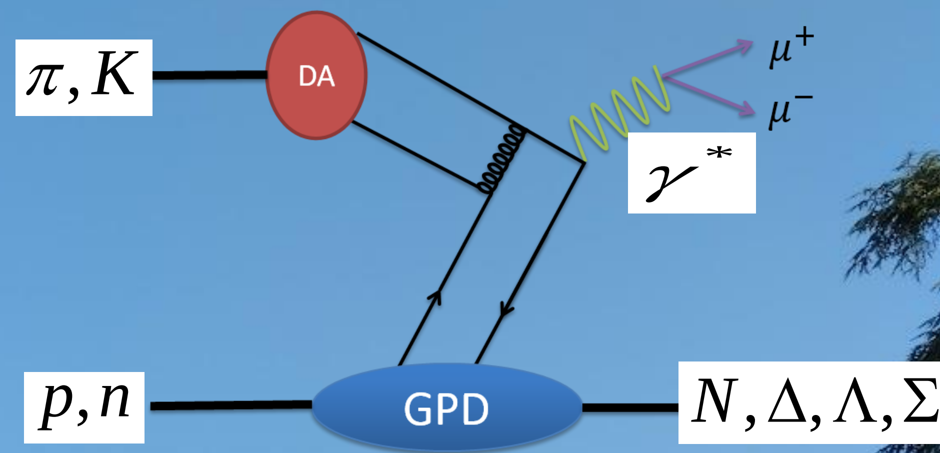
FONDAZIONE BRUNO KESSLER

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

ECT*-APCTP joint workshop: exploring resonance structure with transition GPDS

Aug 21 – 25, 2023



Transition GPDs at J-PARC

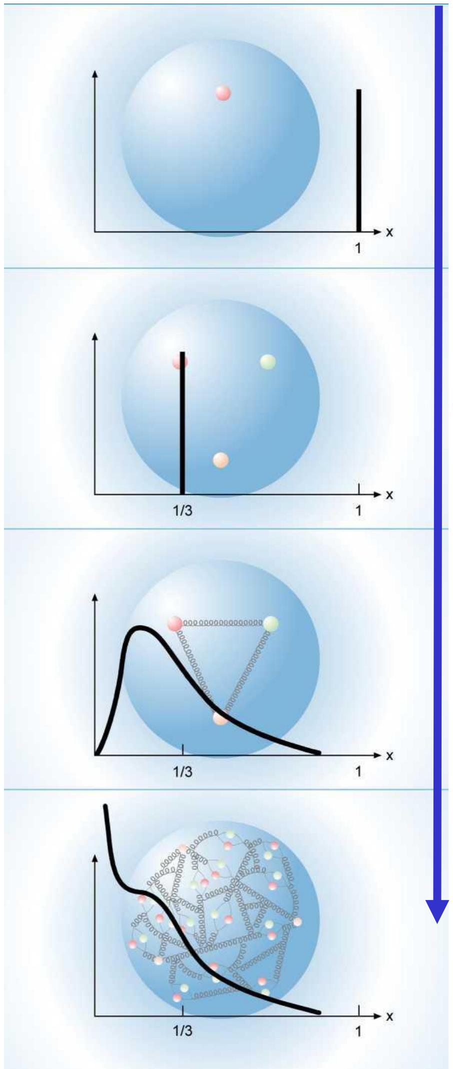
Wen-Chen Chang 章文箴

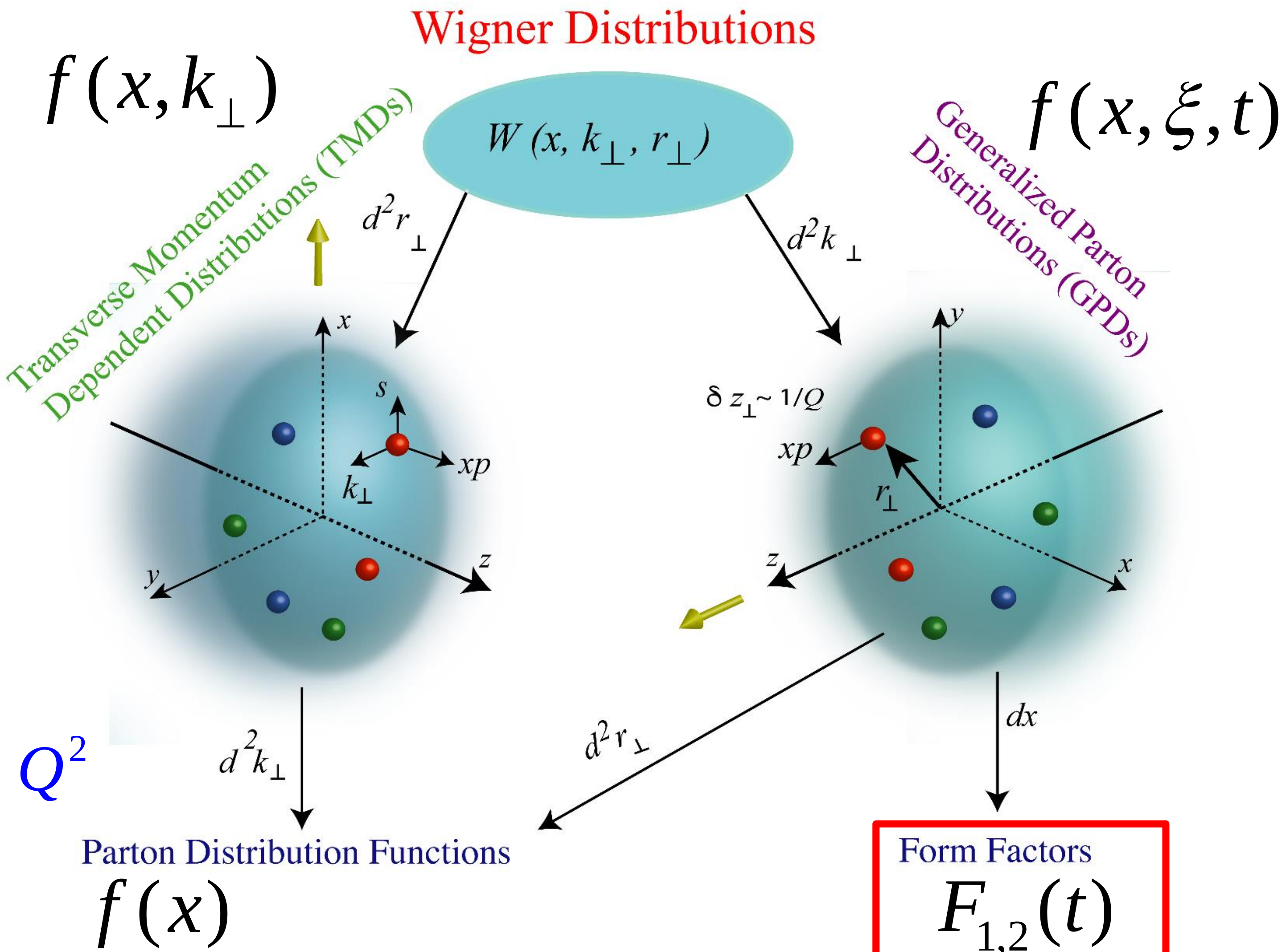
Institute of Physics, Academia Sinica

Outline

- Exclusive Drell-Yan Process:
  measuring GPDs in a ***time-like*** approach
- High-momentum beamline at J-PARC
  - Transition GPDs with pion beams and E50 spectrometer [PRD93 (2016) 114034]
  - Transition GPDs with proton beams and E16 spectrometer [PRD80 (2009) 074003]
- Summary

