Measurements of Generalized Parton Distribution functions using lepton and hadron beam

研究会「EICで展開する新たな原子核・素粒子物理」

2024/May/30

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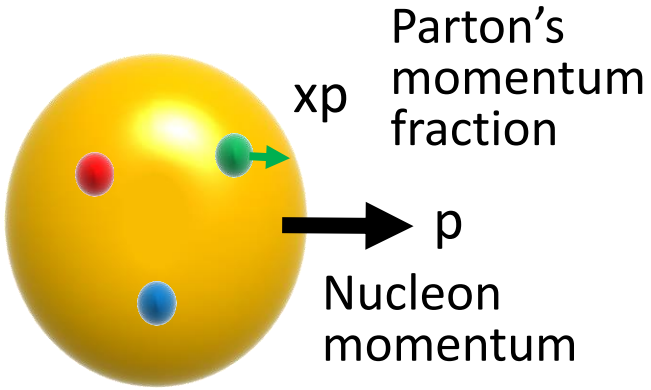
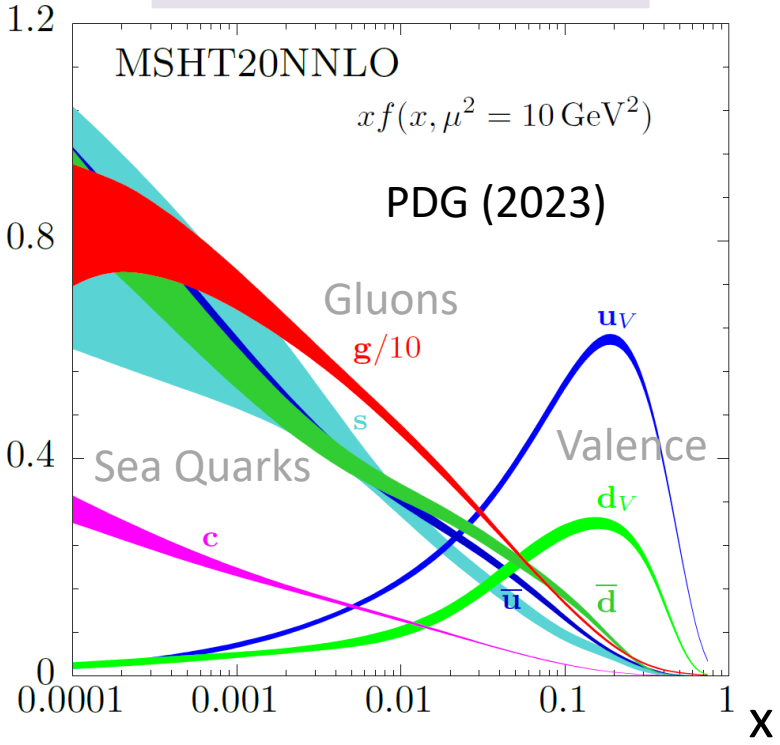
Kyoto University

Parton Distribution Functions (PDFs)

- 1-dimentional Parton Distribution Functions
- Function of Bjorken x
  (Parton's longitudinal momentum fraction)

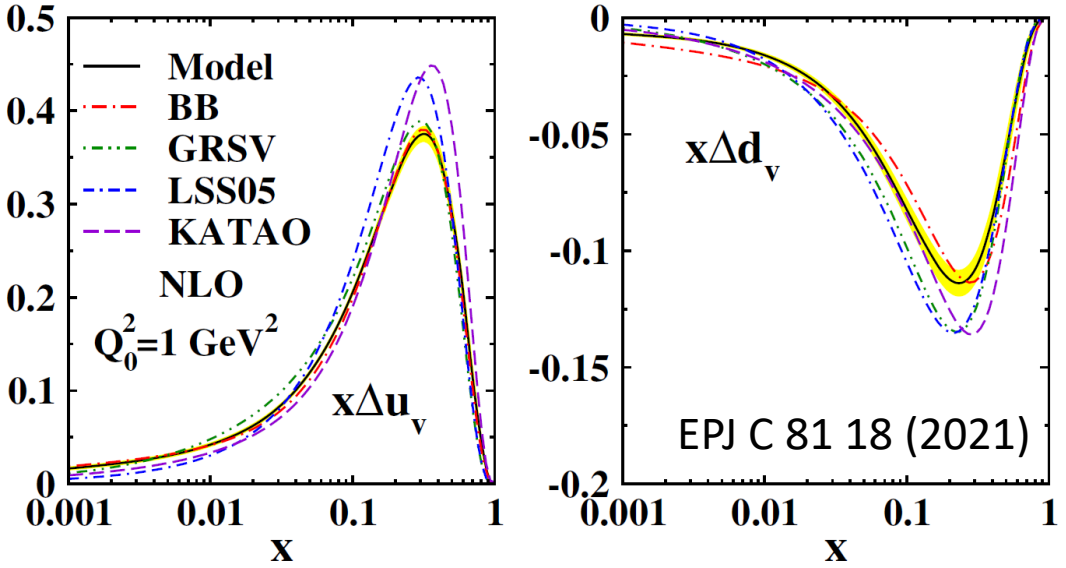


Unpolarized Parton Distribution



Polarized Parton Distribution

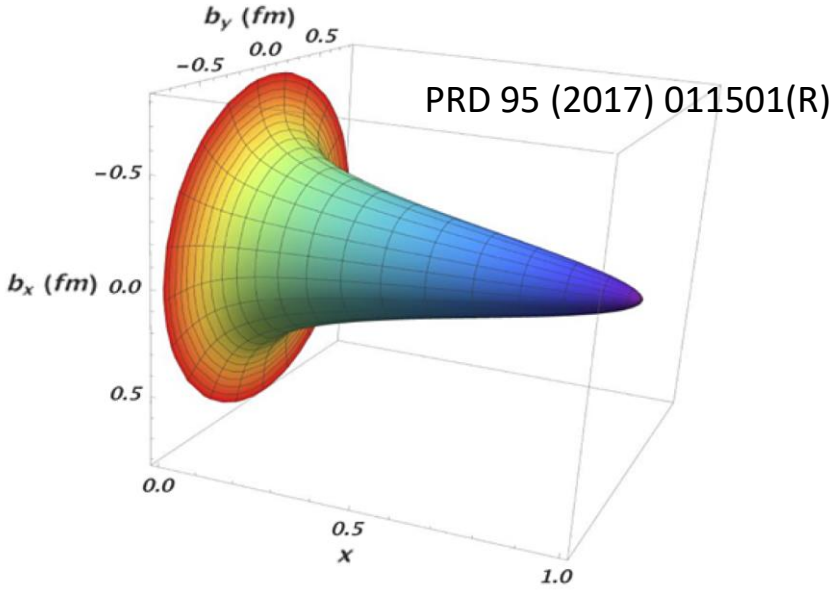
Integral -> Quark spin



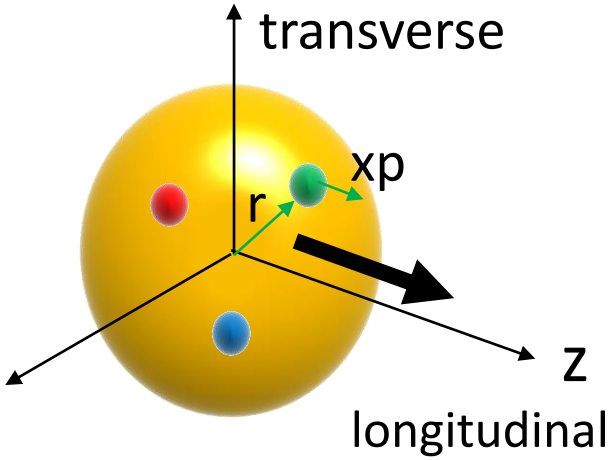
3D Parton Distributions

Generalized Parton Distributions (GPDs)

