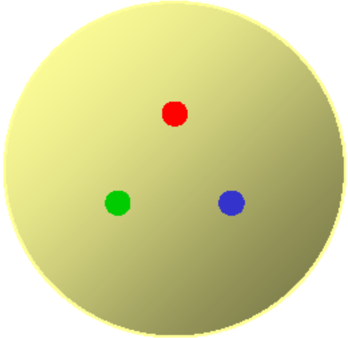
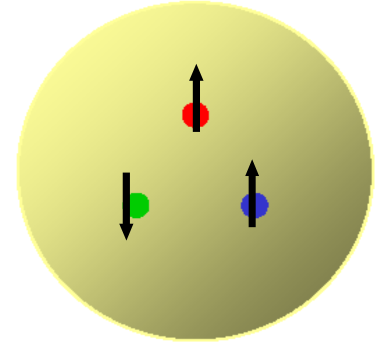
Novel aspect of hadron structure from Drell-Yan processes at J-PARC

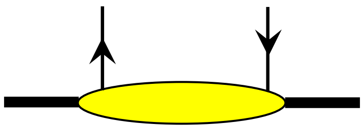
Kazuhiro Tanaka (Juntendo U)

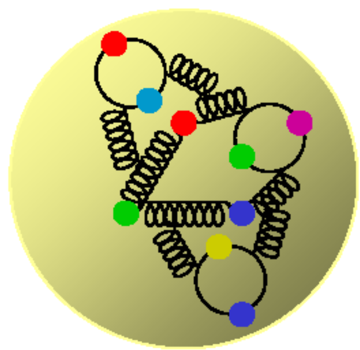




$$\int d\eta e^{ik\eta} \langle P | \psi^\dagger(0)\psi(\eta) | P \rangle \qquad \langle PS | \bar{\psi}(0)\Gamma\psi(\eta) | PS \rangle$$

$$\Gamma = \gamma^\mu\gamma_5,\ \sigma^{\mu\nu},\ \ldots$$



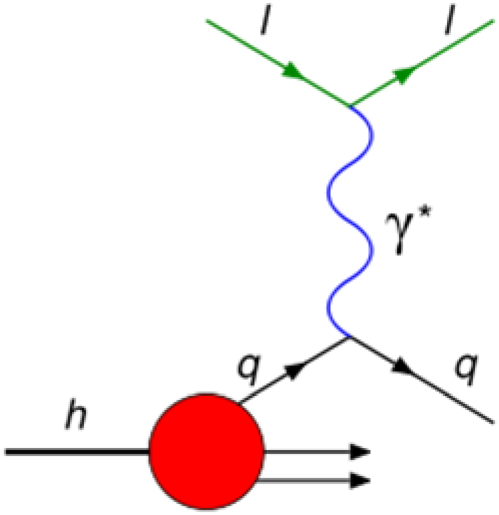


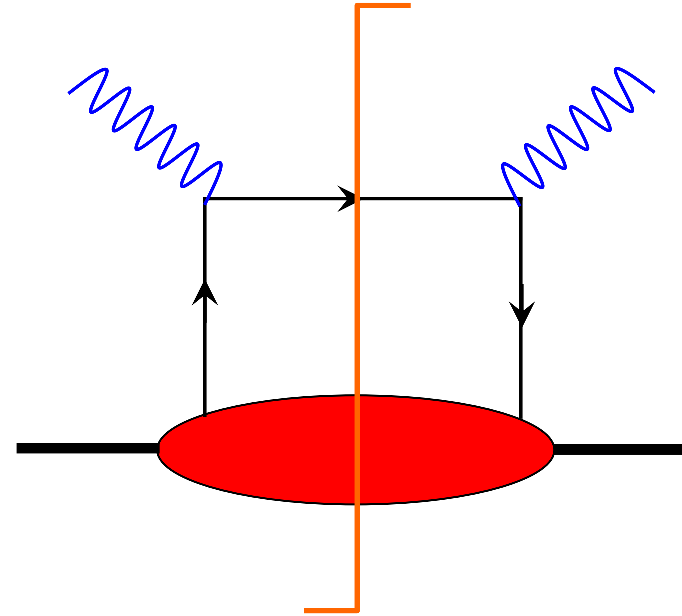
$$\langle P | \bar{\psi}(\xi_1)\bar{\psi}(\xi_2)\cdots\ \psi(\eta_1)\psi(\eta_2)\cdots\ F_{\mu\nu}(\zeta_1)F_{\alpha\beta}(\zeta_2)\cdots | P \rangle$$

exotic components: ***renorm. scale-dep.***

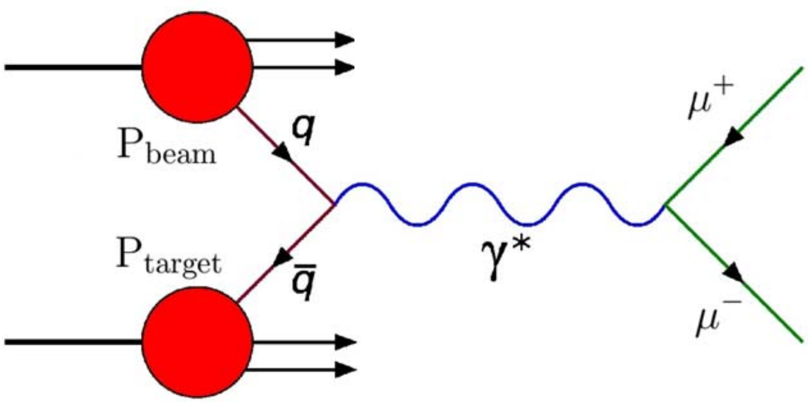
not direct observable

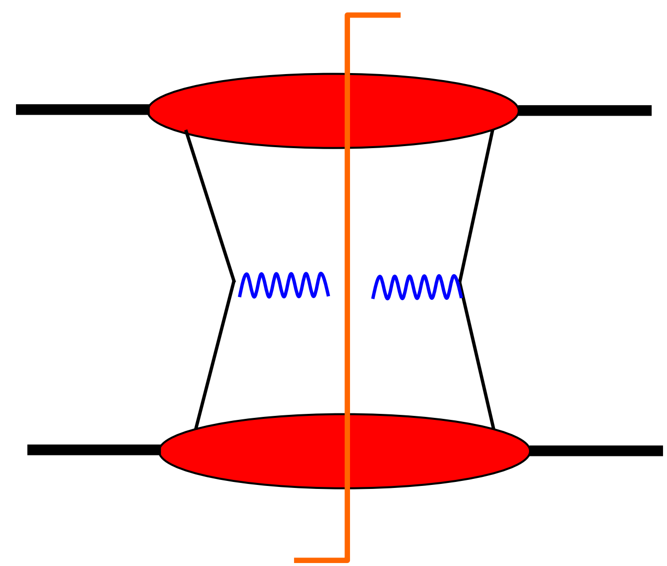
DIS



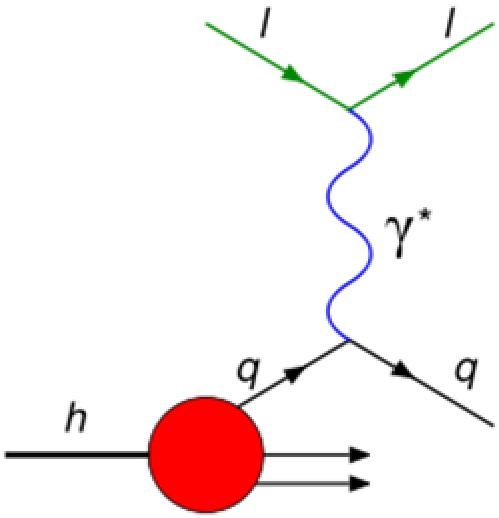


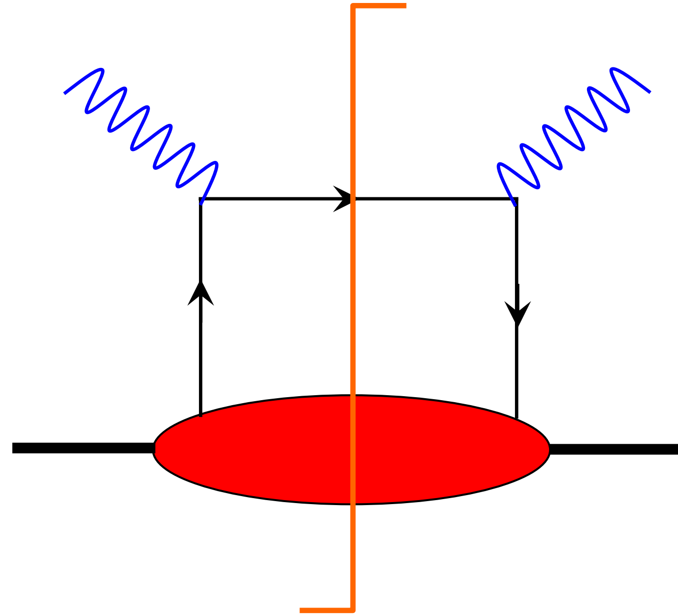
DY



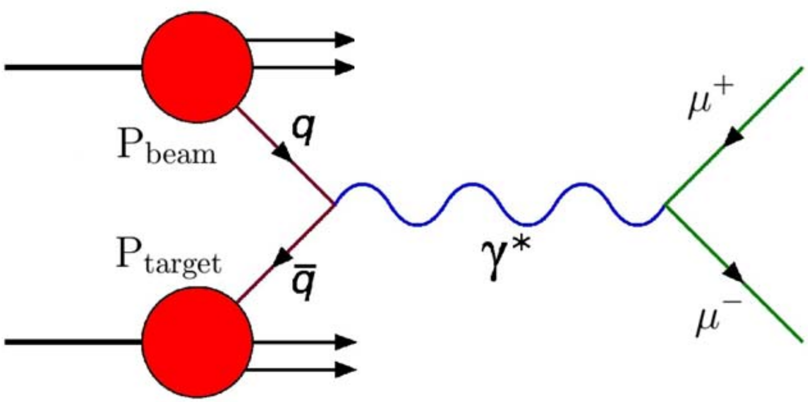


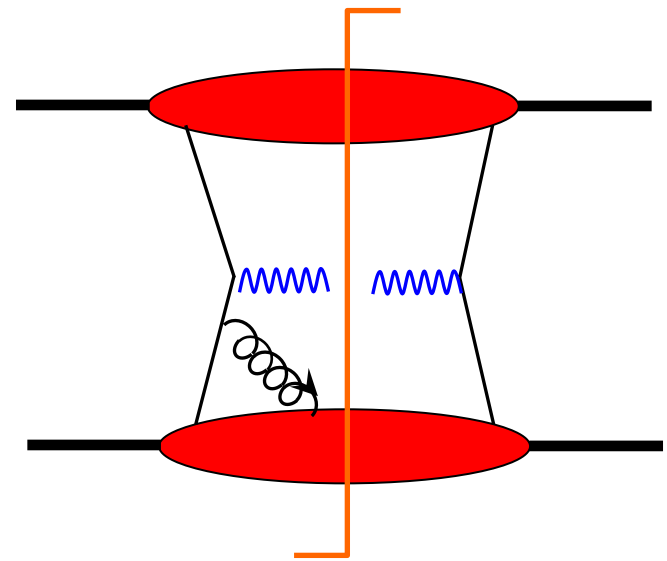
DIS

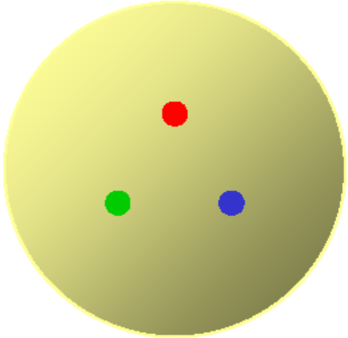


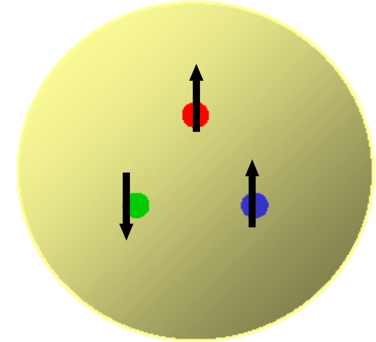


DY





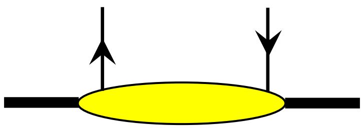


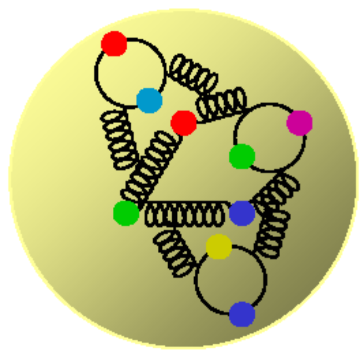


$$\int d\eta e^{ik\eta} \langle P | \psi^\dagger(0)\psi(\eta) | P \rangle$$

$$\langle PS | \overline{\psi}(0)\Gamma\,\psi(\eta) | PS \rangle$$

$$\Gamma = \gamma^\mu \gamma_5,\ \sigma^{\mu\nu},\ \ldots$$





$$\langle P | \overline{\psi}(\xi_1)\overline{\psi}(\xi_2)\cdots\ \psi(\eta_1)\psi(\eta_2)\cdots\ F_{\mu\nu}(\zeta_1)F_{\alpha\beta}(\zeta_2)\cdots | P \rangle$$