Multi-dimensional Partonic Structures

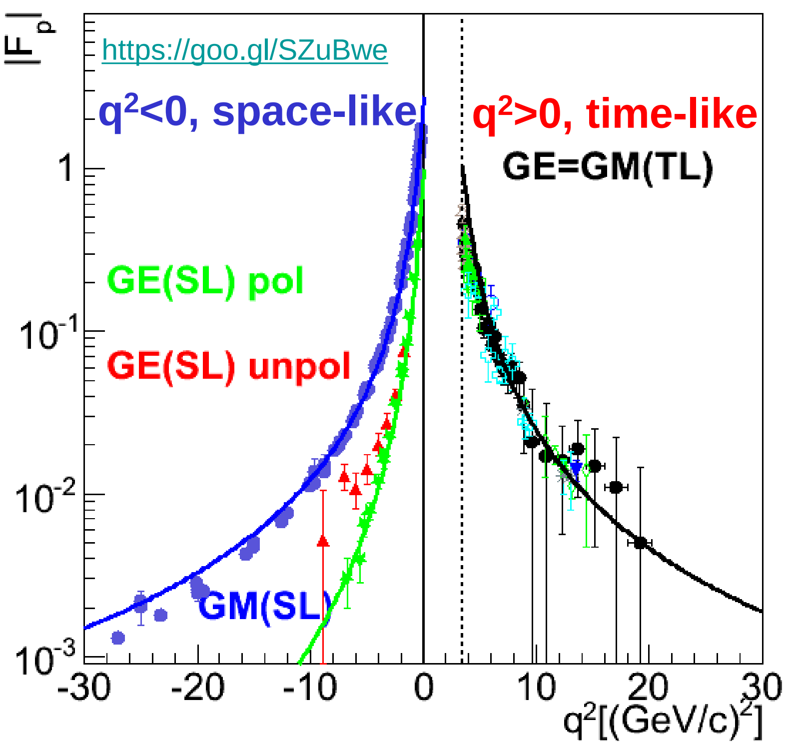




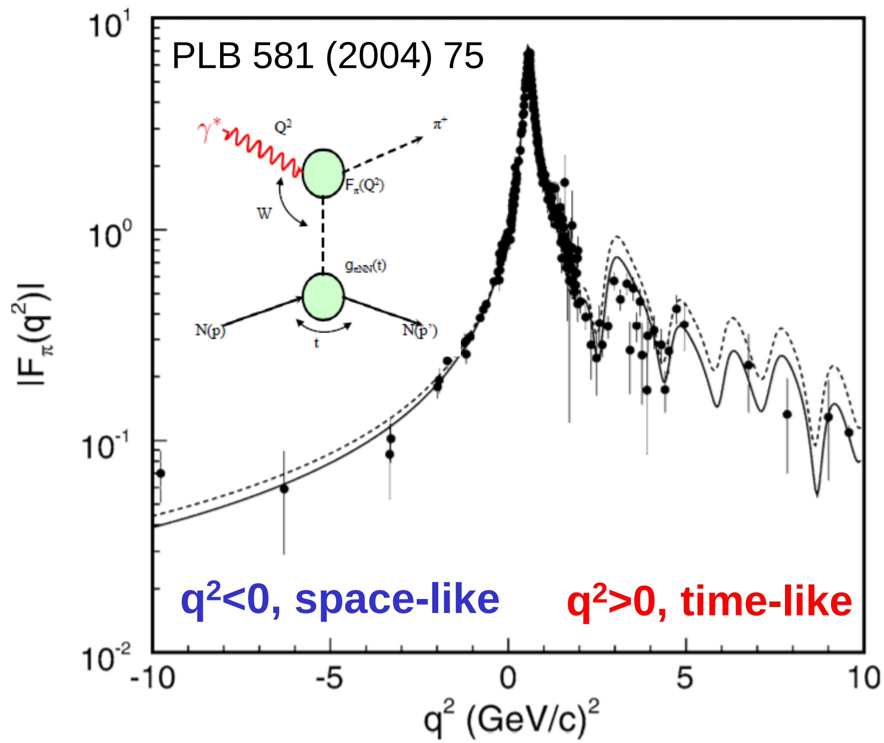
http://www.int.washington.edu/PROGRAMS/17-3/