- Transverse position & longitudinal momentum fraction of partons

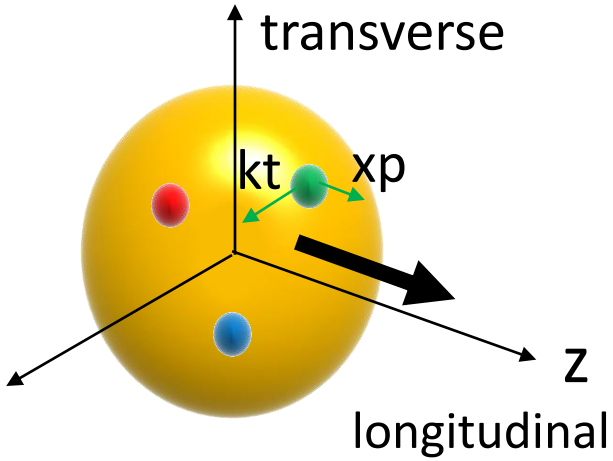


PRD 95 (2017) 011501(R)



Transverse Momentum Dependent Parton Distributions (TMDs)

- Transverse momentum & longitudinal momentum fraction of partons



Generalized Parton Distributions (GPDs)

Four Quark GPDs

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

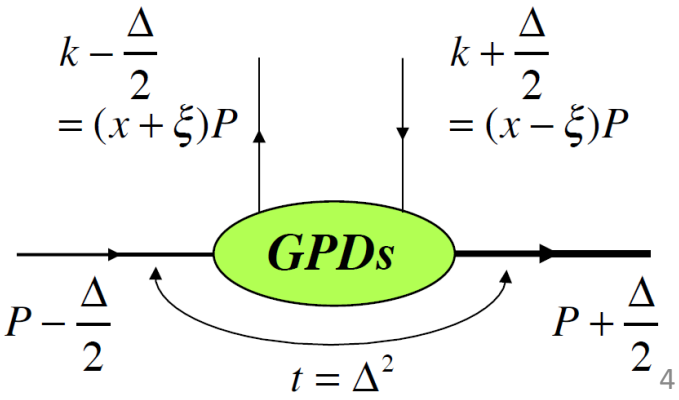
3 variables
- x : Fraction of longitudinal momentum
- ξ : Fraction of transferred momentum
- t : Four momentum transfer

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



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

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

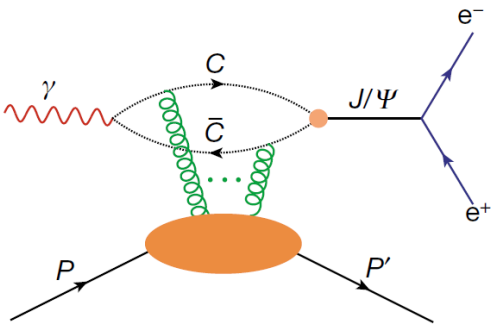
Mass Pressure

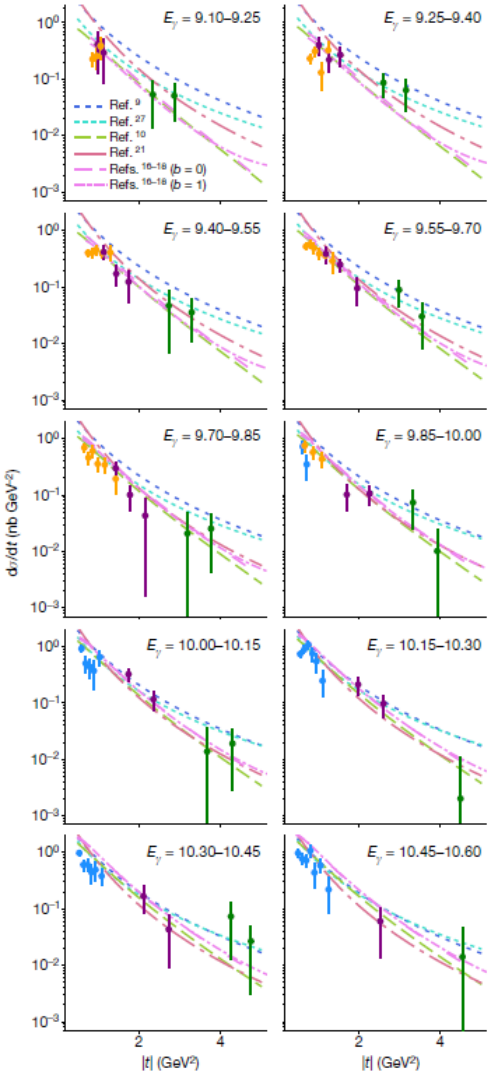
can probe the origin of nucleon spin and mass

x dependence is important

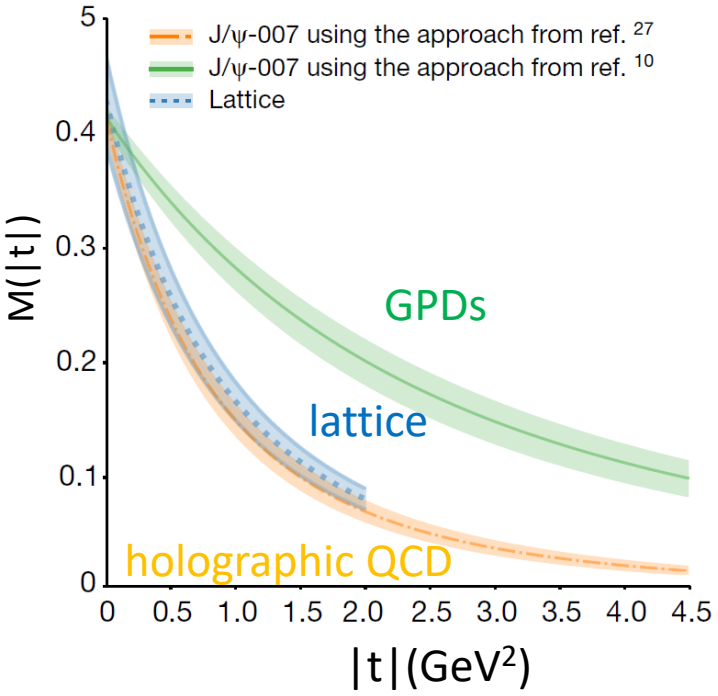
Gluon Gravitational Form factor M(t)

