Tomography of hadrons by generalized distribution amplitudes

Shunzo Kumano

High Energy Accelerator Research Organization (KEK)
J-PARC Center (J-PARC)
Graduate University for Advanced Studies (SOKENDAI)
http://research.kek.jp/people/kumanos/

JLab-theory-center seminar
Jefferson Laboratory, Newport News, Virginia, USA, March 14, 2018
https://www.jlab.org/div_dept/theory/seminars/2018-spring-theory-seminar.html

March 14, 2018

Contents

- Introduction to hadron tomography
- Constituent counting rule for exotics
- Possible GPD studies at J-PARC
- GPDs for exotic hadrons

  GPD (Generalized Parton Distribution)
- GDAs and possible KEKB/ILC project

  GDA (Generalized Distribution Amplitude)

  Gravitational radii for hadrons
- Summary

Motivations

- 3D structure of hadrons
- Nucleon spin structure
- Exotic hadrons
- Gravitational properties of hadrons (from microscopic quarks and gluons)?

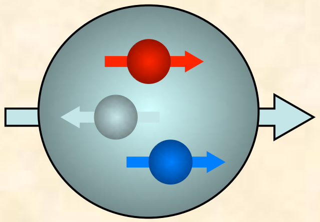
…

Hadron tomography: 3D structure functions are (will be) investigated at high-energy lepton and hadron facilities

(BNL, JLab, Fermilab, CERN, J-PARC, KEKB, GSI, IHEP@China & Russia, EIC, LHeC, ILC, ...).

Recent progress on origin of nucleon spin

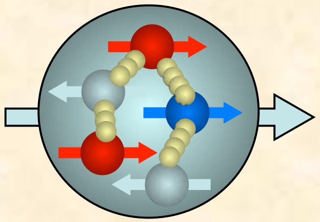
"old" standard model



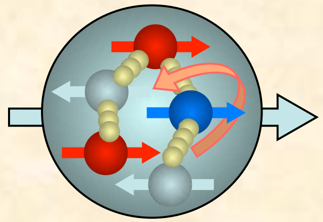
$$p_{\uparrow} = \frac{1}{3\sqrt{2}}\left(uud\left[2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow\right] + \text{permutations}\right)$$

$$\Delta q(x) \equiv q_{\uparrow}(x) - q_{\downarrow}(x)$$

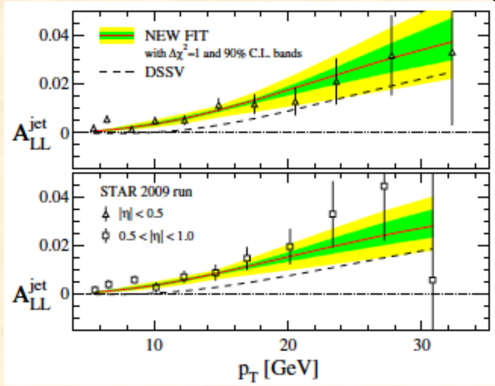
$$\Delta\Sigma = \sum_i \int dx\left[\Delta q_i(x) + \Delta\bar{q}_i(x)\right] \to 1\ (100\%)$$

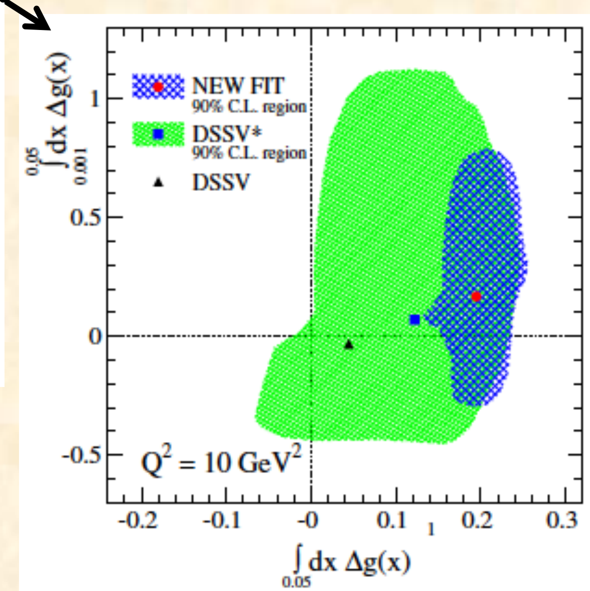


gluon spin



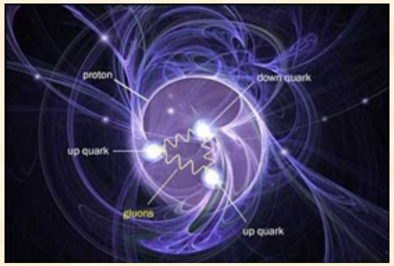
angular momentum





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

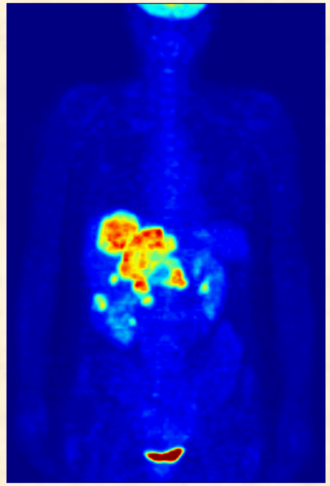
CNN (2014)



Scientific American (2014)

Nucleon (hadron) tomography

PET (Positron Emission Tomography)



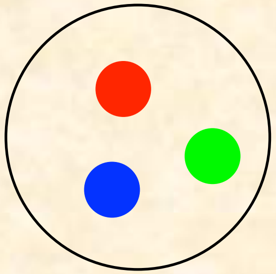
Classical density distribution

3D picture of nucleon

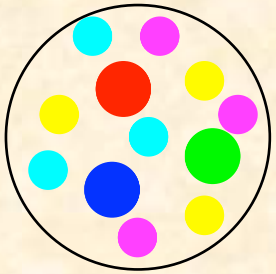
(Density distribution of quantum system: Quantum tomography)

1D(Bjorken-*x*) picutre@HERA

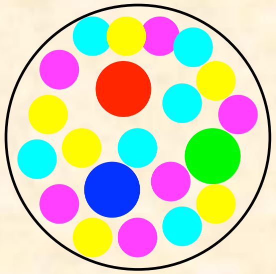
Low energy



Intermediate energy



High energy



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
…

- $\Theta^+(1540)$???: 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?
- $P_c(4380)$, $P_c(4450)$: LHCb
- …
  $u\bar{c}udc$, $\bar{D}(u\bar{c})\Sigma_c^*(udc)$, $\bar{D}^*(u\bar{c})\Sigma_c(udc)$ molecule?

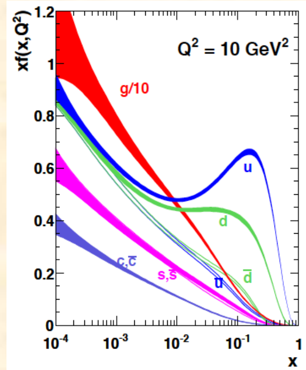
Wigner distribution and various structure functions

Form factor

$\int dx\, d^2k_T$

PDF (Parton Distribution Function)

$\int d^2k_T,\ \Delta \to 0$



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

$\Delta = p' - p$

$\int d^2k_T$

3D world

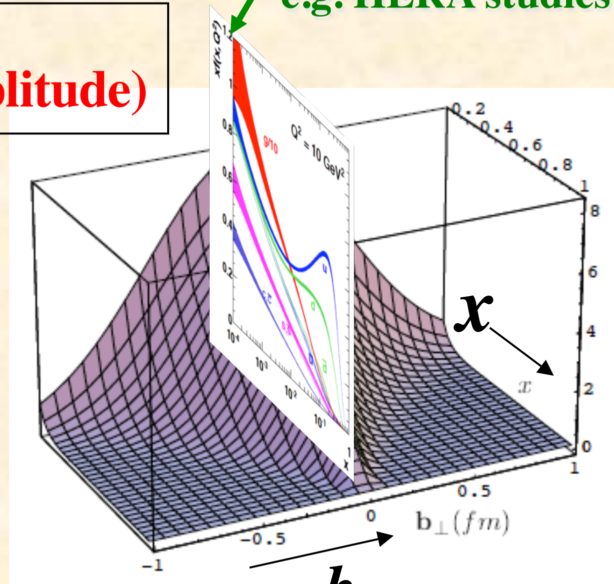
e.g. HERA studies

GPD (Generalized Parton Distribution)

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

$\Delta \to 0$

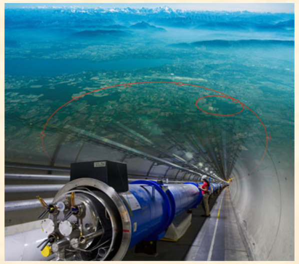
TMD (Transverse Momentum Dependent) parton distribution



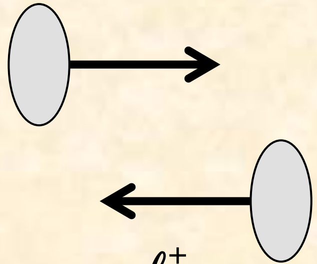
Our work by the two-photon process $\gamma\gamma \to h\bar{h}$.

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

RHIC
LHC

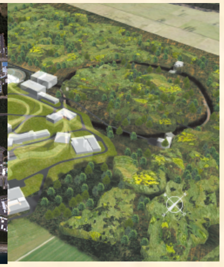


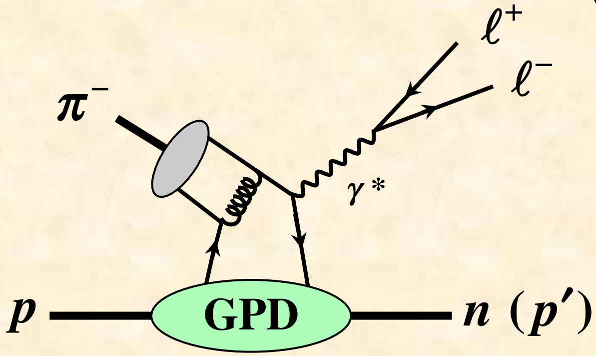

Ultra-peripheral collisions
for $\gamma^* \gamma \to h\bar{h}$??



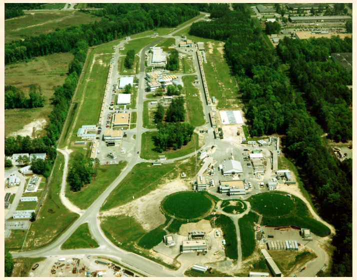
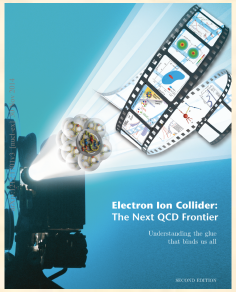
Fermilab
J-PARC
GSI-FAIR

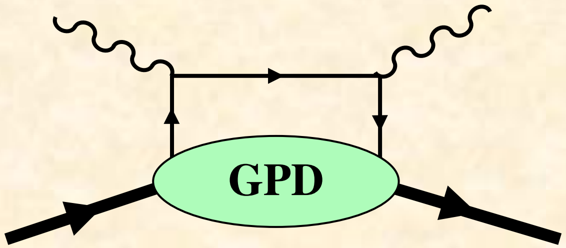




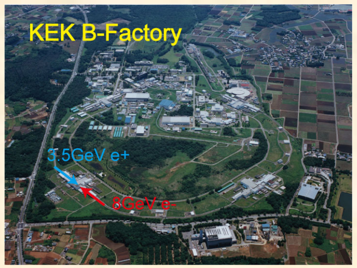


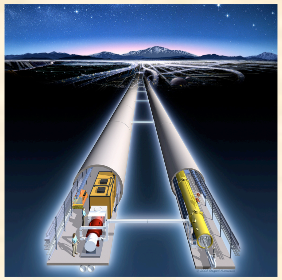
JLab
COMPASS
EIC

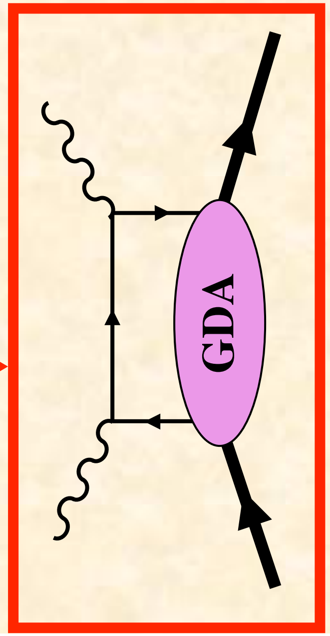


KEKB
ILC

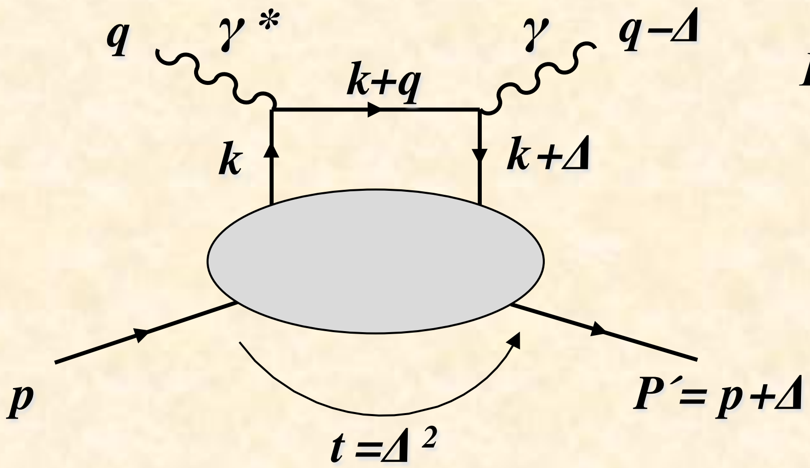




We studied this process.



Generalized Parton Distributions (GPDs)



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

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

Momentum transfer squared $t = \Delta^2$

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

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

First moments: Form factors

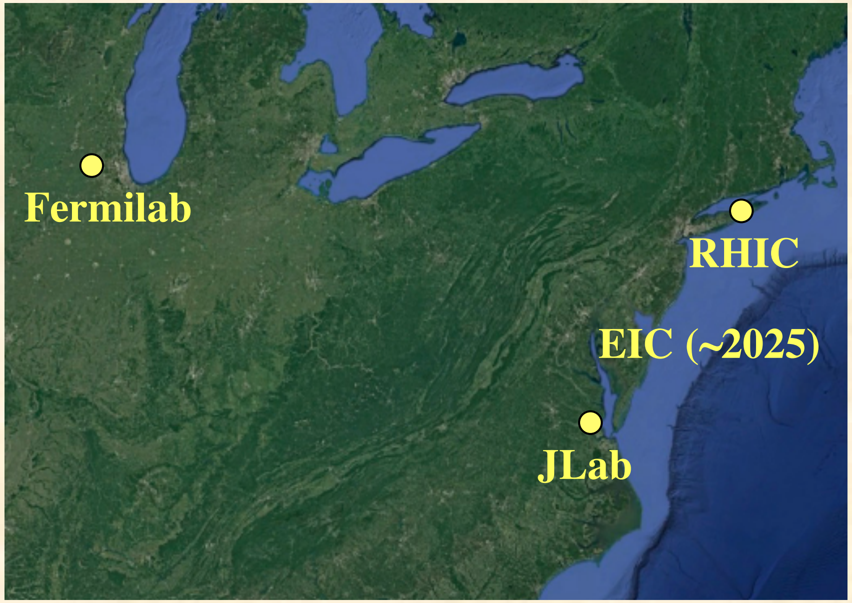
Dirac and Pauli form factors F_1, F_2 $\int_{-1}^{1} dx\, H(x,\xi,t) = F_1(t), \quad \int_{-1}^{1} dx\, E(x,\xi,t) = F_2(t)$

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

Hadron-tomography studies in US and Europe



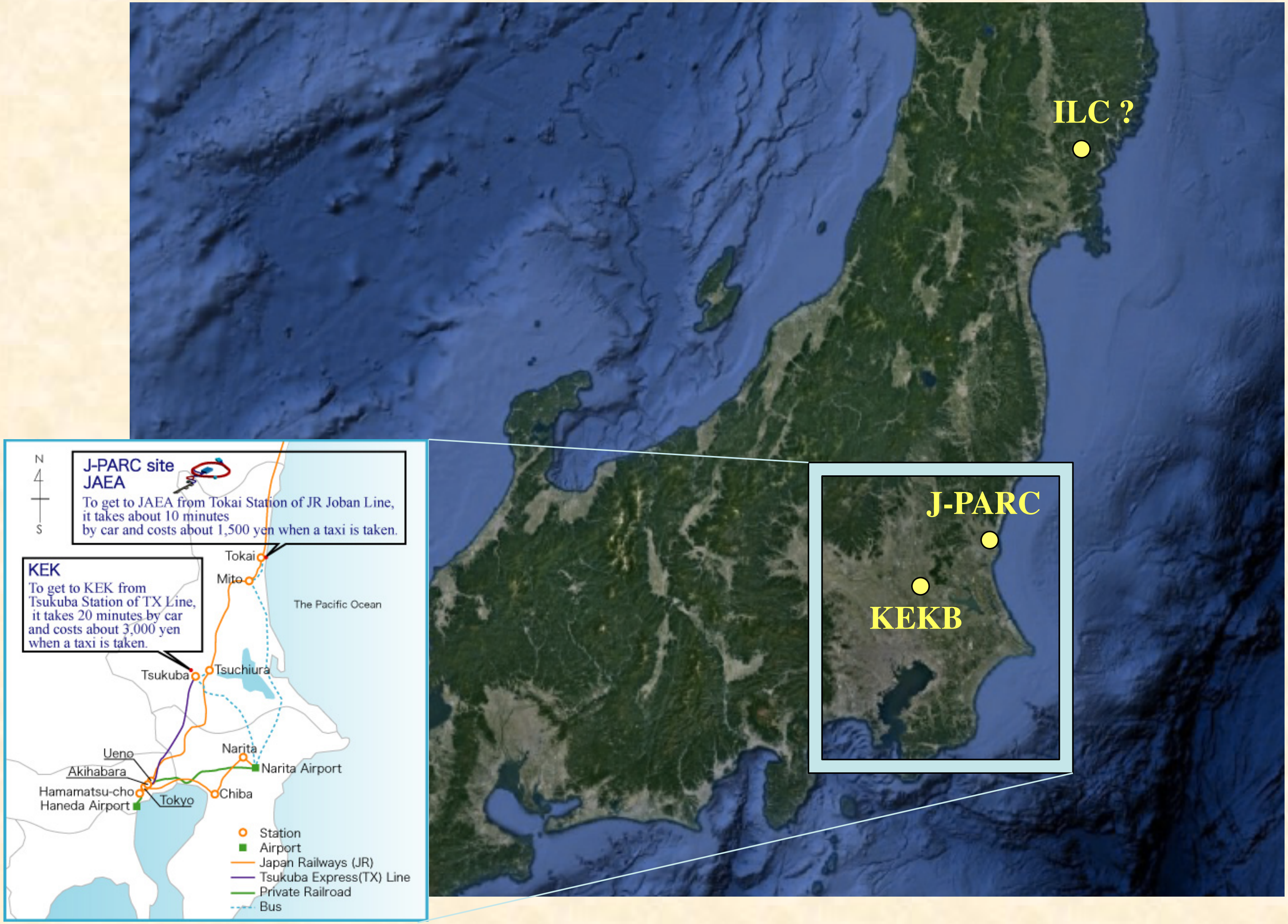
Fermilab: Main Injector (120 GeV proton),
Neutrino (Minerva, several GeV)