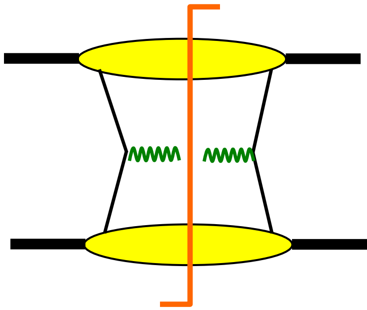
exotic components: ***renorm. scale-dep.***

not direct observable

DY

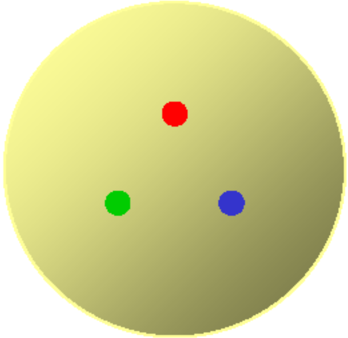
experiment	particles	energy	x_1 or x_2	luminosity
COMPASS	$\pi^{\pm} + p\uparrow$	160 GeV $\sqrt{s} = 17.4$ GeV	$x_2 = 0.2$ - 0.3	2×10^{33} cm^{-2}s^{-1}
COMPASS (low mass)	$\pi^{\pm} + p\uparrow$	160 GeV $\sqrt{s} = 17.4$ GeV	$x_2 \sim 0.05$	2×10^{33} cm^{-2}s^{-1}
PAX	$p\uparrow + \bar{p}$	collider $\sqrt{s} = 14$ GeV	$x_1 = 0.1$ - 0.9	2×10^{30} cm^{-2}s^{-1}
PANDA (low mass)	$\bar{p} + p\uparrow$	15 GeV $\sqrt{s} = 5.5$ GeV	$x_2 = 0.2$ - 0.4	2×10^{32} cm^{-2}s^{-1}
NICA	$p\uparrow + p$	collider $\sqrt{s} = 20$ GeV	$x_1 = 0.1$ - 0.8	10^{30} cm^{-2}s^{-1}
PHENIX/STAR	$p\uparrow + \bar{p}$	collider $\sqrt{s} = 500$ GeV	$x_1 = 0.05$ - 0.1	2×10^{32} cm^{-2}s^{-1}
AnDY	$p\uparrow + \bar{p}$	collider $\sqrt{s} = 500$ GeV	$x_1 = 0.1$ - 0.5	?? cm^{-2}s^{-1}
SeaQuest	$p\uparrow + p$	120 GeV $\sqrt{s} = 15$ GeV	$x_1 = 0.3$ - 0.9	2×10^{36} cm^{-2}s^{-1}
RHIC Internal Target	$p\uparrow + p$	250 GeV $\sqrt{s} = 22$ GeV	$x_1 = 0.2$ - 0.6	3×10^{34} cm^{-2}s^{-1}
J-PARC	$p\uparrow + p$	50 GeV $\sqrt{s} = 10$ GeV	$x_1 = 0.5$ - 0.9	10^{35} cm^{-2}s^{-1}

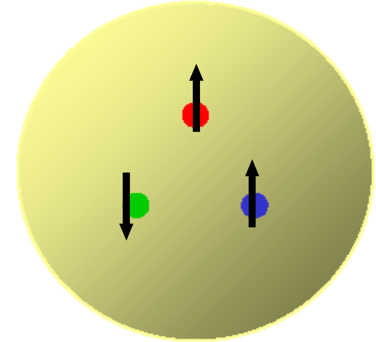
valence



sea

exotic components in a normal hadron

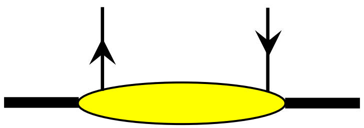


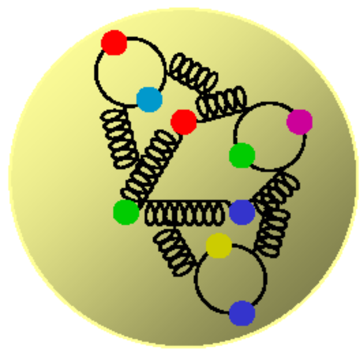


$$\int d\eta e^{ik\eta} \langle P | \psi^\dagger(0)\psi(\eta) | P \rangle$$

$$\langle PS | \bar{\psi}(0)\Gamma\psi(\eta) | PS \rangle$$

$$\Gamma = \gamma^\mu\gamma_5,\ \sigma^{\mu\nu},\ \ldots$$





$$\langle P | \bar{\psi}(\xi_1)\bar{\psi}(\xi_2)\cdots\ \psi(\eta_1)\psi(\eta_2)\cdots\ F_{\mu\nu}(\zeta_1)F_{\alpha\beta}(\zeta_2)\cdots | P \rangle$$

exotic components: ***renorm. scale-dep.***

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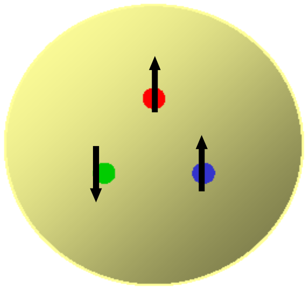
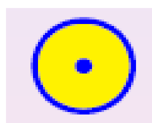


$$\int d\eta e^{ixP\eta} \langle PS | \bar{\psi}(0) \Gamma \psi(\eta) | PS \rangle$$

$$\Gamma = \gamma^{\mu},\ \gamma^{\mu}\gamma_5,\ \sigma^{\mu\nu}$$

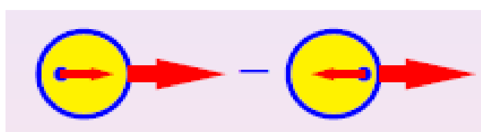
Unpolarized

$$q(x)$$



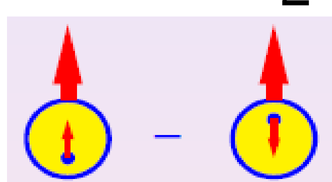
Helicity

$$\Delta q(x)$$



Transversity

$$\Delta_T q(x)$$



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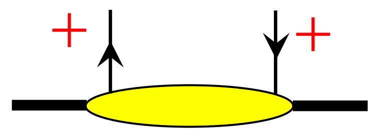
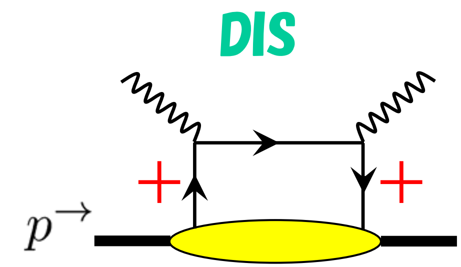
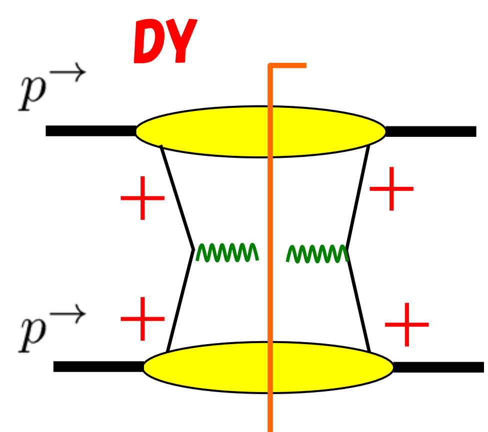




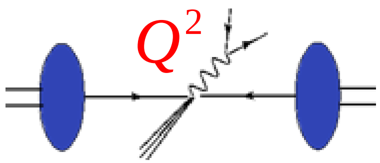
Chiral-even

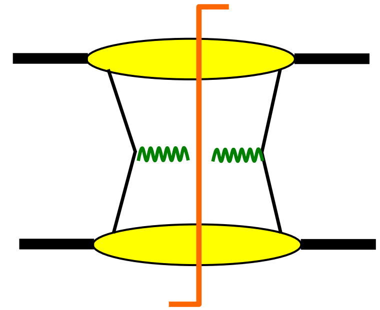
$$\frac{1}{2} = L_{q+g} + \frac{1}{2}\Delta q + \Delta g$$



$$p + p \rightarrow \ell^+ \ell^- + X$$

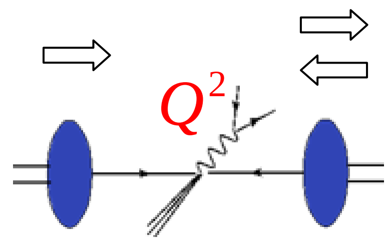
$$x_{1,2} = \frac{Q}{\sqrt{S}} e^{\pm y}$$





$$d\sigma \propto \sum_q e_q^2 \left[q(x_1, Q^2)\bar{q}(x_2, Q^2) + \bar{q}(x_1, Q^2) q(x_2, Q^2) \right] + \cdots$$

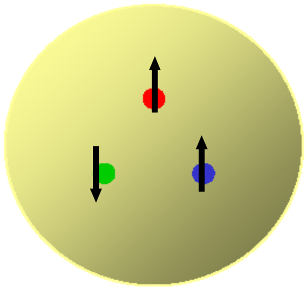
$$p^{\rightarrow} + p^{\rightarrow} \rightarrow \ell^+ \ell^- + X$$



$$d\sigma^{\rightarrow\rightarrow} - d\sigma^{\rightarrow\leftarrow} \propto \sum_q e_q^2 \left[\Delta q(x_1, Q^2)\Delta\bar{q}(x_2, Q^2) + \Delta\bar{q}(x_1, Q^2)\Delta q(x_2, Q^2) \right] + \cdots$$

$$A_{LL} = \frac{d\sigma^{\rightarrow\rightarrow} - d\sigma^{\rightarrow\leftarrow}}{d\sigma^{\rightarrow\rightarrow} + d\sigma^{\rightarrow\leftarrow}}$$

$$\propto \frac{\sum_q e_q^2 \left[\Delta q(x_1, Q^2)\Delta\bar{q}(x_2, Q^2) + \Delta\bar{q}(x_1, Q^2)\Delta q(x_2, Q^2) \right] + \cdots}{\sum_q e_q^2 \left[q(x_1, Q^2)\bar{q}(x_2, Q^2) + \bar{q}(x_1, Q^2) q(x_2, Q^2) \right] + \cdots}$$

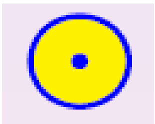


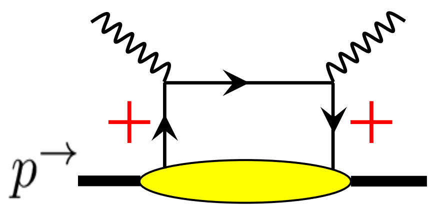
$$\int d\eta\, e^{ixP\eta} \langle PS | \bar{\psi}(0) \Gamma \psi(\eta) | PS \rangle$$

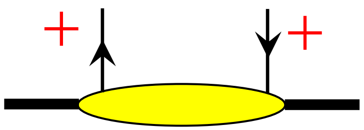
$$\Gamma = \gamma^{\mu},\ \gamma^{\mu}\gamma_5,\ \sigma^{\mu\nu}$$

