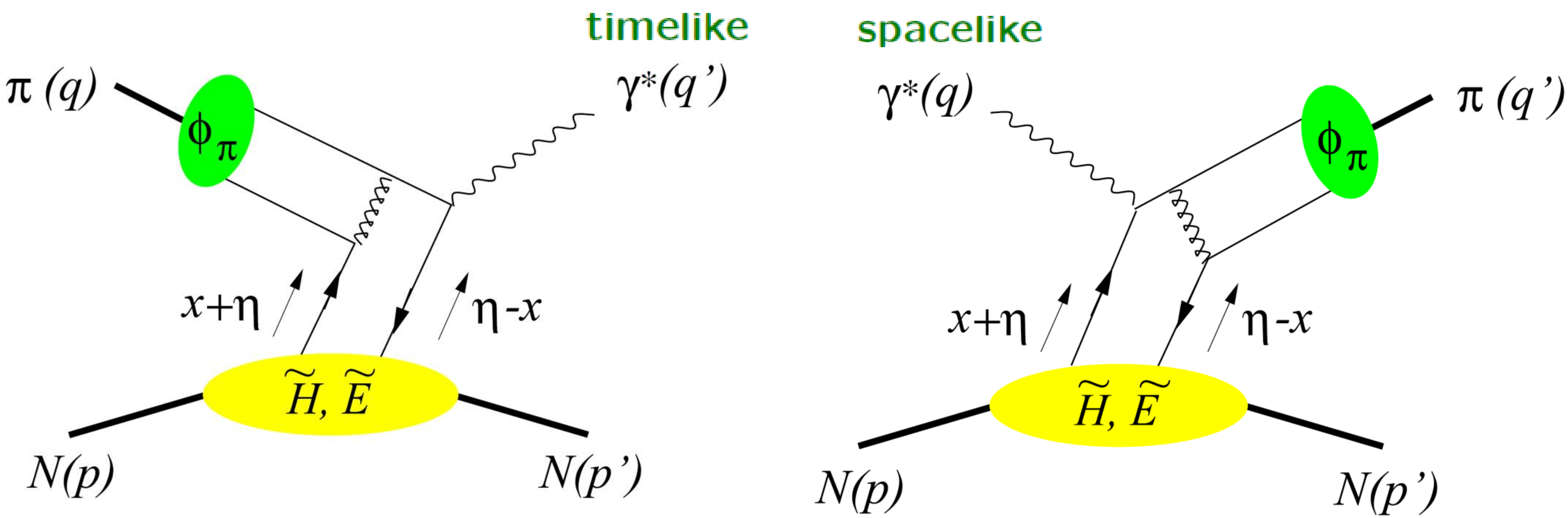
- Secondary beam (pion)

E = 15-20GeV





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



DVMP@JLab

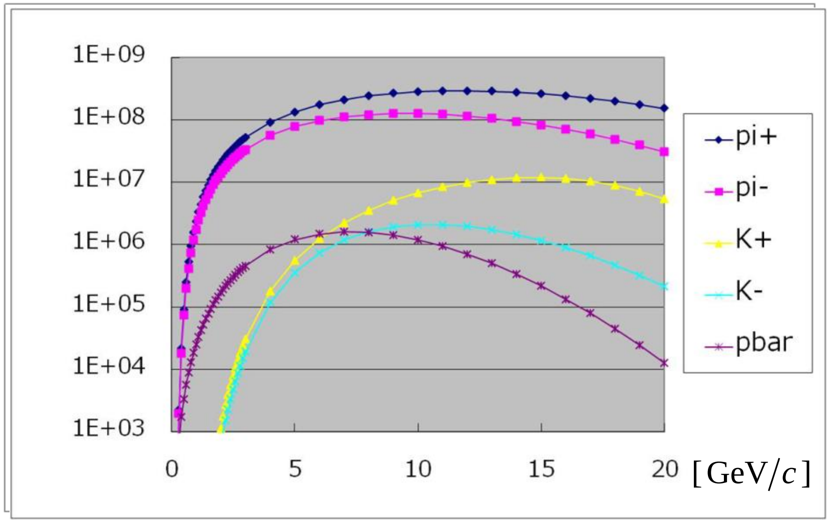
High-momentum beamline

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

Unseparated Secondary Beam Intensity

beam loss limit @ SM1:15kW

(limited by the thickness of the tunnel wall)



0° extraction angle

high intensity

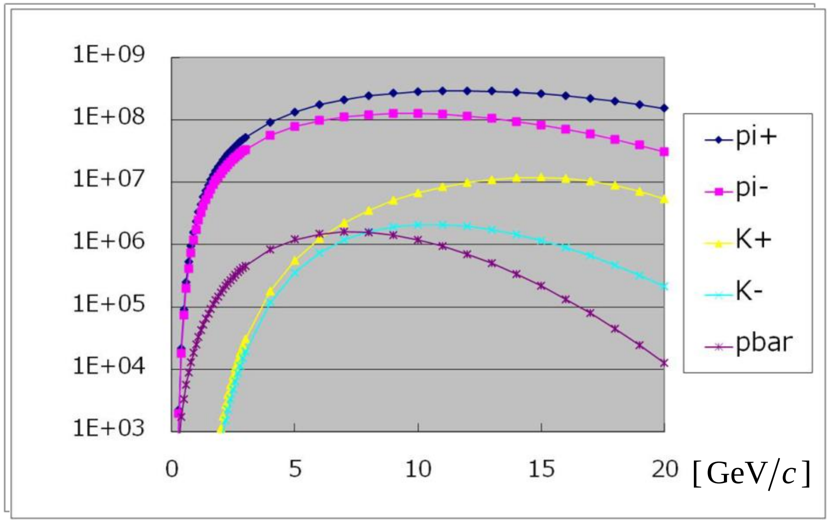
High-momentum beamline

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

Unseparated Secondary Beam Intensity

beam loss limit @ SM1:15kW

(limited by the thickness of the tunnel wall)



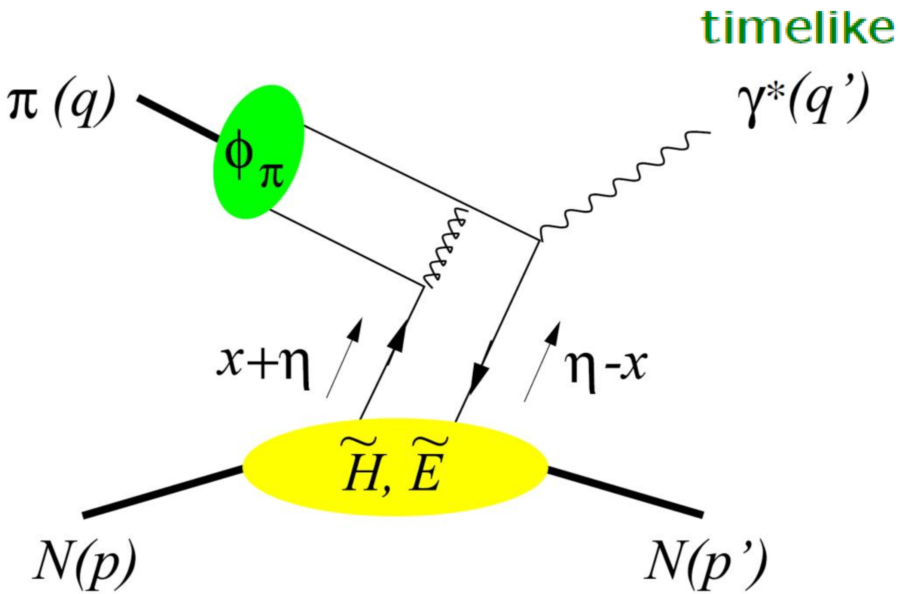
0° extraction angle

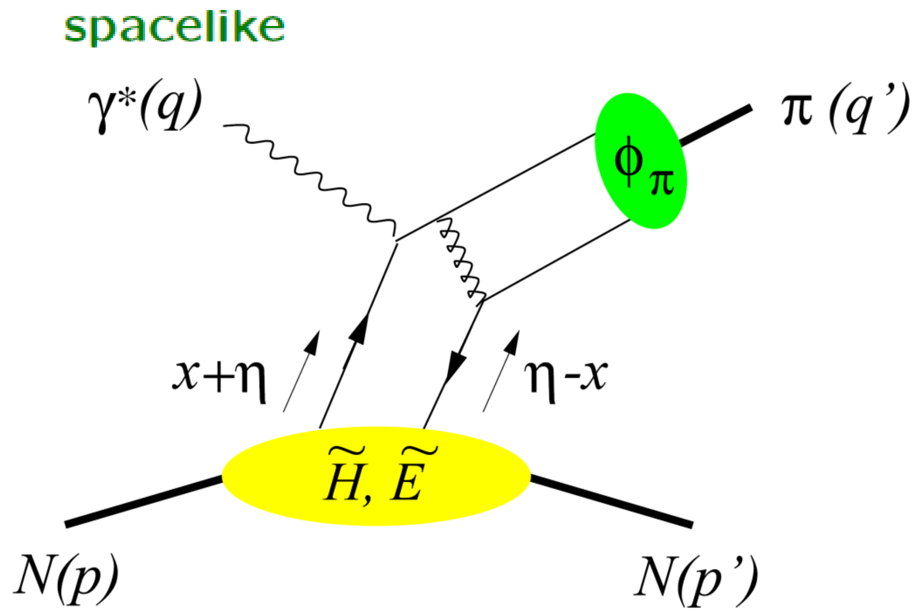
high intensity

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

best suited to study meson-induced hard exclusive processes

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



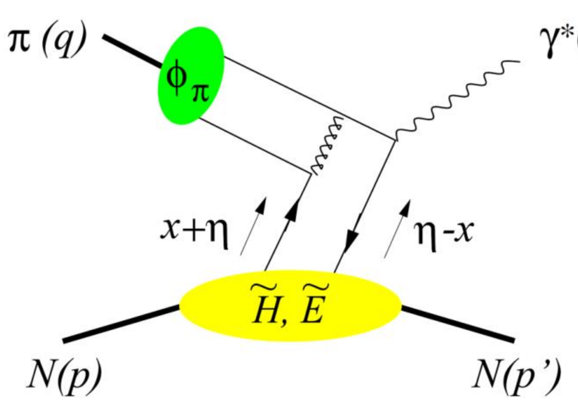


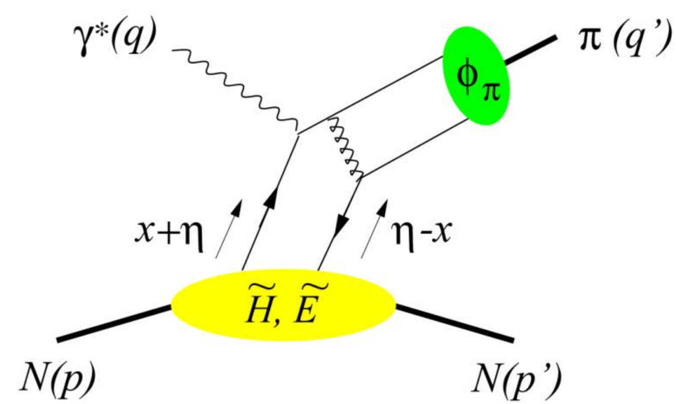
@J-PARC

DVMP@JLab

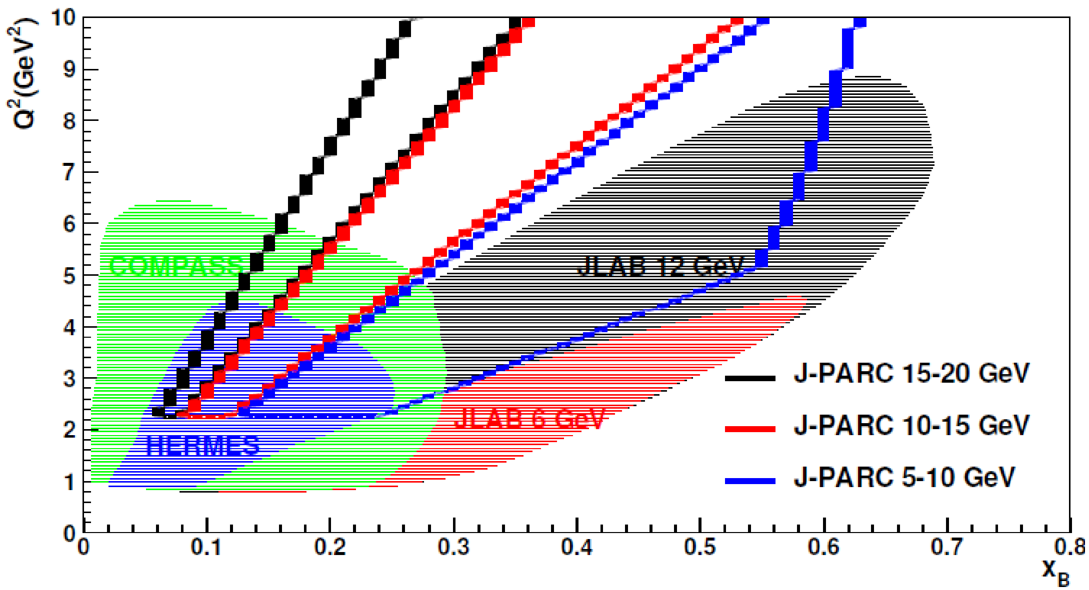
Pion beams reveal $\tilde{H}, \tilde{E}$ Generalized Parton distributions