RHIC: Spin (polarized p + polarized p)
Heavy ion (*e.g.* UPC: Ultra-Peripheral Collision)

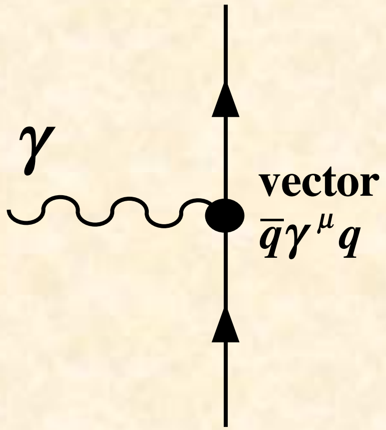
EIC (Electron Ion Collider, ~2025)

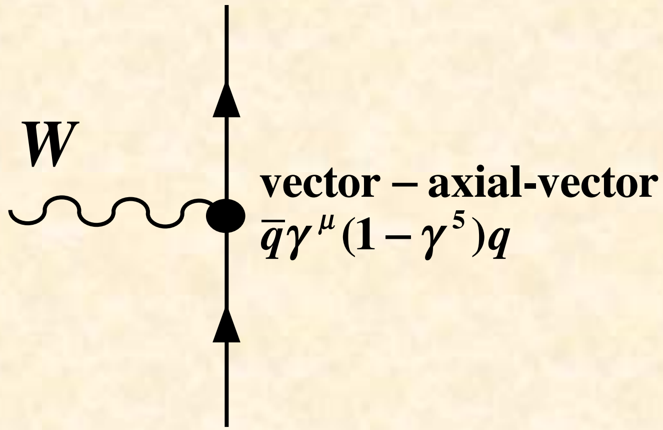
CERN: COMPASS (μ, π beams)
LHC Heavy ion
(*e.g.* UPC: Ultra-Peripheral Collision)

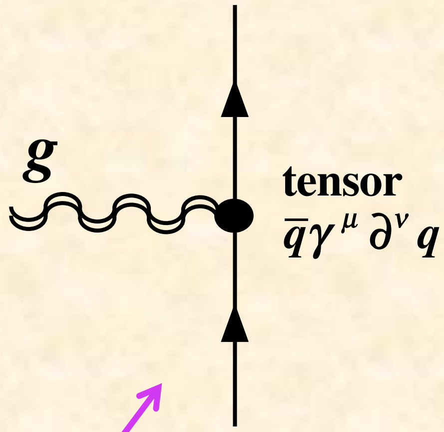
Possible hadron-tomography studies at J-PARC, KEKB, ILC?



Why gravitational interactions with hadrons ?







Electron-proton elastic scattering cross section:

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

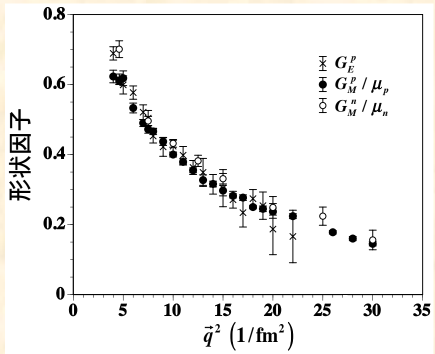
$$F(\vec{q})=\int d^3x\, e^{i\vec{q}\cdot\vec{x}}\rho(\vec{x})=\int d^3x\left[1-\frac{1}{2}(\vec{q}\cdot\vec{x})^2+\cdots\right]\rho(\vec{x})$$

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

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

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

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



How about gravitational radius?

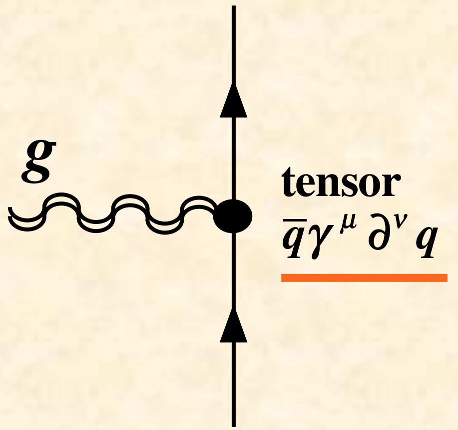
Proton-charge-radius puzzle:

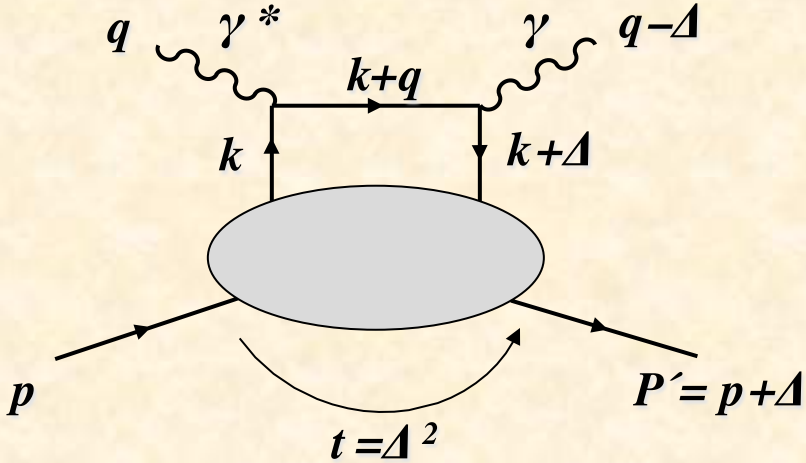
$R_{\text{electron scattering}}$ = 0.8775 fm

⇕

$R_{\text{muonic atom}}$ = 0.8418 fm

Gravitational interactions and 3D structure functions





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

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

Non-local operator of GPDs/GDAs:

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

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

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

= source of gravitiy

References

GPDs at J-PARC

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

T. Sawada, Wen-Chen Chang, S. Kumano, Jen-Chieh Peng, S. Sawada, K. Tanaka, PRD 93 (2016) 114034.

GPDs and GDAs (including exotic hadrons)

H. Kawamura, SK, PRD 89 (2014) 054007.

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

Related topics: Constituent counting rule:

H. Kawamura, SK, T. Sekihara, PRD 88 (2013) 034010.

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

Constituent-counting rule for exotic hadrons

H. Kawamura, S. Kumano, T. Sekihara,
Phys. Rev. 88 (2013) 034010.
W.-C. Chang, S. Kumano, and T. Sekihara,
Phys. Rev. D 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.

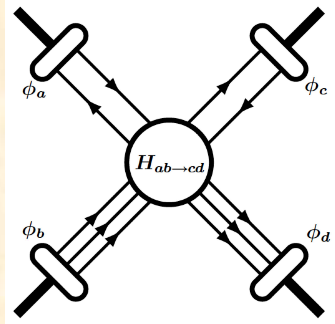
Constituent-counting rule could be used because it counts internal constituents.

(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.

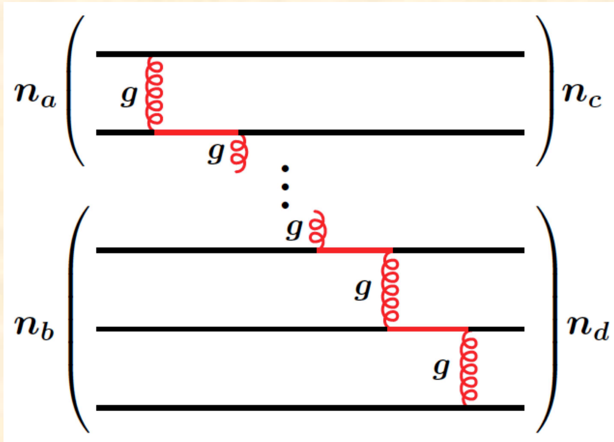
There are $n/2-1$ gluon propagators $\sim 1/(P^2)^{n/2-1}$.

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



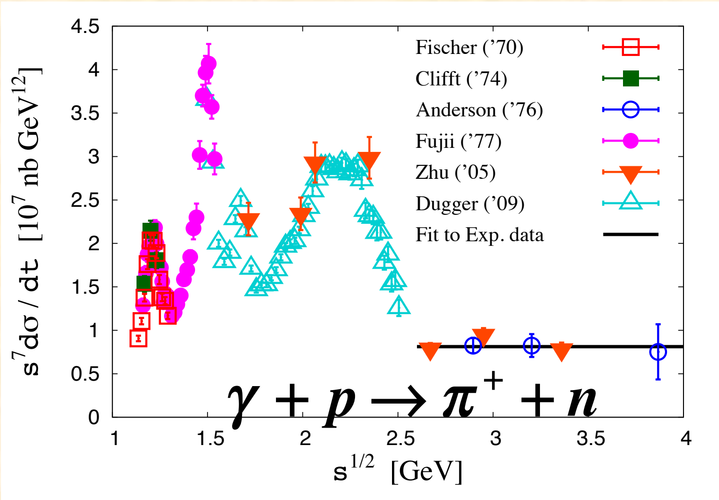
$$M_{ab\to cd} \sim \frac{1}{(P^2)^{n/2-1}}\frac{1}{(P)^{n/2-2}}(\sqrt{P})^n = \frac{(P)^{n/2}}{(P)^{n-2}(P)^{n/2-2}} = \frac{1}{(P)^{n-4}} \sim \frac{1}{s^{n/2-2}}$$

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

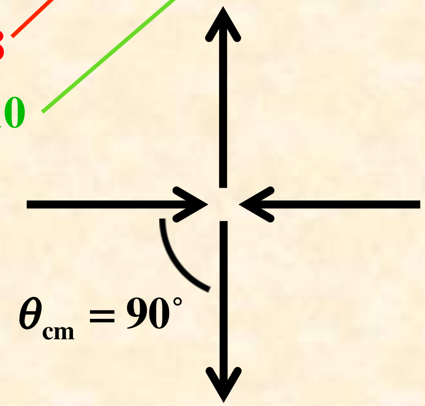
BNL experiment

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

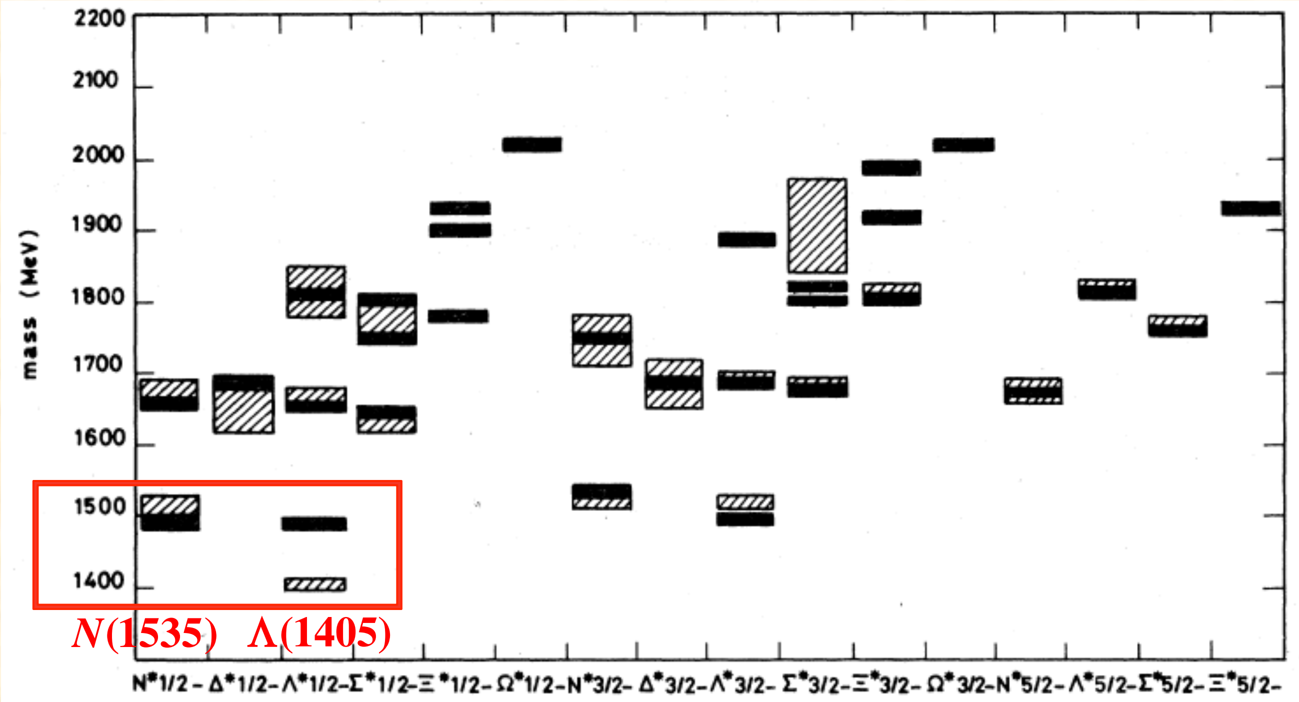
$n-2$: $(2+3+2+3)-2=8$

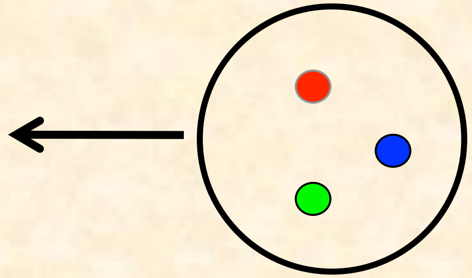
$(3+3+3+3)-2=10$

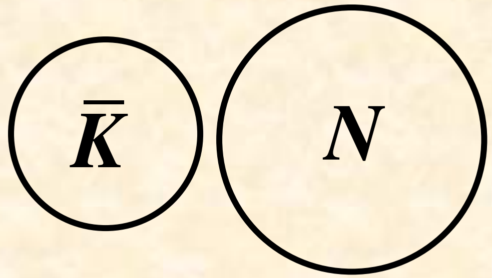


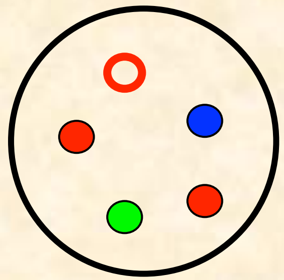
Λ(1405): exotic hadron?

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





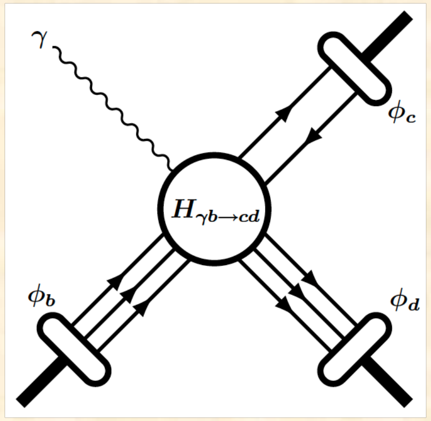


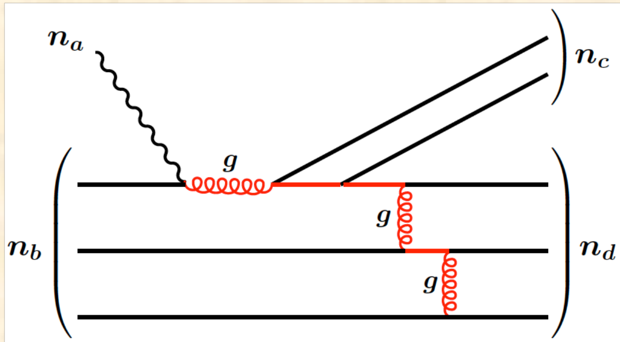


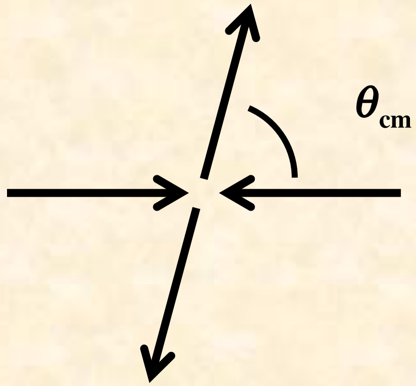
Most spectra agree with the ones by a 3*q*-picture

- 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 ($qqqq\bar{q}$)?