- JLab $\gamma + p \rightarrow J/\psi + X$





Nature 615 815 (2023)

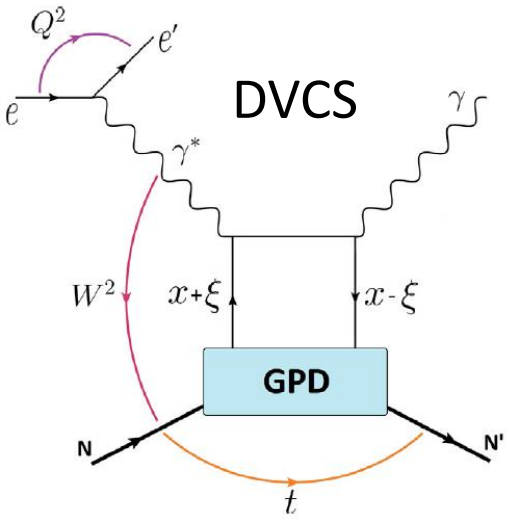


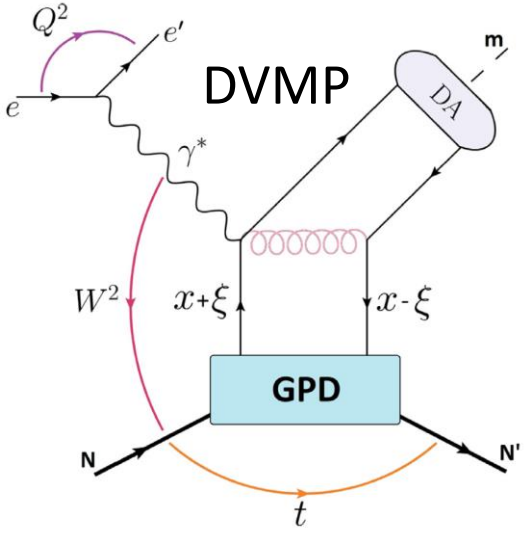
	Radius (fm)
Holographic QCD	0.755±0.035
GPDs	0.472±0.042
Charge	~0.85

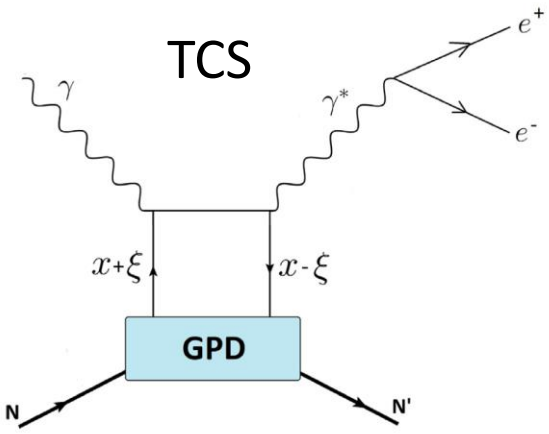
- Gluon mass radius smaller than charge radius
- Gluon inner core

GPDs measurement until now

- Deeply Virtual Compton Scattering (DVCS) : l + p → l' + p' + γ
- Deeply Virtual Meson Production (DVMP) : l + p → l' + p' + M
- Time-like Compton Scattering (TCS) : γ + p → l^+ + l^- + p'



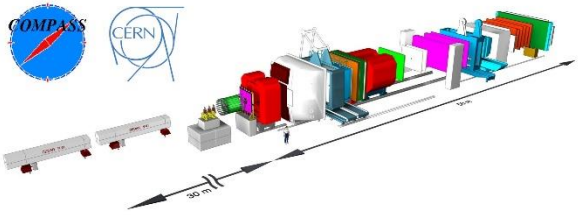




HERMES(ep collider)

JLab(e,γ beam)

COMPASS(μ beam)



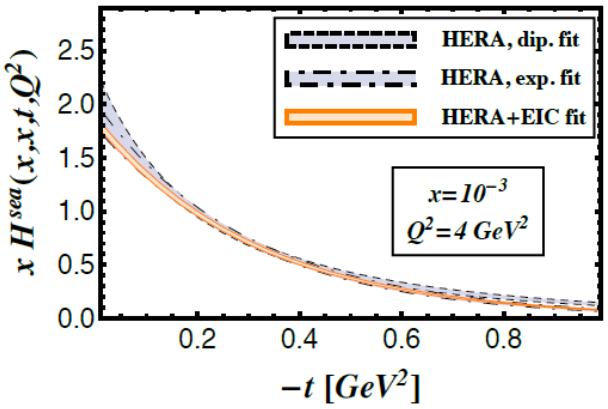
GPDs measurement @ EIC

- DVCS in wider phase space ⇒ gluon and sea quarks
- DVMP of heavy meson (J/ψ,Υ), light vector and pseudoscalar meson

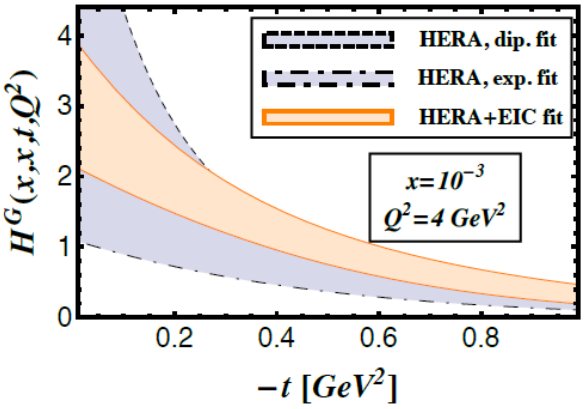
  ⇒ gluon @ low x, flavor separation, chiral odd GPDs