timelike spacelike





@J-PARC **DVMP@JLab**



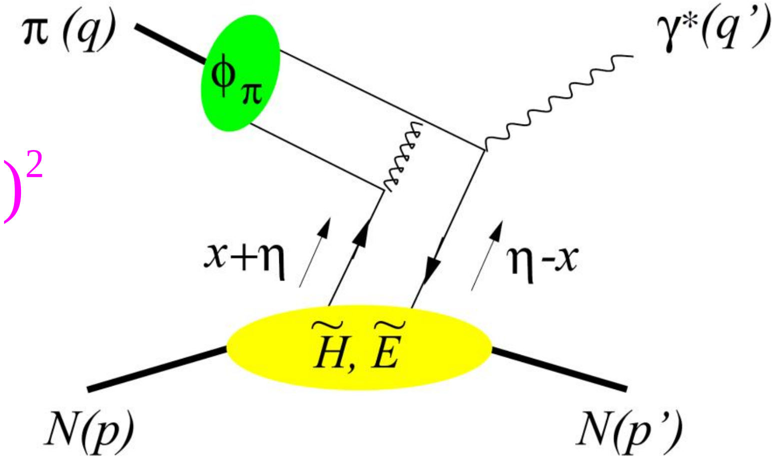
Exclusive lepton pair production in πN scattering

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

Berger, Diehl, Pire, PLB523(2001)265

"exclusive limit of DY"

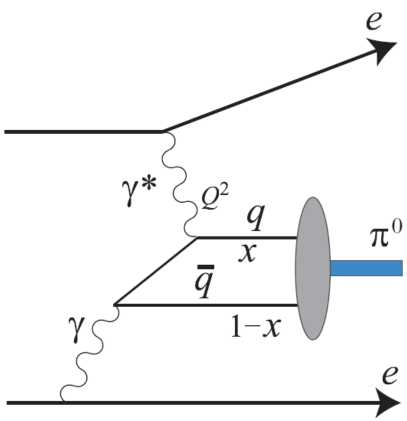
small $t = \Delta^2 = (q - q')^2$



Exclusive lepton pair production in πN scattering

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

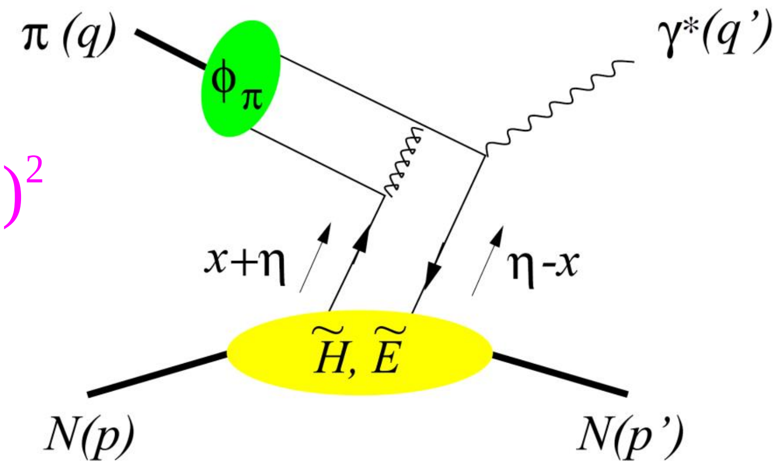
Berger, Diehl, Pire, PLB523(2001)265



@Belle, Babar

"exclusive limit of DY"

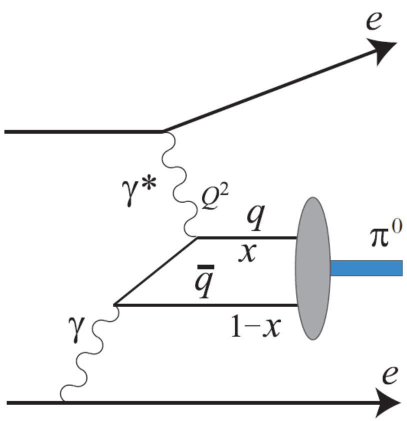
small $t = \Delta^2 = (q - q')^2$



Exclusive lepton pair production in πN scattering

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

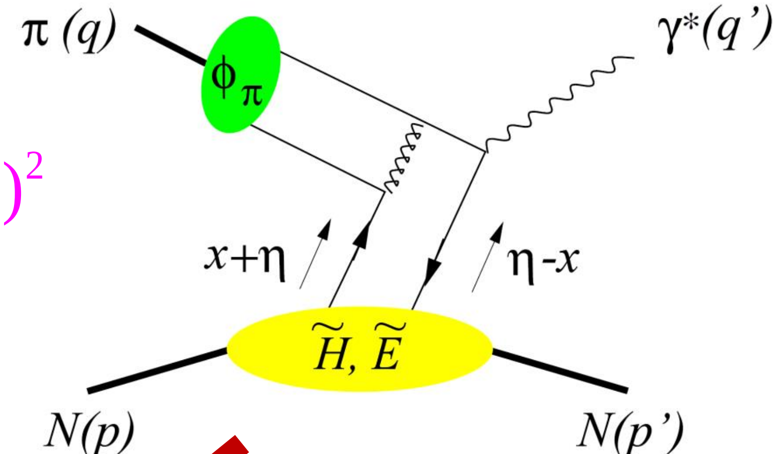
Berger, Diehl, Pire, PLB523(2001)265



@Belle, Babar

"exclusive limit of DY"

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



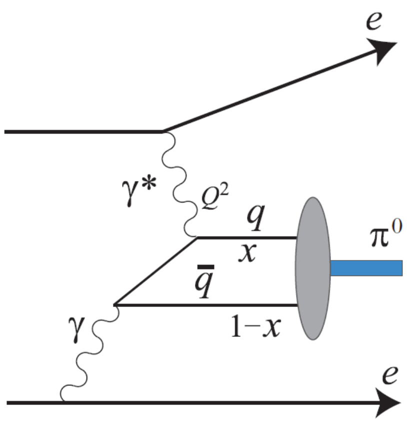
$t \to 0$

$\Delta q(x)$

Exclusive lepton pair production in πN scattering

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

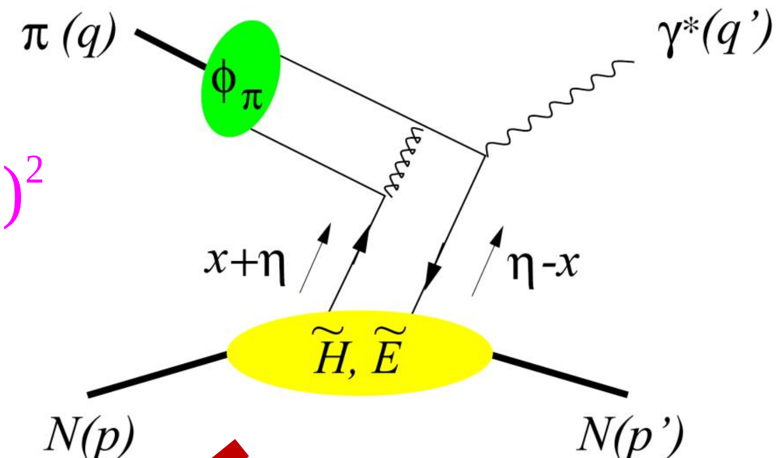
Berger, Diehl, Pire, PLB523(2001)265



@Belle, Babar

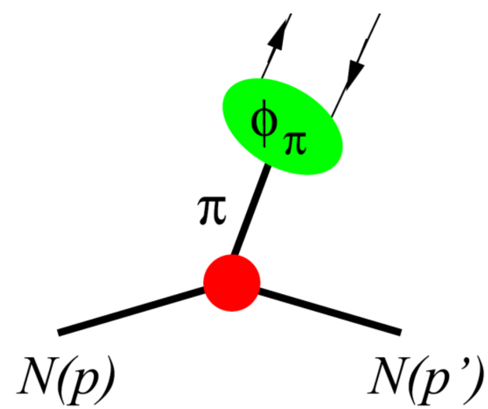
"exclusive limit of DY"