Unpolarized CTEQ, GRV, MRSTW, $\cdots$

$$q(x)$$

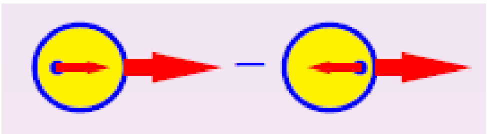




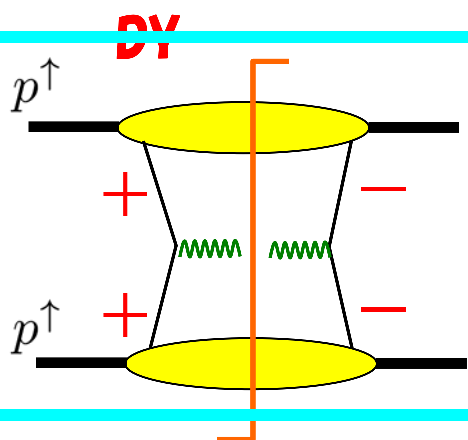


Helicity GRSV, LSS, ACC, DSSV, $\cdots$

$$\Delta q(x)$$

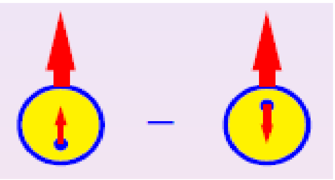


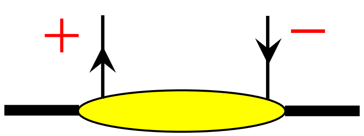
Chiral-even



Transversity **Little known**

$$\Delta_T q(x)$$

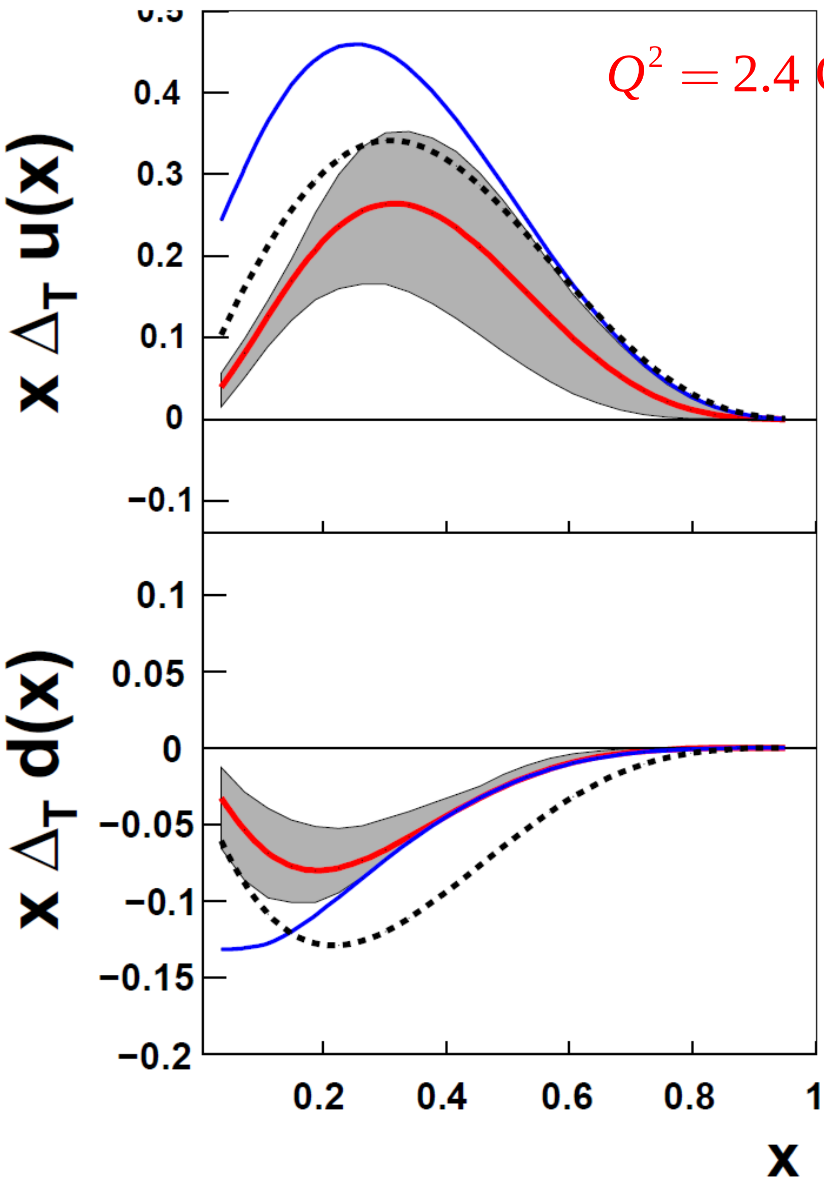




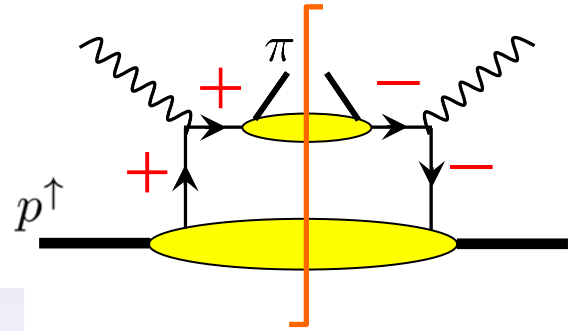
Chiral-odd

LO fit using SIDIS data

Anselmino et al., PRD75 ('07) 054032
NPB(Proc. Suppl.) 191 ('09) 98



SIDIS



1. Solid red line – transversity distribution

$$\Delta_T q(x)$$

2. Solid blue line – Soffer bound

$$\left|\Delta_T q(x)\right| \leq \frac{q(x) + \Delta q(x)}{2}$$

3. Dashed line – helicity distribution

$$\Delta q(x)$$

$$\mathcal{N}(x) = N\, x^{\alpha}(1-x)^{\beta}\, \frac{(\alpha+\beta)^{(\alpha+\beta)}}{\alpha^{\alpha}\beta^{\beta}}$$

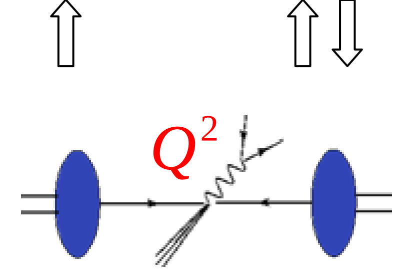
no data for $x > 0.4$

$$\Delta_T \bar{q}(x) = 0$$

$$p^{\uparrow} + p^{\uparrow} \rightarrow \ell^{+}\ell^{-} + X$$

@J-PARC

$$\sqrt{S} \lesssim 10 \text{ GeV}$$



$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}}$$

$$\propto \frac{\sum_q e_q^2 \left[\Delta_T q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + \Delta_T \bar{q}(x_1,Q^2)\Delta_T q(x_2,Q^2)\right] + \cdots}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + \bar{q}(x_1,Q^2)q(x_2,Q^2)\right] + \cdots}$$

$$x_{1,2} = \frac{Q}{\sqrt{S}} e^{\pm y}$$

$$p^{\uparrow} + \bar{p}^{\uparrow} \rightarrow \ell^{+}\ell^{-} + X$$

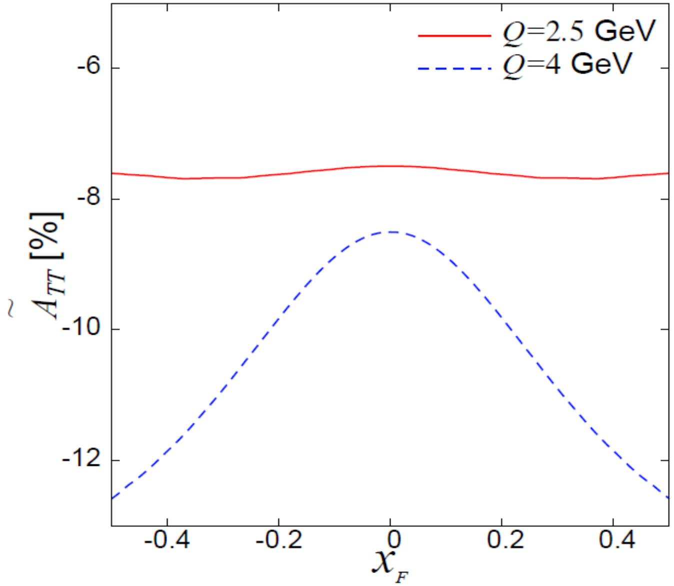
@GSI

$$\sqrt{S} \lesssim 15 \text{ GeV}$$

$$A_{TT} \propto \frac{\sum_q e_q^2 \left[\Delta_T q(x_1,Q^2)\Delta_T q(x_2,Q^2) + \Delta_T \bar{q}(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2)\right] + \cdots}{\sum_q e_q^2 \left[q(x_1,Q^2)q(x_2,Q^2) + \bar{q}(x_1,Q^2)\bar{q}(x_2,Q^2)\right] + \cdots}$$

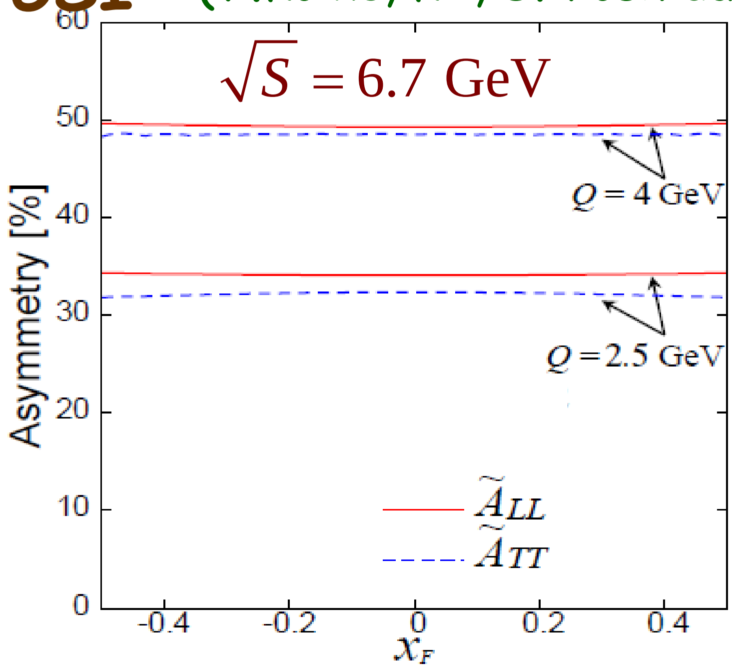
@J-PARC (S. Yoshida)

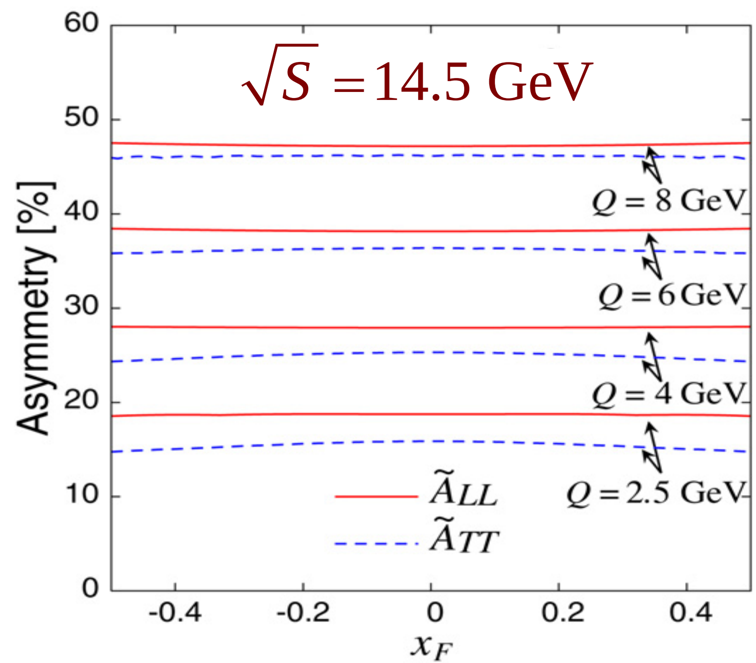
$\sqrt{S} = 10$ GeV



$$x_F = x_1 - x_2$$

@GSI (Y.Koike, KT, S. Yoshida, PLB668 ('08) 286)

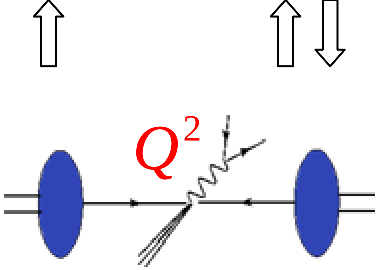




$$p^{\uparrow} + p^{\uparrow} \rightarrow \ell^{+}\ell^{-} + X$$

@J-PARC

$$\sqrt{S} \lesssim 10 \text{ GeV}$$



$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}}$$

$$\propto \frac{\sum_q e_q^2 \left[\Delta_T q(x_1, Q^2) \Delta_T \bar{q}(x_2, Q^2) + \Delta_T \bar{q}(x_1, Q^2) \Delta_T q(x_2, Q^2) \right] + \cdots}{\sum_q e_q^2 \left[q(x_1, Q^2) \bar{q}(x_2, Q^2) + \bar{q}(x_1, Q^2) q(x_2, Q^2) \right] + \cdots}$$

$$x_{1,2} = \frac{Q}{\sqrt{S}} e^{\pm y}$$

$$p^{\uparrow} + \bar{p}^{\uparrow} \rightarrow \ell^{+}\ell^{-} + X$$

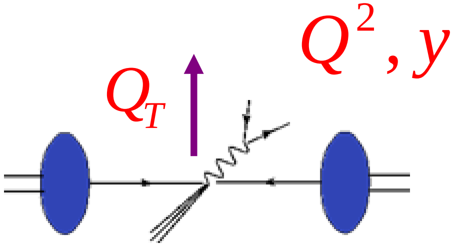
@GSI

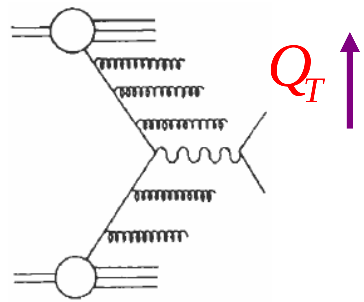
$$\sqrt{S} \lesssim 15 \text{ GeV}$$

$$A_{TT} \propto \frac{\sum_q e_q^2 \left[\Delta_T q(x_1, Q^2) \Delta_T q(x_2, Q^2) + \Delta_T \bar{q}(x_1, Q^2) \Delta_T \bar{q}(x_2, Q^2) \right] + \cdots}{\sum_q e_q^2 \left[q(x_1, Q^2) q(x_2, Q^2) + \bar{q}(x_1, Q^2) \bar{q}(x_2, Q^2) \right] + \cdots}$$