  H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$

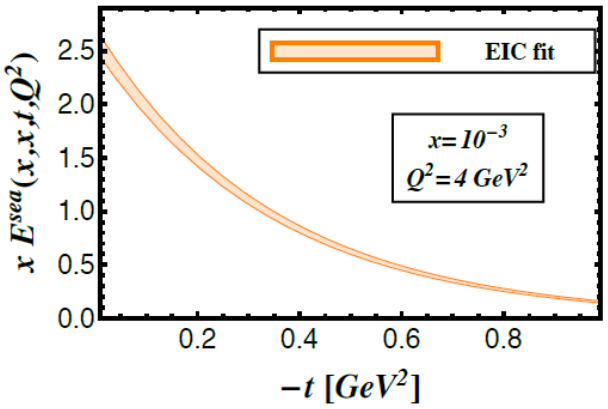
sea quark H



gluon



sea quark E

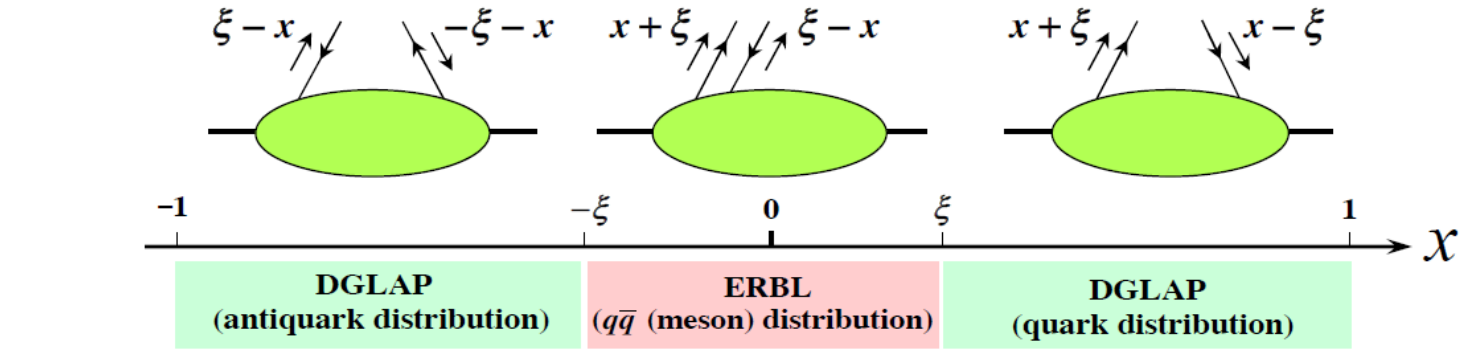


EIC Yellow Paper(2021)

current data EIC pseudodata

GPDs measurement until now

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

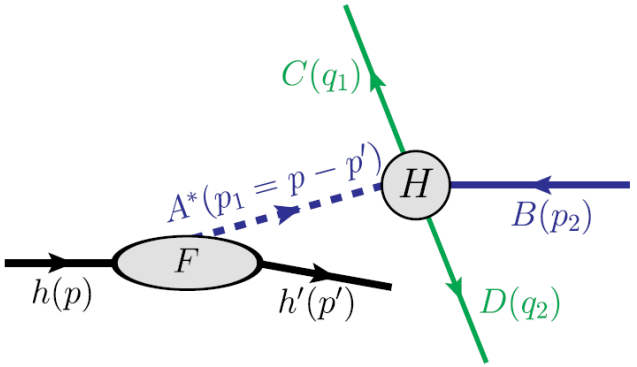


Single Diffractive Hard Exclusive Process

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

Recently proposed

Generalization of process for GPDs measurements



B + p → C + D + p' (2→3 process)

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

Diffractive production of A*:

p → A* + p'

Exclusive 2→2 scattering :

