Study of 3D nucleon structure at the J-PARC π20 beamline

3D Hadron Structure from Next-Generation Scattering Experiment and Lattice QCD

The 2023 Fall meeting of the Division of Nuclear Physics of the American Physics Society and the Physical Society of Japan (HAWAII2023)
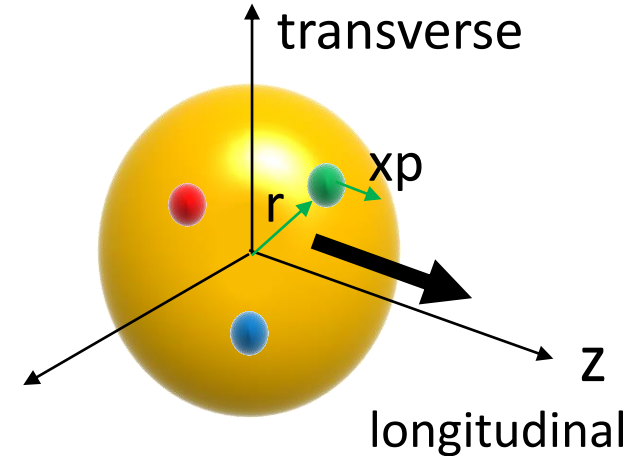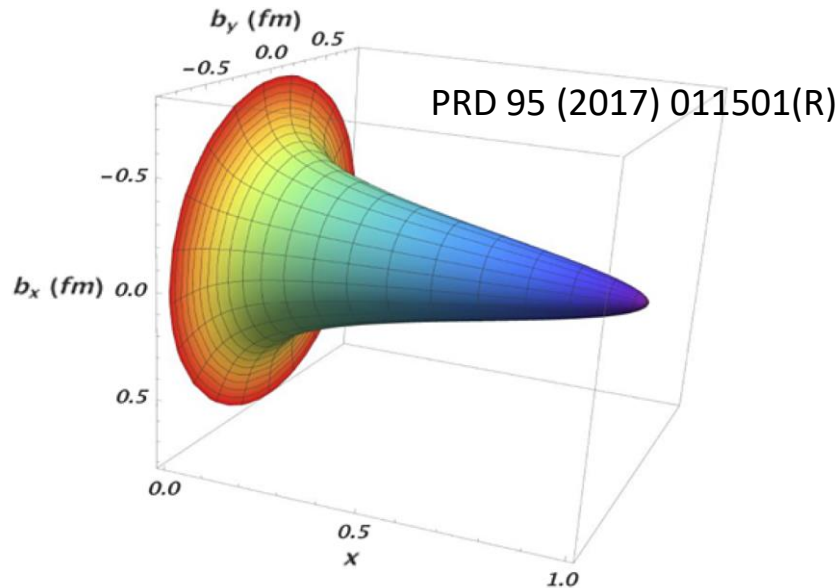
Hilton Waikoloa Village, Hawaii, the USA
2023/Nov/26-Dec/1

Natsuki TOMIDA
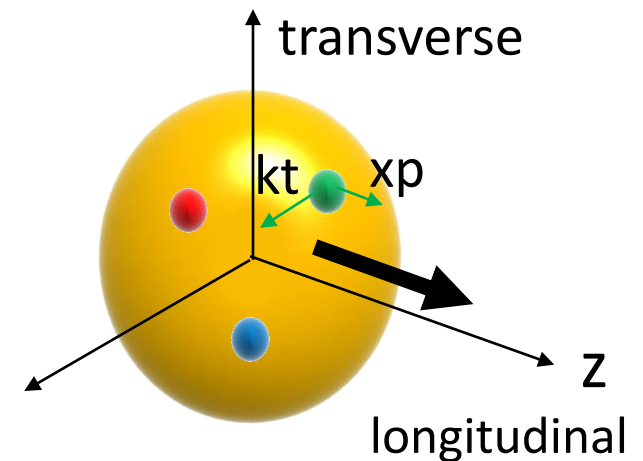Kyoto University

Nucleon 3D structure

Generalized Parton Distributions (GPDs)

- Transverse position &
  longitudinal momentum of partons

PRD 95 (2017) 011501(R)

transverse

xp

r

z

longitudinal

Transverse Momentum Dependent
Parton Distributions (TMDs)

- Transverse momentum &
  longitudinal momentum of partons

transverse

kt   xp

z

longitudinal
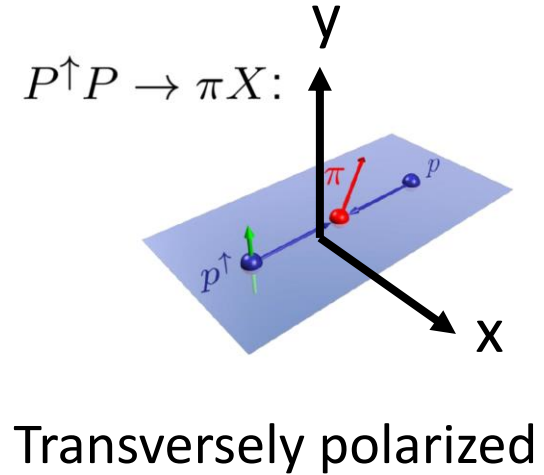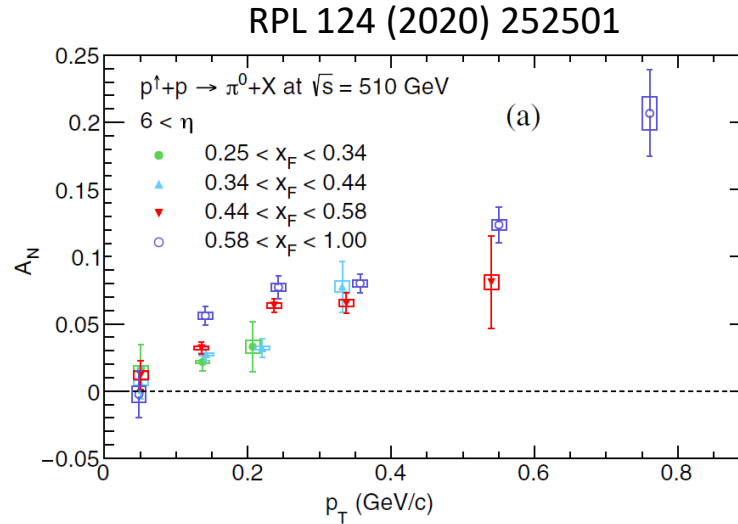
Transverse Momentum Dependent Parton Distributions (TMDs)

Single spin asymmetry

$$A_N = \frac{d\sigma_{left} - d\sigma_{right}}{d\sigma_{left} + d\sigma_{right}}$$

RPL 124 (2020) 252501

$p^\uparrow + p \rightarrow \pi^0 + X$ at $\sqrt{s}$ = 510 GeV
$6 < \eta$

- $0.25 < x_F < 0.34$
- $0.34 < x_F < 0.44$
- $0.44 < x_F < 0.58$
- $0.58 < x_F < 1.00$

$P^\uparrow P \rightarrow \pi X$:

Transversely polarized

https://www.int.washington.edu/PROGRAMS/17-3/

$x f_1(x, k_T, S_T)$
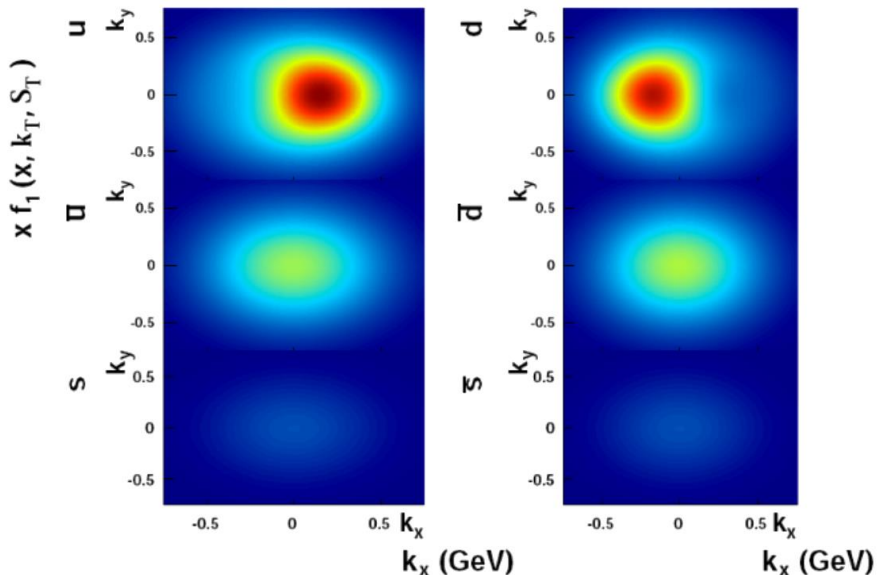
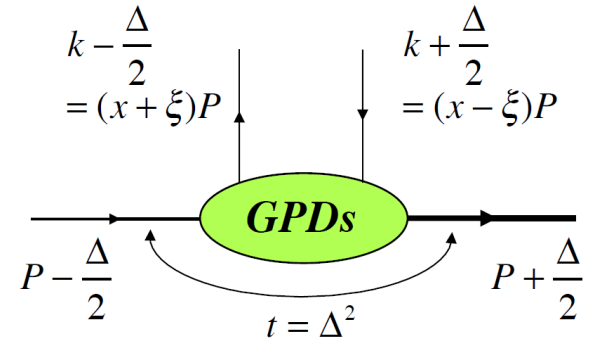Asymmetric quark momentum distributions

Described with TMDs

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Generalized Parton Distributions