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



$\Delta q(x)$

$t \to 0$

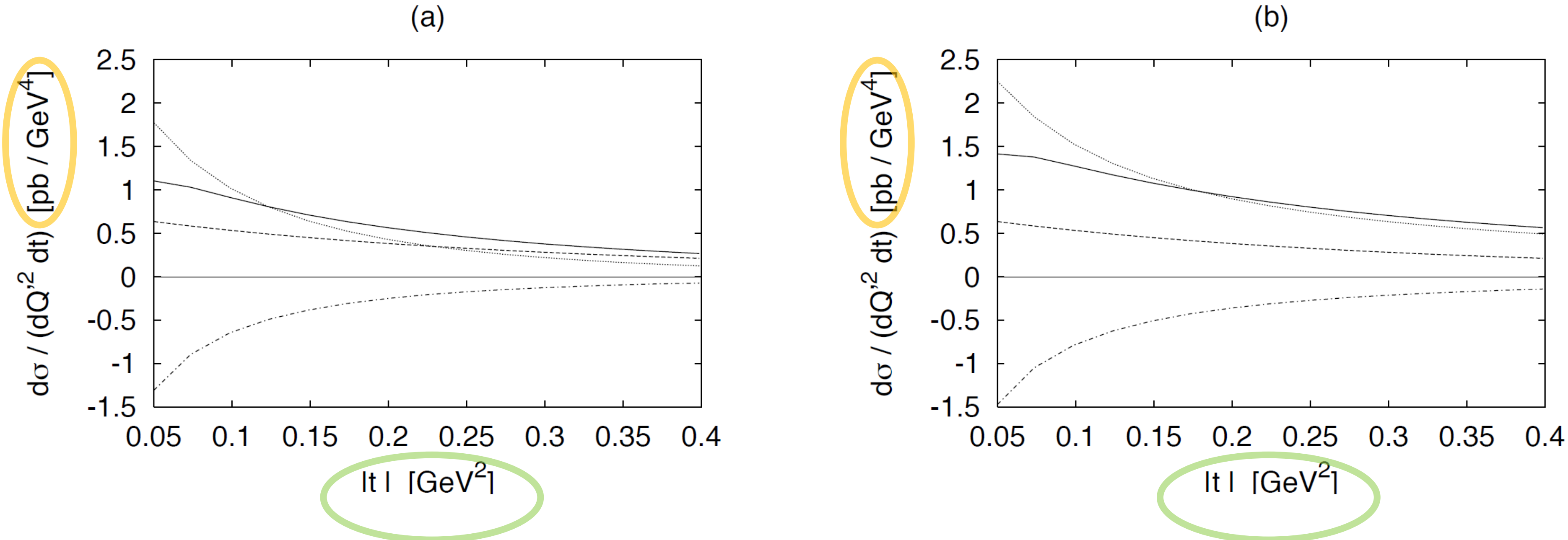


LO Estimates

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

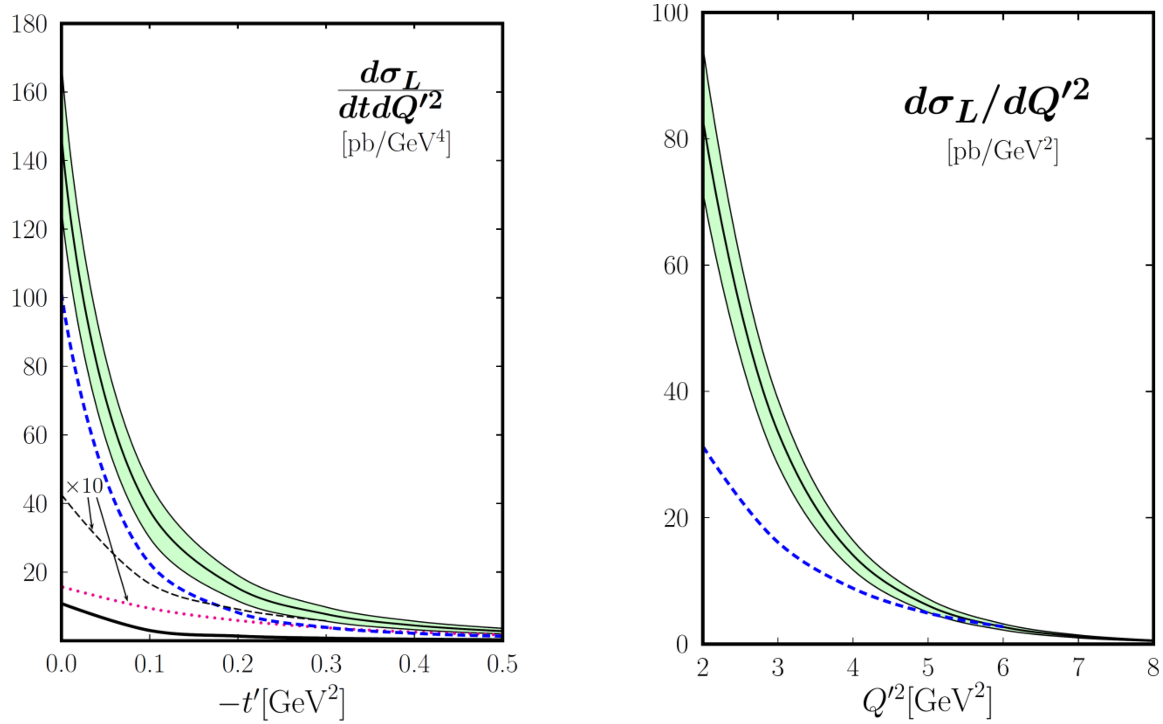
Berger, Diehl, Pire, PLB523(2001)265

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



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

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



$Q'^2 = 4\,\text{GeV}^2$ and $s = 20(30)\,\text{GeV}^2$ solid (blue dashed)lines with error bands

solid (dotted, dashed) line: interference, $|\langle \widetilde{H}^{(3)} \rangle|^2$, leading-twist contribution

time-like pion FF: $Q'^2|F_\pi(Q'^2)| = 0.88 \pm 0.04\,\text{GeV}^2$ (CLEO, BaBar, $J/\Psi \to \pi^+\pi^-$)

phase from disp. rel. Belicka et al(11) for $Q'^2 < 7\,\text{GeV}^2$

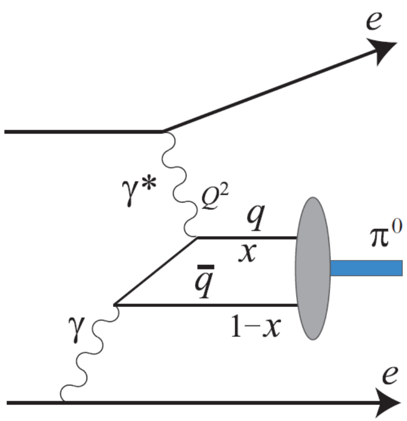
$\delta = 182.6^\circ + 11.2^\circ(Q'^2 - 2\,\text{GeV}^2) - 1.67^\circ(Q'^2 - 2\,\text{GeV}^2)^2$

for $Q'^2 \geq 8.9\,\text{GeV}^2$: $\delta = 180^\circ$, pQCD result

Exclusive lepton pair production in πN scattering

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

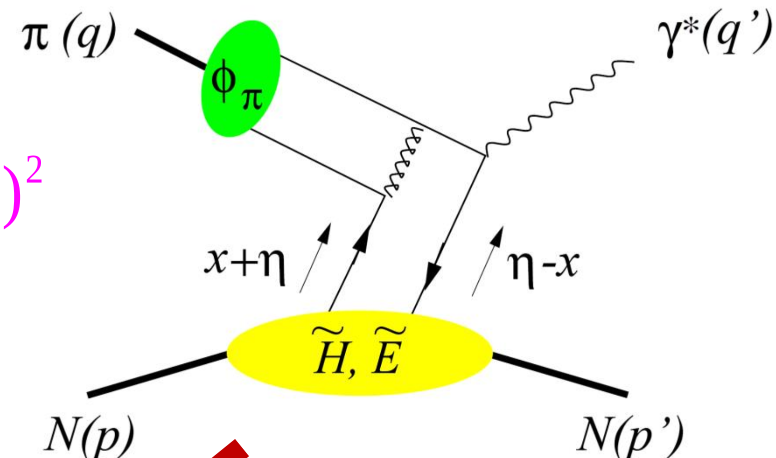
Berger, Diehl, Pire, PLB523(2001)265



@Belle, Babar

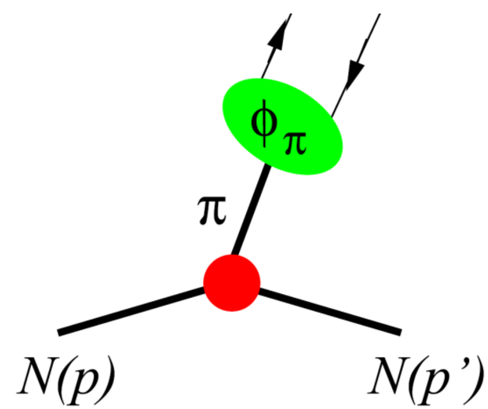
“exclusive limit of DY”

