# GPDs measurement at J-PARC using hadron beams

3D Structure of the Nucleon via Generalized Parton Distributions

2024/Jun/25-28

Natsuki TOMIDA
Kyoto University

# Generalized Parton Distributions (GPDs)

Four Quark GPDs

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

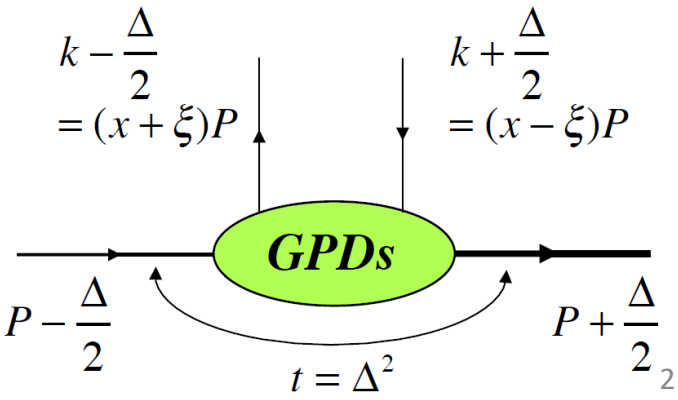
3 variables
- x : Fraction of longitudinal momentum
- $\xi$ : Fraction of transferred momentum
- t : Four momentum transfer

H : Helicity conserve
E : Helicity flip
H,E : unpolarized
$\tilde{H}$,$\tilde{E}$ : polarized

Many functions and variables

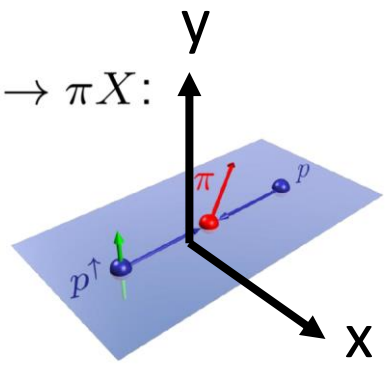
Need to determine GPDs using global fits of different measurements

A lot of data in different kinematics is necessary to determine GPDs



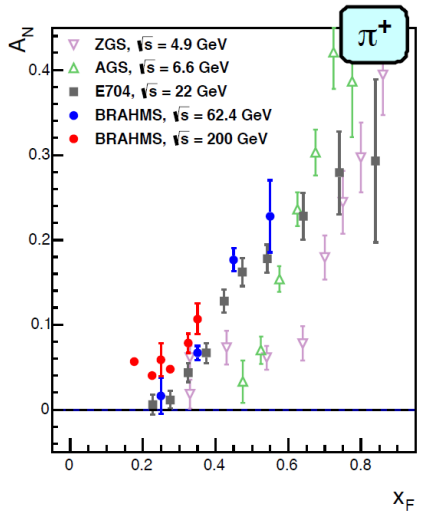
# Single Spin Asymmetry

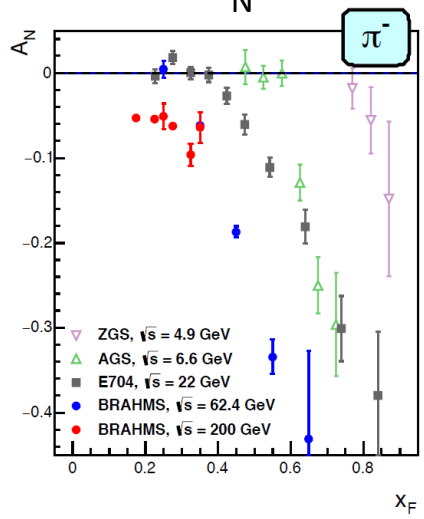
$P^{\uparrow}P \to \pi X$:

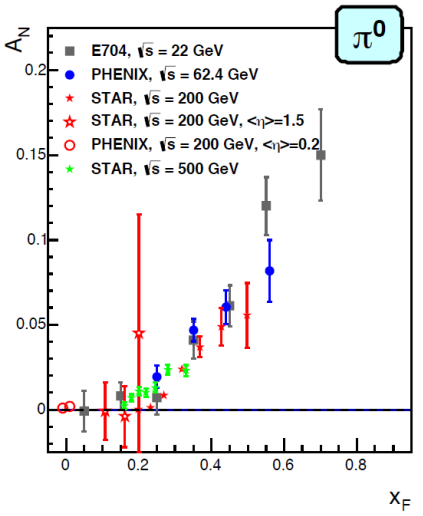



$$A_N = \frac{d\sigma_{left} - d\sigma_{right}}{d\sigma_{left} + d\sigma_{right}}$$

$A_N$



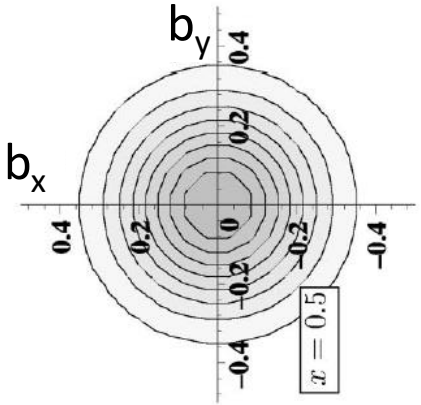



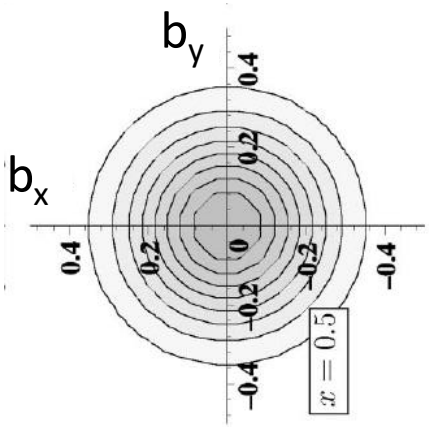

The RHIC cold QCD plan, arXiv:1602.03922

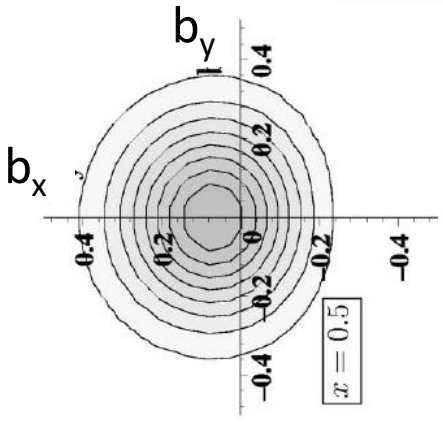
## Quark distributions expressed with GPDs

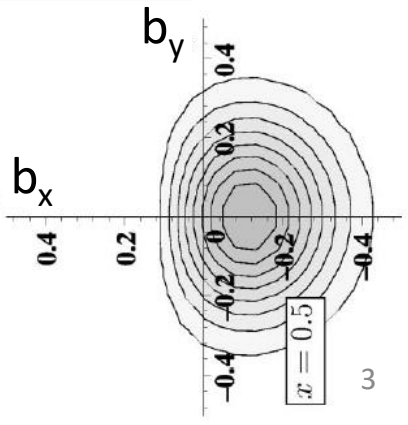
PRD 66 114005 (2002)

u Unpolarized d x = 0.5 u Transversely Polarized d



# GPDs contain rich information

- $\xi \to 0, t \to 0$ : 1D parton distribution (PDFs)

$H^q(x,0,0) = q(x)$ Unpolarized $\qquad \tilde{H}^q(x,0,0) = \Delta q(x)$ Polarized

- 1st moment of x : Form factor

$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$ Dirac $\qquad \int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$ Pauli

$\int_{-1}^{1} dx \tilde{H}^q(x,\xi,t) = g_A^q(t)$ Axial $\qquad \int_{-1}^{1} dx \tilde{E}^q(x,\xi,t) = g_P^q(t)$ Pseudoscalar

- 2nd moment of x : Gravitational Form Factor

$$\int_{-1}^{1} dx\, x\big(H(x,\xi,t) + E(x,\xi,t)\big) = 2J^Q(t)$$

Total Spin

$$\int_{-1}^{1} dx\, x H(x,\xi,t) = M_2^Q(t) + \frac{4}{5} d^Q(t)\xi^2$$

Mass Pressure

can probe the origin of nucleon spin and mass

x dependence is important

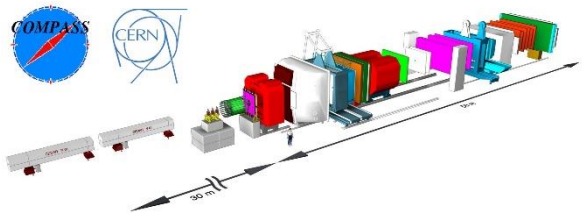
# GPDs measurements till now

- Deeply Virtual Compton Scattering (DVCS) : $l + p \rightarrow l' + p' + \gamma$
- Deeply Virtual Meson Production (DVMP) : $l + p \rightarrow l' + p' + M$
- Time-like Compton Scattering (TCS) $\gamma + p \rightarrow l^+ + l^- + p'$

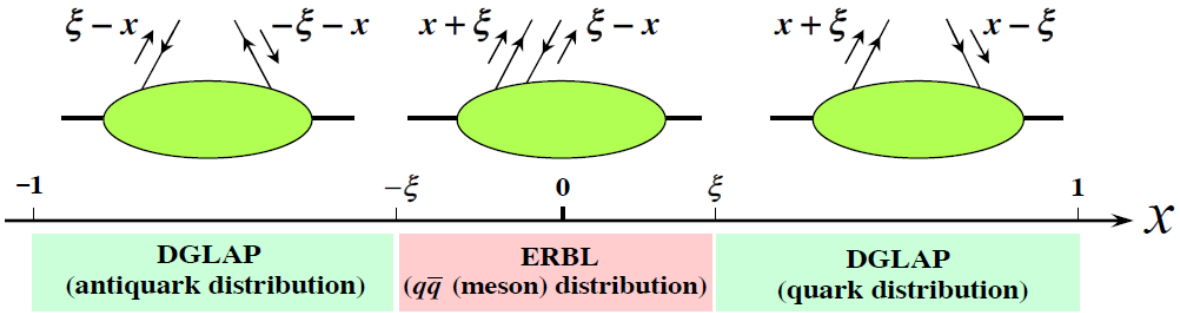
HERMES(ep collider)


JLab(e, $\gamma$ beam)

COMPASS($\mu$ beam)




- Cross sections depend on integral of x $\Rightarrow$ x dependence cannot be measured
- Access only the DGLAP region




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

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

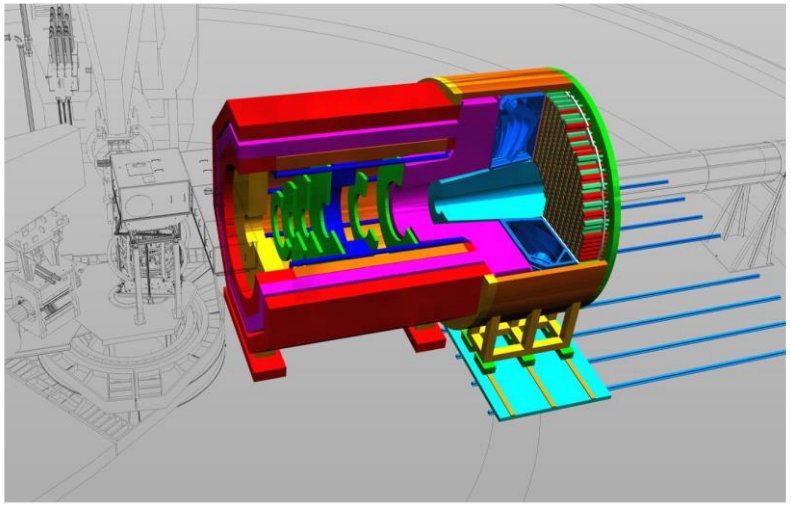
# New experiments

CERN AMBER（μ beam）

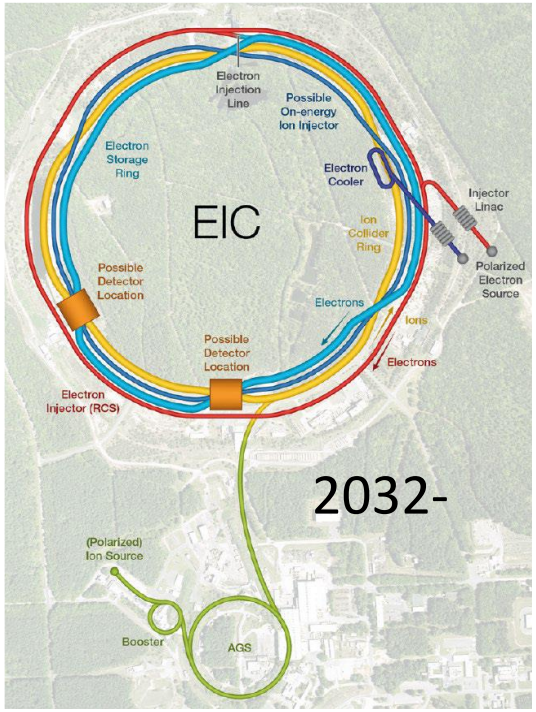
AMBER

Apparatus for Meson and Baryon Experimental Research

JLab SoLID (e beam)