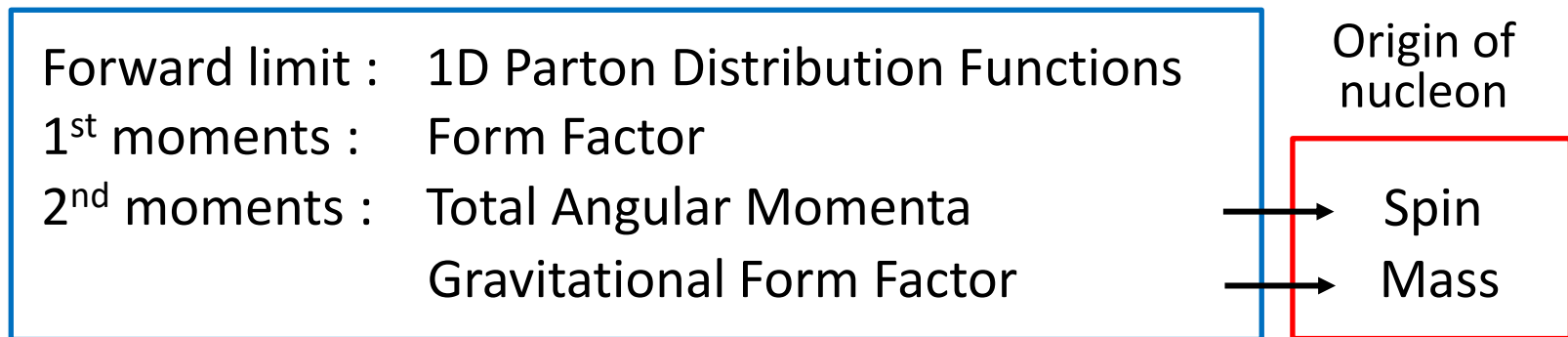$$\int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle p'|\bar{q}(-y/2)\gamma^+ q(y/2)|p\rangle_{y^+=\vec{y}_\perp=0}$$
$$= \frac{1}{2P^+}\bar{u}(p')\left[H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t)\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N}\right]u(p),$$

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

$k-\frac{\Delta}{2}$
$= (x+\xi)P$

$k+\frac{\Delta}{2}$
$= (x-\xi)P$

GPDs

$P-\frac{\Delta}{2}$

$t = \Delta^2$

$P+\frac{\Delta}{2}$

GPDs
- x : Bjorken variable
- ξ : Skewness
- t : Momentum transfer

average quark momentum fraction

transferred quark momentum fraction

Forward limit : 1D Parton Distribution Functions
1st moments :   Form Factor
2nd moments :   Total Angular Momenta
                Gravitational Form Factor

Origin of nucleon

Spin

Mass

Global analysis

Measurement in different reactions and in different kinematics is important

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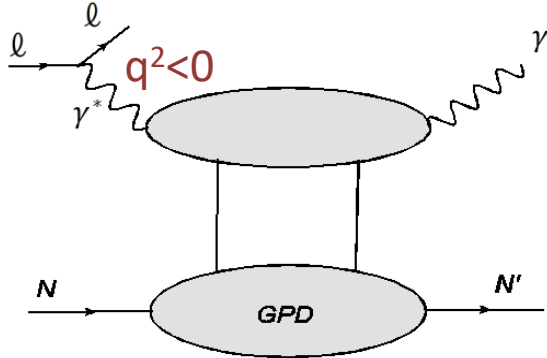# Future activities for probing 3D nucleon structure

EIC

AMBER

Apparatus for Meson and Baryon Experimental Research

SoLID

J-PARC
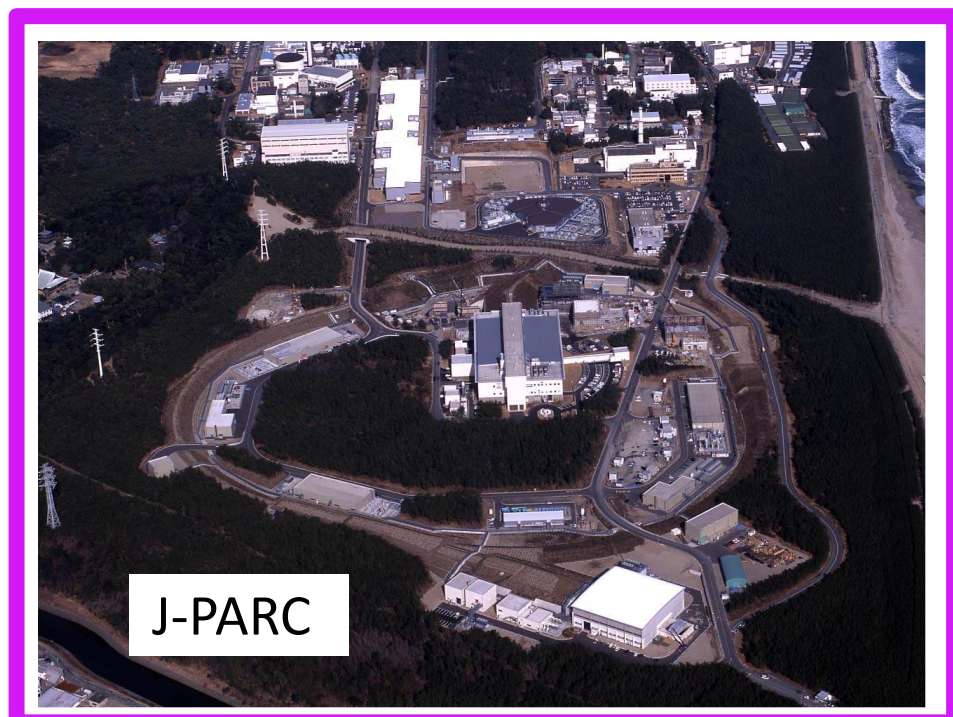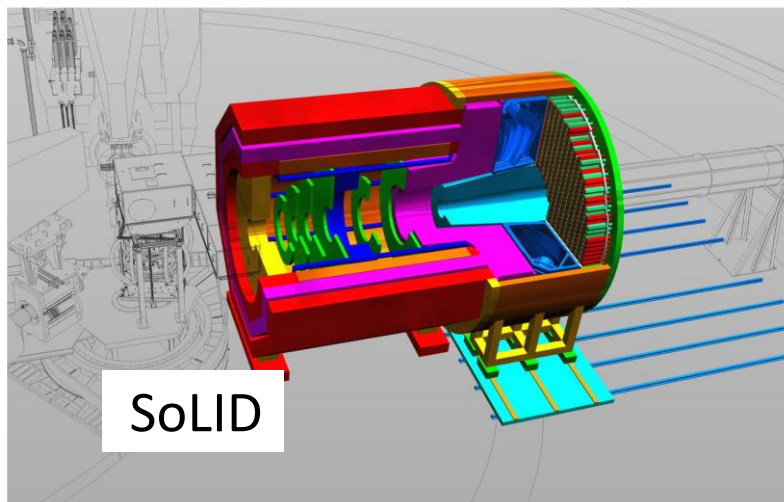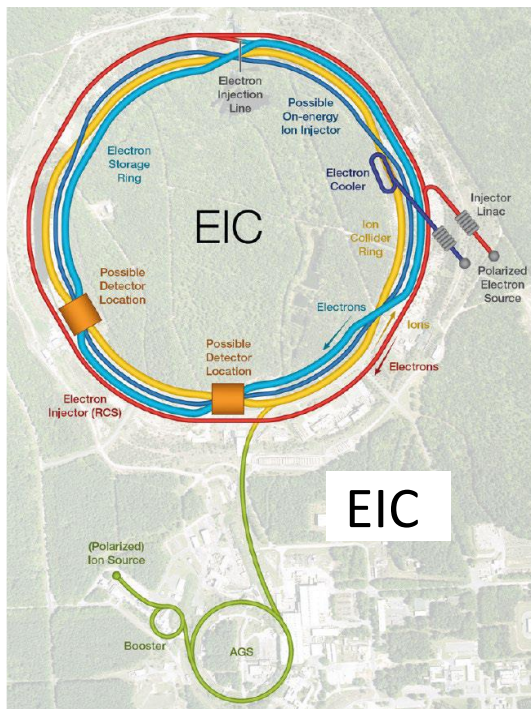
Reactions for GPDs measurements

Space-like

PRD 86 031502(R) (2012)

Time-like

Deeply Virtual Compton Scattering (DVCS)

$q^2<0$

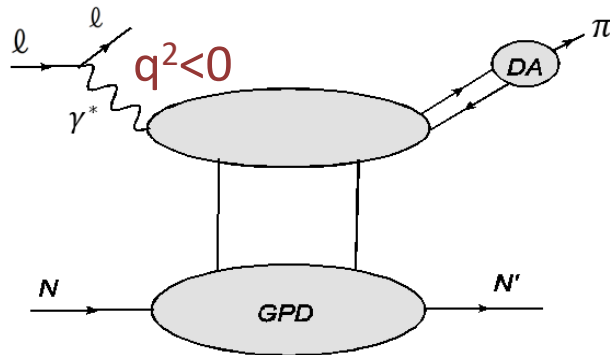**Time-like Compton Scattering (TCS)**

$q^2>0$
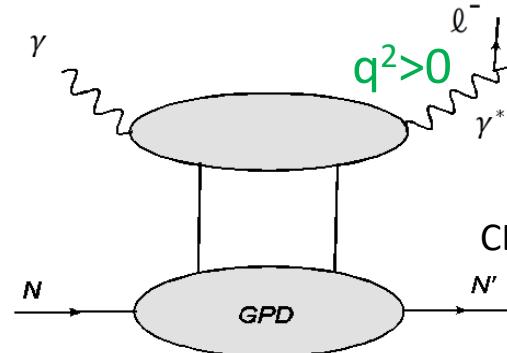
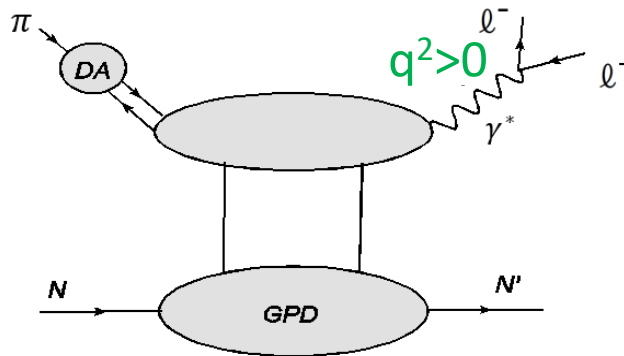1st measurement reported in 2021

