High-energy hadron physics at J-PARC

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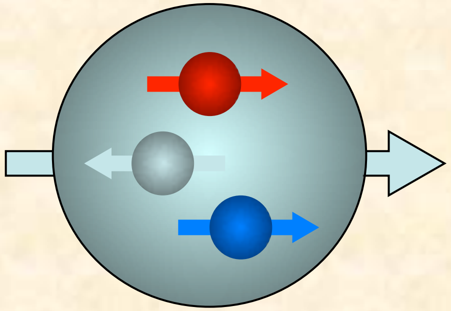
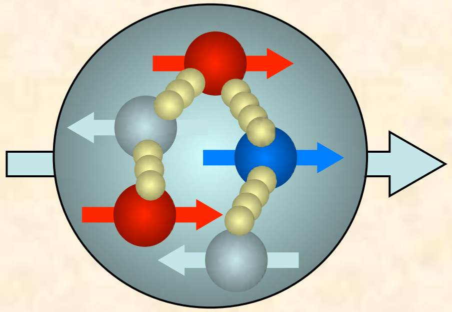
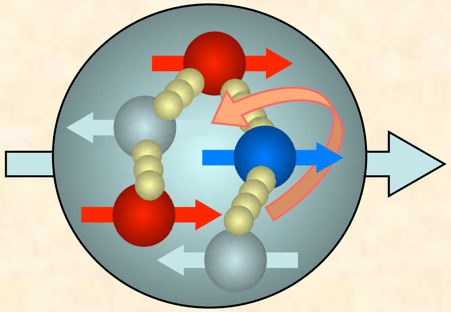
Meeting on High-Energy QCD and Nucleon Structure
November 1, 2014
Tokyo Institute of Technology, Tokyo, Japan
http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1653

Nucleon Spin







Naïve Quark Model

$\Delta\Sigma = \Delta u_v + \Delta d_v = 1$

Electron / muon scattering

$\Delta\Sigma \approx 0.3$

Almost none of nucleon spin is carried by quarks!

QCD

Sea-quarks and gluons?

Gluon: ΔG

Sea-quarks: Δq_{sea}

ΔG ?

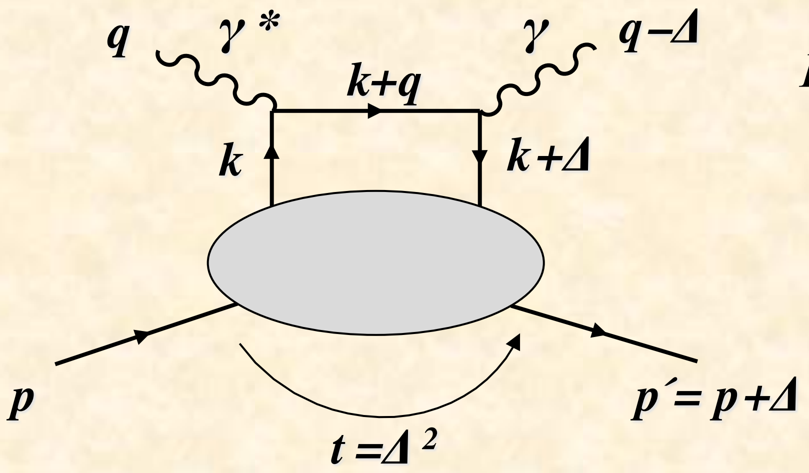
Orbital angular momenta ?

L_q, L_g

3D view of nucleon (Tomography)

Nucleon Spin: $$\frac{1}{2} = \underbrace{\frac{1}{2}\left(\Delta u_v + \Delta d_v + \Delta q_{sea}\right)}_{\Delta\Sigma} + \Delta G + L_q + L_g$$

Generalized Parton Distributions (GPDs)



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

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:

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

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

First moments: Form factors

Dirac and Pauli form factors F_1, F_2 $\int dx\, H(x,\xi,t) = F_1(t), \quad \int dx\, E(x,\xi,t) = F_2(t)$

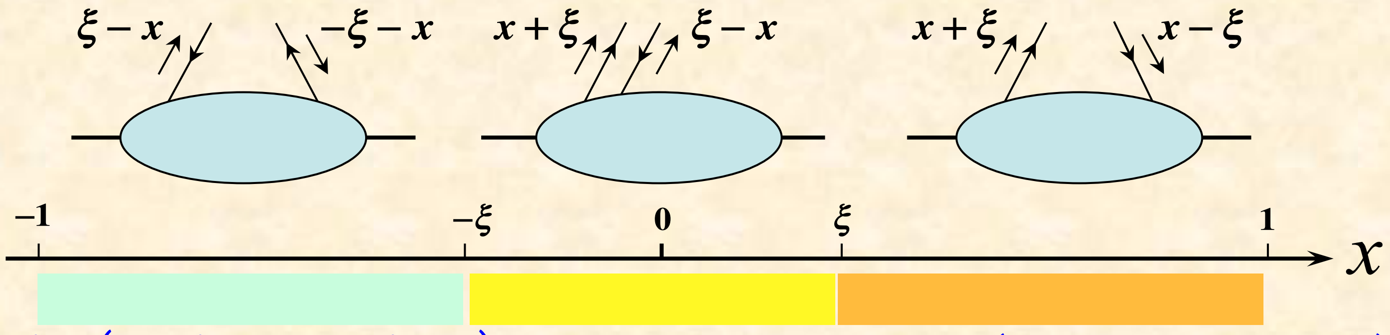
Second moments: Angular momenta

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

GPDs in the ERBL region

at hadron facilities

GPDs in different x regions and GPDs at hadron facilities



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

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

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

Quark distribution

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

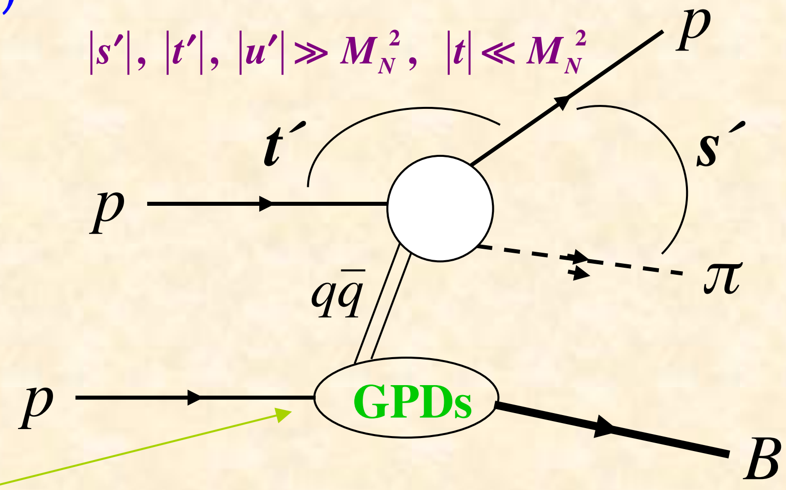
Meson-like distribution amplitude

Emission of quark with momentum fraction $x+\xi$
Emission of antiquark with momentum fraction ξ-x

Antiquark distribution

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

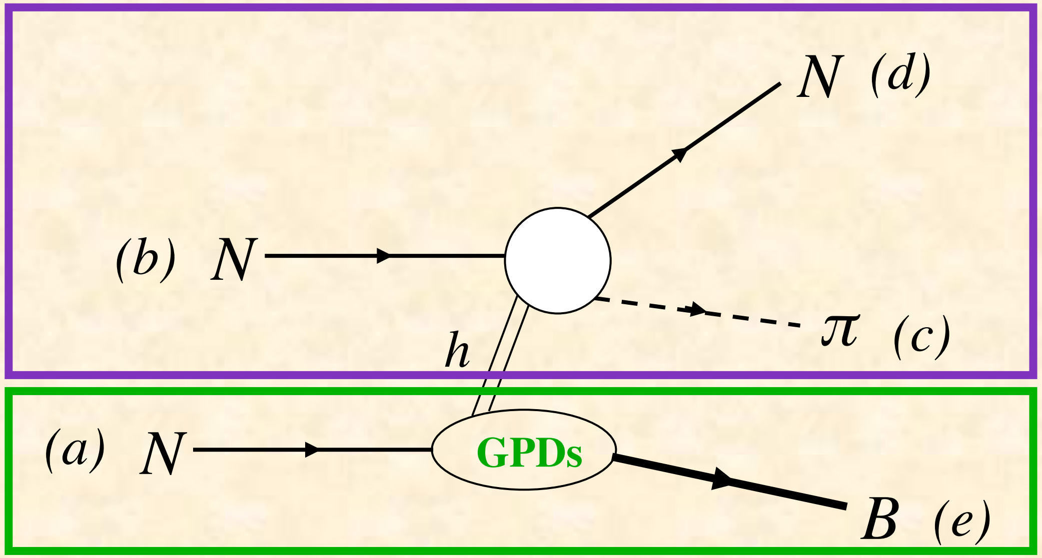
Consider a hard reaction with
$|s'|,\ |t'|,\ |u'| \gg M_N^2,\ \ |t| \ll M_N^2$



