Hadron tomography
for gravitational and spin physics

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Two topics: (1) GPDs/GDAs for gravitational form factors
(2) Structure functions of spin-1 deuteron

International workshop on "The Nature of Hadron Mass and Quark-Gluon Confinement from JLab Experiments in the 12-GeV Era"
APCTP, Pohang, South Korea, July 1-4, 2018
https://www.apctp.org/plan.php/JLab-12GeV/

July 2, 2018

Hadron Tomography

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- **Introduction**

  → **Origin of nucleon spin:** Decomposition into internal spin components

  → **Origin of nucleon mass:** Decomposition into internal mass components

  Hadron tomography: We study these topics through **3-dimensional structure functions.**

- **GPDs and GDAs for hadron tomography**

  GPD (Generalized Parton Distribution)

  GDA (Generalized Distribution Amplitude) = "Timelike GPDs"

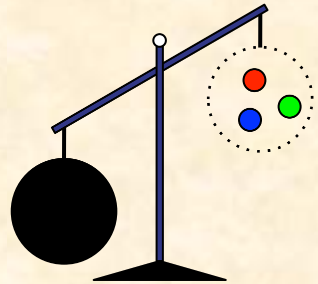
- **Gravitational sources in hadrons**

  Gravitational-mass distributions from microscopic quark-gluon level

- **Summary I (tomography part)**

Origins of nucleon spin and mass

Motivations: Unsolved mysteries in physics

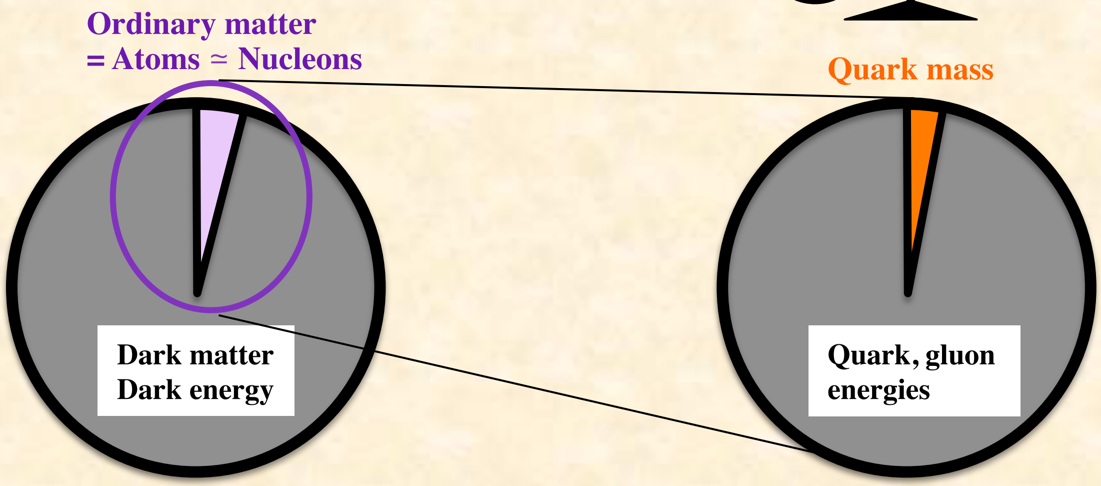


Mass and spin of the nucleon are two of fundamental quantities in physics.

Nucleon mass: $M = \left\langle p \middle| \int d^3x \, T^{00}(x) \middle| p \right\rangle$

Energy-momentum tensor:

$$T^{\mu\nu}(x) = \frac{1}{2}\bar{q}(x) i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)} q(x) + \frac{1}{4} g^{\mu\nu} F^2(x) - F^{\mu\alpha}(x) F^{\nu}_{\ \alpha}(x)$$

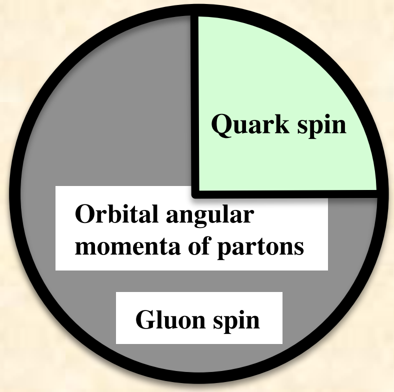


Dark matter | **Origin of nucleon mass**

Nucleon spin: $\frac{1}{2} = \left\langle p \middle| J^3 \middle| p \right\rangle$

3rd component of total angular momentum: $J^3 = \frac{1}{2}\varepsilon^{3jk} \int d^3x \, M^{3jk}(x)$

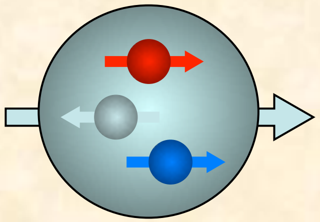
Angular-momentum density: $M^{\alpha\mu\nu}(x) = T^{\alpha\nu}(x) x^{\mu} - T^{\alpha\mu}(x) x^{\nu}$

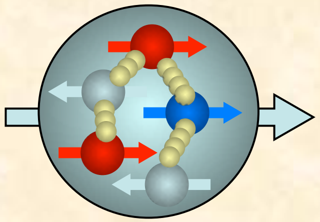


Origin of nucleon spin
(“Dark spin”)

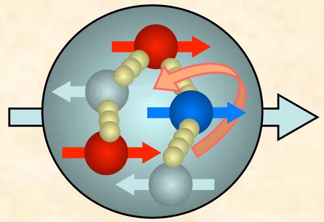
Recent progress on origin of nucleon spin

"old" standard model





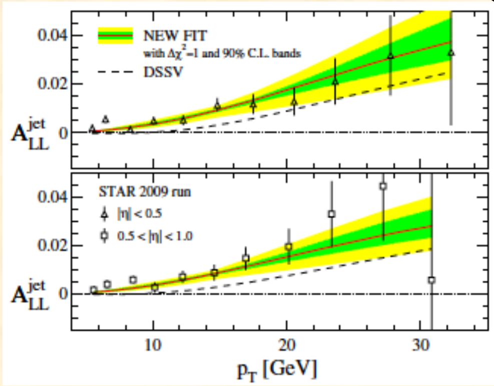
gluon spin

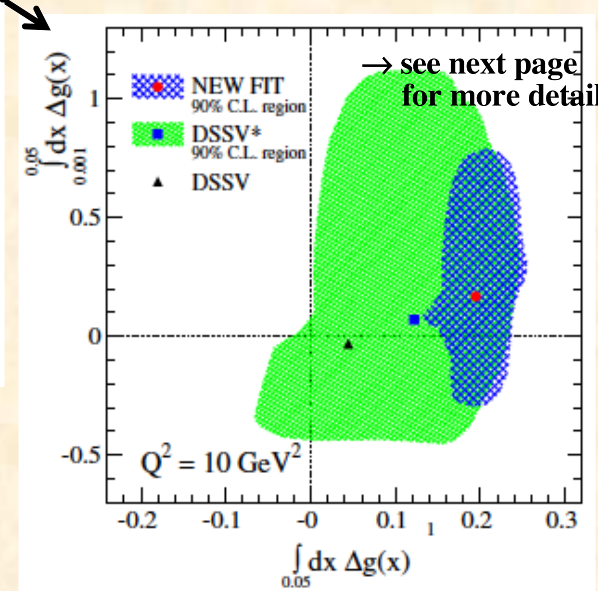


angular momentum

$$p_{\uparrow} = \frac{1}{3\sqrt{2}}\left(uud\left[2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow\right] + \text{permutations}\right)$$

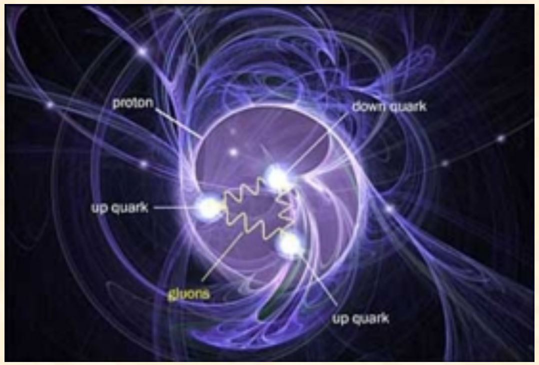
$$\boxed{\begin{aligned} &\Delta q(x) \equiv q_{\uparrow}(x) - q_{\downarrow}(x) \\ &\Delta\Sigma = \sum_i \int dx \left[\Delta q_i(x) + \Delta\bar{q}_i(x)\right] \to 1\ (100\%) \end{aligned}}$$





$\rightarrow$ see next page for more details

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

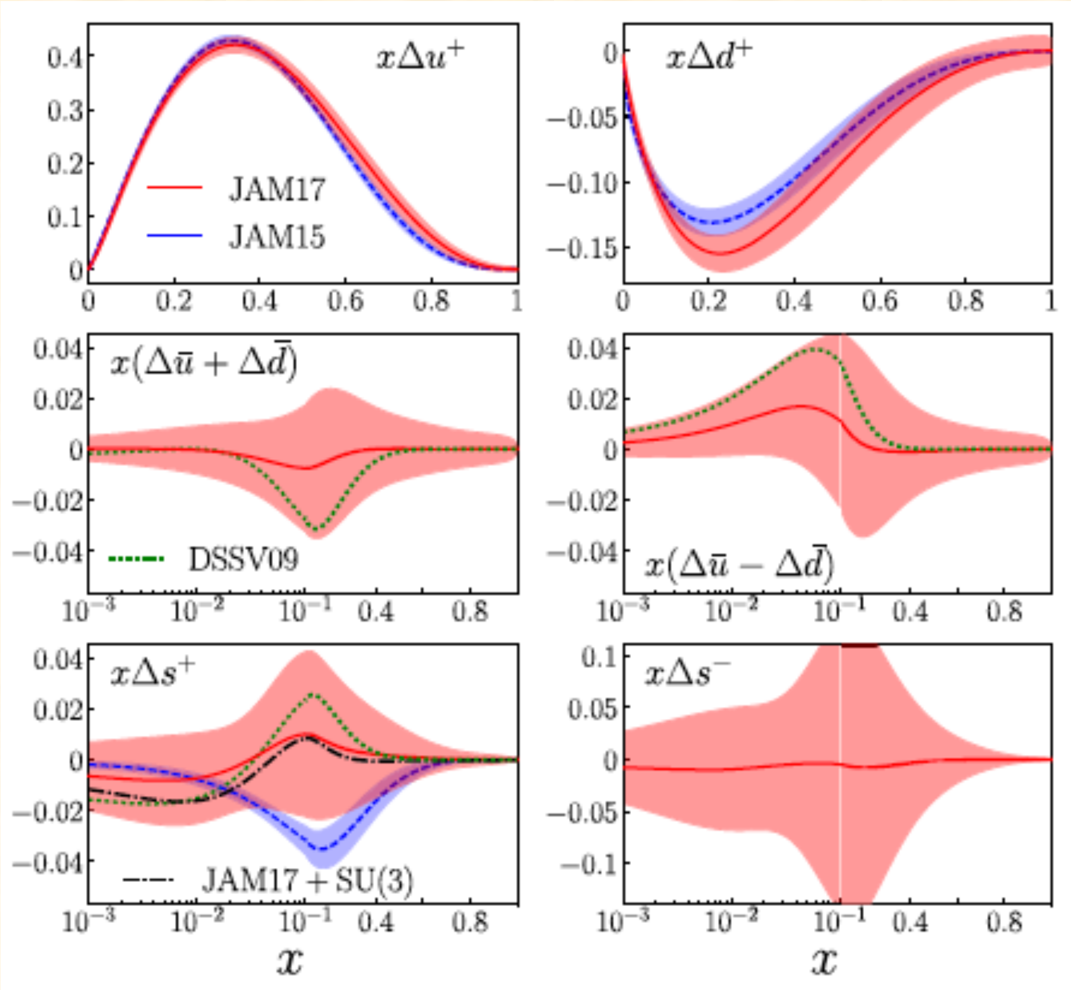


Scientific American (2014)

Toward "real" global analysis

J. J. Ethier, N. Sato, W. Melnitchouk, PRL 119 (2017) 132001

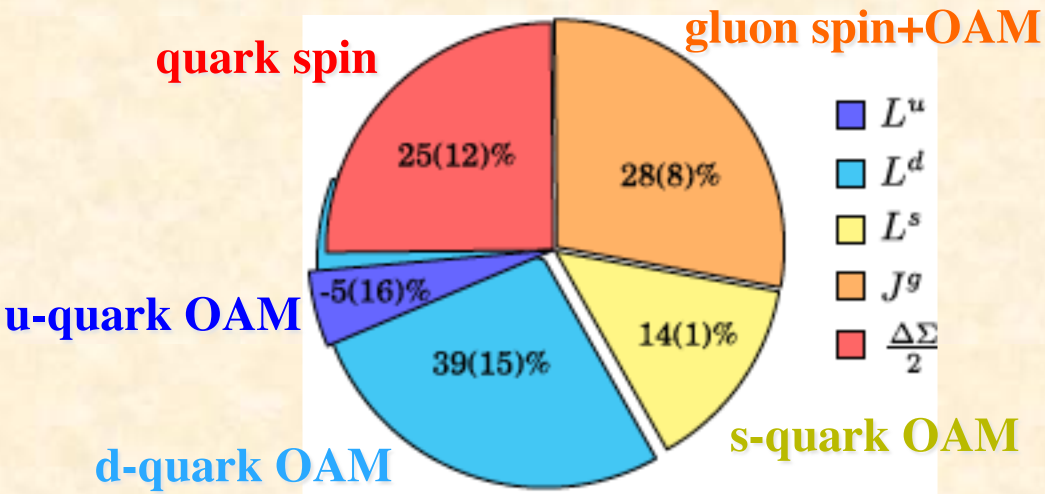
JAM: Analysis of Longitudinal-polarization data + Fragmentation data
CTEQ: Analysis of Unpolarized nucleon data + Nuclear data



"Real" global analysis
= unpolarized data
+ longitudinally-polarized
+ fragmentation
+ nuclear
+ transversity
+ spin-1 deuteron
+ • • •

Origin of nucleon spin: decomposition

$$\frac{1}{2} = \left\langle p \middle| J^3 \middle| p \right\rangle = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g, \quad J^3 = \frac{1}{2}\varepsilon^{3jk}\int d^3x\, M^{3jk}(x), \;\; M^{\alpha\mu\nu}(x) = T^{\alpha\nu}(x)x^\mu - T^{\alpha\mu}(x)x^\nu$$



Lattice QCD estimate in M. Deke *et al*., PRD 91 (2015) 0145505

Spin decomposion

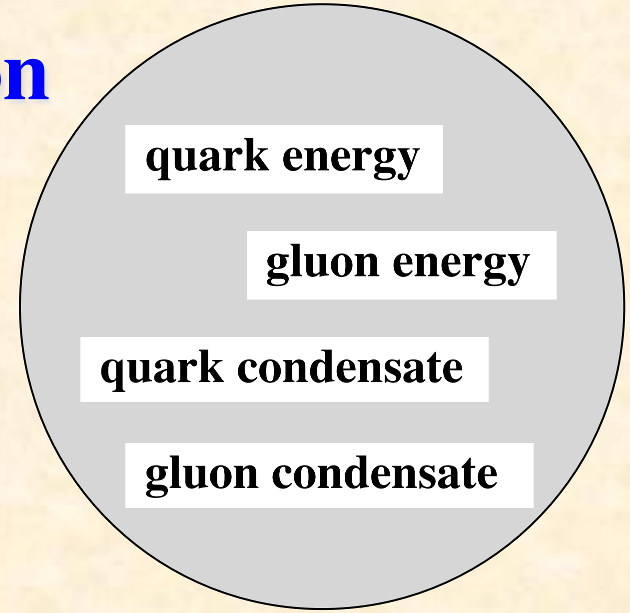
- quark spin 25%
- quark OAM 45%
- gluon spin + OAM 30%

Origin of nucleon mass: decomposition

Nucleon mass: $M = \left\langle p \middle| H \middle| p \right\rangle, \quad H = \int d^3x\, T^{00}(x)$

Energy-momentum tensor:

$$T^{\mu\nu}(x) = \frac{1}{2}\bar{q}(x) i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)} q(x) + \frac{1}{4} g^{\mu\nu} F^2(x) - F^{\mu\alpha}(x) F^{\nu}_{\ \alpha}(x)$$



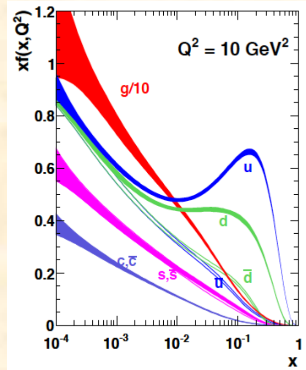
We need theoretical and experimental efforts
to decompose nucleon mass for finding its origin.

Hadron tomography
(3D structure functions)

Wigner distribution and various structure functions

Form factor $\xleftarrow{\int dx\, d^2k_T}$

PDF (Parton Distribution Function) $\xleftarrow{\int d^2k_T,\ \Delta \to 0}$



GTMD $W(x, \vec{k}_T, \Delta) \xrightarrow[\Delta^+ \to 0]{}$ **Wigner** $W(x, \vec{k}_T, \vec{r}_T)$

3D world

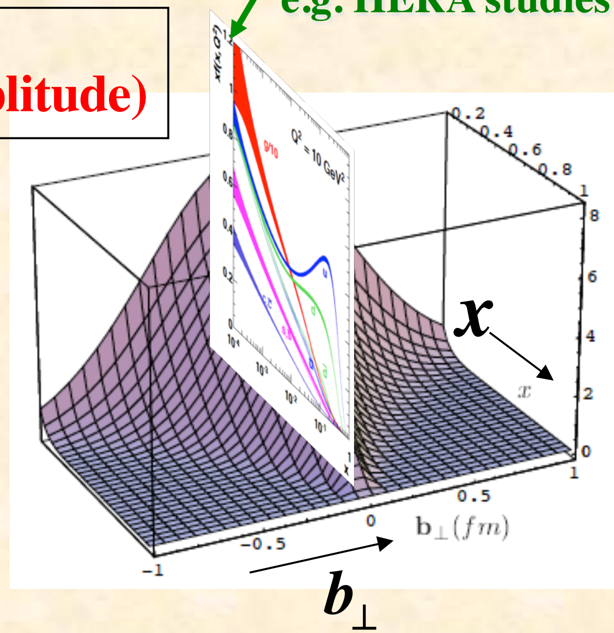
$\Delta = p' - p$

$\int d^2k_T$

GPD (Generalized Parton Distribution)

$\xrightarrow[s \leftrightarrow t]{}$ **GDA (Generalized Distribution Amplitude)**

e.g. HERA studies

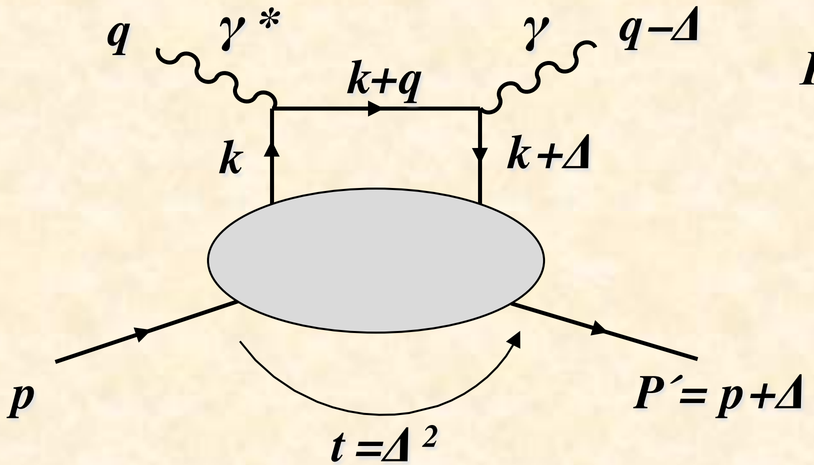


$\Delta \to 0$

TMD (Transverse Momentum Dependent) parton distribution

Our work by the two-photon process $\gamma\gamma \to h\bar{h}$.

Generalized Parton Distributions (GPDs)



$$P = \frac{p+p'}{2}, \quad \Delta = p' - p$$

Bjorken variable $\quad x = \dfrac{Q^2}{2p \cdot q}$

Momentum transfer squared $\quad t = \Delta^2$

Skewdness parameter $\quad \xi = \dfrac{p^+ - p'^+}{p^+ + p'^+} = -\dfrac{\Delta^+}{2P^+}$

GPDs are defined as correlation of off-forward matrix:

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p' | \bar{\psi}(-z/2)\gamma^+\psi(z/2) | p \rangle \big|_{z^+=0, \vec{z}_\perp=0} = \frac{1}{2P^+}\left[H(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E(x,\xi,t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(p)\right]$$

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p' | \bar{\psi}(-z/2)\gamma^+\gamma_5\psi(z/2) | p \rangle \big|_{z^+=0, \vec{z}_\perp=0} = \frac{1}{2P^+}\left[\tilde{H}(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}(x,\xi,t)\bar{u}(p')\frac{\gamma_5\Delta^+}{2M}u(p)\right]$$

Forward limit: PDFs

$$H(x,\xi,t)\big|_{\xi=t=0} = f(x), \quad \tilde{H}(x,\xi,t)\big|_{\xi=t=0} = \Delta f(x),$$

First moments: Form factors

Dirac and Pauli form factors F_1, F_2 $\quad \int_{-1}^{1} dx\, H(x,\xi,t) = F_1(t), \quad \int_{-1}^{1} dx\, E(x,\xi,t) = F_2(t)$

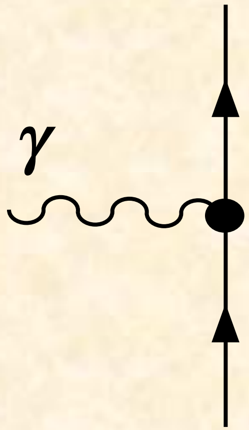
Axial and Pseudoscalar form factors G_A, G_P $\quad \int_{-1}^{1} dx\, \tilde{H}(x,\xi,t) = g_A(t), \quad \int_{-1}^{1} dx\, \tilde{E}(x,\xi,t) = g_P(t)$

Second moments: Angular momenta

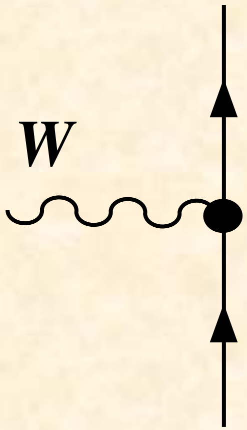
Sum rule: $J_q = \dfrac{1}{2}\int_{-1}^{1} dx\, x\left[H_q(x,\xi,t=0) + E_q(x,\xi,t=0)\right], \quad J_q = \dfrac{1}{2}\Delta q + L_q$

⇒ probe L_q, key quantity to solve the spin puzzle!

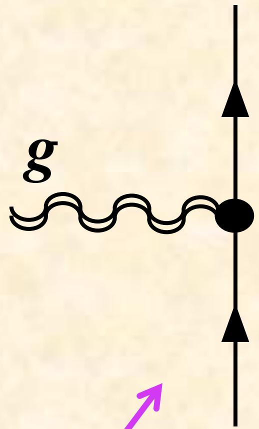
Why gravitational interactions with hadrons ?



vector
$\bar{q}\gamma^{\mu}q$



vector – axial-vector
$\bar{q}\gamma^{\mu}(1-\gamma^{5})q$



tensor
$\bar{q}\gamma^{\mu}\partial^{\nu}q$

How about gravitational radius?