JLab hyperon productions







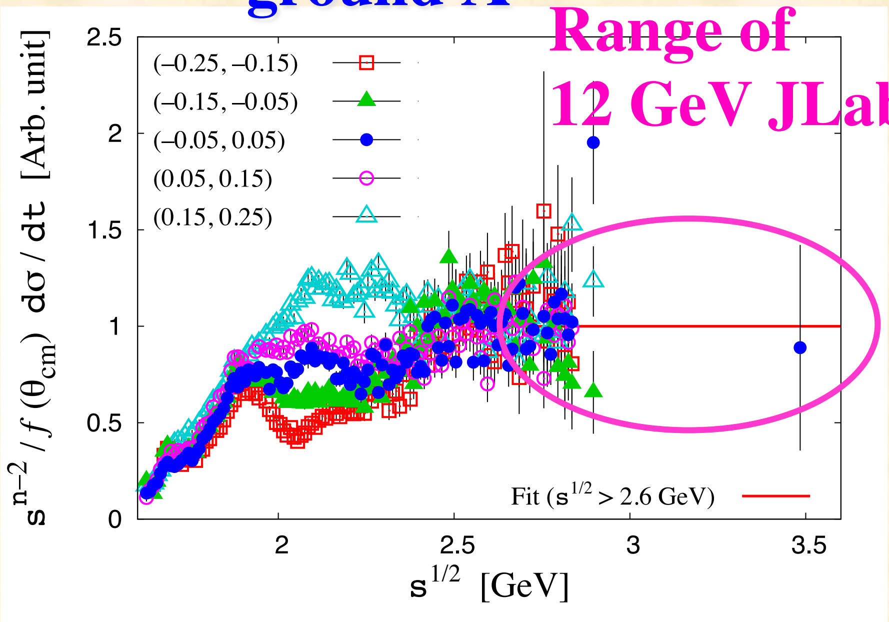
5 bins: $-0.25 < \cos\theta_{cm} < -0.15$, ⋯, $0.15 < \cos\theta_{cm} < 0.25$

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

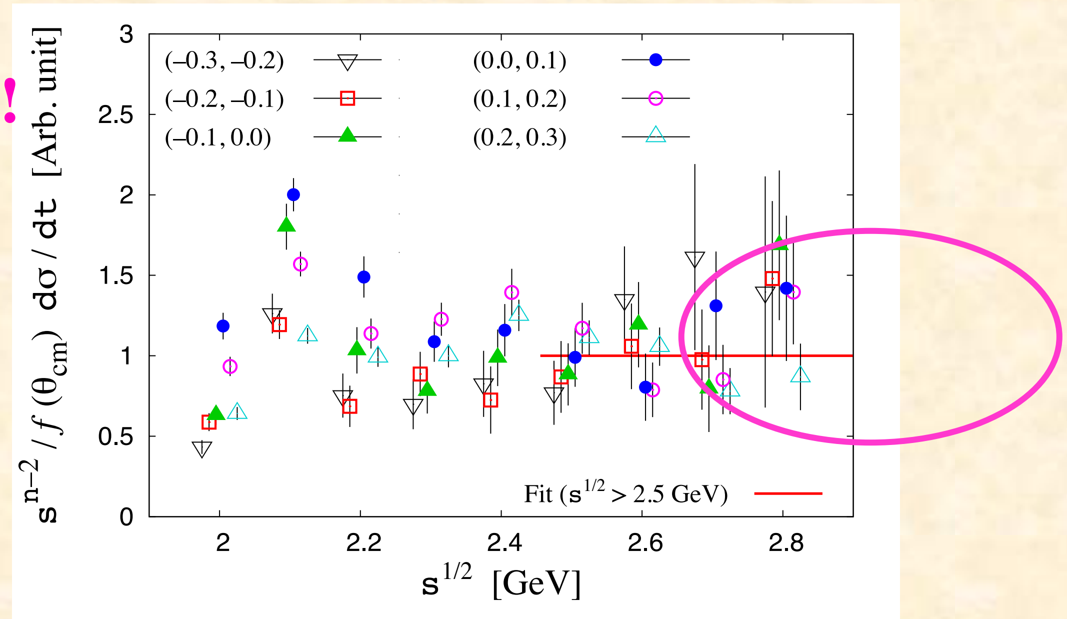
...

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

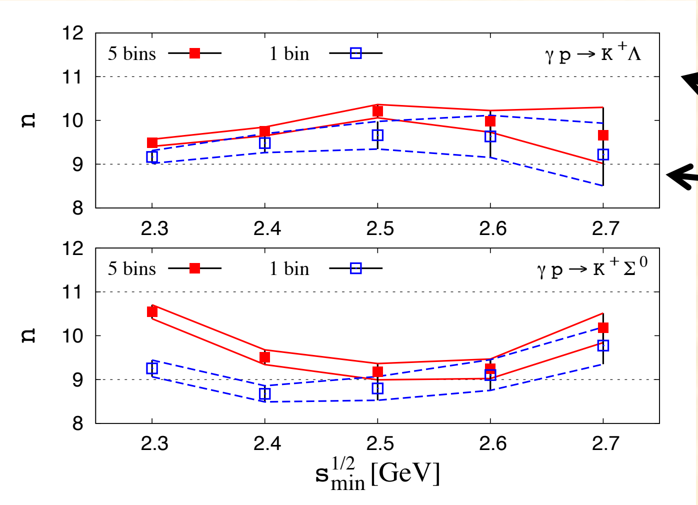
ground Λ



Λ(1405)

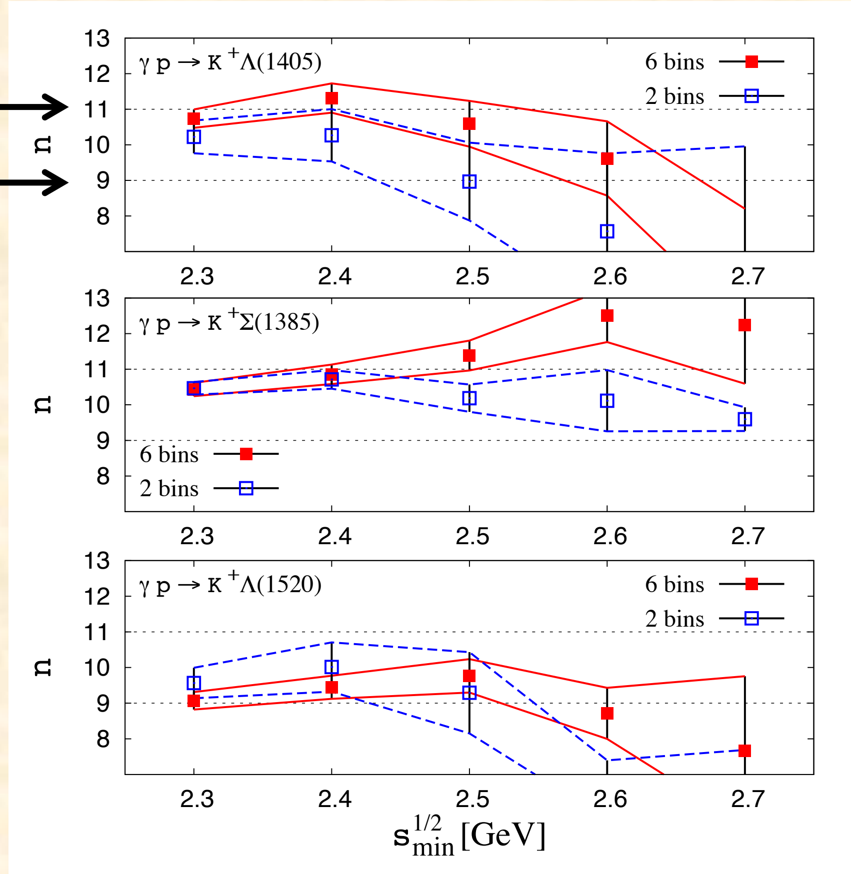


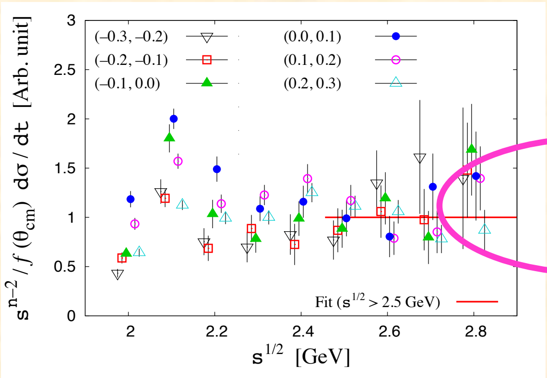
JLab hyperon productions including Λ(1405)



$n_\Lambda = 5$

$n_\Lambda = 3$





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!

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.

- $\gamma + p \to K^+ + \Lambda(1405)$ is studied.
  $\Lambda(1405)$ = pentaquark at low energies
  = 3-quark baryon at high energies ???
  $\to$ Measurements of extended kinematical range are necessary (12 GeV JLab).

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

Generalized Parton Distributions (GPDs)

and J-PARC project

Comments on

J-PARC project

T. Sawada, W.-C. Chang, S. Kumano, J.-C. Peng,
S. Sawada, and K. Tanaka,
Phys. Rev. D93 (2016) 114034;
S. Kumano, M. Strikman, and K. Sudoh,
Phys. Rev. D 80 (2009) 074003.

Aerial photograph

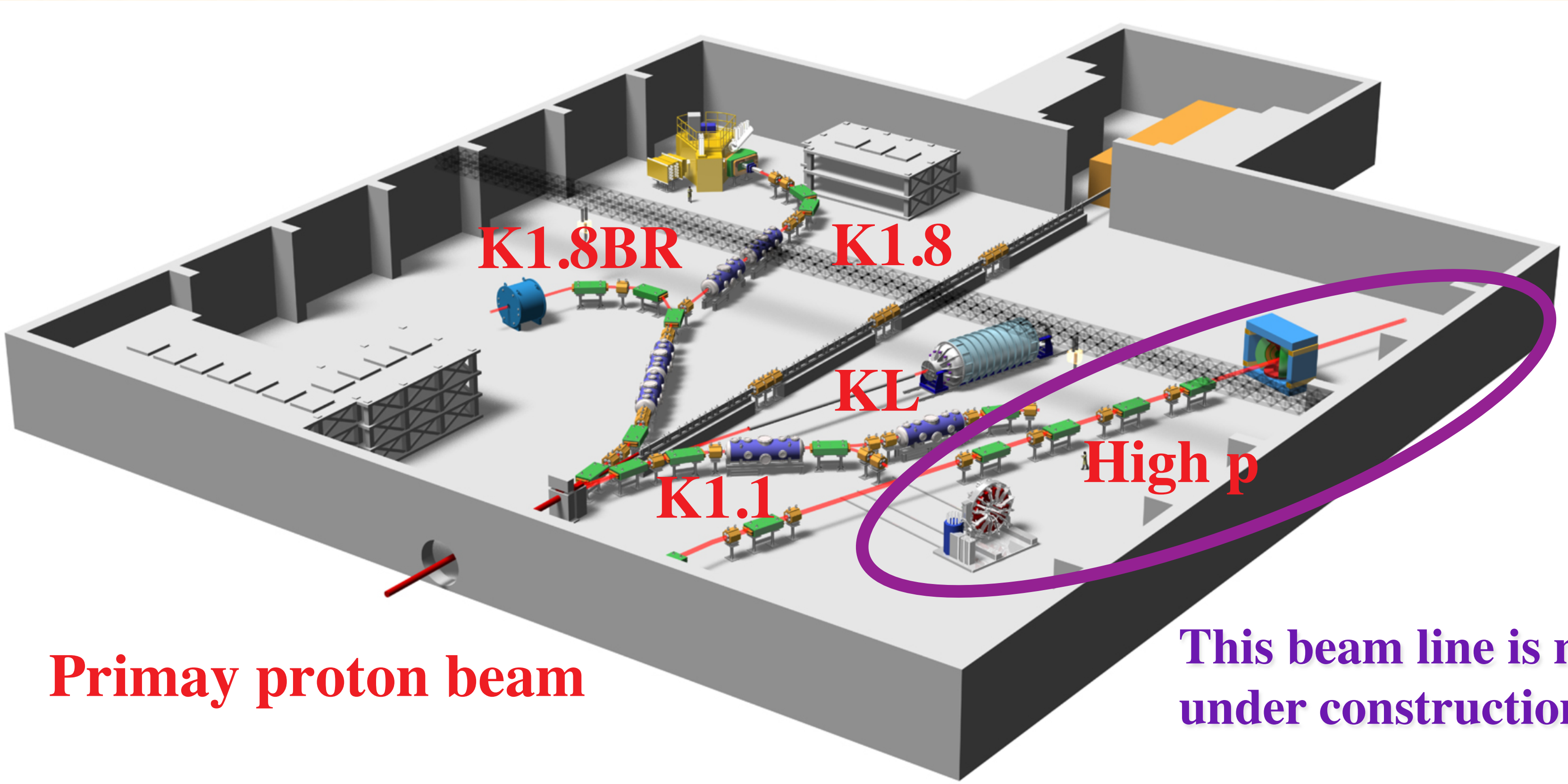
KEK Tokai campus

Neutrino facility

Hadron facility

Hadron facility

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



Primay proton beam

This beam line is now under construction.

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

Toward a new proposal at J-PARC

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

Exclusive Drell-Yan: $\pi^- + p \rightarrow \mu^+ \mu^- + n$

PHYSICAL REVIEW D 93, 114034 (2016)

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

Takahiro Sawada* and Wen-Chen Chang†
Institute of Physics, Academia Sinica, Taipei 11529, Taiwan

Shunzo Kumano‡
KEK Theory Center, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), 1-1, Oho, Tsukuba, Ibaraki 305-0801, Japan and J-PARC Branch, KEK Theory Center, Institute of Particle and Nuclear Studies, KEK, 203-1, Shirakata, Tokai, Ibaraki 319-1106, Japan

Jen-Chieh Peng§
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

Shinya Sawada¶
High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Kazuhiro Tanaka**
Department of Physics, Juntendo University, Inzai, Chiba 270-1695, Japan and J-PARC Branch, KEK Theory Center, Institute of Particle and Nuclear Studies, KEK, 203-1, Shirakata, Tokai, Ibaraki 319-1106, Japan
(Received 15 May 2016; published 29 June 2016)

Generalized parton distributions (GPDs) encoding multidimensional information of hadron partonic structure appear as the building blocks in a factorized description of hard exclusive reactions. The nucleon GPDs have been accessed by deeply virtual Compton scattering and deeply virtual meson production with lepton beam. A complementary probe with hadron beam is the exclusive pion-induced Drell-Yan process. In this paper, we discuss recent theoretical advances on describing this process in terms of nucleon GPDs and pion distribution amplitudes. Furthermore, we address the feasibility of measuring the exclusive pion-induced Drell-Yan process $\pi^- p \rightarrow \mu^+ \mu^- n$ via a spectrometer at the High Momentum Beamline being constructed at J-PARC in Japan. Realization of such measurement at J-PARC will provide a new test of perturbative QCD descriptions of a novel class of hard exclusive reactions. It will also offer the possibility of experimentally accessing nucleon GPDs at large timelike virtuality.

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

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

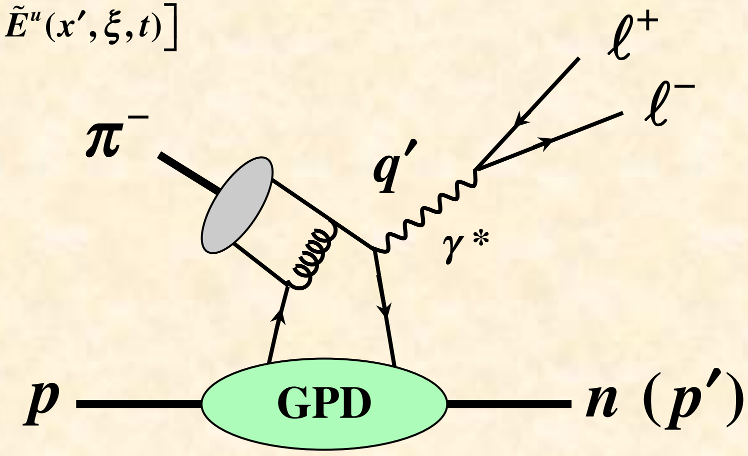
$$Q'^2 = q'^2,\ \ t = (p-p')^2,\ \tau = \frac{Q'^2}{2p\cdot q_\pi} \simeq \frac{Q'^2}{s-m_N^2}$$

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

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

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

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

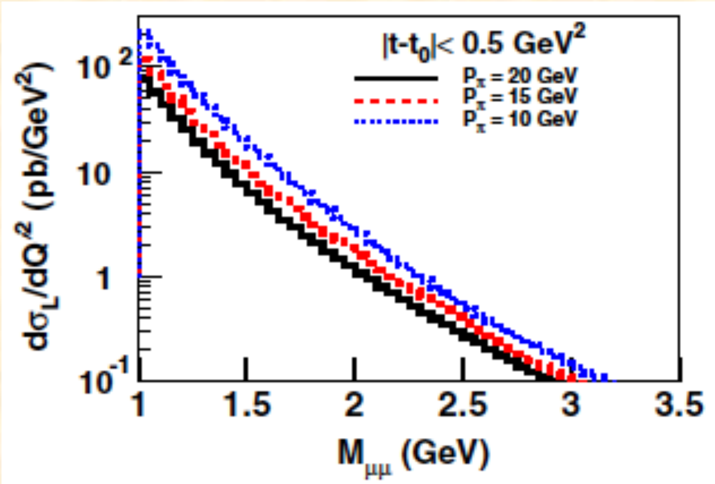


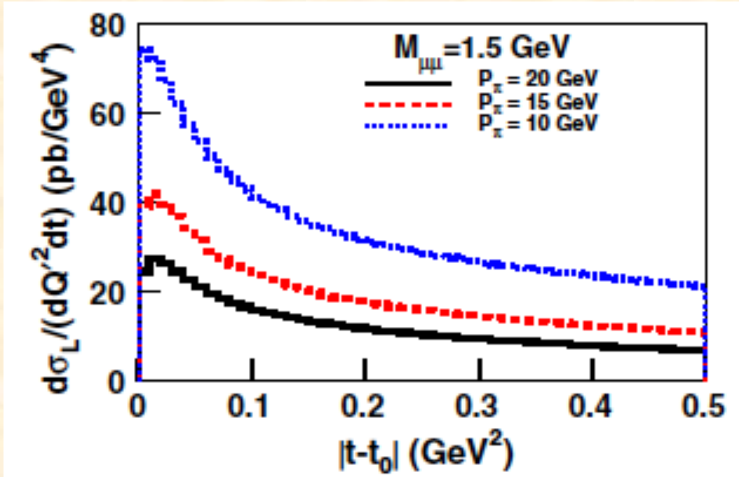
$$\pi^-(\bar{u}d) + p(uud) \to n(udd) + \gamma^*(\to \ell^+\ell^-)$$

Expected Drell-Yan events at J-PARC

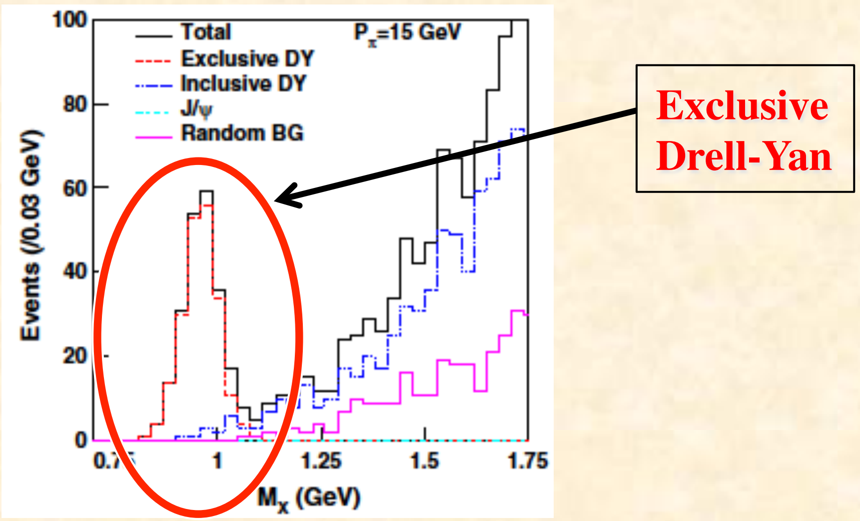
$$Q'^2 = q'^2,\ t = (p - p')^2,\ \tau = \frac{Q'^2}{2p \cdot q_\pi} \simeq \frac{Q'^2}{s - m_N^2}$$

