26th International Symposium on Spin Physics
A Century of Spin

Unveiling Nucleon GPDs through Drell-Yan Processes

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Outline

- Exclusive Drell-Yan Process:
  measuring nucleon ***GPDs*** in a ***time-like*** approach
- High-momentum beamline at J-PARC
  - GPDs with pion beams: exclusive DY
    [PRD93 (2016) 114034]
  - GPDs with proton beams: 2-to-3 hard reactions
    [PRD80 (2009) 074003]
- Summary

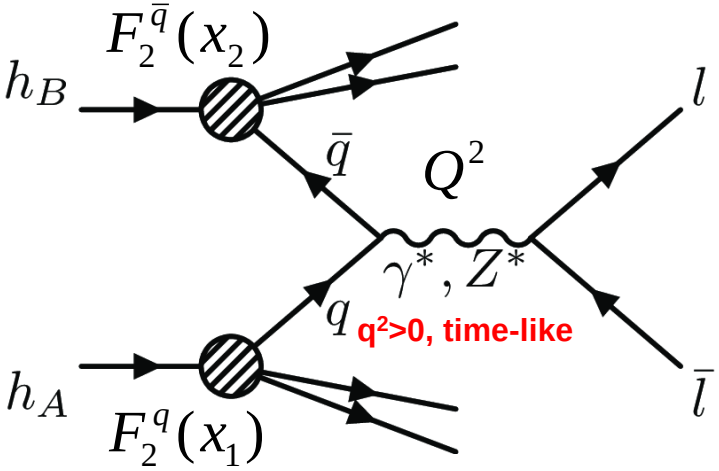
Drell-Yan Process

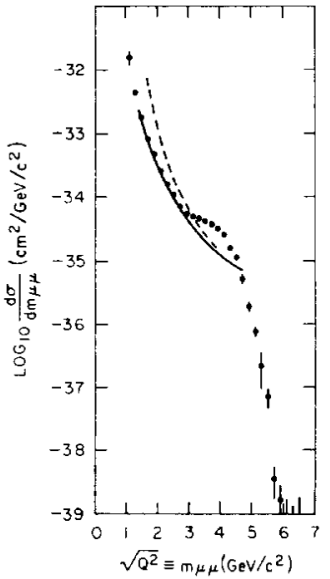
S.D. Drell and T.M. Yan, PRL 25 (1970) 316

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.



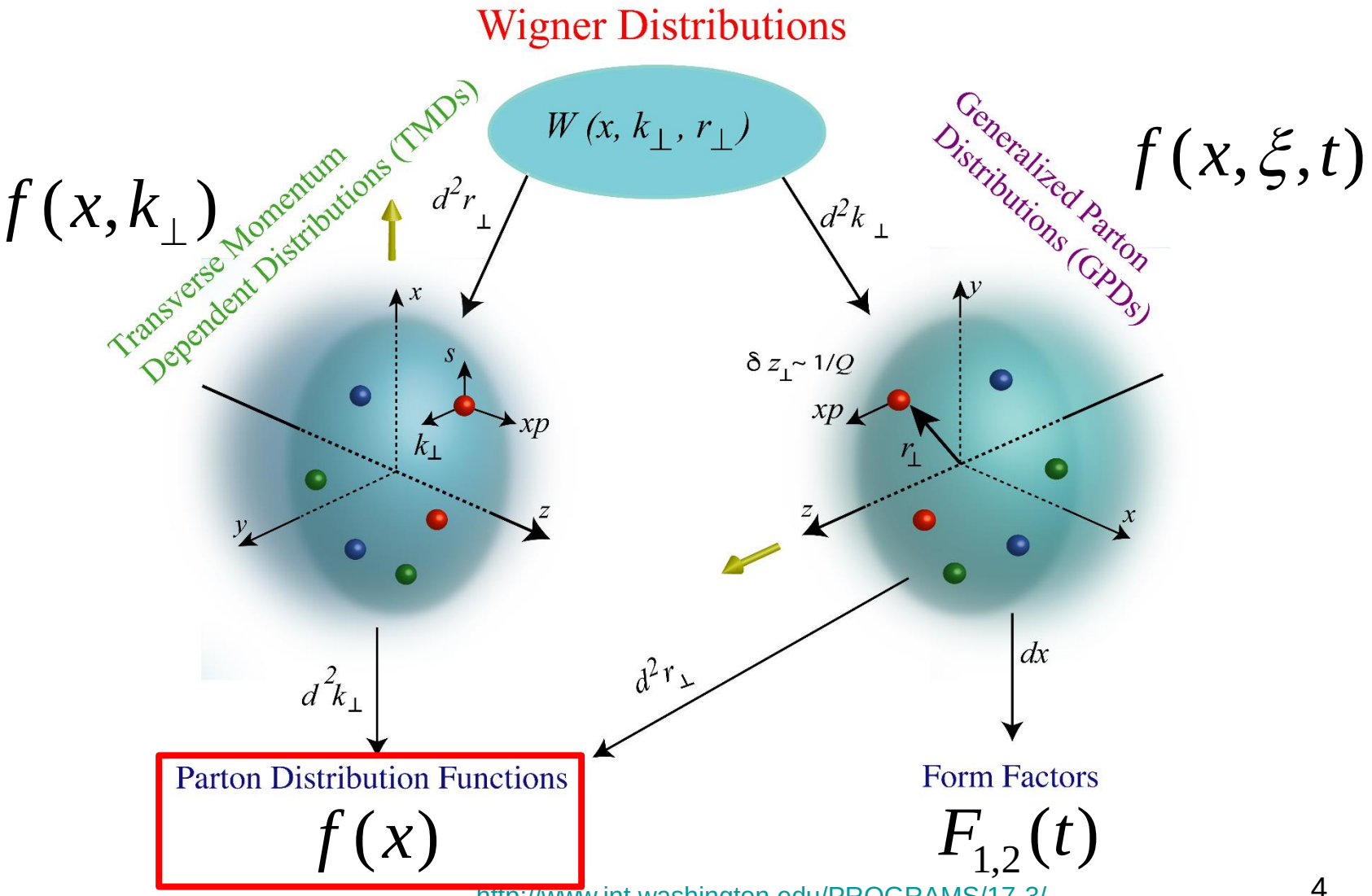


PRL 25 (1970) 1523

$$\tau = \frac{Q^2}{s} = x_1 x_2$$

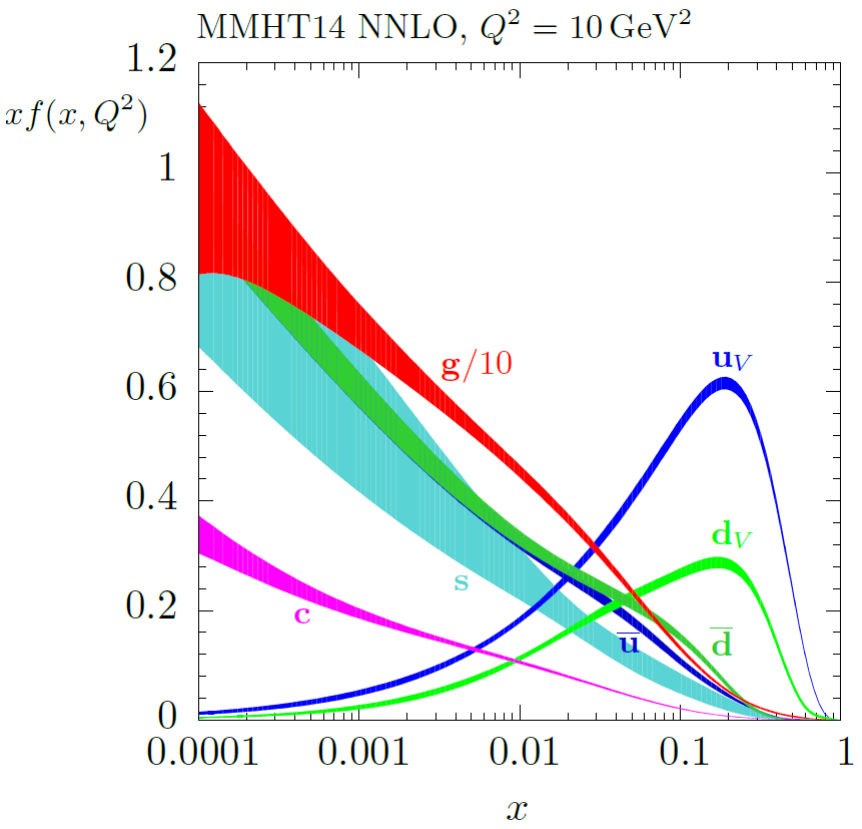
$$\frac{d\sigma}{dQ^2} = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\mathcal{F}(\tau) = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\int_0^1 dx_1 \int_0^1 dx_2 \delta(x_1 x_2 - \tau) \sum_a \lambda_a{}^{-2} F_{2a}(x_1) F_{2\bar{a}}{}'(x_2),$$