EIC (ep collider)

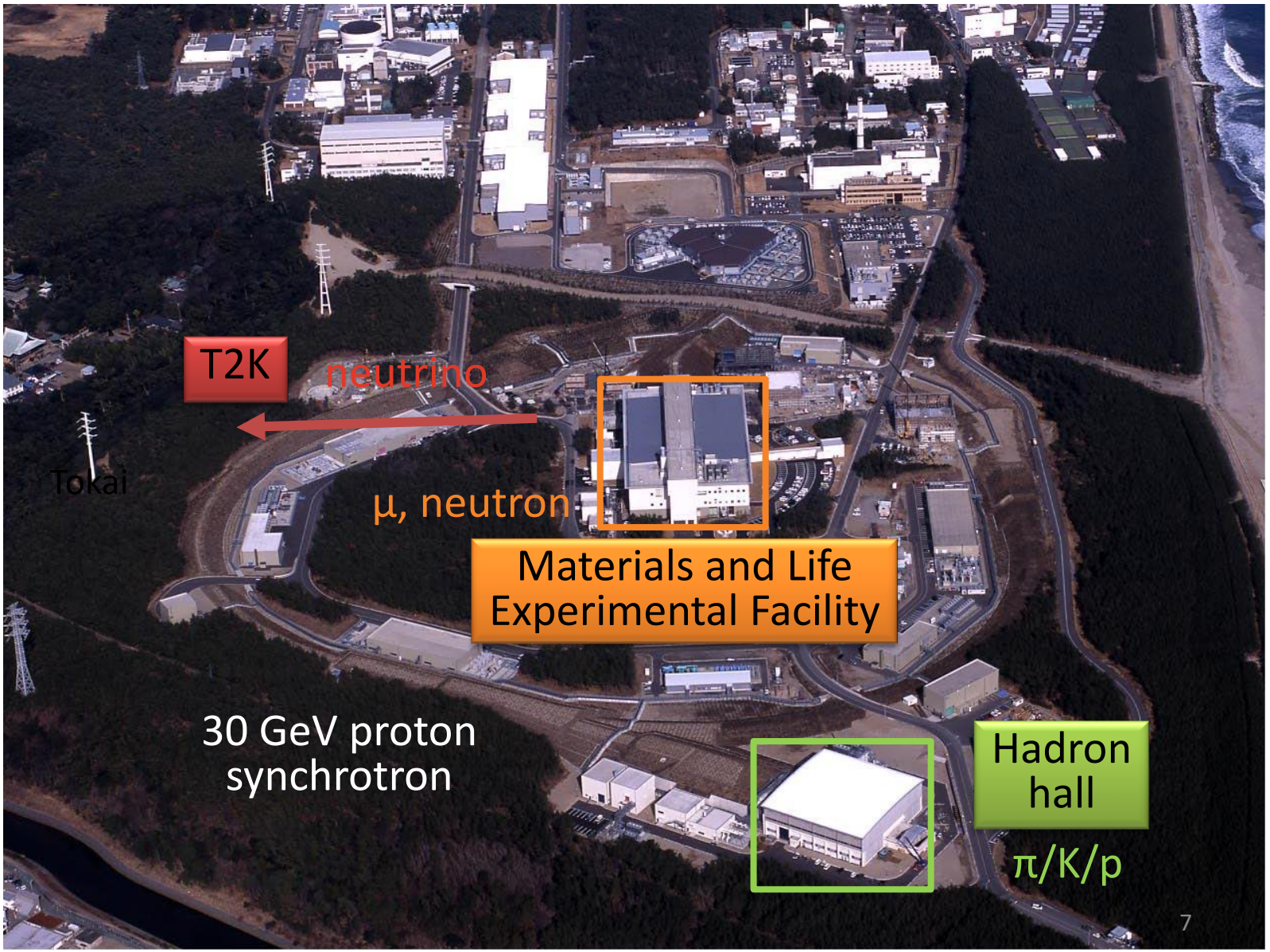



J-PARC (hadron beam)

Unique reactions & kinematics

# J-PARC

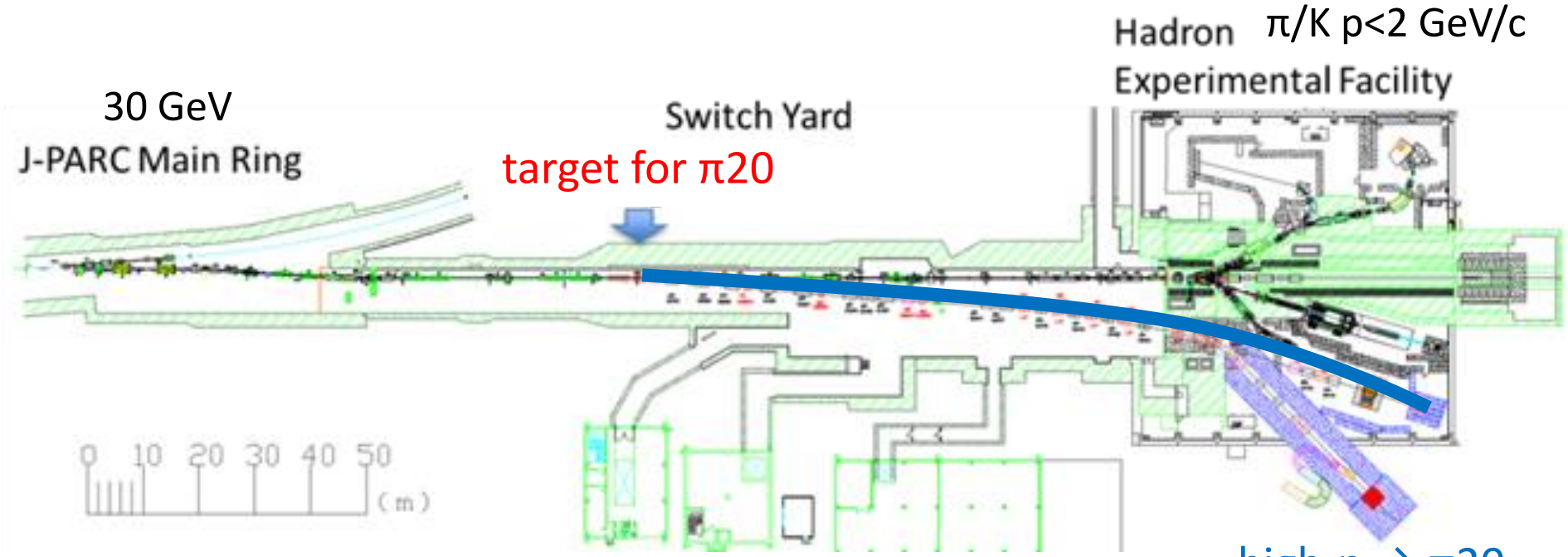
**J**apan **P**roton **A**ccelerator **R**esearch **C**omplex (in Tokai)



# High momentum beamline @ J-PARC

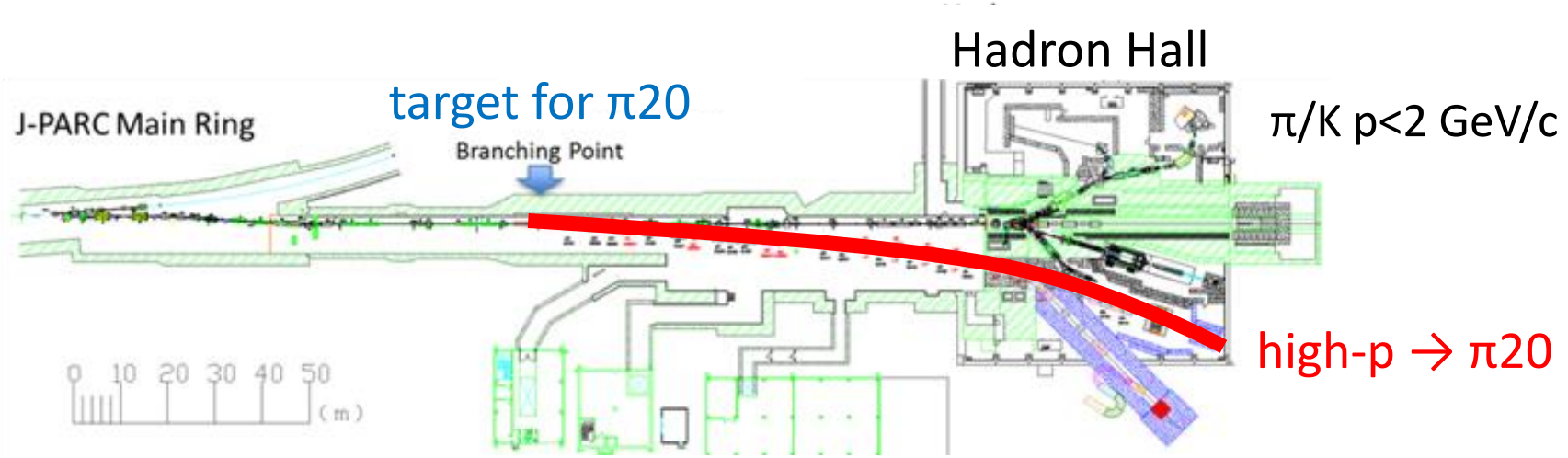
- -2020 : Secondary beam up to 2 GeV/c
- 2020- : Primary 30 GeV proton beam is now available at the high-p beamline
- Construction of the secondary π/K/p beamline up to 20 GeV/c (= π20 beamline) is planned

We can carry out large $Q^2$ experiments at J-PARC !




high-p → π20
30 GeV p → < 20 GeV π/K/p

# Status and plan of the high-p beamline




- 2020 : First 30 GeV primary proton beam
- 2024or2025 : First 30 GeV proton physics run (E16 experiment)

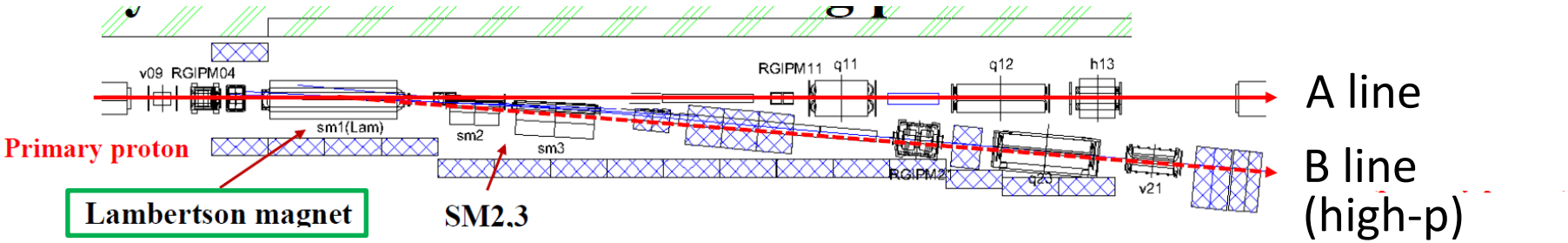
- 202X : Secondary π/K/p at 2-20 GeV/c (π20 beamline)
  - Phase 1 ($10^5$/spill): in a few years
  - Phase 2 (a few $10^6$/spill)
  - Phase 3 ($6 \times 10^7$/spill)

