Possible studies on high-energy hadron physics at future HIAF

HIAF: 9.3 GeV
→ 25 GeV
→ even higher ???

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惠州强子谱仪HHaS合作组2005年年会
(Annual meeting of
the Huizhou Hadron Spectrometer HHaS Collaboration in 2025)
IMP, Huizhou, China, November 28-30, 2025
https://indico.itp.ac.cn/event/375/timetable/#all.detailed

November 30, 2025

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- Comments: tensor-polarization physics
- Color transparency

  may skip
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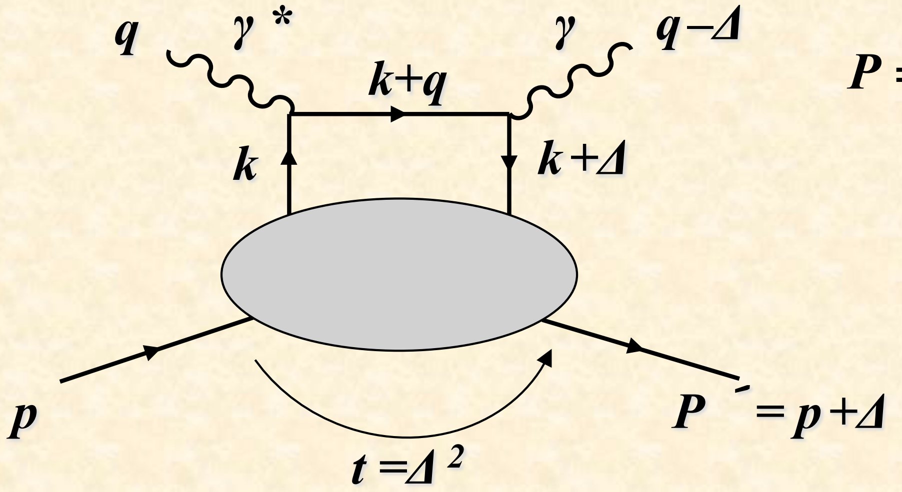
Motivations for studying high-energy hadron physics at HIAF

Generalized Parton Distributions (GPDs)



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

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:

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

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p'|\bar{\psi}(-z/2)\gamma^+\gamma_5\psi(z/2)|p\rangle\Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[\tilde{H}(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5u(p) + \tilde{E}(x,\xi,t)\bar{u}(p')\frac{\gamma_5\Delta^+}{2M}u(p)\right]$$

Forward limit: PDFs $\quad H(x,\xi,t)\Big|_{\xi=t=0} = f(x),\quad \tilde{H}(x,\xi,t)\Big|_{\xi=t=0} = \Delta f(x),$

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

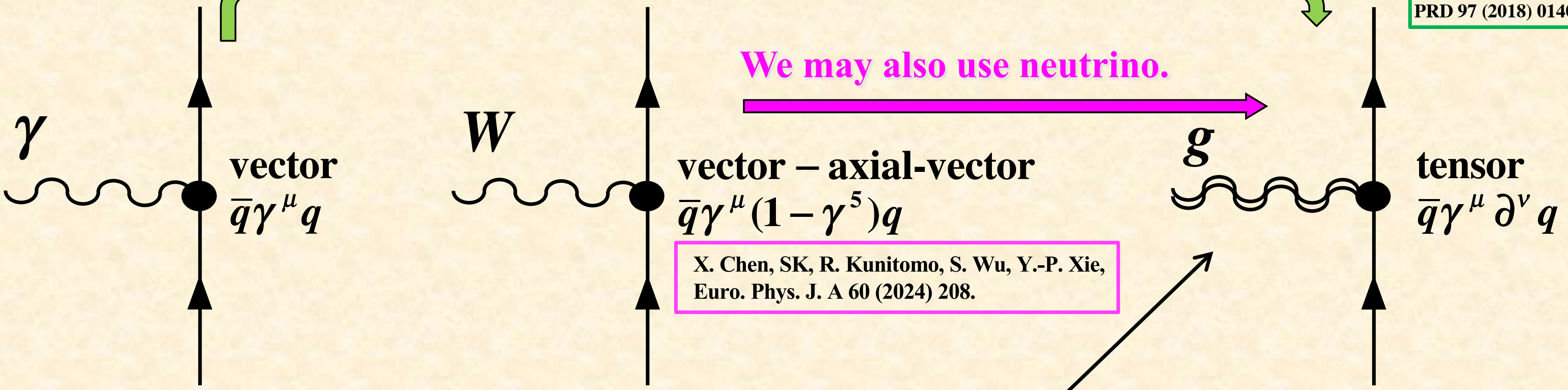
$\Rightarrow$ probe L_q, key quantity to solve the spin puzzle!

Why "gravitational" interactions with quarks

We studied in 2017-2018.

S. Kumano, Q.-T. Song, O. Teryaev, PRD 97 (2018) 014020.

We may also use neutrino.



X. Chen, SK, R. Kunitomo, S. Wu, Y.-P. Xie, Euro. Phys. J. A 60 (2024) 208.

It is possible to probe gravitational sources in the microscopic level without gravitons.

GPDs (Generalized Parton Distributions), GDAs (Generalized Distribution Amplitudes) = timelike GPDs

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

Non-local operator of GPDs/GDAs:

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

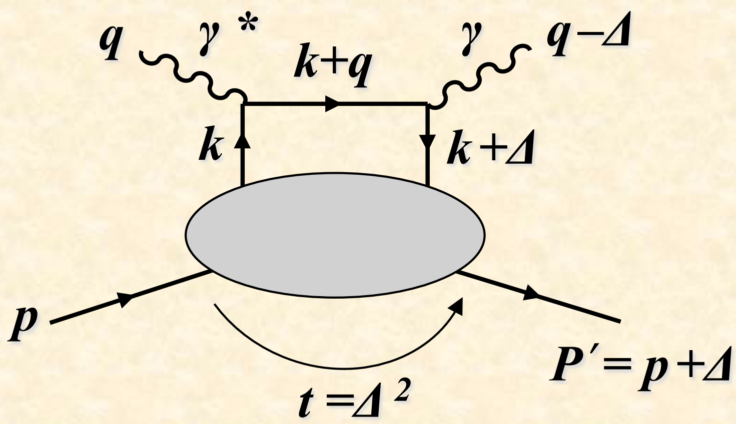
$$= \left(i\frac{\partial}{\partial z^-}\right)^{n-1}\left[\bar{q}(-z/2)\gamma^+ q(z/2)\right]_{z=0}$$

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

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

= source of gravitiy

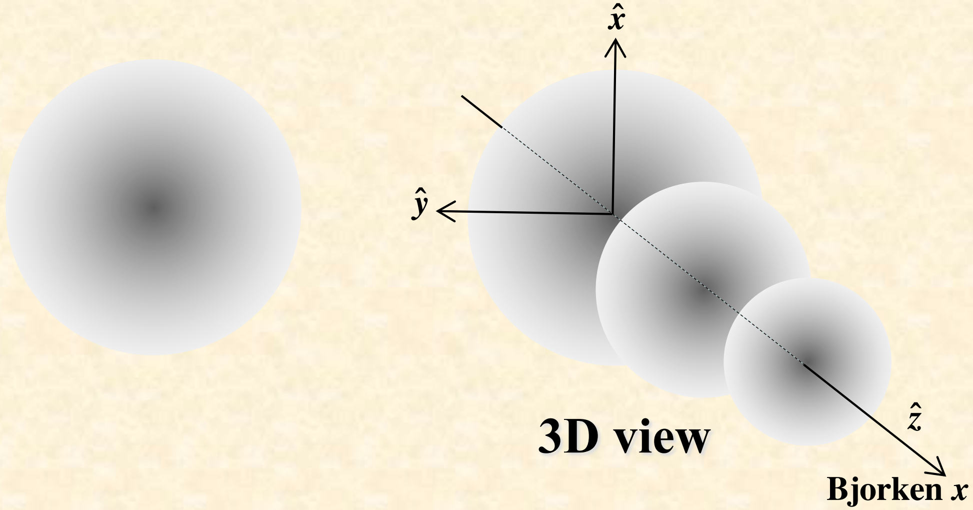
Virtual Compton
or (timelike) two-photon process



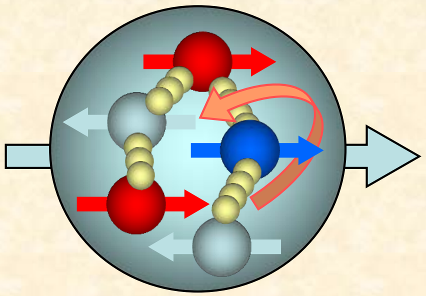
Proton (hadrons) puzzle studies by the GPDs

Hadron tomography

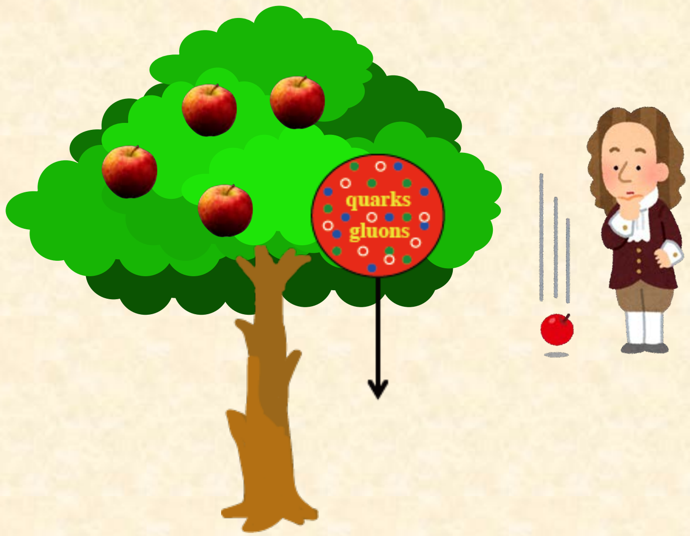
Proton radius puzzle



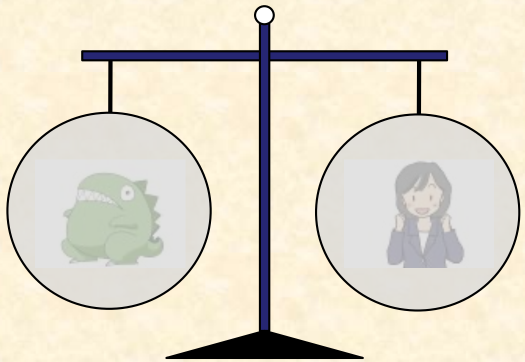
Origin of nucleon spin



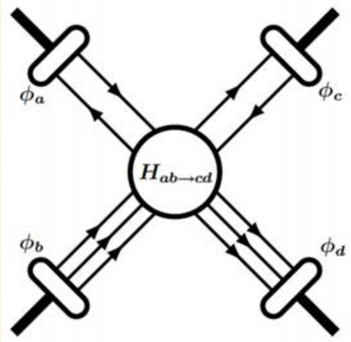
Source of gravity (mass)



Exotic hadrons



Constituent-counting rule in perturbative QCD: Hard exclusive processes $a+b \to c+d$



Consider the hard exclusive hadron reaction $a+b \to c+d$

$$M_{ab\to cd} = \int d[x_a]d[x_b]d[x_c]d[x_d]\phi_c([x_c])\phi_d([x_d])H_M([x_a],[x_b],[x_c],[x_d],Q^2)\phi_a([x_a])\phi_b([x_b])$$

ϕ_p = proton distribution amplitude, H_M = hard amplitude (calculated in pQCD)

Rule for estimating $M_{ab\to cd}$

(1) Feynman diagram: Draw leading and connected Feynman diagram by connecting $n/2$ quark lines by gluons.

(2) Gluon propagators: The factor $1/P^2$ is assigned for each gluon propagator.

There are $n/2-1$ gluon propagators $\sim 1/(P^2)^{n/2-1}$.

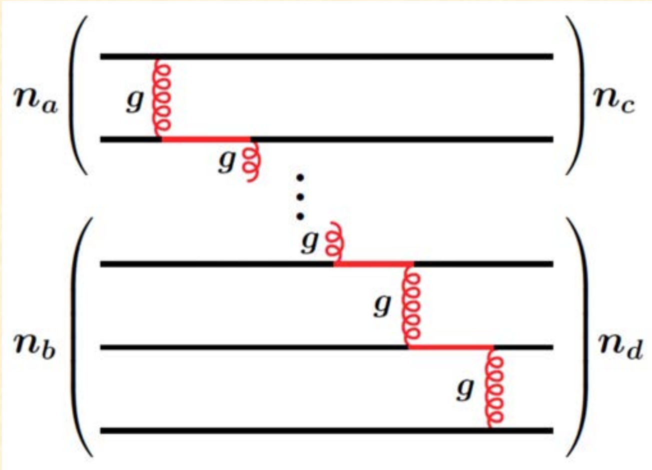
(3) Quark propagators: The factor $1/P$ is assigned for each quark propagator.

$\boxed{n = n_a + n_b + n_c + n_d}$

There are $n/2-2$ gluon propagators $\sim 1/(P)^{n/2-2}$.

(4) External quarks: The factor $\sqrt{P}$ is assigned for each external quark.

There are n gluon propagators $\sim (\sqrt{P})^n$.



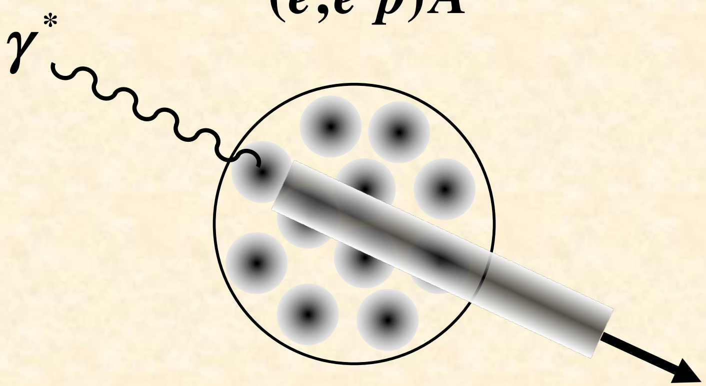
$$M_{ab\to cd} \sim \frac{1}{(P^2)^{n/2-1}}\frac{1}{(P)^{n/2-2}}(\sqrt{P})^n = \frac{(P)^{n/2}}{(P)^{n-2}(P)^{n/2-2}} = \frac{1}{(P)^{n-4}} \sim \frac{1}{s^{n/2-2}}$$

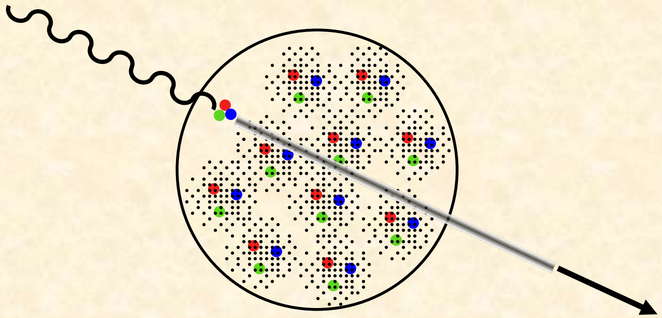
Cross section: $$\frac{d\sigma_{ab\to cd}}{dt} \simeq \frac{1}{16\pi^2}\overline{\sum_{spol}}\left|M_{ab\to cd}\right|^2 \sim \frac{1}{s^{n-2}}$$

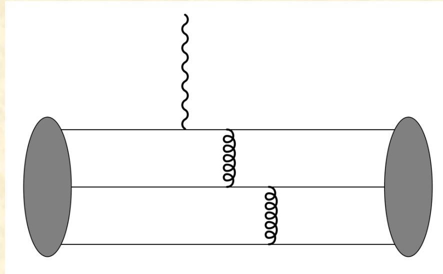
It is interesting to use this for exotic-hadron candidates.

Color transparency and hadronization

$(e,e'p)A$







Hard gluon exchanges at high energies
$\rightarrow$ quarks are close with each other
$\rightarrow$ struck nucleon should be compact
$\rightarrow$ nucleon could pass though the medium
without interaction (color transparency)

Interact strongly in the nuclear medium

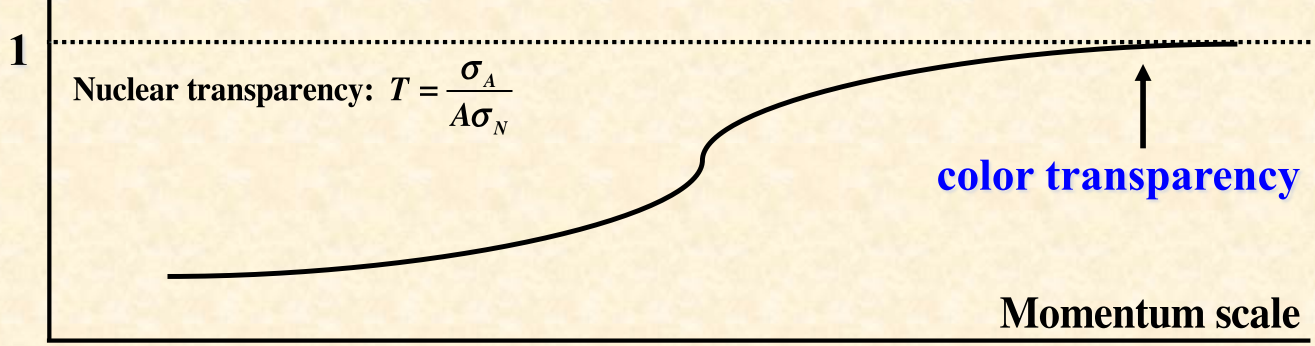
No interaction in the nuclear medium

$\leftarrow$ **Low energies:** Hadron degrees of freedom

$\rightarrow$ **High energies:** Quark-gluon degrees of freedom

At large momentum transfer, a small-size hadron could freely pass through nuclear medium. (Transparent)

$$T = \frac{\sigma_A}{A\sigma_N}$$



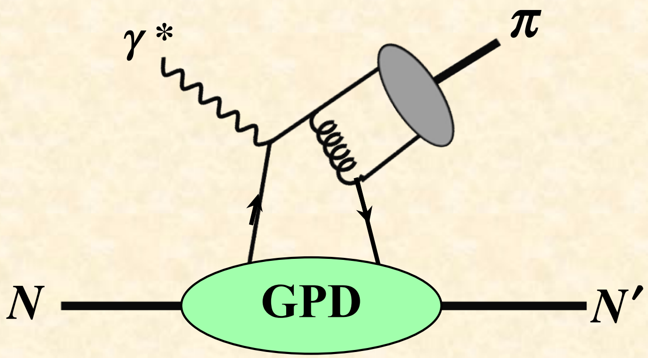
The color transparency is an important phenomena to understand the quark-hadron many-body systems from low to high energies and from low to high densities.