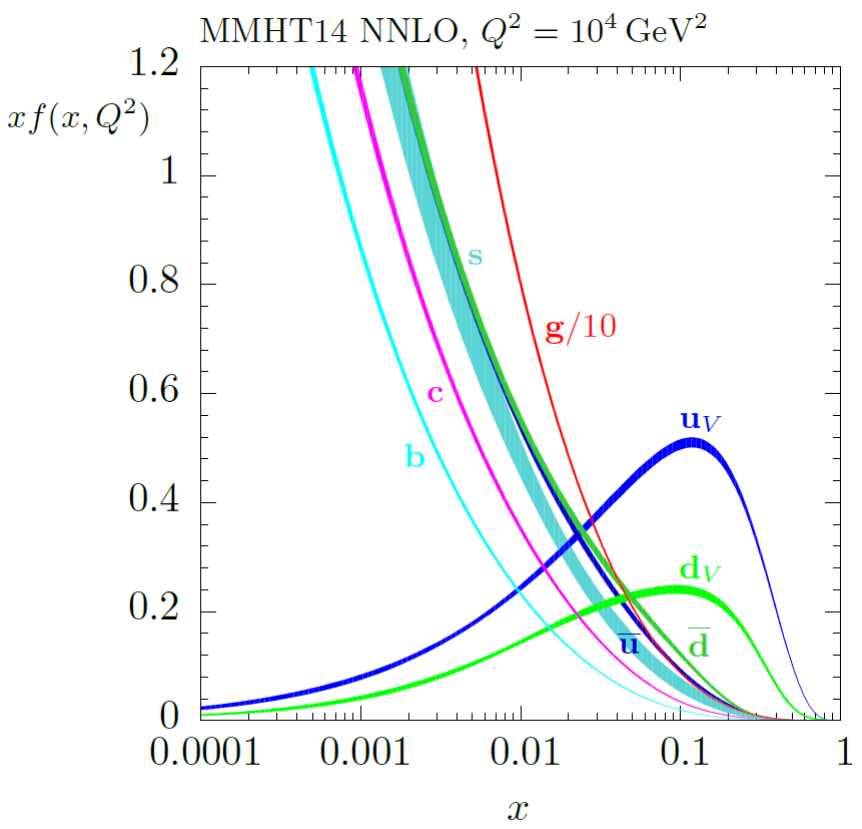
Multi-dimensional Partonic Structures



http://www.int.washington.edu/PROGRAMS/17-3/

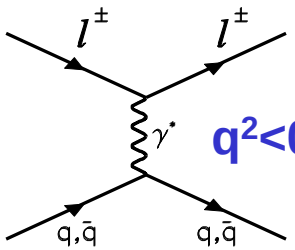
Parton Density Function (PDF)
MMHT 2014



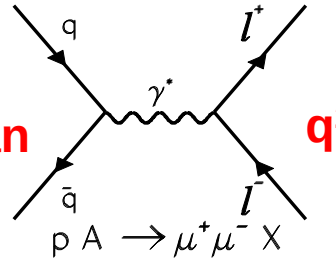


L. A. Harland-Lang, A. D. Martin, P. Motylinski, R.S. Thorne, arXiv:1412.3989

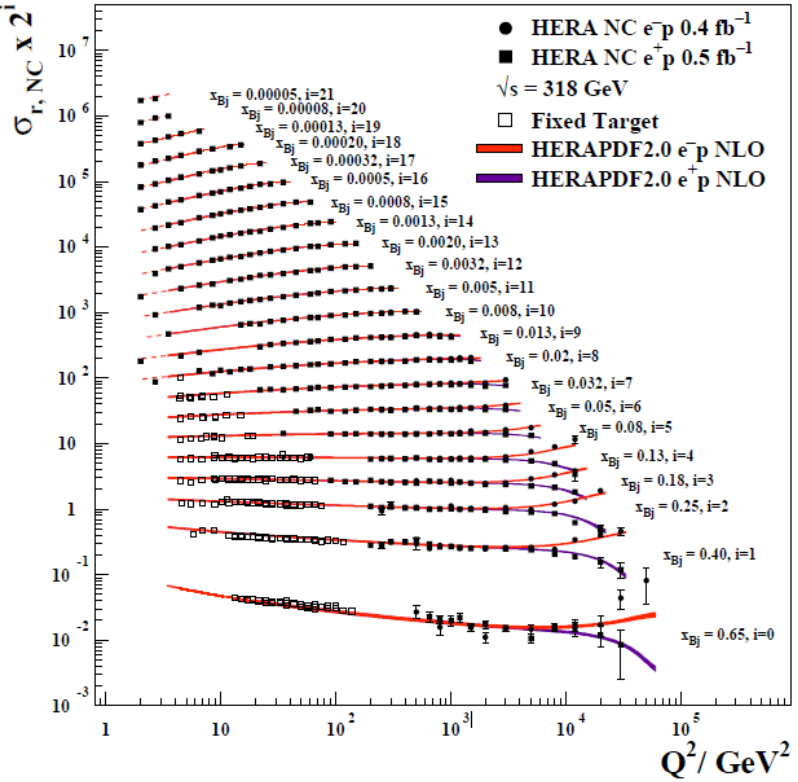
Factorization of Hard Processes

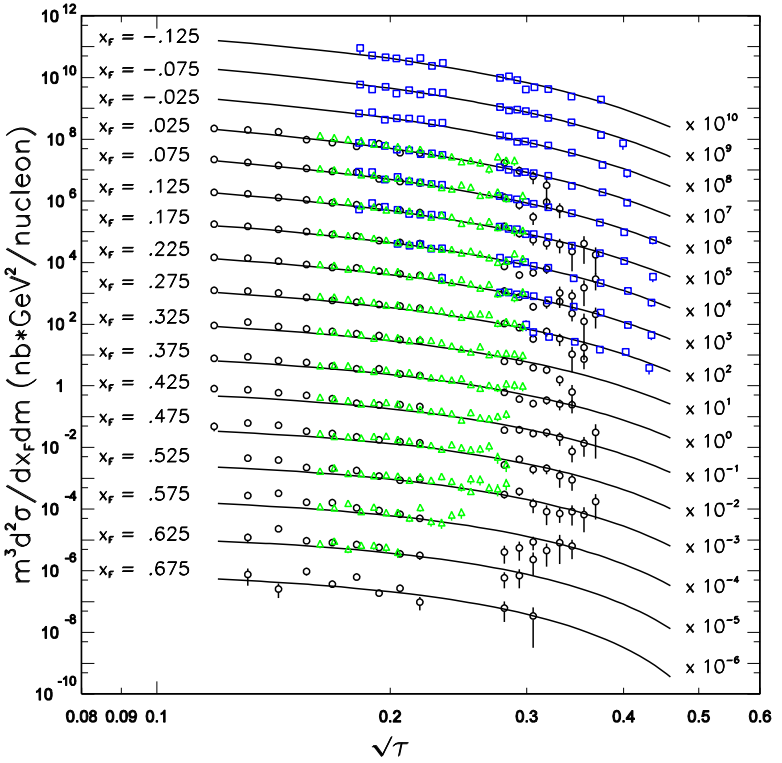


DIS $q^2<0$, space-like



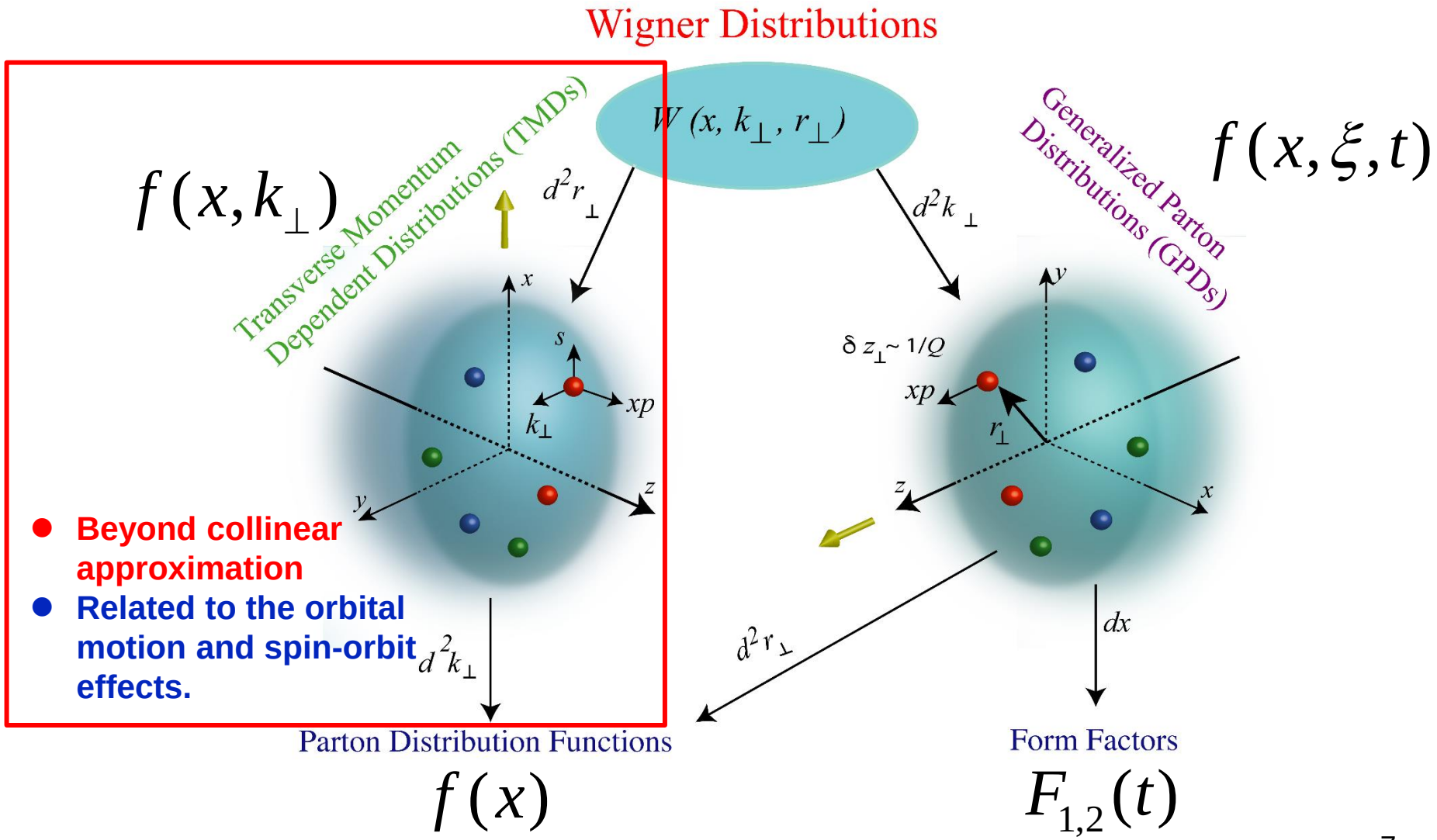
Drell-Yan $q^2>0$, time-like





$$\sigma_{proton}(x,Q^2) \sim PDF_{nucleon}(x,Q^2) \otimes \hat{\sigma}_{hard}(Q^2)$$

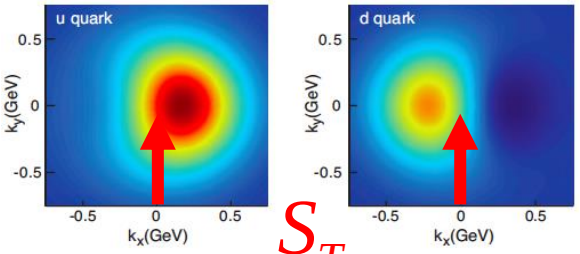
Multi-dimensional Partonic Structures



- **Beyond collinear approximation**
- **Related to the orbital motion and spin-orbit effects.**

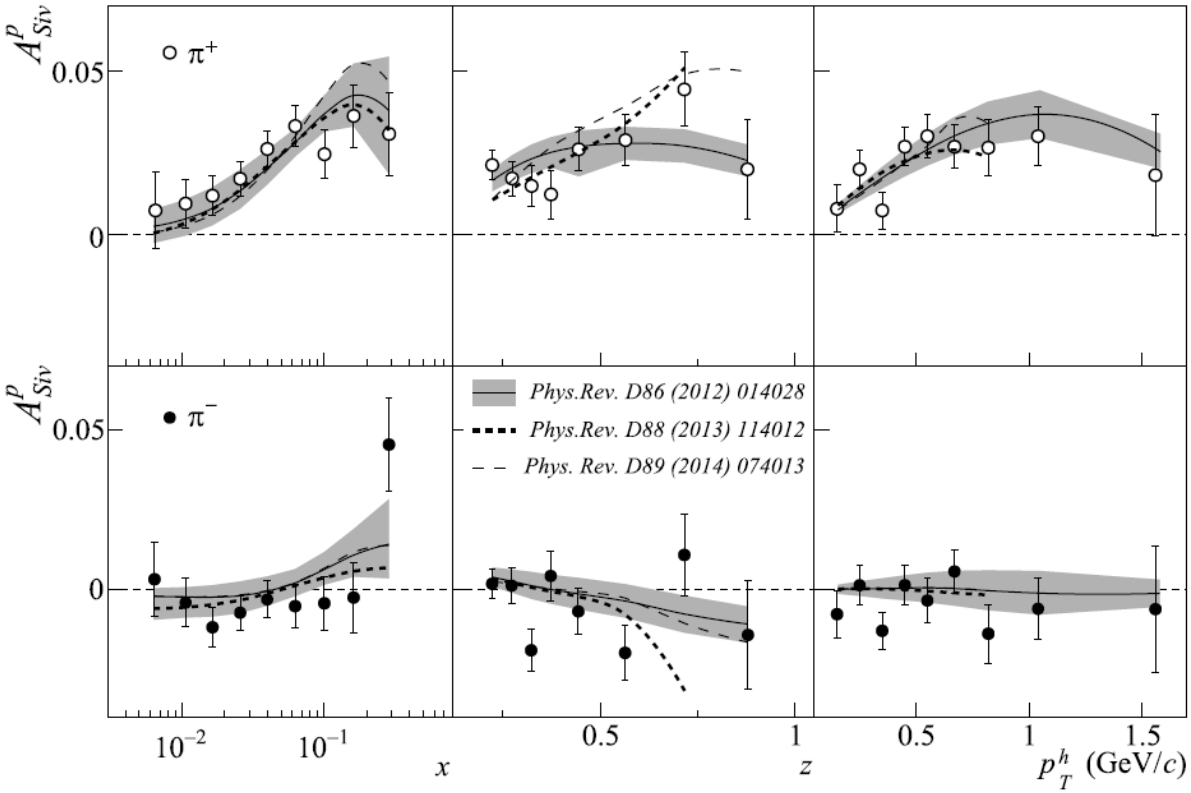
http://www.int.washington.edu/PROGRAMS/17-3/

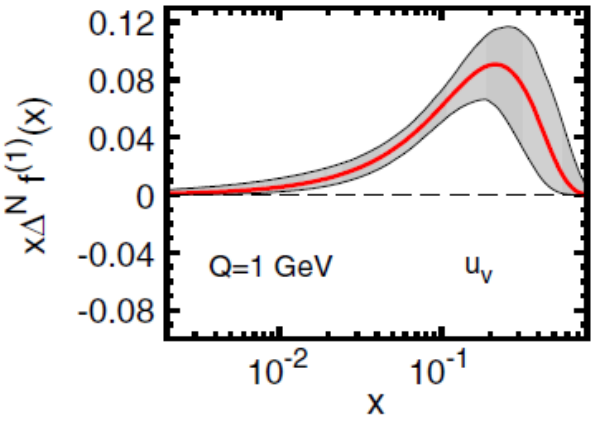
Nonzero Sivers Asymmetries from SIDIS

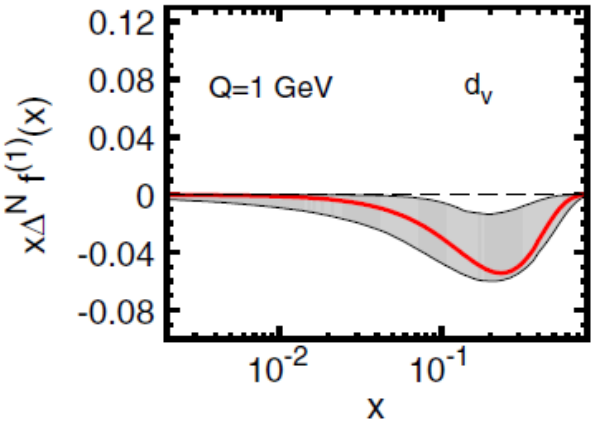


S_T Sivers Functions

COMPASS, PLB 744 (2015) 250







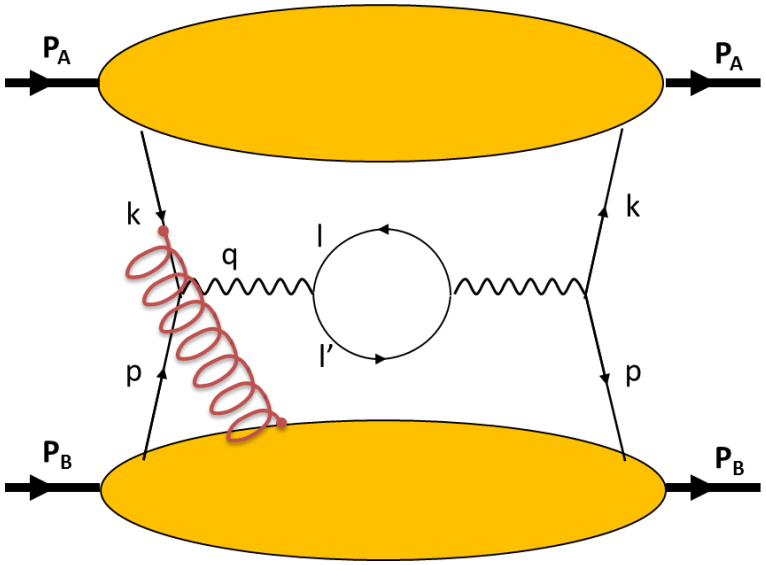
SIDIS $\gamma^*(q^2 < 0)p_\uparrow \rightarrow hX$

PRD 86, 014028 (2012) [arXiv:1204.1239]

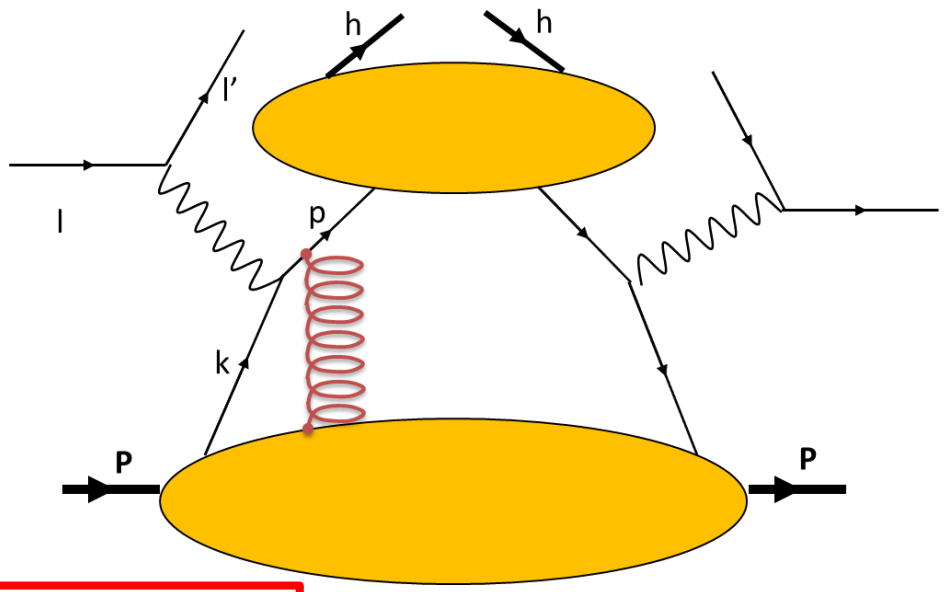
Non-Universality of Sivers Function

J.C. Collins, Phys. Lett. B 536 (2002) 43
A.V. Belitsky, X. Ji, F. Yuan, Nucl. Phys. B 656 (2003) 165
D. Boer, P.J. Mulders, F. Pijlman, Nucl. Phys. B 667 (2003) 201
Z.B. Kang, J.W. Qiu, Phys. Rev. Lett. 103 (2009) 172001

Drell-Yan $q^2>0$, time-like



SIDIS $q^2<0$, space-like



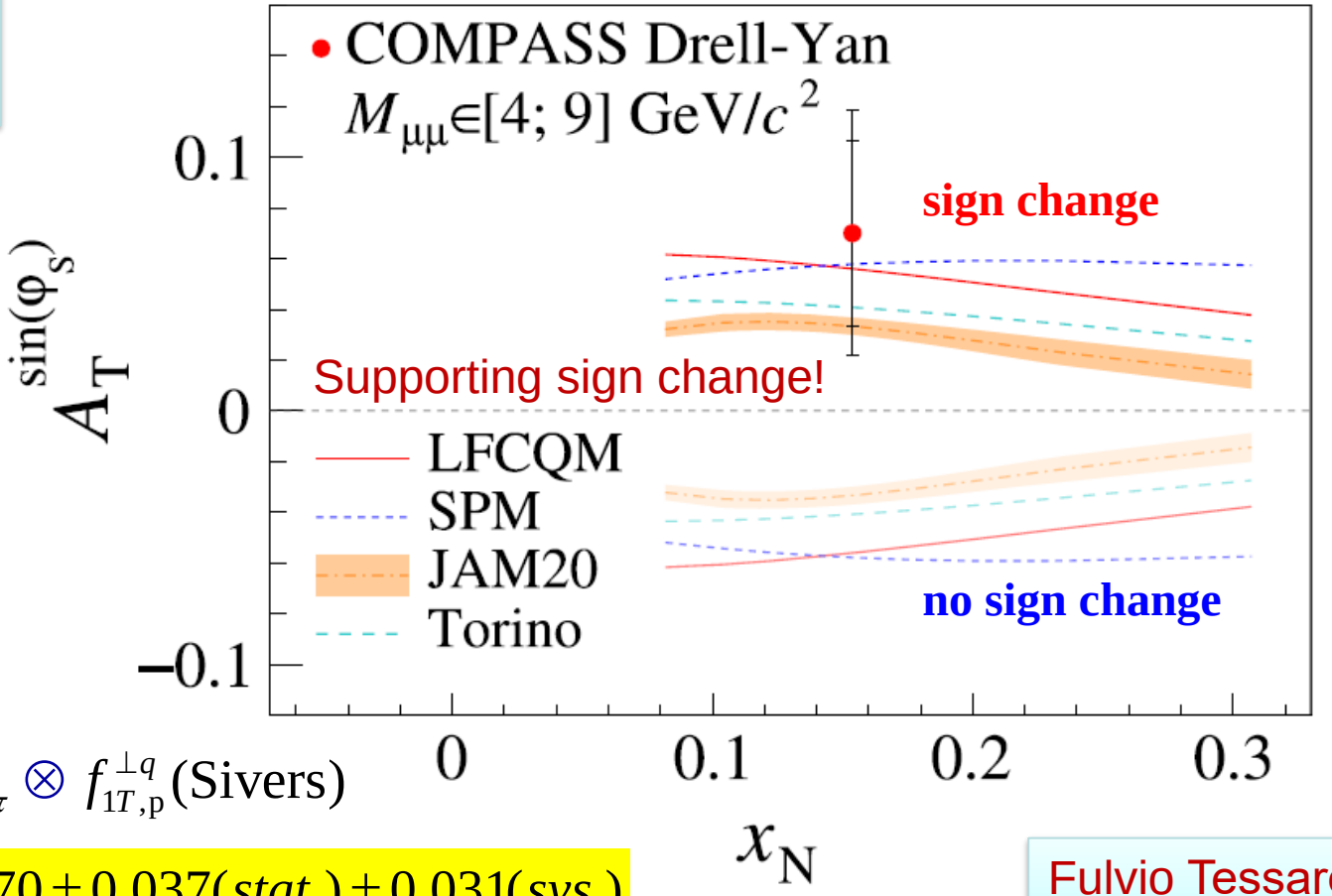
$hp_\uparrow \to \gamma^*(q^2>0)X$ $\quad$ $\text{Sivers}\,|_{DY} = -\text{Sivers}\,|_{SIDIS}$ $\quad$ $\gamma^*(q^2<0)p_\uparrow \to hX$

