

# Study of the nucleon structure using hadron beam at J-PARC

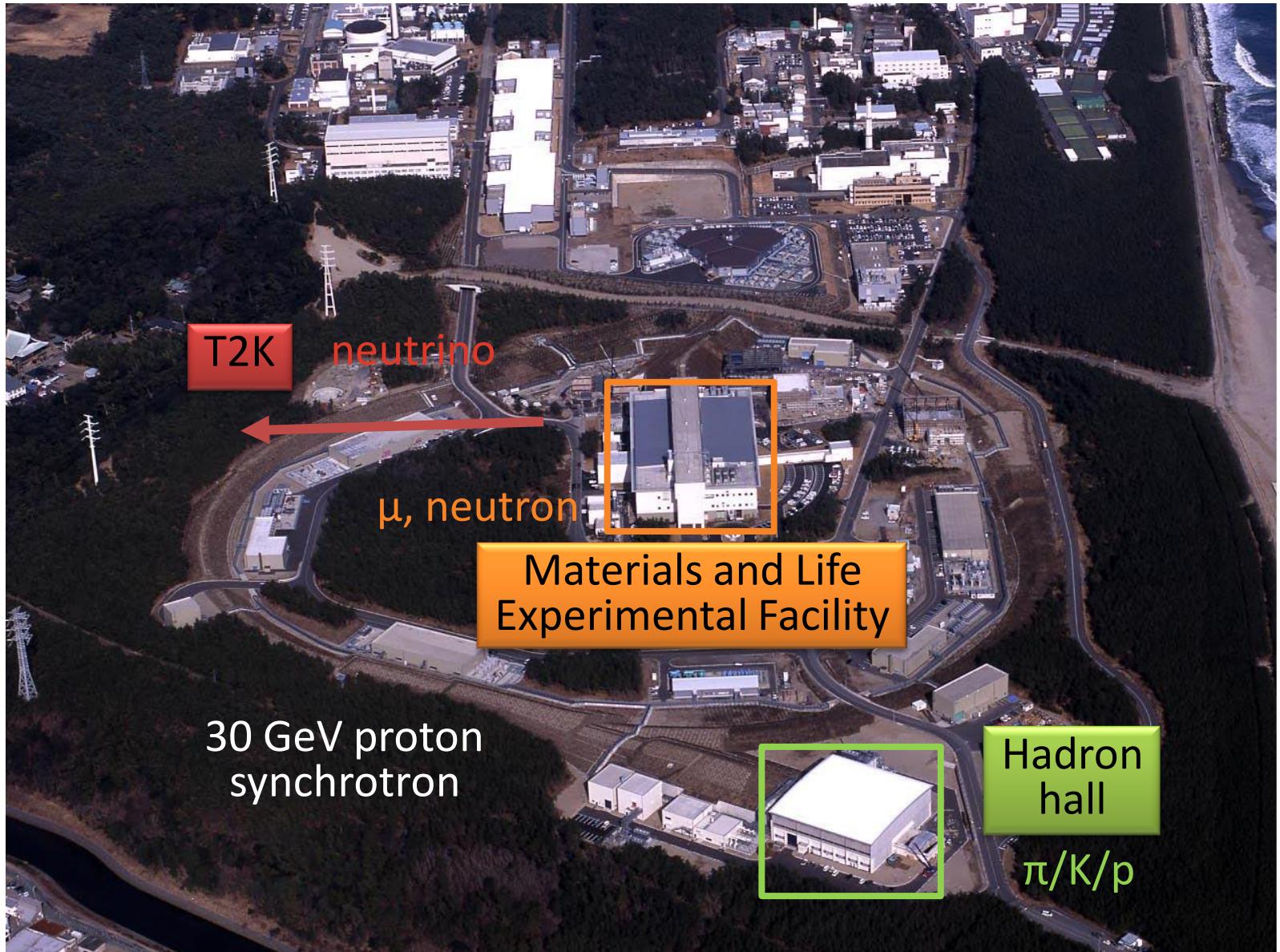
The 16<sup>th</sup> International Conference on Meson-Nucleon  
Physics and the Structure of the Nucleon (MENU2023)