Electron-proton elastic scattering cross section:

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2 E_f \cos^2\frac{\theta}{2}}{4E_i^3\sin^4(\theta/2)}\left[\frac{G_E^2+\tau G_M^2}{1+\tau}+2\tau G_M^2\tan^2\frac{\theta}{2}\right],\quad \tau=-\frac{q^2}{4M^2}$$

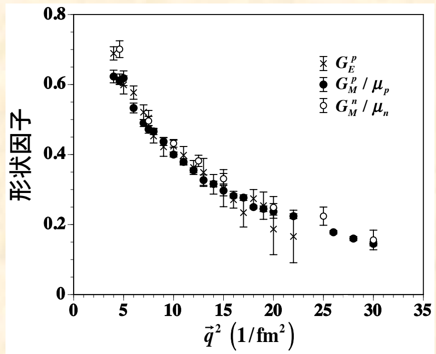
$$F(\vec{q})=\int d^3x\, e^{i\vec{q}\cdot\vec{x}}\rho(\vec{x})=\int d^3x\left[1-\frac{1}{2}(\vec{q}\cdot\vec{x})^2+\cdots\right]\rho(\vec{x})$$

$$\langle r^2\rangle=\int d^3x\, r^2\rho(\vec{x}),\quad r=|\vec{x}|$$

$$\sqrt{\langle r^2\rangle}=\text{root-mean-square (rms) radius}$$

$$F(\vec{q})=1-\frac{1}{6}\vec{q}^{\,2}\langle r^2\rangle+\cdots,\qquad \langle r^2\rangle=-6\left.\frac{dF(\vec{q})}{d\vec{q}^{\,2}}\right|_{\vec{q}^2\to 0}$$

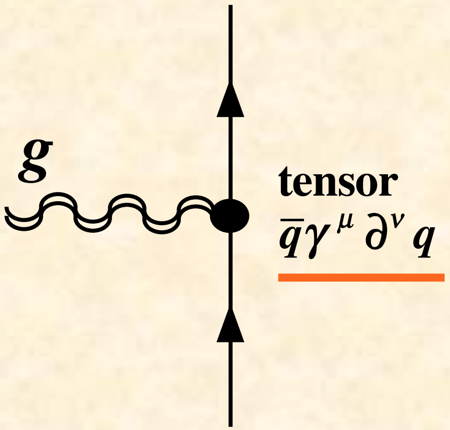
$$\rho(r)=\frac{\Lambda^3}{8\pi}e^{-\Lambda r}\ \Leftrightarrow\ \text{Dipole form: } F(q)=\frac{1}{\left(1+|\vec{q}|^2/\Lambda^2\right)^2},\quad \Lambda^2\simeq 0.71\ \text{GeV}^2$$

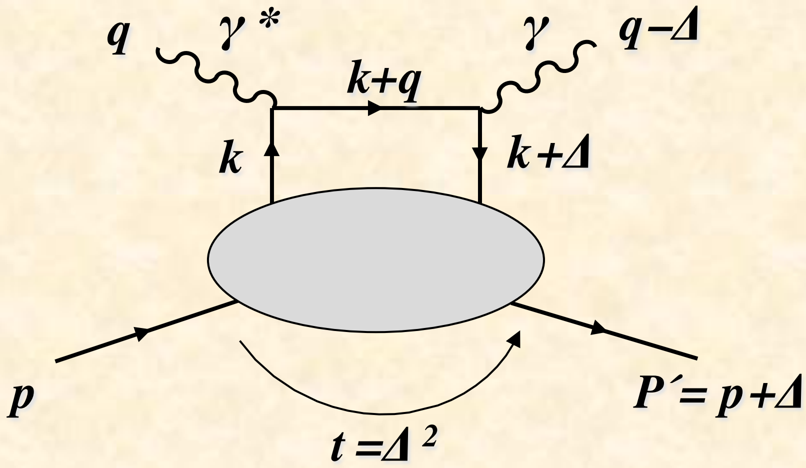


Proton-charge-radius puzzle:

$R_{\text{electron scattering}}$ = 0.8775 fm
⇕
$R_{\text{muonic atom}}$ = 0.8418 fm

Gravitational sources and 3D structure functions





GPDs: $$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \left\langle p' \middle| \bar{q}(-z/2)\gamma^+ q(z/2) \middle| p \right\rangle \Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[H(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E(x,\xi,t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(p) \right]$$

Angular momentum: $J_q = \frac{1}{2}\int_{-1}^{1} dx\, x\left[H_q(x,\xi,t=0) + E_q(x,\xi,t=0) \right]$, $J_q = \frac{1}{2}\Delta q + L_q$

Non-local operator of GPDs/GDAs:

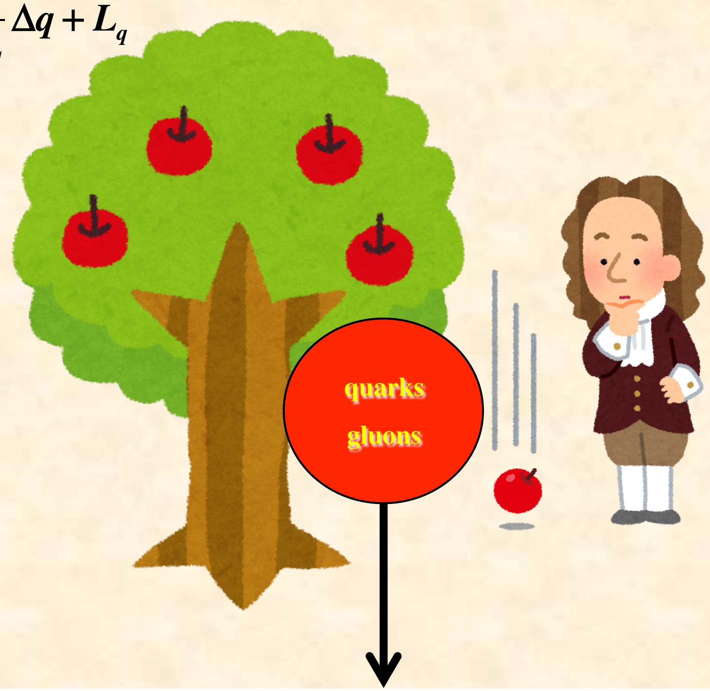
$$\left(P^+\right)^n \int dx x^{n-1} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left[\bar{q}(-z/2)\gamma^+ q(z/2) \right]_{z^+=0,\vec{z}_\perp=0}$$

$$= \left(i\frac{\partial}{\partial z^-} \right)^{n-1} \left[\bar{q}(-z/2)\gamma^+ q(z/2) \right]_{z=0}$$

$$= \bar{q}(0)\gamma^+ \left(i\overleftrightarrow{\partial}^+ \right)^{n-1} q(0)$$

= energy-momentum tensor of a quark for $n = 2$
(electromagnetic for $n = 1$)

= source of gravitiy

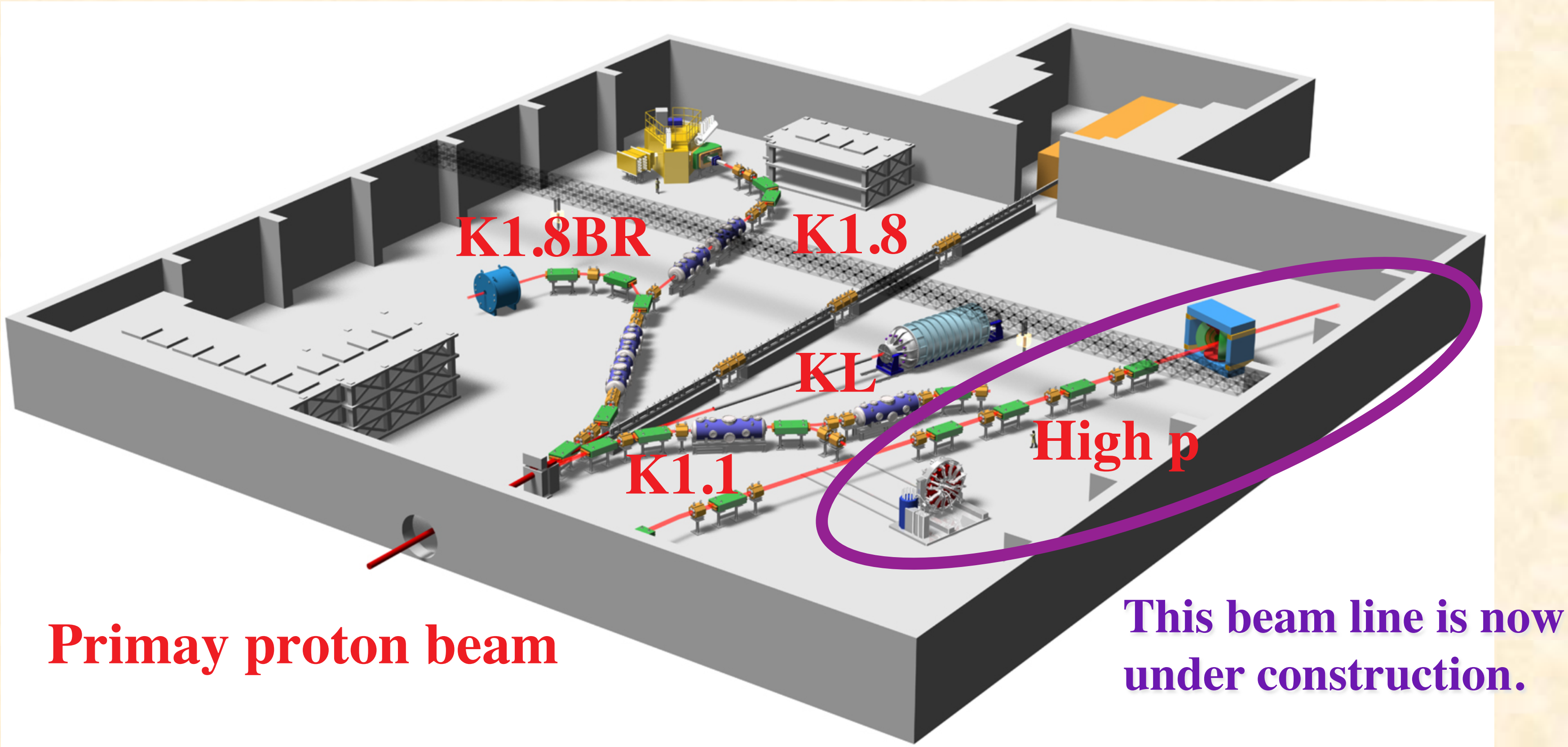


Generalized Parton Distributions (GPDs)

and J-PARC project

Hadron facility

Workshops on high-momentum beamline physics,
http://www-conf.kek.jp/hadron1/j-parc-hm-2013/
http://research.kek.jp/group/hadron10/j-parc-hm-2015/.



- Proton beam up to 30 GeV
- Unseparated hadron (pion, …) beam up to 15~20 GeV

Exclusive Drell-Yan $\pi^- + p \to \mu^+\mu^- + n$ and GPDs

$$\frac{d\sigma_L}{dQ'^2 dt} = \frac{4\pi\alpha^2}{27}\frac{\tau^2}{Q'^2} f_\pi^2 \left[(1-\xi^2)\left|\tilde{H}^{du}(-\xi,\xi,t)\right|^2 - 2\xi^2 \,\mathrm{Re}\left\{ \tilde{H}^{du}(-\xi,\xi,t)^* \tilde{E}^{du}(-\xi,\xi,t) \right\} - \xi^2 \frac{t}{4m_N^2}\left|\tilde{E}^{du}(-\xi,\xi,t)\right|^2 \right]$$

$$Q'^2 = q'^2, \;\; t = (p-p')^2, \; \tau = \frac{Q'^2}{2p\cdot q_\pi} \simeq \frac{Q'^2}{s-m_N^2}$$

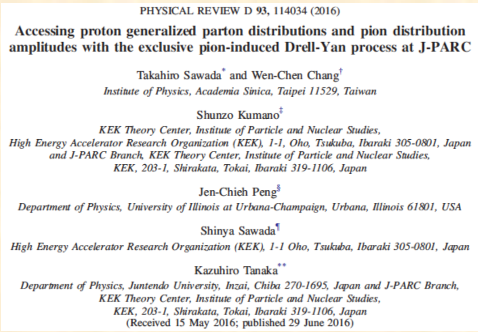
$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p(p')|\,\bar{q}(-z/2)\gamma^+\gamma_5 q(z/2)\,|p(p)\rangle\Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[\tilde{H}_p^q(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}_p^q(x,\xi,t)\bar{u}(p')\frac{\gamma_5\Delta^+}{2M}u(p) \right]$$

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle n(p')|\,\bar{q}_d(-z/2)\gamma^+\gamma_5 q_u(z/2)\,|p(p)\rangle\Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[\tilde{H}_{p\to n}^{du}(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}_{p\to n}^{du}(x,\xi,t)\bar{u}(p')\frac{\gamma_5\Delta^+}{2M}u(p) \right]$$

$$\tilde{H}^{du}(x,\xi,t) = \frac{8}{3}\alpha_s \int_{-1}^{1} dz \frac{\phi_\pi(z)}{1-z^2}\int_{-1}^{1} dx' \left[\frac{e_d}{x-x'-i\varepsilon} - \frac{e_u}{x+x'-i\varepsilon} \right]\left[\tilde{H}^d(x',\xi,t) - \tilde{H}^u(x',\xi,t) \right]$$

$$\tilde{E}^{du}(x,\xi,t) = \frac{8}{3}\alpha_s \int_{-1}^{1} dz \frac{\phi_\pi(z)}{1-z^2}\int_{-1}^{1} dx' \left[\frac{e_d}{x-x'-i\varepsilon} - \frac{e_u}{x+x'-i\varepsilon} \right]\left[\tilde{E}^d(x',\xi,t) - \tilde{E}^u(x',\xi,t) \right]$$

T. Sawada, W.-C. Chang, S. Kumano, J.-C. Peng, S. Sawada, and K. Tanaka, PRD93 (2016) 114034.



PHYSICAL REVIEW D 93, 114034 (2016)

Accessing proton generalized parton distributions and pion distribution amplitudes with the exclusive pion-induced Drell-Yan process at J-PARC

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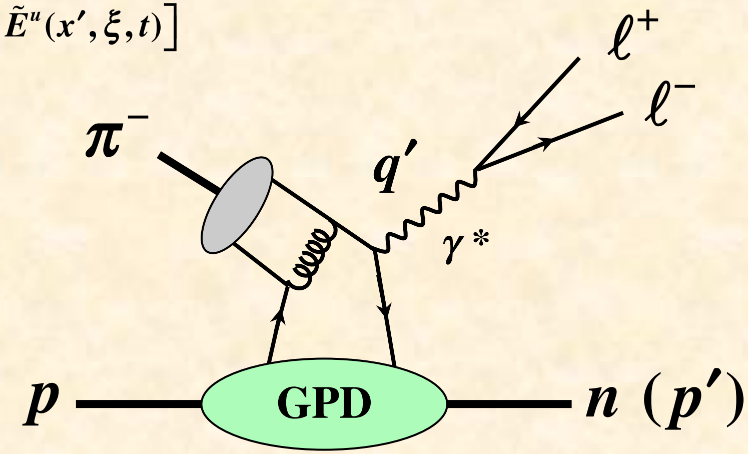
(Received 15 May 2016; published 29 June 2016)

LoI under consideration for a J-PARC experiment

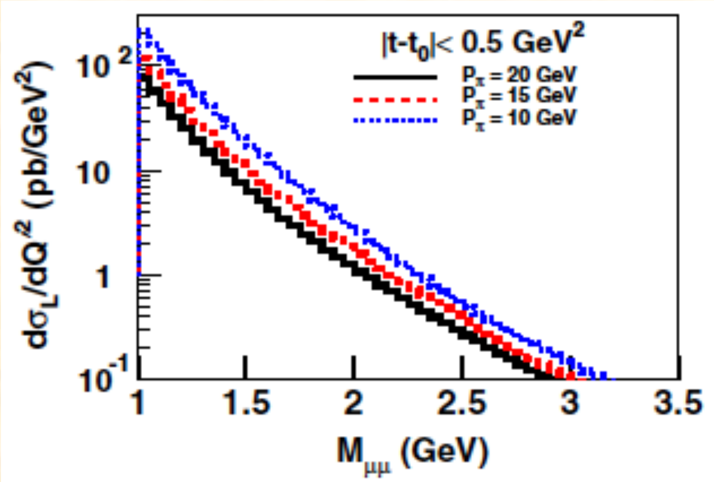


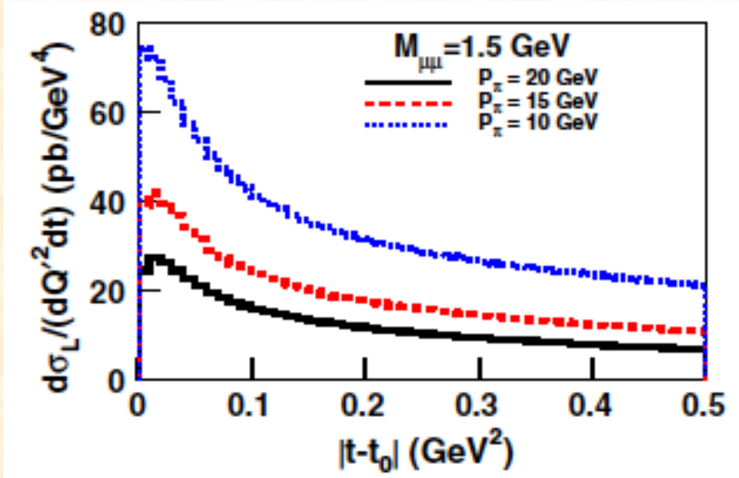
$$\pi^-(\bar{u}d) + p(uud) \to n(udd) + \gamma^*(\to \ell^+\ell^-)$$

Expected Drell-Yan events at J-PARC

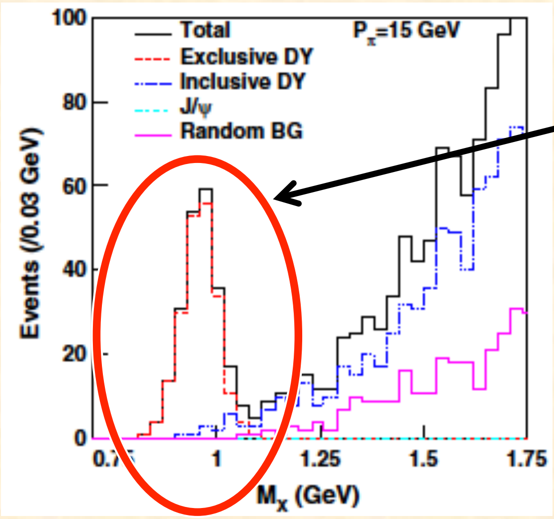
$$Q'^2 = q'^2,\; t = (p - p')^2,\; \tau = \frac{Q'^2}{2p\cdot q_\pi} \simeq \frac{Q'^2}{s - m_N^2}$$

$$\boxed{\frac{d\sigma_L}{dQ'^2 dt} = \frac{4\pi\alpha^2}{27}\frac{\tau^2}{Q'^2} f_\pi^2 \left[(1-\xi^2)\left|\tilde{H}^{du}(-\xi,\xi,t)\right|^2 - 2\xi^2 \,\mathrm{Re}\left\{\tilde{H}^{du}(-\xi,\xi,t)^* \tilde{E}^{du}(-\xi,\xi,t)\right\} - \xi^2 \frac{t}{4m_N^2}\left|\tilde{E}^{du}(-\xi,\xi,t)\right|^2 \right]}$$

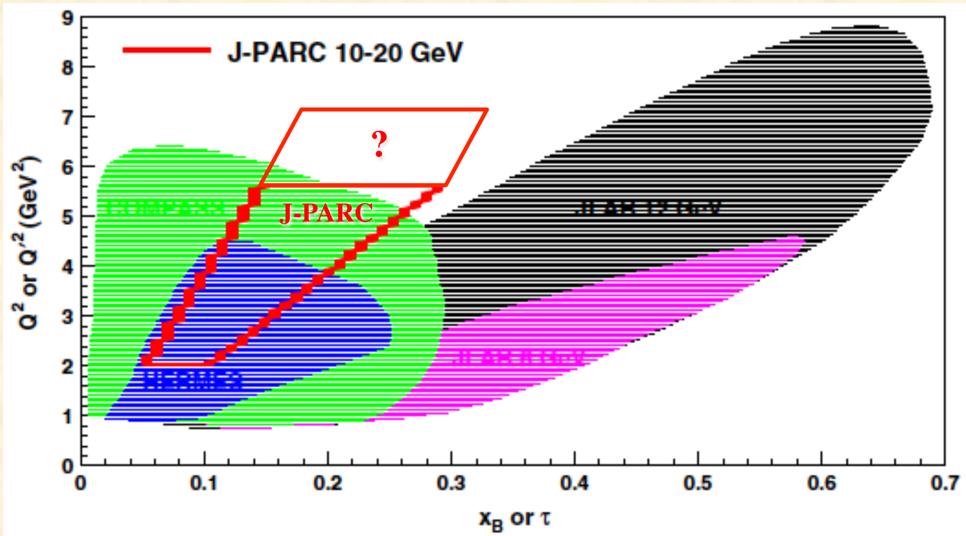




Missing mass



Exclusive Drell-Yan



Generalized Distribution Amplitudes (GDAs)

and KEKB/ILC project

H. Kawamura and S. Kumano,
Phys. Rev. D 89 (2014) 054007.

S. Kumano, Q.-T. Song, O. Teryaev,
Phys. Rev. D 97 (2018) 014020.

GPD $H_q^h(x,\xi,t)$ and GDA $\Phi_q^{hh}(z,\zeta,W^2)$

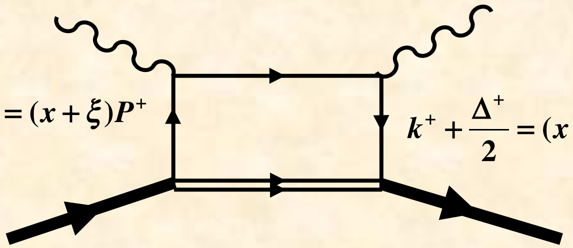
GPD: $H_q(x,\xi,t) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle h(p') | \bar{\psi}(-y/2)\gamma^+\psi(y/2) | h(p)\rangle \Big|_{y^+=0,\vec{y}_\perp=0}$, $\quad P^+ = \frac{(p+p')^+}{2}$

GDA: $\Phi_q(z,\zeta,s) = \int \frac{dy^-}{2\pi} e^{izP^+y^-} \langle h(p)\bar{h}(p') | \bar{\psi}(-y/2)\gamma^+\psi(y/2) | 0\rangle \Big|_{y^+=0,\vec{y}_\perp=0}$

DA: $\Phi_q^\pi(z,\zeta,s) = \int \frac{dy^-}{2\pi} e^{izP^+y^-} \langle \pi(p) | \bar{\psi}(-y/2)\gamma^+\gamma_5\psi(y/2) | 0\rangle \Big|_{y^+=0,\vec{y}_\perp=0}$

$H_q^h(x,\xi,t)$ $\longleftrightarrow$ $\Phi_q^{hh}(z,\zeta,W^2)$

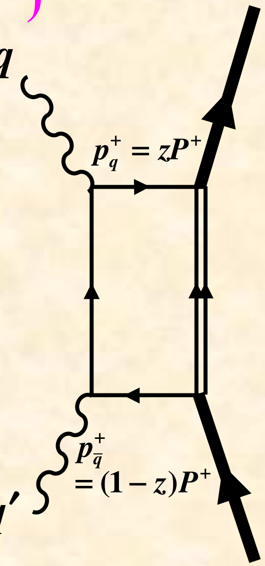
***s*-*t* crossing**



$k^+ - \frac{\Delta^+}{2} = (x+\xi)P^+$ $\quad k^+ + \frac{\Delta^+}{2} = (x-\xi)P^+$

$p^+ = \left(P - \frac{\Delta}{2}\right)^+$ $\quad p'^+ = \left(P + \frac{\Delta}{2}\right)^+$

$$z \Leftrightarrow \frac{1-x/\xi}{2}$$
$$\zeta \Leftrightarrow \frac{1-1/\xi}{2}$$
$$W^2 \Leftrightarrow t$$



$p^+ = \zeta P^+$

q, $\quad p_q^+ = zP^+$

q', $\quad p_{\bar{q}}^+ = (1-z)P^+$

$p'^+ = (1-\zeta)P^+$

JLab / COMPASS $\qquad$ **KEKB**

$P = \frac{p+p'}{2}$, $\Delta = p' - p$

Bjorken variable: $x = \frac{Q^2}{2p\cdot q}$

Momentum transfer squared: $t = \Delta^2$

Skewdness parameter: $\xi = \frac{p^+ - p'^+}{p^+ + p'^+} = -\frac{\Delta^+}{2P^+}$

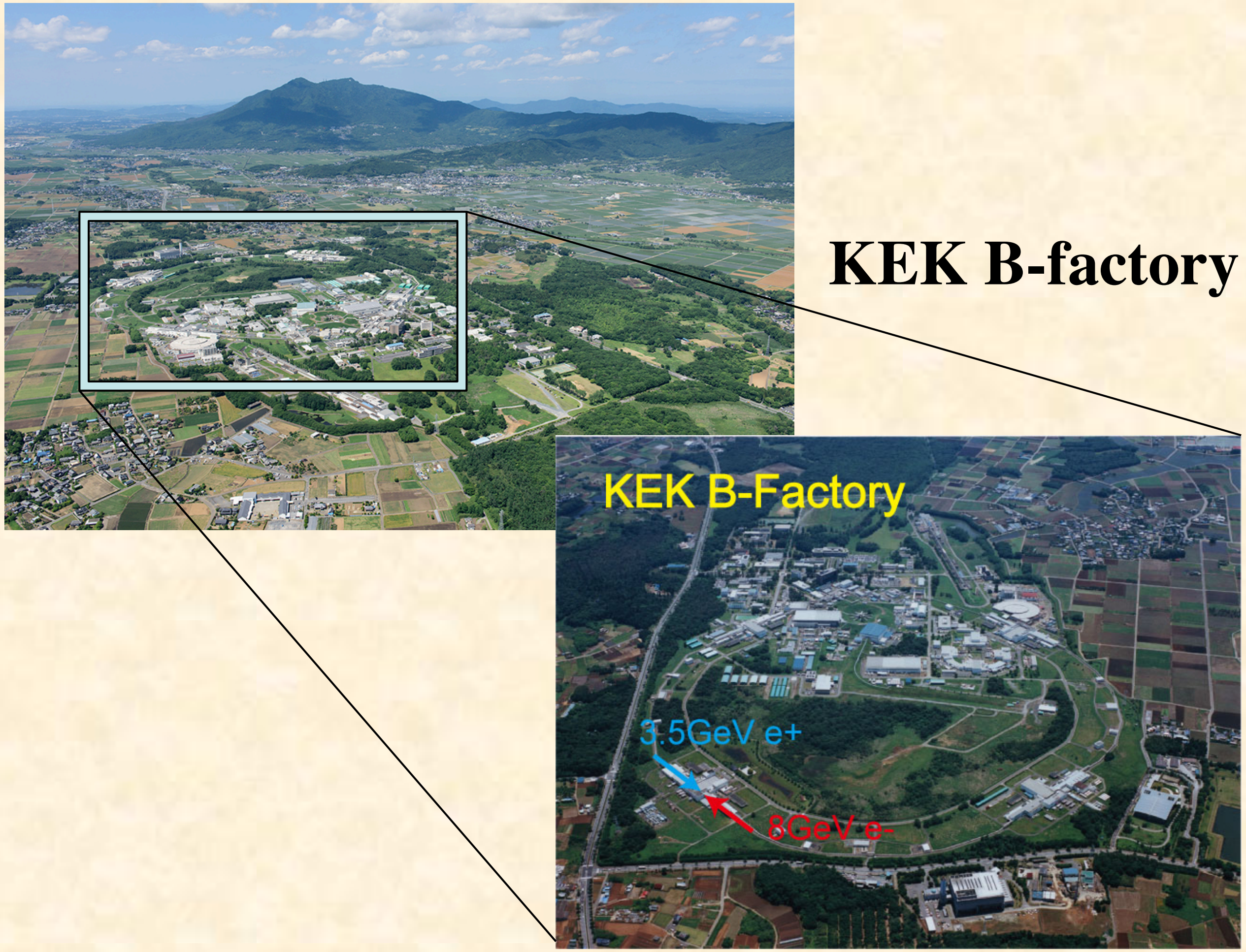
Bjorken variable for $\gamma\gamma^*$: $z = \frac{Q^2}{2q\cdot q'}$

Light-cone momentum ratio for a hadron in $h\bar{h}$: $\zeta = \frac{p^+}{P^+} = \frac{1+\beta\cos\theta}{2}$

Invariant mass of $h\bar{h}$: $W^2 = (p+p')^2$

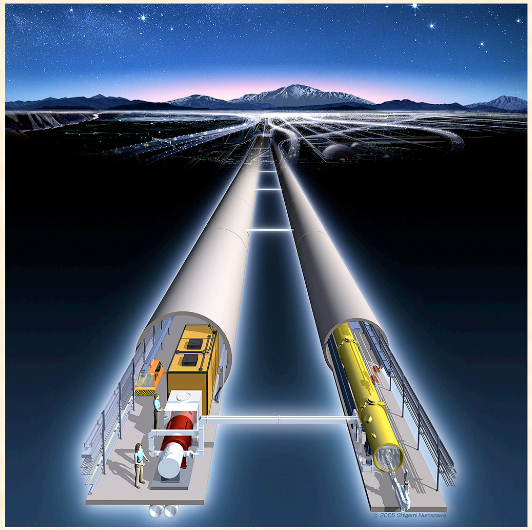
Experimental studies of GDAs in future

$\gamma\gamma \to h\bar{h}$ **for internal structure of exotic hadron candidate** h



KEK B-factory

Linear Collider ?



