Studies of exotic-hadron candidates in high-energy reactions

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May 29, 2024

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   Fermilab
   NICA
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References on our works

1. Exotic-hadron signature in fragmentation functions

M. Hirai, SK, M. Oka, and K. Sudoh, Phys. Rev. D77 (2008) 017504.

2. Constituent counting rule in perturbative QCD

H. Kawamura, SK, and T. Sekihara, Phys. Rev. D88 (2013) 034010;

W.-C. Chang, SK, and T. Sekihara, Phys. Rev. D93 (2016) 034006.

3. Internal structure of hadrons by GPDs

H. Kawamura and SK, Phys. Rev. D89 (2014) 054007;

SK, Qin-Tao Song, and O.V. Teryaev, Phys. Rev. D97 (2018) 014020;

SK, M. Strikman, and K. Sudoh, Phys. Rev. D80 (2009) 074003;

T. Sawada, W.-C. Chang, SK, J.-C. Peng, S. Sawada, and K. Tanaka, Phys. Rev. D93 (2016) 114034.

(Transition GPDs) S. Diehl *et al*. (SK, 15th author), arXiv:2405.15386, Eur. Phys. J. A.

4. "Exotic" signatures in deuteron in DIS and Drell-Yan

W. Cosyn, Yu-Bing Dong, SK, and M. Sargsian, Phys. Rev. D95 (2017) 074036;

SK and Qin-Tao Song, Phys. Rev. D97 (2018) 014020; arXiv:1910.12523;

SK, J. Phys. Conf. Ser. 543 (2014) 012001; Phys. Rev. D94 (2016) 054022.

(Spin-1, short summary) SK, to be submitted for Eur. Phys. J. A.

Introduction

Progress in exotic hadrons

$q\bar{q}$ Meson
q^3 Baryon

$q^2\bar{q}^2$ Tetraquark
$q^4\bar{q}$ Pentaquark
q^6 Dibaryon
…
$q^{10}\bar{q}$ e.g. Strange tribaryon
…
gg Glueball
…

- Θ^+(1540)???: LEPS
  Pentaquark?

  $uudd\bar{s}$?

- Kaonic nuclei: KEK-PS, ...
  Strange tribaryons, …

  $K^- pnn$, $K^- ppn$?
  $K^- pp$?

- X (3872), Y(3940): Belle
  Tetraquark, D$\bar{D}$ molecule

  $c\bar{c}$
  $D^0(c\bar{u})\bar{D}^0(\bar{c}u)$
  $D^+(c\bar{d})D^-(\bar{c}d)$?

- D_{sJ}(2317), D_{sJ}(2460): BaBar, CLEO, Belle
  Tetraquark, DK molecule

  $c\bar{s}$
  $D^0(c\bar{u})K^+(u\bar{s})$
  $D^+(c\bar{d})K^0(d\bar{s})$?

- Z (4430): Belle
  Tetraquark, …

  $c\bar{c}u\bar{d}$, D molecule?

- P_c (4380), T_{cc} (3875): LHCb
- …

  $u\bar{c}udc$: $\bar{D}(u\bar{c})\Sigma_c^*(udc)$, $\bar{D}^*(u\bar{c})\Sigma_c(udc)$ molecule?
  $cc\bar{u}\bar{d}$: $D^0(\bar{u}c)D^{*+}(\bar{d}c)$ molecule?

Scalar mesons $J^P = 0^+$ at $M \sim 1$ GeV

based on my past experience

Naïve quark-model

$a_1(1230)$

1.0 GeV

$a_0(980)$ $f_0(980)$

$\rho(770)$

0.5 GeV

$f_0(500) = \sigma$

$$\sigma = f_0(500) = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

$$f_0(980) = s\bar{s} \quad \rightarrow \text{denote } f_0 \text{ in this talk}$$

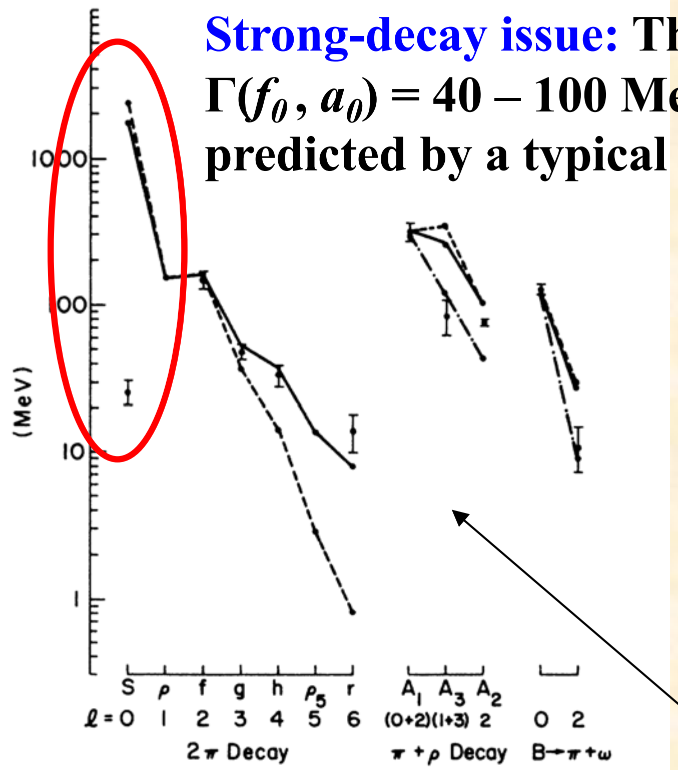
$$a_0(980) = u\bar{d}, \quad \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}), \quad d\bar{u}$$

Naive model: $m(\sigma) \sim m(a_0) < m(f_0)$

$\Updownarrow$ **contradiction**

Experiment: $m(\sigma) < m(a_0) \sim m(f_0)$

Strong-decay issue: The experimental widths $\Gamma(f_0, a_0) = 40 - 100$ MeV are too small to be predicted by a typical quark model.



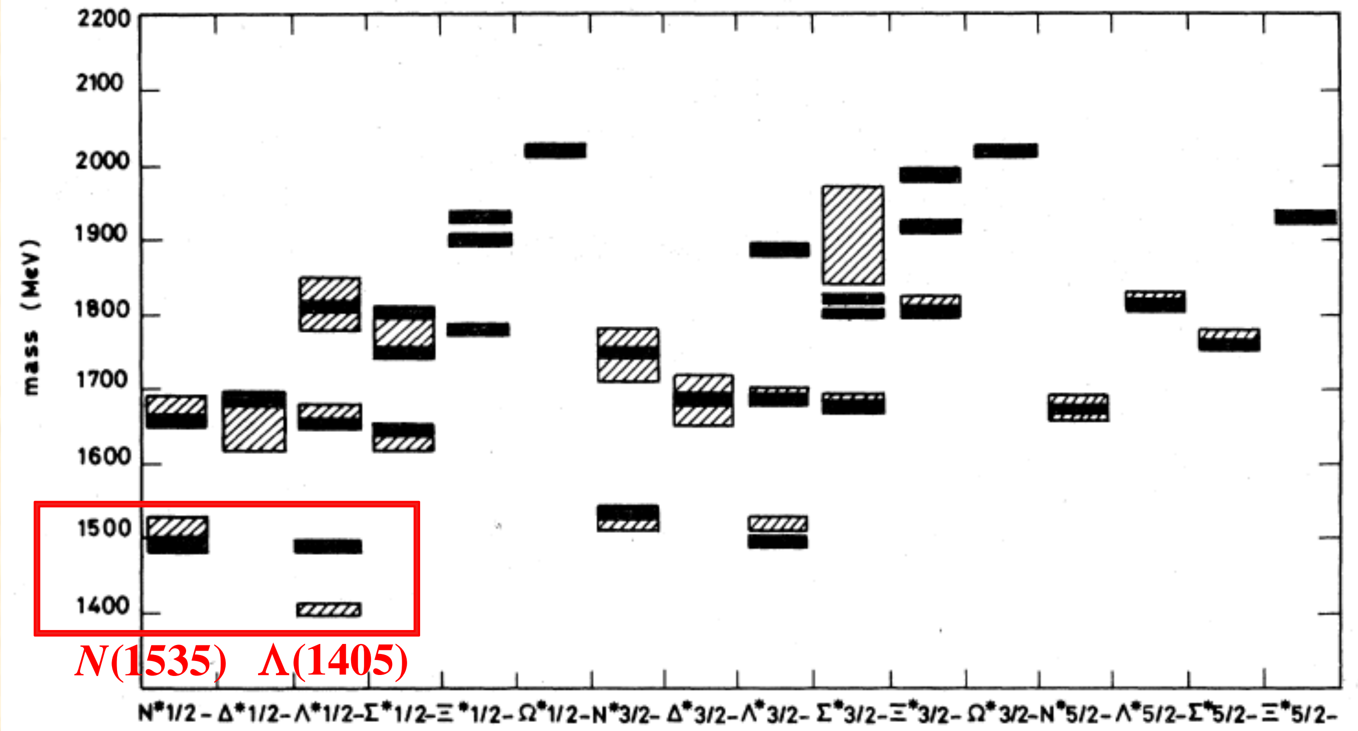
These issues could be resolved
if f_0 is a tetraquark ($q q \bar{q} \bar{q}$) or a $K\bar{K}$ molecule,
namely an "exotic" hadron.

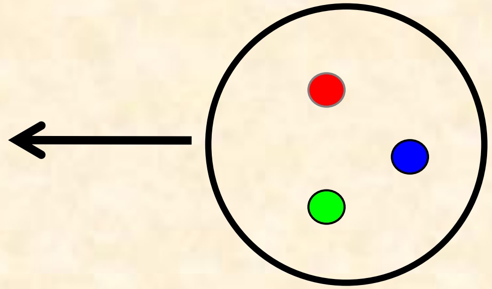
Radiative decay: F. E. Close, N. Isgur, and SK, Nucl. Phys. B389 (1993) 513.

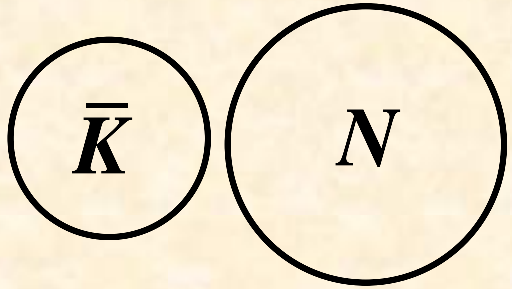
SK and V. R. Pandharipande, Phys. Rev. D38 (1988) 146.

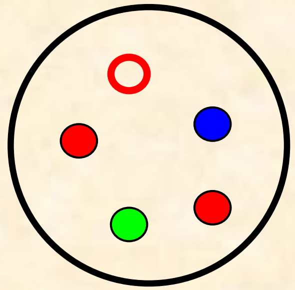
Λ(1405): exotic hadron?

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



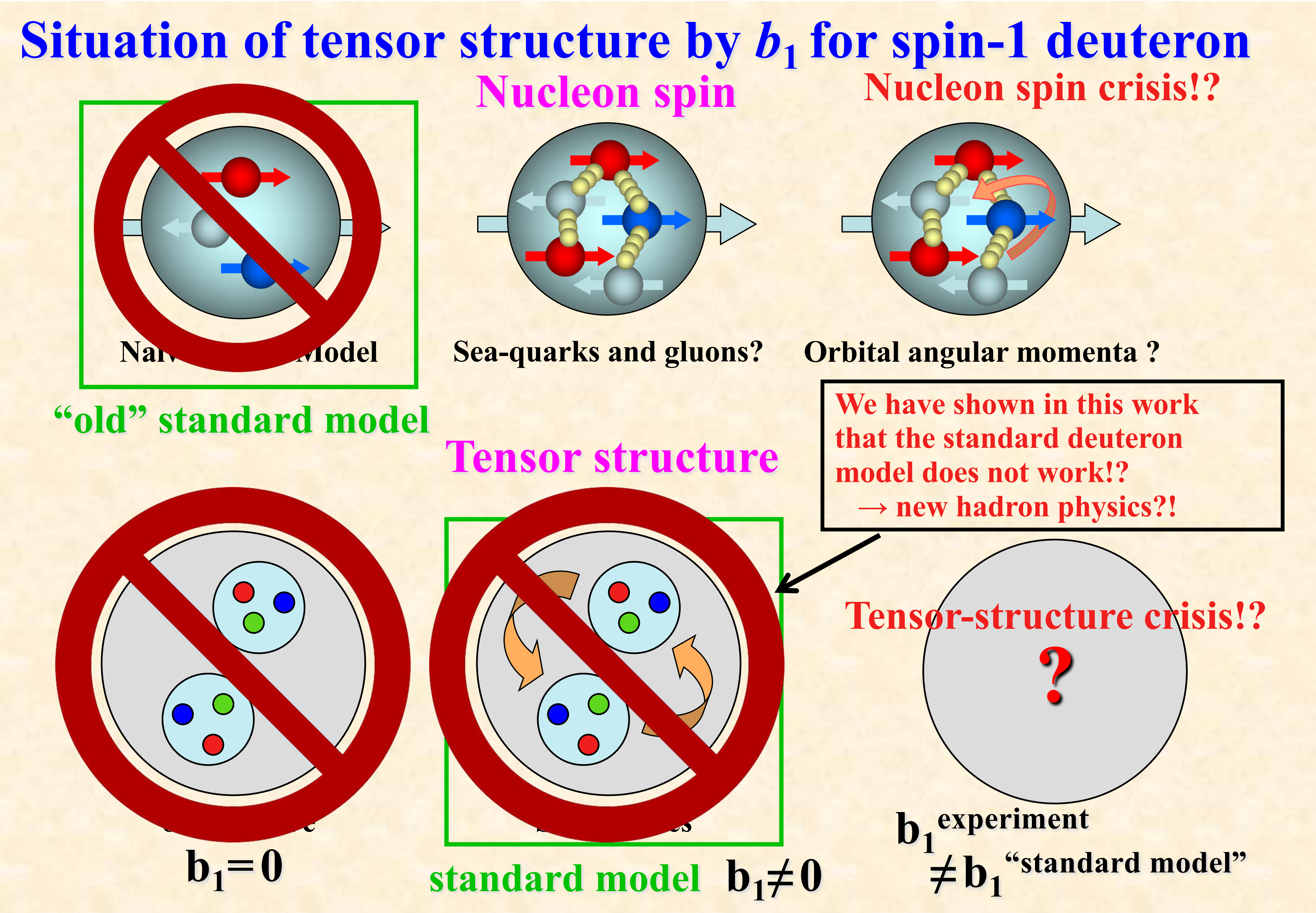






Most spectra agree with the ones by a 3*q*-picture

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


Situation of tensor structure by b1 for spin-1 deuteron
Nucleon spin
Nucleon spin crisis!?
Sea-quarks and gluons?
Orbital angular momenta ?
"old" standard model
Tensor structure
We have shown in this work that the standard deuteron model does not work!?
→ new hadron physics?!
Tensor-structure crisis!?
?
b1=0
standard model
b1≠0
b1 experiment
≠b1 "standard model"

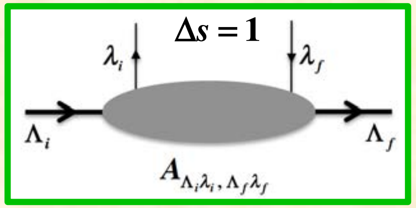
Gluon transversity $\Delta_T g$

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

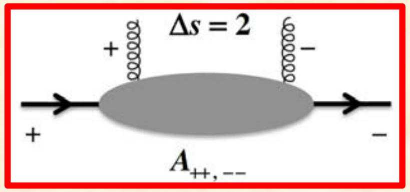
Helicity amplitude $A(\Lambda_i, \lambda_i, \Lambda_f, \lambda_f)$, **conservation** $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$

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

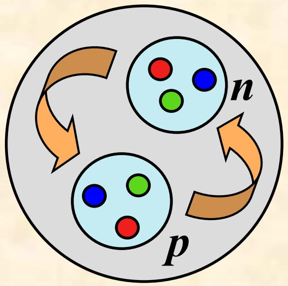
Quark transversity in nucleon: $\Delta_T q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ -\frac{1}{2}-\frac{1}{2}\right)$, $\lambda_i = +\frac{1}{2} \to \lambda_f = -\frac{1}{2}$ **quark spin flip** ($\Delta s = 1$)



Gluon transversity in deuteron: $\Delta_T g(x) \sim A(+1+1,\ -1-1)$, ~~$A\left(+\frac{1}{2}+1,\ -\frac{1}{2}-1\right)$~~ **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???)

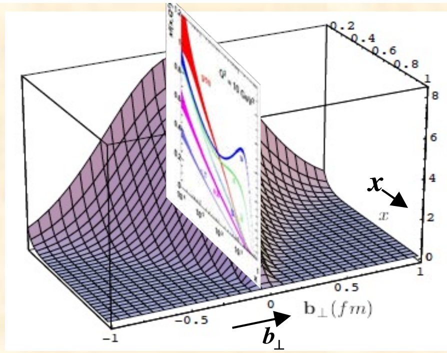
Exotic hadrons by GPDs

(Generalized Parton Distributions)

H. Kawamura and SK,
Phys. Rev. D89 (2014) 054007.

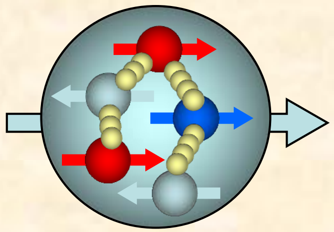
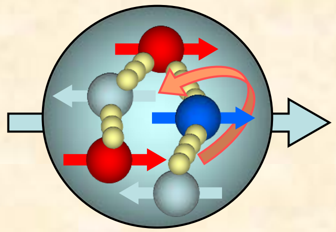
By hadron tomography

3D view of hadrons

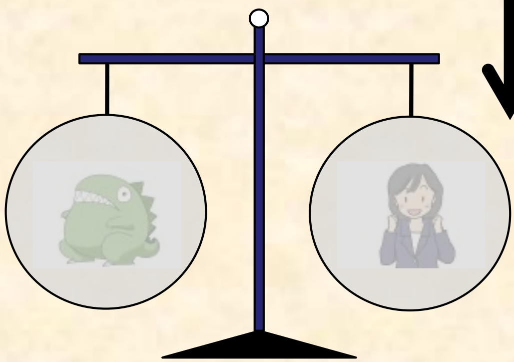


Origin of nucleon spin

By the tomography, we determine

 or  .