Erbacher Hof, Mainz, Germany  
2023/Oct/17

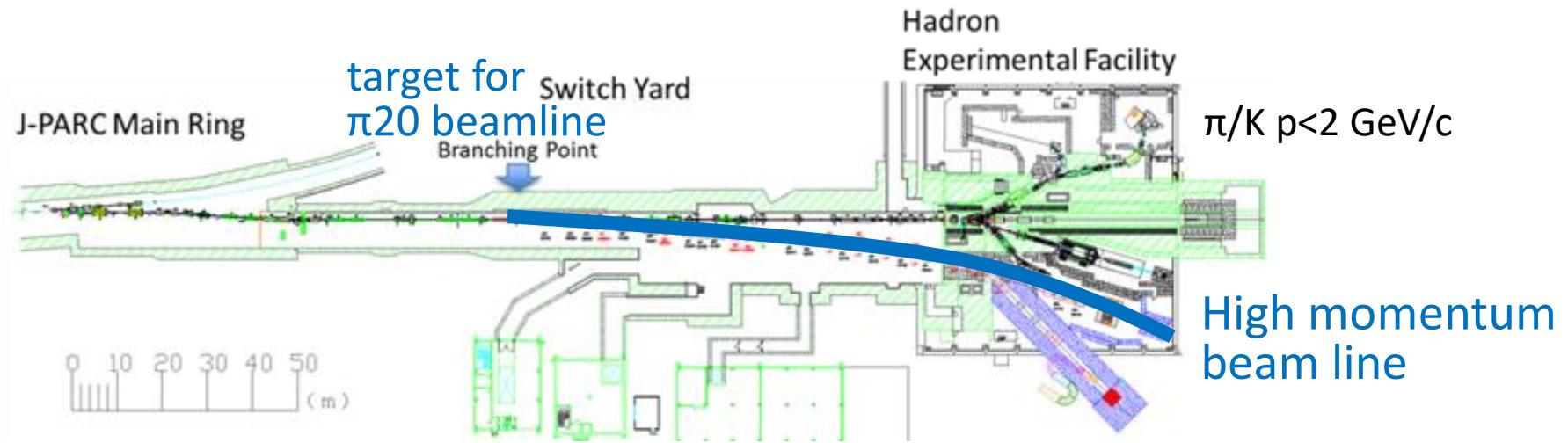
Natsuki TOMIDA  
Kyoto University

# J-PARC

## Japan Proton Accelerator Research Complex



# High momentum beam is now available at J-PARC !

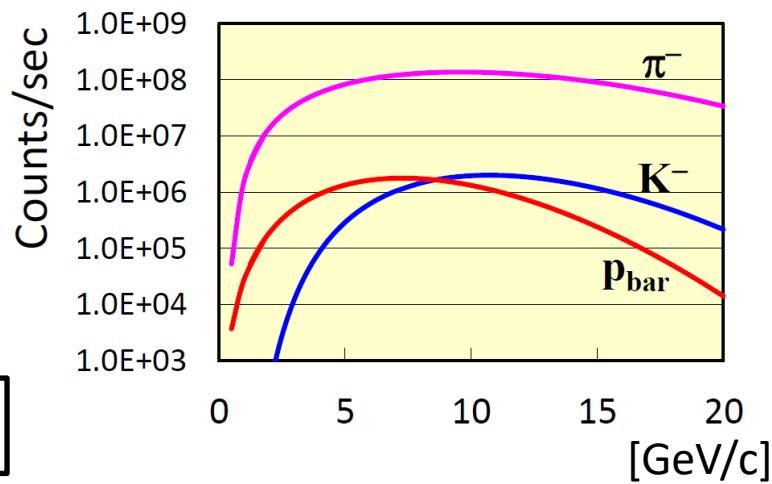


- 2020- : primary proton beam (30 GeV)
- 202X- : positive/negative high momentum secondary beam

**π20 beamline**



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



# Experimental ideas at J-PARC

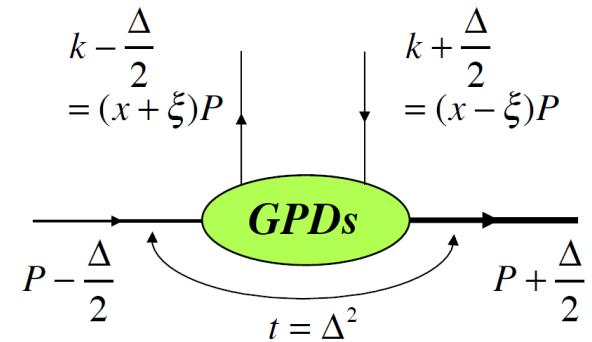
- **High intensity proton beam** ( $10^{10}$  protons/spill, 30 GeV)
- **Wide momentum secondary beam** ( $\pi/K/p$ , 2-20 GeV/c)
- Hadron beam at  $p \sim O(10 \text{ GeV}/c)$  ⇒ **Not explored much**  
large cross section in exclusive reactions
- Multi purpose spectrometer for  $\pi^+$  beamline is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

- 30 GeV proton beam
  - GPDs measurement with  $p+p \rightarrow p+\pi+B$  reaction ( $\mu b$ )
  - Drell-Yan measurements (nb)
- Positive secondary beam (<20 GeV/c)
  - Color transparency search (nb-pb, depends on momentum)
- Negative secondary beam (<20 GeV/c)
  - $\pi/K$  induced Drell-Yan (nb)
  - Exclusive Drell-Yan (pb)

# Generalized Parton Distributions

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

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



- GPDs**
- $x$  : Bjorken variable
  - $\xi$  : Skewness
  - $t$  : Momentum transfer
- |                                 |                                     |
|---------------------------------|-------------------------------------|
| average quark momentum fraction | transferred quark momentum fraction |
|---------------------------------|-------------------------------------|

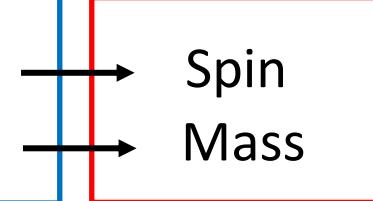


Forward limit : 1D Parton Distribution Functions

1<sup>st</sup> moments : Form Factor

2<sup>nd</sup> moments : Total Angular Momenta  
Gravitational Form Factor

Origin of nucleon



Global analysis

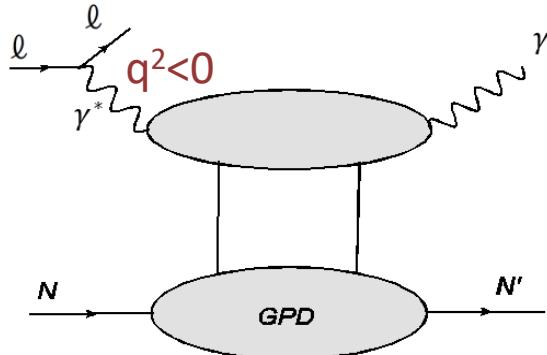
Measurement in different reactions and in different kinematics is important