A* + B → C + D

Factorization

Cross section depends on GPDs

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

We can access GPDs via reactions other than DVCS, DVMP or TCS

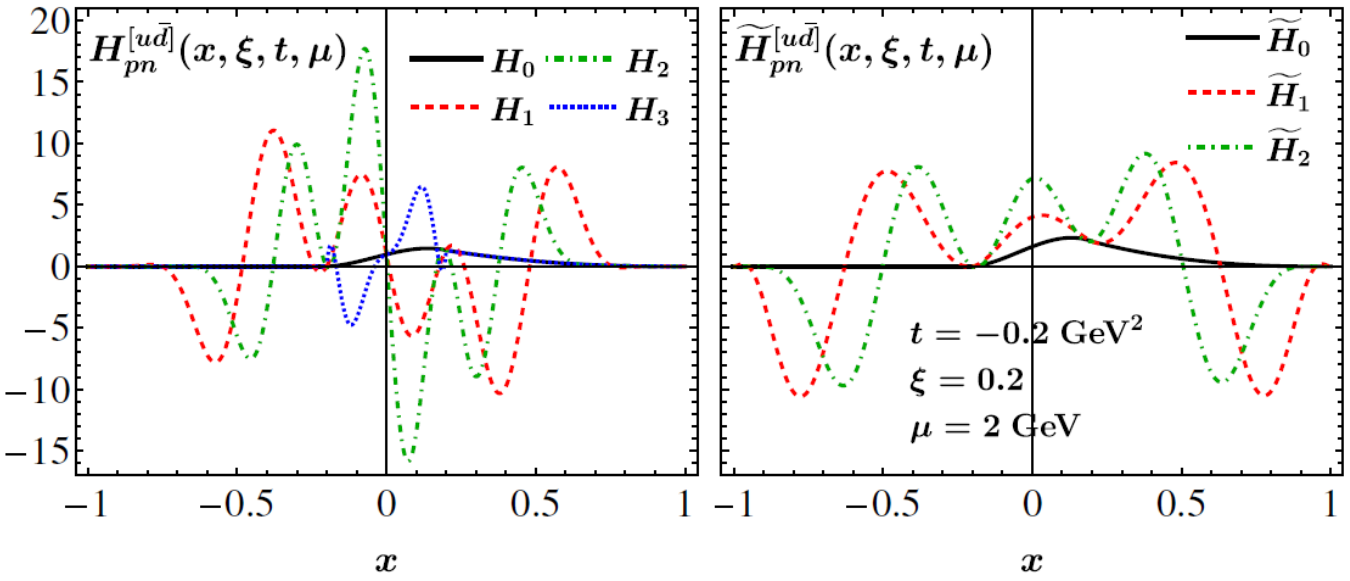
Hadronic reaction

Some reactions can access

- **x-dependence of GPDs**
- **ERBL region of GPDs**

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

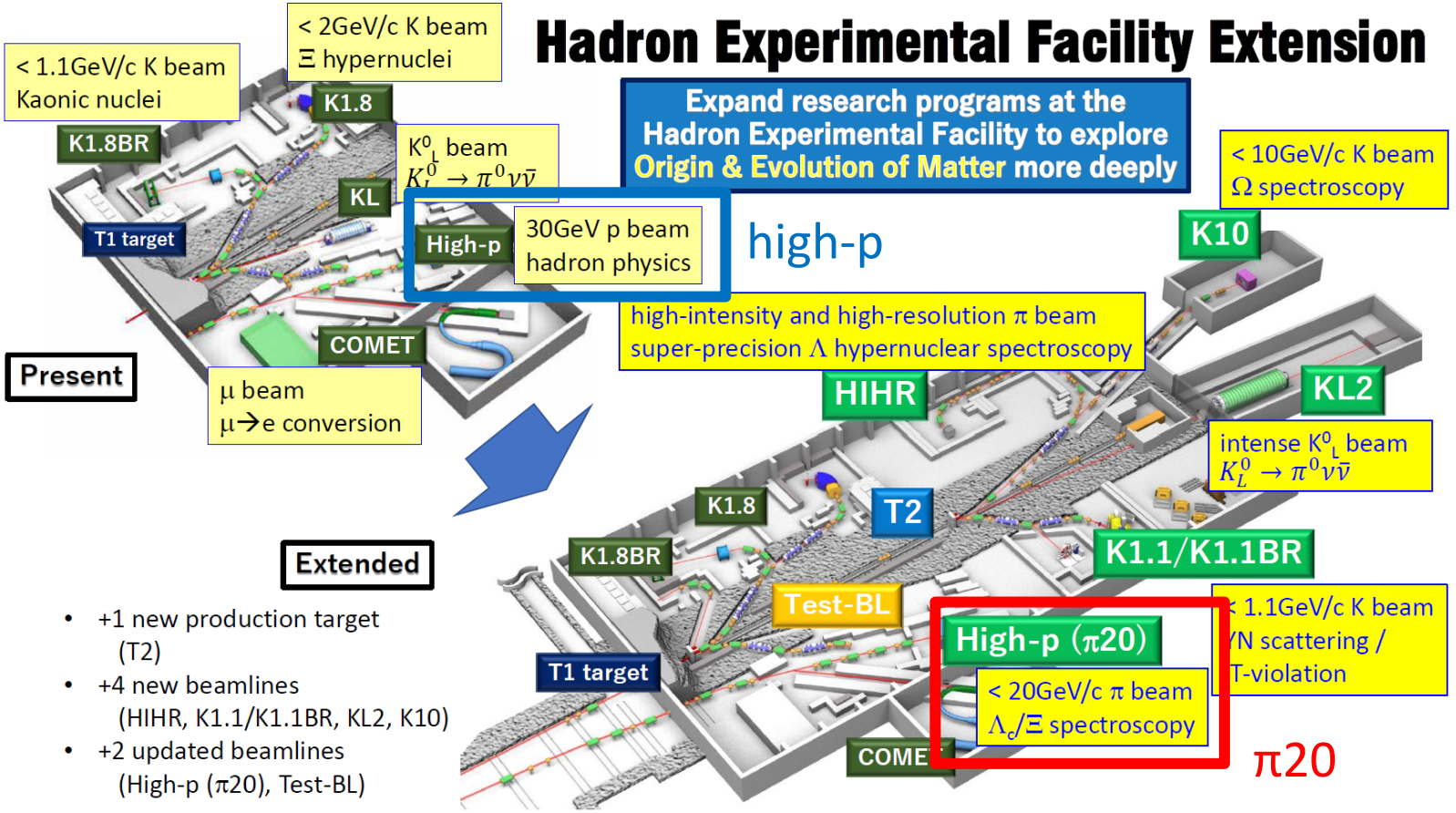
- J.-W. Qiu and Z. Yu • PRD 109 (2024) 074023
- Large and opposite transverse momentum of $\gamma\gamma$
- Large sensitivity to the DGLAP region near $x = \pm\xi$
- **Can access x dependence = distinguish shadow GPDs and real GPDs**



High momentum beamline @ J-PARC

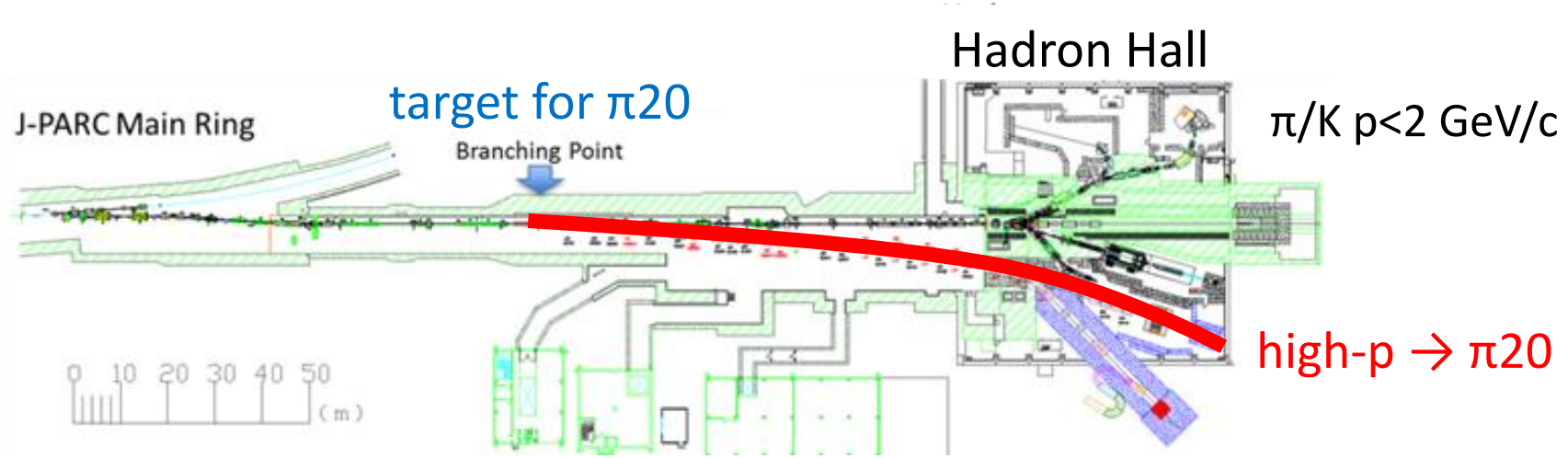
- Primary 30 GeV proton beam is now available at the high-p beamline
- Construction of the secondary π/K/p beamline up to 20 GeV/c (= π20 beamline) is planned with the hadron hall extension

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



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

Status and plan of the high-p beamline



- 2020 : First 30 GeV primary proton beam
- 2024? : First 30 GeV proton physics run (E16)
- 202X : Secondary π/K/p at 2-20 GeV/c (π20 beamline)
  - Phase 1 (10^5/spill): Beam study(P93), $\pi^-p\rightarrow\Phi n$(P95), $\pi^-p\rightarrow\eta n$(LoI)
  - Phase 2 (a few 10^6/spill): I=3 Dibaryon(E79), Cascade(E97), Λp(LoI)
  - Phase 3 (6×10^7/spill): Charm(E50), exclusive Drell-Yan(LoI)

Nucleon structure studies in J-PARC

Current 30 GeV proton beam

- GPDs study with p+p→p+π+B (μb)
- p induced Drell-Yan (nb)

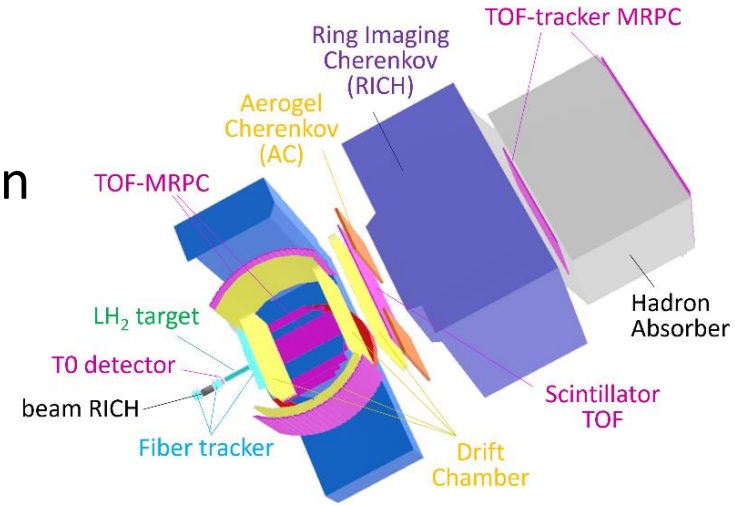
Positive secondary beam (<20 GeV/c)

