GPDs studies using hadron beams at J-PARC

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The 13th Circum-Pan-Pacific Symposium on High Energy Spin Physics (PacificSPIN 2026)

Academia Sinica

Outline

- Generalize Parton Distributions (GPDs) measurement

- Lepton beams (DVCS, DDVCS)
- Single Diffractive Hard Exclusive Process (SDHEP)
- Hadron beams
    - $p + p \rightarrow p + \pi + n/\Delta$ (pure hadronic reaction)
    - $\pi^- + p \rightarrow \gamma + \gamma + n$ (di-photon production)
    - $\pi^- + p \rightarrow l^+ + l^- + n$ (Exclusive Drell-Yan)

- J-PARC
- Status & plan of the π20 beamline / MARQ experiment
    - 2027/Jun beamtime

Generalized Parton Distributions (GPDs)

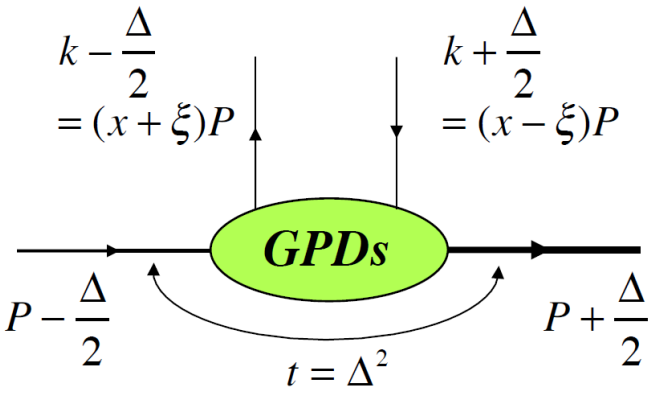
Four quark GPDs
(Lowest order)

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

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

3 variables

- x : Fraction of longitudinal momentum
- ξ : Fraction of transferred momentum
- t : Four momentum transfer



Determine from the global analysis of world-wide experimental data

Moments of GPDs

- $\xi \to 0$, $t \to 0$: 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

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

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

- 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

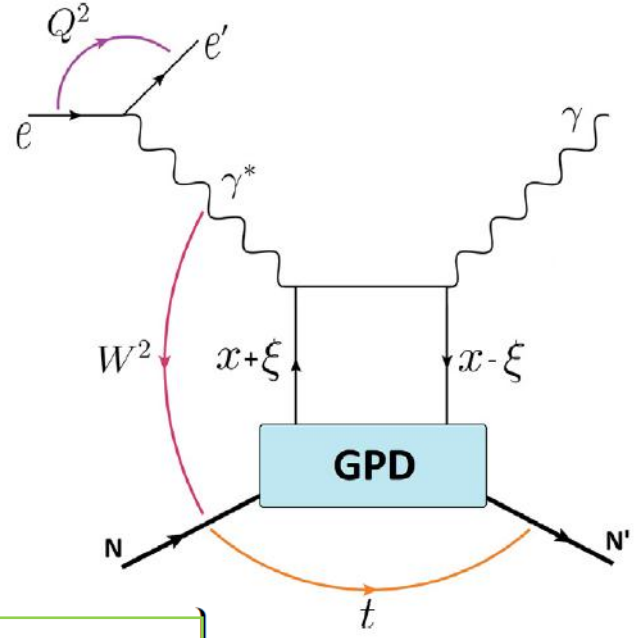
$$\int_{-1}^{1} dx\, x H(x,\xi,t) = M_2^Q(t) + \frac{4}{5} d^Q(t)\xi^2$$

Mass Pressure

- GPDs in full x,ξ,t space
- x-dependence

Deeply Virtual Compton Scattering (DVCS)

- Cleanest, golden channel to access GPDs
- HERA, JLab, COMPASS, and EIC



$$d\sigma_{DVCS}^{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

CFFs

$$c_0^{DVCS} = \frac{1}{(2-x_B)^2} \times \Big\{ 4(1-x_B)\left(\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right) - x_B^2\left(\mathcal{H}\mathcal{E}^* + \mathcal{E}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{E}}^* + \widetilde{\mathcal{E}}\widetilde{\mathcal{H}}^*\right) - \left(x_B^2 + k\,(2-x_B)^2\right)\mathcal{E}\mathcal{E}^* - x_B^2\,k\,\widetilde{\mathcal{E}}\widetilde{\mathcal{E}}^* \Big\},$$

$$\mathcal{H}(\xi,t) = \sum_q e_q^2 \left\{ \mathcal{P}\int_{-1}^{1} dx \left[H^q(x,\xi,t) - H^q(-x,\xi,t) \right] \left[\frac{1}{\xi - x} + \frac{1}{\xi + x} \right] + i\pi \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t) \right] \right\}$$

GPDs GPDs

- Integral of x ⇒ x dependence cannot be accessed
- Sensitivity only around x = ±ξ

Need data from other reactions to understand full GPDs

Double Deeply Virtual Compton Scattering

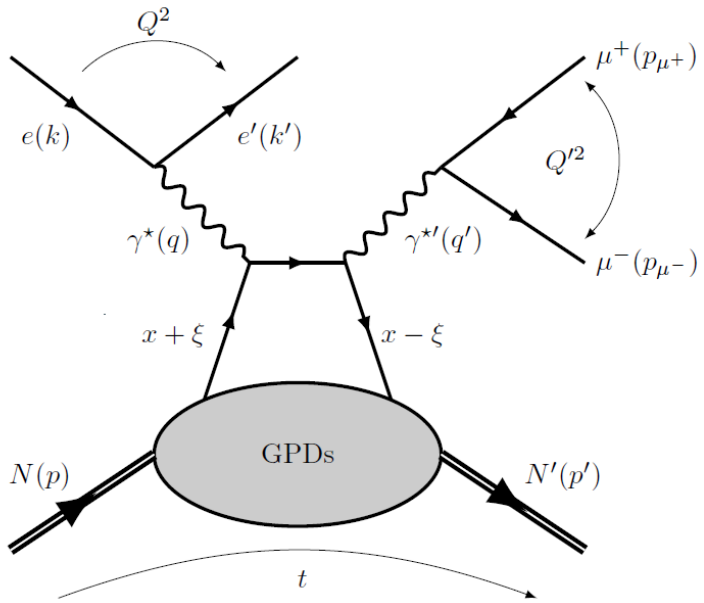
$$\mathcal{F}^{\pm}(\xi',\xi,t) = \mathcal{P}\int dx \left(\frac{1}{\xi'-x} \mp \frac{1}{\xi'+x}\right)\sum_q e_q^2 F^q(x,\xi,t)$$

$$+ i\pi \sum e_q^2 [F^q(\xi',\xi,t) \mp F^q(-\xi',\xi,t)],$$ GPDs

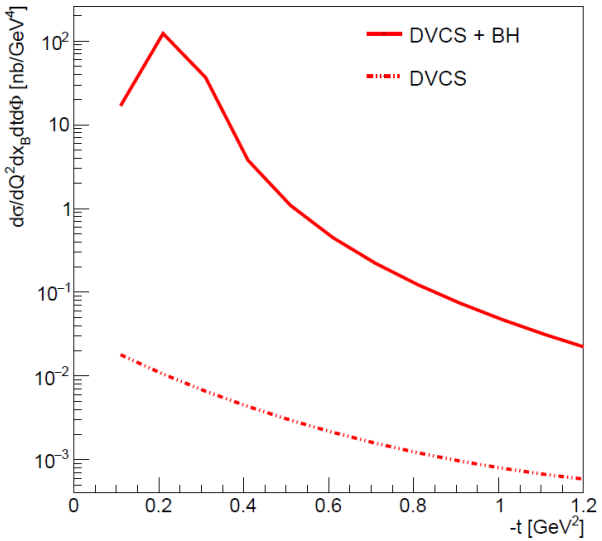
$$\xi = \frac{\sqrt{(Q^2+Q'^2)^2 + t^2 + 2t(Q^2-Q'^2)}}{2Q^2/x_B - Q^2 - Q'^2 + t},$$

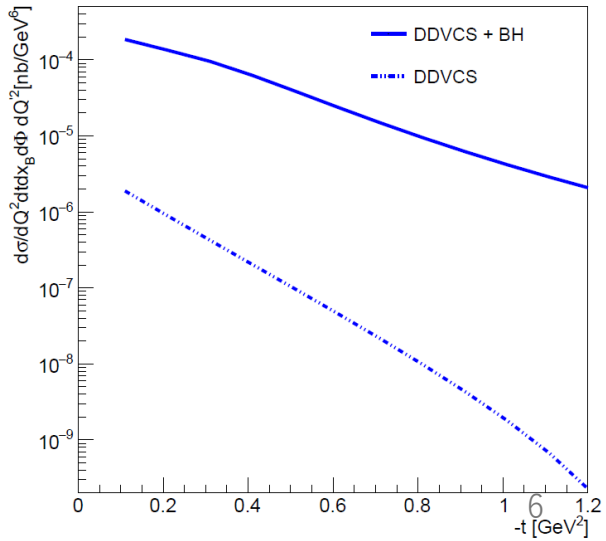
$$\xi' = \xi \frac{Q^2 - Q'^2 + t}{Q^2 + Q'^2 + t},$$

arXiv:2605.11690



- One can map x = ξ’ and ξ
- Cross section : 10^{-6} of DVCS





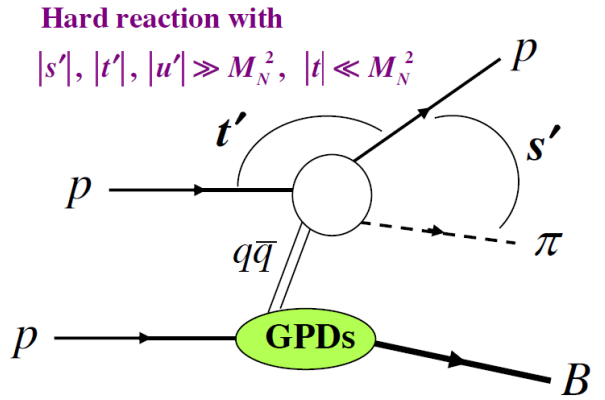
p + p → p + π + n/Δ

PHYSICAL REVIEW D **80,** 074003 (2009)

