“Progress on J-PARC hadron physics in 2016”
J-PARC, March 2-4, 2016

Study Hadron Partonic Structure at High-P Beamline at J-PARC

Wen-Chen Chang 章文箴

Institute of Physics, Academia Sinica

in collaboration with

Takahiro Sawada (Academia Sinica)

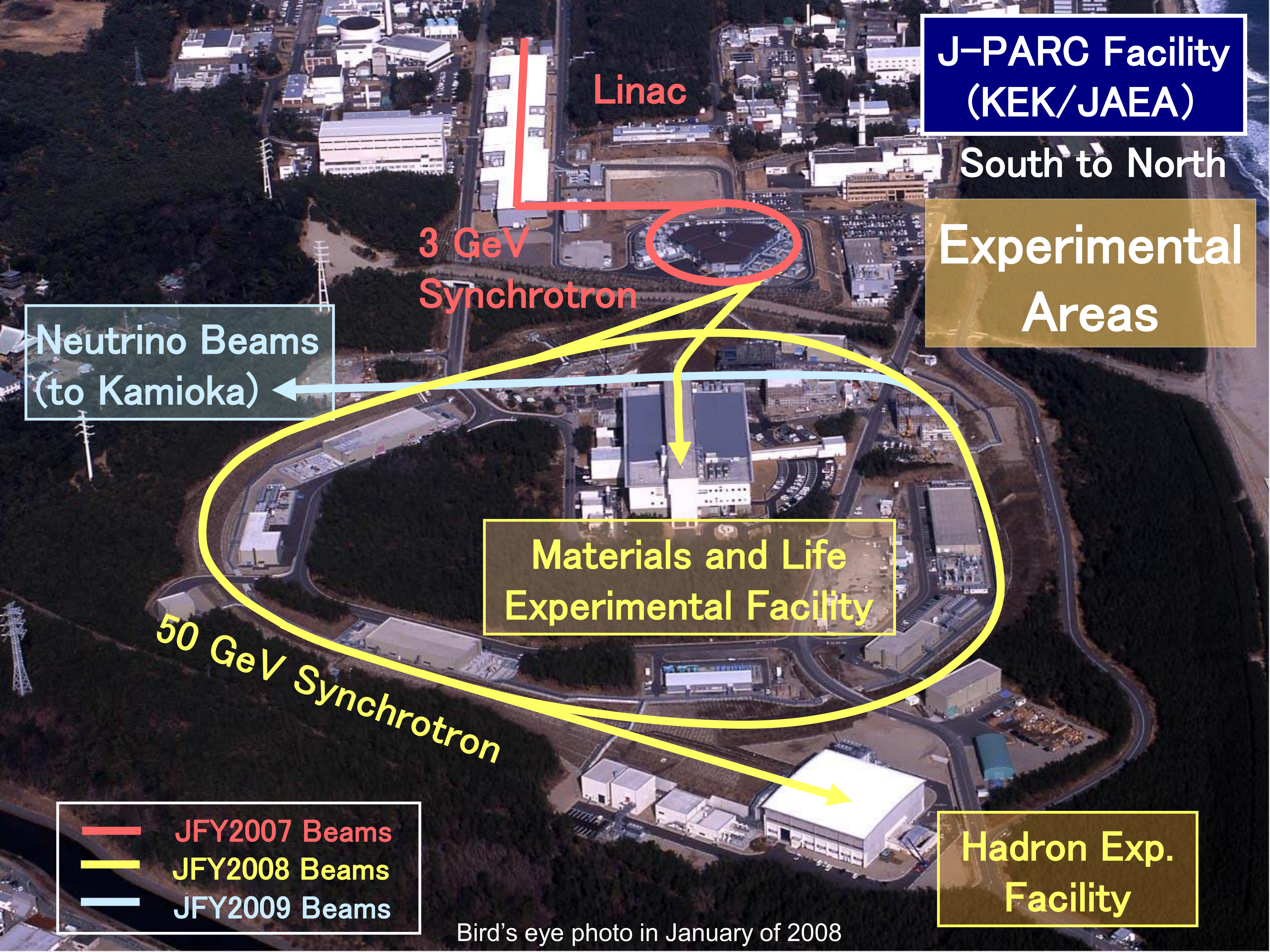
Jen-Chieh Peng (UIUC)

Shunzo Kumano, Shinya Sawada *(KEK)*

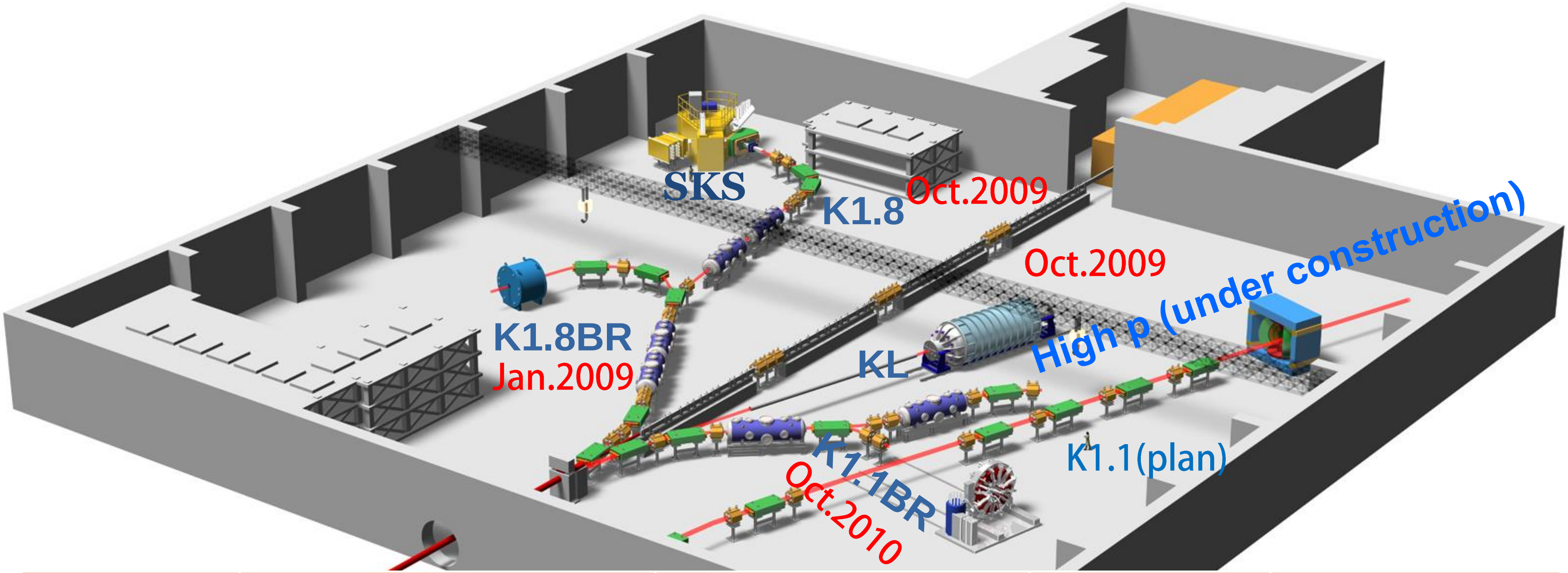
Kazuhiro Tanaka *(Juntendo)*

Outline

- High-momentum beamline at J-PARC
- Physics processes:
  - **Charm and strangeness production**
  - **Hard exclusive process**
  - **Exclusive Drell-Yan process**
- Summary & final remarks


J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Experimental
Areas
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
50 GeV Synchrotron
Hadron Exp.
Facility
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

Hadron Experimental Facility (HEF)

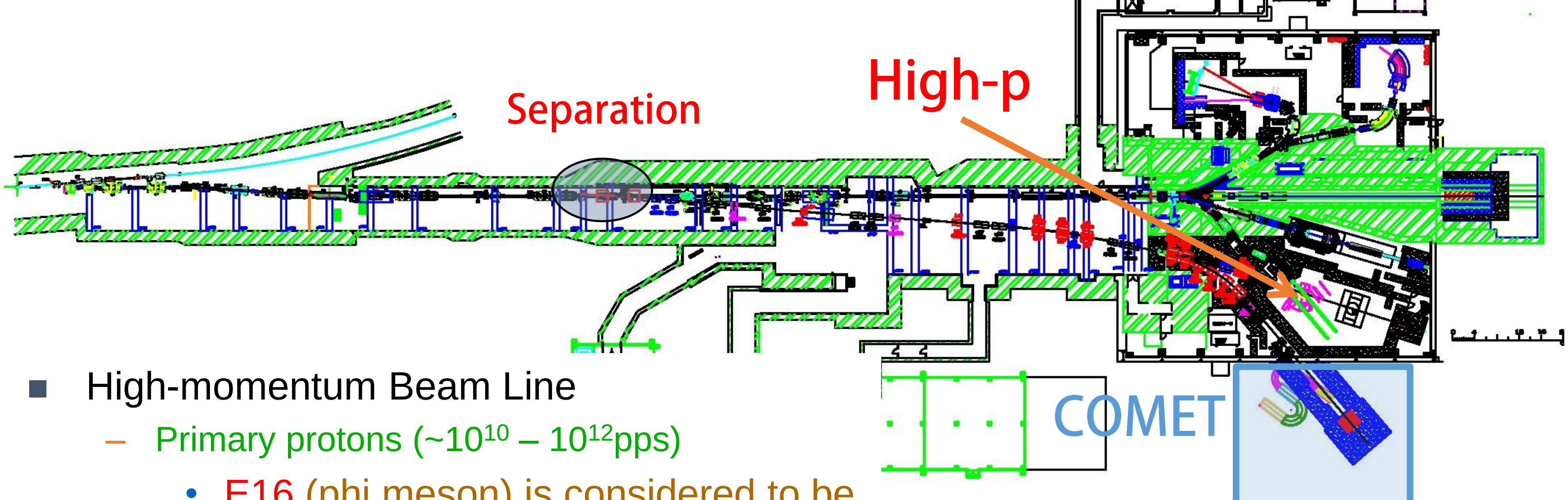


Beam Lines	Experiment	Secondary particles	Max. Mom.	Max. Intensity
K1.8	Hypernuclei, Hadron Physics with S	π, K, p (2 separators)	< 2.0 GeV/c	~10^5 Hz for K^+
K1.8BR	Hadron Physics with S	π, K, p (1 separator)	< 1.0 GeV/c	~10^4 Hz for K^+
K1.1BR	Lepton Flavor violation	π, K, p (1 separator)	< 1.1 GeV/c	~10^4 Hz for K^+
KL	Neutral K rare decay	Neural Kaon	~ 2 GeV/c	~10^6 Hz

Intense pion, kaon beam in the momentum range of ~ 1 GeV/c

New Primary Proton Beam Line

- New primary Proton Beam Line
= High-momentum BL + COMET BL = has been funded and the construction started.

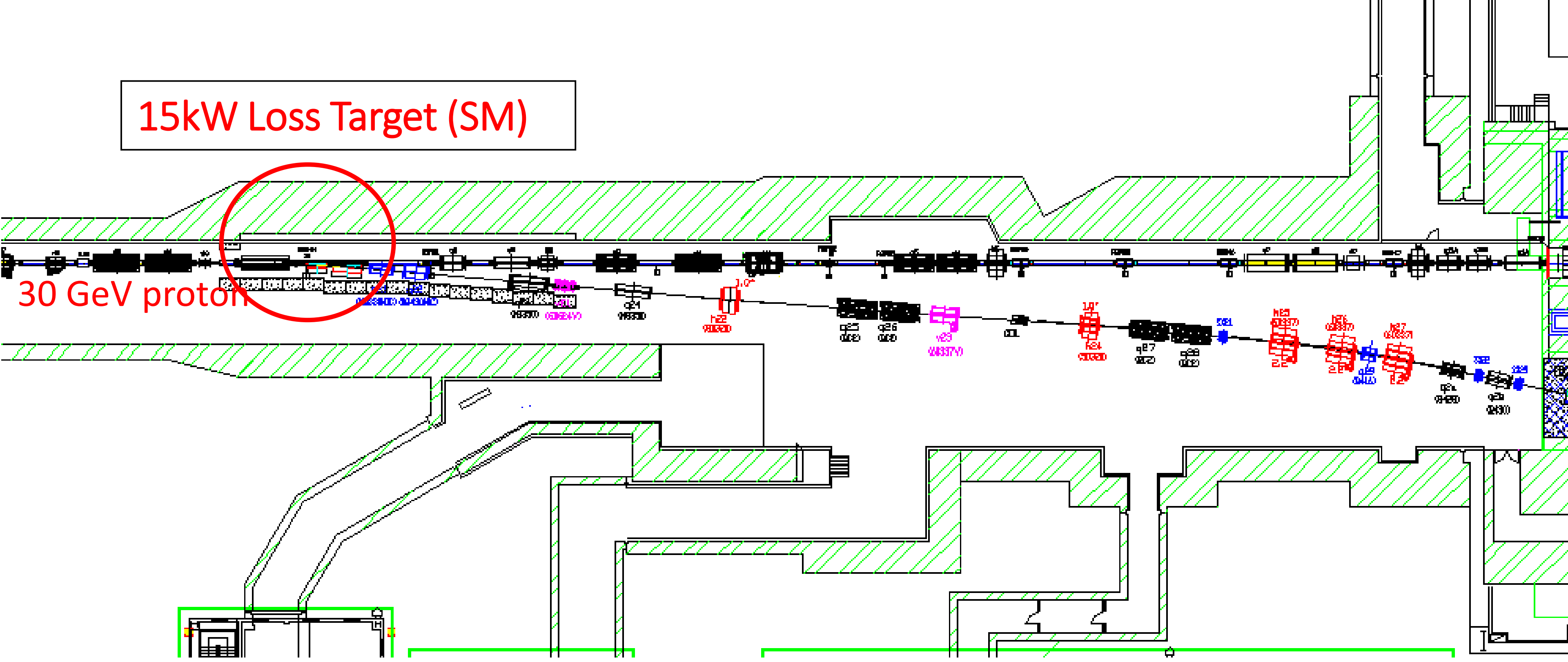


- High-momentum Beam Line
  - Primary protons (~10^{10} – 10^{12}pps)
    - E16 (phi meson) is considered to be the first experiment.
  - Unseparated secondary particles (pi, …)
    - High-resolution secondary beam by adding several quadrupole and sextupole magnets.

- COMET
  - Search for μ to e conversion
  - 8 GeV, 50 kW protons
  - Branch from the high-momentum BL
  - Annex building is being built at the south side.

J-PARC High-momentum Beam Line (Hi-P BL)

- High-intensity secondary Pion beam
- High-resolution beam: Δp/p ~ 0.1%



J-PARC High-momentum Beam Line (Hi-P BL)

- High-intensity secondary Pion beam
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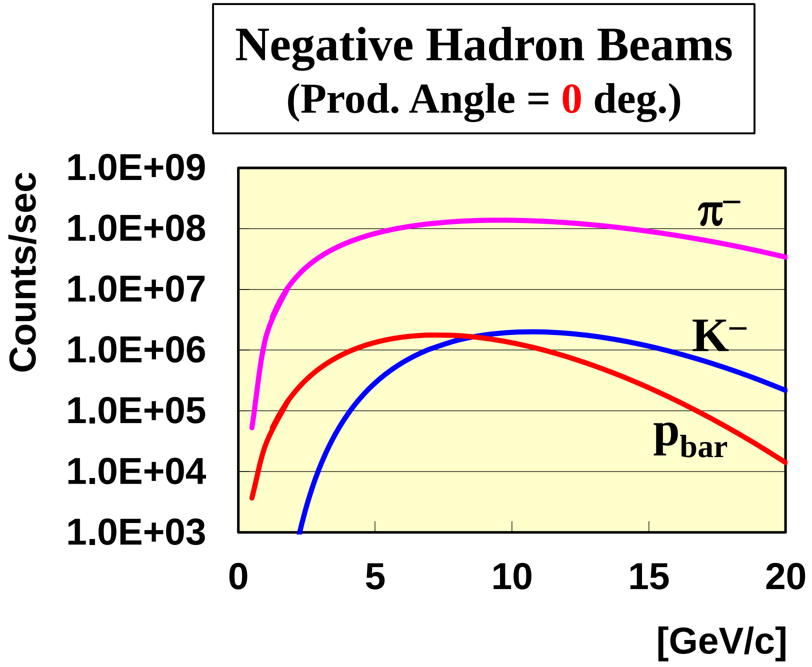
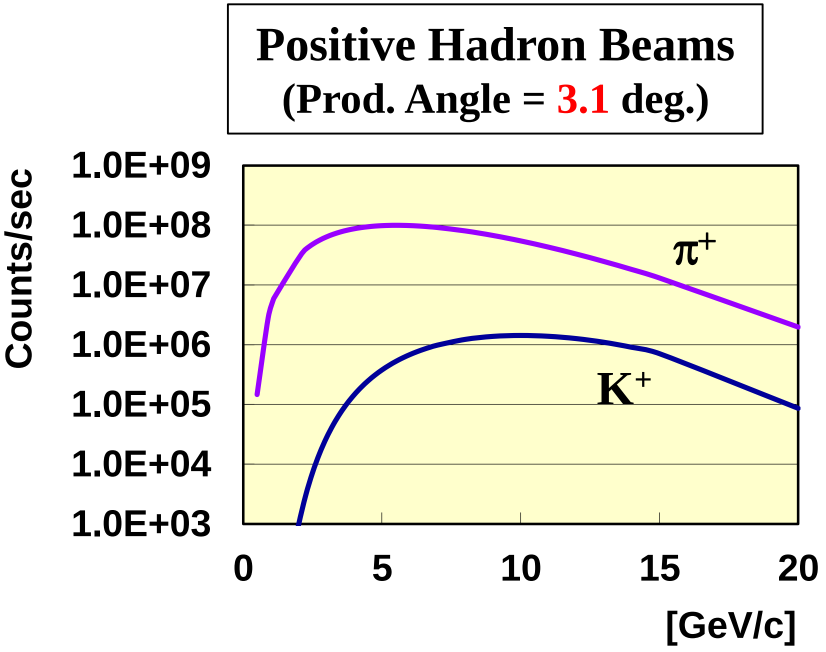




*** Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m**

http://www-conf.kek.jp/hadron1/j-parc-hm-2013/

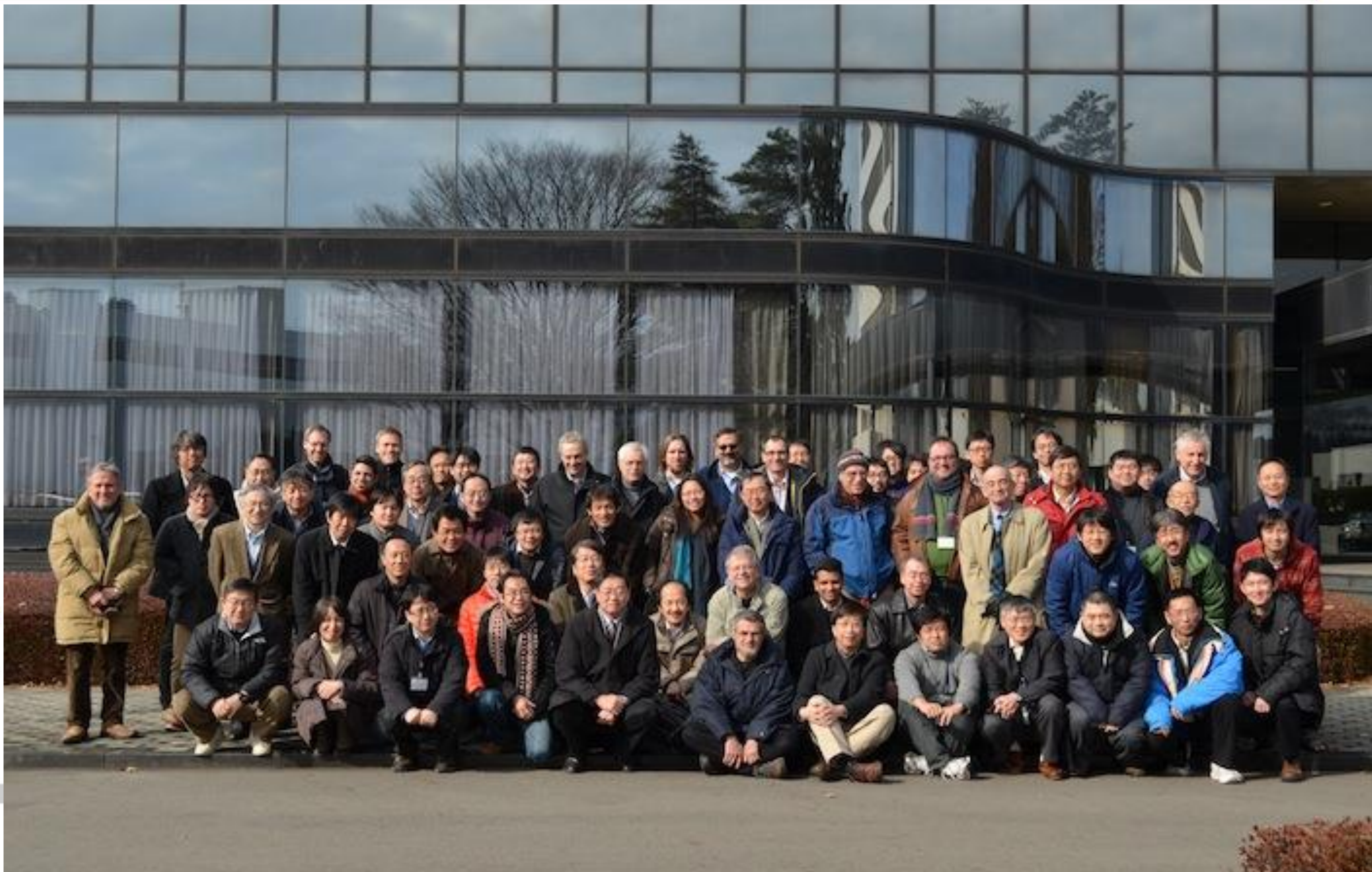
KEK theory center workshop on
Hadron physics with high-momentum hadron beams at J-PARC in 2013