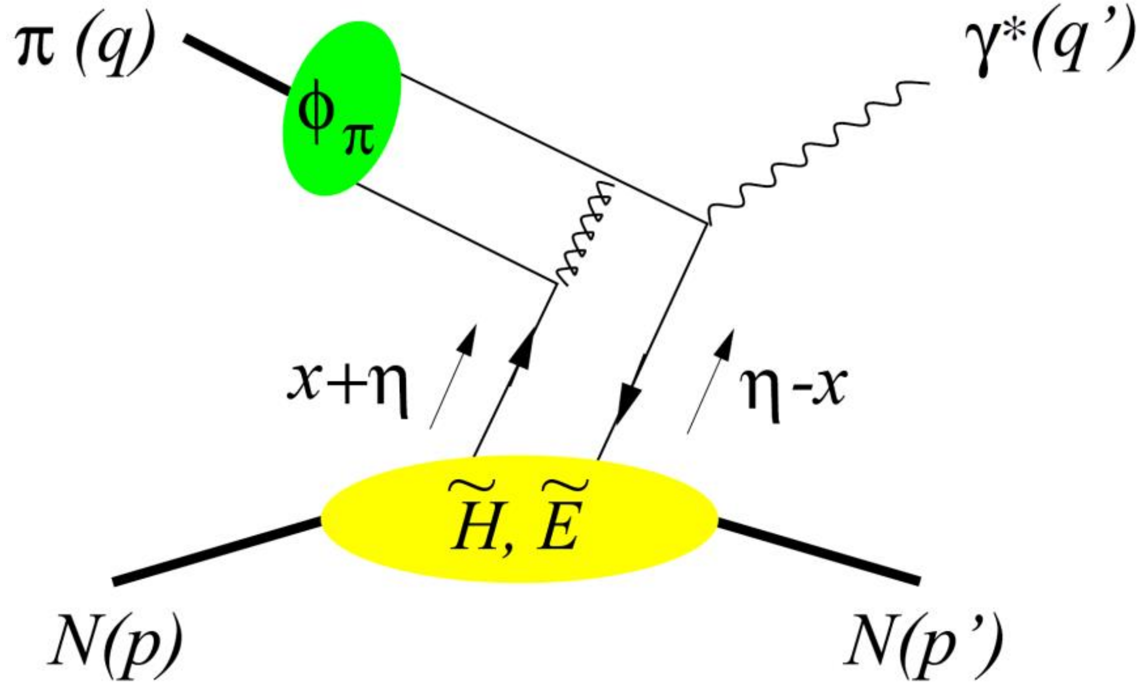
small $t = \Delta^2 = (q - q')^2$



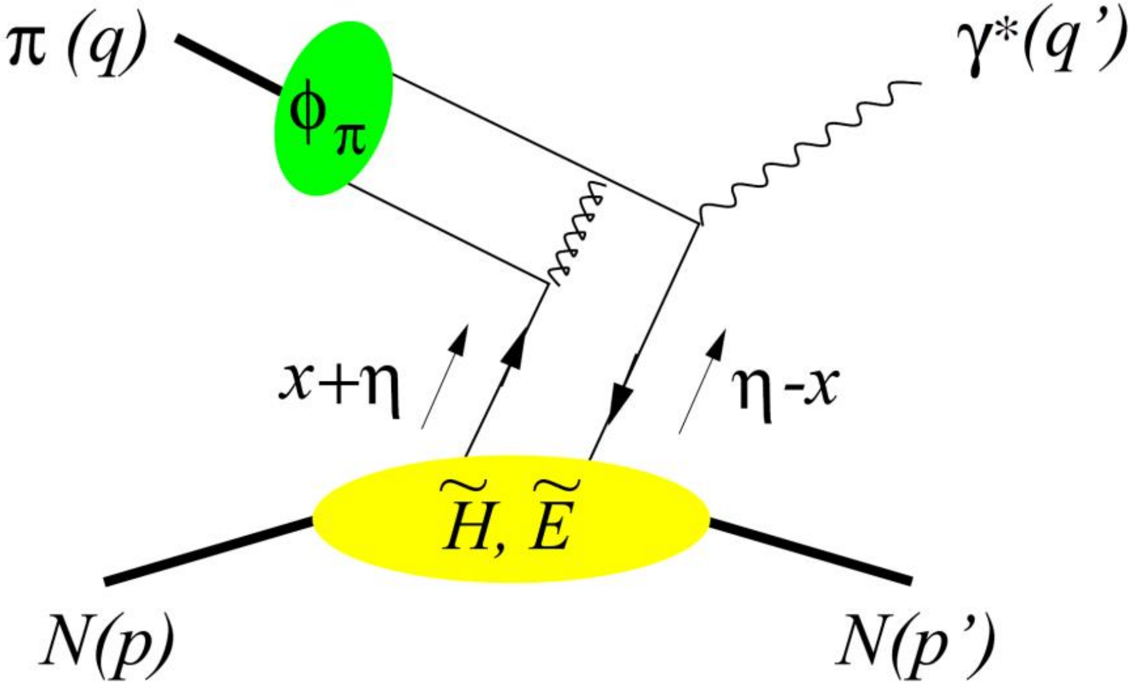
$t \to 0$

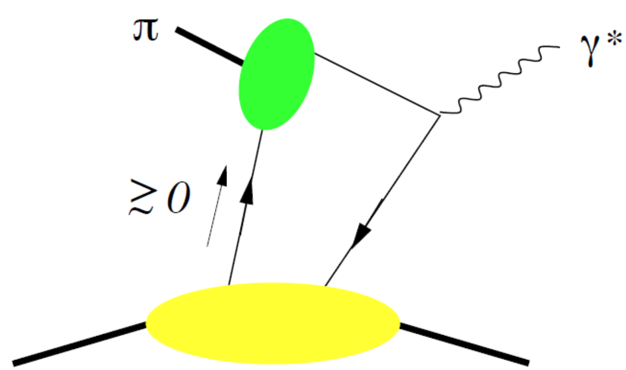
$\Delta q(x)$



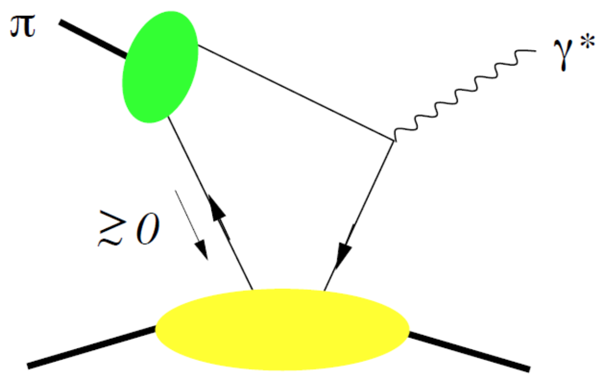


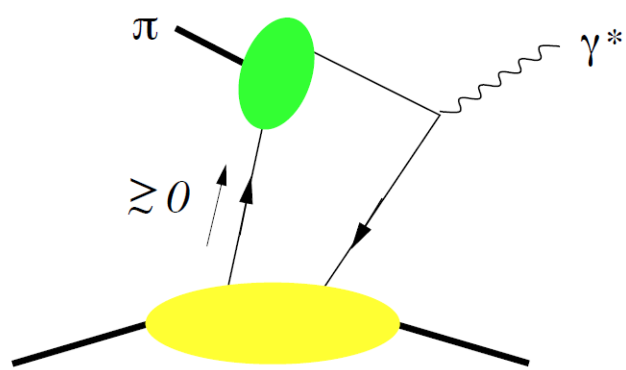
π (q)
φ_π
γ*(q')
x+η
η-x
H̃, Ẽ
N(p)
N(p')


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

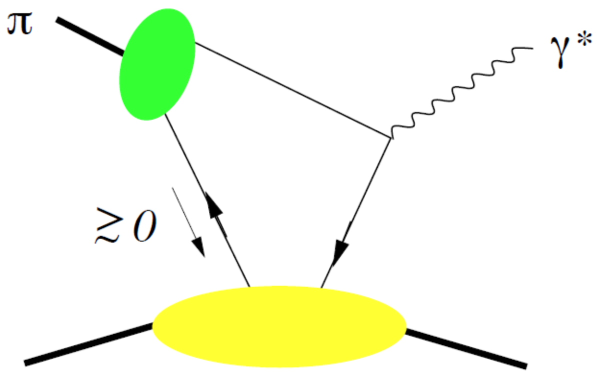

π
γ*
≳ 0

“nonfactorizable” mechanism

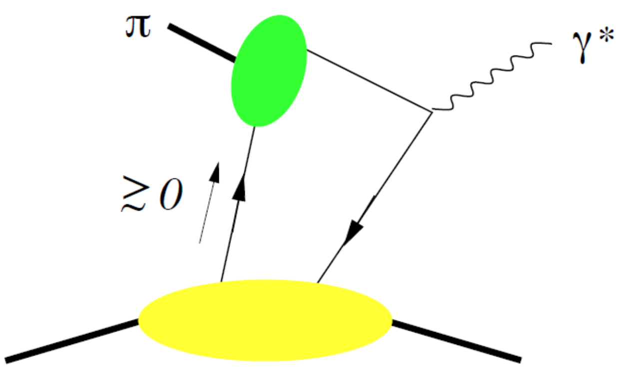




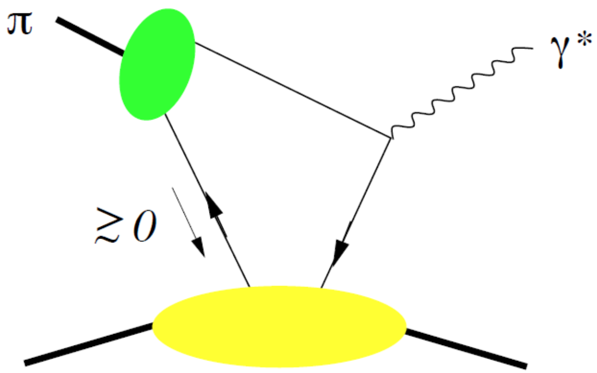
“nonfactorizable” mechanism



lower order in α_s

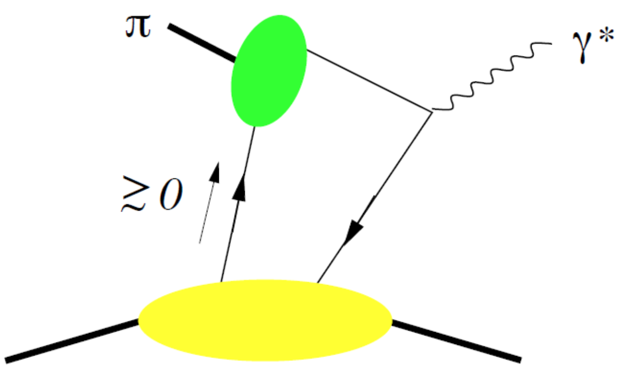


“nonfactorizable” mechanism

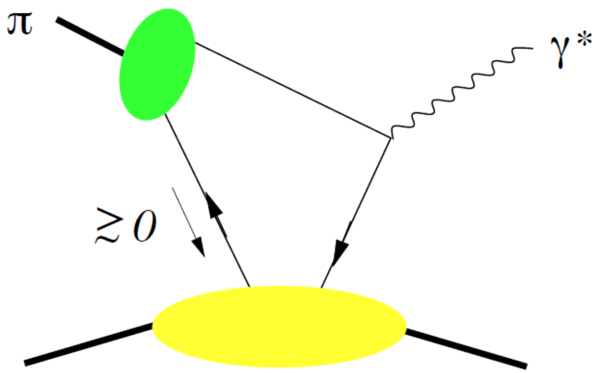


lower order in α_s

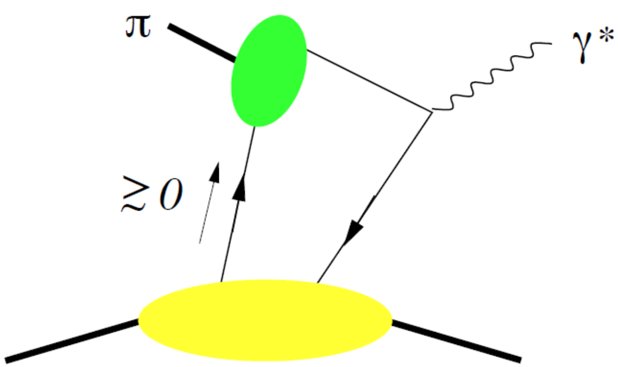
“Feynman mechanism”



“nonfactorizable” mechanism

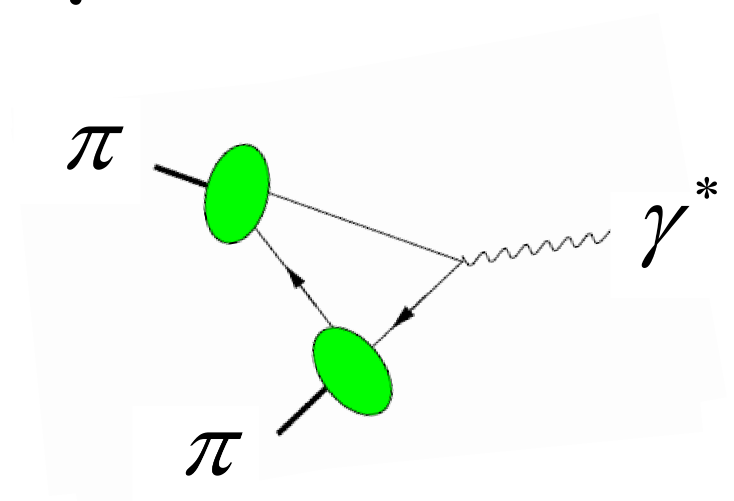


lower order in α_s



(d)

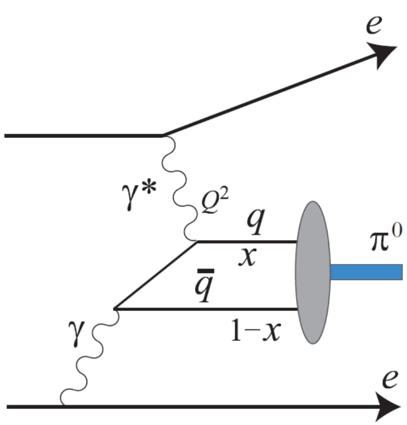
“Feynman mechanism”



Exclusive lepton pair production in πN scattering

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

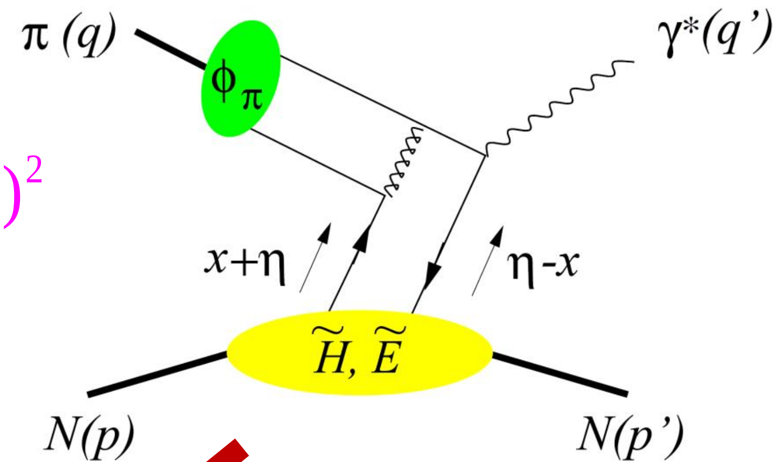
Berger, Diehl, Pire, PLB523(2001)265



@Belle, Babar

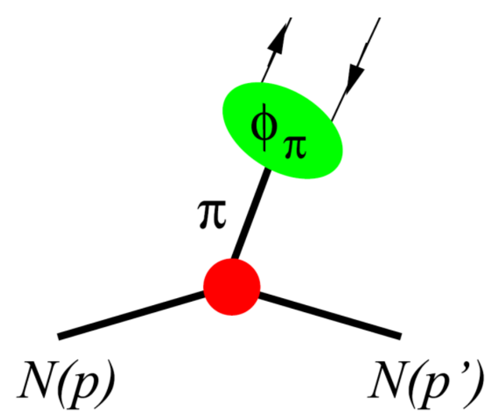
"exclusive limit of DY"