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]

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



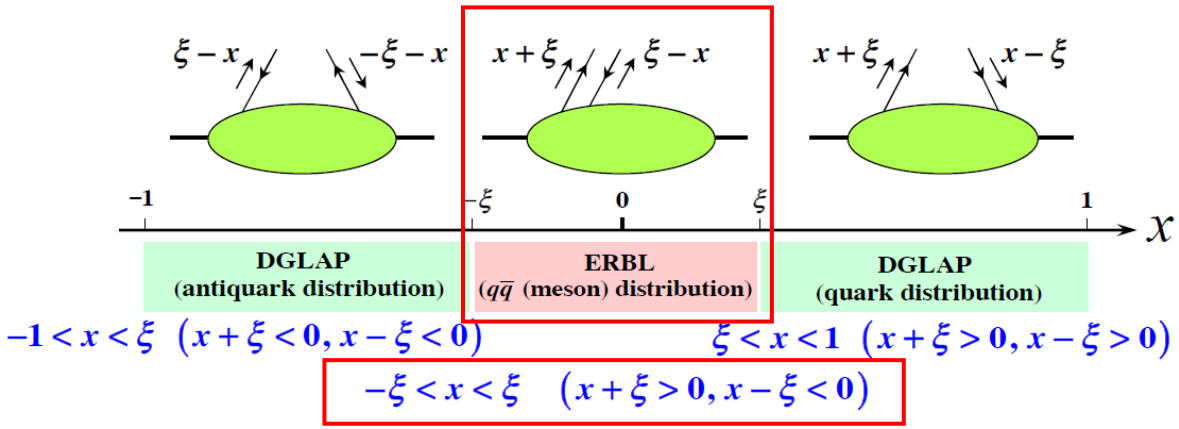
$$\frac{d\sigma_{NN\to N\pi B}}{dtdt'} = \int_{y_{\min}}^{y_{\max}} dy \frac{s}{16(2\pi)^2 m_N p_N} \sqrt{\frac{(ys - t - m_N^2)^2 - 4m_N^2 t}{(s - 2m_N^2)^2 - 4m_N^4}} \frac{d\sigma_{MN\to\pi N}(s' = ys, t')}{dt'} \sum_{\lambda_a,\lambda_e} \frac{1}{[\phi_M(z)]^2} |\mathcal{M}_{N\to B}|^2,$$

S. Kumano, MDPI Physics 4 565 (2022)

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

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

GPDs



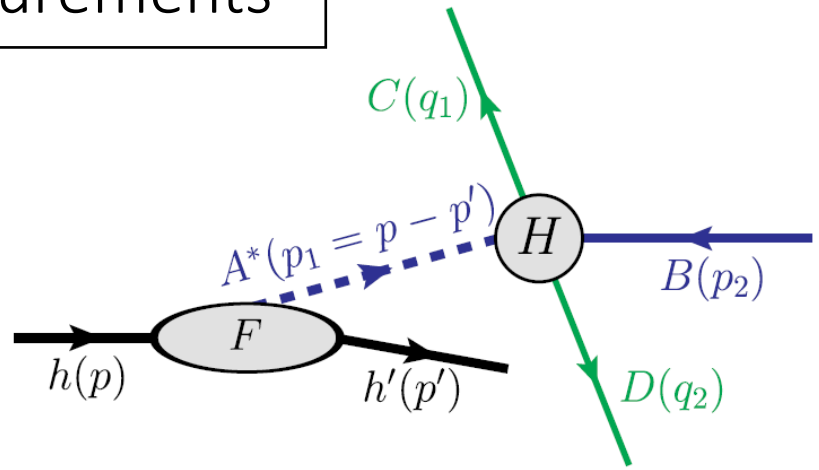
- Access to the ERBL region
- Large cross section (O μb)
- x-dependence

Single Diffractive Hard Exclusive Process (SDHEP)

Generalization of processes for GPDs measurements

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

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

← **Factorization**

Cross section depends on GPDs

$$\mathcal{M}^{(2)}_{he\to h'eM_D} = \sum_{i,j}\int_{-1}^{1} dx \int_0^1 dz_D \times F_i^{hh'}(x,\xi,t) C_{ie\to ej}(x,\xi;z_D;q_T)\phi_{j/D}(z_D).$$

We can access GPDs using any beam

Single Diffractive Hard Exclusive Process (SDHEP)

Lepton beam
- $l + N \rightarrow l' + \gamma + N'$ (DVCS)
- $l + N \rightarrow l' + l^+ + l^- + N'$ (DDVCS)
- $l + N \rightarrow l' + M + N'$ (Deeply Virtual Meson Production)

We can study GPDs using variety of beams

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

γ beam
- $\gamma + N \rightarrow l^+ + l^- + N'$ (Time-like Compton Scattering)
- $\gamma + N \rightarrow \gamma + \gamma + N'$ • $\gamma + N \rightarrow \gamma + M + N'$ • $\gamma + N \rightarrow M + M + N'$

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

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

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

N. Tomida, PoS(HADRON2025) 244 (2025)

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

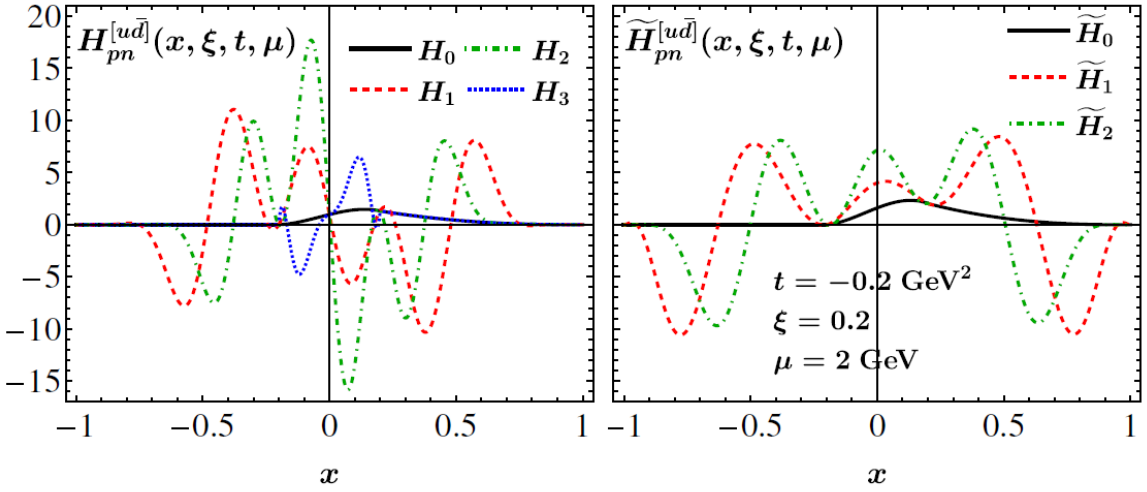
$\pi^- + p \rightarrow \gamma + \gamma + n$

- Probe x-dependence of GPDs

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

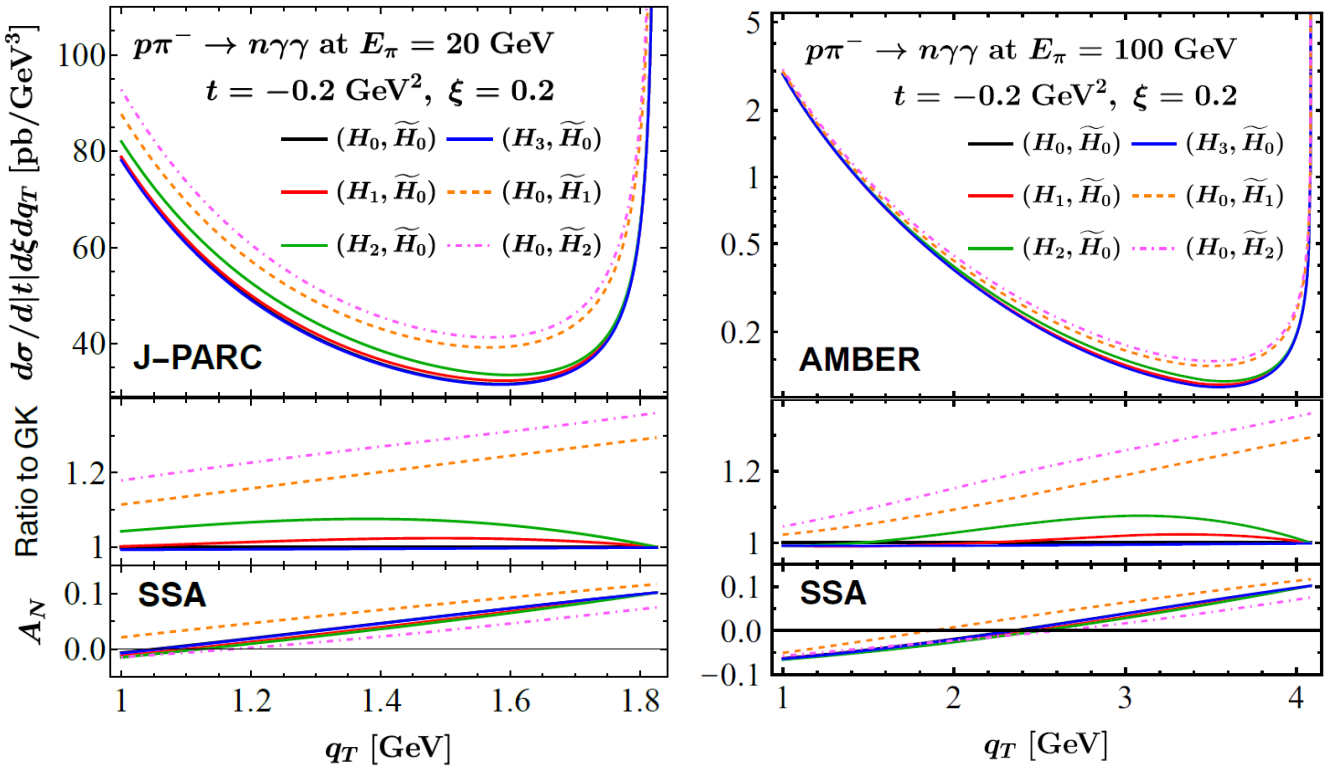
- Differentiation of shadow GPDs and real GPDs