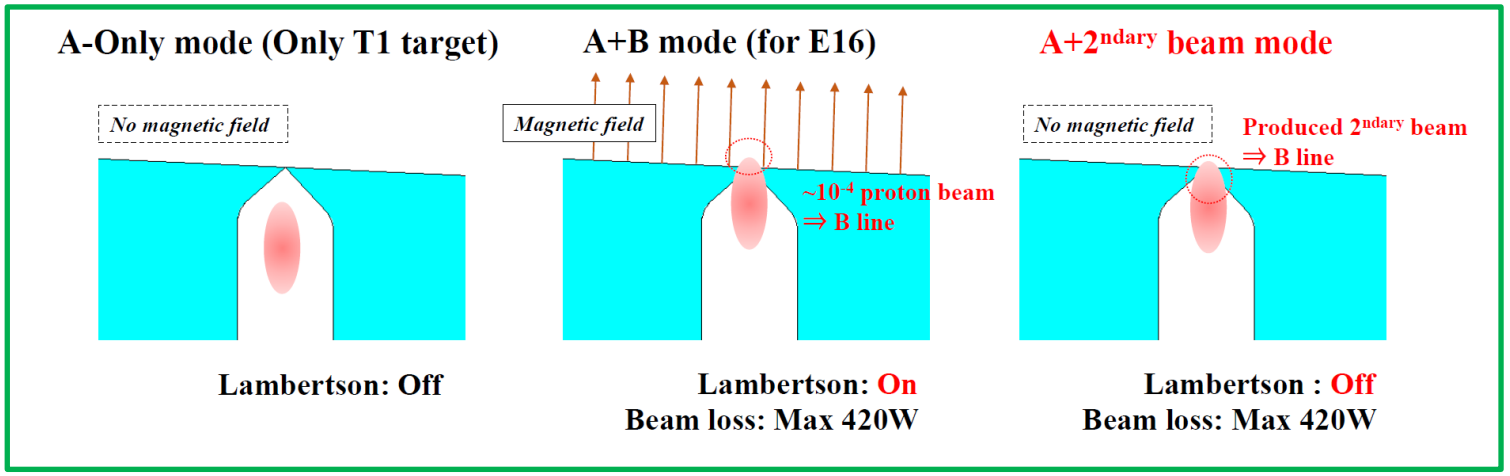
1 spill = 2s

**MARQ** (**M**ulti-Purpose **A**nalyzer for **R**esonance and **Q**uark dynamics) collaboration & MARQ spectrometer

# π20 staging plan

- **Phase 1 : Minimum modification of the current beamline : $10^5$/spill**
  - Use the Lambertson magnet as a production target
  - Polarity change devices ⇒ negative beam delivery



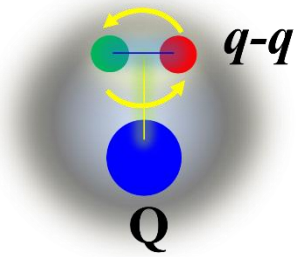



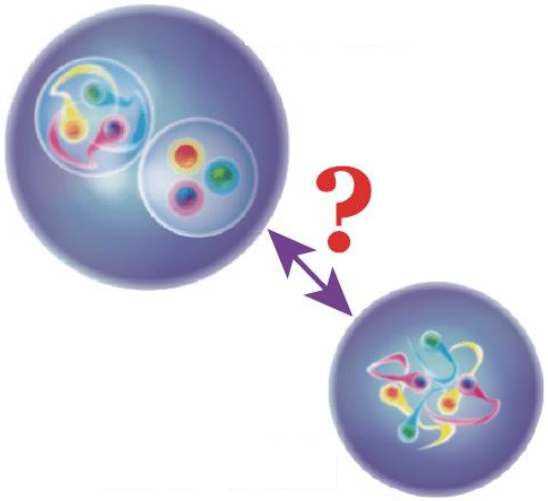

P93
PAC

- **Phase 2 : Target & Swinger magnet : a few $10^6$/spill**
- **Phase 3 : Radiation shields : $6 \times 10^7$/spill**

# Physics program @ π20 beamline

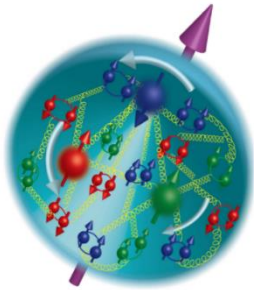
- **Hadron structure**
  - Charmed baryon spectroscopy
  - Ξ (s=-2) baryon spectroscopy




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

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

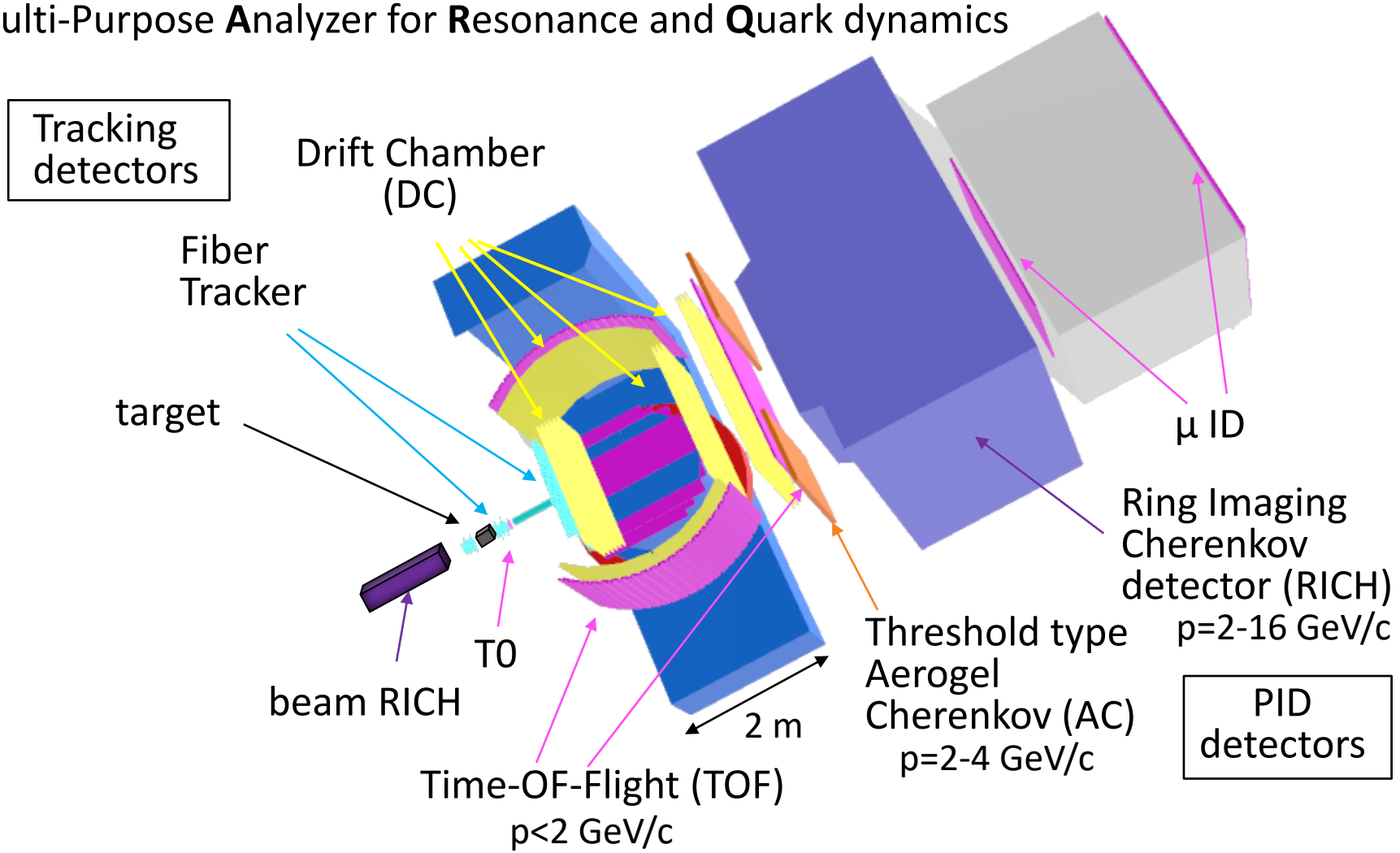


- **Elementary cross sections**
  - Λp scattering cross section
  - Hadronic cross sections for neutrino experiments

**MARQ collaboration**

# MARQ Spectrometer

**M**ulti-Purpose **A**nalyzer for **R**esonance and **Q**uark dynamics




- Streaming DAQ : no hardware trigger, online filtering
- High rate stability : 1MHz/1 mm @ center
- Large acceptance • High momentum resolution

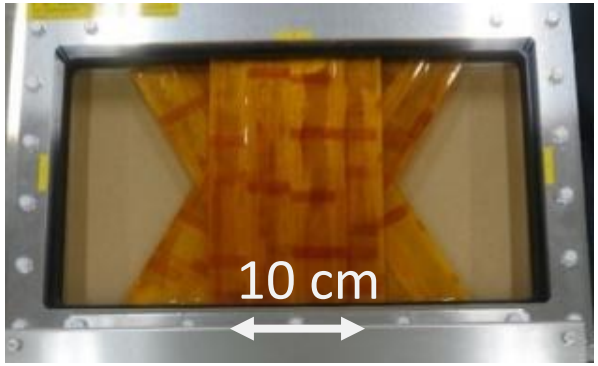
R. Honda et al., PTEP 123H01 (2021)

# Tracking detectors

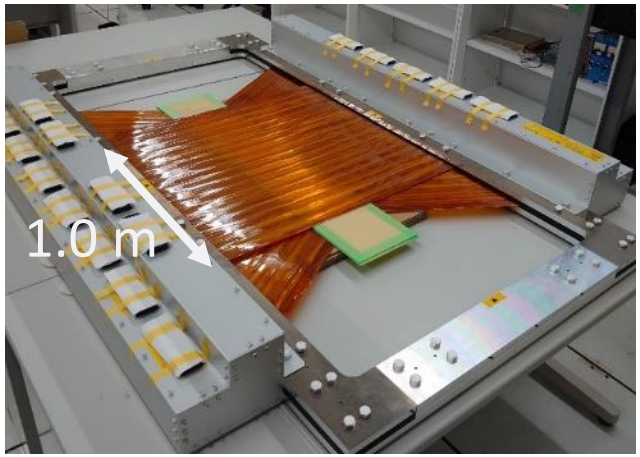
## Fiber Trackers

- High rate : 1 MHz/mm
- Fiber scintillators

Beam Fiber Tracker (0.5 mm Φ)




Scattered Fiber Tracker (1.0 mm Φ)