# Reactions for GPDs measurements

Space-like

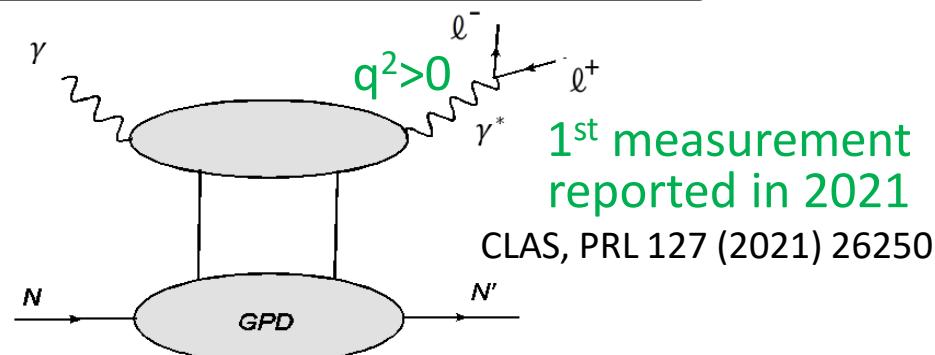
PRD 86 031502(R) (2012)

## Deeply Virtual Compton Scattering (DVCS)

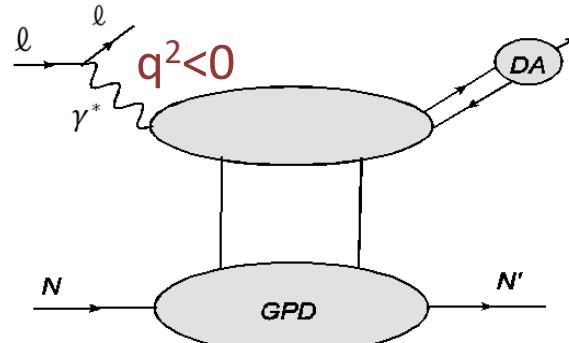


Time-like

## Time-like Compton Scattering (TCS)

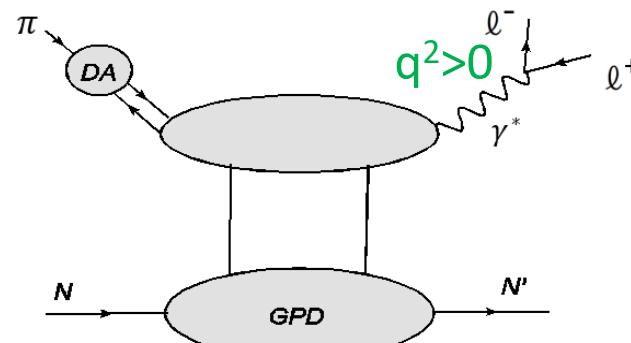


## Deeply Virtual Meson Production (DVMP)



Factorization proved

## Exclusive meson-induced DY



Not proved

First measurement of  
exclusive DY at J-PARC

# $p + p \rightarrow N + \pi + B$

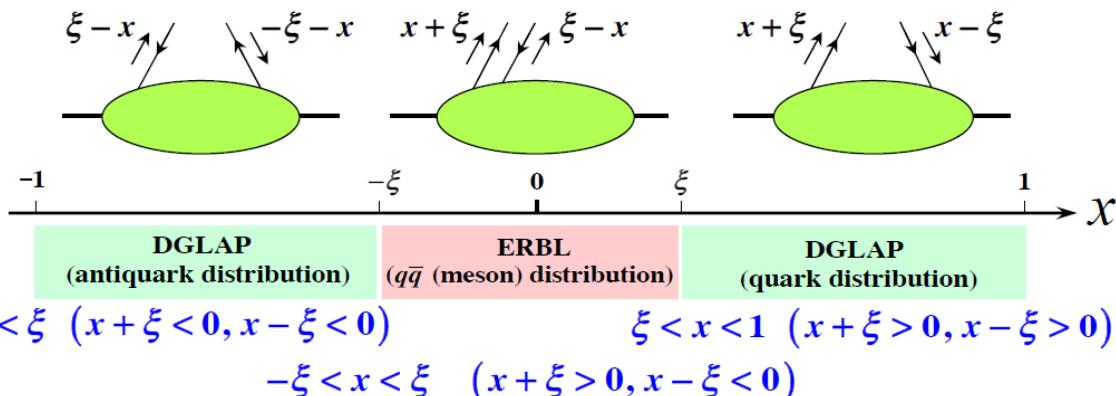
S. Kumano et al., PRD 80 074003 (2009)

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

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

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

Generalize Parton Distribution Functions

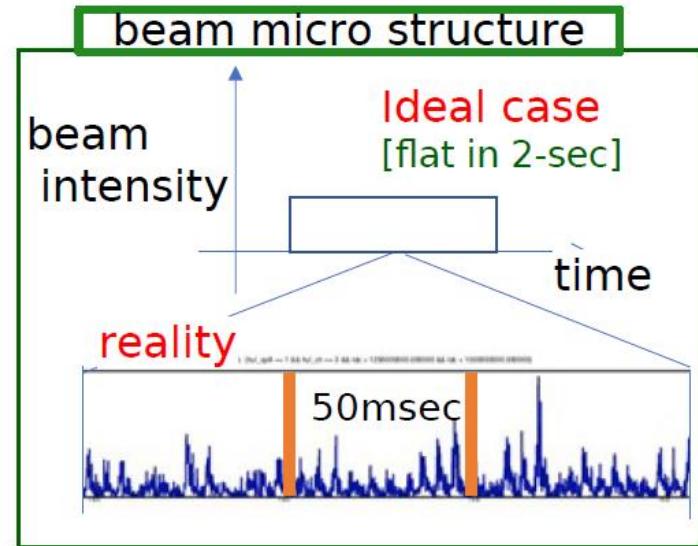


- Novel idea to measure GPDs with hadron reactions
- Access to ERBL region which cannot be accessed with DIS reactions