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

Efremov-Radyushkin -Brodsky-Lepage (ERBL) region

Cross section estimates



$\frac{d\sigma(s',t')}{dt'}$ so as to explain

AGS experimental data on

$\pi + p \to \pi + p,\ \pi + p \to \rho + p$

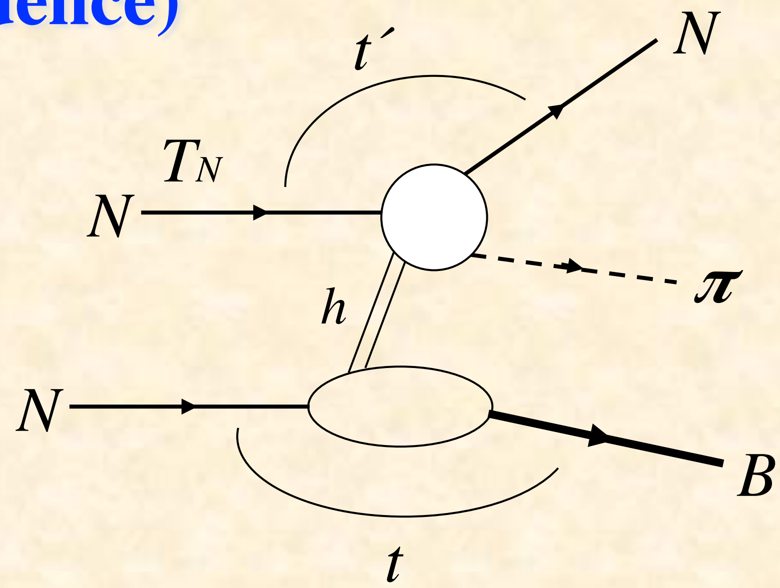
This part is expressed by GPDs.

Purposes of our studies:

(1) The ultimate purpose is to extract the GPDs in the ERBL region by measurements at hadron facilities in addition to lepton ones.

(2) Since our work is the first one to point out the GPD studies at hadron reactions, we estimate the order of magnitude of cross sections simply by using meson-pole expressions of the GPDs.
→ For experimental feasibility studies.

Cross section estimate (ξ dependence)

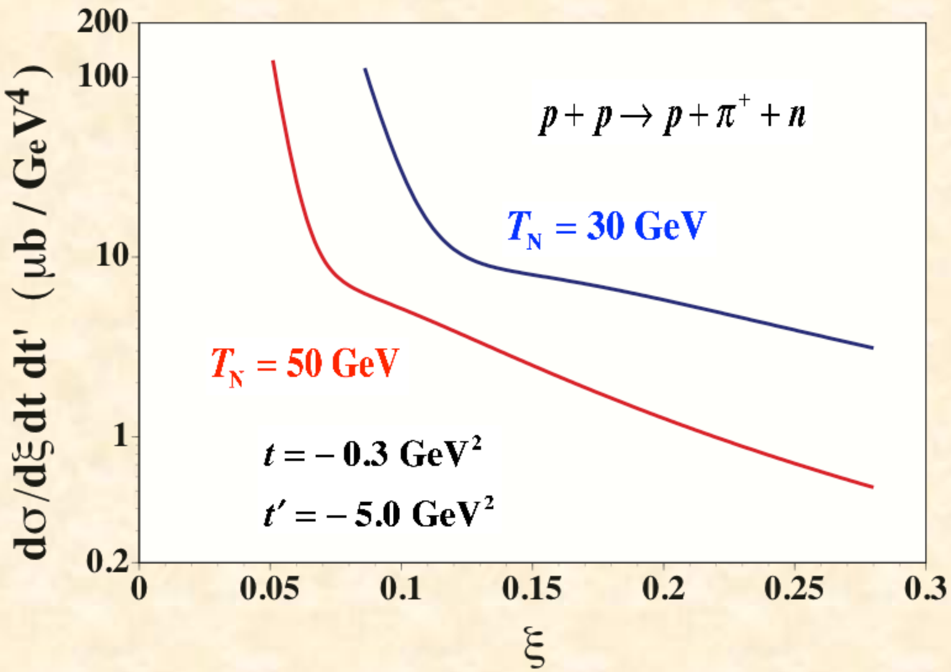


Skewdness parameter: $\xi = \dfrac{p_N^+ - p_B^+}{p_N^+ + p_B^+}$

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

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

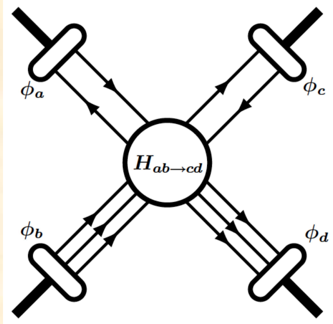
$t = -\,0.3\ \mathrm{GeV}^2, \quad t' = -\,5\ \mathrm{GeV}^2.$



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

Constituent-counting rule for exotic hadrons

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



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

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

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

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

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

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

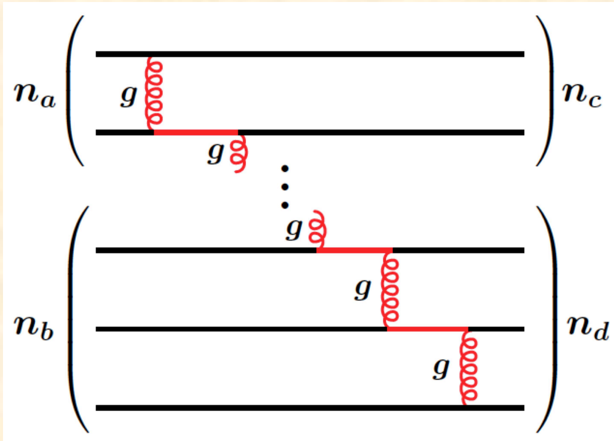
There are $n/2-1$ gluon propagators $\sim 1/(P^2)^{n/2-1}$.

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

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



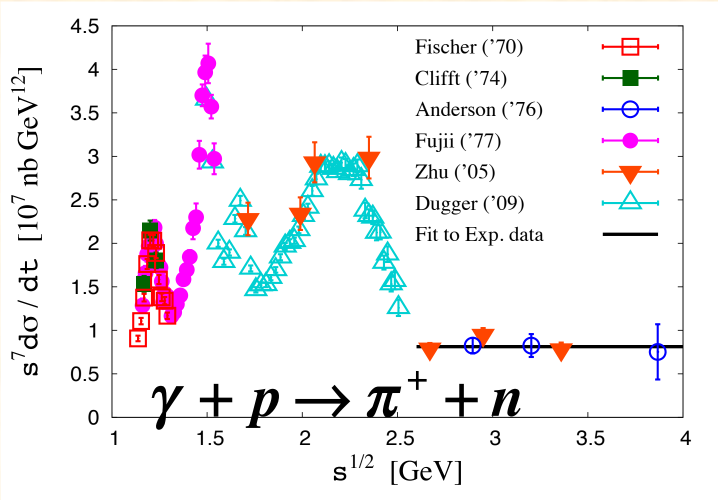
$$M_{ab\to cd} \sim \frac{1}{(P^2)^{n/2-1}} \frac{1}{(P)^{n/2-2}} (\sqrt{P})^n = \frac{(P)^{n/2}}{(P)^{n-2}(P)^{n/2-2}} = \frac{1}{(P)^{n-4}} \sim \frac{1}{s^{n/2-2}}$$