$$A_{TT} \gtrsim 10\%$$

Golden channel



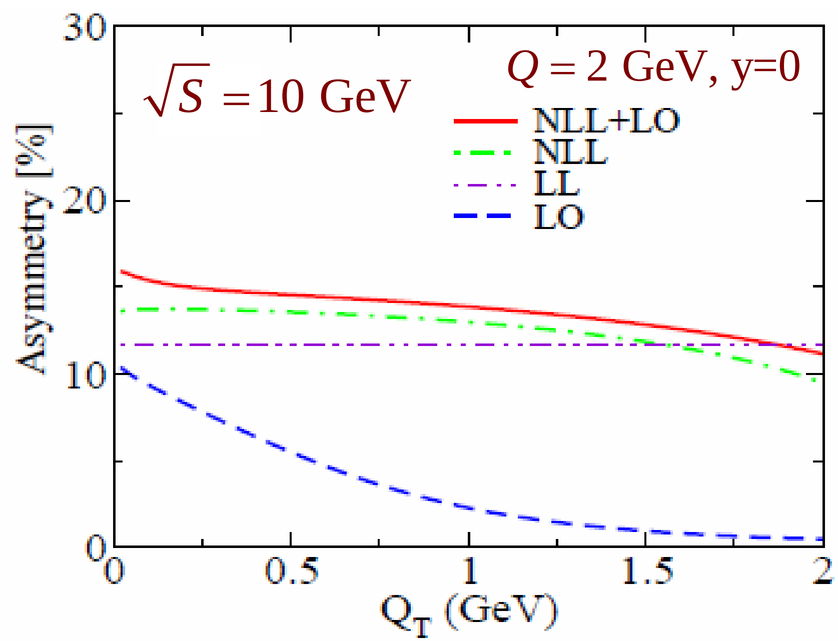


$$\alpha_s \ln^2\left(Q^2/Q_T^2\right)$$
$$\alpha_s \ln\left(Q^2/Q_T^2\right)$$

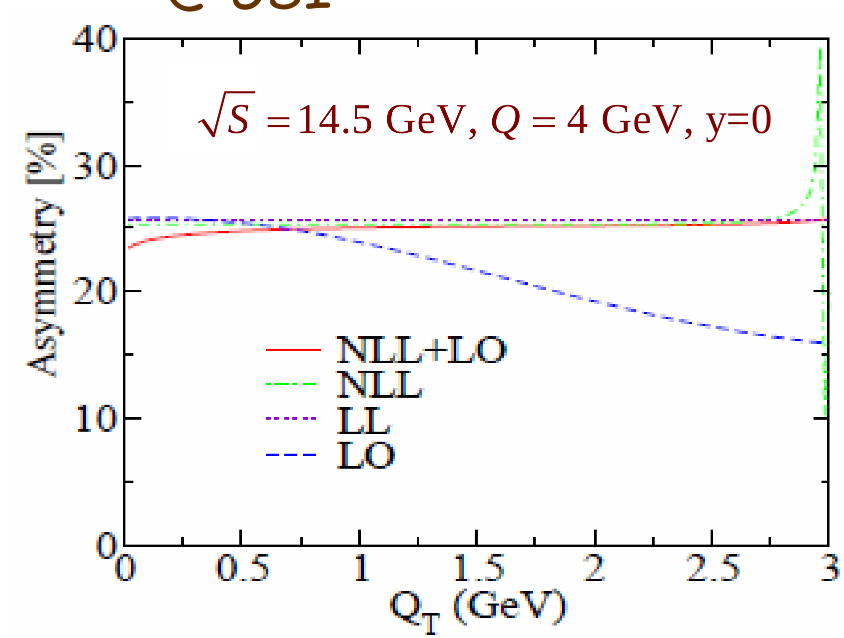
resummation

H. Kawamura, J. Kodaira, KT, NPB777 ('07) 203, PTP 118 ('07) 581
PLB662 ('08) 139

@ J-PARC

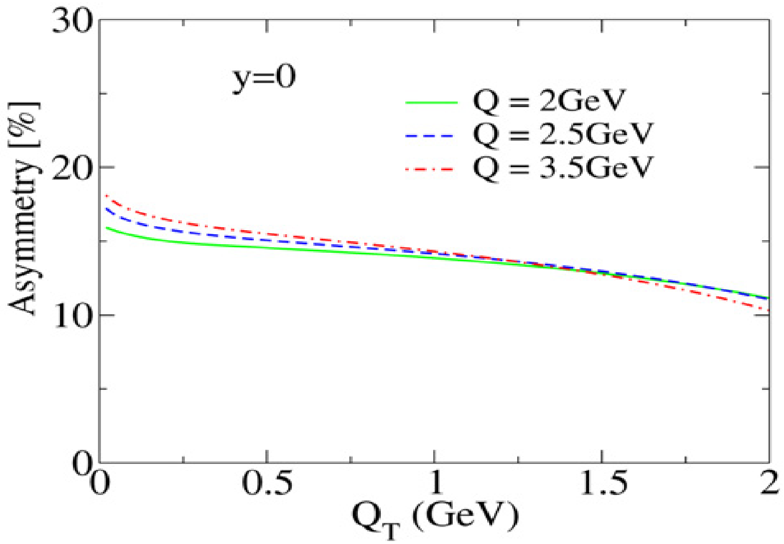


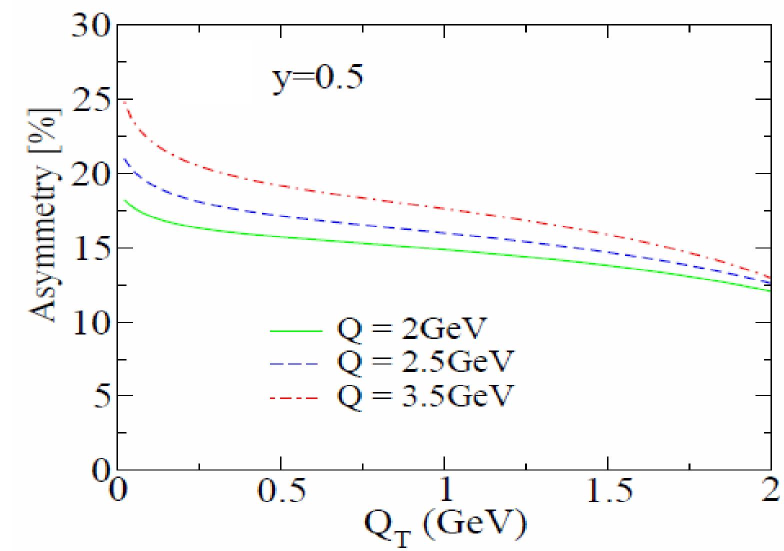
@ GSI



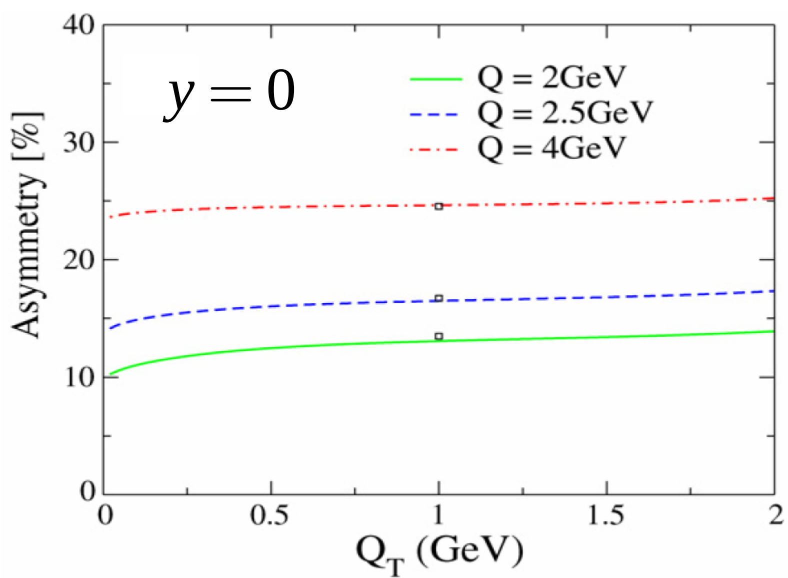
H. Kawamura, J. Kodaira, KT, NPB777 ('07) 203, PTP 118 ('07) 581
PLB662 ('08) 139

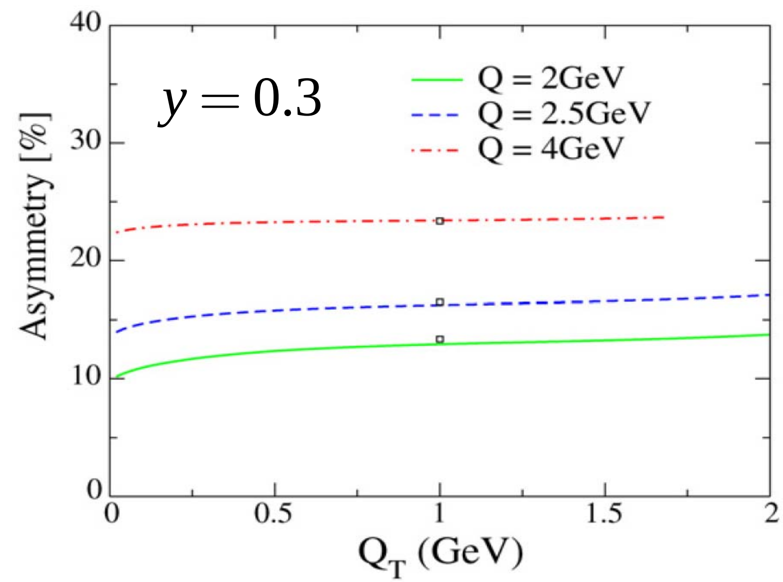
@ J-PARC $\sqrt{S} = 10$ GeV





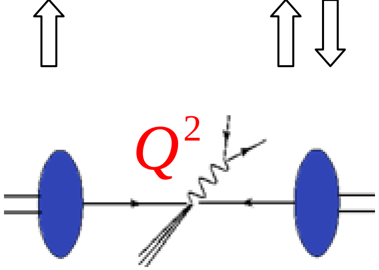
@ GSI $\sqrt{S} = 6.7$ GeV





$p^{\uparrow} + p^{\uparrow} \rightarrow \ell^{+}\ell^{-} + X$ **@J-PARC**

$\sqrt{S} \lesssim 10$ GeV



$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}}$$

$$\propto \frac{\sum_q e_q^2 \left[\Delta_T q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + \Delta_T \bar{q}(x_1,Q^2)\Delta_T q(x_2,Q^2)\right] + \cdots}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + \bar{q}(x_1,Q^2)q(x_2,Q^2)\right] + \cdots}$$

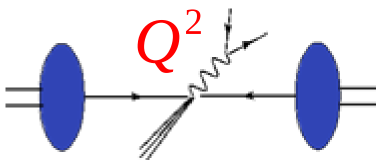
$$x_{1,2} = \frac{Q}{\sqrt{S}} e^{\pm y}$$

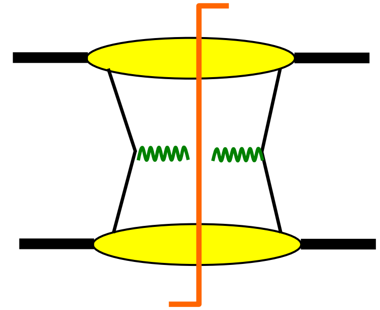
$p^{\uparrow} + \bar{p}^{\uparrow} \rightarrow \ell^{+}\ell^{-} + X$ **@GSI** $\sqrt{S} \lesssim 15$ GeV

$$A_{TT} \propto \frac{\sum_q e_q^2 \left[\Delta_T q(x_1,Q^2)\Delta_T q(x_2,Q^2) + \Delta_T \bar{q}(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2)\right] + \cdots}{\sum_q e_q^2 \left[q(x_1,Q^2)q(x_2,Q^2) + \bar{q}(x_1,Q^2)\bar{q}(x_2,Q^2)\right] + \cdots}$$

$A_{TT} \gtrsim 10\%$ ***Golden channel***

$$p + p \rightarrow \ell^+ \ell^- + X$$

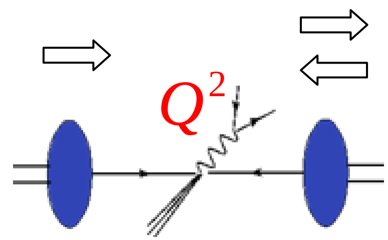




$$x_{1,2} = \frac{Q}{\sqrt{S}} e^{\pm y}$$

$$d\sigma \propto \sum_q e_q^2 \left[q(x_1, Q^2) \bar{q}(x_2, Q^2) + \bar{q}(x_1, Q^2) q(x_2, Q^2) \right] + \cdots$$

$$p^{\rightarrow} + p^{\rightarrow} \rightarrow \ell^+ \ell^- + X$$

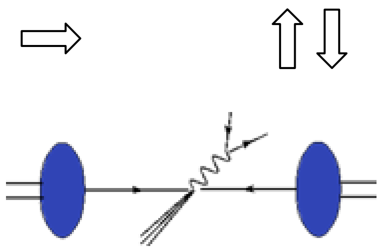


$$d\sigma^{\rightarrow\rightarrow} - d\sigma^{\rightarrow\leftarrow} \propto \sum_q e_q^2 \left[\Delta q(x_1, Q^2) \Delta\bar{q}(x_2, Q^2) + \Delta\bar{q}(x_1, Q^2) \Delta q(x_2, Q^2) \right] + \cdots$$