Possible studies on GPDs at hadron accelerator facilities

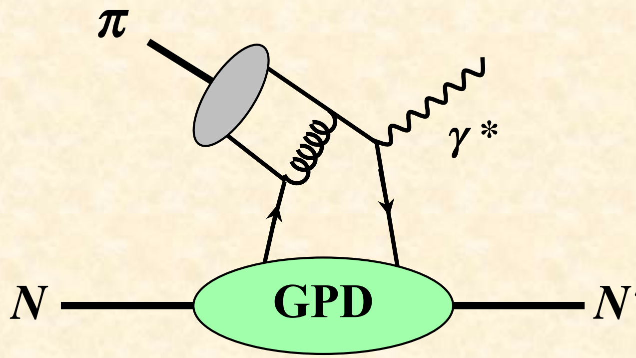
SK, M. Strikman, K. Sudoh,
PRD 80 (2009) 074003;
T. Sawada, W.-C. Chang, SK, J.-C. Peng, S. Sawada, and K. Tanaka,
PRD 93 (2016) 114034.
J-PARC LoI 2019-07, J.-K. Ahn *et al*. (2019).
J-PARC proposal under preparation,
Please get in touch with W.-C. Chang, N. Tomida
if you are interested in this project.

GPD projects at Jlab/EicC/EIC and HIAF/J-PARC

JLab / EicC / EIC

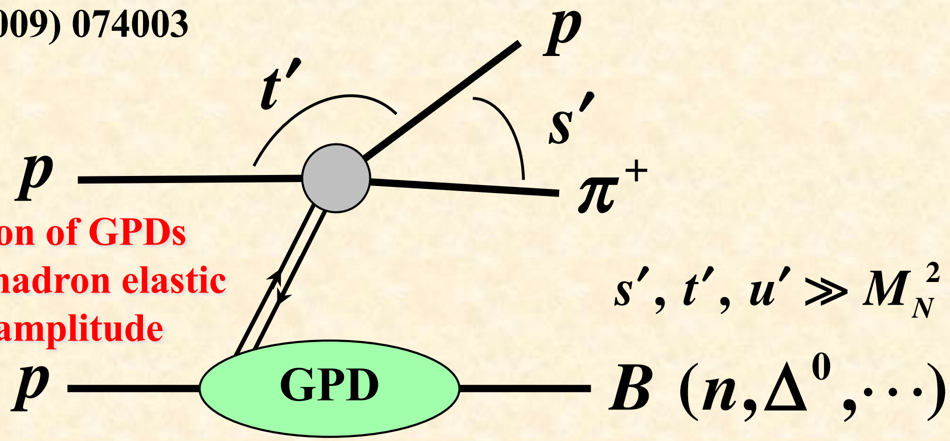


HIAF / J-PARC



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

SK, M. Strikman, K. Sudoh,
PRD 80 (2009) 074003



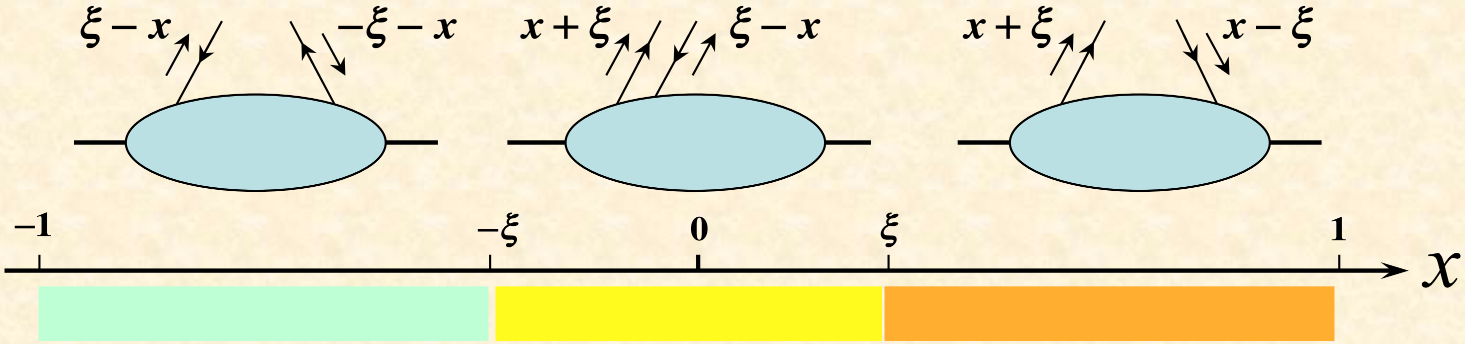
Investigation of GPDs
with 2→3 hadron elastic
scattering amplitude

$s',\ t',\ u' \gg M_N^2$

J-W. Qiu and Z. Yu,
JHEP 08 (2022) 103;
PRD 107 (2023) 014007.

$$\pi + N \to \gamma + \gamma + N'$$
$$h + M_B \to h' + \gamma + M_D$$
$$h + M_B \to h' + M_C + M_D$$

GPDs in different x regions and GPDs at hadron facilities



$-1 < x < \xi \quad (x + \xi < 0,\ x - \xi < 0)$

$\xi < x < 1 \quad (x + \xi > 0,\ x - \xi > 0)$

$-\xi < x < \xi \quad (x + \xi > 0,\ x - \xi < 0)$

Quark distribution

Emission of quark with momentum fraction x+ξ
Absorption of quark with momentum fraction x-ξ

q$\bar{\text{q}}$(meson)-like distribution amplitude

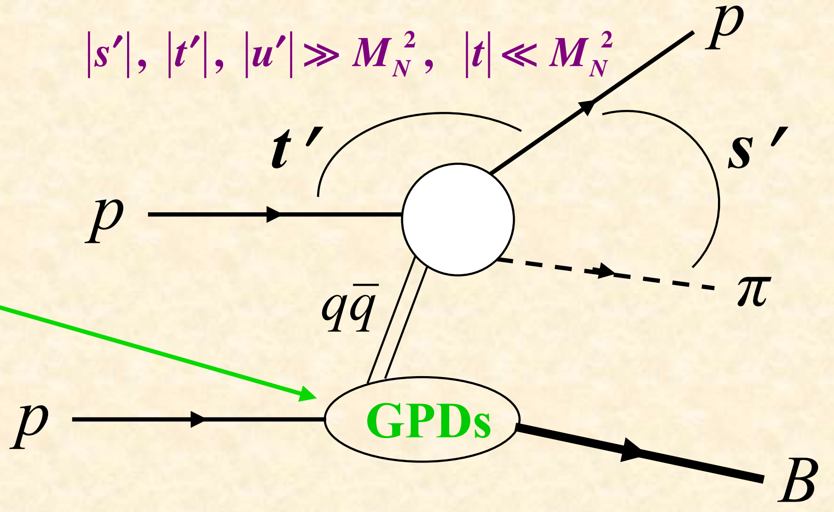
Emission of quark with momentum fraction x+ξ
Emission of antiquark with momentum fraction ξ-x

Antiquark distribution

Emission of antiquark with momentum fraction ξ-x
Absorption of antiquark with momentum fraction -ξ-x

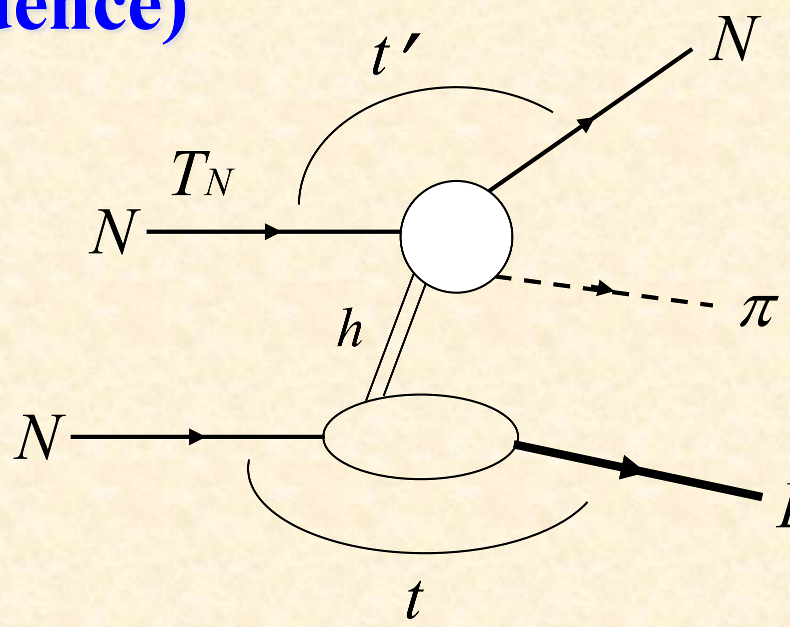
Consider a hard reaction with

$|s'|,\ |t'|,\ |u'| \gg M_N^2,\ \ |t| \ll M_N^2$



Efremov-Radyushkin -Brodsky-Lepage (ERBL) region

Cross section estimate (ξ dependence)



Skewdness parameter: $\xi = \dfrac{p_N^+ - p_B^+}{p_N^+ + p_B^+}$

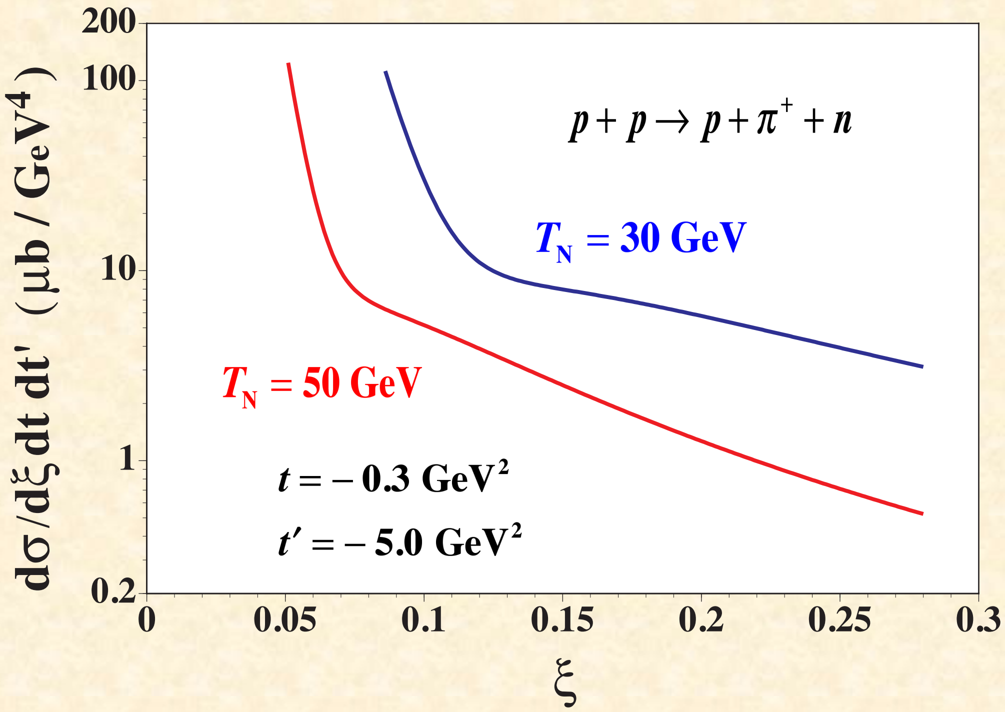
$\dfrac{d\sigma}{d\xi dt dt'} \left(\dfrac{\mu \mathrm{b}}{\mathrm{GeV}^2} \right)$ as a function of ξ

at fixed $T_N = 30\ (50)$ GeV,

$t = -0.3\ \mathrm{GeV}^2, \quad t' = -5\ \mathrm{GeV}^2.$

At this stage, our numerical results are for rough order of magnitude estimates on cross sections by assuming π- and ρ-like intermediate states.

For the details, please look at our PRD paper in 2009.



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

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

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

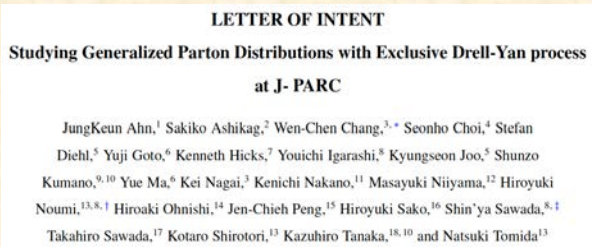
$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \left\langle p(p') \right| \bar{q}(-z/2)\gamma^+\gamma_5 q(z/2) \left| p(p) \right\rangle \Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[\tilde{H}_p^q(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}_p^q(x,\xi,t)\bar{u}(p')\frac{\gamma_5\Delta^+}{2M}u(p)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

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

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

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

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

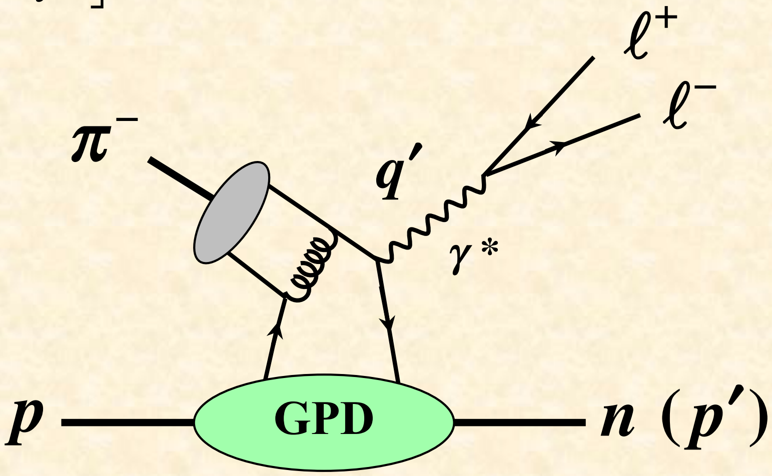


LETTER OF INTENT

Studying Generalized Parton Distributions with Exclusive Drell-Yan process at J- PARC

JungKeun Ahn,[1] Sakiko Ashikag,[2] Wen-Chen Chang,[3,*] Seonho Choi,[4] Stefan Diehl,[5] Yuji Goto,[6] Kenneth Hicks,[7] Youichi Igarashi,[8] Kyungseon Joo,[5] Shunzo Kumano,[9,10] Yue Ma,[6] Kei Nagai,[3] Kenichi Nakano,[11] Masayuki Niiyama,[12] Hiroyuki Noumi,[13,8,†] Hiroaki Ohnishi,[14] Jen-Chieh Peng,[15] Hiroyuki Sako,[16] Shin'ya Sawada,[8,‡] Takahiro Sawada,[17] Kotaro Shirotori,[13] Kazuhiro Tanaka,[18,10] and Natsuki Tomida[13]

LoI for a J-PARC experiment

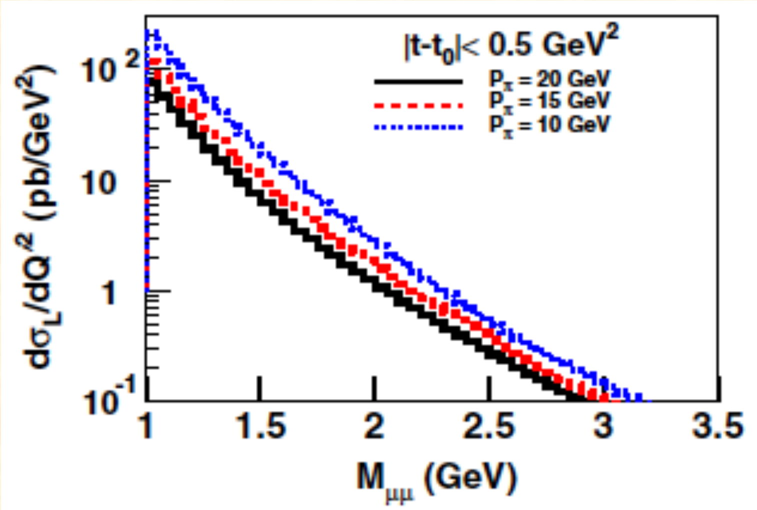


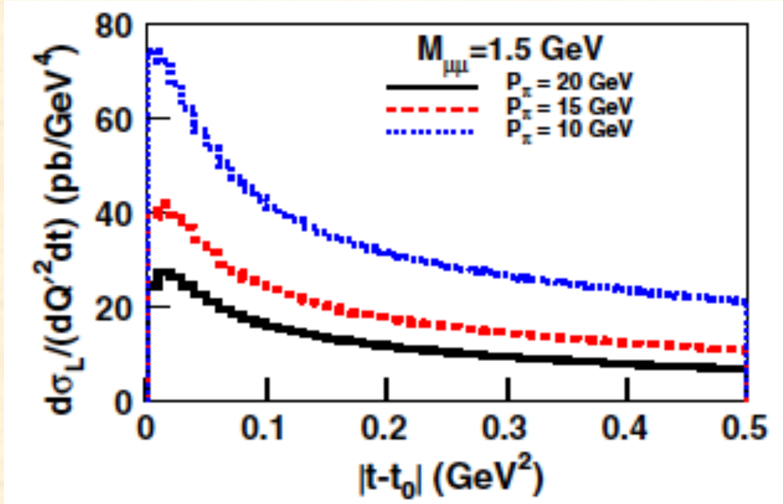
$$\pi^-(\bar{u}d) + p(uud) \to n(udd) + \gamma^*(\to \ell^+\ell^-)$$

Expected Drell-Yan events at J-PARC

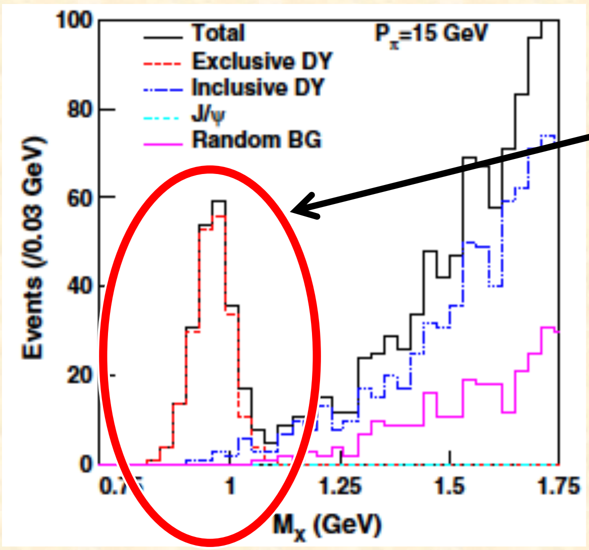
$$Q'^2 = q'^2,\ \ t = (p - p')^2,\ \ \tau = \frac{Q'^2}{2p \cdot q_\pi} \simeq \frac{Q'^2}{s - m_N^2}$$

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





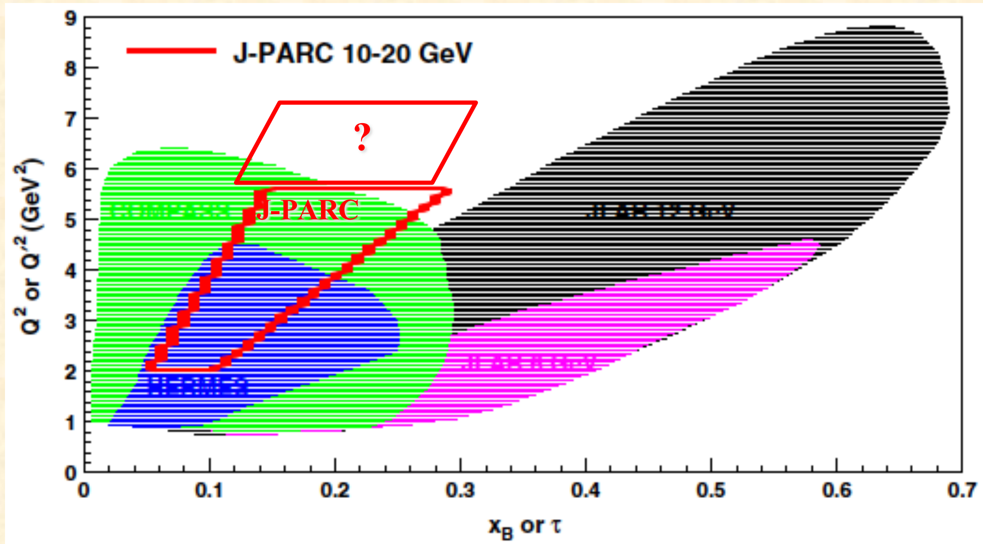
Missing mass



Exclusive
Drell-Yan

$$M_X^2 = (q + p - q')^2$$

$$q = p_\pi,\ \ p = p_p,\ \ q = p_{\mu^+\mu^-}$$



GPDs for exotic hadrons

(If transition GPDs could be studied, this exotic-hadron project becomes more realistic.)