CLAS, PRL 127 (2021) 262501

Deeply Virtual Meson Production (DVMP)

$q^2<0$

Exclusive meson-induced DY

$q^2>0$

Factorization proved

Not proved

First measurement of exclusive DY at J-PARC

p + p → N + π + B

Novel two-to-three hard hadronic processes and possible studies of generalized parton distributions at hadron facilities

S. Kumano,[1,2] M. Strikman,[3] and K. Sudoh[1,4]

$$p + p \rightarrow p + \pi^+ + \Delta^0$$

$$p + p \rightarrow p + \pi^- + \Delta^{++}$$

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

$$\frac{d\sigma_{NN \rightarrow N\pi B}}{dt\,dt'} = \int_{y_{min}}^{y_{max}} dy \frac{s}{16(2\pi)^2 m_N p_N} \sqrt{\frac{(ys - t - m_N^2)^2 - 4m_N^2 t}{(s - 2m_N^2)^2 - 4m_N^4}} \frac{d\sigma_{MN \rightarrow \pi N}(s' = ys, t')}{dt'} \sum_{\lambda_a, \lambda_e} \frac{1}{[\phi_M(z)]^2} |\mathcal{M}_{N \rightarrow B}|^2,$$

$$\sum_{\lambda_N, \lambda_{N'}} |\mathcal{M}_N^V|^2 = I_N^2 \left[8(1 - \xi^2)\{H(x, \xi, t)\}^2 \right.$$

$$+ 16\xi^2 H(x, \xi, t) E(x, \xi, t)$$

$$\left. - \frac{t}{m_N^2}(1 + \xi)^2 \{E(x, \xi, t)\}^2 \right].$$

$$\sum_{\lambda_N, \lambda_{N'}} |\mathcal{M}_N^A|^2 = I_N^2 \left[8(1 - \xi^2)\{\tilde{H}(x, \xi, t)\}^2 \right.$$

$$+ 18\xi^2 \tilde{H}(x, \xi, t) \tilde{E}(x, \xi, t)$$

$$\left. - \frac{2t\xi^2}{m_N^2} \{\tilde{E}(x, \xi, t)\}^2 \right].$$

GPDs

- Novel idea to measure GPDs with hadron reactions

- Large cross section!

p + p → N + π + B

Novel two-to-three hard hadronic processes and possible studies of generalized parton distributions at hadron facilities

S. Kumano,[1,2] M. Strikman,[3] and K. Sudoh[1,4]

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

$$-\xi < x < \xi \quad (x+\xi > 0, x-\xi < 0)$$
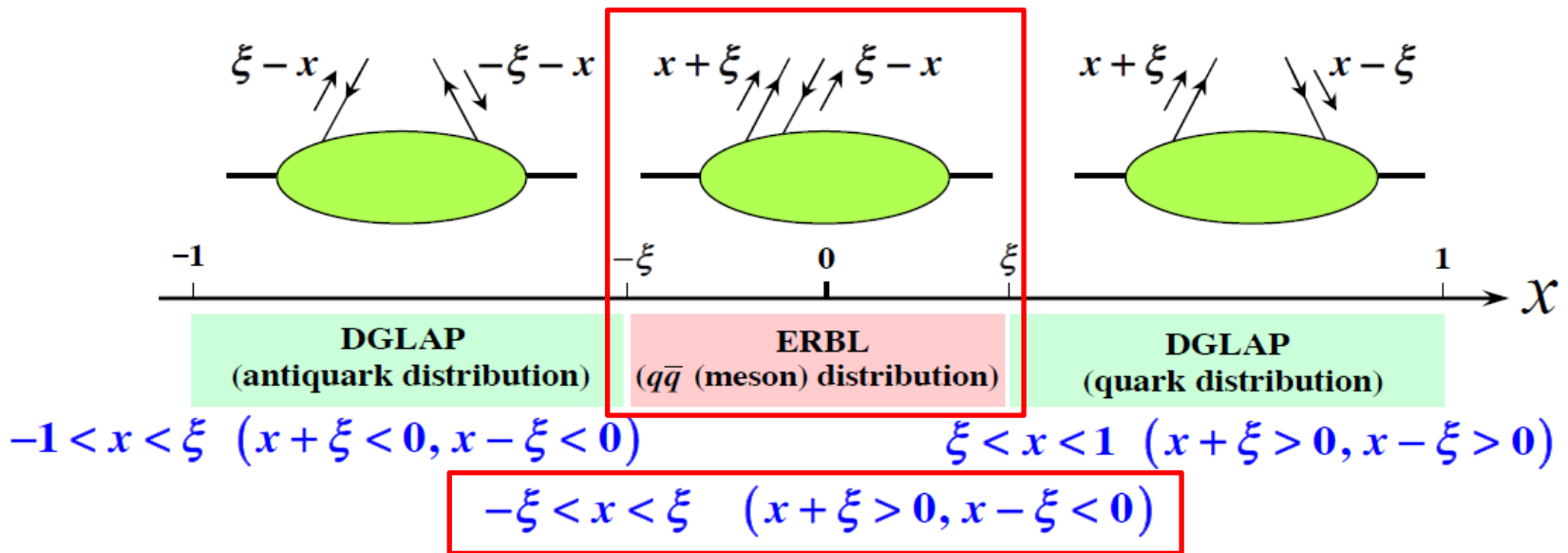
- Access to Efremov-Radyushkin-Brodsky-Lepage (ERBL) region which cannot be accessed with DIS reactions

J-PARC
Japan Proton Accelerator Research Complex (in Tokai)

T2K
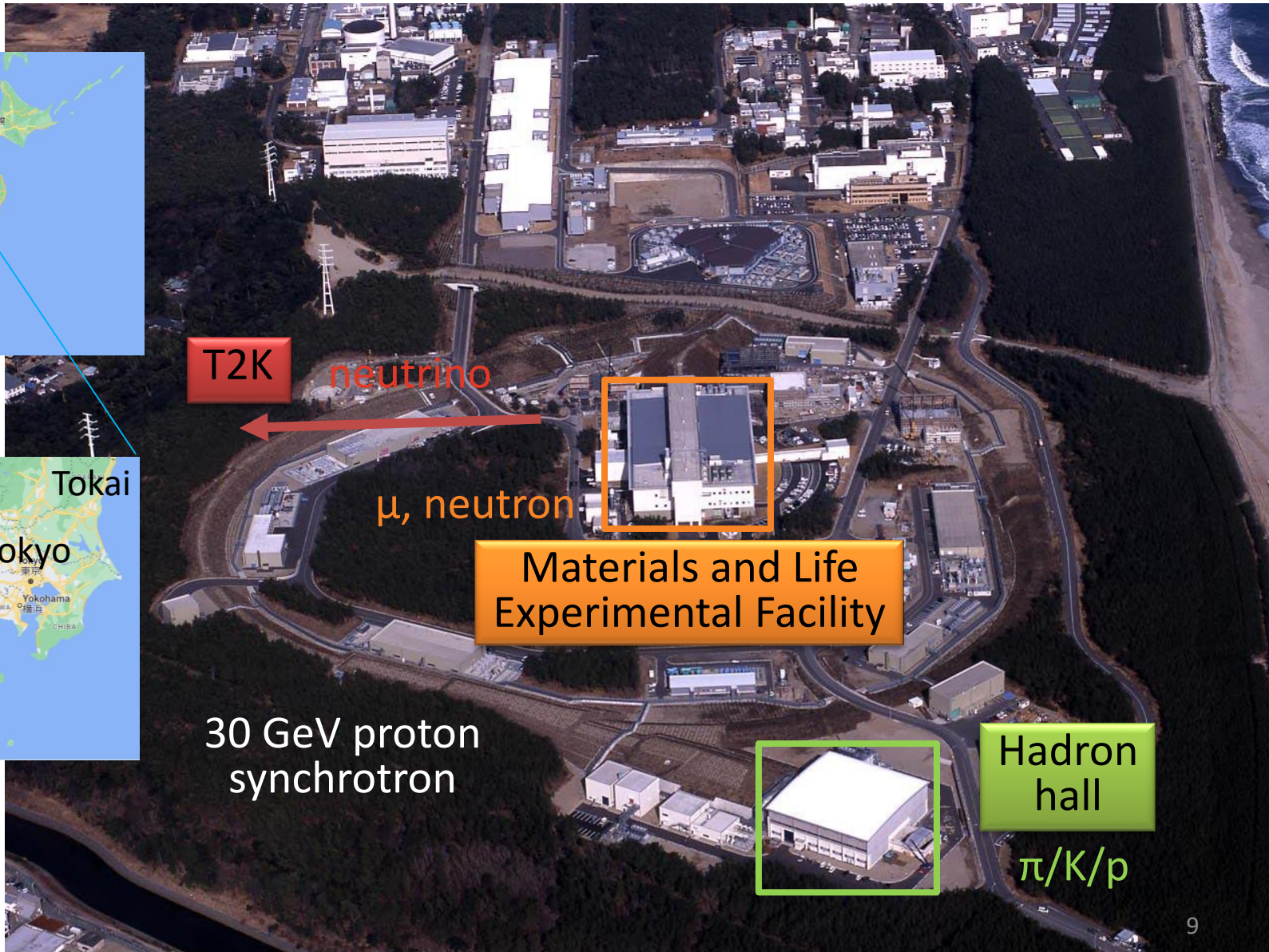
neutrino

μ, neutron

Materials and Life Experimental Facility

30 GeV proton synchrotron

Tokai

Tokyo

Hadron hall

π/K/p

High momentum beam is now available at J-PARC !