Kobayashi Hall, 1st Floor, Kenkyu-Honkan (15th, 18th)
Seminar Hall, 1st Floor, 3rd buildling (16th, 17th)
January 15 – 18, 2013,   KEK, Tsukuba, Japan

MENU

- 1st circular
- 2nd circular
- Program (slides)
- Participants
- Location: KEK
- Kenkyu-Honkan (M01)
- Kobayashi Hall
- Lounge for banquet
- Seminar Hall
- Visitor information (English)
- Visitor information (Japanese)
- How to reach KEK (General guide)
- Bus/taxi to KEK (Our original guide)
- to Urban hotel (Our original guide)
- KEK restaurant hours
- Nearby restaurants

[Update]
2012.08.09
Home page,
1st circular



http://research.kek.jp/group/hadron10/j-parc-hm-2015/

KEK theory center workshop on
Hadron physics with high-momentum hadron beams at J-PARC in 2015

Kobayashi Hall, 1st Floor, Kenkyu-Honkan
March 13 - 16, 2015, KEK, Tsukuba, Japan

MENU

- Previous workshop (2013)

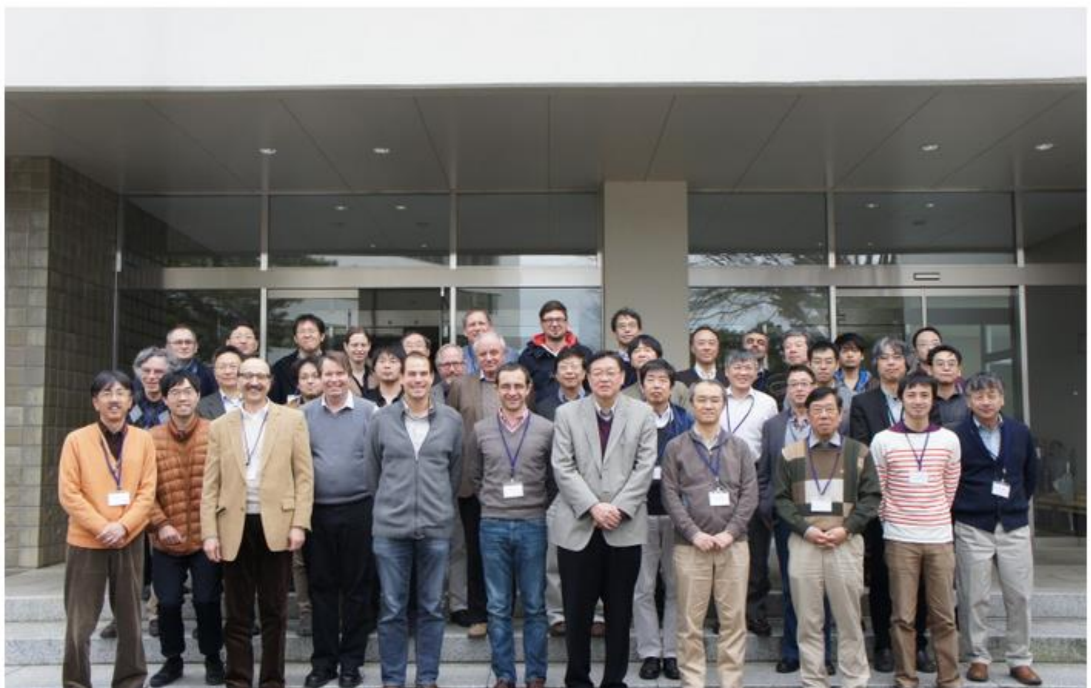
- 1st circular
- 2nd circular

- Program [slides]
- Participant list

- Location: KEK
- Kenkyu-Honkan (M01)
- Kobayashi Hall
- Coffee lounge
- Meeting room 1

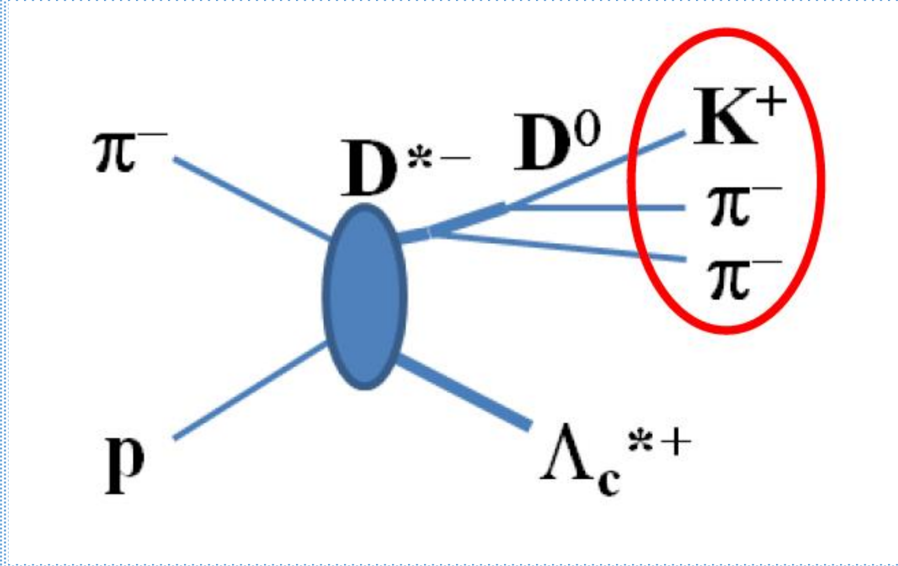
- Visitor information (English)
- Visitor information (Japanese)
- How to reach KEK
- From Narita/Haneda airports

- KEK restaurant
- KEK Cafeteria
- KEK Cafe Prime
- Nearby restaurants



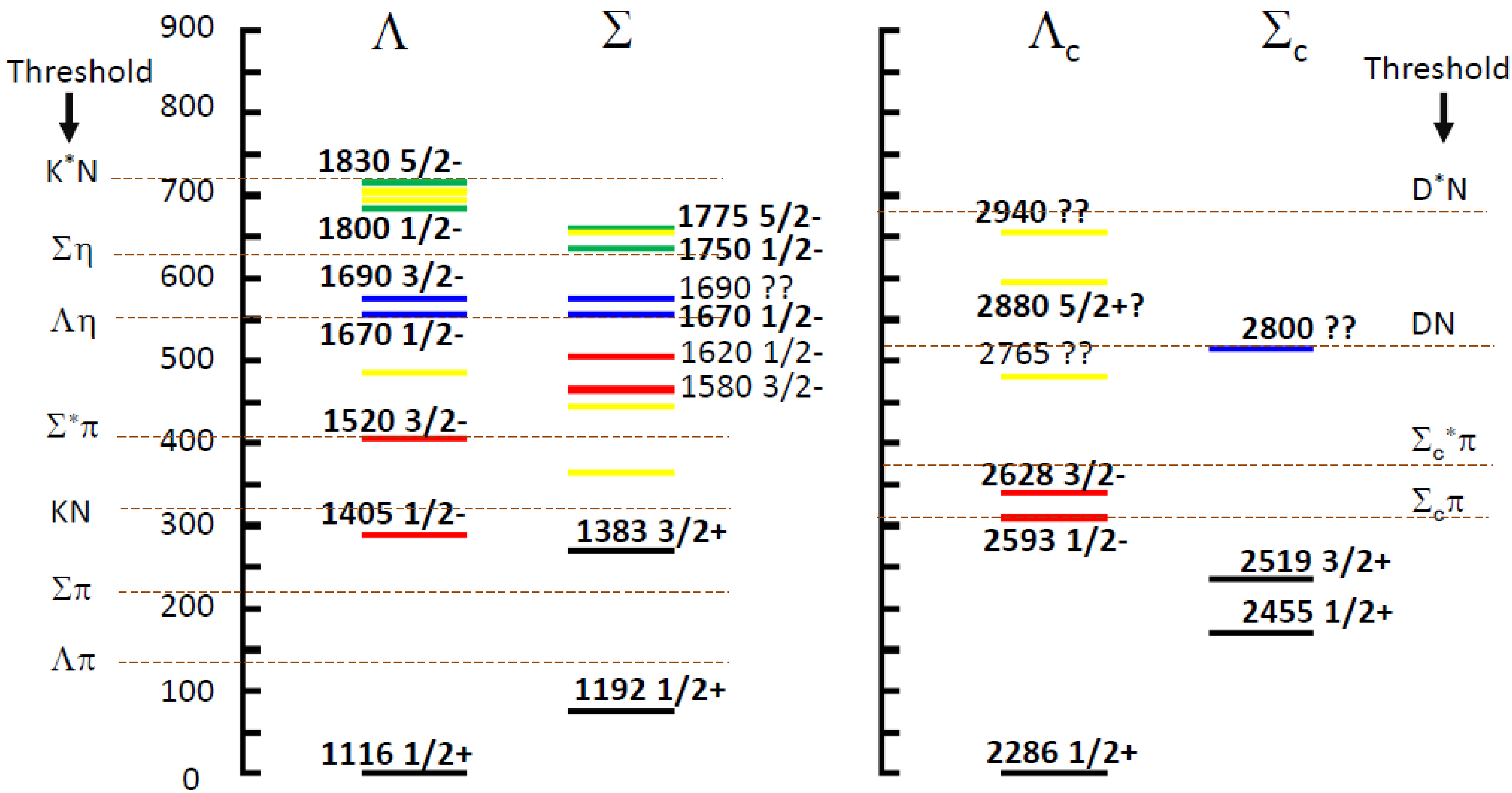
Physics Programs

- **Charm and Strange production**
- **Hard exclusive process**
  - Exclusive $\Lambda(1405)$ production at large angles
    - Valence quark structure of $\Lambda(1405)$
- **Drell-Yan process**
  - Exclusive pion-induced Drell-Yan
    - GPD of proton
    - Pion DA
  - Inclusive pion-induced Drell-Yan:
    - $d(x)/u(x)$ at large x
    - Violation of Lam-Tung relation, BM functions
    - Pion PDF



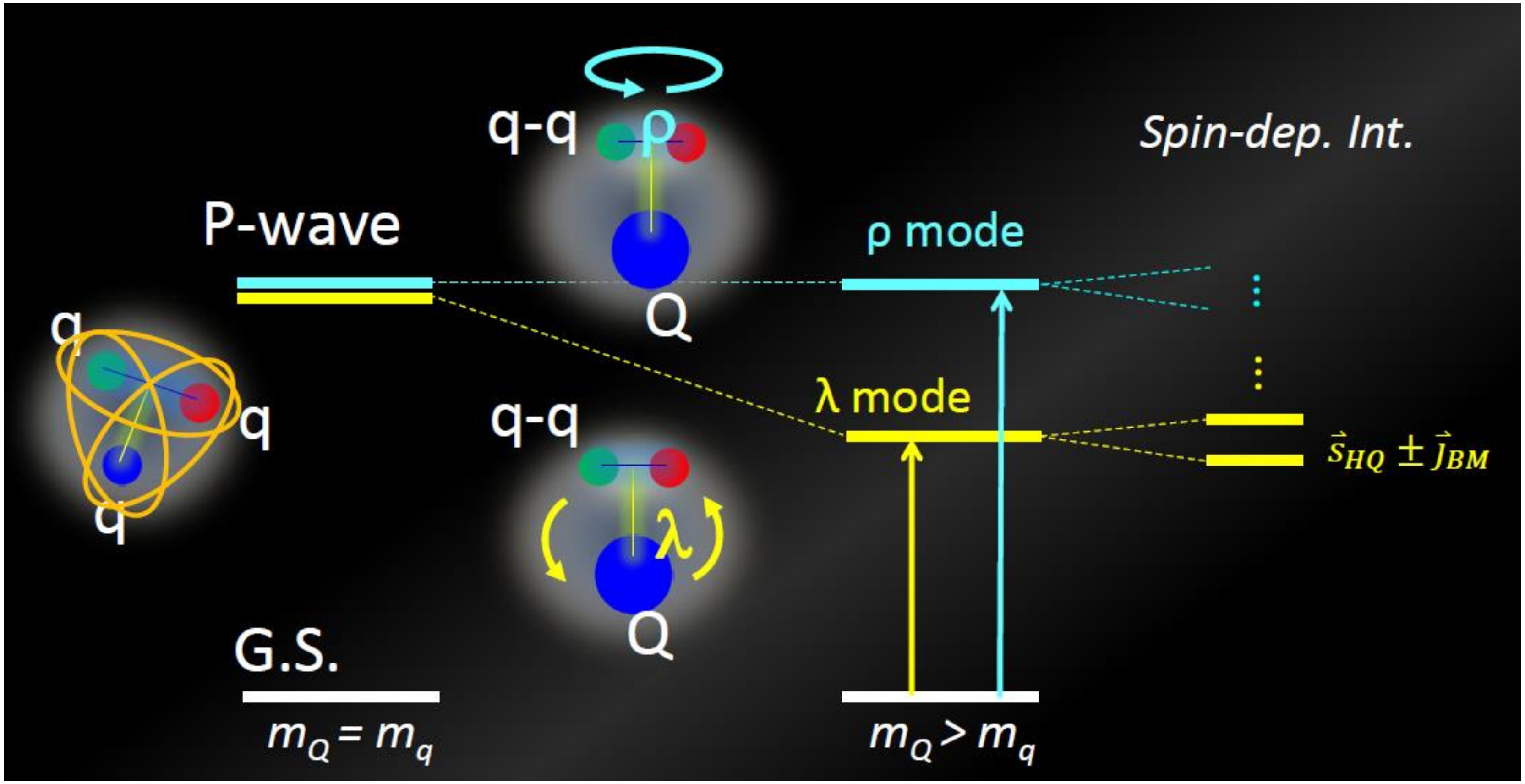
Charm and Strange production process

Charmed Baryon Spectroscopy



H. Noumi, KEK workshop 2015

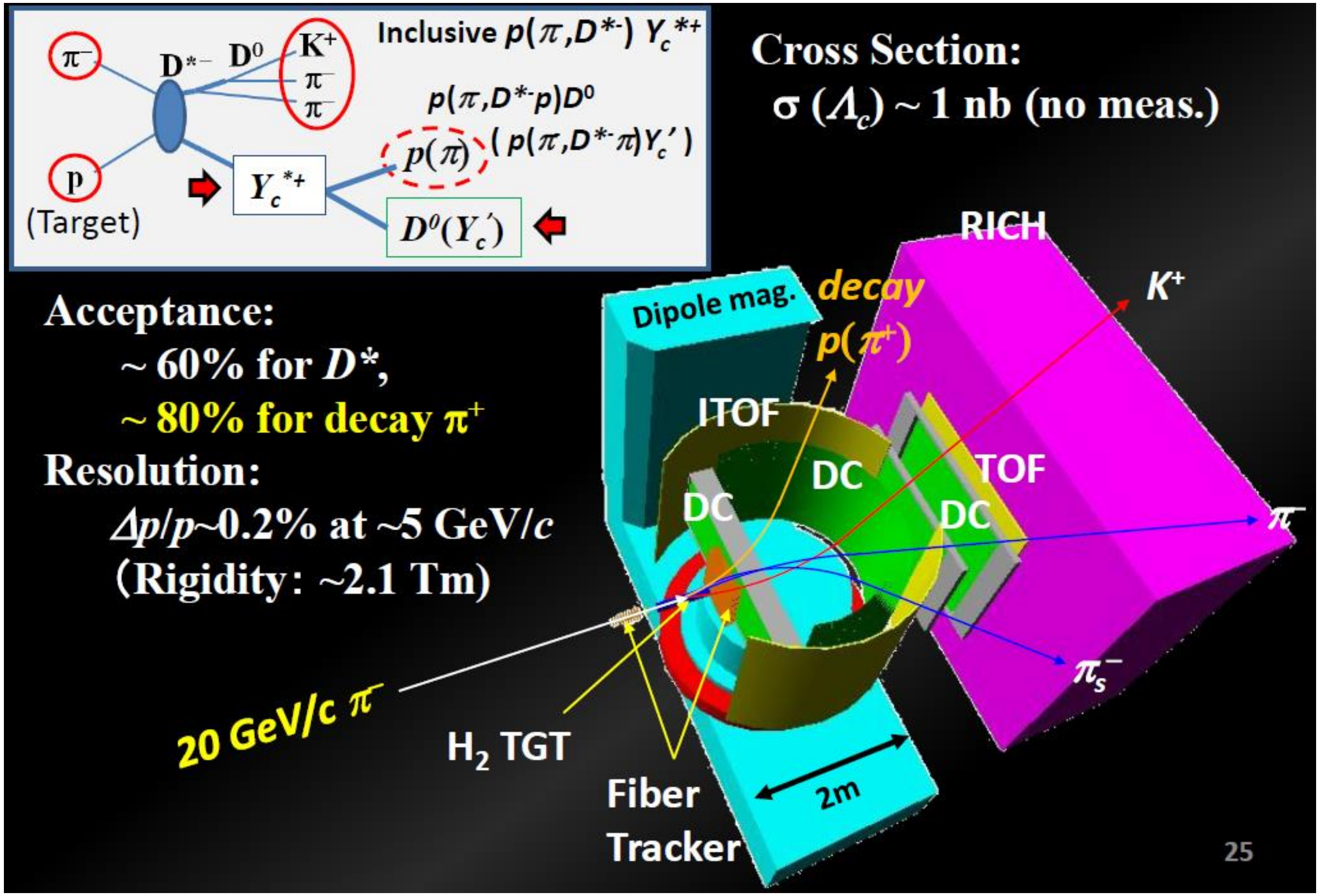
Di-quark Correlation in Heavy-quark system



A. Hosaka, this workshop; *H. Noumi, KEK workshop 2015*

J-PARC E50

Stage-1 approved by J-PARC PAC-18, August 12, 2014.



K. Shirotori, this workshop; *H. Noumi, KEK workshop 2015*

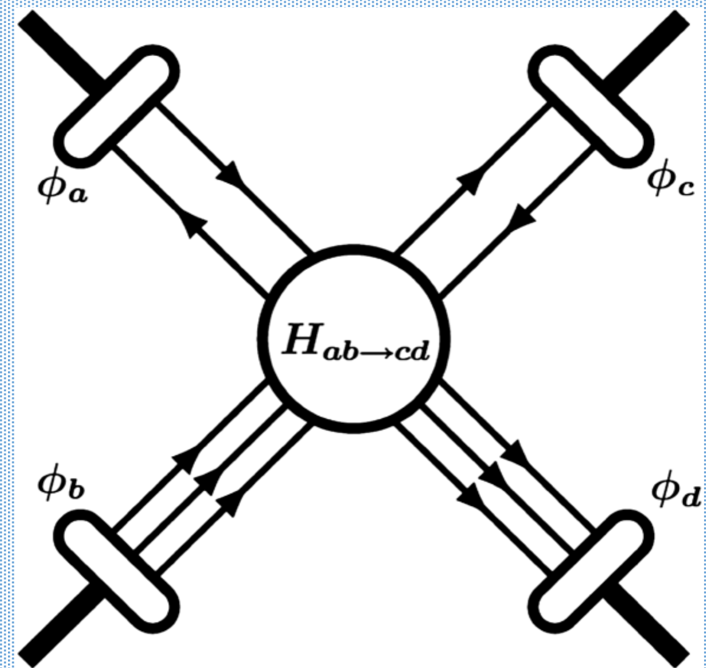
Ξ Baryon Spectroscopy (LOI)

Ξ Baryon Spectroscopy with High-momentum Secondary Beam

M. Naruki and K. Shirotori
Department of Physics, Kyoto University, Kyoto, 606-8502, Japan and
Research Center for Nuclear Physics (RCNP), 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
(Dated: April 14, 2014)

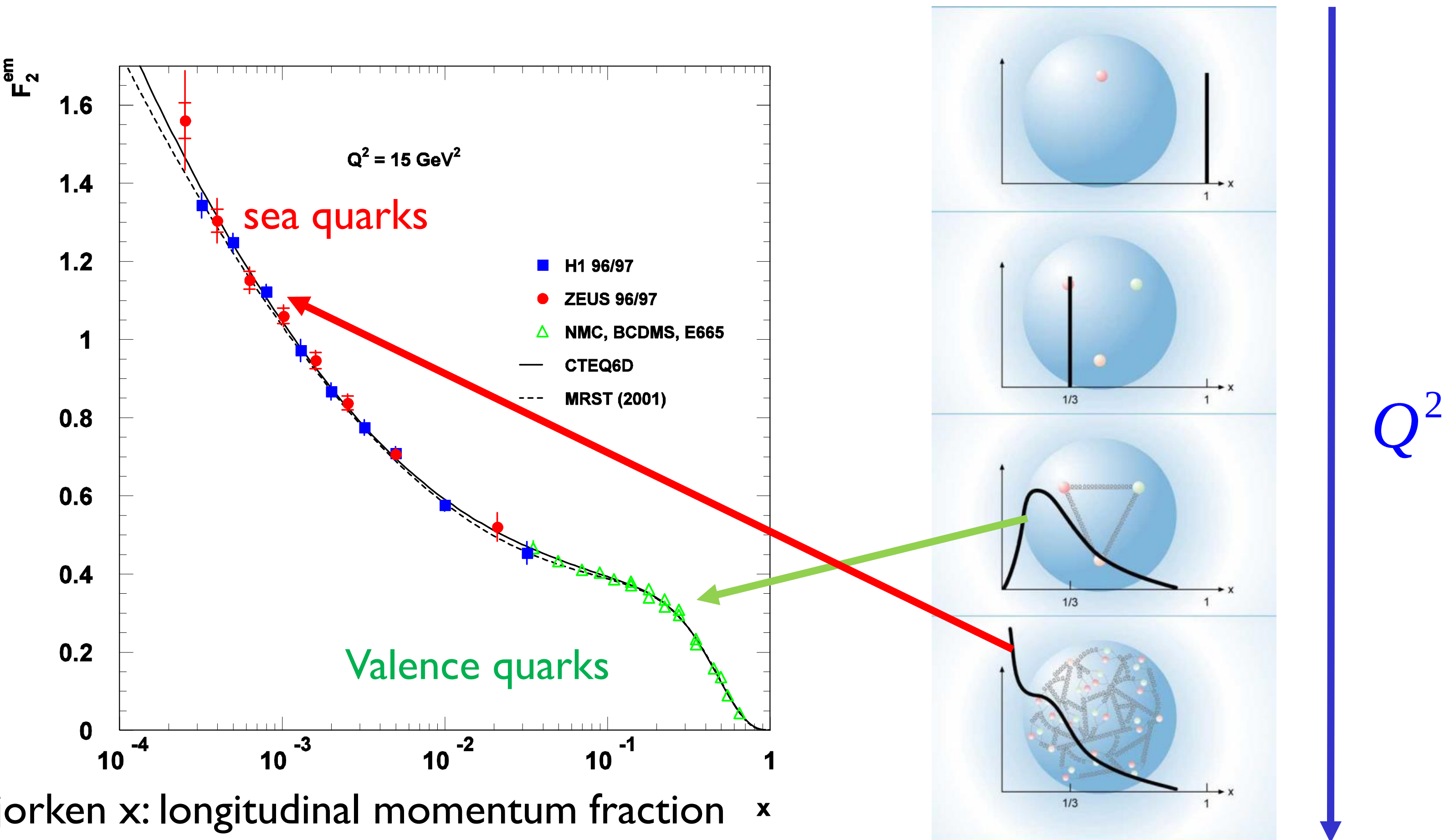
We express our interest in performing the Ξ baryon spectroscopy with high-momentum secondary beams. The experimental information on the excited states of Ξ baryon is largely lacking. The physics cases and possibilities to investigate Ξ^* states using the high-momentum beam line is discussed. The enough sensitivity is expected to determine the excited state up to 2 GeV/c^2 systematically with a reasonable beam time in both kaon and π induced reactions. The high intense secondary beam provide an opportunity to investigate an unknown field of Ξ^* baryons.