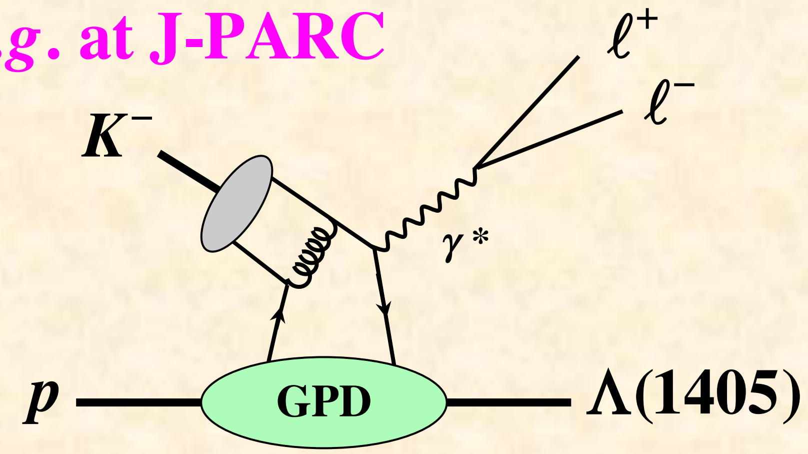
GPDs for exotic hadrons !?

Because stable targets do not exit for exotic hadrons,
it is not possible to measure their GPDs in a usual way.

→ Transition GPDs

or → $s \leftrightarrow t$ crossed qunatity = GDAs at KEKB, Linear Collider

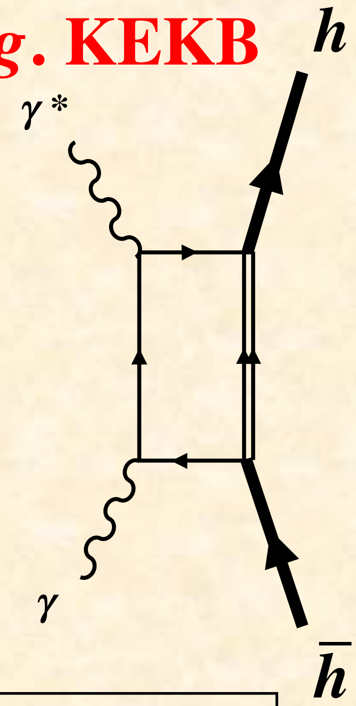
e.g. at J-PARC



$K^-(\bar{u}s) + p(uud) \to \Lambda_{1405}(uud\bar{u}s) + \gamma^*$

Λ_{1405} = pentaquark ($\bar{K}N$ molecule) candidate

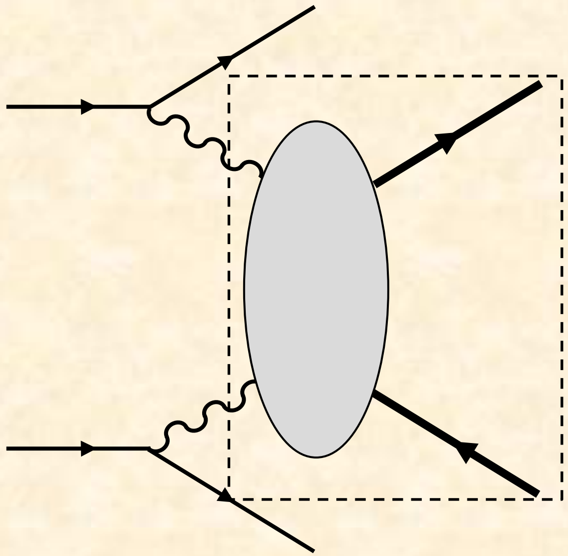
e.g. KEKB



See also H. Kawamura, SK, T. Sekihara, PRD 88 (2013) 034010;
W.-C. Chang, SK, and T. Sekihara, PRD 93 (2016) 034006
for constituent-counting rule for exotic hadron candidates.

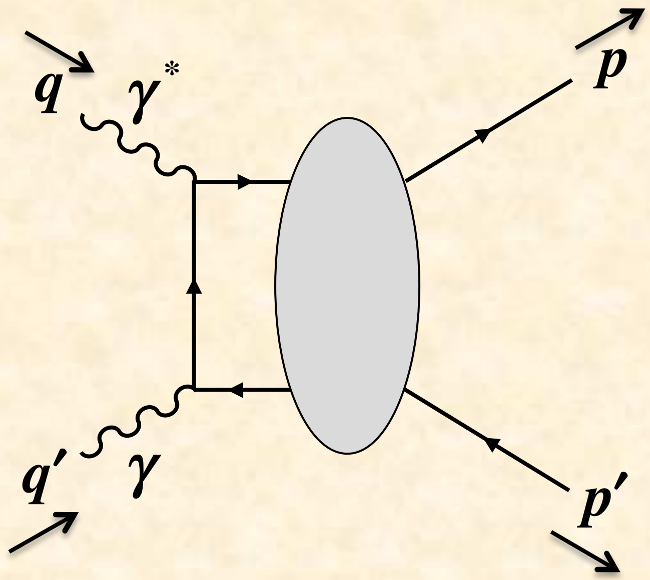
Generalized Distribution Amplitudes (GDAs) for pion

from KEKB measurements



$$\gamma\gamma \to h\bar{h}$$

Cross section for $\gamma^* \gamma \to \pi^0 \pi^0$



$$d\sigma = \frac{1}{4\sqrt{(q\cdot q')^2 - q^2 q'^2}} (2\pi)^4 \delta^4(q+q'-p-p') \overline{\sum_{\lambda,\lambda'}} |\mathcal{M}|^2 \frac{d^3 p}{(2\pi)^3 2E} \frac{d^3 p'}{(2\pi)^3 2E'}$$

$$q = (q^0,\ 0,\ 0,\ |\vec{q}|),\ \ q' = (|\vec{q}|,\ 0,\ 0,\ -|\vec{q}|),\ \ \ q'^2 = 0 \text{ (real photon)}$$

$$p = (p^0,\ |\vec{p}|\sin\theta,\ 0,\ |\vec{p}|\cos\theta),\ \ p = (p^0,\ -|\vec{p}|\sin\theta,\ 0,\ -|\vec{p}|\cos\theta)$$

$$\beta = \frac{|\vec{p}|}{p^0} = \sqrt{1 - \frac{4m_\pi^2}{W^2}}$$

$$\frac{d\sigma}{d(\cos\theta)} = \frac{1}{16\pi(s+Q^2)} \sqrt{1 - \frac{4m_\pi^2}{s}} \overline{\sum_{\lambda,\lambda'}} |\mathcal{M}|^2$$

$$\mathcal{M} = \varepsilon_\mu^\lambda(q) \varepsilon_\nu^{\lambda'}(q') T^{\mu\nu},\quad T^{\mu\nu} = i\int d^4\xi\, e^{-i\xi\cdot q} \left\langle \pi(p)\pi(p') \middle| T J_{em}^\mu(\xi) J_{em}^\nu(0) \middle| 0 \right\rangle$$

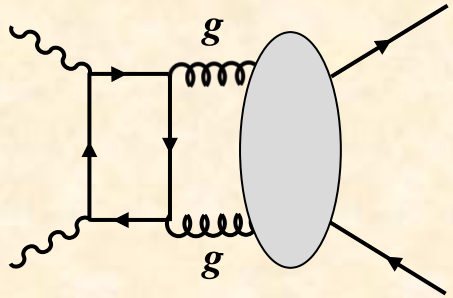
$$\mathcal{M} = e^2 A_{\lambda\lambda'} = 4\pi\alpha A_{\lambda\lambda'}$$

$$A_{\lambda\lambda'} = \frac{1}{e^2} \varepsilon_\mu^\lambda(q) \varepsilon_\nu^{\lambda'}(q') T^{\mu\nu} = -\varepsilon_\mu^\lambda(q) \varepsilon_\nu^{\lambda'}(q') g_T^{\mu\nu} \sum_q \frac{e_q^2}{2} \int_0^1 dz \frac{2z-1}{z(1-z)} \Phi_q^{\pi\pi}(z,\zeta,W^2)$$

$$\text{GDA:}\quad \Phi_q^{\pi\pi}(z,\zeta,s) = \int \frac{dy^-}{2\pi} e^{izP^+y^-} \left\langle \pi(p)\pi(p') \middle| \overline{\psi}(-y/2)\gamma^+ \psi(y/2) \middle| 0 \right\rangle \Big|_{y^+=0,\vec{y}_\perp=0}$$

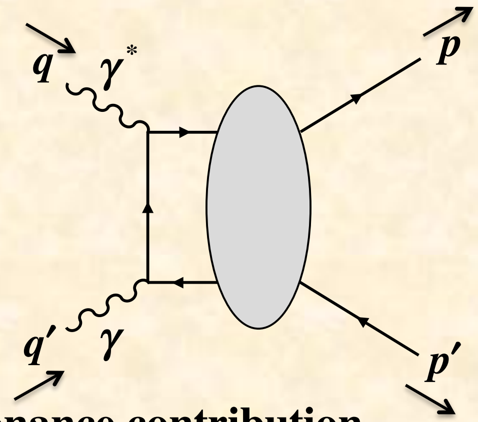
$$A_{++} = \sum_q \frac{e_q^2}{2} \int_0^1 dz \frac{2z-1}{z(1-z)} \Phi_q^{\pi\pi}(z,\zeta,W^2),\quad \varepsilon_\mu^+(q)\varepsilon_\nu^+(q') g_T^{\mu\nu} = -1$$

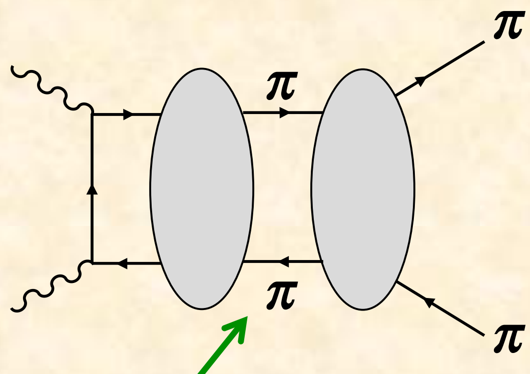
$$\frac{d\sigma}{d(\cos\theta)} \simeq \frac{\pi\alpha^2}{4(s+Q^2)} \sqrt{1 - \frac{4m_\pi^2}{s}} |A_{++}|^2$$



Gluon GDA is higher-order term, and it is not included in our analysis,

GDA parametrization for pion





Including intermediate resonance contributions

$$\frac{d\sigma}{d(\cos\theta)} = \frac{\pi\alpha^2}{4(s+Q^2)}\sqrt{1-\frac{4m^2}{s}}\,|A_{++}|^2$$

$$A_{++} = \sum_q \frac{e_q^2}{2}\int_0^1 dz\,\frac{2z-1}{z(1-z)}\,\Phi_q^{\pi\pi}(z,\zeta,W^2)$$

- **Continuum: GDAs without intermediate-resonance contribution**

$$\Phi_q^{\pi\pi}(z,\zeta,W^2) = N_\pi z^\alpha (1-z)^\alpha (2z-1)\zeta(1-\zeta)F_q^\pi(s)$$

$$F_q^\pi(s) = \frac{1}{\left[1+(s-4m_\pi^2)/\Lambda^2\right]^{n-1}},\quad n = 2 \text{ according to constituent counting rule}$$

- **Resonances: Tthere exist resonance contributions to the cross section.**

$$\sum_q \Phi_q^{\pi\pi}(z,\zeta,W^2) = 18N_f z^\alpha(1-z)^\alpha(2z-1)\left[\tilde{B}_{10}(W)+\tilde{B}_{12}(W)P_2(\cos\theta)\right]$$

$$P_2(x) = \frac{1}{2}(3x^2-1)$$

$$\tilde{B}_{10}(W) = \text{resonance } \left[f_0(500)\equiv\sigma,\ f_0(980)\equiv f_0\right] + \text{continuum}$$

$$\tilde{B}_{12}(W) = \text{resonance}\left[f_2(1270)\right] + \text{continuum}$$

$f_0(500)$ or σ [g]
was $f_0(600)$

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = (400\text{–}550)$ MeV
Full width $\Gamma = (400\text{–}700)$ MeV

$f_0(980)$ [j]

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 990 \pm 20$ MeV
Full width $\Gamma = 10$ to 100 MeV

$f_2(1270)$

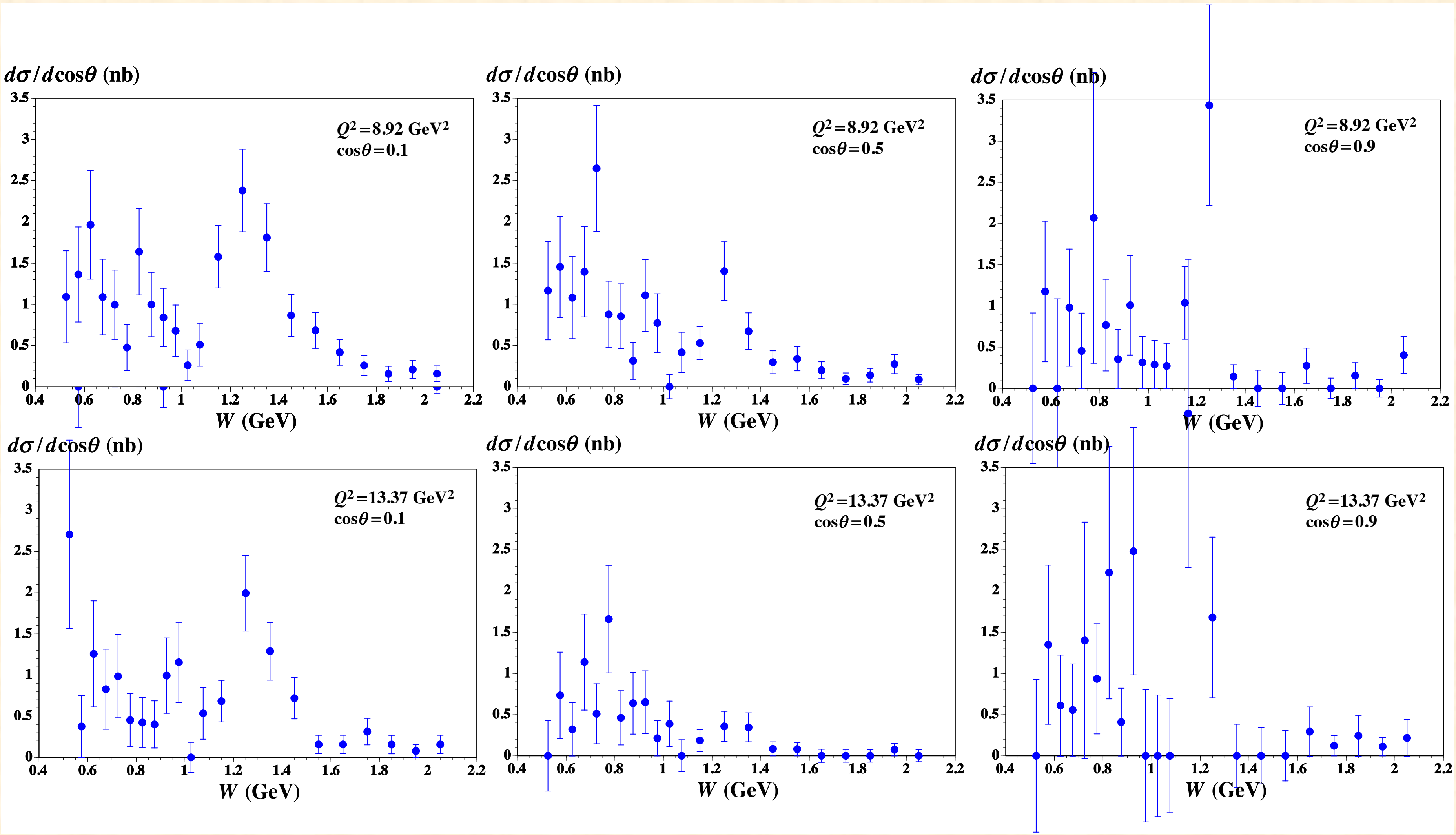
$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 1275.5 \pm 0.8$ MeV
Full width $\Gamma = 186.7^{+2.2}_{-2.5}$ MeV (S = 1.4)

Analysis of Belle data on $\gamma\gamma^* \to \pi^0\pi^0$

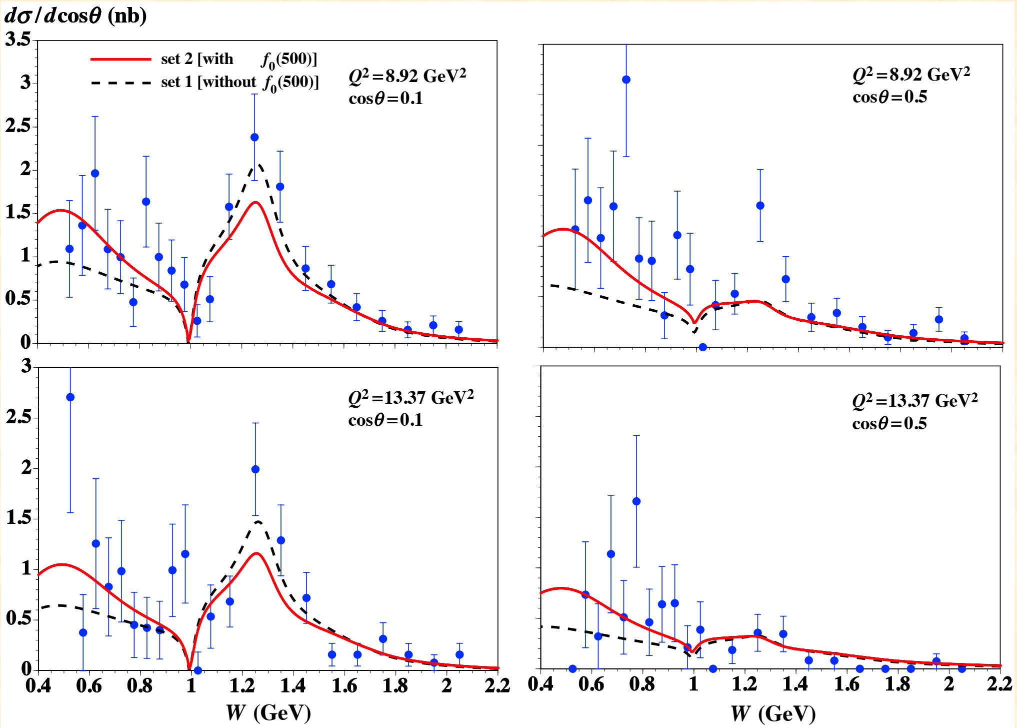
$Q^2 = 8.92,\ 13.37\ \text{GeV}^2$

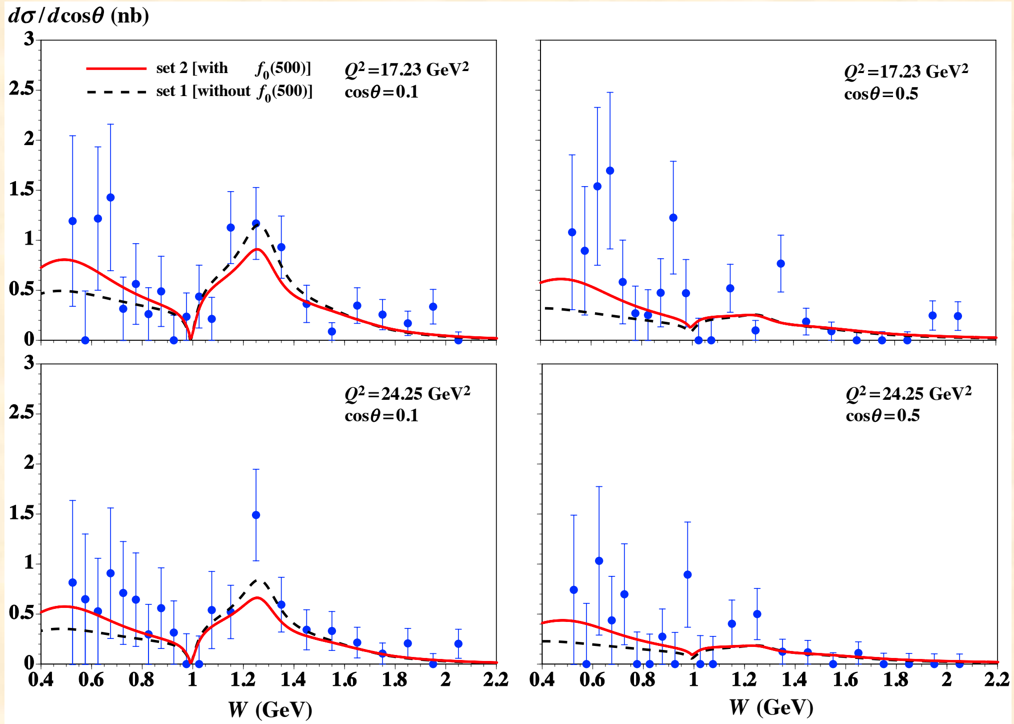
Belle measurements:
M. Masuda *et al.*,
PRD93 (2016) 032003.