J-PARC Main Ring

target for π20 beamline

Switch Yard
Branching Point

Hadron Experimental Facility

π/K p<2 GeV/c

High momentum beam line

0 10 20 30 40 50 (m)
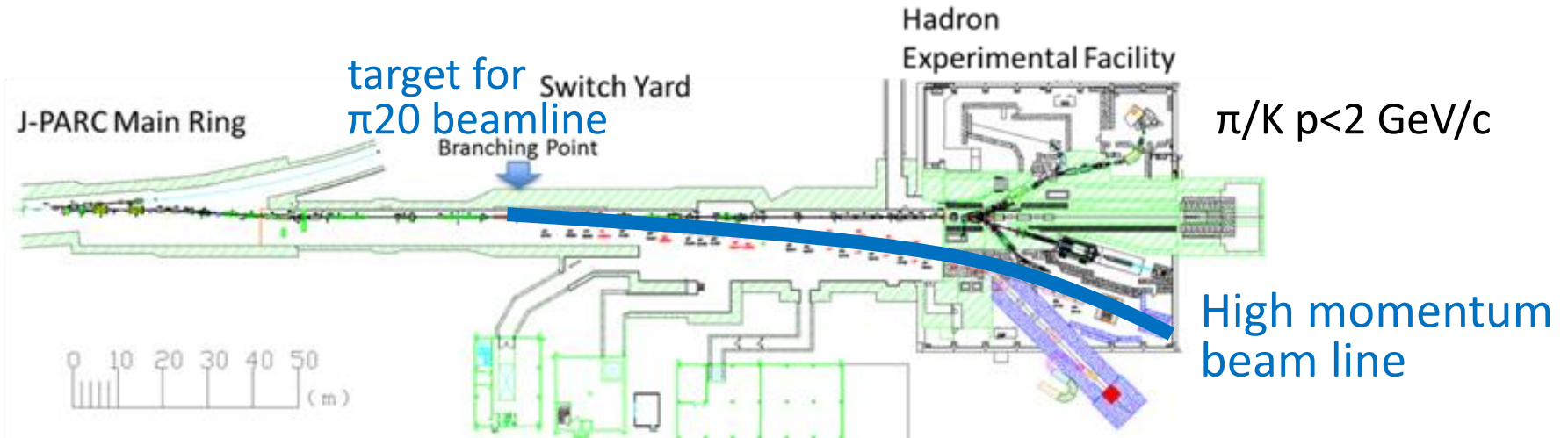
- 2020- : **primary proton beam (30 GeV)**

- 202X- : positive/negative high momentum **π/K/p secondary beam**   **π20 beamline**

Experiments with middle-large Q^2 at J-PARC

Experimental ideas at J-PARC

- **High intensity proton beam** (10^{10} protons/spill, 30 GeV, 2 s/5.2 s cycle)
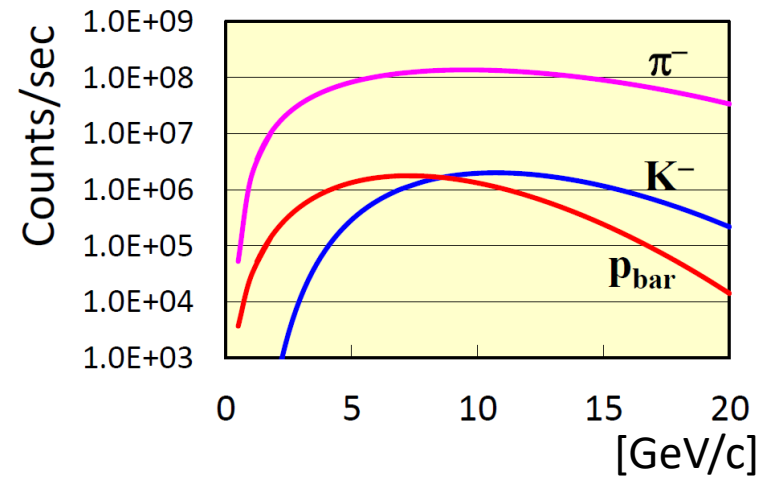- **Wide momentum secondary beam** (π/K/p, 2-20 GeV/c)
- Hadron beam at p~O(10 GeV/c) $\Rightarrow$ **Not explored much**
  large cross section in exclusive reactions
- Multi purpose spectrometer for π20 beamline is under preparation

- 30 GeV proton beam
  - GPDs measurement with p+p→p+π+B reaction (μb)
  - Drell-Yan measurements (nb)

- Positive secondary beam (<20 GeV/c)
  - Color transparency search (nb-pb, depends on momentum)

- Negative secondary beam (<20 GeV/c)
  - π/K induced Drell-Yan (nb)
  - GPDs measurement with Exclusive Drell-Yan (pb)
  - GPDs measurements with $\pi^- + p \rightarrow n + \gamma + \gamma$ (pb)
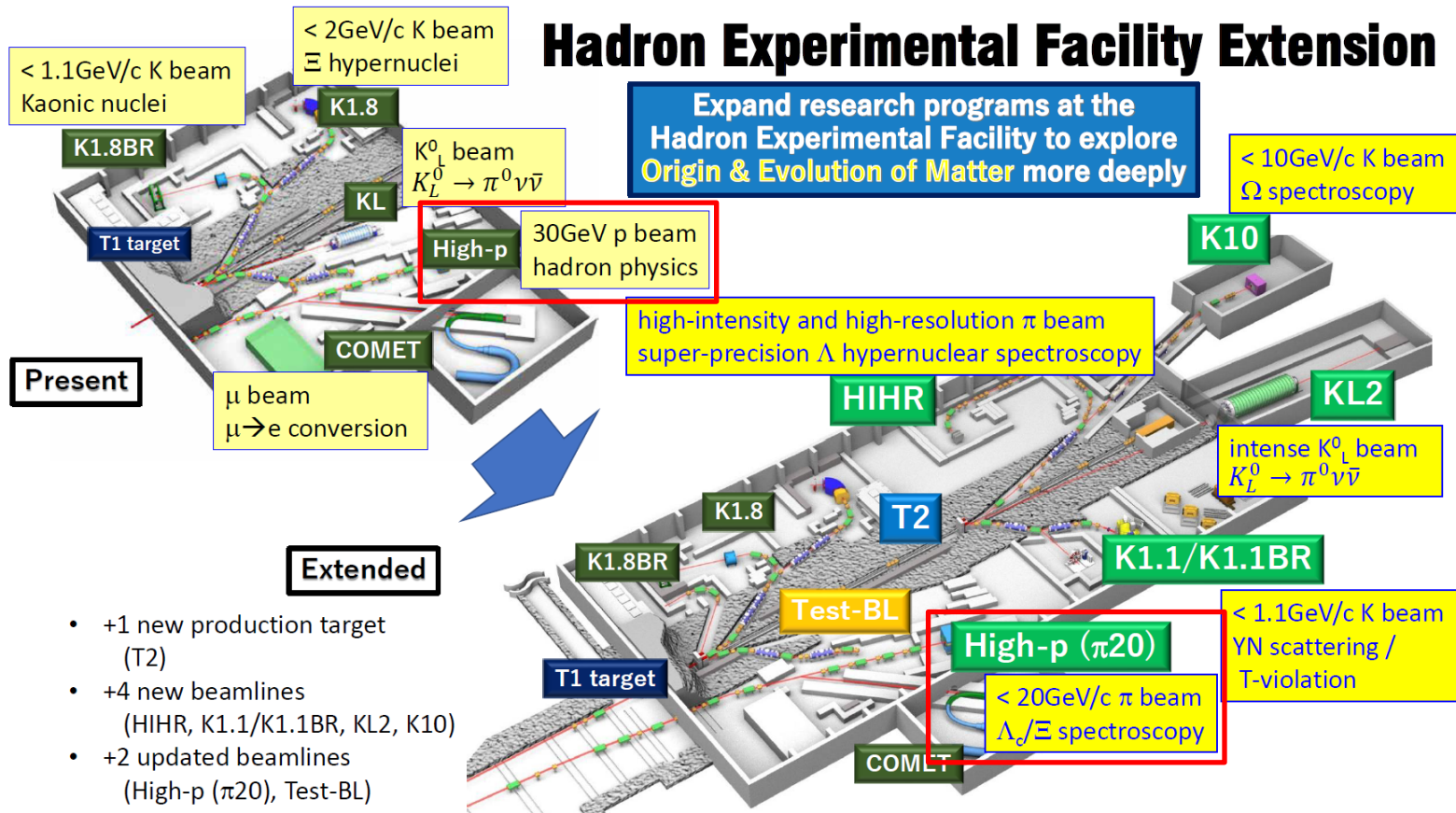
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30 GeV primary proton beam