- QCD gluon gauge link (Wilson line) in the initial state (DY) vs. final state interactions (SIDIS).
- ***Fundamental predictions from TMD physics will be tested.***

Sivers in Polarized Drell-Yan

Statistics:
2015: 35K
2018: 37K

COMPASS, PRL 133, 071902 (2024)



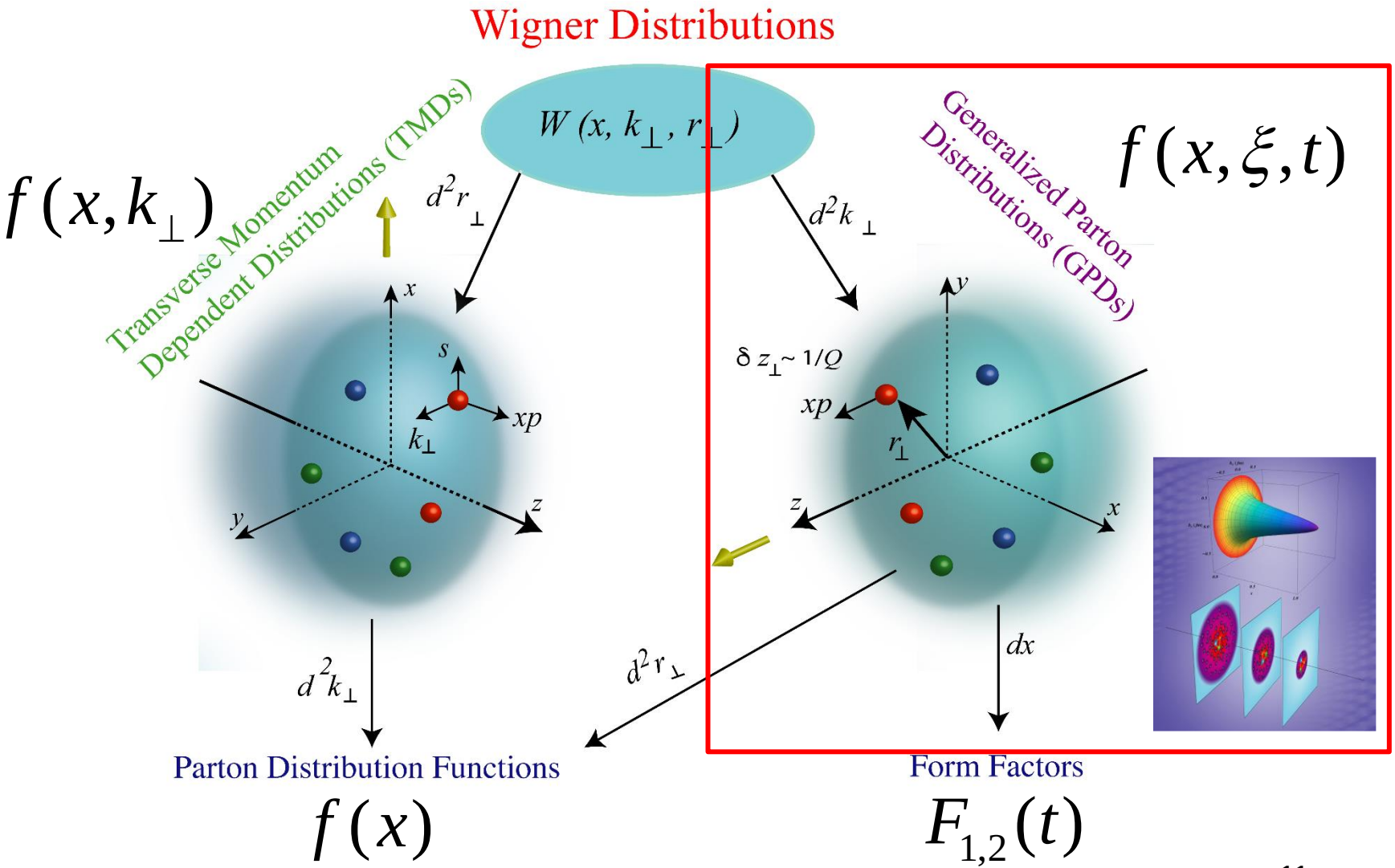
$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,\mathrm{p}}^{\perp q}(\text{Sivers})$$

$$A_T^{\sin\varphi_s} = 0.070 \pm 0.037(stat.) \pm 0.031(sys.)$$

Fulvio Tessarotto's talk

Agreeing with the sign-change of Sivers function!

Multi-dimensional Partonic Structures

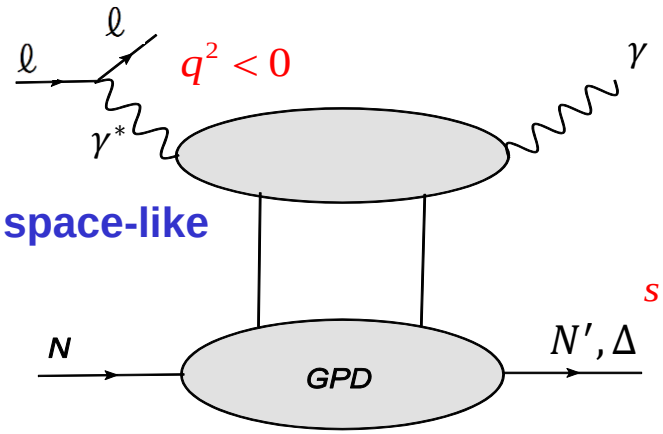


http://www.int.washington.edu/PROGRAMS/17-3/

Experimental Approach

Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering

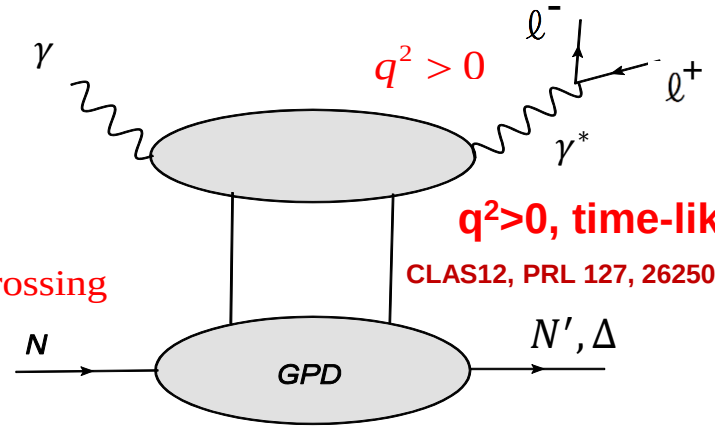


q^2<0, space-like

Ji, PRL 78, 610 (1997); Radyushkin, PLB 380, 417 (1996)

$s \leftrightarrow u$ channel crossing

Time-like Compton Scattering

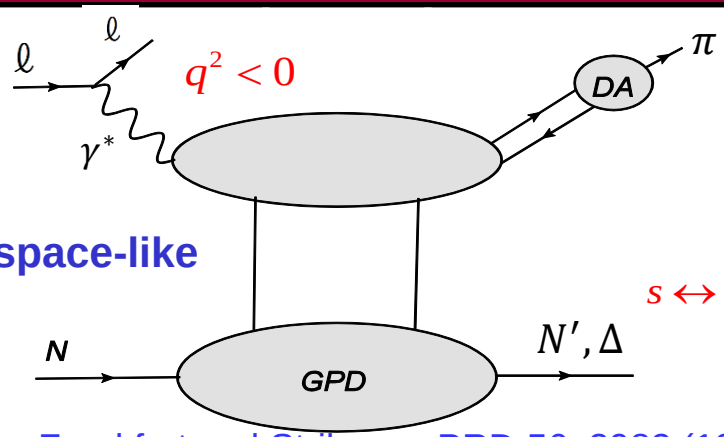


q^2>0, time-like

CLAS12, PRL 127, 262501 (2021)

Berger, Diehl, and Pire, EPJC 23, 675 (2002)

Deeply Virtual Meson Production

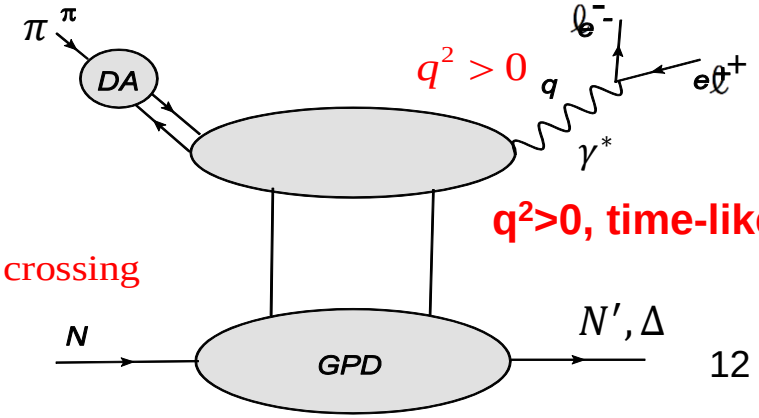


q^2<0, space-like

Collins, Frankfurt and Strikman, PRD 56, 2982 (1997)

$s \leftrightarrow u$ channel crossing

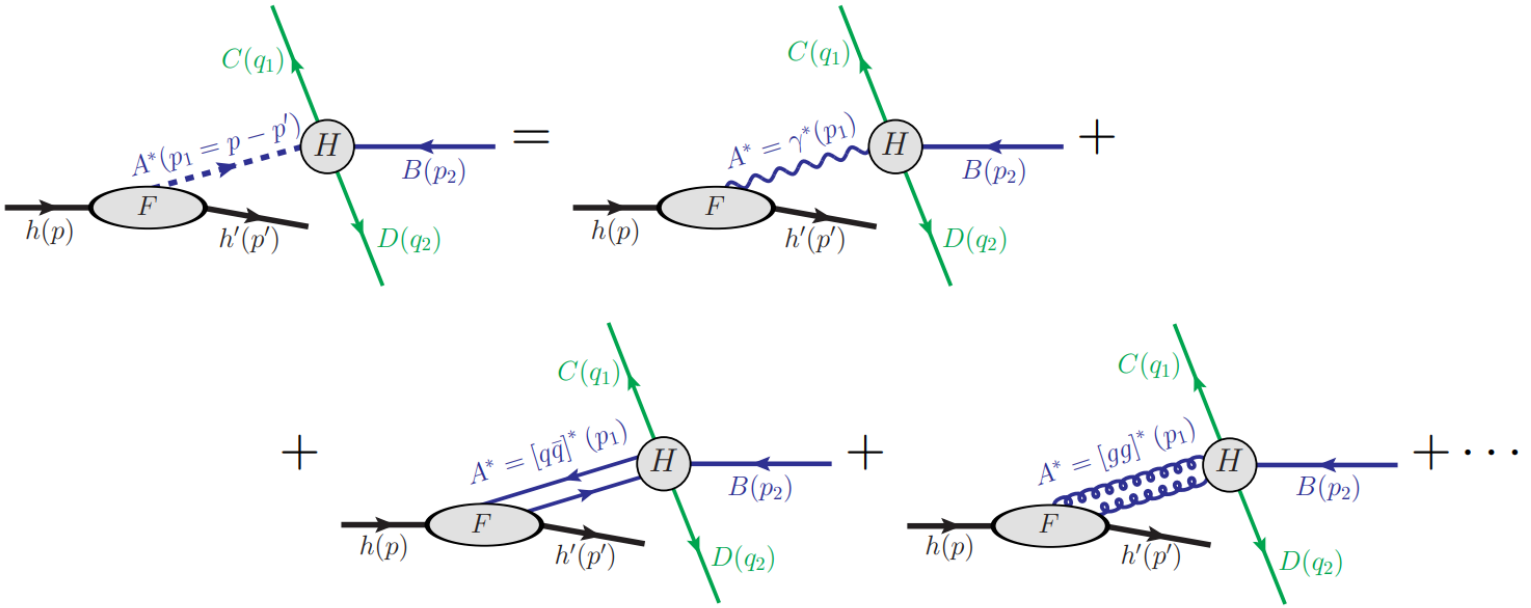
Exclusive meson-induced DY



q^2>0, time-like

Single Diffractive Hard 2-to-3 Processes

$$B(p_2) + h(p) \to C(q_1) + D(q_2) + h'(p')$$



The x-dependence of GPDs can be extracted in these processes!

Jian-Wei Qiu and Zhite Yu

JHEP 08 (2022) 103; PRD 107 (2023) 014007; PRL 131 (2023) 161902

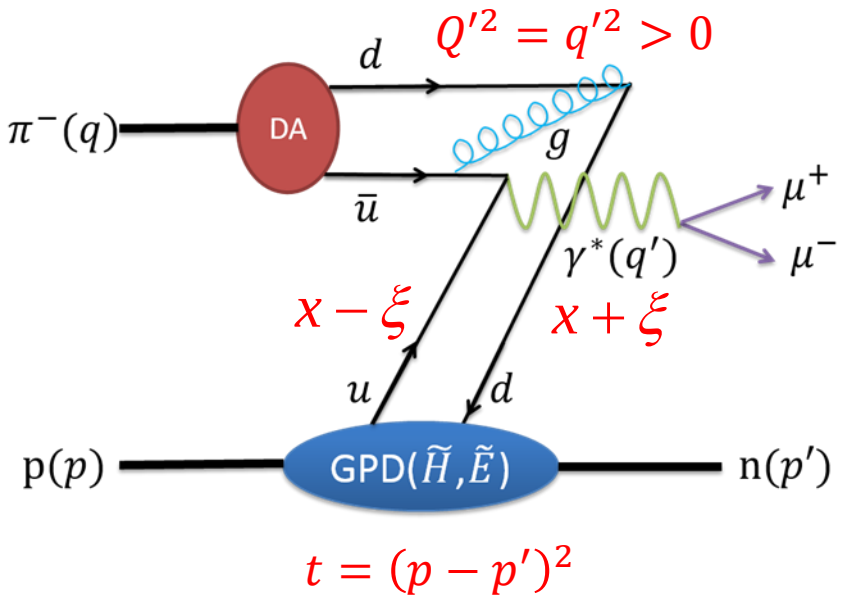
Single Diffractive Hard 2-to-3 Process

$$B(p_2) + h(p) \to C(q_1) + D(q_2) + h'(p')$$

B	h	C	D	Process
γ^*	N	γ		DVCS
γ^*	N	$\pi, \phi, J/\psi$		DVMP
γ	N	l^+	l^-	TCS
γ	N	γ	$\pi, \phi, J/\psi$	
γ	N	γ	γ	
γ	N	$\pi, \phi, J/\psi$	$\pi, \phi, J/\psi$	
π	N	l^+	l^-	Exclusive Drell-Yan
π	N	γ	$\pi, \phi, J/\psi$	
π	N	γ	γ	
π	N	γ	$\pi, \phi, J/\psi$	
N	N	meson	Baryon	S. Kumano et al., PRD 80 (2009) 074003

$\pi N \to l^+ l^- N$ (handbag diagram)

E.R. Berger, M. Diehl, B. Pire, PLB 523 (2001) 265



$$\tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s - M_N^2} \qquad \xi = \frac{(p-p')^+}{(p+p')^+} = \frac{\tau}{2-\tau}$$

$$\tilde{x} = -\frac{(q+q')^2}{2(p+p')\cdot(q+q')} \approx -\frac{Q'^2}{2s - Q'^2} = -\xi$$

$$\frac{d\sigma}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi} = \frac{\alpha_{\rm em}}{256\pi^3}\frac{\tau^2}{Q'^6}\sum_{\lambda',\lambda}\left|M^{0\lambda',\lambda}\right|^2 \sin^2\theta,$$

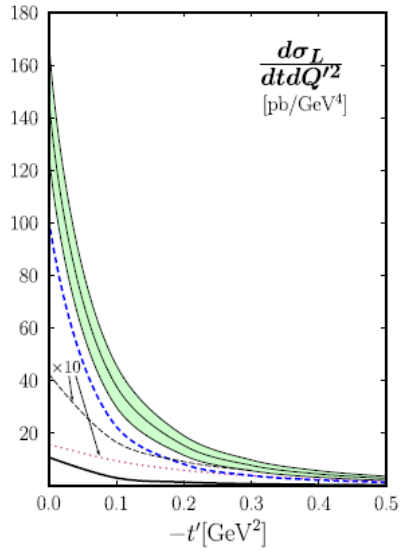
$$\left.\frac{d\sigma_L}{dt dQ'^2}\right|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \left[(1-\xi^2)\left|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)\right|^2 - 2\xi^2 {\rm Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^* \tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2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

