GPDs at J-PARC

Towards improved hadron femtography with hard exclusive reactions, edition IV

Jefferson Laboratory

2025/Jul/28-31

Natsuki TOMIDA

Kyoto University

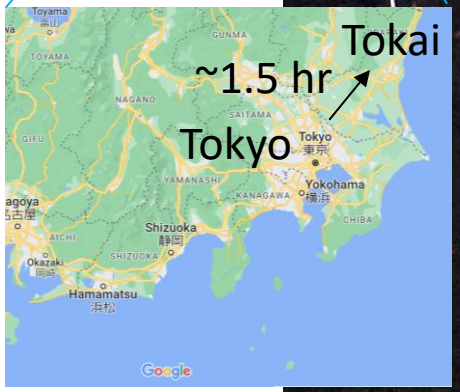
Outline

- J-PARC high momentum beamline
  - Introduction
  - Status : 2025/Jan first delivery of secondary beams
  - MARQ spectrometer

- GPDs measurements using hadron beams
  - $M + N \rightarrow \gamma + \gamma + N'$
  - $M + N \rightarrow l^+ + l^- + N'$
  - $N + N \rightarrow M + B + N'$

J-PARC

Japan **P**roton **A**ccelerator **R**esearch **C**omplex (in Tokai)



500 m

T2K

neutrino

μ, neutron

Materials and Life Experimental Facility

30 GeV proton synchrotron

Hadron hall

π/K/p

Hadron Experimental Facility

- 2010- : Start experiment Strangeness nuclear physics

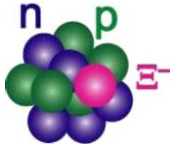
< 1.0 GeV/c K/π

K1.8BR

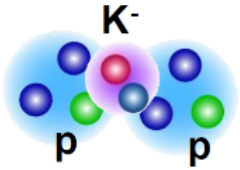
K1.8

< 2.0 GeV/c K/π

Hyper nuclei



Kaonic nuclei



T1 target

30 GeV proton

KL

K^0_L

$K_L \rightarrow \pi^0 \nu\nu$ search

arXiv:2110.04462 [nucl-ex]

Hadron Experimental Facility

- 2020 : High-p and COMET beamlines built

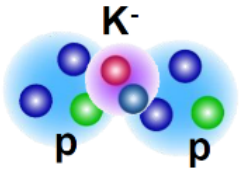
< 1.0 GeV/c K/π

< 2.0 GeV/c K/π

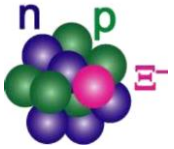
K1.8

K1.8BR

Kaonic nuclei



Hyper nuclei



T1 target

30/8 GeV proton

KL

K^0_L

$K_L \rightarrow \pi^0 \nu\nu$ search

high-p

30 GeV p

=> Large Q^2

COMET

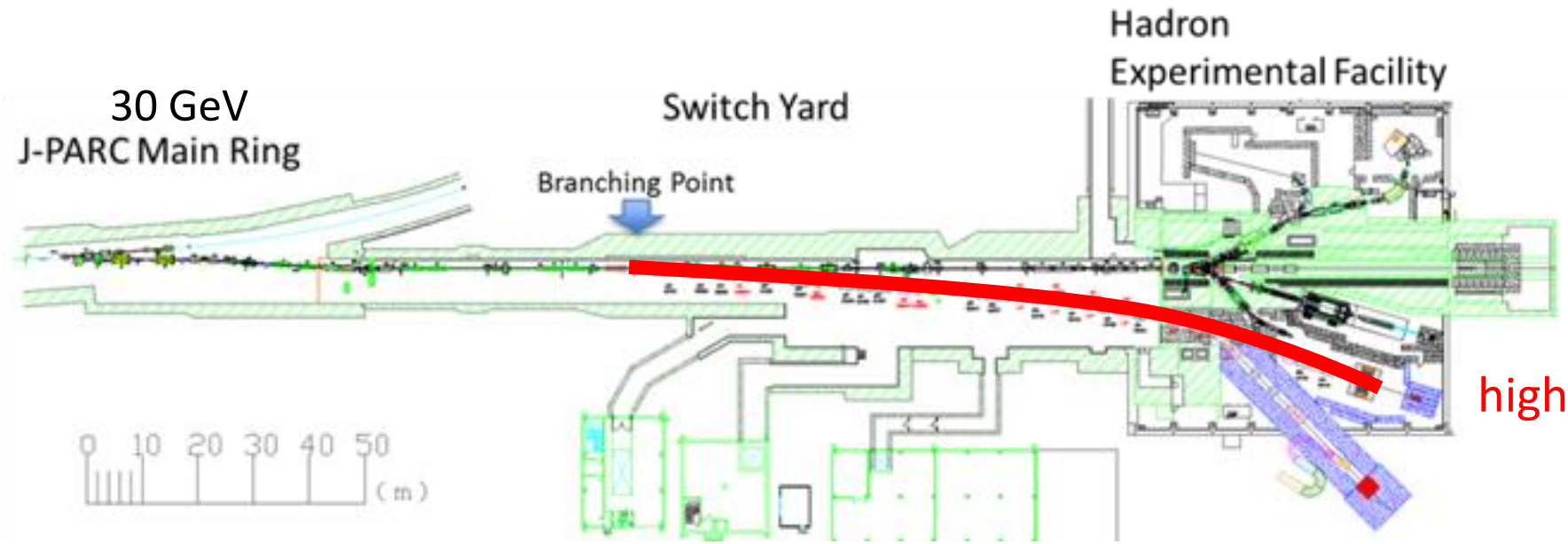
μ^-

8 GeV p

μ-e conversion

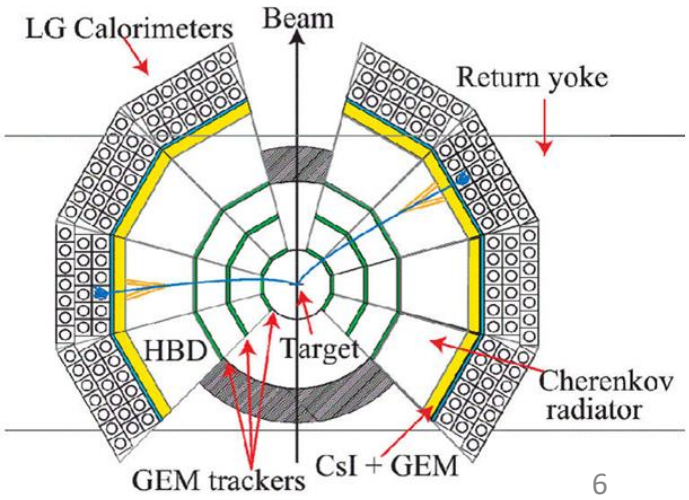
arXiv:2110.04462 [nucl-ex]

Current high momentum beamline

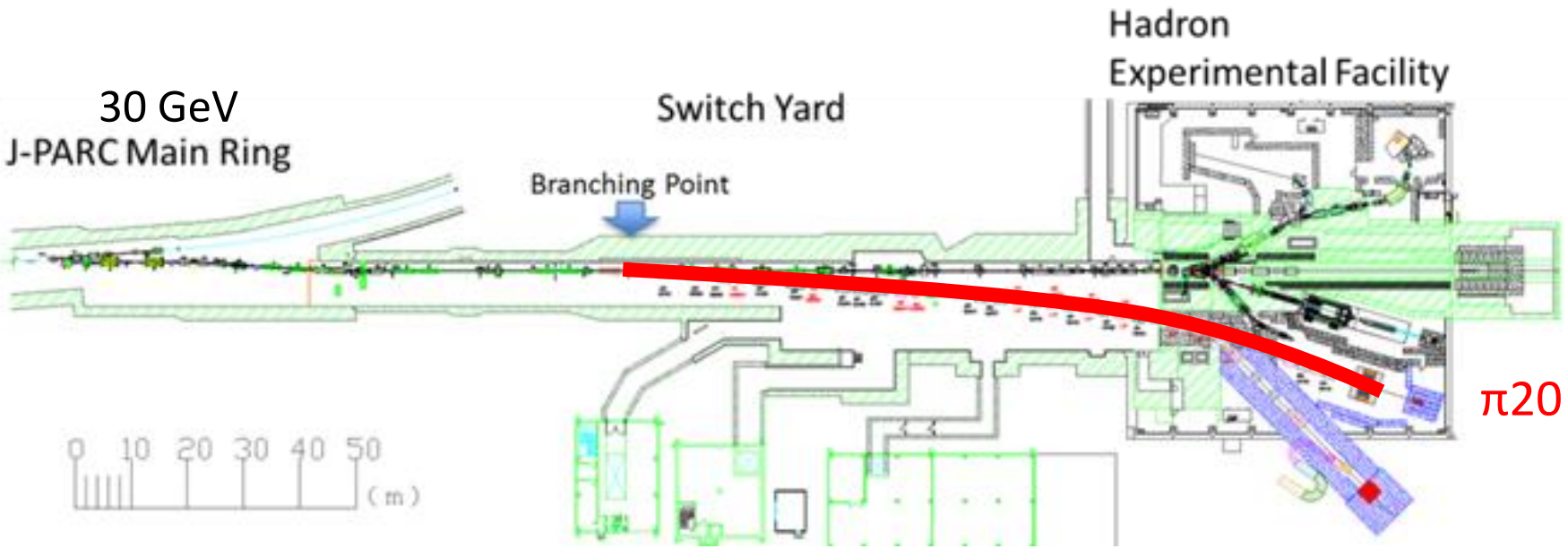


- Derive 30 GeV primary proton from Main Ring
- High intensity : 10^{10}/spill (2s)
  - Strict radiation control
  - Detectors cannot be installed in forward
  - Beam momentum cannot be measured
- Low momentum e^+e^- spectrometer installed
  - Start first physics run in FY2025
    (E16 exp: $\Phi \rightarrow e^+e^-$ in nuclei)