- 10^{10}/spill beam (designed value) is already delivered
- Problems in beam spill structure
- Physics run starts soon
  - E16 experiment (Φ meson in nucleus)
    - 2020,2021 : run0a-0c
    - 2022 : Main Ring upgrade
    - 2023 : Fire accidents, run0d
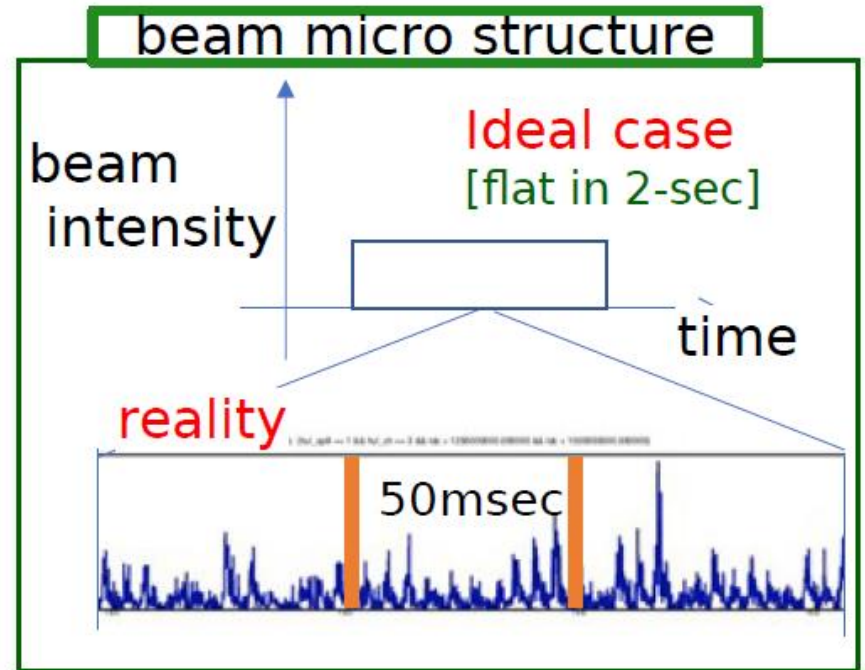
S. Yokkaichi, 3rd J-PARC HEF-ex WS
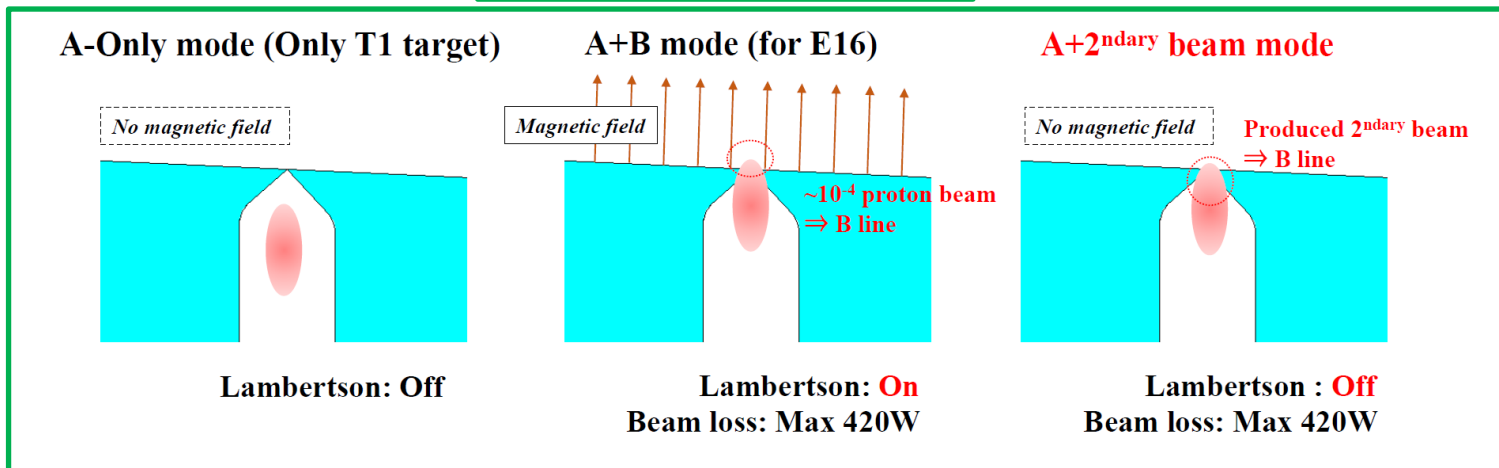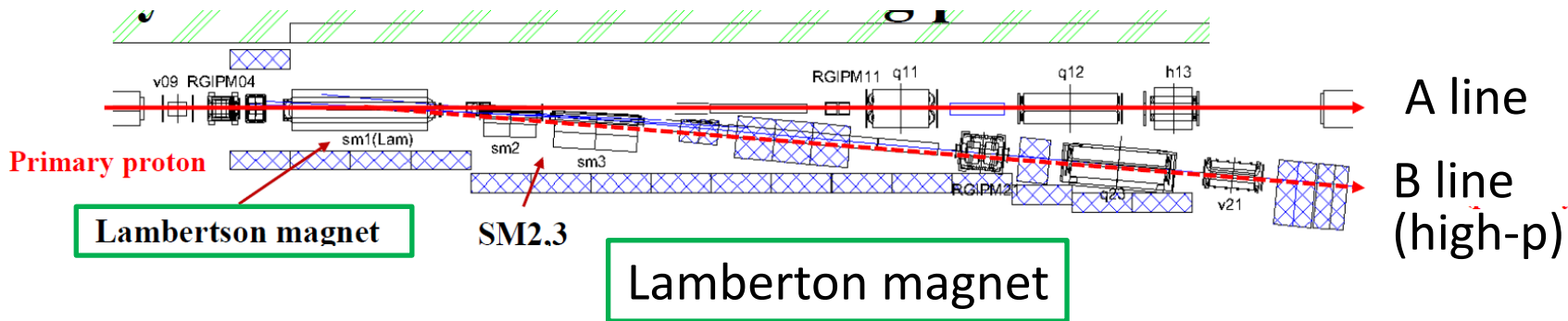
Secondary beam (π20 beamline)

- Budget request within Hadron Hall extension plan
- Hadron Hall extension was selected as the top priority in the KEK mid-term plan (KEK-PIP2022-2027)
- However, previous PIP program is still leftover

Hadron Experimental Facility Extension

Expand research programs at the Hadron Experimental Facility to explore **Origin & Evolution of Matter** more deeply

< 1.1GeV/c K beam
Kaonic nuclei

< 2GeV/c K beam
Ξ hypernuclei

K1.8

K1.8BR

K^0_L beam
$K^0_L \to \pi^0 \nu \bar{\nu}$

KL

T1 target

High-p

30GeV p beam
hadron physics

< 10GeV/c K beam
Ω spectroscopy

K10

COMET

high-intensity and high-resolution π beam
super-precision Λ hypernuclear spectroscopy

Present

HIHR

KL2

μ beam
μ→e conversion

intense K^0_L beam
$K^0_L \to \pi^0 \nu \bar{\nu}$

Extended

K1.8

T2

K1.8BR

K1.1/K1.1BR

Test-BL

High-p (π20)

< 1.1GeV/c K beam
YN scattering /
T-violation

T1 target

< 20GeV/c π beam
Λ_c / Ξ spectroscopy

COMET

- +1 new production target (T2)
- +4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10)
- +2 updated beamlines (High-p (π20), Test-BL)

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Toward realization of the π20 beamline

P93 (Proposal for a test experiment to evaluate the performance of the secondary beam in the high-momentum beam line) (K. Shirotori)
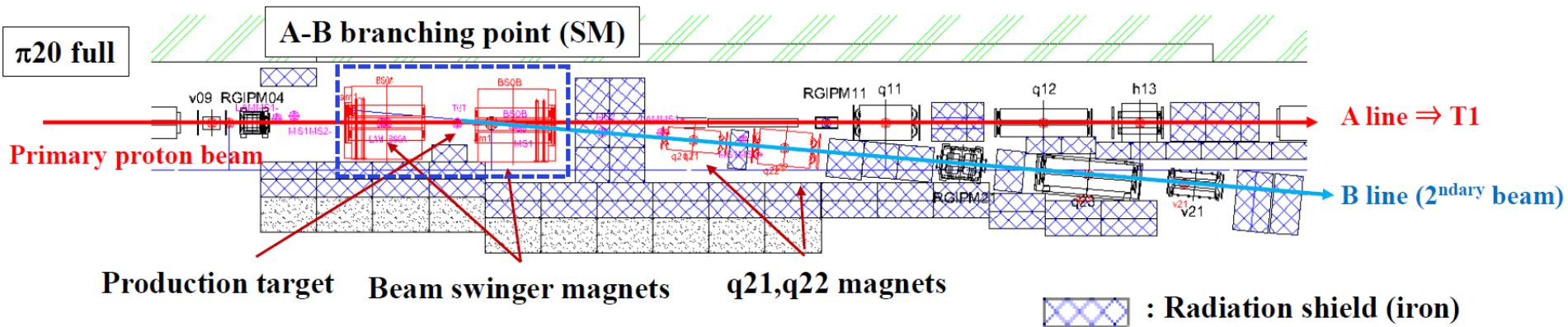
- **Phase 1 : Minimum modification of beam line : ~10^5/spill**
  - Use the Lamberton magnet as a target for secondary beam
  - Polarity change device → negative beam

Primary proton

Lambertson magnet

SM2,3

A line

B line (high-p)

Lamberton magnet

A-Only mode (Only T1 target)   **A+B mode (for E16)**   **A+2^{ndary} beam mode**

No magnetic field   Magnetic field   No magnetic field

Produced 2^{ndary} beam ⇒ B line

~10^{-4} proton beam ⇒ B line

Lambertson: Off   Lambertson: On
Beam loss: Max 420W   Lambertson : Off
Beam loss: Max 420W

Toward realization of the π20 beamline

P93 (Proposal for a test experiment to evaluate the performance of the secondary beam in the high-momentum beam line) (K. Shirotori)

- **Phase 2 : Installation of beam Swinger Magnet : 10^6/spill**
- **Phase 3 : Full radiation shield : 10^7/spill**