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

Recent study on Zc(3900),
C. Han, X. Wang, W. Kou, X. Chen,
Eur. Phys. J. C 84 (2024) 1067.

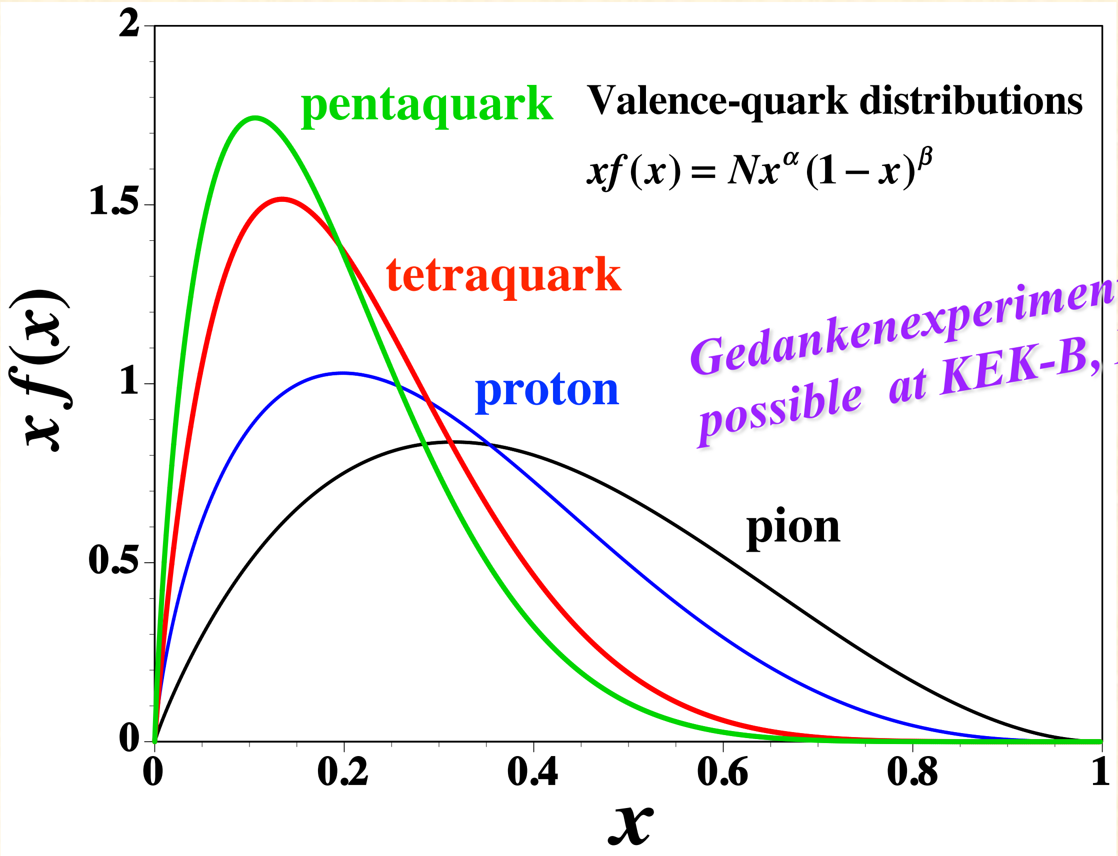
Simple function of GPDs

$$\boxed{H_q^h(x,t) = f(x)F(t,x)}$$

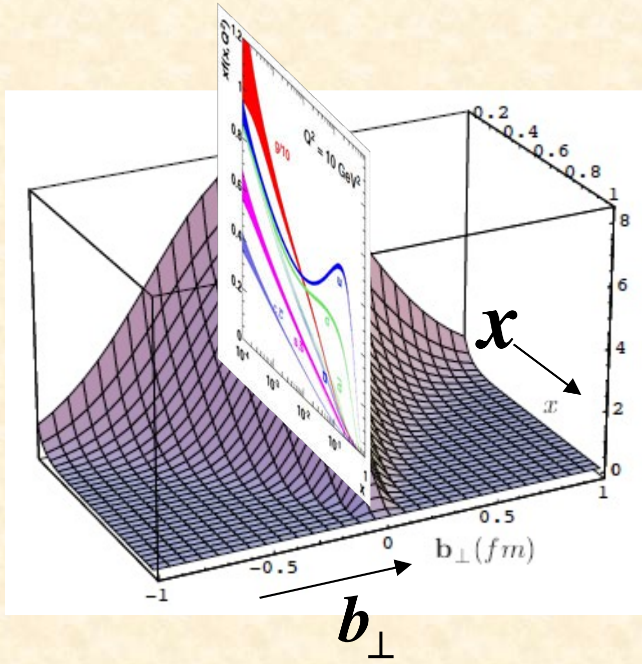
M. Guidal, M.V. Polyakov, A.V. Radyushkin, M. Vanderhaeghen, PRD 72, 054013 (2005).

Longitudinal-momentum distribution (PDF) for valence quarks: $f(x) = q_v(x) = c_n x^{\alpha_n}(1-x)^{\beta_n}$

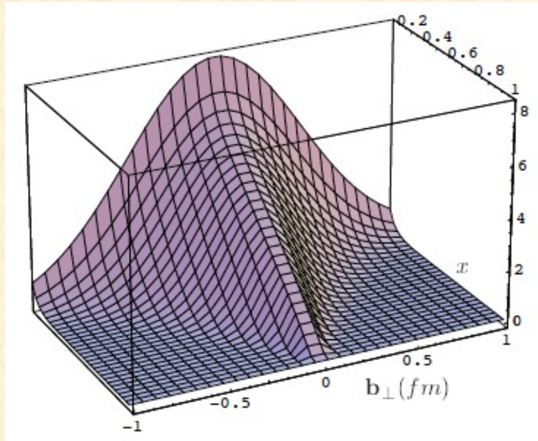
- Valence-quark number sum rule (charge and baryon numbers): $\int_0^1 dx f(x) = n$
- Constituent conting rule at $x \to 1$: $\beta_n = 2n - 3 + 2\Delta S$ (n = number of constituents)
- Momentum carried by quarks $\langle x \rangle_q \simeq \int_0^1 dx\, x f(x)$



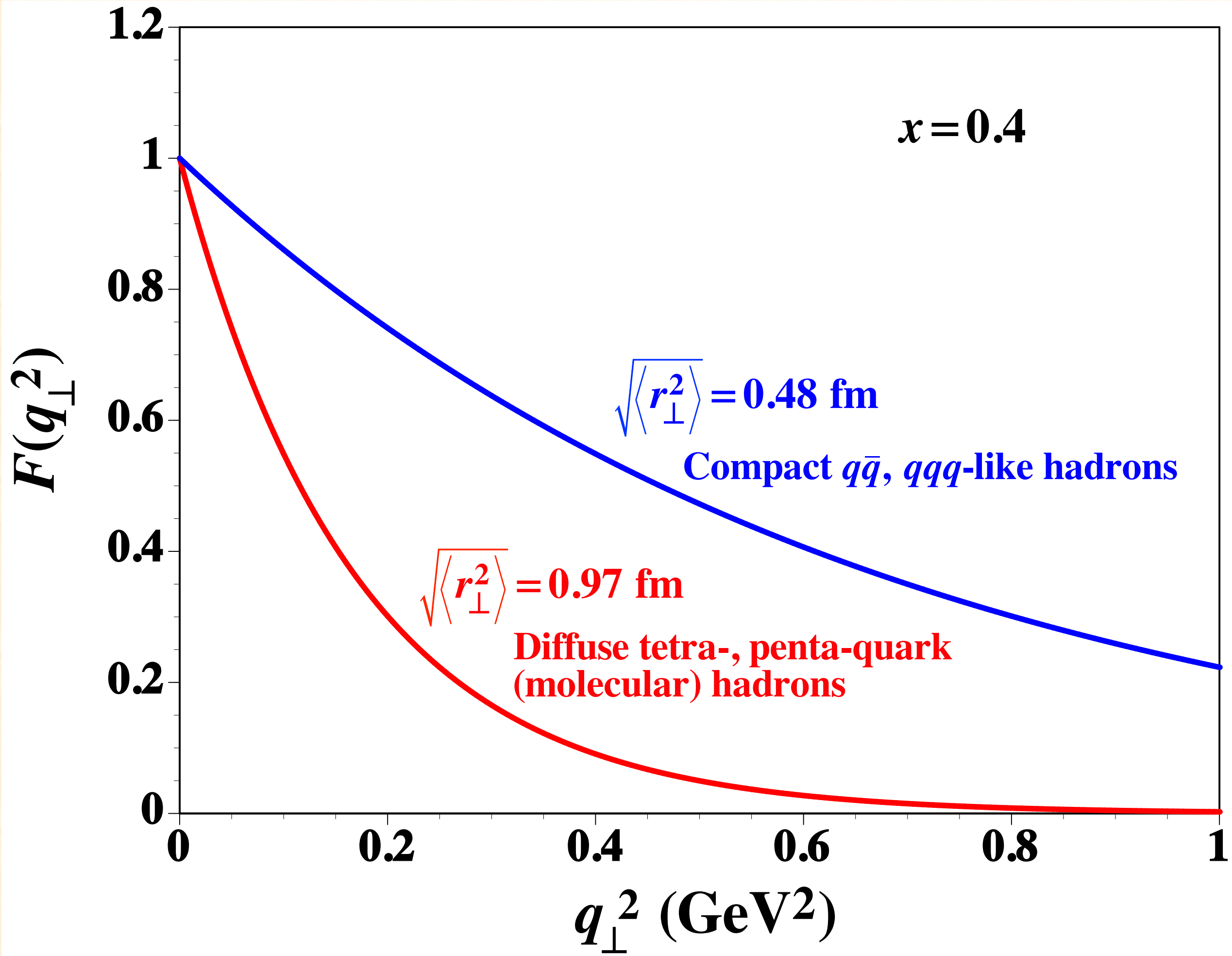
Gedankenexperiment, but possible at KEK-B, ILC, ...



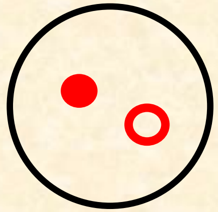
Two-dimensional transverse form factor



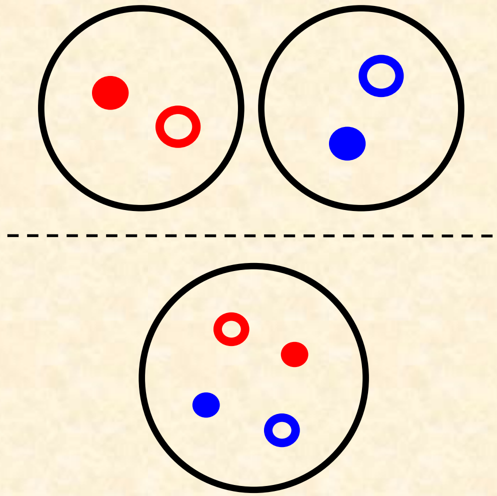
$$\boxed{F(t,x) = e^{(1-x)t/(x\Lambda^2)}, \quad \langle r_\perp^2 \rangle = \frac{4(1-x)}{x\Lambda^2}}$$



Ordinaly $q\bar{q}$



Molecule $K\bar{K}$
or tetra-quark $qq\bar{q}\bar{q}$



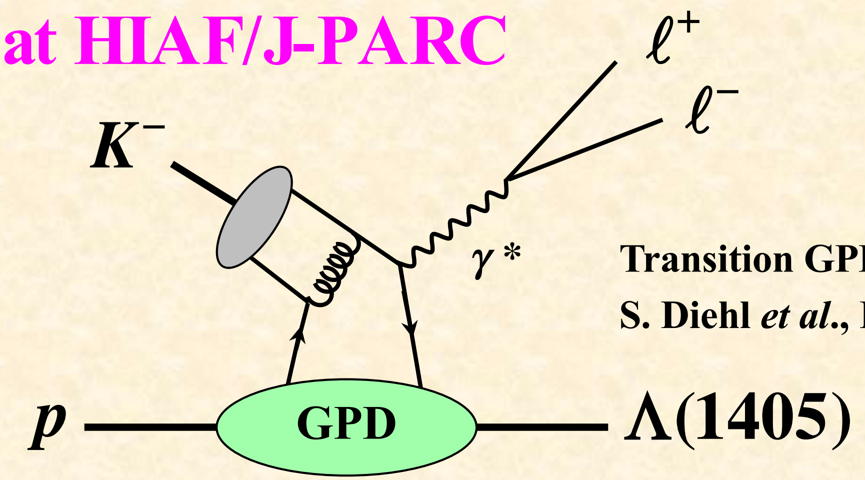
GPDs for exotic hadrons !?

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

$\rightarrow$ Transition GPDs

or $\rightarrow$ $s \leftrightarrow t$ crossed qunatity = GDAs at BES/Tau-charm/KEKB,
Circular/Linear Collider

e.g. at HIAF/J-PARC

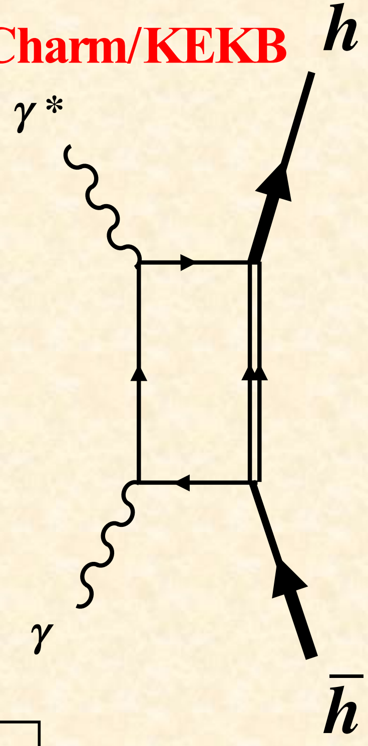


$K^-(\bar{u}s) + p(uud) \rightarrow \Lambda_{1405}(uud\bar{u}s) + \gamma^*$

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

Transition GPDs:
S. Diehl *et al.*, Euro. Phys. J. A 61 (2025) 131.

e.g. BES/Tau-Charm/KEKB



See 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.

Possible GPD studies at neutrino facilities

X. Chen, SK, R. Kunitomo, S. Wu, Y.-P. Xie,

Euro. Phys. J. A 60 (2024) 208.

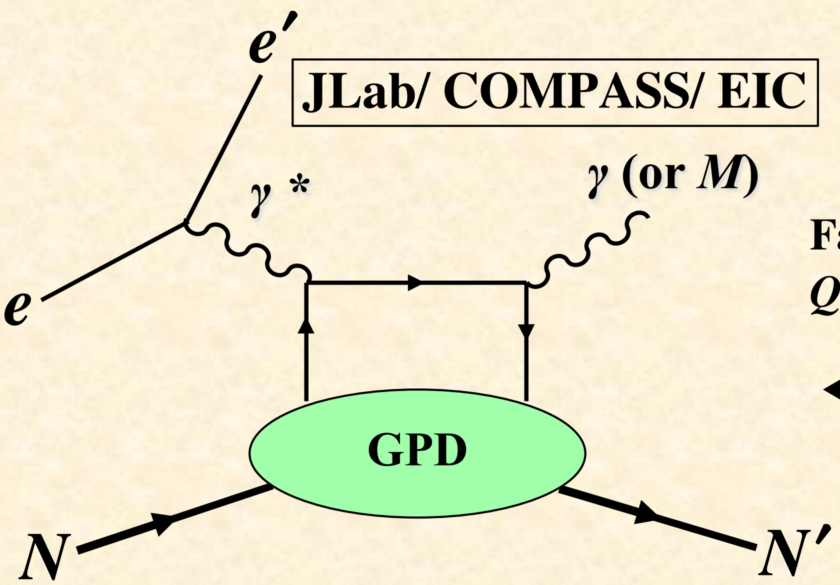
See also

SK, EPJ Web Conf. 208 (2019) 07003.

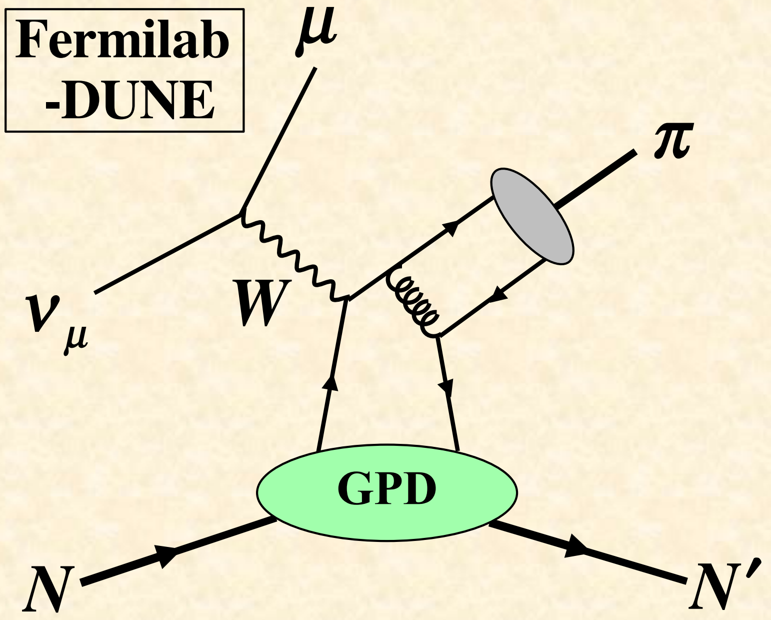
EIC yellow report, R. Abdul Khalek *et al*., arXiv:2103.05419, Sec. 7.5.2, Neutrino physics by SK and R. Petti.