Reaction	σ [μb]	Beam [/spill]	B.R.	Acceptance [%]	Y_{Total}	$Y_{Decay/bin}$
$K^- p \to \Xi^{*-} K^+$	1.0	10^6	1.0	50	3.1×10^5	2500
$K^- p \to \Xi^{*-} K^{*+}$	1.0	10^6	0.23	50	0.7×10^5	580
$K^- p \to \Xi^{*0} K^{*0}$	1.0	10^6	0.67	50	2.1×10^5	1700
$\pi^- p \to \Xi^{*-} K^{*0} K^+$	0.1	10^7	0.67	50	3.1×10^5	2500



Hard exclusive production process

Proton Structure Function

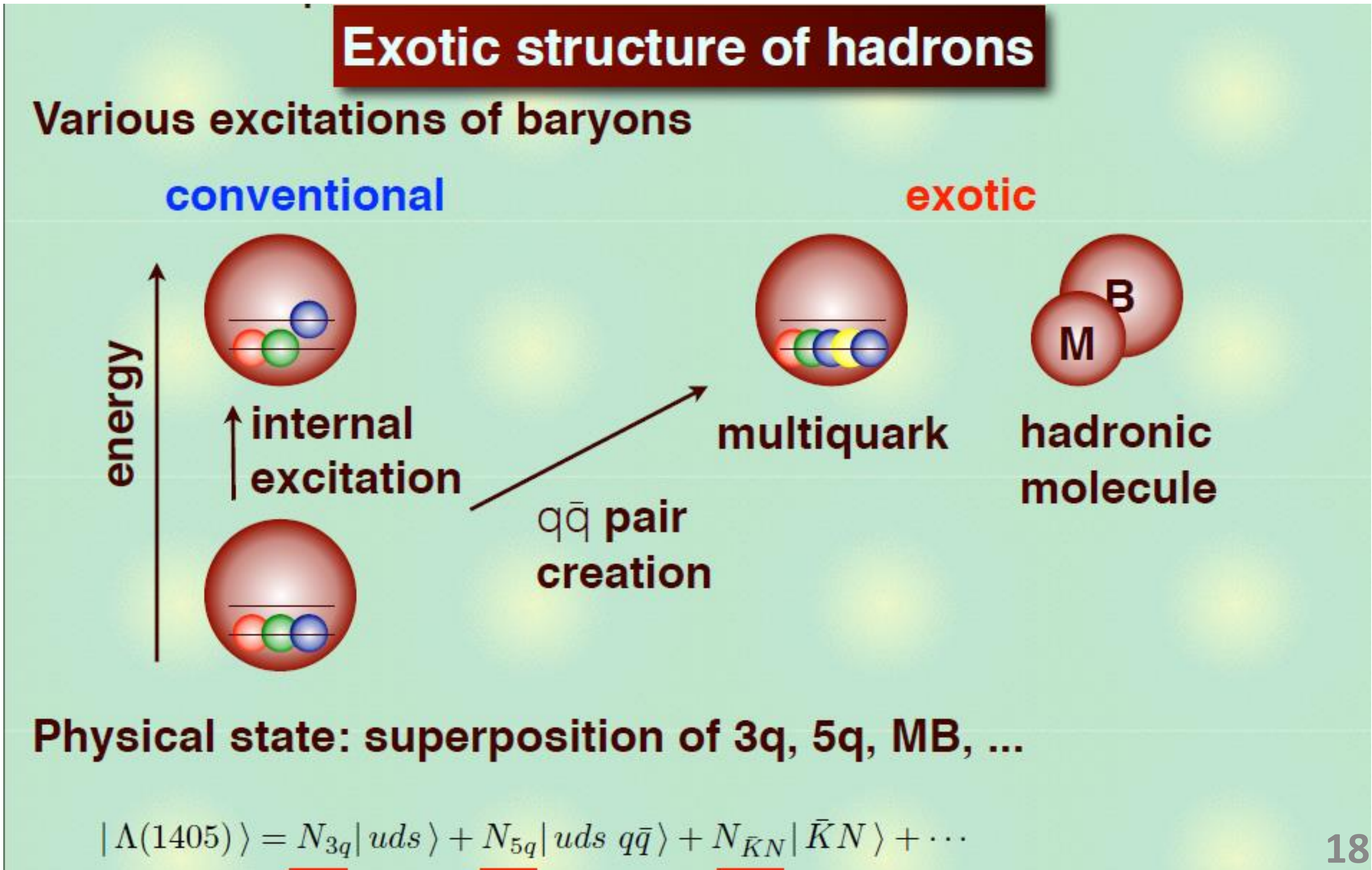


Bjorken x: longitudinal momentum fraction

Lots of partons at small x!

Quark Structure of Exotic Hadrons

T. Hyodo, NSTAR 2015



K. Inoue's and Y. Kamiya's talks

$\Lambda(1405)$

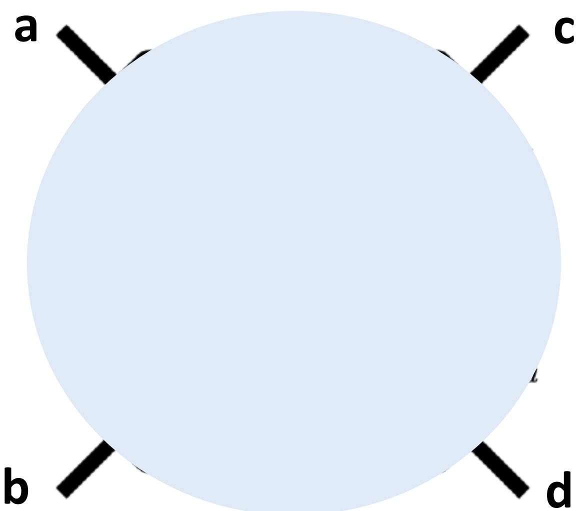
- *Y. Kamiya and T. Hyodo [1509.00146]:* **compositeness property, $\bar{K}$N molecule**.
- *K. Miyahara and T. Hyodo [PRC 93, 015201 (2016); 1506.05724]:* **KN local potential based on chiral SU(3) dynamics**
- *J. Hall et al. [PRL 114, 132002 (2015); 1411.3402]:* **Lattice QCD, $\bar{K}$N molecule**.
- *T. Sekihara and S. Kumano [PRC 89, 025202 (2014); 1311.4637]:* **radiative decay for determining the compositeness**.
- *L. Roca and E. Oset [PRC 87, 055201 (2013); 1301.5741]:* **Two-pole structures, $\bar{K}$N and $\pi\Sigma$**.
- *T. Hyodo [Int. J. Mod. Phys. A, 28, 1330045 (2013); 1310.1176]:* **compositeness property**.
- *T. Sekihara et al. [Phys.Rev.C83:055202(2011); 1012.3232]:* **meson-baryon coupled-channels chiral dynamics, $\bar{K}$Nmolecule**.
- …

Production channels, decay, size and medium effect …

Large-angle (Hard) Exclusive Process

$$a + b \rightarrow c + d$$

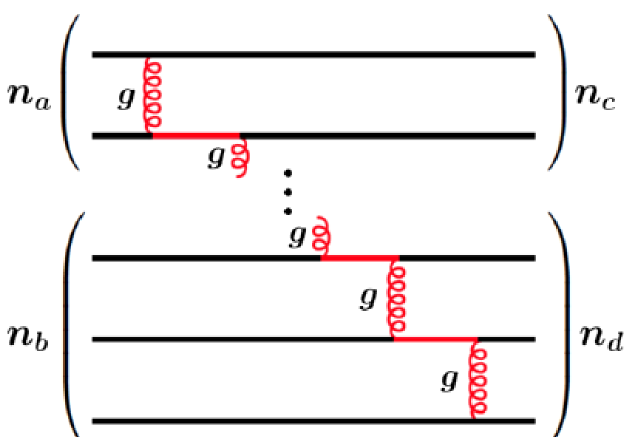
H. Kawamura et al., PRD 88, 034010 (2013)



$$\frac{d\sigma_{ab\to cd}}{dt} \simeq \frac{1}{16\pi s^2}\overline{\sum_{\text{pol}}}|M_{ab\to cd}|^2,$$

$$s,\ |\mathrm{t}| \gg m_i^2 (i = a, b, c, d)$$

$$M_{ab\to cd} = \int [dx_a][dx_b][dx_c][dx_d]\phi_c([x_c])\phi_d([x_d]) \times H_{ab\to cd}([x_a],[x_b],[x_c],[x_d],Q^2)\phi_a([x_a])\phi_b([x_b]),$$



Leading and connected Feynman diagrams

Gluon propagator

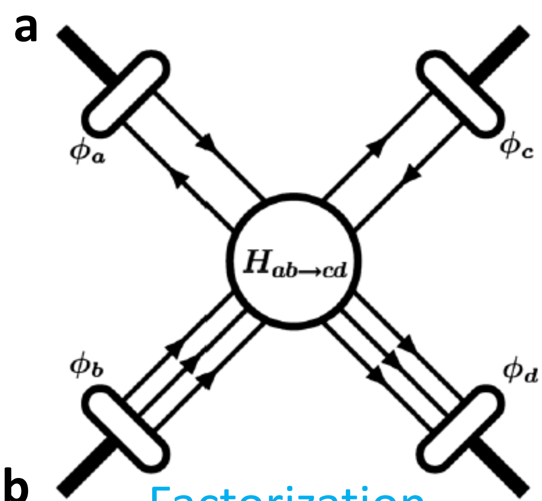
External quarks

$$[\hat{M}_{ab\to cd}] = \left[\boxed{\frac{1}{(P^2)^{n/2-1}}}\boxed{\frac{1}{P^{n/2-2}}}\boxed{P^{n/2}}\right] = \left[\frac{1}{s^{n/2-2}}\right].$$

Quark propagator

Large-angle (Hard) Exclusive Process
$a + b \to c + d$

H. Kawamura et al., PRD 88, 034010 (2013)

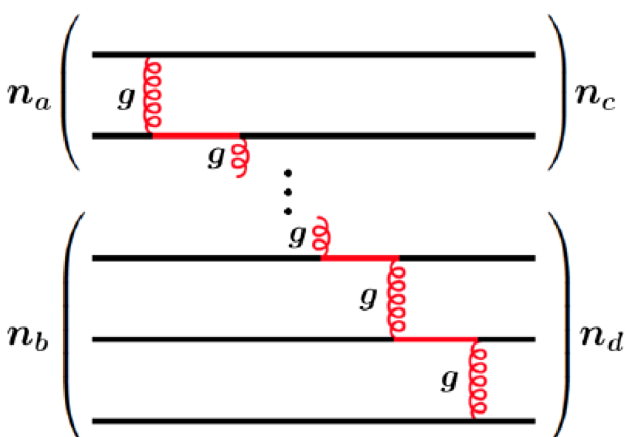


Factorization

$$\frac{d\sigma_{ab\to cd}}{dt} \simeq \frac{1}{16\pi s^2}\overline{\sum_{\rm pol}}|M_{ab\to cd}|^2,$$

$$s,\ |t| \gg m_i^2 (i = a, b, c, d)$$

$$M_{ab\to cd} = \int [dx_a][dx_b][dx_c][dx_d]\phi_c([x_c])\phi_d([x_d]) \times H_{ab\to cd}([x_a],[x_b],[x_c],[x_d],Q^2)\phi_a([x_a])\phi_b([x_b]),$$



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Quark propagator

Constituent-Counting Rule in Hard Exclusive Process

H. Kawamura et al., PRD 88, 034010 (2013)

$$\frac{d\sigma}{dt}(a+b\to c+d)=\frac{1}{s^{n-2}}f(\theta_{CM}) \quad n=n_a+n_b+n_c+n_d$$

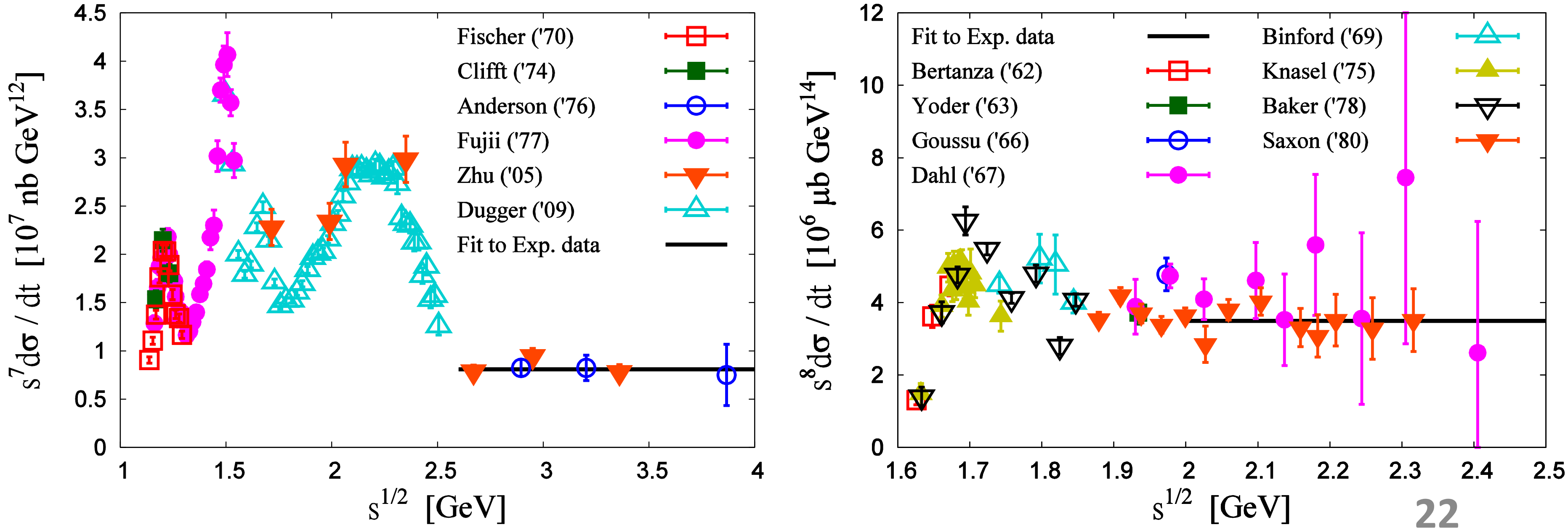
G. P. Lepage and S. J. Brodsky, PRD 22, 2157 (1980).

$n=1+3+2+3=7$

$\gamma+p\to\pi^{+}+n$

$n=2+3+2+3=8$

$\pi^{-}+p\to K^{0}+\Lambda$



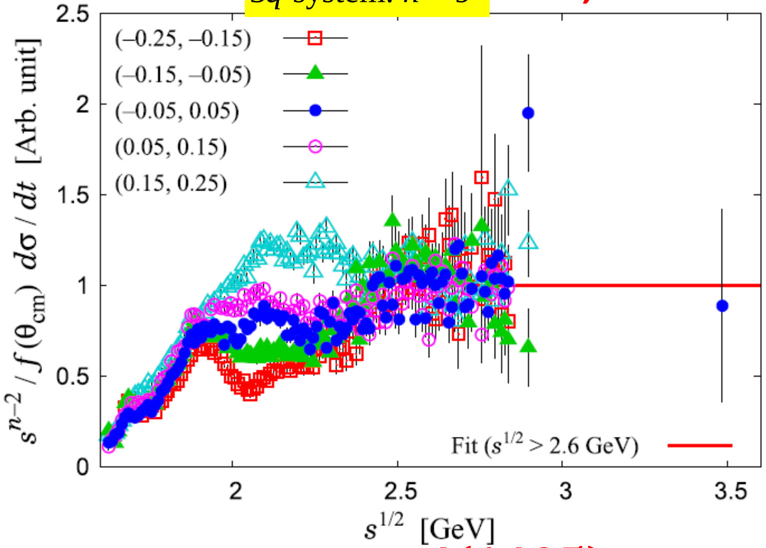
Constituent-Counting Rule in Photoproduction of Hyperons

Chang, Kumano, Sekihara, PRD 93, 034006 (2016)

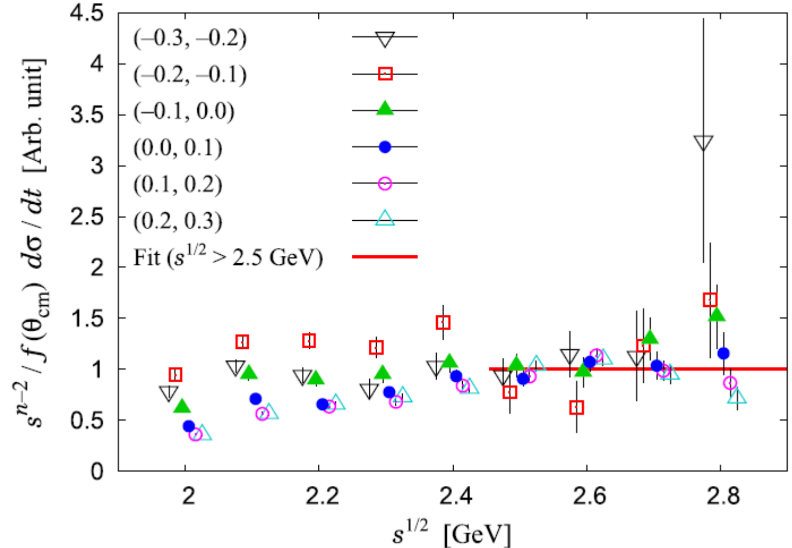
5q system: $n = 11$

3q system: $n = 9$

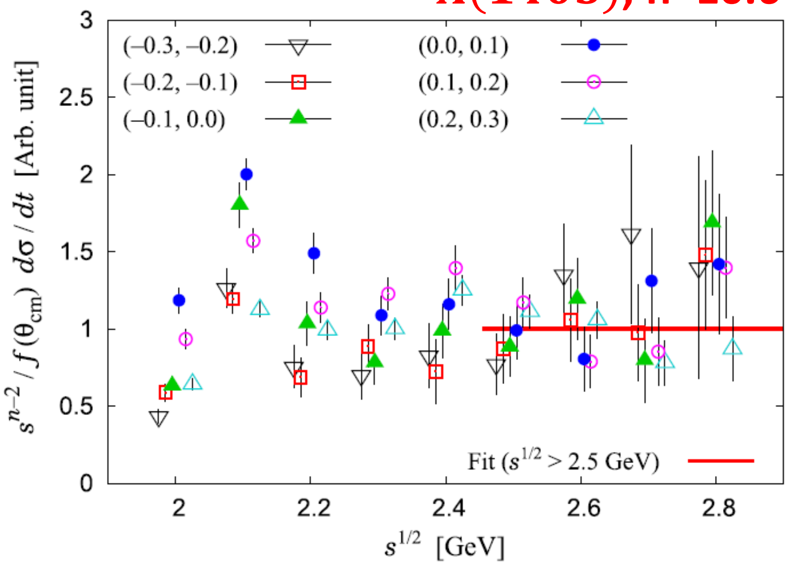
Λ; n=10.0



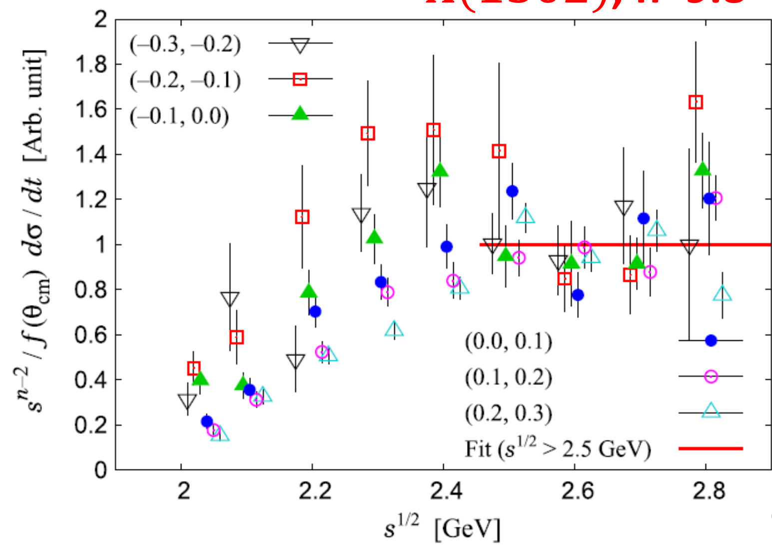
Σ; n=11.4



$\Lambda(1405)$; n=10.6



$\Lambda(1502)$; n=9.8



Constituent-Counting Rule in Photoproduction of Hyperons

Chang, Kumano, Sekihara, PRD 93, 034006 (2016)