π20 full

A-B branching point (SM)
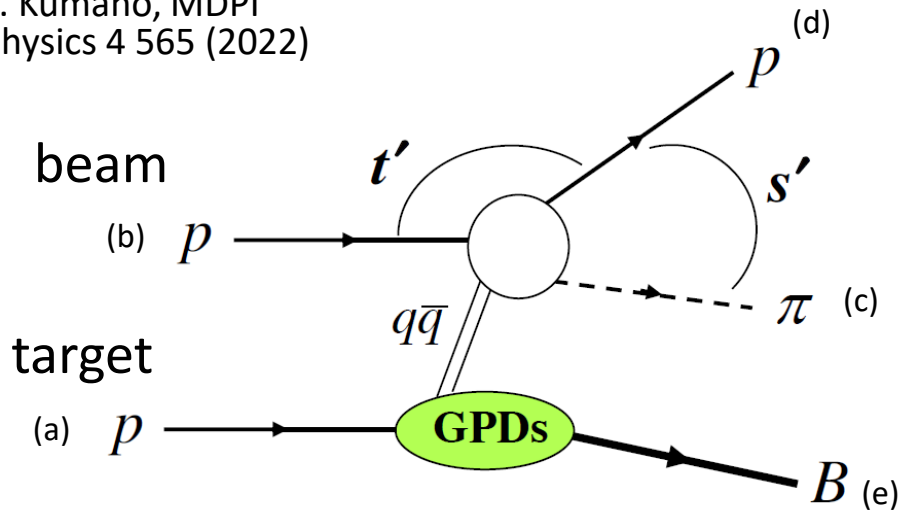
Primary proton beam

A line ⇒ T1

B line (2^{ndary} beam)

Production target   Beam swinger magnets   q21,q22 magnets

: Radiation shield (iron)

Experimental ideas at J-PARC

- **High intensity proton beam** (10^{10} protons/spill, 30 GeV)
- **Wide momentum secondary beam** (π/K/p, 2-20 GeV/c)
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  - GPDs measurements with $\pi^- + p \rightarrow n + \gamma + \gamma$

p + p → N + π + B reaction

beam

(b) p

target

(a) p

t'

$q\bar{q}$

GPDs

(d) p

s'

π (c)

B (e)

$$p + p \rightarrow p + \pi^+ + \Delta^0$$

$$p + p \rightarrow p + \pi^- + \Delta^{++}$$

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

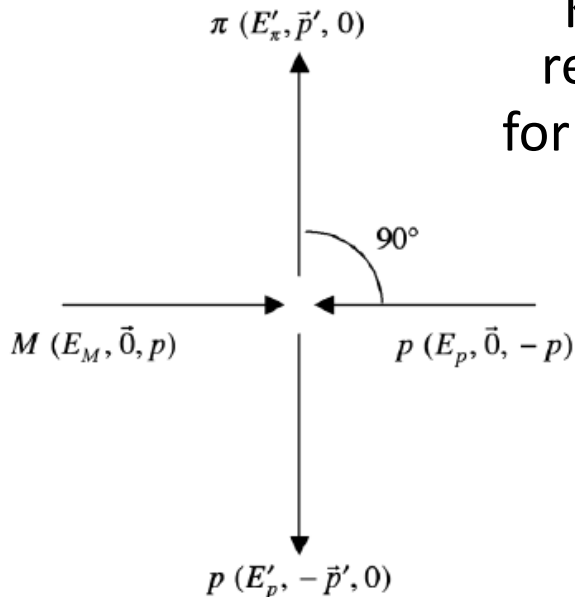$$s = (p_a + p_b)^2, \qquad t = (p_a - p_e)^2,$$

$$s' = (p_c + p_d)^2, \qquad t' = (p_b - p_d)^2$$

3<-t'<8 GeV²

Kinematical
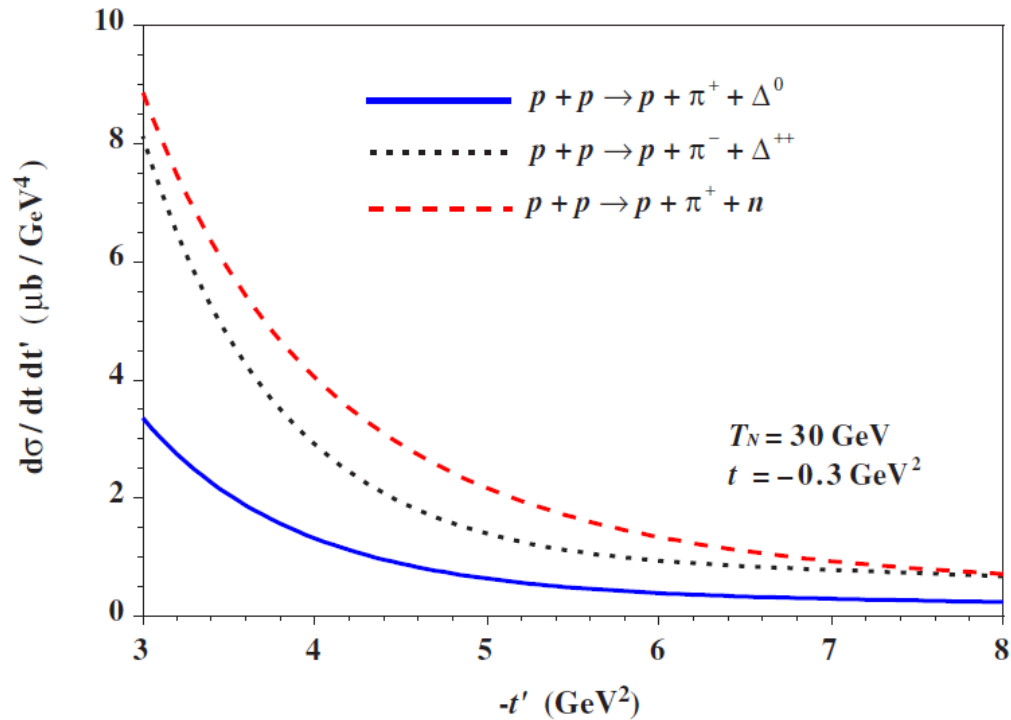requirements
for factorization

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

$\pi\ (E'_\pi, \vec{p}\,', 0)$

90°

$M\ (E_M, \vec{0}, p)$

$p\ (E_p, \vec{0}, -p)$

$p\ (E'_p, -\vec{p}\,', 0)$

p and π : large and nearly
opposite transverse momenta
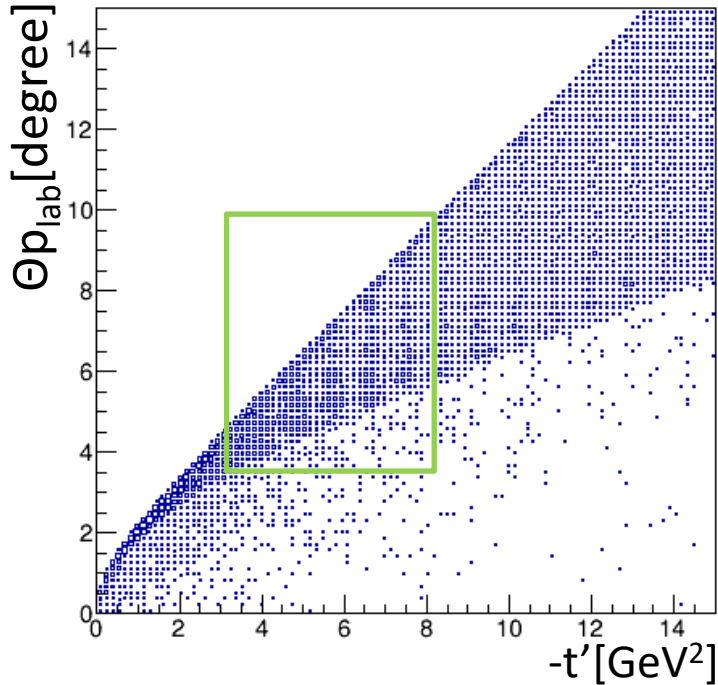& large invariant energy

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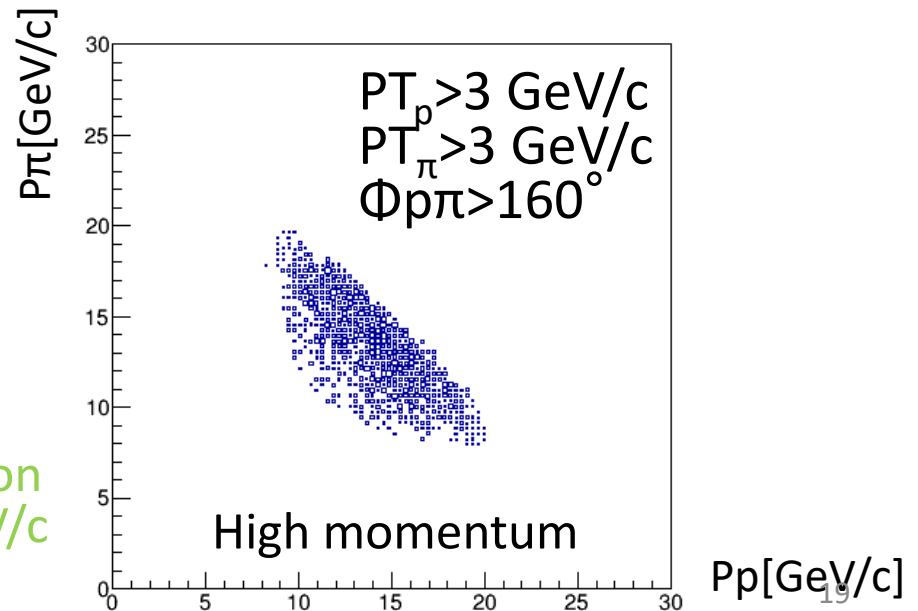# Expected cross section
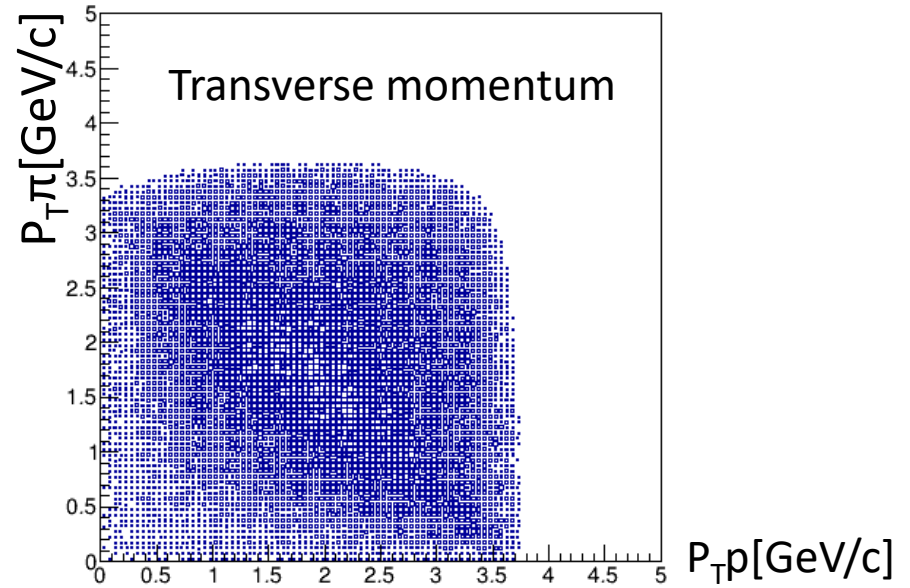