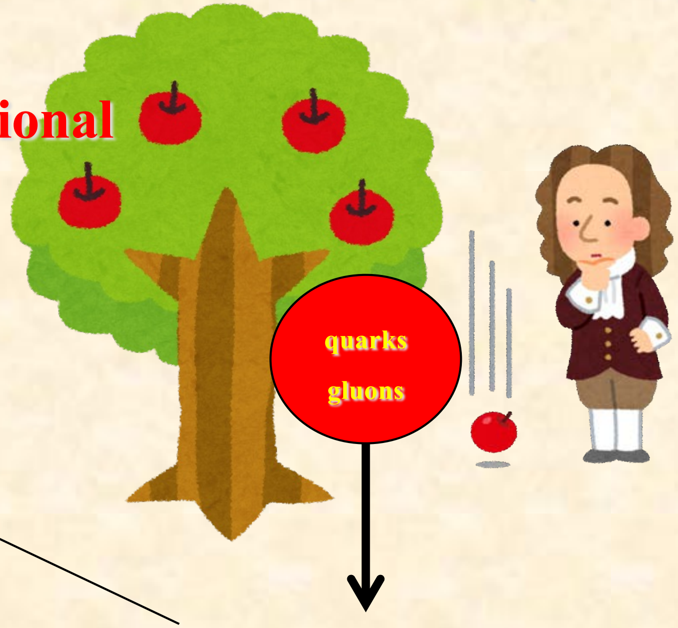
Exotic hadrons



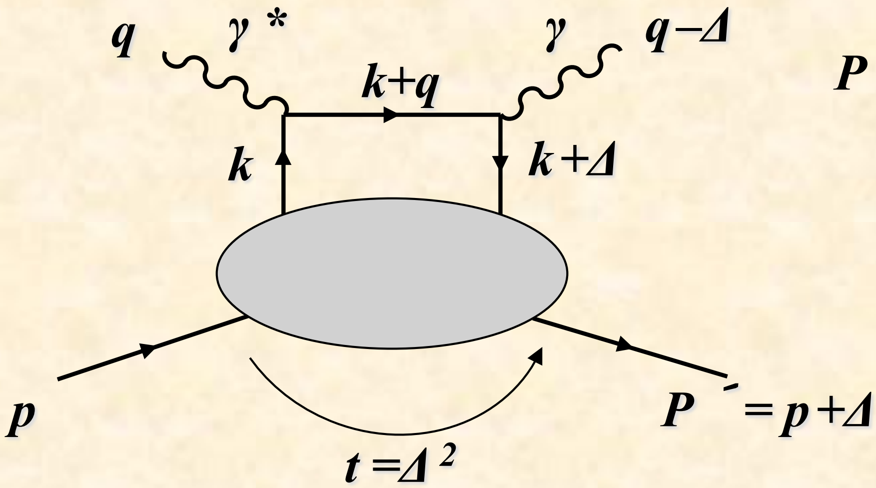
By tomography, we determine  or  .

Origin of gravitational source (mass)

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



Generalized Parton Distributions (GPDs)



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

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

Momentum transfer squared $t = \Delta^2$

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

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

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

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!

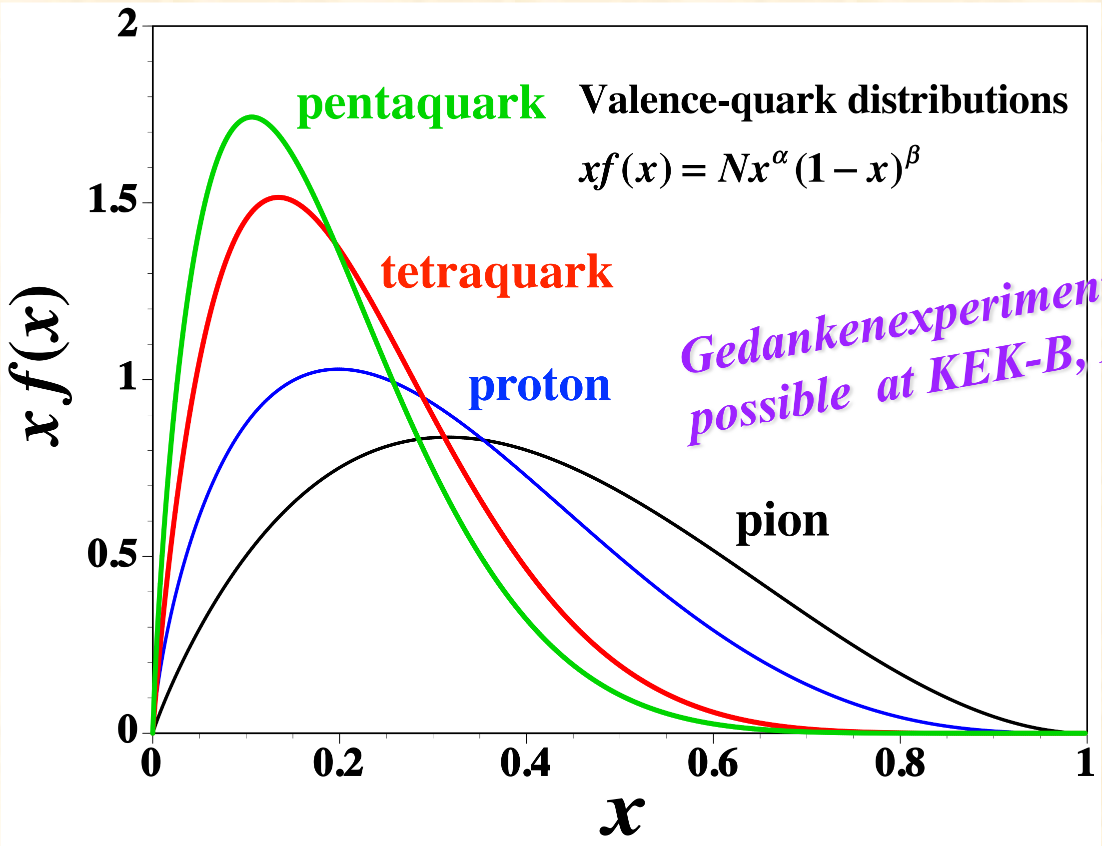
Simple function of GPDs

$H_q^h(x,t) = f(x) F(t,x)$

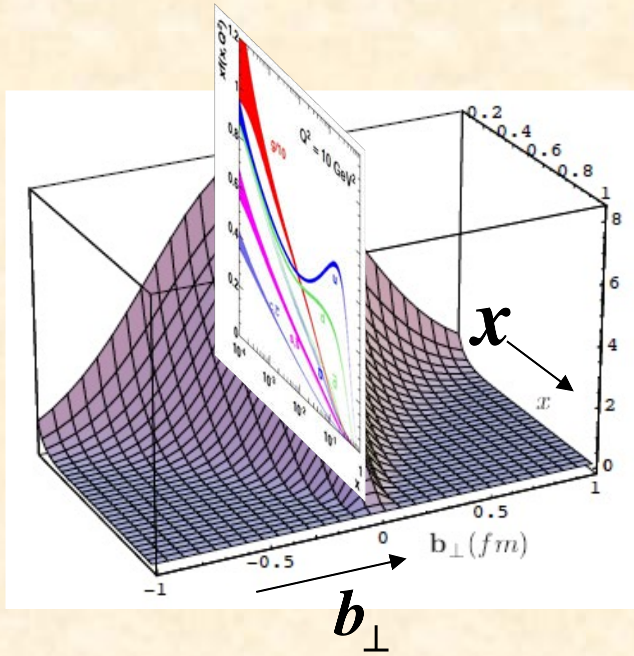
M. Guidal, M.V. Polyakov, A.V. Radyushkin, M. Vanderhaeghen, PRD 72, 054013 (2005).

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 $\langle x \rangle_q \simeq \int_0^1 dx\, x f(x)$

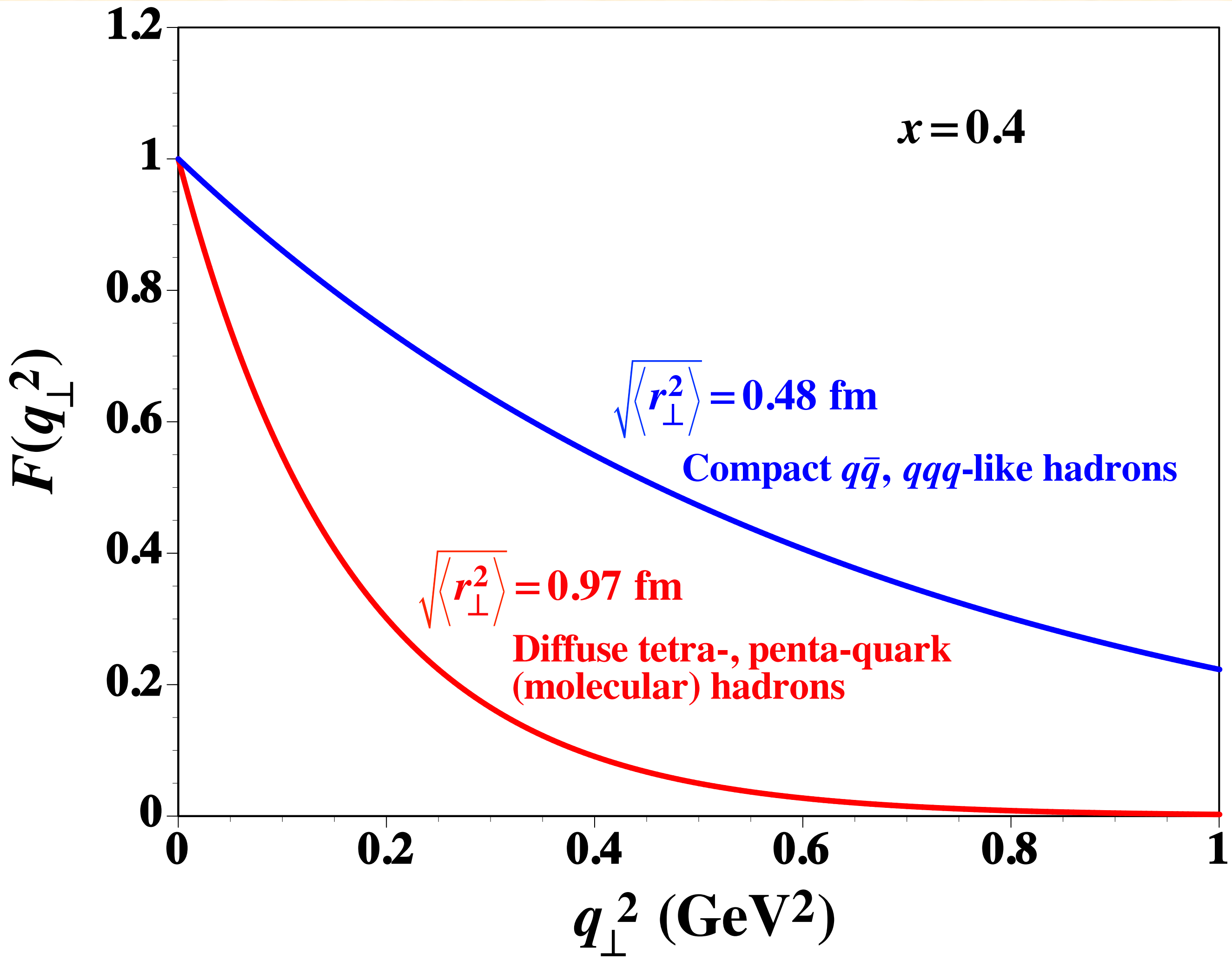


Gedankenexperiment, but possible at KEK-B, ILC, ...

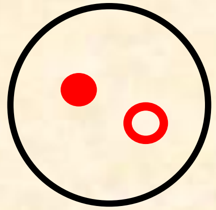


Two-dimensional form factor

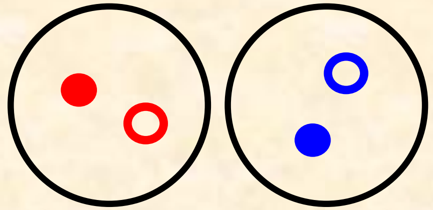
$$H_q^h(x,t) = f(x)F(t,x), \quad F(t,x) = e^{(1-x)t/(x\Lambda^2)}, \quad \langle r_\perp^2 \rangle = \frac{4(1-x)}{x\Lambda^2}$$

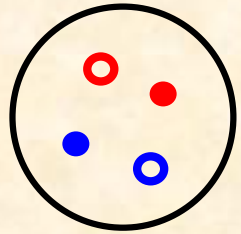


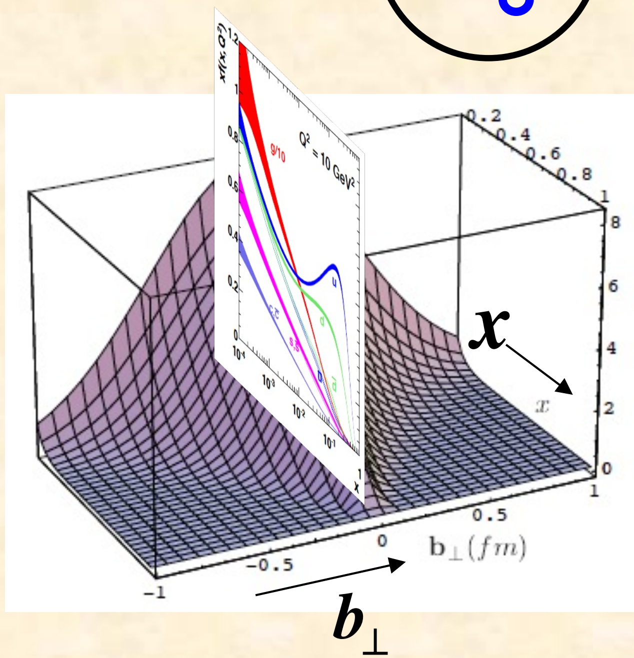
Ordinaly $q\bar{q}$



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







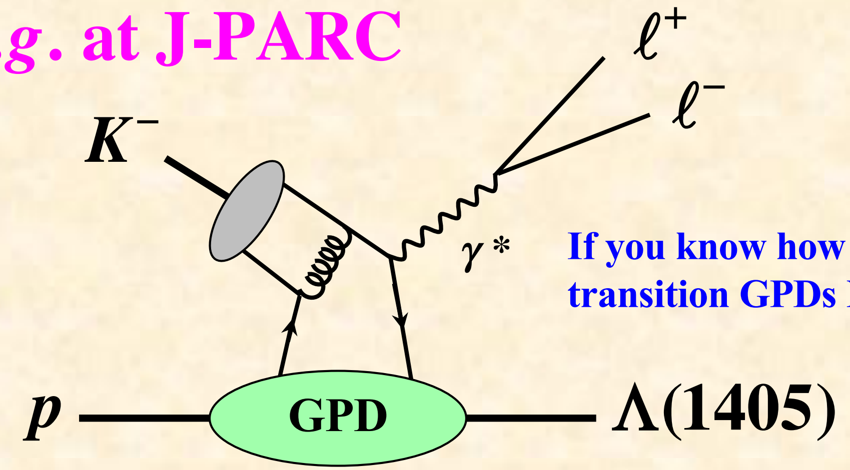
GPDs for exotic hadrons !?

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

→ Transition GPDs

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

$e.g.$ at J-PARC

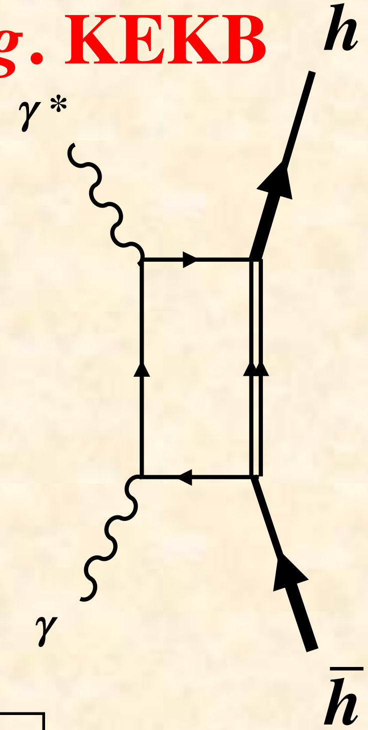


If you know how to handle this kind of transition GPDs N→Λ, please inform me.