Analysis results for $\cos\theta = 0.1,\ 0.5$

$Q^2 = 8.92,\ 13.37\ \mathrm{GeV}^2$ $\qquad$ $Q^2 = 17.23,\ 24.25\ \mathrm{GeV}^2$





Gravitational form factors and radii for pion

$$\int_0^1 dz(2z-1)\Phi_q^{\pi^0\pi^0}(z,\zeta,s) = \frac{2}{(P^+)^2}\langle \pi^0(p)\pi^0(p')|T_q^{++}(0)|0\rangle$$

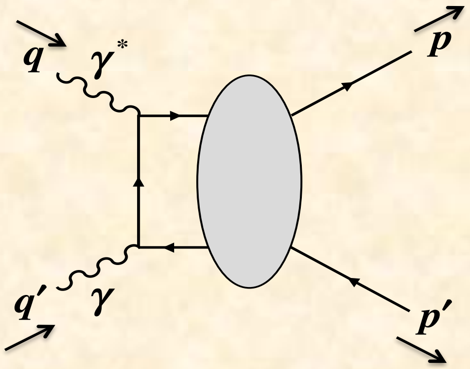
$$\langle \pi^0(p)\pi^0(p')|T_q^{\mu\nu}(0)|0\rangle = \frac{1}{2}\left[\left(sg^{\mu\nu} - P^\mu P^\nu\right)\Theta_{1,q}(s) + \Delta^\mu\Delta^\nu\Theta_{2,q}(s)\right]$$

$$P = \frac{p+p'}{2}, \qquad \Delta = p' - p$$

See also Hyeon-Dong Son, Hyun-Chul Kim, PRD90 (2014) 111901.

$T_q^{\mu\nu}$: energy-momentum tensor for quark

$\Theta_{1,q}$, $\Theta_{2,q}$: gravitational form factos for pion



Analyiss of $\gamma^*\gamma \to \pi^0\pi^0$ cross section

$\Rightarrow$ Generalized distribution amplitudes $\Phi_q^{\pi^0\pi^0}(z,\zeta,s)$

$\Rightarrow$ Timelike gravitational form factors $\Theta_{1,q}(s)$, $\Theta_{2,q}(s)$

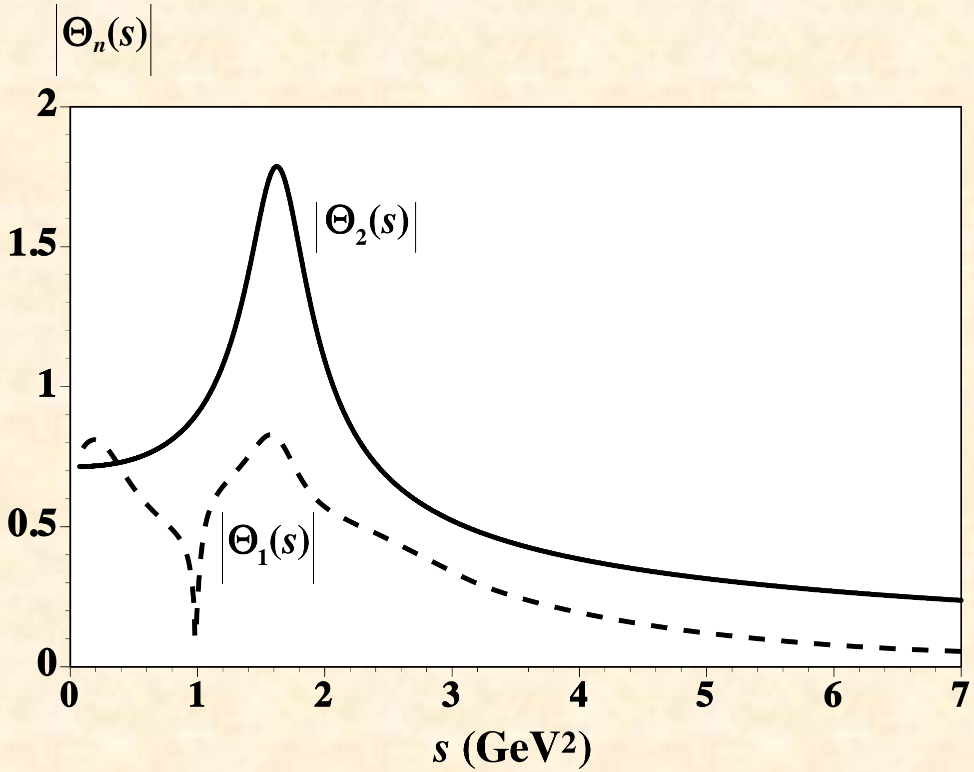
$\Rightarrow$ Spacelike gravitational form factors $\Theta_{1,q}(t)$, $\Theta_{2,q}(t)$

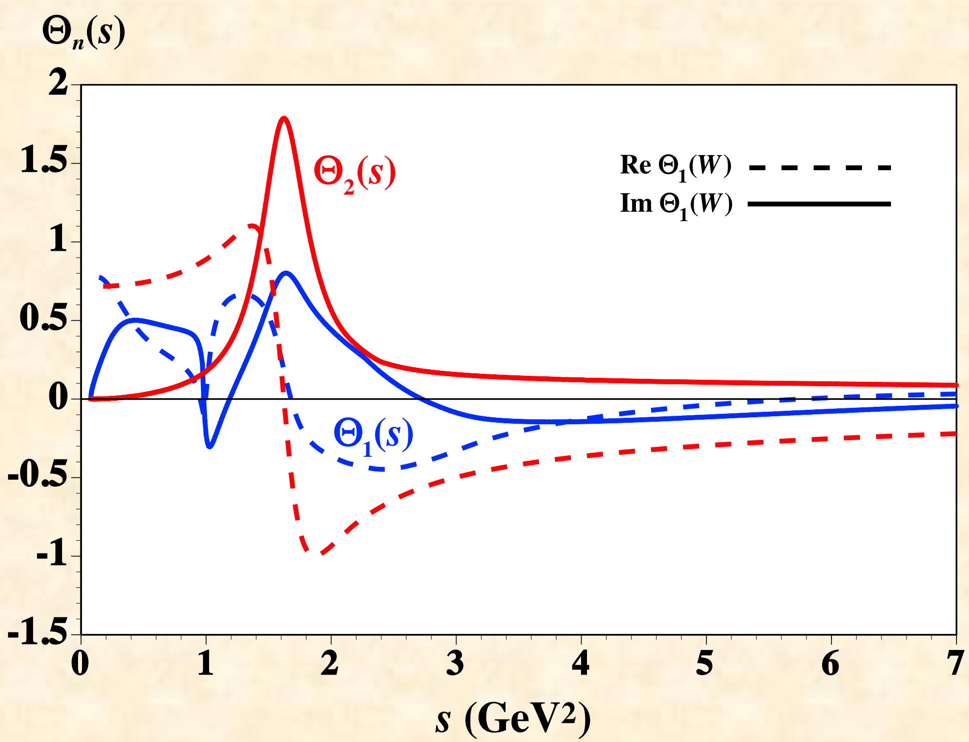
$\Rightarrow$ Gravitational radii of pion

Timelike gravitational form factors for pion

$$\langle \pi^a(p)\pi^b(p')|T_q^{\mu\nu}(0)|0\rangle = \frac{\delta^{ab}}{2}\left[(sg^{\mu\nu} - P^\mu P^\nu)\Theta_{1(q)}(s) + \Delta^\mu\Delta^\nu\Theta_{2(q)}(s)\right], \quad P = p + p', \quad \Delta = p' - p$$

- $\Theta_{1(q)}(s) = -\frac{3}{10}\tilde{B}_{10}(W^2) + \frac{3}{20}\tilde{B}_{12}(W^2) = -4B_{(q)}(s)$
- $\Theta_{2(q)}(s) = \frac{9}{20\beta^2}\,\tilde{B}_{12}(W^2) = A_{(q)}(s)$





Spacelike gravitational form factors and radii for pion

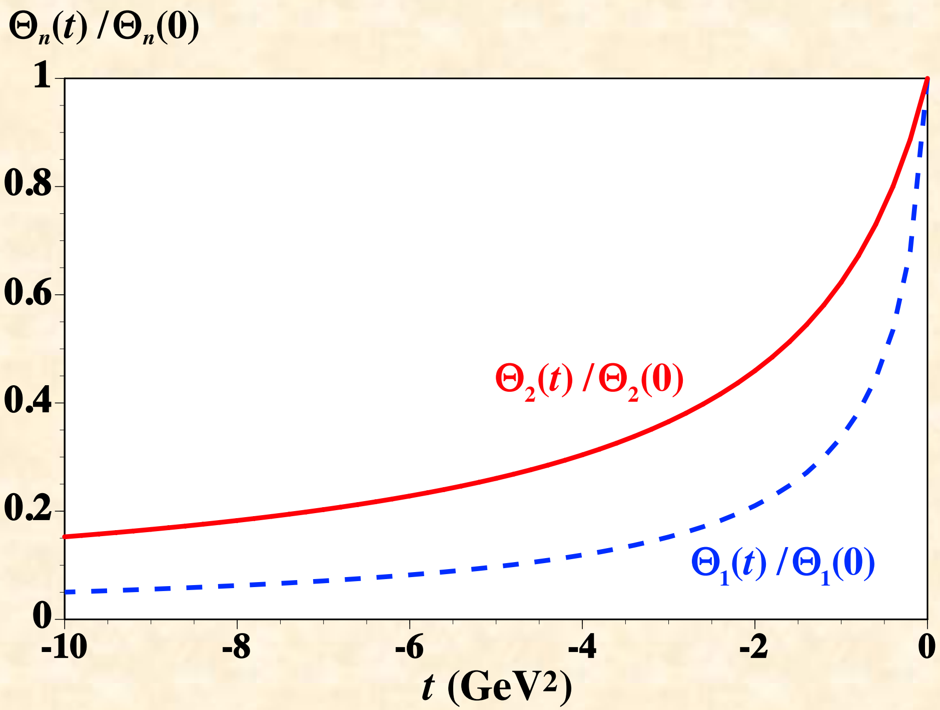
$$F(s)=\Theta_1(s),\ \Theta_1(s),\quad F(t)=\int_{4m_\pi^2}^{\infty} ds \frac{\operatorname{Im} F(s)}{\pi(s-t-i\varepsilon)},\quad \rho(r)=\frac{1}{(2\pi)^3}\int d^3q e^{-i\vec{q}\cdot\vec{r}} F(q)=\frac{1}{4\pi^2}\frac{1}{r}\int_{4m_\pi^2}^{\infty} ds\, e^{-\sqrt{s}r} \operatorname{Im} F(s)$$

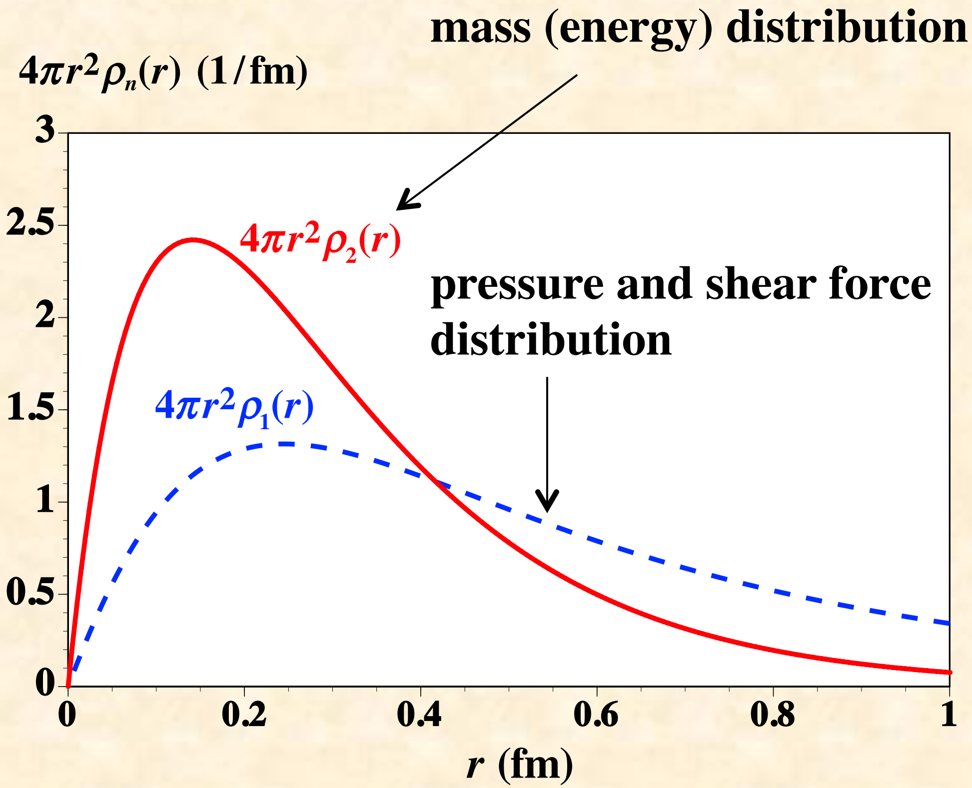
This is the first report on gravitational radii of hadrons from actual experimental measurements.

$$\sqrt{\langle r^2 \rangle_{\text{mass}}}=0.56\sim 0.69 \text{ fm},\quad \sqrt{\langle r^2 \rangle_{\text{mech}}}=1.45\sim 1.56 \text{ fm}$$

First finding on gravitational radius from actual experimental measurements

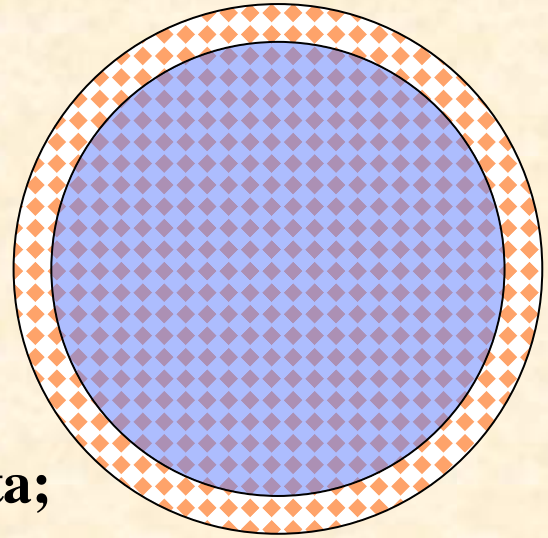
$$\Leftrightarrow \sqrt{\langle r^2 \rangle_{\text{charge}}}=0.672\pm 0.008 \text{ fm}$$





First finding gravitational radii for pion from experimental data

$$\sqrt{\langle r^2 \rangle_{\text{mass}}} = 0.56 \sim 0.69 \text{ fm} \Leftrightarrow \sqrt{\langle r^2 \rangle_{\text{charge}}} = 0.672 \pm 0.008 \text{ fm}$$



Comments and prospects:

It is too early to discuss the difference from experimenal data; however, it is interesting to investigate it theoretically.

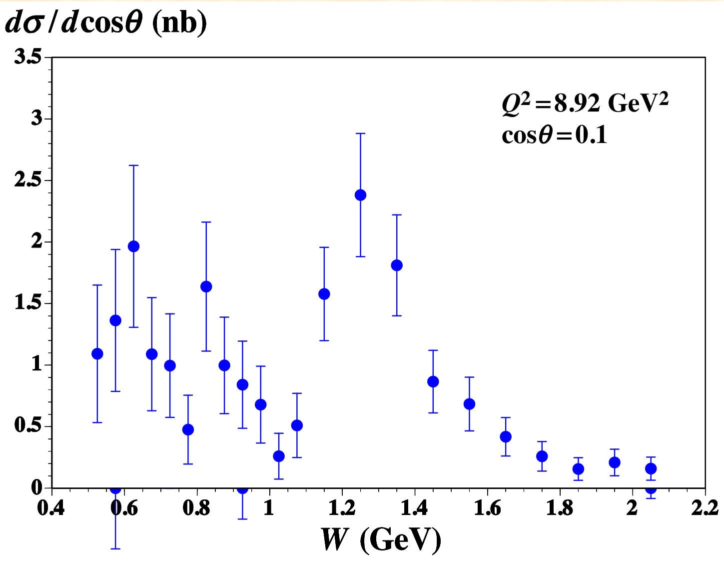
For example, quarks contribute to both charge and mass distributions, but gluons contribute to only the mass distribution.

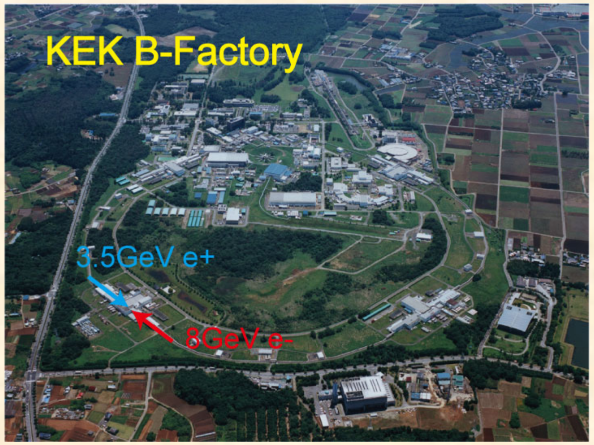
Gravitational physisc has been investigated for macrosopic phenomena. It could be studied also in the microscopic and fundamental quark-gluon level together with the topic of nucleon mass origin.

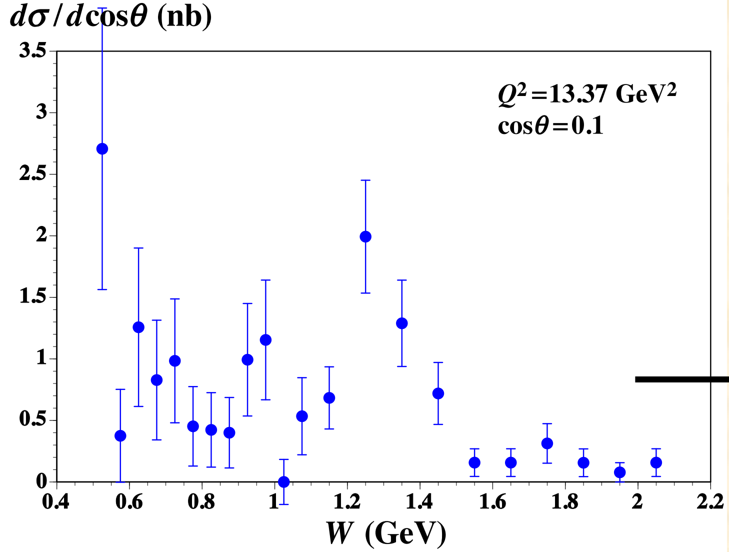
Prospects & Summary

Super KEKB

The errors are dominated by statistical errors, and they will be significantly reduced by super-KEKB.





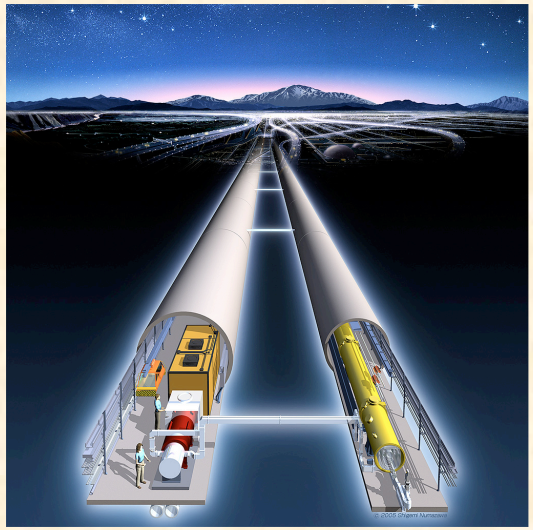


From KEKB to ILC

- Very Large Q^2
- Large W^2

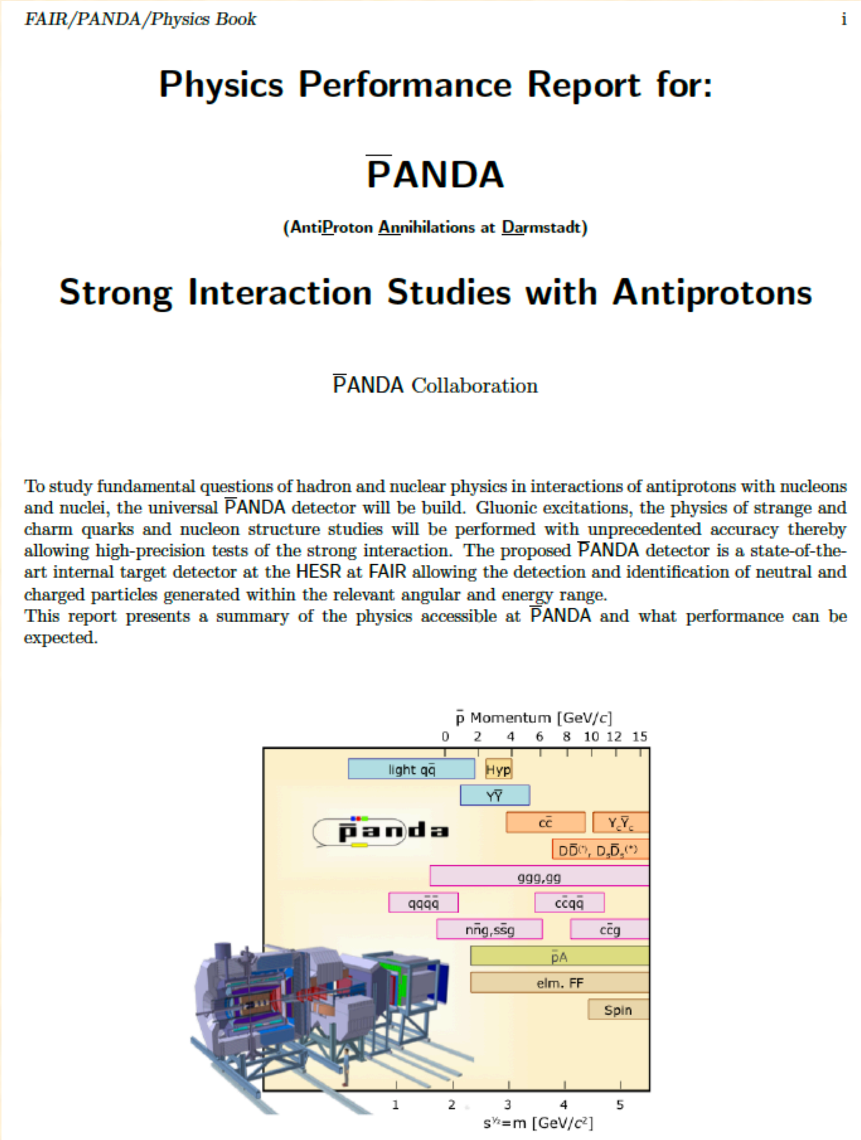
for extracting GDAs

ILC



GSI-FAIR (PANDA)

arXiv:0903.3905 [hep-ex]



FAIR/PANDA/Physics Book i

Physics Performance Report for:

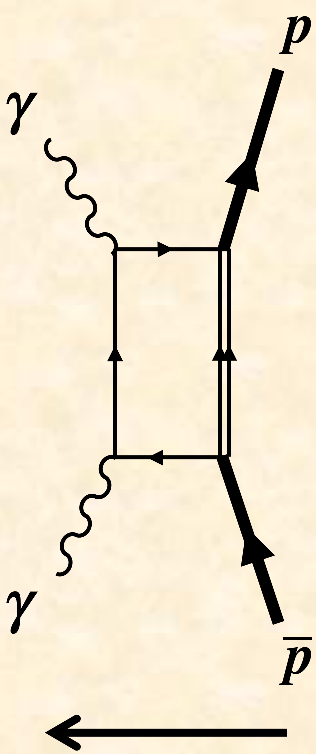
$\overline{\text{P}}$ANDA

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

$\overline{\text{P}}$ANDA Collaboration

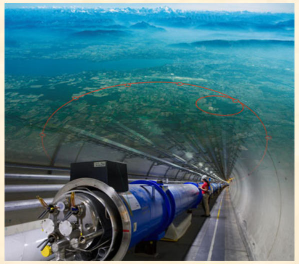
To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed $\overline{\text{P}}$ANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.
This report presents a summary of the physics accessible at $\overline{\text{P}}$ANDA and what performance can be expected.



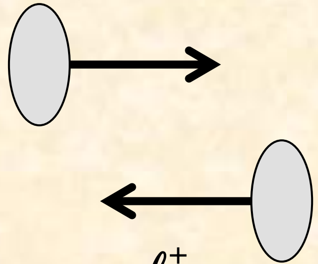
GDAs for the proton!
(super-KEKB?)