$5q$ system: $n = 11$

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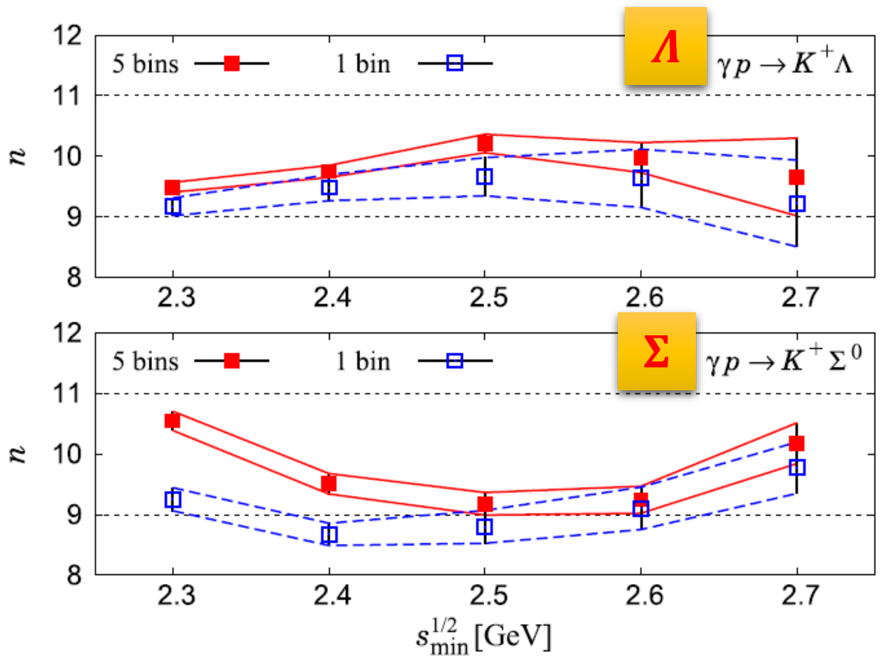
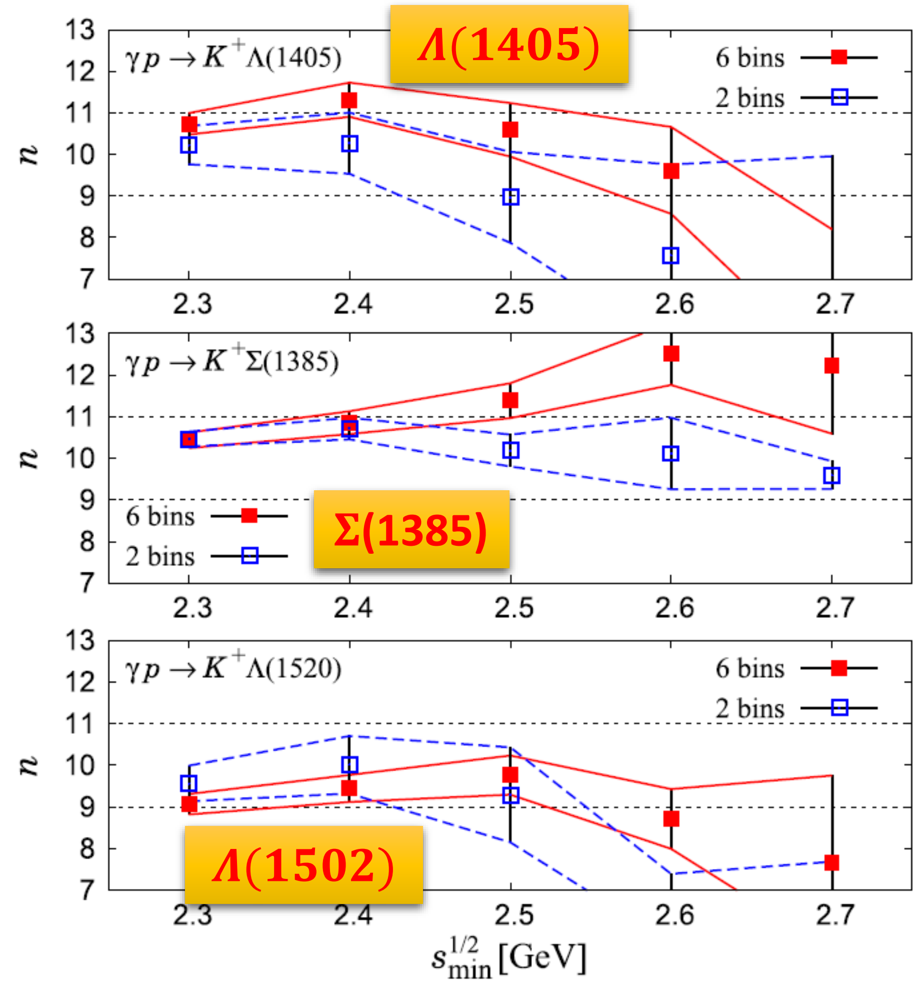
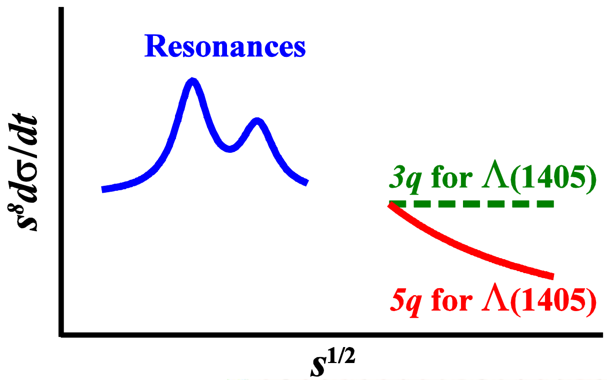


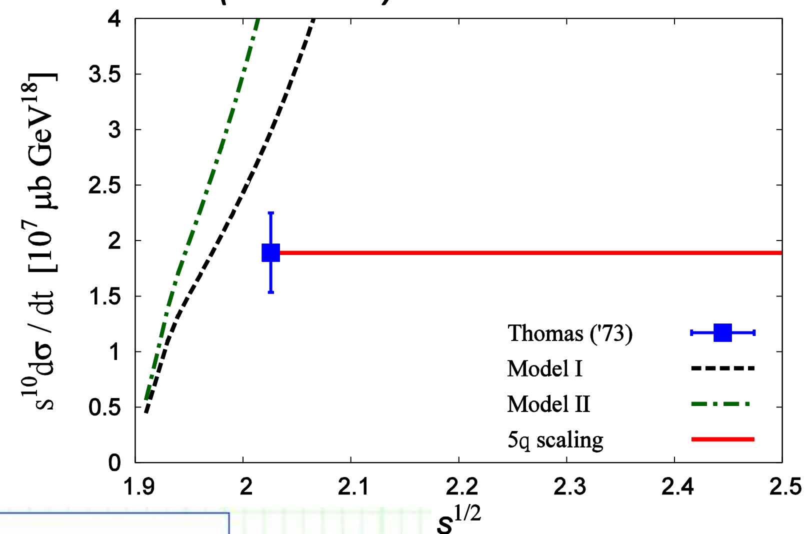


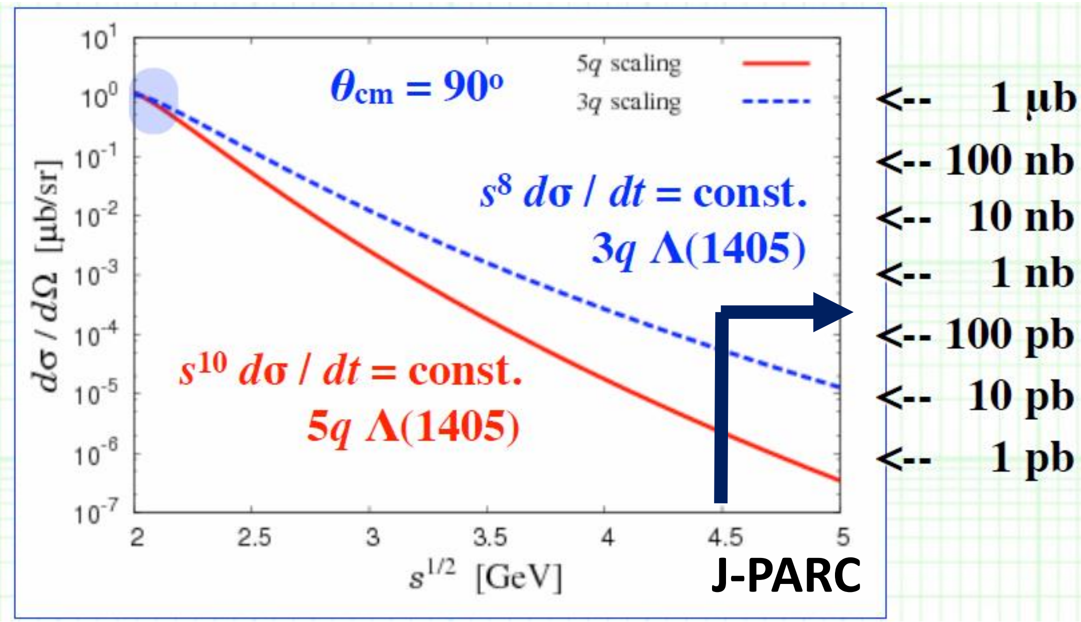
Valence-Quark Degrees of Λ(1405)

H. Kawamura et al., PRD 88, 034010 (2013)

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



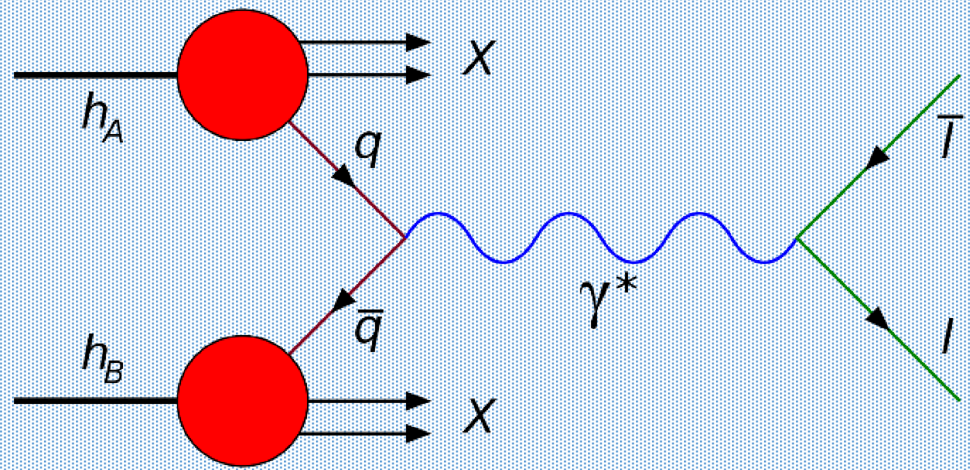




T. Sekihara
KEK workshop 2015

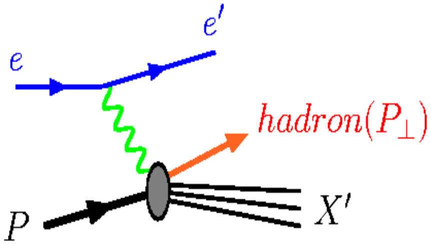
Uniqueness of hadron physics studied at Hi-P BL of J-PARC

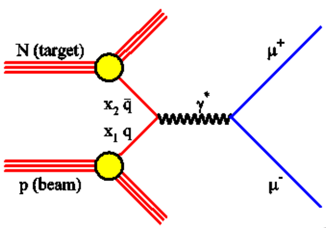
- The **5-15** GeV hadron beam energy at J-PARC ($\sqrt{s} = 3 - 5.5$ GeV) is unique for discerning the quark-hadron transition in the **hard exclusive processes**.
  - **Sensitivity to the quark structures of hadrons**, compared to the interactions at low-energy regime.
  - **Reasonably large cross sections**, compared to the interactions at high-energy regime.



Drell-Yan process

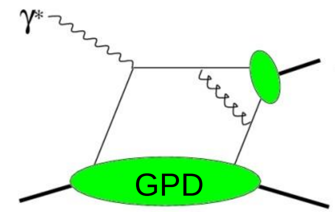
Quark and Gluon Distributions in Protons





Wigner Distribution
$W(\vec{r}, x, \vec{k}_T)$

Ji, PRL91,062001(2003)



$\int d\vec{r}$

$\int e^{i\vec{q}\cdot\vec{r}} d\vec{r} d\vec{k}_T$

$\xi = q^z / 2E_q,\ t = -\vec{q}^2$

Transverse Momentum Dependent PDF $f(x, \vec{k}_T)$

Generalized Parton Distr. $F(x, \xi, t)$

$\int d\vec{k}_T$

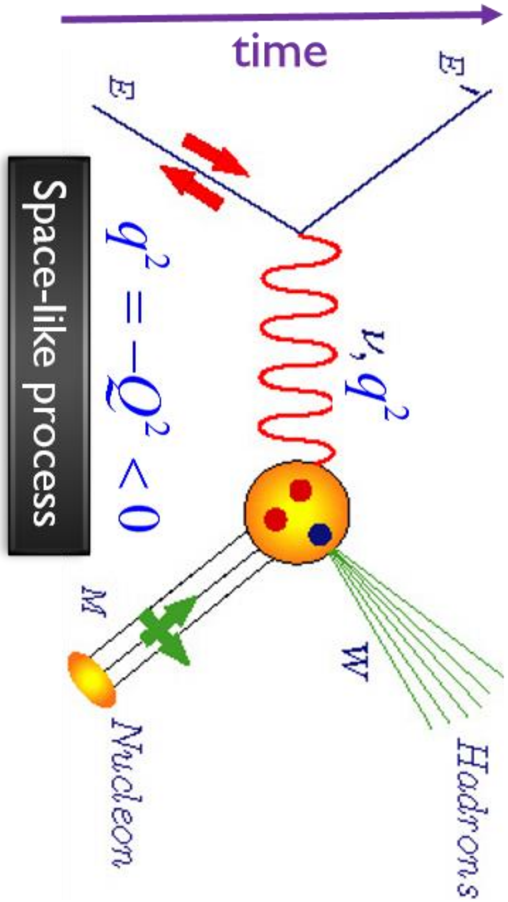
$x = 0\ \&\ \xi = 0$

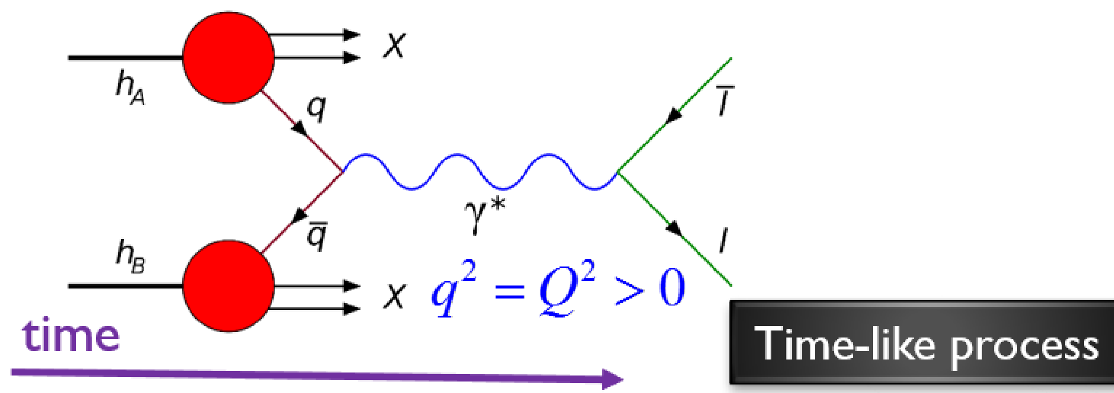
$\int dx$

PDF
$f(x)$

Form Factors
$F_1(t), F_2(t)$

Deep Inelastic Scattering (DIS) and Drell-Yan Processes

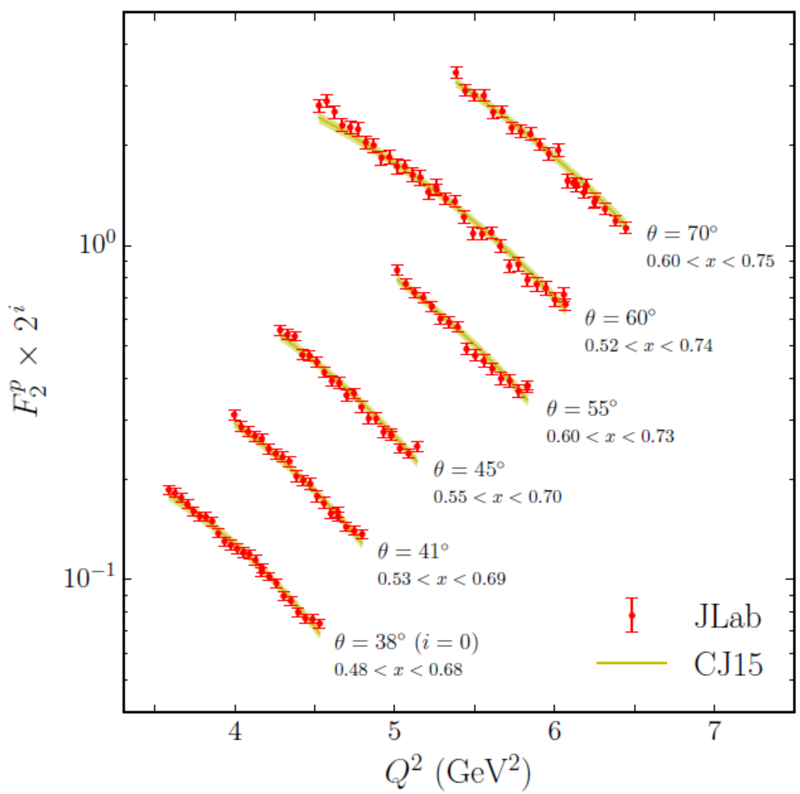


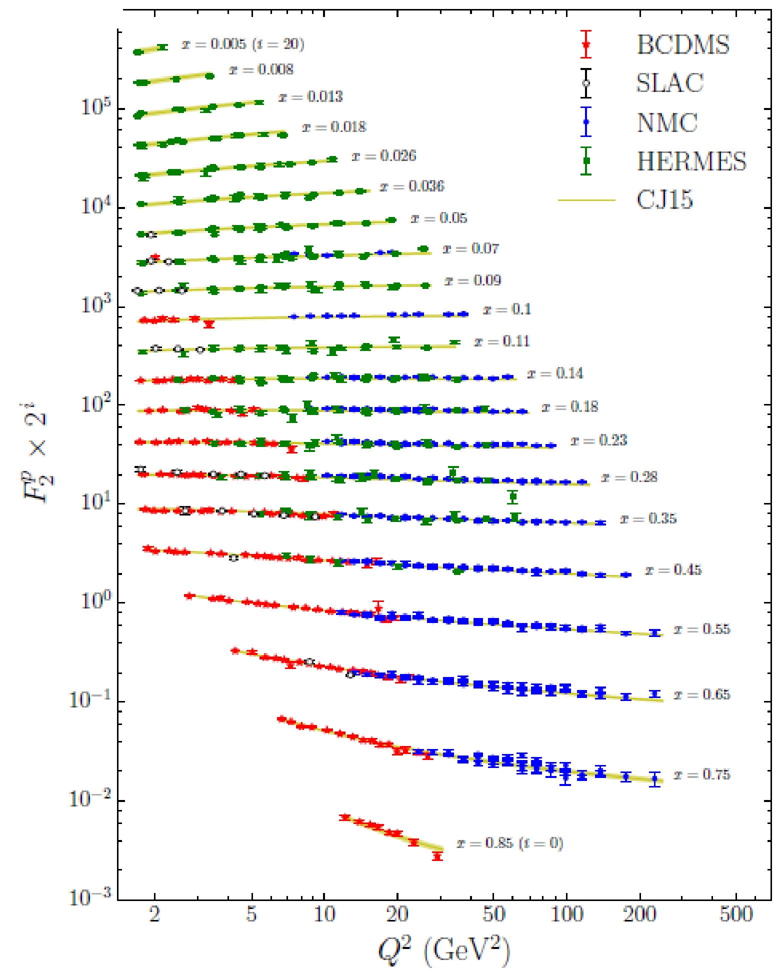


Global Analysis of DIS, Drell-Yan Data

$$xf(x,Q_0^2) = a_0\, x^{a_1}(1-x)^{a_2}\,(1+a_3\sqrt{x}+a_4 x).$$

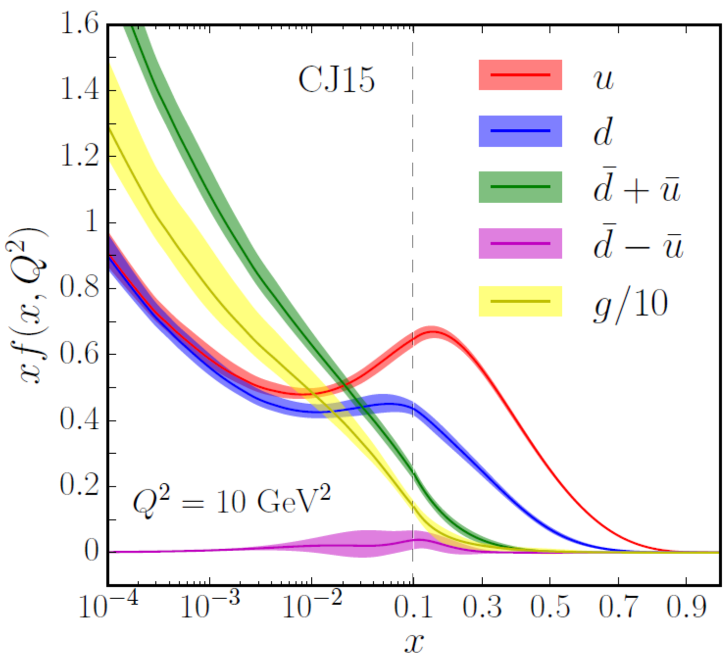
CJ15 (1602.03154)