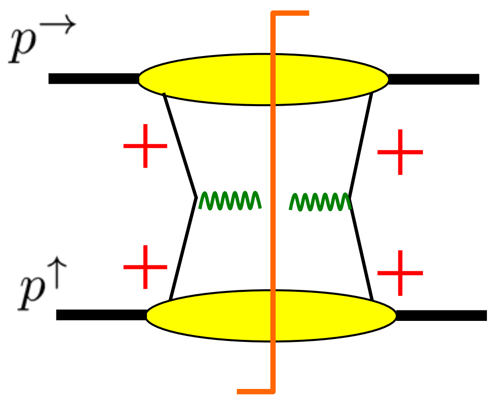
$$A_{LL} = \frac{d\sigma^{\rightarrow\rightarrow} - d\sigma^{\rightarrow\leftarrow}}{d\sigma^{\rightarrow\rightarrow} + d\sigma^{\rightarrow\leftarrow}}$$

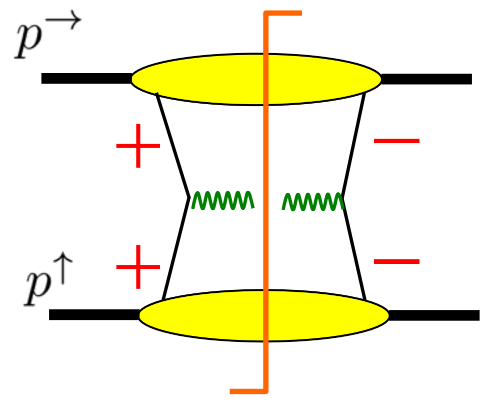
$$\propto \frac{\sum_q e_q^2 \left[\Delta q(x_1, Q^2) \Delta\bar{q}(x_2, Q^2) + \Delta\bar{q}(x_1, Q^2) \Delta q(x_2, Q^2) \right] + \cdots}{\sum_q e_q^2 \left[q(x_1, Q^2) \bar{q}(x_2, Q^2) + \bar{q}(x_1, Q^2) q(x_2, Q^2) \right] + \cdots}$$

$$A_{LT} = \frac{d\sigma^{\rightarrow\uparrow} - d\sigma^{\rightarrow\downarrow}}{d\sigma^{\rightarrow\uparrow} + d\sigma^{\rightarrow\downarrow}}$$

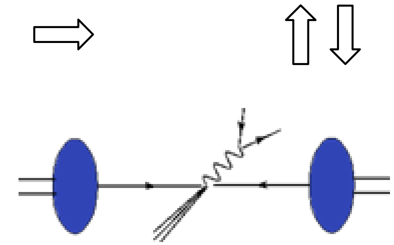


$$\propto \frac{\sum_q e_q^2 \left[\Delta q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + \Delta \bar{q}(x_1,Q^2)\Delta_T q(x_2,Q^2)\right]}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + \bar{q}(x_1,Q^2) q(x_2,Q^2)\right]}$$





$$A_{LT} = \frac{d\sigma^{\rightarrow\uparrow} - d\sigma^{\rightarrow\downarrow}}{d\sigma^{\rightarrow\uparrow} + d\sigma^{\rightarrow\downarrow}}$$



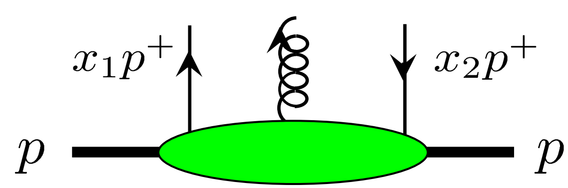
$$\propto \frac{\sum_q e_q^2 \left[\Delta q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + \Delta \bar{q}(x_1,Q^2)\Delta_T q(x_2,Q^2) \right]}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + q(x_1,Q^2) q(x_2,Q^2) \right]}$$

$$\propto \frac{\sum_q e_q^2 \left[\Delta q(x_1,Q^2) x_2 g_T^{\bar{q}}(x_2,Q^2) + x_1 h_L^q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + (q \leftrightarrow \bar{q}) \right]}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + \bar{q}(x_1,Q^2) q(x_2,Q^2) \right]}$$

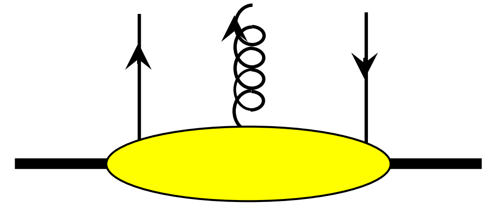
g_T, h_L : twist-3 parton distributions

$$g_T^q(x,Q^2) = \int_x^1 dy \frac{\Delta q(y,Q^2)}{y} + \text{"genuine twist-3"}$$

$$h_L^q(x,Q^2) = 2x \int_x^1 dy \frac{\Delta_T q(y,Q^2)}{y^2} + \text{"genuine twist-3"}$$



"3-body"



$$= \frac{S_\perp^\mu P^+}{8M^2}\int\frac{dz^-}{2\pi}e^{ixP^+z^-}\int_0^1 du\int_{-u}^{u} dt$$

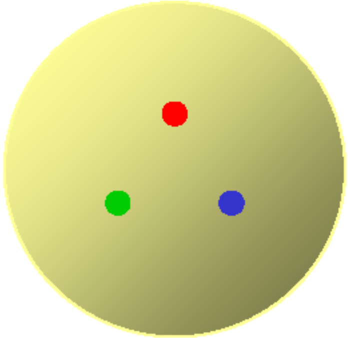
$$\times\langle PS_\perp|\bar{\psi}(\frac{-uz^-}{2})\not{z}\left[ug\widetilde{F}_{\mu\nu}(\frac{tz^-}{2})-itgF_{\mu\nu}(\frac{tz^-}{2})\gamma_5\right]z^\nu\psi(\frac{uz^-}{2})|PS_\perp\rangle$$

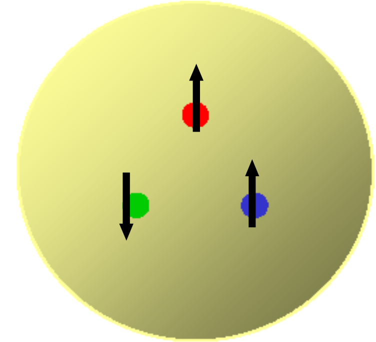
for $g_T(x,Q^2)$

$$= \frac{iP^+}{8M}\int\frac{dz^-}{2\pi}e^{ixP^+z^-}\int_0^1 du\, u\int_{-u}^{u} dt\, t$$

$$\times\langle PS_\parallel|\bar{\psi}(\frac{-uz^-}{2})i\sigma^{\alpha\nu}\gamma_5 gF_{\mu\nu}(\frac{tz^-}{2})z_\alpha z^\nu\psi(\frac{uz^-}{2})|PS_\parallel\rangle$$

for $h_L(x,Q^2)$

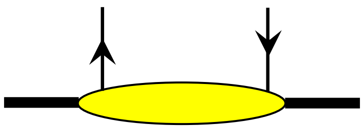


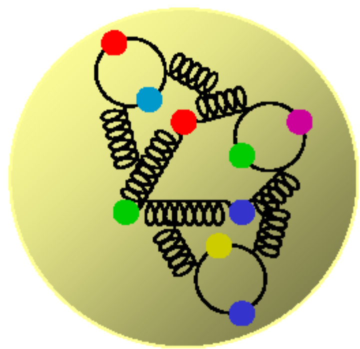


$$\int d\eta e^{ik\eta} \langle P | \psi^\dagger(0)\psi(\eta) | P \rangle$$

$$\langle PS | \overline{\psi}(0)\Gamma \psi(\eta) | PS \rangle$$

$$\Gamma = \gamma^\mu \gamma_5,\ \sigma^{\mu\nu},\ \ldots$$



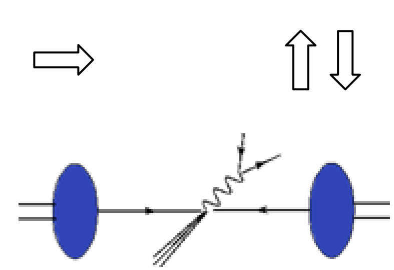


$$\langle P | \overline{\psi}(\xi_1)\overline{\psi}(\xi_2)\cdots\ \psi(\eta_1)\psi(\eta_2)\cdots\ F_{\mu\nu}(\zeta_1)F_{\alpha\beta}(\zeta_2)\cdots | P \rangle$$

exotic components: ***renorm. scale-dep.***

not direct observable

$$A_{LT} = \frac{d\sigma^{\rightarrow\uparrow} - d\sigma^{\rightarrow\downarrow}}{d\sigma^{\rightarrow\uparrow} + d\sigma^{\rightarrow\downarrow}}$$



$$\propto \frac{\sum_q e_q^2 \left[\Delta q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + \Delta\bar{q}(x_1,Q^2)\Delta_T q(x_2,Q^2) \right]}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + q(x_1,Q^2)q(x_2,Q^2) \right]}$$

$$\propto \frac{\sum_q e_q^2 \left[\Delta q(x_1,Q^2)x_2 g_T^{\bar{q}}(x_2,Q^2) + x_1 h_L^q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + \left(q \leftrightarrow \bar{q}\right) \right]}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + \bar{q}(x_1,Q^2)q(x_2,Q^2) \right]}$$

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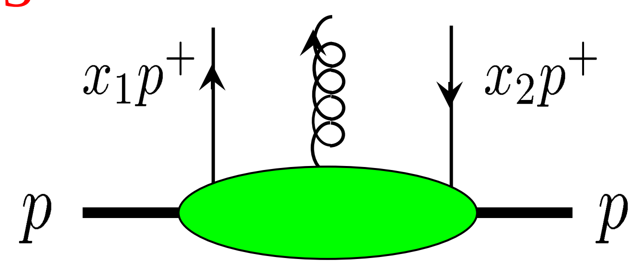
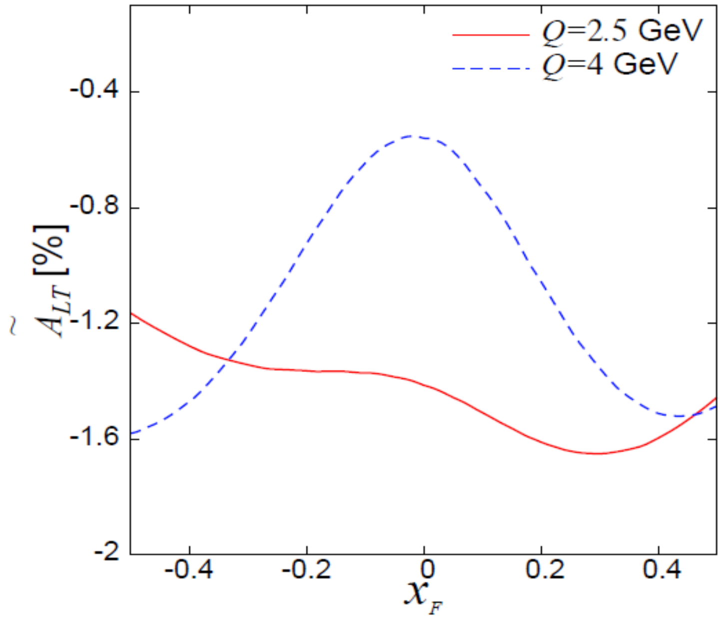
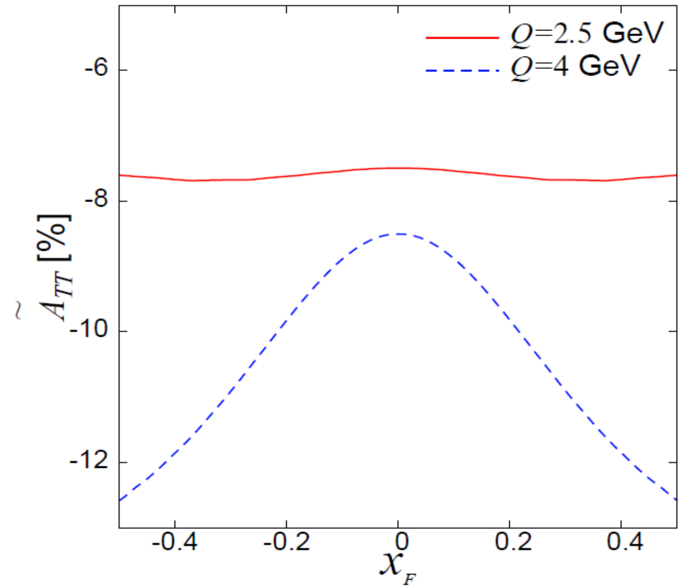


@J-PARC $\sqrt{S}=10$ GeV (S. Yoshida)