Facilities to probe 3D structure functions (GPD, GDA)

RHIC
LHC

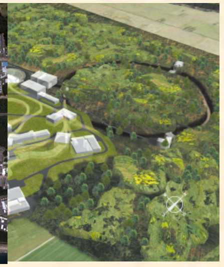


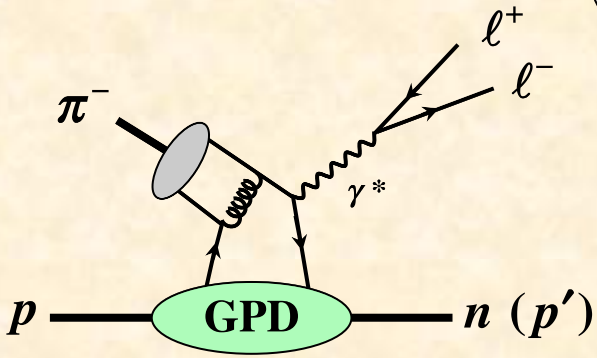

Ultra-peripheral collisions
for $\gamma^*\gamma \to h\bar{h}$??



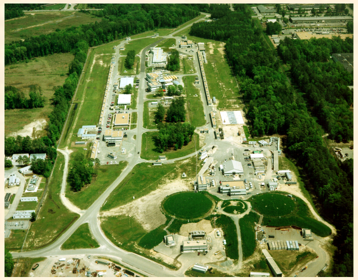
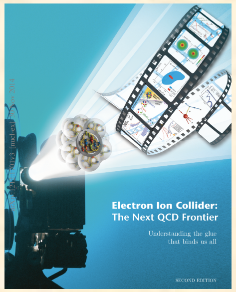
Fermilab
J-PARC
GSI-FAIR

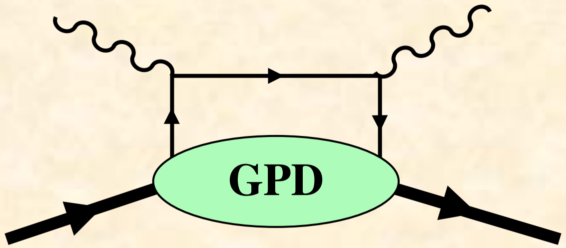




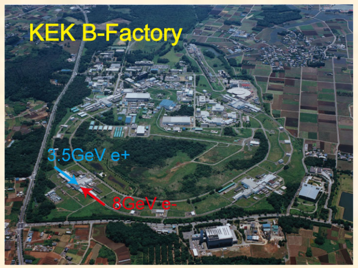


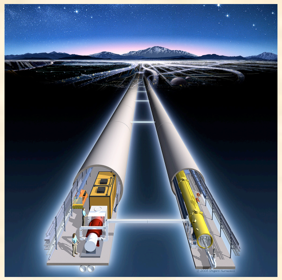
JLab
COMPASS
EIC

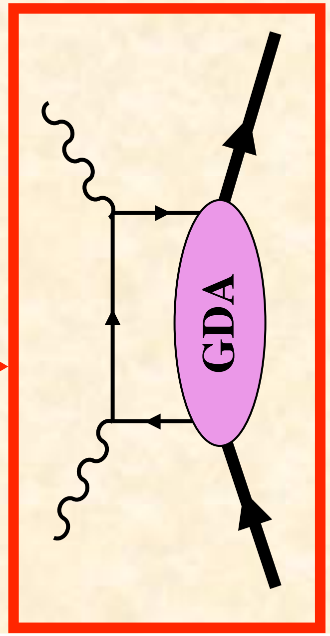


KEKB
ILC



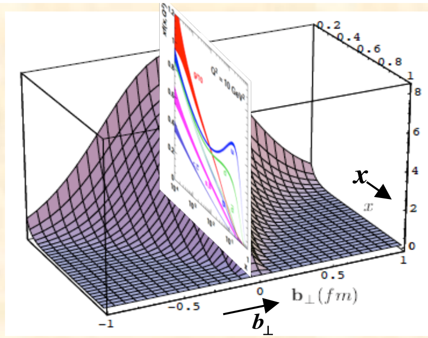


We studied this process.



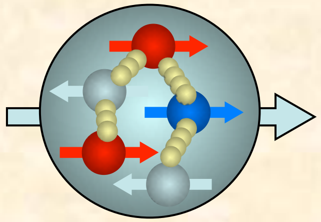
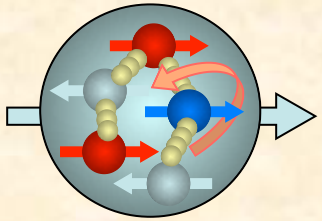
By hadron tomography

3D view of hadrons

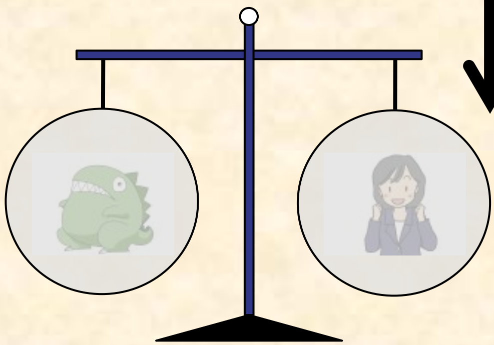


Origin of nucleon spin

By the tomography, we determine

 or  .

Exotic hadrons



By tomography, we determine  or  .

Origin of gravity

By tomography,
we determine gravitational
sources in terms of
quarks and gluons.

Summary I (tomography part)

Hadron tomography studies are important
for solving the origin of the nucleon spin,
for probing internal structure of exotic hadrons,
for probing gravitational sources (masses) in quark/gluon level.

GPDs at J-PARC

GPDs could be measured at hadron facilities such as J-PARC by exclusive Drell-Yan and other exclusive processes.

GDAs at KEKB / ILC

3D structure of hadrons can be investigated by GDAs ($s \Leftrightarrow t$).

Related experimental projects

RHIC, Fermilab, CERN-COMPASS, JLab, BES, ILC,
LHC (UPC), GSI, EIC, LHeC, …

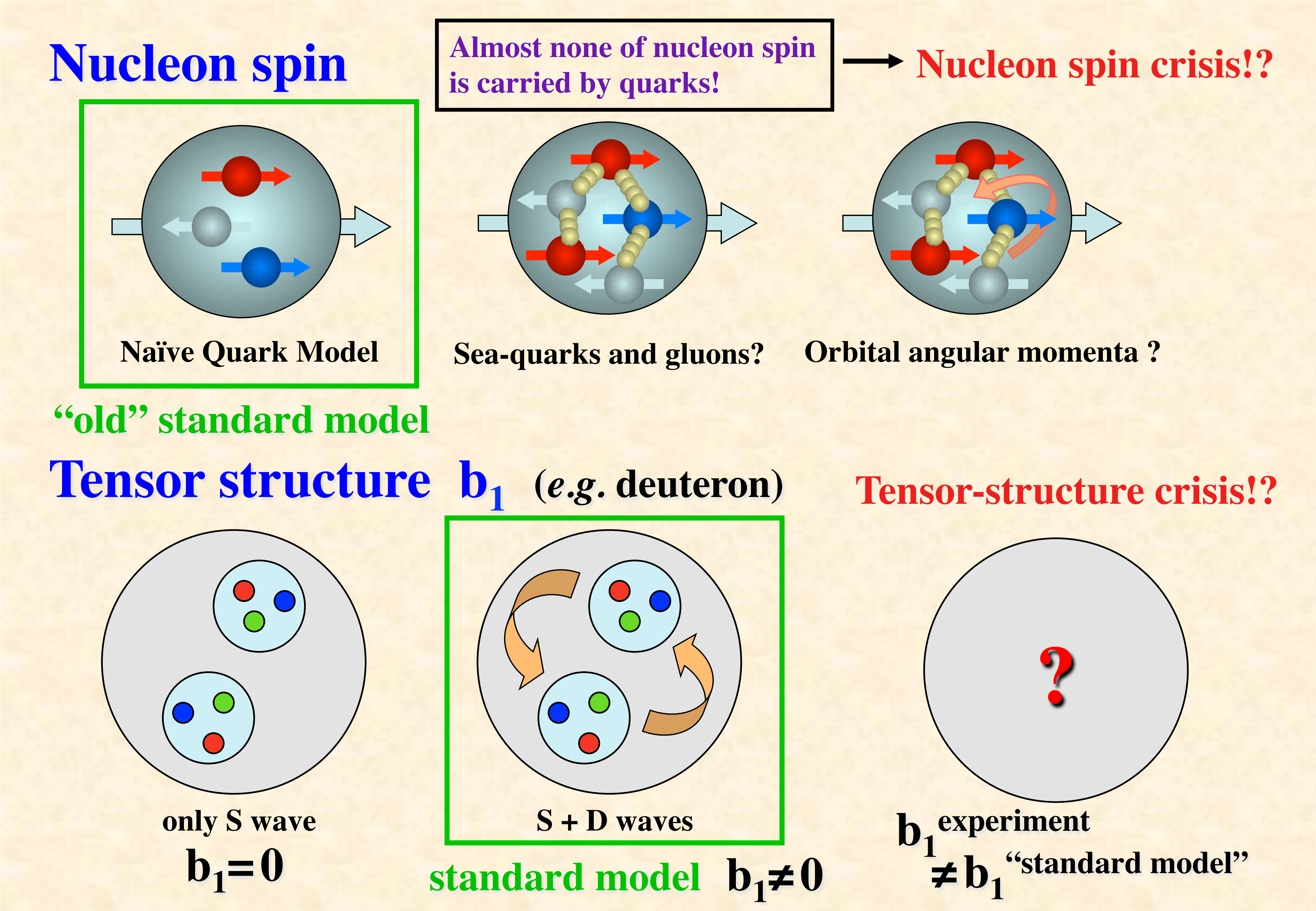
Gravitational form factors can be obtained for hadrons by GPDs and GDAs!

Spin-1 structure functions

Contents

1. Introduction
   • Introduction to deep-inelastic lepton-deuteron scattering: Tensor structure functions (b_1, …, b_4) for deuteron
2. "Standard" convolution-model prediction
   • Convolution model for b_1
   • Comparison with HERMES data
3. Estimate for spin asymmetry in Fermilab p-d Drell-Yan
   • Tensor polarized PDFs for explaining HERMES data
   • Tensor-polarized asymmetry in Drell-Yan
4. EIC and prospects
5. Summary II (spin-1 part)

Polarized PDFs for spin-1 hadrons (deuteron)


Nucleon spin
Almost none of nucleon spin is carried by quarks!
Nucleon spin crisis!?
Naïve Quark Model
Sea-quarks and gluons?
Orbital angular momenta ?
"old" standard model
Tensor structure b_1 (*e.g.* deuteron)
Tensor-structure crisis!?
?
only S wave
$b_1 = 0$
S + D waves
standard model $b_1 \neq 0$
$b_1^{\text{experiment}} \neq b_1^{\text{"standard model"}}$

Situation

- **Spin structure of the spin-1/2 nucleon**

Nucleon spin puzzle: This issue is not solved yet,

but it is rather well studied theoretically and experimentally.

- **Spin-1 hadrons (e.g. deuteron)**

There are some theoretical studies especially on tensor structure in electron-deuteron deep inelastic scattering.

→ HERMES experimental results →JLab experiment

No experimental measurement has been done for hadron (p, π, …) - polarized deuteron processes.

→ Hadron facility (Fermilab, J-PARC, RHIC, COMPASS, GSI, …) experiment ?

Electron scattering from a spin-1 hadron

P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571.
[L. L. Frankfurt and M. I. Strikman, NP A405 (1983) 557.]

$$W_{\mu\nu} = \boxed{-F_1 g_{\mu\nu} + F_2 \frac{p_\mu p_\nu}{\nu} + g_1 \frac{i}{\nu} \varepsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + g_2 \frac{i}{\nu^2} \varepsilon_{\mu\nu\lambda\sigma} q^\lambda \left(p \cdot q s^\sigma - s \cdot q p^\sigma \right)}$$

spin-1/2, spin-1

$$\boxed{-b_1 r_{\mu\nu} + \frac{1}{6} b_2 \left(s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu} \right) + \frac{1}{2} b_3 \left(s_{\mu\nu} - u_{\mu\nu} \right) + \frac{1}{2} b_4 \left(s_{\mu\nu} - t_{\mu\nu} \right)}$$

spin-1 only

Note: Obvious factors from $q^\mu W_{\mu\nu} = q^\nu W_{\mu\nu} = 0$ are not explicitly written.

$E^\mu =$ polarization vector

$$\nu = p \cdot q, \quad \kappa = 1 + M^2 Q^2 / \nu^2, \quad E^2 = -M^2, \quad s^\sigma = -\frac{i}{M^2} \varepsilon^{\sigma\alpha\beta\tau} E^*_\alpha E_\beta p_\tau$$

$b_1, \cdots, b_4$ tems are defined so that they vanish by spin average.

$$r_{\mu\nu} = \frac{1}{\nu^2} \left(q \cdot E^* q \cdot E - \frac{1}{3} \nu^2 \kappa \right) g_{\mu\nu}, \quad s_{\mu\nu} = \frac{2}{\nu^2} \left(q \cdot E^* q \cdot E - \frac{1}{3} \nu^2 \kappa \right) \frac{p_\mu p_\nu}{\nu}$$

$$t_{\mu\nu} = \frac{1}{2\nu^2} \left(q \cdot E^* p_\mu E_\nu + q \cdot E^* p_\nu E_\mu + q \cdot E p_\mu E^*_\nu + q \cdot E p_\nu E^*_\mu - \frac{4}{3} \nu p_\mu p_\nu \right)$$

$$u_{\mu\nu} = \frac{1}{\nu} \left(E^*_\mu E_\nu + E^*_\nu E_\mu + \frac{2}{3} M^2 g_{\mu\nu} - \frac{2}{3} p_\mu p_\nu \right)$$

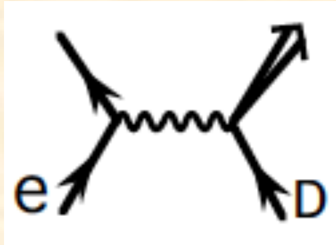
b_1, b_2 tems are defined to satisfy $2xb_1 = b_2$ in the Bjorken scaling limit.

$2xb_1 = b_2$ in the scaling limit $\sim O(1)$

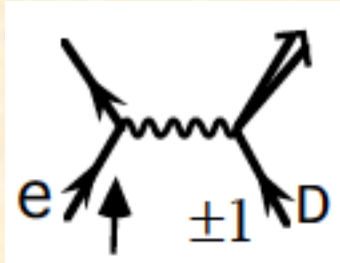
b_3, b_4 = twist-4 $\sim \frac{M^2}{Q^2}$

Structure Functions

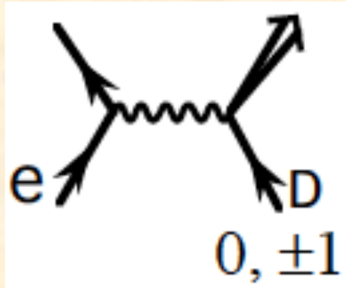
$$F_1 \propto \langle d\sigma \rangle$$



$$g_1 \propto d\sigma(\uparrow,+1) - d\sigma(\uparrow,-1)$$



$$b_1 \propto d\sigma(0) - \frac{d\sigma(+1) + d\sigma(-1)}{2}$$



note: $\sigma(0) - \frac{\sigma(+1)+\sigma(-1)}{2} = 3\langle\sigma\rangle - \frac{3}{2}[\sigma(+1)+\sigma(-1)]$

Parton Model

$$F_1 = \frac{1}{2}\sum_i e_i^2 \left(q_i + \bar{q}_i\right) \qquad q_i = \frac{1}{3}\left(q_i^{+1} + q_i^{0} + q_i^{-1}\right)$$

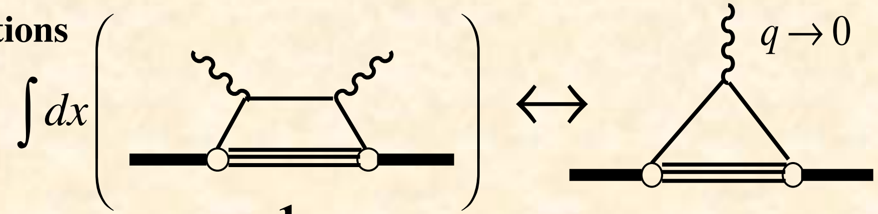
$$g_1 = \frac{1}{2}\sum_i e_i^2 \left(\Delta q_i + \Delta\bar{q}_i\right) \qquad \Delta q_i = q_{i\uparrow}^{+1} - q_{i\downarrow}^{+1}$$

$$\left[q_\uparrow^H\left(x,Q^2\right)\right] \qquad b_1 = \frac{1}{2}\sum_i e_i^2 \left(\delta_T q_i + \delta_T \bar{q}_i\right) \qquad \delta_T q_i = q_i^0 - \frac{q_i^{+1} + q_i^{-1}}{2}$$

Constraint on valence-tensor polarization (sum rule)

F.E.Close and SK, PRD42, 2377 (1990).

Folow Feynman's book on Photon-Hadron Interactions



Intuitive derivation without calculation:

$$\int dx\, b_1(x) = \text{ dimensionless quantity}$$
$$= (\text{mass})^2 \cdot (\text{quadrupole moment})$$

$$\int dx\, b_1^D(x) = \frac{5}{18}\int dx\left[\delta_T u_v + \delta_T d_v\right] + \frac{1}{18}\int dx\left[8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D\right]$$

$$b_1 = \frac{1}{2}\sum_i e_i^2\left(\delta_T q_i + \delta_T \bar{q}_i\right)$$
$$\delta_T q_i = q_i^0 - \frac{q_i^{+1} + q_i^{-1}}{2}$$
$$\delta_T q_v \equiv \delta_T q - \delta_T \bar{q}$$

Elastic amplitude in a parton model

$$\Gamma_{H,H} = \langle p,H | J_0(0) | p,H\rangle = \sum_i e_i \int dx\left[q_{i\uparrow}^H + q_{i\downarrow}^H - \bar{q}_{i\Uparrow}^H - \bar{q}_{i\Downarrow}^H\right]$$

$$\frac{1}{2}\left[\Gamma_{0,0} - \frac{1}{2}\left(\Gamma_{1,1} + \Gamma_{-1,-1}\right)\right] = \frac{1}{3}\int dx\left[\delta_T u_v(x) + \delta_T d_v(x)\right]$$

Macroscopically

$$\Gamma_{0,0} = \lim_{t\to 0}\left[F_c(t) - \frac{t}{3}F_Q(t)\right],\quad \Gamma_{+1,+1} = \Gamma_{-1,-1} = \lim_{t\to 0}\left[F_c(t) + \frac{t}{6}F_Q(t)\right]$$

$$\frac{1}{2}\left[\Gamma_{0,0} - \frac{1}{2}\left(\Gamma_{1,1} + \Gamma_{-1,-1}\right)\right] = -\lim_{t\to 0}\frac{t}{2}F_Q(t)$$

Constraint on tensor-polarized valence quarks: $\int dx\, \delta_T q_v(x) = 0$

$$\int dx\, b_1^D(x) = \frac{5}{9}\frac{3}{2}\left[\Gamma_{0,0} - \frac{1}{2}\left(\Gamma_{1,1} + \Gamma_{-1,-1}\right)\right] + \frac{1}{18}\int dx\left[8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D\right]$$

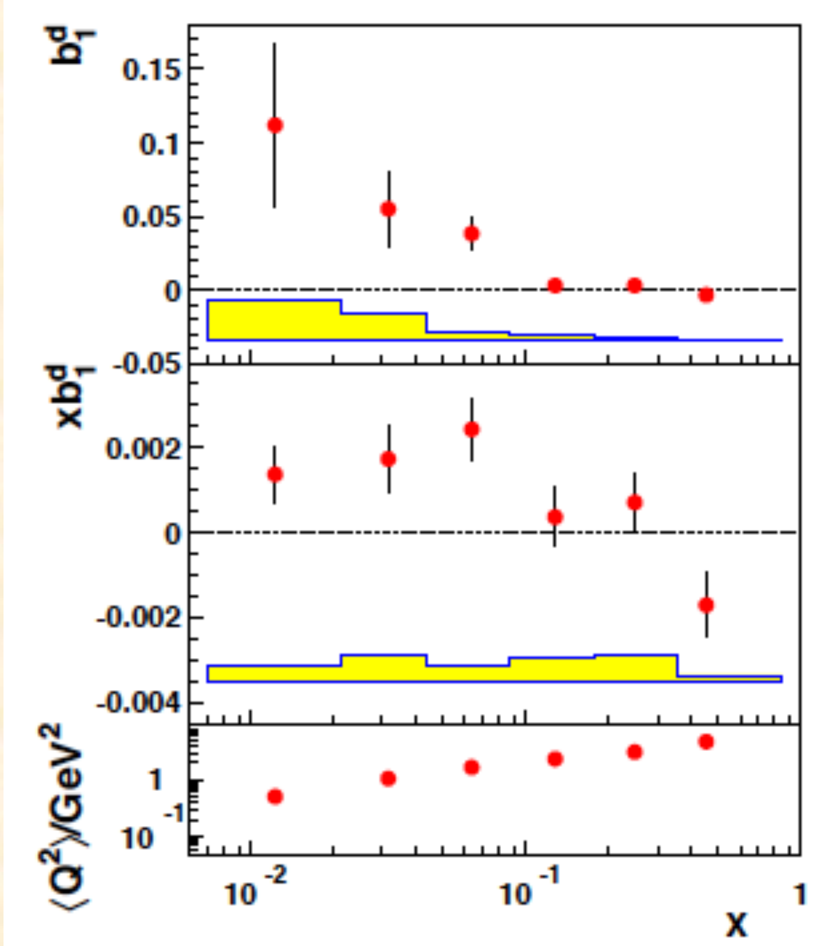
$$= \underline{-\frac{5}{6}\lim_{t\to 0} tF_Q(t)} + \underline{\frac{1}{18}\int dx\left[8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D\right]} = 0\ (\text{valence}) + \frac{1}{18}\int dx\left[8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D\right]$$

$$\int_0^1 \frac{dx}{x}\left[F_2^p(x) - F_2^n(x)\right] = \underline{\frac{1}{3}} + \underline{\frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]}$$

As the Gottfried-sum-rule violation indicated $\bar{u} < \bar{d}$,
the b_1-sum-rule violation suggests
a finite tensor polarization for antiquarks ($\delta_T \bar{u} \neq 0$).

HERMES results on b_1

A. Airapetian *et al.* (HERMES), PRL 95 (2005) 242001.



27.6 GeV/c $\rightleftarrows$, 0

positron **deuteron**

b_1 measurement in the kinematical region

$$0.01 < x < 0.45, \;\; 0.5 \text{ GeV}^2 < Q^2 < 5 \text{ GeV}^2$$

b_1 sum rule

$$\int_{0.002}^{0.85} dx\, b_1(x) = \left[1.05 \pm 0.34(\text{stat}) \pm 0.35(\text{sys})\right] \times 10^{-2}$$

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

In the restricted Q^2 range $Q^2 > 1 \text{ GeV}^2$

$$\int_{0.02}^{0.85} dx\, b_1(x) = \left[0.35 \pm 0.10(\text{stat}) \pm 0.18(\text{sys})\right] \times 10^{-2}$$

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

$$\int dx\, b_1^D(x) = \lim_{t \to 0} -\frac{5}{12}\frac{t}{M^2} F_Q(t) + \underline{\frac{1}{9}\left(\delta Q + \delta\bar{Q}\right)_{\text{sea}}} = 0\ ?$$

$$\int \frac{dx}{x}\left[F_2^p(x) - F_2^n(x)\right] = \frac{1}{3}\int dx\left[u_v - d_v\right] + \underline{\frac{2}{3}\int dx\left[\bar{u} - \bar{d}\right]} \neq 1/3$$

Drell-Yan experiments probe these antiquark distributions.

“Standard” deuteron model prediction for b_1

W. Cosyn, Yu-Bing Dong, S. Kumano, M. Sargsian, Phys. Rev. D 95 (2017) 074036.

Basic convolution model calculation for b_1 .

If future measurements deviate from our esitmate, there could be an interesting new mechanism.