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

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

$e.g.$ KEKB

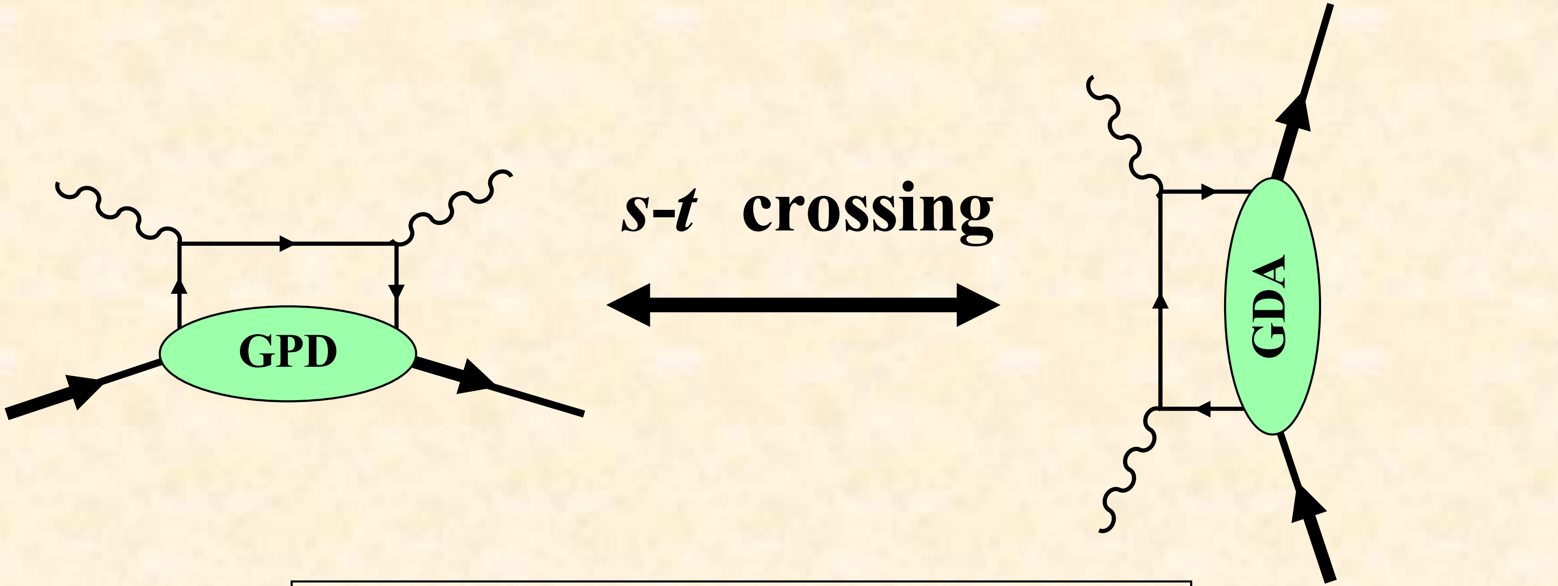


See H. Kawamura, SK, T. Sekihara, PRD 88 (2013) 034010;
W.-C. Chang, SK, and T. Sekihara, PRD 93 (2016) 034006
for constituent-counting rule for exotic hadron candidates.

Timelike GPDs
= Generalized Distribution Amplitudes (GDAs) and extraction of gravitational form factors from KEKB data

Spacelike GPDs

GDA = Timelike GPDs



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

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

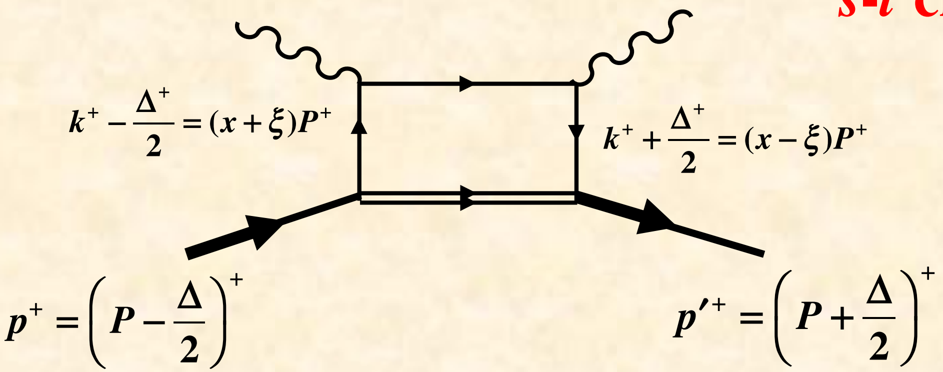
GPD: $H_q(x,\xi,t) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle h(p') | \bar{\psi}(-y/2)\gamma^+\psi(y/2) | h(p) \rangle \Big|_{y^+=0,\vec{y}_\perp=0}$, $\quad P^+ = \frac{(p+p')^+}{2}$

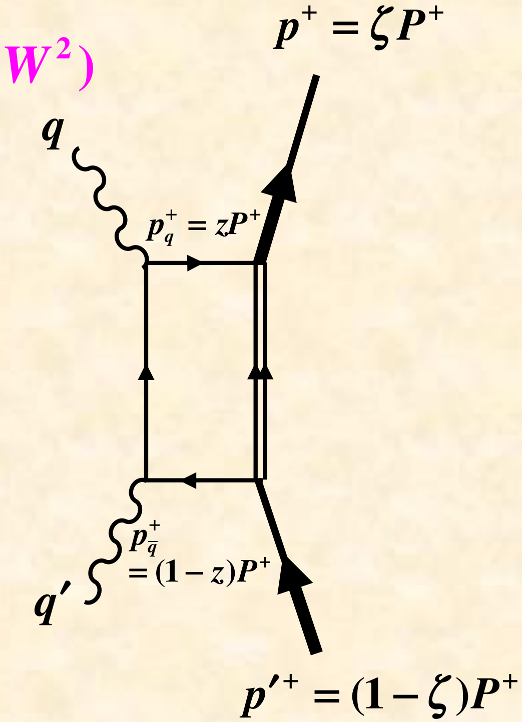
GDA: $\Phi_q(z,\zeta,s) = \int \frac{dy^-}{2\pi} e^{izP^+y^-} \langle h(p)\bar{h}(p') | \bar{\psi}(-y/2)\gamma^+\psi(y/2) | 0 \rangle \Big|_{y^+=0,\vec{y}_\perp=0}$

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

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

s-*t* crossing





$z \Leftrightarrow \frac{1-x/\xi}{2}$

$\zeta \Leftrightarrow \frac{1-1/\xi}{2}$

$W^2 \Leftrightarrow t$

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

JLab / COMPASS

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

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

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

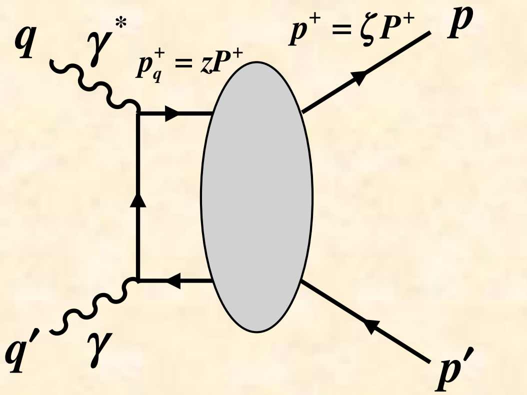
KEKB

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

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



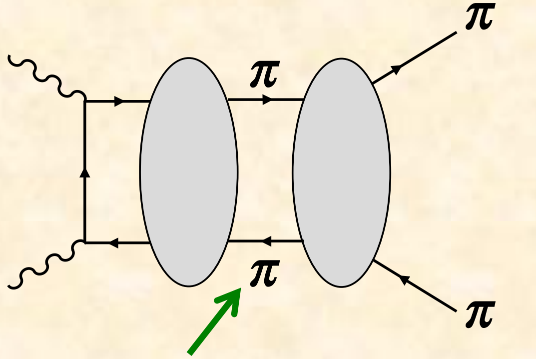
$$\frac{d\sigma}{d(\cos\theta)} = \frac{1}{16\pi(s+Q^2)}\sqrt{1-\frac{4m_\pi^2}{s}}\,\overline{\sum_{\lambda,\lambda'}}|\mathcal{M}|^2$$

$$\mathcal{M} = \varepsilon_\mu^\lambda(q)\varepsilon_\nu^{\lambda'}(q')T^{\mu\nu} = e^2 A_{\lambda\lambda'}, \quad T^{\mu\nu} = i\int d^4\xi\, e^{-i\xi\cdot q}\left\langle \pi(p)\pi(p')\left| T J_{em}^\mu(\xi) J_{em}^\nu(0)\right| 0\right\rangle$$

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

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

$$\frac{d\sigma}{d(\cos\theta)} \simeq \frac{\pi\alpha^2}{4(s+Q^2)}\sqrt{1-\frac{4m_\pi^2}{s}}\,|A_{++}|^2, \quad A_{++} = \sum_q \frac{e_q^2}{2}\int_0^1 dz\,\frac{2z-1}{z(1-z)}\Phi_q^{\pi\pi}(z,\zeta,W^2)$$



Including intermediate resonance contributions

- 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: There exist resonance contributions to the cross section.

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

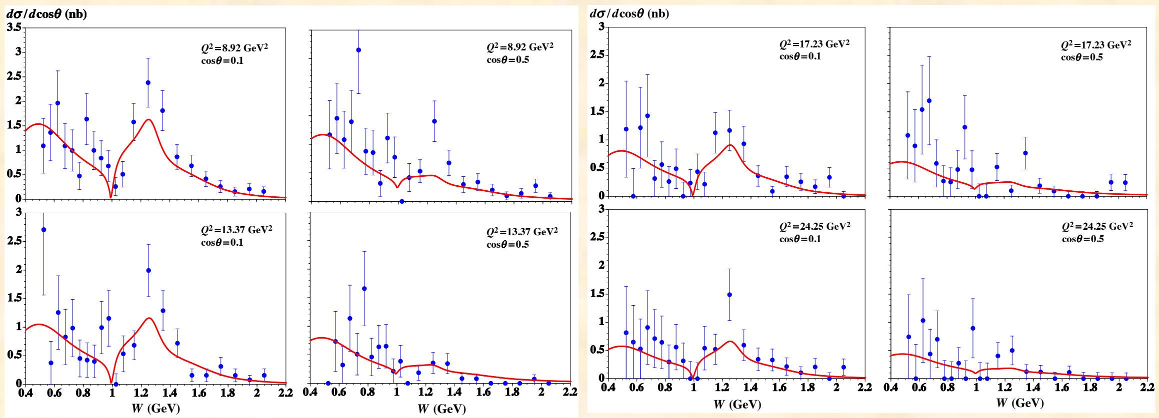
$$P_2(x) = \frac{1}{2}(3x^2-1)$$

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

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

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

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



Gravitational form factors and radii for pion

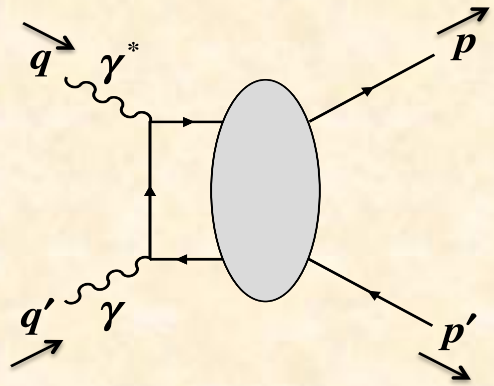
$$\int_0^1 dz(2z-1)\Phi_q^{\pi^0\pi^0}(z,\zeta,s) = \frac{2}{(P^+)^2}\langle \pi^0(p)\pi^0(p')|T_q^{++}(0)|0\rangle$$

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

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

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

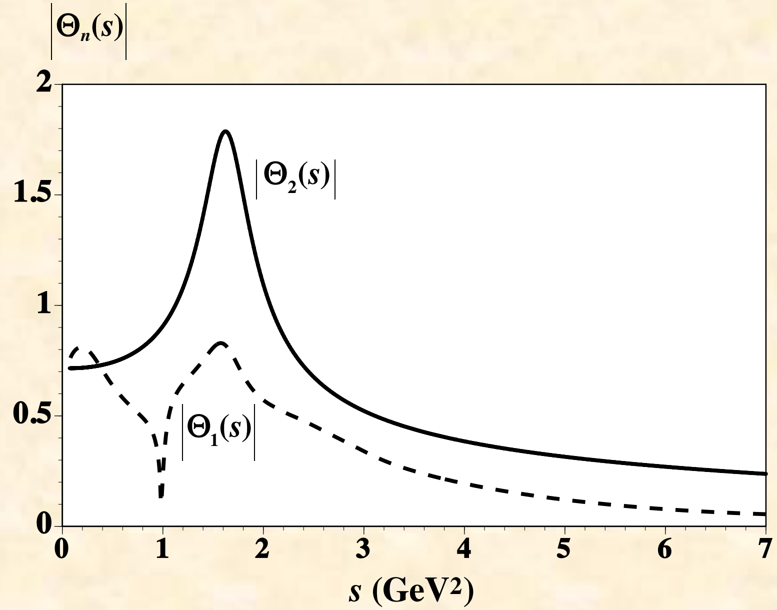
$\Theta_{1,q}$, $\Theta_{2,q}$: gravitational form factos for pion

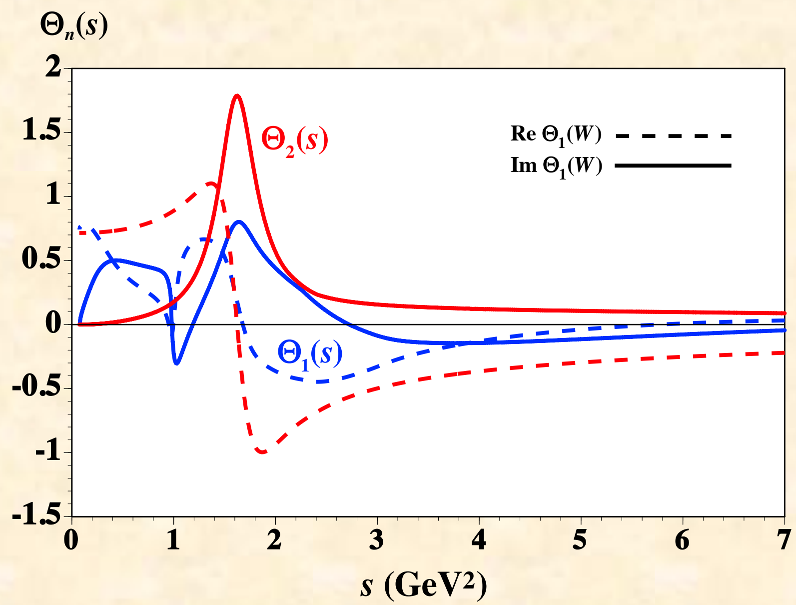


See also Hyeon-Dong Son, Hyun-Chul Kim, PRD90 (2014) 111901.

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

Gravitational form factors:
Original definition: H. Pagels, Phys. Rev. 144 (1966) 1250.
Operator relations: K. Tanaka, Phys. Rev. D 98 (2018) 034009;
Y. Hatta, A. Rajan, and K. Tanaka, JHEP 12 (2018) 008;
K. Tanaka, JHEP 01 (2019) 120.





Spacelike gravitational form factors and radii for pion

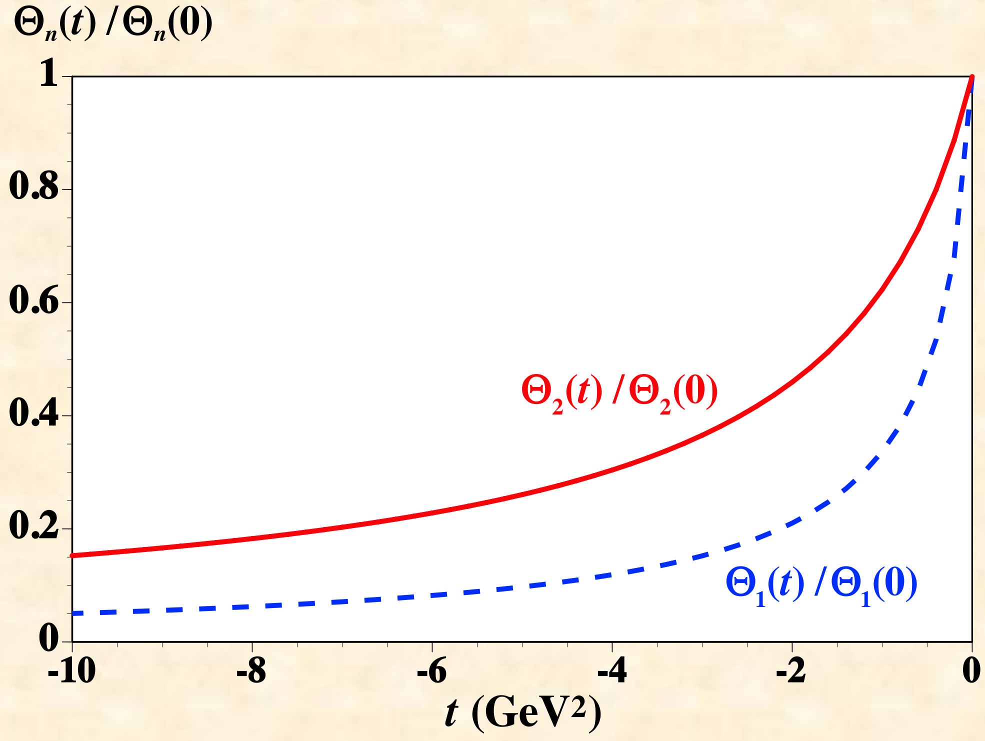
$$F(s) = \Theta_1(s),\ \Theta_1(s),\quad F(t) = \int_{4m_\pi^2}^{\infty} ds \frac{\mathrm{Im}\, F(s)}{\pi(s-t-i\varepsilon)},\quad \rho(r) = \frac{1}{(2\pi)^3}\int d^3q e^{-i\vec{q}\cdot\vec{r}} F(q) = \frac{1}{4\pi^2}\frac{1}{r}\int_{4m_\pi^2}^{\infty} ds\, e^{-\sqrt{s}r}\, \mathrm{Im}\, F(s)$$