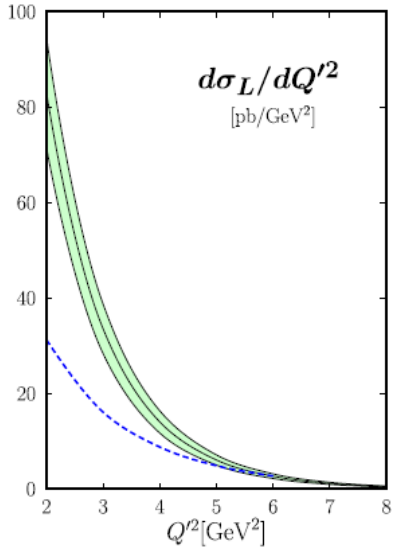
Beyond the Leading Twist

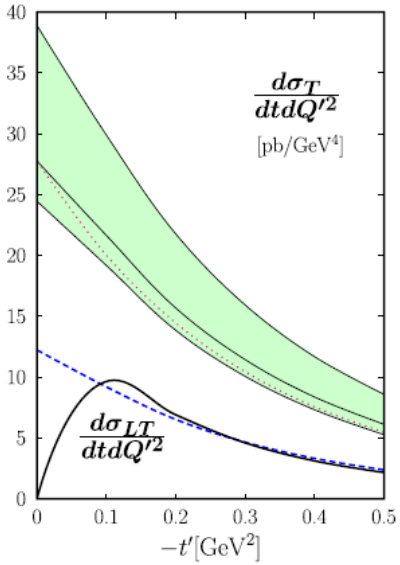
S.V. Goloskokov, P. Kroll, PLB 748 (2015) 323

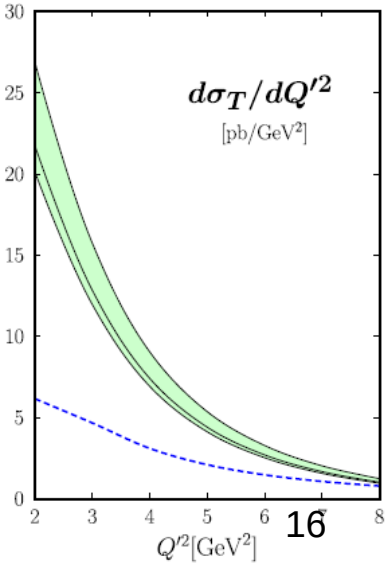
$$\frac{d\sigma}{dtdQ'^2 d\cos\theta d\varphi} = \frac{3}{8\pi}\left(\sin^2\theta\frac{d\sigma_L}{dtdQ'^2} + \frac{1+\cos^2\theta}{2}\frac{d\sigma_T}{dtdQ'^2} + \frac{\sin 2\theta\cos\varphi}{\sqrt{2}}\frac{d\sigma_{LT}}{dtdQ'^2} + \sin^2\theta\cos 2\varphi\frac{d\sigma_{TT}}{dtdQ'^2}\right)$$

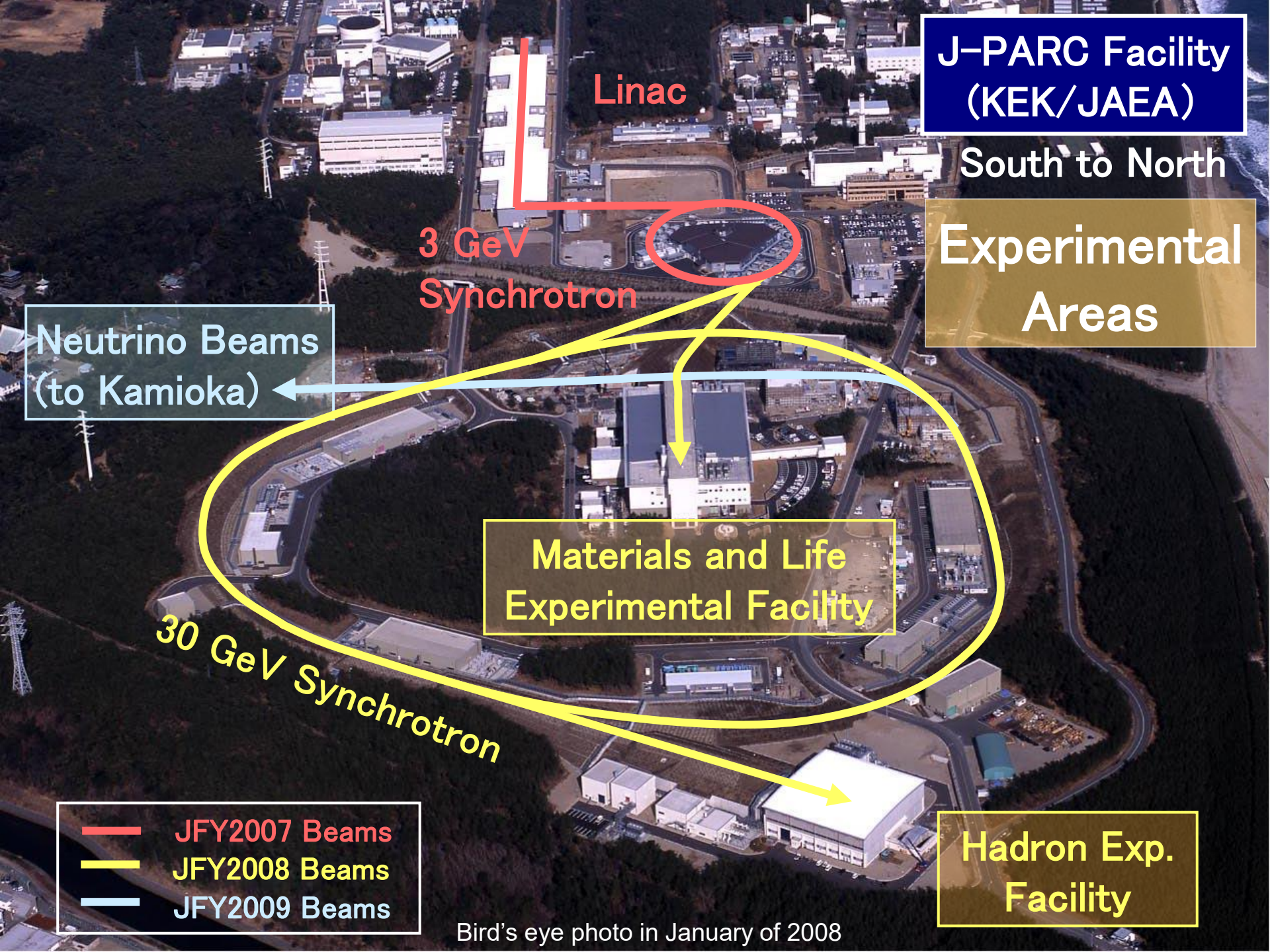
Transversity GPDs: H_T, $\bar{E}_T$





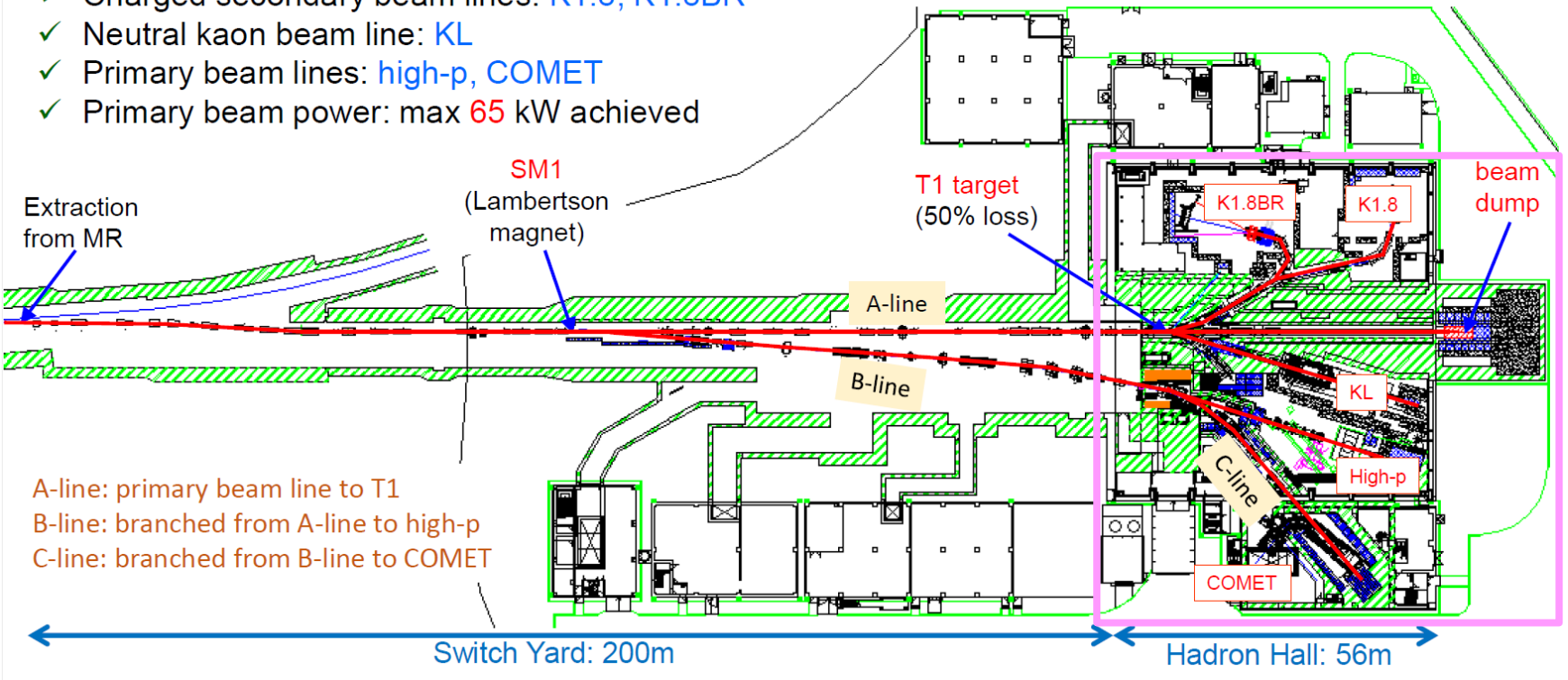





J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Experimental
Areas
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
30 GeV Synchrotron
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Hadron Exp.
Facility
Bird's eye photo in January of 2008

J-PARC Hadron Hall (Current Status)

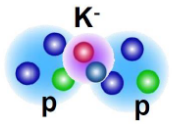
- ✓ Only one production target: T1
- ✓ Charged secondary beam lines: K1.8, K1.8BR
- ✓ Neutral kaon beam line: KL
- ✓ Primary beam lines: high-p, COMET
- ✓ Primary beam power: max 65 kW achieved



https://kds.kek.jp/event/44086/contributions/232014/attachments/165527/215424/hd-facility.pdf

J-PARC Hadron Hall (Current Status)

Current Hadron Facility

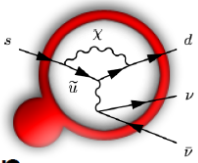


- < 1.1 GeV/c
- ~ 5x10^5 K$^-$/spill
- **Kaon in nuclei**

K1.8BR

K1.8

- < 2.0 GeV/c
- ~ 10^6 K$^-$/spill
- **S=-1 and S=-2 hypernuclei**



primary proton beams

A-line

B-line

T1 target

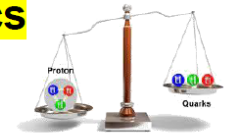
KL

- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^7 K^0_L/spill
- $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

high-p

- 30 GeV proton ~ 10^{10}
- **Hadron physics**

E16



- Au Target
- Indirectly cooled
- max 95 kW (5.2s)
- 65kW achieved

C-line

COMET

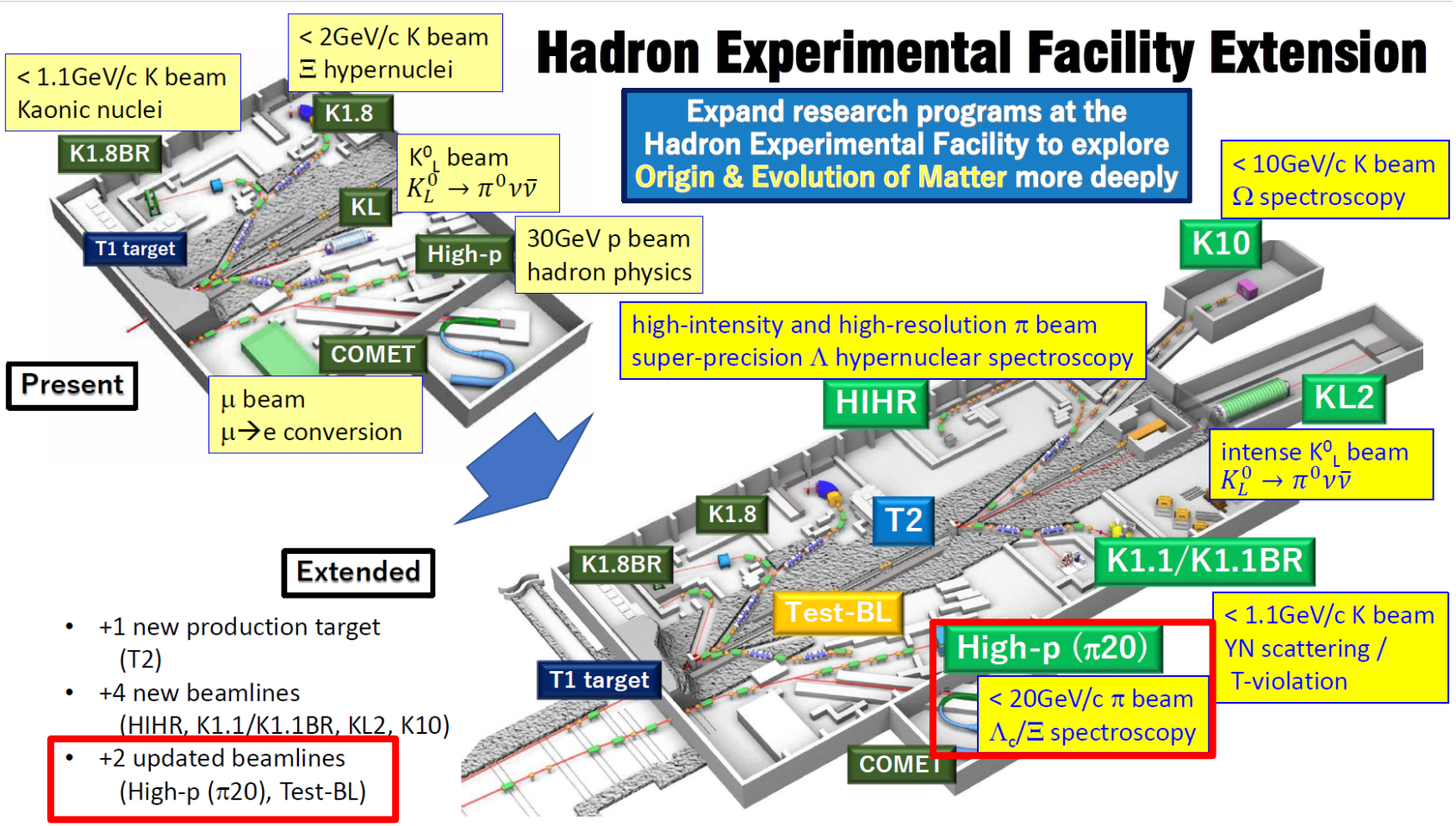
- μ$^-$ beam
- **μ-e conversion**

First beam in Feb 2023!!

https://kds.kek.jp/event/44086/contributions/232014/attachments/165527/215424/hd-facility.pdf

Hadron Hall Extension

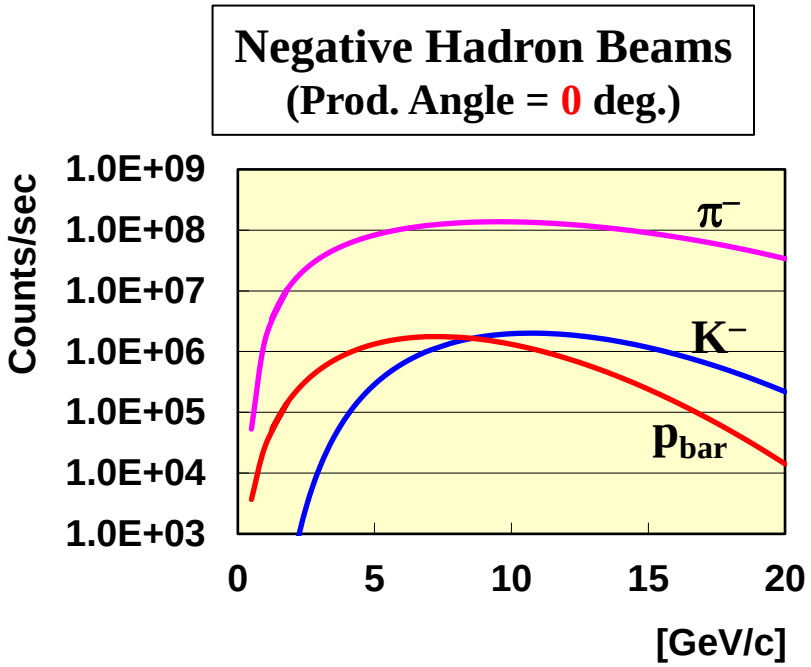
Hadron extension project was selected as the top priority in the KEK mid-term plan (KEK-PIP2022)!