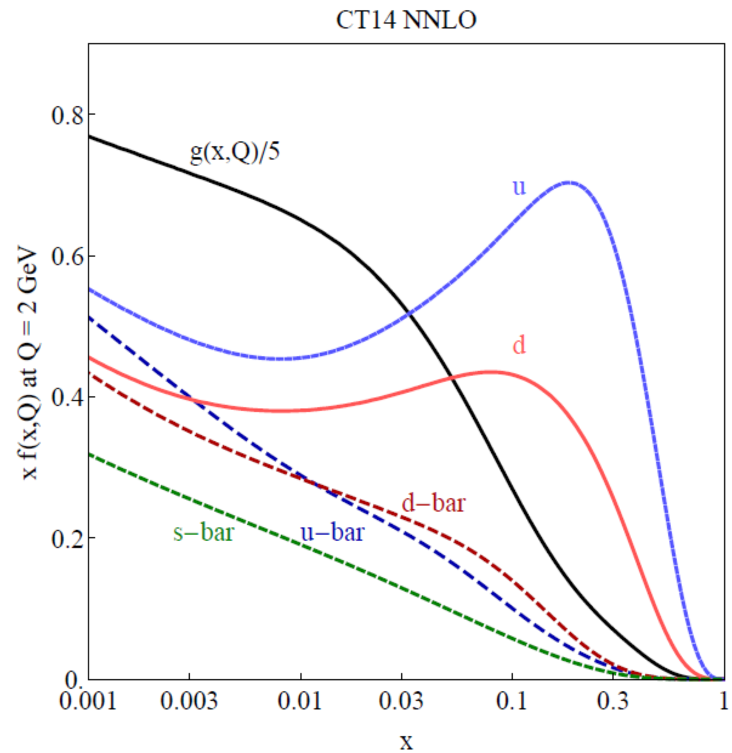


Parton Distribution Function (PDF) of Proton

CJ15 (1602.03154)



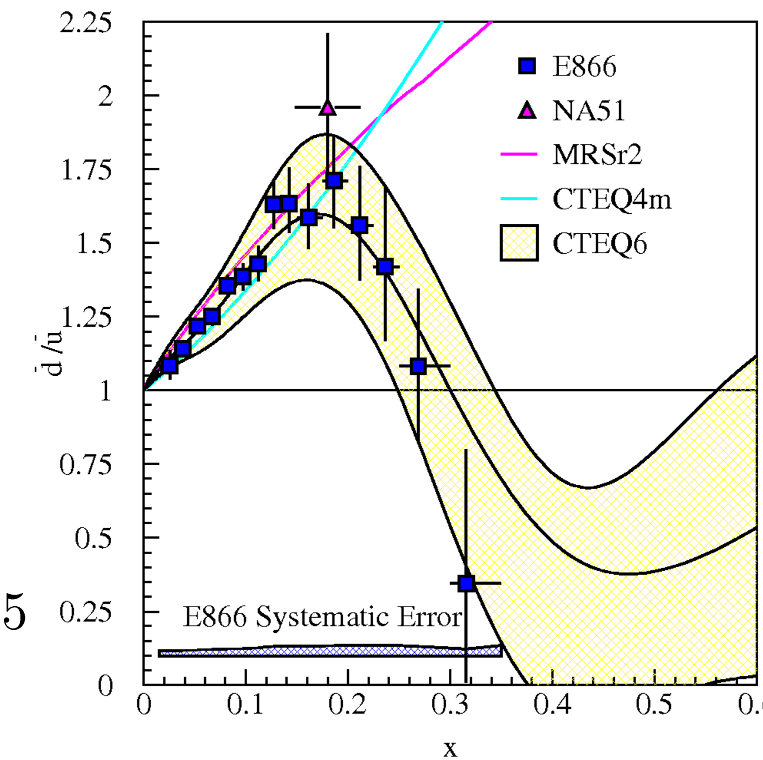
CT14 (1506.07443)

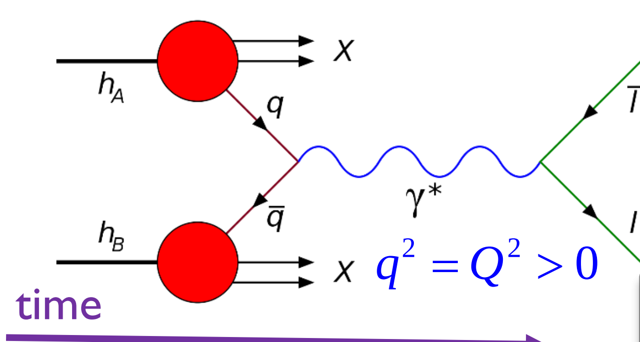


NNPDF3.0 (1410.8849), MMHT2014 (1412.3989); JR14 (1403.1852)

Light Antiquark Flavor Asymmetry:
Drell-Yan Experiments with Proton Beam

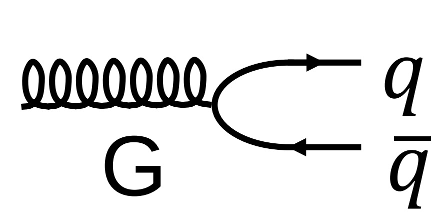
- Naïve Assumption: $\bar{d}(x) = \bar{u}(x)$
- NMC (Gottfried Sum Rule):
  $\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$
- NA51 (Drell-Yan, 1994):
  $\bar{d} > \bar{u}$ at $x = 0.18$
- E866/NuSea (Drell-Yan, 1998):
  $\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$





Time-like process

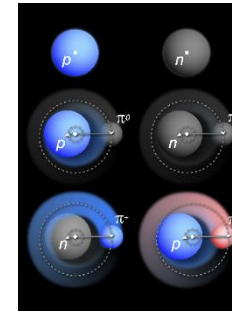
Origin of $\bar{u}(x) \neq \bar{d}(x)$: Perturbative QCD effect?



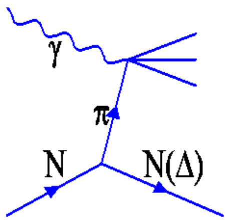
- Pauli blocking
  - $g \to u\bar{u}$ is more suppressed than $g \to d\bar{d}$ in the proton since |p>=|uud> (Field and Feynman 1977)
  - pQCD calculation (Ross, Sachrajda 1979)
  - Bag model calculation (Signal, Thomas, Schreiber 1991)
- Chiral quark-soliton model (Pobylitsa et al. 1999)
- Instanton model (Dorokhov, Kochelev 1993)
- Statistical model (Bourrely et al. 1995; Bhalerao 1996)
- Balance model (Zhang, Ma 2001)

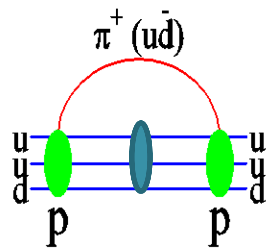
The valance-quark configuration affects the gluon splitting.

Origin of $\bar{u}(x) \neq \bar{d}(x)$: Non-perturbative QCD effect?



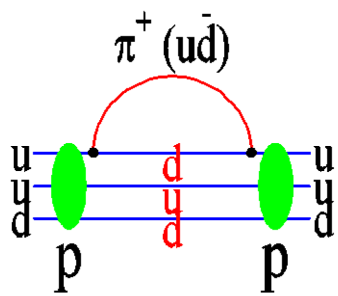
- Meson cloud in the nucleons (Thomas 1983, Kumano 1991): Sullivan process in DIS.





$$p \to N\pi;\ \pi^+ : \pi^0 : \pi^- = 2:1:0$$

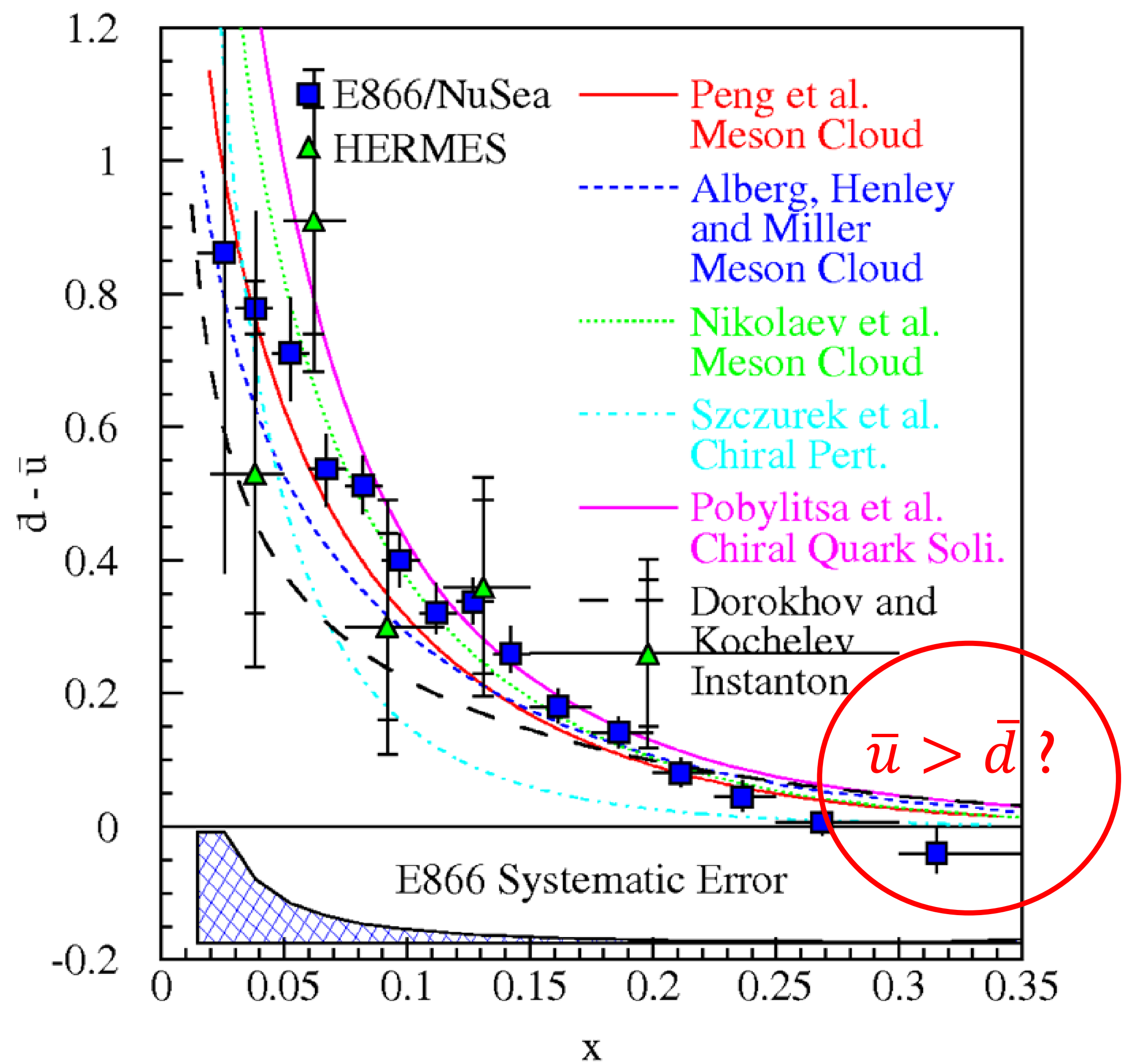
- Chiral quark model (Eichten et al. 1992; Wakamatsu 1992): Goldstone bosons couple to valence quarks.



$$q \to q\pi;\ \pi^+ : \pi^0 : \pi^- = 4:3:2$$

Pion cloud is a source of antiquarks in the protons and it lead to $\bar{d} > \bar{u}$.

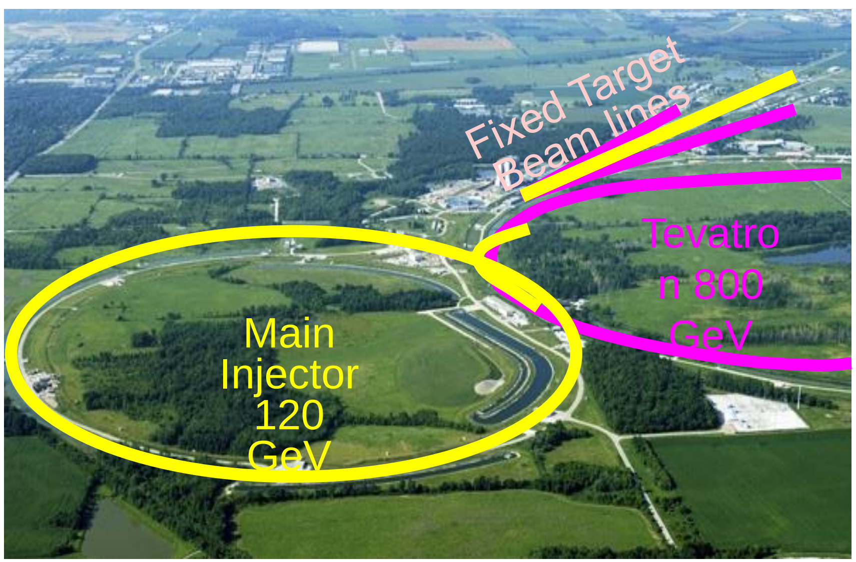
$\bar{d}(x) - \bar{u}(x)$ vs. Theoretical Models



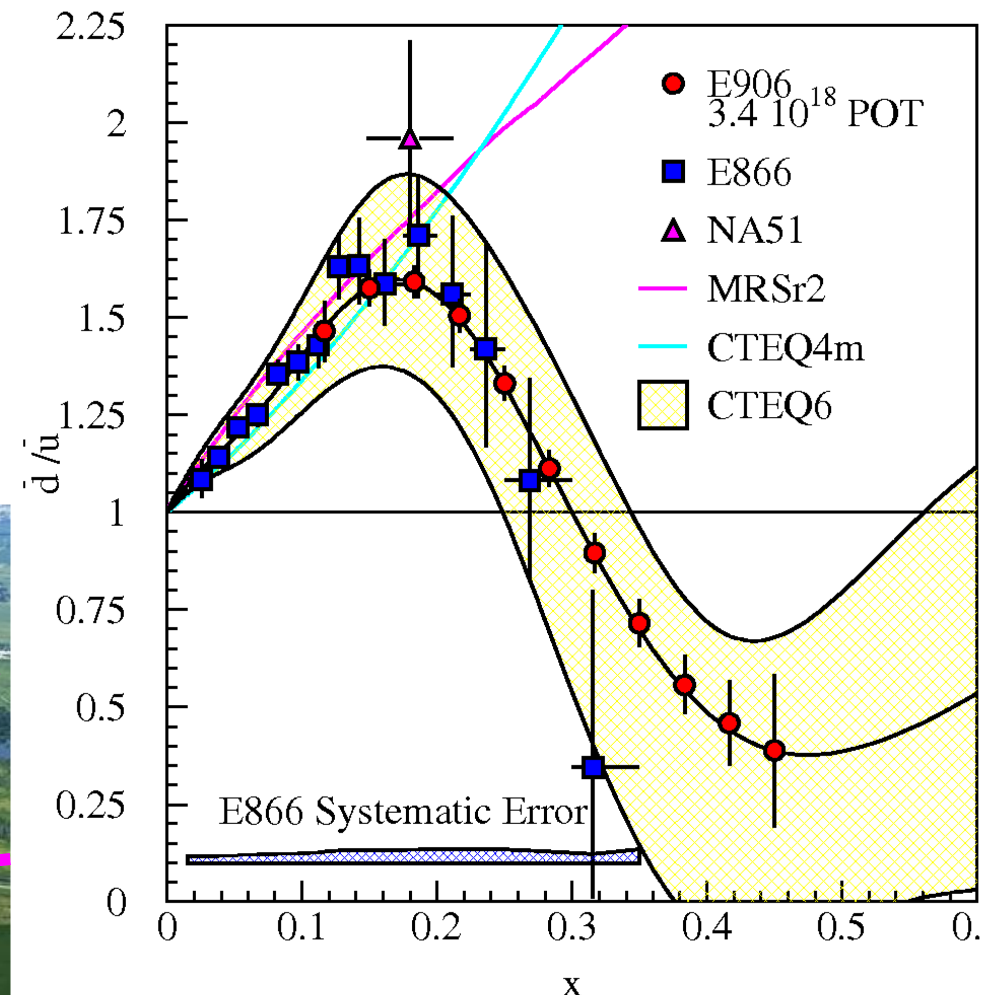
$\bar{d}/\bar{u}(x)$ Measured by FNAL E906/SeaQuest

Fermilab E906

- Physics data taking: Nov, 2013 – July, 2015.
- ^1H, ^2H, and nuclear targets
- Unpolarized Drell-Yan using 120 GeV proton beam



KEK, RIKEN, Tokyo Tech, Yamagata



$(\bar{d}(x)/\bar{u}(x))$ up to $x \sim 0.45$

の世界

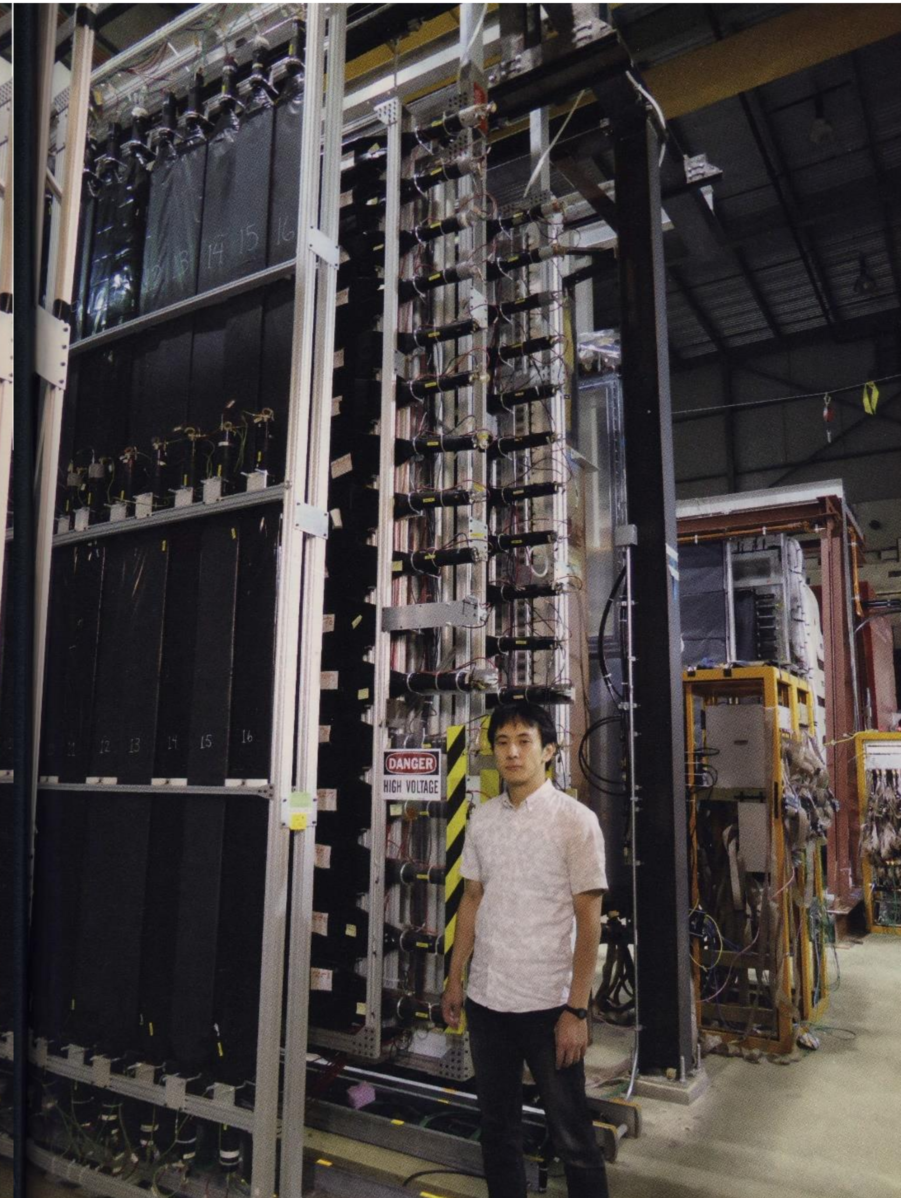
反粒子の反クォークで満ちている。ただし，クォークと反クォークの数の比は1対1からほんの少しだけずれていて，クォークから反クォークを引き算すると，3つだけクォークが多い。粒子と反粒子の間にわずかな不均衡が生じている。