Basic convolution approach

Convolution model: $A_{hH,\,hH}(x,Q^2)=\int\frac{dy}{y}\sum_s f_s^H(y)\hat{A}_{hs,hs}(x/y,\,Q^2)\equiv\sum_s f_s^H(y)\otimes\hat{A}_{hs,hs}(y,Q^2)$

$$A_{hH,\,h'H'}=\varepsilon_{h'}^{*\mu}W_{\mu\nu}^{H'H}\varepsilon_h^{\nu},\quad b_1=A_{+0,+0}-\frac{A_{++,++}+A_{+-,+-}}{2}$$

$$\hat{A}_{+\uparrow,+\uparrow}=F_1-g_1,\quad \hat{A}_{+\downarrow,+\downarrow}=F_1+g_1$$

Momentum distribution: $f^H(y)=\int d^3p\;y\,|\phi^H(\vec{p})|^2\delta\left(y-\frac{E-p_z}{M_N}\right)$

$$y=\frac{Mp\cdot q}{M_N P\cdot q}\simeq\frac{2p^-}{P^-},\qquad f^H(y)\equiv f_\uparrow^H(y)+f_\downarrow^H(y)$$

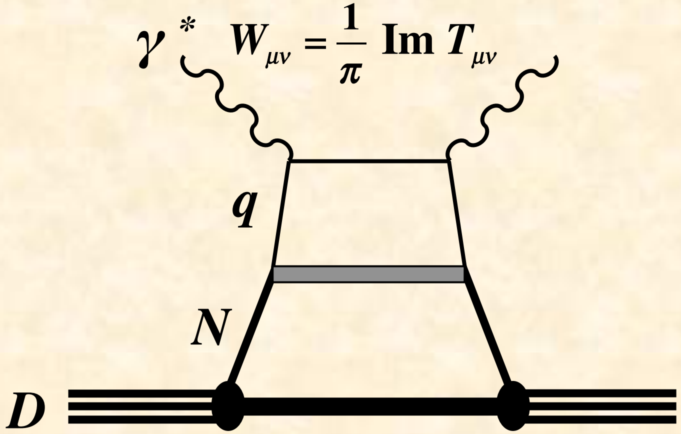
D-state admixture: $\phi^H(\vec{p})=\phi_{\ell=0}^H(\vec{p})+\phi_{\ell=2}^H(\vec{p})$

$\Downarrow$

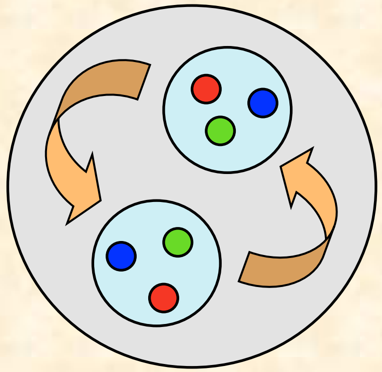
$$b_1(x)=\int\frac{dy}{y}\delta_T f(y)F_1^N(x/y,\,Q^2)$$

$$\delta_T f(y)=f^0(y)-\frac{f^+(y)+f^-(y)}{2}$$

$$=\int d^3p\;y\left[-\frac{3}{4\sqrt{2}\pi}\phi_0(p)\phi_2(p)+\frac{3}{16\pi}|\phi_2(p)|^2\right](3\cos^2\theta-1)\delta\left(y-\frac{p\cdot q}{M_N\nu}\right)$$

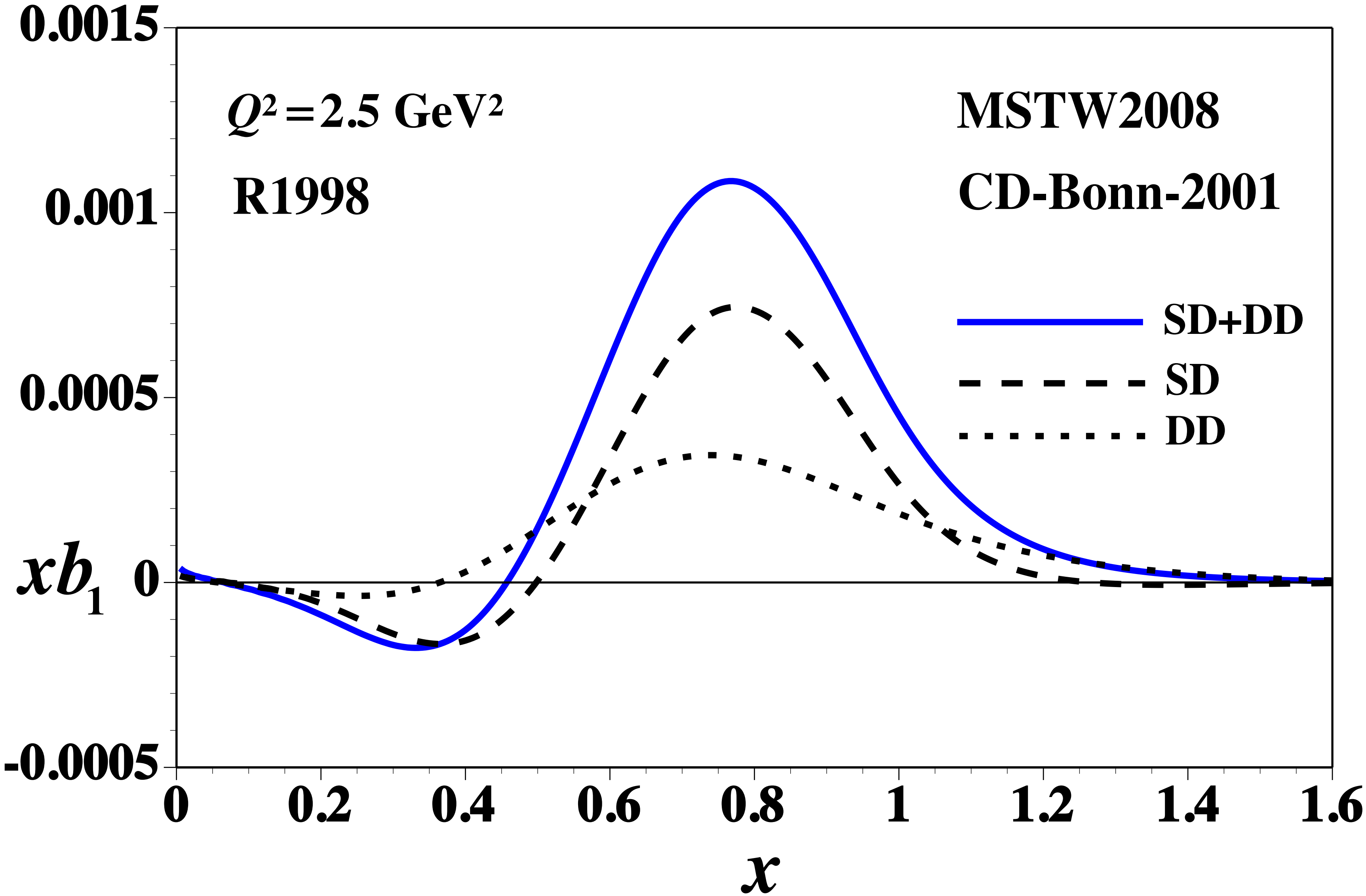


Standard model of the deuteron



S + D waves

Results on b_1 in the convolution description



Results on b_1 in the convolution description

Very different from

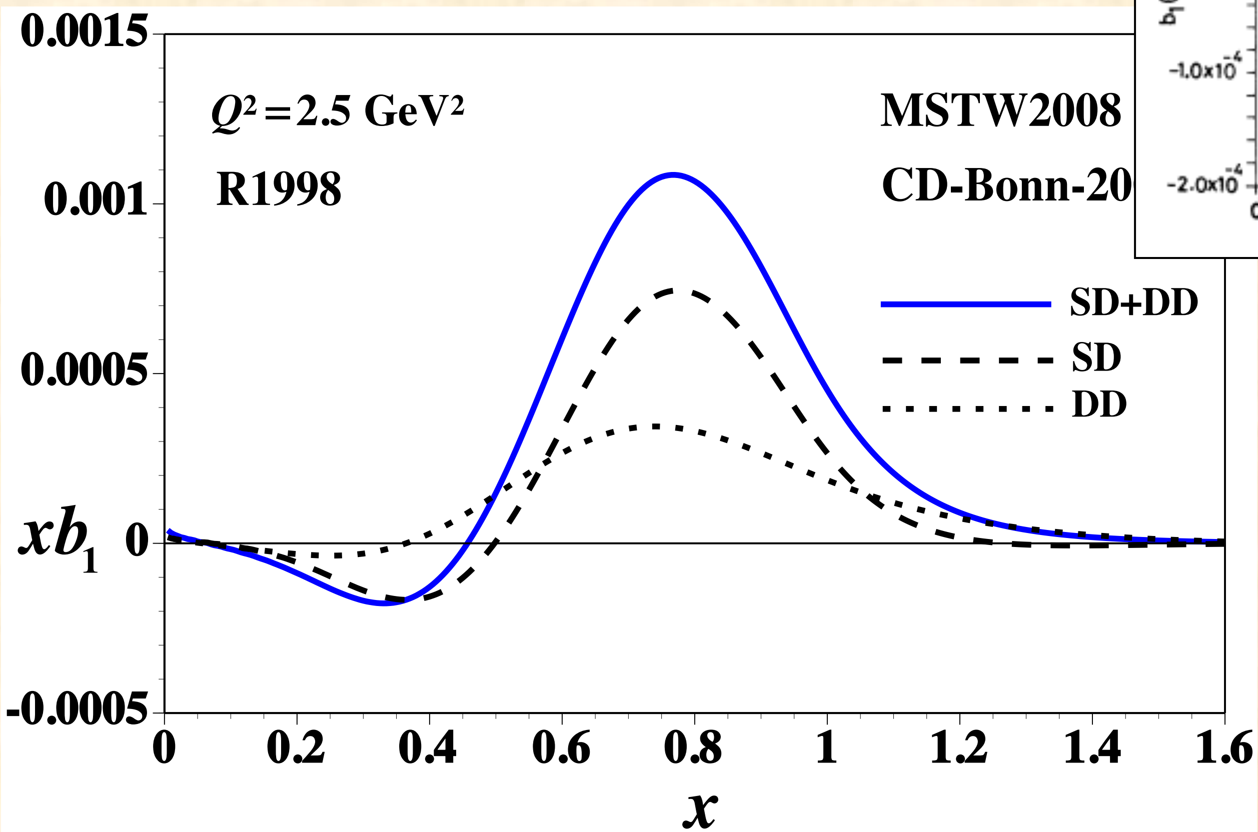
P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571;

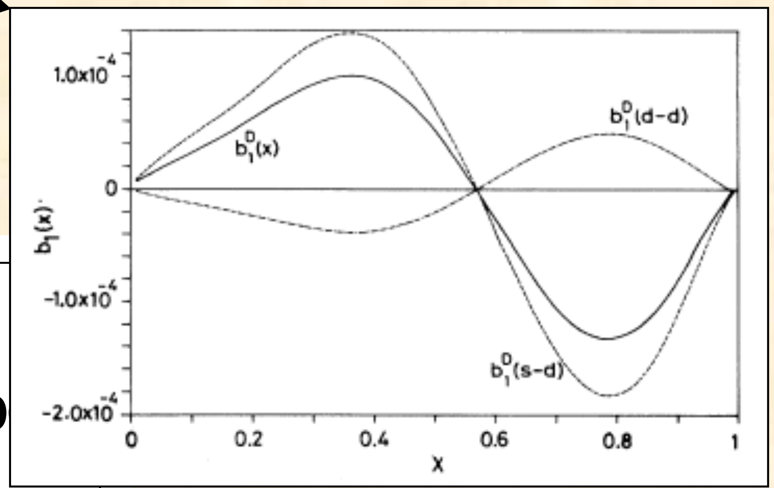
H. Khan and P. Hoodbhoy, PRC44 (1991) 1219.

(1) SD term is opposite,

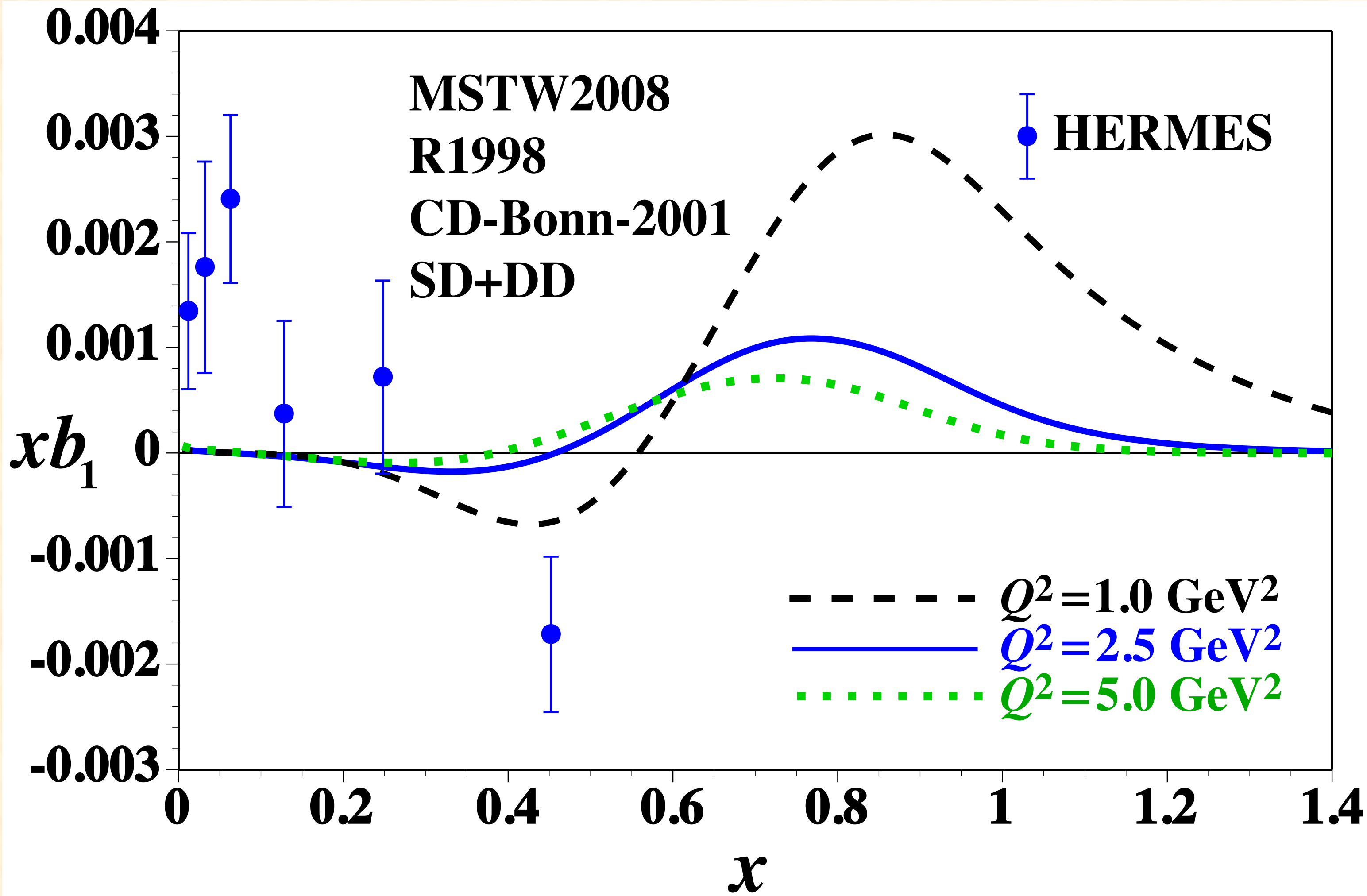
(2) $b_1(x)$ exists even at $x > 1$,

(3) $|b_1(\text{CDKS})| = 10^{-3} \gg |b_1(\text{KH})| = 10^{-4}$.

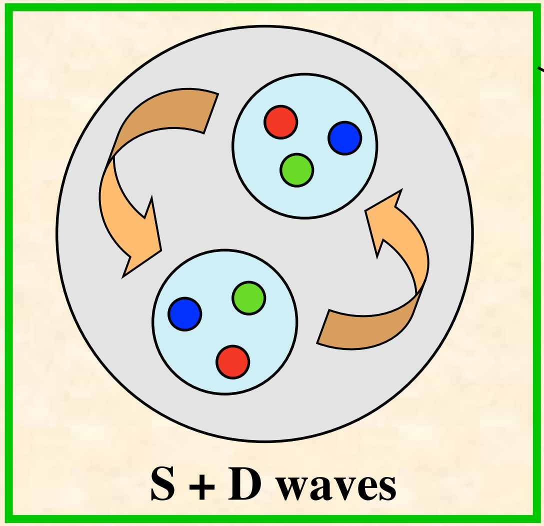




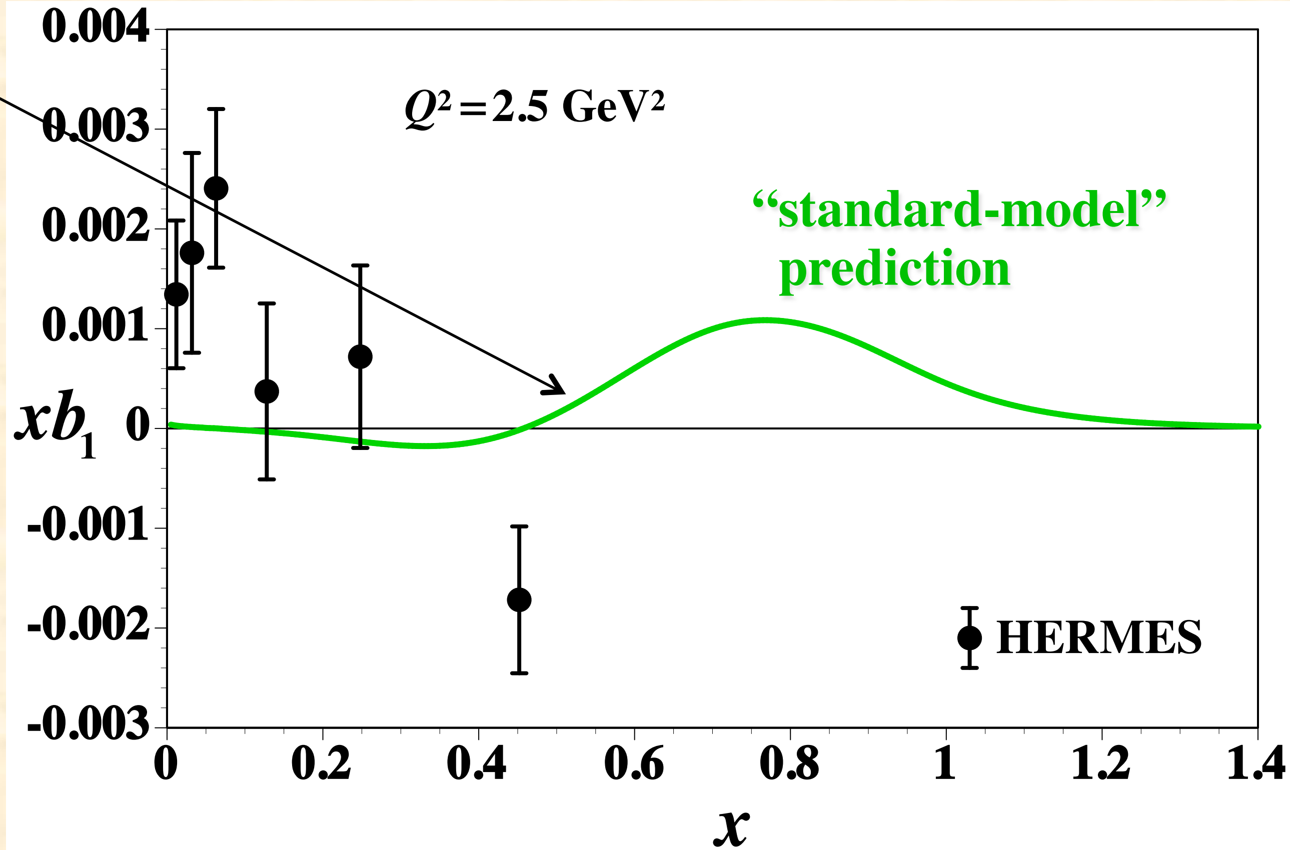
Comparison with HERMES measurements



Comparison with HERMES measurements



standard model



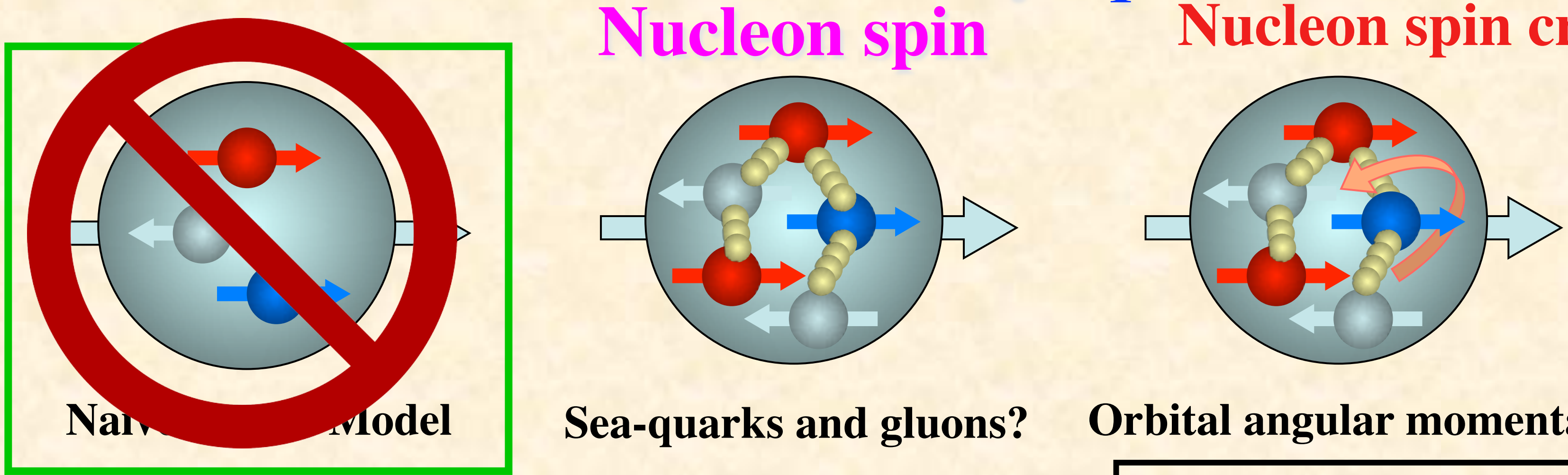
$|b_1(\text{theory})| \ll |b_1(\text{HERMES})|$
at $x < 0.5$

Standard convolution model does not work for the deuteron tensor structure?
→ New hadron physics !?

Situation of tensor structure by b_1

Nucleon spin

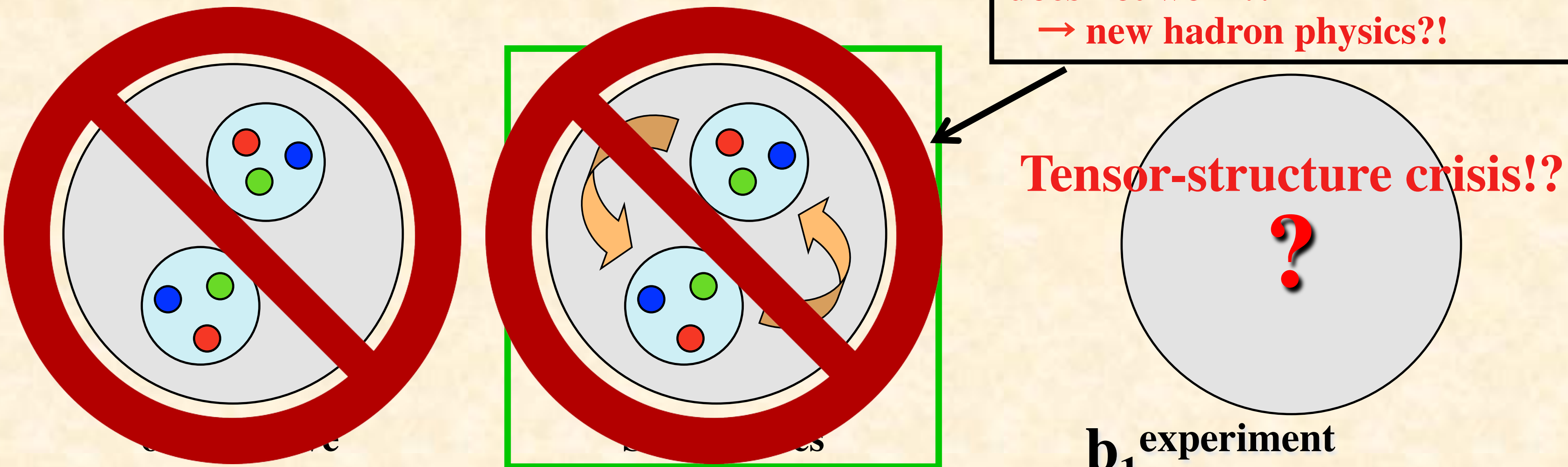
Nucleon spin crisis!?



"old" standard model

Tensor structure

We have shown in this work
that the standard deuteron model
does not work!?
→ new hadron physics?!