S. Kumano et al.,
PRD 80 074003 (2009)

- 5 μb/GeV^4, 10^{10}/spill, 2 cm LH2, acc × eff = 5% ⇒ 10^7 /day/GeV^4

Kinematics

p + p → p + π⁺ + n

Θp_lab[degree] vs -t'[GeV²]

Forward angle

p/π separation
@ 10-20 GeV/c

Transverse momentum

$P_T\pi$[GeV/c] vs P_Tp[GeV/c]

PT_p>3 GeV/c
PT_π>3 GeV/c
Φpπ>160°

Pπ[GeV/c] vs Pp[GeV/c]

High momentum
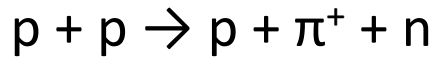
Possible setup

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

- Missing mass $p + p \rightarrow p + \pi^+ + X$

  - Missing mass resolution to identify X=n

  - p beam : momentum spread ~0.05% => no momentum measurement

  - E50 fiber tracker : 0.6% @ 15 GeV/c

- p/π separation

  - Gas Cherenkov

- Multiplicity cut

- Liquid hydrogen target

- FM magnet

- JAM simulation

  ⇒ Clear identification of X=n peak

p   **π⁺**

Gas Cherenkov

Fiber Tracker

LH2 target

Charge veto

30 GeV p

X=n

$p + p \rightarrow p + \pi^+ + X$

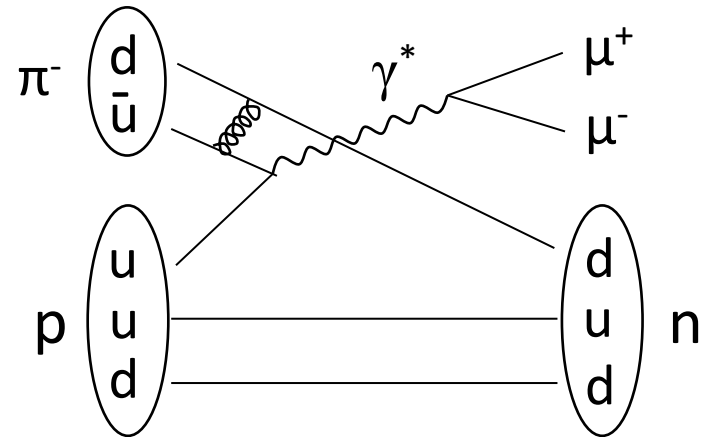$M_{p\pi+} > 1.5 \text{ GeV}/c^2$

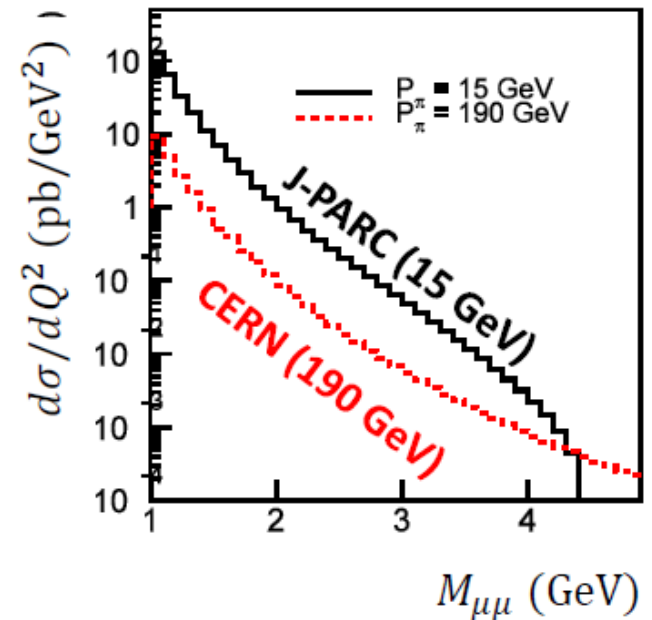JAM simulation

Missing mass [GeV/c²]
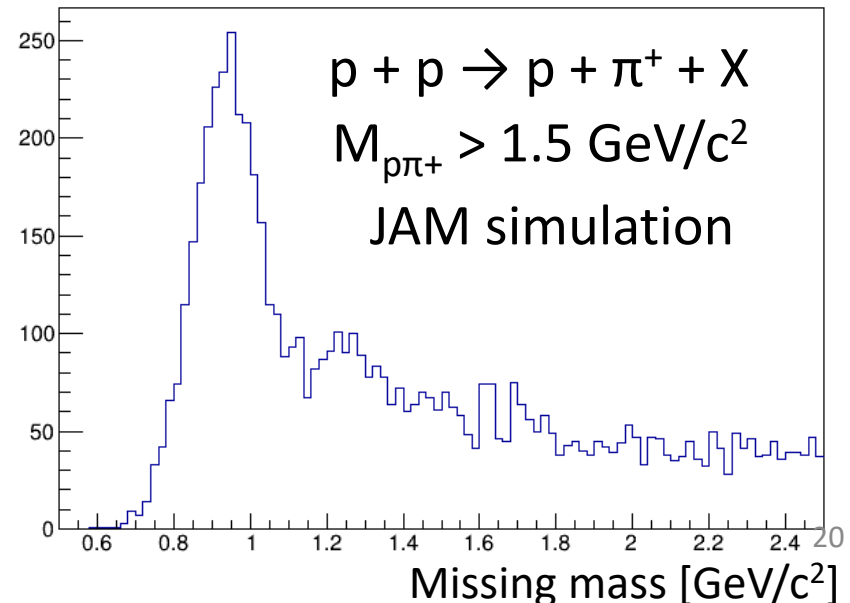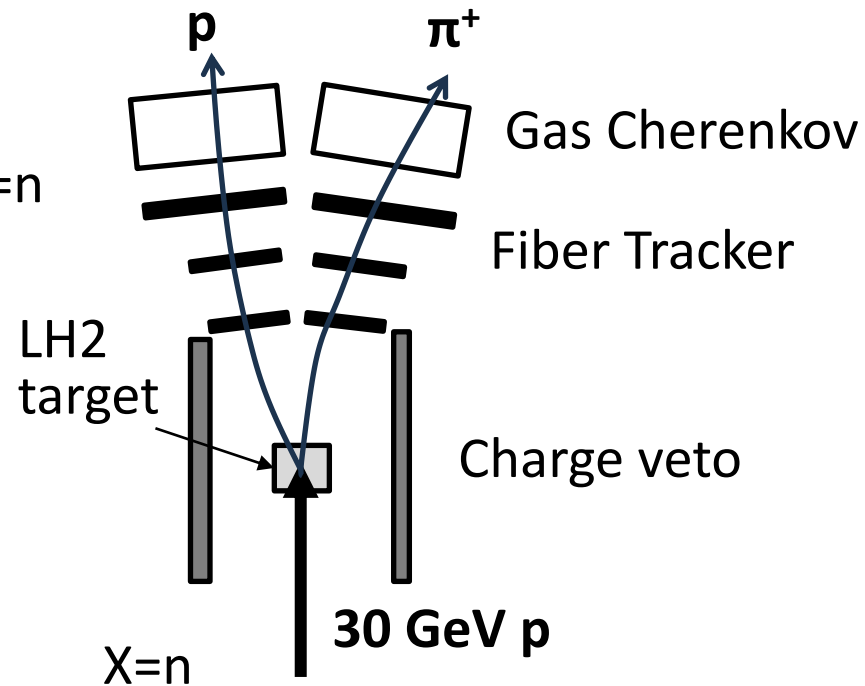
Exclusive Drell-Yan