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



BNL: 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

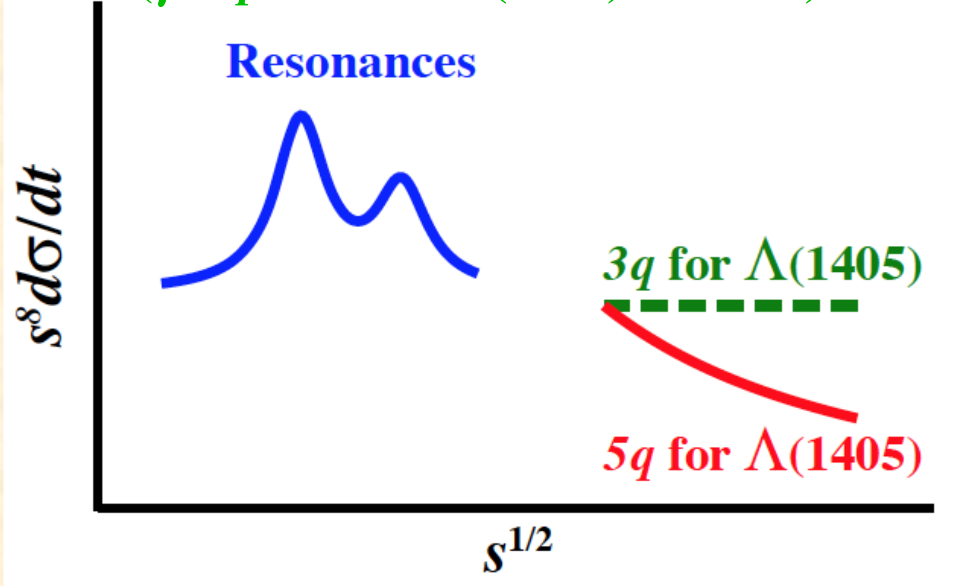
Our idea

- Transition from hadron d.o.f to quark d.o.f. for exotic-hadron production
- Internal structure of exotic hadrons by constituent-counting scaling

Exotic hadron production

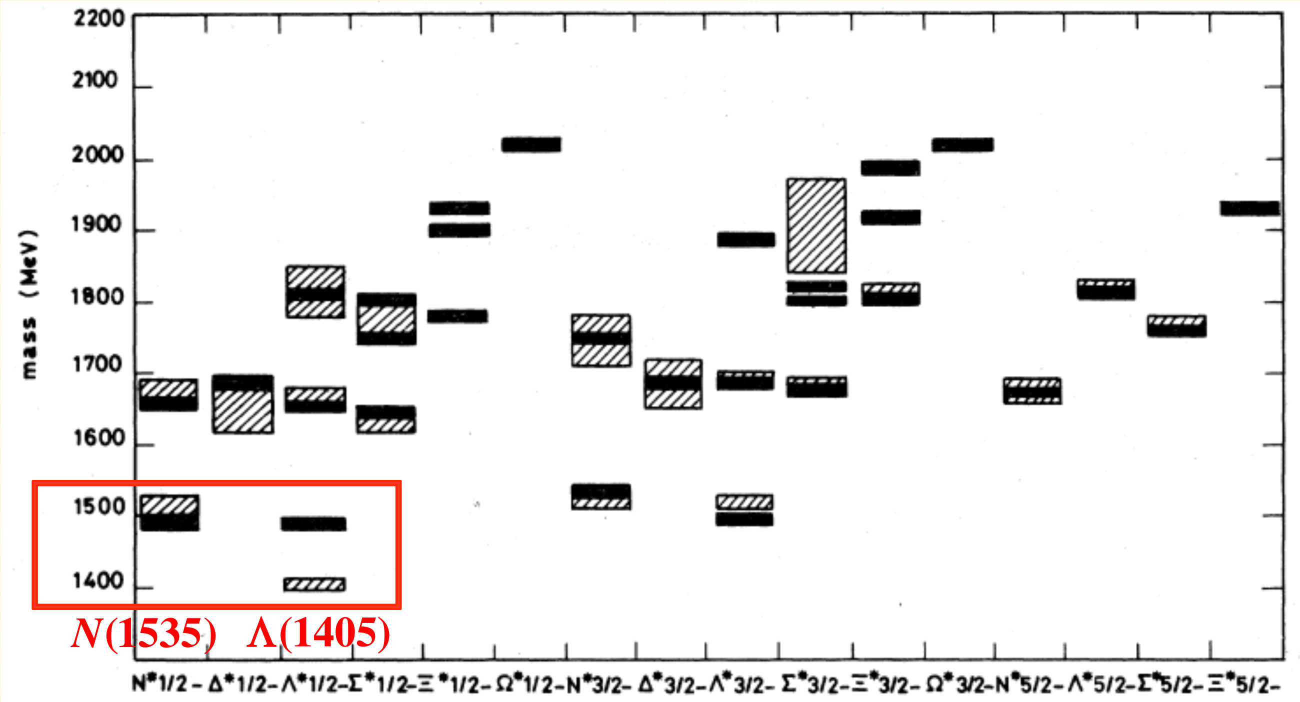
$$\pi^- + p \to K^0 + \Lambda(1405)$$

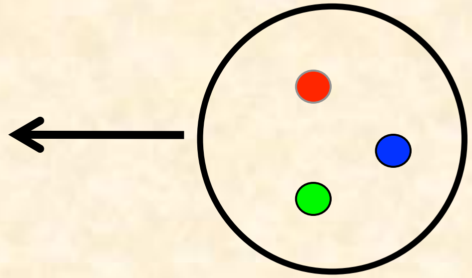
$$(\gamma + p \to K^+ + \Lambda(1405) \text{ at JLab})$$

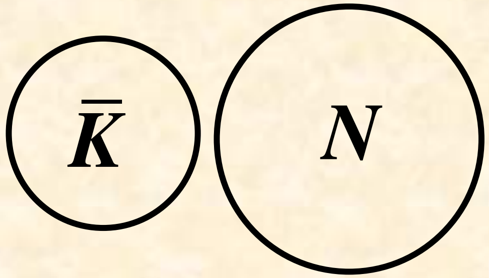


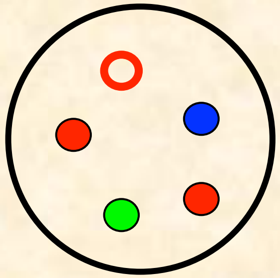
Λ(1405): exotic hadron?

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







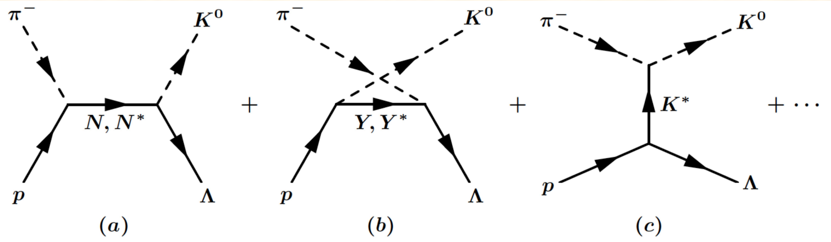


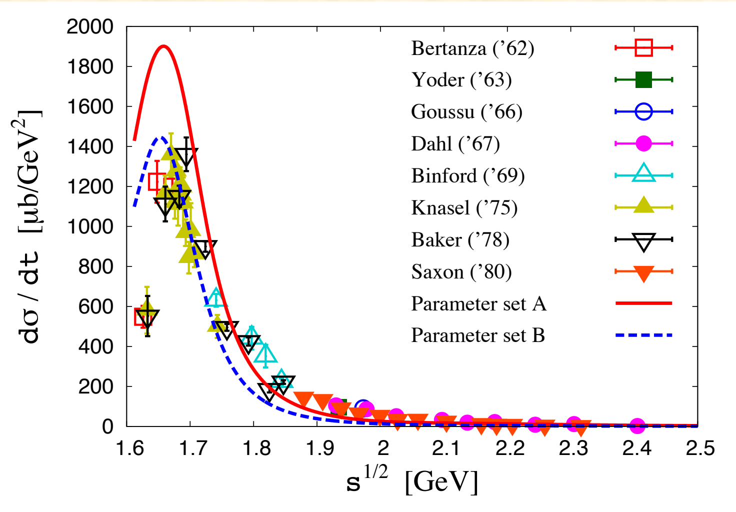
Most spectra agree with the ones by a 3*q*-picture

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

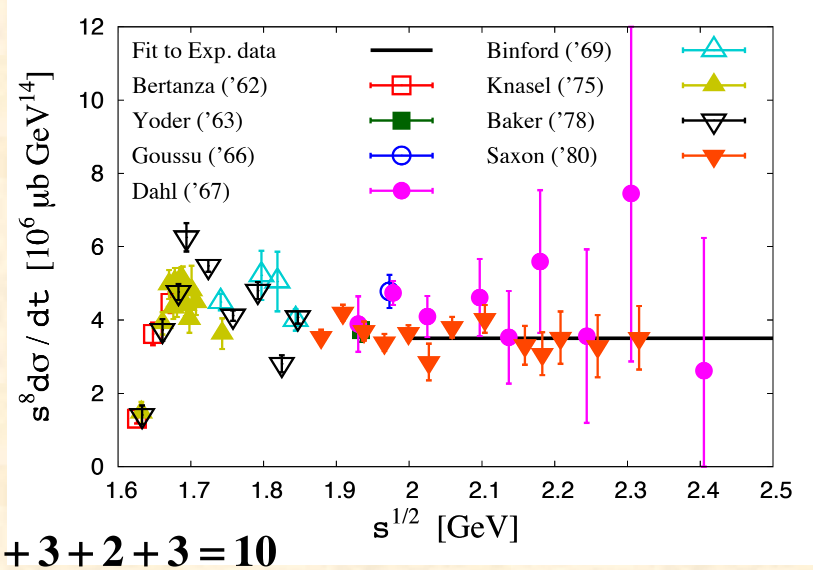
Ordinary-hadron production $\pi^- + p \to K^0 + \Lambda$ as a reference