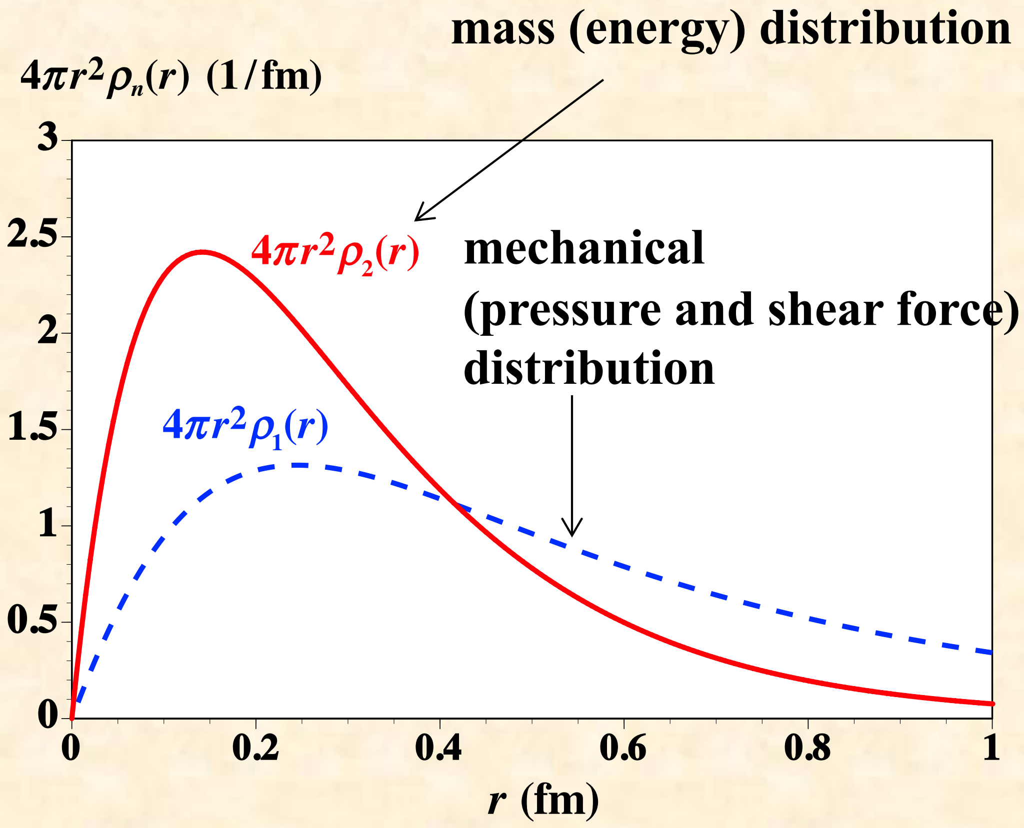
This is the first report on gravitational radii of hadrons from actual experimental measurements.

$$\sqrt{\langle r^2 \rangle_{\text{mass}}} = 0.32 \sim 0.39 \text{ fm},\quad \sqrt{\langle r^2 \rangle_{\text{mech}}} = 0.82 \sim 0.88 \text{ fm}$$

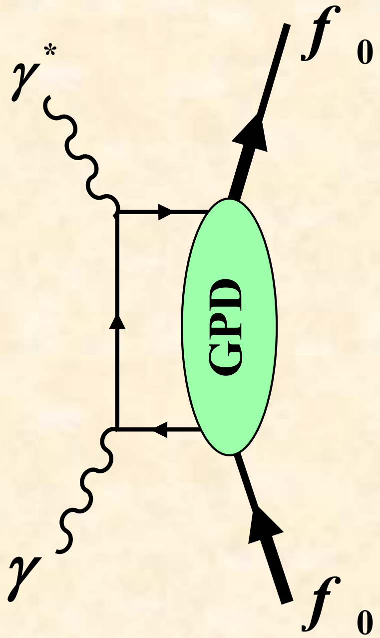
← First finding on gravitational radius from actual experimental measurements

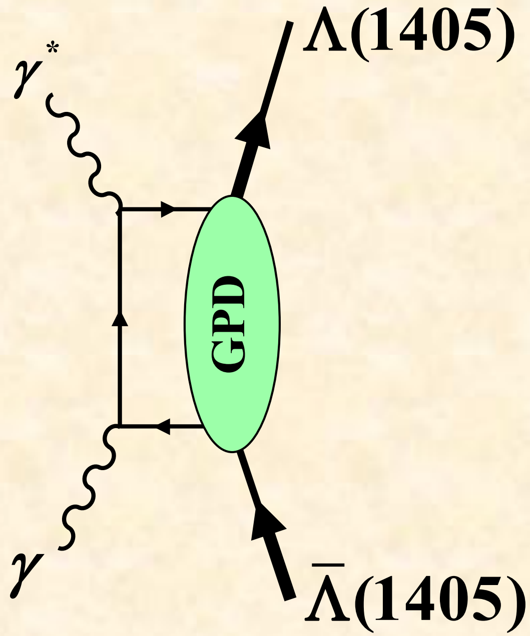
$$\Leftrightarrow \sqrt{\langle r^2 \rangle_{\text{charge}}} = 0.672 \pm 0.008 \text{ fm}$$





Timelike GPDs for exotic hadrons





Possible at super-KEKB?

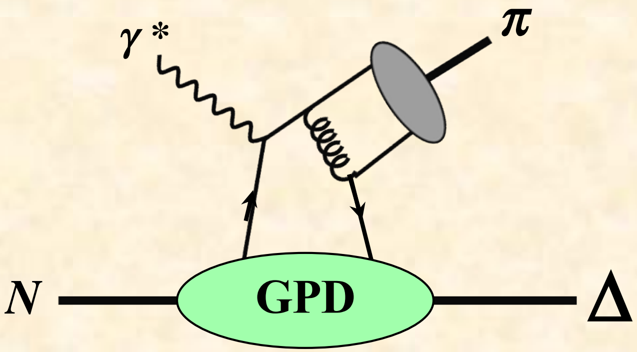
Difficult even at super-KEKB?

Transition GPDs for exotic hadrons

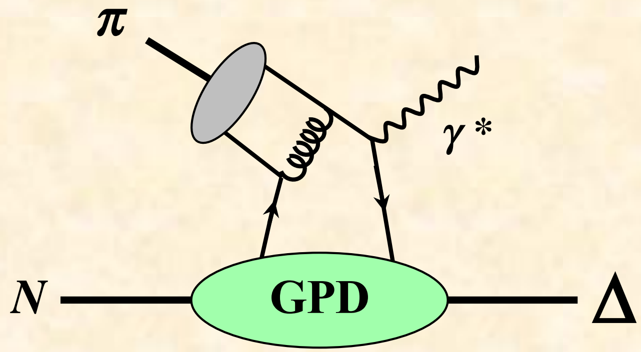
S. Diehl *et al*. (SK, 15th author),
arXiv:2405.15386, submitted for Eur. Phys. J. A

Transition GPDs from *N* to Δ

JLab / EIC



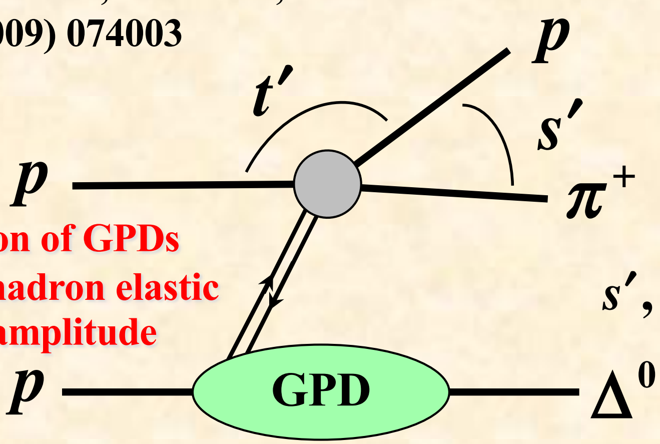
J-PARC



In future

$K^- + p \rightarrow \Lambda_{1405} + \gamma^*$?

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.

$\pi + N \rightarrow \gamma + \gamma + N'$

$h + M_B \rightarrow h' + \gamma + M_D$

$h + M_B \rightarrow h' + M_C + M_D$

$N \to \Delta$ transition GPDs

A. V. Belitsky, A. V. Radyushkin, Phys. Rept. 418 (2005) 1;
P. Kroll, K. Passek-Kumericki, Phys. Rev. D 107 (2023) 054009;
S. Diehl *et al.*, arXiv:2405.15386, submitted to Eur. Phys. J.

$$\frac{1}{2}\int\frac{dz^-}{2\pi}e^{ixP\cdot z}\left\langle \Delta^{++}(p',\lambda')\middle|\bar{u}\left(-\frac{1}{2}z\right)\gamma^+ d\left(\frac{1}{2}z\right)\middle|p(p,\lambda)\right\rangle_{z^+=0,\vec{z}_\perp=0}$$

$$=\frac{1}{2P^+}\bar{u}_\delta(p',\lambda')\left[\frac{\Delta^\delta n^\mu-\Delta^\mu n^\delta}{M_N}\left\{\gamma_\mu G_1(x,\xi,t)+\frac{P_\mu}{M_N}G_2(x,\xi,t)+\frac{\Delta_\mu}{M_N}G_3(x,\xi,t)\right\}+\frac{\Delta^+\Delta^\delta}{M_N^2}G_4(x,\xi,t)\right]\gamma_5 u(p,\lambda)$$

$$\frac{1}{2}\int\frac{dz^-}{2\pi}e^{ixP\cdot z}\left\langle \Delta^{++}(p',\lambda')\middle|\bar{u}\left(-\frac{1}{2}z\right)\gamma^+\gamma^5 d\left(\frac{1}{2}z\right)\middle|p(p,\lambda)\right\rangle_{z^+=0,\vec{z}_\perp=0}$$

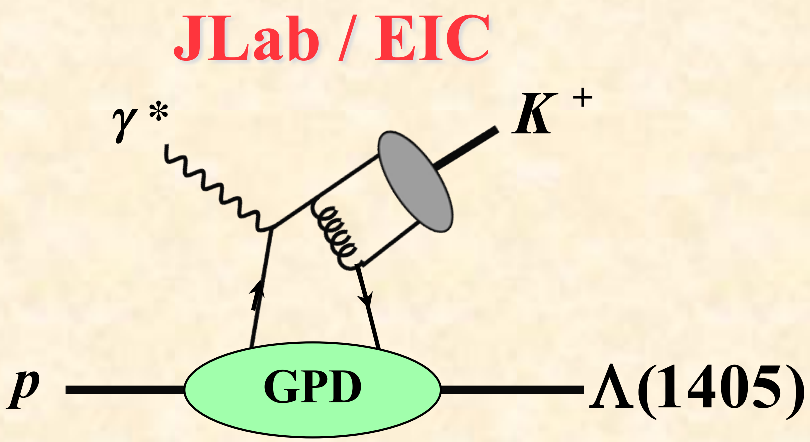
$$=\frac{1}{2P^+}\bar{u}_\delta(p',\lambda')\left[\frac{\Delta^\delta n^\mu-\Delta^\mu n^\delta}{M_N}\left\{\gamma_\mu \tilde{G}_1(x,\xi,t)+\frac{P_\mu}{M_N}\tilde{G}_2(x,\xi,t)+\frac{\Delta_\mu}{M_N}\tilde{G}_3(x,\xi,t)\right\}+\frac{\Delta^+\Delta^\delta}{M_N^2}\tilde{G}_4(x,\xi,t)\right]u(p,\lambda)$$

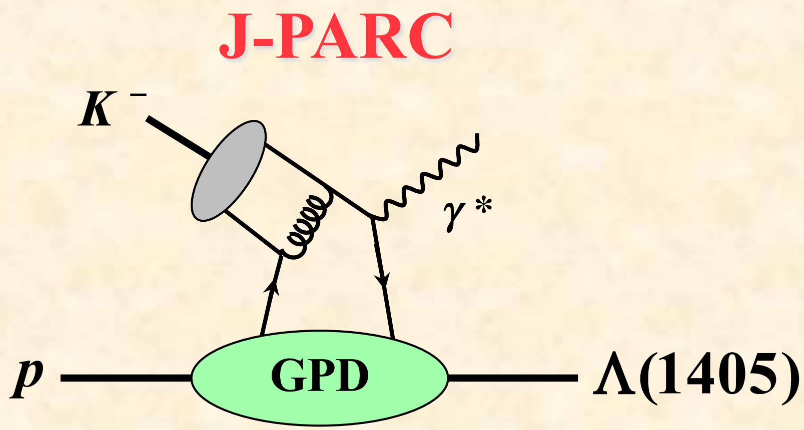
$$\frac{1}{2}\int\frac{dz^-}{2\pi}e^{ixP\cdot z}\left\langle \Delta^{++}(p',\lambda')\middle|\bar{u}\left(-\frac{1}{2}z\right)i\sigma^{+j} d\left(\frac{1}{2}z\right)\middle|p(p,\lambda)\right\rangle_{z^+=0,\vec{z}_\perp=0}$$

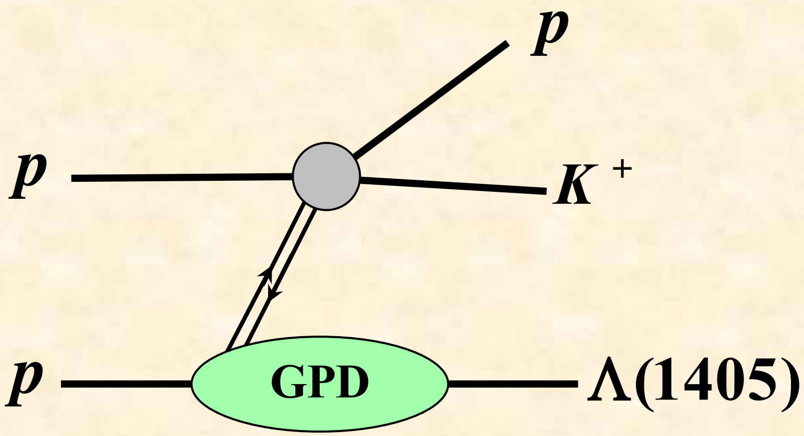
$$=\frac{1}{2P^+}\bar{u}_\delta(p',\lambda')\left[\frac{p^\delta}{M_N}i\sigma^{+j}G_{1T}(x,\xi,t)+p^\delta\frac{P^+\Delta^j-\Delta^+P^j}{M_N^3}G_{2T}(x,\xi,t)+p^\delta\frac{\gamma^+\Delta^j-\Delta^+\gamma^j}{2M_N^2}G_{3T}(x,\xi,t)\right.$$
$$\left.+p^\delta\frac{\gamma^+P^j-P^+\gamma^j}{2M_N^2}G_{4T}(x,\xi,t)+(n^\delta\gamma^j-\gamma^\delta n^j)G_{5T}(x,\xi,t)+\frac{n^\delta\Delta^j-\Delta^\delta n^j}{M_N}G_{6T}(x,\xi,t)\right]\gamma_5 u(p,\lambda)$$
$$+\frac{1}{2P^+}\left[\left\{\bar{u}^+(p',\lambda')\gamma^j-\bar{u}^j(p',\lambda')\gamma^+\right\}G_{7T}(x,\xi,t)+\frac{\bar{u}^+(p',\lambda')\Delta^j-\bar{u}^j(p',\lambda')\Delta^+}{M_N}G_{8T}(x,\xi,t)\right]\gamma_5 u(p,\lambda)$$

Rarita-Schwinger: $u^\alpha(p,\lambda)=\sum_{\rho,\sigma}\left\langle 1\rho;\frac{1}{2}\sigma\middle|\frac{3}{2}\lambda\right\rangle\varepsilon^\alpha(p,\rho)u(p,\sigma)$

Transition GPDs for exotic hadrons







However, there is no theoretical study on the N→Λ(1405) transition GPDs at this stage.

Constituent-counting rule for exotic hadrons

H. Kawamura, S. Kumano, T. Sekihara,
Phys. Rev. 88 (2013) 034010.

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

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

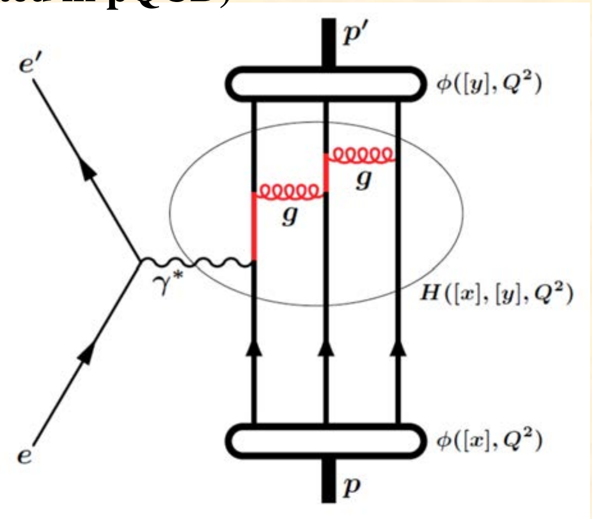
Constituent-counting rule in perturbative QCD: Form factor

Consider the magnetic form factor of the proton

$$\langle p'|J^\mu|p\rangle \simeq \bar{u}(p')\gamma^\mu G_M(Q^2)u(p) \text{ at } Q^2 = -q^2 \gg m_N^2$$

$$G_M(Q^2) = \int d[x]d[y]\phi_p([y])H_M([x],[y],Q^2)\phi_p([x])$$

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



In the Breit frame with $q = (0, \vec{q}), \quad |\vec{p}| = |\vec{p}'| \equiv P \sim O(Q)$.