# Current status of the high-p beamline

# 30 GeV proton beam

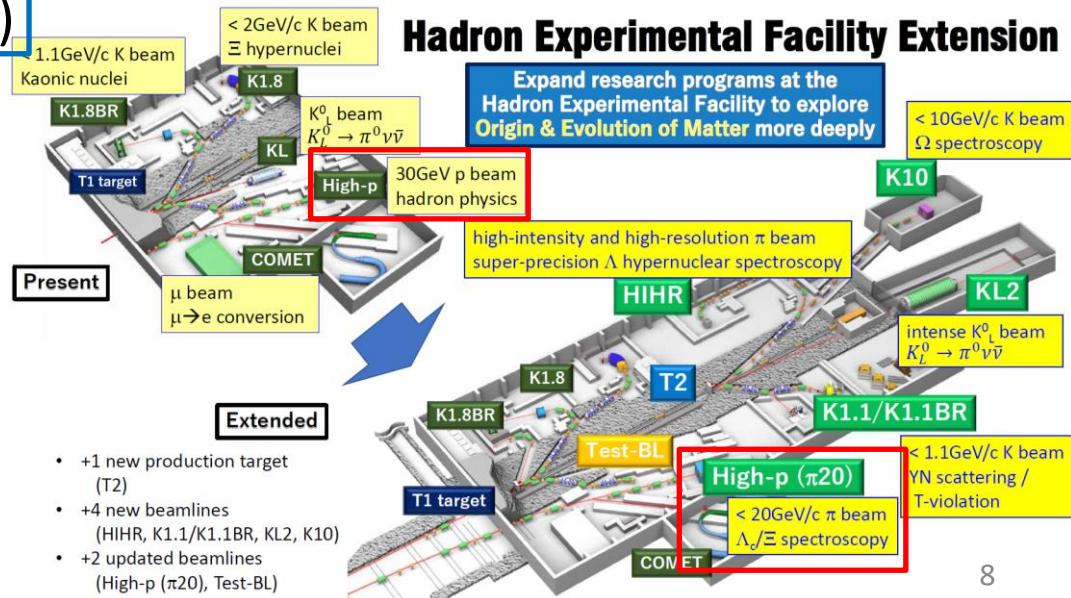
- $10^{10}$ /spill beam is delivered
  - Problems in beam spill structure
  - Physics run starts soon
    - E16 experiment ( $\Phi$  meson in nucleus)
      - 2020,2021 : run0a-0c
      - 2022 : Main Ring upgrade
      - 2023 : Fire accidents, run0d



S. Yokkaichi, 3rd J-PARC HEF-ex WS

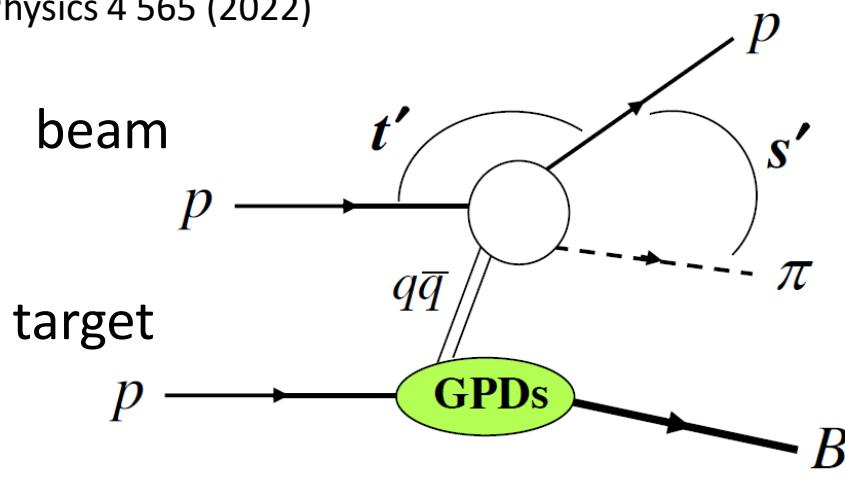
## Secondary beam ( $\pi$ 20 beamline)

- 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)