SK and R. Petti, PoS (NuFact2021) 092.

Neutrino reactions for gravitational form factors @Fermilab-DUNE (Origins of hadron masses and pressures)

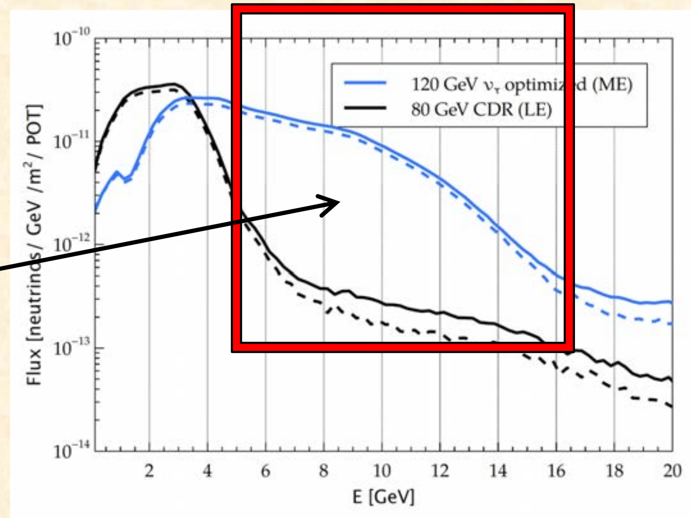


Factorization condition:
$Q^2 \gg |t|, \Lambda^2_{QCD}$



Deep Underground Neutrino Experiment (DUNE) at Long-Baseline Neutrino Facility (LBNF)

High-energy part of the LBNF ν beam can be used for the GPD studies.



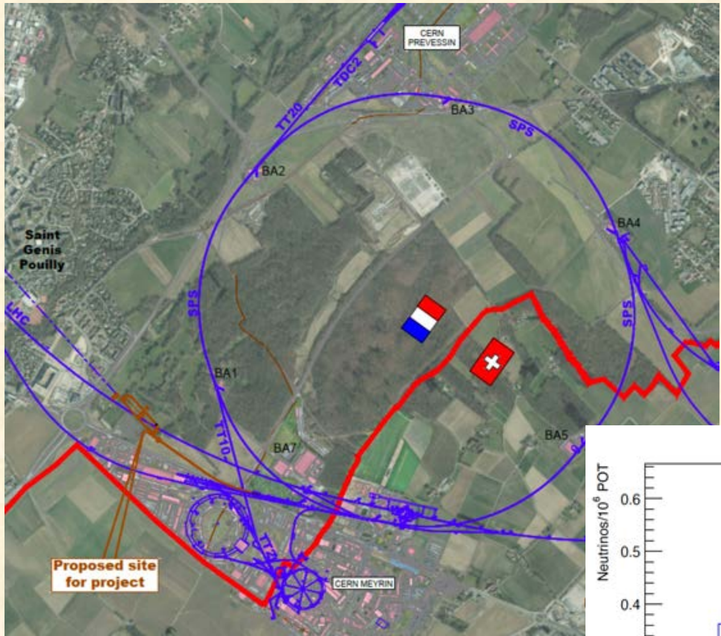
J. Rout *et al*., PRD 102 (2020) 116018

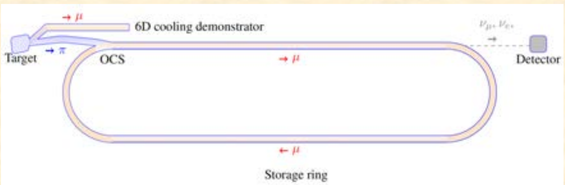
nuSTORM (Neutrinos from Stored Muons)

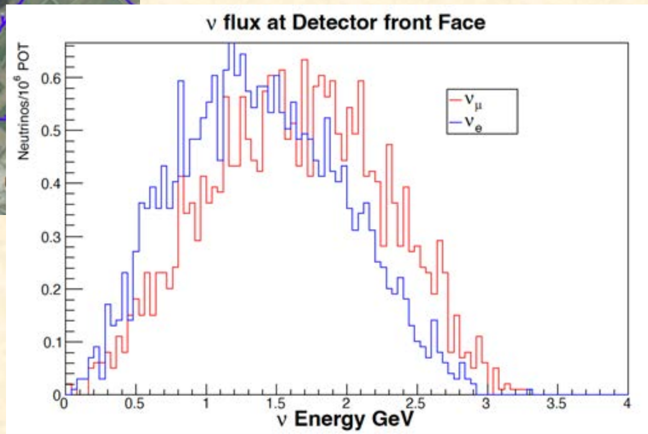
Fermilab

Feasibility Study, C. C. Ahdida *et al.*, (2020);
L. A. Ruso *et al.*, arXiv:2203.07545.

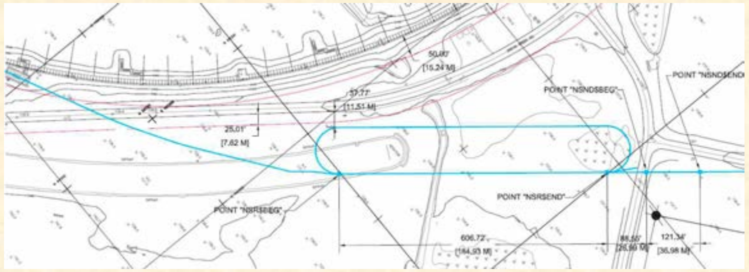
CERN

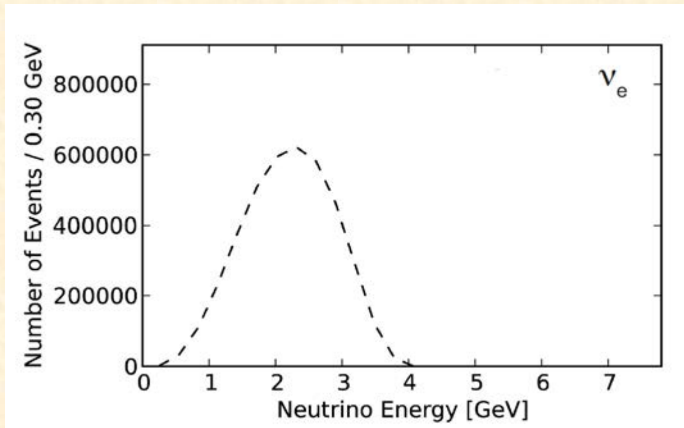






Letter of Intent, arXiv:1206.0294,
P. Kyberd *et al*. (2012);
Proposal, D. Adey *et al.*, arXiv:1308.6822.
No recent update.

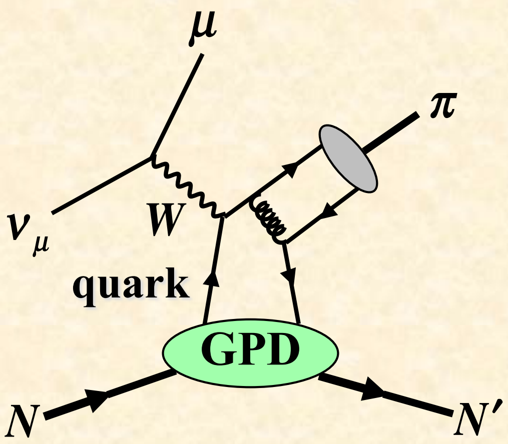




At this stage, the considered beam energy
is not high enough for structure-function studies;
however, high-energy option could be possible.
(personal communications: Xianguo Lu)
→ SK’s talk at the nuSTORM-collaboration meeting
on July 15, 2024
They could be interested in the higher-energy possibility.

Cross section formalism

B. Pire, L. Szymanowski, J. Wagner,
Phys. Rev. D 95, 114029 (2017).

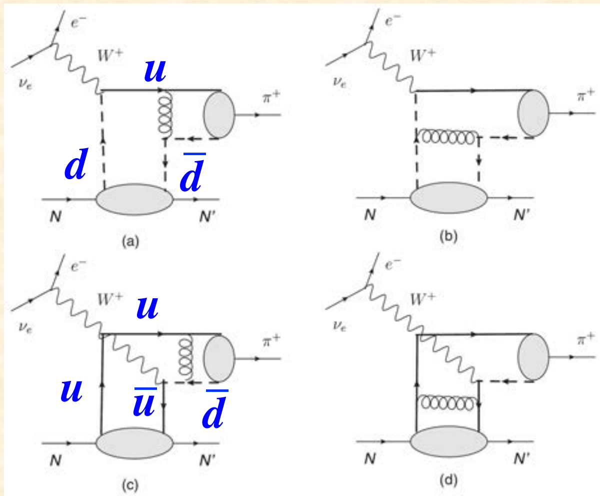


Cross section

$$\frac{d\sigma(\nu_\ell N \to \ell^- N'\pi)}{dy\, dQ^2\, dt\, d\phi} = \Gamma\,\varepsilon\,\sigma_L, \quad \varepsilon \simeq \frac{1-y}{1-y+y^2/2}, \quad \Gamma = \frac{G_F^2\, Q^2}{32\,(2\pi)^4\,(s-m_N^2)^2\, y\,(1-\varepsilon)\sqrt{1+4x^2 m_N^2/Q^2}}$$

$$\sigma_L = \varepsilon_L^{*\mu} W_{\mu\nu} \varepsilon_L^{\nu} = \frac{1}{Q^2}\Bigg[(1-\xi^2)\left\{\left|C_q\mathcal{H}_q + C_g\mathcal{H}_g\right|^2 + \left|C_q\tilde{\mathcal{H}}_q\right|^2\right\} + \frac{\xi^4}{1-\xi^2}\left\{\left|C_q\mathcal{E}_q + C_g\mathcal{E}_g\right|^2 + \left|C_q\tilde{\mathcal{E}}_q\right|^2\right\}$$
$$-2\xi^2\,\mathrm{Re}\left\{(C_q\mathcal{H}_q + C_g\mathcal{H}_g)(C_q\mathcal{E}_q + C_g\mathcal{E}_g)^*\right\} - 2\xi^2\,\mathrm{Re}\left\{C_q\tilde{\mathcal{H}}_q(C_q\tilde{\mathcal{E}}_q)^*\right\}\Bigg]$$

Quark contributions



$$T_q = -i\,\frac{C_q}{2Q}\,N(p')\left[\mathcal{H}_q\hat{n} + \mathcal{E}_q\,\frac{i\sigma^{\mu\nu}n_\mu\Delta_\nu}{2m_N} - \tilde{\mathcal{H}}_q\hat{n}\gamma_5 - \tilde{\mathcal{E}}_q\,\frac{\gamma_5 n\cdot\Delta}{2m_N}\right]N(p)$$

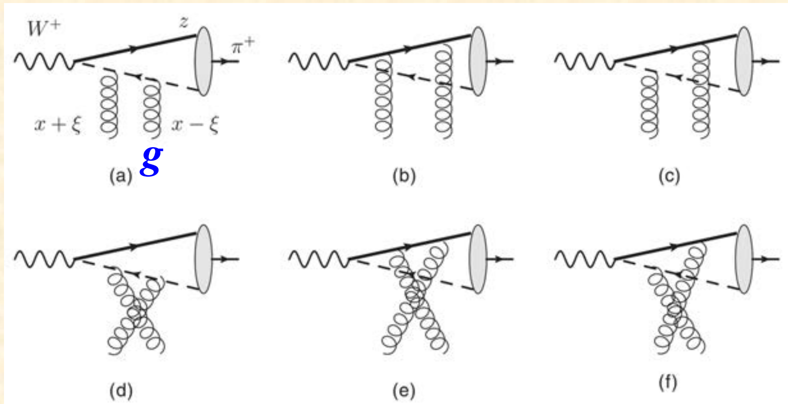
$$\mathcal{F}_q = 2f_\pi\int\frac{dz\;\phi_\pi(z)}{1-z}\int dx\,\frac{F_q(x,\xi,t)}{x-\xi+i\varepsilon}$$

$$= (\text{pion distribution amplitude})\cdot(\text{quark GPD})$$

$$F_q(x,\xi,t) \equiv F_d(x,\xi,t) - F_u(-x,\xi,t)$$

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

Gluon contributions



$$T_g = -i\,\frac{C_g}{2Q}\,N(p')\left[\mathcal{H}^g\hat{n} + \mathcal{E}^g\,\frac{i\sigma^{\mu\nu}n_\mu\Delta_\nu}{2m_N}\right]N(p)$$

$$\mathcal{F}_g = \frac{8f_\pi}{\xi}\int\frac{dz\;\phi_\pi(z)}{z(1-z)}\int dx\,\frac{F_g(x,\xi,t)}{x-\xi+i\varepsilon}$$

Cross sections

π^+ production: $\nu p \to \ell^- \pi^+ p$

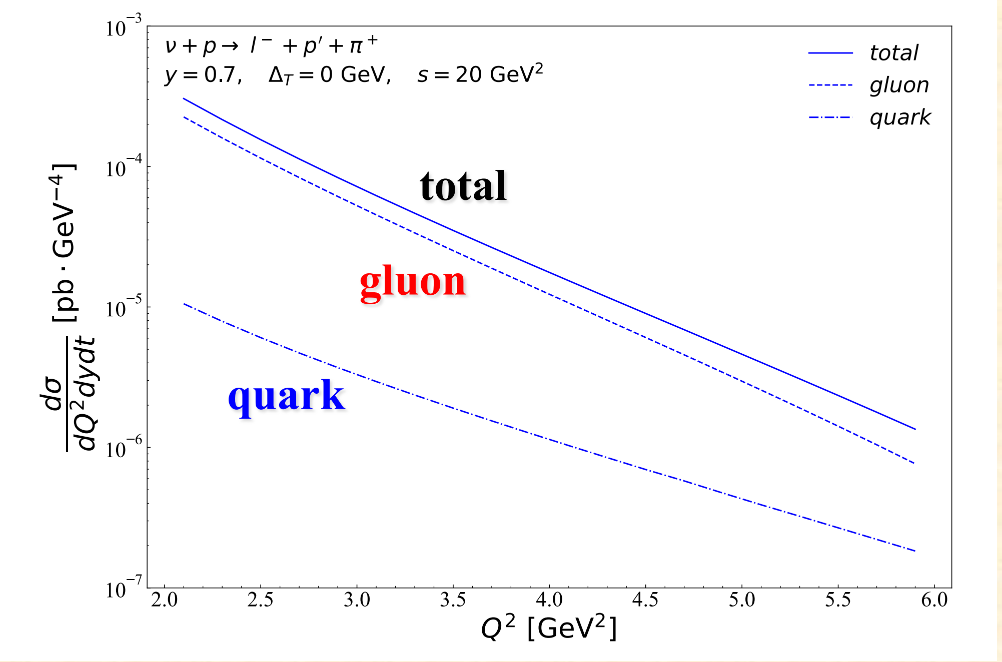
$$\mathcal{F}_q = 2 f_\pi \int \frac{dz\, \phi_\pi(z)}{1-z} \int dx \frac{F_q(x,\xi,t)}{x-\xi+i\varepsilon}$$

$$\mathcal{F}_g = \frac{8 f_\pi}{\xi} \int \frac{dz\, \phi_\pi(z)}{z(1-z)} \int dx \frac{F_g(x,\xi,t)}{x-\xi+i\varepsilon}$$

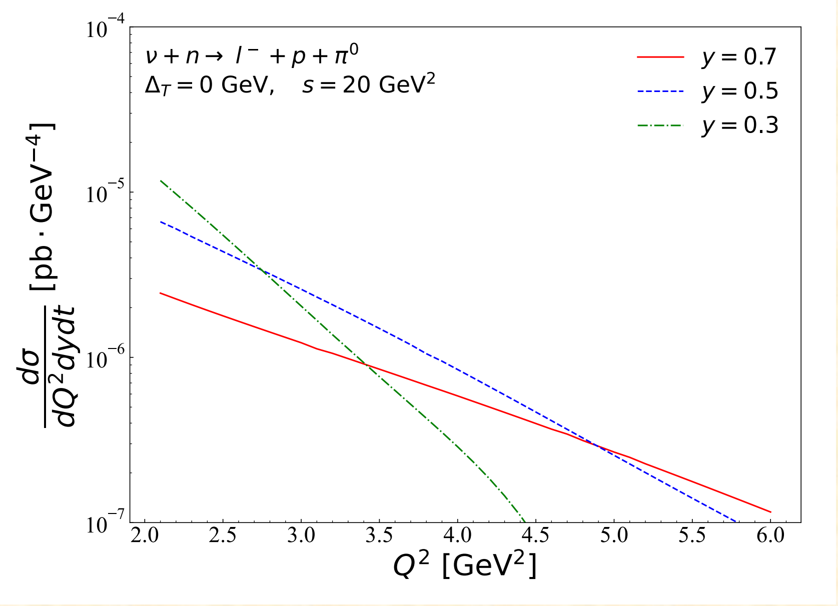
$$\frac{\mathcal{F}_q}{\mathcal{F}_g} \sim \frac{\xi}{8} = \frac{0.1 \sim 0.3}{8} = 0.01 \sim 0.04$$

