J-PARCにおける核子構造の物理：コメント

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第４回 核子構造WGオープンミーティング
http://indico.riken.jp/indico/

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Hadron physics at J-PARC

Possibilities

Approved proposals

Hadron and Nuclear Physics

1st project

Next projects

Need major upgrades

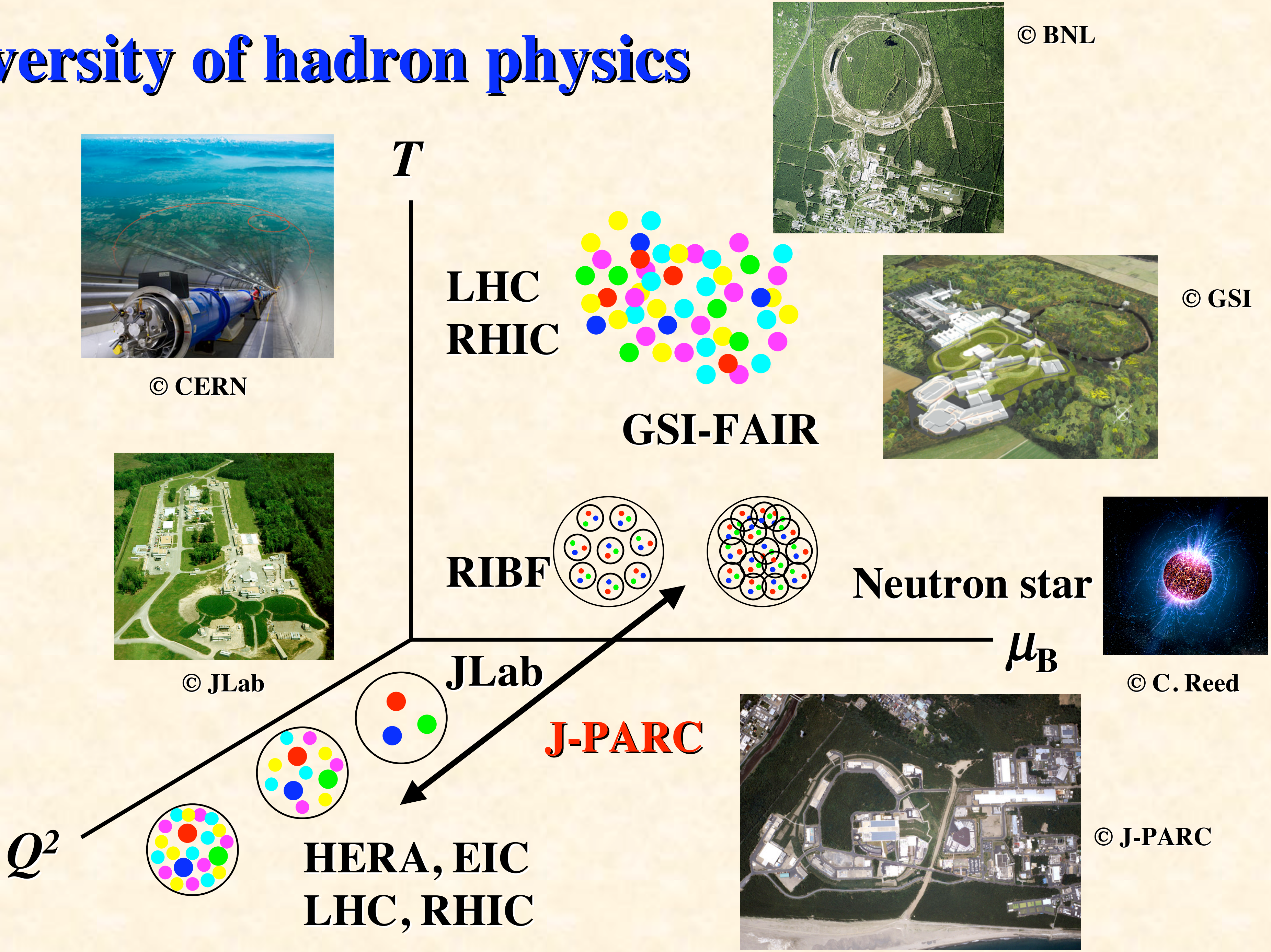
- Strangeness nuclear physics (1st experiment)
- Exotic hadrons
- Hadrons in nuclear medium
- Hard processes (→ 50 GeV)
- Nucleon spin (proton polarization)
- Quark-hadron matter (heavy ion?)

Hadron Physics at J-PARC

Note: **Hadron Physics**

≡ (narrow sense) Hadron Physics + Nuclear Physics
in my talk.

Diversity of hadron physics



J-PARCにおける高エネルギーハドロン物理の「Q & A(最後に)」

・AGSの残飯整理では？

・構造関数の物理はHERAで終わりでは？

・大きい$x_{Bjorken}$領域の小さい構造関数を測定して意味があるか？

・摂動論的QCDの補正が大きく、分布関数を取り出せないのでは？

・世界的な研究動向は？　世界の研究者が興味を持つか？

・次世代を担う研究者がいるか？　５－１０年後にユーザがいるか？

・ノーベル賞を取れる様な重要な成果を出せるのか？

・大強度ビームの特徴を生かしているのか？

・ハドロン実験が基本相互作用に関して何の貢献ができるのか？

現時点(30 GeV)で可能な
研究課題例

AGSの残飯整理では？

残飯整理 →（重要な）未解決問題の解決

AGSの測定結果で疑問視されているもの

・偏極*pp*弾性散乱の非対称度

・Color transparency

・・・

AGS以後に発展した課題の解明

・ハドロンのスピン構造

・一般化パートン分布

・短距離の核力

・パートンエネルギー損失

・・・

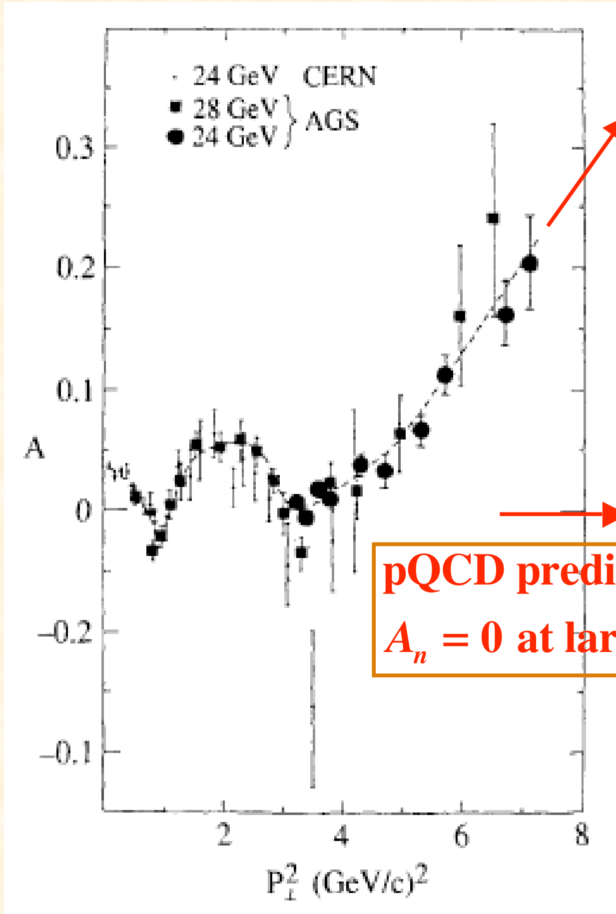
Spin asymmetry in pp elastic scattering

Single spin asymmetry in $p\vec{p}$ elastic: $A_n = \dfrac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$

J-PARC 30 GeV is the same as the AGS energy.
(The kinematical range is similar.)

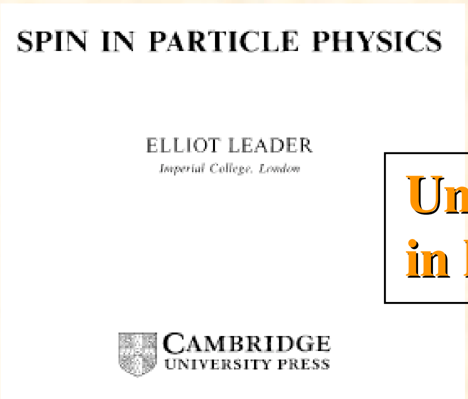
For a possible J-PARC experiment,

- **New observable should be investigated for providing a clue to pin down a possible mechanism of producing the asymmetry at large p_T.**



???

pQCD predictv
$A_n = 0$ at large p_T



Unsolved problem
in high-energy spin physics

From Spin in Particle Physics, E. Leader, Cambridge University press (2001);
D. G. Crabb et al., PRL65 (1990) 3241.