# $p + p \rightarrow N + \pi + B$ reaction

S. Kumano, MDPI  
Physics 4 565 (2022)



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

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

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

$$s = (p_a + p_b)^2,$$

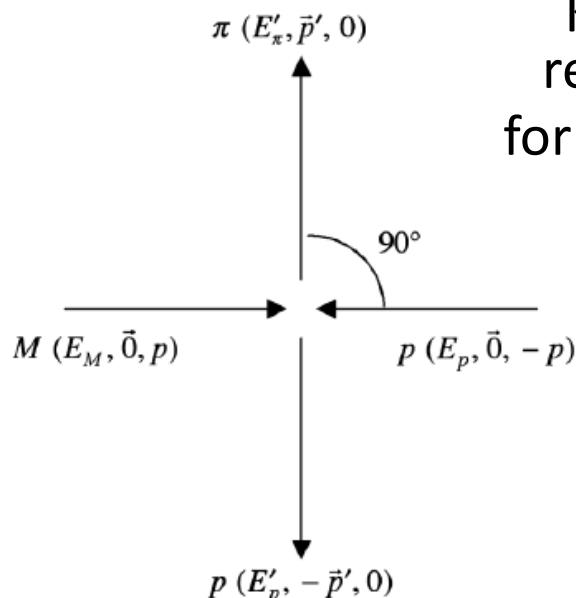
$$s' = (p_c + p_d)^2,$$

$$t = (p_a - p_e)^2,$$

$$t' = (p_b - p_d)^2$$

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

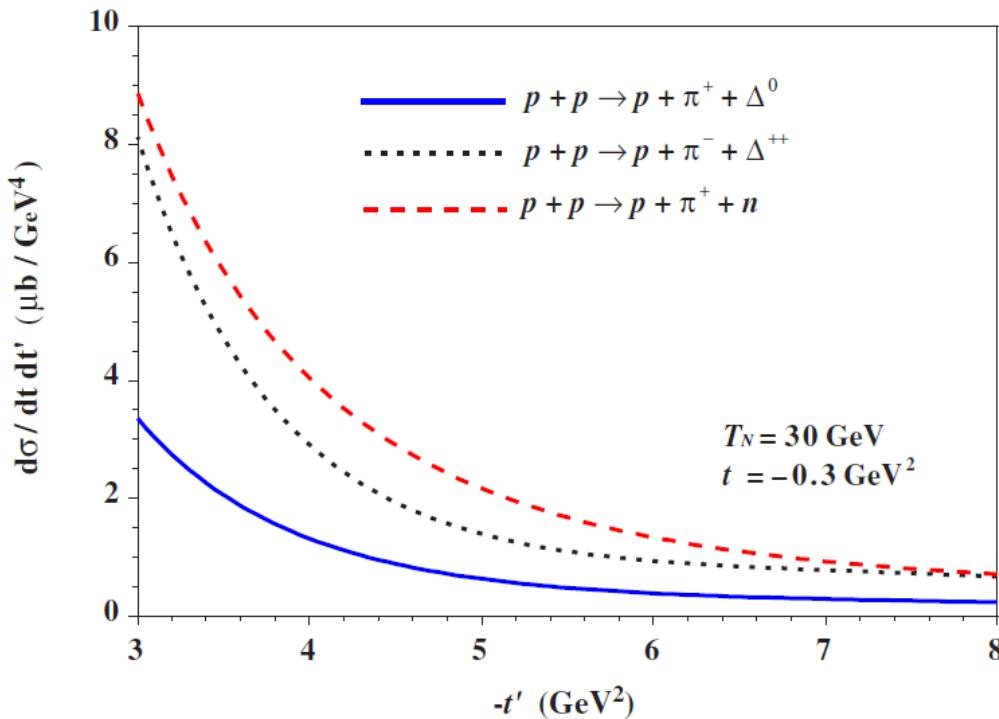
Kinematical requirements for factorization



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

$p$  and  $\pi$  : large and nearly opposite transverse momenta & large invariant energy

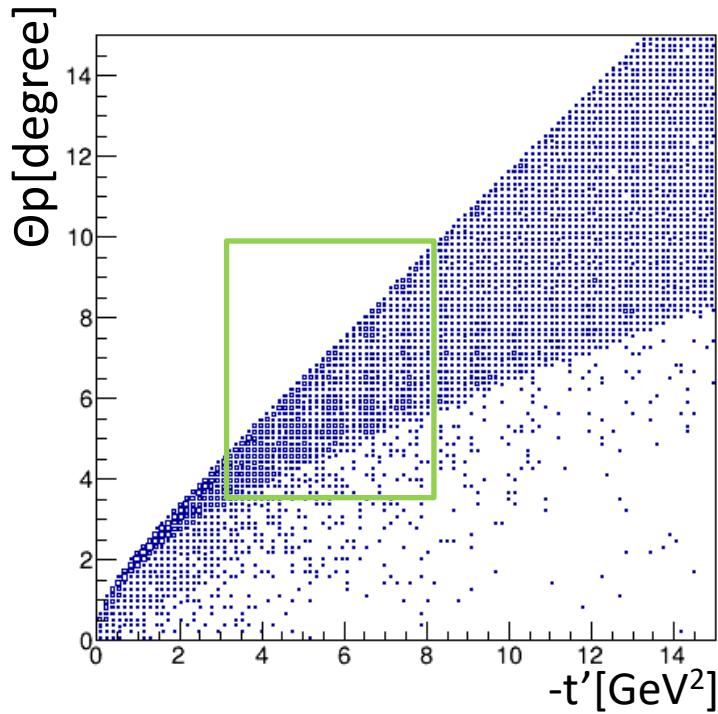
# Expected cross section



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

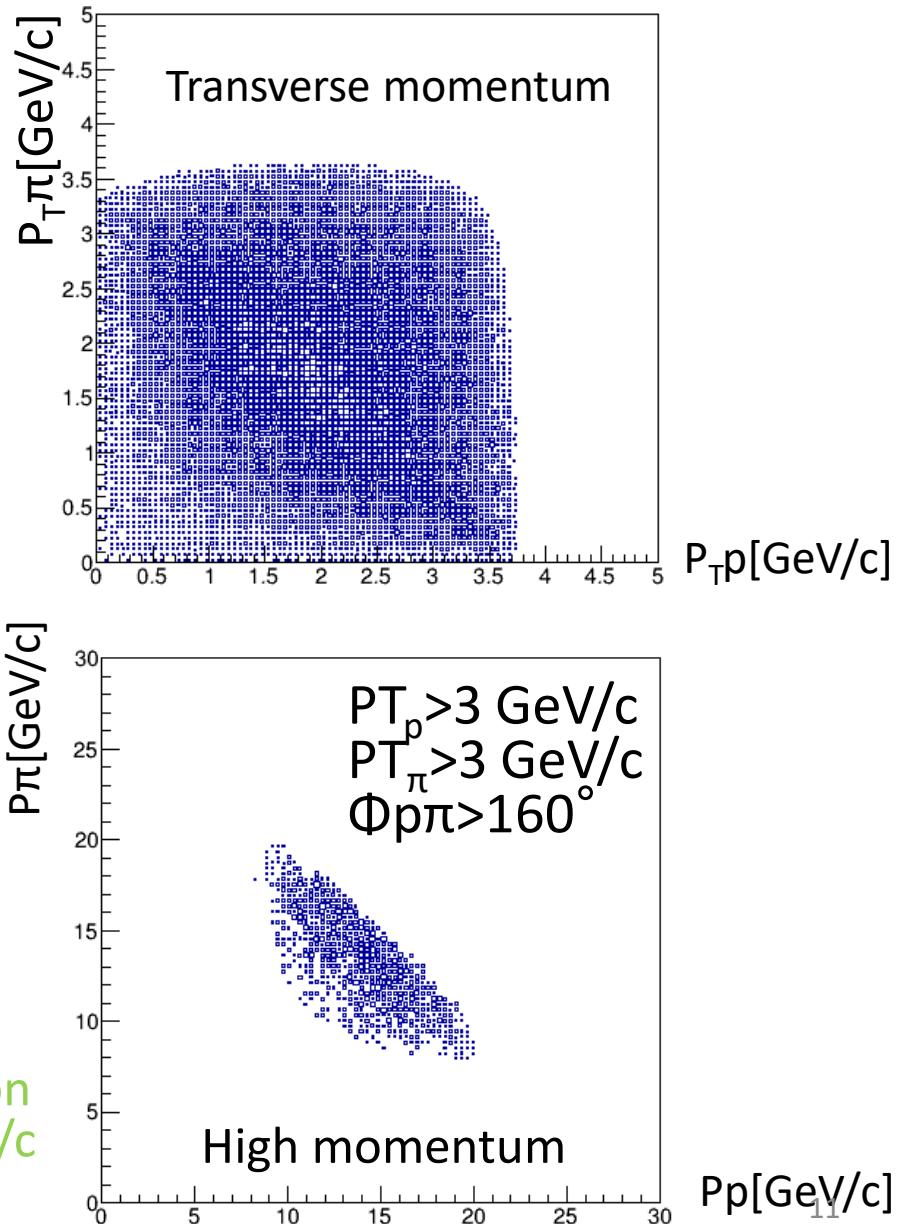
- $5 \mu\text{b}/\text{GeV}^4, 10^{10}/\text{spill}, 2 \text{ cm LH2, acc} \times \text{eff} = 5\% \Rightarrow 10^7/\text{day}/\text{GeV}^4$