E16 spectrometer



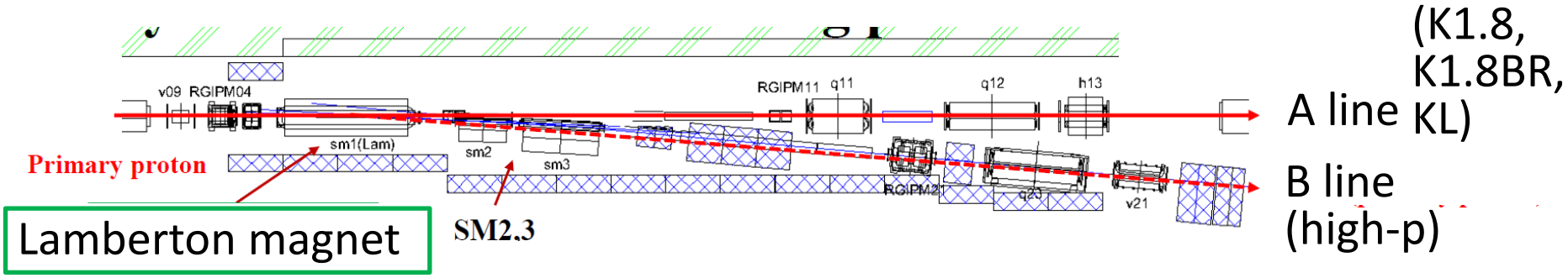
High momentum secondary (π20) beamline

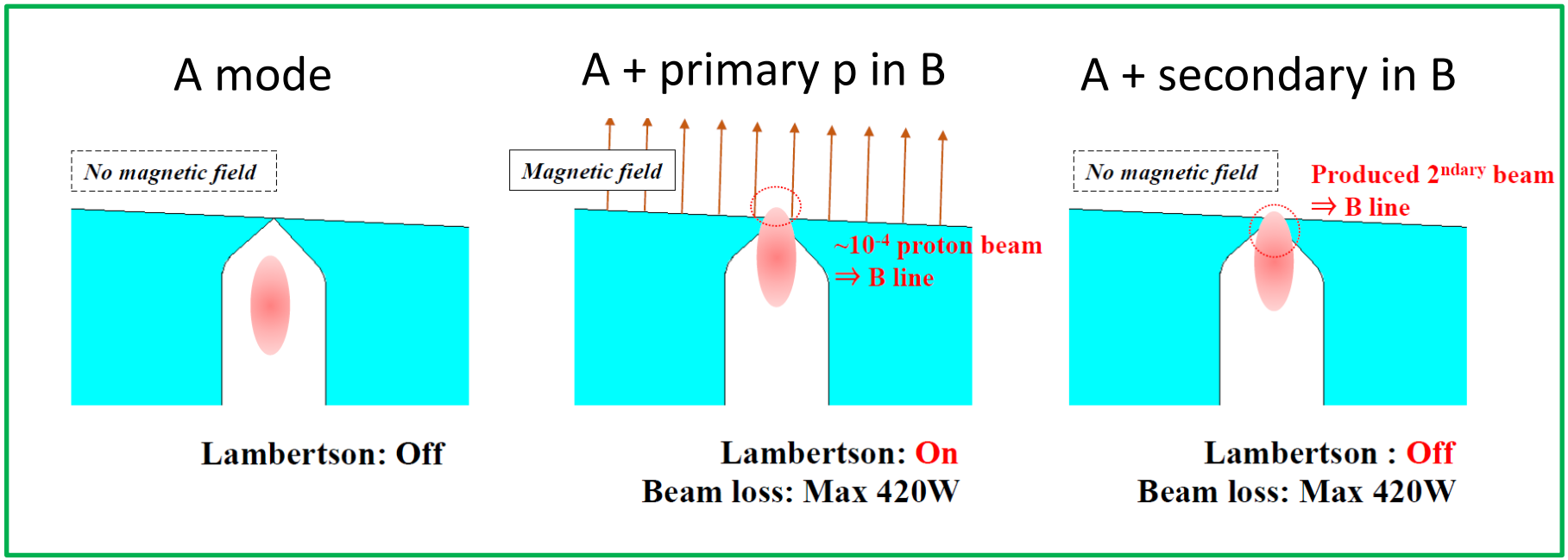


- Place a target at the branching point
- Deliver negative/positive unseparated secondary beam (π/K/pbar/μ) up to 20 GeV/c
- Phase 1 : Use the existing magnet at the branching point as a target
  - Positive beam → **First delivery in 2025/Jan !!**
  - Negative beam → **Polarity change devices will be installed in FY2025**
- Phase 2 : Install a target & swinger magnet
- Phase 3 : Radiation shields for full intensity