これらクォークと反クォークは激しく動き回っているが，それは私たちになじみがある重力や電磁気力の作用ではなく，それらをはるかにしのぐ別種の強大な力，その名も「強い力」によっている。強い力は超強力な引力になったり，ほとんど作用しないこともある。この奇妙な力はクォークや反クォークの間でグルーオンという素粒子がキャッチボールされることによって伝わる。グルーオンは物理的な力を及ぼすだけではない。クォークは三原色になぞらえられるカラーを，反クォークは三原色の補色になぞらえられる反カラーを持つが，グルーオンをやり取りすると，そのカラーや反カラーの種類が変わる，いわば“変色”する場合がある。力の作用で粒子や反粒子のタイプがころころと変化するわけだ。さらに強い力はクォークと反クォークに質量ももたらす。先に話題になったヒッグス粒子は万物に質量を与える素粒子だが，クォークについてはヒッグス粒子に関連する質量よりも，強い力の作用で生じる質量の方がはるかに大きい。

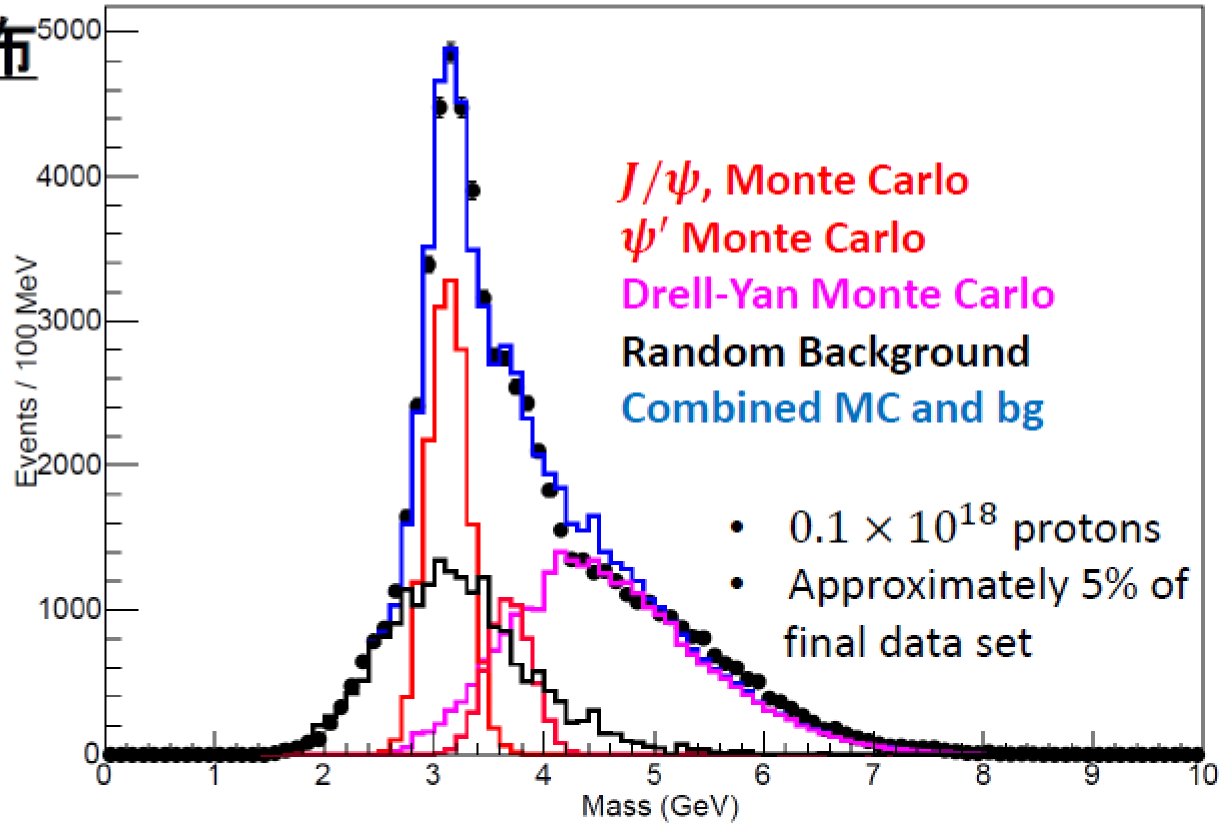
クォークと反クォークに満ちた核子内部は，一人何役も果たす「強い力」が支配する別世界だ。私たちは強い力の振る舞いが量子色力学（QCD）によって記述されることは知っているが，QCDがいったいどんな物質世界を構築しているのか，わからないことの方が多い。日本を含む世界の研究機関が様々な実験によって，この世界を探っている。（編集部）

陽子の内部を覗く 陽子内部はクォークや反クォークに満ちている。左はそのイメージ。全体を包む球殻が陽子，球殻内の色つきの球はクォーク，球の色はクォークが持つカラー（色荷）を表す。クォークをつなぐスプリング状のものは，強い力を担うグルーオンを表す。クォークやグルーオンなどは自転角運動量になぞらえられるスピンという物理量を持ち，その総体が陽子が持つスピン（図中の矢印）になるとされるが，陽子スピンの由来はそのかなりの部分が謎のままだ。陽子など核子の内部世界を探るため，国際協力で大がかりな実験が進んでいる。右ページは米国立フェルミ加速器研究所で進んでいるSeaQuest実験の施設。日本からは東京工業大学を中心とするグループが参加している。写真中の人物は研究グループの中心メンバーである中野健一東京工業大学助教。

柴田利明（東京工業大学）

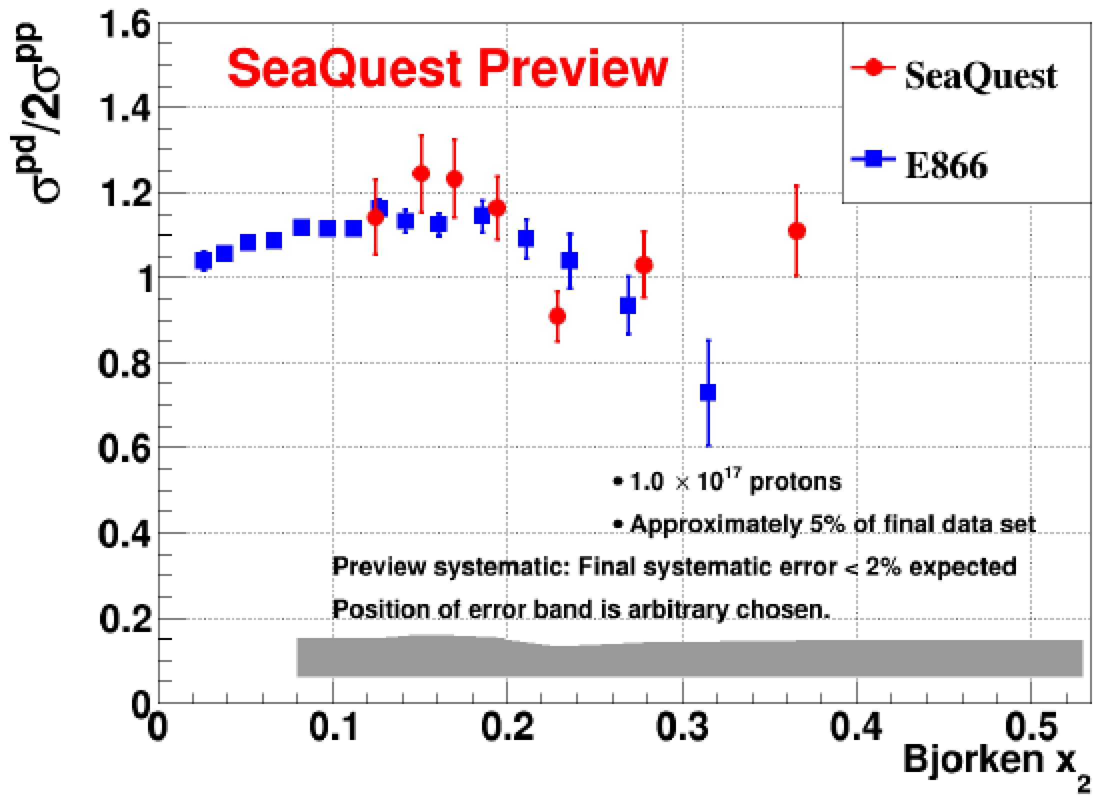


Mass 分布



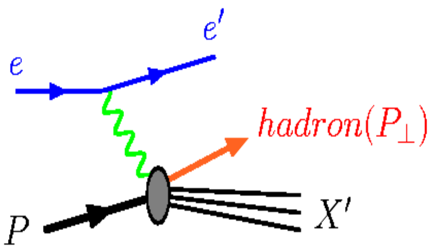
- Run2 の極一部のデータを用いた（最終的なデータ総量の約 5%）
- 検出器は想定通りに働いている
- イベント再構成に成功
- 良い Mass 分解能を持つ（~180 MeV）、MC の予想と一致

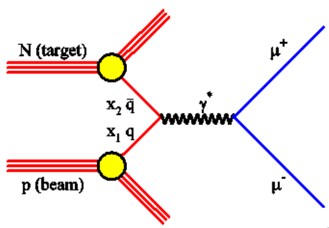
Cross section ratio, $\sigma^{pd}/2\sigma^{pp}$ vs Bjorken x_2



- Run2 の極一部のデータを用いた（最終的なデータ総量の約 5% ）
- Systematic error は study 中。最終的には 2% 以下になる見積もり
- 妥当なデータを取得している
- 現在は Run3 の QA を行っている

Quark and Gluon Distributions in Protons

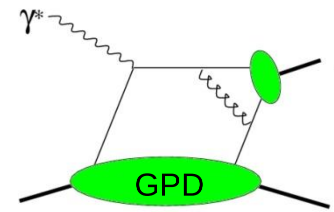




Wigner Distribution

$W(\vec{r}, x, \vec{k}_T)$

Ji, PRL91,062001(2003)



$\int d\vec{r}$

$\int e^{i\vec{q}\cdot\vec{r}} d\vec{r} d\vec{k}_T$

$\xi = q^z / 2E_q,\ t = -\vec{q}^2$

Transverse Momentum Dependent PDF $f(x, \vec{k}_T)$

Generalized Parton Distr. $F(x, \xi, t)$

$\int d\vec{k}_T$

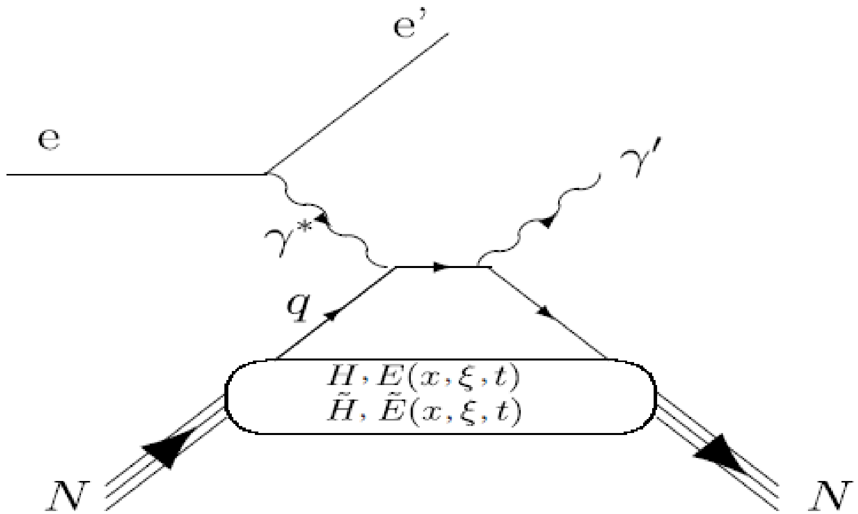
$x = 0 \ \&\ \xi = 0$

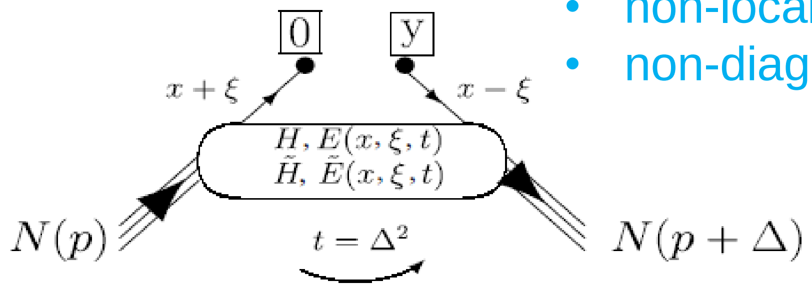
$\int dx$

PDF $f(x)$

Form Factors $F_1(t), F_2(t)$

Generalized Parton Distribution (GPD)





- non-local
- non-diagonal

Deeply virtual Compton scattering (DVCS)

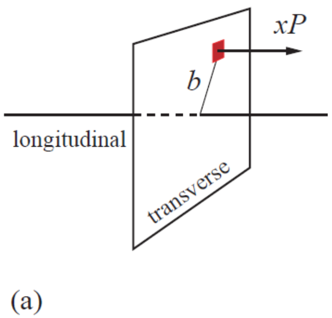
$$\frac{P^+}{2\pi}\int dy^- e^{ixP^+y^-}\langle p'|\bar{\psi}_q(0)\gamma^+\psi_q(y)|p\rangle\Big|_{y^+=\vec{y}_\perp=0}$$
$$= H^q(x,\xi,t)\,\bar{N}(p')\gamma^+N(p)$$
$$+ E^q(x,\xi,t)\,\bar{N}(p')i\sigma^{+\nu}\frac{\Delta_\nu}{2m_N}N(p),$$

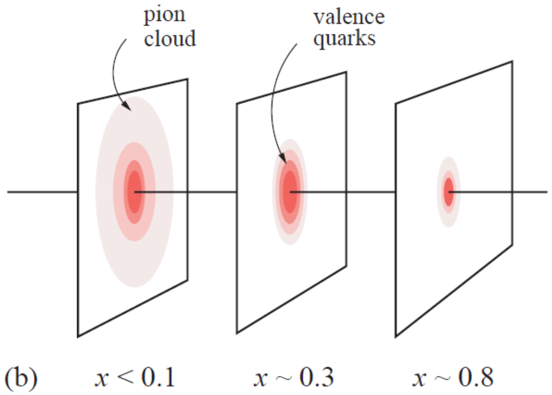
$$\frac{P^+}{2\pi}\int dy^- e^{ixP^+y^-}\langle p'|\bar{\psi}_q(0)\gamma^+\gamma^5\psi_q(y)|p\rangle\Big|_{y^+=\vec{y}_\perp=0}$$
$$= \tilde{H}^q(x,\xi,t)\,\bar{N}(p')\gamma^+\gamma_5N(p)$$
$$+ \tilde{E}^q(x,\xi,t)\,\bar{N}(p')\gamma_5\frac{\Delta^+}{2m_N}N(p),$$

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

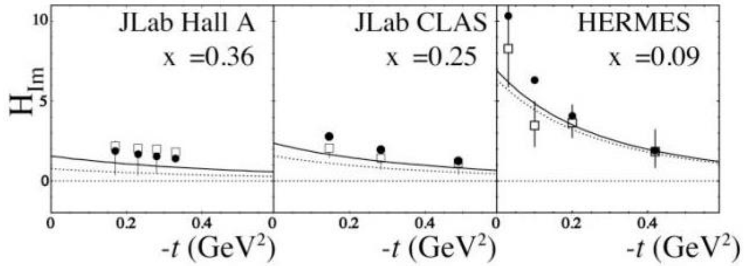
M. Guidal, H. Moutarde and M. Vanderhaeghen, Rep. Prog. Phys. 76 (2013) 066202.

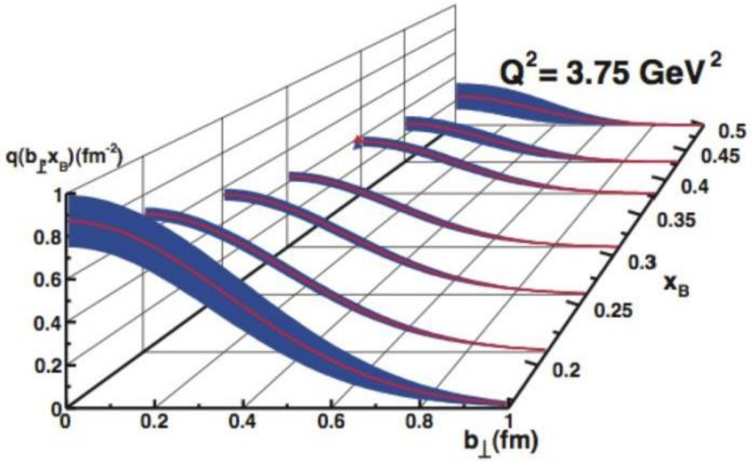
Generalized Parton Distribution

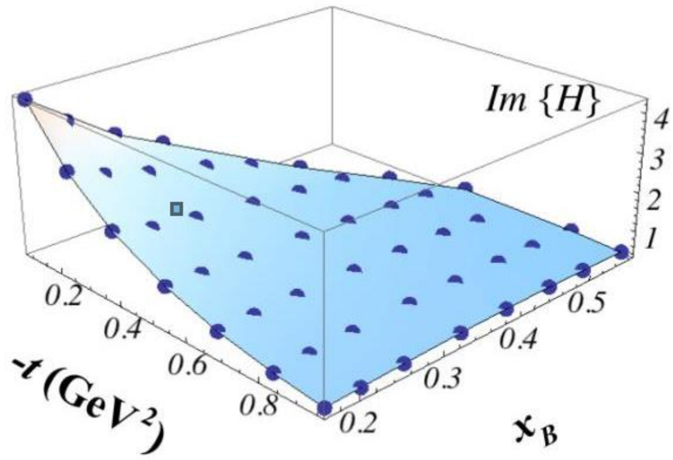




JLAB12 CDR, arXiv:1208.1244

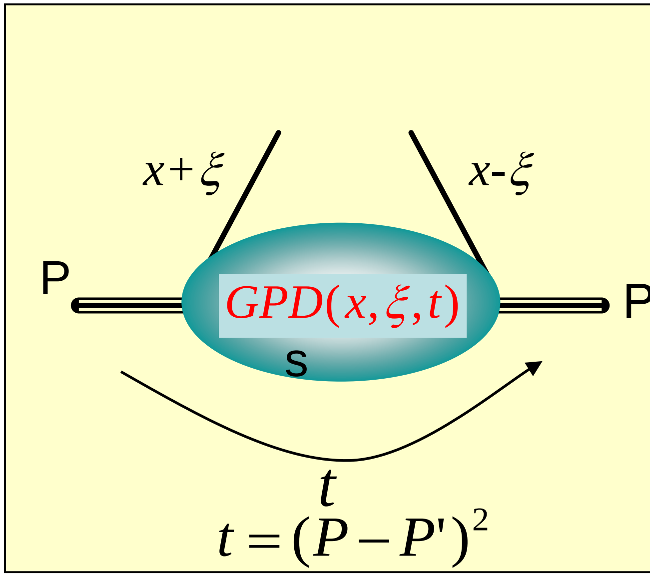






- 1+2D description of the nucleon structure
- Correlations among longitudinal momenta and transverse positions
- Connection to quark orbital angular momentum

Generalized Parton Distribution (GPD)



$t=\xi=0$

$$H_f(x,0,0)=q_f(x)=-\bar{q}_f(-x)$$

$$\tilde{H}_f(x,0,0)=\Delta q_f(x)=-\Delta\bar{q}_f(-x)$$

The first moments

$$\int_{-1}^{1} dx \sum_f H_f(x,\xi,t)=F_1(-t)$$

$$\int_{-1}^{1} dx \sum_f E_f(x,\xi,t)=F_2(-t)$$

$$\int_{-1}^{1} dx \sum_f \tilde{H}_f(x,\xi,t)=G_A(-t)$$

$$\int_{-1}^{1} dx \sum_f \tilde{E}_f(x,\xi,t)=G_p(-t)$$

The second moments

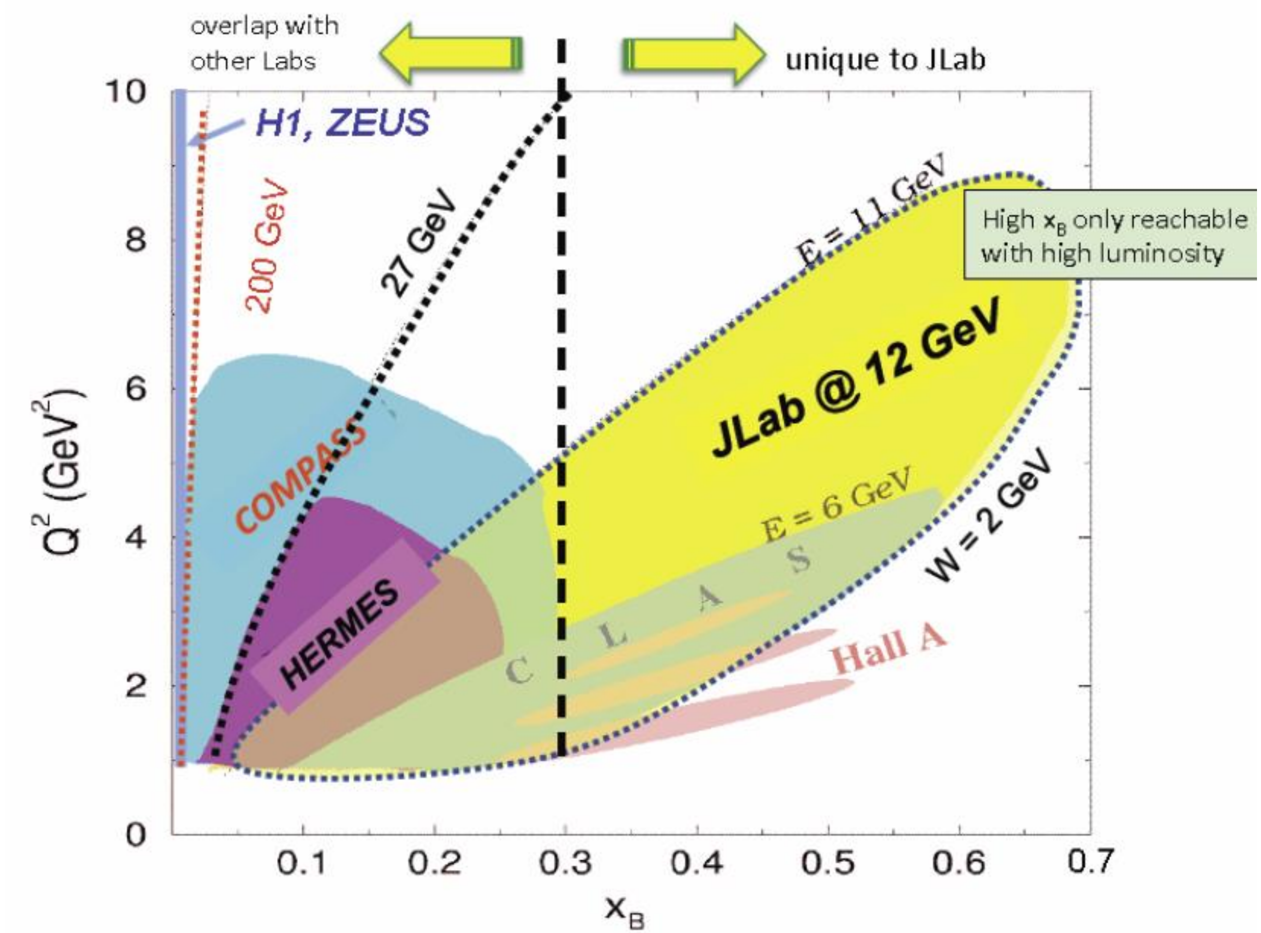
	γ^μ	$\gamma^\mu\gamma^5$
no spin flip	$H_f(x,\xi,t)$	$\tilde{H}_f(x,\xi,t)$
spin flip	$E_f(x,\xi,t)$	$\tilde{E}_f(x,\xi,t)$

Ji's sum rule

$$J_f=\frac{1}{2}\Delta\Sigma^f+L^f=\frac{1}{2}\int_{-1}^{1} xdx\,[H_f(x,\xi,0)+E_f(x,\xi,0)]$$

The orbital angular momentum of quarks can be known.