# Kinematics



Forward angle

p/ $\pi$  separation  
@ 10-20 GeV/c



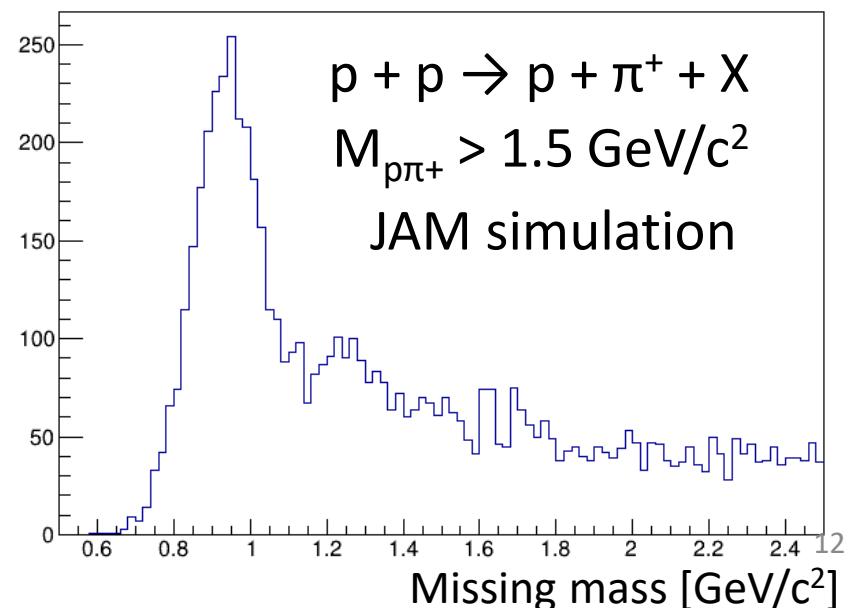
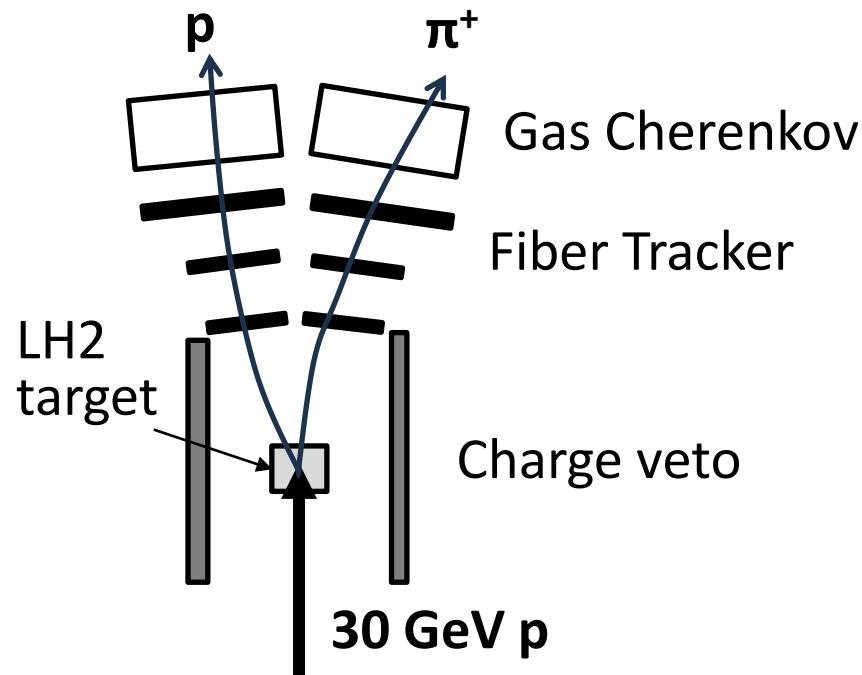
High momentum

$Pp$  [GeV/c]



# Possible setup

- Missing mass
  - Good resolution is not required
  - $p$  beam : momentum spread  $\sim 0.05\% \Rightarrow$  no momentum measurement
  - E50 fiber tracker : 0.6% @ 15 GeV/c
- $p/\pi$  separation
  - Gas Cherenkov
- Multiplicity cut
- Liquid hydrogen target
- FM magnet
- JAM simulation  
 $\Rightarrow$  Clear identification of n peak