  Same value after integrating over x



E_π = 20 GeV

E_π = 100 GeV



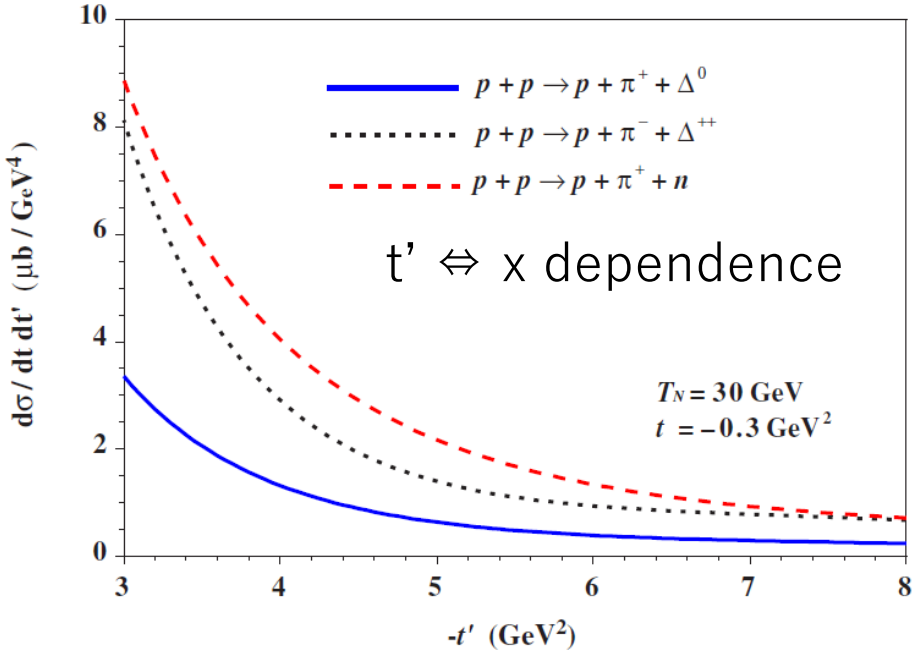
J-PARC

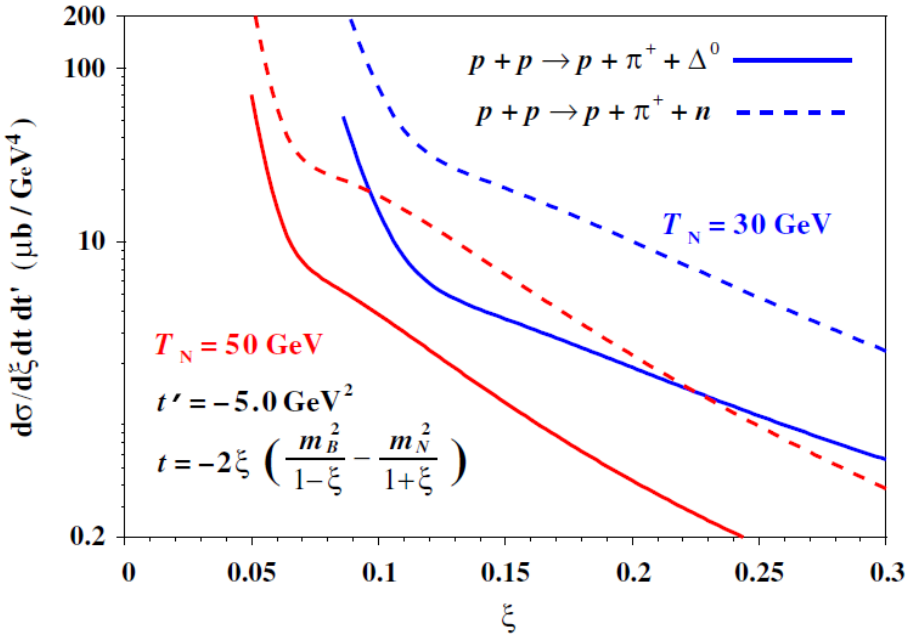
AMBER

p + p → p + π + n/Δ

- Proposed when J-PARC starts operation S. Kumano et al., PRD 80 (2009) 074003

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





- Large cross section (O μb)
- -ξ < x < +ξ (ERBL region)
- N→Δ Transition GPDs
- x-dependence

J-PARC

N. Tomida, PoS(HADRON2025) (2025) 244

GSI

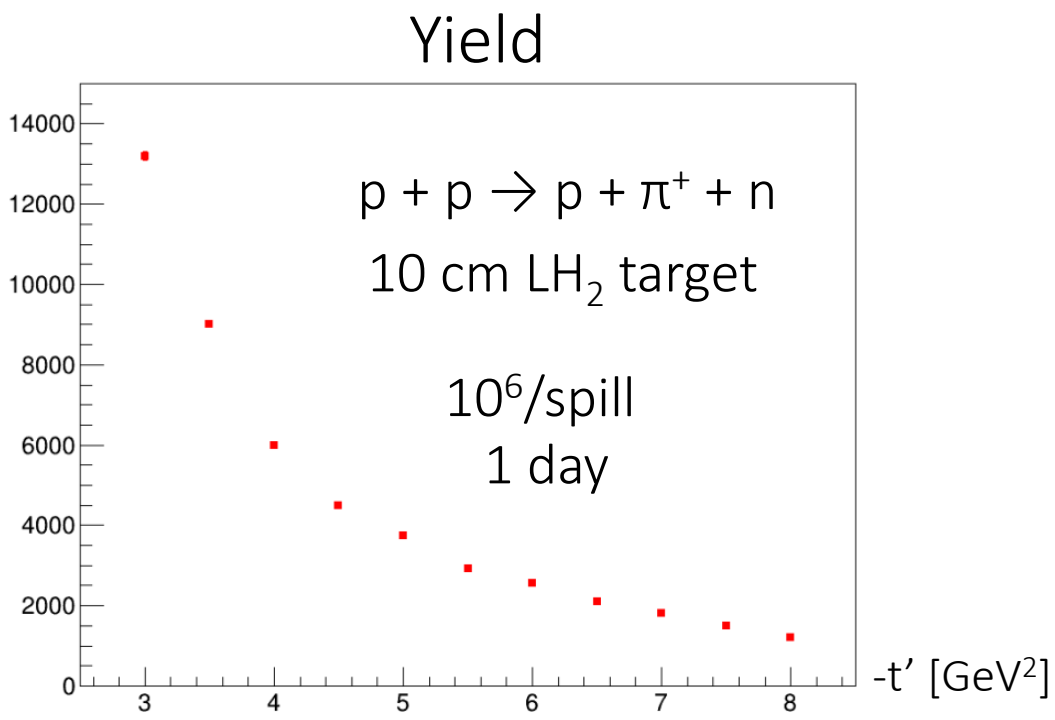
J. G. Messchendorp et al, arXiv2512.15986

- Calculation with 20 GeV/c beam (S.Kumano private comm.)

$p + p \rightarrow p + \pi + n/\Delta$

- Large cross section → Less than 1 day beam time is enough even in phase-1 intensity
- No full PID detectors required because of un-necessity of Kaon ID

⇒ Early-stage experiment

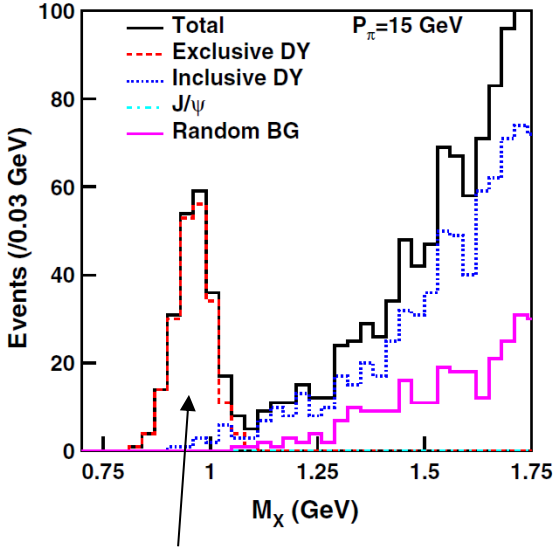


- Simultaneous measurement of other reactions thanks to unseparated beam/streaming DAQ
  - $p + p \rightarrow p + \pi^+ + \Delta^0$
  - $p + p \rightarrow p + \pi^- + \Delta^{++}$
  - $\pi + p \rightarrow \pi + \pi + B$