π20 phase-I

- Use the Lambertson magnet as a production target

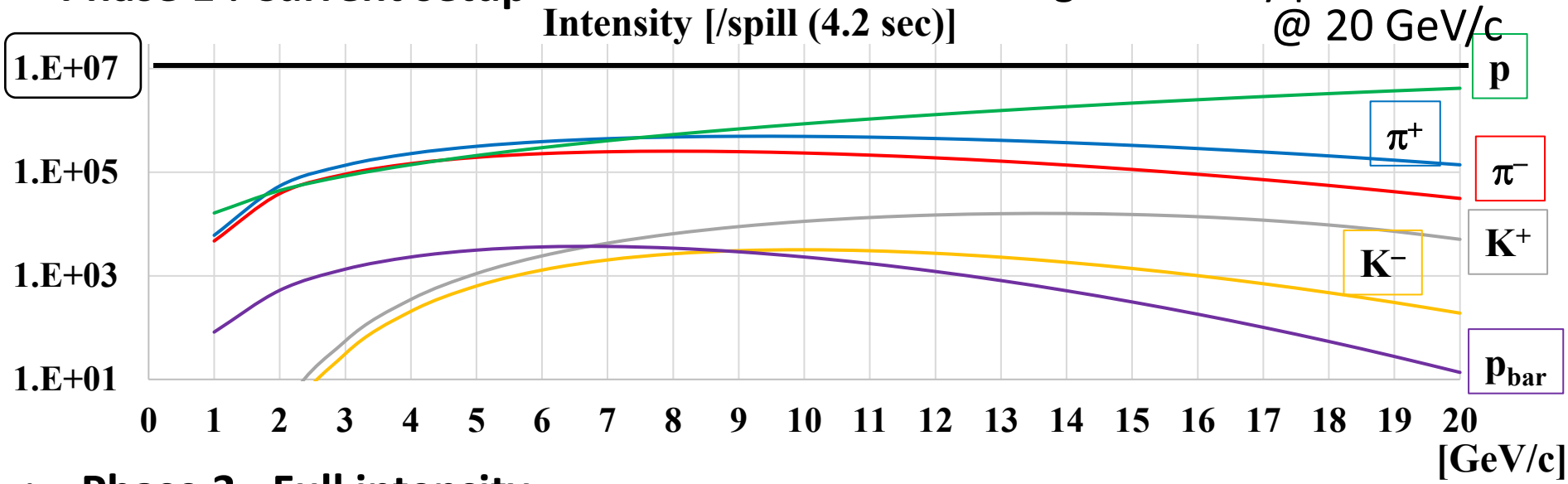




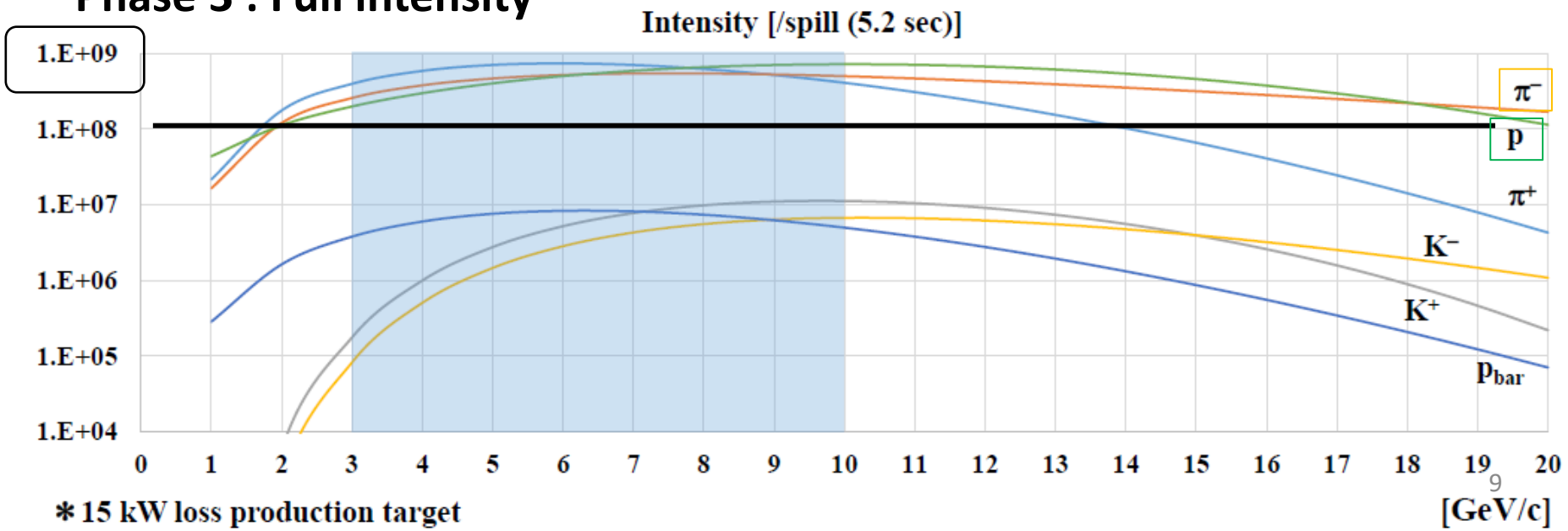
Expected beam intensity

- **Phase 1 : Current setup**

high intensity p available @ 20 GeV/c



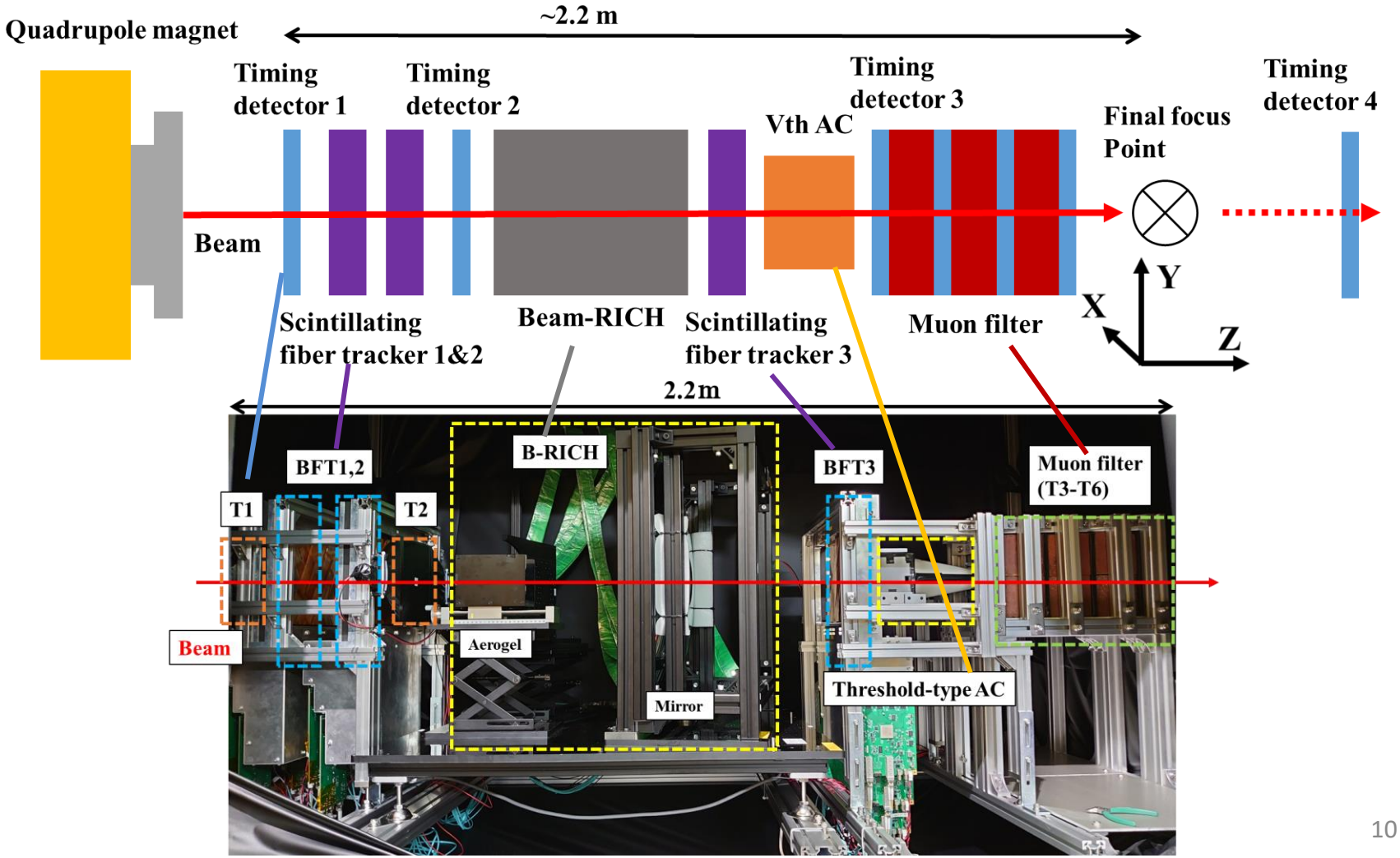
- **Phase 3 : Full intensity**



∗15 kW loss production target

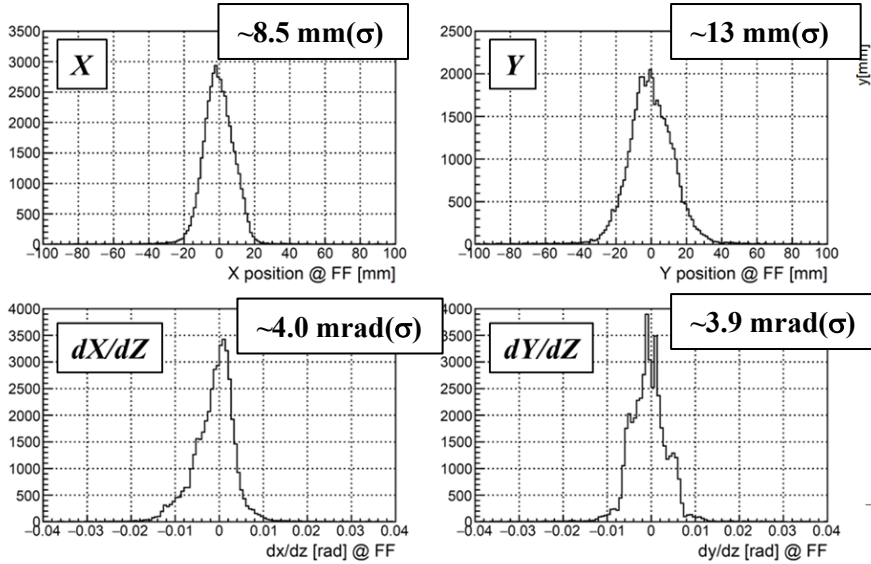
2025/Jan beam study

- 1st delivery of secondar beams at the high momentum beam line in J-PARC
- Study of secondary beam property (beam size, particle fraction)
- Positive 3/5/10 GeV/c