$$= \text{a few } \% \ll 1$$

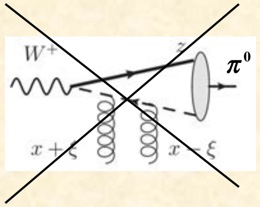
gluon $\gg$ quark



π^0 production: $\nu n \to \ell^- \pi^0 p$



no gluon



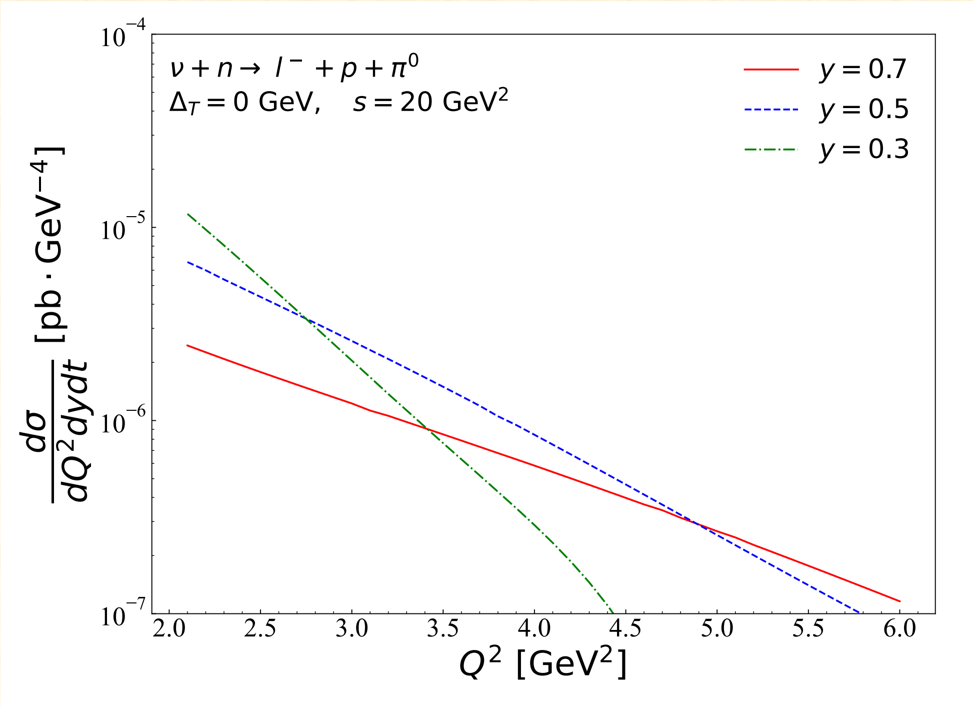
no gluon for π^0

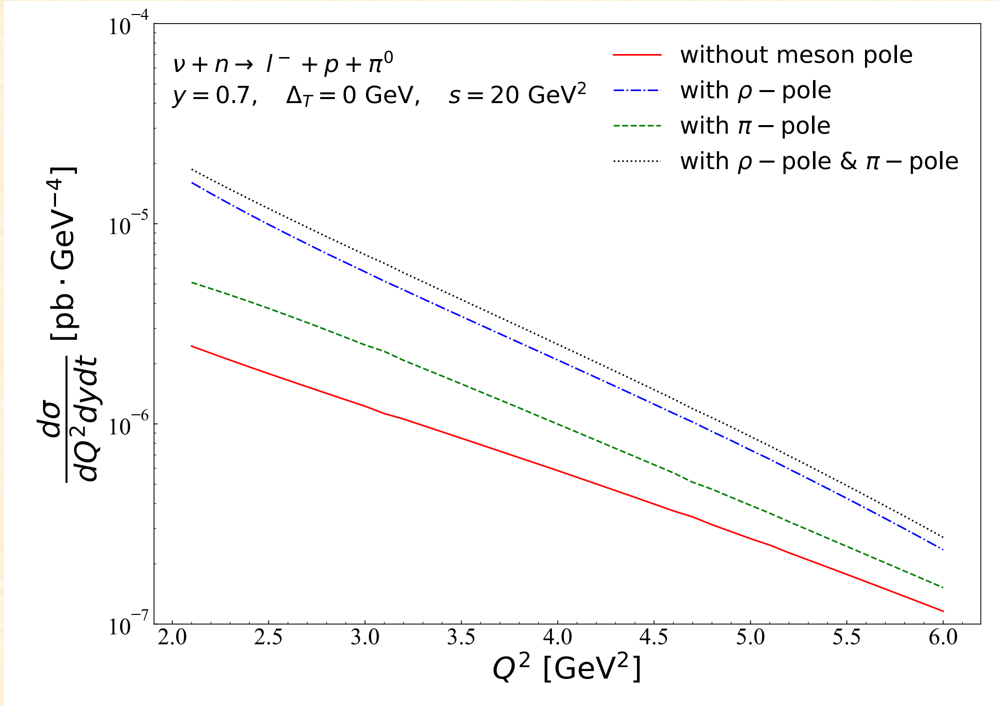
Neutrino GPD studies are complementary to the charged-lepton projects.

- **Gluon GPDs could be probed in charged-pion production.**
- **Quark GPDs could be probed in π^0 production.**
- **Flavor dependece of quark GPDs could be investigated.**

Contribution of each term to the π^0-production cross section

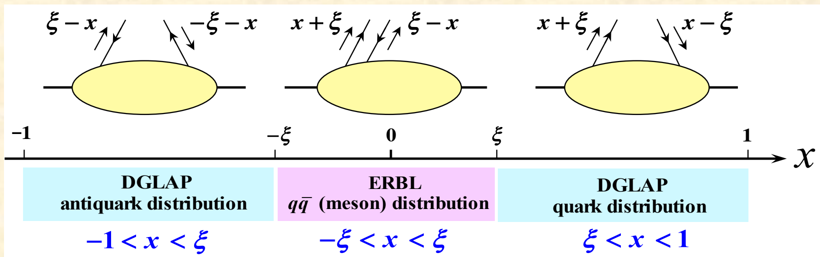
$$\frac{d\sigma(\nu_\ell N \to \ell^- N'\pi)}{dy\, dQ^2\, dt\, d\phi} \propto \frac{1}{Q^2}\Bigg[(1-\xi^2)\left\{\left|C_q\mathcal{H}_q + \cancel{C_g\mathcal{H}_g}\right|^2 + \left|C_q\tilde{\mathcal{H}}_q\right|^2\right\} + \frac{\xi^4}{1-\xi^2}\left\{\left|C_q\mathcal{E}_q + \cancel{C_g\mathcal{E}_g}\right|^2 + \left|C_q\tilde{\mathcal{E}}_q\right|^2\right\}$$
$$-2\xi^2\,\mathrm{Re}\left\{(C_q\mathcal{H}_q + \cancel{C_g\mathcal{H}_g})(C_q\mathcal{E}_q + \cancel{C_g\mathcal{E}_g})^*\right\} - 2\xi^2\,\mathrm{Re}\left\{C_q\tilde{\mathcal{H}}_q(C_q\mathcal{E}_q)^*\right\}\Bigg]$$





$$\cancel{H_g} > H_q > \tilde{H}_q > E_q,\ \tilde{E}_q,\ \cancel{E_g}$$

- π^0 production is senstive to quark $\mathcal{H}_q$.
- GPDs in the ERBL (Efremov-Radyushkin-Brodsky-Lepage) region could be probed.



Constituent-counting rule
for exotic hadrons

H. Kawamura, SK, T. Sekihara, PRD 88 (2013) 034010;
W.-C. Chang, SK, T. Sekihara, PRD 93 (2016) 034006.

Research purposes

It is not easy to find undoubted evidence for exotic hadrons by global observables (mass, spin, parity, decay width) at low energies.

(1) Determination of internal structure of exotic hadrons by high energy processes, where quark-gluon degrees of freedom appear.

Constituent-counting rule could be used because it counts internal constituents.

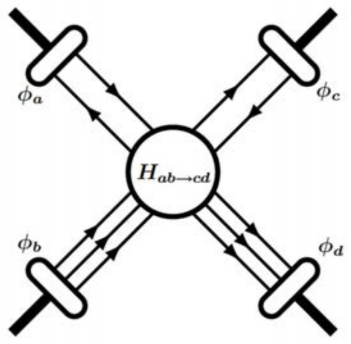
(2) Investigation on transition from hadron degrees of freedom to quark-gluon degrees of freedom for exotic hadrons.

$$\frac{d\sigma_{a+b\to c+d}}{dt} \simeq \frac{1}{16\pi s^2}\overline{\sum_{pol}}\left|M_{a+b\to c+d}\right|^2 \;\Rightarrow\; \frac{d\sigma_{a+b\to c+d}}{dt} = \frac{1}{s^{n-2}} f_{a+b\to c+d}(t/s)$$

consituent-counting rule

$$n = n_a + n_b + n_c + n_d$$

Constituent-counting rule in perturbative QCD: Hard exclusive processes $a+b \to c+d$



Consider the hard exclusive hadron reaction $a+b \to c+d$

$$M_{ab\to cd} = \int d[x_a]d[x_b]d[x_c]d[x_d]\phi_c([x_c])\phi_d([x_d])H_M([x_a],[x_b],[x_c],[x_d],Q^2)\phi_a([x_a])\phi_b([x_b])$$

ϕ_p = proton distribution amplitude, H_M = hard amplitude (calculated in pQCD)

Rule for estimating $M_{ab\to cd}$

(1) Feynman diagram: Draw leading and connected Feynman diagram by connecting $n/2$ quark lines by gluons.

(2) Gluon propagators: The factor $1/P^2$ is assigned for each gluon propagator.

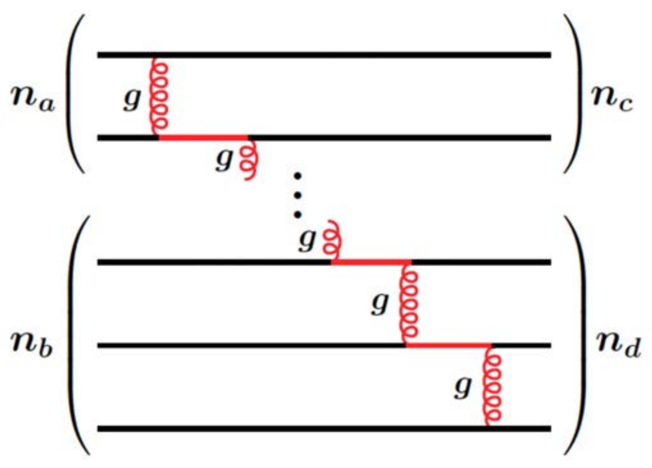
There are $n/2-1$ gluon propagators $\sim 1/(P^2)^{n/2-1}$.

(3) Quark propagators: The factor $1/P$ is assigned for each quark propagator.

There are $n/2-2$ gluon propagators $\sim 1/(P)^{n/2-2}$.

(4) External quarks: The factor $\sqrt{P}$ is assigned for each external quark.

There are n gluon propagators $\sim (\sqrt{P})^n$.



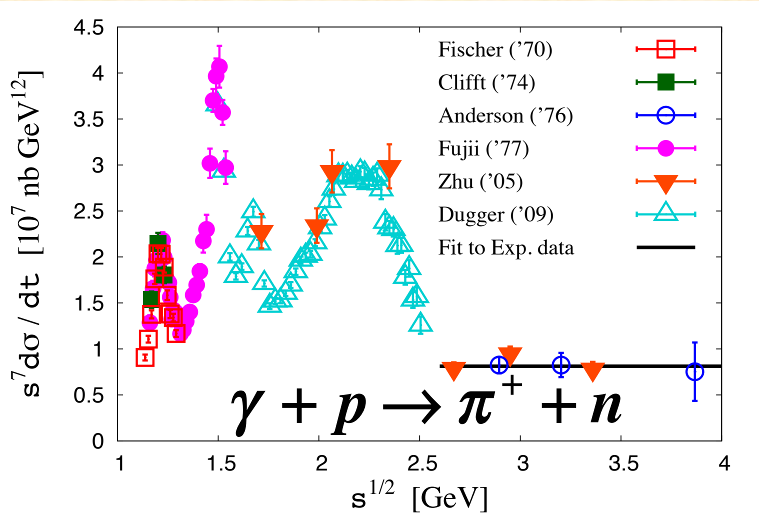
$$M_{ab\to cd} \sim \frac{1}{(P^2)^{n/2-1}}\frac{1}{(P)^{n/2-2}}(\sqrt{P})^n = \frac{(P)^{n/2}}{(P)^{n-2}(P)^{n/2-2}} = \frac{1}{(P)^{n-4}} \sim \frac{1}{s^{n/2-2}}$$

Cross section: $$\frac{d\sigma_{ab\to cd}}{dt} \simeq \frac{1}{16\pi^2}\overline{\sum_{spol}}|M_{ab\to cd}|^2 \sim \frac{1}{s^{n-2}}$$

Constituent-counting rule, Transition from hadron degrees of freedom to quark-gluon ones

Typical current situation

- Transition from hadron d.o.f to quark d.o.f.
- (Looks like) Constituent-counting scaling



JLab: L.Y. Zhu *et al.*, PRL 91, 022003 (2003);
PRC 71, 044603 (2005);
W. Chen *et al.*, PRL 103, 012301 (2009).

see R. A. Schumacher and M. M. Sargsian,
PRC 83 (2011) 025207 for hyperon production

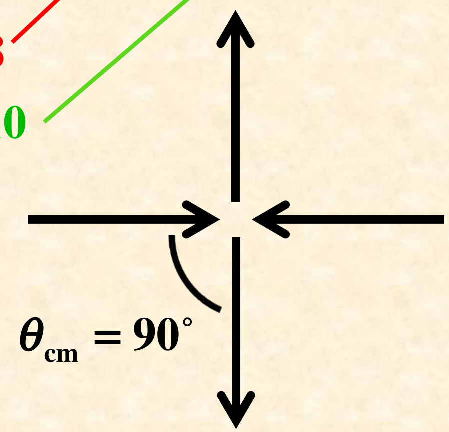
BNL experiment

C. White it et al., PRD 49 (1994) 58.

No.	Interaction	Cross section E838	Cross section E755	n-2 ($\frac{d\sigma}{dt} \sim 1/s^{n-2}$)
1	$\pi^+ p \to p\pi^+$	132 ± 10	4.6 ± 0.3	6.7 ± 0.2
2	$\pi^- p \to p\pi^-$	73 ± 5	1.7 ± 0.2	7.5 ± 0.3
3	$K^+ p \to pK^+$	219 ± 30	3.4 ± 1.4	$8.3^{+0.6}_{-1.0}$
4	$K^- p \to pK^-$	18 ± 6	0.9 ± 0.9	≥ 3.9
5	$\pi^+ p \to p\rho^+$	214 ± 30	3.4 ± 0.7	8.3 ± 0.5
6	$\pi^- p \to p\rho^-$	99 ± 13	1.3 ± 0.6	8.7 ± 1.0
13	$\pi^+ p \to \pi^+ \Delta^+$	45 ± 10	2.0 ± 0.6	6.2 ± 0.8
15	$\pi^- p \to \pi^+ \Delta^-$	24 ± 5	≤ 0.12	≥ 10.1
17	$pp \to pp$	3300 ± 40	48 ± 5	9.1 ± 0.2
18	$\bar{p}p \to p\bar{p}$	75 ± 8	≤ 2.1	≥ 7.5

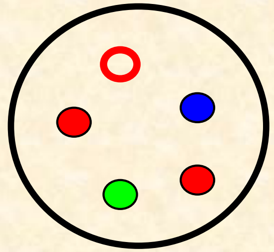
$n-2$: $(2+3+2+3)-2 = 8$

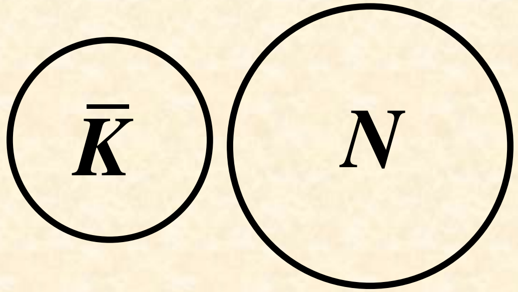
$(3+3+3+3)-2 = 10$

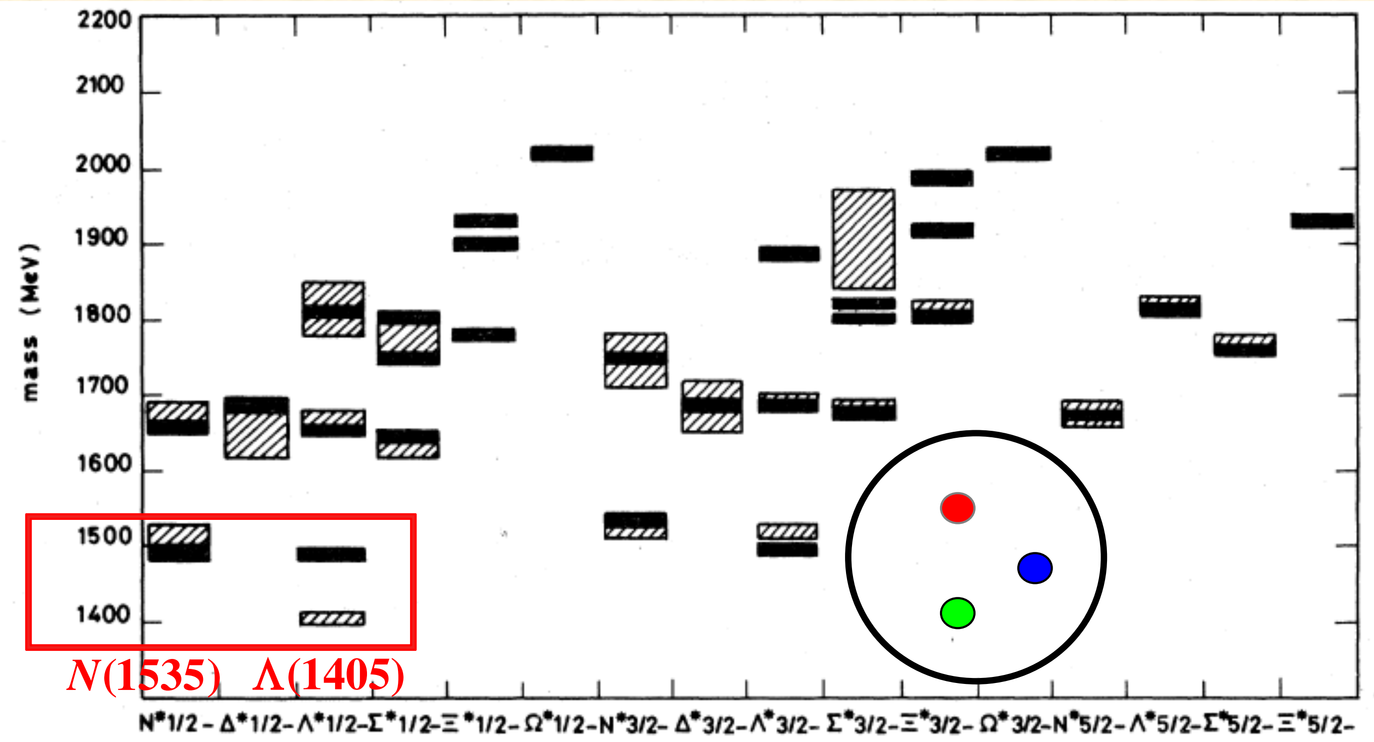


$\Lambda(1405)$: exotic hadron?

Negative-parity baryons
N. Isgur and G. Karl,
PRD 18 (1978) 4187.







Our proposal:

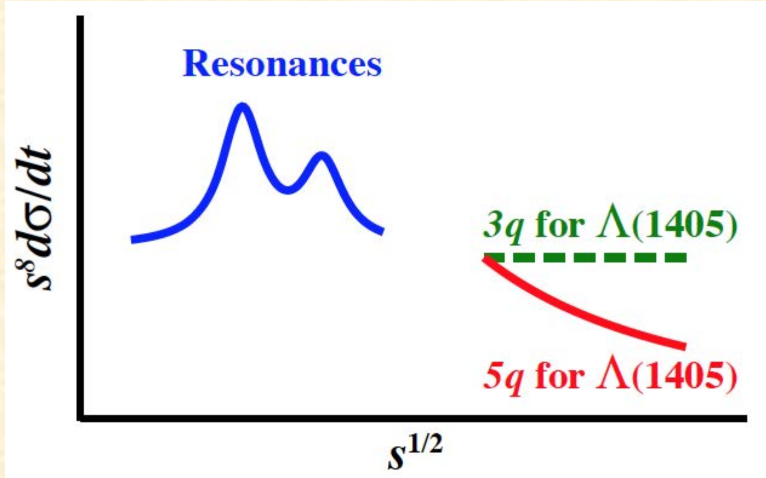
Exotic hadron production

$\pi^- + p \rightarrow K^0 + \Lambda(1405)$: J-PARC, COMPASS?