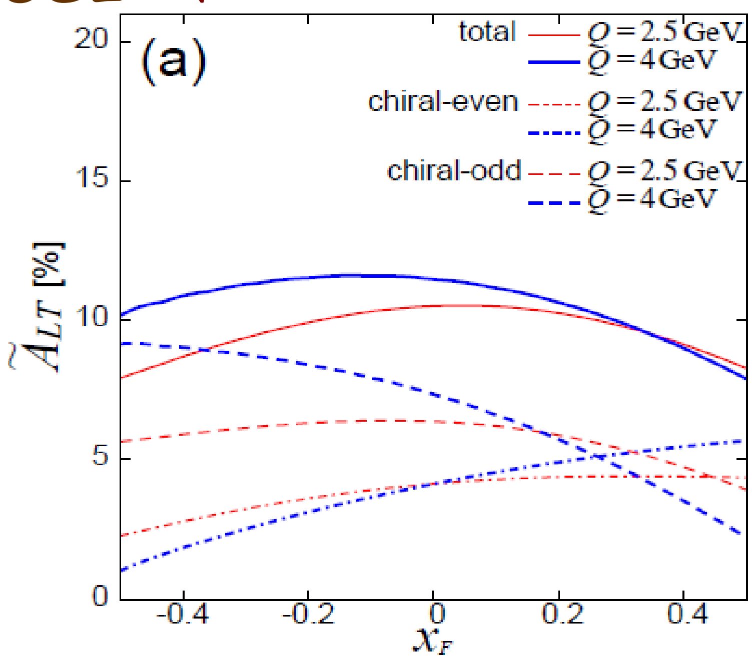


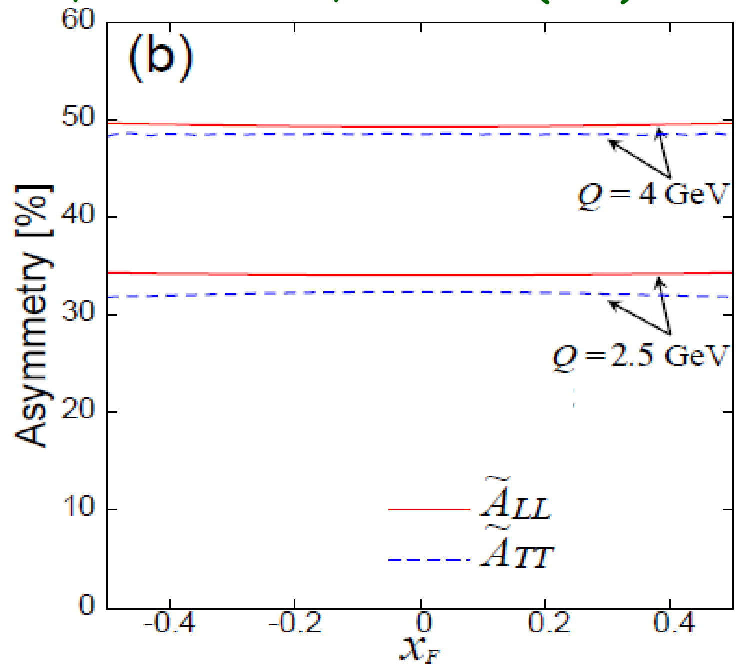


$x_F = x_1 - x_2$

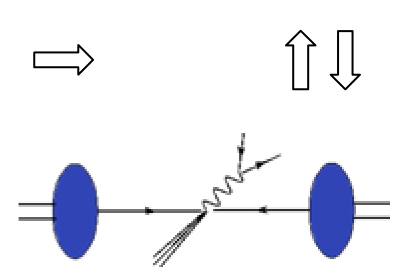
@GSI $\sqrt{S}=6.7$ GeV

Y. Koike, KT, S. Yoshida, PLB668('08)286





$$A_{LT} = \frac{d\sigma^{\rightarrow\uparrow} - d\sigma^{\rightarrow\downarrow}}{d\sigma^{\rightarrow\uparrow} + d\sigma^{\rightarrow\downarrow}}$$



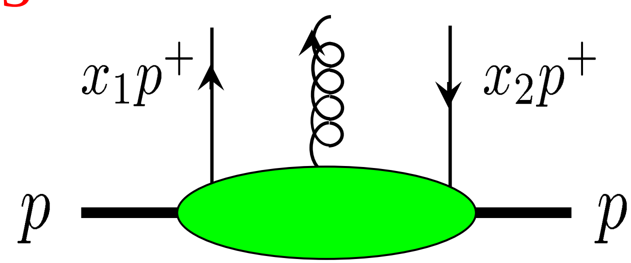
$$\propto \frac{\sum_q e_q^2 \left[\Delta q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + \Delta \bar{q}(x_1,Q^2)\Delta_T q(x_2,Q^2) \right]}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + q(x_1,Q^2) q(x_2,Q^2) \right]}$$

$$\propto \frac{\sum_q e_q^2 \left[\Delta q(x_1,Q^2) x_2 g_T^{\bar{q}}(x_2,Q^2) + x_1 h_L^q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + (q \leftrightarrow \bar{q}) \right]}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + \bar{q}(x_1,Q^2) q(x_2,Q^2) \right]}$$

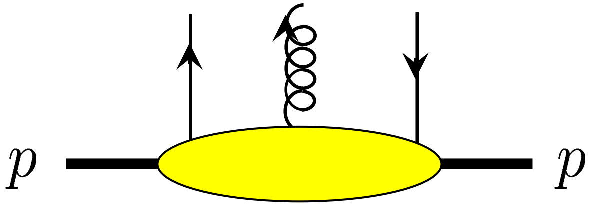
h_L, g_T : twist-3 parton distributions

$$h_L^q(x,Q^2) = 2x\int_x^1 dy \frac{\Delta_T q(y,Q^2)}{y^2} + \text{"genuine twist-3"}$$

$$g_T^q(x,Q^2) = \int_x^1 dy \frac{\Delta q(y,Q^2)}{y} + \text{"genuine twist-3"}$$



"3-body"



$$= \frac{S_\perp^\mu P^+}{8M^2} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \int_0^1 du \int_{-u}^{u} dt$$

$$\times \langle PS_\perp | \bar{\psi}(\frac{-uz^-}{2}) \not{z} \left[ug\tilde{F}_{\mu\nu}(\frac{tz^-}{2}) - itgF_{\mu\nu}(\frac{tz^-}{2})\gamma_5 \right] z^\nu \psi(\frac{uz^-}{2}) | PS_\perp \rangle$$

for $g_T(x, Q^2)$

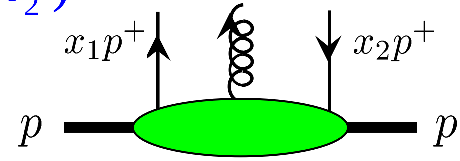
$$= \frac{iP^+}{8M} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \int_0^1 du\, u \int_{-u}^{u} dt\, t$$

$$\times \langle PS_\parallel | \bar{\psi}(\frac{-uz^-}{2}) i\sigma^{\alpha\nu}\gamma_5 gF_{\mu\nu}(\frac{tz^-}{2}) z_\alpha z^\nu \psi(\frac{uz^-}{2}) | PS_\parallel \rangle$$

for $h_L(x, Q^2)$

$$\int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\zeta(x_2 - x_1)} \langle p\ S_\perp | \bar{\psi}(0) g F^{\mu +}(\zeta n) \psi(\lambda n) | p\ S_\perp \rangle$$

$$= \frac{M_N}{4} \not{p} S_{\perp\alpha} p_\beta \varepsilon^{\alpha\beta\mu +} G_F(x_1, x_2) + i \frac{M_N}{4} \gamma_5 \not{p} S_\perp^\mu \widetilde{G}_F(x_1, x_2)$$

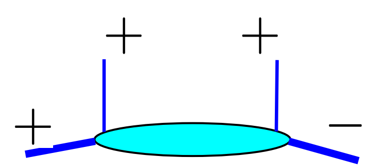


$$f_{1T}^\perp(x, k_\perp) = \int \frac{dx'}{x'} \Big[C_{SGP}(x, x'; k_\perp) G_F(x', x') + C_{HPo}(x, x'; k_\perp) G_F(x, x')$$

$$+ C_{HPn}(x, x'; k_\perp) G_F(x, x - x') + C_{HPnT}(x, x'; k_\perp) \widetilde{G}_F(x, x - x')$$

$$+ C_{HPoT}(x, x'; k_\perp) \widetilde{G}_F(x, x') \ + \cdots$$

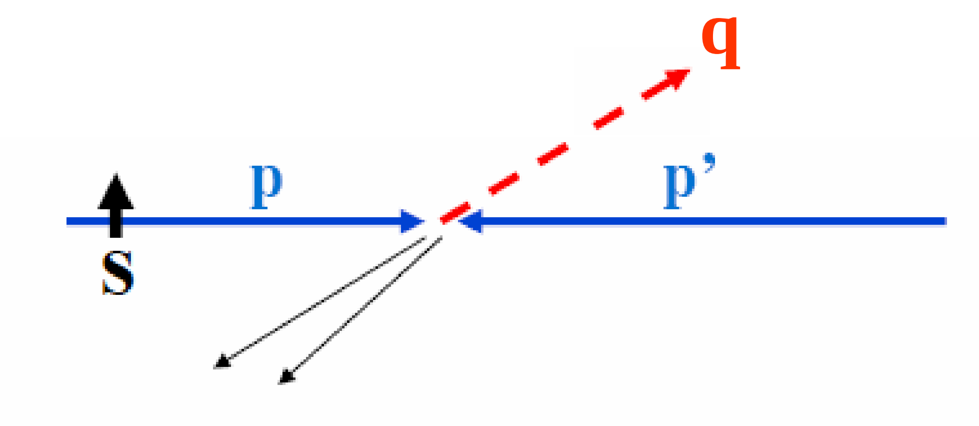
$$\sim \int d\eta e^{ik\eta} \left\langle P S_\perp \middle| \psi^\dagger(0) U(\mathbf{A}_\perp) \psi(\eta) \middle| P S_\perp \right\rangle$$



TMD (Sivers function)

$$\sim p \cdot (\mathbf{k}_\perp \times \mathbf{S}_\perp)$$

Single (Transverse) Spin Asymmetry SSA

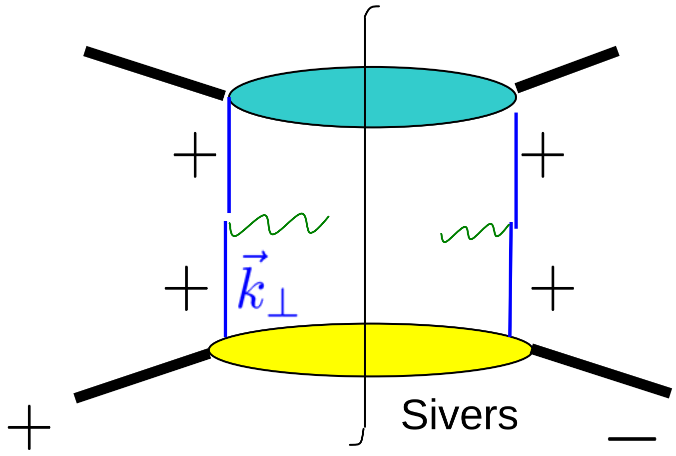


$$d\sigma^{\uparrow} \sim \mathbf{S}_{\perp} \cdot (\mathbf{p} \times \mathbf{q})$$

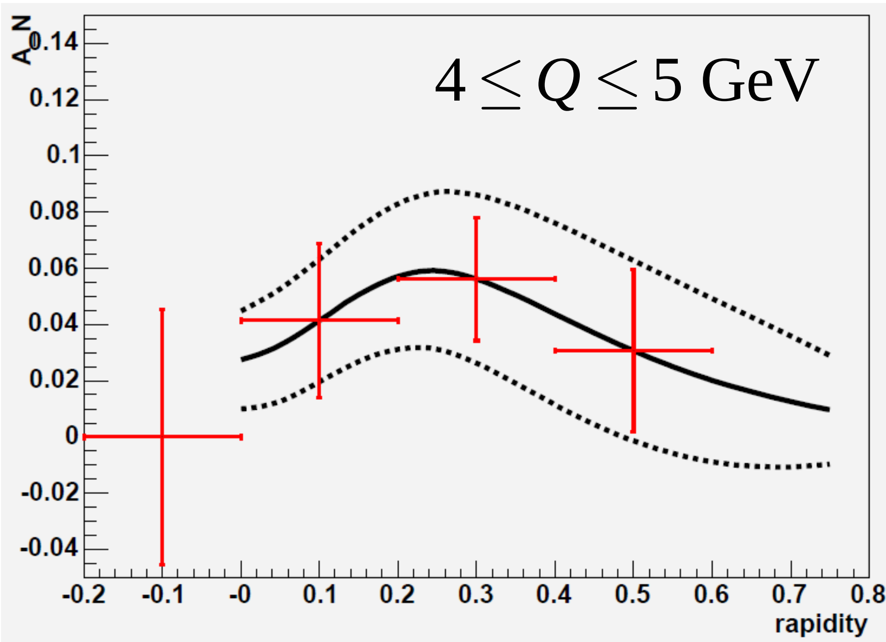
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$p^{\uparrow}p \rightarrow \ell^{+}\ell^{-}X$

J-PARC, GSI, ...