Color Transparency

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

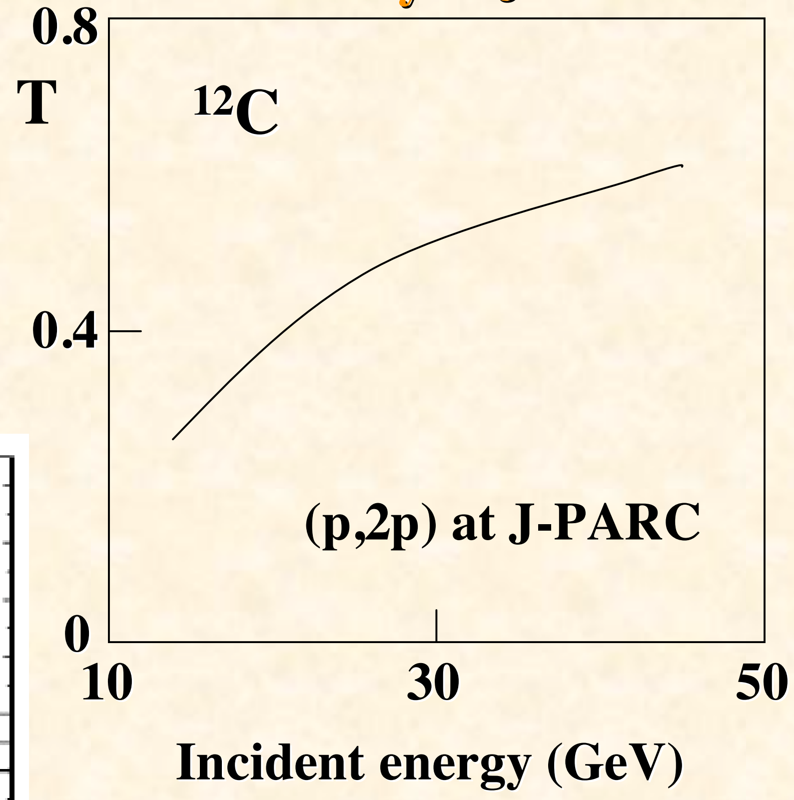
Investigate $pA \to pp(A\text{–}1)$

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

Color transparency:

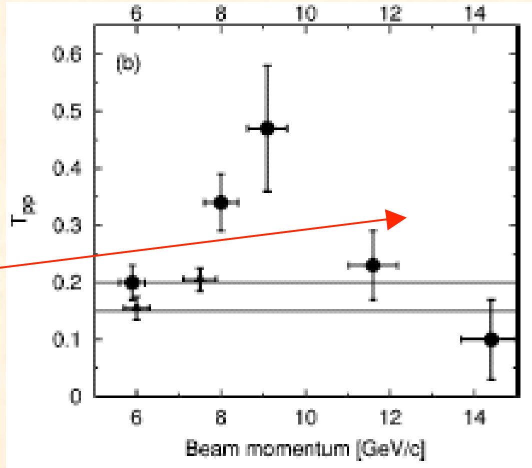
$T \to$ larger, as the hard scale $\to$ larger

Possibility at J-PARC



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

reason for this drop?

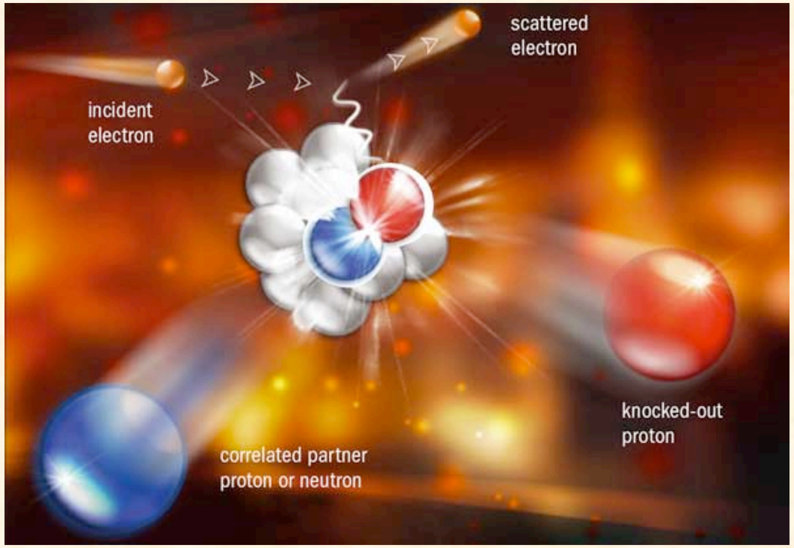


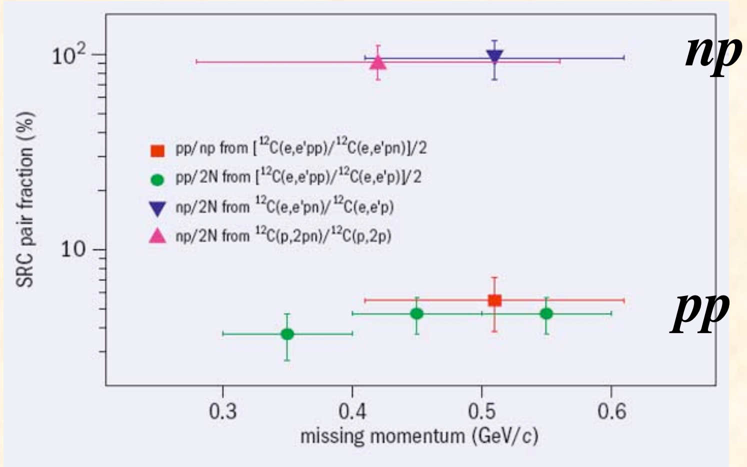
Short-range NN interaction

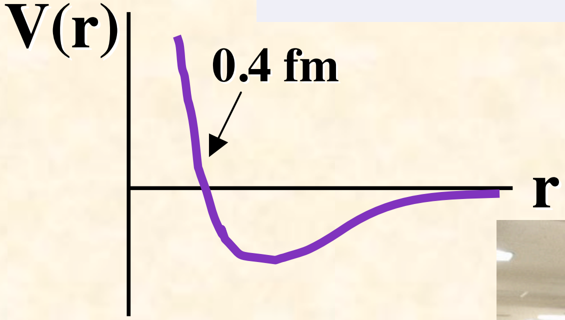
High-momentum $\frac{np}{pp} \simeq 20$!

E. Piasetzky *et al.*, PRL97 (2006) 162504

D. Higinbotham, E. Piasetzky, and M. Strikman
CERN Courier 49 (2009) 22.







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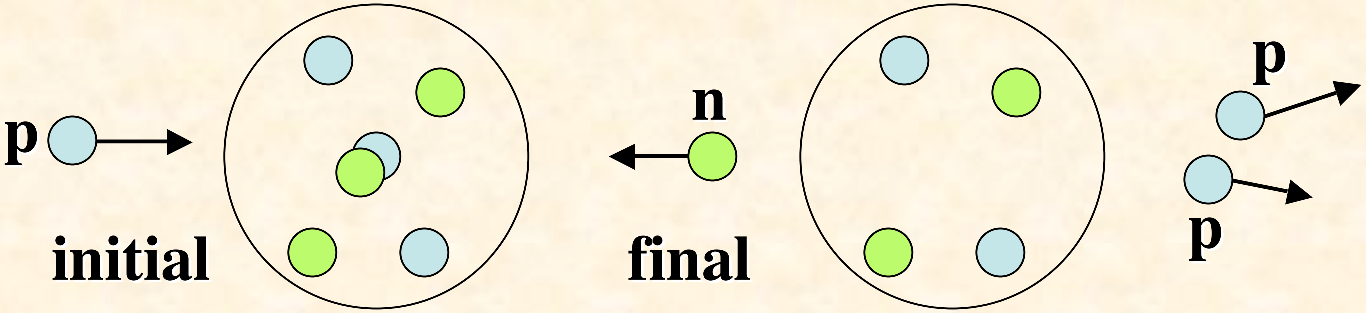
Nuclear force on lattice