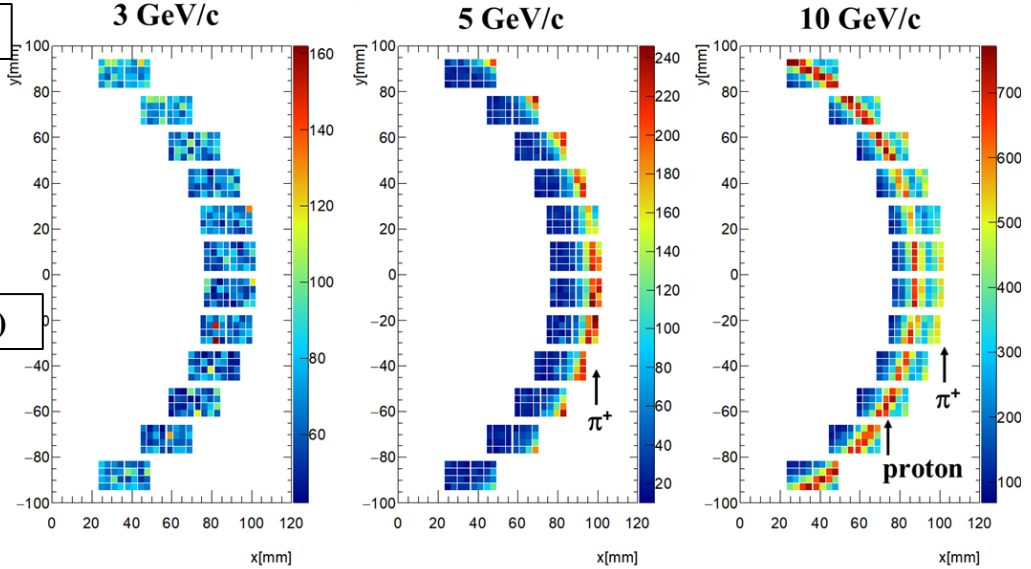


2025/Jan beam study

Beam size



beam RICH

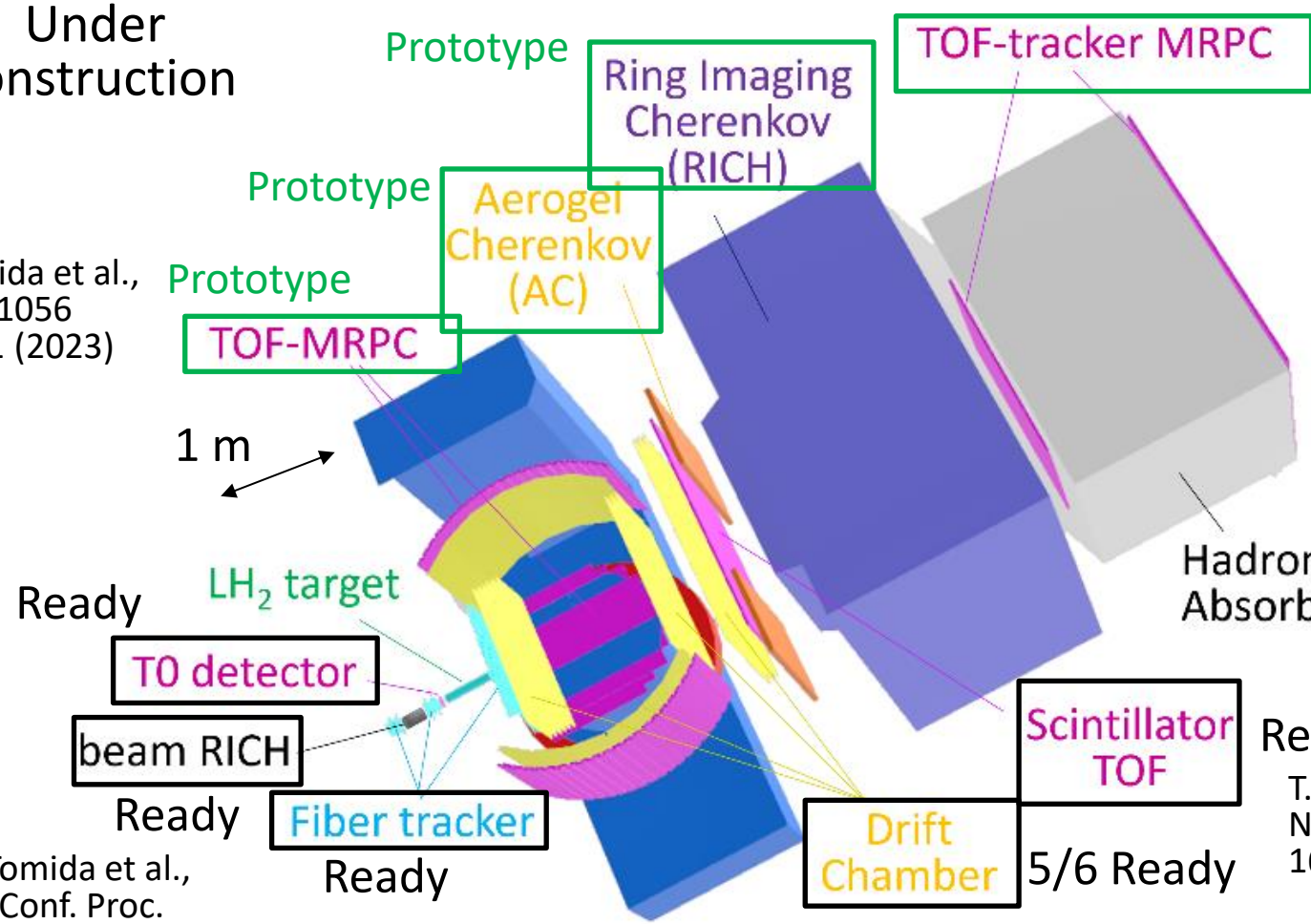


- Successfully delivered/measured secondary beams
- $p:\pi^+$ = 0.66:0.34, 0.60:0.40, 0.39:0.61 (3, 5, 10 GeV/c)
- Consistent with simulation

FY2025/2026

- Install polarity change devices to deliver negative beams
- Study beams at -2, -5, -8, -10, -15, ±20 GeV/c

MARQ spectrometer



Multi purpose spectrometer

Streaming DAQ

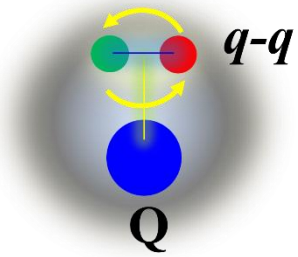
High momentum resolution

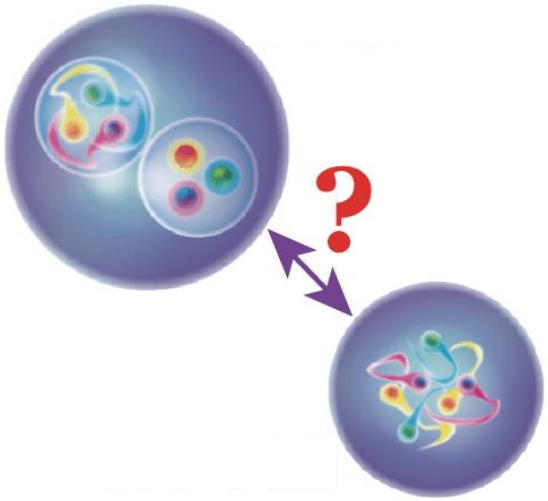
PID < 16 GeV/c

High rate stability : 1 MHz/1 mm

Physics program in MARQ

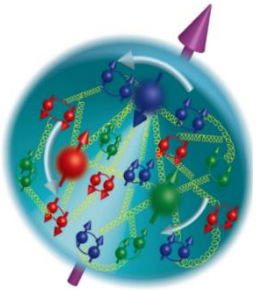
- **Hadron structure**
  - Charmed baryon spectroscopy
  - Ξ (s=-2) baryon spectroscopy





- **Exotic hadrons**
  - High isospin dibaryon search
  - P_s Pentaquark search

- **Elementary cross sections**
  - Λp scattering cross section
  - Hadronic cross sections for neutrino experiments



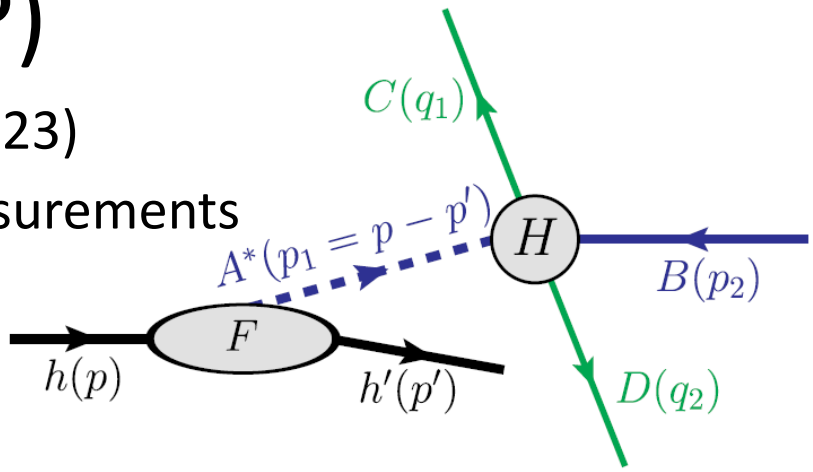
- **Nucleon structure**
  - Measurement of Generalized Parton Distribution Functions (GPDs)
  - Color Transparency

You are welcome to join us

Single Diffractive Hard Exclusive Process (SDHEP)

- J.-W. Qiu and Z. Yu PRD 107 014007 (2023)

Generalization of processes for GPDs measurements



B + p → C + D + p' (2→3 process)

Diffractive production of A* : p → A* + p'

Exclusive 2→2 scattering : A* + B → C + D

- **B, C, D can be lepton, gamma or hadron**
- **C, D : large transverse momentum >> four momentum transfer**

Cross section depends on GPDs

$$\mathcal{M}^{(2)}_{he\to h'eM_D} = \sum_{i,j}\int_{-1}^{1}\mathrm{d}x\int_{0}^{1}\mathrm{d}z_D \times F_i^{hh'}(x,\xi,t)\,C_{ie\to ej}(x,\xi;z_D;q_T)\,\phi_{j/D}(z_D).$$

Single Diffractive Hard Exclusive Process (SDHEP)

PRD 107 014007 (2023)

Lepton beam
- $l + N \rightarrow l' + \gamma + N'$ (DVCS)
- $l + N \rightarrow l' + M + N'$ (DVMP)

γ beam
- $\gamma + N \rightarrow l^+ + l^- + N'$ (TCS)
- $\gamma + N \rightarrow \gamma + \gamma + N'$
- $\gamma + N \rightarrow \gamma + M + N'$ Jul/29 morning session
- $\gamma + N \rightarrow M + M + N'$

Meson beam
- $M + N \rightarrow l^+ + l^- + N'$ (Exclusive Drell-Yan) E.R. Berger, PLB 523 (2001) 265, S.V. Goloskokov, PLB 748 (2015) 323
- $M + N \rightarrow \gamma + \gamma + N'$ J.-W. Qiu and Z. Yu PRD 109 (2024) 074023
- $M + N \rightarrow \gamma + M + N'$
- $M + N \rightarrow M + M + N'$

Proton beam
- $N + N \rightarrow M + B + N'$ S. Kumano et al., PRD 80 (2009) 074003

Neutrino beam
- $\nu + N \rightarrow l + \pi + N'$ X. Chen et al., EPJ A 60 (2024) 208

We can study GPDs using variety of beams

GPDs studies at J-PARC

Meson beam

- $M + N \rightarrow \gamma + \gamma + N'$: O(10-100) pb
- $M + N \rightarrow l^+ + l^- + N'$: O(1-10) pb

Proton beam

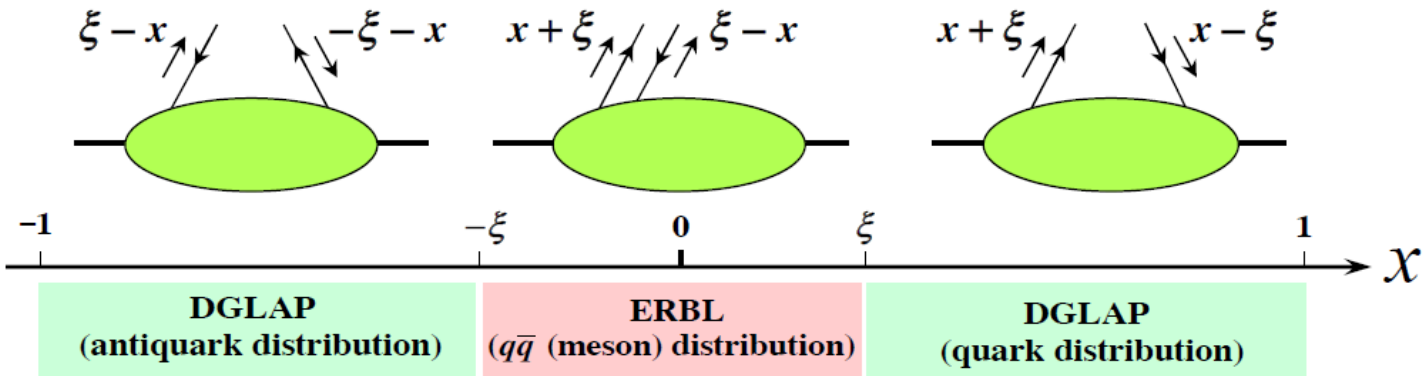
- $N + N \rightarrow M + B + N'$: **O μb**