At low energies





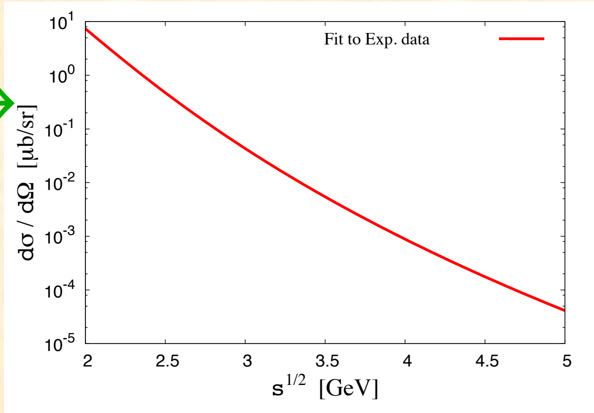
From low to higher energies



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

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

Our prediction at high energies →



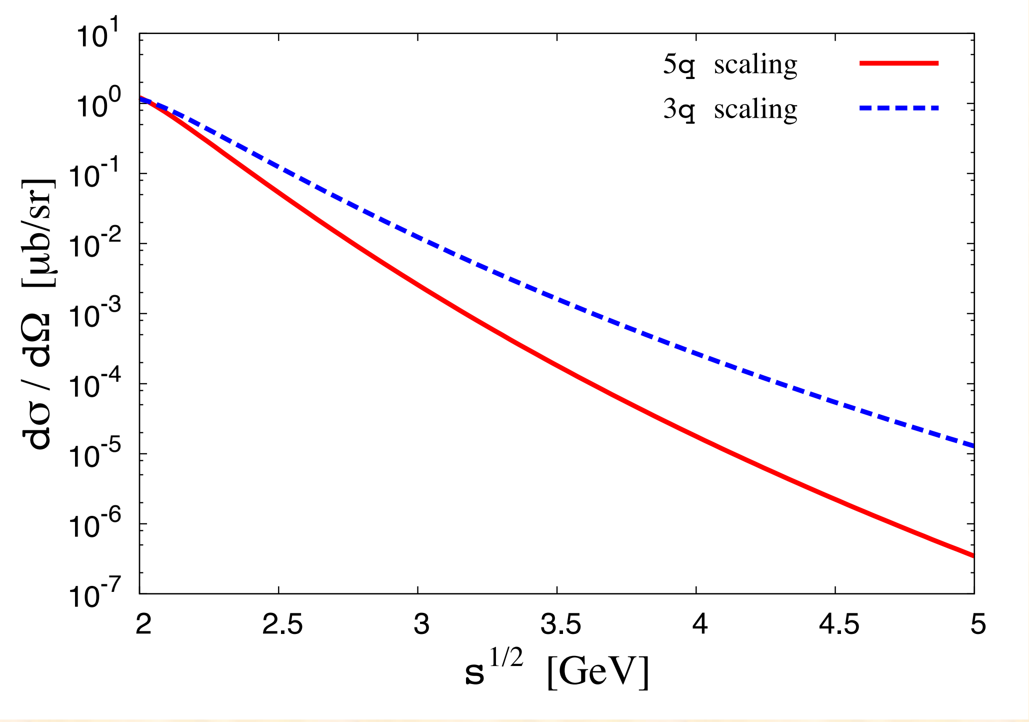
Exotic-hadron production $\pi^- + p \to K^0 + \Lambda(1405)$