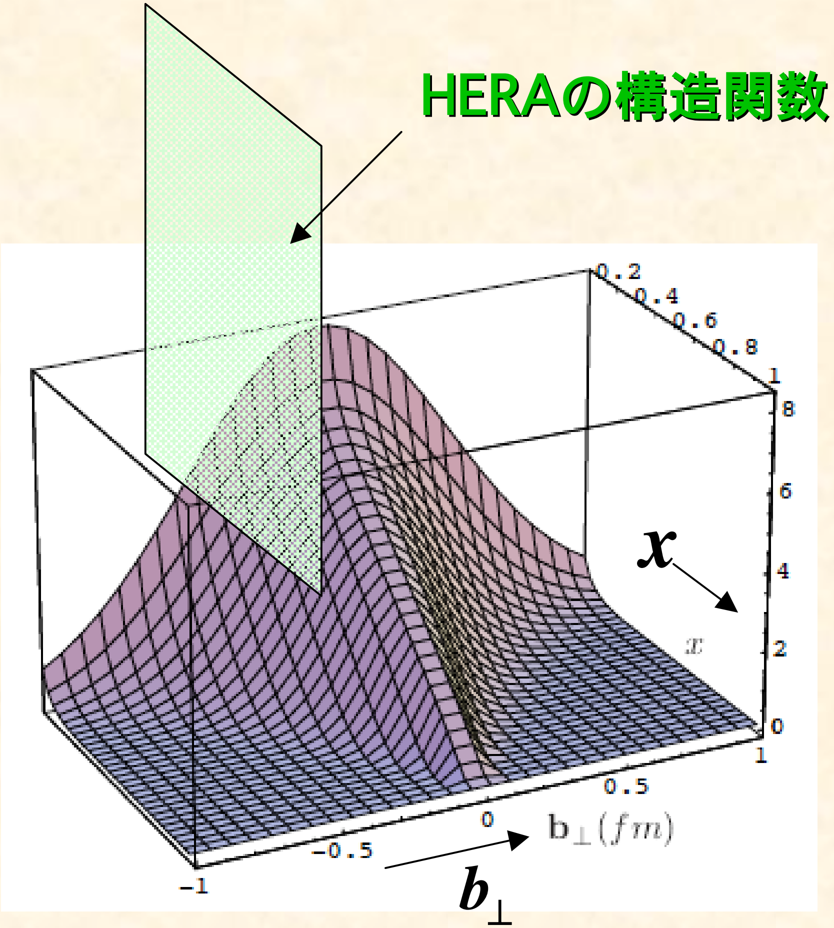
J-PARC: A(p, 2pN)X experiment for short-range correlation



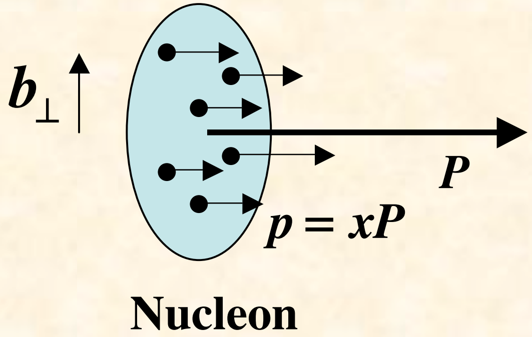
構造関数の物理はHERAで終わりでは？

GPDの定義は次のページ

3D picture of nucleon by Generalized Parton Distributions (GPDs)
(Nucleon tomography)



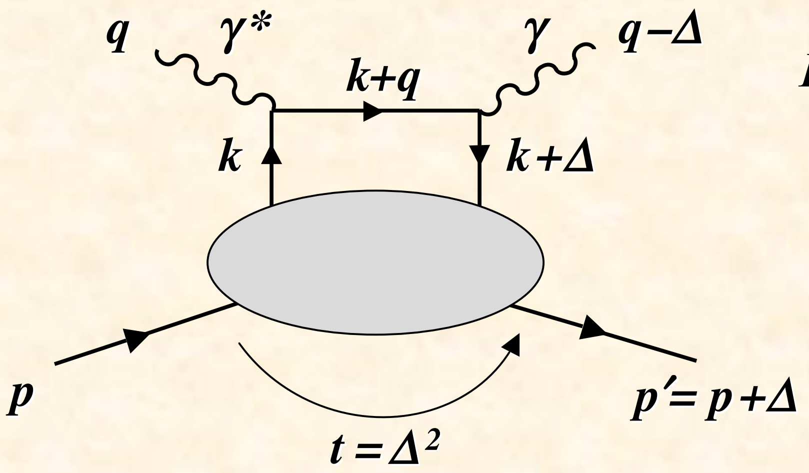
$$H(x,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} H(x,\xi=0,-\vec{\Delta}_\perp^2)$$



HERAの後に、なぜいまさらGPD？

- 核子スピン構造の起源解明
  （パートン軌道角運動量の寄与）
- 非摂動論的QCDの検証と確立
- 核子の３次元描像の確立

Generalized Parton Distributions (GPDs) at lepton facilities



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

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

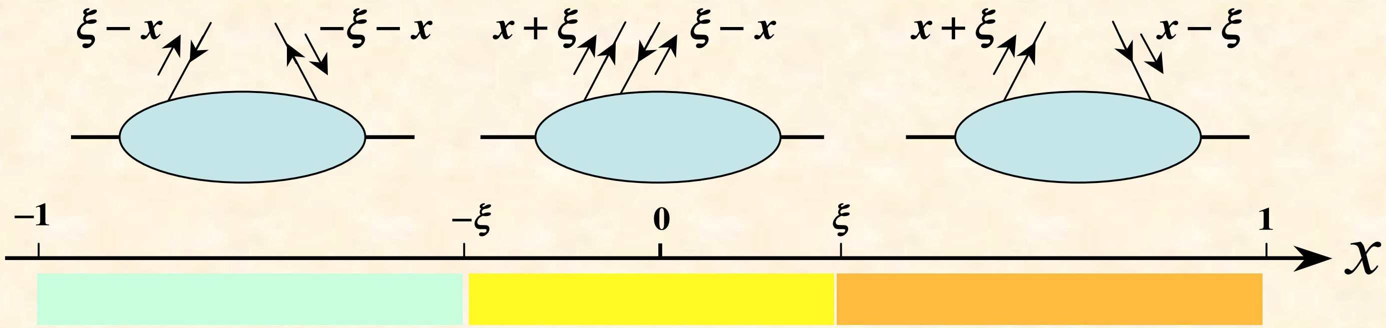
First moments: Form factors

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 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 $\xi-x$

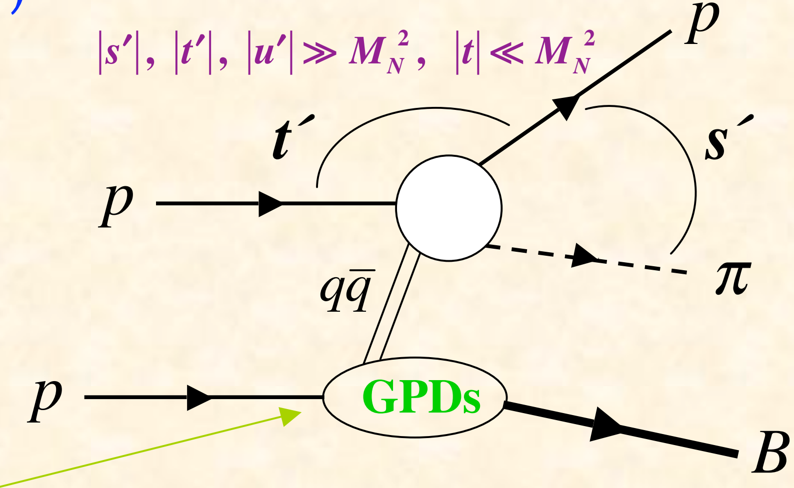
Antiquark distribution

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

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

Consider a hard reaction with

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



GPDs at J-PARC: PRD 80 (2009) 074003.

Efremov-Radyushkin -Brodsky-Lepage (ERBL) region

50 GeVが望ましい
研究課題例

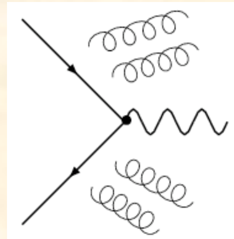
Applicability of perturbative QCD

Cross section = pQCD × non-pQCD (PDFs)

In order to extract the hadron-structure part, pQCD should be understood.

Large contributions come from the partonic threshold region

$$z = \frac{M_{\mu\mu}^2}{\hat{s}} \sim 1.$$



Soft-gluon resummation is needed.