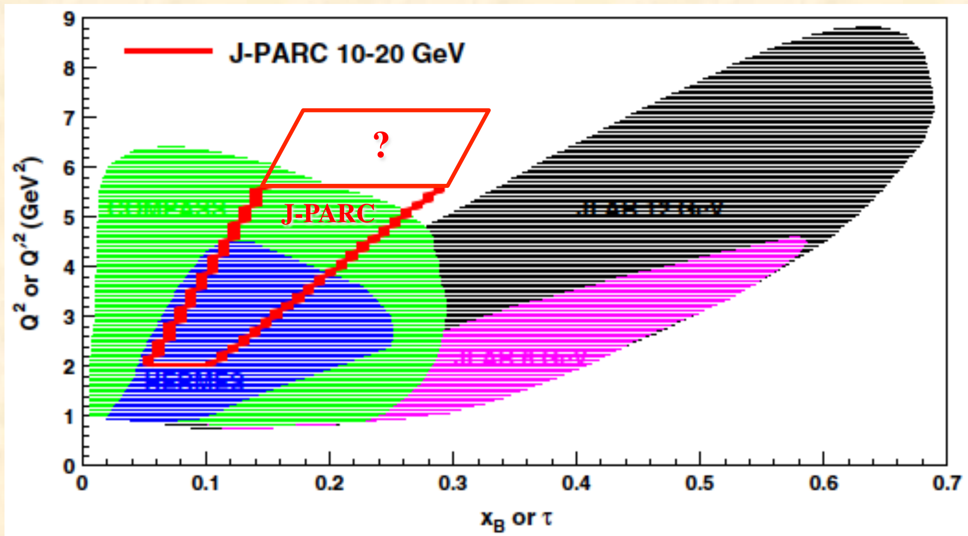
$$\frac{d\sigma}{dQ'^2 dt} = \frac{4\pi\alpha^2}{27}\frac{\tau^2}{Q'^2} f_\pi^2 \left[(1-\xi^2)\left|\tilde{H}^{du}(-\xi,\xi,t)\right|^2 - 2\xi^2 \,\mathrm{Re}\left\{\tilde{H}^{du}(-\xi,\xi,t)^* \tilde{E}^{du}(-\xi,\xi,t)\right\} - \xi^2 \frac{t}{4m_N^2}\left|\tilde{E}^{du}(-\xi,\xi,t)\right|^2 \right]$$



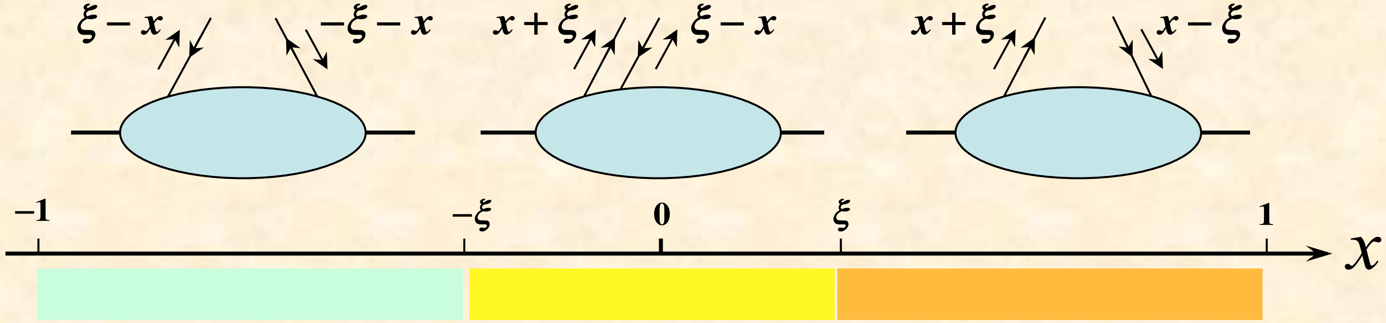


Missing mass





GPDs in different x regions and GPDs at hadron facilities



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

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

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

Quark distribution

Emission of quark with momentum fraction $x+\xi$

Absorption of quark with momentum fraction $x-\xi$

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

Emission of quark with momentum fraction $x+\xi$

Emission of antiquark with momentum fraction $\xi-x$

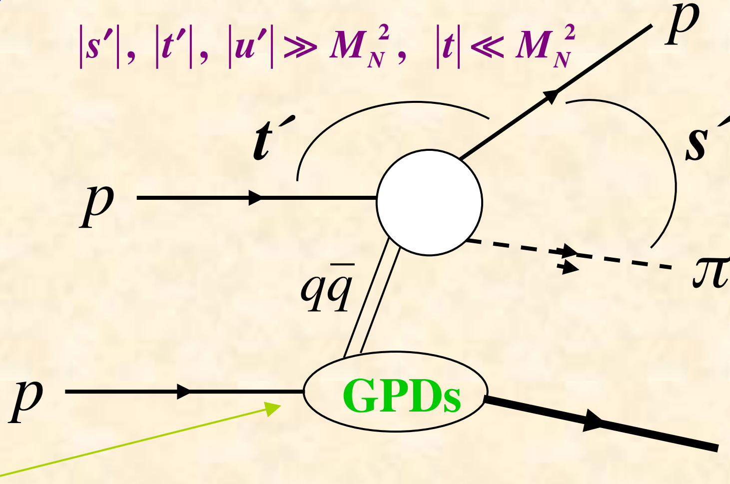
Antiquark distribution

Emission of antiquark with momentum fraction $\xi-x$

Absorption of antiquark with momentum fraction $-\xi-x$

Consider a hard reaction with

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



GPDs at J-PARC: S. Kumano, M. Strikman, and K. Sudoh, PRD 80 (2009) 074003.

Efremov-Radyushkin -Brodsky-Lepage (ERBL) region

GPDs for exotic hadrons

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

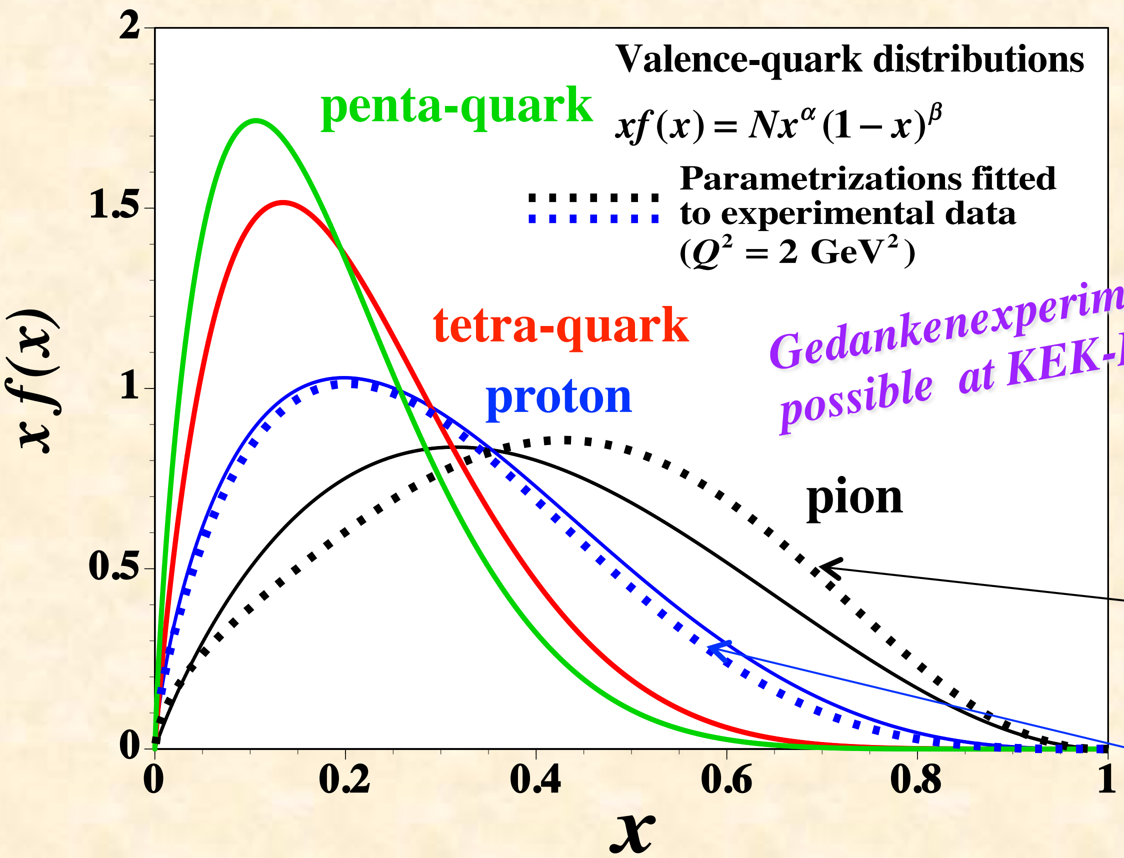
Simple function of GPDs

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

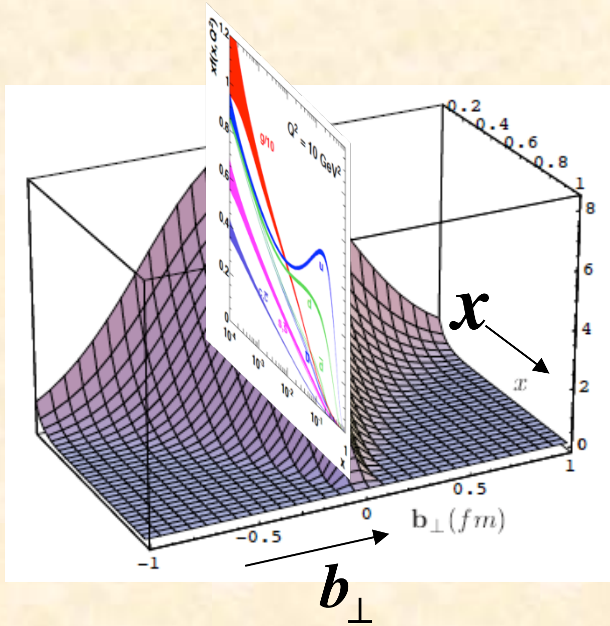
M. Guidal, M.V. Polyakov, A.V. Radyushkin, M. Vanderhaeghen, PRD 72, 054013 (2005).

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, ...

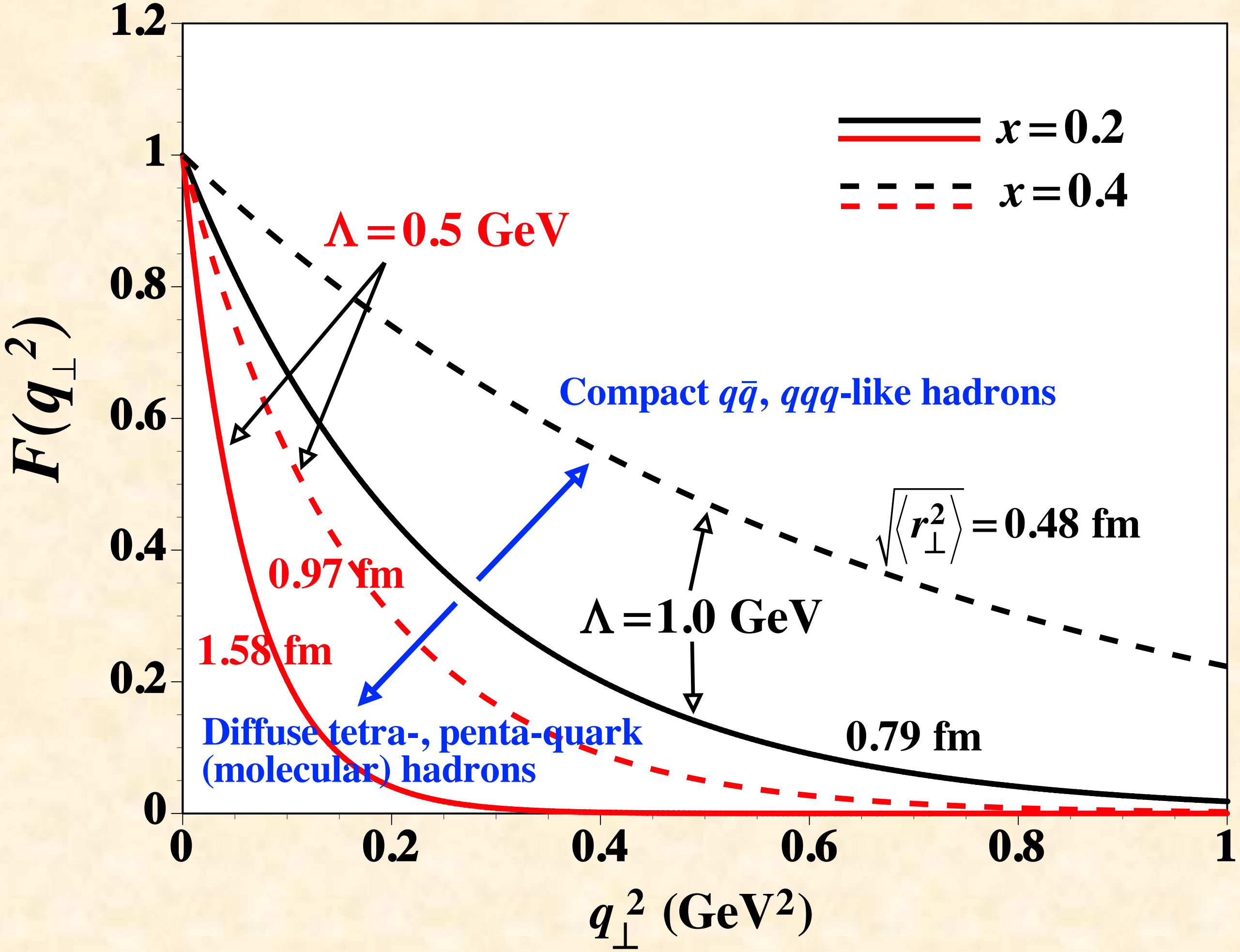


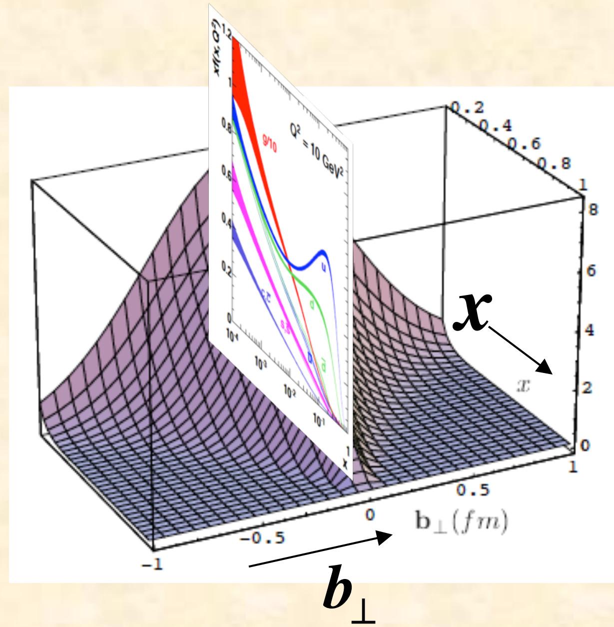
π: M. Aicher, A. Schafer, W. Vogelsang, PRL 105 (2010) 252003.

p: A. D. Martin, R. G. Roberts, W. J. Stirling, PLB 636, 259 (2006)

Two-dimensional form factor

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



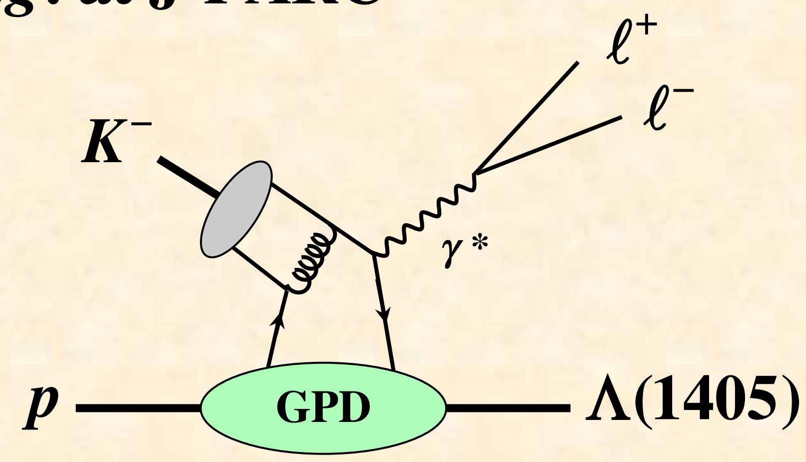


GPDs for exotic hadrons

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

→ Transition GPDs

***e.g.* at J-PARC**



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

Generalized Distribution Amplitudes (GDAs)

and KEKB/ILC project

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

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

GPDs for exotic hadrons !?

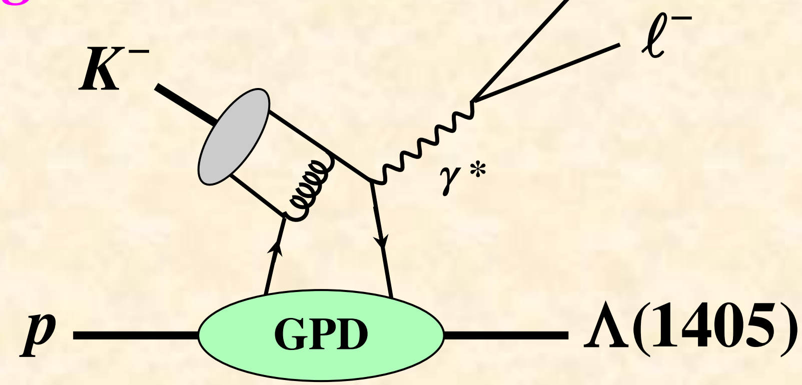
Because stable targets do not exit for exotic hadrons,
it is not possible to measure their GPDs in a usual way.