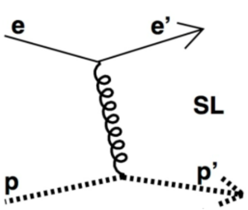
Electromagnetic Form Factors

proton

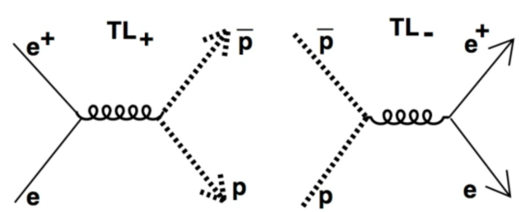


pion



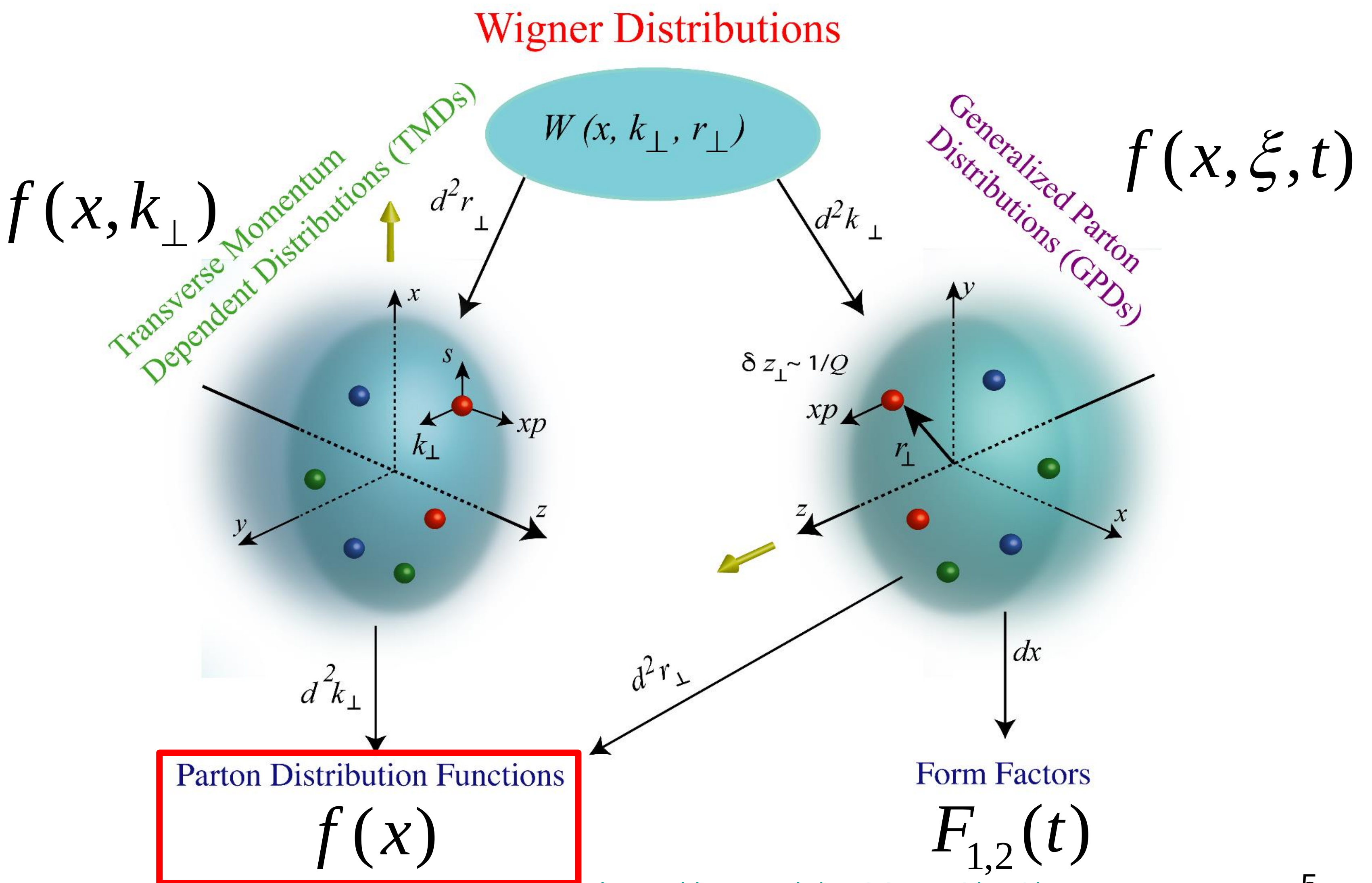


Space-like ($q^2 < 0$):
elastic scattering



Time-like ($q^2 > 0$):
e+e- or hadron pair
annilhlation

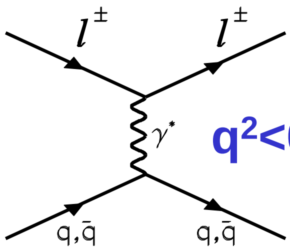
Multi-dimensional Partonic Structures



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

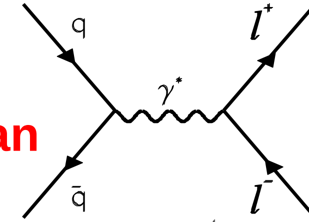
Factorization of Hard Processes

DIS



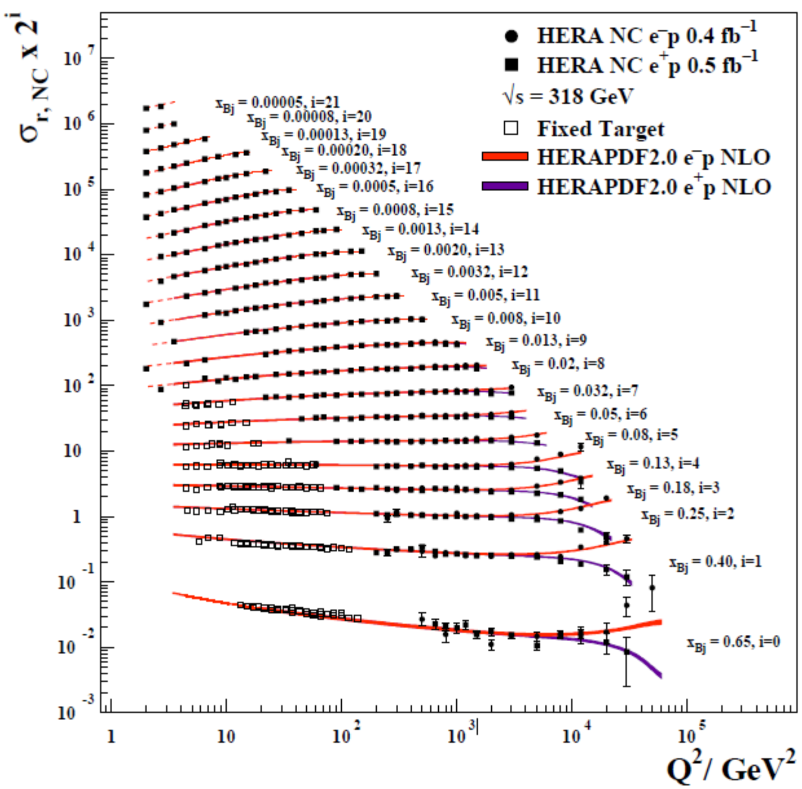
$q^2<0$, space-like

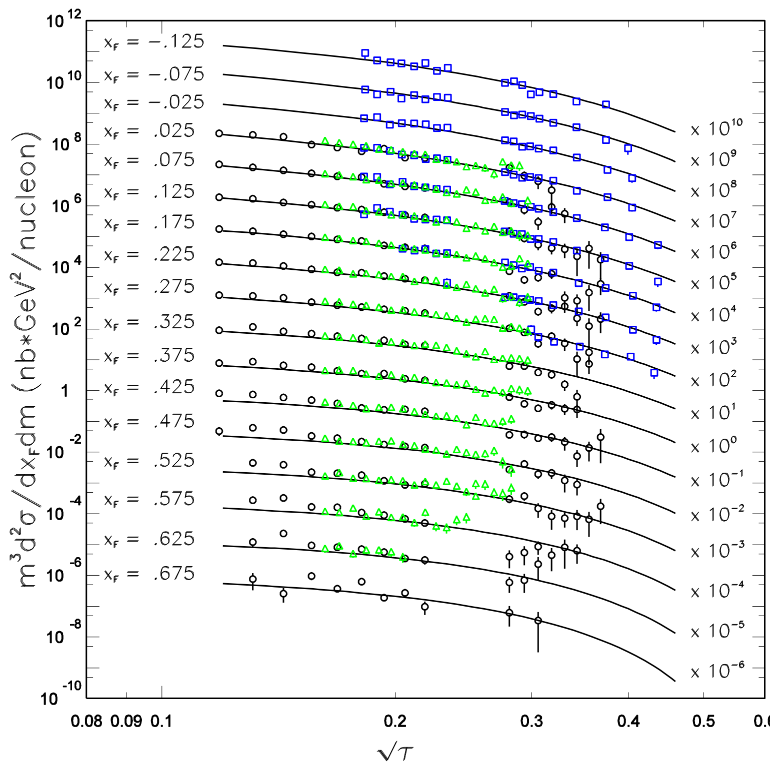
Drell-Yan



$p\,A \rightarrow \mu^+\mu^- X$

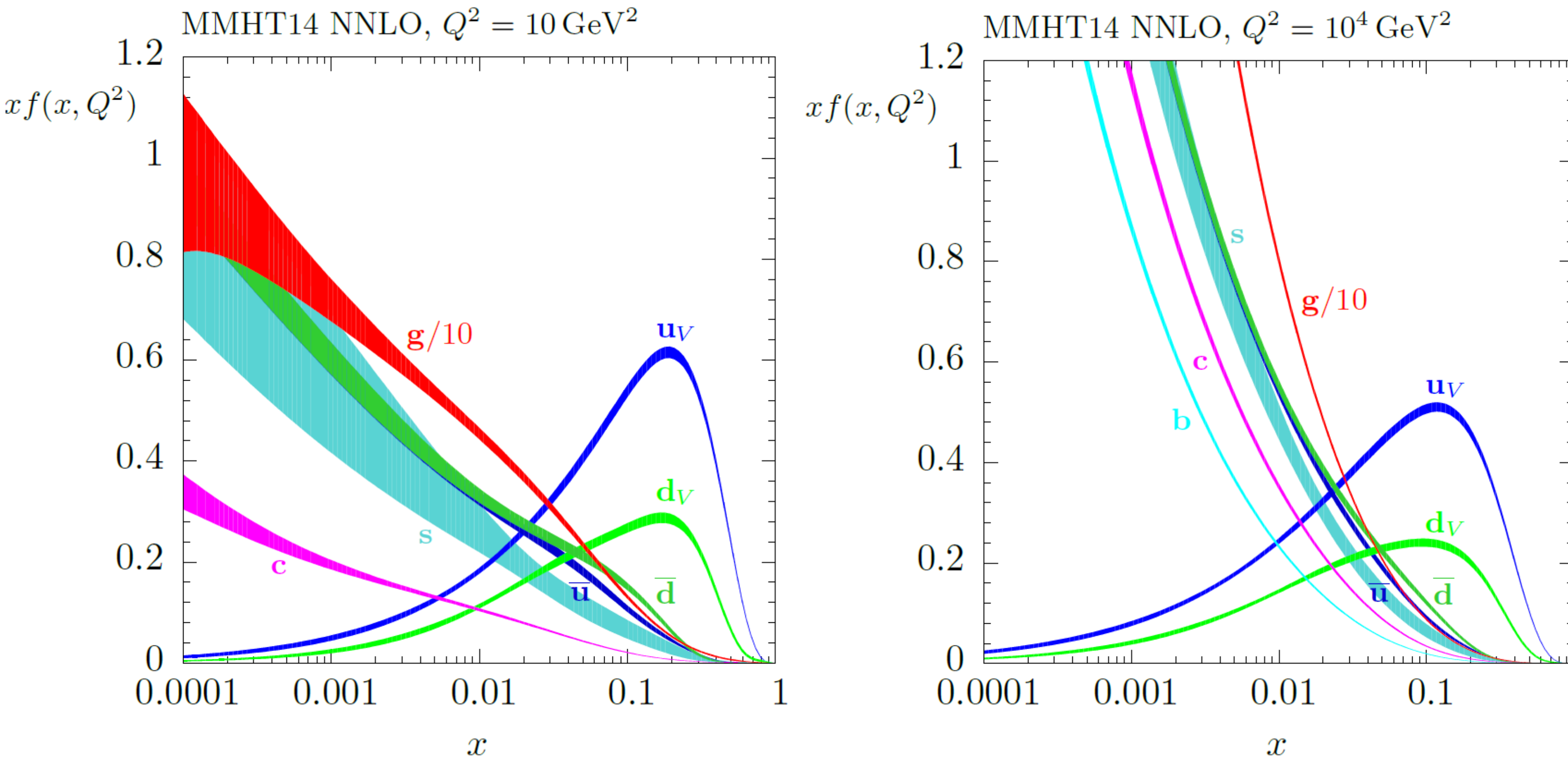