Cross sections estimated

N. Tomida,
EPJ Web Conf. 303 (2024) 03005

Some processes can access to

- x-dependence of GPDs
- ERBL region

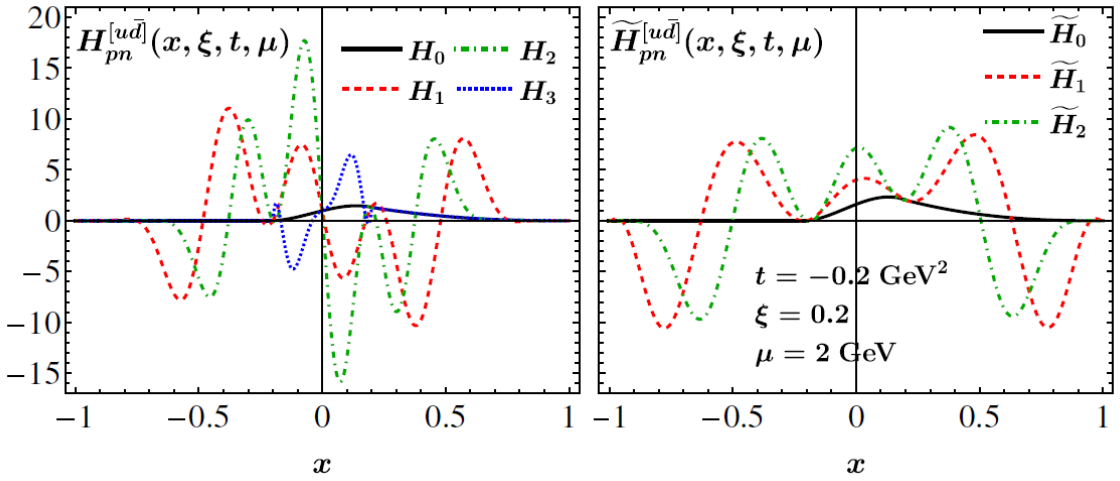


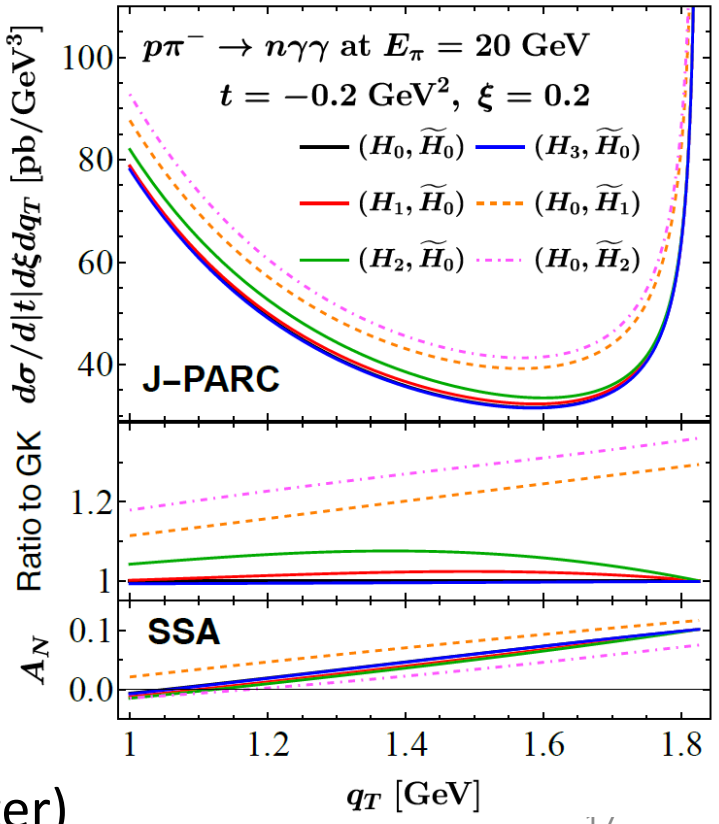
$-1 < x < \xi \quad (x+\xi < 0, x-\xi < 0)$ $\qquad$ $\xi < x < 1 \quad (x+\xi > 0, x-\xi > 0)$

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

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

- J.-W. Qiu and Z. Yu, PRD 109 (2024) 074023
- $\gamma\gamma$: Large opposite transverse momentum
- **x dependence of GPDs can be measured**
- **Can differentiate shadow GPDs and real GPDs**





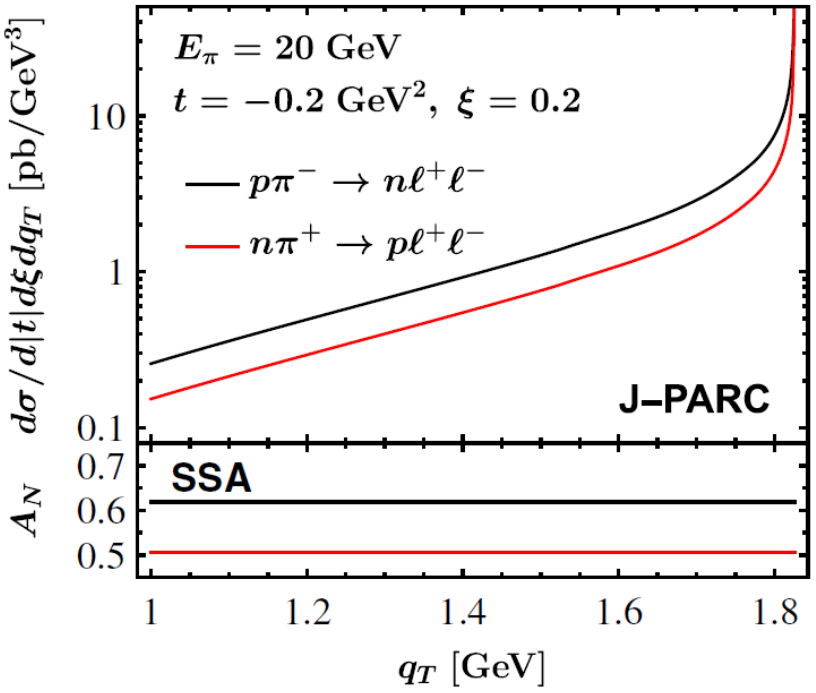
- O(10-100) pb
- Need full intensity π20 beam
- Need an electromagnetic calorimeter

(Not included in the current MARQ spectrometer)

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

- Exclusive Drell-Yan
- Inverse reaction of Deeply Virtual Meson Production (DVMP)
- We can access to polarized GPDs

- E.R. Berger, PLB 523 (2001) 265
- S.V. Goloskokov, PLB 748 (2015) 323
- S. Sawada et al., PRD 93 (2016) 114034 → Feasibility study the MARQ spectrometer
- J.-W. Qiu and Z. Yu, PRD 109 (2024) 074023

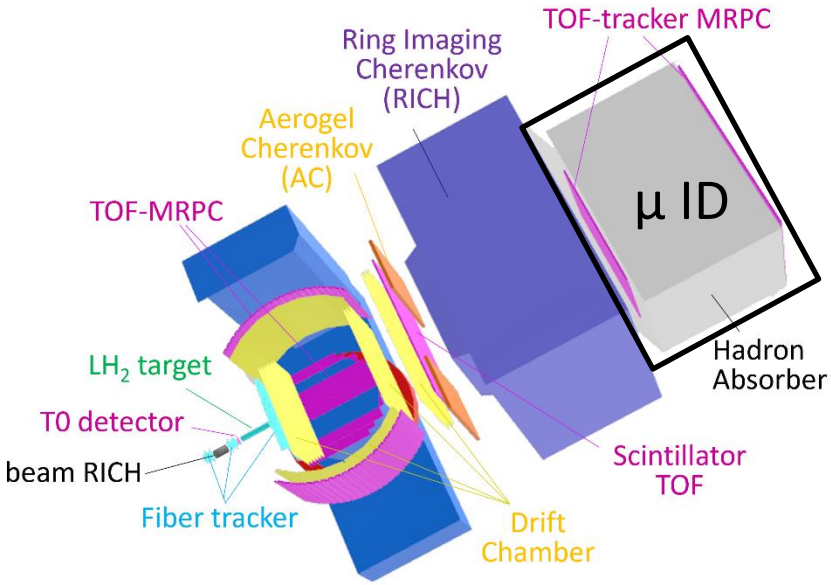


J.-W. Qiu and Z. Yu,
PRD 109 (2024) 074023

- We cannot access to the x-dependence of GPDs

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

- Feasibility using the MARQ spectrometer



S. Sawada et al., PRD 93 (2016) 114034

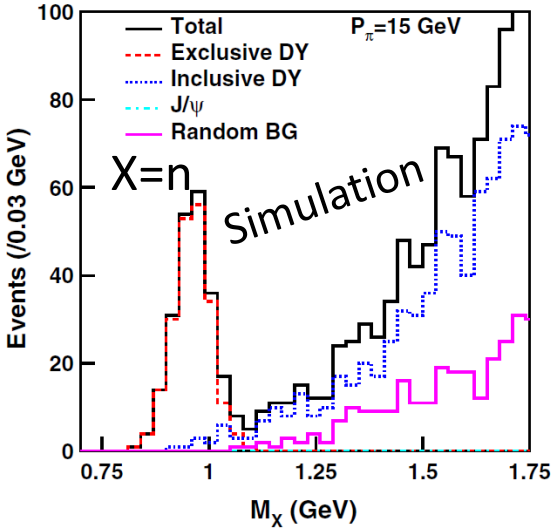
Upstream (COMPASS, Sea Quest)