Worldwide Activities for Measuring GPD



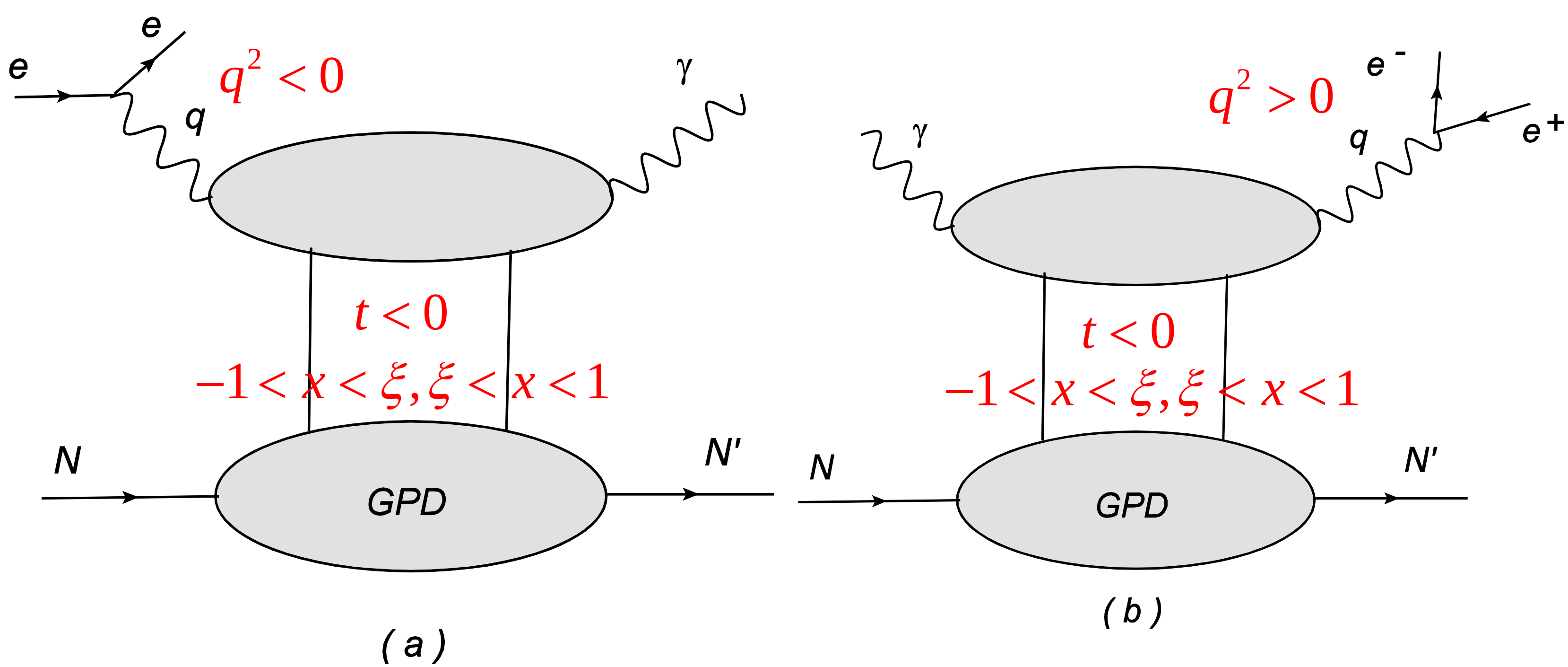
arXiv:1208.1244

Measurement of GPDs: Spacelike vs. Timelike Processes

Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering

Timelike Compton Scattering



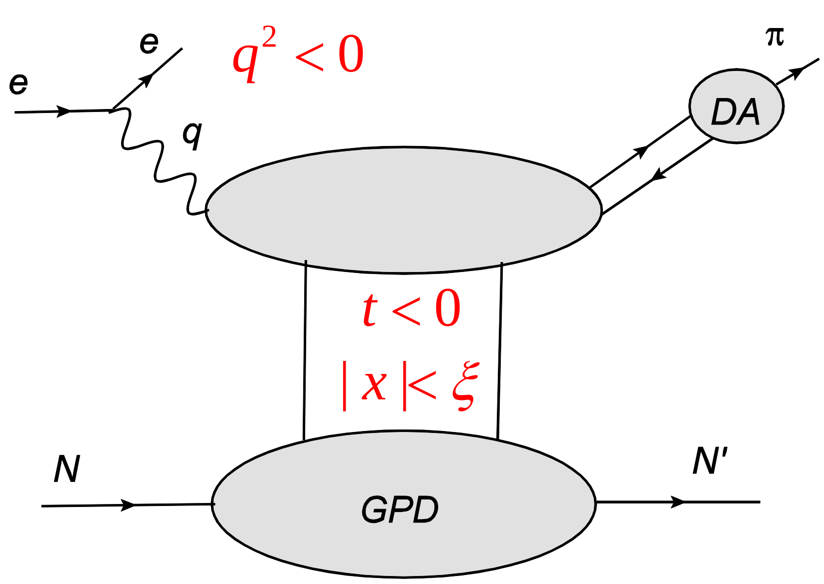
$$\mathcal{F}(\xi = \eta, t, \mathcal{Q}^2) \overset{\mathrm{SL}\to\mathrm{TL}}{\Rightarrow} \mathcal{F}(\xi = -\eta, t, -\mathcal{Q}^2),$$

$$\mathcal{F}(\xi, t, \mathcal{Q}^2) = \int_{-1}^{1} dx \sum_{i=u,d,\cdots,g} {}^{S}T^i(x, \xi) F^i(x, \xi, t, \mu^2),$$

Measurement of GPDs: Spacelike vs. Timelike Processes

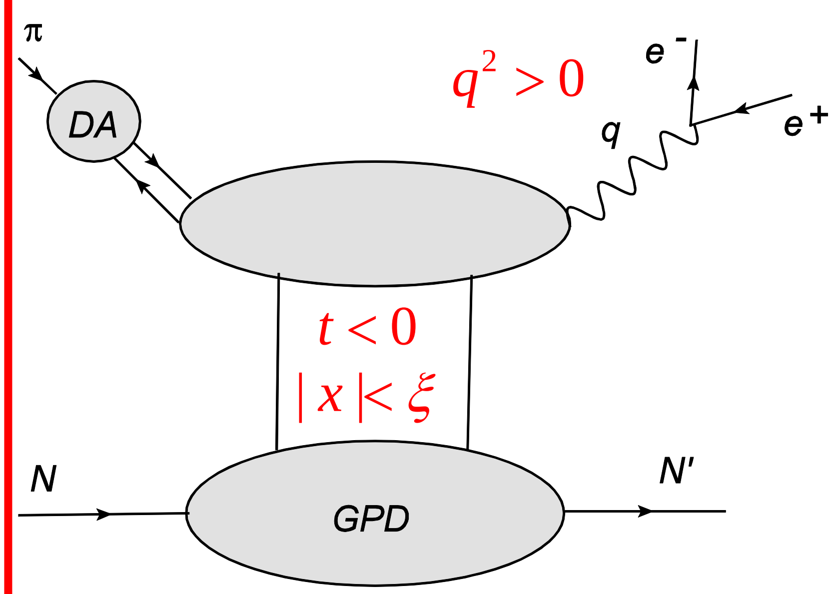
Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Meson Production



(c)

Exclusive Meson-induced DY

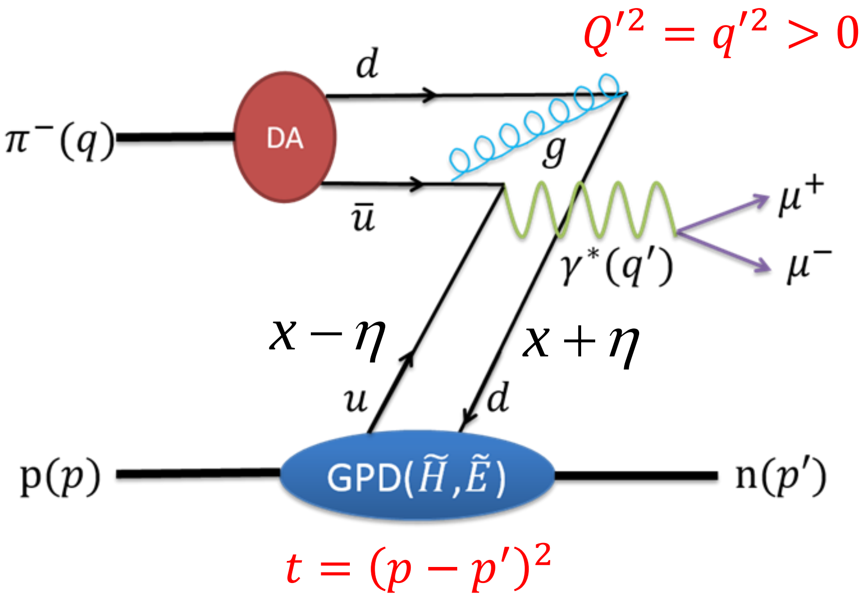


(d)

To be measured with hadron beams.

πN→→μ+μ-N

E.R. Berger, M. Diehl, B. Pire, PLB 523 (2001) 265



$$\tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s - M_N^2} \qquad \eta = \frac{(p-p')^+}{(p+p')^+}$$

$$\frac{d\sigma}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = \frac{\alpha_{\mathrm{em}}}{256\pi^3}\frac{\tau^2}{Q'^6}\sum_{\lambda',\lambda}|M^{0\lambda',\lambda}|^2\sin^2\theta,$$

$$M^{0\lambda',\lambda}(\pi^- p \to \gamma^* n) = -ie\frac{4\pi}{3}\frac{f_\pi}{Q'}\frac{1}{(p+p')^+}\bar{u}(p',\lambda') \times \left[\gamma^+\gamma_5\widetilde{\mathcal{H}}^{du}(-\eta,\eta,t) + \gamma_5\frac{(p'-p)^+}{2M}\widetilde{\mathcal{E}}^{du}(-\eta,\eta,t)\right]u(p,\lambda).$$

$$\widetilde{\mathcal{I}}^{du}(\xi,\eta,t) = \frac{8}{3}\alpha_S\int_{-1}^{1} dz\,\frac{\phi_\pi(z)}{1-z^2} \times \int_{-1}^{1} dx\left[\frac{e_d}{\xi - x - i\epsilon} - \frac{e_u}{\xi + x - i\epsilon}\right] \times \left[\widetilde{H}^d(x,\eta,t) - \widetilde{H}^u(x,\eta,t)\right],$$

Differential Cross Sections (Q^2,t,τ)

E.R. Berger, M. Diehl, B. Pire, PLB 523 (2001) 265

$$
\frac{d\sigma}{dQ'^2\,dt}(\pi^- p \to \gamma^* n)
$$

$$
= \frac{4\pi\alpha_{\mathrm{em}}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \;\times \Big[\big(1-\eta^2\big)\big|\widetilde{\mathcal{H}}^{du}\big|^2 - 2\eta^2\,\mathrm{Re}\big(\widetilde{\mathcal{H}}^{du*}\widetilde{\mathcal{E}}^{du}\big) - \eta^2\frac{t}{4M^2}\big|\widetilde{\mathcal{E}}^{du}\big|^2 \Big],
$$

$$
t = (p - p')^2 \qquad \tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s - M_N^2} = x_B
$$

$$
Q'^2 = q'^2 > 0 \qquad \eta = \frac{(p-p')^+}{(p+p')^+} = \frac{\tau}{2-\tau}
$$

GPD $\widetilde{H}(x,\eta,t)$ Double Integration

E.R. Berger, M. Diehl, B. Pire, EPJC 23, 675 (2002)

$$\widetilde{H}^u(x,\eta,t) - \widetilde{H}^d(x,\eta,t)$$
$$= \left[\widetilde{h}^u(x,\eta) - \widetilde{h}^d(x,\eta)\right] g_A(t)/g_A(0). \qquad (6)$$

We take the parameterization $g_A(t)/g_A(0) = (1 - t/M_A^2)^{-2}$ with $M_A = 1.06$ GeV from [17]. The functions

$$\boxed{\begin{aligned} \tilde{h}^q(x,\eta) &= \int_0^1 \mathrm{d}x' \int_{-1+x'}^{1-x'} \mathrm{d}y' \\ &\quad \times \delta(x - x' - \eta y') \Delta q_{\mathrm{V}}(x') \pi(x', y'), && (38) \\ \pi(x', y') &= \frac{3}{4} \frac{(1-x')^2 - y'^2}{(1-x')^3}. && (39) \end{aligned}}$$

$\widetilde{H}(x, \eta = 0, t = 0)$=polarized valance distribution

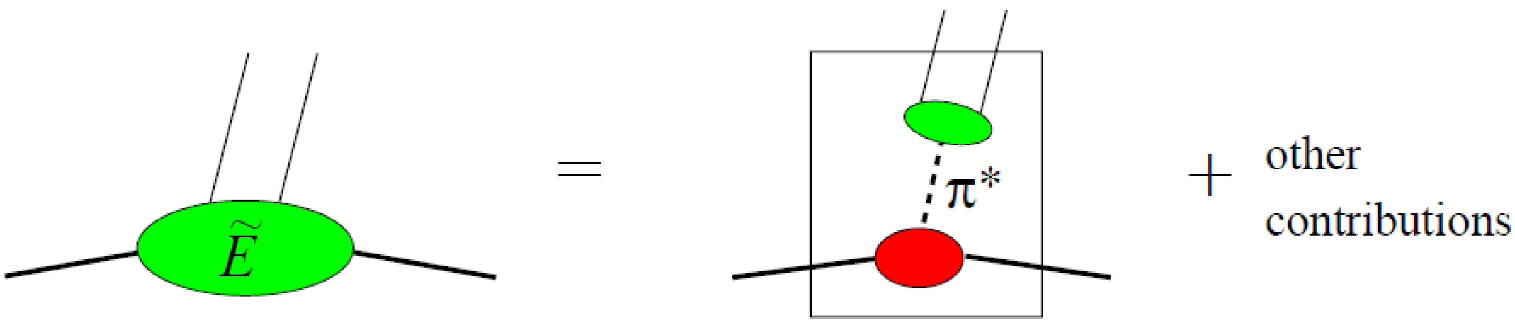
GPD $\tilde{E}(x, \eta, t)$ Pion-pole Dominance

E.R. Berger, M. Diehl, B. Pire, EPJC 23, 675 (2002)

$$\widetilde{E}^u(x, \eta, t) - \widetilde{E}^d(x, \eta, t)$$
$$= \Theta\left(\eta - |x|\right) \frac{1}{\eta} \boxed{\phi_\pi\left(\frac{x}{\eta}\right)} F(t)$$

$$F(t) = \frac{4.4\ \mathrm{GeV}^2}{m_\pi^2 - t}\left[1 - \frac{B(m_\pi^2 - t)}{(1 - Ct)^2}\right] \qquad (8)$$

with $B = 1.7\ \mathrm{GeV}^{-2}$ and $C = 0.5\ \mathrm{GeV}^{-2}$. Note



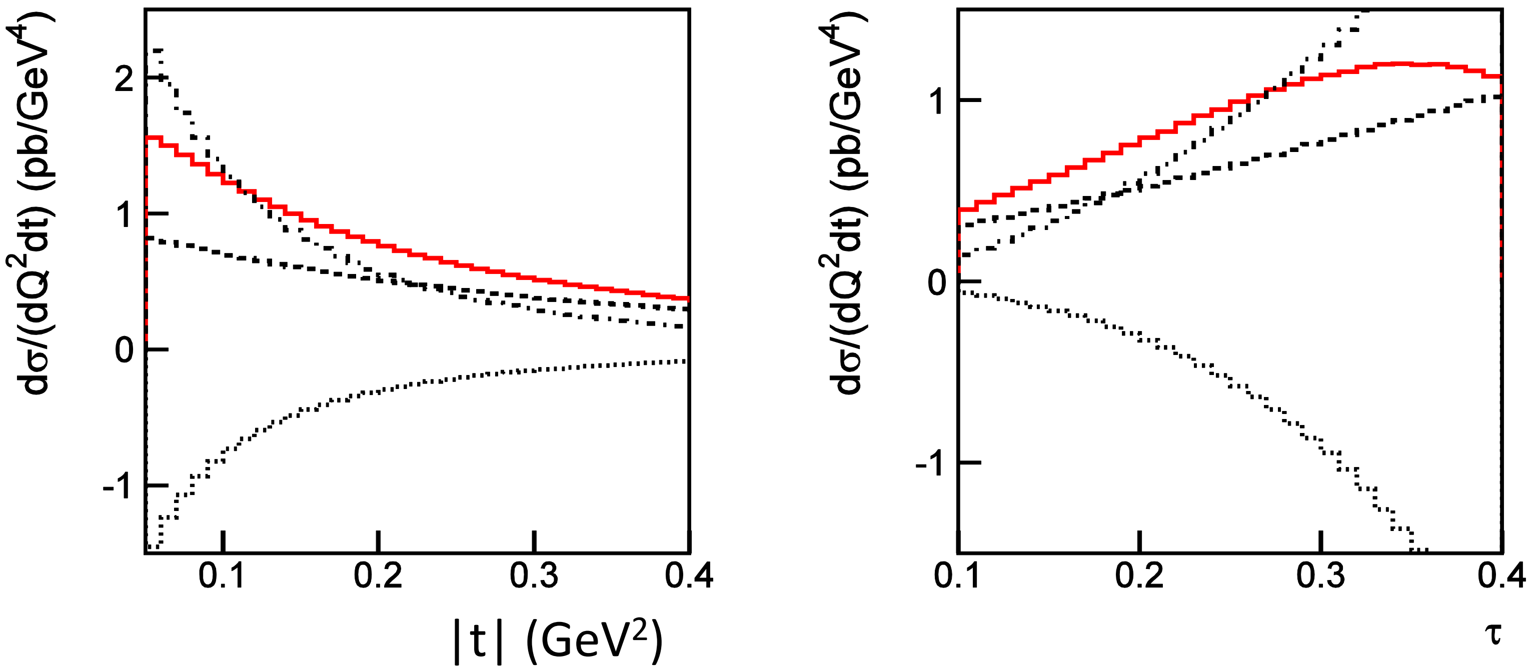
$$\tilde{E}^{u-d}(x, \xi, t) \overset{t \to m_\pi^2}{\longrightarrow} \theta(|x| < |\xi|) \frac{1}{2|\xi|}\, \phi_\pi\left(\frac{x + \xi}{2\xi}\right) \frac{4m^2 g_A(0)}{m_\pi^2 - t}$$

$\pi N \to \mu^+ \mu^- N$

E.R. Berger, M. Diehl, B. Pire, PLB 523 (2001) 265

Cross sections increase toward small s!