$b_1 = 0$

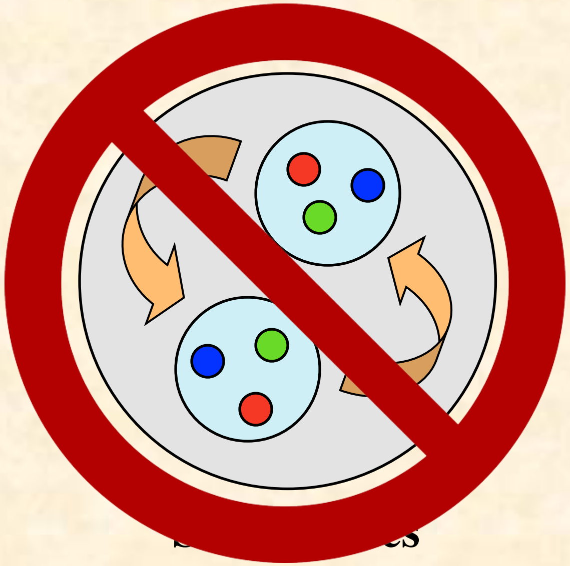
standard model $b_1 \neq 0$

$b_1^{\text{experiment}} \neq b_1^{\text{"standard model"}}$

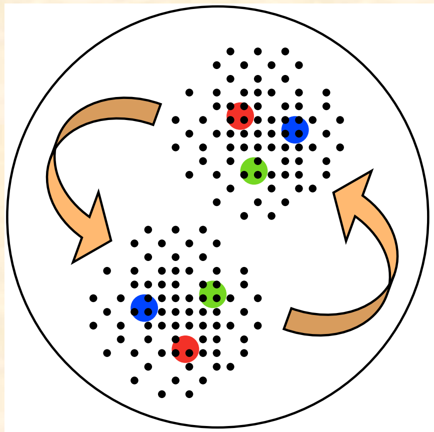
Summary on convolution calculation

Spin-1 structure functions of the deuteron

- new spin structure
- tensor structure in quark-gluon degrees of freedom
- new exotic signature in hadron-nuclear physics?
- experiments: Jlab (approved), Fermilab, ... , EIC, ILC, ...
- EIC → appropriate to study tensor-polarized antiquark distributions at small-x, Q^2 evolution of b_1



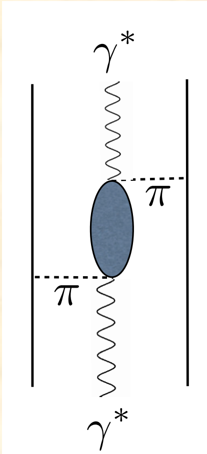
standard model

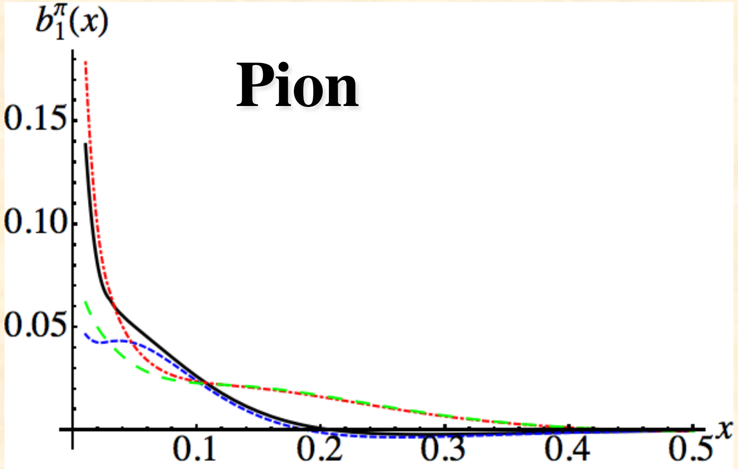


? new exotic mechanism?

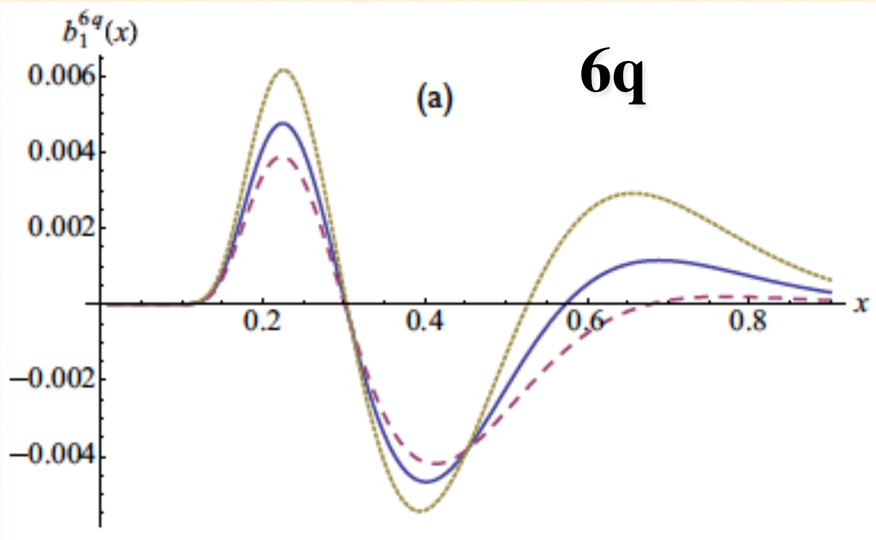
Recent work: Pion, Hidden-color, Six-quark

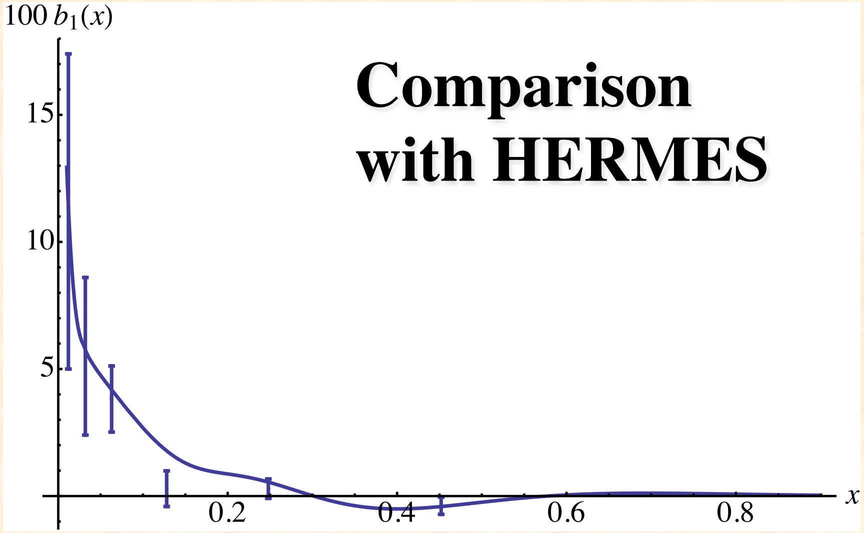
G. A. Miller,
PRC 89 (2014) 045203.





$$|6q\rangle = |NN\rangle + |\Delta\Delta\rangle + |CC\rangle + \cdots$$





JLab PAC-38 (Aug. 22-26, 2011) proposal, PR12-11-110

The Deuteron Tensor Structure Function b_1

A Proposal to Jefferson Lab PAC-38.
(Update to LOI-11-003)

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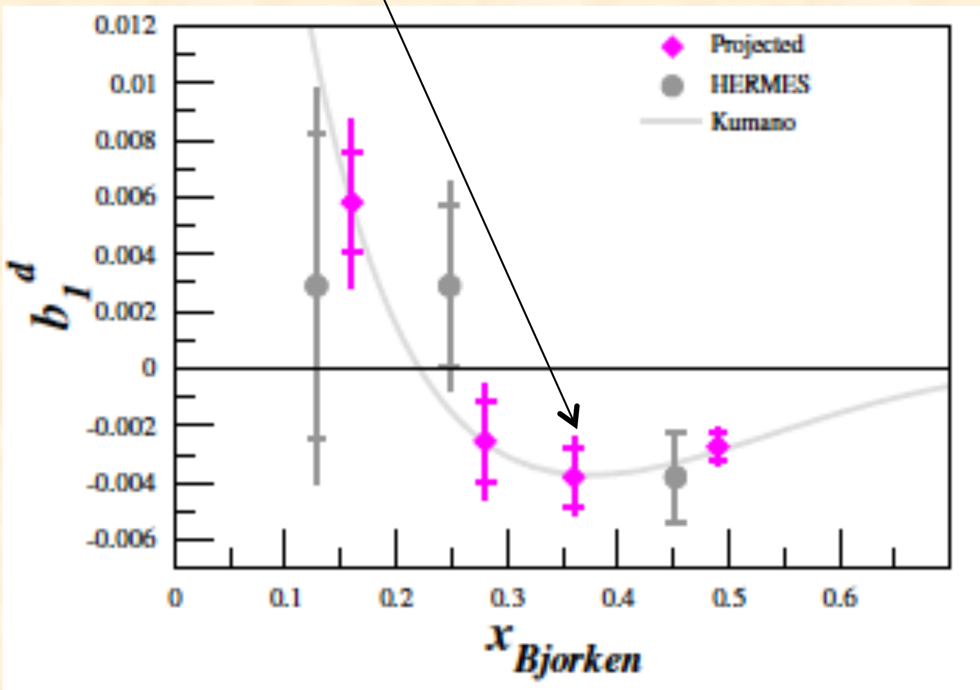
Approved!

Expected errors by JLab



Theoretical estimation on tensor-polarization asymmetry in Drell-Yan at Fermilab

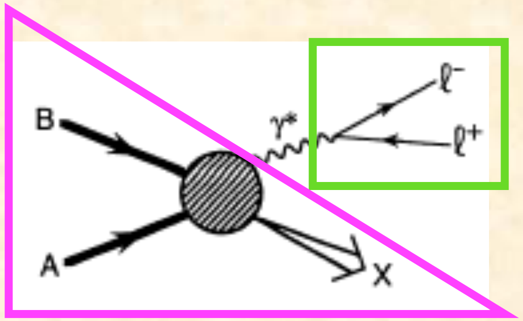
S. Kumano and Qin-Tao Song,
Phys. Rev. D94 (2016) 054022.

Drell-Yan cross section and hadron tensor

$$d\sigma = \frac{1}{4\sqrt{(P_A \cdot P_B)^2 - M_A^2 M_B^2}} \sum_{S_{l^-} S_{l^+}} \sum_X (2\pi)^4 \delta^4\left(P_A + P_B - k_{l^+} - k_{l^-} - P_X\right) \left|\langle l^+ l^- X | T | AB\rangle\right|^2 \frac{d^3 k_{l^+}}{(2\pi)^3 2E_{l^+}} \frac{d^3 k_{l^-}}{(2\pi)^3 2E_{l^-}}$$

$$\langle l^+ l^- X | T | AB\rangle = \underline{\bar{u}\left(k_{l^-}, \lambda_{l^-}\right) e\gamma_\mu \upsilon\left(k_{l^+}, \lambda_{l^+}\right)} \frac{g^{\mu\nu}}{\left(k_{l^+} + k_{l^-}\right)^2} \underline{\langle X | eJ_\nu(0) | AB\rangle}$$

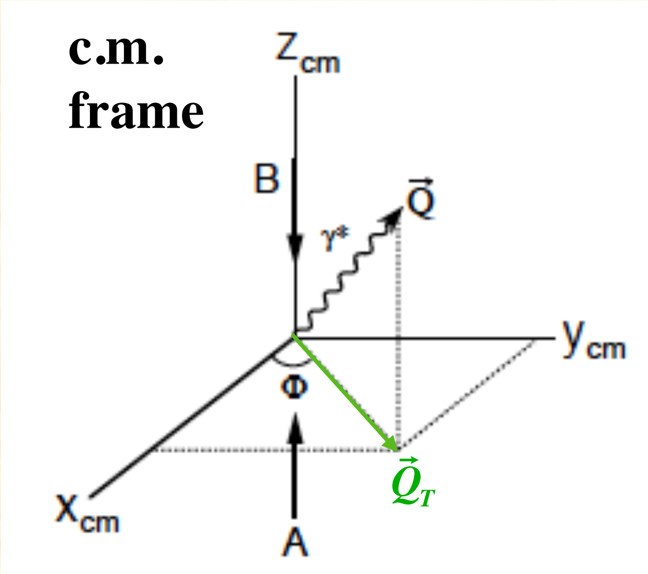
$$\frac{d\sigma}{d^4 Q d\Omega} = \frac{\alpha^2}{2sQ^4} \underline{L_{\mu\nu}}\, \underline{W^{\mu\nu}} \qquad W^{\mu\nu} \equiv \int \frac{d^4\xi}{(2\pi)^4} e^{iQ\cdot\xi} \langle P_A S_A P_B S_B | J^\mu(0) J^\nu(\xi) | P_A S_A P_B S_B\rangle$$



For the details, see

- M. Hino and SK, Phys. Rev. D59 (1999) 094026.
- M. Hino and SK, Phys. Rev. D60 (1999) 054018.

Formalism of *pd* Drell-Yan process



See Ref. PRD59 (1999) 094026.

	proton-proton	proton-deuteron	
Number of structure functions	48	108	Additional structure functions due to tensor structure
After integration over $\vec{Q}_T$ (or $\vec{Q}_T \to 0$)	11	22	
In parton model	3	4	I explain in the next page.

Spin asymmetries in the parton model

unpolarized: q_a, longitudinally polarized: Δq_a,

transversely polarized: $\Delta_T q_a$, tensor polarized: δq_a

Unpolarized cross section

$$\left\langle \frac{d\sigma}{dx_A dx_B d\Omega} \right\rangle = \frac{\alpha^2}{4Q^2}\left(1+\cos^2\theta\right)\frac{1}{3}\sum_a e_a^2\left[q_a(x_A)\bar{q}_a(x_B)+\bar{q}_a(x_A)q_a(x_B)\right]$$

Spin asymmetries

$$A_{LL} = \frac{\sum_a e_a^2\left[\Delta q_a(x_A)\Delta\bar{q}_a(x_B)+\Delta\bar{q}_a(x_A)\Delta q_a(x_B)\right]}{\sum_a e_a^2\left[q_a(x_A)\bar{q}_a(x_B)+\bar{q}_a(x_A)q_a(x_B)\right]}$$

$$A_{TT} = \frac{\sin^2\theta\cos(2\phi)}{1+\cos^2\theta}\frac{\sum_a e_a^2\left[\Delta_T q_a(x_A)\Delta_T\bar{q}_a(x_B)+\Delta_T\bar{q}_a(x_A)\Delta_T q_a(x_B)\right]}{\sum_a e_a^2\left[q_a(x_A)\bar{q}_a(x_B)+\bar{q}_a(x_A)q_a(x_B)\right]}$$

$$A_{UQ_0} = \frac{\sum_a e_a^2\left[q_a(x_A)\delta_T\bar{q}_a(x_B)+\bar{q}_a(x_A)\delta_T q_a(x_B)\right]}{2\sum_a e_a^2\left[q_a(x_A)\bar{q}_a(x_B)+\bar{q}_a(x_A)q_a(x_B)\right]}$$

$$A_{LT} = A_{TL} = A_{UT} = A_{TU} = A_{TQ_0} = A_{UQ_1}$$
$$= A_{LQ_1} = A_{TQ_1} = A_{UQ_2} = A_{LQ_2} = A_{TQ_2} = 0$$

Advantage of the hadron reaction ($\delta\bar{q}$ measurement)

$$A_{UQ_0}(\text{large } x_F) \approx \frac{\sum_a e_a^2 q_a(x_A)\delta_T\bar{q}_a(x_B)}{2\sum_a e_a^2 q_a(x_A)\bar{q}_a(x_B)}$$

Note: $\delta \neq$ transversity in my notation

Functional form of parametrization

Assume flavor-symmetric antiqurk distributions: $\delta_T \bar{q}^D \equiv \delta_T \bar{u}^D = \delta_T \bar{d}^D = \delta_T s^D = \delta_T \bar{s}^D$

$$b_1^D(x)_{LO} = \frac{1}{18}\left[4\delta_T u_v^D(x) + \delta_T d_v^D(x) + 12\ \delta_T \bar{q}^D(x)\right]$$

At $Q_0^2 = 2.5$ GeV^2, $\delta_T q_v^D(x, Q_0^2) = \delta_T w(x) q_v^D(x, Q_0^2)$, $\delta_T \bar{q}^D(x, Q_0^2) = \alpha_{\bar{q}} \delta_T w(x) \bar{q}^D(x, Q_0^2)$

Certain fractions of quark and antiquark distributions are tensor polarized and such probabilities are given by the function $\delta_T w(x)$ and an additional constant $\alpha_{\bar{q}}$ for antiquarks in comparison with the quark polarization.

$$b_1^D(x, Q_0^2)_{LO} = \frac{1}{18}\left[4\delta_T u_v^D(x, Q_0^2) + \delta_T d_v^D(x, Q_0^2) + 12\delta_T \bar{q}^D(x, Q_0^2)\right]$$

$$= \frac{1}{36}\delta_T w(x)\left[5\left\{u_v(x, Q_0^2) + d_v(x, Q_0^2)\right\} + 4a_{\bar{q}}\left\{2\bar{u}(x, Q_0^2) + 2\bar{d}(x, Q_0^2) + s(x, Q_0^2) + \bar{s}(x, Q_0^2)\right\}\right]$$

$$\delta_T w(x) = a x^b (1-x)^c (x_0 - x)$$

Two types of analyses

Set 1: $\delta_T \bar{q}^D(x) = 0$ **Tensor-polarized antiquark distributions are terminated** ($\alpha_{\bar{q}} = 0$),

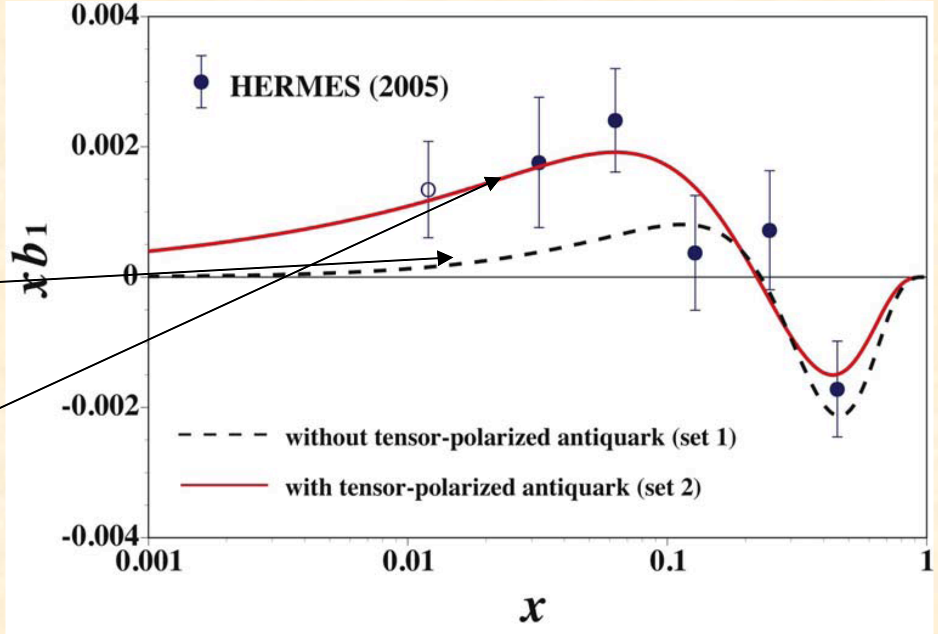
Set 2: $\delta_T \bar{q}^D(x) \neq 0$ **Finite tensor-polarized antiquark distributions are allowed** ($\alpha_{\bar{q}} \neq 0$).

Results

SK, PRD 82 (2010) 017501

Two-types of fit results:

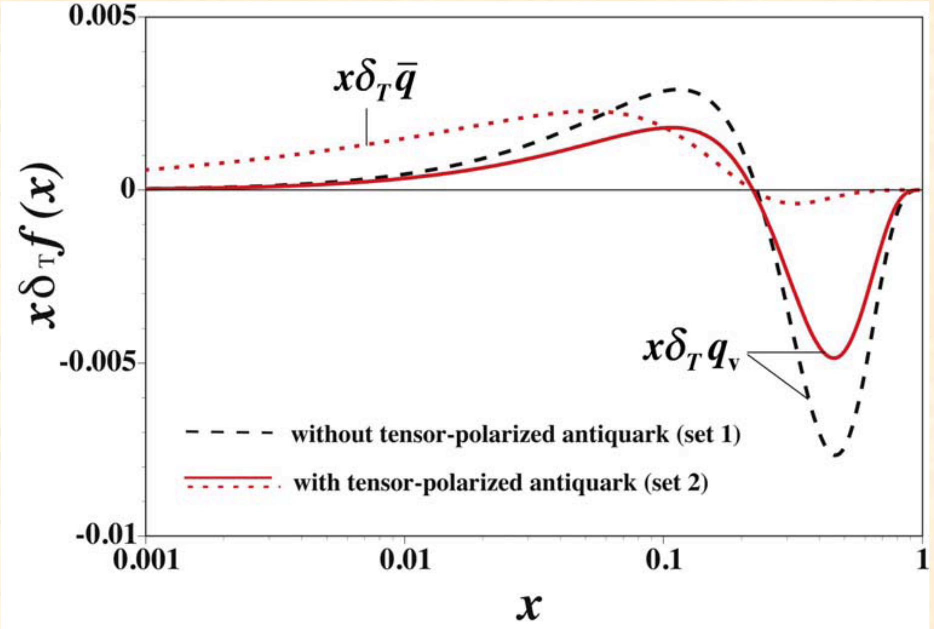
- set-1: $\chi^2 / \text{d.o.f.} = 2.83$
  Without $\delta_T q$, the fit is not good enough.
- set-2: $\chi^2 / \text{d.o.f.} = 1.57$
  With finite $\delta_T q$, the fit is reasonably good.



Obtained tensor-polarized distributions
$\delta_T q(x)$, $\delta_T \bar{q}(x)$ from the HERMES data.

→ They could be used for

- experimental proposals,
- comparison with theoretical models.