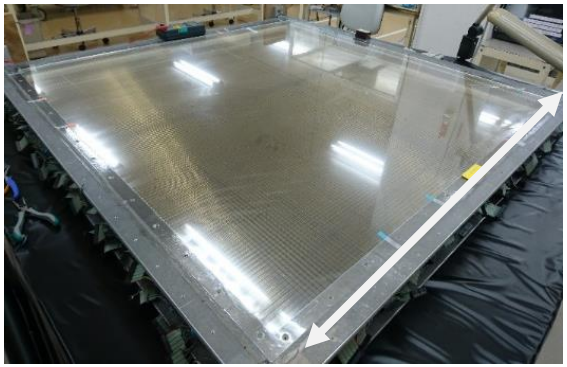



x6 : Ready

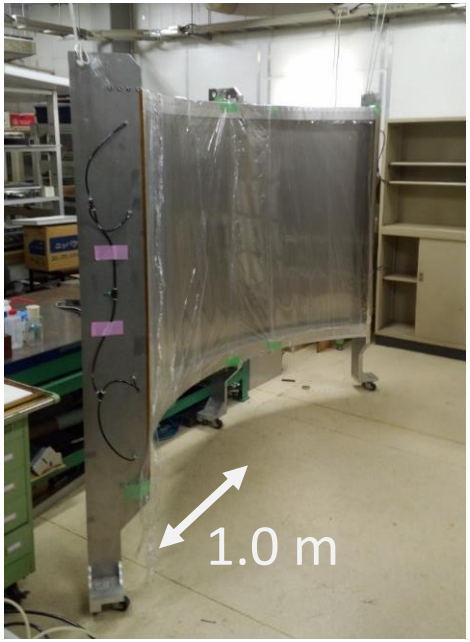
## Drift Chamber (DC)

- Large acceptance

Target Downstream DC



Inner DC

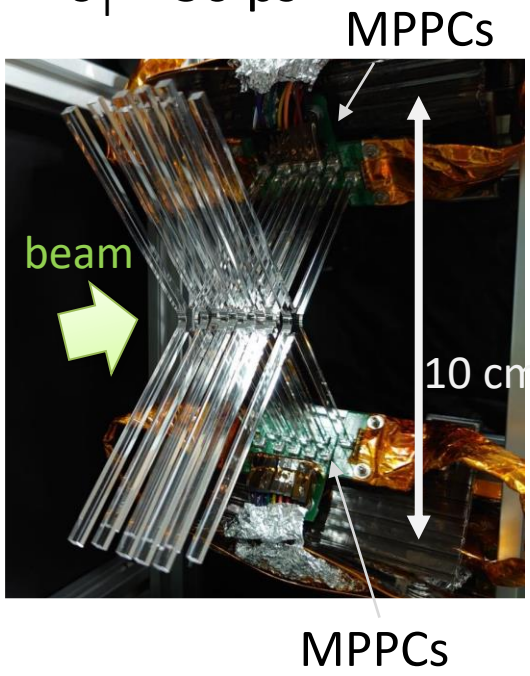



x4 : ready
x1 : ready in 2024
x1 : planned

# TOF detectors

## T0

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



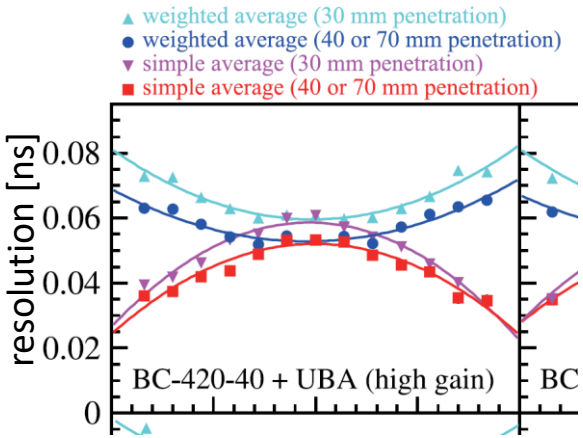

Ready

## Forward TOF

- 1.8 m-long scintillator + PMT

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

Ready

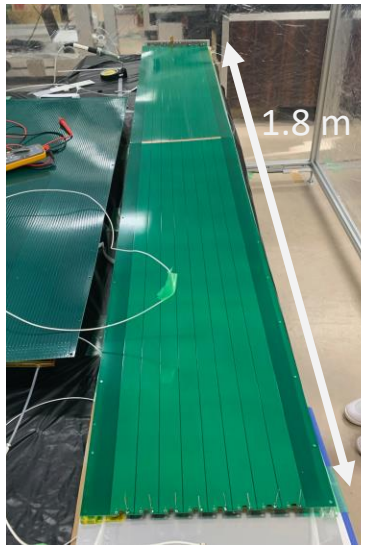



## Side TOF

- 1.8 m-long Resistive Place Chamber (RPC)

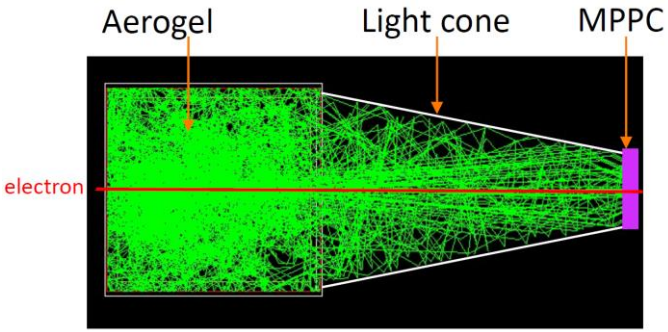
N. Tomida et al.,
NIM A 1056 (2023)
168581

Prototype tests



# PID detectors

## Threshold type Aerogel Cherenkov




Geant4 simulation

Light cone + MPPC : design completed

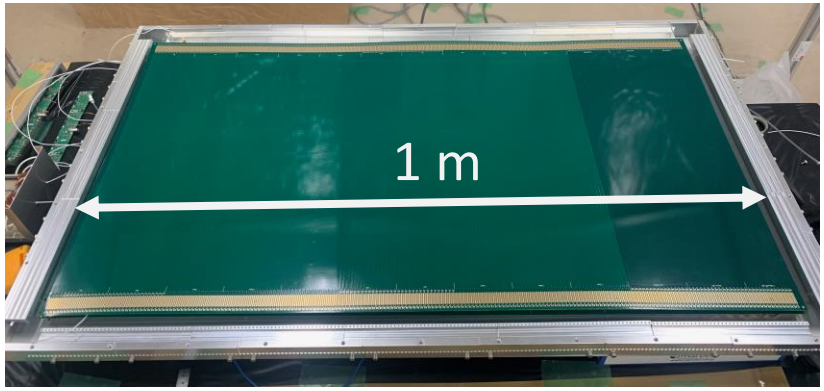
## Ring Imaging Cherenkov detector (RICH)


- MPPC + light guide cone

Prototype test

## μ ID tracker

- Multigap Resistive Plate Chamber (MRPC) based tracker

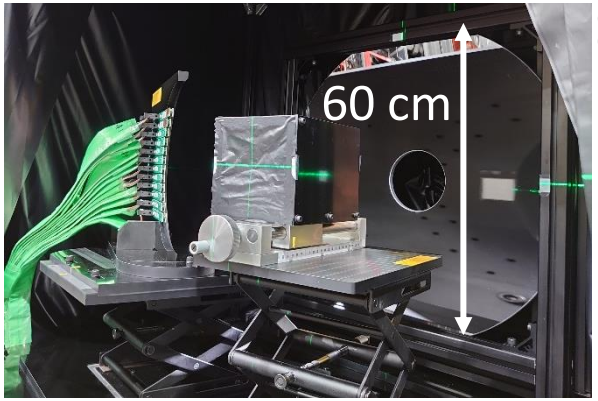



R. Uda et al., NIM A 1056 (2023) 168580

Prototype test

## beam RICH (bRICH)

- MPPC Design completed



# Electronics

## ASAGI

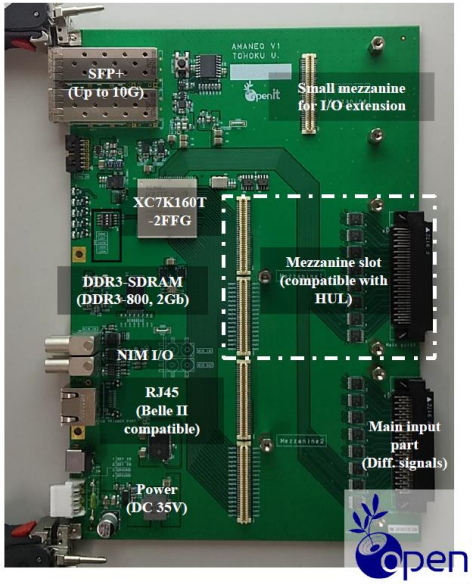
- Amp-Shaper-Discriminator Card for DCs
- Ready

## CIRASAME

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

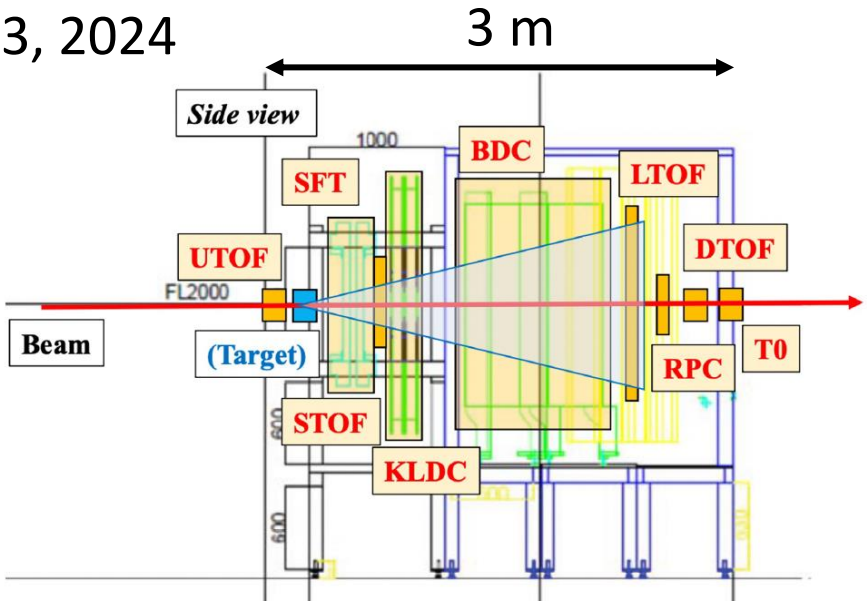

## AMANEQ

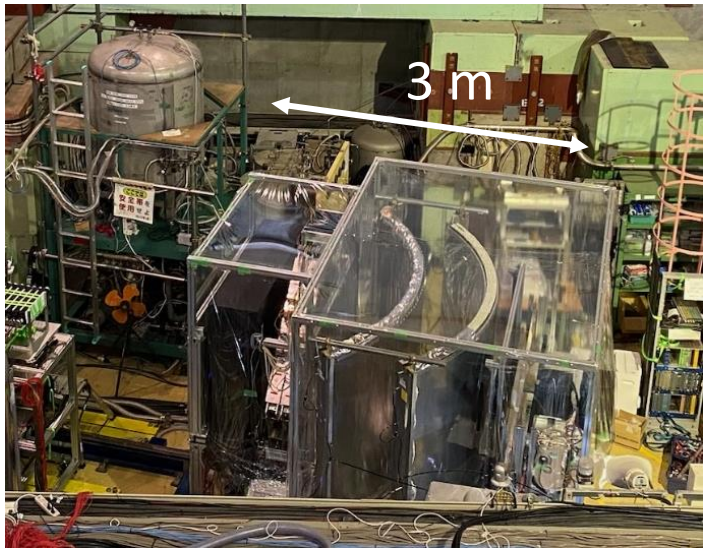
- The main electronics board for the streaming data acquisition system
  - Mezzanine card
    - HR-TDC
    - LR-TDC
    - Clock distribution
- Ready