→ Transition GPDs

or

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

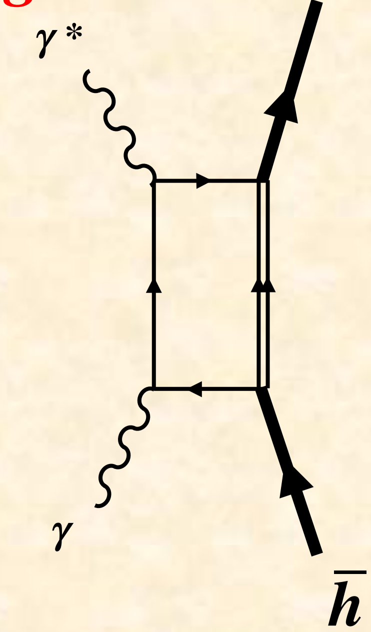
e.g. at J-PARC



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

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

e.g. KEKB



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

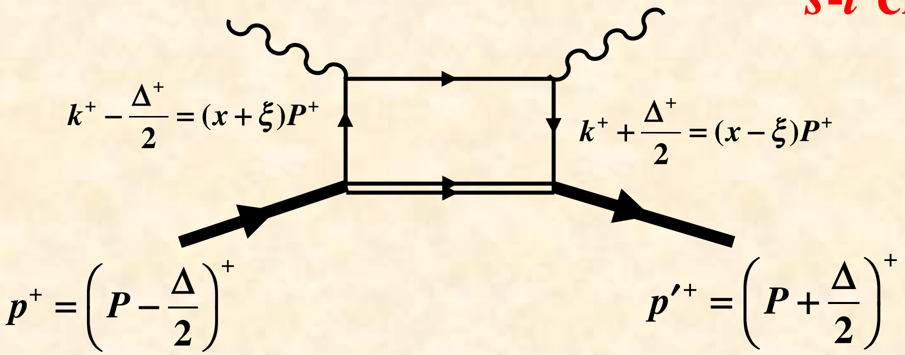
GPD: $H_q(x,\xi,t)=\int \frac{dy^-}{4\pi} e^{ixP^+y^-}\langle h(p')|\bar\psi(-y/2)\gamma^+\psi(y/2)|h(p)\rangle\Big|_{y^+=0,\vec y_\perp=0}$, $\quad P^+=\frac{(p+p')^+}{2}$

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

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

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

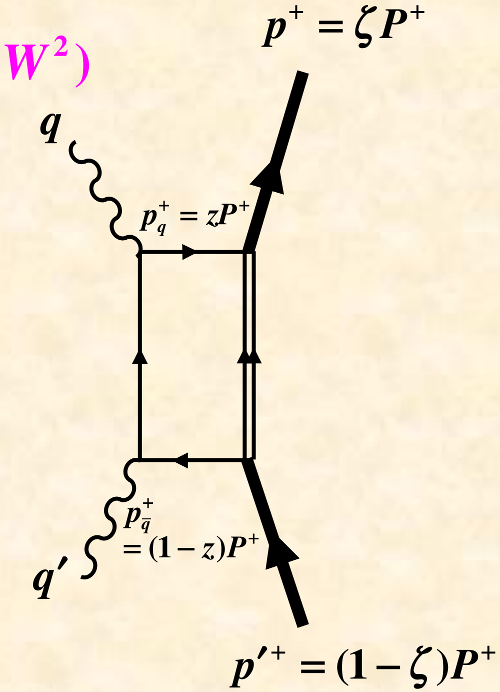
***s*-*t* crossing**



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

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

$W^2 \Leftrightarrow t$



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

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

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

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

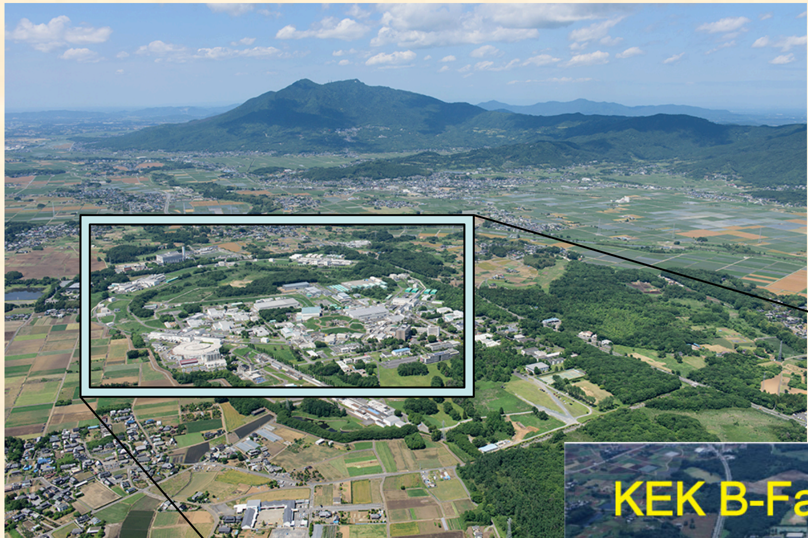
Bjorken variable for $\gamma\gamma^*$: $z=\frac{Q^2}{2q\cdot q'}$

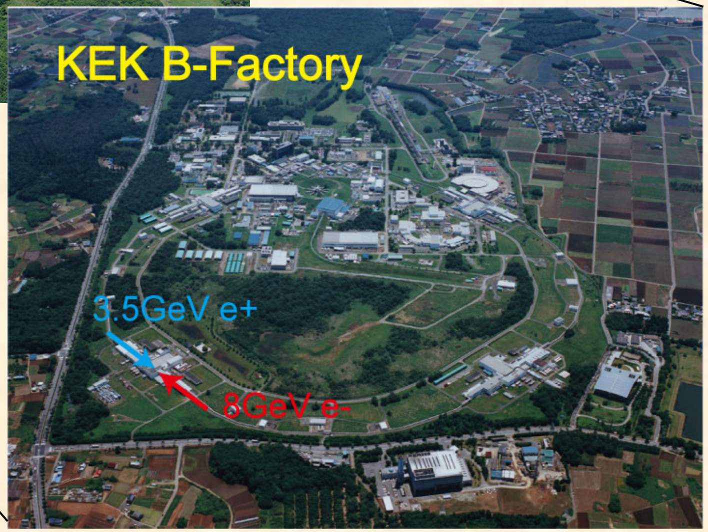
Light-cone momentum ratio for a hadron in $h\bar h$: $\zeta=\frac{p^+}{P^+}=\frac{1+\beta\cos\theta}{2}$

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

Experimental studies of GDAs in future

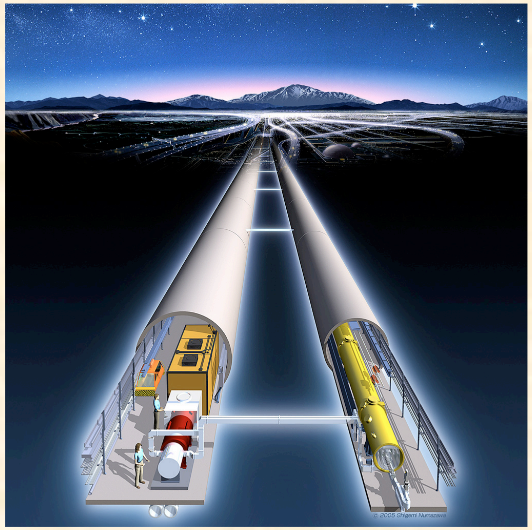
$\gamma\gamma \to h\bar{h}$ for internal structure of exotic hadron candidate h





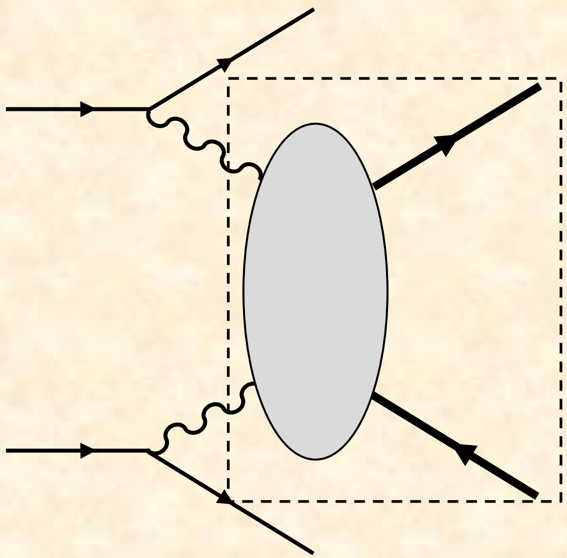
KEK B-factory

Linear Collider ?



Generalized Distribution Amplitudes (GDAs) for pion

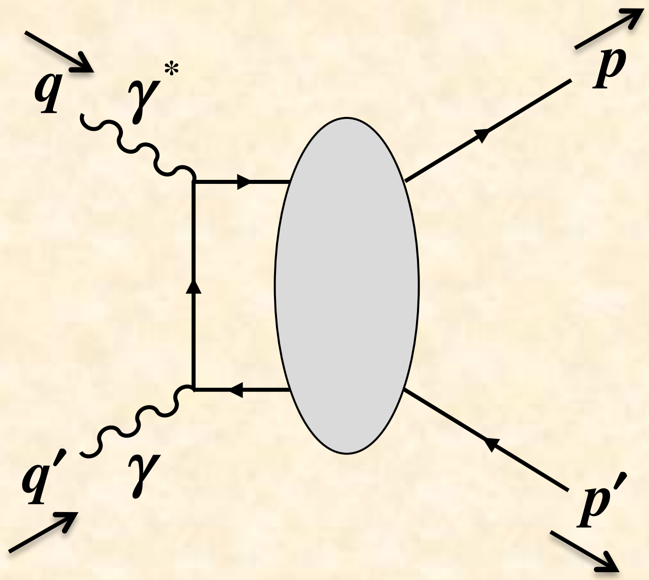
from KEKB measurements



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

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

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



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

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

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

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

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

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

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

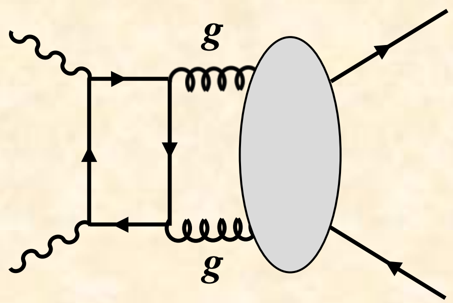
$$A_{\lambda\lambda'} = \frac{1}{e^2}\varepsilon_\mu^\lambda(q)\varepsilon_\nu^{\lambda'}(q')T^{\mu\nu} = -\varepsilon_\mu^\lambda(q)\varepsilon_\nu^{\lambda'}(q')g_T^{\mu\nu} \sum_q \frac{e_q^2}{2}\int_0^1 dz \frac{2z-1}{z(1-z)} \Phi_q^{\pi\pi}(z,\zeta,W^2)$$

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

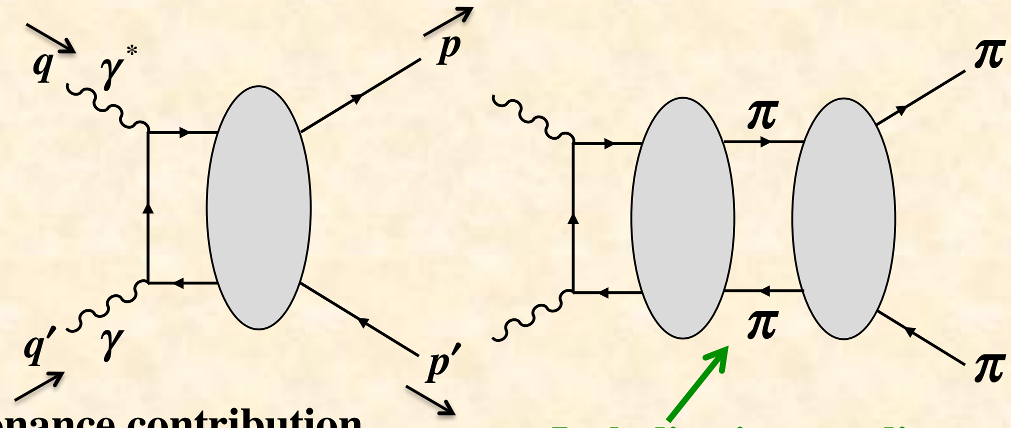
$$A_{++} = \sum_q \frac{e_q^2}{2}\int_0^1 dz \frac{2z-1}{z(1-z)} \Phi_q^{\pi\pi}(z,\zeta,W^2),\quad \varepsilon_\mu^+(q)\varepsilon_\nu^+(q')g_T^{\mu\nu} = -1$$

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

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



GDA parametrization for pion



Including intermediate resonance contributions

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

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

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

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

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

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

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

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

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

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

$f_0(500)$ or σ [g]
was $f_0(600)$

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

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

$f_0(980)$ [j]

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

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

$f_2(1270)$

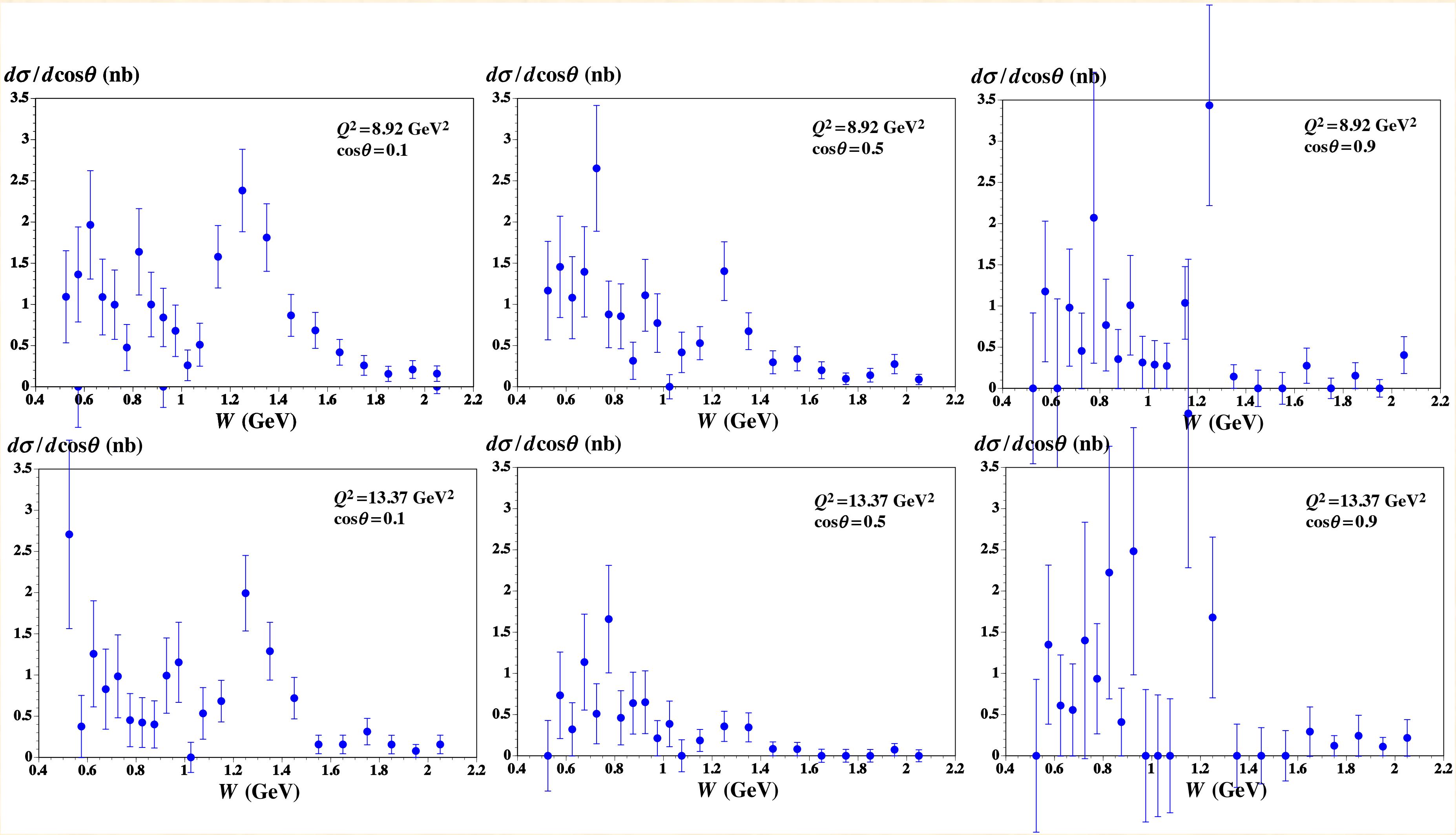
$I^G(J^{PC}) = 0^+(2^{++})$

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

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

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

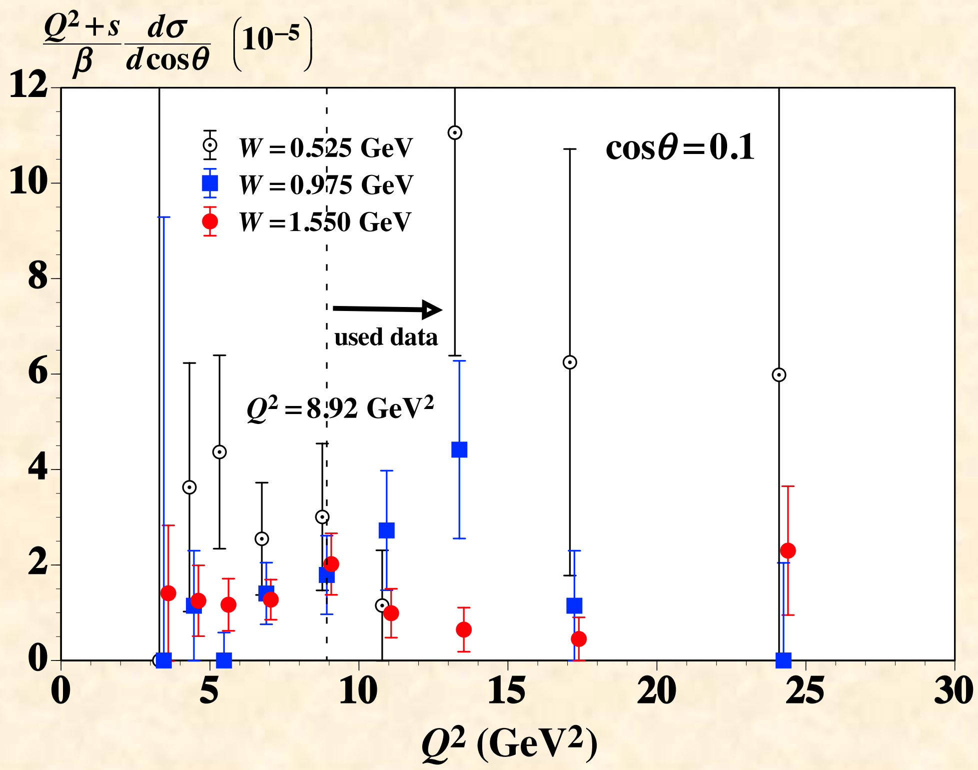
Belle measurements:
M. Masuda *et al.*,
PRD93 (2016) 032003.