$q^2>0$, time-like





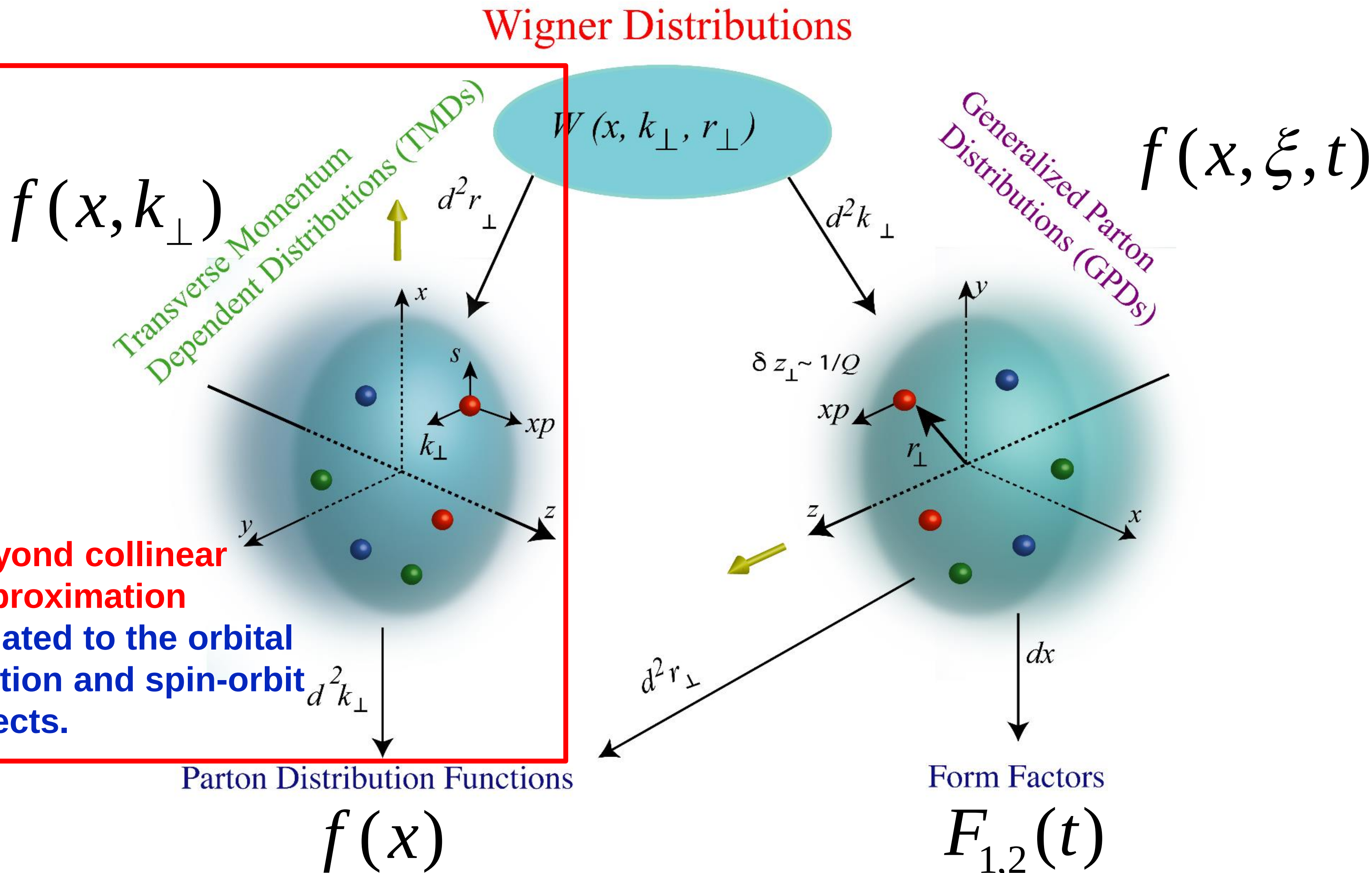
$$\sigma_{proton}(x,Q^2) \sim PDF_{nucleon}(x,Q^2) \otimes \hat{\sigma}_{hard}(Q^2)$$

Parton Density Function (PDF) MMHT 2014



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

Multi-dimensional Partonic Structures



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

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

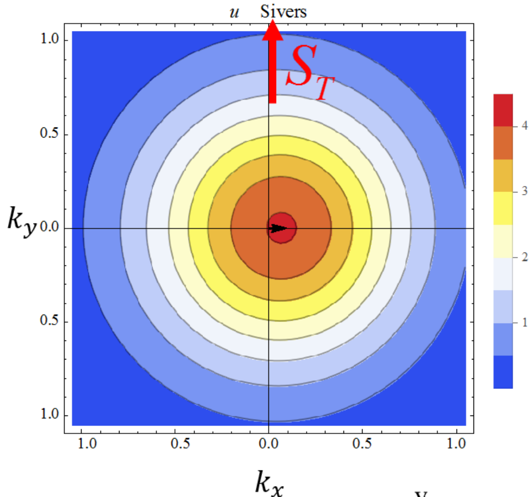
Leading-Twist Transverse-momentum Dependent **Parton Density Function** (TMDs)

- **spin of the nucleon**
- **spin of the parton**
- **k_T of the parton**

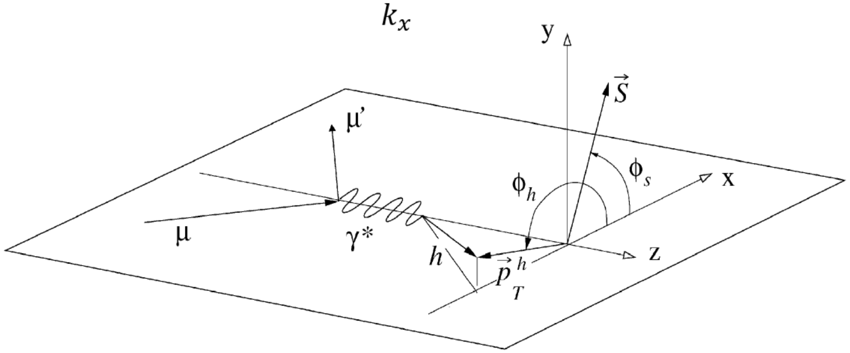
Quark / Nucleon	U	L	T