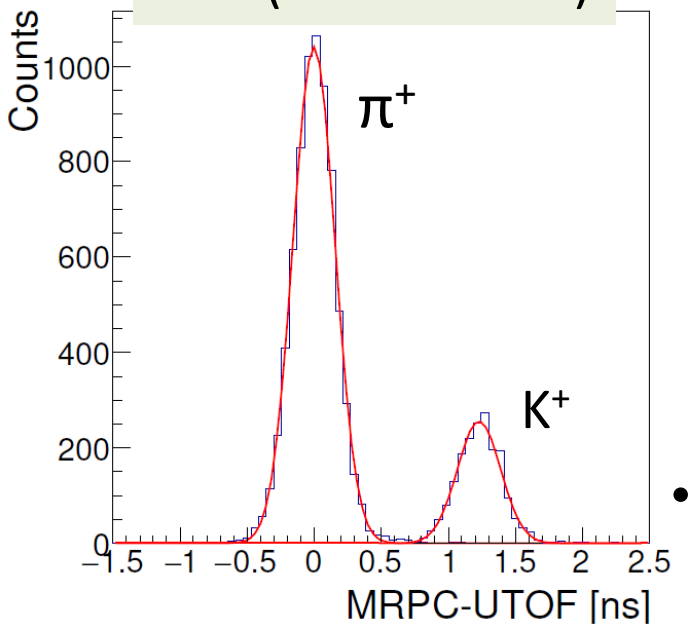
# Detector Test @ J-PARC K1.8BR beamline

- 2023, 2024



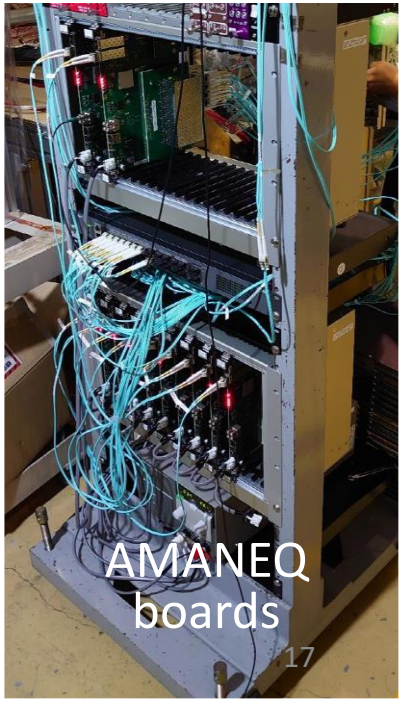




TOF (UTOF-MRPC)




- First streaming DAQ test
  ⇒ success !!
- Online filtering works

- π/K separation with TOF



# Nucleon structure studies in J-PARC

Current 30 GeV proton beam

- GPDs study with $p+p \rightarrow p+\pi+B$ (μb)
- p induced Drell-Yan (nb)

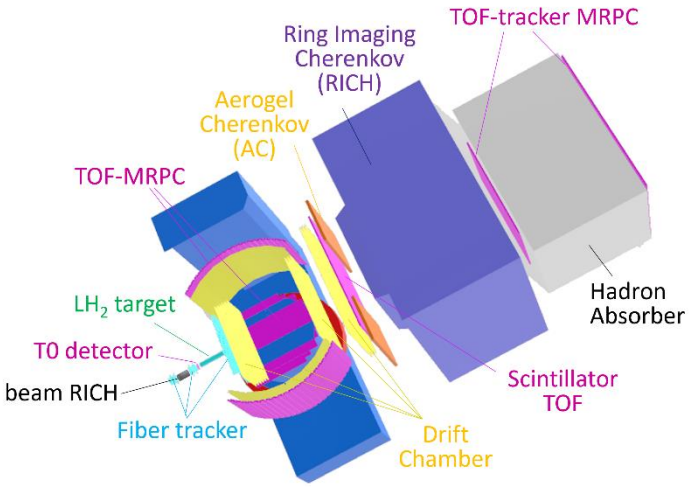
Positive secondary beam (<20 GeV/c)

- Color transparency search (nb-pb, depends on momentum)

Negative secondary beam (<20 GeV/c)

- π/K induced Drell-Yan (nb)
- GPDs study with $\pi^- + p \rightarrow \gamma + \gamma + n$ (O(10-100) pb)
- GPDs study with $\pi^- + p \rightarrow \mu^+ + \mu^- + n$ (exclusive Drell-Yan) (O(1-10) pb)

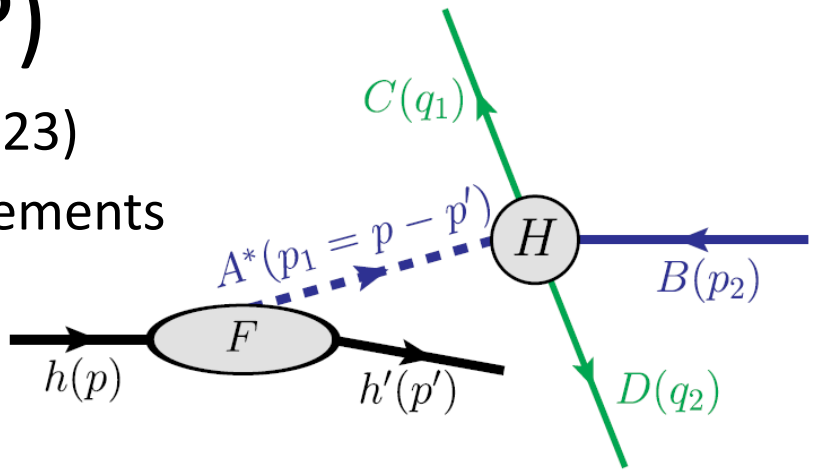
with MARQ collaboration



# Single Diffractive Hard Exclusive Process (SDHEP)

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

Recent theoretical study 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)

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

$\gamma$ beam
- $\gamma + N \rightarrow l^+ + l^- + N'$ (TCS)
- $\gamma + N \rightarrow \gamma + \gamma + N'$
- $\gamma + N \rightarrow \gamma + M + N'$
- $\gamma + N \rightarrow M + M + N'$

Meson beam
- $M + N \rightarrow l^+ + l^- + N'$ (Exclusive Drell-Yan)
- $M + N \rightarrow \gamma + \gamma + N'$
- $M + N \rightarrow \gamma + M + N'$
- $M + N \rightarrow M + M + N'$

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

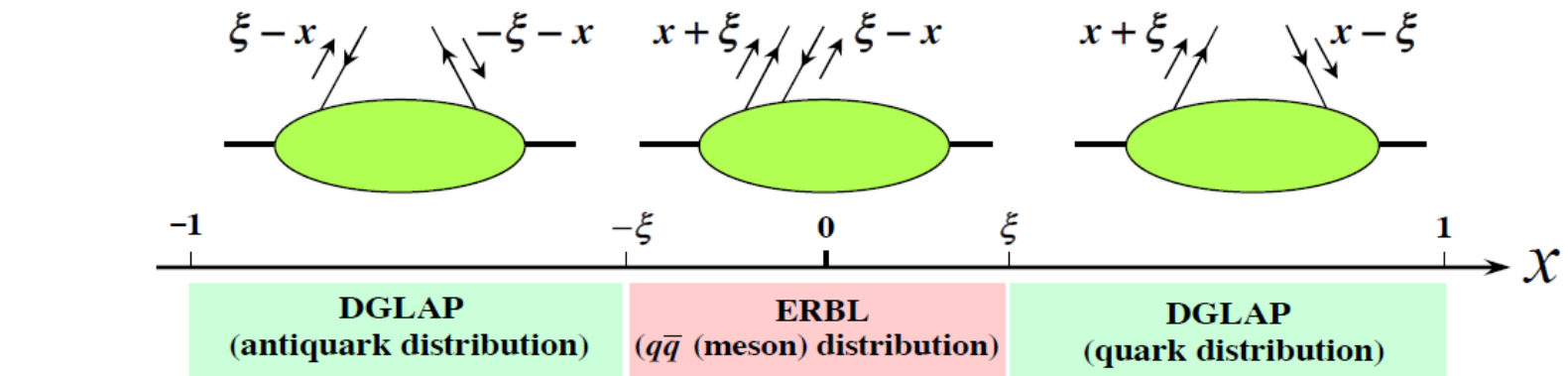
Factorization proved

PRD 107 014007 (2023)

# Single Diffractive Hard Exclusive Process (SDHEP)

Some processes

- can access x-dependence of GPDs
- can access ERBL region




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

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

# SDHEPs measurement at J-APRC

Lepton beam

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

$\gamma$ beam

- $\gamma + N \rightarrow l^+ + l^- + N'$ (TCS)
- $\gamma + N \rightarrow \gamma + \gamma + N'$
- $\gamma + N \rightarrow \gamma + M + N'$
- $\gamma + N \rightarrow M + M + N'$

Feasibility study done

Meson beam

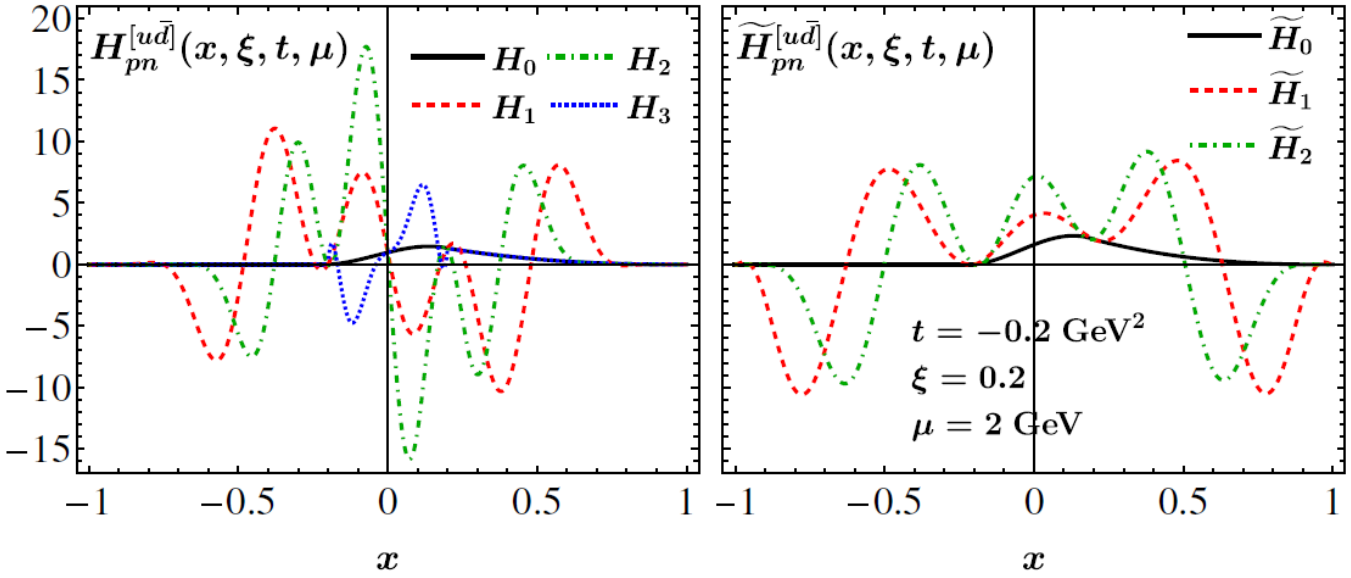
- $M + N \rightarrow l^+ + l^- + N'$ (Exclusive Drell-Yan) **PLB 523 (2001) 265** **PLB 748 (2015) 323**
- $M + N \rightarrow \gamma + \gamma + N'$ **PRD 109 (2024) 074023**
- $M + N \rightarrow \gamma + M + N'$
- $M + N \rightarrow M + M + N'$