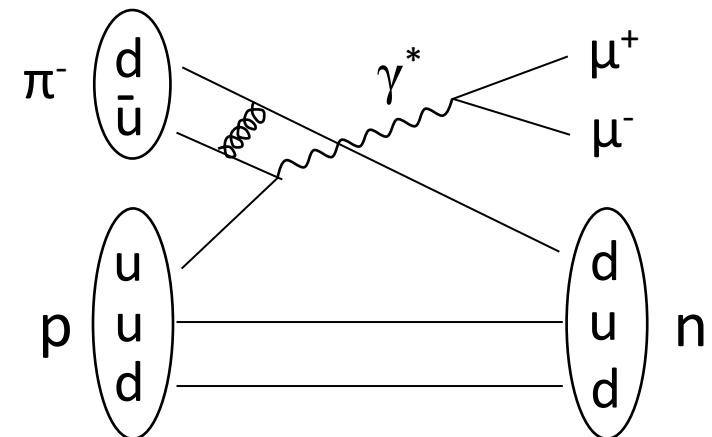


# Exclusive Drell-Yan

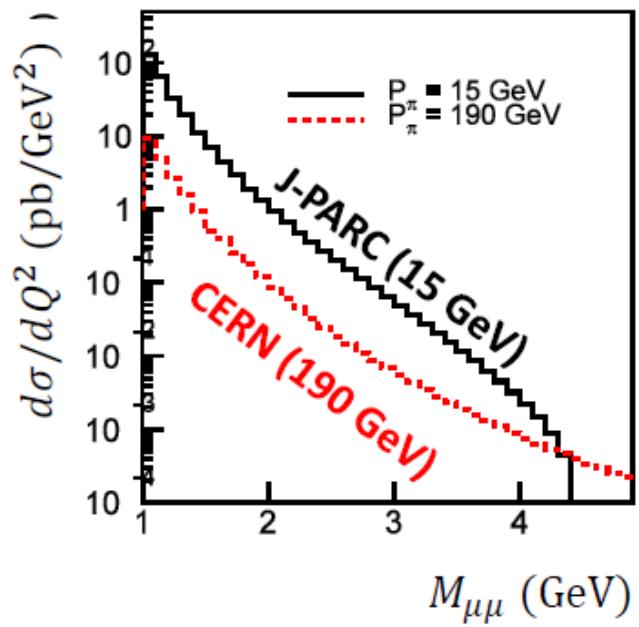
Exclusive Drell-Yan

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

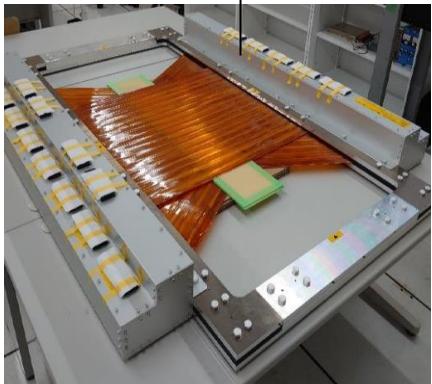
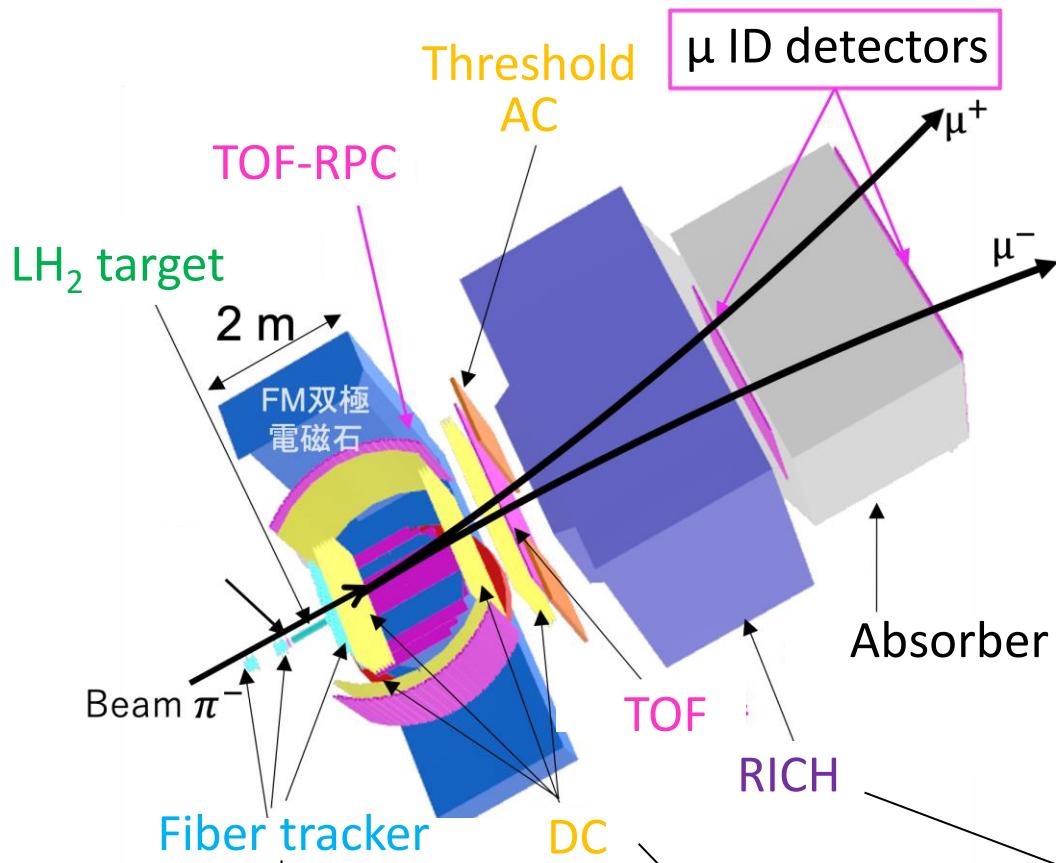
$$\frac{d\sigma_L}{dt dQ'^2} \Big|_{\tau} = \frac{4\pi\alpha_{\text{em}}^2}{27} \frac{\tau^2}{Q'^8} f_\pi^2 \left[ (1-\xi^2) |\tilde{\mathcal{H}}^{du}(\tilde{x}, \xi, t)|^2 \right. \\ \left. - 2\xi^2 \text{Re}(\tilde{\mathcal{H}}^{du}(\tilde{x}, \xi, t)^* \tilde{\mathcal{E}}^{du}(\tilde{x}, \xi, t))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