Drell-Yan cross section

Ref. H. Shimizu *et al.*, PRD 71 (2005) 114007

$$\frac{\tau d\sigma}{d\tau d\phi} \sim \sum_{a,b} \int_\tau^1 \frac{dx_a}{x_a} \int_{\tau/x_a}^1 \frac{dx_b}{x_b} f_a(x_a,\mu^2) f_b(x_b,\mu^2) \omega_{ab}(z, M_{\mu\mu}^2/\mu^2, \alpha_s)$$

$$\tau = M_{\mu\mu}^2 / s, \quad z = \tau/(x_a x_b) = M_{\mu\mu}^2 / \hat{s}$$

$e.g.$ in transverse spin asymmetry

$$\omega_{ab}(z, M_{\mu\mu}^2/\mu^2, \alpha_s) = \omega_{q\bar{q}}^{(0)}(z) + \frac{\alpha_s}{\pi} \omega_{q\bar{q}}^{(1)}(z, M_{\mu\mu}^2/\mu^2) + \cdots$$

$$\omega_{q\bar{q}}^{(1)}(z, M_{\mu\mu}^2/\mu^2) = C_F \left[4z \left(\frac{\ln(1-z)}{1-z} \right)_+ + \cdots \right]$$

note: large contribution from the region $z \to 1$

Mellin transformation: $\int_0^1 dx\, x^{N-1} F(x)$

$$\frac{d\sigma^N}{d\phi} \sim \sum_f f^N(\mu^2) \bar{f}^N(\mu^2) \omega^N(M_{\mu\mu}^2/\mu^2, \alpha_s)$$

$$\omega_{q\bar{q}}^{(1)N}(M_{\mu\mu}^2/\mu^2) = C_F \left[2\ln^2(N e^{\gamma_E}) + \cdots \right]$$

A large term at $z \to 1$ corresponds to a large term in the Mellin space at $N \to \infty$.

fixed order →

resummation ↓

LO	1	
NLO	$\alpha_s L^2$	$\alpha_s L$
⋮	⋮	⋮
N[k]LO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$
	LL	NLL

$L \equiv \ln N$

Applicability of perturbative QCD in Drell-Yan

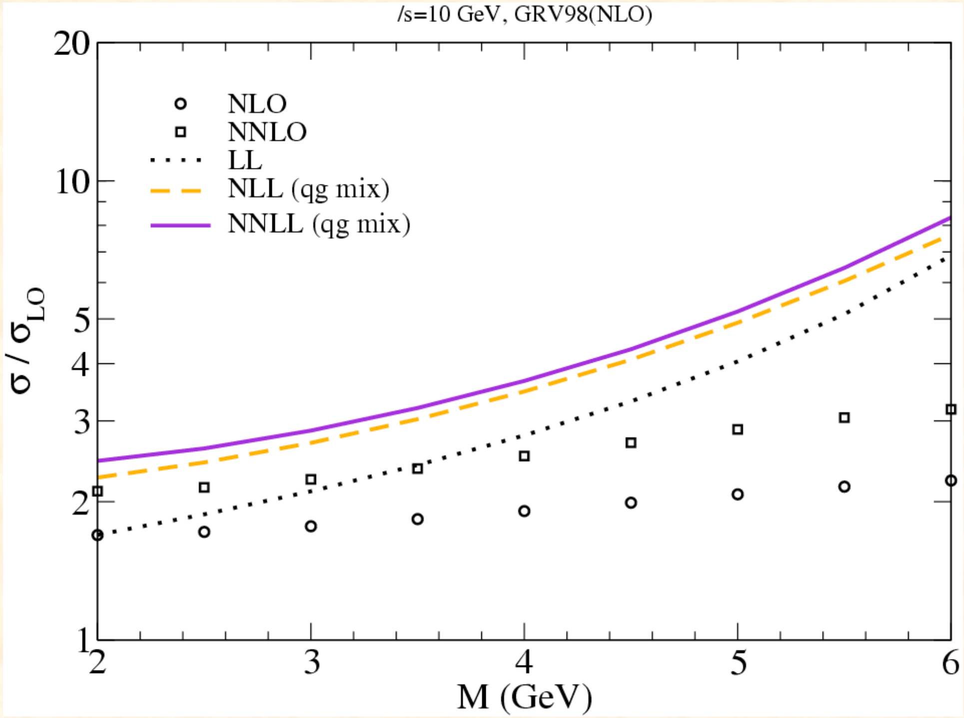
- Higher-order α_s corrections
- Resummations

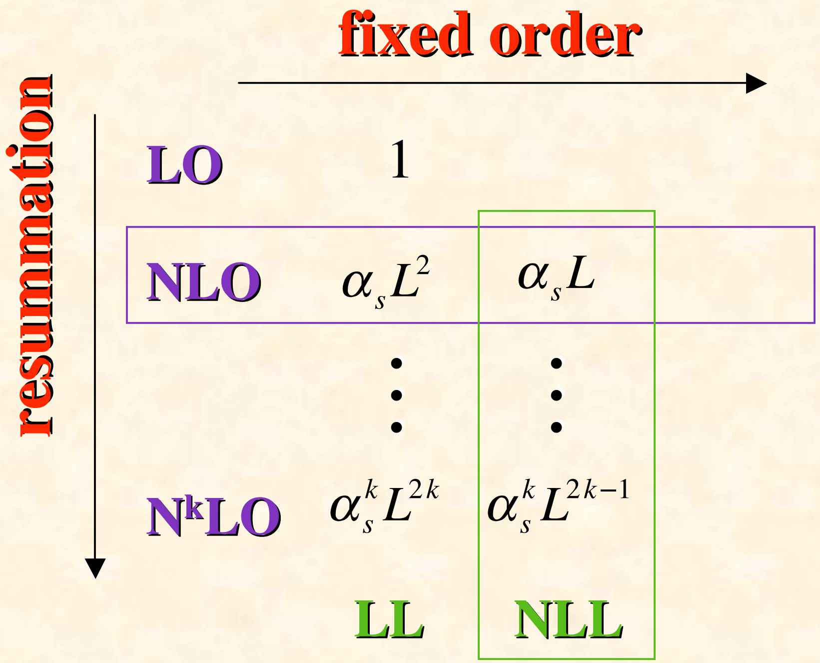
Yokoya@High-energy J-PARC
http://www-conf.kek.jp/hadron08/hehp-jparc/

H. Yokoya and W. Vogelsang,
AIP Conf. Proc. 915 (2007) 595.

pQCD corrections are shown by $\dfrac{\sigma}{\sigma_{\text{Leading Order (LO)}}}$

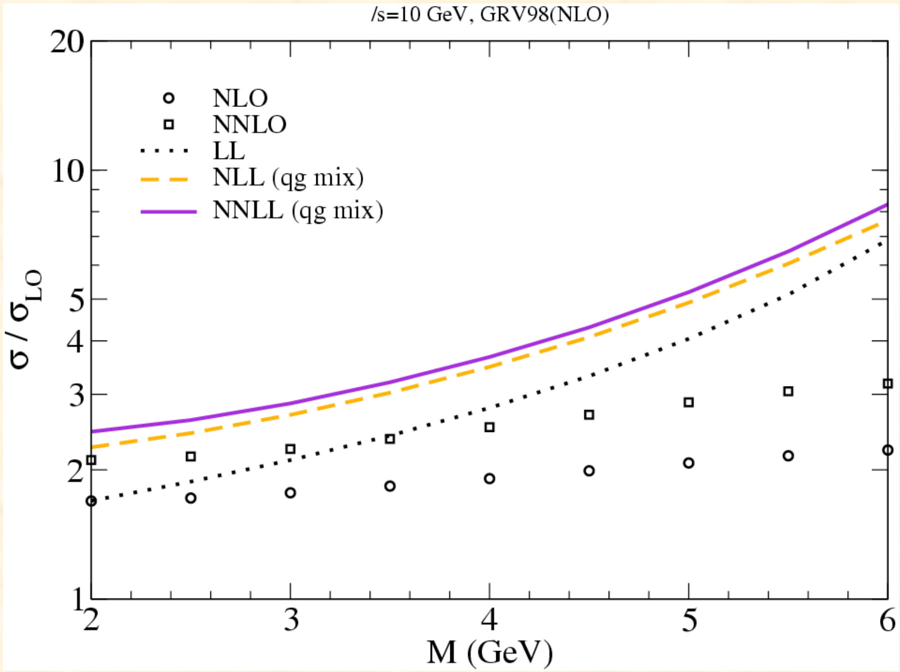
as a function of the dimuon mass $M_{\mu^+\mu^-}$.