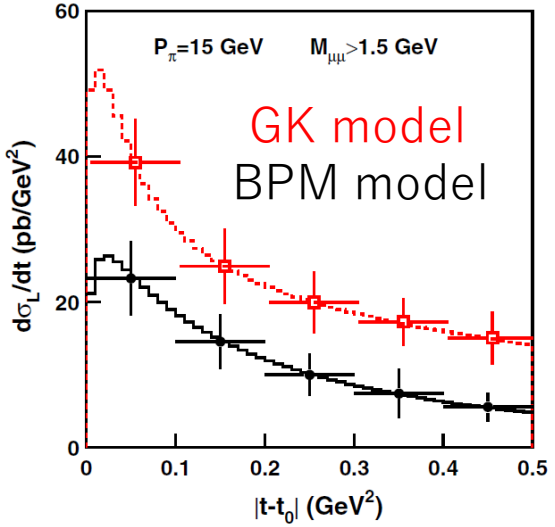
Exclusive DY

- $\pi^- + p \rightarrow \mu^+ + \mu^- + n$
- Feasibility study for J-PARC
  - S. Sawada et al., PRD 93 (2016) 114034
  - W.-C. Chang, J-PARC LoI (2019)
- Hadron absorber placing downstream of the tracking detectors
  → Good missing mass resolution

Missing mass



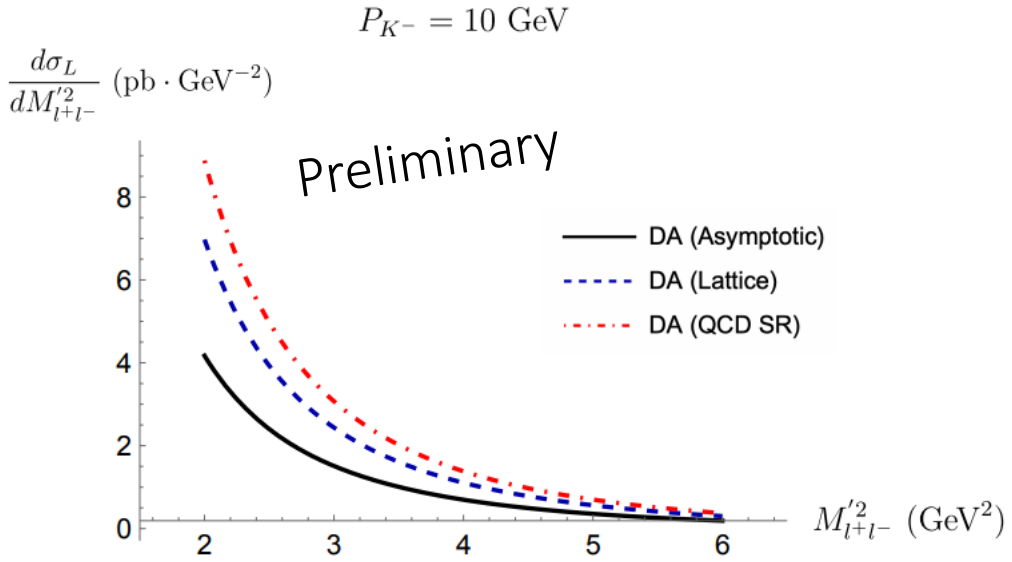
Cross section



- Clear exclusive peak

- $K^- + p \rightarrow \mu^+ + \mu^- + \Lambda$
- N → Λ Transition GPDs
  - P. Kroll, Eur. Phys. J A 55 76 (2019)
  - S. Son, preliminary

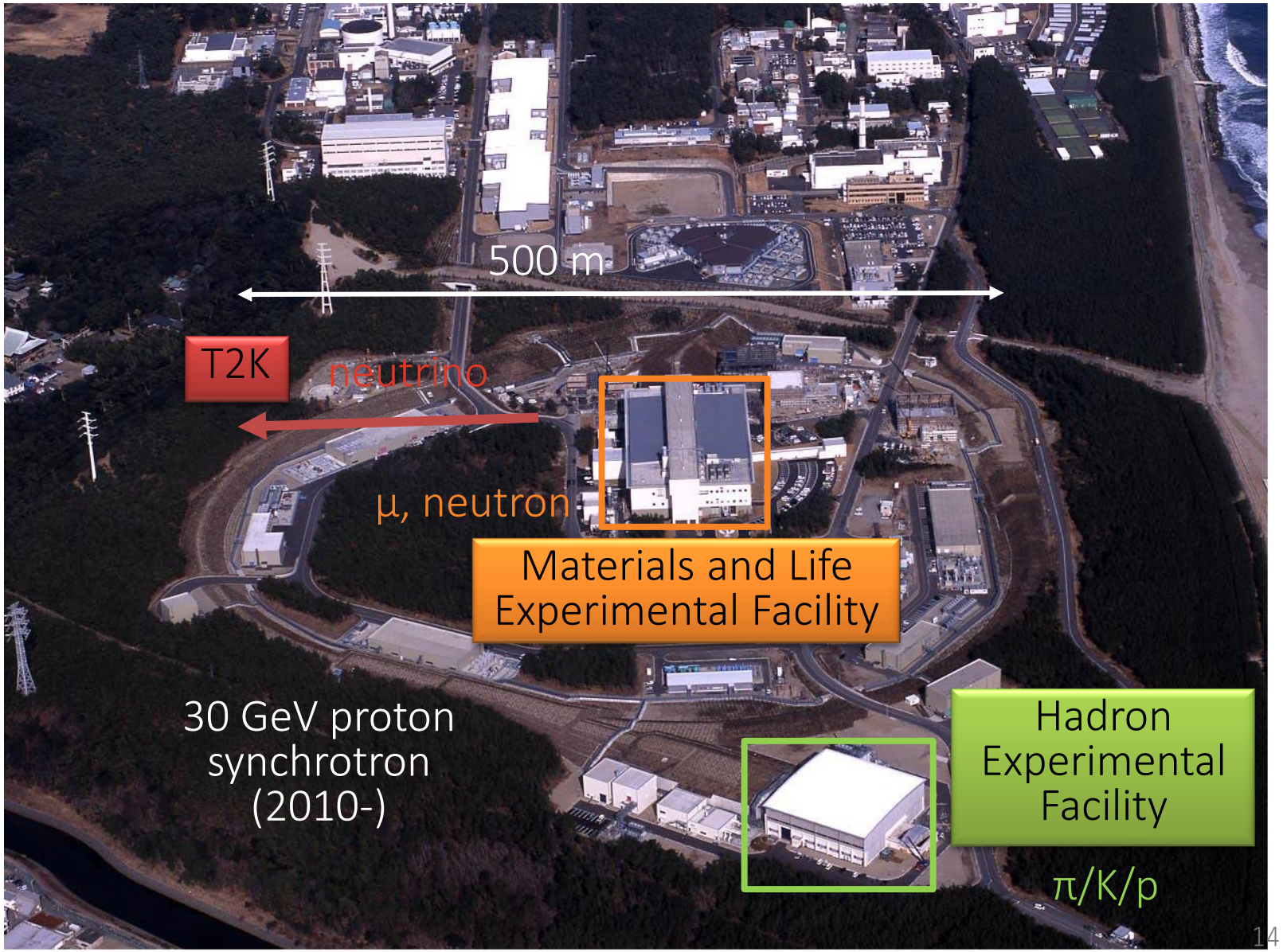
J-PARC π20&K10 beamline workshop
https://indico.rcnp.osaka-u.ac.jp/event/2904/



J-PARC


札幌
函館
日本海
日本
東京
大阪
福岡


Tokai
Tokyo
Toyama
GUNMA
TOYAMA
NAGANO
SAITAMA
GIFU
YAMANASHI
Yokohama
KANAGAWA
CHIBA
AICHI
Shizuoka
SHIZUOKA
Okazaki
Hamamatsu
Google


500 m
T2K
neutrino
μ, neutron
Materials and Life Experimental Facility
30 GeV proton synchrotron (2010-)
Hadron Experimental Facility
π/K/p