U	number density $f_1^{q,g}(x, k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x, k_T^2)$
L		Helicity $g_{1L}^{q,g}(x, k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x, k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x, k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x, k_T^2)$	Transversity $h_1^{q,g}(x, k_T^2)$ Pretzelosity $h_{1T}^{\perp q,g}(x, k_T^2)$

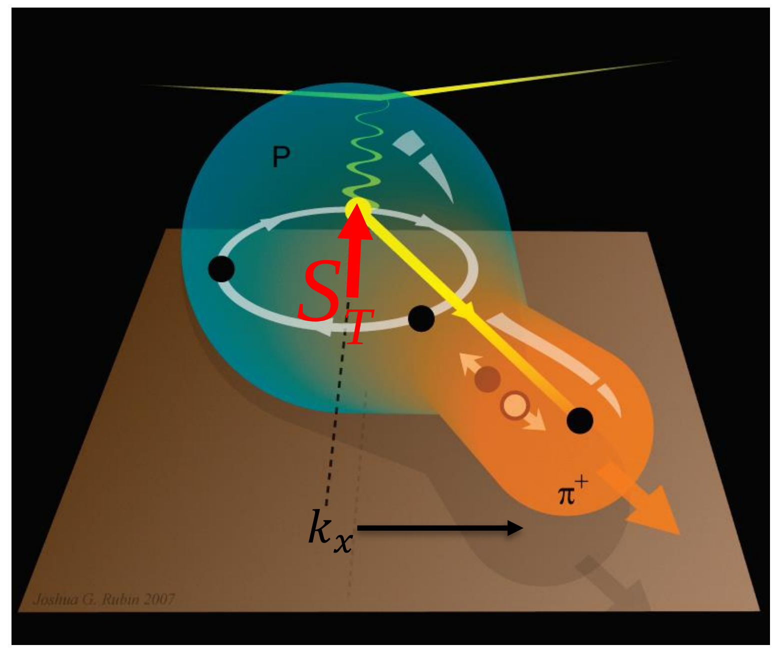
Sivers Asymmetry A_{Siv} in SIDIS (Left-Right Asymmetry w.r.t. S_T)

$$f_{q/p\uparrow}(x,\overrightarrow{k_T},\overrightarrow{S_T}) = f_{q/p}(x,k_T^2) - \frac{1}{M_N} f_{1T}^{\perp q}(x,k_T^2)\overrightarrow{S_T}\cdot(\hat{p}_N \times \overrightarrow{k_T})$$