- 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 high-p collaboration



MARQ Spectrometer

p + p → N + π + B

- S. Kumano, M. Strikman and K. Sudoh, PRD 80 (2009) 074003
- Can be measured at the current high-p beamline

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

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

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

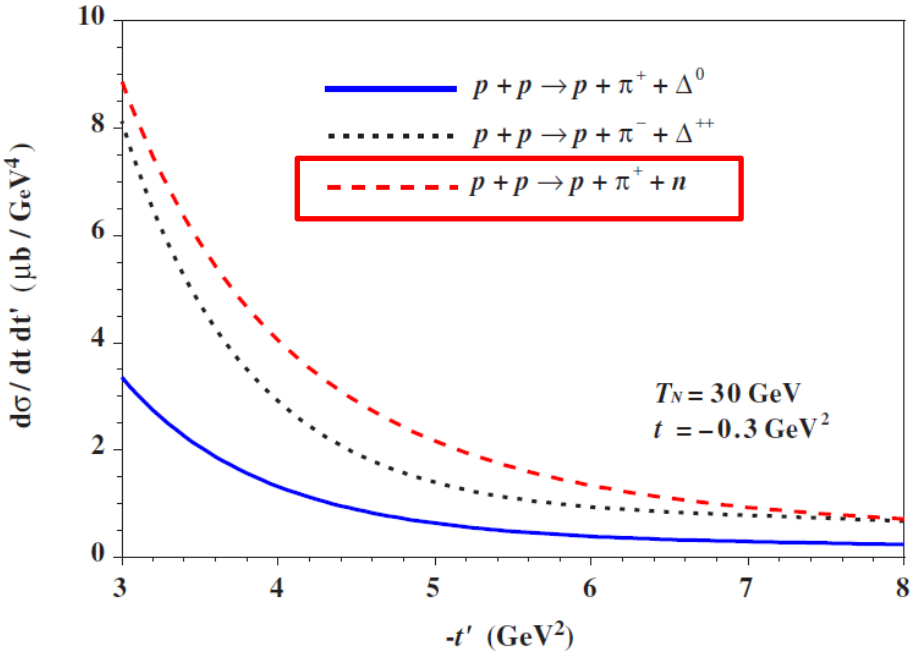
GPDs

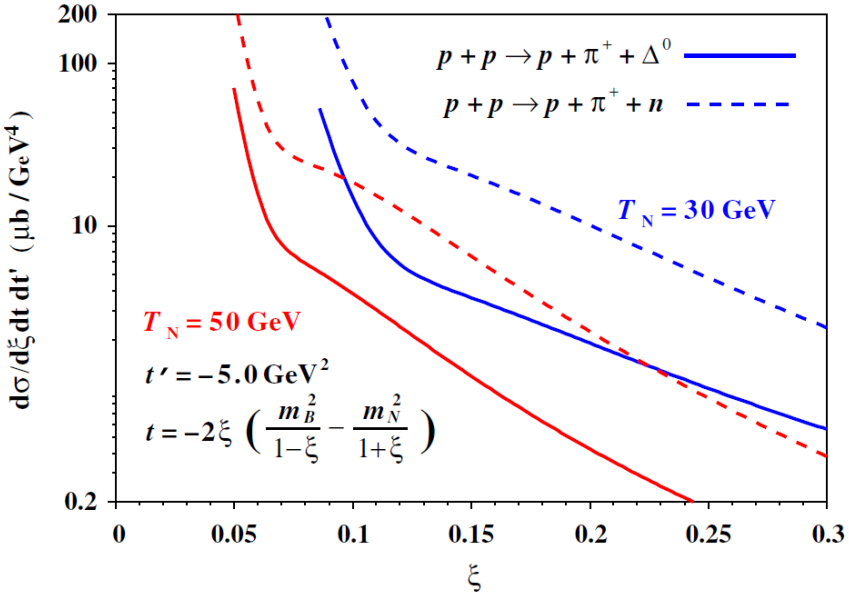
- Pure hadronic rection → very large cross section

- Can probe x dependence of GPDs
- Can access the ERBL region

Can be an earliest stage experiment @ high-p beamline

Estimated cross sections





Rough estimation, anyway **μb** order

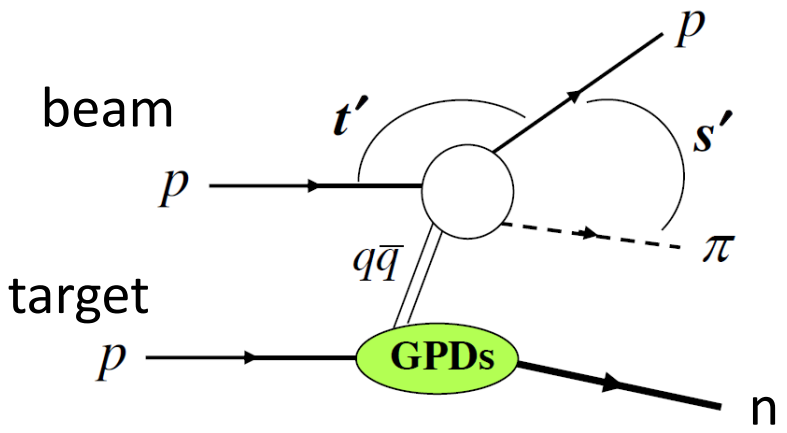
- 5 μb/GeV^4, 10^{10}/spill, 2 cm LH2, acc × eff = 5%