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



$t \to 0$

$\Delta q(x)$

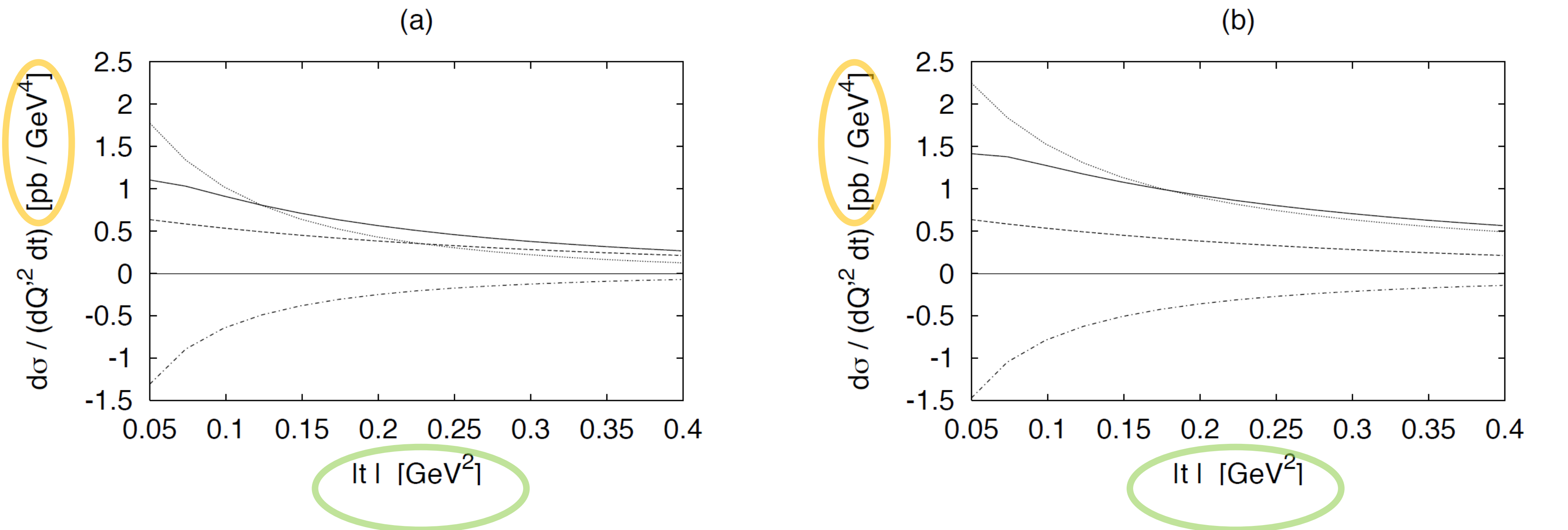


LO Estimates

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

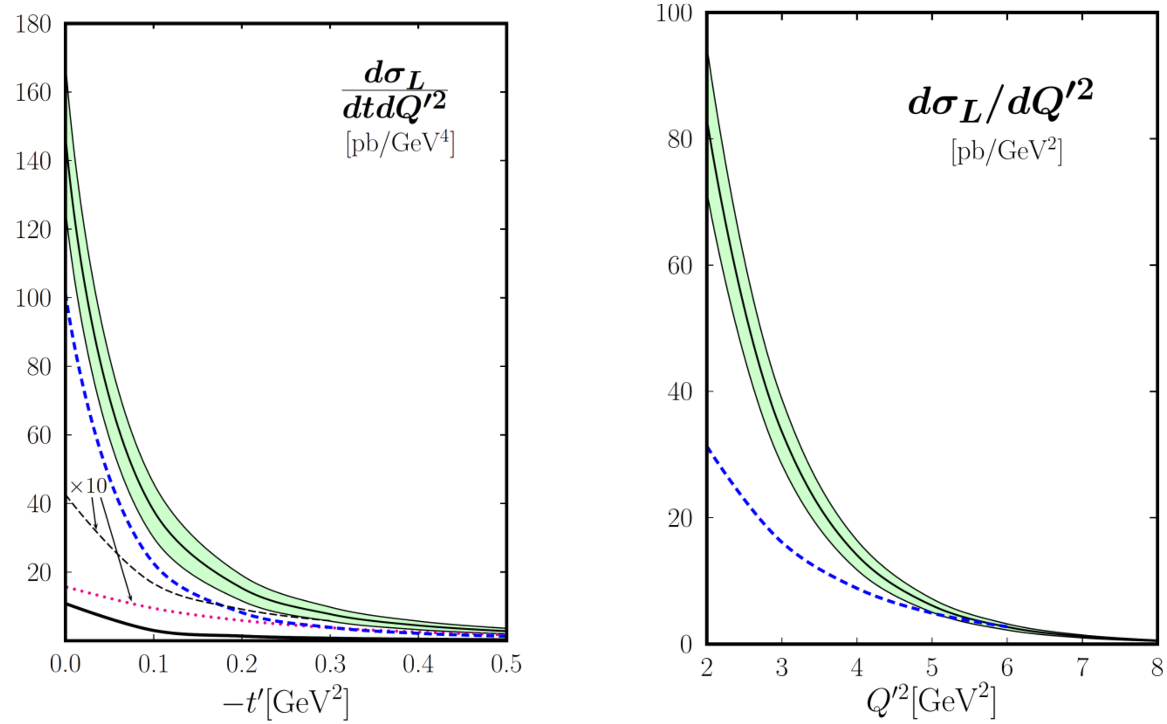
Berger, Diehl, Pire, PLB523(2001)265

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



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

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



$Q'^2 = 4\,\mathrm{GeV}^2$ and $s = 20(30)\,\mathrm{GeV}^2$ solid (blue dashed)lines with error bands

solid (dotted, dashed) line: interference, $|\langle \widetilde{H}^{(3)}\rangle|^2$, leading-twist contribution

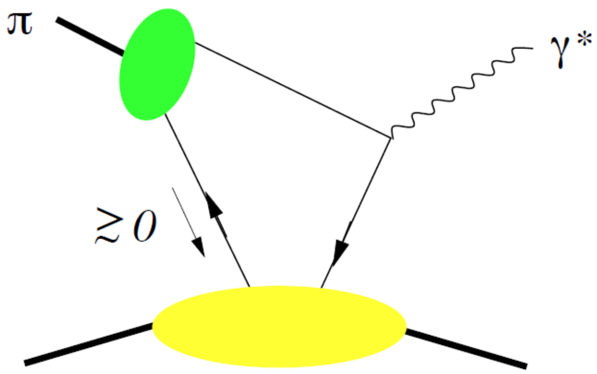
time-like pion FF: $Q'^2|F_\pi(Q'^2)| = 0.88 \pm 0.04\,\mathrm{GeV}^2$ (CLEO, BaBar, $J/\Psi \to \pi^+\pi^-$)

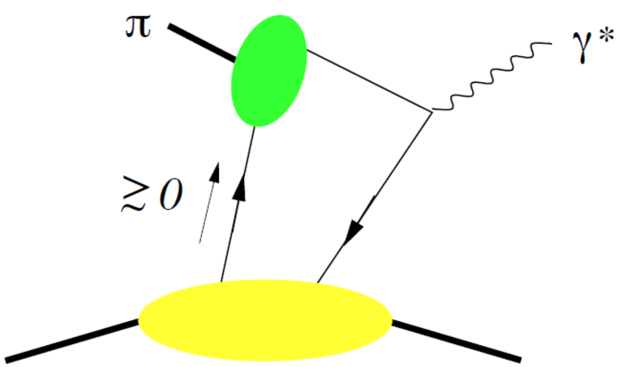
phase from disp. rel. Belicka et al(11) for $Q'^2 < 7\,\mathrm{GeV}^2$

$\delta = 182.6^\circ + 11.2^\circ(Q'^2 - 2\,\mathrm{GeV}^2) - 1.67^\circ(Q'^2 - 2\,\mathrm{GeV}^2)^2$

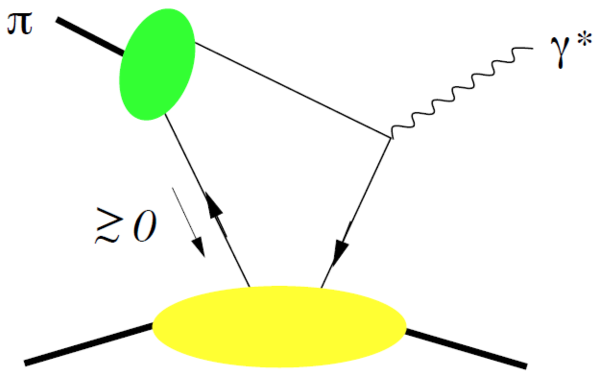
for $Q'^2 \geq 8.9\,\mathrm{GeV}^2$: $\delta = 180^\circ$, pQCD result