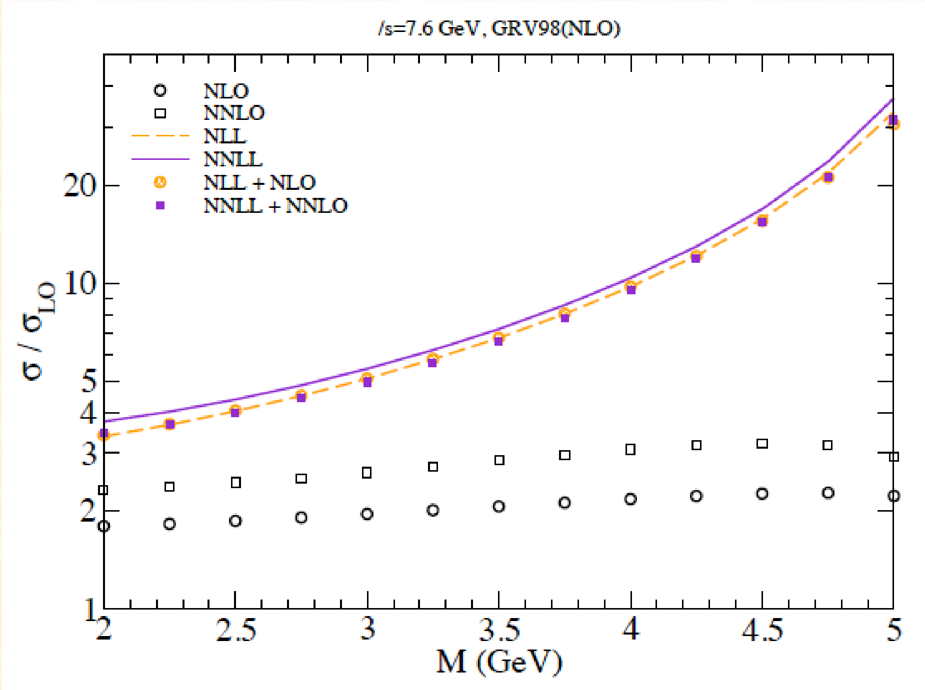


Higher-order corrections are large at J-PARC (50 GeV); however, the pQCD terms could be under control in Drell-Yan.

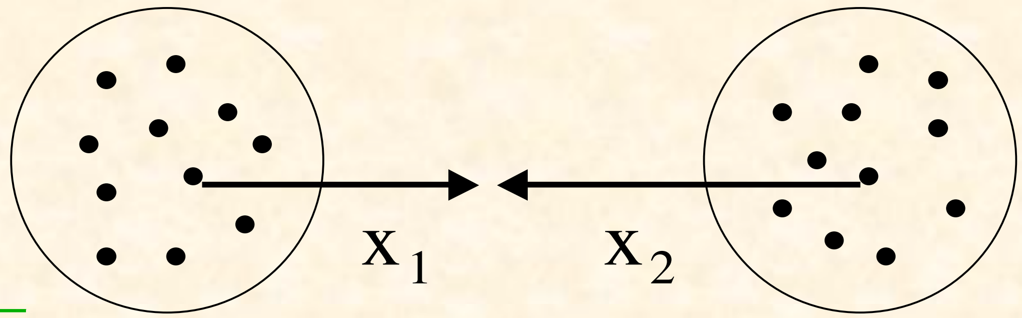
50-GeV beam



30-GeV beam



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

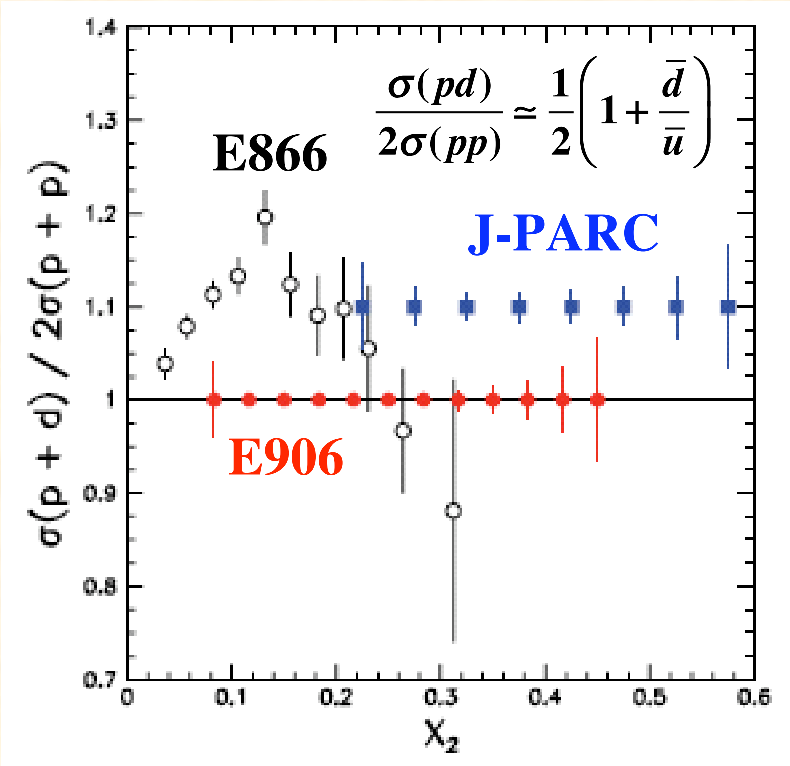
e.g. Quark spin content: $\Delta q = \int_0^1 dx \Delta q(x)$
= Integral from small *x* (RHIC)
to large *x* (J-PARC).

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

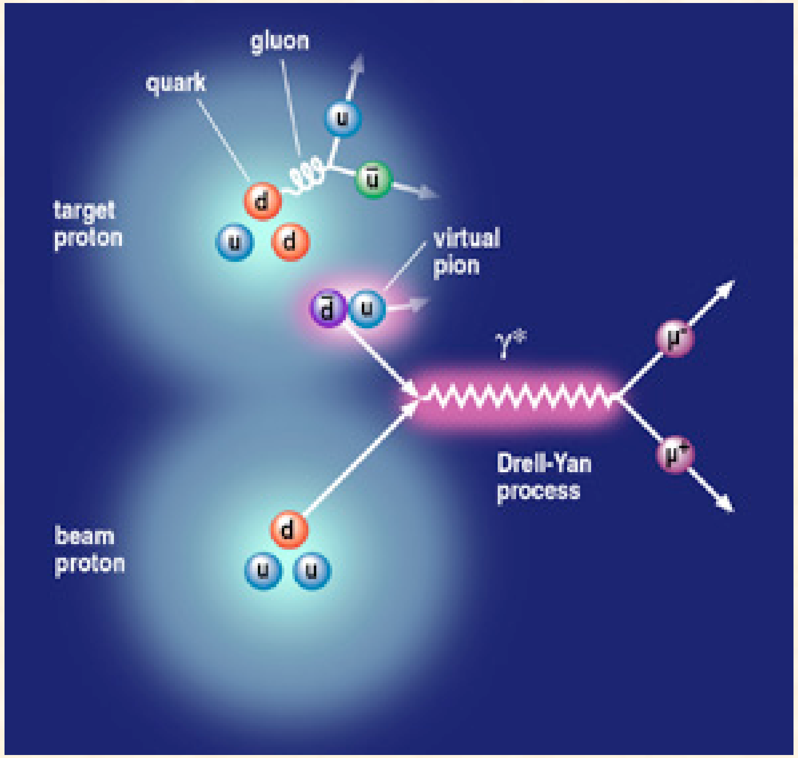
$\geq \frac{3}{200} = 0.02$ RHIC

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

Flavor asymmetric antiquark distributions: $\bar{u}$ / $\bar{d}$



J-PARC proposal, M. Bai *et al.* (2007)