  ⇒ 10^7 /day/GeV^4

Small acceptance & Short beam time

t′ ⇔ x dependence

ξ = 0.1～0.3



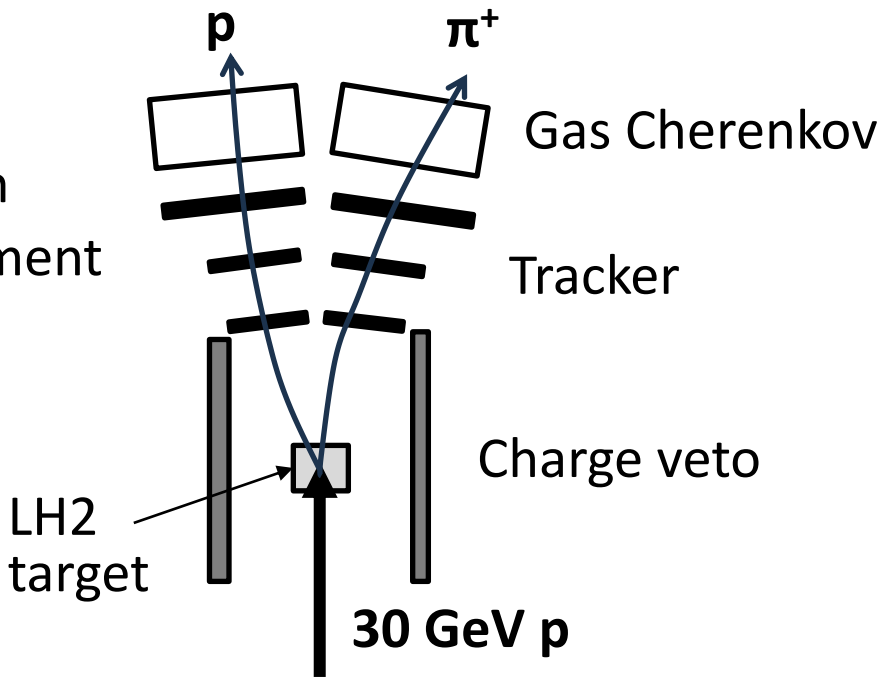
S. Kumano, MDPI Physics 4 565 (2022)

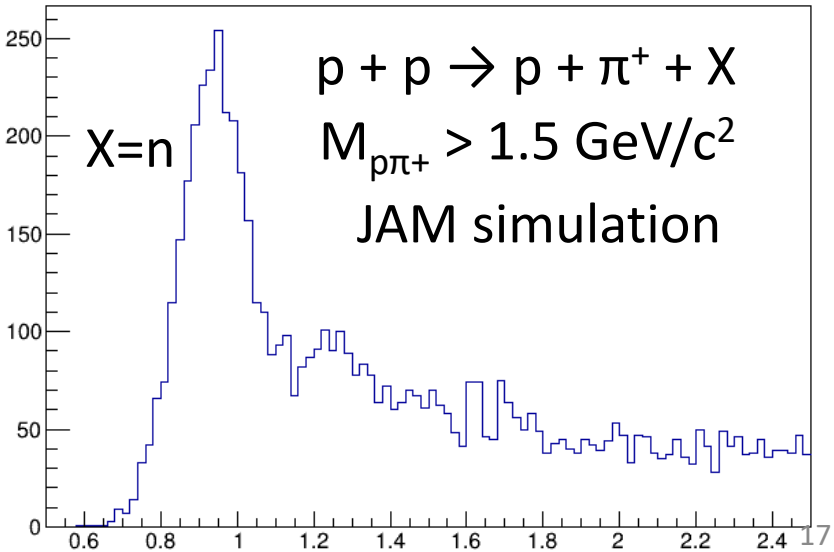
$p + p \rightarrow p + \pi^+ + n$

Possible setup

- Missing mass $p + p \rightarrow p + \pi^+ + X$
  - Missing mass method to identify X=n
  - p beam => no momentum measurement
  - 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





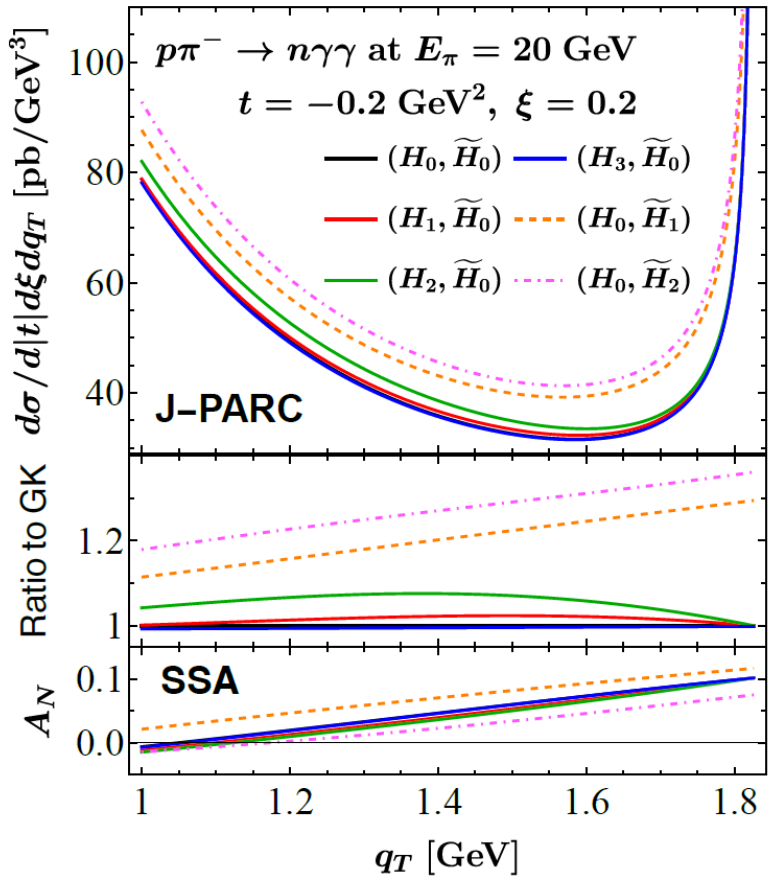
$\pi^- + p \rightarrow \gamma + \gamma + n$