High momentum beams at J-PARC

High-p primary beamline

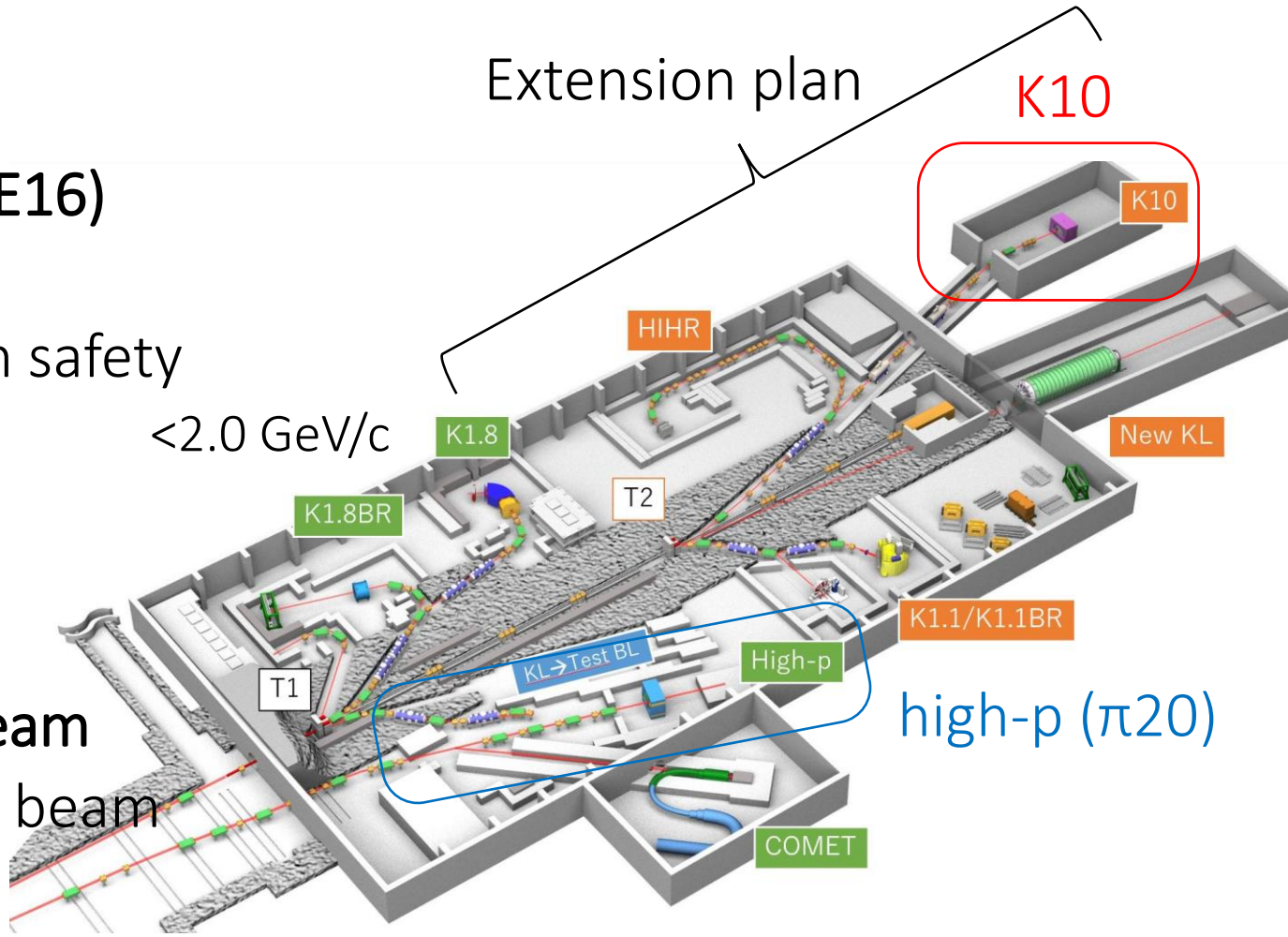
- 30 GeV p
- **2025/Nov : First physics experiment (E16)**
- 10^{10}/spill (2s)
- No detector in beamline for radiation safety

High-p secondary (π20) beamline

- Unseparated 2-20 GeV/c π/K/p
- Separated μ
- **2025/Jan : First delivery of positive beam**
- 2027/Jun? : First delivery of negative beam

K10 beamline

- Separated 2-10 GeV/c K/p̄
- Extension plan



We can study structure functions at J-PARC

K10 collaboration

- 2026/Oct : K10 collaboration kicked-off
- Korean-Japan relationship
- 80+ people
- Transition GPD (N→Λ) is one of programs

- You are welcome to join

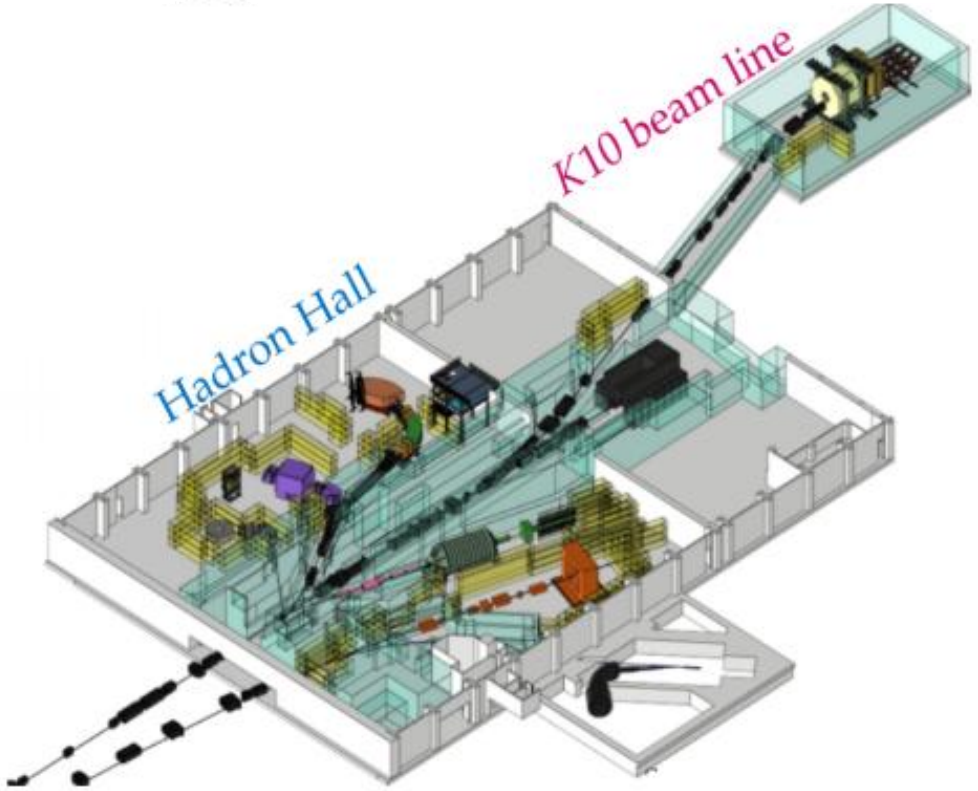
  https://research.kek.jp/group/k10beamline/index.html

  Contact : j-parc-k10mb_at_rcnp.osaka-u.ac.jp
- Yellow report coming soon

KDREAMS

K10 Detector for Research on
Exotics, Antihyperons, Multistrangeness,
and Structure of hadrons

How do quarks build *hadrons?*



π20 beamline staging plan

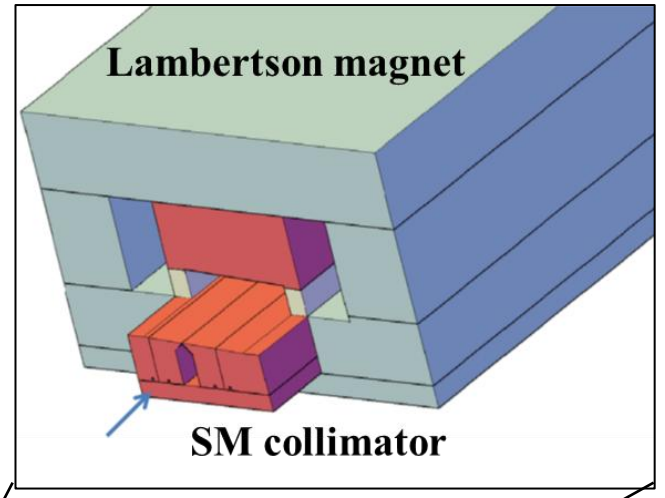
- Phase 1 : Use the magnet for primary beam extraction as a target
  - Positive beam → Successful delivery in 2025
  - Negative beam → Polarity change device installation in FY2026

Realize

- Phase 1.5 : Place a target in front of the magnet

Coexistence with primary beam

- Phase 2 : Replace with a magnet for secondary beam
- Phase 3 : Add radiation shields for full intensity