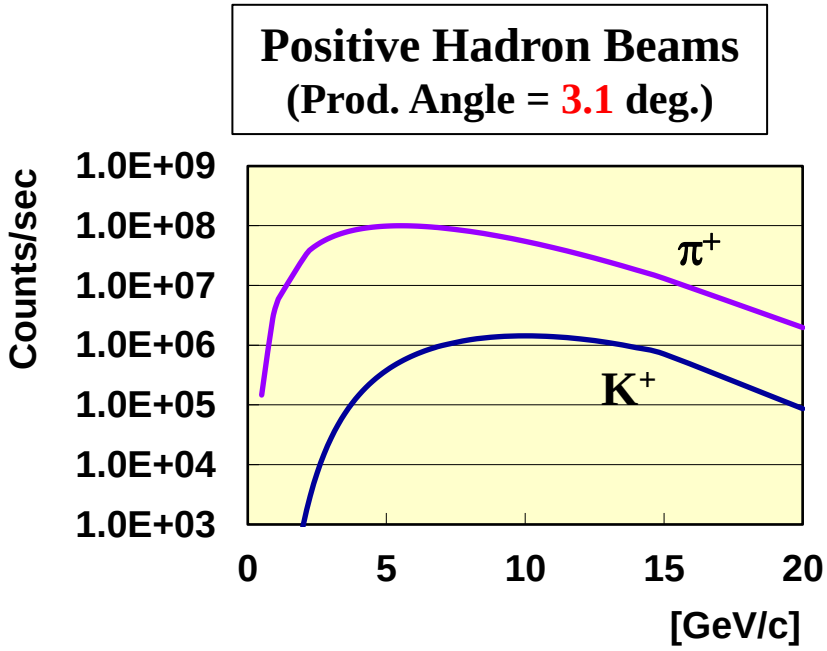


https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html
https://arxiv.org/abs/2110.04462

Hadron Experimental Facility
π20 Beam Line

- High-intensity secondary pion beam
- High-resolution beam: Δp/p ~ 0.1%





*** Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m**

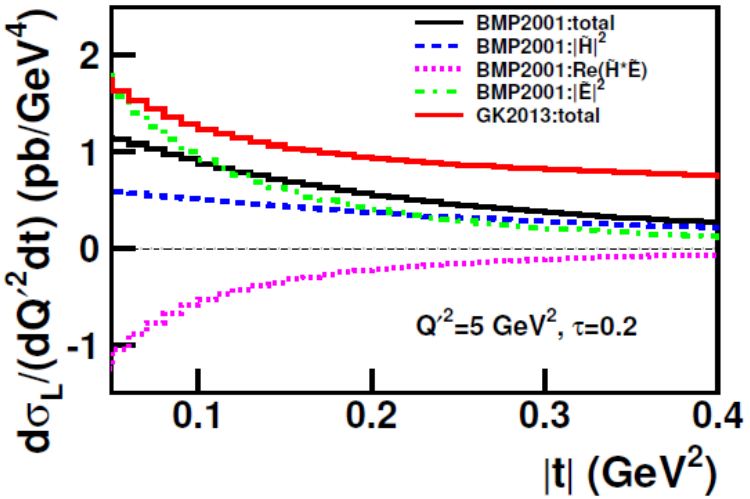
Differential Cross Sections of $\pi N \to l^+ l^- N$

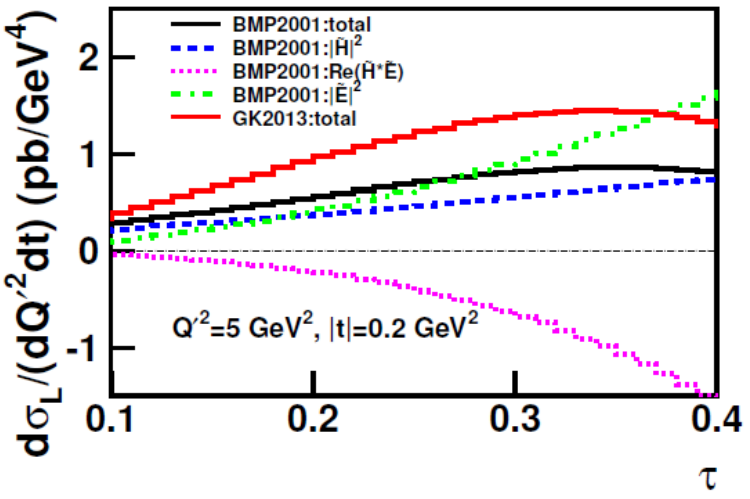
$$\left.\frac{d\sigma_L}{dtdQ'^2}\right|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \left[(1-\xi^2)|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)|^2 - 2\xi^2 {\rm Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^* \tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2 \frac{t}{4m_N^2}|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)|^2\right],$$

$$Q'^2 = q'^2 = 5\ GeV^2$$

at $\tau = \dfrac{Q'^2}{2pq} \approx \dfrac{Q'^2}{s - M_N^2} = 0.2$

at $t = (p - p')^2 = -0.2\ GeV^2$





Production is dominant at forward angles

Cross sections increase toward small s (→ low beam energy)

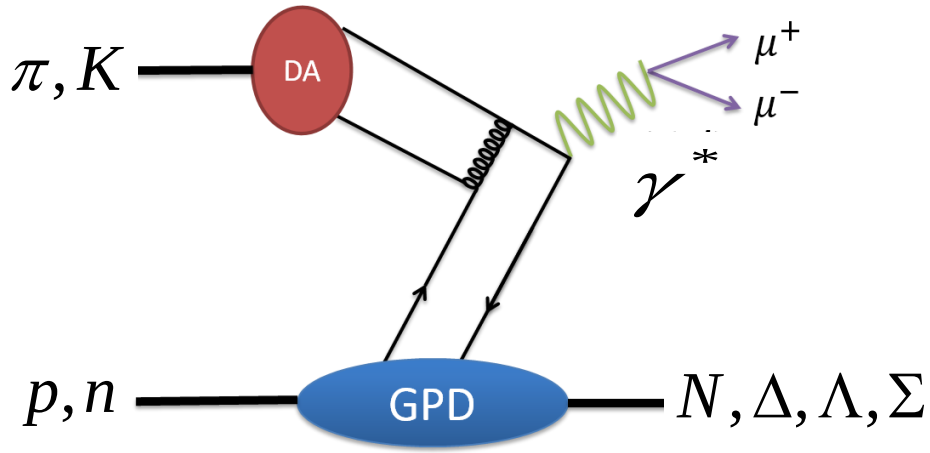
Transition GPDs

"Transition GPD": L. L. Frankfurt et al., PRD 60, 014010 (1999)

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

- $K^- \mathrm{p} \to \gamma^* \Lambda$
- $K^- \mathrm{p} \to \gamma^* \Lambda(1405)$
- $K^- \mathrm{p} \to \gamma^* \Lambda(1520)$
- $K^- \mathrm{n} \to \gamma^* \Sigma^-$
- $K^+ \mathrm{n} \to \gamma^* \Theta^+$

J-PRAC Hadron Hall Extension



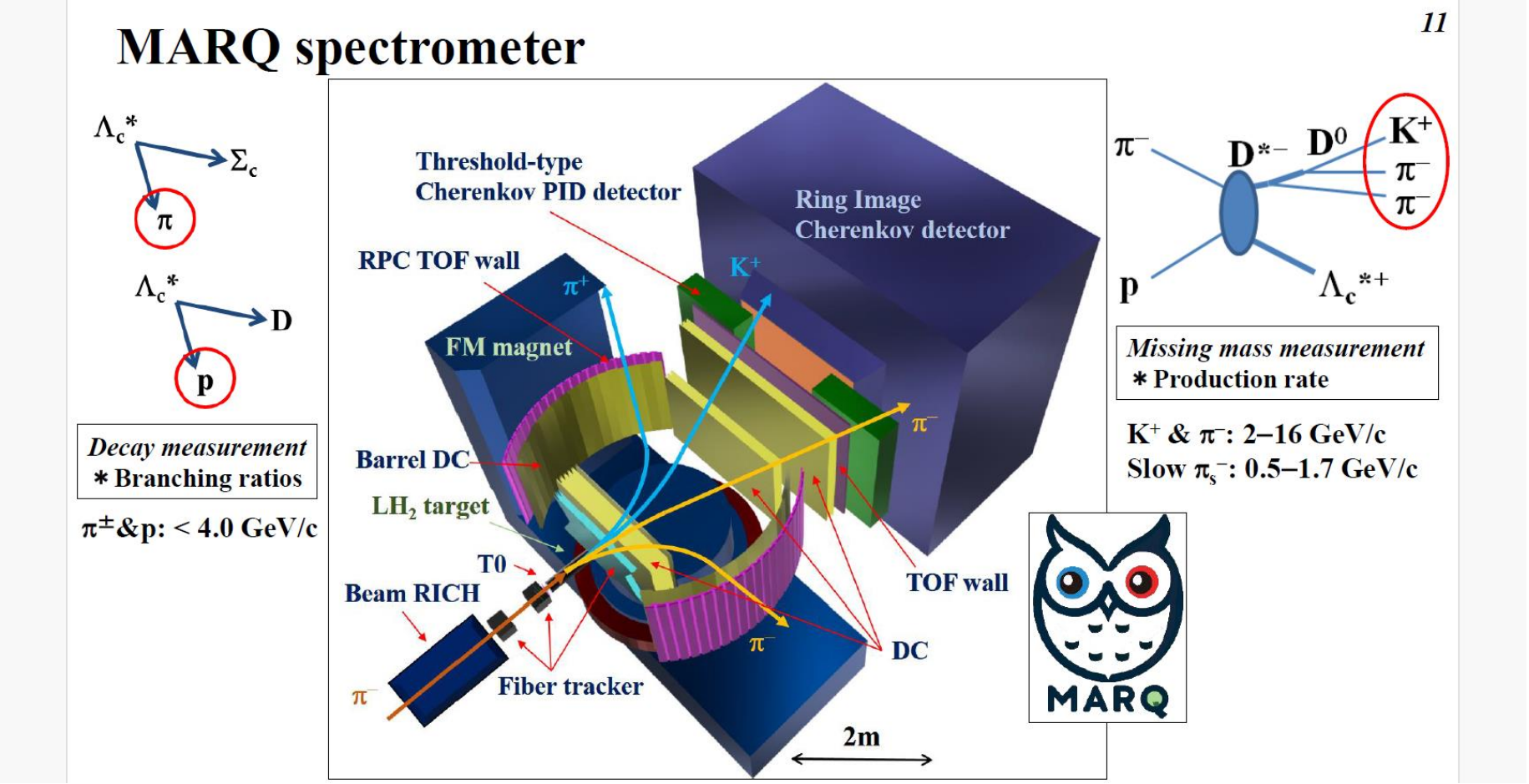
Exclusive Drell-Yan Measurement

- **Factorization**: $Q^2 \gg 1\ GeV^2$
- **Cross sections**:
  - Cross sections decrease rapidly with an increase of Q^2. $Q^2 < 9\ GeV^2$
  - $\sqrt{s}$ should be small enough to keep $\sqrt{\tau} = \frac{Q}{\sqrt{s}} = \sqrt{x_\pi x_N}$ large enough. Take $Q = 2\ GeV$, $\sqrt{\tau} = \sqrt{0.5 * 0.3} = 0.39$, $\sqrt{s} = 5\ GeV$, pion beam momentum should be less than 15 GeV.
- **Exclusivity**: missing-mass technique
  - Good resolution for missing mass
  - Open aperture without the hadron absorber before measuring the momentum of lepton tracks
  - Reasonably low track multiplicity

The 10-20 GeV π^- beam planned in high-momentum beam line at J-PARC ($\sqrt{s} = \mathbf{4} - \mathbf{6}$ GeV) is most appropriate!

J-PARC E50/MARQ Experiment

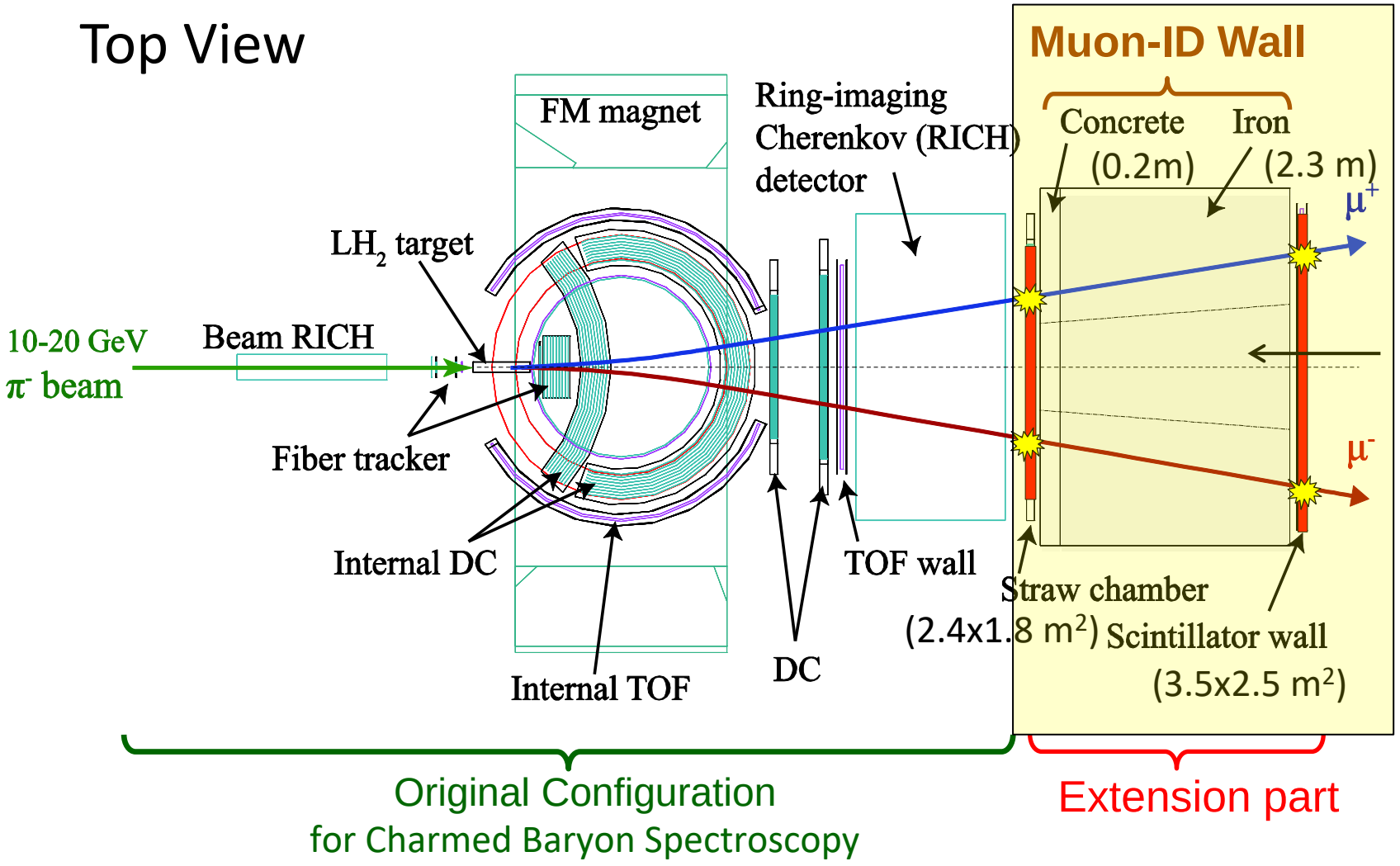
(Charmed Baryon Spectroscopy)