↕

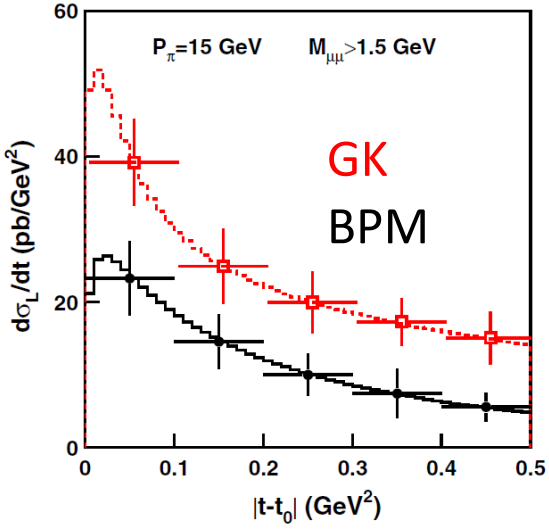
Absorber @ downstream of the tracker

⇒ Good momentum resolution enough to identify exclusive reaction

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



Cross section

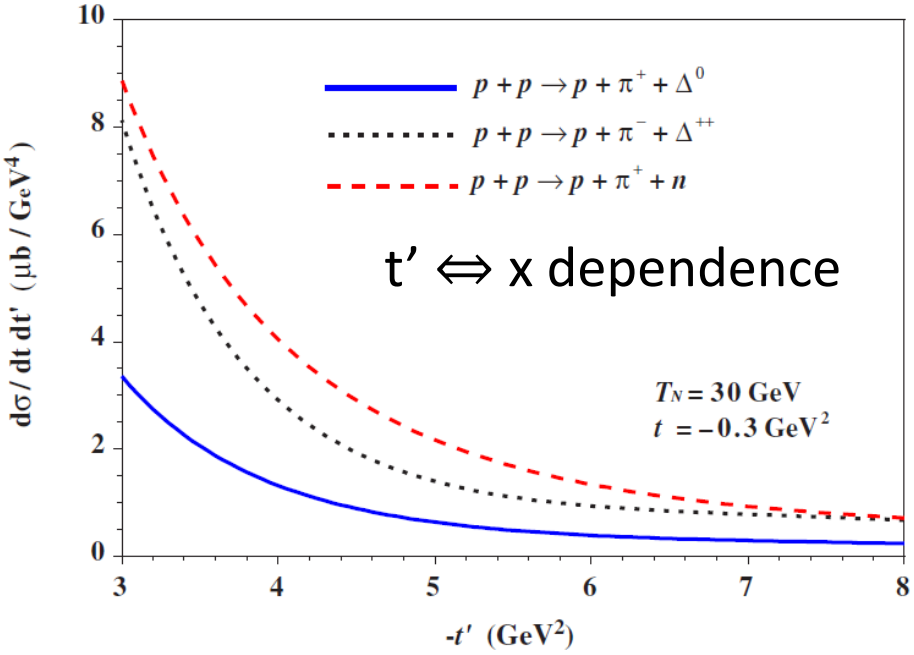


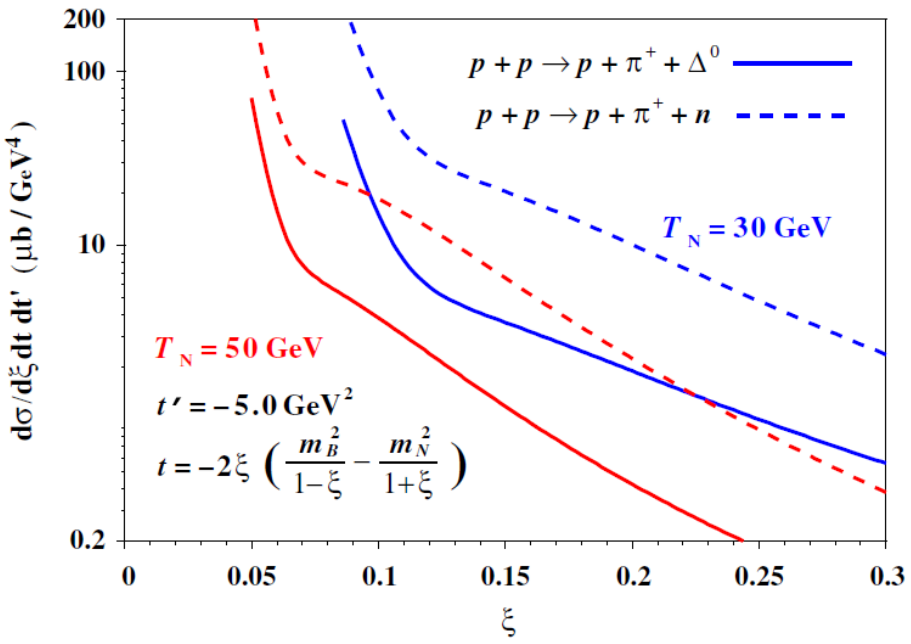
- O(1-10) pb
- Need full intensity π20 beam

p + p → p + π + B

- S. Kumano et al., PRD 80 (2009) 074003
- p and π : large and nearly opposite transverse momenta & large invariant energy

$$p + p \to p + \pi^+ + \Delta^0$$
$$p + p \to p + \pi^- + \Delta^{++}$$
$$p + p \to p + \pi^+ + n$$





- **Pure hadronic rection → very large cross section (O μb)**
- **Can probe x dependence of GPDs**
- **Can access the ERBL region**
- **Transition GPDs**

$p + p \rightarrow p + \pi + B$

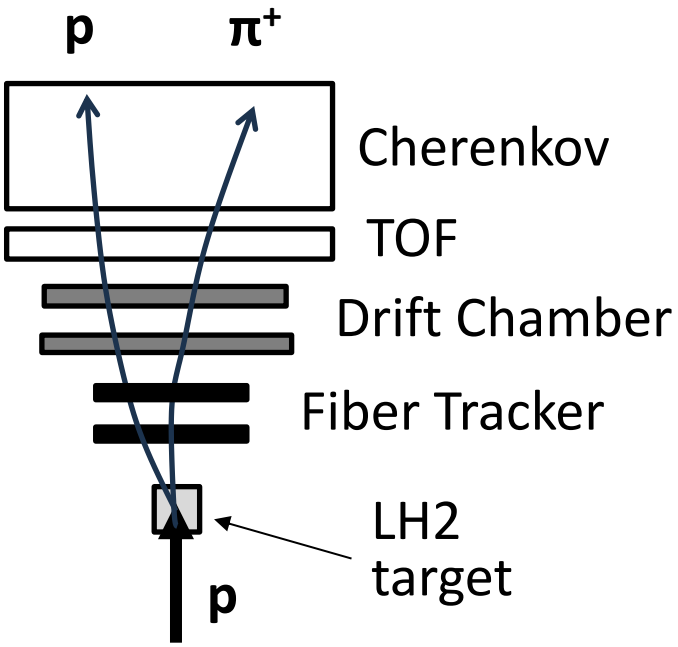
$p + p \rightarrow p + \pi^+ + n$

- Forward PID detectors (p, π^+ in $\Theta<10^\circ$)
- Missing Mass : $p+p \rightarrow p+\pi^+ + X$

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

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

- Side PID detectors
- Invariant mass : $\Delta^0 \rightarrow p+\pi^-$, $\Delta^{++} \rightarrow p+\pi^+$

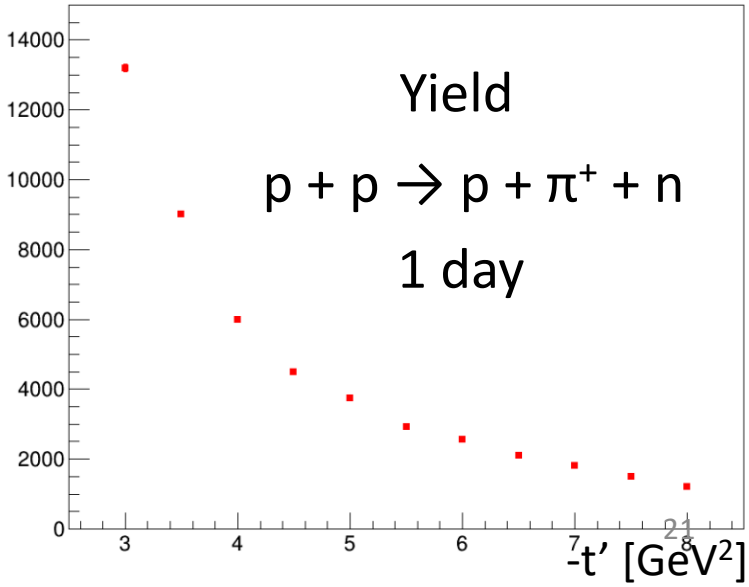


mini MARQ spectrometer

- FM magnet + Trackers (ready) +
  Gas Cherenkov Detector (p/π PID)