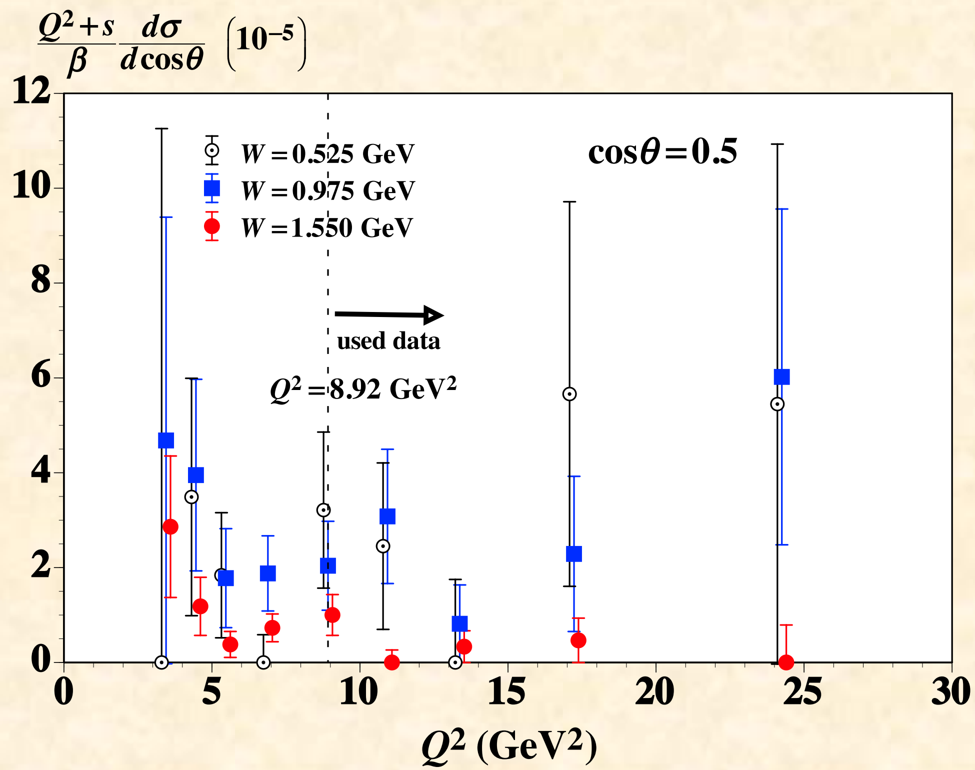


Scaling of Belle data

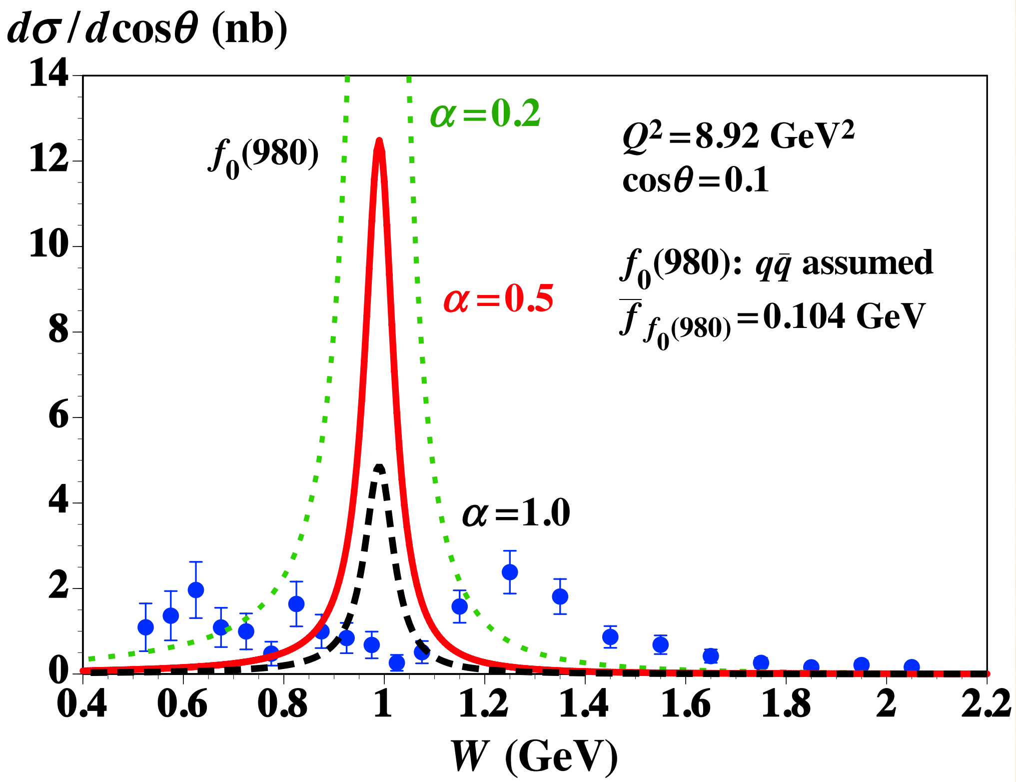
$$\frac{d\sigma}{d(\cos\theta)} = \frac{\pi\alpha^2}{4(s+Q^2)}\sqrt{1-\frac{4m_\pi^2}{s}}\left|A_{++}\right|^2,\;\; A_{++} = \sum_q \frac{e_q^2}{2}\int_0^1 dz\,\frac{2z-1}{z(1-z)}\Phi_q^{\pi\pi}(z,\zeta,W^2),\quad \varepsilon_\mu^+(q)\varepsilon_\nu^+(q')g_T^{\mu\nu} = -1$$

$\frac{s+Q^2}{\beta}\frac{d\sigma}{d(\cos\theta)} = \frac{\pi\alpha^2}{4}\left|A_{++}\right|^2$ is plotted as the function of Q^2.





Analysis results: $f_0(980)$ contribution



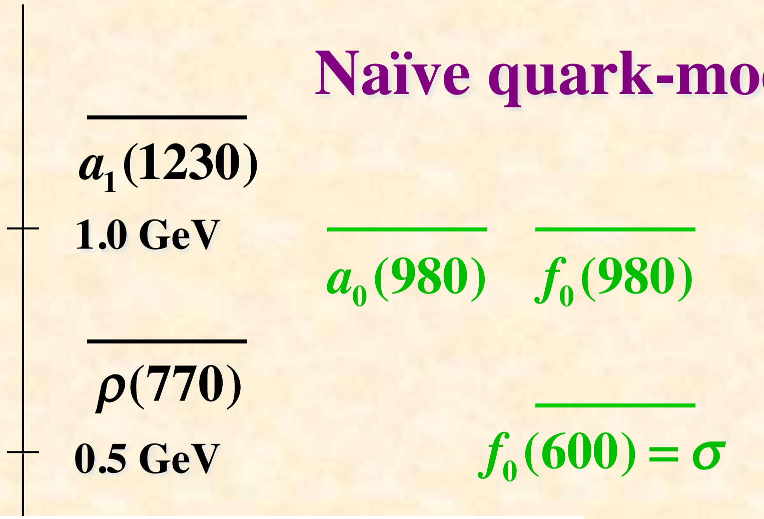
- $f_0(980)$ decay constant is calculated so far by assuming $q\bar{q}$ configuration.
- $f_0(980)$ decay constant is calculated so far by assuming $q\bar{q}$ configuration.

→ not consistent with data

→ $f_0(980)$ is not a $q\bar{q}$ state but likely to be tetra quark or $K\bar{K}$ molecule.

→ $f_0(980)$ is not included in our analysis.

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



$$\sigma = f_0(600) = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

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

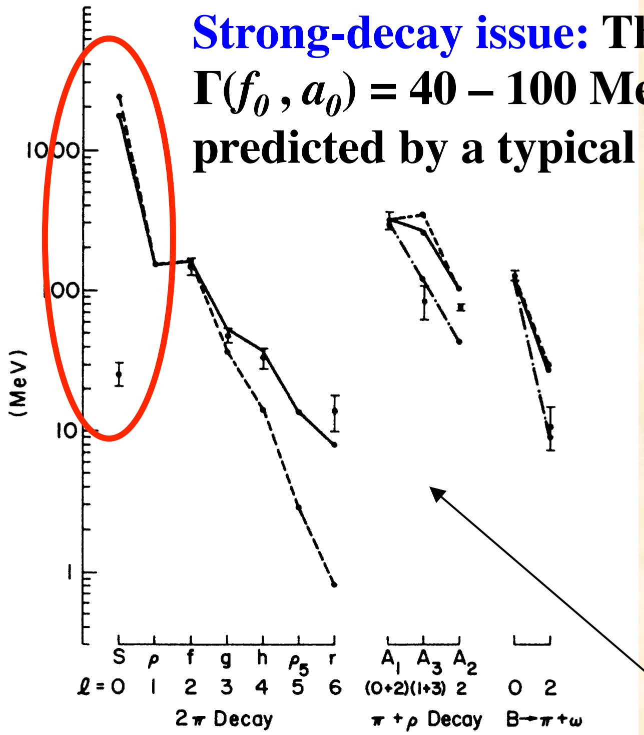
$$a_0(980) = u\bar{d}, \;\; \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}), \;\; d\bar{u}$$

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

⇕ 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.

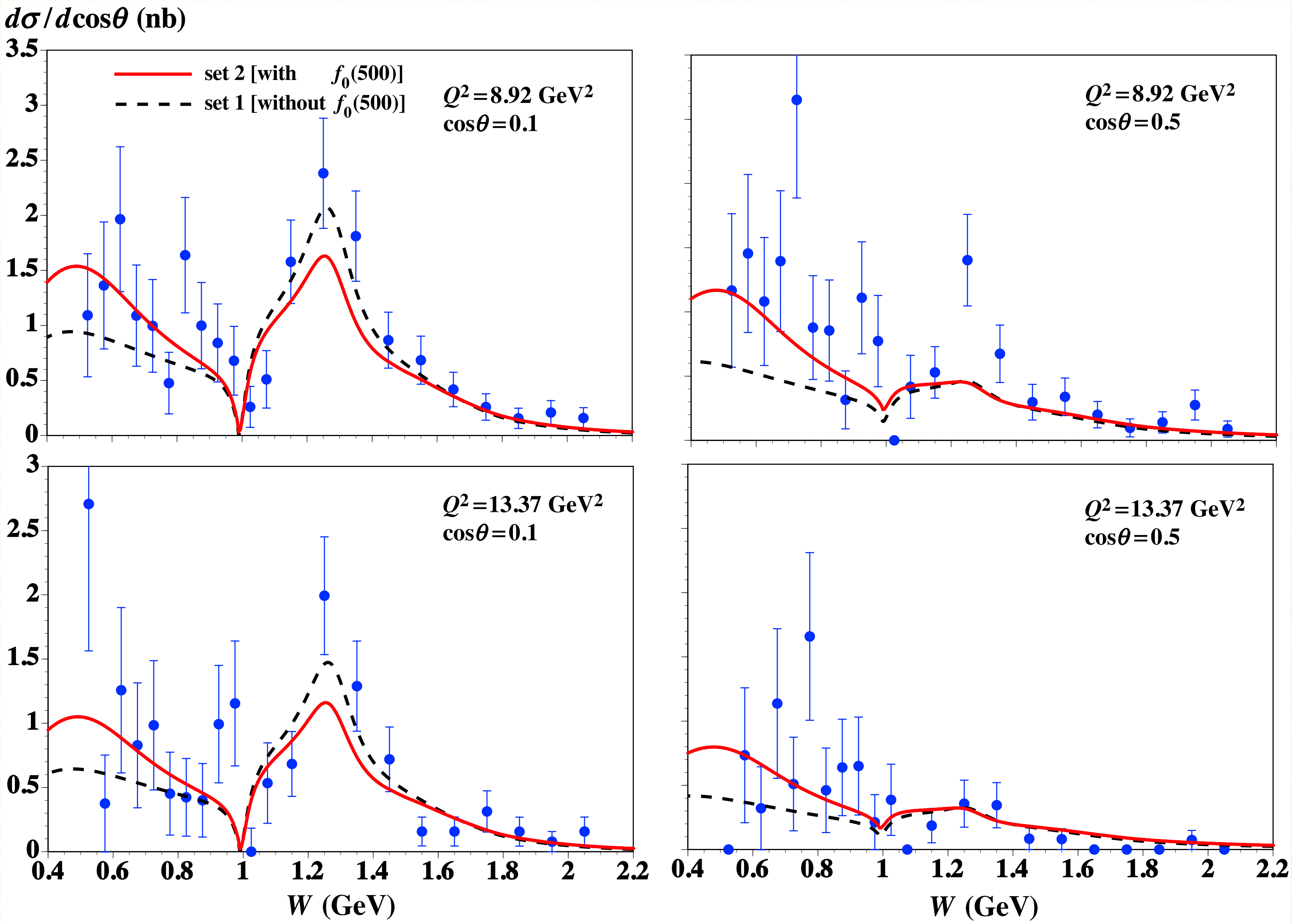


These issues could be resolved
if f_0 is a tetraquark $(qq\bar{q}\bar{q})$ or a $K\bar{K}$ molecule,
namely an "exotic" hadron.

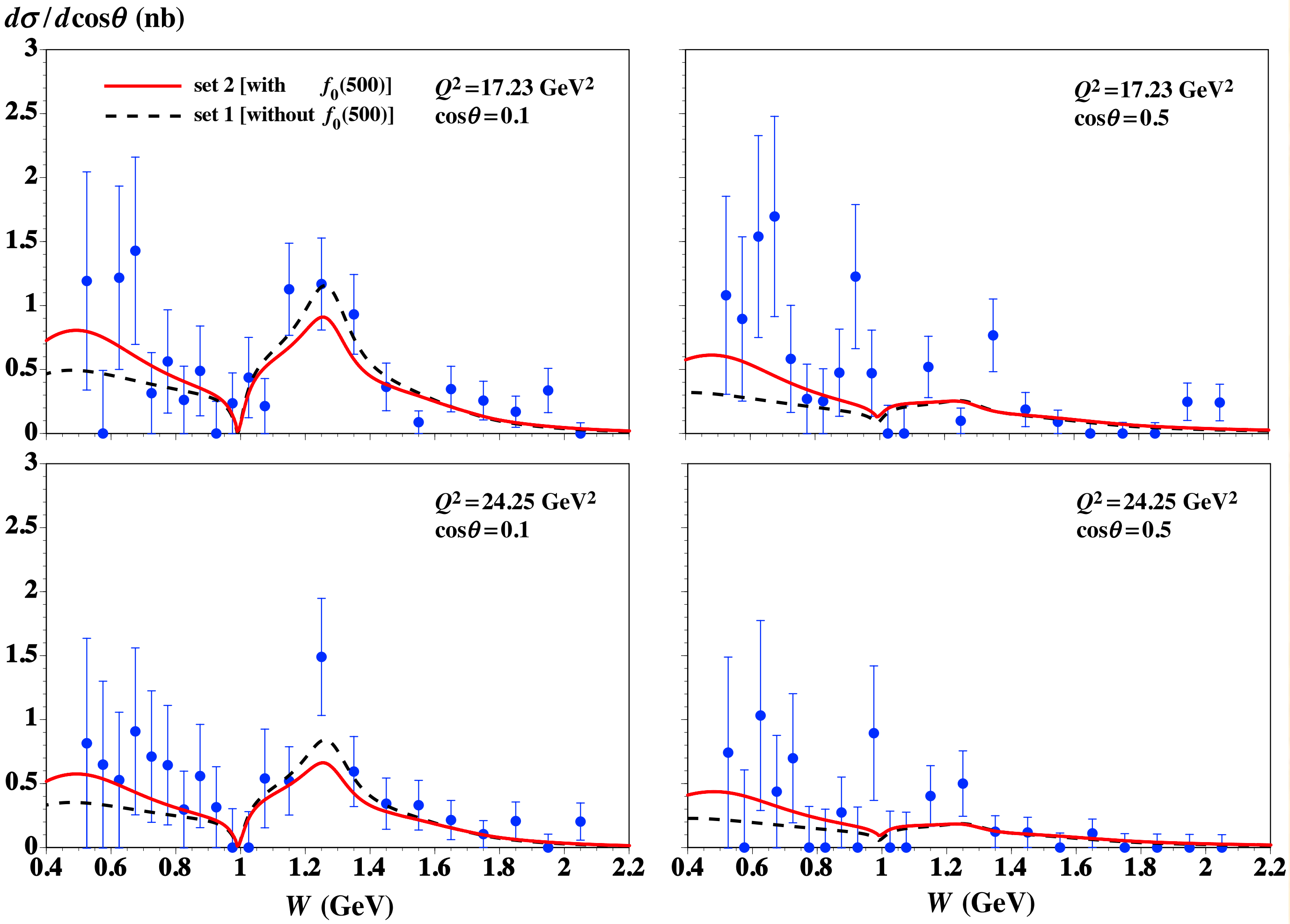
Radiative decay: F. E. Close, N. Isgur, and SK, Nucl. Phys. B389 (1993) 513.