- Larger cross section @ lower momentum
- Experimental feasibility study :  
T. Sawada et al., PRD 93 (2016) 114034
- Lol submitted
- Proposal under preparation  
(W.C. Chang, Po-Ju Lin, Po-Hung Wang  
(Academia Sinica))



# E50 Spectrometer for $\pi$ 20 beamline



- Multi purpose
  - E50 (Charmed Baryon Spectroscopy)
  - E79, E97, etc...
- New generation
  - Streaming DAQ
  - MPPCs
  - 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 ( $\sim pb$ )  $\Leftrightarrow$  Large hadron background ( $\sim mb$ )

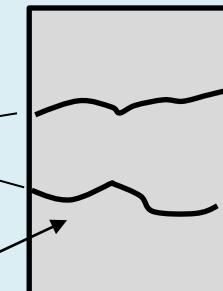
Usual DY experimental set up

(CERN)  
(Fermilab)

High intensity  
hadron beam

target

Multiple  
scattering



Hadron  
absorber

Tracker

Bad momentum resolution @ tracker

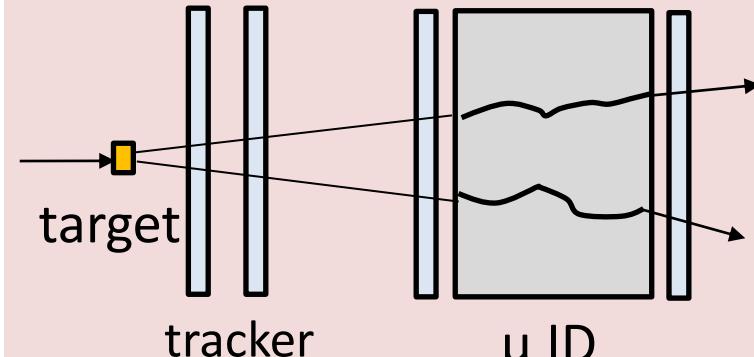


Bad missing mass resolution



Only inclusive measurement

Our setup



Momentum analysis @  
upstream of absorber



Good missing mass resolution

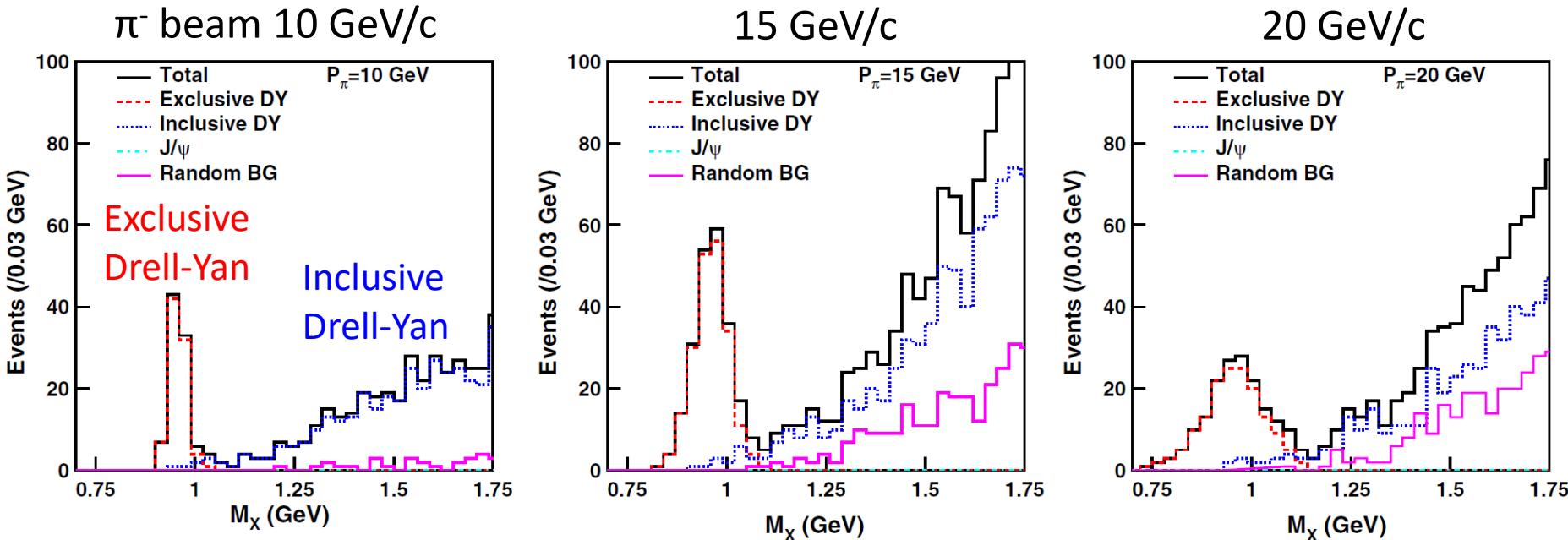


1<sup>st</sup> measurement of exclusive reaction

# Exclusive Drell-Yan measurement

Expected Missing Mass Spectra (50 days)

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



- 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

- High momentum proton beam is now available at J-PARC
- Secondary high momentum beam will be available
- Study nucleon structure @ J-PARC
- GPDs measurement with
  - 30 GeV proton beam
    - $p+p \rightarrow p+\pi+B$  ( $\mu b$ )
  - Negative secondary beam (<20 GeV/c)
    - Exclusive Drell-Yan (pb)