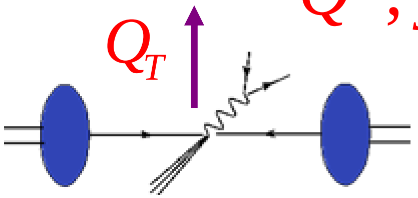


@J-PARC (F. Yuan, W. Vogelsang)

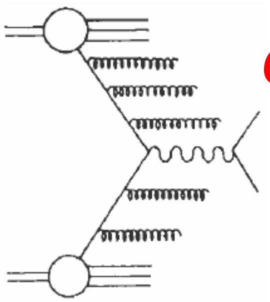


$p^{\uparrow} + p^{\uparrow} \to \ell^{+}\ell^{-} + X$ **@J-PARC**

Q^2, y



$$A_{TT} \propto \frac{\sum_q e_q^2 \left[\Delta_T q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + \Delta_T \bar{q}(x_1,Q^2)\Delta_T q(x_2,Q^2)\right] + \cdots}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + \bar{q}(x_1,Q^2) q(x_2,Q^2)\right] + \cdots}$$

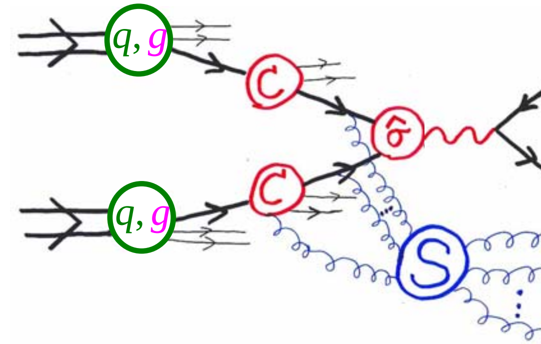


Q_T

$$\alpha_s \ln^2\left(Q^2/Q_T^2\right)$$

$$\alpha_s \ln\left(Q^2/Q_T^2\right)$$

resummation



Q_T

$$d\sigma = \int d^2 b\, e^{i\mathbf{b}\cdot\mathbf{Q}_T} e^{S(b,Q)} \sum_q e_q^2 \left[q(x_1,1/b^2)\bar{q}(x_2,1/b^2) + \bar{q}(x_1,1/b^2) q(x_2,1/b^2)\right] + \cdots$$

$e^{S(b,Q)}$ **is universal !**

$$S(b,Q) = -\int_{1/b^2}^{Q^2} \frac{d\mu^2}{\mu^2}\left\{\left(\ln\frac{Q^2}{\mu^2}\right) A\left(\alpha_s(\mu^2)\right) + B\left(\alpha_s(\mu^2)\right)\right\}$$

$$A(\alpha_s) = C_F\frac{\alpha_s}{\pi} + \frac{1}{2}C_F\left\{\left(\frac{67}{18} - \frac{\pi^2}{6}\right)C_G - \frac{5}{9}N_f\right\}\left(\frac{\alpha_s}{\pi}\right)^2$$

$$B(\alpha_s) = -\frac{3}{2}C_F\frac{\alpha_s}{\pi}$$

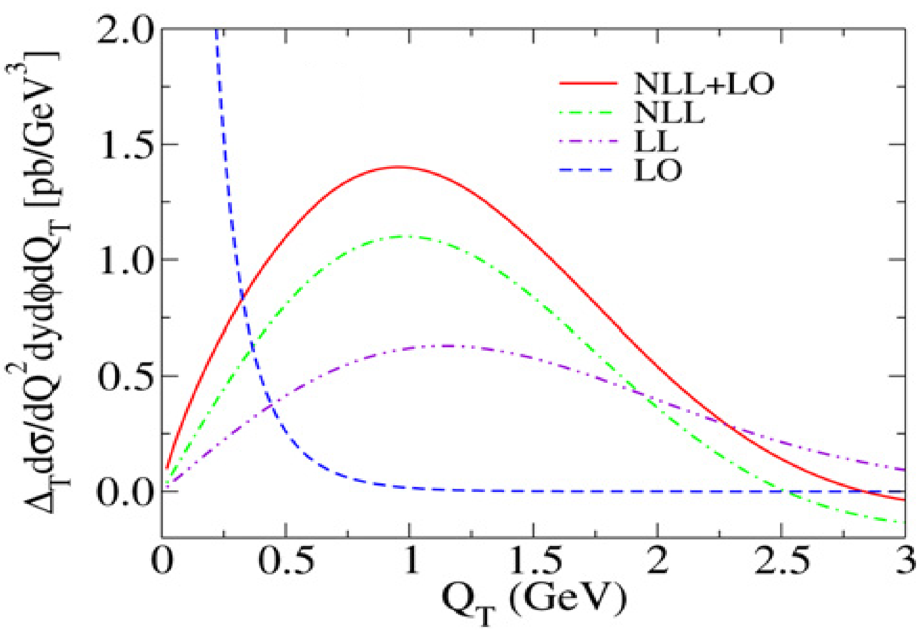
H. Kawamura, J. Kodaira, KT, NPB777 ('07) 203

@J-PARC

$\sqrt{S} = 10$ GeV

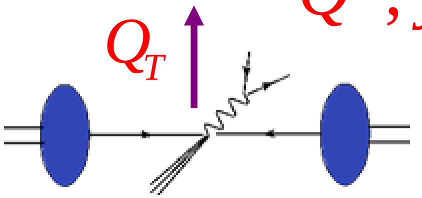
$Q = 2$ GeV

$y = 0$

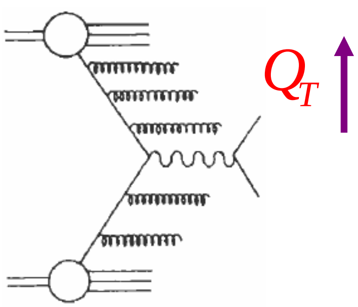


$p^{\uparrow} + p^{\uparrow} \to \ell^{+}\ell^{-} + X$ **@J-PARC**

Q^2, y



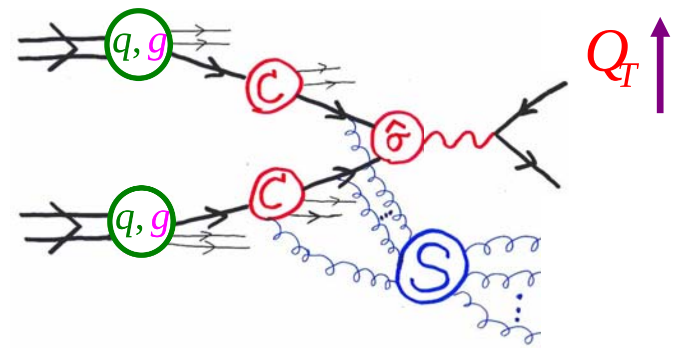
$$A_{TT} \propto \frac{\sum_q e_q^2 \left[\Delta_T q(x_1,Q^2)\Delta_T \bar{q}(x_2,Q^2) + \Delta_T \bar{q}(x_1,Q^2)\Delta_T q(x_2,Q^2)\right] + \cdots}{\sum_q e_q^2 \left[q(x_1,Q^2)\bar{q}(x_2,Q^2) + \bar{q}(x_1,Q^2) q(x_2,Q^2)\right] + \cdots}$$



$\alpha_s \ln^2\left(Q^2/Q_T^2\right)$

$\alpha_s \ln\left(Q^2/Q_T^2\right)$

resummation



$$d\sigma = \int d^2 b\, e^{i\mathbf{b}\cdot\mathbf{Q}_T} e^{S(b,Q)} \sum_q e_q^2 \left[q(x_1,1/b^2)\bar{q}(x_2,1/b^2) + \bar{q}(x_1,1/b^2) q(x_2,1/b^2)\right] + \cdots$$

$e^{S(b,Q)}$ **is universal !**

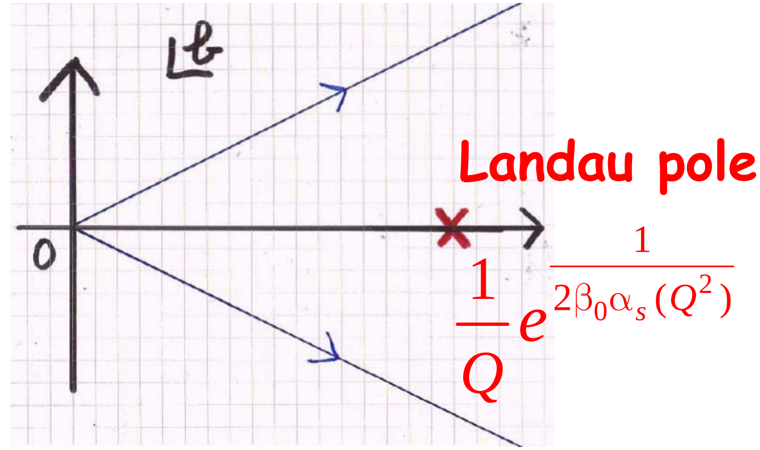
$$e^{S(b,Q)} \to e^{S(b,Q)} e^{-g_{NP} b^2}$$

$$g_{NP} = g_1 + g_2 \ln\left(Q/2Q_0\right)$$

All-order resummation → IR Landau pole

$$\int d^2b\, e^{i\mathbf{b}\cdot\mathbf{Q}_T} e^{S(b,Q)} \cdots$$

$$= 2\pi \int_0^\infty db\, b\, \underbrace{J_0(bQ_T)}_{\displaystyle \frac{H_0^{(1)}(bQ_T)+H_0^{(2)}(bQ_T)}{2}} e^{S(b,Q)} \cdots$$



$$\frac{1}{Q} e^{\frac{1}{2\beta_0 \alpha_s(Q^2)}}$$

1. cut-off at b_{max} : $b \to b_* = \dfrac{b}{\sqrt{1+b^2/b_{max}^2}}$

J. Collins, D. Soper, G. Sterman ('82)
A. Kulesza, W. Stirling ('02)
C. Balazs, C. Yuan ('00)

Global fit $g_1 = 0.016\ \mathrm{GeV}^2,\ g_2 = 0.54\ \mathrm{GeV}^2 \quad \left(b_{max} = 0.5\ \mathrm{GeV}^{-1}\right)$

F. Landry, R. Brock, P. Nadolsky. C. Yuan ('03)

2. Contour deformation

E. Laenen, G. Sterman, W. Vogelsang ('00)

A. Kulesza, G. Sterman, W. Vogelsang ('02)

G. Bozzi, S. Catani, D. de Florian, M. Grazzini ('02)

H. Kawamura, J. Kodaira, KT ('07)

Global fit using contour deformation

M. Hirai, H. Kawamura, KT ('12)

Experimental data sets

	Exp	√s (GeV)	Target	Q_T range (GeV)	Q range (GeV)	# of data (pT < 22 GeV)
DY	R209	62	P-P	0.2 – 1.8	5.0 - 8.0	5
	R209	62	P-P	0.2 – 1.8	8.0 - 11.0	5
Z^0	CDF run-0	1800	P-Pbar	0.0 – 22.8	75 - 105	7
	CDF run-1	1800	P-Pbar	0.0 – 22.0	66 - 116	33
	D0 run-1	1800	P-Pbar	0.0 – 22.0	75 - 105	15

$$d\sigma = \int d^2 b e^{i\mathbf{b}\cdot\mathbf{Q}_T} e^{S(b,Q)} \sum_q e_q^2 \left[q(x_1, 1/b^2)\bar{q}(x_2, 1/b^2) + \bar{q}(x_1, 1/b^2) q(x_2, 1/b^2) \right] + \cdots$$