Exclusive Drell-Yan
$\pi^- + p \rightarrow \gamma^* + n \rightarrow \mu^+ + \mu^- + n$
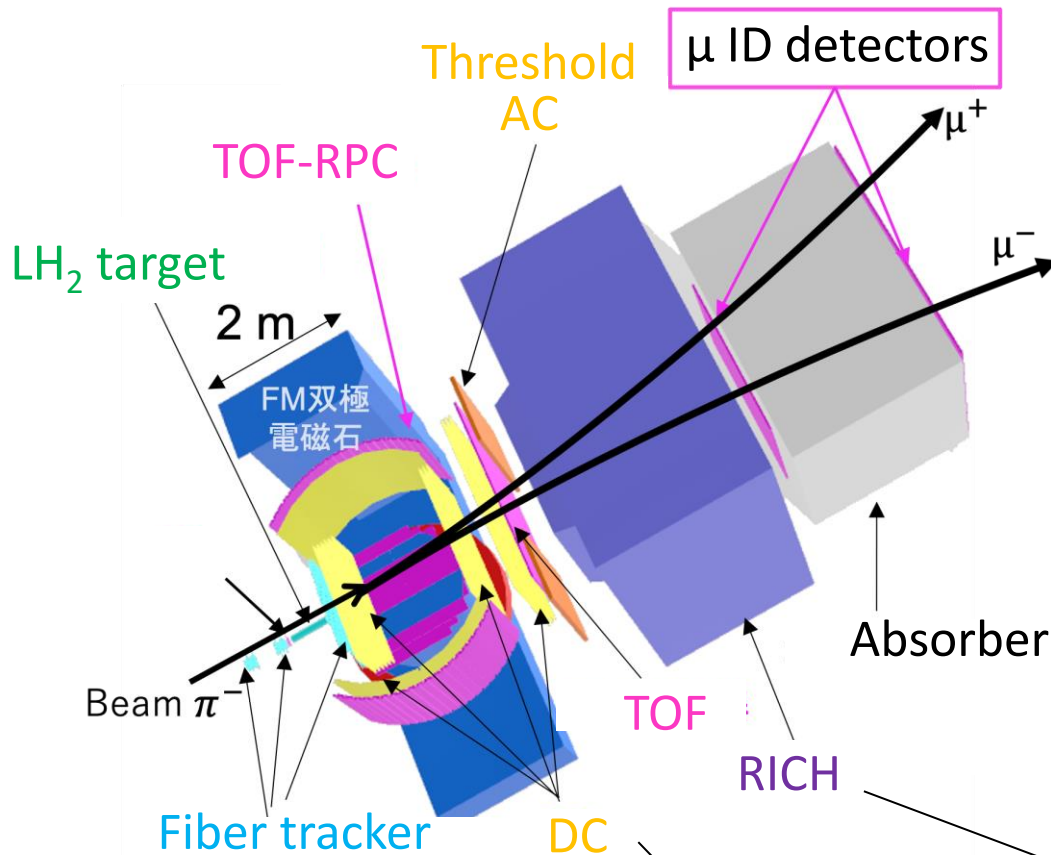
$$\frac{d\sigma_L}{dt dQ'^2}\bigg|_\tau = \frac{4\pi\alpha_{em}^2}{27}\frac{\tau^2}{Q'^8}f_\pi^2\left[(1-\xi^2)\left|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)\right|^2\right.$$

$$\left.-2\xi^2\text{Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^*\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right)-\xi^2\frac{t}{4m_N^2}\left|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right|^2\right]$$

GPDs

- Larger cross section @ lower momentum

- Experimental feasibility study :
  T. Sawada et al., PRD 93 (2016) 114034

- LoI submitted

- Proposal under preparation
 (W.C. Chang, Po-Ju Lin, Po-Hung Wang
  (Academia Sinica, Taiwan))

E.R. Berger et al., PLB 523 (2001) 265

E50 Spectrometer for π20 beamline

μ ID detectors

Threshold AC

TOF-RPC

LH₂ target

2 m

FM双極電磁石

Beam π⁻

μ⁺

μ⁻

Absorber

TOF

RICH

Fiber tracker

DC

- Multi purpose
  - E50 (Charmed Baryon Spectroscopy)
  - E79, E97, etc…

- New generation
  - Streaming DAQ
  - SiPMs
  - PID @ <20 GeV/c
  - High rate (10^8 Hz beam)

Construction on-going
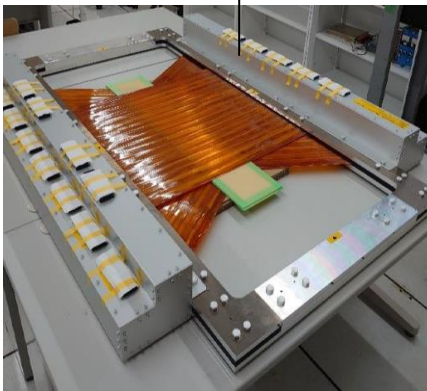
Exclusive Drell-Yan measurement

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

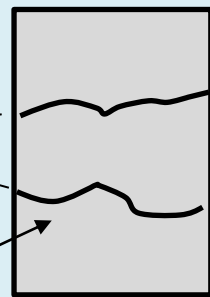Inclusive Drell-Yan $\pi^-p \rightarrow \gamma^* X \rightarrow \mu^+\mu^- X$

Small cross section (~pb) ⇔ Large hadron background (~mb)

Usual DY experimental set up (CERN) (Fermilab)

Our setup

High intensity hadron beam

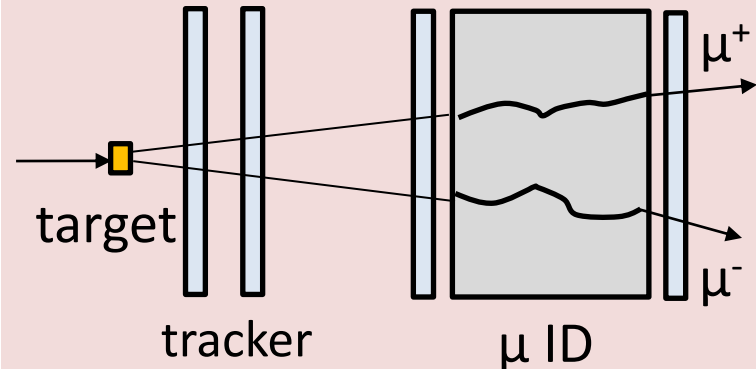target

Multiple scattering

Hadron absorber

Tracker

μ^+

μ^-

Bad momentum resolution @ tracker

Bad missing mass resolution

Only inclusive measurement

target

tracker

μ ID
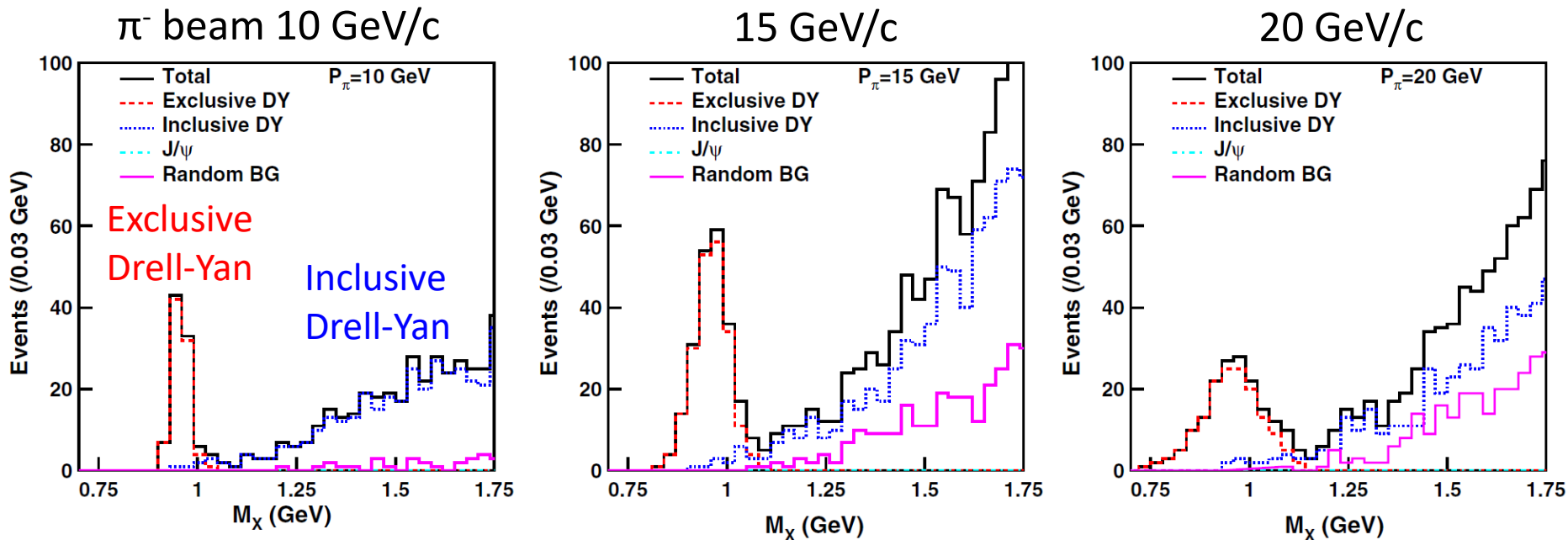
μ^+

μ^-

Momentum analysis @ upstream of absorber

Good missing mass resolution

1st measurement of exclusive reaction

Exclusive Drell-Yan measurement

Expected Missing Mass Spectra (50 days)

$$\pi^- p \to \mu^+ \mu^- X$$

- Clear identification of exclusive Drell-Yan events
- MC simulation with the latest spectrometer setup and optimization of the absorber thickness is on-going
- Multiplicity cut can be applied additionally

Summary

- Study 3D nucleon structure @ J-PARC

- High momentum proton beam (30 GeV) is now available
- Secondary high momentum beam (π/K/p<20 GeV/c) will be available

- GPDs measurement with

  - 30 GeV proton beam
    - p+p→p+π+B (μb)

  - Negative secondary beam (<20 GeV/c)
    - Exclusive Drell-Yan (pb)

  - Unique and complemental kinematical coverage to other experiments