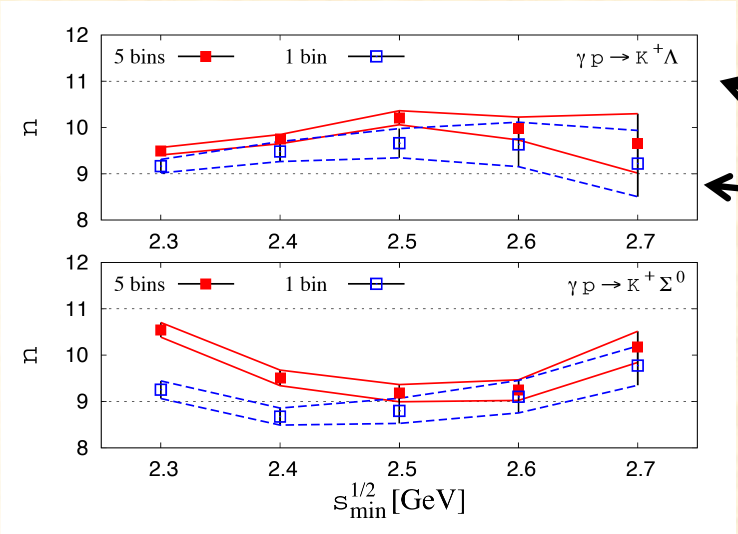
$\gamma + p \rightarrow K^+ + \Lambda(1405)$: JLab

Most spectra agree with the ones by a 3q-picture

- Only $\Lambda(1405)$ deviates from the measurement.
- Difficult to understand the small mass of $\Lambda(1405)$ in comparison with $N(1535)$.
  → $\bar{K}N$ molecure or penta-quark ($qqqq\bar{q}$)?

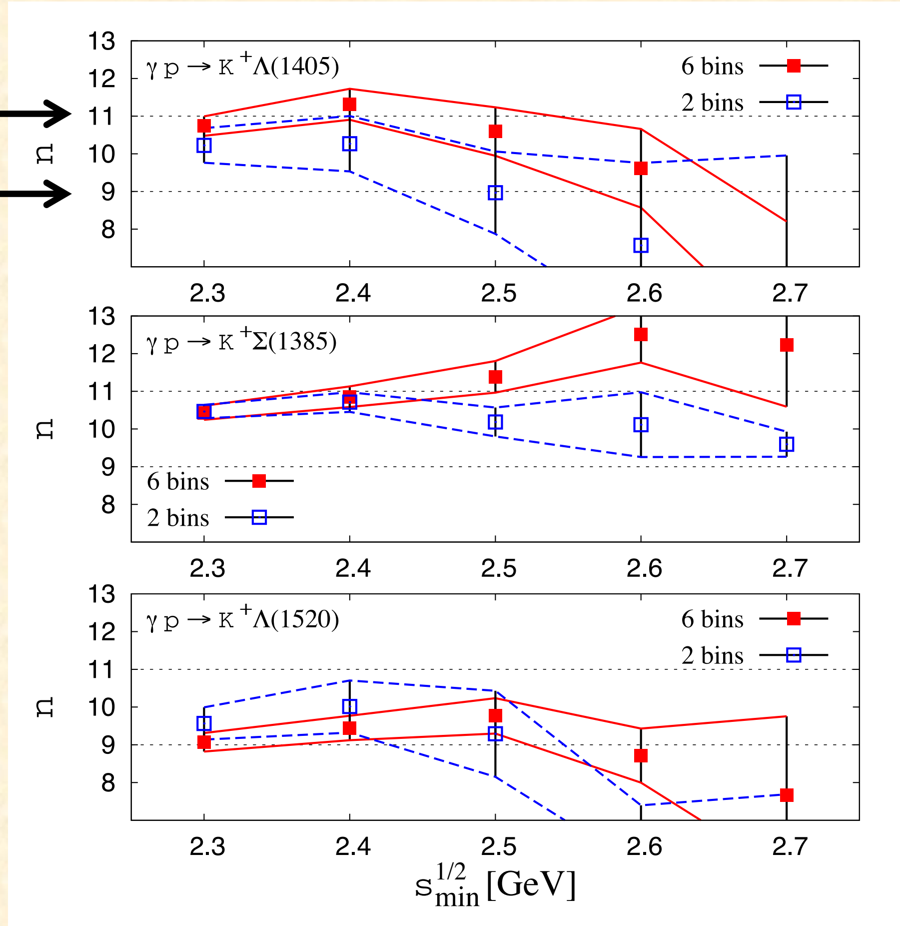


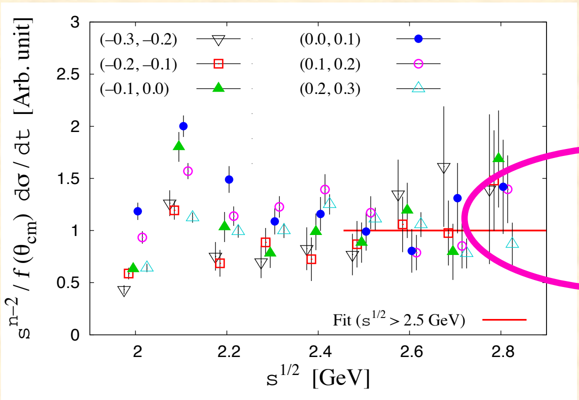
JLab hyperon productions including Λ(1405)



$n_\Lambda = 5$

$n_\Lambda = 3$





Range of
12 GeV JLab!

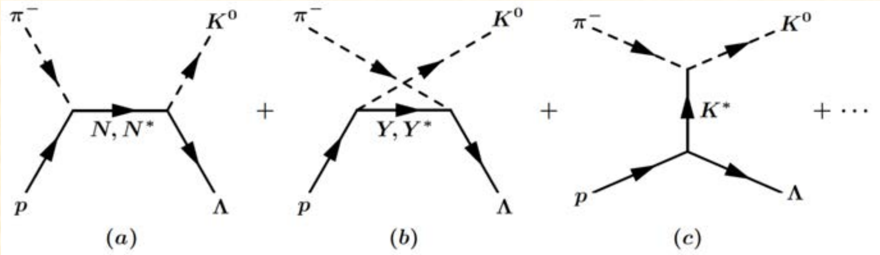
- Λ, Λ(1520), and Σ seem to be consistent with ordinary baryons with $n = 3$.
- Λ(1405) looks penta-quark at low energies but $n \sim 3$ at high energies???
- Σ(1385) : $n = 5$???

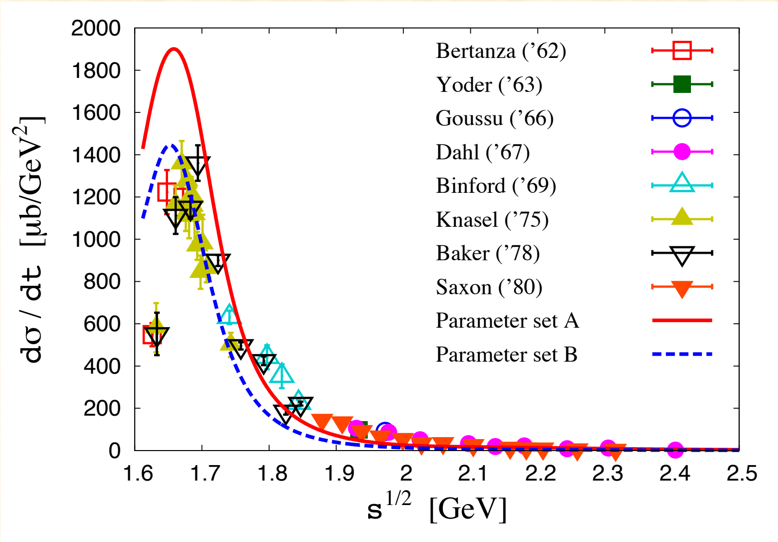
→ In order to clarify the nature of Λ(1405) $\left[qqq,\ \bar{K}N,\ qqqq\bar{q}\right]$, the JLab 12-GeV experiment plays an important role!

W.-C. Chang, SK, T. Sekihara, PRD 93 (2016) 034006.

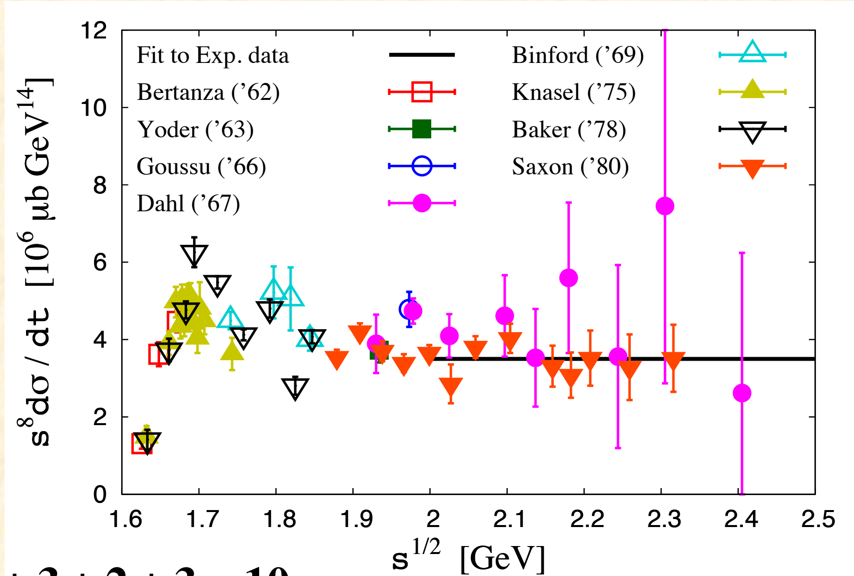
Ordinary-hadron production $\pi^- + p \to K^0 + \Lambda$ as a reference

At low energies





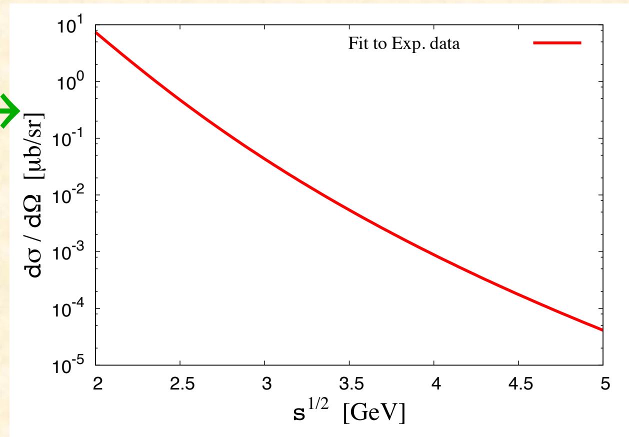
From low to higher energies



$$n = 2 + 3 + 2 + 3 = 10$$

$$\frac{d\sigma_{ab\to cd}}{dt} = \frac{\text{const}}{s^{n-2}}, \quad n = 10.1 \pm 0.6, \text{ encouraging!}$$

Our prediction at high energies →



Exotic-hadron production $\pi^- + p \to K^0 + \Lambda(1405)$

Theoretical and experimental situation is no as good as the one for the ground Λ.

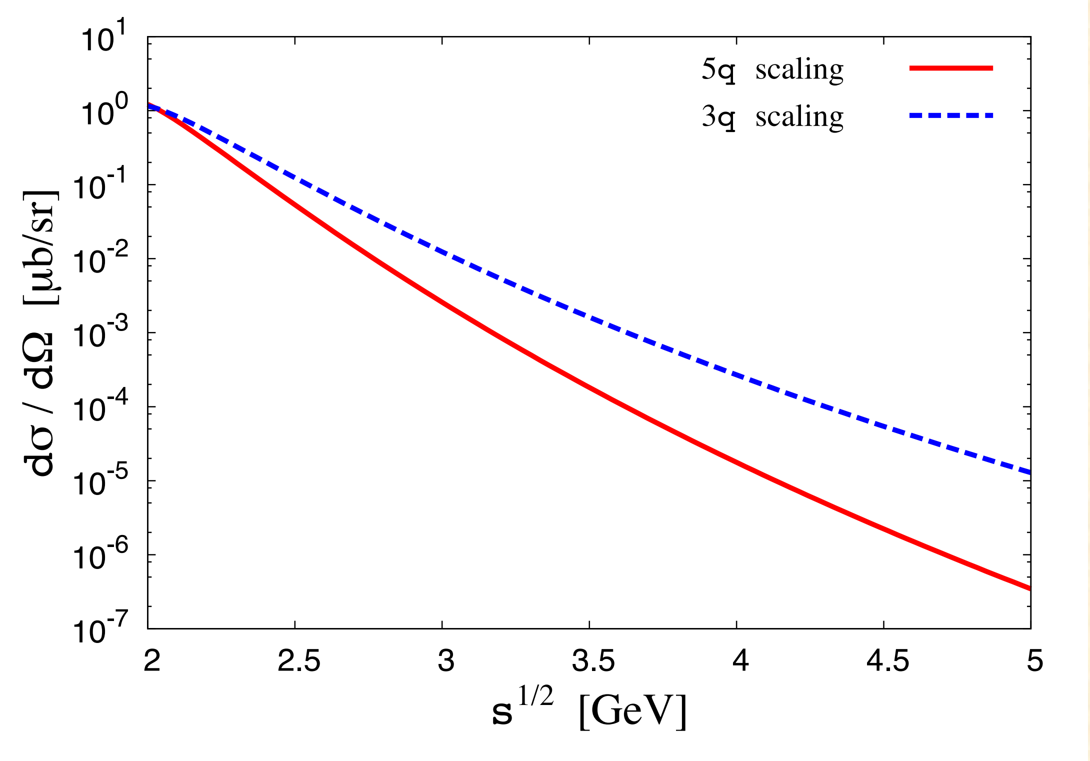
$$n = 2+3+2+3 = 10 \quad \text{if } \Lambda(1405) = \text{three-quark state}$$

$$= 2+3+2+5 = 12 \quad \text{if } \Lambda(1405) = \text{five-quark state}$$

(including $\bar{K}N$ molecule)

$$\frac{d\sigma_{ab\to cd}}{dt} = \frac{\text{const}}{s^{n-2}}, \quad n = 10 \text{ or } 12$$

Our prediction at high energies



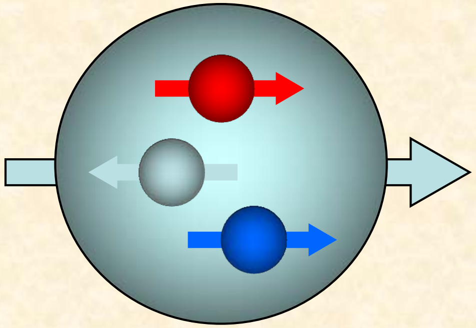
Comments:

Tensor-polarization physics

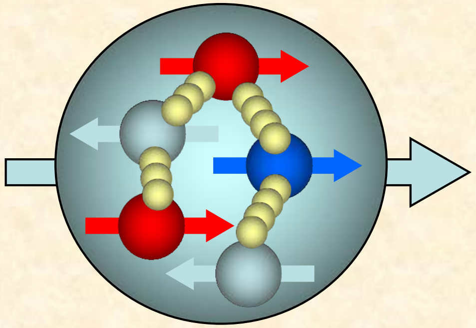
S. Kumano, Euro. Phys. J. A 60 (2024) 205.

Nucleon spin

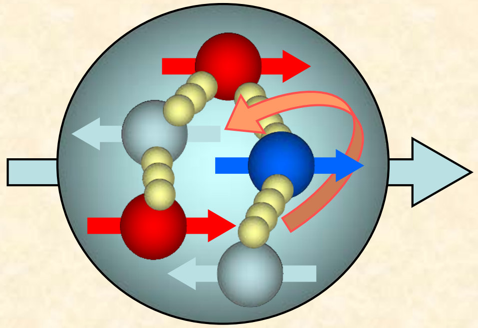
Almost none of nucleon spin is carried by quarks! → **Nucleon spin puzzle!?**



Naïve Quark Model



Sea-quarks and gluons?

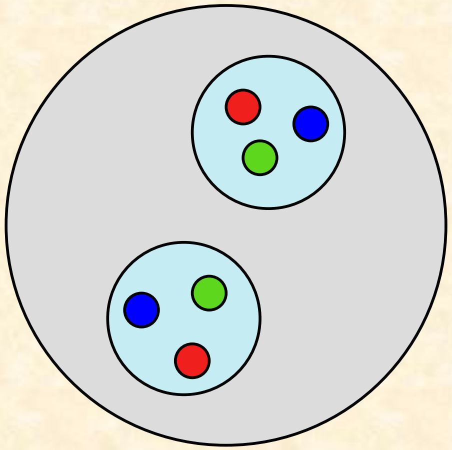


Orbital angular momenta ?

"old" standard model

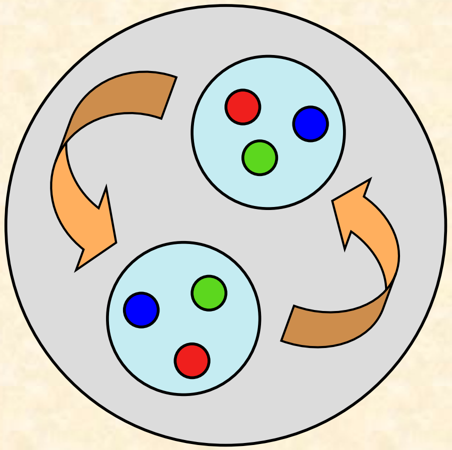
Tensor structure b_1 (*e.g.* deuteron)

Tensor-structure puzzle!?