Proton beam

- $N + N \rightarrow M + B + N'$ **PRD 80 (2009) 074003**

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

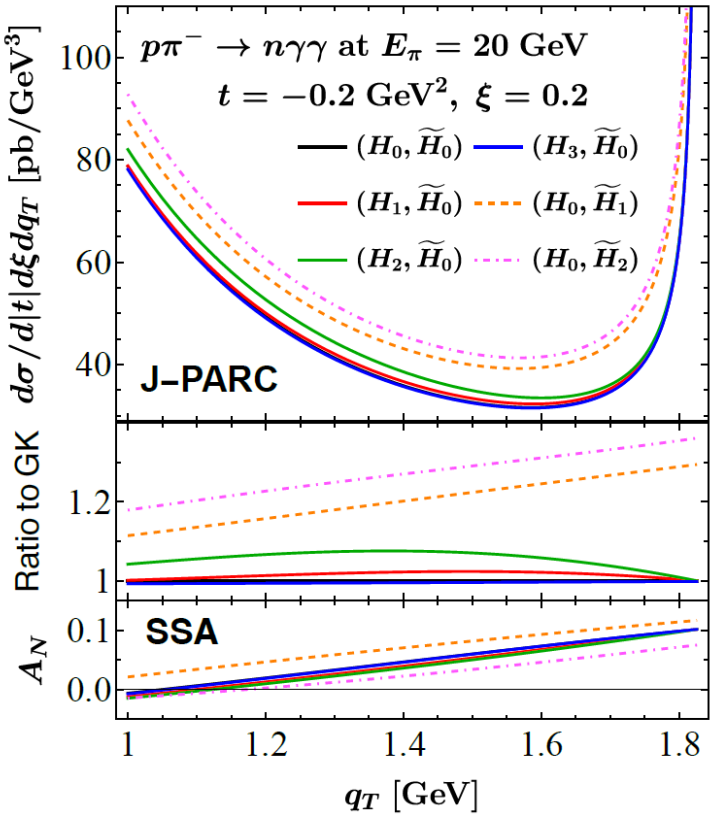
- J.-W. Qiu and Z. Yu
- PRD 109 (2024) 074023
- $\gamma\gamma$ : Large opposite transverse momentum
- **x dependence of GPDs can be measured**
- **Can differentiate shadow GPDs and real GPDs**




- Large sensitivity to the DGLAP region near x = $\pm\xi$

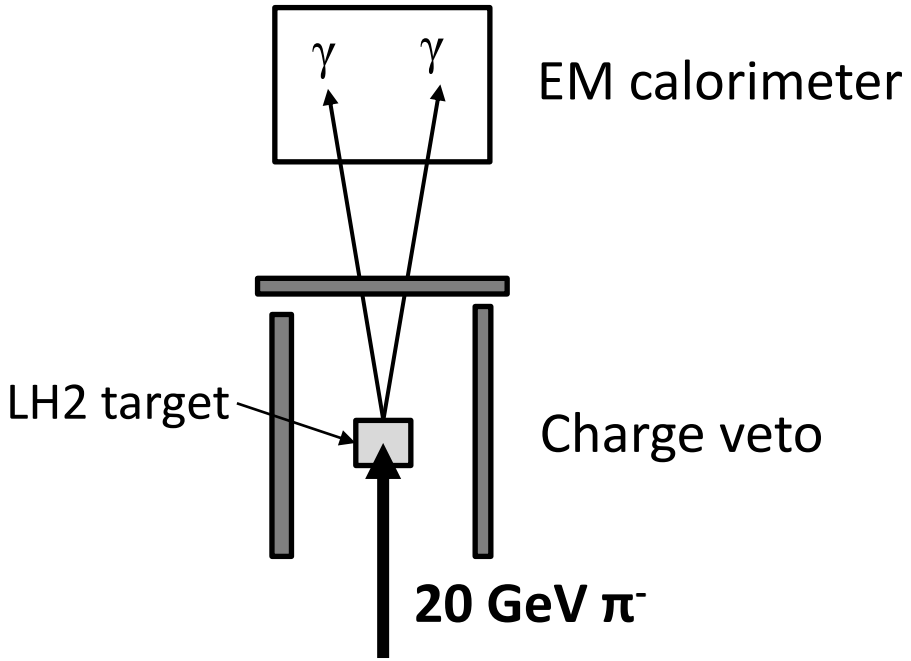
# $\pi^- + p \rightarrow \gamma + \gamma + n$

Estimated cross section




- Feasible at π20 Phase 3 (full intensity)

Necessary setup




- Need an EM calorimeter which is not included to the MARQ spectrometer design

# p + p → N + π + B

- PRD 80 (2009) 074003
- Studied by S. Kumano, M. Strikman and K. Sudoh independent from discussions on SDHEP
- **Can be measured at the current high-p beamline**
- N, π : large opposite transverse momentum

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

$$\sum_{\lambda_N,\lambda_{N'}} |\mathcal{M}_N^V|^2 = I_N^2 \Big[ 8(1-\xi^2)\{H(x,\xi,t)\}^2 + 16\xi^2 H(x,\xi,t) E(x,\xi,t) - \frac{t}{m_N^2}(1+\xi)^2 \{E(x,\xi,t)\}^2 \Big].$$

$$\sum_{\lambda_N,\lambda_{N'}} |\mathcal{M}_N^A|^2 = I_N^2 \Big[ 8(1-\xi^2)\{\tilde{H}(x,\xi,t)\}^2 + 18\xi^2 \tilde{H}(x,\xi,t)\tilde{E}(x,\xi,t) - \frac{2t\xi^2}{m_N^2}\{\tilde{E}(x,\xi,t)\}^2 \Big].$$

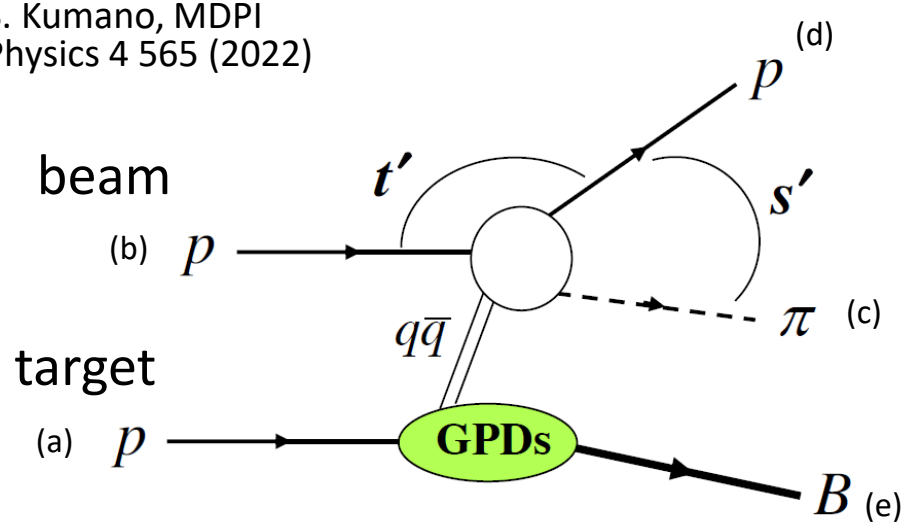
GPDs

Unique features

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

# p + p → N + π + B

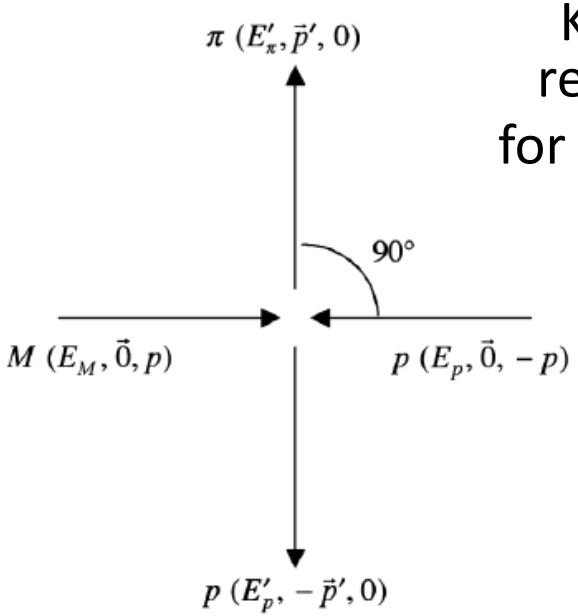
S. Kumano, MDPI
Physics 4 565 (2022)