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



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

GPDs and GDAs

for exotic hadrons

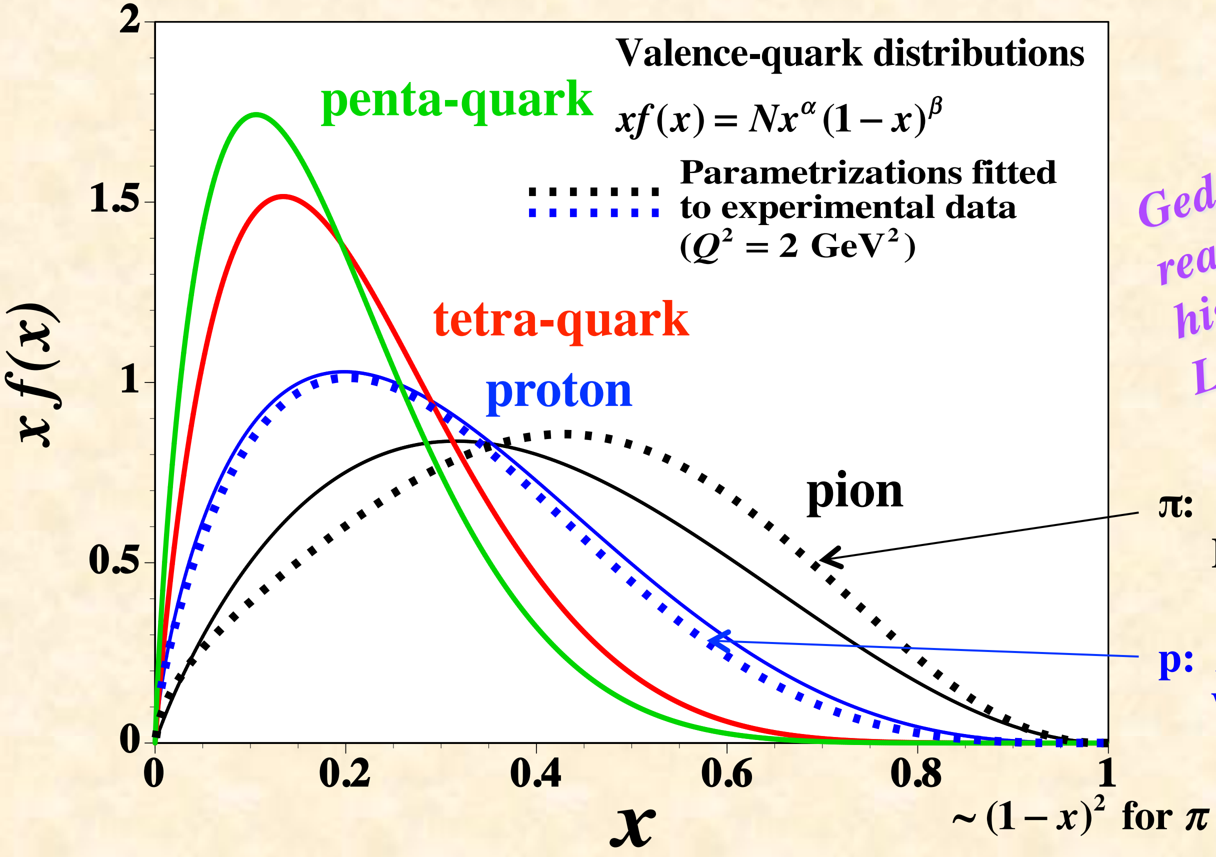
Simple function of GPDs

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

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



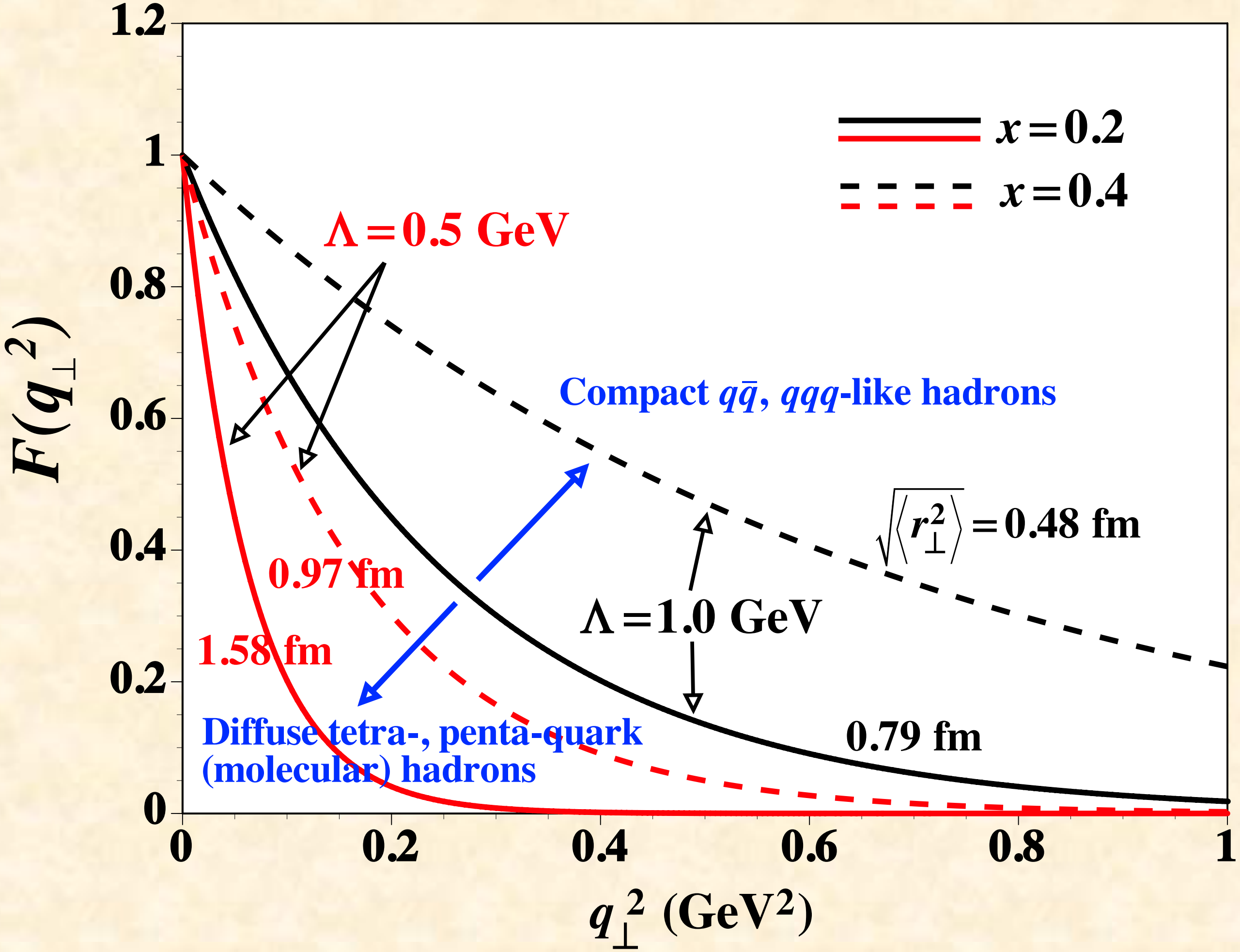
Gedankenexperiment, but …
read our paper for studying exotics in high-energy processes at KEK-B, Linear Collider, ….

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 !?

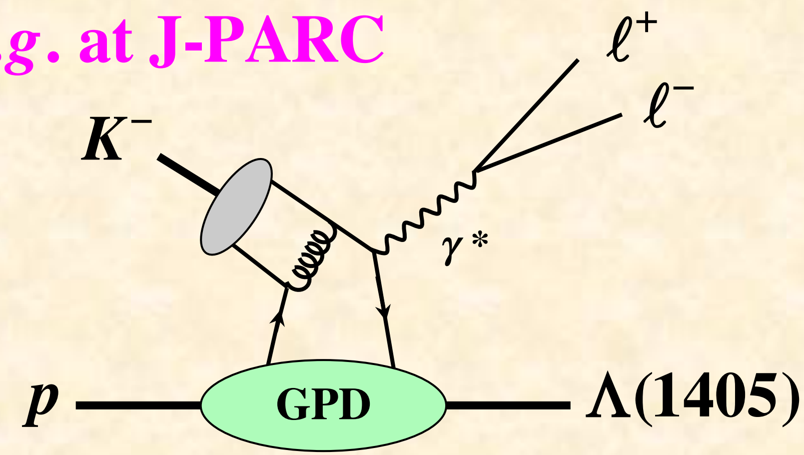
Because stable targets do not exit for exotic hadrons,
it is not possible to measure their GPDs in a usual way.

→ Transition GPDs

or

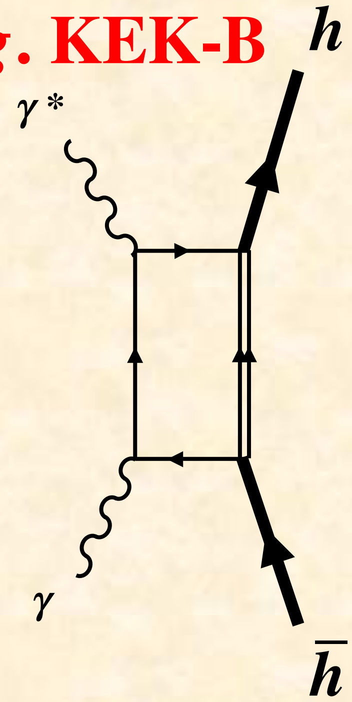
→ $s \leftrightarrow t$ crossed qunatity = GDAs at KEK-B, Linear Collider

e.g. at J-PARC



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

e.g. KEK-B



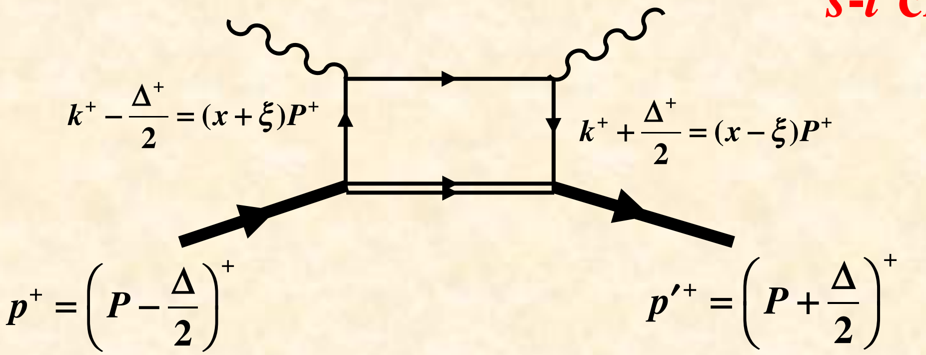
GPD $H_q^h(x,\xi,t)$ and GDA $\Phi_q^{h\bar{h}}(z,\zeta,W^2)$

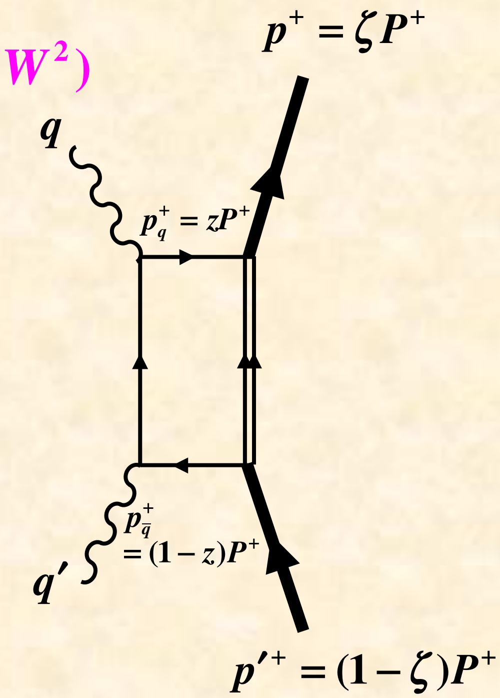
GPD: $H_q(x,\xi,t) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle h(p')|\bar{\psi}(-y/2)\gamma^+\psi(y/2)|h(p)\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$, $\quad P^+ = \frac{(p+p')^+}{2}$

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

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





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

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

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

Skewness 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 h 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: form factor dependence