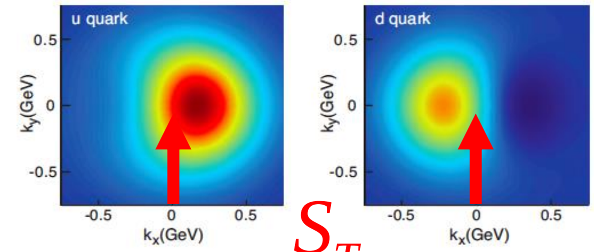
The orbital motion of an u quark inside a proton causes positive-charged pions ($u\bar{d}$) to fly off predominantly to beam-left.





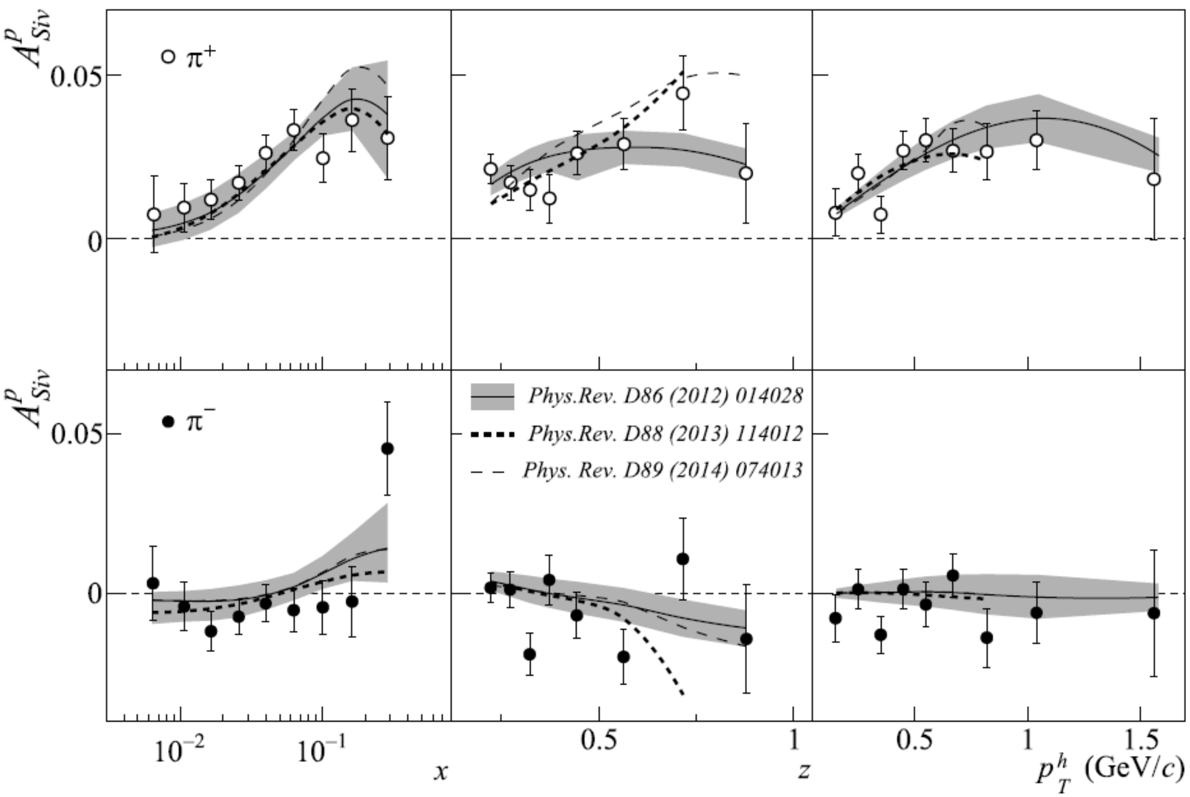
$$A_T^h \equiv \frac{d\sigma(\vec{S}_T) - d\sigma(-\vec{S}_T)}{d\sigma(\vec{S}_T) + d\sigma(-\vec{S}_T)} = \left|\vec{S}_T\right| \cdot [D_{NN} \cdot A_{Coll} \cdot \sin(\phi_h + \phi_S - \pi) + A_{Siv} \cdot \sin(\phi_h - \phi_S)]$$