$u^\dagger u = 2E \quad \Rightarrow$ External quark line: $u \sim \sqrt{P} \sim \sqrt{Q}$

$$\langle p'|J^\mu|p\rangle \simeq \bar{u}(p')\gamma^\mu G_M(Q^2)u(p) \sim (\sqrt{Q})^2 G_M(Q^2)$$

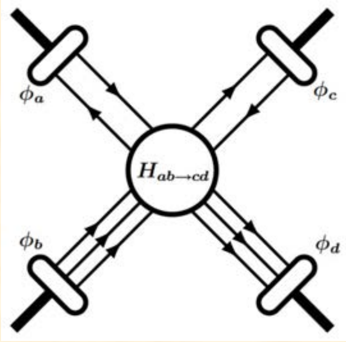
- Two quark propagators: $\dfrac{1}{Q^2}$
- Two gluon propagators: $\dfrac{1}{(Q^2)^2}$
- Six external quark lines: $(\sqrt{Q})^6$

$$\langle p'|J^\mu|p\rangle \sim \frac{1}{Q^2}\frac{\alpha_s(Q^2)}{(Q^2)^2}(\sqrt{Q})^6 = \frac{\alpha_s(Q^2)}{(Q^2)^{3/2}}$$

$$\Rightarrow G_M(Q^2) \sim \frac{1}{(\sqrt{Q})^2}\langle p'|J^\mu|p\rangle \sim \frac{1}{(Q^2)^{1/2}}\frac{\alpha_s(Q^2)}{(Q^2)^{3/2}} = \frac{\alpha_s(Q^2)}{(Q^2)^2} \sim \frac{1}{t^{n_N-1}}, \quad n_N = 3, \quad -t = Q^2$$

Counting rule for the form factor: $G_M(Q^2) \sim \dfrac{1}{t^{n_N-1}}, \ n_N = 3$

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.

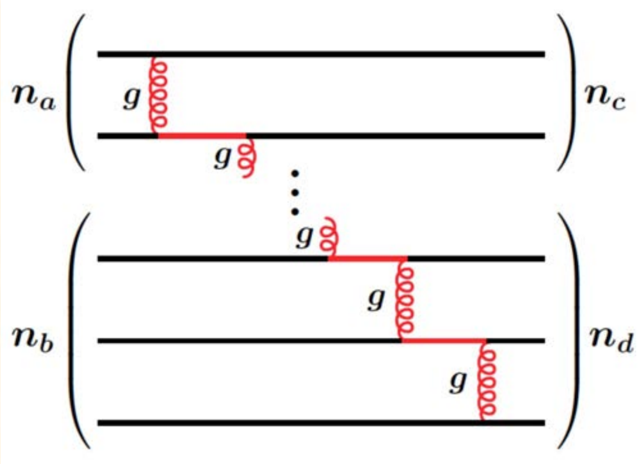
There are $n/2-1$ gluon propagators $\sim 1/(P^2)^{n/2-1}$.

(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 $\sim (\sqrt{P})^n$.



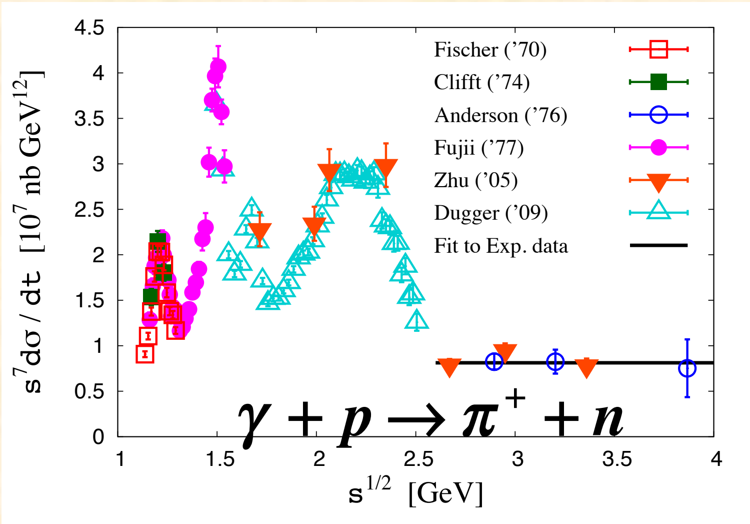
$$M_{ab\to cd} \sim \frac{1}{(P^2)^{n/2-1}}\frac{1}{(P)^{n/2-2}}(\sqrt{P})^n = \frac{(P)^{n/2}}{(P)^{n-2}(P)^{n/2-2}} = \frac{1}{(P)^{n-4}} \sim \frac{1}{s^{n/2-2}}$$

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

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

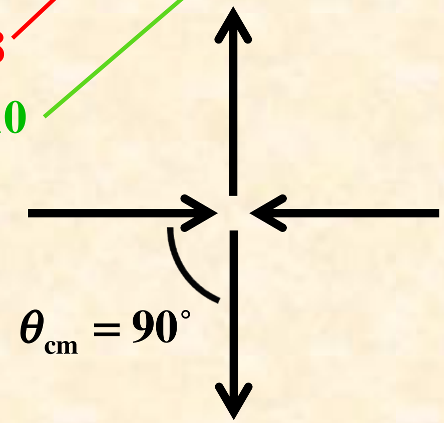
BNL experiment

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

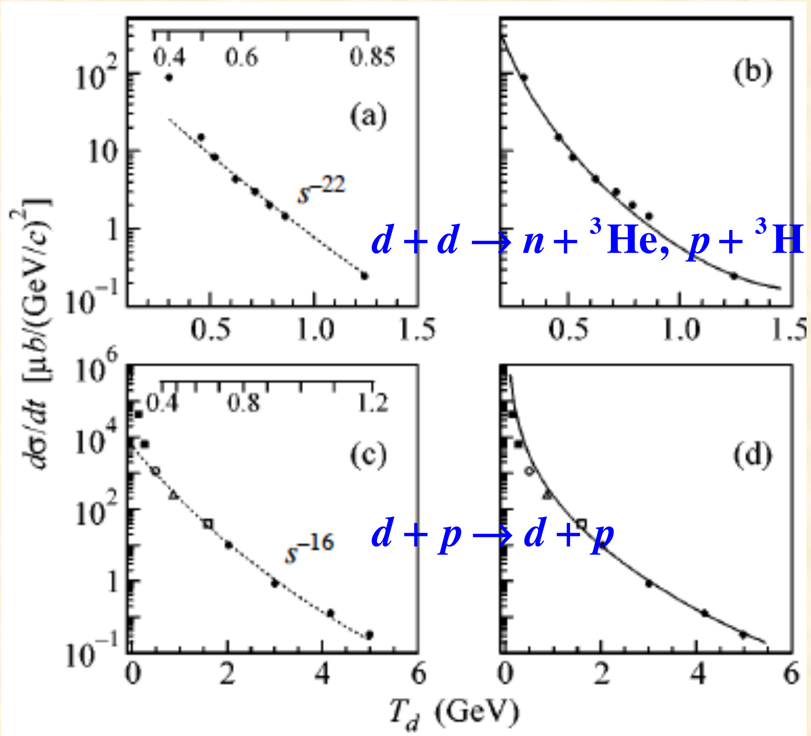
$n-2$: $(2+3+2+3)-2=8$

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



Constituent-counting rule for "molecular" systems

Y. N. Uzikov, JETP Lett. 81, 303 (2005).



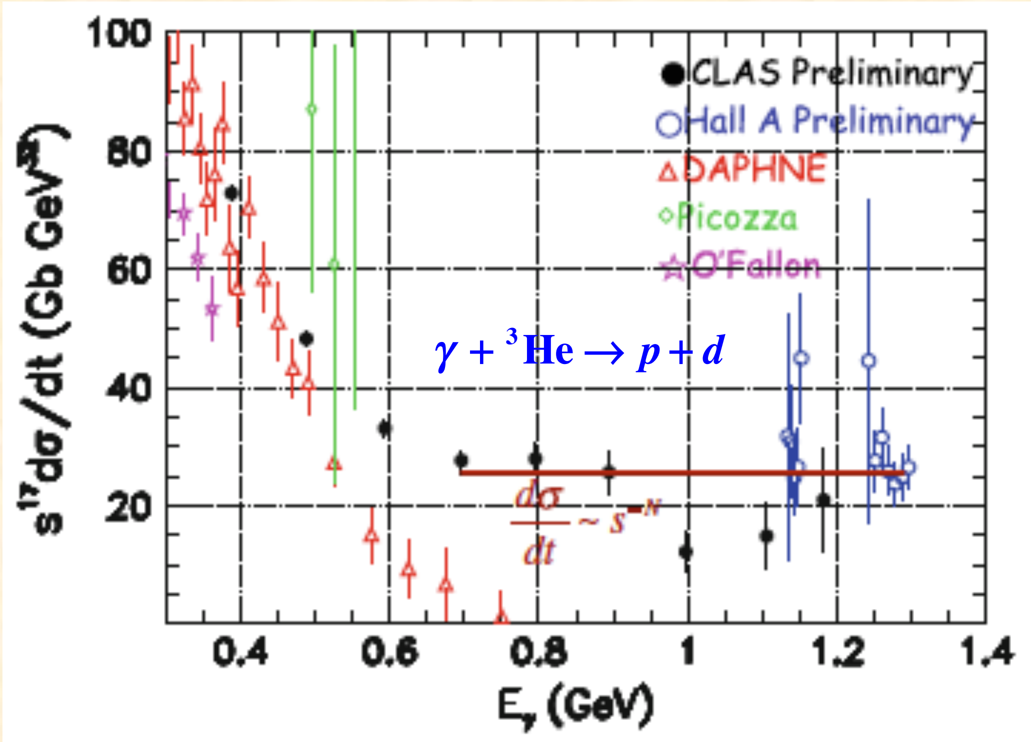
$$d + d \to n + {}^3\mathrm{He},\ p + {}^3\mathrm{H}$$

$$n - 2 = (6 + 6 + 3 + 9) - 2 = 22$$

$$d + p \to d + p$$

$$n - 2 = (6 + 3 + 6 + 3) - 2 = 16$$

Y. Ilieva, Few Body Syst. 54, 989 (2013).

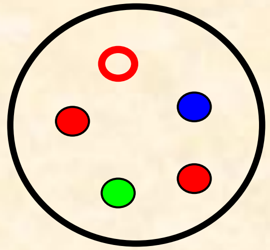


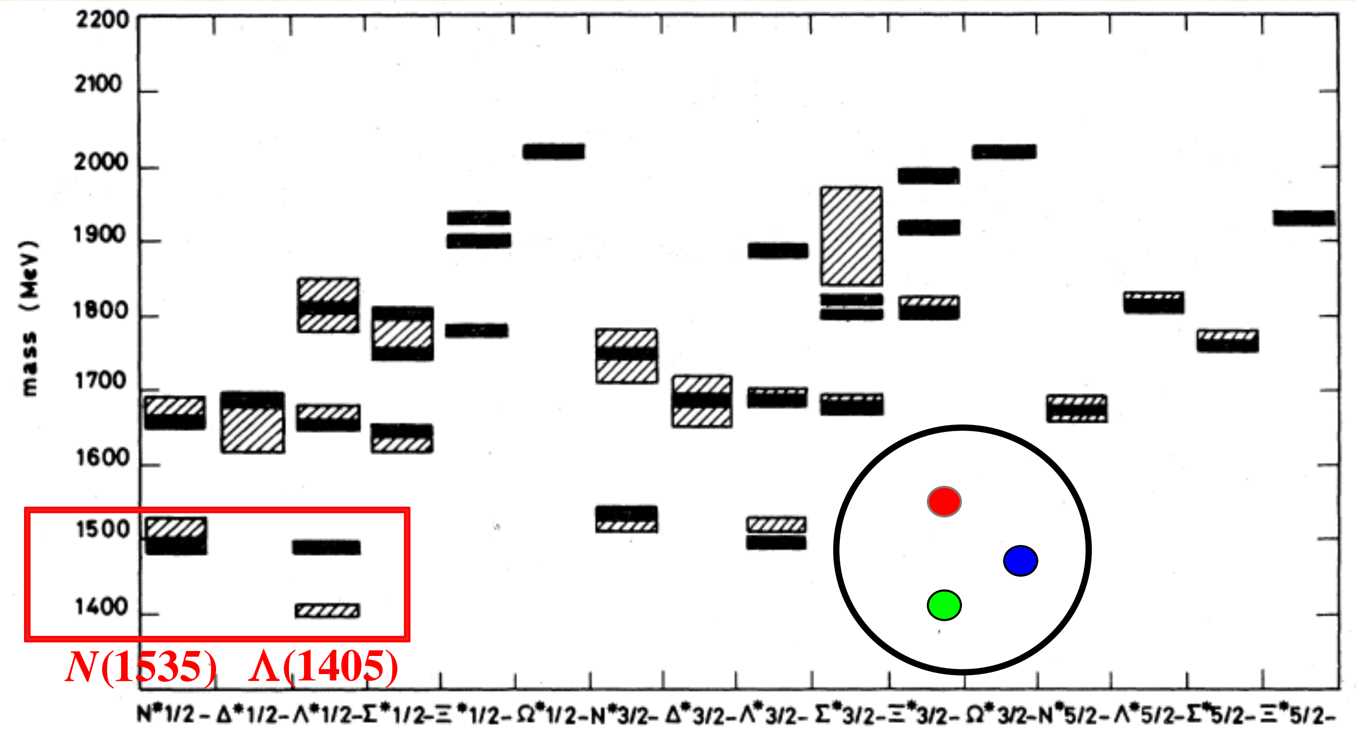
$$\gamma + {}^3\mathrm{He} \to p + d$$

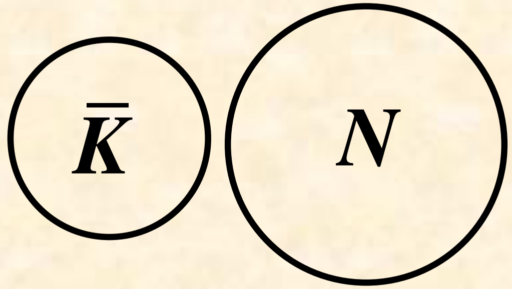
$$n - 2 = (1 + 9 + 3 + 6) - 2 = 17$$

$\Lambda(1405)$: exotic hadron?

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







Our proposal:

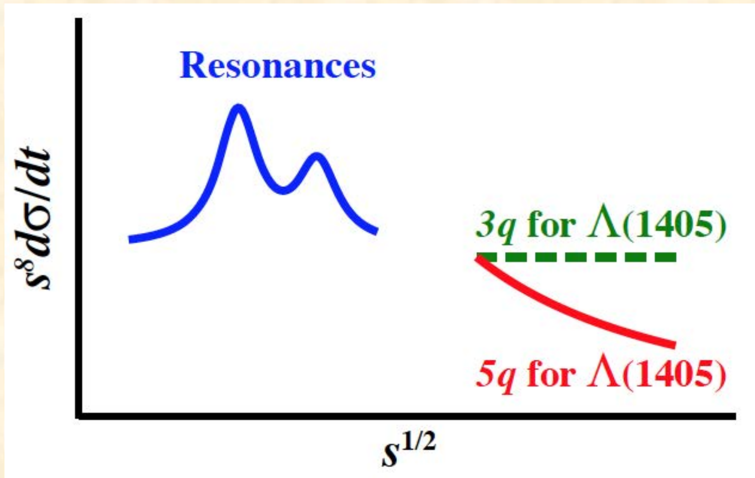
Exotic hadron production

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

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

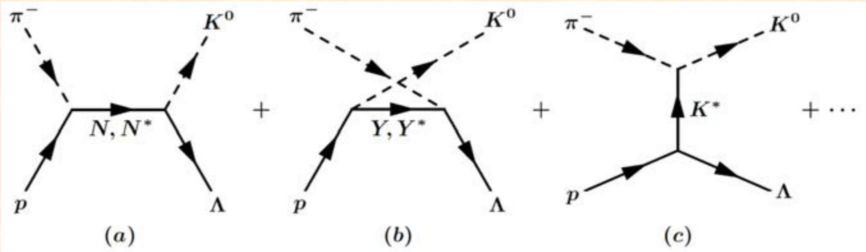
Most spectra agree with the ones by a 3q-picture

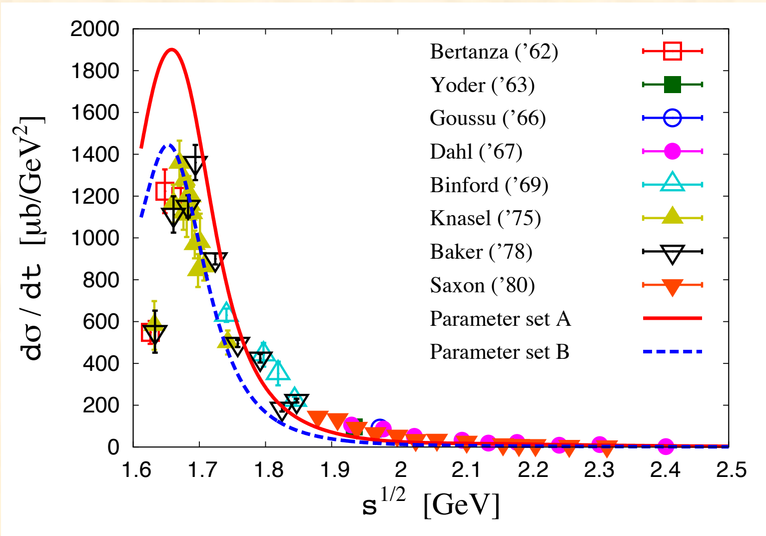
- Only $\Lambda(1405)$ deviates from the measurement.
- Difficult to understand the small mass of $\Lambda(1405)$ in comparison with $N(1535)$.
  $\to \bar{K}N$ molecure or penta-quark ($qqqq\bar{q}$)?