$$\Phi_q^{h\bar{h}(I=0)}(z,\zeta,W^2) \propto F_h(W^2)$$

$$F_h(W^2) = \frac{1}{\left[1+(W^2-4m_h^2)/\Lambda^2\right]^{n-1}}$$

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

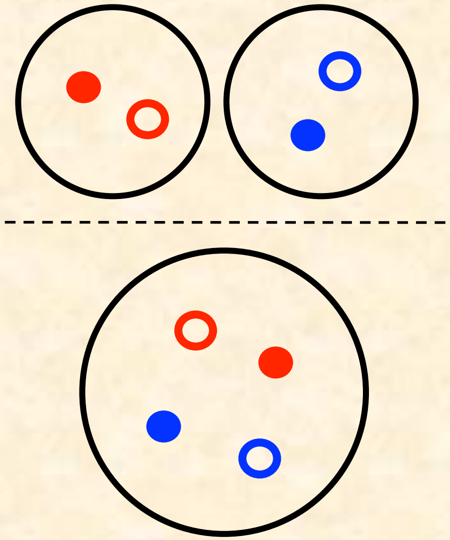
Constituent-counting rule

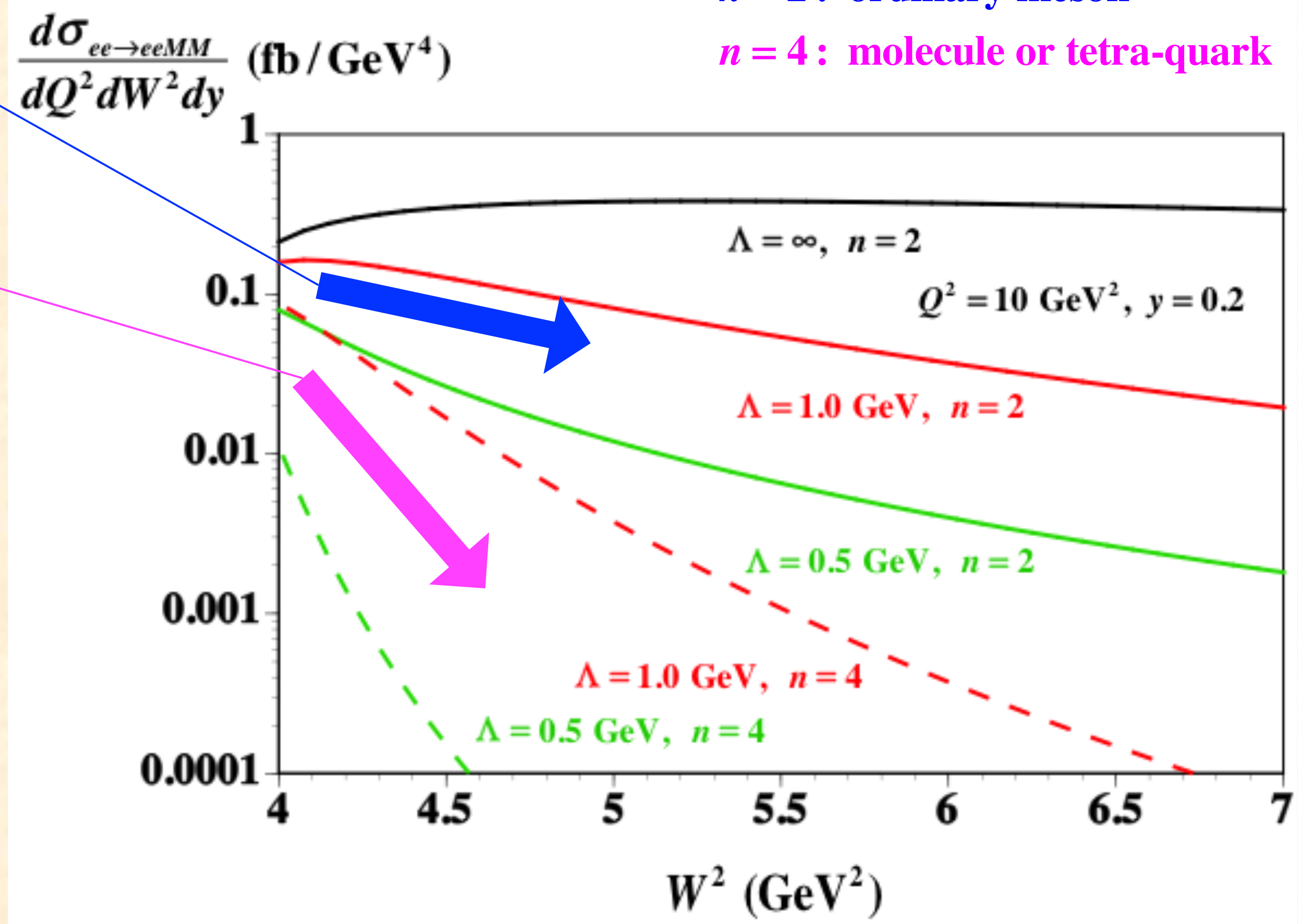
$n=2$: ordinary meson

$n=4$: molecule or tetra-quark

Ordinal $q\bar{q}$

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





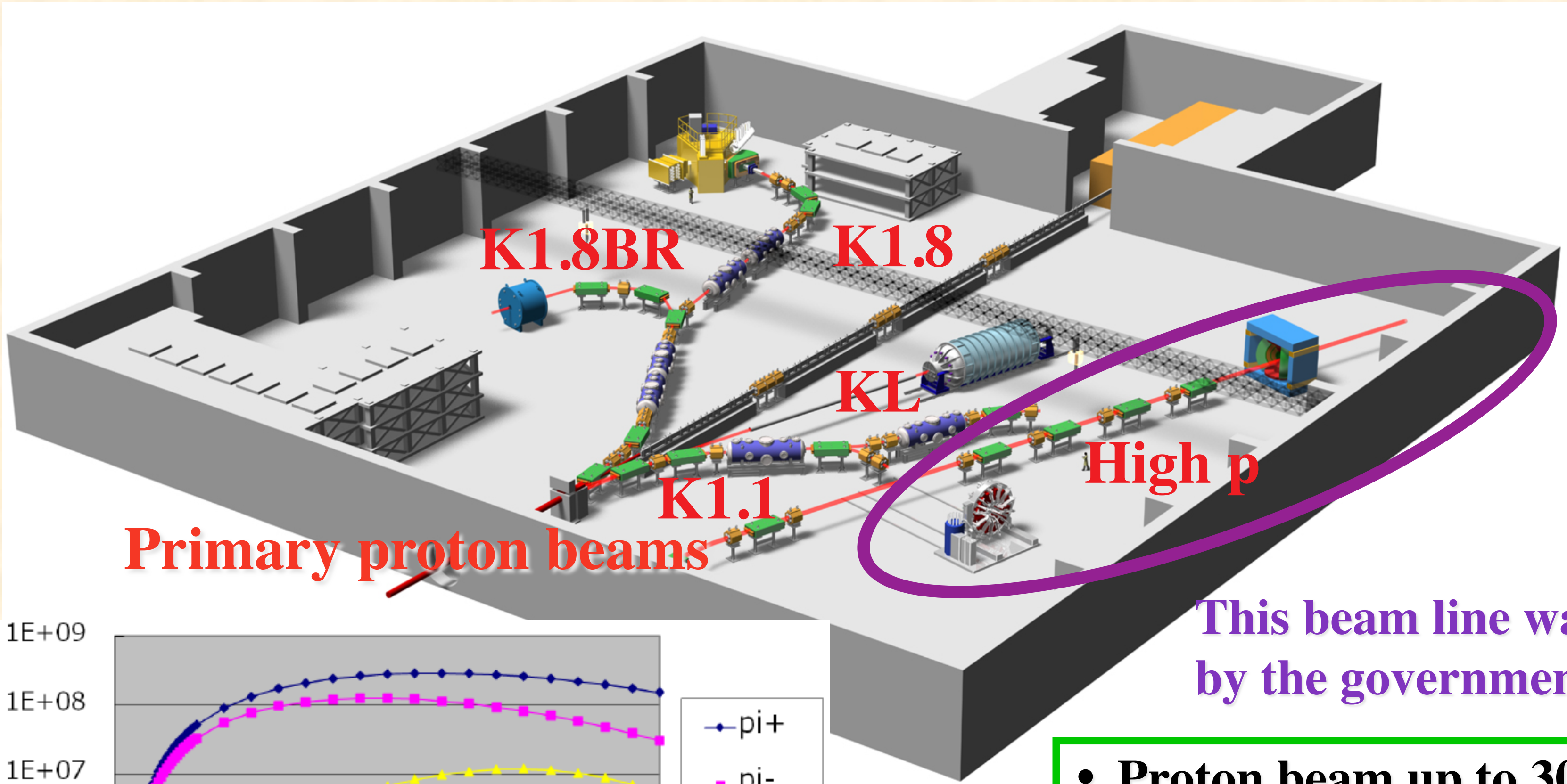
Discussions in progress toward J-PARC project

Recent efforts of
Wen-Chen Chang, Takahiro Sawada (Academia Sinica)
Jen-Chieh Peng (U. Illinois)

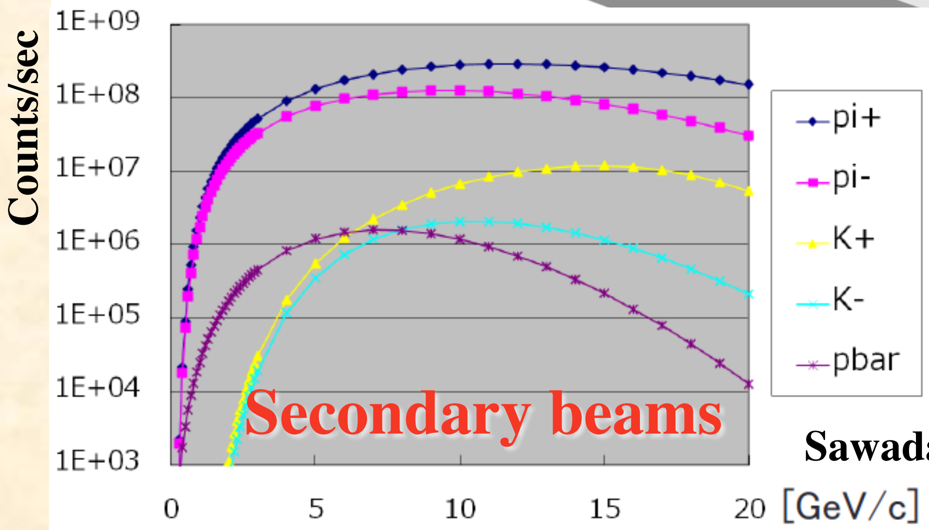
Refs. (1) Wen-Chen Chang at the J-PARC workshop in 2014:
http://j-parc-th.kek.jp/workshops/2014/02-10/
(2) Peng, Tanaka, Kawamura's talks on Feb. 13, 2014:
http://j-parc-th.kek.jp/collabo/2014/02-13/hadron-sf-2014-02-13.html.
(3) Peng, Sawada, Tanaka's talks on Oct. 7, 2014
at the APS-JPS join meeting in Hawaii.