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

Analysis results: Q^2 = 8.92, 13.37 GeV^2, cosθ=0.1, 0.5



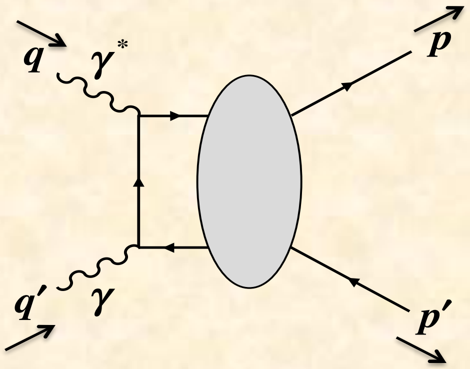
Analysis results: $Q^2 = 17.23,\ 24.25\ \text{GeV}^2,\ \cos\theta = 0.1,\ 0.5$



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

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

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

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

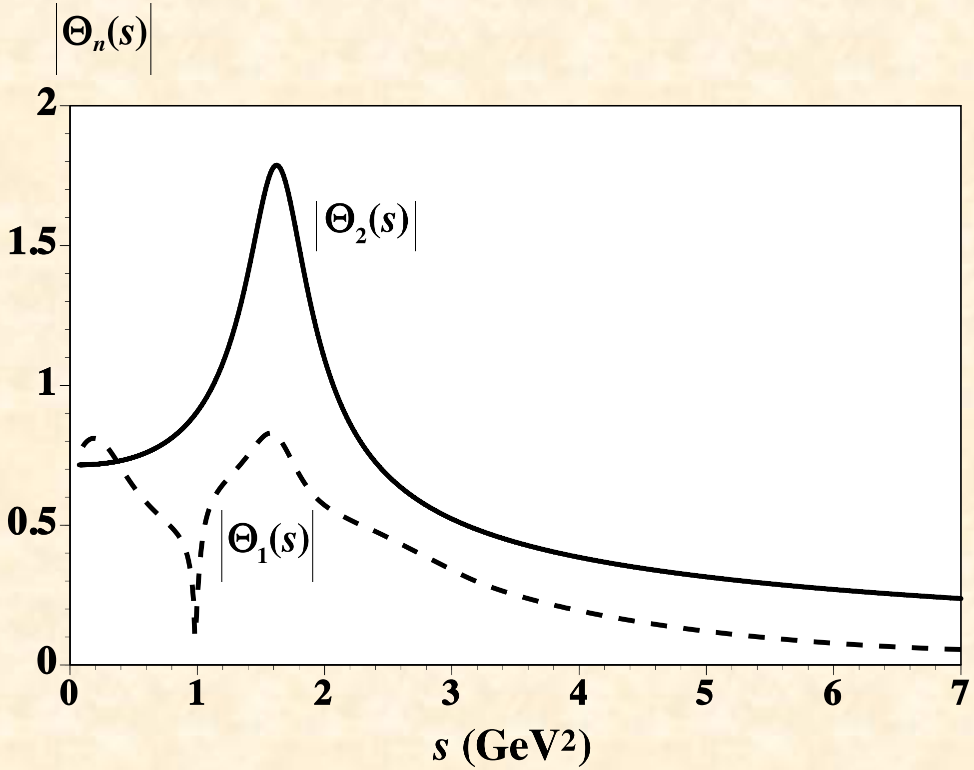
⇒ Spacelike gravitational form factors $\Theta_{1,q}(t)$, $\Theta_{2,q}(t)$

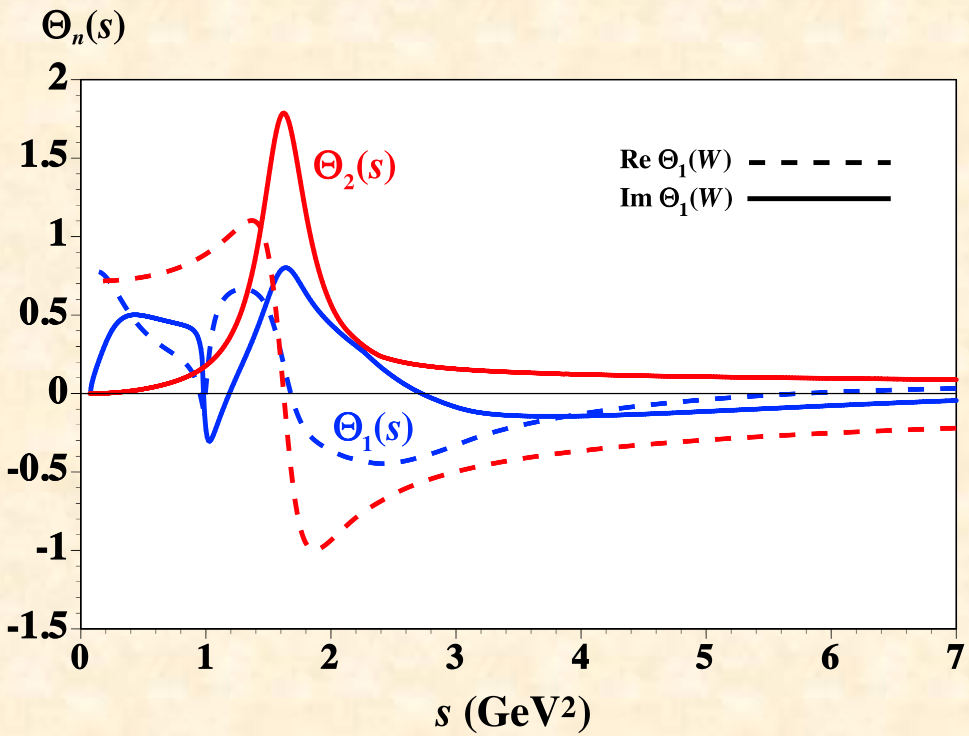
⇒ Gravitational radii of pion

Timelike gravitational form factors for pion

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

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





Spacelike gravitational form factors and radii for pion

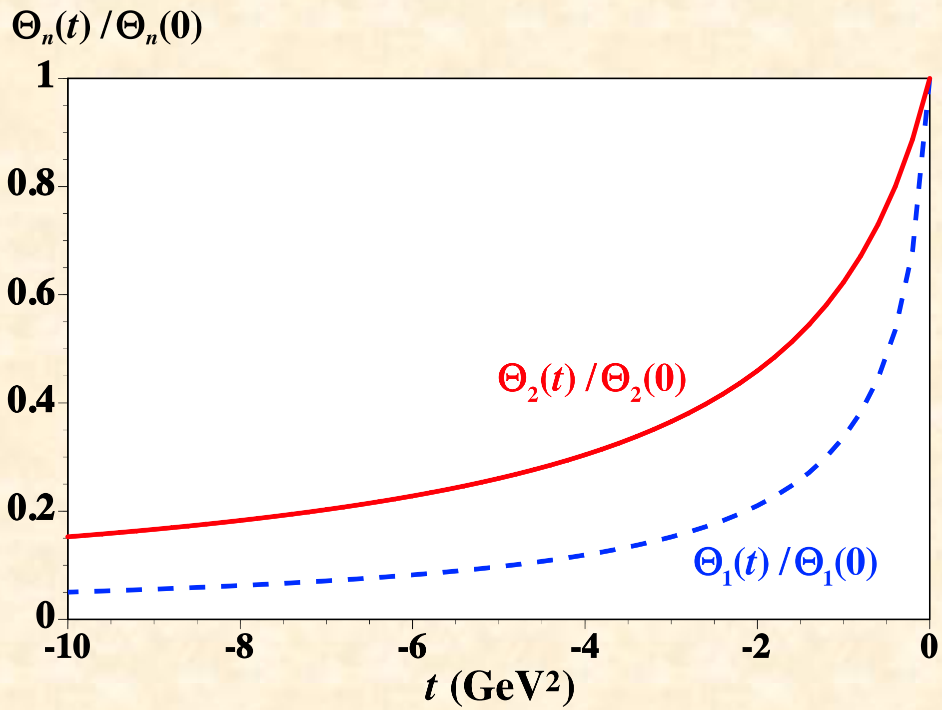
$$F(s) = \Theta_1(s),\ \Theta_1(s),\quad F(t) = \int_{4m_\pi^2}^{\infty} ds \frac{\mathrm{Im}\,F(s)}{\pi(s-t-i\varepsilon)},\quad \rho(r) = \frac{1}{(2\pi)^3}\int d^3q e^{-i\vec{q}\cdot\vec{r}} F(q) = \frac{1}{4\pi^2}\frac{1}{r}\int_{4m_\pi^2}^{\infty} ds\, e^{-\sqrt{s}r}\,\mathrm{Im}\,F(s)$$

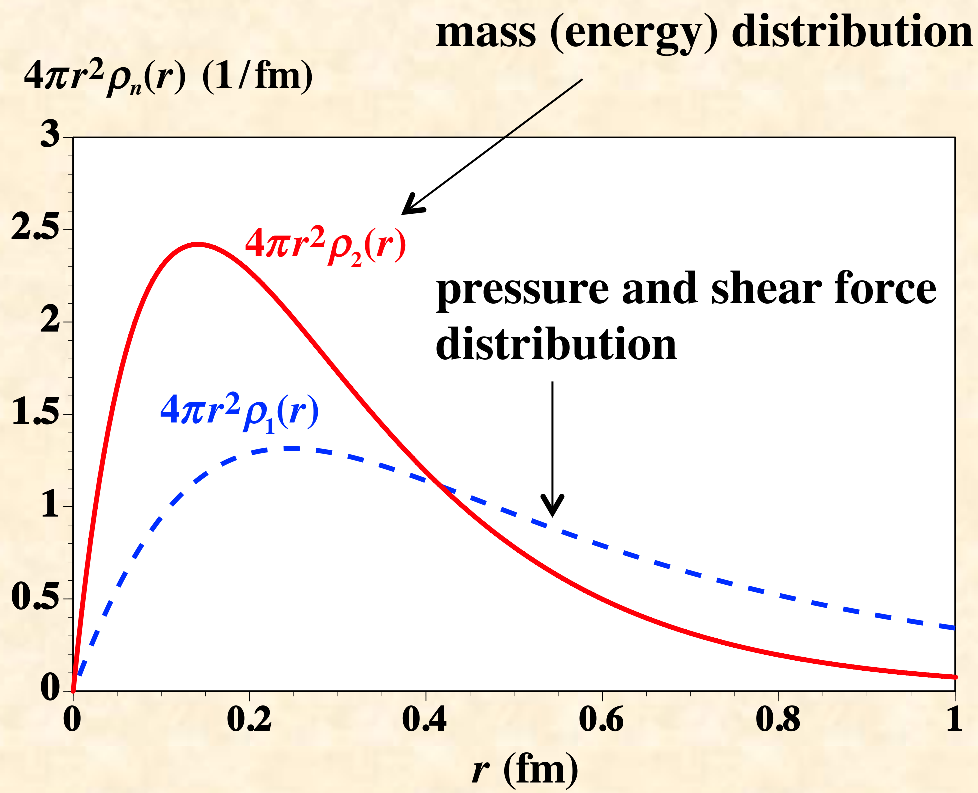
This is the first report on gravitational radii of hadrons from actual experimental measurements.

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

← **First finding on gravitational radius from actual experimental measurements**

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





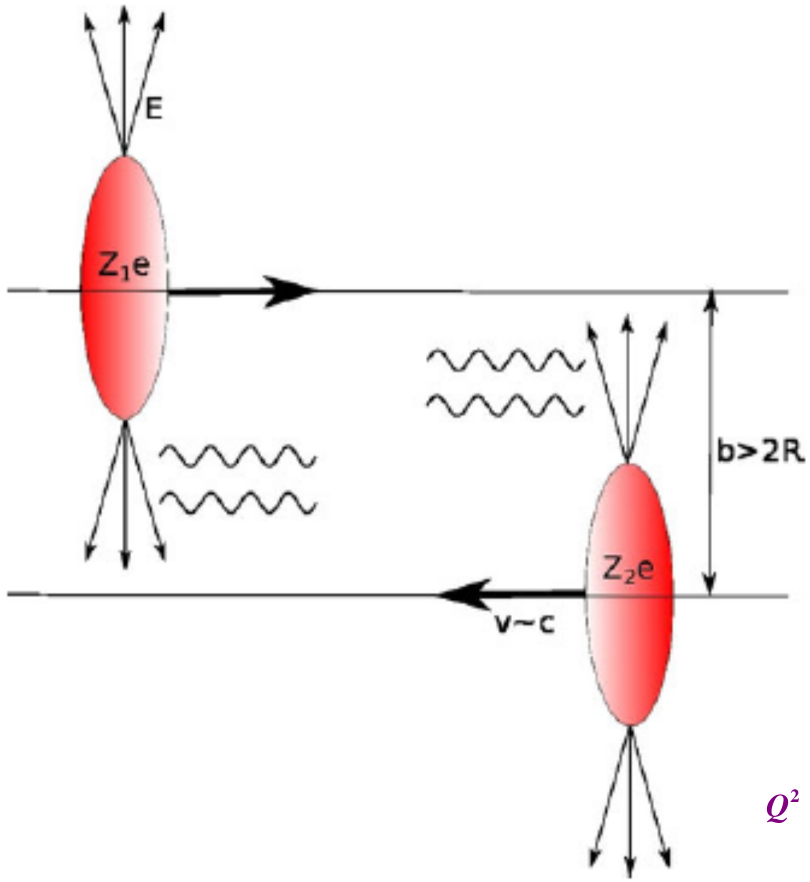
Prospects & Summary

Ultra-Peripheral Collision (UPC) @ LHC/RHIC

INT Workshop INT-17-65W

Probing QCD in Photon-Nucleus Interactions at RHIC and LHC: the Path to EIC

February 13 - 17, 2017



$Q^2 \gg \Lambda^2_{QCD}$ **may not be possible at LHC?**

GSI-FAIR (PANDA)

arXiv:0903.3905 [hep-ex]

Physics Performance Report for:

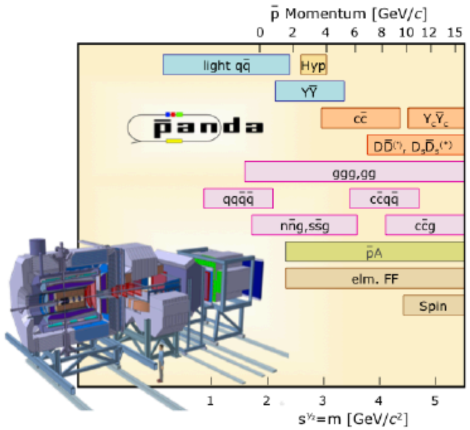
$\overline{\text{P}}$ANDA

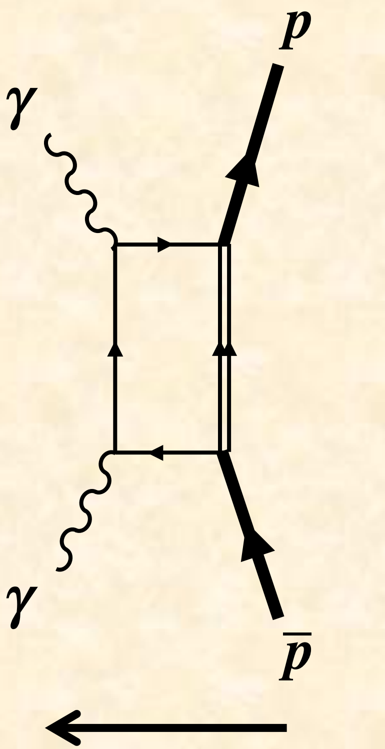
(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

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

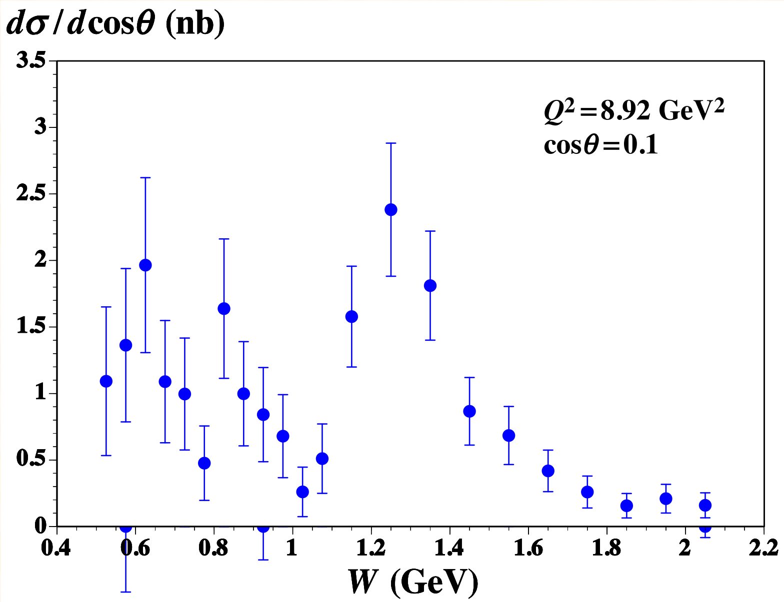
To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented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

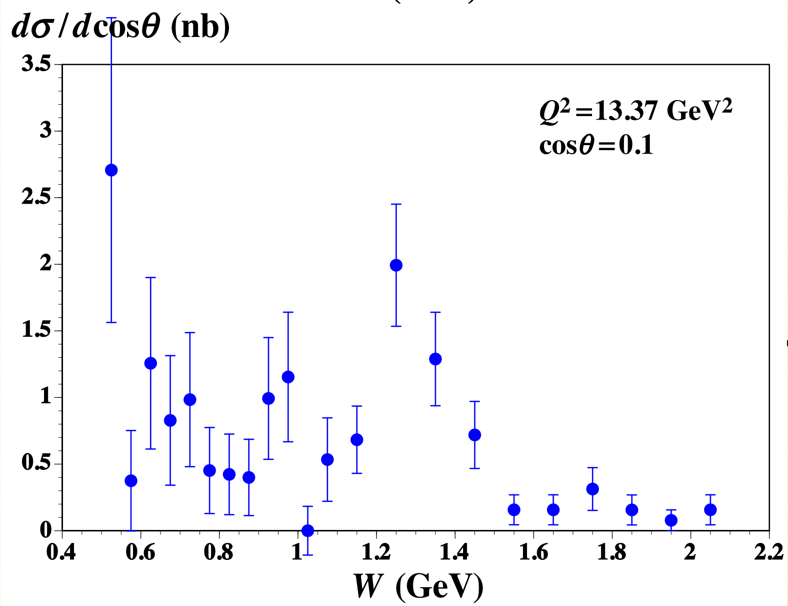




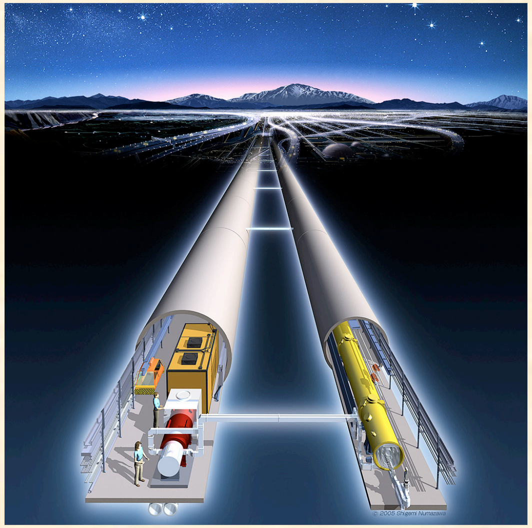
GDAs for the proton!
(super-KEKB?)