Nonzero Sivers Asymmetries from SIDIS

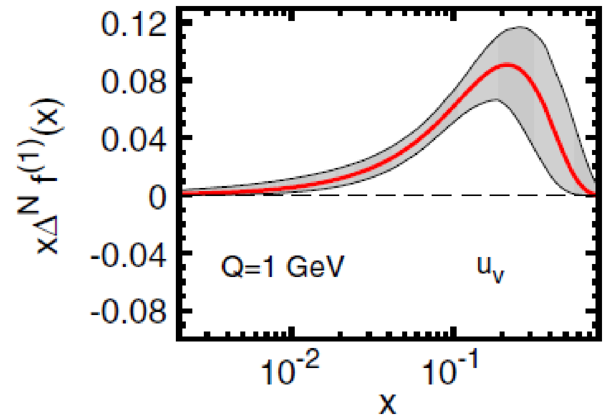


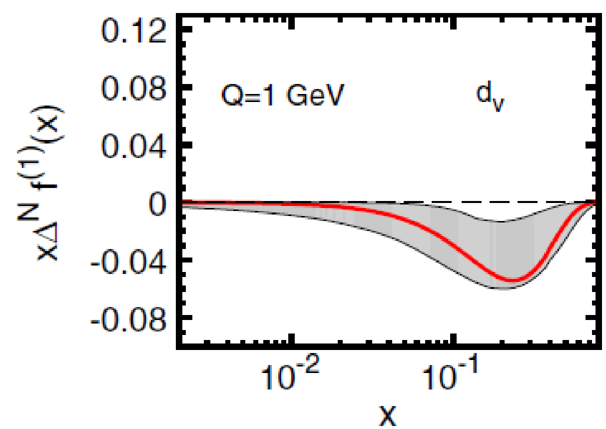
S_T

COMPASS, PLB 744 (2015) 250



Sivers Functions





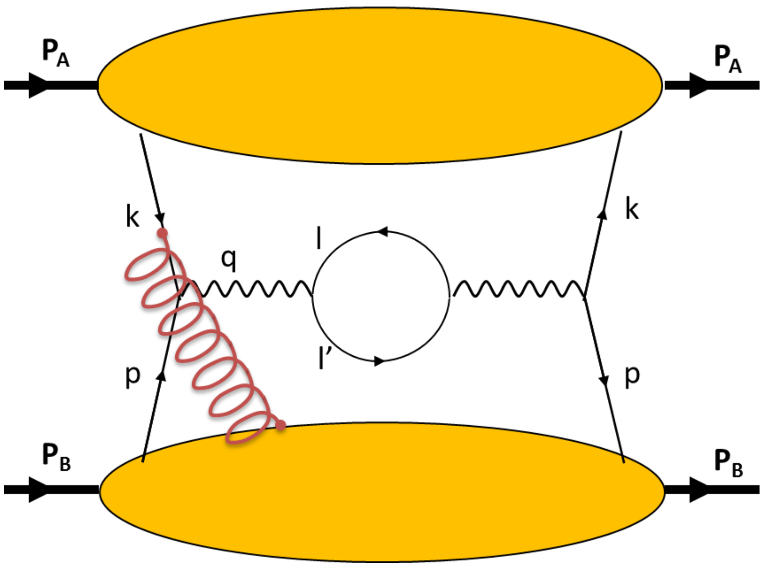
SIDIS $\gamma^*(q^2 < 0)p_\uparrow \to hX$

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

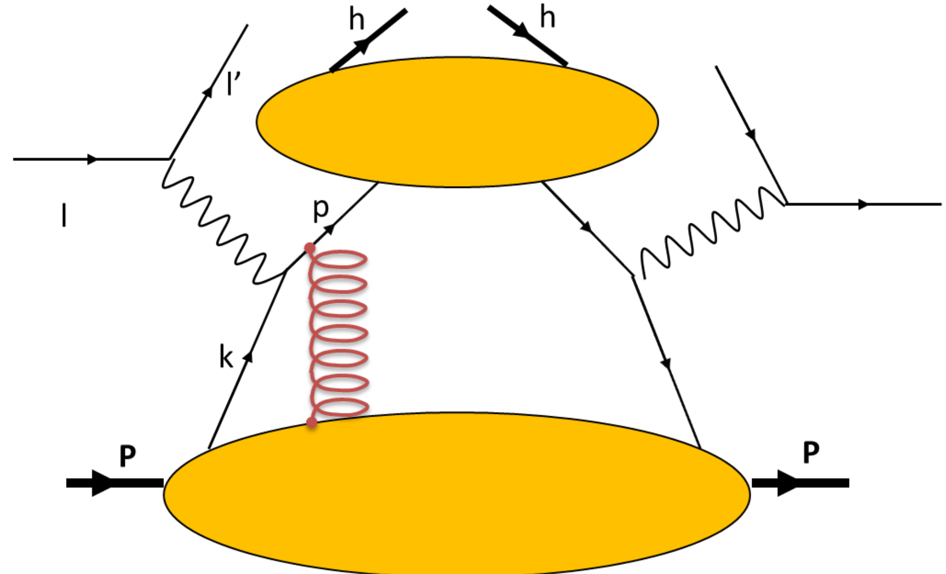
Non-Universality of Sivers Function

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**

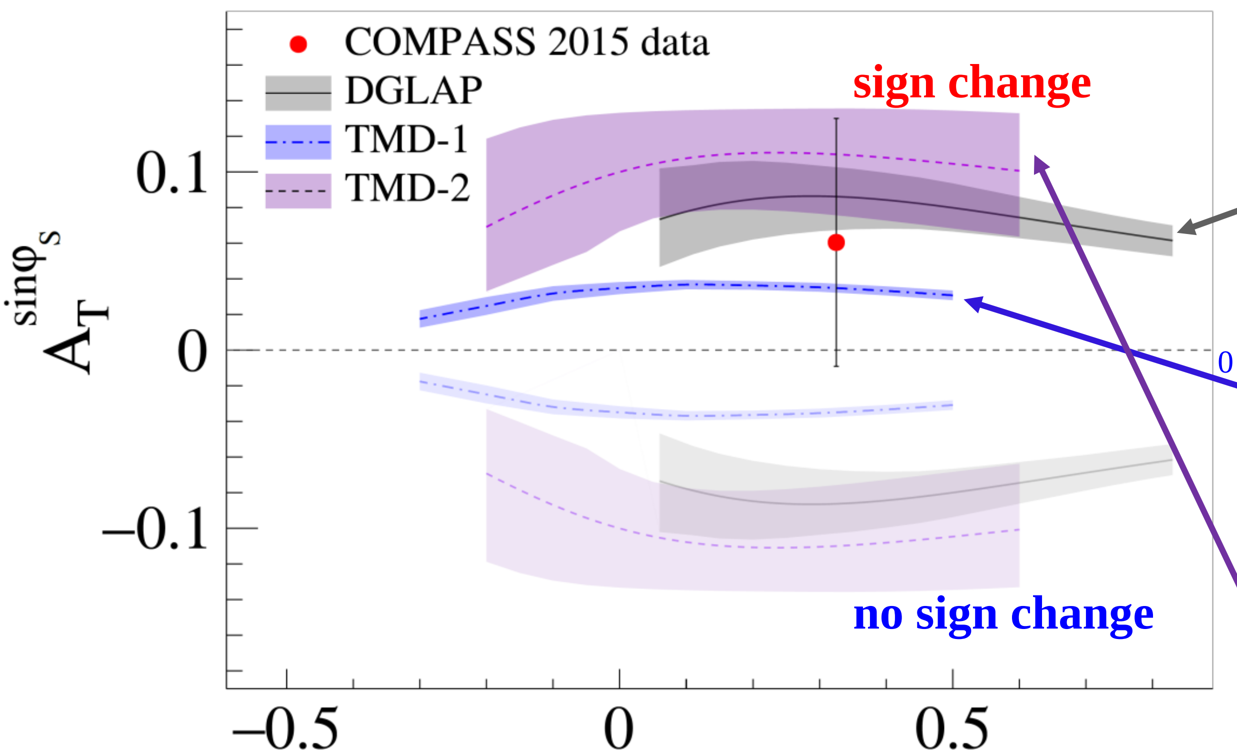


$hp_{\uparrow} \rightarrow \gamma^*(q^2 > 0)X$ $\quad$ $\text{Sivers}\,|_{DY} = -\text{Sivers}\,|_{SIDIS}$ $\quad$ $\gamma^*(q^2 < 0)p_{\uparrow} \rightarrow hX$

- 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 Asymmetry in Drell-Yan:
Hint of Sign Change!