“nonfactorizable” mechanism

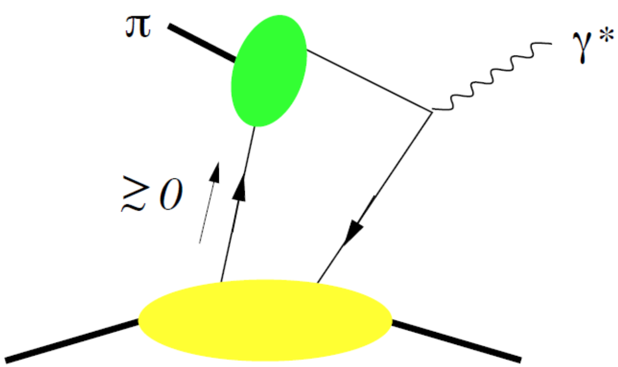




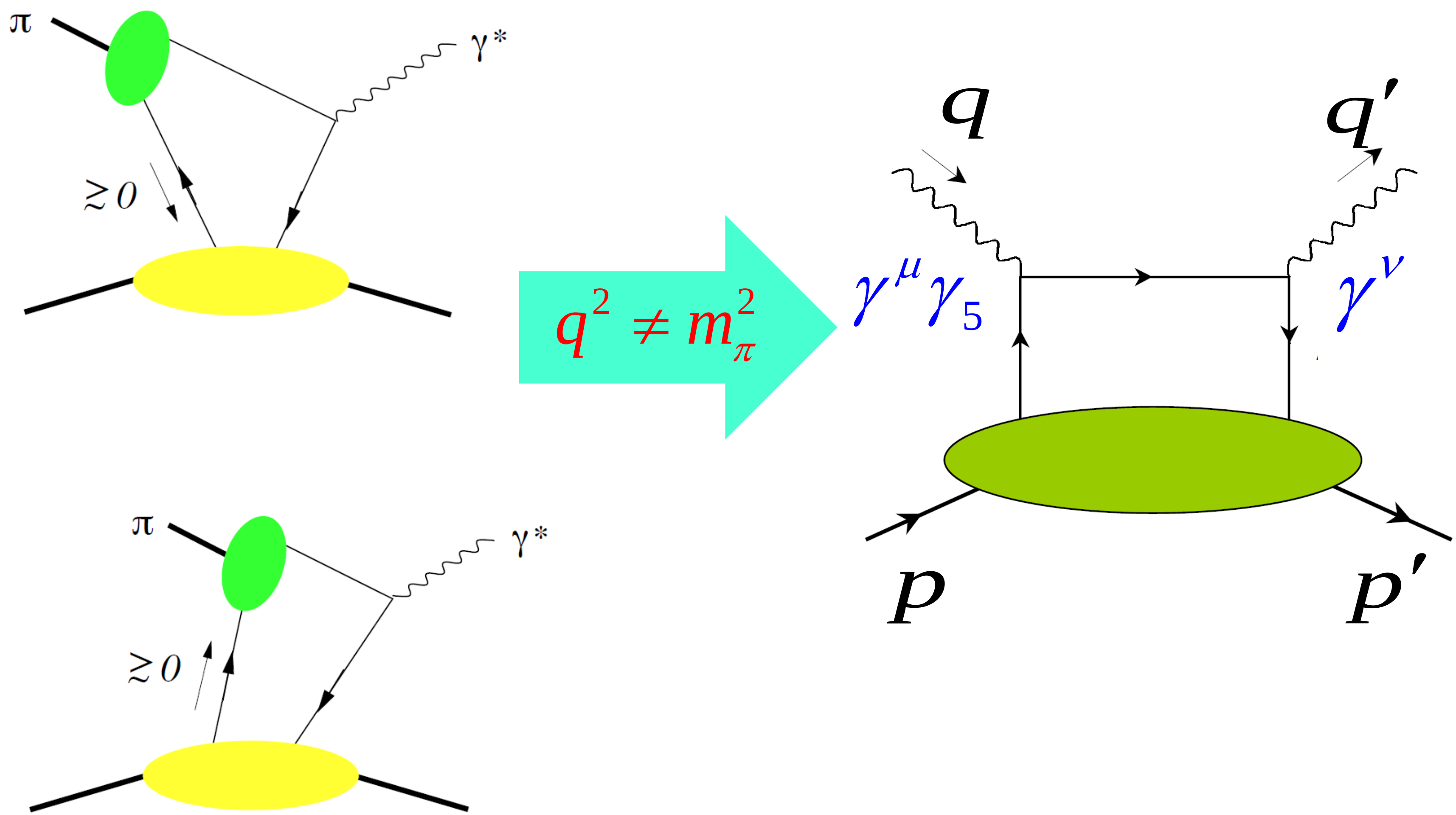
“nonfactorizable” mechanism



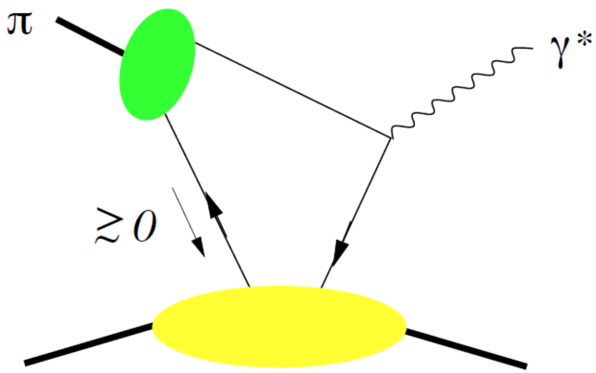
$$q^2 \neq m_\pi^2$$

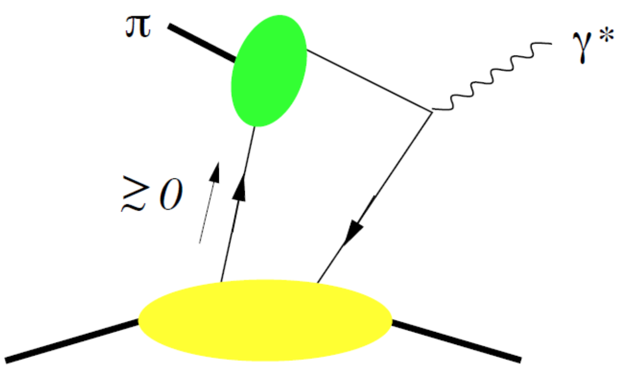


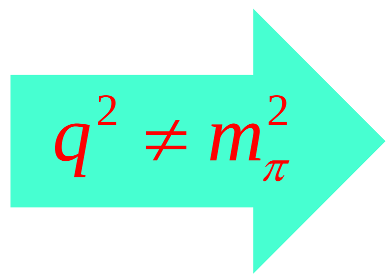
"nonfactorizable" mechanism

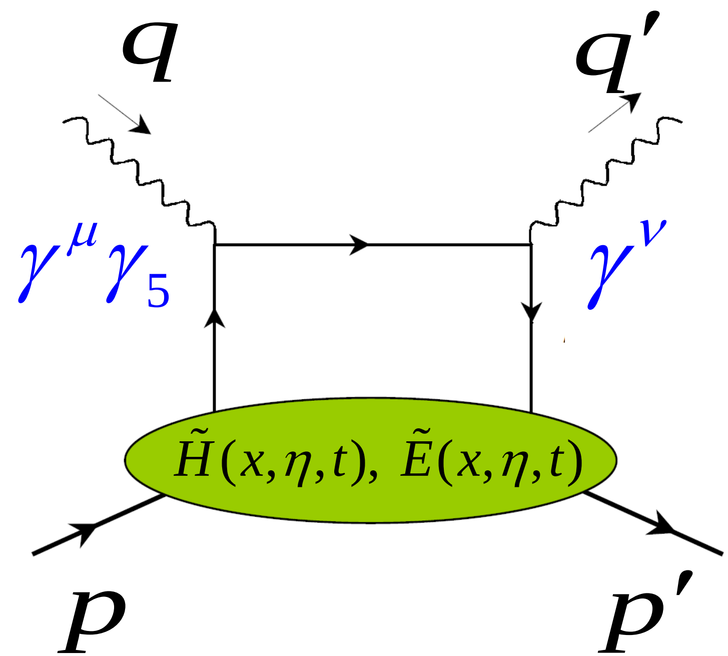


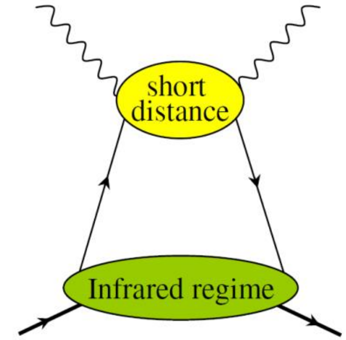
“nonfactorizable” mechanism



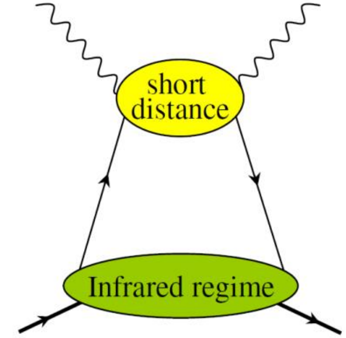


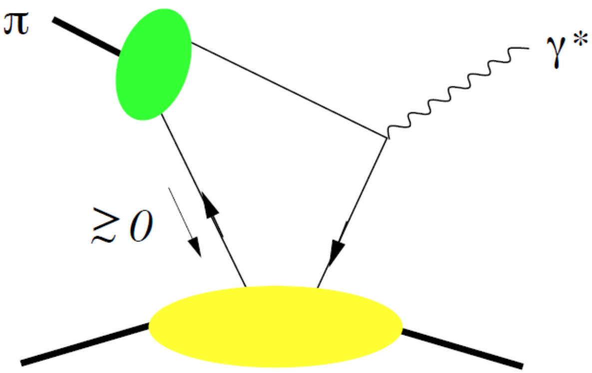




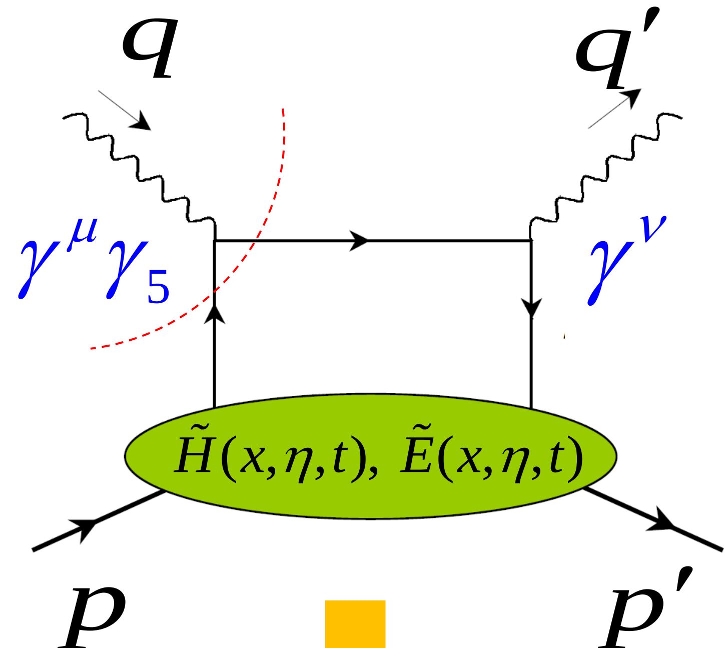


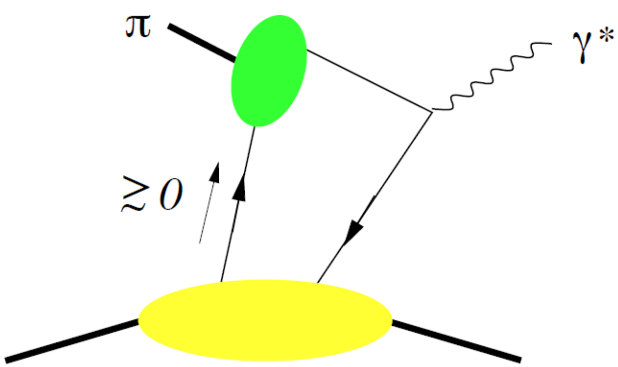
“nonfactorizable” mechanism





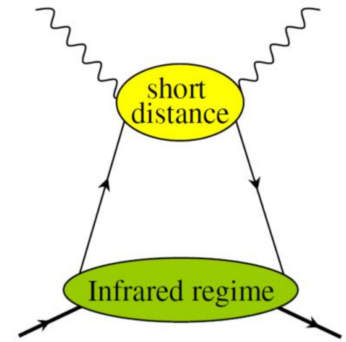
$q^2 \neq m_\pi^2$

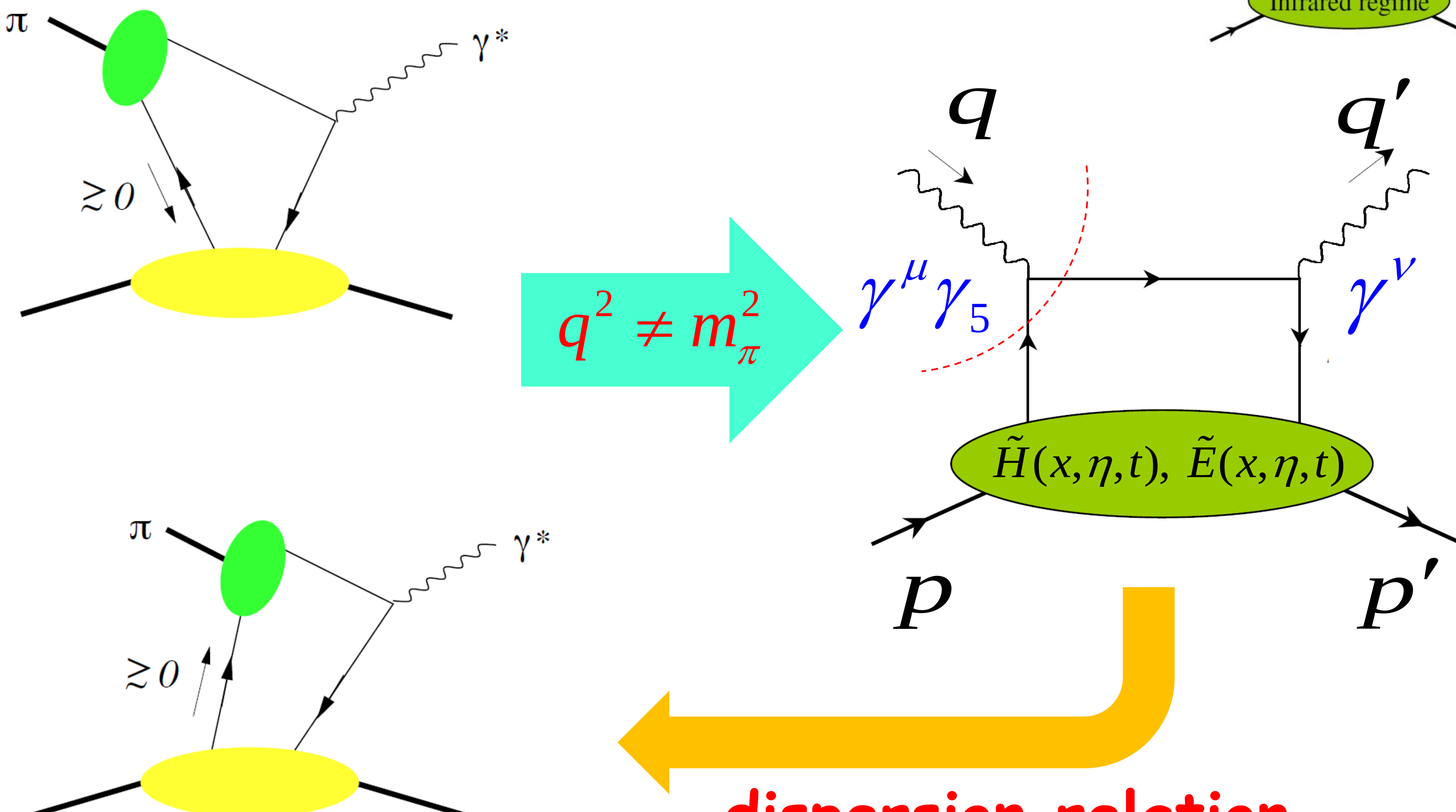




dispersion relation

“nonfactorizable” mechanism





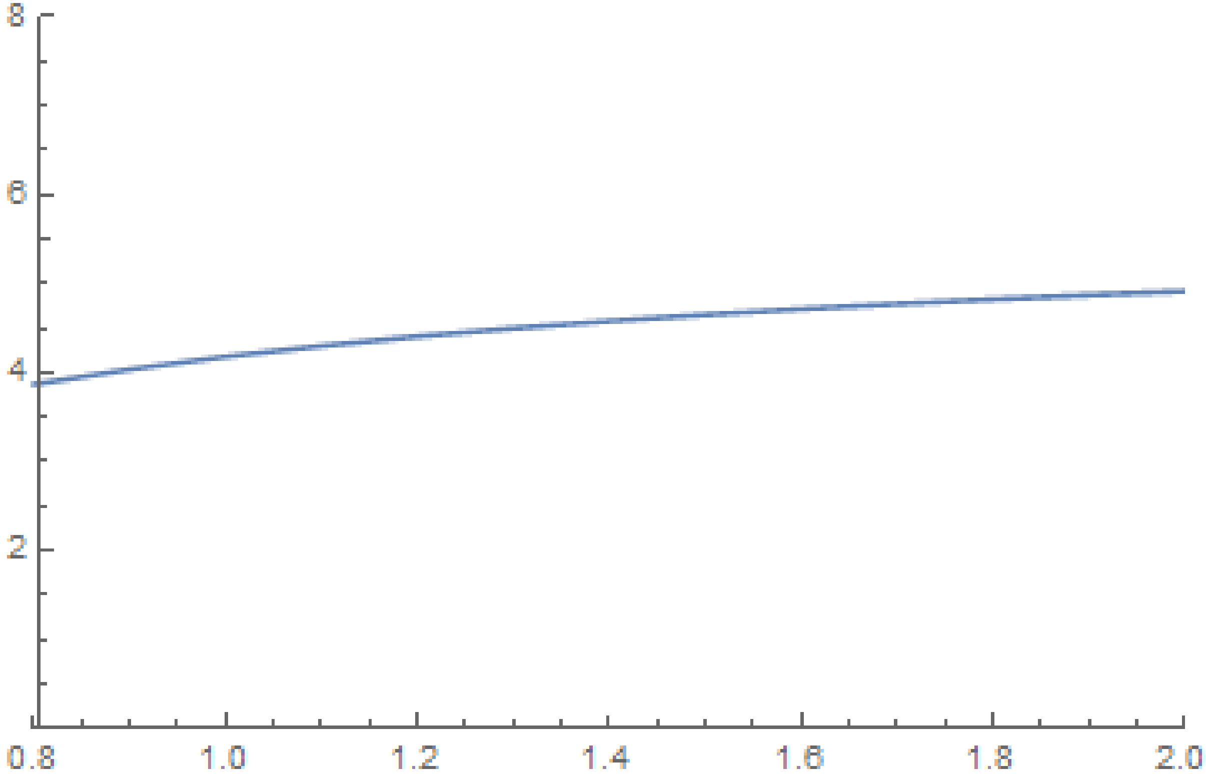
dispersion relation

quark-hadron duality