Large acceptance, PID, good momentum resolution

Extension of J-PARC E50 Experiment for Drell-Yan measurement

Top View

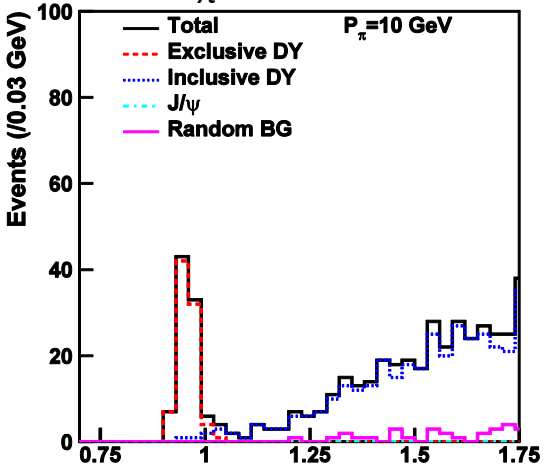


$\pi^- N \to \mu^+ \mu^- X$ Missing-mass M_X

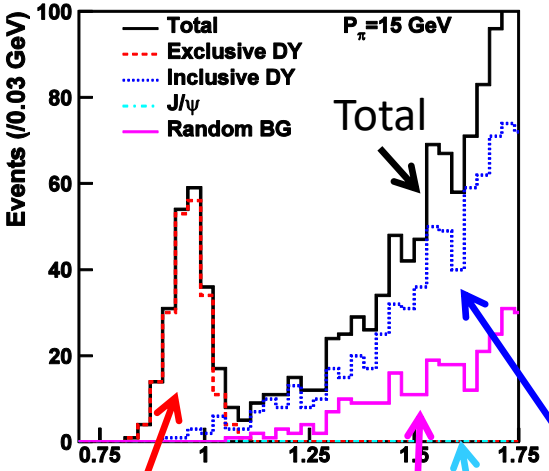
Takahiro Sawada, Wen-Chen Chang, Shunzo Kumano, Jen-Chieh Peng, Shinya Sawada, Kazuhiro Tanaka, PRD 93 (2016) 114034

π^- Beam Momentum

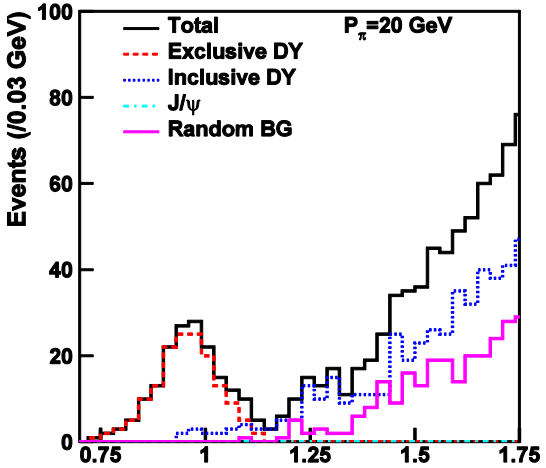
P_π = 10 GeV



15 GeV



20 GeV



Total

Exclusive Drell-Yan

J/ψ

Random backgrounds

Inclusive Drell-Yan

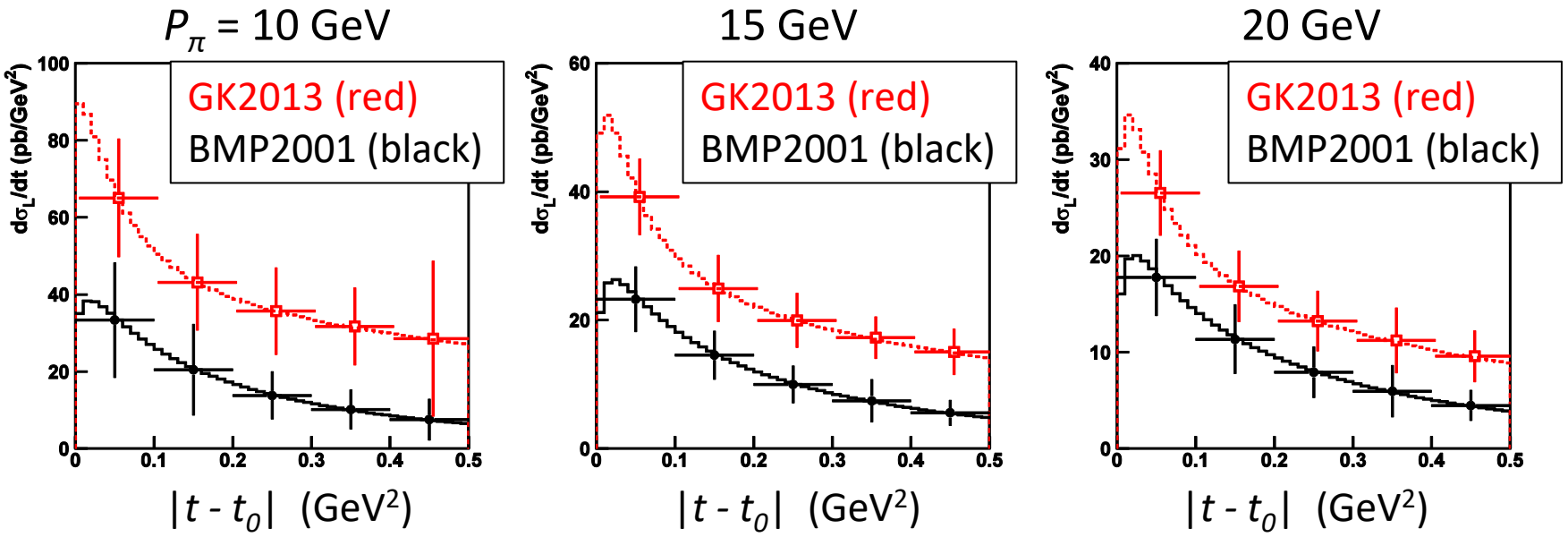
- Data Taking: 50 days
- $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV
- $|t - t_0| < 0.5$ GeV^2
- "GK2013" GPDs

The exclusive Drell-Yan events could be identified by the signature peak at the nucleon mass in the missing-mass spectrum for all three pion beam momenta.

Sensitivity to N GPDs

Takahiro Sawada, Wen-Chen Chang, Shunzo Kumano, Jen-Chieh Peng, Shinya Sawada, Kazuhiro Tanaka, PRD 93 (2016) 114034

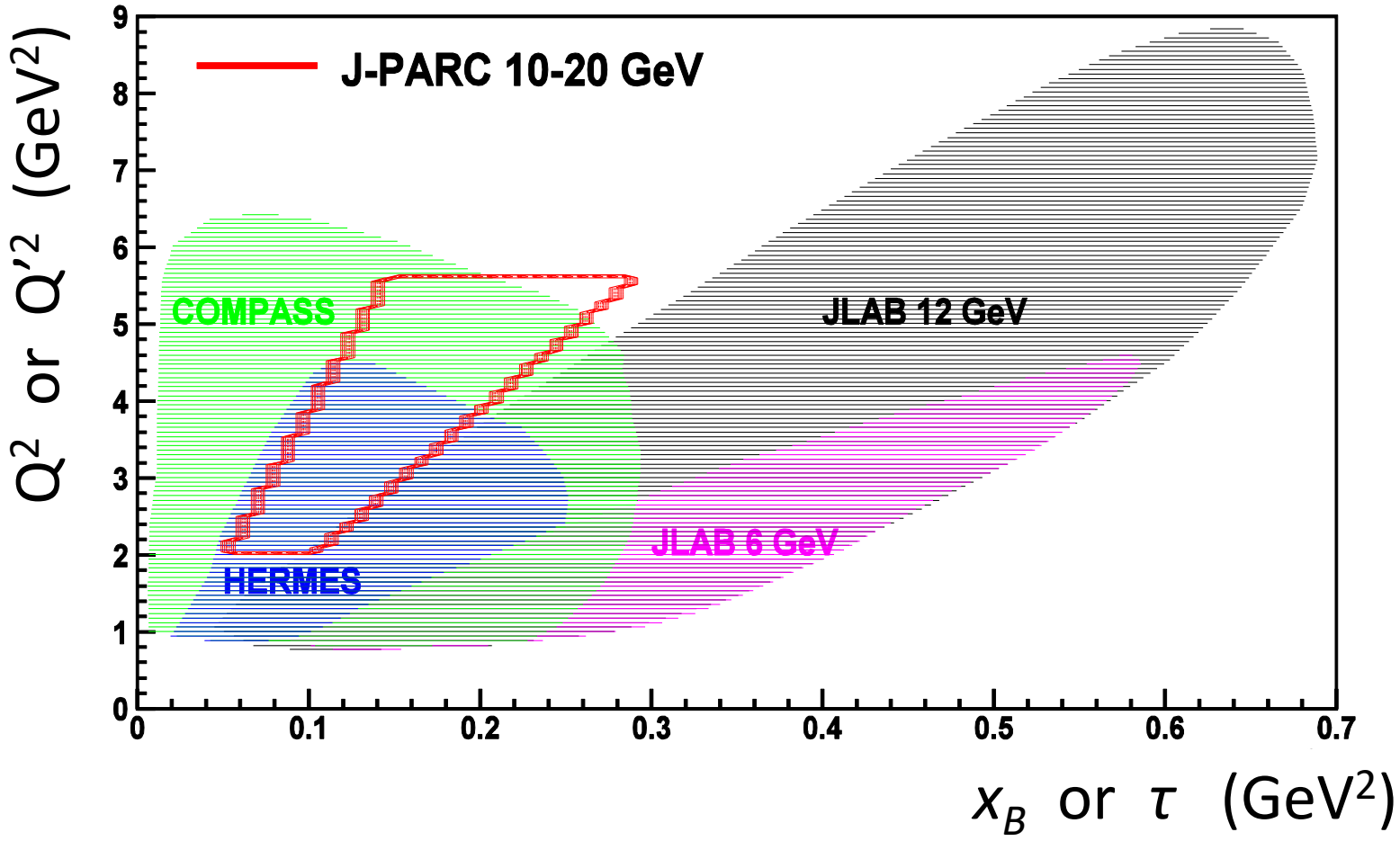
π^- Beam Momentum



- Data Taking: 50 days
- $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV
- $|t - t_0| < 0.5$ GeV^2

The statistics sensitivity is good enough for discriminating the predictions from two current GPD models.

Universality of GPDs

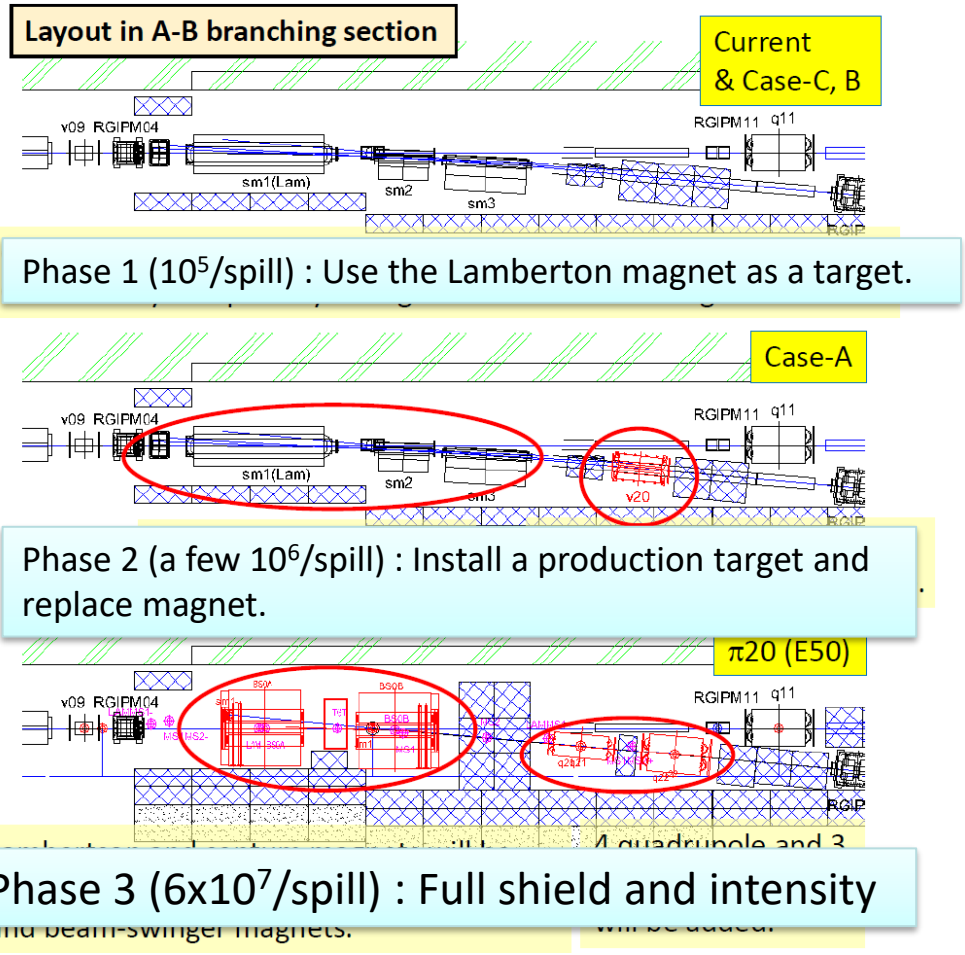


- JLAB, HERMES, COMPASS → Space-like approach
- J-PARC → Time-like approach

Staging Plan of π20 Beamline

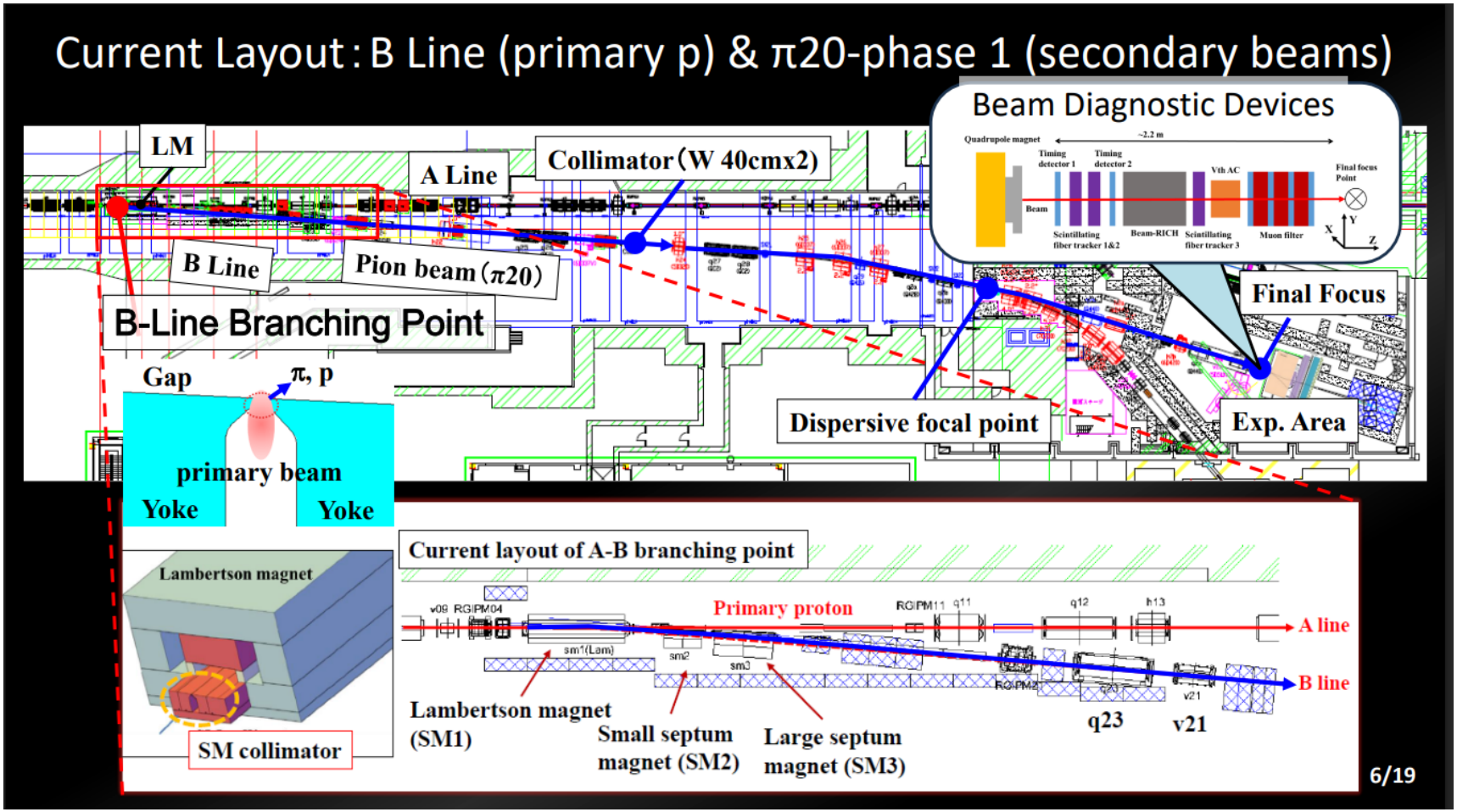
Toward π20

- Use of secondary beams in B-Line was proposed in PAC.
  - Secondary-beam production by minimum modification of current B-line.
  - Only uses beam loss at Lambertson magnet (< 420W) for secondary-particle production.
  - Needs polarity-change devices to deliver negatively charged beam (Case-B), and an additional steering magnet to improve beam intensity and profile (Case-A).
- Under discussion by users, beam-line group, radiation-control group, and KEK/J-PARC directorates.