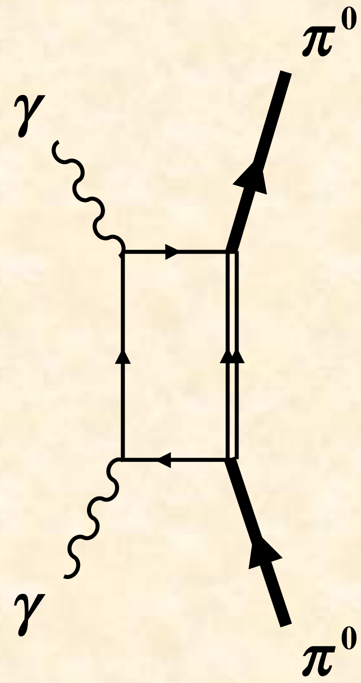
From KEKB to ILC





Linear Collider ?





- Very Large Q^2
- Large W^2

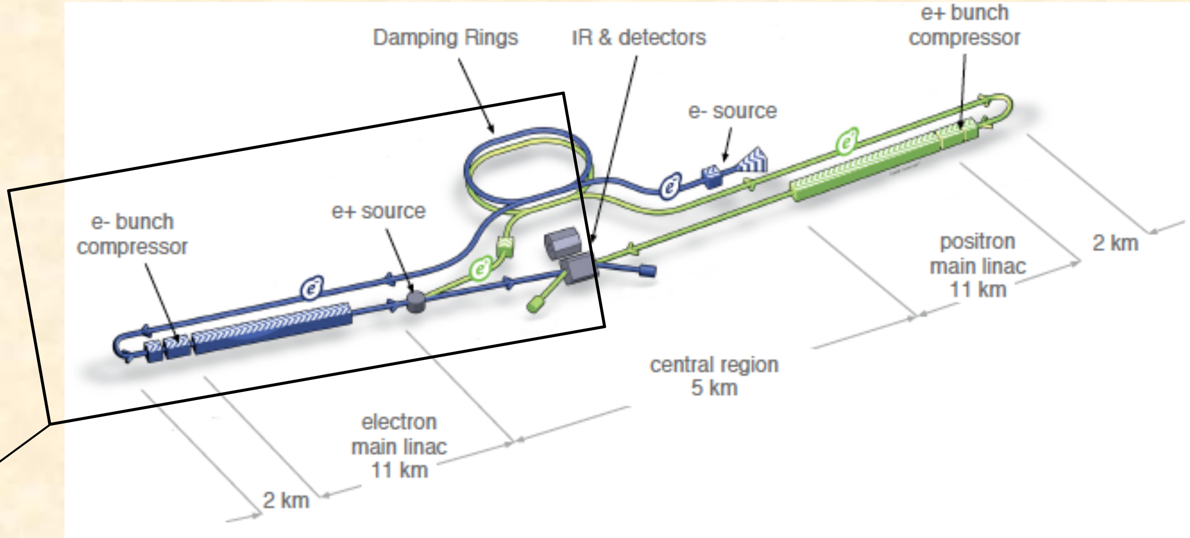
for extracting GDAs

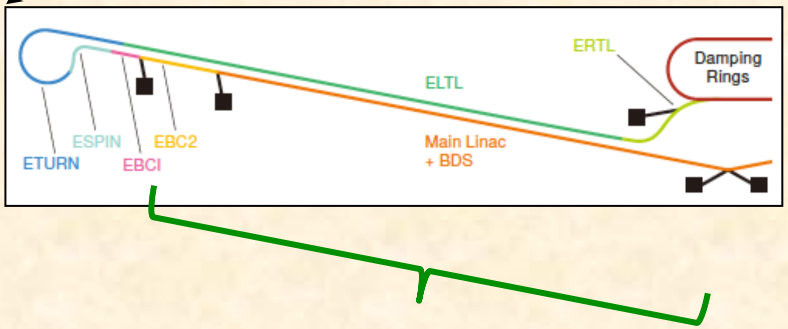
→ **ILC**

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

ILC TDR (Technical Design Report)

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





5 – 250 GeV electron beams
for fixed target experiments

Possibilities for hadron and nuclear physics

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

→ No serious studies about these feasibilities.

Electron-ion collider projects and ILC

arXiv:1108.1713 (551 pages)

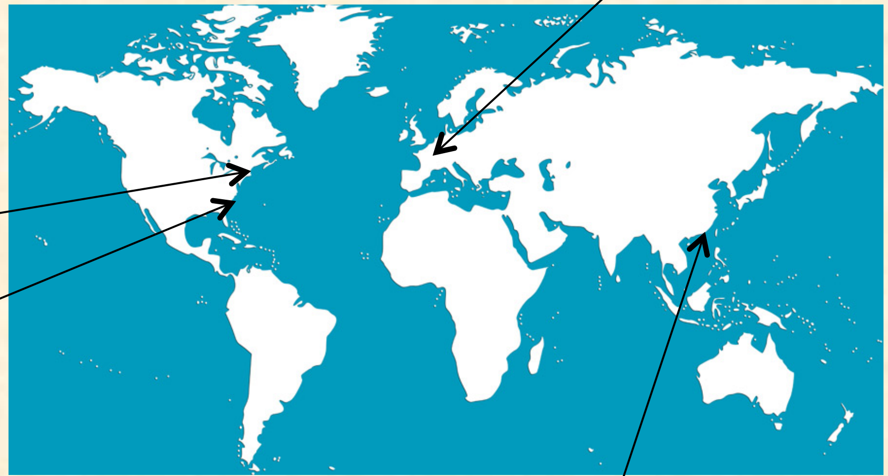
The EIC Science case: a report on the joint BNL/INT/JLab program

Gluons and the quark sea at high energies: distributions, polarization, tomography

CERN

BNL

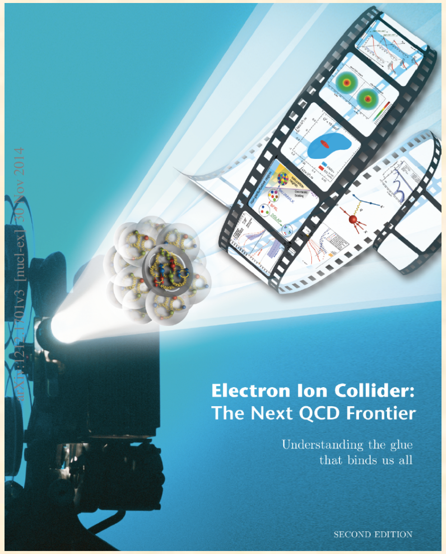
JLab

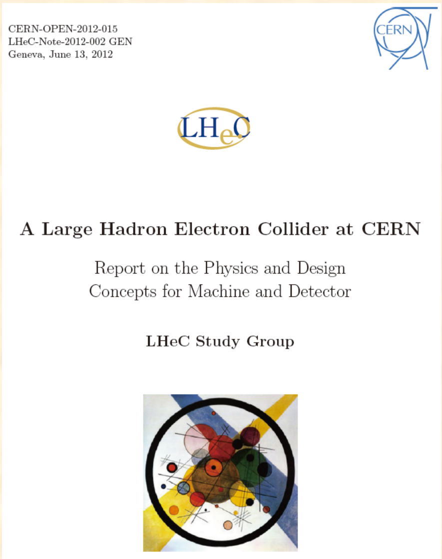


High Intensity Heavy Ion Accelerator Facility (HIAF)

arXiv:1212.1701 (180 pages)

J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001(632 pages)





CERN-OPEN-2012-015
LHeC-Note-2012-002 GEN
Geneva, June 13, 2012

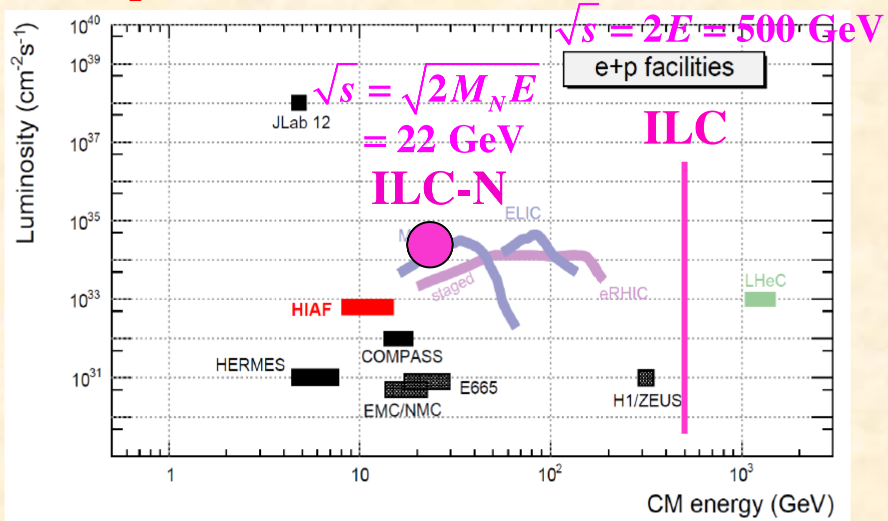
LHeC

A Large Hadron Electron Collider at CERN

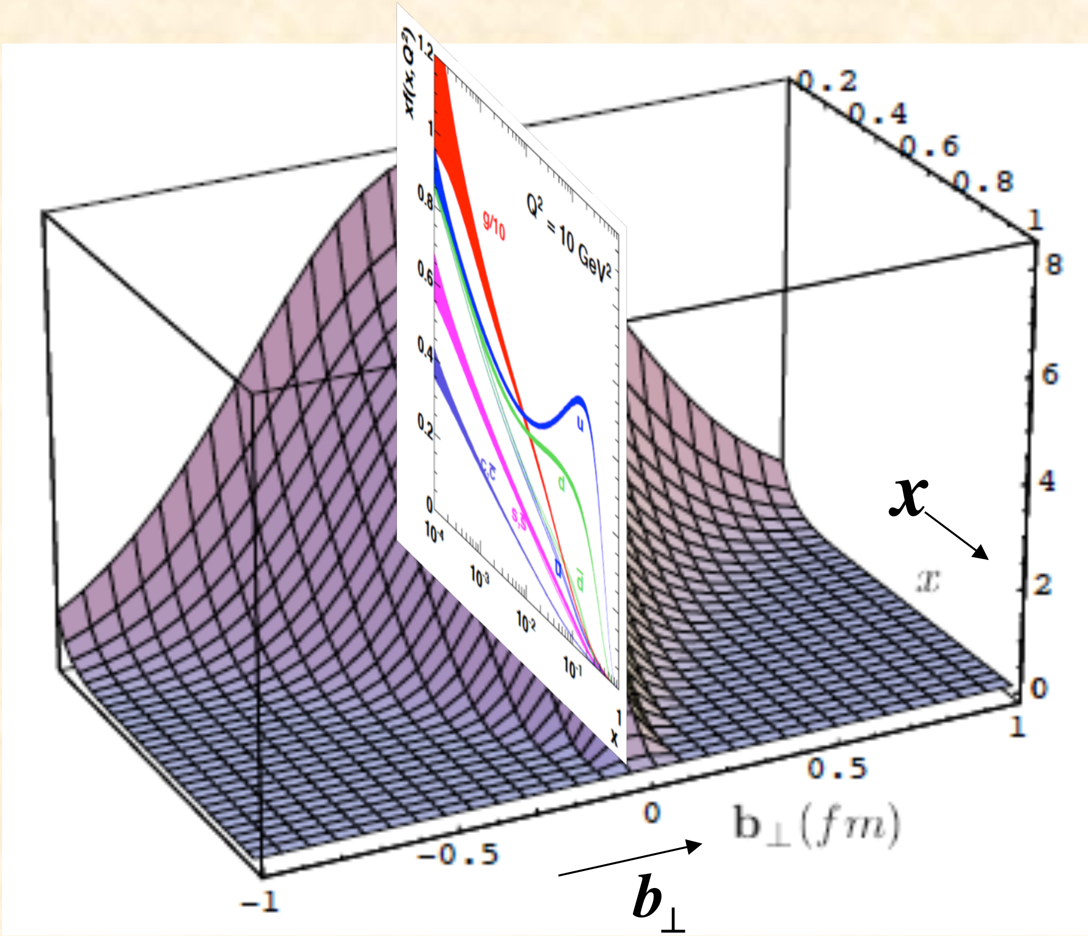
Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

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

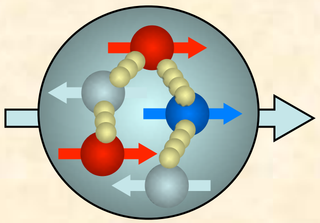
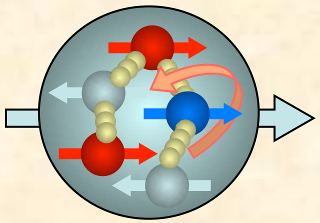


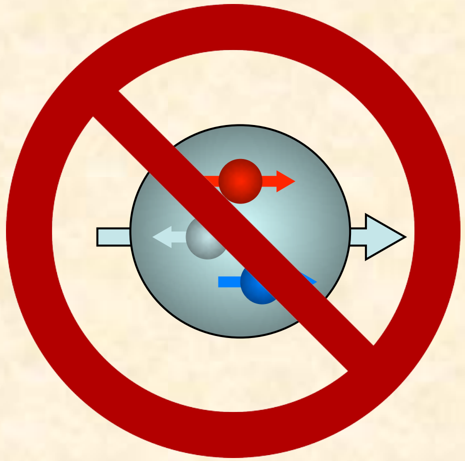
3D view of hadrons



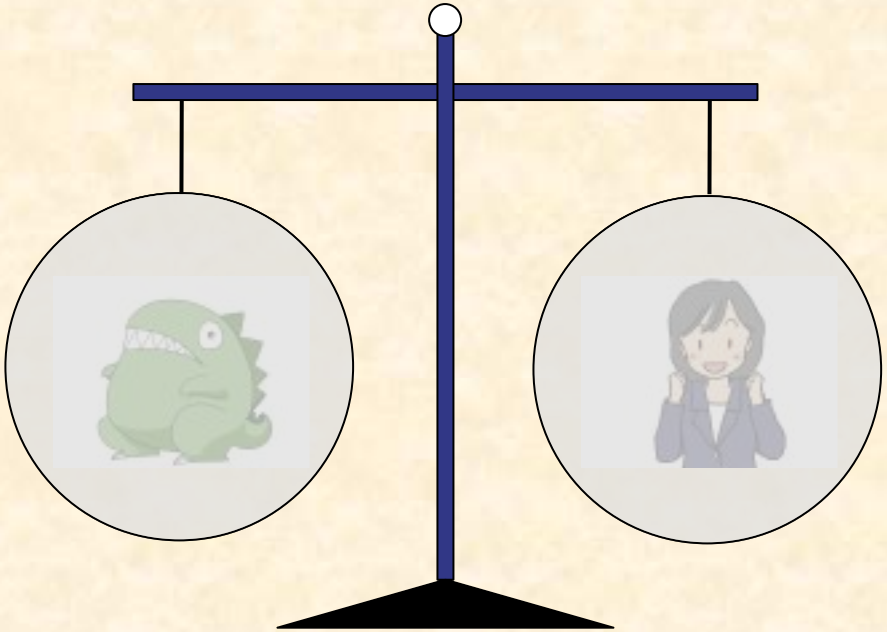
Origin of nucleon spin …

By the tomography, we determine

 or  .



Search for exotic hadrons …



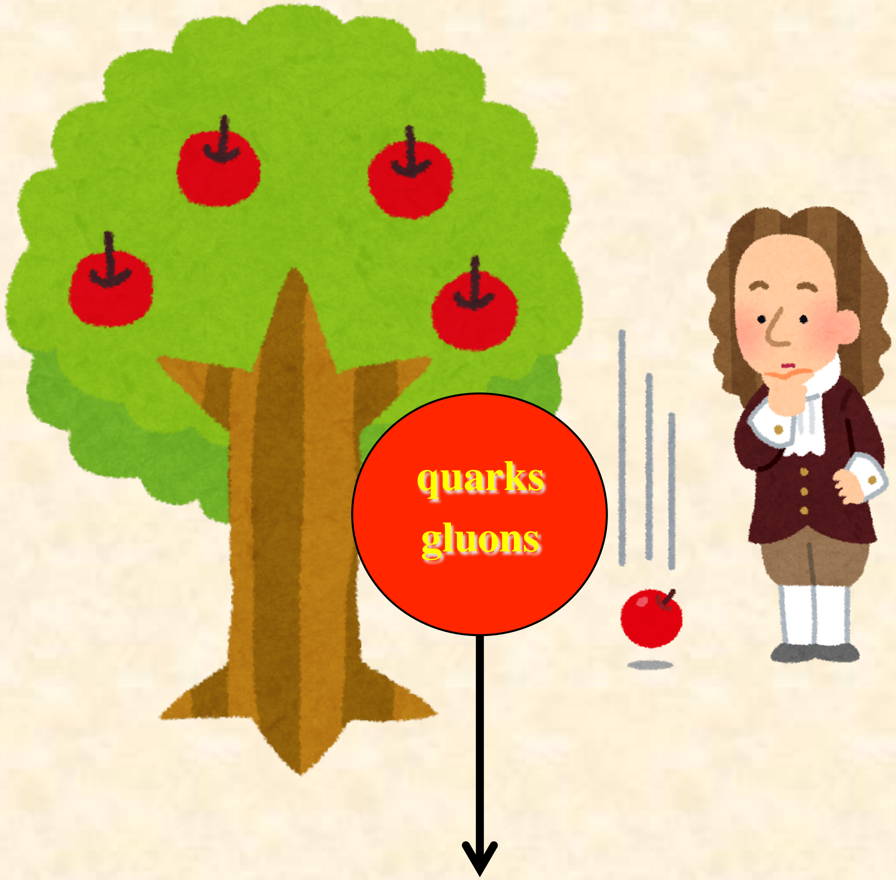
It is difficult to determine whether or not a hadron is exotic by low-energy observables, masses, decay widths, …

(Already, history of a half century)

By the tomography, we determine

 or  .

Origin of gravity in terms of quarks and gluons…



By the tomography, we determine gravitational sources (interactions) with quarks and gluons.

8th International Conference on Quarks and Nuclear Physics

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

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

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

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

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

Summary

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

GPDs for exotics

Internal structure of exotic hadron candidates could be probed by GPDs; however, they are not easily measured because they are unstable for fixed target experiments.
→ It is possible by GDAs.

GDAs at KEKB

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

Related experimental projects

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

Gravitational radii can be obtained for hadrons!

The End

The End