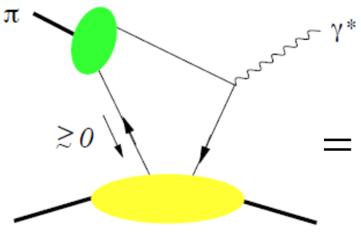
K. Tanaka, in progress

"Light-cone QCD SR (LCSR)"

$\tilde{\mathscr{H}}^{du}_{LCSR}(\eta,t)$



M_B^2 **(Borel parameter)**



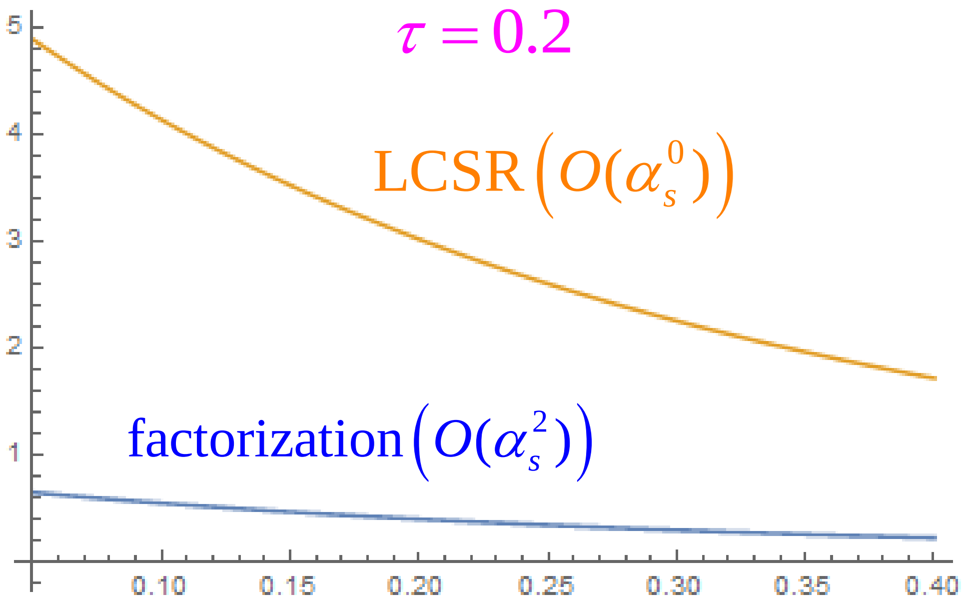
$$= -ie\frac{1}{(p+p')^+}\bar{u}(p',\lambda')\left[\gamma^+\gamma_5\tilde{\mathscr{H}}^{du}_{LCSR}(\eta,t)+\gamma_5\frac{(p'-p)^+}{2M}\tilde{\mathscr{E}}^{du}_{LCSR}(\eta,t)\right]u(p,\lambda)$$

K. Tanaka, in progress

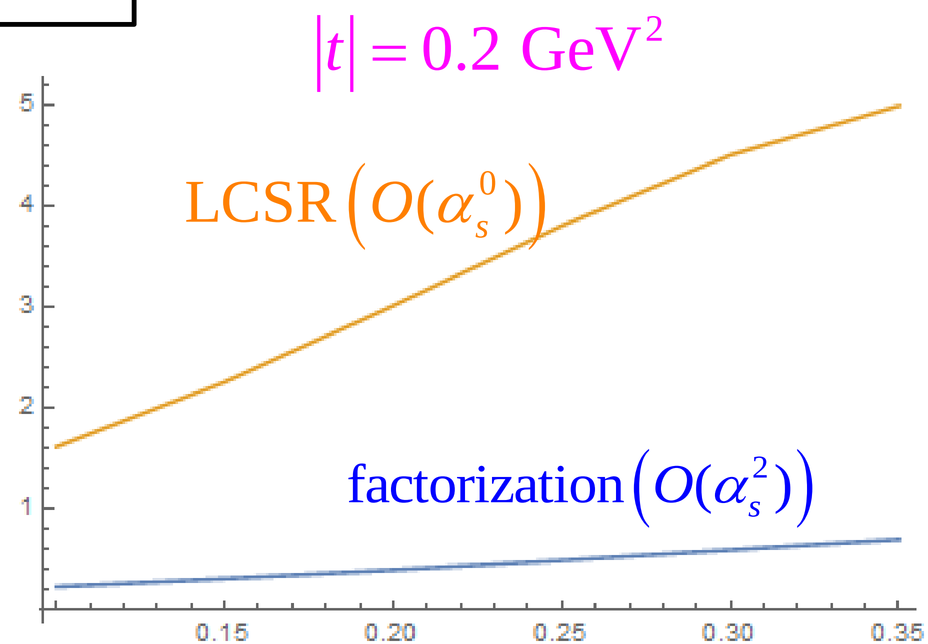
$$\frac{d\sigma}{dQ'^2\,dt}(\pi^- p \to \gamma^* n) = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2\left[(1-\eta^2)|\mathscr{H}^{du}|^2 - 2\eta^2\,\mathrm{Re}\left(\mathscr{H}^{du*}\mathscr{E}^{du}\right) - \eta^2\frac{t}{4M^2}|\mathscr{E}^{du}|^2\right]$$

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

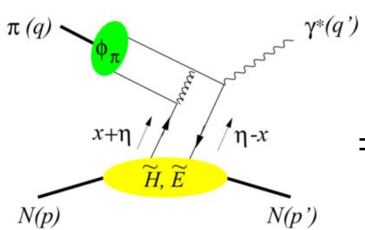
$\frac{d\sigma}{dQ'^2\,dt}\ \left[\mathrm{pb/GeV}^4\right]$