μb cross section

- Enough statistics within 1 day beam time



Can be an early-stage experiment in MARQ

You are welcome to join

Summary

- High momentum secondary beam is now available in J-PARC (π20 beamline)
- Multi-purpose MARQ spectrometer is under construction

- Single Diffractive Hard Exclusive Processes (SDHEP) to measure GPDs
  - $B + p \rightarrow C + D + p'$
  - B, C, D can be lepton, gamma or **hadron**
  - C, D : large transverse momentum >> four momentum transfer

- Feasibility study at J-PARC
  - $\pi^- + p \rightarrow \gamma + \gamma + n$: full intensity π20, EM calorimeter
  - $\pi^- + p \rightarrow \mu^+ + \mu^- + n$: full intensity π20, MARQ spectrometer + μ ID
  - $p + p \rightarrow p + \pi + B$: can be an early-stage experiment at MARQ

x dependence of GPDs, ERBL region

- Other possible measurements at J-PARC
  - $M + N \rightarrow \gamma + M + N'$
  - $M + N \rightarrow M + M + N'$

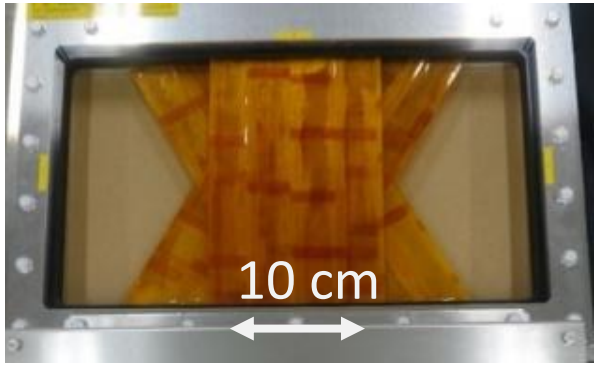
Backup

Tracking detectors

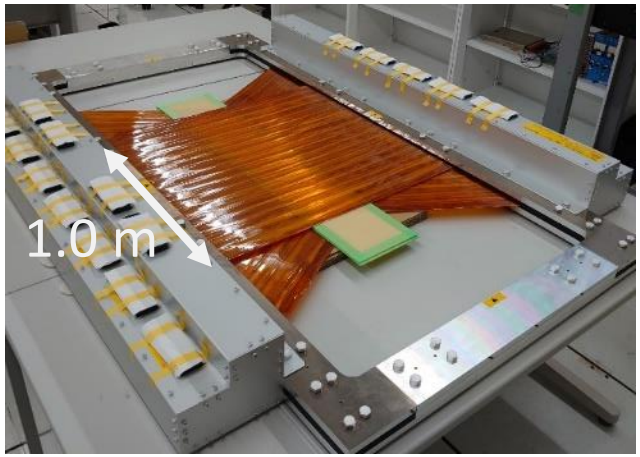
Fiber Trackers

- High rate : 1 MHz/mm
- Fiber scintillators

Beam Fiber Tracker (0.5 mm Φ)



Scattered Fiber Tracker (1.0 mm Φ)

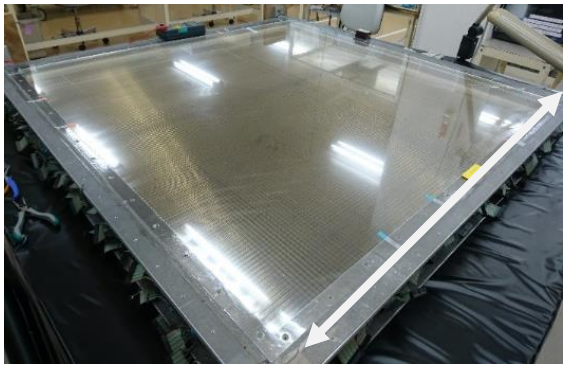


x6 : Ready

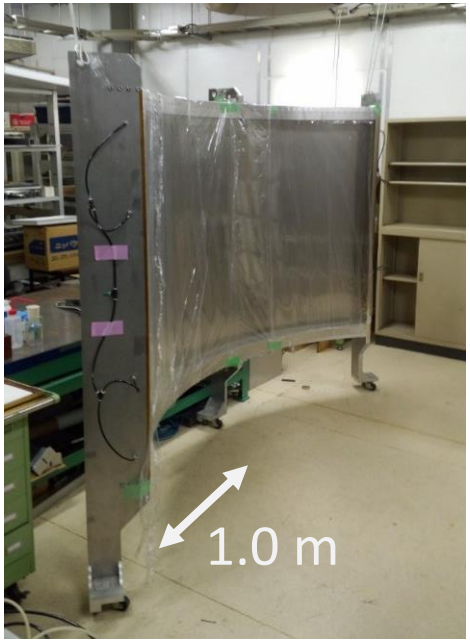
Drift Chamber (DC)

- Large acceptance

Target Downstream DC



Inner DC



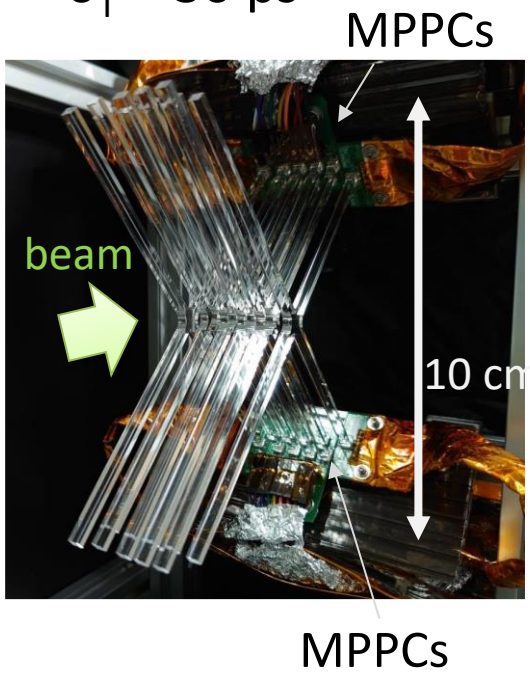
x5 : ready

x1 : planned

TOF detectors

T0

- Cherenkov + MPPC
- Suppression of dark currents using shot key barrier diode
- σ_T ~ 30 ps



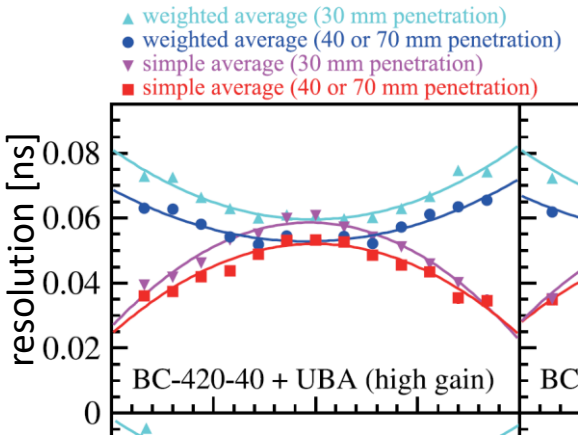
Ready

Forward TOF

- 1.8 m-long scintillator + PMT

T. Ishikawa et al.,
NIM A 1039 (2022)
167164

Ready

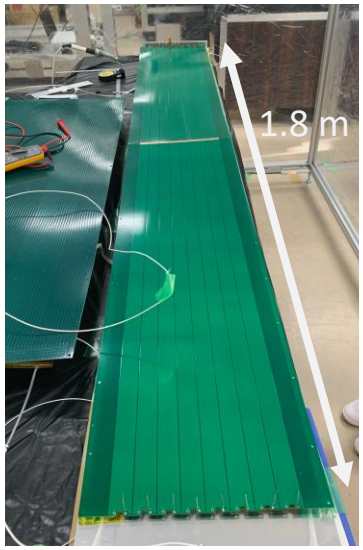


Side TOF

- 1.8 m-long Resistive Place Chamber (RPC)

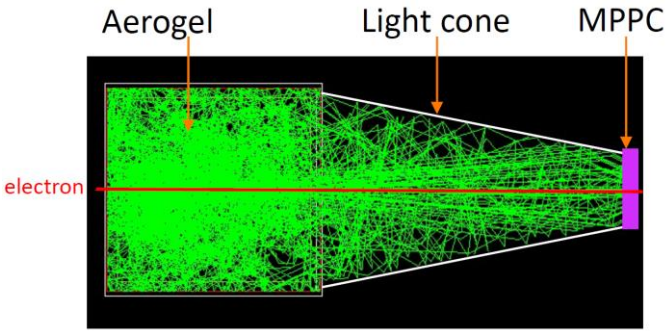
N. Tomida et al.,
NIM A 1056 (2023)
168581

Prototype tests



PID detectors

Threshold type Aerogel Cherenkov



Geant4 simulation

Light cone + MPPC : design completed

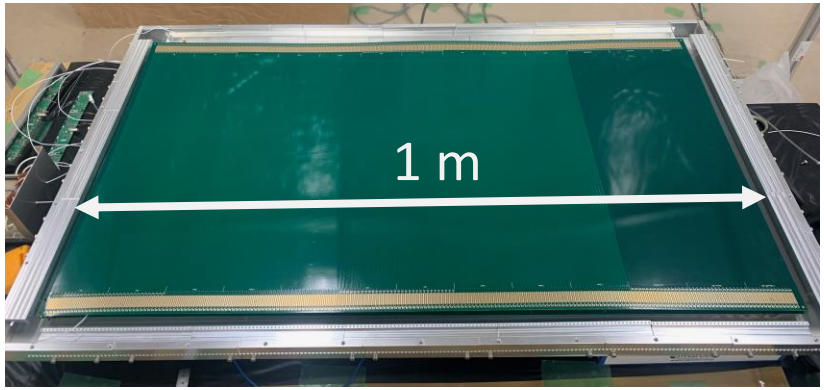
Ring Imaging Cherenkov detector (RICH)