Hadron facility

Recent workshop on high-momentum beamline physics, January 15 - 18, 2013, KEK, http://www-conf.kek.jp/hadron1/j-parc-hm-2013/



This beam line was approved by the government in 2013.



Sawada (2014)

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

You may propose your experiments!

Proposals on high-energy hadron physics

http://j-parc.jp/researcher/Hadron/en/Proposal_e.html

J. C. Peng, S. Sawada *et al.*

Proposal

Measurement of High-Mass Dimuon Production at the 50-GeV Proton Synchrotron

Y. Goto *et al.*

Proposal

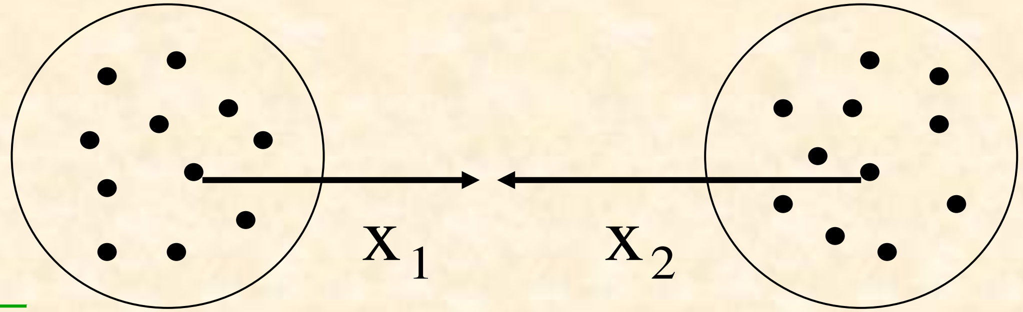
Polarized Proton Acceleration at J-PARC

The high-momentum had not been approved financially until 2013, so these proposals were deferred.

W.-C. Chang, J.-C. Peng, S. Sawada *et al.*, possible J-PARC experiment?

New LoI / proposal under consideration!

Hadron facilities



e.g. Drell-Yan: $x_1 x_2 = \frac{m_{\mu\mu}^2}{s}$ $\longrightarrow$ $x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}}$

$p + p(A) \rightarrow \mu^+\mu^- + X \quad (q\bar{q} \rightarrow \mu^+\mu^-)$

- $s = (p_1 + p_2)^2$

  J-PARC: $\sqrt{s} = 10$ GeV
  RHIC: $\sqrt{s} = 200$ GeV
  LHC: $\sqrt{s} = 14$ TeV

- $m_{\mu\mu} \geq 3$ GeV

e.g. Quark spin content: $\Delta q = \int_0^1 dx \Delta q(x)$
= Integral from small *x* (RHIC)
to large *x* (J-PARC).

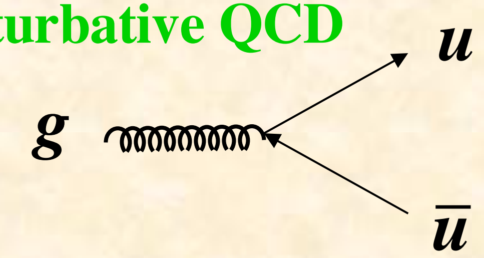
$x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}} \geq \frac{3}{10} = 0.3$ J-PARC (Fermilab-120 GeV) **Large-*x* facility**

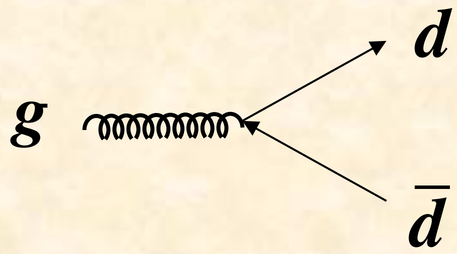
$\geq \frac{3}{200} = 0.02$ RHIC (COMPASS)

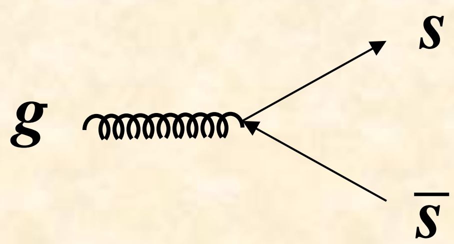
$\geq \frac{3}{14000} = 0.0002$ LHC **Small-*x* facility**

Flavor dependence of antiquark distributions

Perturbative QCD



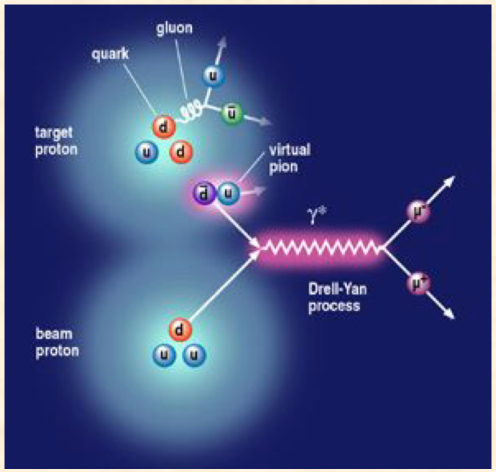




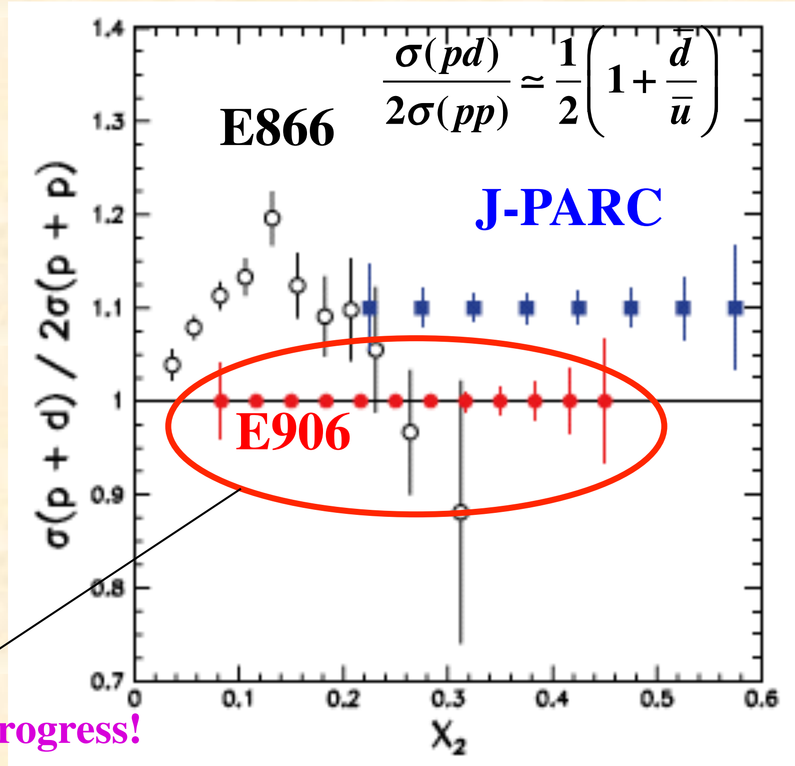
Because of $m_u^2,\ m_u^2,\ m_u^2 \ll Q^2$, we expect $\bar{u} = \bar{d} = \bar{s}$ from the antiquark creaction by the gluon splitting $g \to q\bar{q}$ in perturbative QCD.