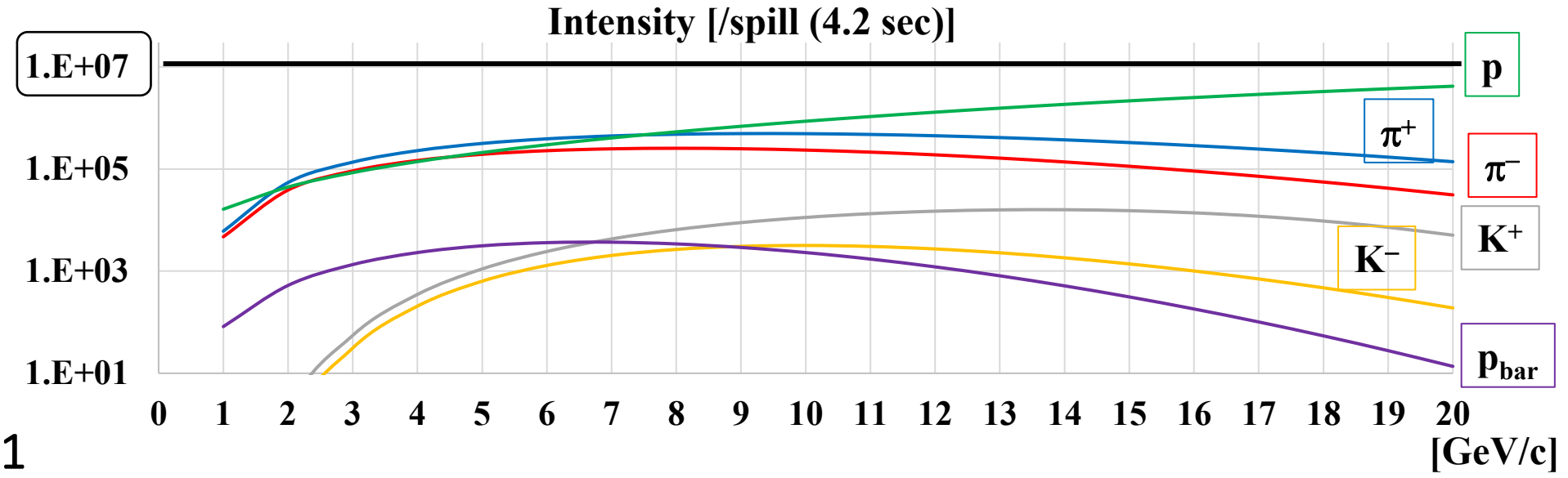


π20 beam : intensity

Simulation by K. Shirotori

Phase 1 : Current setup

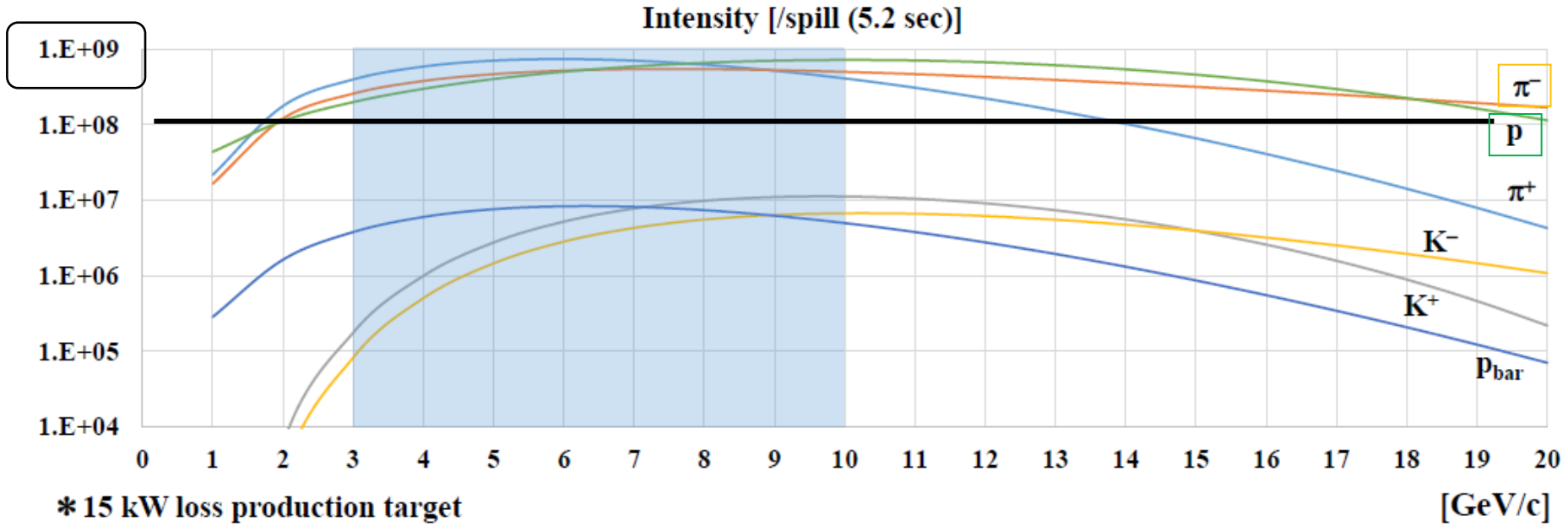
- $p + p \rightarrow p + \pi + n/\Delta$
- $\pi^- + p \rightarrow K + \Lambda(1405)$
  (S. Kumano on Oct/29)



Phase 1.5: x10 of phase 1

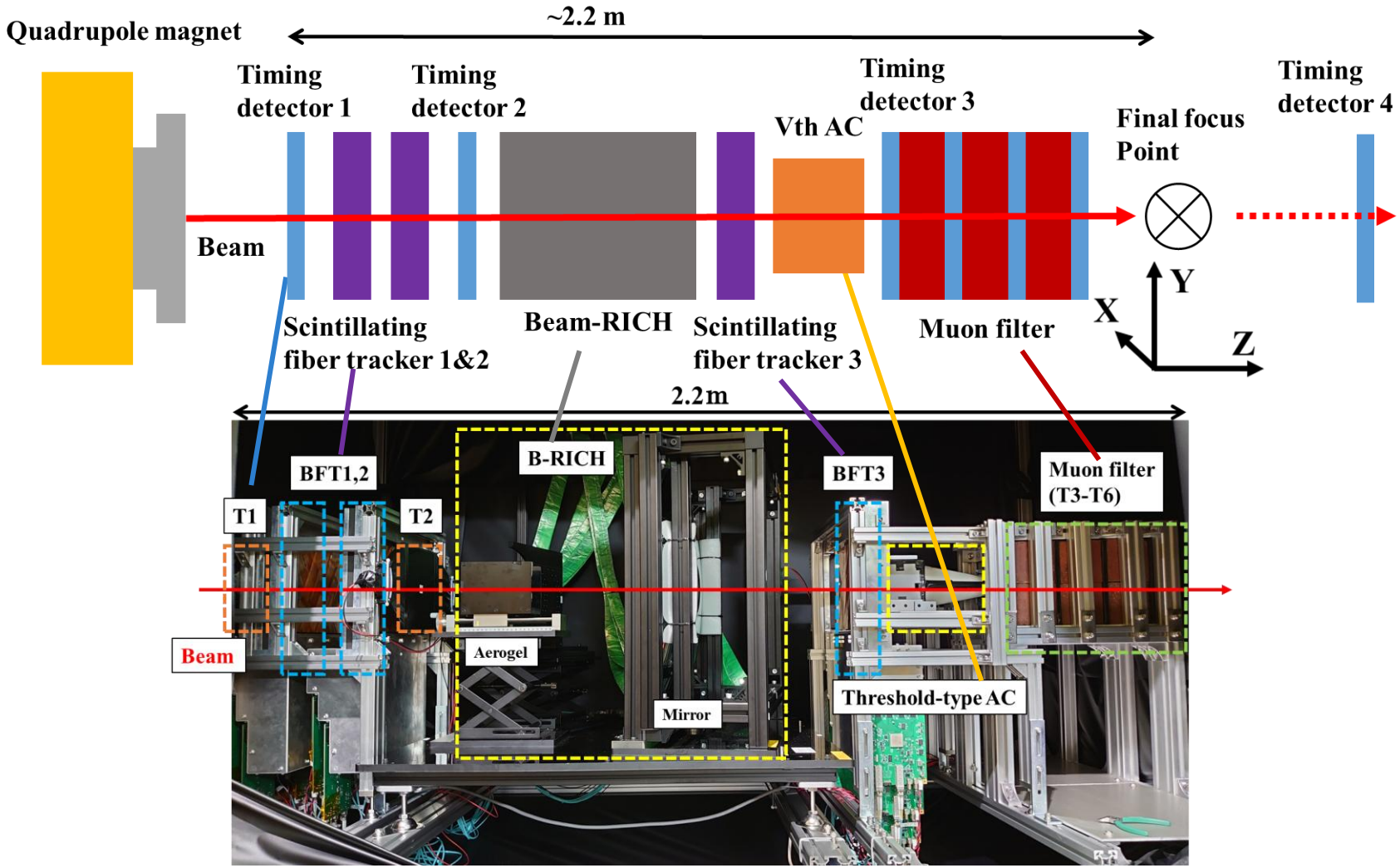
Phase 3: Full intensity

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



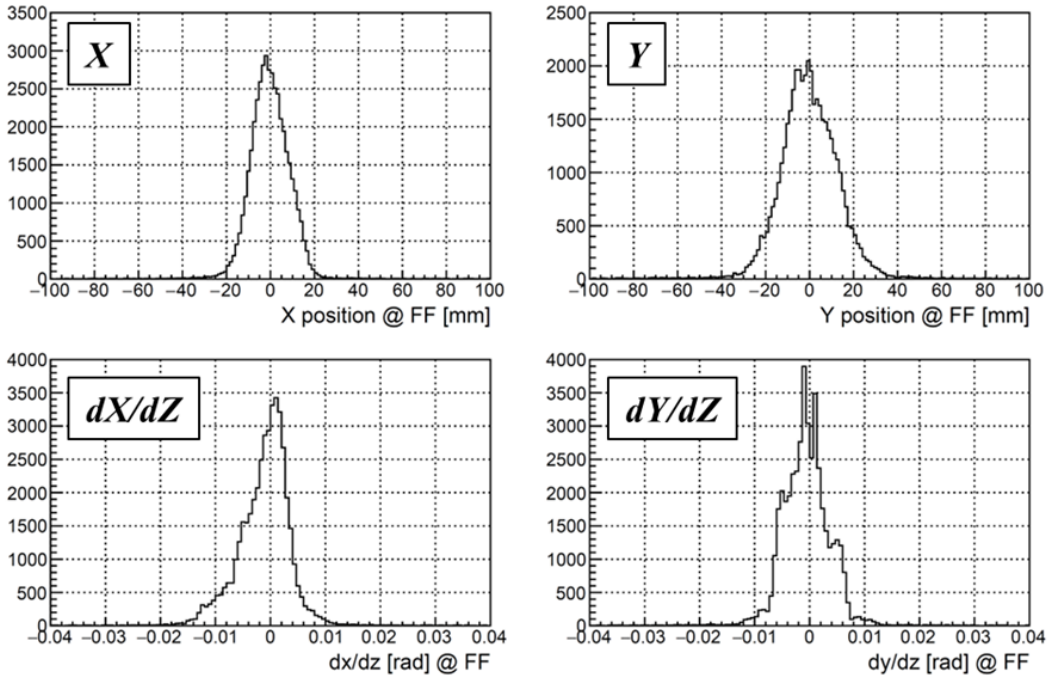
First delivery of secondary beam (2025/Jan)

- Positive 3/5/10 GeV/c
- Study of secondary beam property (beam size, particle fraction)