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

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

$3 < -t' < 8\ \text{GeV}^2$



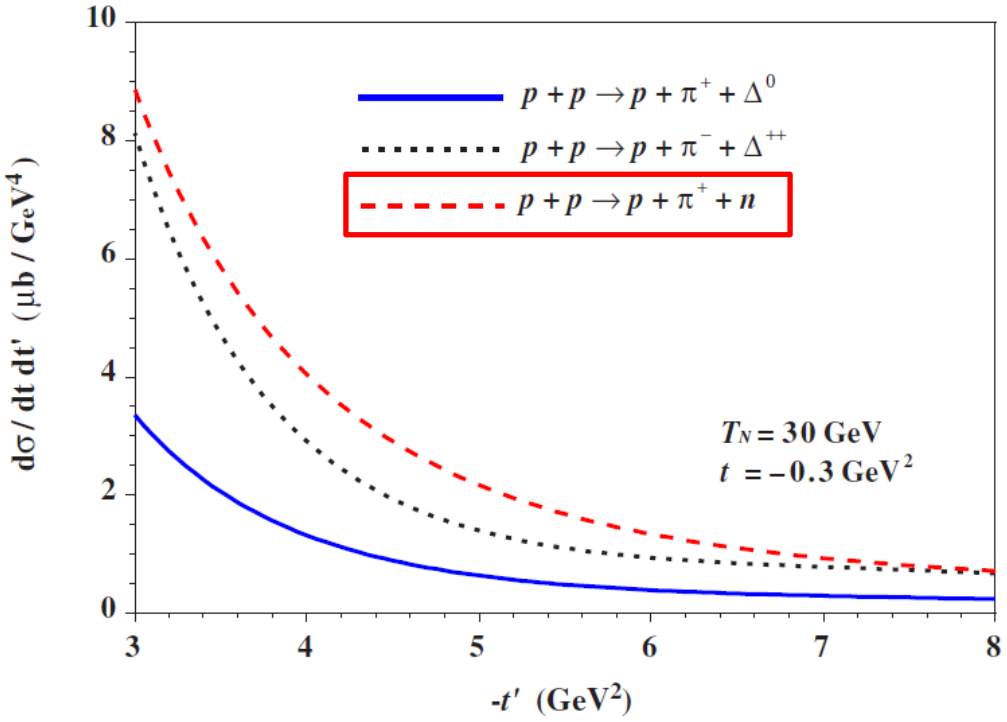

Kinematical requirements for factorization

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

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

# Estimated cross sections

- 30 GeV p



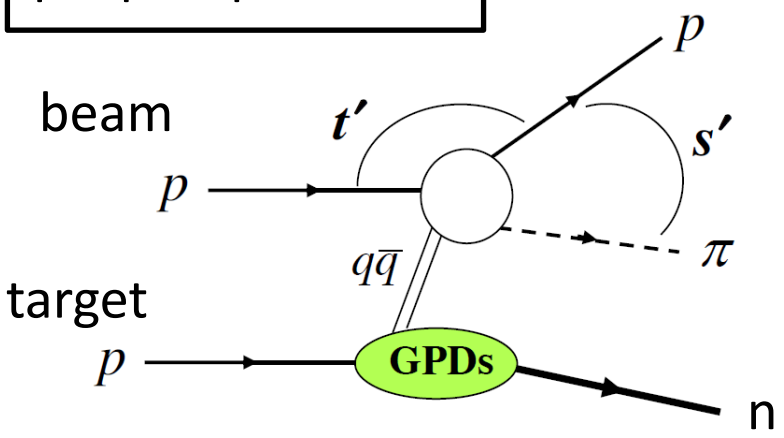

S. Kumano et al.,
PRD 80 074003 (2009)

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

Small acceptance & Short beam time

# Kinematical Requirement

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



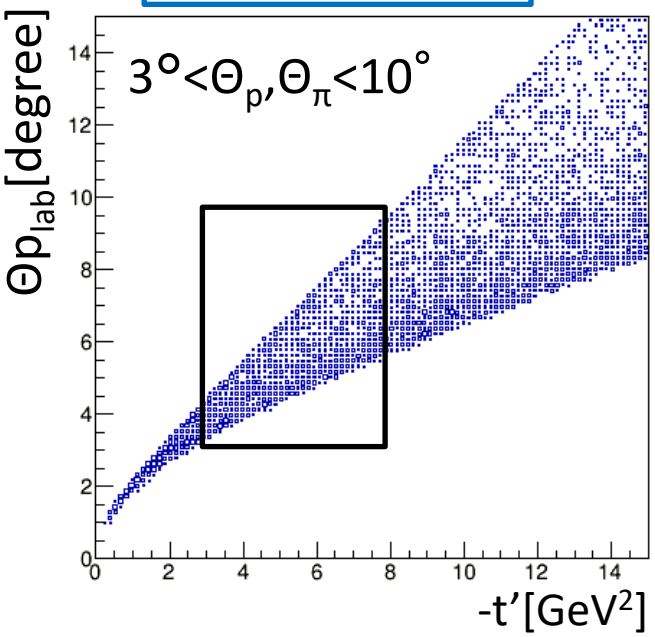

S. Kumano, MDPI Physics 4 565 (2022)

p,π : Opposite large transverse momentum

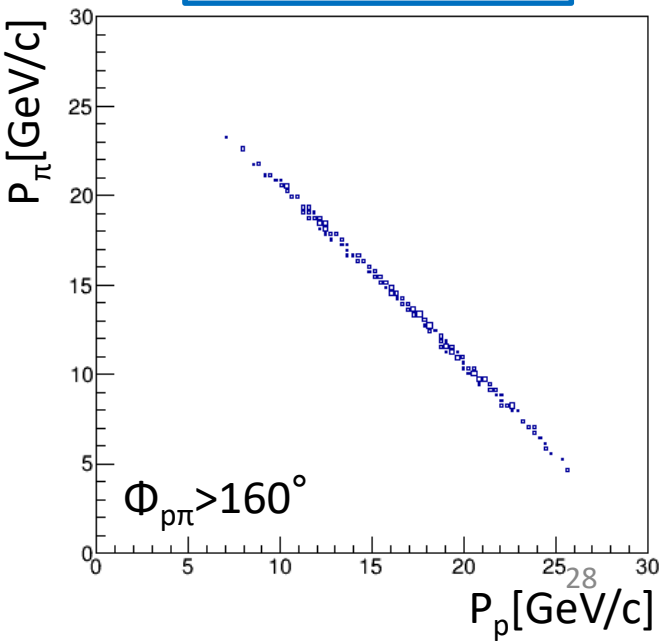
$t' = (p_{beam} - p_{scatter})^2$

$3 < -t' < 8\ GeV^2$

p,π : Forward




p,π < 25 GeV/c



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

# Possible setup

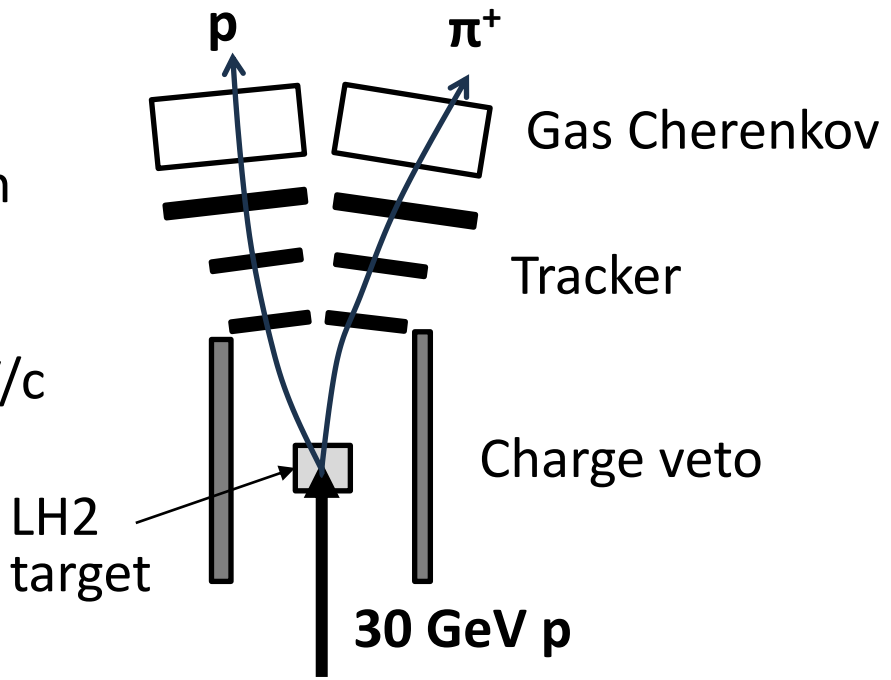
- Missing mass $p + p \rightarrow p + \pi^+ + X$
  - Missing mass method to identify X=n
  - p beam momentum cannot be measured
  - MARQ fiber tracker : 0.6% @ 15 GeV/c

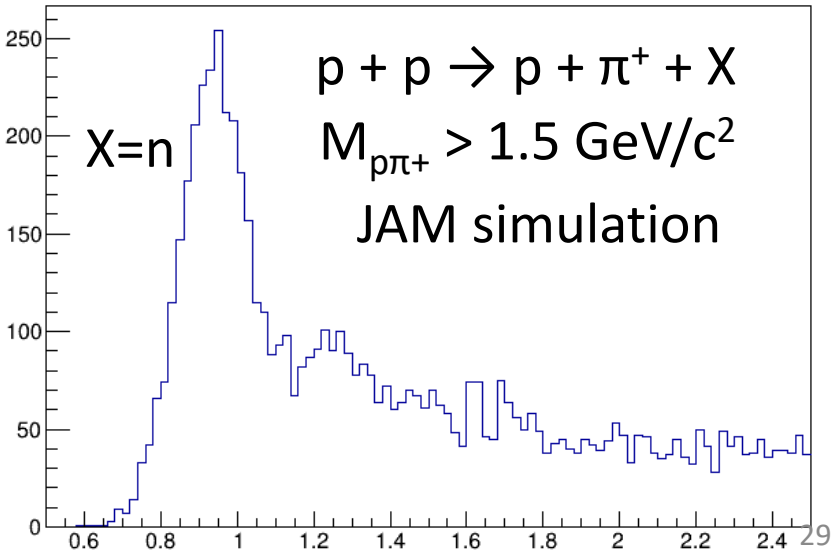
- p/π separation
  - Gas Cherenkov

- Multiplicity cut
- Liquid hydrogen target
- FM magnet

- JAM simulation

  ⇒ Clear identification of X=n peak



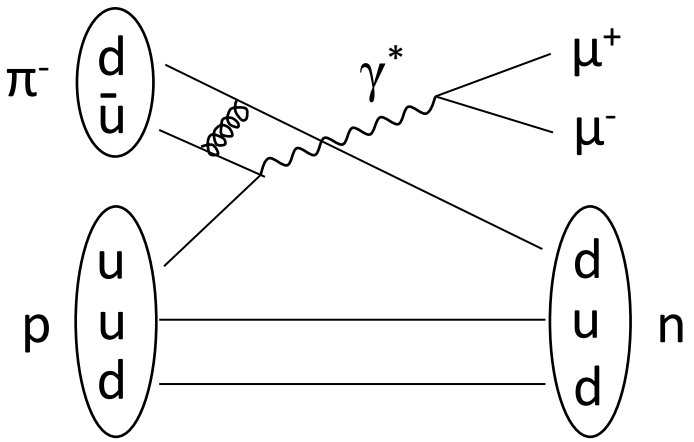



# $\pi^- + p \rightarrow \mu^+ + \mu^- + n$

Exclusive Drell-Yan

PLB 523 (2001) 265
PLB 748 (2015) 323

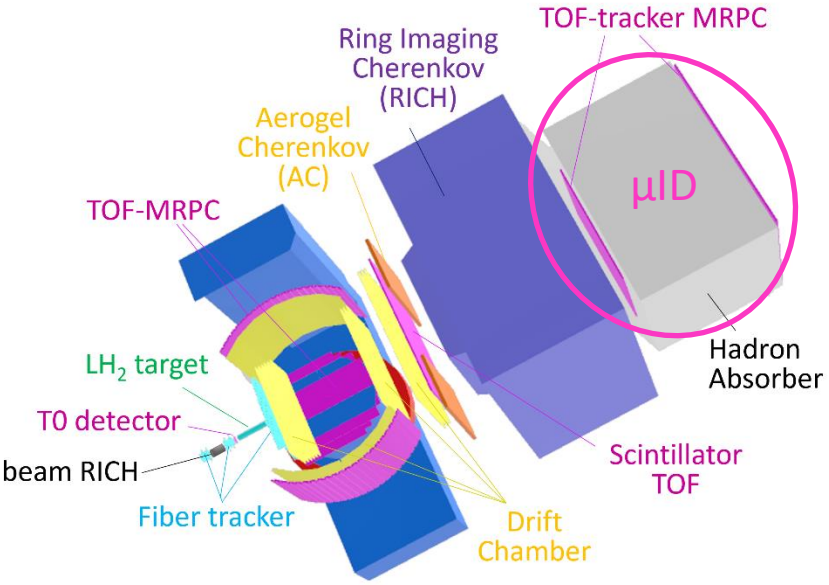
(Inverse reaction of DVMP)




$$\left.\frac{d\sigma_L}{dtdQ'^2}\right|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8}f_\pi^2\left[(1-\xi^2)\left|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)\right|^2 - 2\xi^2\mathrm{Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^*\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2\frac{t}{4m_N^2}\left|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right|^2\right]$$

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

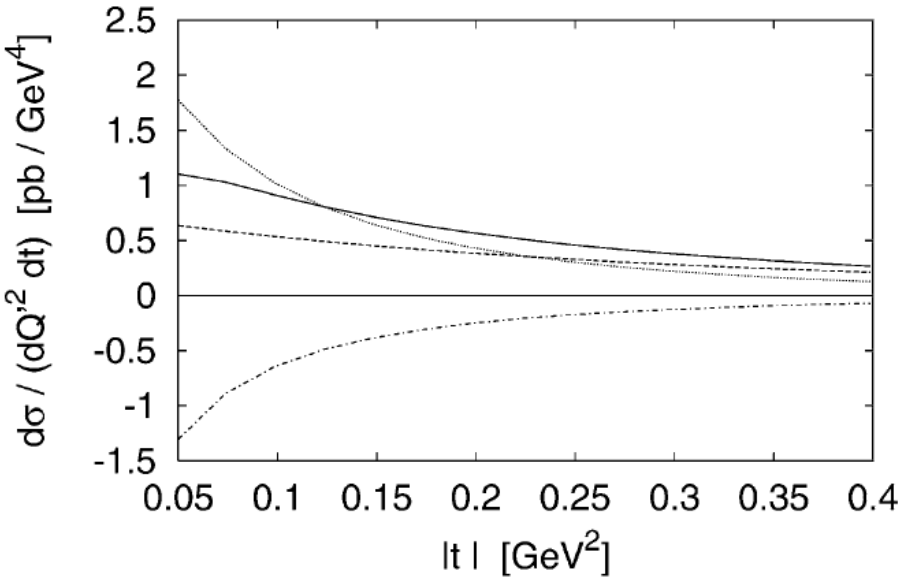
- Can access polarized GPDs without polarized beam/target
- μID system with the MARQ spectrometer
- LoI submitted (W.C. Chang)



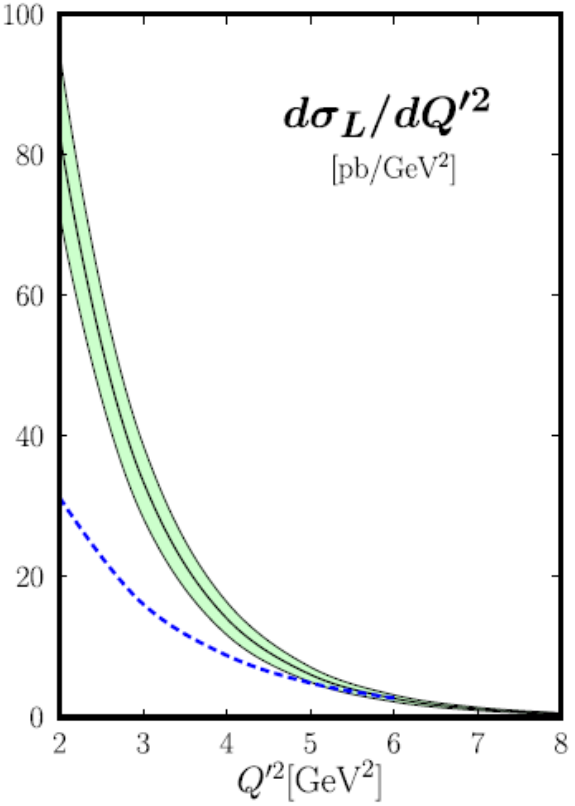
# $\pi^- + p \rightarrow \mu^+ + \mu^- + n$