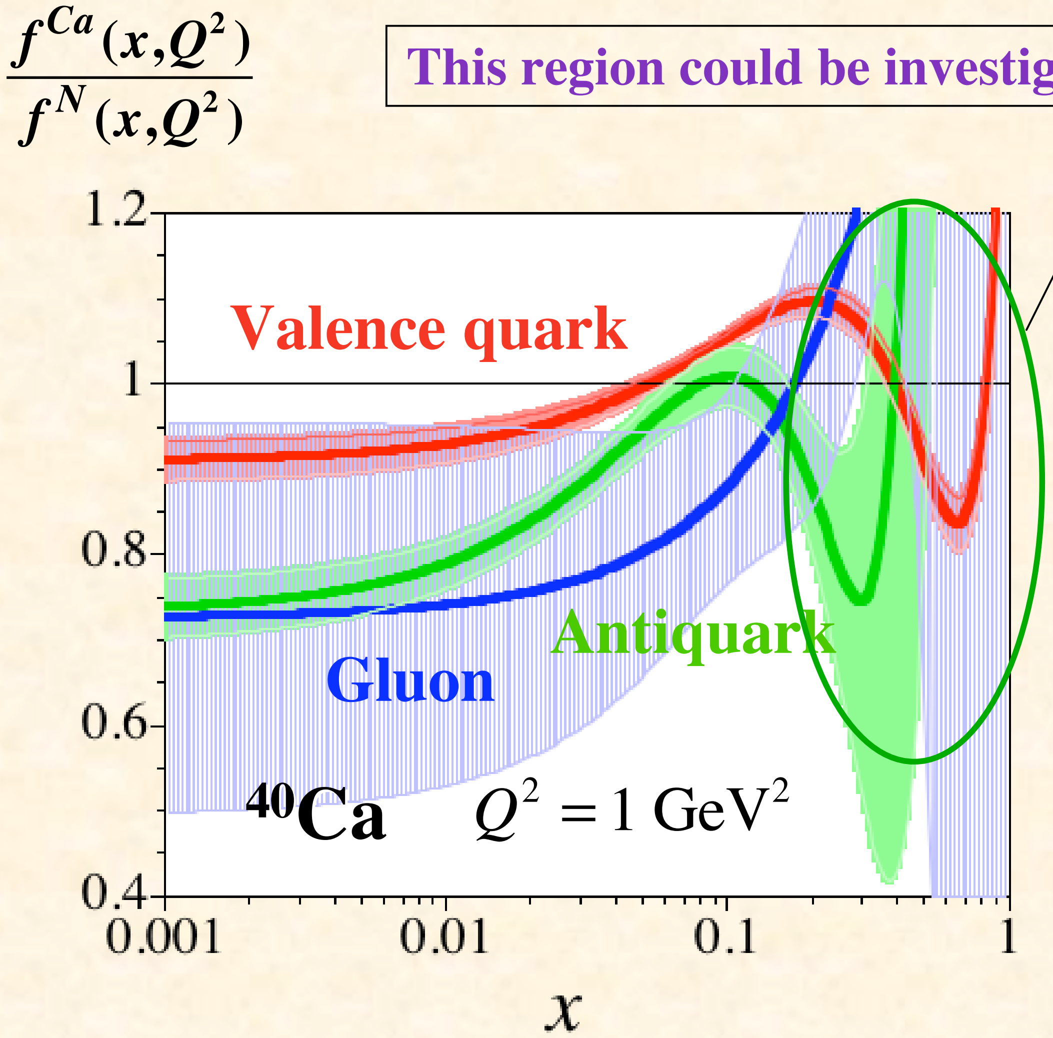
http://www.acuonline.edu/academics/cas/physics/research/e906.html

This project is suitable for probing "peripheral structure" of the nucleon.

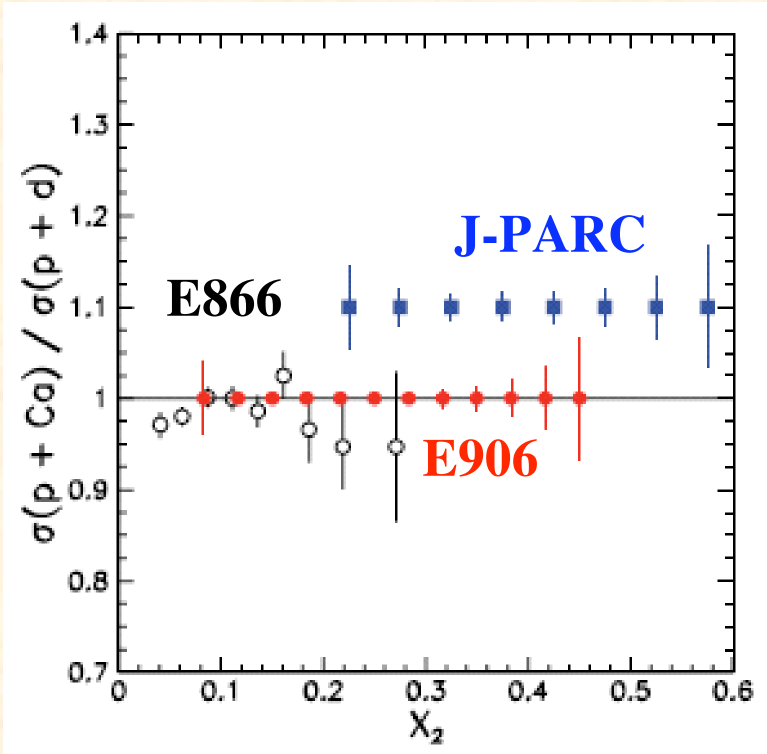
SK, Phys. Rep. 303 (1998) 183;
G. T. Garvey and J.-C. Peng, Prog. Part. Nucl. Phys. 47 (2001) 203.

Nuclear corrections on parton distribution functions

This region could be investigated by J-PARC.