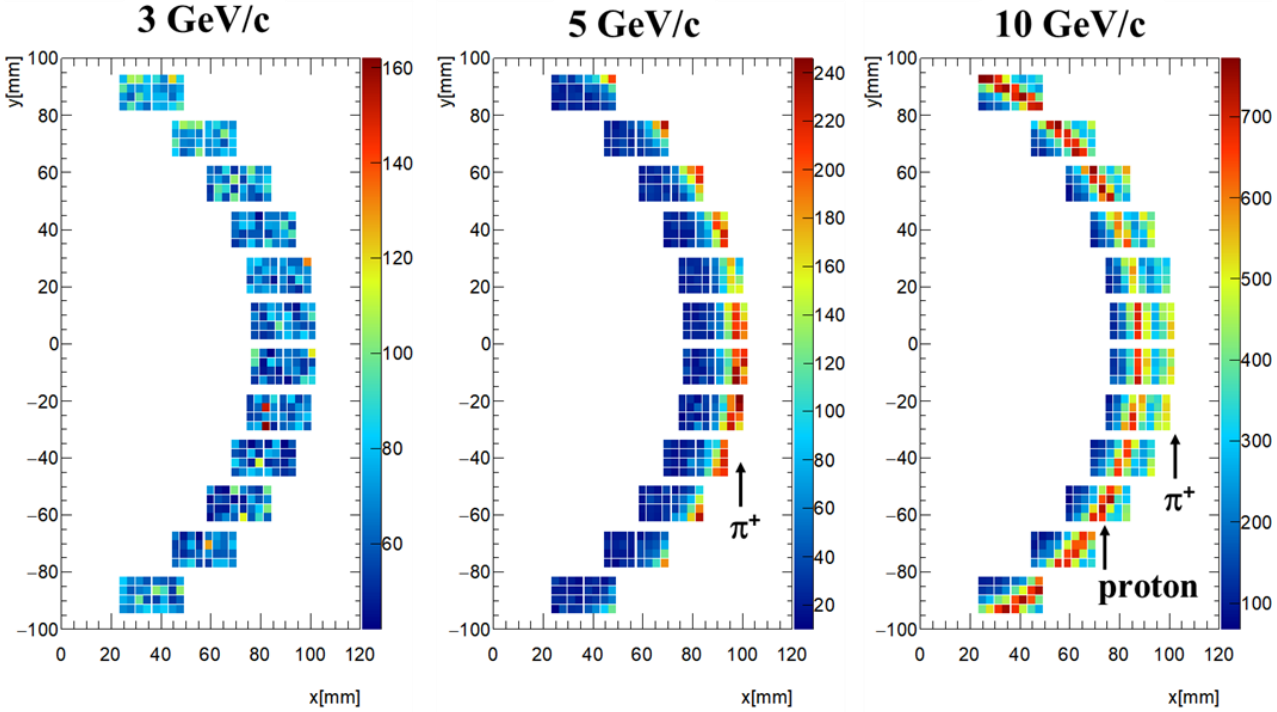


First delivery of secondary beam (2025/Jan)

Beam profile



Ring image with beam RICH



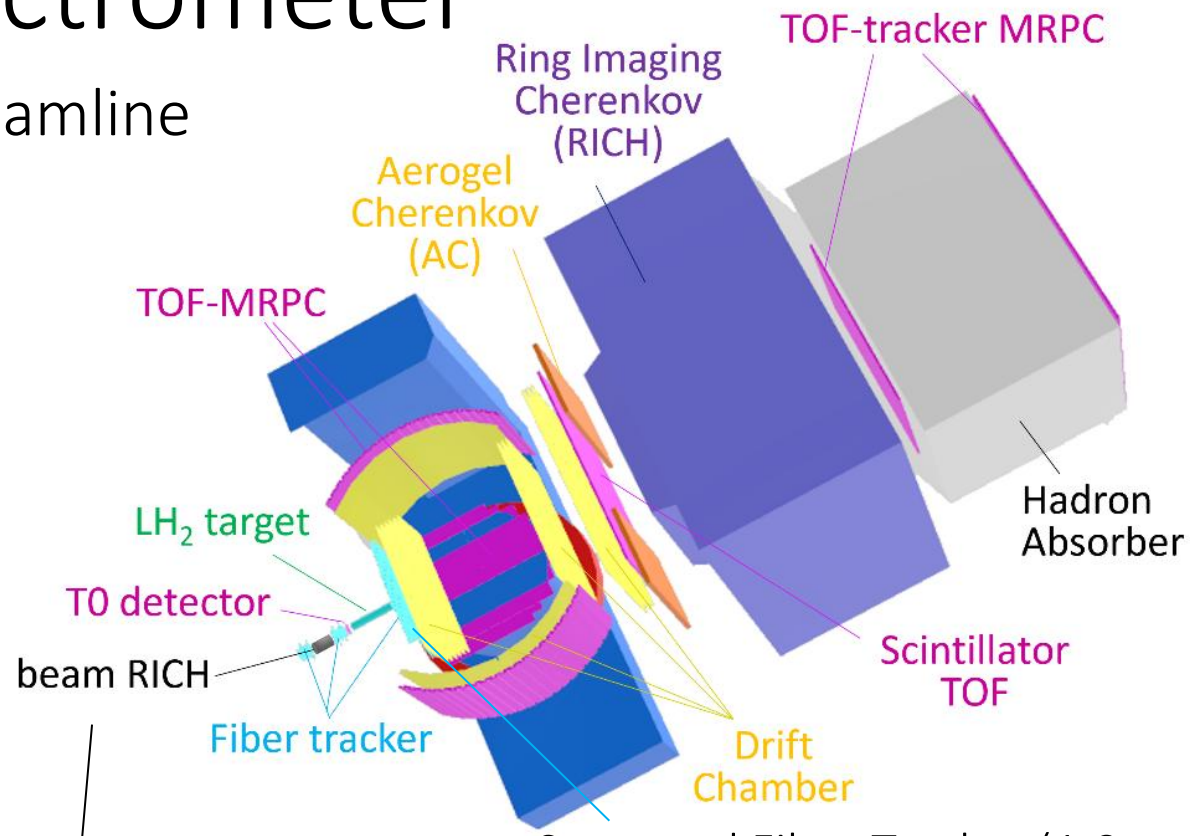
- Successfully measured secondary beams
- $p:\pi^+$ = 0.66:0.34, 0.60:0.40, 0.39:0.61 (3, 5, 10 GeV/c)
- Consistent with simulation
- High purity muons also delivered [K. Shirotori et al., PTEP 103H03 (2026)]

MARQ spectrometer

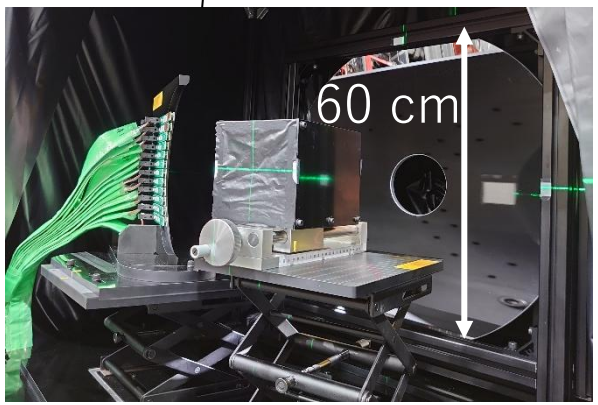
- Multi-purpose spectrometer for the π20 beamline
- MARQ collaboration
  - Baryon spectroscopy (E50)
  - Exotic hadrons
  - GPDs studies

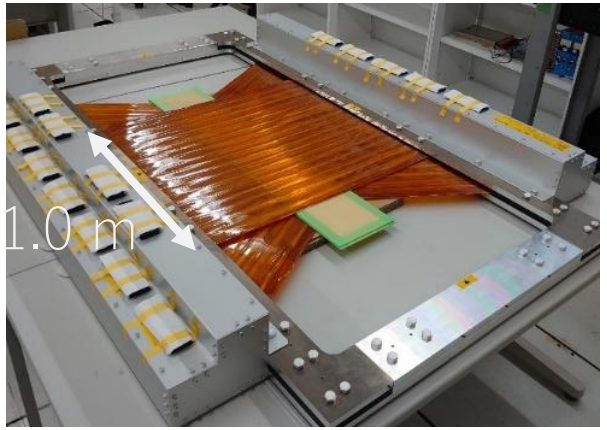
- Good momentum resolution
- PID up to 16 GeV/c
- High-rate capability : 1 MHz/mm
- Streaming DAQ

- Tracker/FEE/DAQs : almost ready
- PID detectors : under construction
- LH_2 target : not ready