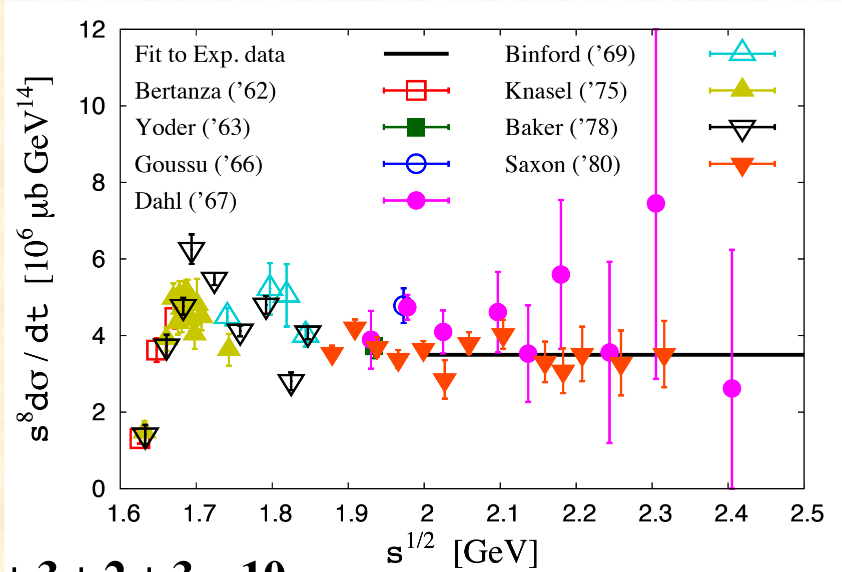
Ordinary-hadron production $\pi^- + p \to K^0 + \Lambda$ as a reference

At low energies





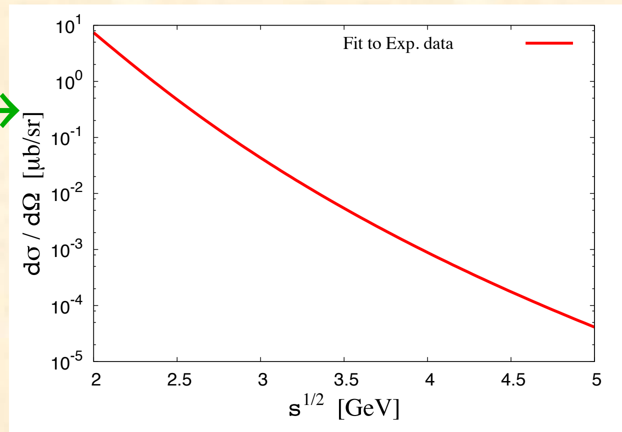
From low to higher energies



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

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

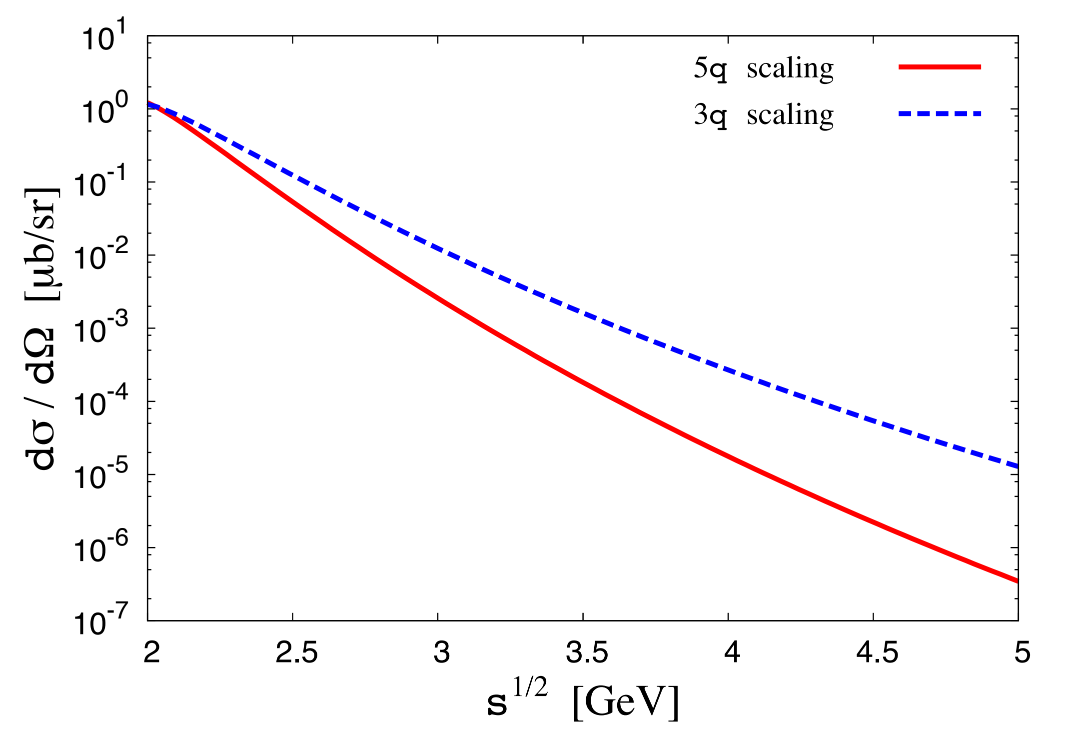
$$n = 2+3+2+3 = 10 \quad \text{if } \Lambda(1405) = \text{three-quark state}$$

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

(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

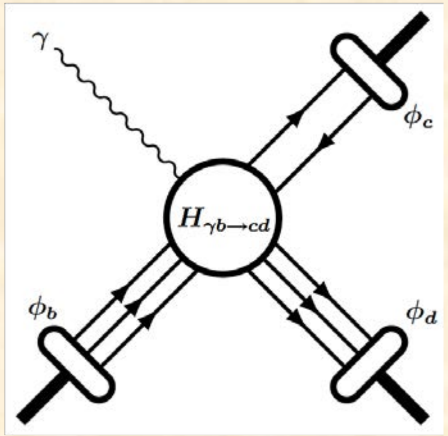


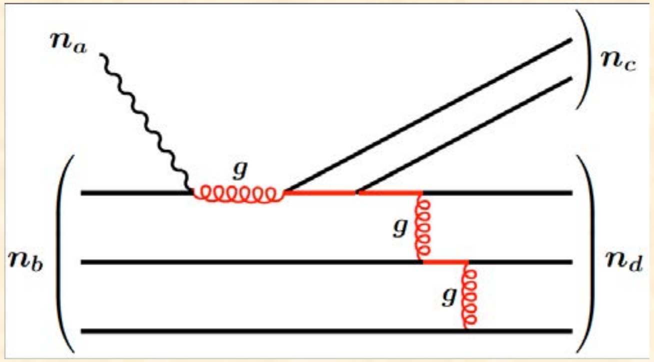
Hard production of hyperons

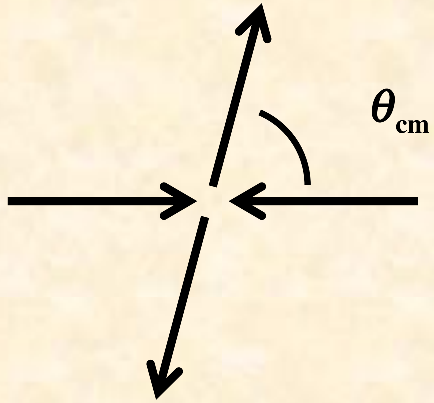
W.-C. Chang, S. Kumano, and T. Sekihara

Phys. Rev. D 93 (2016) 034006 (arXiv:1512.06647).

JLab hyperon productions







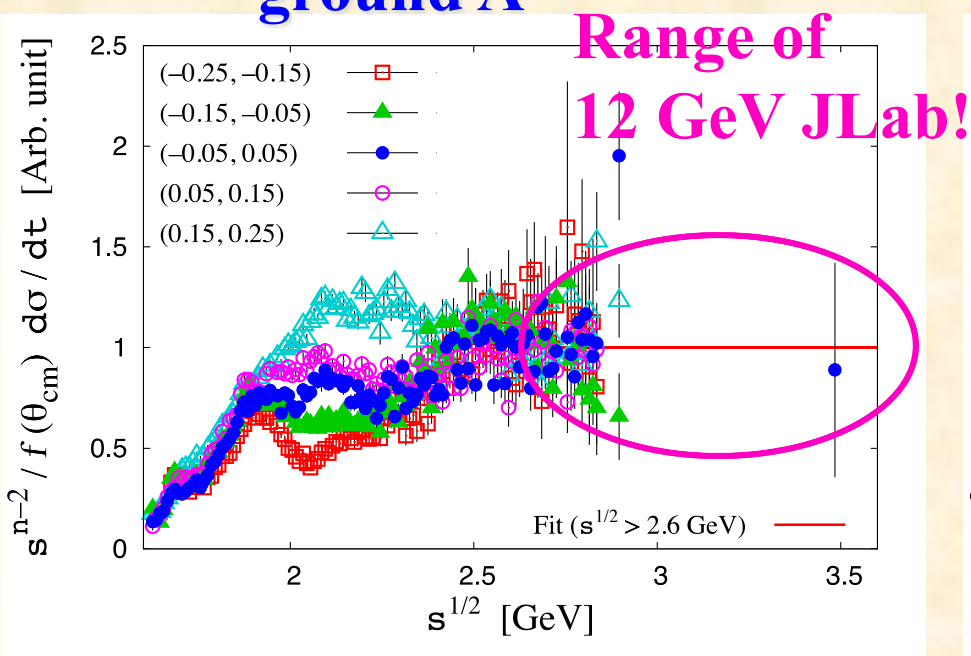
5 bins: $-0.25 < \cos\theta_{cm} < -0.15, \cdots, 0.15 < \cos\theta_{cm} < 0.25$

4 bins: $-0.20 < \cos\theta_{cm} < -0.10, \cdots, 0.10 < \cos\theta_{cm} < 0.20$

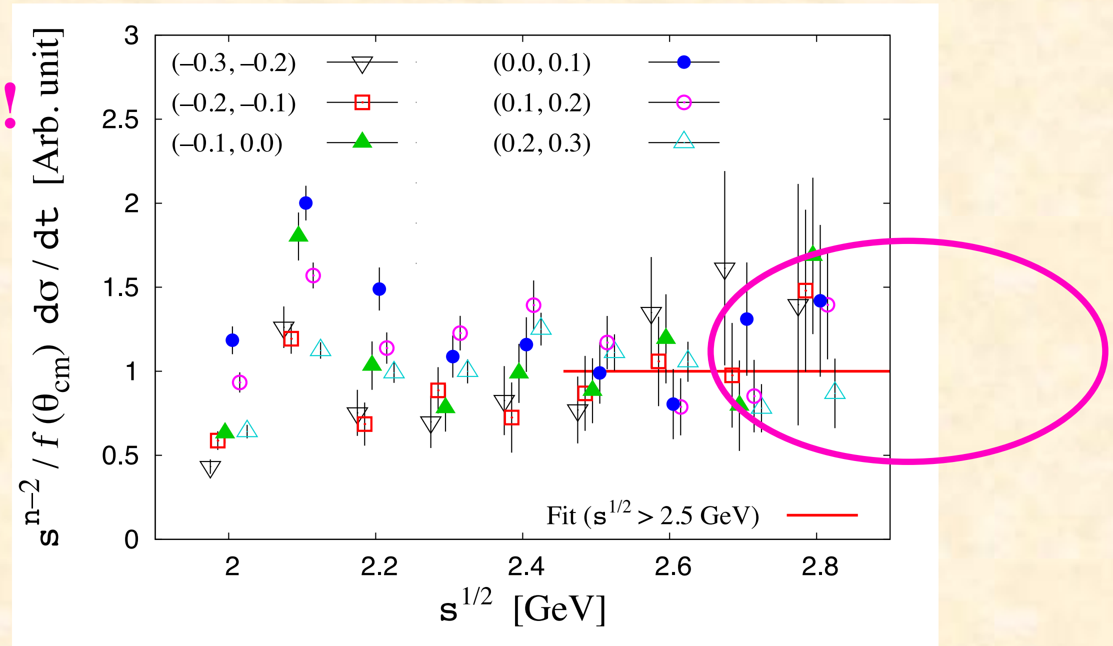
...

1 bin: $-0.05 < \cos\theta_{cm} < +0.05$

ground Λ

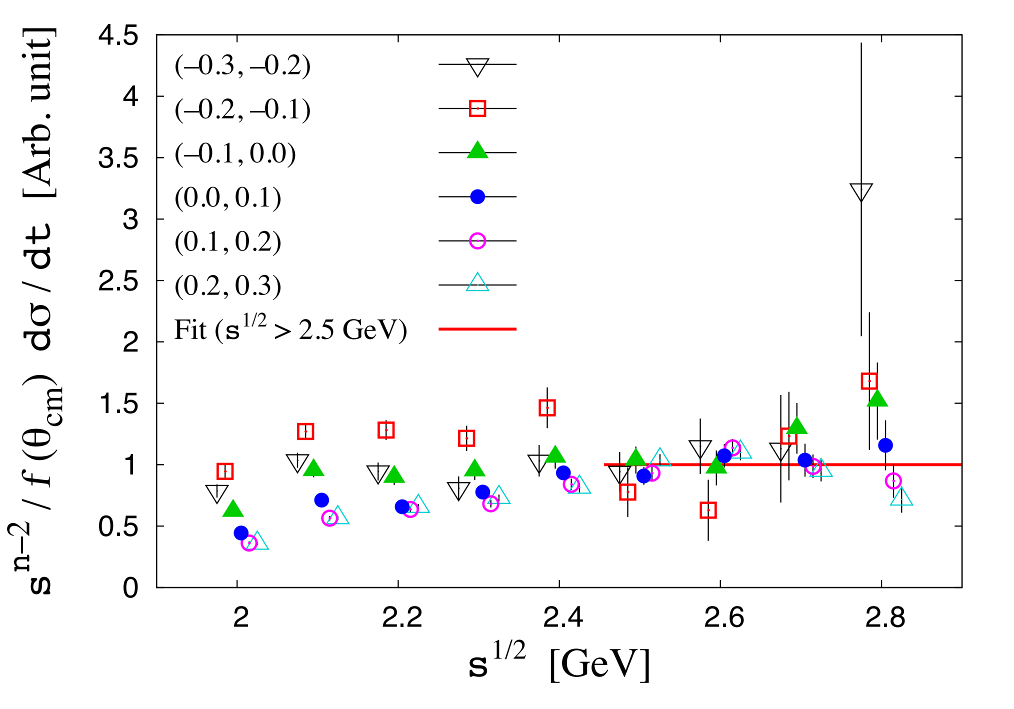


Λ(1405)