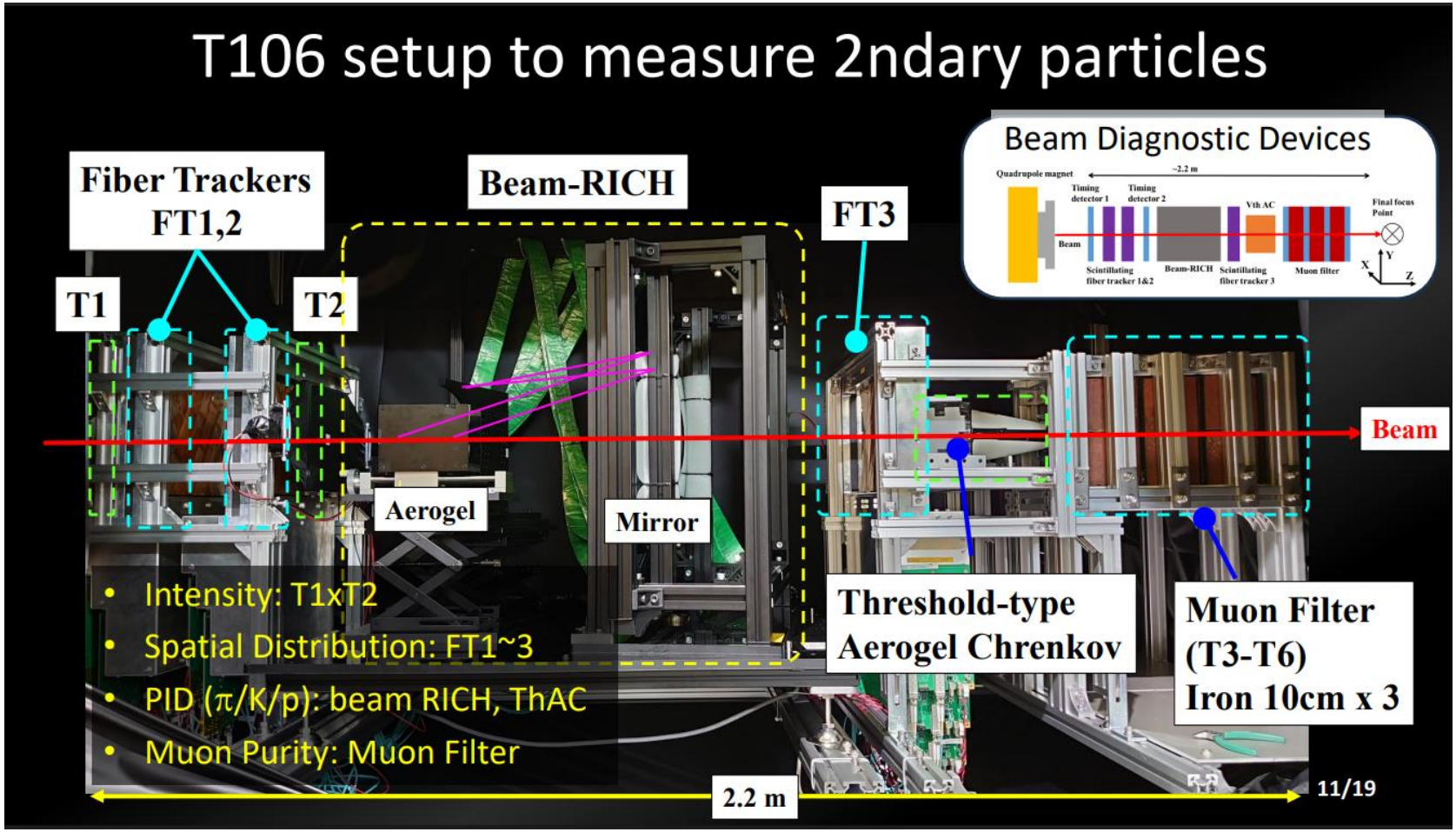
https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html
https://arxiv.org/abs/2110.04462

T106: First Measurement of Secondary Beams at the J-PARC High-Momentum Beam Line (Jan. 2025)



Hadron 2025, H. Noumi

T106: First Measurement of Secondary Beams at the J-PARC High-Momentum Beam Line (Jan. 2025)



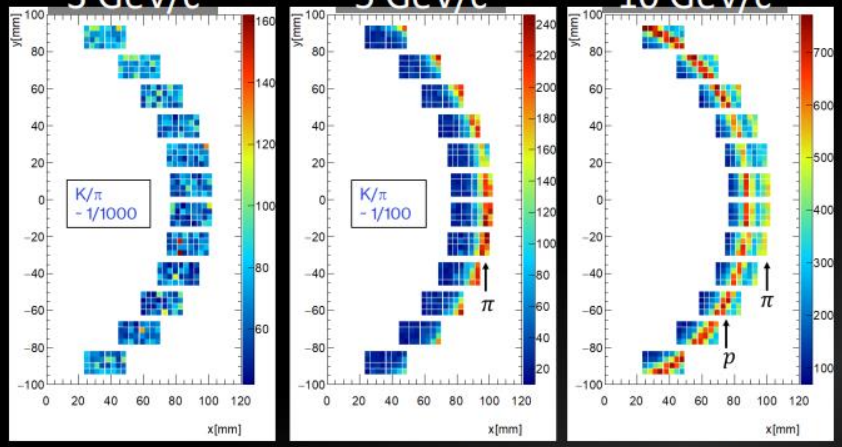
Hadron 2025, H. Noumi

T106: First Measurement of Secondary Beams at the J-PARC High-Momentum Beam Line (Jan. 2025)

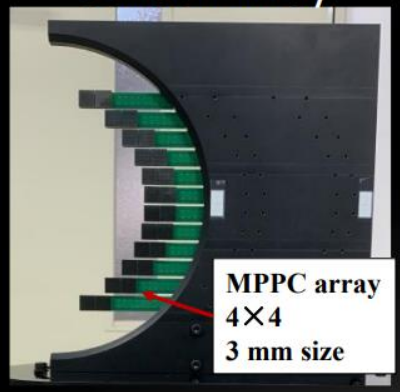
PID: beam RICH

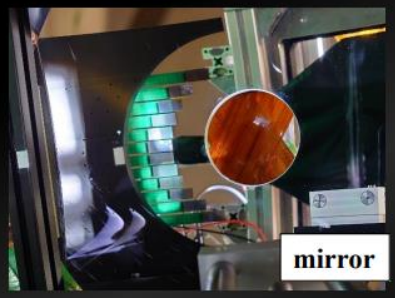
→T. Toda, Poster #53

Measured Ring Images →

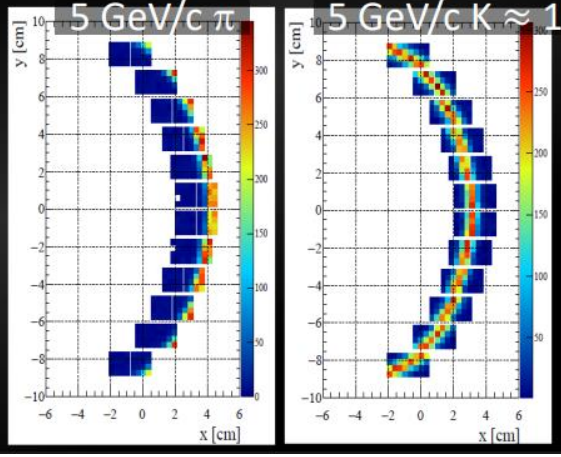


Ring Image Sensor Array





Simulation →



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GPDs with Proton Beams

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

Novel two-to-three hard hadronic processes and possible studies of generalized parton distributions at hadron facilities

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[2]*Department of Particle and Nuclear Studies, Graduate University for Advanced Studies, 1-1, Ooho, Tsukuba, Ibaraki, 305-0801, Japan*

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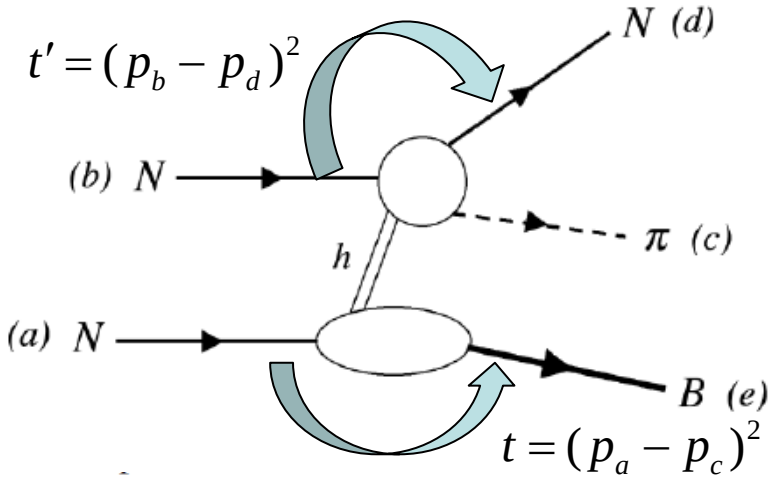
[4]*Nishogakusha University, 6-16, Sanbancho, Chiyoda, Tokyo, 102-8336, Japan*

(Received 10 May 2009; published 2 October 2009)

We consider a novel class of hard branching hadronic processes $a + b \to c + d + e$, where hadrons c and d have large and nearly opposite transverse momenta and large invariant energy, which is a finite fraction of the total invariant energy. We use color transparency logic to argue that these processes can be used to study quark generalized parton distributions (GPDs) for baryons and mesons in hadron collisions, hence complementing and adding to the studies of GPDs in the exclusive deep inelastic scattering processes. We propose that a number of GPDs can be investigated in hadron facilities such as Japan Proton Accelerator Research Complex facility and Gesellschaft für Schwerionenforschung -Facility for Antiproton and Ion Research project. In this work, the GPDs for the nucleon and for the $N \to \Delta$ transition are studied in the reaction $N + N \to N + \pi + B$, where N, π, and B are a nucleon, a pion, and a baryon (nucleon or Δ), respectively, with a large momentum transfer between B (or π) and the incident nucleon. In particular, the Efremov-Radyushkin-Brodsky-Lepage region of the GPDs can be measured in such exclusive reactions. We estimate the cross section of the processes $N + N \to N + \pi + B$ by using current models for relevant GPDs and information about large angle πN reactions. We find that it will be feasible to measure these cross sections at the high-energy hadron facilities and to get novel information about the nucleon structure, for example, contributions of quark orbital angular momenta to the nucleon spin. The studies of $N \to \Delta$ transition GPDs could be valuable also for investigating electromagnetic properties of the transition.

DOI: 10.1103/PhysRevD.80.074003 PACS numbers: 13.85.−t, 12.38.−t, 13.60.Le

$N + N \rightarrow N + \pi + B(n, \Delta^0, \Delta^{++})$



It was suggested in Refs. [25,26] that one can investigate the presence of small-size color singlet $q\bar{q}$ and qqq clusters in hadrons using large-angle branching hadronic processes $a + b \rightarrow c + d + e$, where the hadron e is produced in the fragmentation of b with fixed Feynman x_F and fixed transverse momentum $p_T^{(e)}$, while the hadrons c and d are produced with large and near balancing transverse momenta: $p_T^{(c)} \approx -p_T^{(d)}$.

$p_T^{(c)} \approx -p_T^{(d)}$

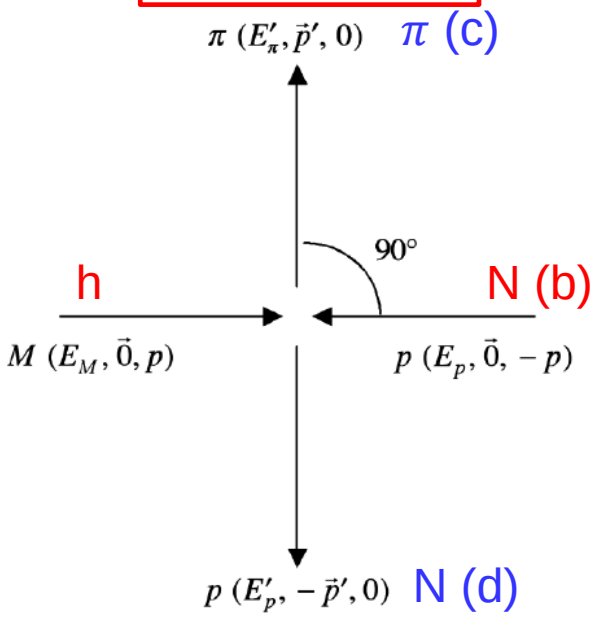
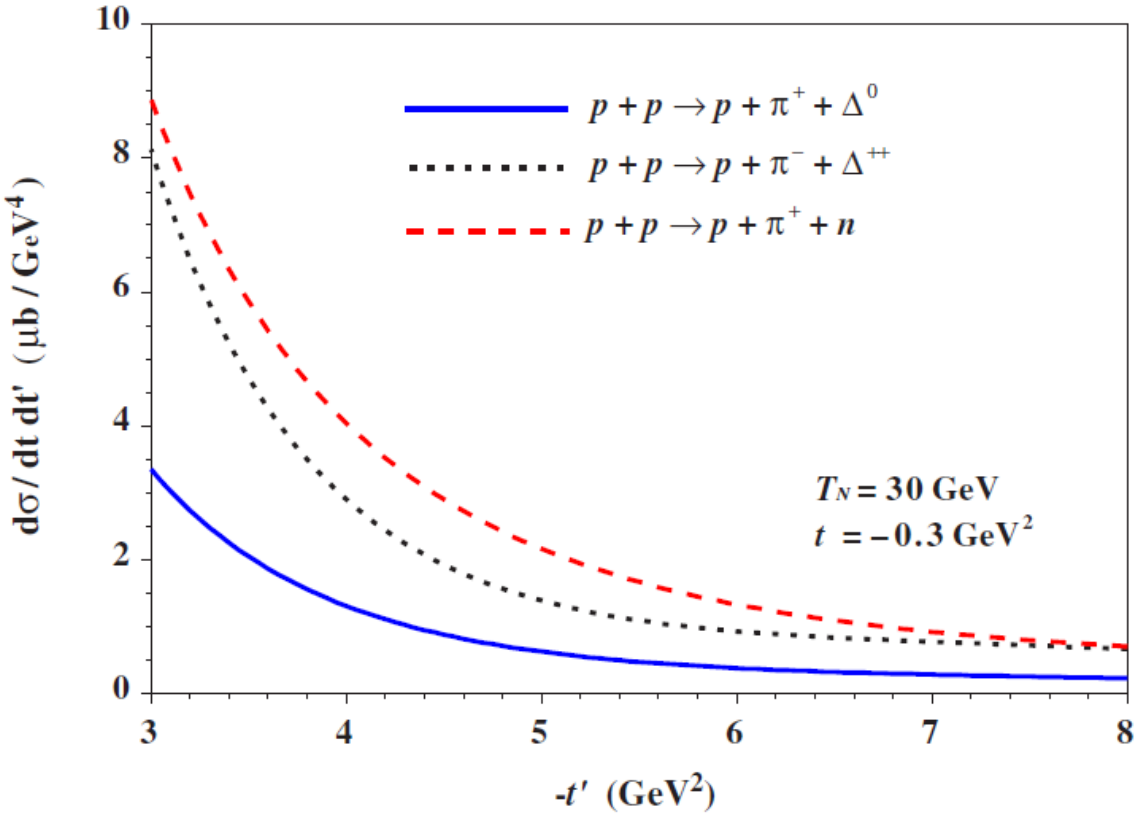


FIG. 8. $Mp \rightarrow \pi p$ elastic scattering at $\theta_{\text{c.m.}} = 90°$.