Finite tensor polarization for antiquarks:

$$\int_0^1 dx b_1(x) = 0.058$$
$$= \frac{1}{9}\int_0^1 dx \left[4\delta_T \bar{u}(x) + \delta_T \bar{d}(x) + \delta_T \bar{s}(x) \right]$$

Experimental possibility at Fermilab

E1039

Polarized fixed-target experiments
at the Main Injector

Drell-Yan experiment with a polarized proton target

Co-Spokespersons: A. Klein, X. Jiang, Los Alamos National Laboratory

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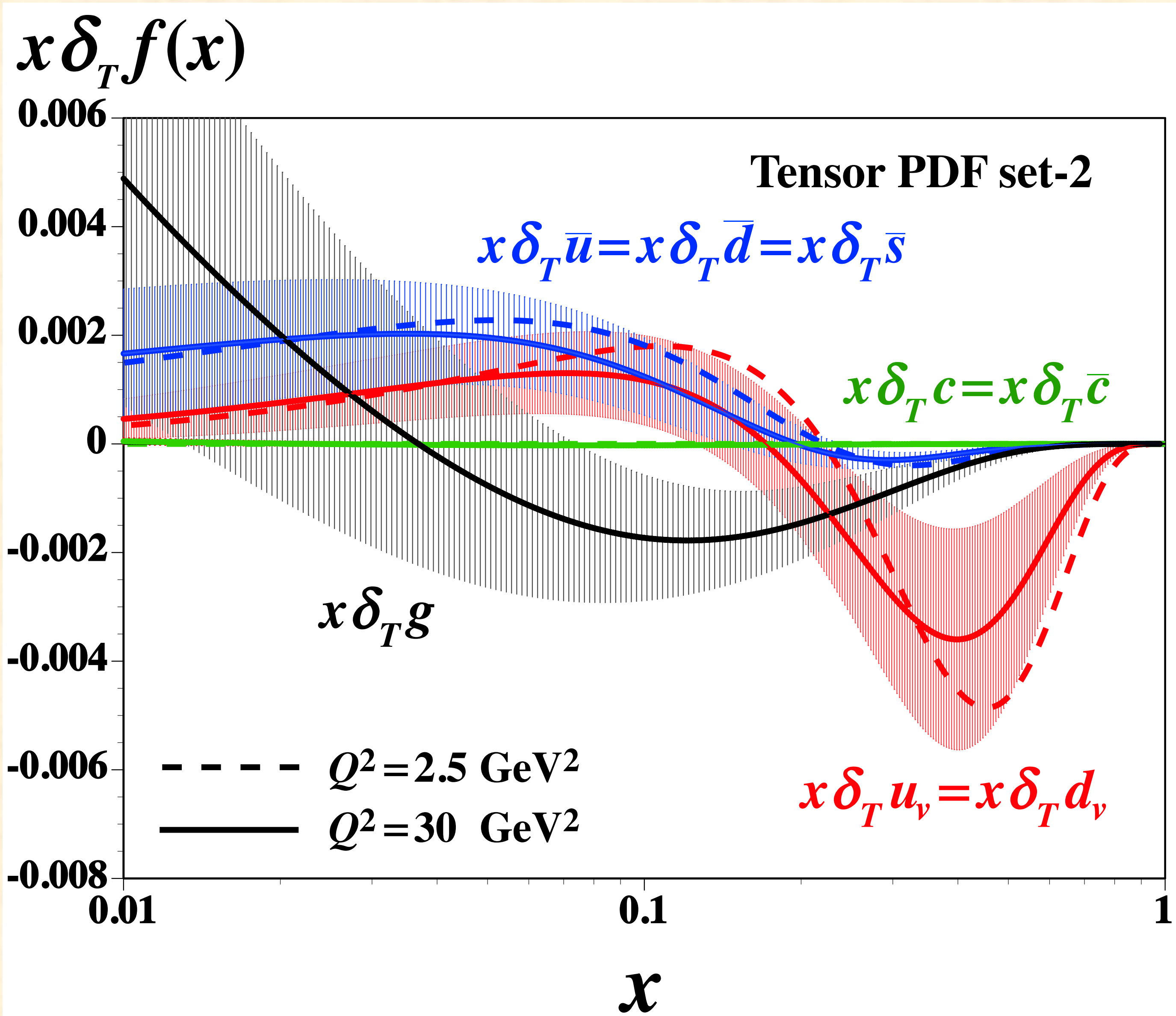
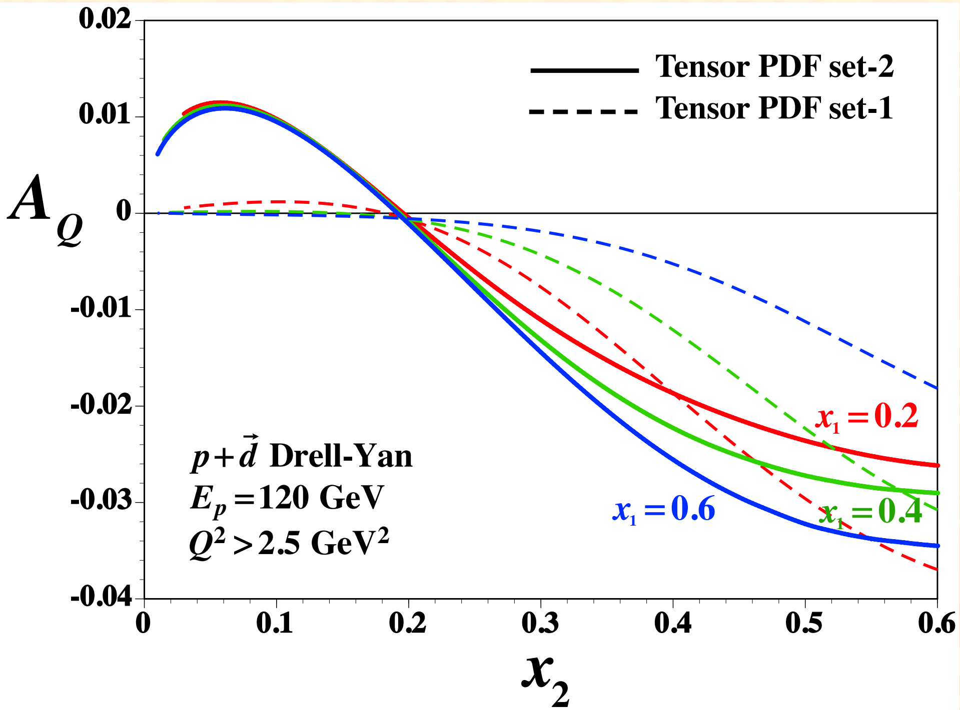
Q^2 evolution

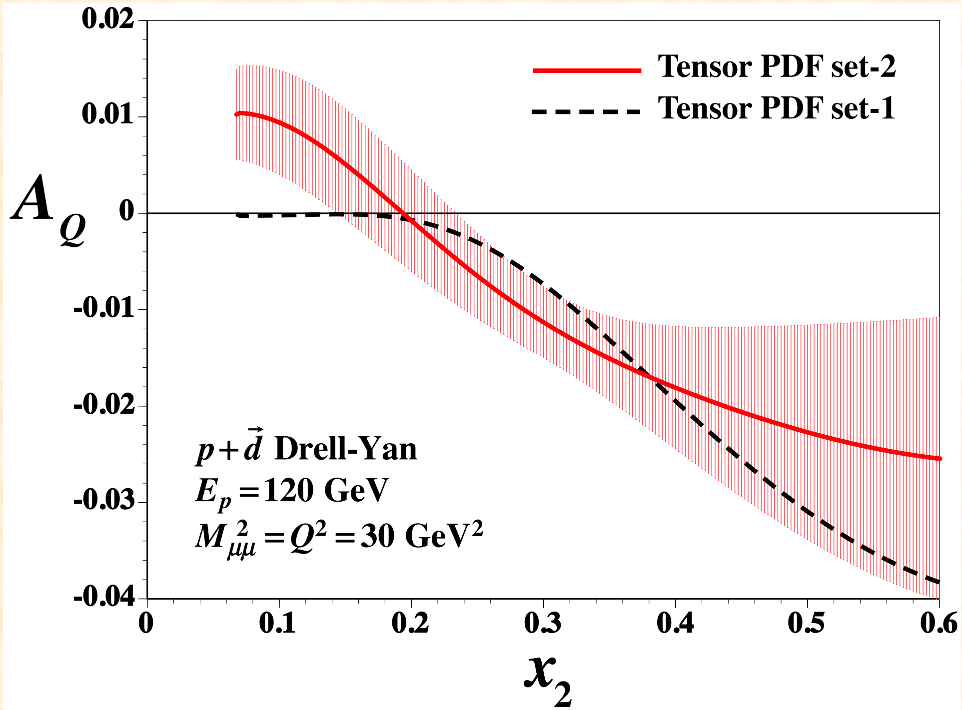
$Q^2 = 2.5\ \text{GeV}^2 \rightarrow 30\ \text{GeV}^2$



Tensor-polarized spin asymmetry

$$A_Q = \frac{\sum_a e_a^2 \left[q_a(x_A)\, \delta_T \bar{q}_a(x_B) + \bar{q}_a(x_A)\, \delta_T q_a(x_B) \right]}{\sum_a e_a^2 \left[q_a(x_A)\, \bar{q}_a(x_B) + \bar{q}_a(x_A)\, q_a(x_B) \right]}$$





S. Kumano and Qin-Tao Song,
Phys. Rev. D94 (2016) 054022.

Summary on Fermilab proton-deuteron Drell-Yan

JLab PR12-11-110 (2019~) : $b_1 = \dfrac{1}{2}\sum_i e_i^{\,2}\left(\delta_T q_i + \delta_T \bar{q}_i\right)$

No separation between $\delta_T q$ and $\delta_T \bar{q}$

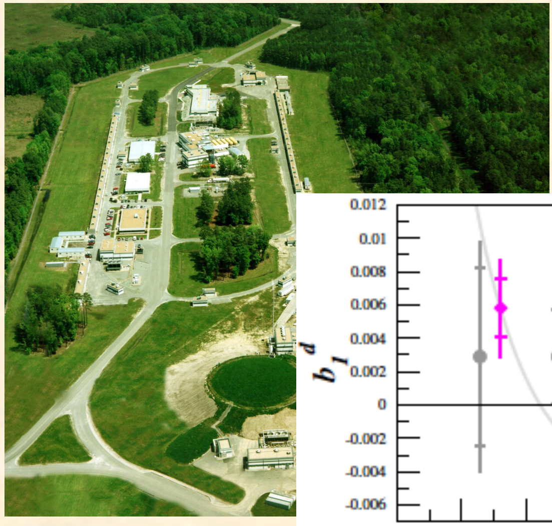
Fermiab E1039 (20xx) : $A_Q\left(\text{large } x_F\right) \approx \dfrac{\sum_a e_a^2 q_a(x_1)\,\delta_T \bar{q}_a(x_2)}{2\sum_a e_a^2 q_a(x_1)\,\bar{q}_a(x_2)}$

Separation of $\delta_T \bar{q}$

$\rightarrow$ possible new exotic hadron physics mechanism

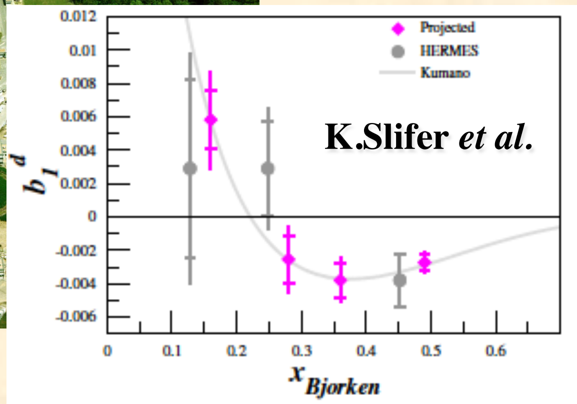
EIC and future prospects

Experimental possibilities

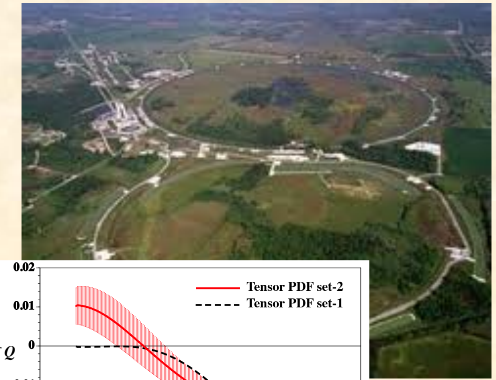


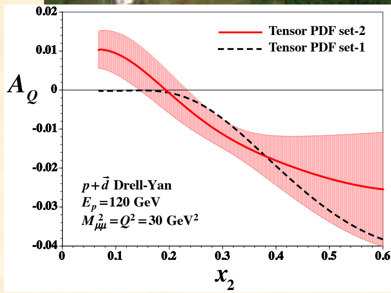
© JLab

Approved experiment! (2019~)



E1039 experiment



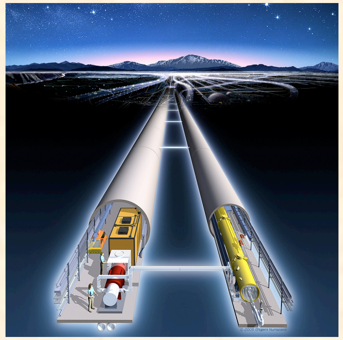


© Fermilab

EIC (arXiv:1212.1701)

Polarized deuteron acceleration is possible at EIC!

Linear Collider
(with fixed target)



Possibilities: Spin-1 projects are possible in principle at other hadron facilities.

© BNL

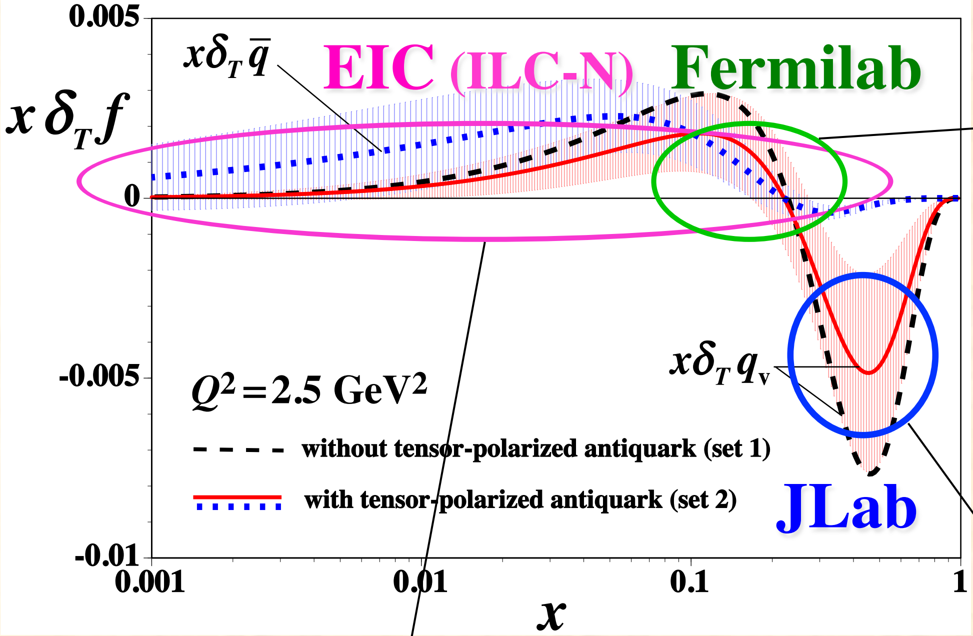
© J-PARC

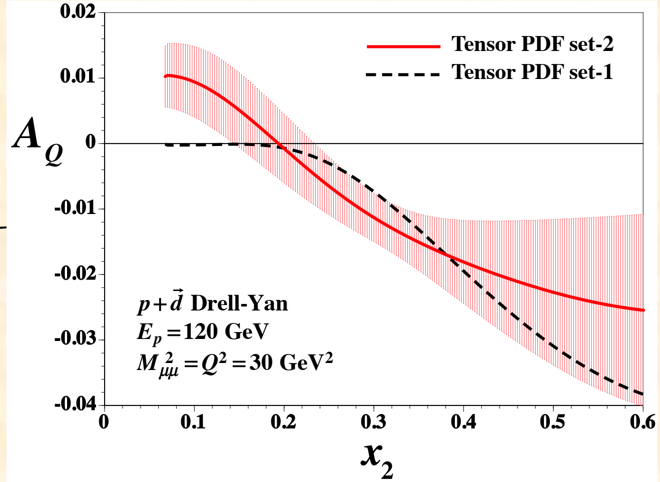
© GSI

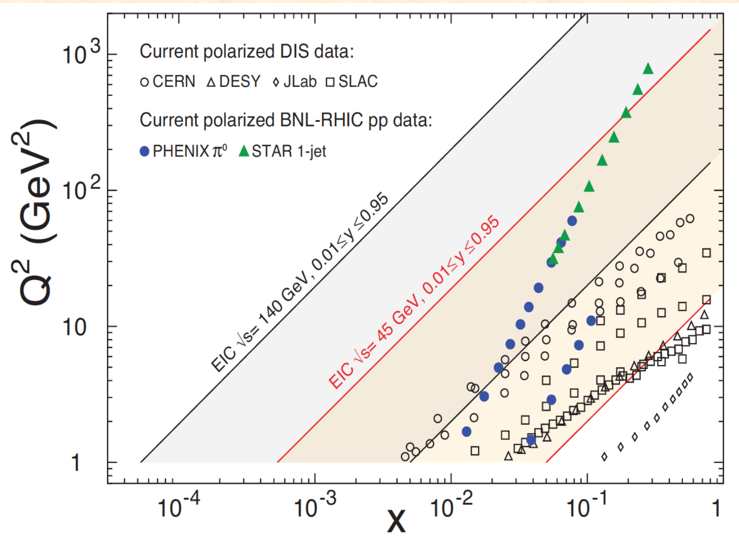
© CERN-COMPASS

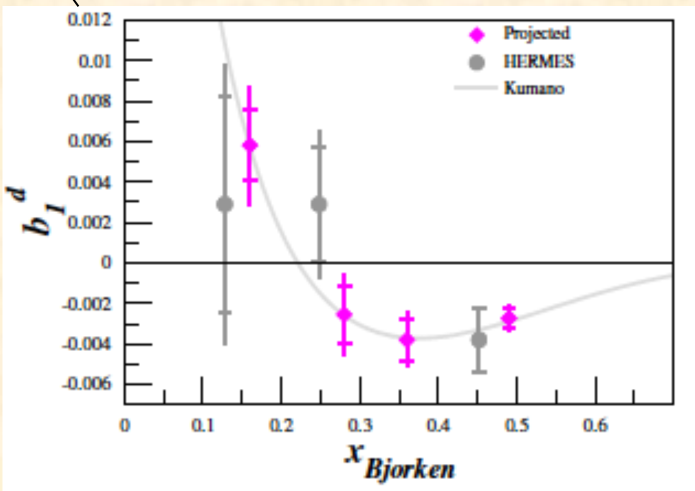
© IHEP, Russia

Future possibilities of b_1

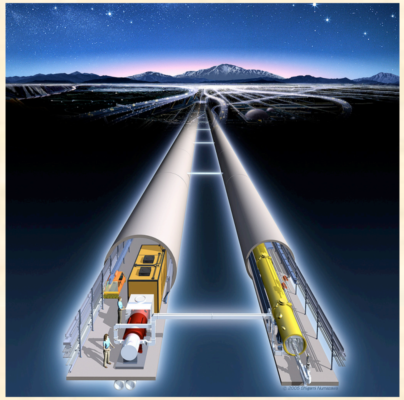








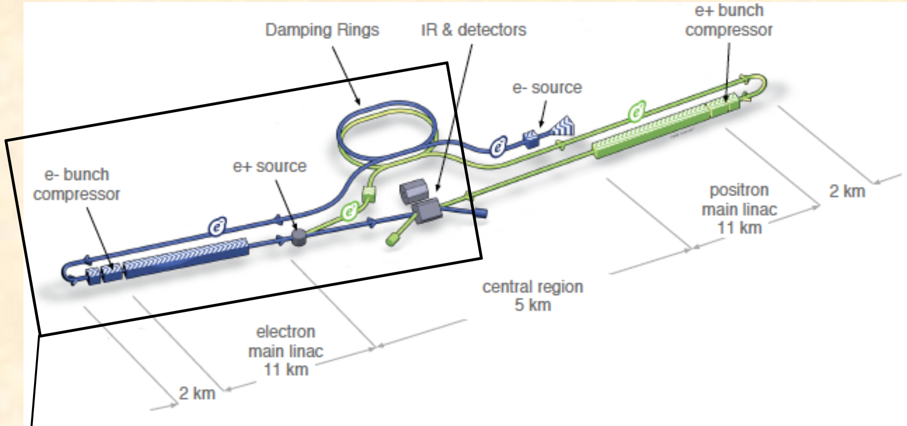
International Linear Collider

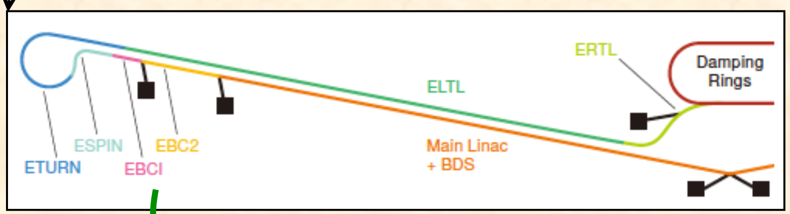


ILC-N (Fixed target option) for hadron physics?

ILC TDR (Technical Design Report)

https://www.linearcollider.org/ILC/Publications/Technical-Design-Report





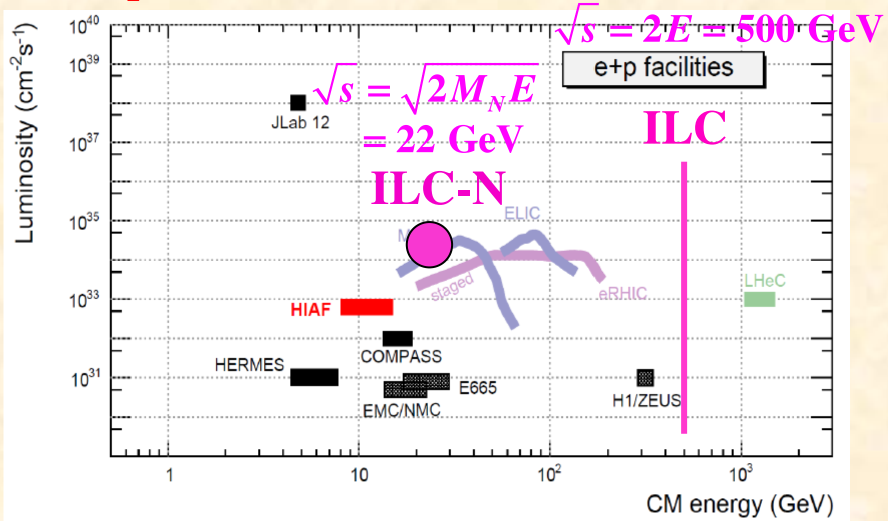
5 – 250 GeV electron beams for fixed target experiments

Possibilities for hadron and nuclear physics

- **e^+e^- annihilation processes**
- **fixed target experiments with 5 – 250 GeV electron beams (ILC-N)**

→ No serious studies about these feasibilities.

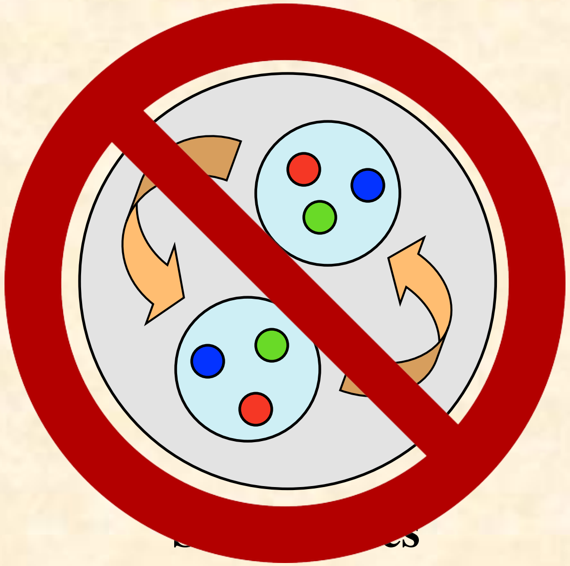
ILC-N is better than on-going COMPASS but it is in competition with EIC in 2025 !



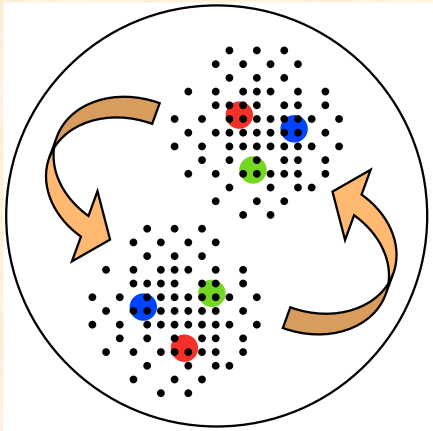
Summary on spin-1 deuteron structure functions

Spin-1 structure functions of the deuteron

- new spin structure
- tensor structure in quark-gluon degrees of freedom
- new exotic signature in hadron-nuclear physics?
- experiments: JLab (approved), Fermilab, ... , EIC, ILC, ...
- EIC → appropriate to study tensor-polarized antiquark distributions at small-x, Q^2 evolution of b_1



standard model



? new exotic mechanism?

8th International Conference on Quarks and Nuclear Physics

November 13-17, 2018, Tsukuba, Japan
http://www-conf.kek.jp/qnp2018/

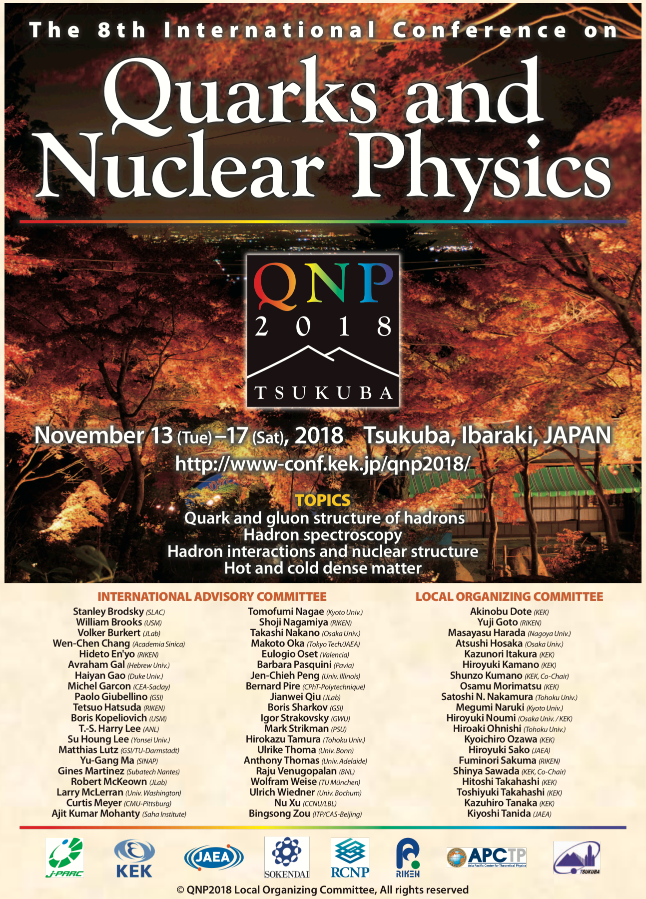
APCTP conference!

Quark and gluon structure of hadrons:
- parton distribution functions, generalized parton distributions,
- transverse momentum distributions, high-energy hadron reactions, …

Hadron spectroscopy:
- heavy quark physics, exotics, N*, ...

Hadron interactions and nuclear structure:
- hypernuclear physics, kaonic nuclei, baryon interactions, ...

Hot and cold dense matter:
- quark-gluon plasma, color glass condensate, dense stars,
- strong magnetic field, mesons in nuclear medium, hadronization, ...



The End

The End