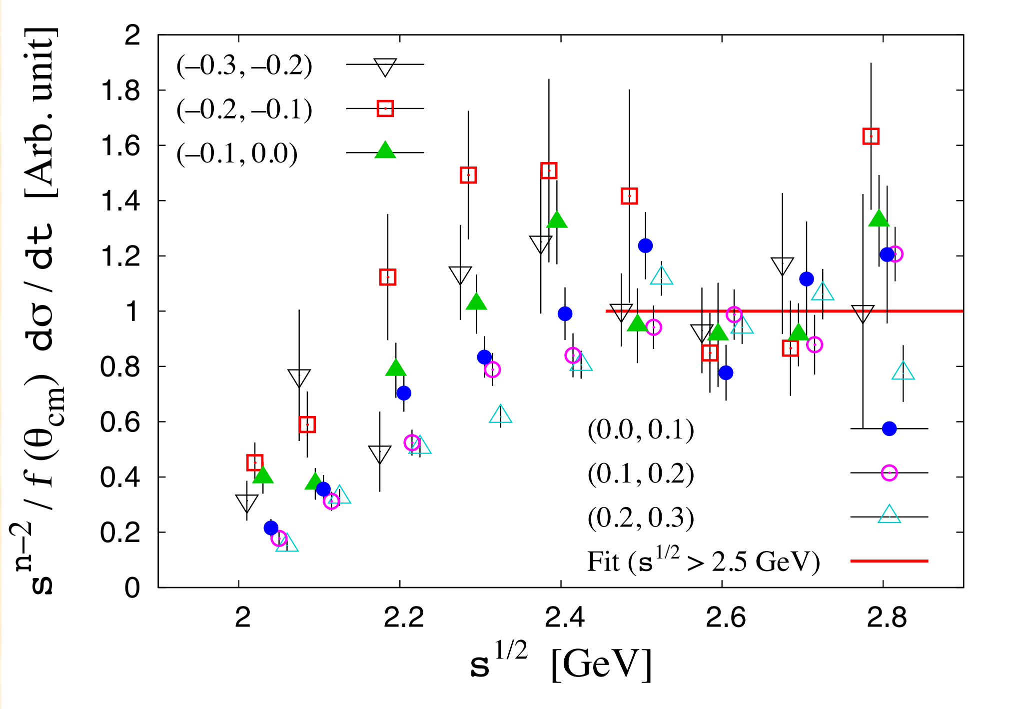


Hyperon productions

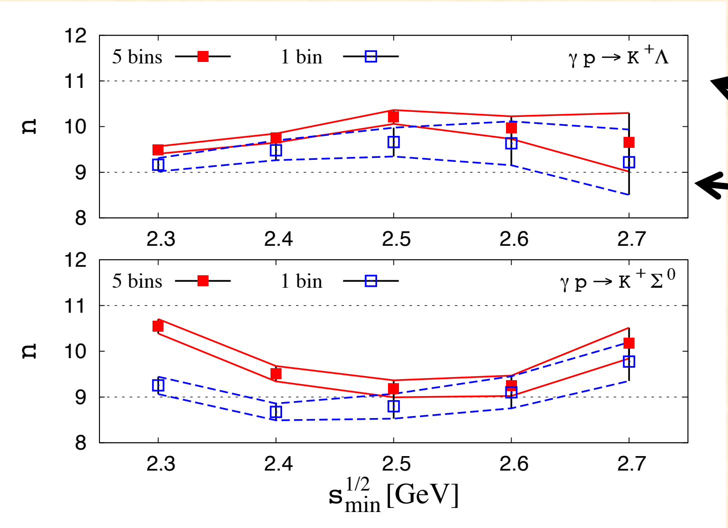
$\Sigma^0(1385)$



$\Lambda(1520)$

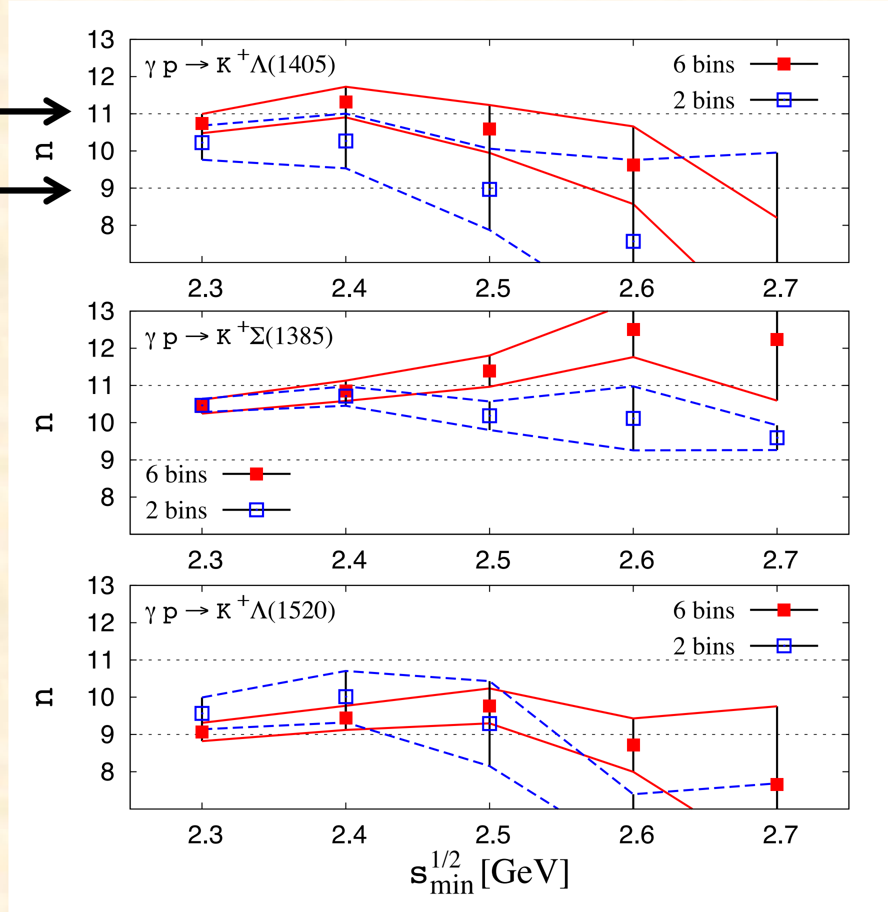


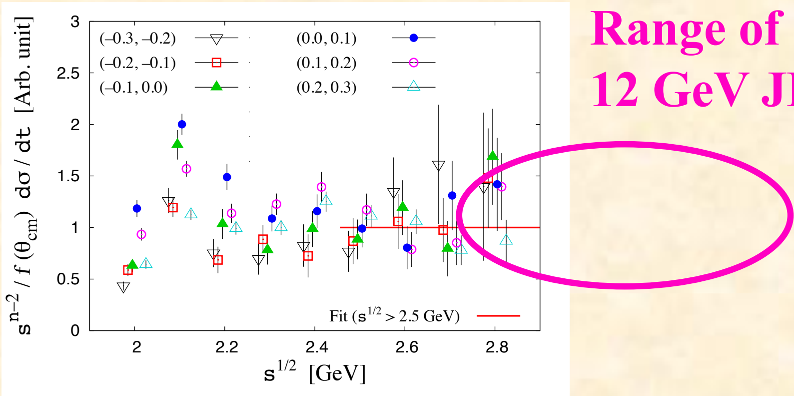
JLab hyperon productions including Λ(1405)



$n_\Lambda = 5$

$n_\Lambda = 3$





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 and EIC experiment plays an important role!

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

Summary on exotic hadron structure by hard exclusive orocesses

- **We propose to use hard exclusive production of exotic hadrons for probing internal quark-gluon structure by the constituent conting rule,** $\frac{d\sigma}{dt} = \frac{\text{const}}{s^{n-2}}$.

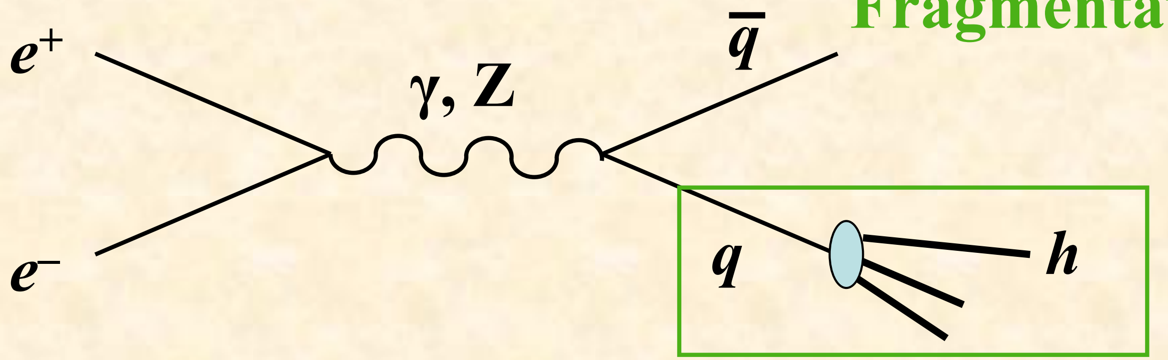
- **As an example,** $\pi^- + p \to K^0 + \Lambda(1405)$ **is studied together with** $\pi^- + p \to K^0 + \Lambda$ **as a reference of an ordinary hadron.**

- **Exclusive processes of exotic hadrons can be investigated at many facilities in the world.**
  For example, J-PARC, KEK-B, JLab, AMBER, EIC, ...
  in general any hadron facilities like GSI, Fermilab, RHIC, LHC, ...

Exotic hadrons by fragmentation functions

M. Hirai, S. Kumano, M. Oka, K. Sudoh,
Phys. Rev. D77 (2008) 017504 (arXiv:0708.1816).

Fragmentation Functions



Fragmentation: hadron production from a quark, antiquark, or gluon

Total fragmentation function is defined by

$$z \equiv \frac{E_h}{\sqrt{s}/2} = \frac{2E_h}{Q} = \frac{E_h}{E_q}, \quad s = Q^2$$

$$F^h(z,Q^2) = \frac{1}{\sigma_{tot}} \frac{d\sigma(e^+e^- \to hX)}{dz}$$

σ_{tot} = total hadronic cross section

Variable z

- Hadron energy / Beam energy
- Hadron energy / Primary quark energy

A fragmentation process occurs from quarks, antiquarks, and gluons, so that F^h is expressed by their individual contributions:

$$F^h(z,Q^2)_{LO} = \sum_i D_i^h(y,Q^2)$$

$D_i^h(z,Q^2)$ = fragmentation function of hadron h from a parton i

Momentum (energy) sum rule

$D_i^h(z, Q^2) =$ probability to find the hadron h from a parton i with the energy fraction z

Energy conservation: $\sum_h \int_0^1 dz\, z\, D_i^h(z, Q^2) = 1$

$h = \pi^+,\ \pi^0,\ \pi^-,\ K^+,\ K^0,\ \bar{K}^0,\ K^-,\ p,\ \bar{p},\ n,\ \bar{n},\ \cdots$

Favored and disfavored fragmentation functions

Differences between them could be used for exotic hadron studies.

Simple quark model: $\pi^+(u\bar{d}),\ K^+(u\bar{s}),\ p(uud),\ \cdots$

Favored fragmentation: $D_u^{\pi^+},\ D_{\bar{d}}^{\pi^+}, \ldots$

(from a quark which exists in a naive quark model)

Disfavored fragmentation: $D_d^{\pi^+},\ D_{\bar{u}}^{\pi^+},\ D_s^{\pi^+}, \ldots$

(from a quark which does not exist in a naive quark model)

Exotic hadrons by fragmentation functions

"Favored" and "disfavored" (unfavored) fragmentation functions
Possibility of finding exotic hadrons in high-energy processes

Hirai, SK, Oka, Sudoh, PRD 77 (2008) 017504.

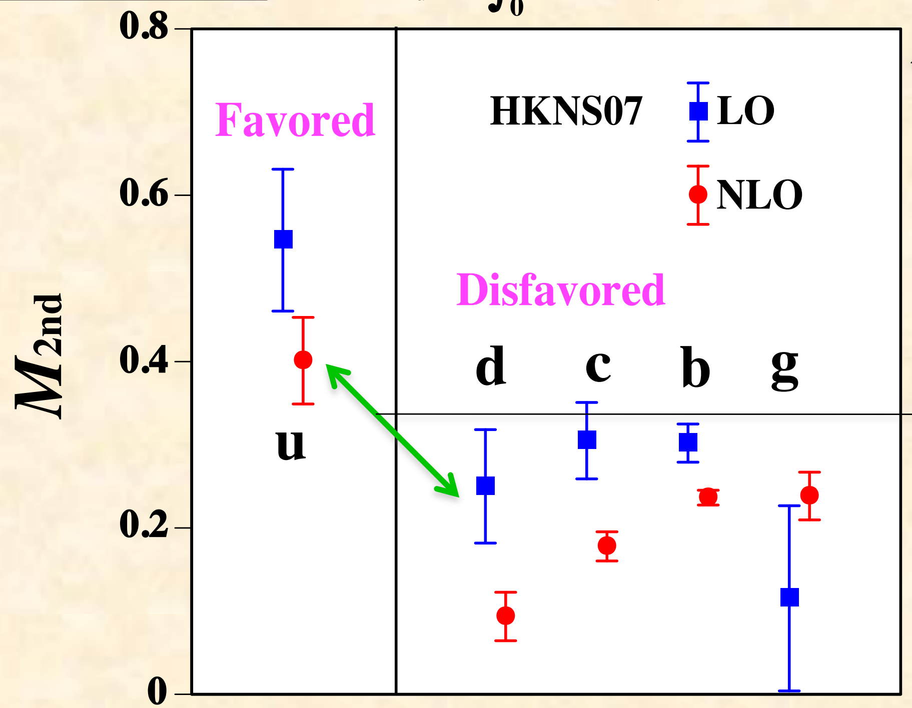
Possibilities for $f_0(980)$: $\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$, $s\bar{s}$, $\frac{1}{\sqrt{2}}(u\bar{u}s\bar{s}+d\bar{d}s\bar{s})$, $K\bar{K}$, or gg

$e.g.$ if $f_0(980)=s\bar{s}$: favored $s, \bar{s} \to f_0$; disfavored $u, d, \bar{u}, \bar{d} \to f_0, \cdots$

f_0(980): Belle analysis is possible in principle.

Pion case

$$M_{2nd} = \int_0^1 dz\, z\, D_i^{\pi^+}(z)$$



2nd moments of
M. Hirai, SK, T.-H. Nagai, K. Sudoh,
PRD 75 (2007) 094009.

There are distinct differences between the favored and disfavored 2nd moments.
→ It could be used for exotic-hadron studies.

Criteria for determining f_0 structure by its fragmentation functions

Possible configurations of $f_0(980)$

(1) ordinary u,d - meson $\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$

(2) strange meson, $s\bar{s}$

(3) tetraquark ($K\bar{K}$), $\frac{1}{\sqrt{2}}(u\bar{u}s\bar{s}+d\bar{d}s\bar{s})$

(4) glueball gg

Contradicts with experimental widths

$\Gamma_{\text{theo}}(f_0 \to \pi\pi) = 500-1000\ \text{MeV} \gg \Gamma_{\text{exp}} = 40-100\ \text{MeV}$

$\Gamma_{\text{theo}}(f_0 \to \gamma\gamma) = 1.3-1.8\ \text{keV} \gg \Gamma_{\text{exp}} = 0.205\ \text{keV}$

Contradicts with lattice-QCD estimate

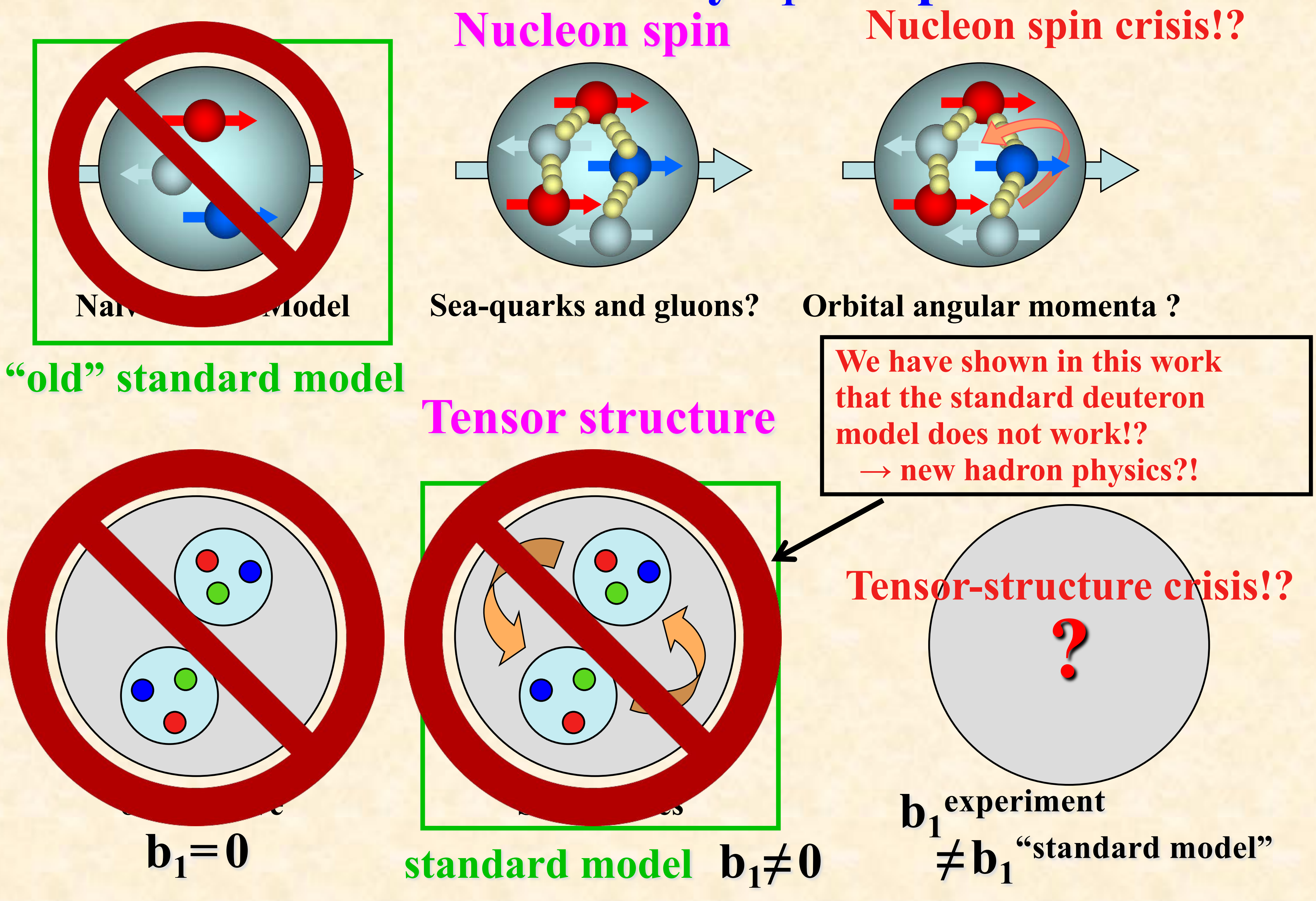
$m_{\text{lattice}}(f_0) = 1600\ \text{MeV} \gg m_{\text{exp}} = 980\ \text{MeV}$

There could difference in fragmentation functions for f_0 depending on its internal structure.