- MPPC + light guide cone

Prototype test

μ ID tracker

- Multigap Resistive Plate Chamber (MRPC) based tracker

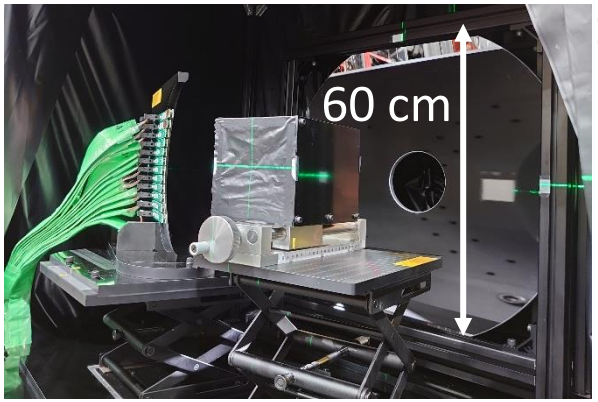


N. Tomida et al., NIM A 1077 170517 (2025)

Prototype test

beam RICH (bRICH)

- MPPC Ready



Electronics

ASAGI

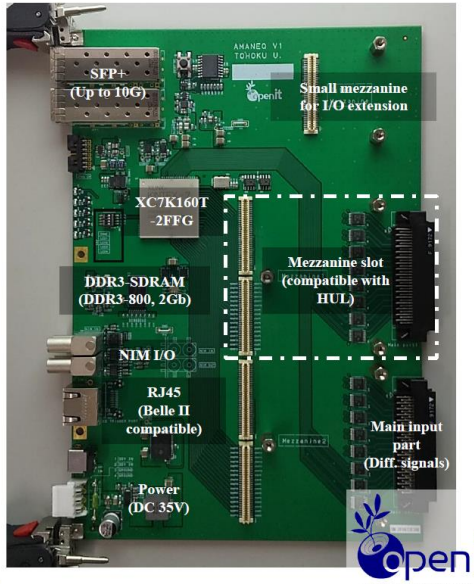
- Amp-Shaper-Discriminator Card for DCs
- Ready

CIRASAME

- Multi MPPC readout card for Fiber Trackers and Cherenkov counters
- Ready

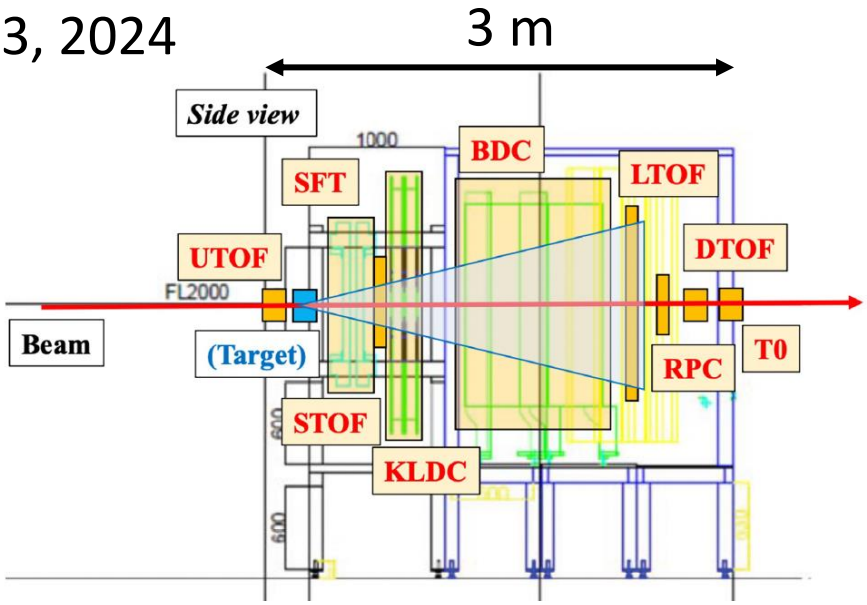
AMANEQ

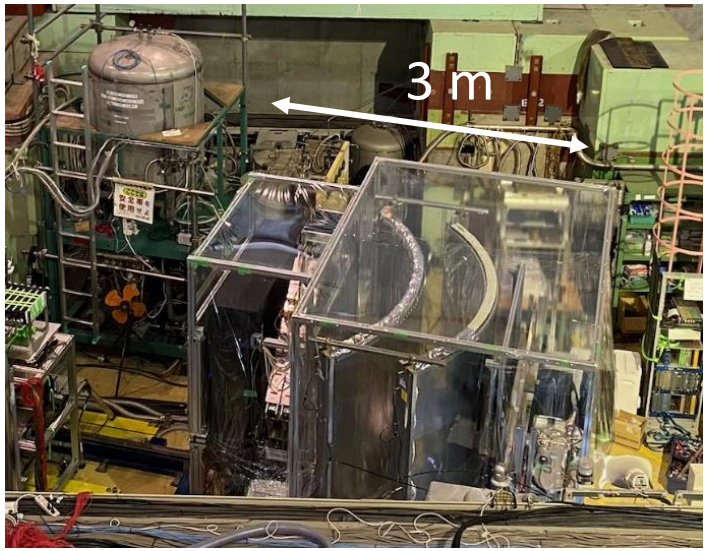
- The main electronics board for the streaming data acquisition system
  - Mezzanine card
    - HR-TDC
    - LR-TDC
    - Clock distribution
- Ready



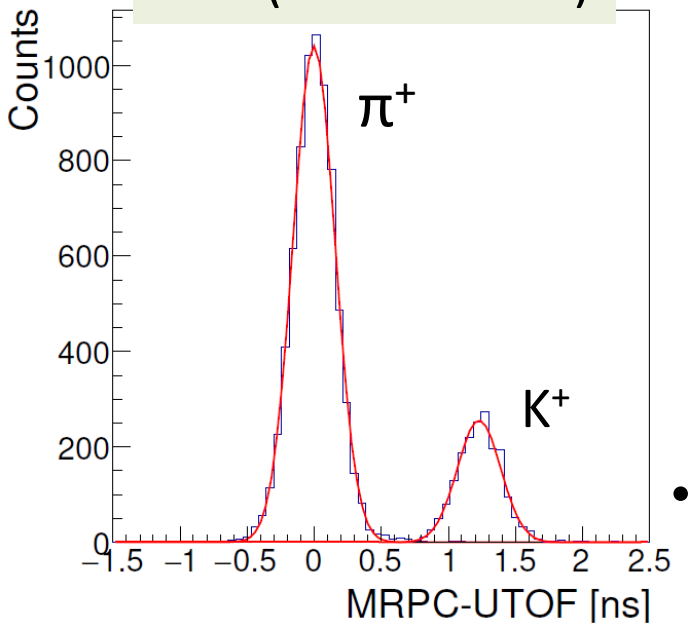
Detector Test @ J-PARC K1.8BR beamline

- 2023, 2024



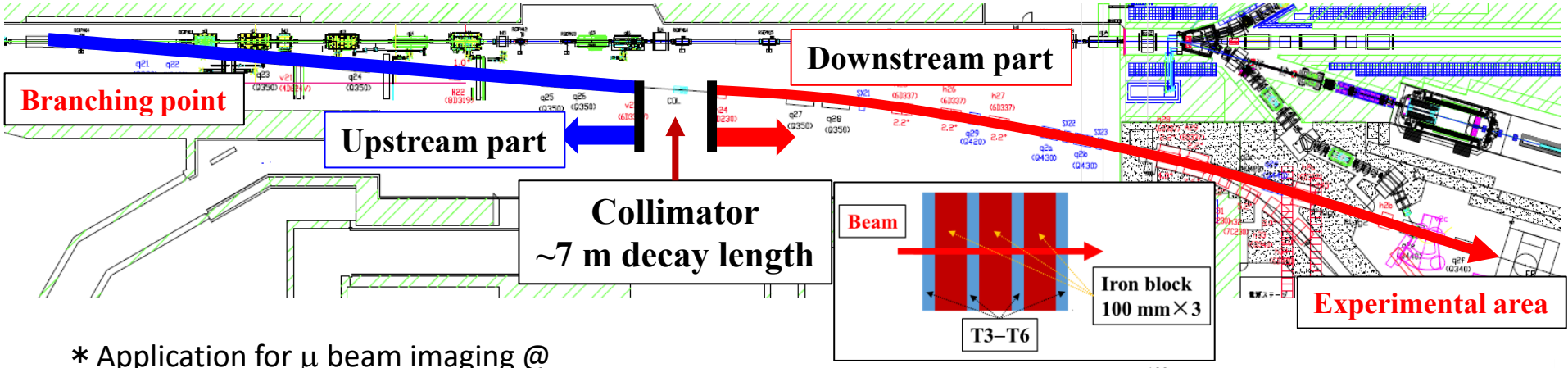


TOF (UTOF-MRPC)



- First streaming DAQ test
  ⇒ success !!
- Online filtering works
- π/K separation with TOF

T106 results: Study of μ beam @ μ20 mode



∗ Application for μ beam imaging @ Several GeV/c

⇒ μ20 mode: Magnet setting [Downstream]/[Upstream] = 60, 75, 80, 85%

∗ Measured μ beam properties @ 5 GeV/c (60%)

- Intensity ~2 k/spill
- Purity ~99%