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

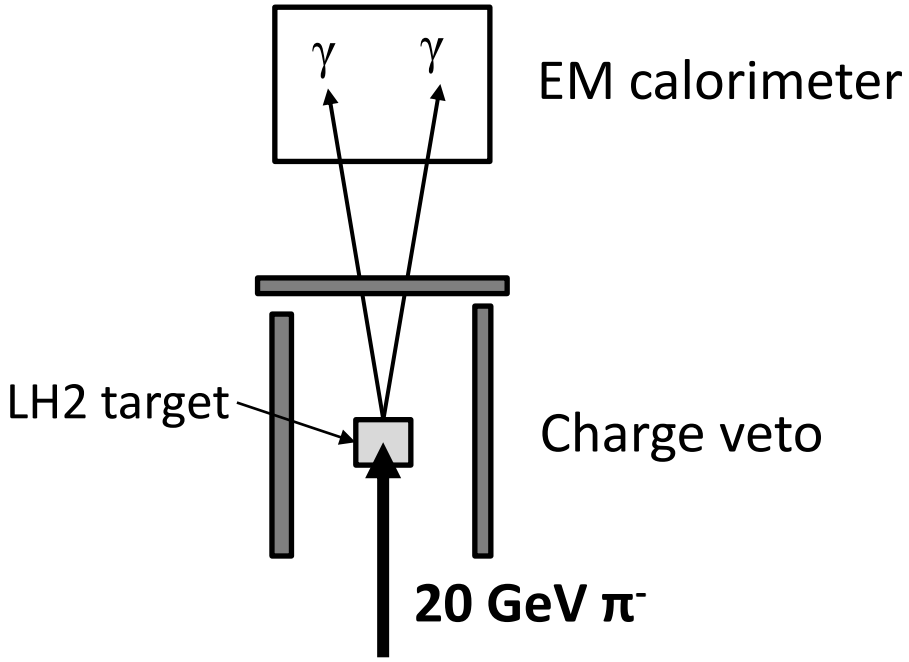
- Can probe x dependence of GPDs

- Simpler reaction
- Smaller cross section than $p+p \rightarrow p+\pi^+ + n$

Estimated cross section



Necessary setup



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

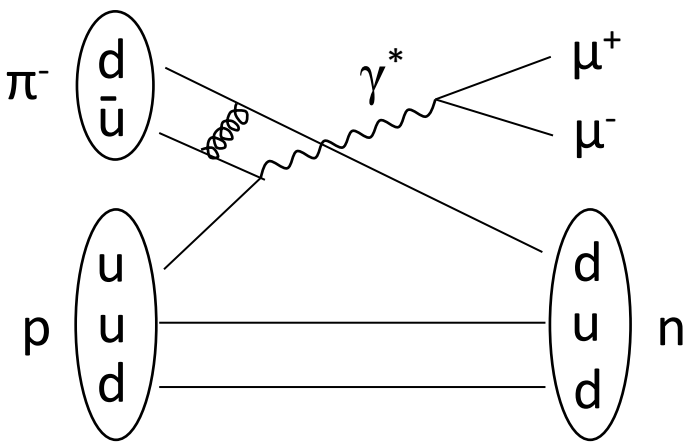
Exclusive Drell-Yan

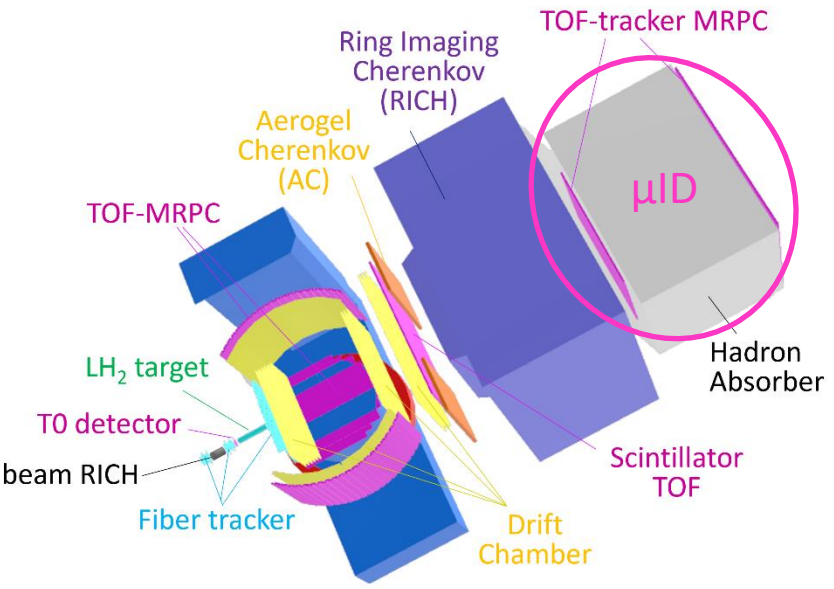
PLB 523 (2001) 265
PLB 748 (2015) 323

(Inverse reaction of DVMP)

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

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





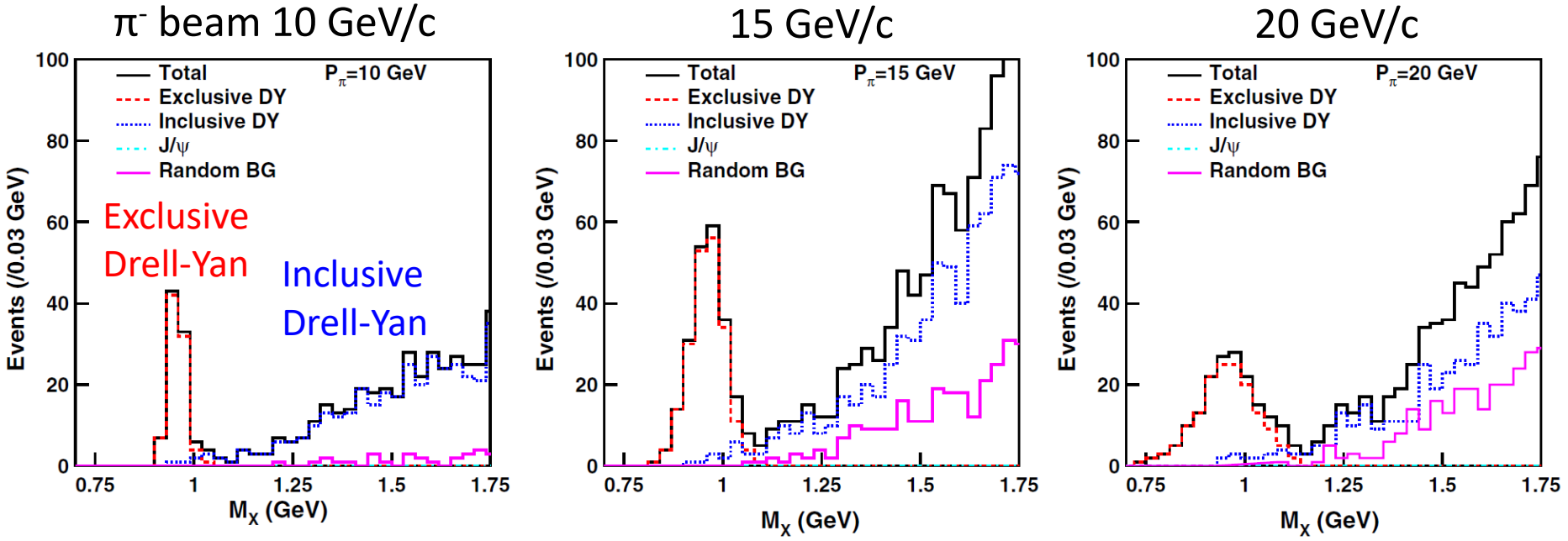
- Can access polarized GPDs without polarized beam/target
- μID system with the MARQ spectrometer
- LoI submitted (W.C. Chang)

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

Summary

- Measurement of Generalized Parton Distributions (GPDs) is one of key to understand the 3D nucleon structure
  - Origin of mass & spin
- Determine GPDs from global analysis of measurements in different reactions and kinematics
- Single Diffractive Hard Exclusive Process (SDHEP) is a new framework of reactions which can access GPDs
- Possible Measurements at J-PARC
  - $p + p \rightarrow p + \pi + B$ Large cross section, ERBL region, x-dependence
  - $\pi^- + p \rightarrow \gamma + \gamma + n$ x-dependence
  - $\pi^- + p \rightarrow \mu^+ + \mu^- + n$ polarized GPDs
  - other reactions coming soon…