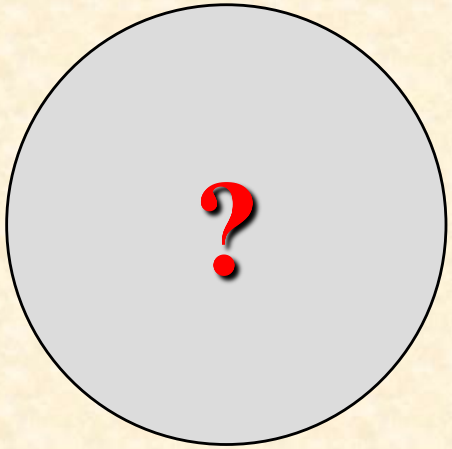
only S wave

$b_1 = 0$



S + D waves

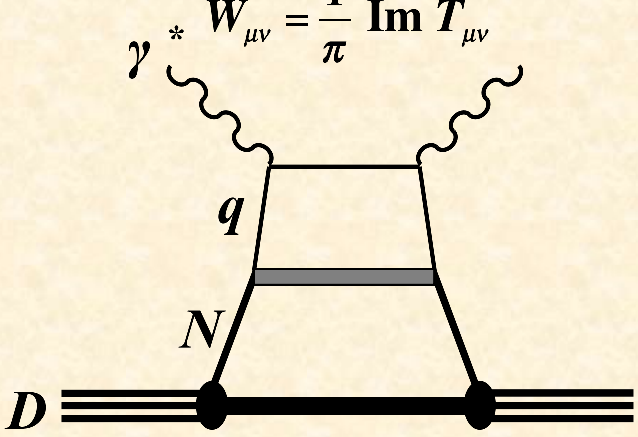
standard model $b_1 \neq 0$



$b_1^{\text{experiment}} \neq b_1^{\text{“standard model”}}$

"Standard-model" prediction for b_1 of deuteron

$$W_{\mu\nu} = \frac{1}{\pi}\,\mathrm{Im}\,T_{\mu\nu}$$



Standard model of the deuteron

$$b_1(x) = \int \frac{dy}{y}\,\delta_T f(y)\,F_1^N(x/y,\,Q^2), \qquad y = \frac{Mp\cdot q}{M_N P\cdot q} \simeq \frac{2p^-}{P^-}$$

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

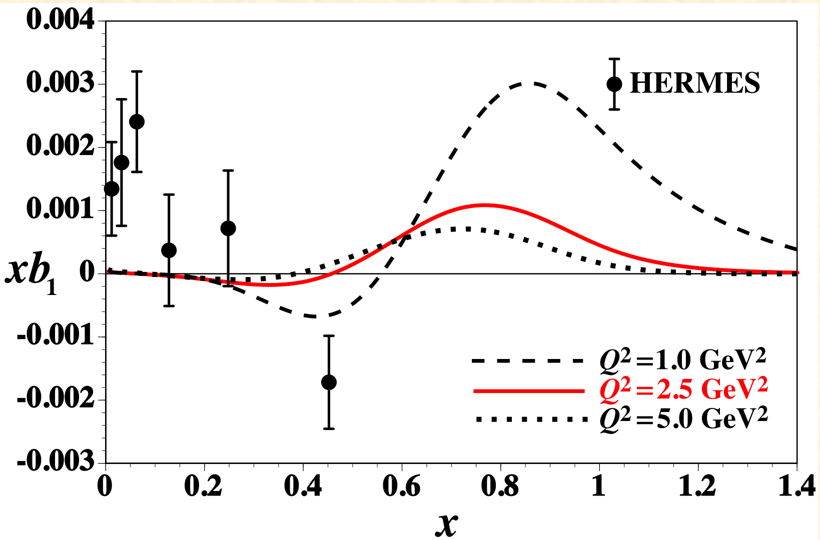
$$= \int d^3p\; y\left[-\frac{3}{4\sqrt{2}\pi}\,\phi_0(p)\phi_2(p) + \frac{3}{16\pi}\,|\phi_2(p)|^2\right](3\cos^2\theta - 1)\,\delta\!\left(y - \frac{p\cdot q}{M_N \nu}\right)$$

S-D term   D-D term

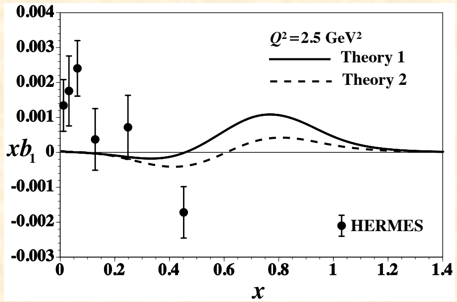
Nucleon momentum distribution:

$$f^H(y) \equiv f_\uparrow^H(y) + f_\downarrow^H(y) = \int d^3p\; y\,|\phi^H(\vec p)|^2\,\delta\!\left(y - \frac{E-p_z}{M_N}\right)$$

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



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



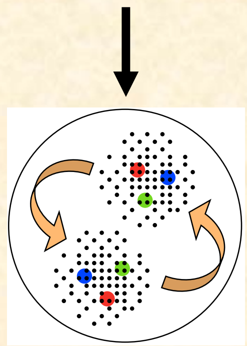
$|b_1(\text{theory})| \ll |b_1(\text{HERMES})|$
at $x < 0.5$

Standard convolution model does not work for the deuteron tensor structure!?

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

Interesting suggestions:
hidden-color, 6-quark, $\cdots$

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



?

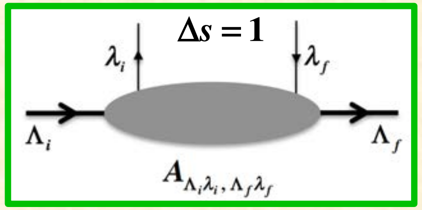
Gluon transversity $\Delta_T g$

Note on our notations:
Tensor-polarized gluon distribution: $\delta_T g$
Gluon transversity: $\Delta_T g$

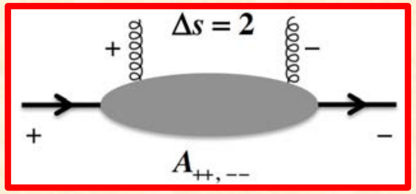
Helicity amplitude $A(\Lambda_i, \lambda_i, \Lambda_f, \lambda_f)$, conservation $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$

Longitudinally-polarized quark in nucleon: $\Delta q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2}, +\frac{1}{2}+\frac{1}{2}\right) - A\left(+\frac{1}{2}-\frac{1}{2}, +\frac{1}{2}-\frac{1}{2}\right)$

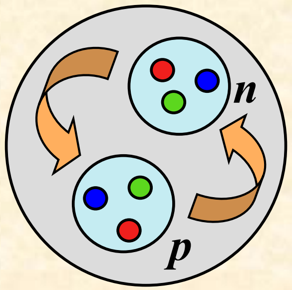
Quark transversity in nucleon: $\Delta_T q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2}, -\frac{1}{2}-\frac{1}{2}\right)$, $\lambda_i = +\frac{1}{2} \rightarrow \lambda_f = -\frac{1}{2}$ quark spin flip ($\Delta s = 1$)



Gluon transversity in deuteron: $\Delta_T g(x) \sim A(+1+1, -1-1)$, $\cancel{A\left(+\frac{1}{2}+1, -\frac{1}{2}-1\right)}$ not possible for nucleon



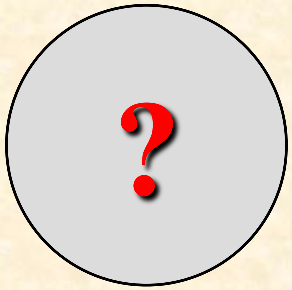
Note: Gluon transversity does not exist for spin-1/2 nucleons.



S + D waves

$b_1\ (\delta_T q,\ \delta_T g) \neq 0 \iff$ still $\Delta_T g = 0$

What would be the mechanism(s) for creating $\Delta_T g \neq 0$?



Physics beyond "the standard model" in nuclear physics?

(Physics beyond the standard model in particle physics???)

JLab PAC-38 (2011) proposal, PR12-11-110

Full approval in 2023

2011

The Deuteron Tensor Structure Function b_1

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

J.-P. Chen (co-spokesperson), P. Solvignon (co-spokesperson),
K. Allada, A. Camsonne, A. Deur, D. Gaskell,
C. Keith, S. Wood, J. Zhang
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

N. Kalantarians (co-spokesperson), O. Rondon (co-spokesperson)
Donal B. Day, Hovhannes Baghdasaryan, Charles Hanretty
Richard Lindgren, Blaine Norum, Zhihong Ye
University of Virginia, Charlottesville, VA 22903

2023

PR12-13-011

The Deuteron Tensor Structure Function b_1

A Proposal to Jefferson Lab PAC-40
(Update to PR12-11-110)

K. Allada, A. Camsonne, J.-P. Chen,[†]
A. Deur, D. Gaskell, M. Jones, C. Keith, J. Pierce,
P. Solvignon,[†] S. Wood, J. Zhang
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O. Rondon Aramayo,[†] D. Crabb, D. B. Day,
C. Hanretty, D. Keller,[†] R. Lindgren, S. Liuti, B. Norum,
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University of Virginia, Charlottesville, VA 22903

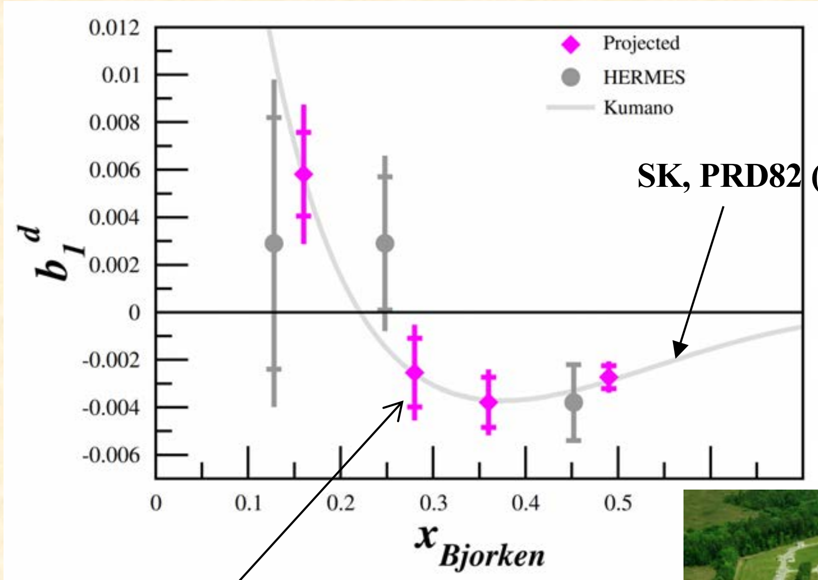
N. Kalantarians[†]
Hampton University, Hampton VA 23668

T. Badman, J. Calarco, J. Dawson,
S. Phillips, E. Long,[†] K. Slifer[†‡], R. Zielinski
University of New Hampshire, Durham, NH 03861

G. Ron
Hebrew University of Jerusalem, Jerusalem

W. Bertozzi, S. Gilad, J. Huang
A. Kelleher, V. Sulkosky
Massachusetts Institute of Technology, Cambridge, MA 02139

***b_1* experiment**



SK, PRD82 (2010) 017501

Expected errors by JLab

See J. Poudel, A. Bacchetta, J.-P. Chen, N. Santiesteban, EPJA 61 (2025) 81 for updated information.

Gluon transversity

A Letter of Intent to Jefferson Lab PAC 44, June 6, 2016

Search for Exotic Gluonic States in the Nucleus

M. Jones, C. Keith, J. Maxwell*, D. Meekins
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

W. Detmold, R. Jaffe, R. Milner, P. Shanahan
Laboratory for Nuclear Science, MIT, Cambridge, MA 02139

D. Crabb, D. Day, D. Keller, O. A. Rondon
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J. Pierce
Oak Ridge National Laboratory, Oak Ridge, TN 37831

Eur. Phys. J. A (2025) 61:81
https://doi.org/10.1140/epja/s10050-025-01558-w

THE EUROPEAN PHYSICAL JOURNAL A

Review

Experimental study of tensor structure function of deuteron

Jiwan Poudel[1,a], Alessandro Bacchetta[2], Jian-Ping Chen[1], Nathaly Santiesteban[3]

[1] Jefferson Lab, 12000 Jefferson Ave, Newport News, VA 23606, USA
[2] University of Pavia, Via Bassi 6, I-27100 Pavia, Italy
[3] University of New Hampshire, 9 Library Way, Durham, NH 03824, USA

Experimental possibility at Fermilab in 2020's

Polarized fixed-target experiments at the Main Injector, Proton beam = 120 GeV © Fermilab

Fermilab-E1039 (SpinQuest)

Drell-Yan experiment with a polarized proton target

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

List of Collaborators:

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Fermi National Accelerator Laboratory, Batavia IL 60510
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Tokyo Institute of Technology, Tokyo 152-8551, Japan
D. Crabb, D. Day, D. Keller, O. Rondon
University of Virginia, Charlottesville, VA 22904

Fermilab experimentalists are interested in the gluon transversity by replacing the E1039 proton target for the deuteron one. (Spokesperson of E1039: D. Keller) However, there was no theoretical formalism until our work.

SK and Q.-T. Song, PRD 101 (2020) 054011 & 094013

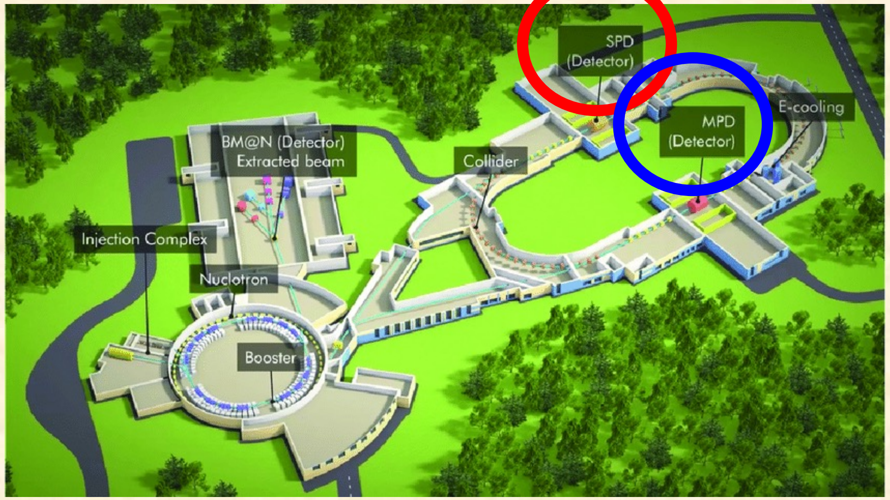
The Transverse Structure of the Deuteron with Drell-Yan

D. Keller[1]

[1] *University of Virginia, Charlottesville, VA 22904*

Proposal for a Fermilab-PAC in 2023.

Nuclotron-based Ion Collider fAcility (NICA)



SPD (Spin Physics Detector for physics with polarized beams)
MPD (MultiPurpose Detector for heavy ion physics)

$$\vec{p}+\vec{p}: \quad \sqrt{s_{pp}} = 12 \sim 27 \text{ GeV}$$

$$\vec{d}+\vec{d}: \quad \sqrt{s_{NN}} = 4 \sim 14 \text{ GeV}$$

$\vec{p}+\vec{d}$ is also possilbe.

On the physics potential to study the gluon content of proton and deuteron at NICA SPD, A. Arbuzov *et al.* (NICA project), Nucl. Part. Phys. 119 (2021) 103858.


Progress in Particle and Nuclear Physics 119 (2021) 103858

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

On the physics potential to study the gluon content of proton and deuteron at NICA SPD

A. Arbuzov [a], A. Bacchetta [b,c], M. Butenschoen [d], F.G. Celiberto [b,c,e,f], U. D'Alesio [g,h], M. Deka [a], I. Denisenko [a], M.G. Echevarria [i], A. Efremov [a], N.Ya. Ivanov [a,j], A. Guskov [a,k,*], A. Karpishkov [l,a], Ya. Klopot [a,m], B.A. Kniehl [d], A. Kotzinian [j,o], S. Kumano [p], J.P. Lansberg [q], Keh-Fei Liu [r], F. Murgia [h], M. Nefedov [l], B. Parsamyan [a,n,o], C. Pisano [g,h], M. Radici [c], A. Rymbekova [a], V. Saleev [l,a], A. Shipilova [l,a], Qin-Tao Song [s], O. Teryaev [a]

Unique opportunity in high-energy spin physics, especially on the deuteron spin physics.

→ Theoretical formalisms need to be developed.

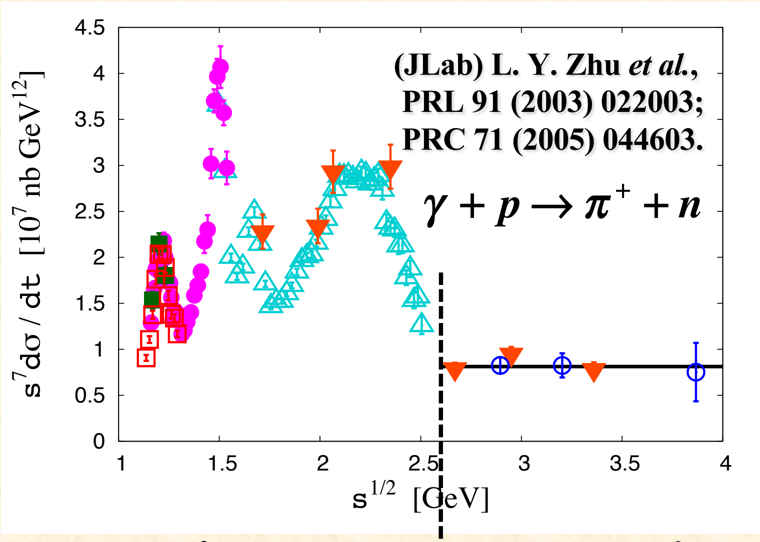
may skip

Future possibility at HIAF
on color transparency

S. Kumano,

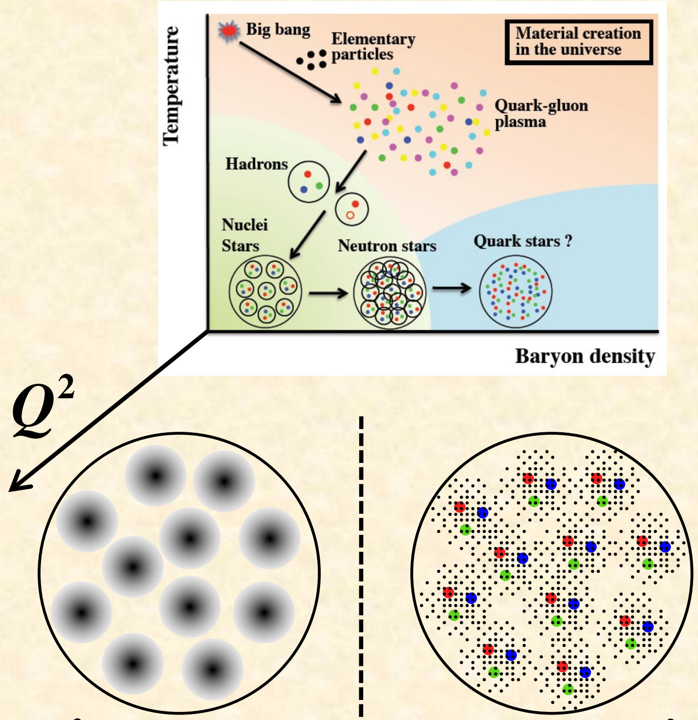
arXiv:2205.03012, Physics 2022, 4, 565-577, Proceedings of the Workshop on the Future of Color Transparency and Hadronization Studies at Jefferson Lab and Beyond, June 7-8, 2021 (Online).

Hadron degrees of freedom (d.o.f.)
⇔ Quark d.o.f.