Estimated cross sections

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




S.V. Goloskokov, PLB 748 (2015) 323

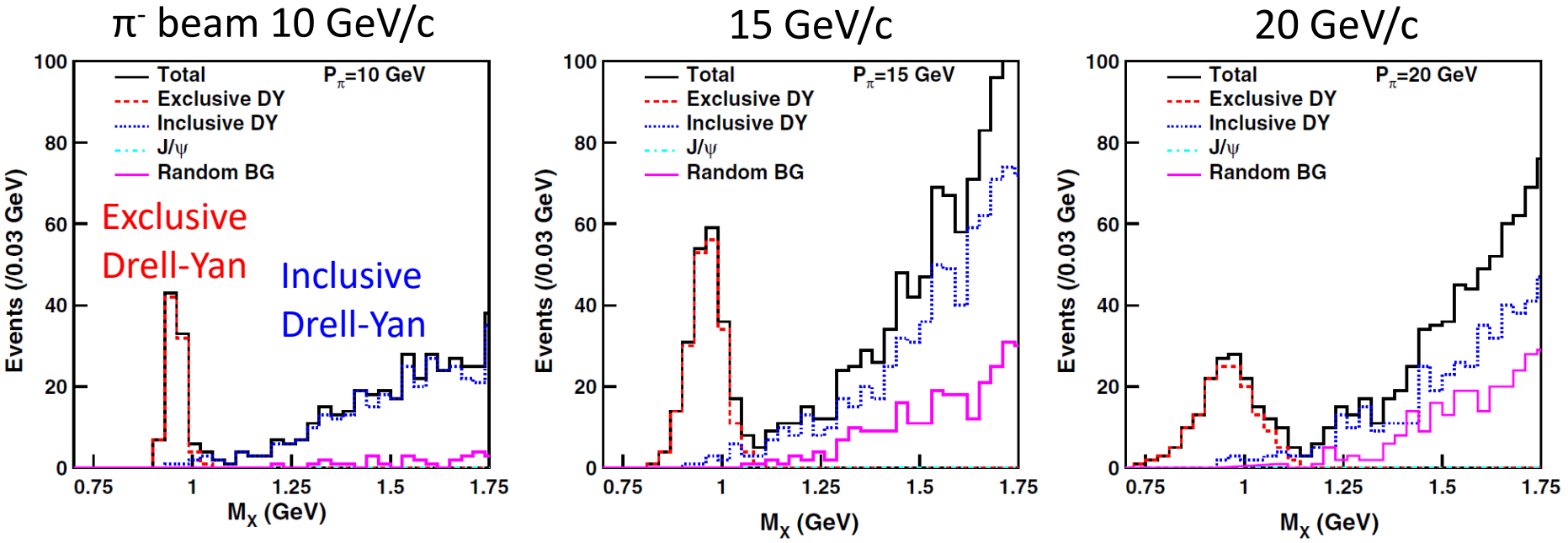


# Expected missing mass spectra

- Feasibility study : PRD 93 (2016) 114034

Missing Mass

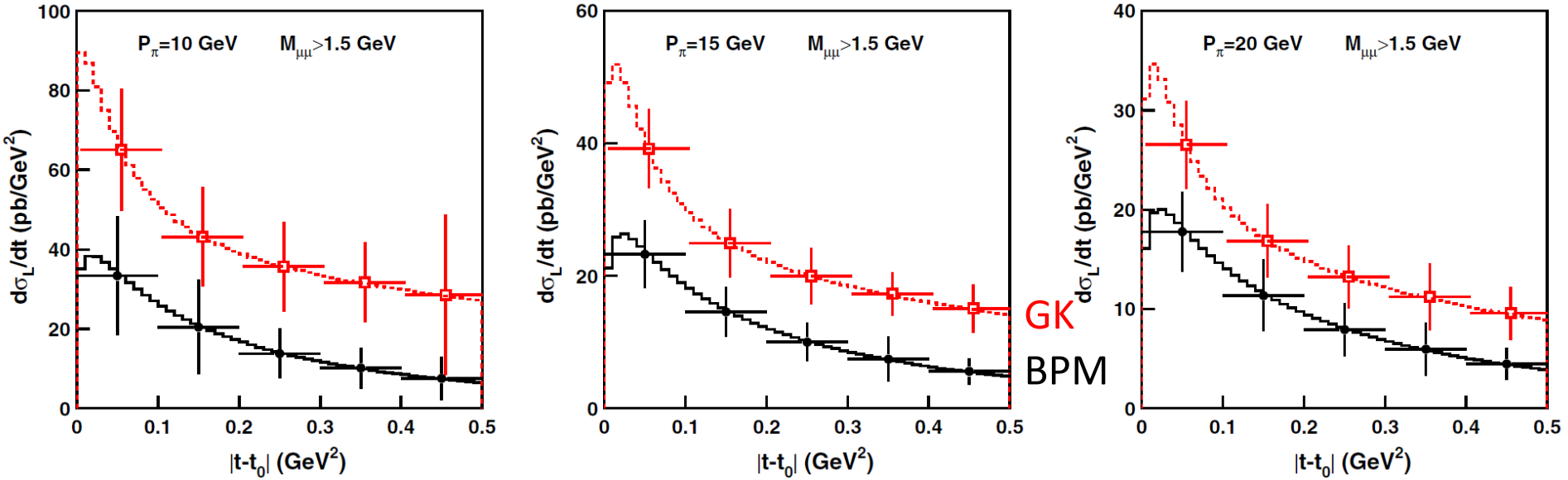
$\pi^- p \rightarrow \mu^+ \mu^- X$ (50 days)




- We can identify exclusive events
- Study on multiplicity cut is on-going ⇒ thinner absorber & larger yield
- Feasible at π20 Phase 3 (full intensity)

# Different GPD models

$\pi^- p \rightarrow \mu^+ \mu^- X$ (50 days) T. Sawada et al., PRD 93 (2016) 114034



# Single Diffractive Hard Exclusive Process (SDHEP)

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

$\gamma$ beam
- $\gamma + N \rightarrow l^+ + l^- + N'$ (TCS)
- $\gamma + N \rightarrow \gamma + \gamma + N'$
- $\gamma + N \rightarrow \gamma + M + N'$
- $\gamma + N \rightarrow M + M + N'$

Meson beam
- $M + N \rightarrow l^+ + l^- + N'$ (Exclusive Drell-Yan)
- $M + N \rightarrow \gamma + \gamma + N'$
- $M + N \rightarrow \gamma + M + N'$
- $M + N \rightarrow M + M + N'$

Study on-going

Other possible measurement at J-PARC

Proton beam
- $N + N \rightarrow M + B + N'$

# Summary

- High momentum beam (30 GeV p) is now available in J-PARC
- Extraction of high momentum secondary beam (π20 beamline) is planned

⇒ We can study large $Q^2$ reactions using hadron beam at J-PARC

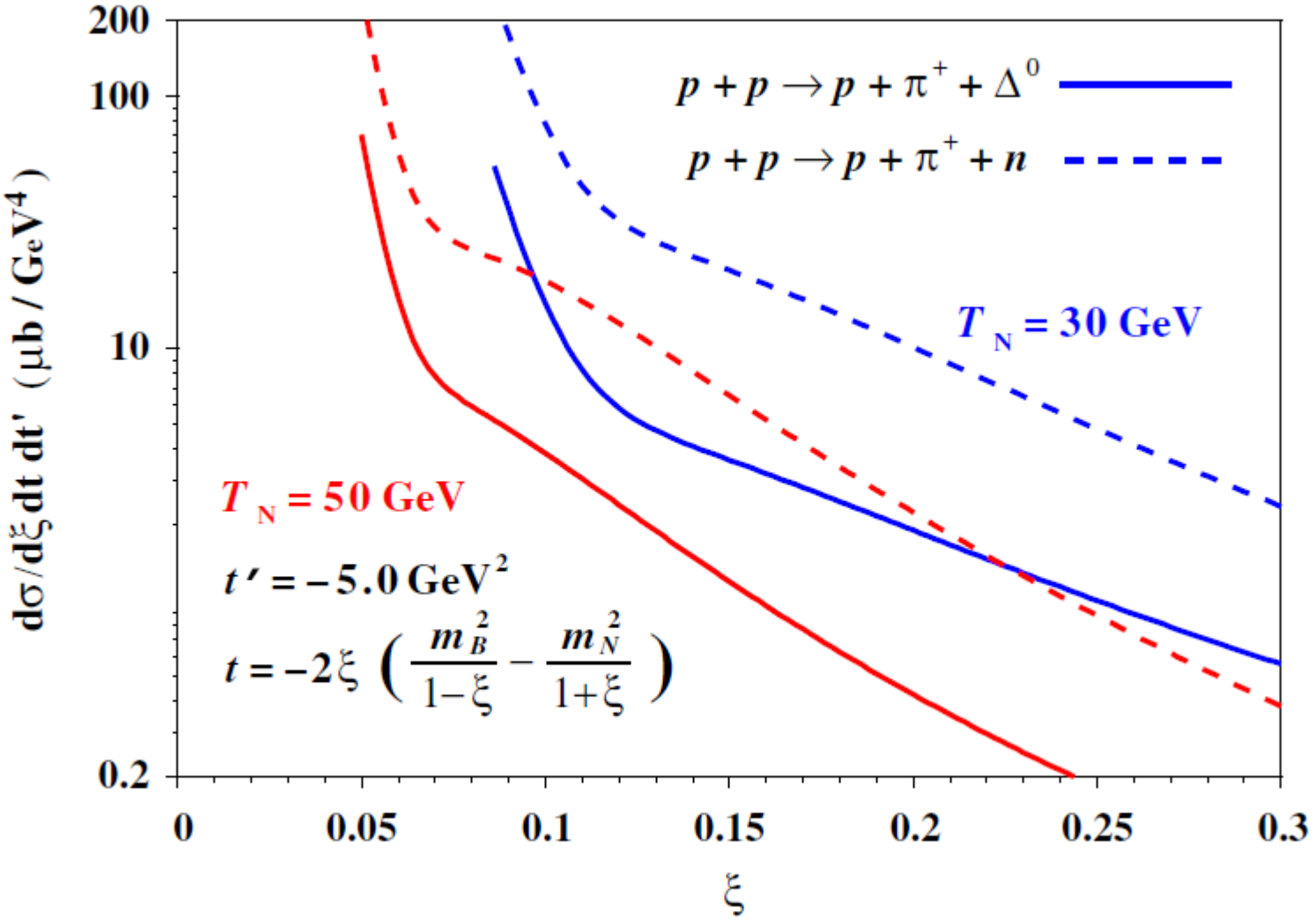
- Single Diffractive Hard Exclusive Processes (SDHEP) to measure GPDs
  - $B + p \rightarrow C + D + p'$
  - B, C, D can be lepton, gamma or hadron
  - C, D : large transverse momentum >> four momentum transfer

- Feasibility study at J-PARC
  - $p + p \rightarrow p + \pi + B$ : can be measured at the current high-p beamline
  - $\pi^- + p \rightarrow \gamma + \gamma + n$ : π20 Phase 3, EM calorimeter
  - $\pi^- + p \rightarrow \mu^+ + \mu^- + n$ : π20 phase 3, MARQ spectrometer + μ ID

**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




- PRD 80 (2009) 074003