Scattered Fiber Tracker (1.0 mm Φ

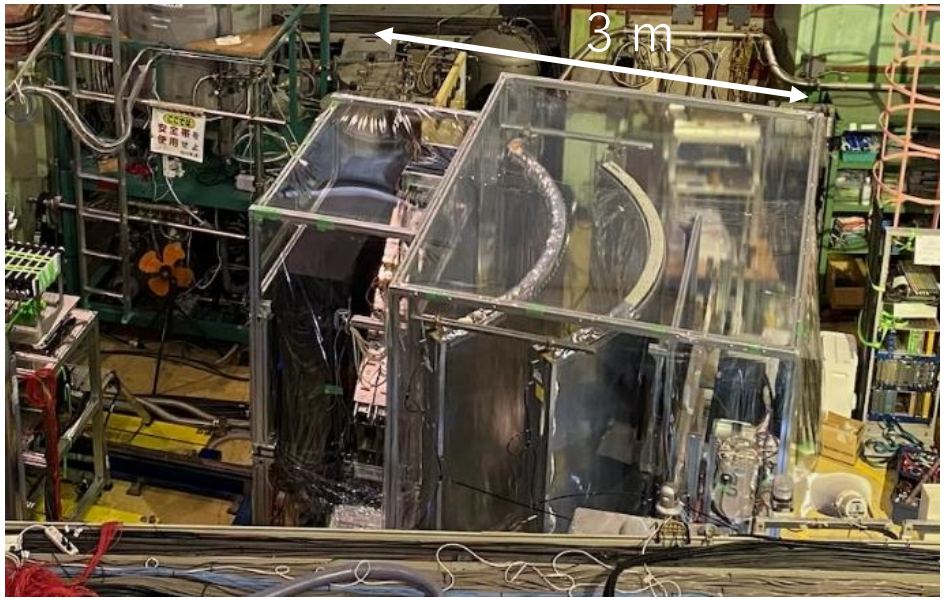


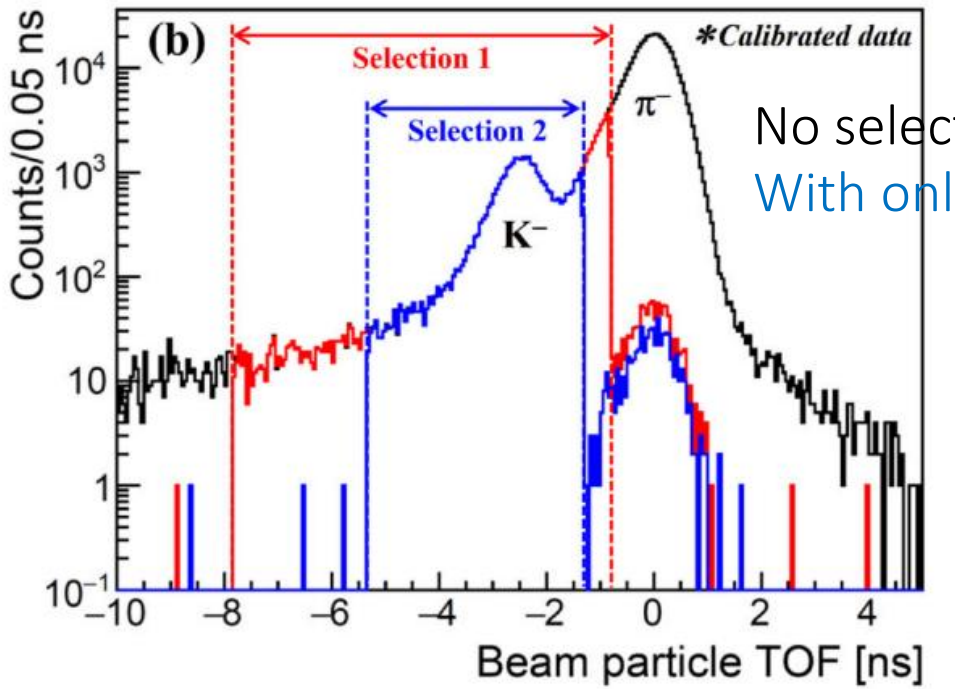


First detector & DAQ test (2024)

- Existing Trackers/FEEs tests with streaming DAQ at J-PARC K1.8BR beamline (2024)
- TOF online filtering works well

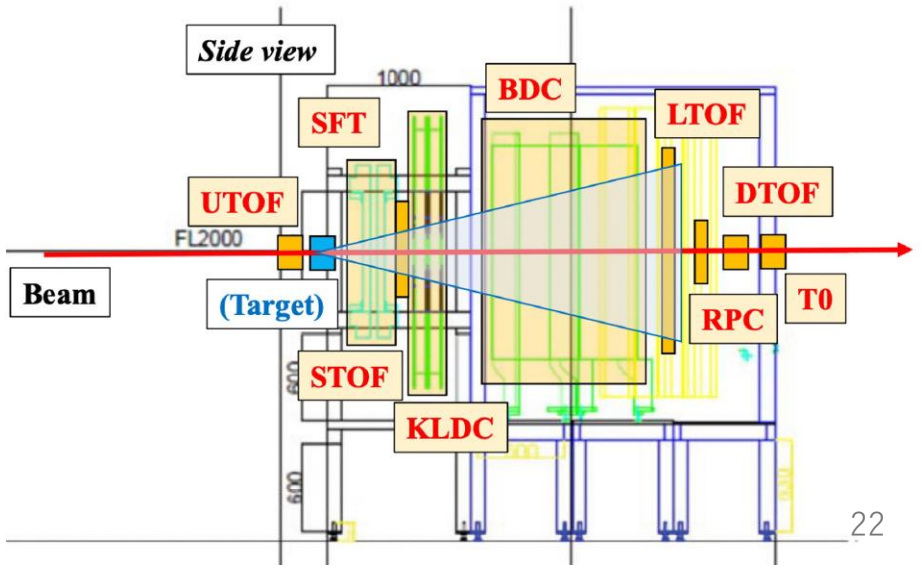
K. Shirotori et al., PTEP 083H01 (2026)





No selection

With online selection

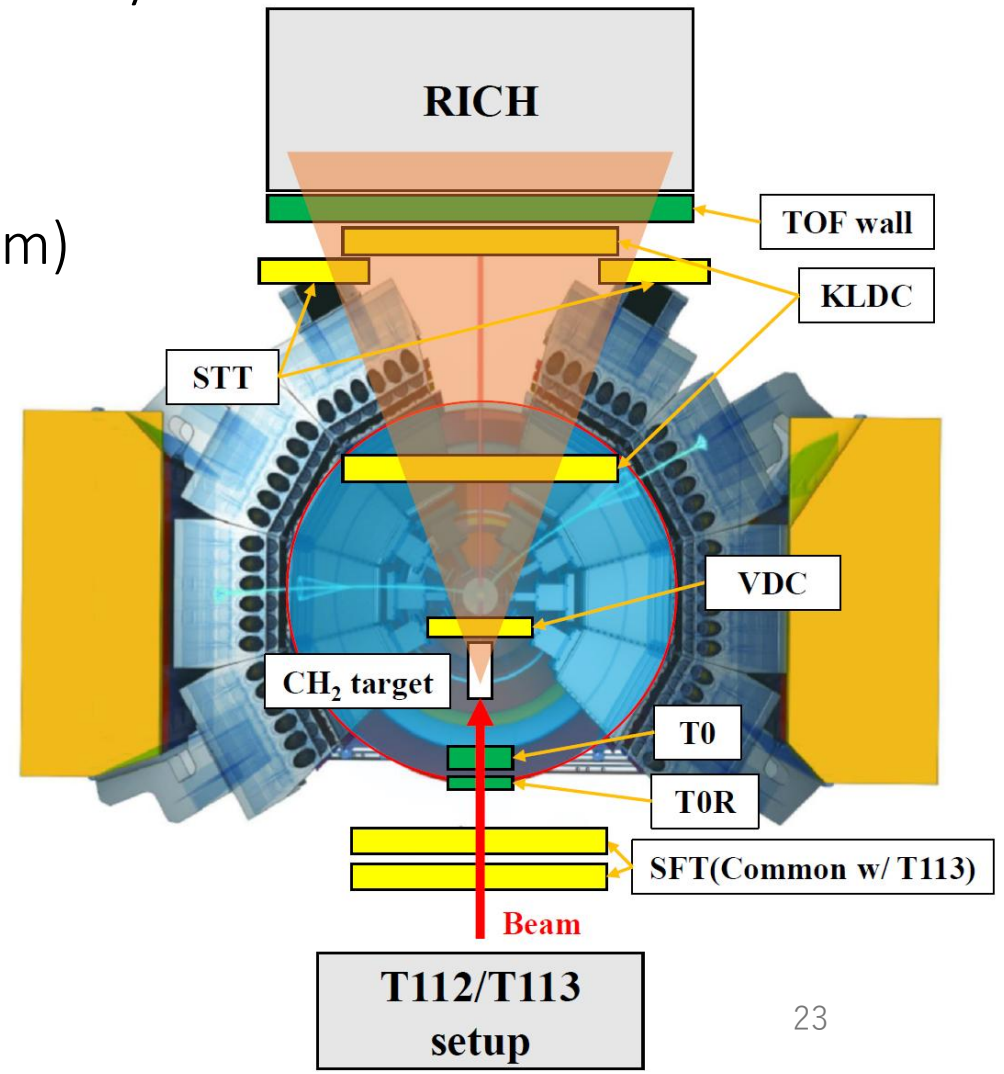


2027/Jun

- 2026/Nov-Dec beam time → E16 experiment (primary beam) phase-1 finish
- 2027/Jun beam time → A chance for secondary beam delivery

- Proposed
  - T112 experiment : Negative beam evaluation
    (2,5,8,10,15,20 GeV/c negative, 20 GeV/c positive beam)
    $p+p \rightarrow p+\pi+n/\Delta$
  - T113 experiment : Negative high purity muon

- New proposal under preparation
  - **T11X experiment : CH_2 target + MARQ detector + E16 magnet**
  - **1st pilot data with 20 GeV/c secondary beam**
  - Construction of detectors in harry



Summary & prospects

- GPDs study using hadron beams

- $p + p \rightarrow p + \pi + n/\Delta$
- $\pi^- + p \rightarrow \gamma + \gamma + n$
- $\pi^-/K^- + p \rightarrow l^+ + l^- + n/\Lambda$

- Large cross section
- x-dependence
- $x \neq \pm\xi$ region
- transition GPDs
- Complementary to the lepton induced reactions

- J-PARC π20 beamline
- MARQ spectrometer

- 2027/Jun beam time → first pilot data
- Start from reactions with large cross sections
- Opens a door of GPDs studies using hadron beam