Low energies:
Hadron degrees of freedom (Resonances)

High energies:
Quark-gluon degrees of freedom (Perturbative QCD: Constituent-counting rule)



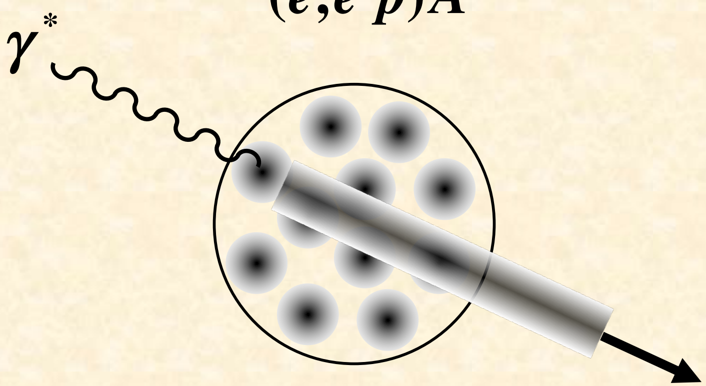
Low energies:
Hadron degrees of freedom

High energies:
Quark-gluon degrees of freedom

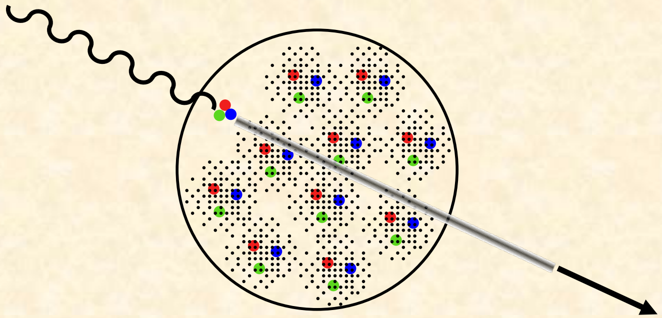
Nuclei should be described by quark and gluon degrees of freedom in principle; however, descriptions in terms of hadron degrees of freedom are often effective.

Color transparency and hadronization

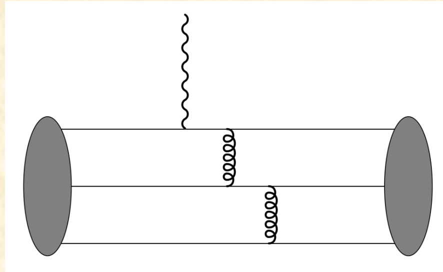
$(e,e'p)A$



Interact strongly
in the nuclear medium



No interaction
in the nuclear medium

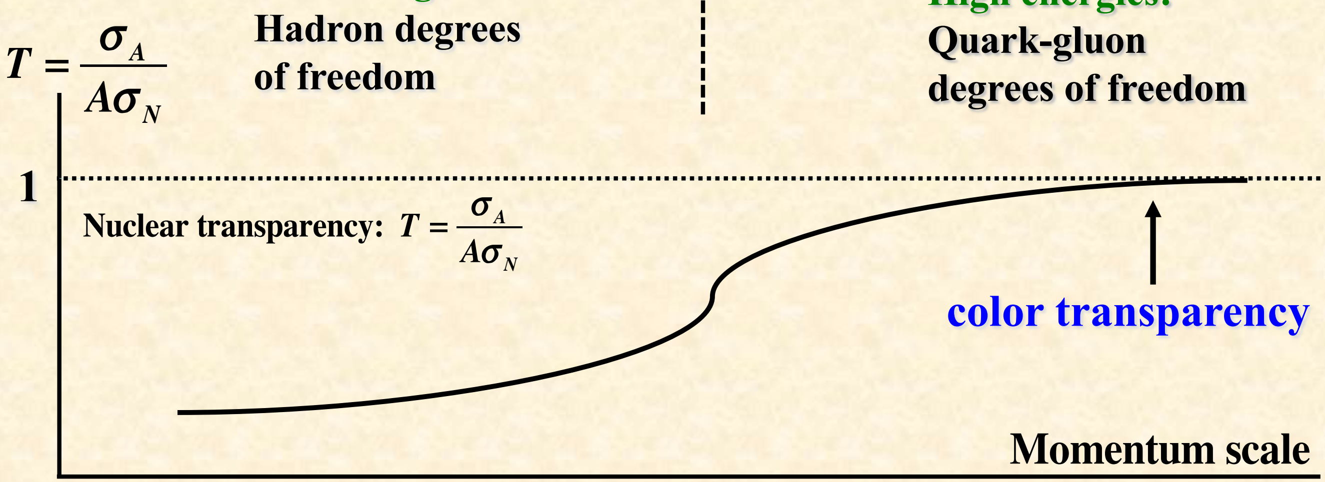


Hard gluon exchanges at high energies
→ quarks are close with each other
→ struck nucleon should be compact
→ nucleon could pass though the medium
without interaction (color transparency)

← Low energies:
Hadron degrees
of freedom

→ High energies:
Quark-gluon
degrees of freedom

At large momentum transfer,
a small-size hadron could freely pass
through nuclear medium. (Transparent)



The color transparency is an important phenomena
to understand the quark-hadron many-body systems
from low to high energies and from low to high densities.

Mystery on color-transparency experiments

At large momentum transfer, a small-size hadron could freely pass through nuclear medium.

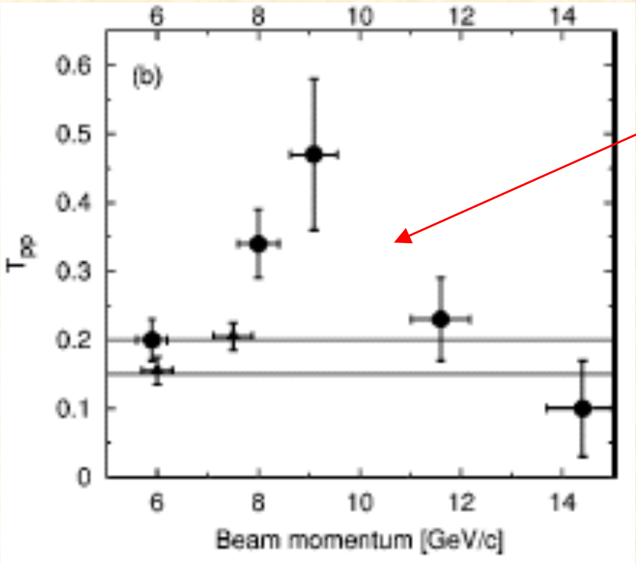
Experimenets: $pA \to pp(A-1), \quad eA \to ep(A-1)$

Nuclear transparency: $T = \dfrac{\sigma_A}{A\sigma_N}$

Color transparency: $T \;\to\;$ larger ($=1$) as the hard scale $\to$ larger

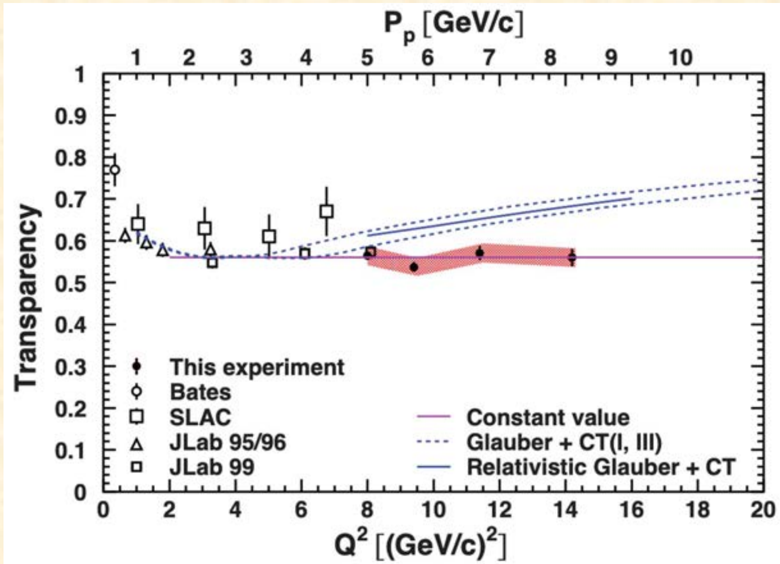
(BNL-EVA) J. Aclander *et al.*, PRC 70 (2004) 015208

JLab (Hall-C): D. Bhetuwal *et al.*, PRL 126 (2021) 082301.



reason for this drop?

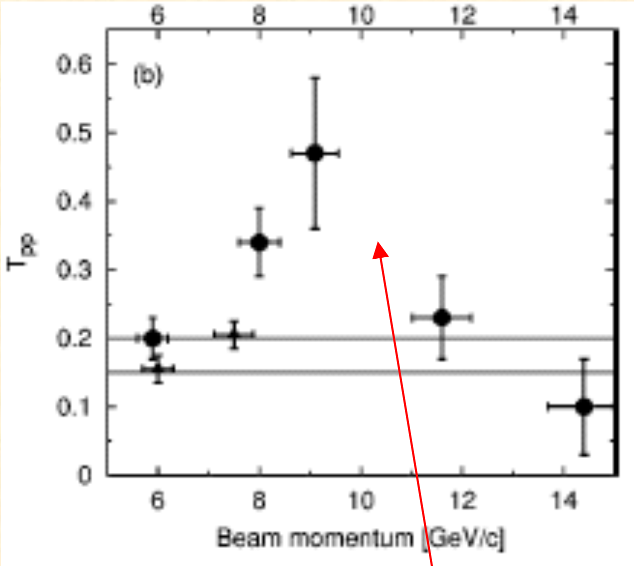
It should be checked at hadron accelerator facilities such as J-PARC.



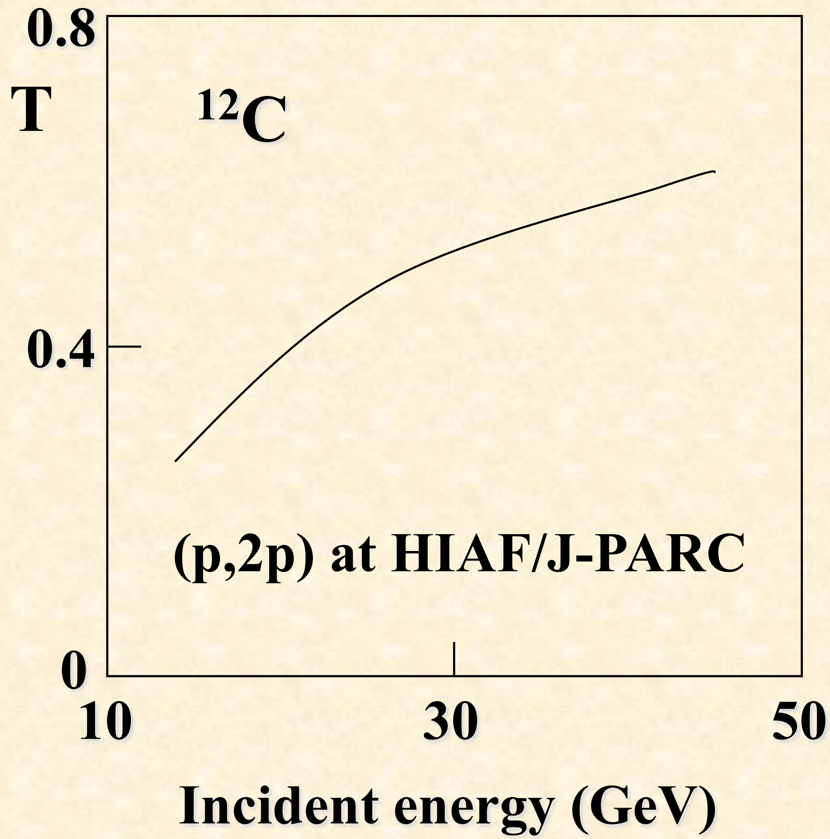
Color transparency at HIAF

The mysterious BNL result could be clarified by possible HIAF/J-PARC experiments.

(BNL-EVA) J. Aclander *et al.*, PRC 70 (2004) 015208

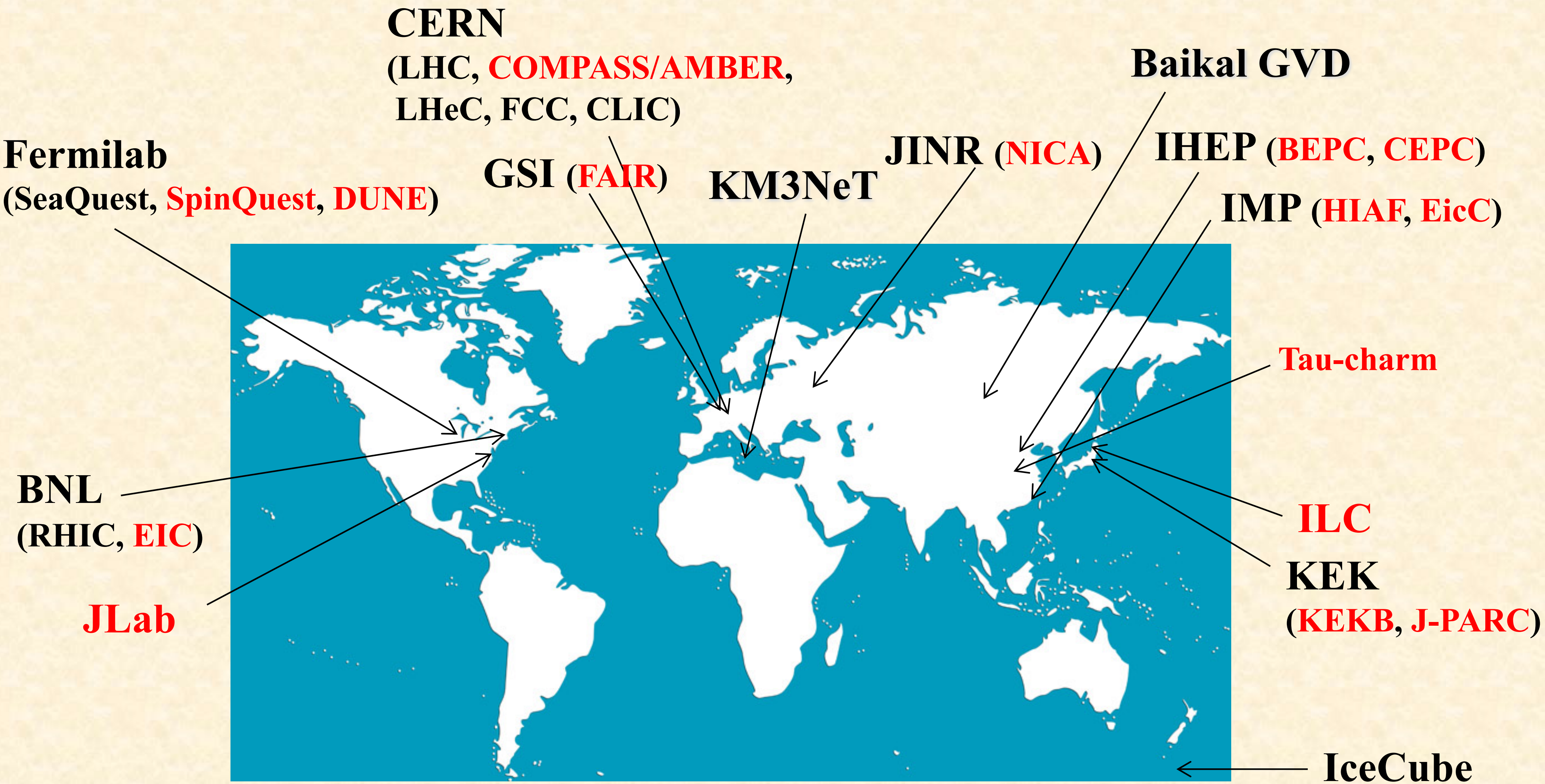


reason for this drop?



Future prospects on high-energy hadron physics at hadron accelerator facilities

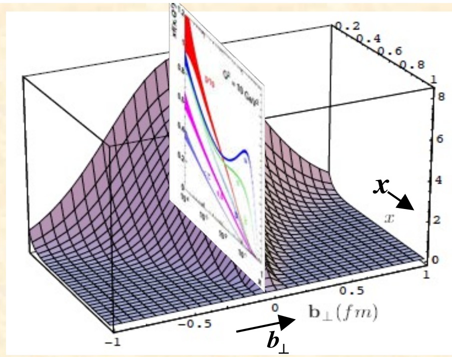
High-energy hadron physics experiments



Facilities on hadron structure functions on GPDs including future possibilities.

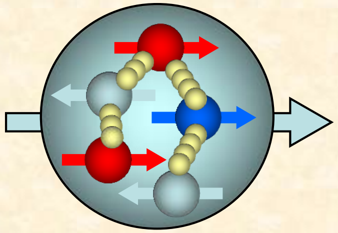
By hadron tomography

3D view of hadrons

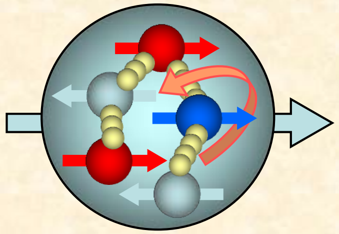


Origin of nucleon spin

By the tomography, we determine



or



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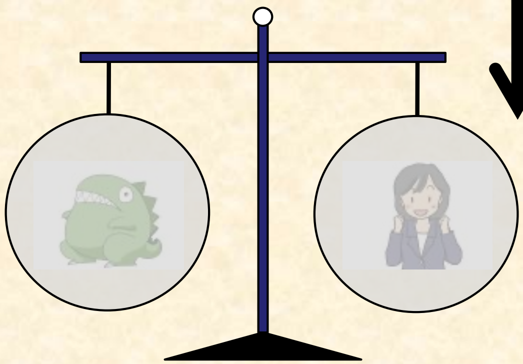
Exotic hadrons



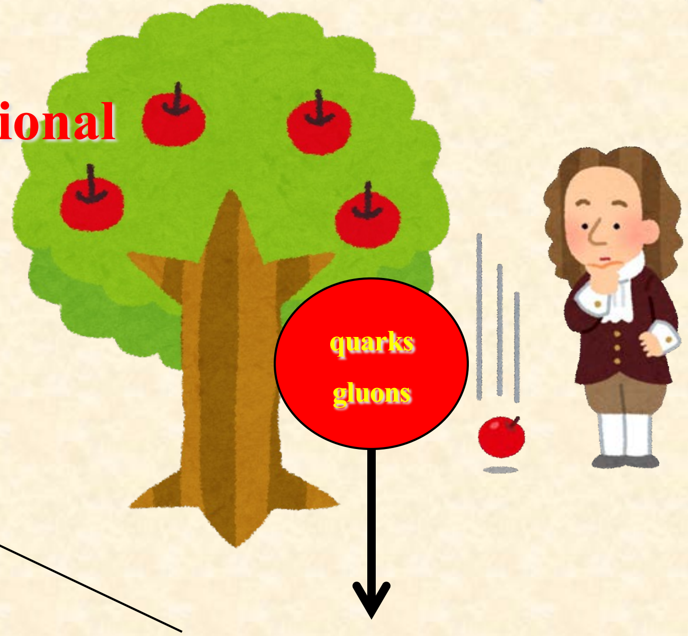
By tomography, we determine

or

.

Origin of gravitational source (mass)

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



Summary

GPDs

3D structure of hadrons, Origin of hadron masses and pressures,
Origin of nucleon spin, Exotic hadron structure

Constituent-counting rule

High energies = Quark and gluon degrees of freedom
It could be appropriate to use high-energy processes
for determination of internal configurations
of exotic-hadron candidates.

Tensor polarization

New aspect in high-energy spin physics.

Color transparency

Hadron interactions in nuclear medium
from low to high energies and from low to high densities.

Hadron-experimental facilities

HIAF, J-PARC, GSI, NICA, Fermilab, LHC, AMBER, …

The End

The End