$$Q'^2 = q'^2 = 5\ GeV^2$$

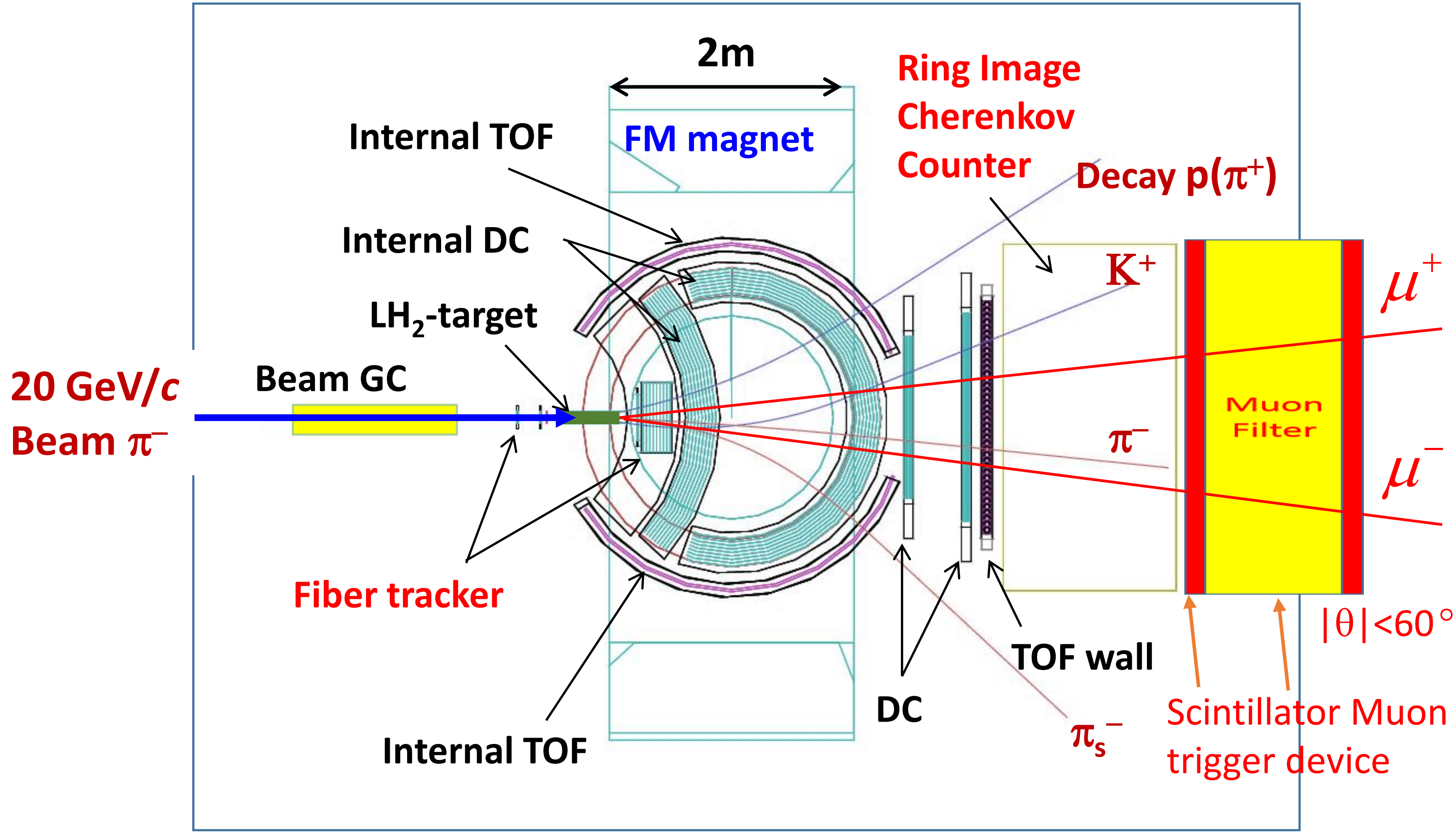


$$t = (p - p')^2 = -0.2\ GeV^2$$

$$\tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s - M_N^2} = 0.2$$

$\pi^- p \rightarrow \mu^+ \mu^- n$

Missing Mass Technique in E-50 Spectrometer + MuID



Acceptance: ~ 60% for *D, ~80% for decay π^+**

Resolution: $\Delta p/p$~0.2% at ~5 GeV/c （Rigidity：~2.1 Tm)

Experimental Conditions

- **Target** : 57cm LH_2 (n_{TGT}=4 g/cm^2)
- **ε(DAQ, Tracking, PID)** = 0.9*0.7*0.9
- **Beam momentum resolution**: $\Delta p/p$ = 0.1 %
- **Detector resolution**: $\Delta M/M$ = 1 %
- **Exclusive DY**: ~ 1.2 events/day/pb for $I_{\mathrm{beam}}=10^7$ π/s
- **Beam Time**: 50 days

Yield Estimation

Event Generator

- Inclusive Drell-Yan

  Pythia 6.4.26

- Exclusive Drell-Yan

  GPD:
  BDP 2001: EPJC 23, 675 (2002)
  GK 2013: EPJC 73, 2278 (2013)
  GK 2015: PLB 748, 323 (2015)

- Background

  JAM 1.132

Particle Transportation + Detector

Geant 4.9.3

(E-50 spectrometer + Muon ID)

Total Cross Section

Inclusive Drell-Yan ($M_{\mu\mu}$>1.5 GeV)

	π^-	π^+
10 GeV	2.11 nb	0.323 nb
15 GeV	2.71 nb	0.493 nb
20 GeV	3.08 nb	0.616 nb

Exclusive Drell-Yan ($M_{\mu\mu}$>1.5 GeV, $|t-t_0|<0.5$ GeV^2)

	π^- (BDP 2001)	π^- (GK 2013)	π^- (GK 2015)
10 GeV	6.28 pb	17.53 pb	140 pb
15 GeV	4.66 pb	10.64 pb	20 pb
20 GeV	3.69 pb	7.24 pb	

Hadronic Background

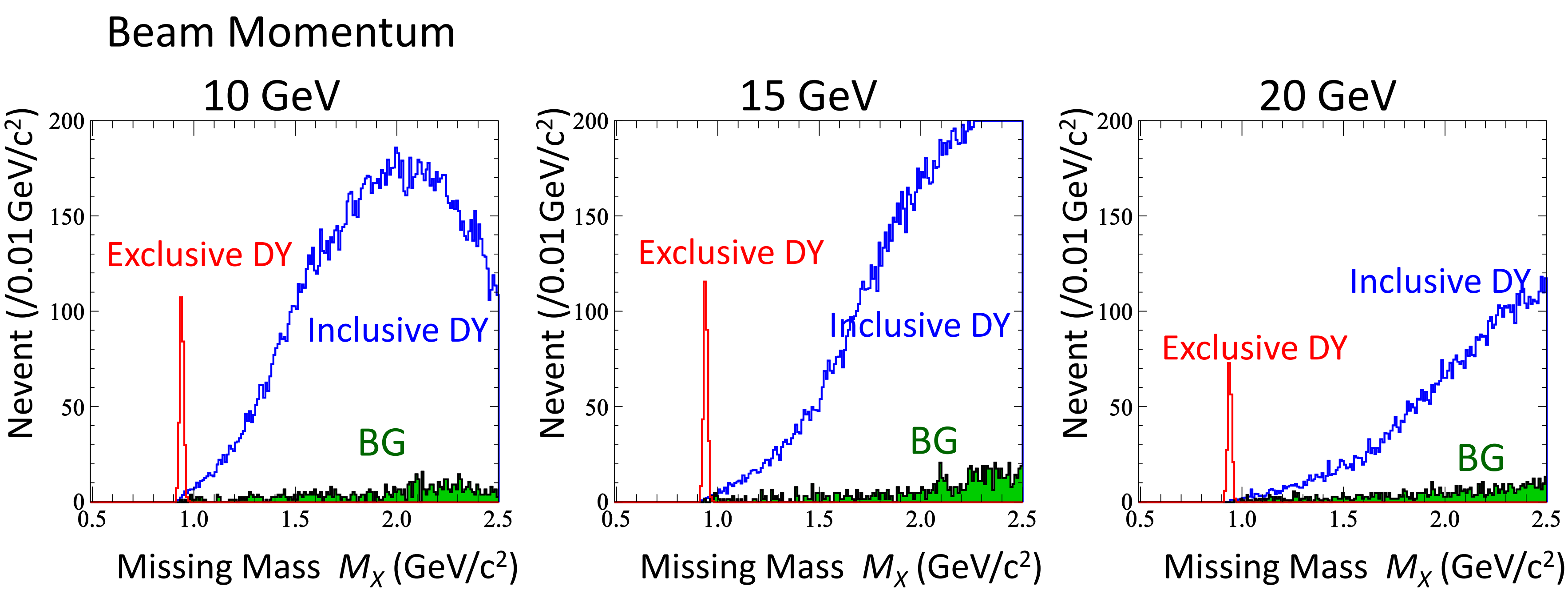
	π^-	π^+
10 GeV	26.9 mb	24.8 mb
15 GeV	25.8 mb	24.1 mb
20 GeV	25.1 mb	23.5 mb

$\pi^- p \rightarrow \mu^+ \mu^- n$

M_X In E-50 Spectrometer + MuID

π⁻ beam 50 days

$1.5 < M_{\mu^+\mu^-} < 2.9$ GeV/c²



- The signal of exclusive Drell-Yan processes can be clearly identified in the missing mass spectrum of dimuon pairs.
- Because of the low event rate, this program could be accommodated into the E50 experiment.

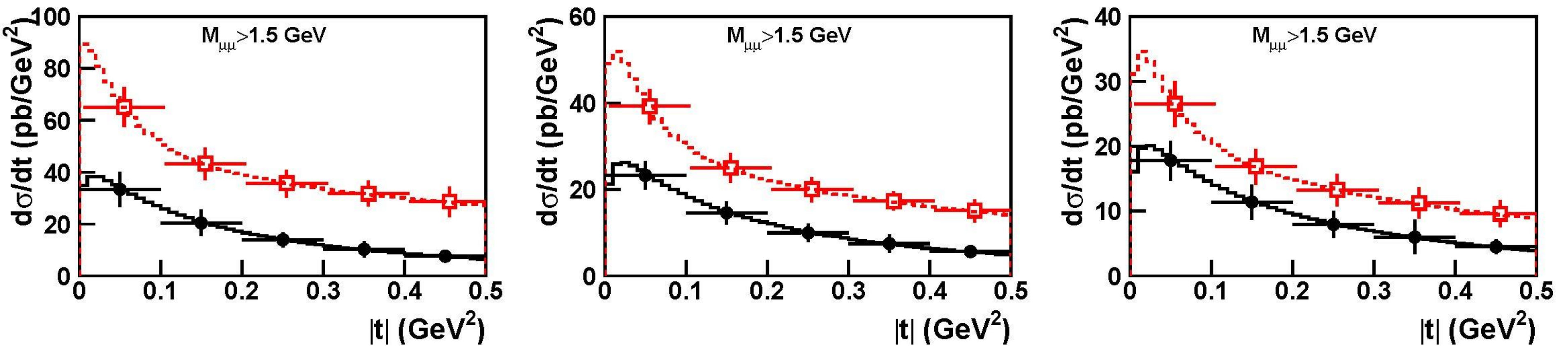
$\pi^- p \rightarrow \mu^+ \mu^- n$

M_X In E-50 Spectrometer + MuID

$\boxed{\pi^- \text{ beam} \quad 50 \text{ days}}$ $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV/c^2

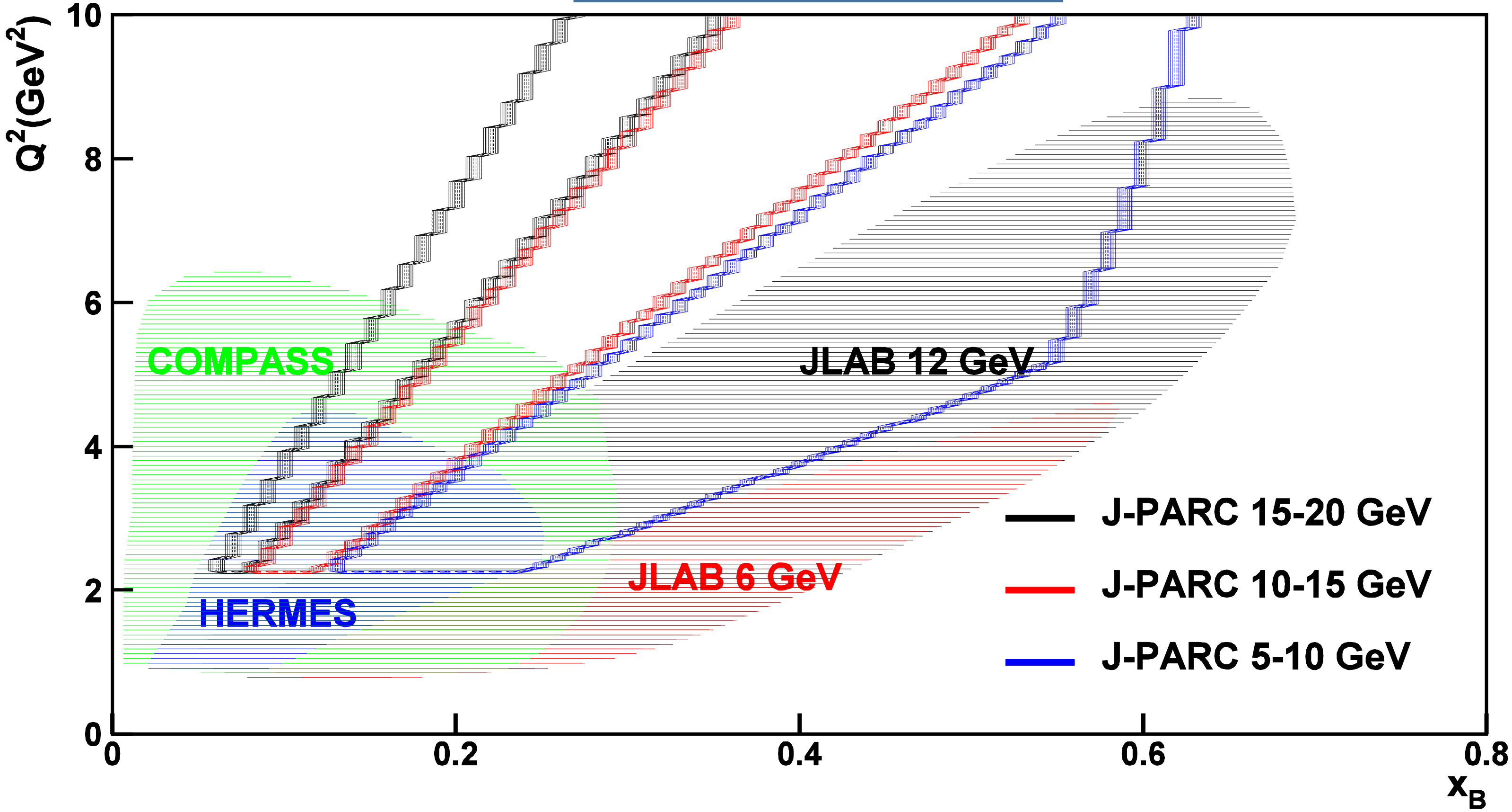
Beam Momentum

10 GeV 15 GeV 20 GeV



GPD(x_B,t;Q^2) from space-like and time-like processes

Large-Q^2 region



- J-PARC: **time-like** approach and **large-Q^2** region.

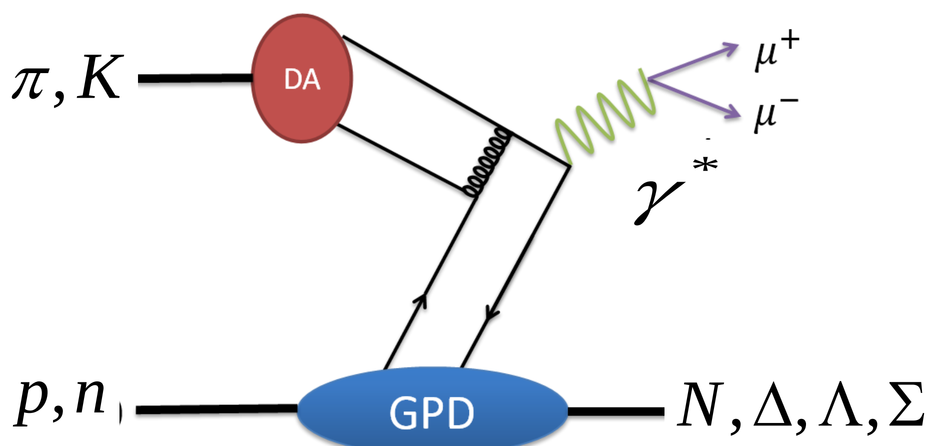
Impacts of GPD measurements at J-PARC

- Information of GPD at large-Q^2 region.
- Test of universality of GPD in space-like and time-like processes.
- Test of QCD-evolution properties of GPD.
- Test of factorization of exclusive Drell-Yan process.

“GPD” and “Transition GPD”

- $\pi^{-}\mathrm{p} \rightarrow \gamma^{*} n$
- $\pi^{-}\mathrm{p} \rightarrow \gamma^{*} \Delta^{0}$
- $\pi^{-}\mathrm{n} \rightarrow \gamma^{*} \Delta^{-}$
- $\pi^{+}\mathrm{n} \rightarrow \gamma^{*} \mathrm{p}$
- $\pi^{+}\mathrm{p} \rightarrow \gamma^{*} \Delta^{++}$
- $\pi^{+}\mathrm{n} \rightarrow \gamma^{*} \Delta^{+}$

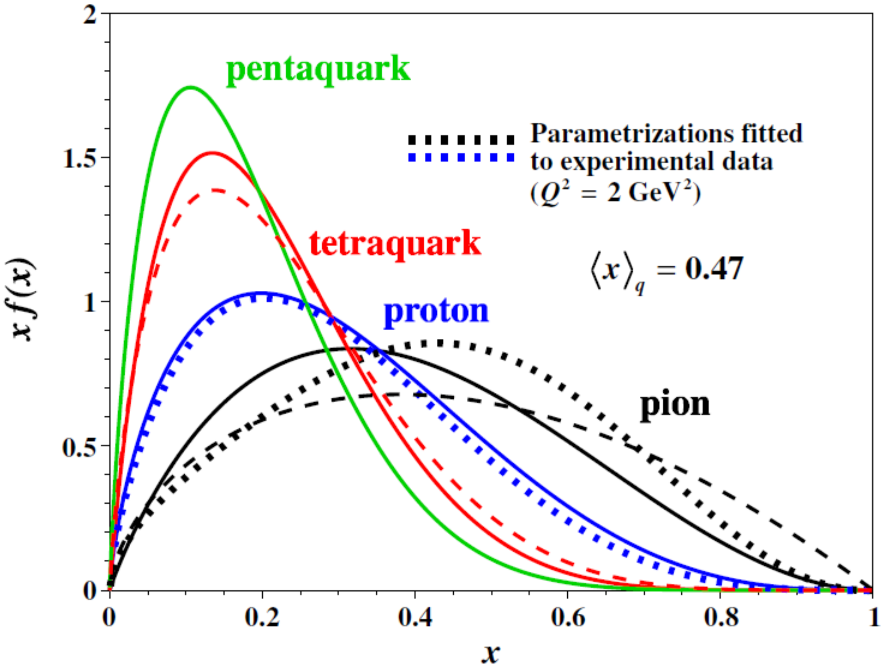
- $K^{-}\mathrm{p} \rightarrow \gamma^{*} \Lambda$
- $K^{-}\mathrm{p} \rightarrow \gamma^{*} \Lambda(1405)$
- $K^{-}\mathrm{p} \rightarrow \gamma^{*} \Lambda(1520)$
- $K^{-}\mathrm{n} \rightarrow \gamma^{*} \Sigma^{-}$
- $K^{+}\mathrm{n} \rightarrow \gamma^{*} \Theta^{+}$

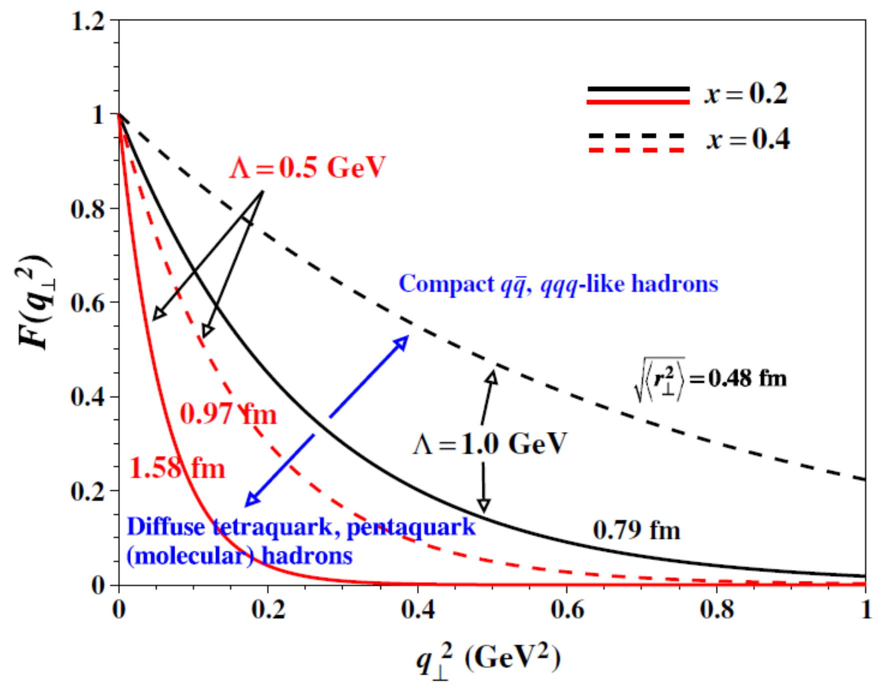


GPD for (unstable) hadrons

H. Kawamura and S. Kumano, PRD 89, 054007 (2014)

$$H_q^h(x, \xi = 0, t) = f_n(x) F_n^h(t, x)$$





Softening of long. mom. fraction x.

Softening of transverse form factor.

Summary

- High-energy hadron beam at J-PARC is unique for studying hard exclusive processes.
- Quark structure of exotic hadrons can be determined by the scaling behavior.
- Measurement of GPD in the exclusive π-induced DY process will offer important understanding on
  - **GPD at large Q2 region**
  - **Universality of GPD in the space-like and time-like processes.**
- Preliminary study shows that such measurement with E-50 spectrometers is feasible.