Kumano, Strikman, and Sudoh, PRD 80, 074003 (2009)

$N + N \rightarrow N + \pi + B(n, \Delta^0, \Delta^{++})$

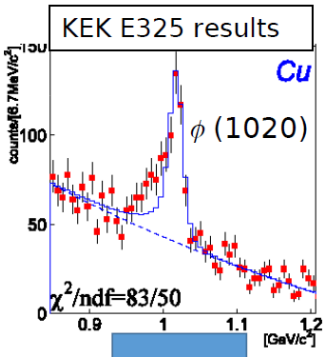


The measurement of –t' (~ qT of forward-moving N) dependence could be used to explore the x-dependence of GPDs.
Qiu & Yu, JHEP 08 (2022) 103, PRD 107 (2023) 014007, arXiv:2305.15397

Kumano, Strikman, and Sudoh, PRD 80, 074003 (2009)

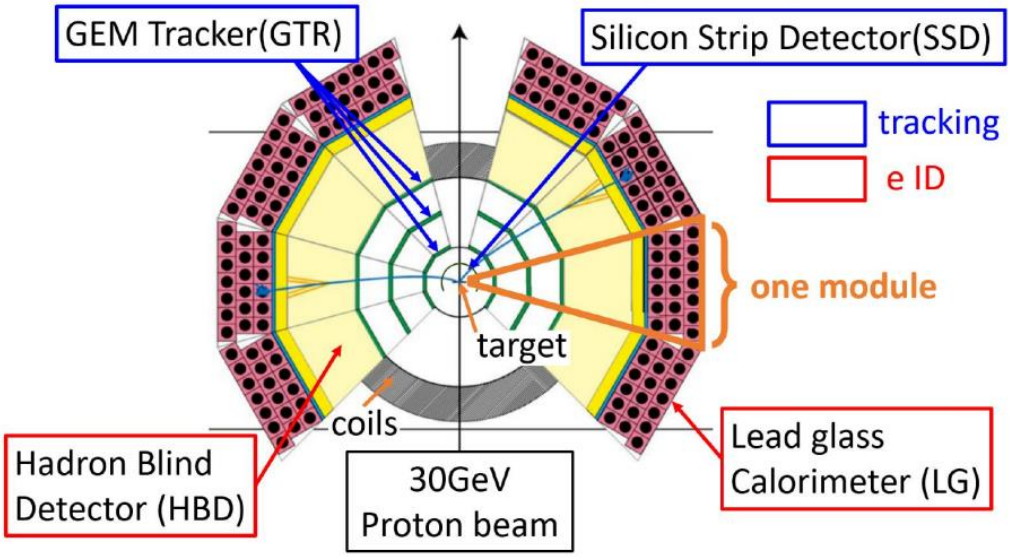
E16 Experiment at J-PARC

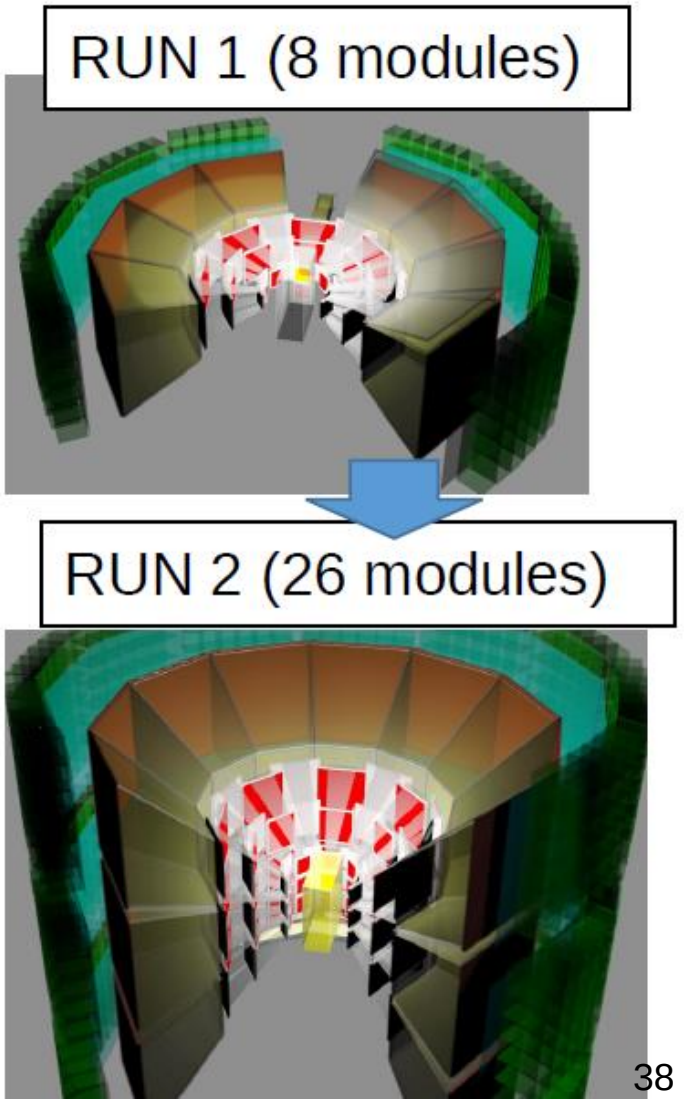
- E16 will measure the e+e- decay of ρ, ω, ϕ mesons produced in 30-GeV p+A (C, Cu, Pb, etc.) reactions.
- Modification of line shapes in nuclear matter as the evidence of chiral symmetry restoration.
- Commission runs (Run 0): 2020,2021,2023,2024.
- **Run 1: Nov/2025**



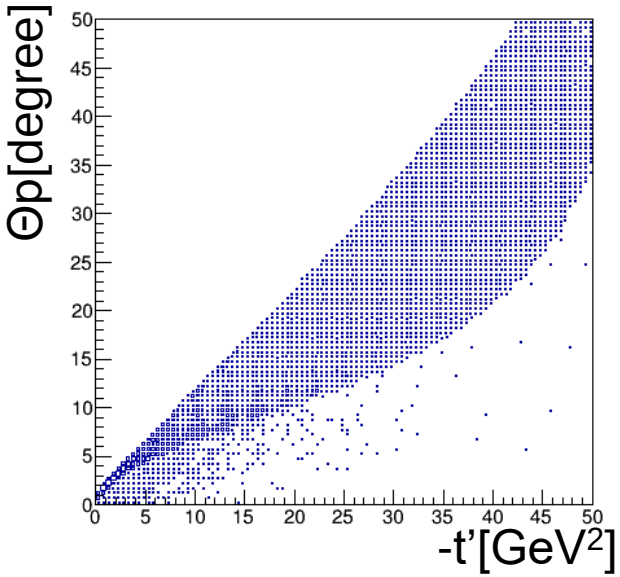
E16 Acceptance/PID Performance

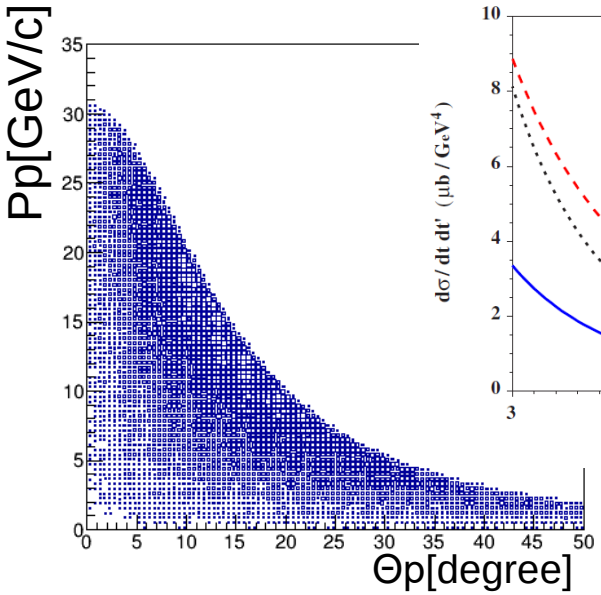
$\theta_{p,\pi} > 15\,\mathrm{deg}$

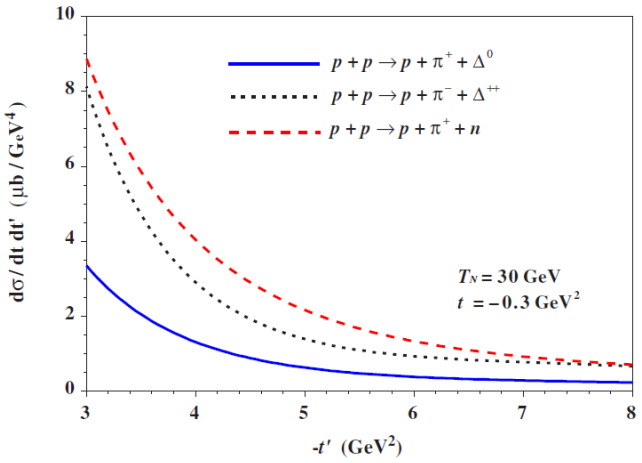




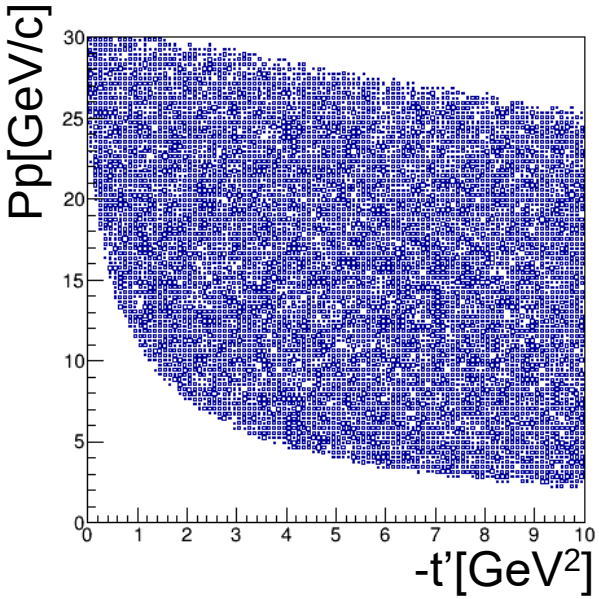
E16: p(30 GeV)p→pπ⁺n

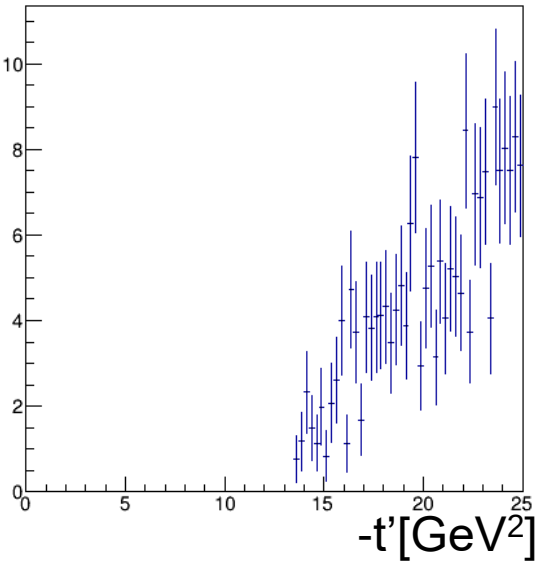






$\theta_{p,\pi} > 15$ deg, $\phi_{p-\pi} > 160$ deg





The forward opening of the current setting significantly limits the acceptance of t'.

“Mini-MARQ”: p(30 GeV)p→pπ+n

Experimental conditions

		Primary (original plan)	Secondary (phase-1)
Beam	Intensity	10^{10} / spill (2 s)	10^{6} / spill
	particle	30 GeV protons	10-20 GeV/c p/π unseparated
	measurement	×	○ **(PID/ Intensity / Momentum)**
Detector geometry		**Avoid around beam (radiation control)**	**Can be installed in the beam axis**

“mini-MARQ spectrometer”

- FM magnet + Trackers (ready)

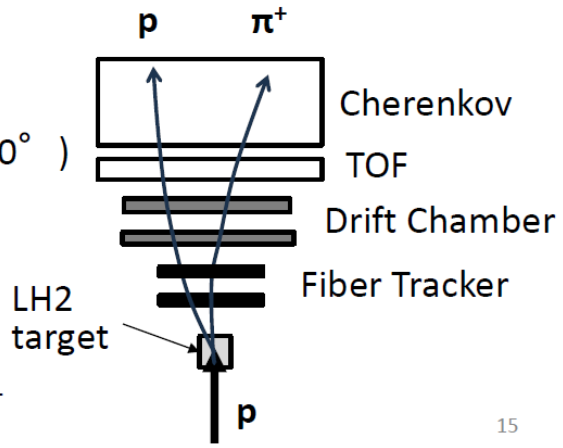
$p + p \rightarrow p + \pi^+ + n$

- 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 : $\Delta^0 \rightarrow p+\pi^-$, $\Delta^{++} \rightarrow p+\pi^+$



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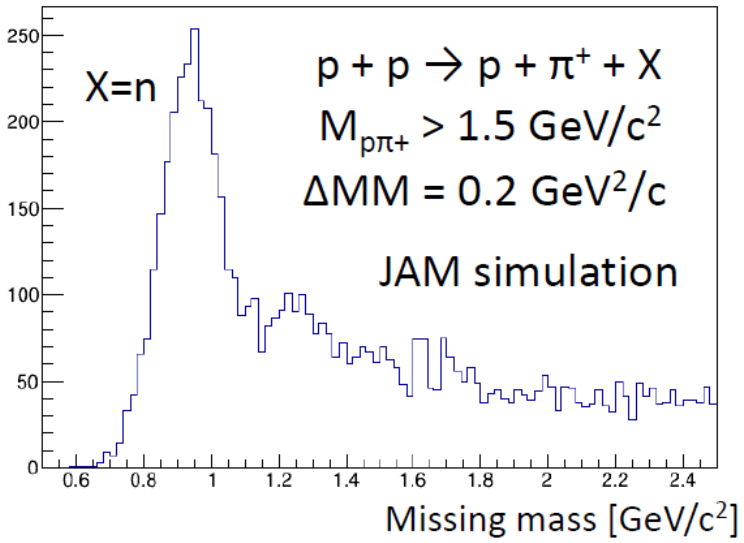
N. Tomida, Hadron 2025

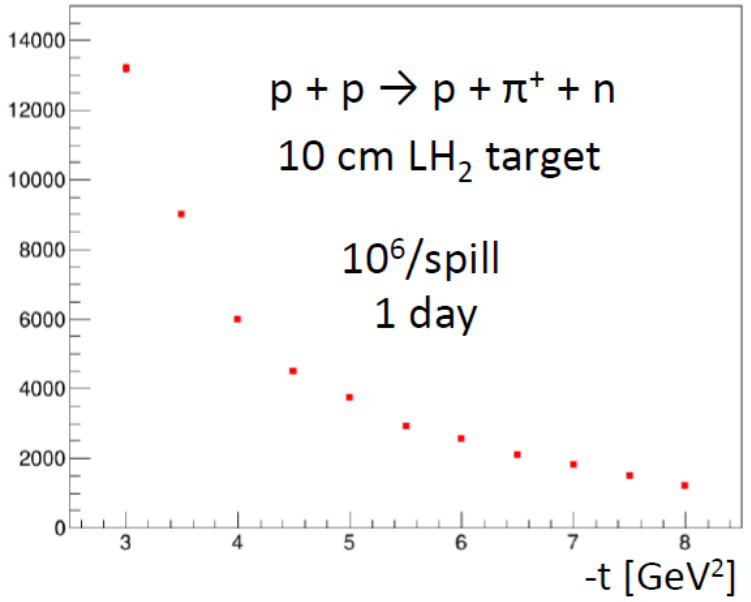
“Mini-MARQ”: p(30 GeV)p→pπ+n

Experimental expectation

Missing mass



Yield



Promising !

N. Tomida, Hadron 2025

Summary

- Hadron structures are explored by both space-like and time-like approaches: FFs, PDFs, TMDs and GPDs.
- Exclusive π-induced Drell-Yan process will a novel approach of measuring GPDs and the measurements at J-PARC will bring important understandings on:
  - Universality of GPDs
  - DA and timelike FFs of pions
  - Color-transparency (with nuclei targets)
  - TDA …
- Because of the immediate availability of 30-GeV proton beam, carrying out the measurement of 2-to-3 hard processes within J-PARC E16 and “Mini-MARQ” experiments are investigated.