$|t|\ \left[\mathrm{GeV}^2\right]$



τ



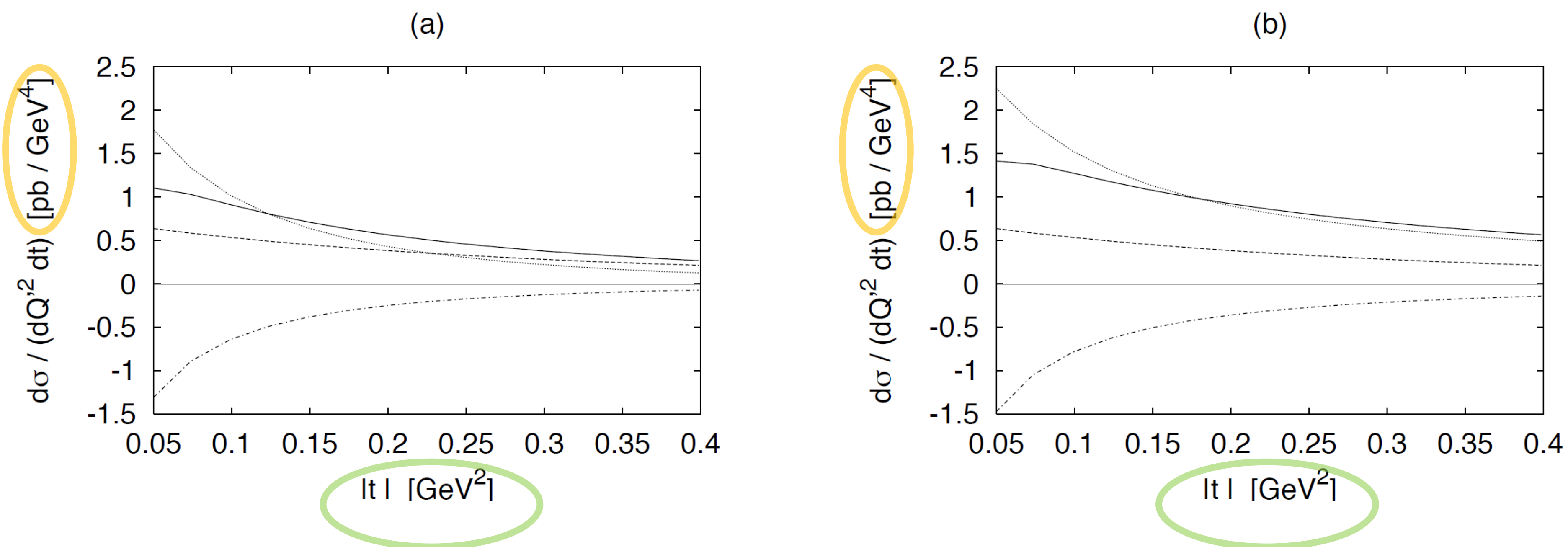
$$= -ie\frac{1}{(p+p')^+}\bar{u}(p',\lambda')\left[\gamma^+\gamma_5\tilde{\mathscr{H}}^{du}(\eta,t) + \gamma_5\frac{(p'-p)^+}{2M}\tilde{\mathscr{E}}^{du}(\eta,t)\right]u(p,\lambda)$$

LO Estimates

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

Berger, Diehl, Pire, PLB523(2001)265

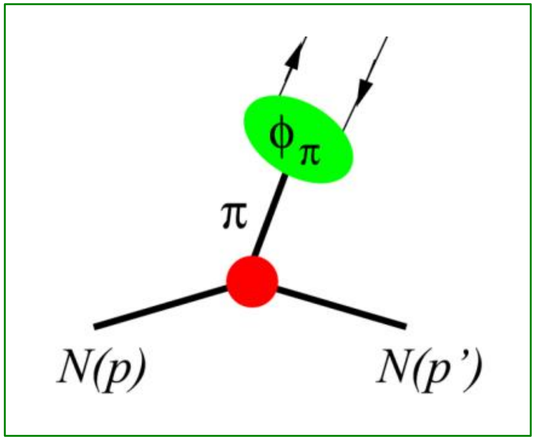
$$Q'^2 = 5 GeV^2 \qquad \tau = 0.2$$

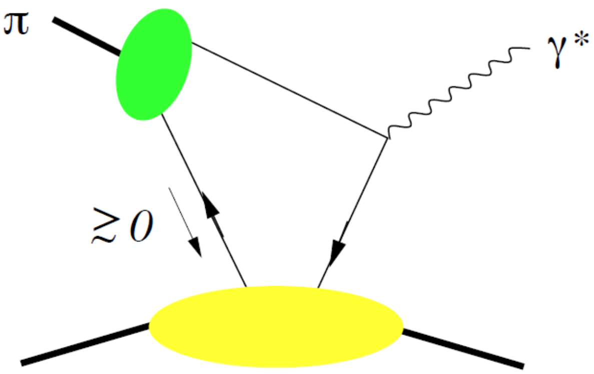


(dashed) $= |\tilde{\mathcal{H}}|^2$; **(dash-dotted)** $=$ **Re**$(\tilde{\mathcal{H}}^* \tilde{\mathcal{E}})$; **(dotted)** $= |\tilde{\mathcal{E}}|^2$

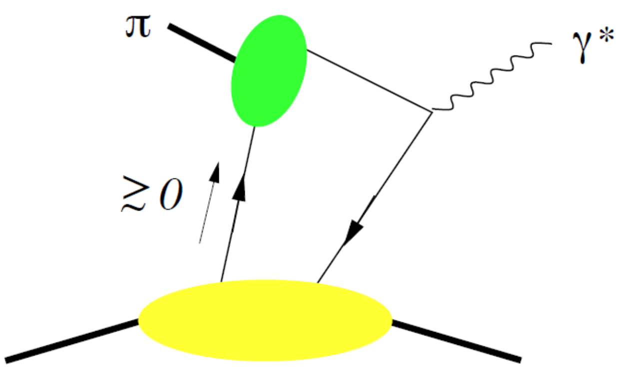
$$\frac{d\sigma}{dQ'^2 dt}(\pi^- p \to \gamma^* n) = \frac{4\pi\alpha_{em}^2}{27} \frac{\tau^2}{Q'^8} f_\pi^2 \left[(1-\eta^2) |\mathscr{H}^{du}|^2 - 2\eta^2 \mathrm{Re}\left(\mathscr{H}^{du*} \mathscr{E}^{du}\right) - \eta^2 \frac{t}{4M^2} |\mathscr{E}^{du}|^2 \right]$$

“nonfactorizable” mechanism



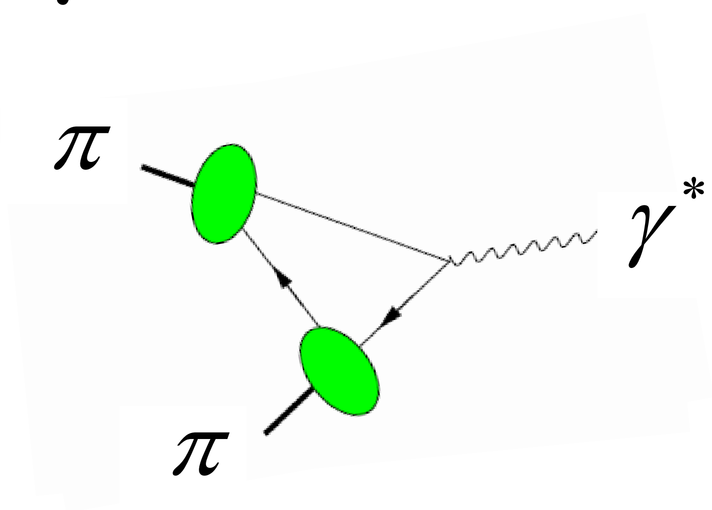


lower order in α_s



(d)

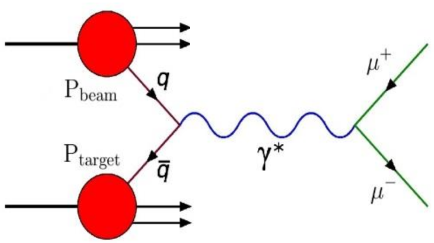
“Feynman mechanism”



Summary

$p, \pi^{\pm}, K^{\pm}, \cdots$ beams at J-PARC

inclusive DY



$f_q(x \sim 1),\quad f_{\bar{q}}(x \sim 1)$

TMD $\quad \langle k_\perp^2 \rangle$ & resum.scheme

L_q

$\text{Sivers}\big|_{DY} = -\,\text{Sivers}\big|_{SIDIS}$

BM & angular distribution

Summary

$p, \pi^{\pm}, K^{\pm}, \cdots$ beams at J-PARC

inclusive DY

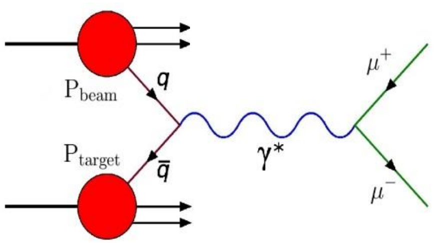
$f_q(x \sim 1)$, $f_{\bar{q}}(x \sim 1)$

TMD $\langle k_\perp^2 \rangle$ & resum.scheme

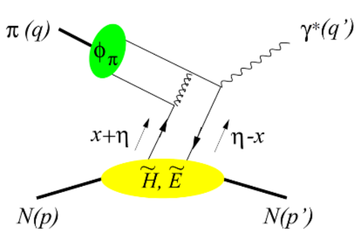
L_q

$\text{Sivers}\big|_{DY} = -\text{Sivers}\big|_{SIDIS}$

BM & angular distribution



exclusive DY GPDs



feasibility study with E50 spectrometer

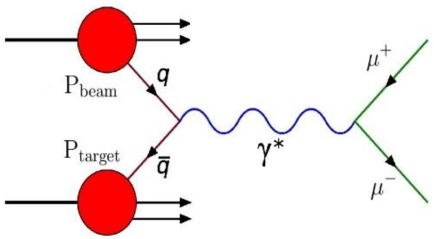
T. Sawada, W.C. Chang, S. Kumano, J.C. Peng, S. Sawada, KT

Summary

$p, \pi^{\pm}, K^{\pm}, \cdots$ **beams at J-PARC**

inclusive DY

$f_q(x \sim 1)$, $f_{\bar{q}}(x \sim 1)$



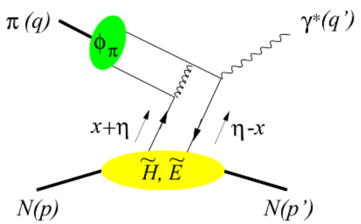
TMD $\langle k_\perp^2 \rangle$ & resum.scheme

L_q

$\text{Sivers}\big|_{DY} = -\text{Sivers}\big|_{SIDIS}$

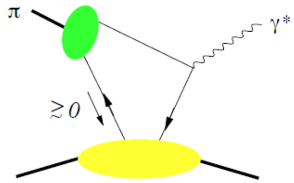
BM & angular distribution

exclusive DY GPDs



feasibility study with E50 spectrometer

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

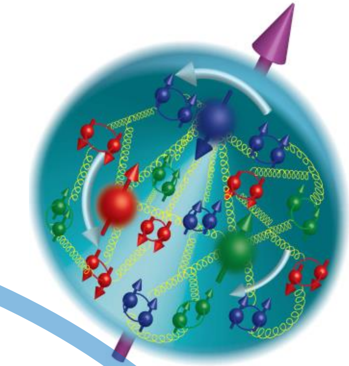


LCSR for nonfactorizable amplitude

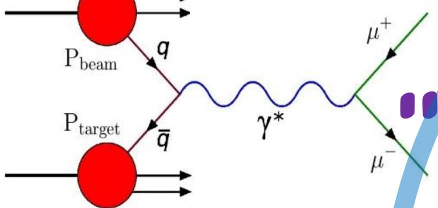
interplay of soft/hard QCD mechanism

Summary

$p, \pi^{\pm}, K^{\pm}, \cdots$ **beams at J-PARC**



inclusive DY $f_q(x \sim 1)$, $f_{\bar{q}}(x \sim 1)$



TMD $\langle k_\perp^2 \rangle$ **& resum.scheme**

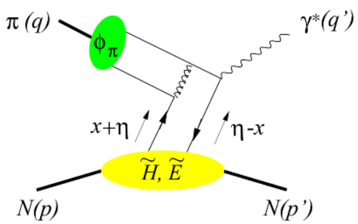
L_q

$\text{Sivers}\big|_{DY} = -\,\text{Sivers}\big|_{SIDIS}$

BM & angular distribution

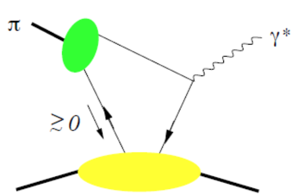
"Wigner" 3D imaging

exclusive DY GPDs



feasibility study with E50 spectrometer

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



LCSR for nonfactorizable amplitude

interplay of soft/hard QCD mechanism