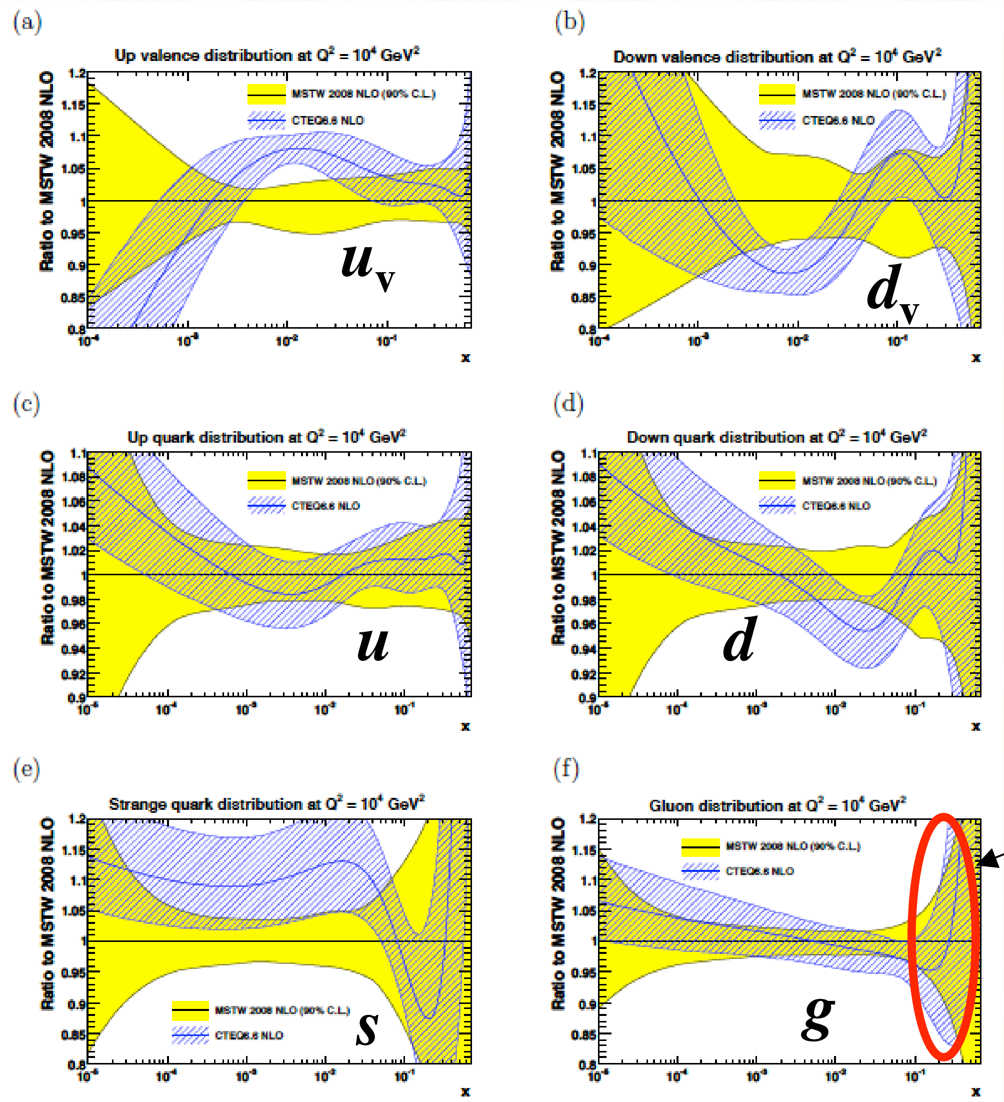
J-PARC proposal P04



Global NPDF analysis result

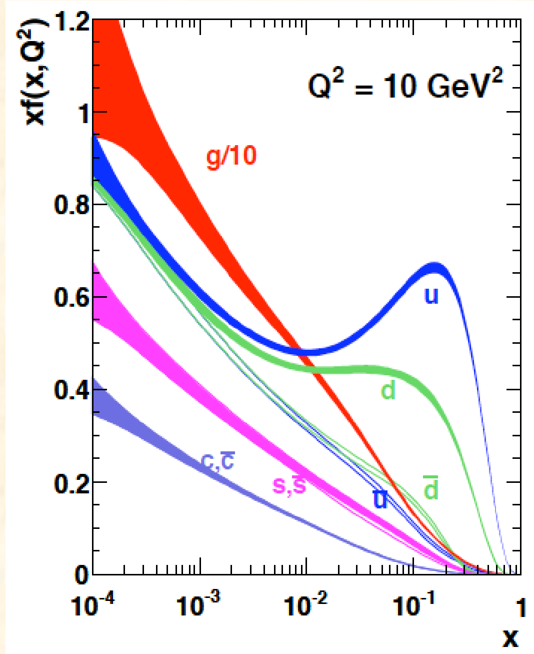
大きいx $_{\text{Bjorken}}$ 領域の小さい構造関数を測定して意味があるか？

PDF (parton distribution function) **uncertainty by MSTW-2009**



MSTW

CTEQ6.6



Important x region for finding an “exotic event” in a high-p_T region at LHC.

J-PARC x region

Quark substructure?

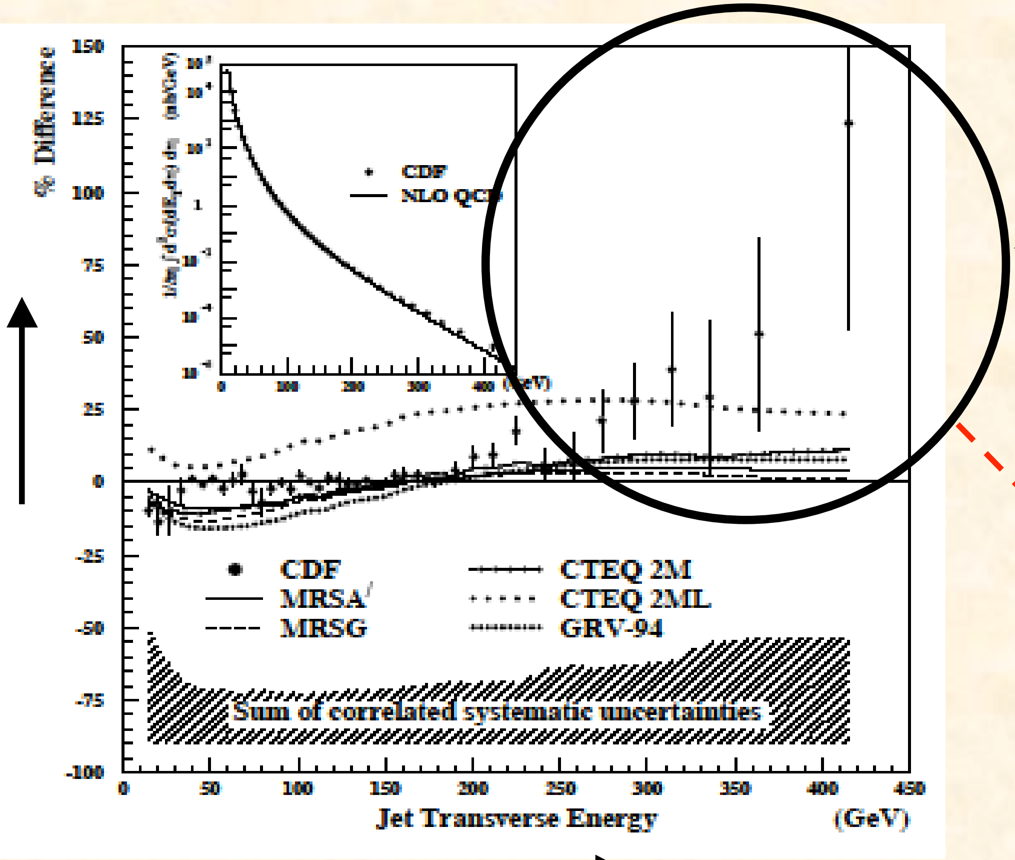
CDF experiment: PRL, 77 (1996) 438.

Comparison of theoretical calculations with CDF experimental data.

$$p + \bar{p} \rightarrow jet + X$$

$$\sqrt{s} = 1.8 \text{ TeV}, \quad E_T^{jet} = 15 - 400 \text{ GeV}$$

Difference between theory and experiment



Jet transverse energy

Subquark signature ???

The same thing could happen at LHC.

Could be explained without substructure

(importance of accurate PDFs)

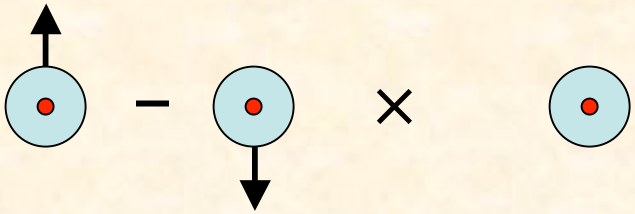
Single spin asymmetry

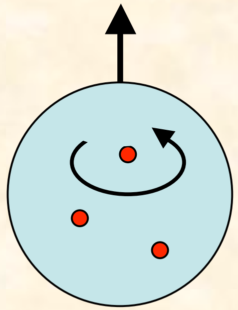
(No polarized proton beam is needed!)

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Sivers effect

$A_N \sim f_{1T}^{\perp} \cdot D_1$ (Sivers function × Unpolarized fragmentation)





The Sivers function describes unpolarized quark in the transversely polarized nucleon.

Probe of angular momentum

- Collins effect

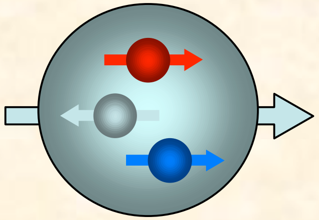
$A_N \sim \delta_T q \cdot H_1^{\perp}$ (Transversity × Collins fragmentation function)

The transversity distribution describes transverse quark polarization in the transversely polarized nucleon.

The Collins fragmentation function describes a fragmentation of polarized quark into unpolarized hadron.

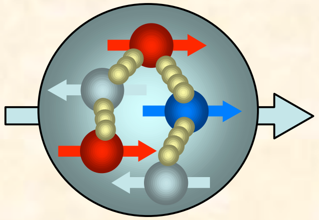
- Higher-twist

Nucleon spin

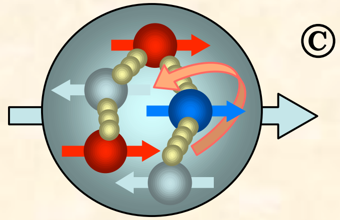


Naïve Quark Model

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



Sea-quarks and gluons?



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Orbital angular momenta ?

Recent data indicate
ΔG is small at $x \sim 0.1$.