$\Rightarrow$ Experimentally, $\dfrac{\bar{s}}{(\bar{u}+\bar{d})/2} \sim 0.4, \quad \dfrac{\bar{d}}{\bar{u}} = 1 \sim 1.4$

Non-perturbative mechanism for the asymmetries?



SK, Phys. Rep. 303 (1998) 183;
J. Speth, A. W. Thomas, Adv.Nucl.Phys. 24 (1997) 83;
G. T. Garvey and J.-C. Peng, Prog. Part. Nucl. Phys. 47 (2001) 203.
J.-C. Peng, J.-W. Qiu, arXiv:1401.0934.



Fermilab experiment in progress!

Proton polarization

Y. Goto *et al.*

Proposal

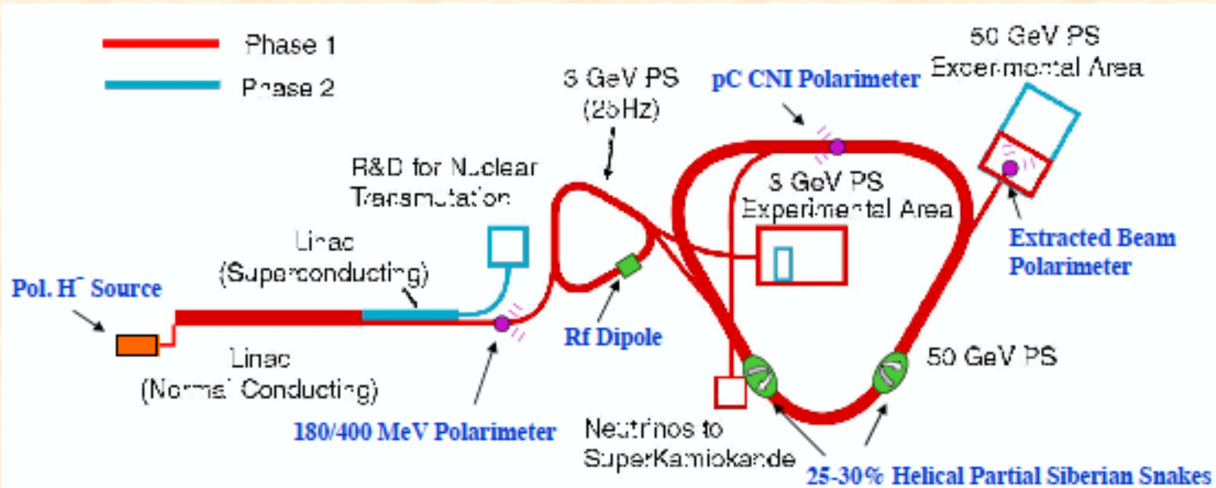
Polarized Proton Acceleration at J-PARC

November 30, 2007

M. Bai[1], M. Brooks[5], J. Chiba[11], N. Doshita[12], Y. Fukao[7], Y. Goto[7,8†], M. Grosse Perdekamp[2], K. Hatanaka[6], H. Huang[1], K. Imai[4], T. Iwata[12], S. Ishimoto[3], X. Jiang[5], K. Kondo[12], G. Kunde[5], K. Kurita[9], M. J. Leitch[5], M. X. Liu[5], A. U. Luccio[1], P. L. McGaughey[5], A. Molodojentsev[3], C. Ohmori[3], J.-C. Peng[2], T. Roser[1], N. Saito[3], H. Sato[3†], S. Sawada[3], R. Seidl[2], T.-A. Shibata[10], J. Takano[3], A. Taketani[7,8], M. Togawa[8], and A. Zelenski[1]

Proton beam polarization is technically possible.

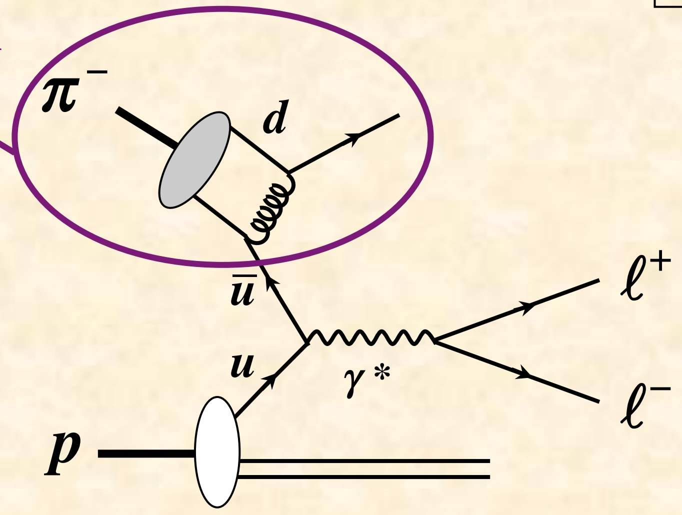
The J-PARC PAC deferred decision.



Toward a new proposal

W.-C. Chang, J.-C. Peng, S. Sawada *et al.*, possible J-PARC experiment?

pion distribution



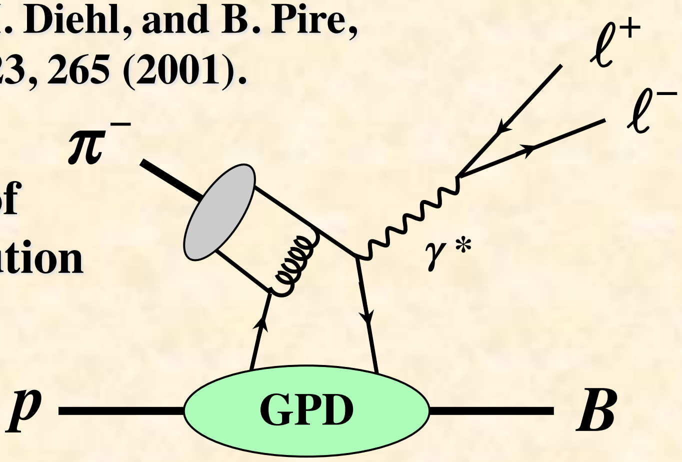
A. Brandenburg, S. J. Brodsky, V. V. Khoze, and D. Müller, Phys. Rev. Lett. 73 (1994) 939.

Investigation of
- Pion distribution amplitude

$$\pi^-(\bar{u}s) + p(uud) \rightarrow \ell^+\ell^- + X$$

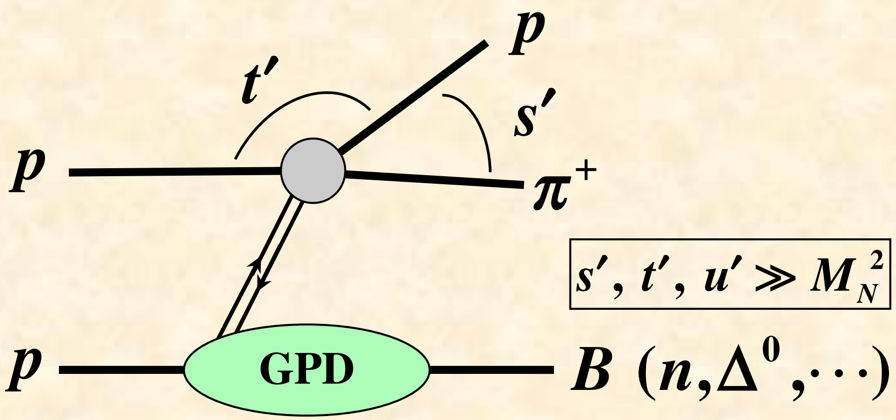
E. R. Berger, M. Diehl, and B. Pire, Phys. Lett. B 523, 265 (2001).

Investigation of
- Pion distribution amplitude
- GPDs



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

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



In progress for LoI / proposal

Wen-Chen Chang (Academia Sinica),
Jen-Chieh Peng (U. Illinois), Sinya Sawada (KEK) …

See the slides of J-PARC workshops in 2014:

http://research.kek.jp/people/kumanos/conf/conf14.html
http://j-parc-th.kek.jp/collabo/2014/02-13/hadron-sf-2014-02-13.html

Physics to be investigated in the high momentum beam line of hadron hall at J-PARC

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Hiroyuki Kawamura and Shunzo Kumano

KEK Theory Center, Institute of Particle and Nuclear Studies,
High Energy Accelerator Research Organization (KEK)

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Shin'ya Sawada

Institute of Particle and Nuclear Studies,
High Energy Accelerator Research Organization (KEK)

Hadron physics with high-momentum hadron beams at J-PARC in 2015

Topics

- High-energy hadron physics (including spin physics)
- Charm-hadron physics
- Hadron-mass modifications in nuclear medium
- New ideas …

March 13-16 (date should be fixed next week), 2015,
Tsukuba campus of KEK, Japan

→ If you are interested in the workshop,
please inform shunzo.kumano @ kek.jp.

The End

The End