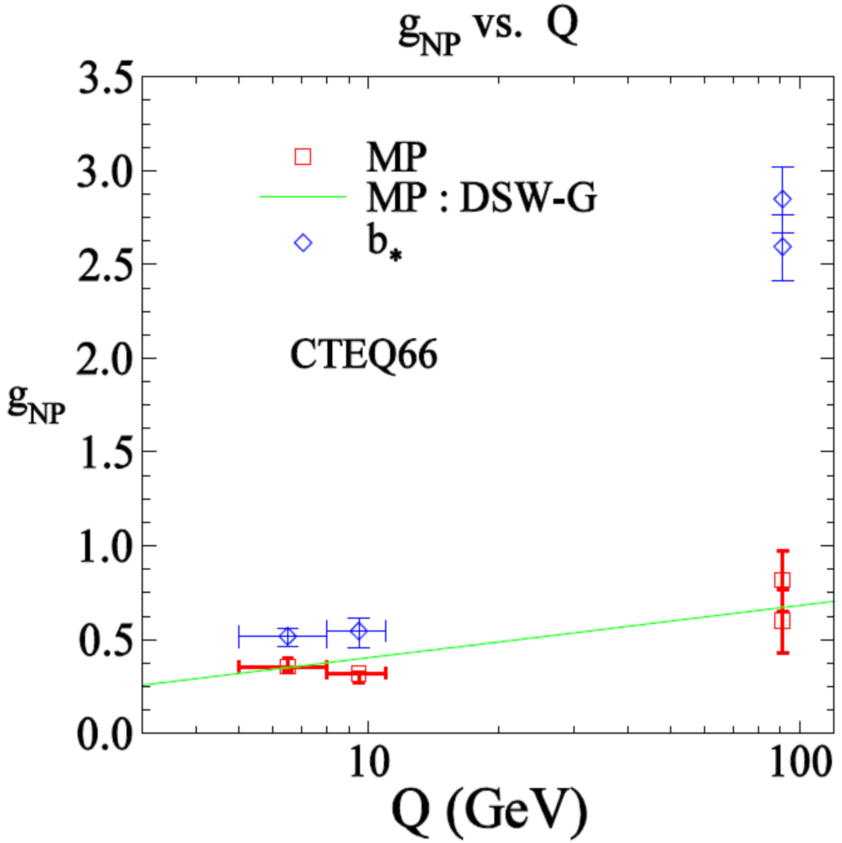
$e^{S(b,Q)}$ **is universal !**

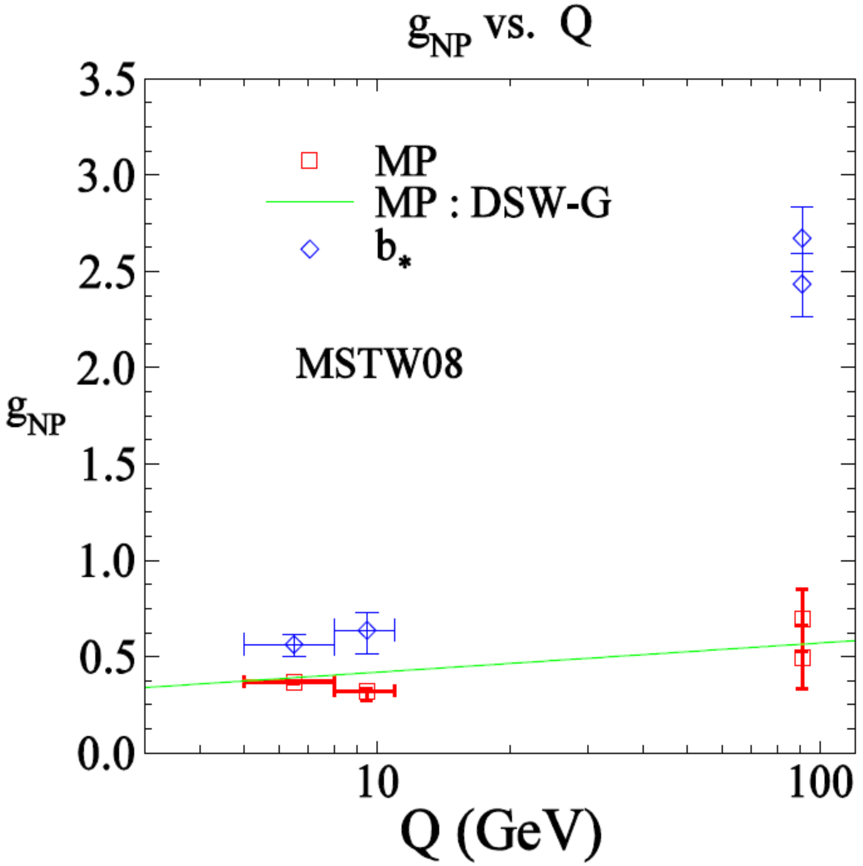
$$e^{S(b,Q)} \to e^{S(b,Q)} e^{-g_{\mathrm{NP}} b^2}$$

$$g_{\mathrm{NP}} = g_1 + g_2 \ln\left(Q/2Q_0\right)$$

1-parameter gaussian fit of $e^{-g_{\mathrm{NP}} b^2}$ **for each set**

M. Hirai, H. Kawamura, KT ('12)



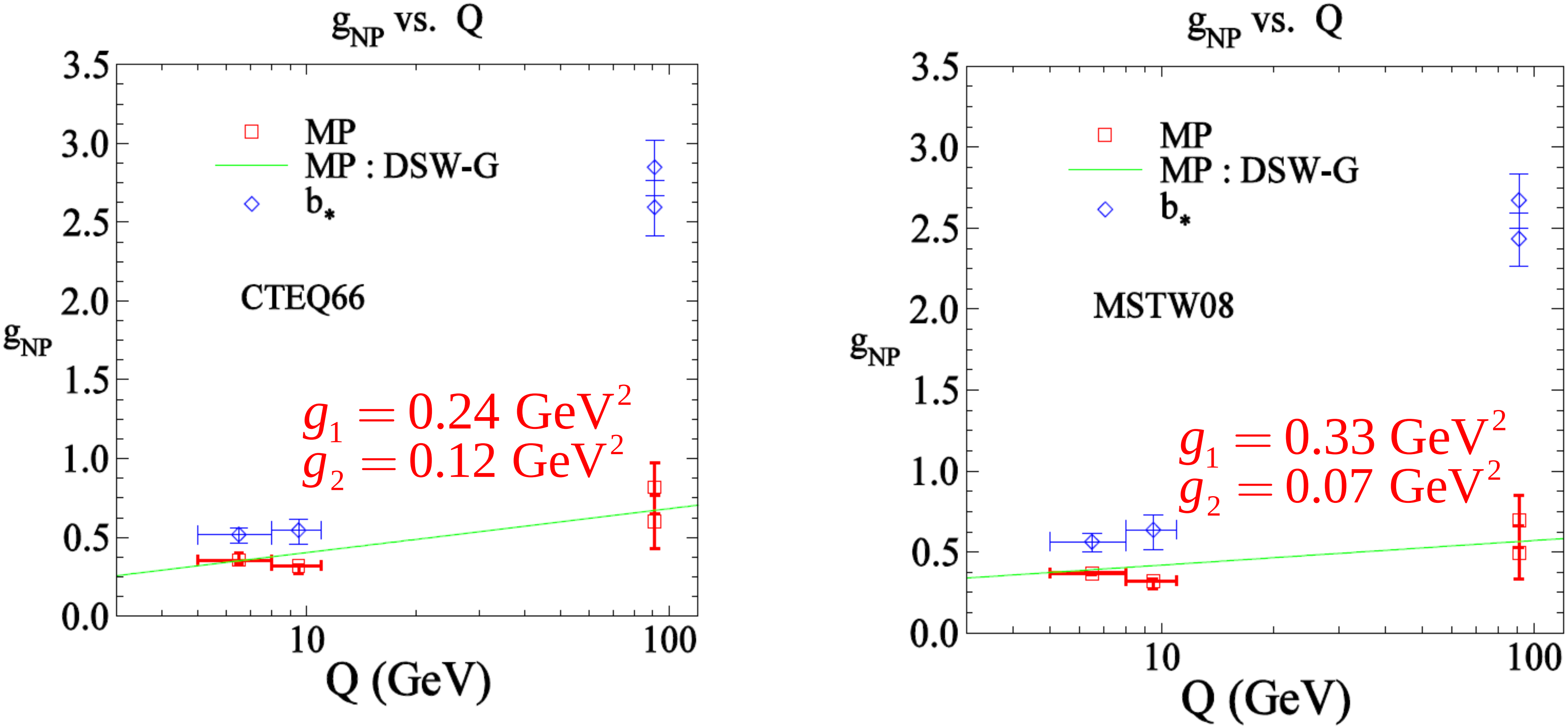


$$g_{\rm NP} = g_1 + g_2 \ln\left(Q/2Q_0\right)$$

$g_1 = 0.016\ \mathrm{GeV}^2,\ g_2 = 0.54\ \mathrm{GeV}^2$

F. Landry, R. Brock, P. Nadolsky. C. Yuan ('03)

M. Hirai, H. Kawamura, KT ('12)



$$g_{\mathrm{NP}} = g_1 + g_2 \ln\left(Q/2Q_0\right)$$

$$\left(Q_0 = 1.3\ \mathrm{GeV}\right)$$

$g_1 = 0.016\ \mathrm{GeV}^2,\ g_2 = 0.54\ \mathrm{GeV}^2$

F. Landry, R. Brock, P. Nadolsky. C. Yuan ('03)

$$e^{-g_{\mathrm{NP}} b^2}$$

$$\langle k_T \rangle \sim \sqrt{g_{\mathrm{NP}}}$$

Global fit using contour deformation

M. Hirai, H. Kawamura, KT ('12)

Experimental data sets

	Exp	√s (GeV)	Target	Q_T range (GeV)	Q range (GeV)	# of data (pT < 22 GeV)
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Z^0	D0 run-1	1800	P-Pbar	0.0 – 22.0	75 - 105	15

$$d\sigma = \int d^2 b\, e^{i\mathbf{b}\cdot\mathbf{Q}_T} e^{S(b,Q)} \sum_q e_q^2 \left[q(x_1, 1/b^2)\bar{q}(x_2, 1/b^2) + \bar{q}(x_1, 1/b^2) q(x_2, 1/b^2) \right] + \cdots$$

$e^{S(b,Q)}$ is universal !

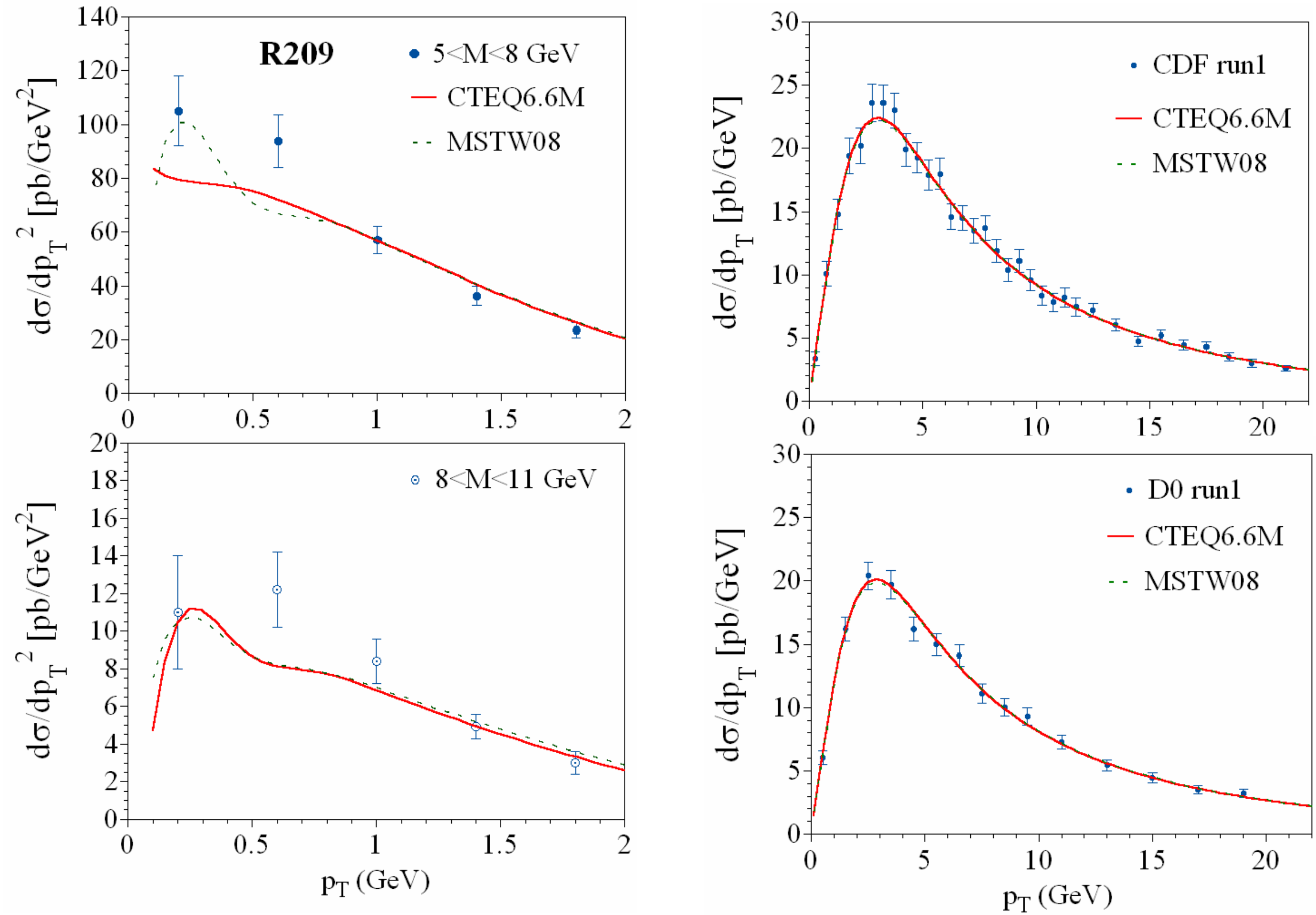
$$e^{S(b,Q)} \rightarrow e^{S(b,Q)} e^{-g_{\rm NP} b^2}$$

$$g_{\rm NP} = g_1 + g_2 \ln(Q/2Q_0)$$

1-parameter gaussian fit of $e^{-g_{\rm NP} b^2}$ for each set

Data vs. Theory

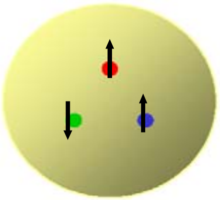
M. Hirai, H. Kawamura, KT ('12)



Summary : Drell-Yan processes at J-PARC

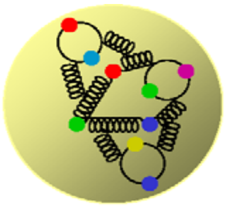
Golden channel to probe exotic components in normal hadron

A_{TT} $\Delta_T q(x),\ \Delta_T \bar{q}(x)$



$\langle PS | \bar{\psi}(0)\sigma^{\mu\nu}\psi(\eta) | PS \rangle$

A_{LT} $h_L(x),\ g_T(x)$



$\langle P | \bar{\psi}(0) F_{\mu\nu}(\zeta)\psi(\eta) | P \rangle$

including large x region & antiquarks

Clean!

Sudakov resummation $e^{S(b,Q)} \rightarrow e^{S(b,Q)} e^{-g_{\mathrm{NP}} b^2}$

constraints to determine $g_{\mathrm{NP}} = g_1 + g_2 \ln(Q/2Q_0)$

$\langle k_T \rangle \sim \sqrt{g_{\mathrm{NP}}}$

Production of W, Higgs,....