- **Favored and disfavored fragmentation functions**
- **2nd moments and functional forms**

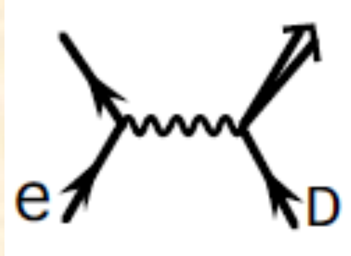
Exotic signatures in deuteron

Situation of tensor structure by b_1 for spin-1 deuteron

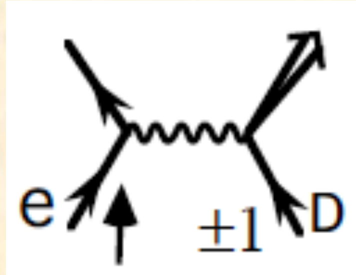


Structure Functions

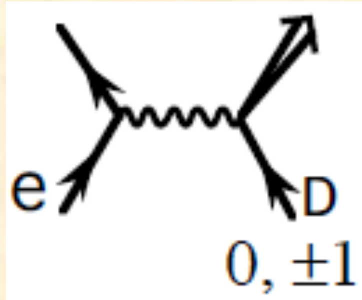
$$F_1 \propto \langle d\sigma \rangle$$



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



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



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

Parton Model

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

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

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

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

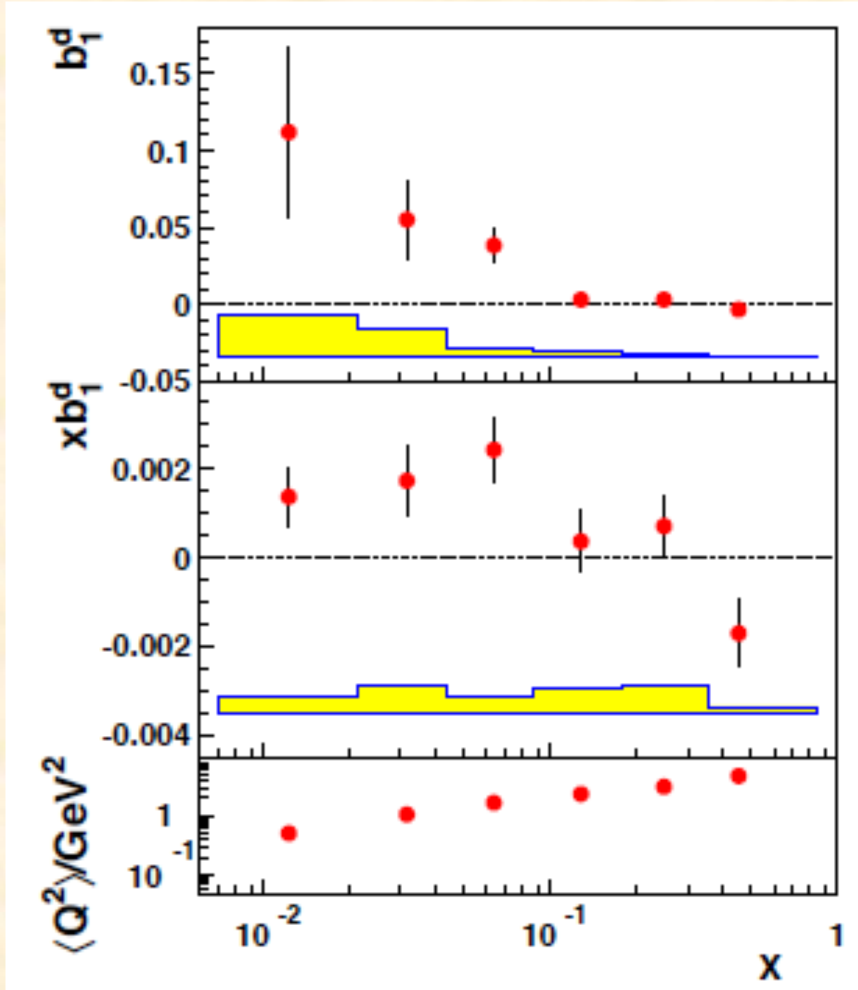
$$\int_{0.002}^{0.85} dx\, b_1(x) = [1.05 \pm 0.34(\text{stat}) \pm 0.35(\text{sys})] \times 10^{-2}$$

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

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

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

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



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

b_1 sum rule: F. E. Close and SK, PRD 42 (1990) 2377.

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

Drell-Yan experiments probe these antiquark distributions.

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

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

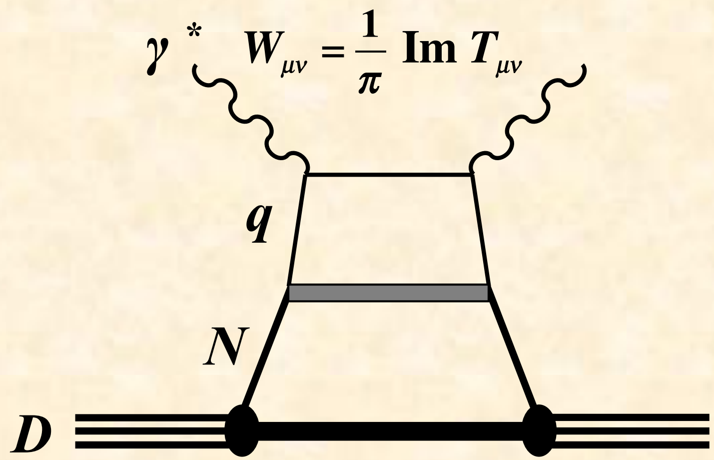
D-state admixture: $\phi^H(\vec{p}) = \phi_{\ell=0}^H(\vec{p}) + \phi_{\ell=2}^H(\vec{p})$

⇓

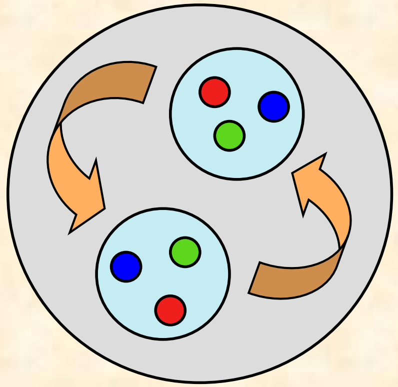
$$b_1(x) = \int \frac{dy}{y} \delta_T f(y) F_1^N(x/y, Q^2)$$

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

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

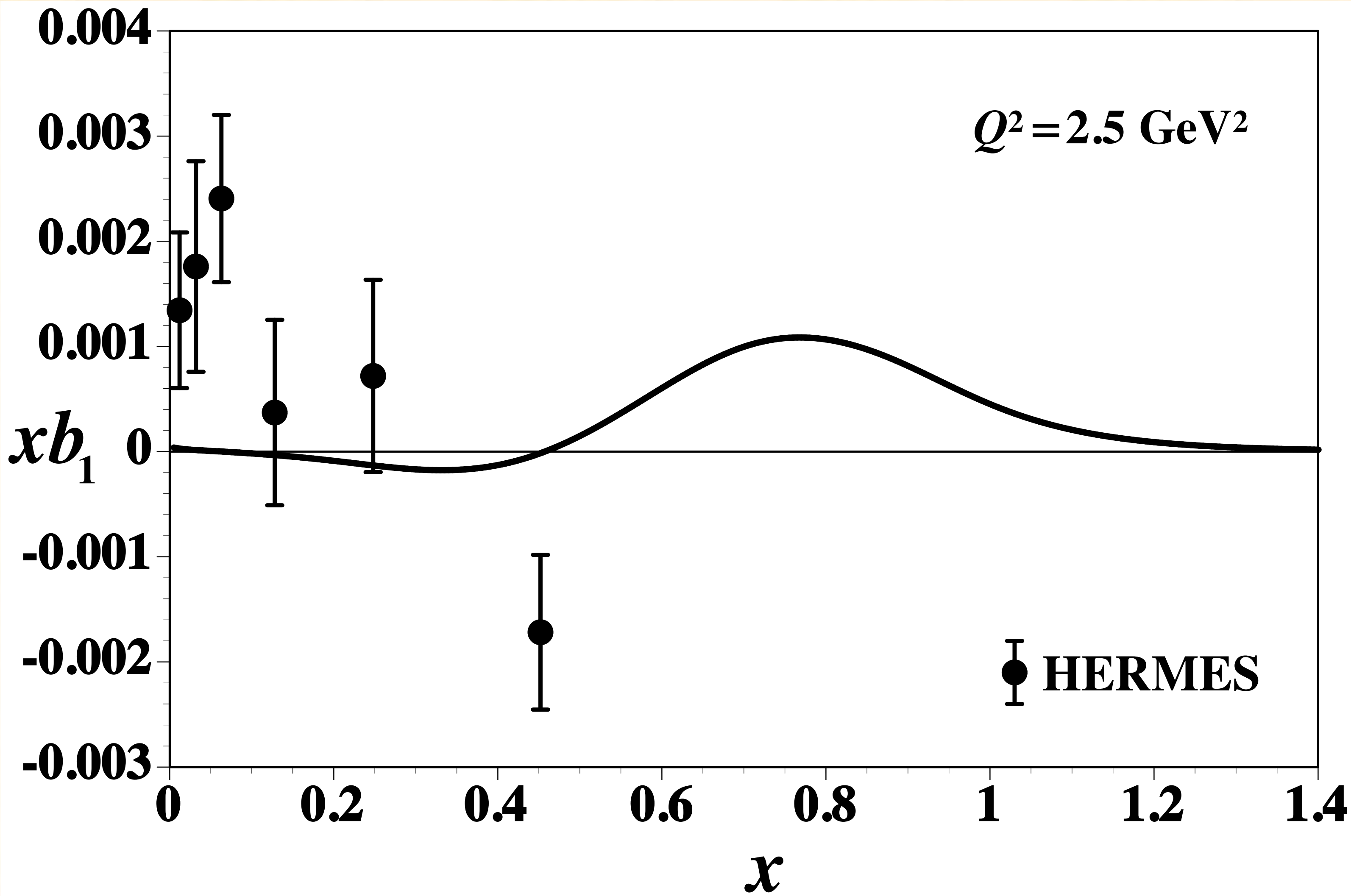


Standard model of the deuteron



S + D waves

Comparison with HERMES measurements



$$|b_1(\text{theory})| \ll |b_1(\text{HERMES})|$$

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

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

(2023 update PR12-13-011)

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)
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PR12-13-011

The Deuteron Tensor Structure Function b_1

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

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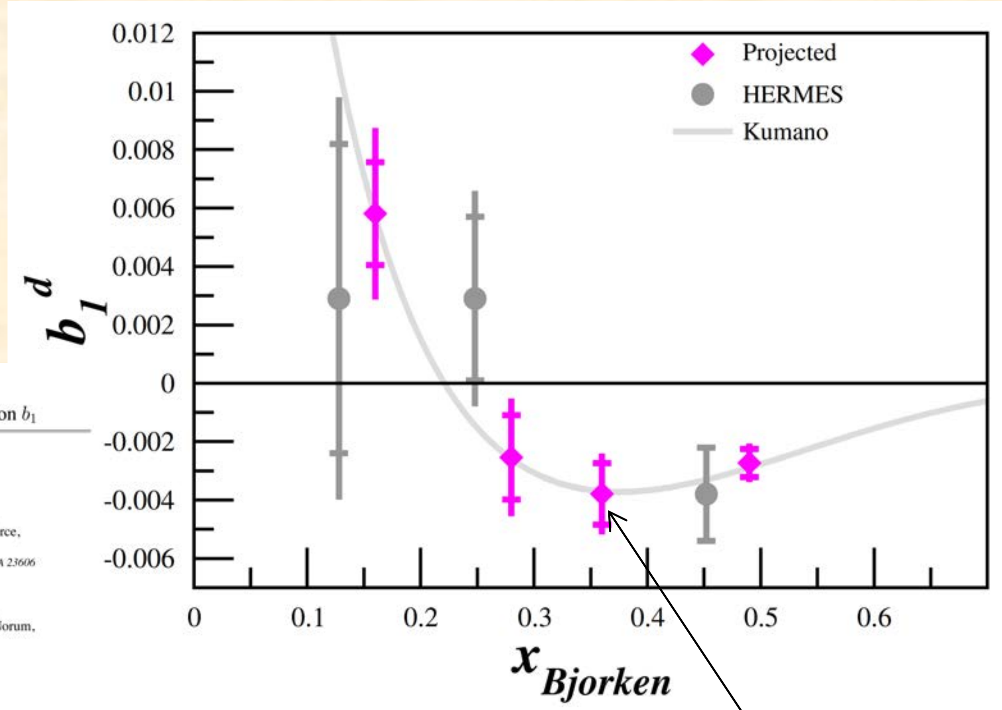
[†]Spokesperson
[‡]Contact

Review paper "Tensor Spin Observables" under preparation for European Physical Journal A.



Expected errors by JLab

Approved!

(Fully approved in 2023.)

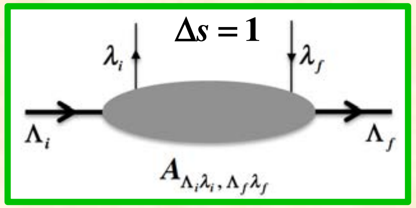
Gluon transversity $\Delta_T g$

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

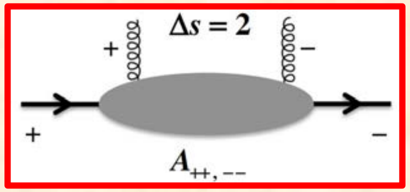
Helicity amplitude $A(\Lambda_i, \lambda_i, \Lambda_f, \lambda_f)$, **conservation** $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$

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

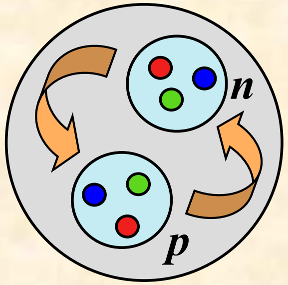
Quark transversity in nucleon: $\Delta_T q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ -\frac{1}{2}-\frac{1}{2}\right)$, $\lambda_i = +\frac{1}{2} \rightarrow \lambda_f = -\frac{1}{2}$ **quark spin flip** ($\Delta s = 1$)



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



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



S + D waves

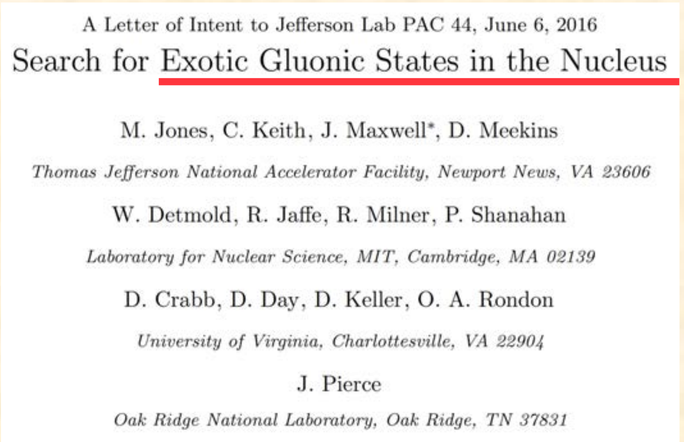
$b_1\ (\delta_T q,\ \delta_T g) \neq 0 \iff$ **still** $\Delta_T g = 0$

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???)

Proposed JLab experiment

LoI, arXiv:1803.11206



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

Search for Exotic Gluonic States in the Nucleus

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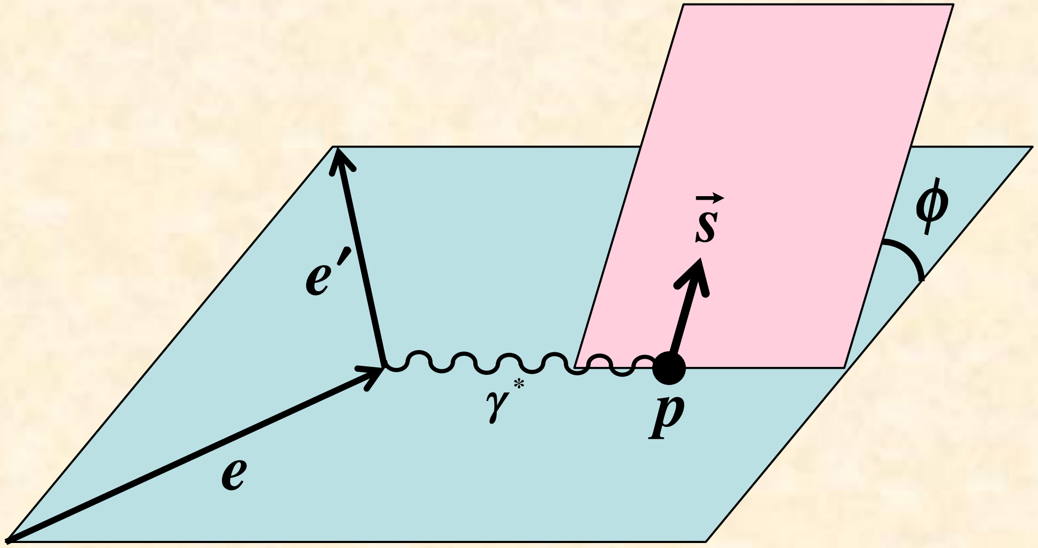

Electron scattering with polarized-proton target

$$\left.\frac{d\sigma}{dx\,dy\,d\phi}\right|_{Q^2\gg M^2} = \frac{e^4 ME}{4\pi^2 Q^4}\left[xy^2 F_1(x,Q^2) + (1-y)F_2(x,Q^2) - \frac{1}{2}x(1-y)\Delta(x,Q^2)\cos(2\phi)\right]$$

$$\Delta(x,Q^2) = \frac{\alpha_s}{2\pi}\sum_q e_q^2 x^2 \int_x^1 \frac{dy}{y^3}\Delta_T g(y,Q^2)$$

By looking at the proton polarization angle ϕ, the quark transversty $\Delta_T g$ can be measured.

Summary

In general, it is not easy to find internal structure of exotic-hadron candidates by global observables, such as mass, spin, …

High energies = Quark and gluon degrees of freedom.

It could be appropriate to use high-energy processes for determination of internal configurations for exotic-hadron candidates.

- **3D tomography by GPDs**
- **Constituent-counting rule**
- **Fragmentation functions**

(• New observables in spin-1 hadrons)

Experimental projects

JLab, J-PARC, KEK-B, AMBER, EIC, …

The End

The End