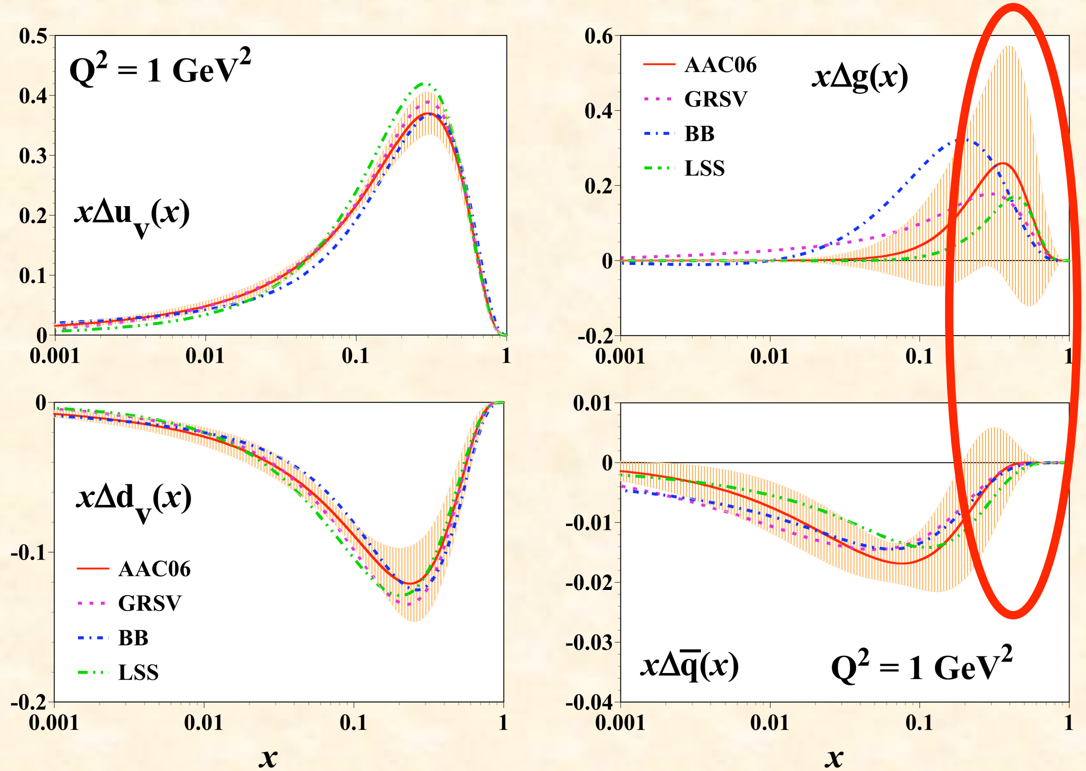
Electron / muon scattering

$\Delta\Sigma \approx 0.2 \sim 0.3$

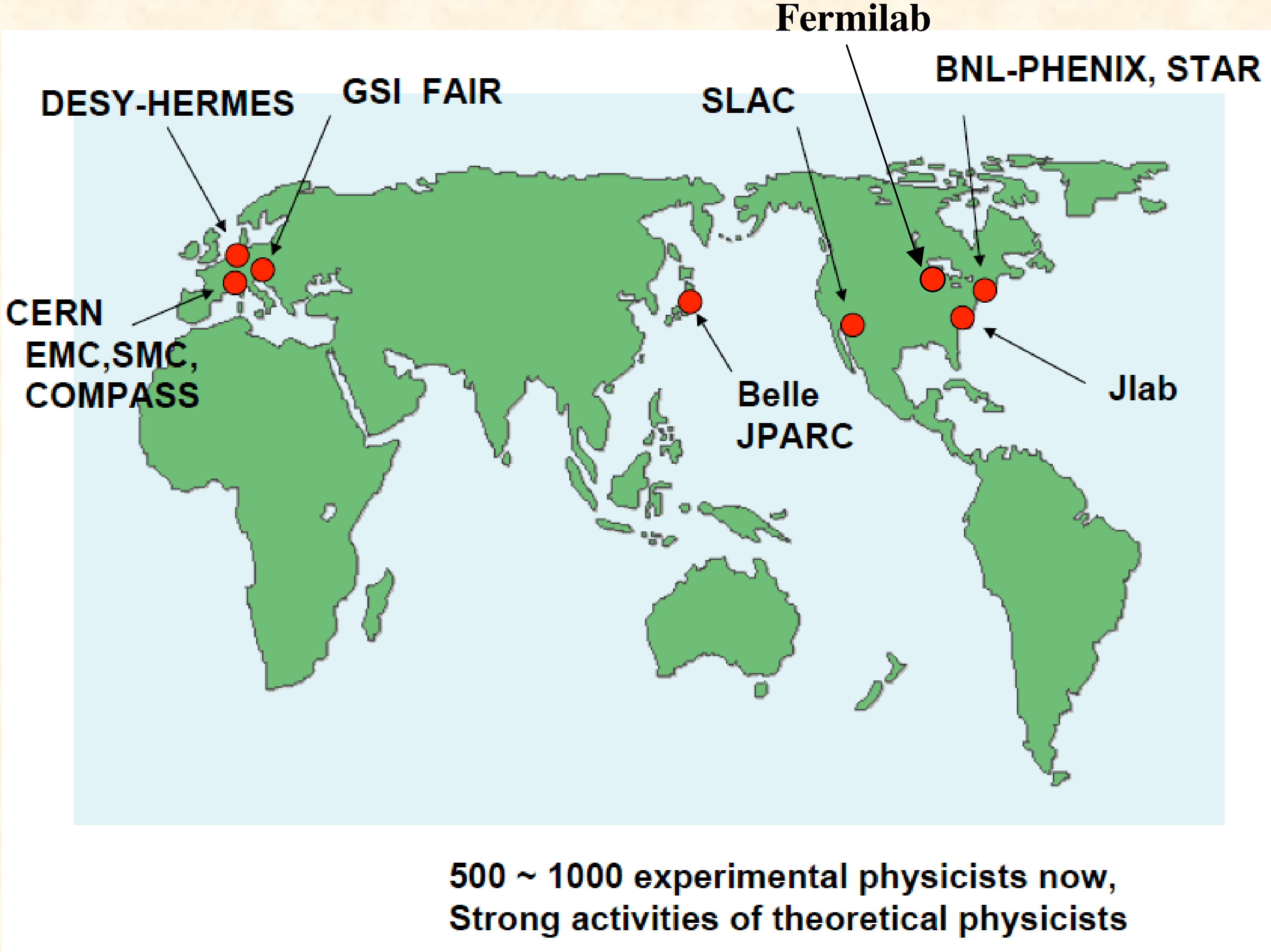
Almost none of nucleon spin is carried by quarks!

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

J-PARC



・世界的な研究動向は？　世界の研究者が興味を持つか？
・次世代を担う研究者がいるか？　５－１０年後にユーザがいるか？



(T.-A. Shibata at the KEK workshop, 2010-01)

まとめ

Hadron physics with 30 – 50 GeV proton beam

現時点(30 GeV)で可能なプロジェクト

- Spin physics in elastic *pp* reaction
- Hadron interactions in nuclear medium
- Short-range *NN* interactions
- J/ψ, charm physics
- Generalized parton distributions
- Drell-Yan? …

50 GeV の陽子ビーム

- Drell-Yan
- Single spin asymmetries
- Spin structure of spin-1 hadrons
- …

50 GeV の偏極陽子ビーム

- Drell-Yan: Double asymmetries (Polarized PDFs)
- Complimentary to RHIC-Spin (large-*x* physics)
- …

J-PARCにおける高エネルギーハドロン物理の「Q＆A」

・AGSの残飯整理では？
  重要な未解決問題あり。AGS以後に発展した課題あり。
・構造関数の物理はHERAで終わりでは？
  核子スピンの起源は不明。核子の３次元描像(GPDs)の研究は始まったばかり。
・大きいｘ$_{\mathrm{Bjorken}}$領域の小さい構造関数を測定して意味があるか？
  スピンの総和（ｘの積分）、ハドロン模型の検証、LHCでの新発見の基礎
・摂動論的QCDの補正が大きく、分布関数を取り出せないのでは？
  グルーオンの再足し上げの研究が進み、Drell-Yanは理解可能。
・世界的な研究動向は？　世界の研究者が興味を持つか？
  RHIC, Fermilab, CERN-COMPASS, JLab, GSI-FAIR, EIC, …
・次世代を担う研究者がいるのか？　５－10年後にユーザがいるか？
  RHIC, HERMES, COMPASS, Fermilabで活躍中の多数の日本人研究者あり。
  RHIC等の実験に関連して活躍中のハドロン理論家が多数あり。
・ノーベル賞を取れる様な重要な成果を出せるのか？
  確実に（また重要な）成果は出せるが、ノーベル賞までには至らないのでは？
  しかし、ノーベル賞に値する新発見のための基礎データは提供可能
・大強度ビームの特徴を生かしているのか？
  小さい断面積まで測定できる。→ 運動学的領域を広げた測定が可能
・ハドロン実験が基本相互作用に関して何の貢献ができるのか？
  QCDの非摂動的側面（カラーの閉じ込め等）に貢献、
  ハドロン物理学は究極物質の構造と性質を研究する分野

“Null experiments” でノーベル賞を
狙うのは良いけれど...

30-50 GeVの陽子ビームがある以上、
着実に成果を出せるプロジェクトを
推進しては？

The End

The End