COMPASS, PRL 119 (2017) 112002

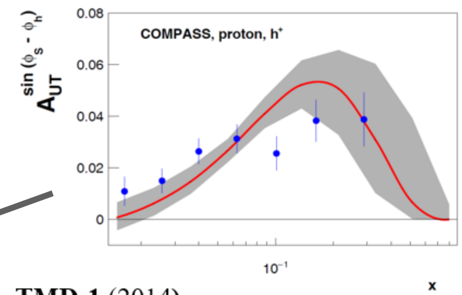


$0 < q_T < 1$ GeV

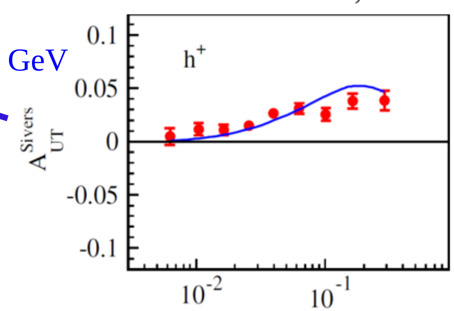
$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

DY $\pi p_\uparrow \rightarrow \gamma^*(q^2 > 0)X$

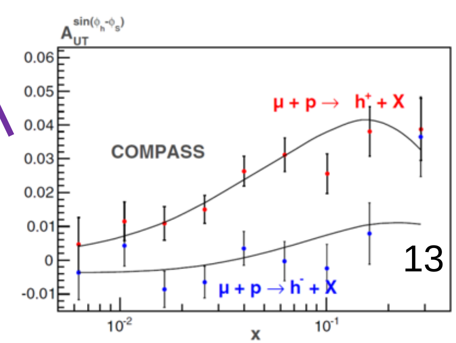
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



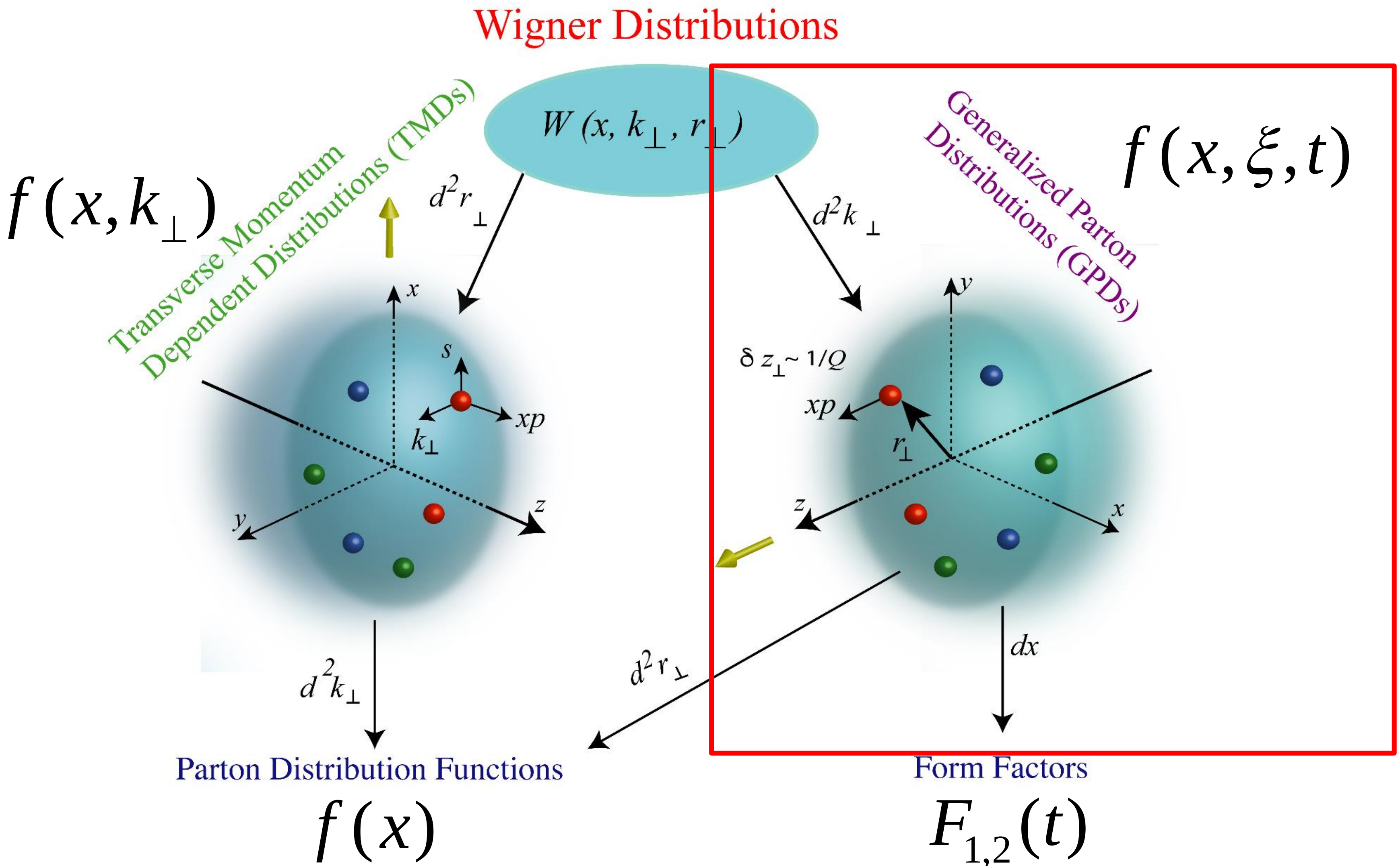
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



Multi-dimensional Partonic Structures

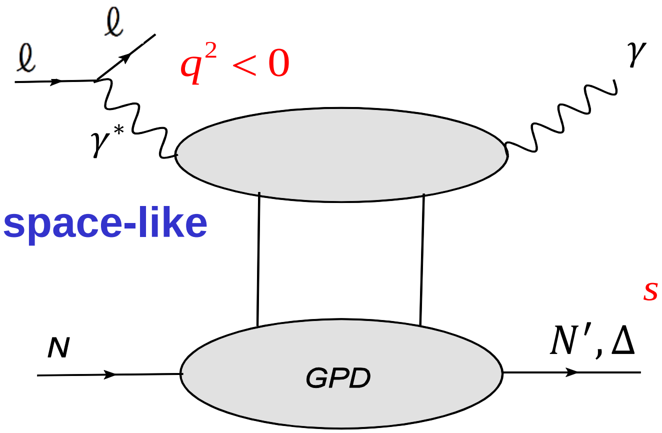


http://www.int.washington.edu/PROGRAMS/17-3/

(Transition) GPDs

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

Deeply Virtual Compton Scattering

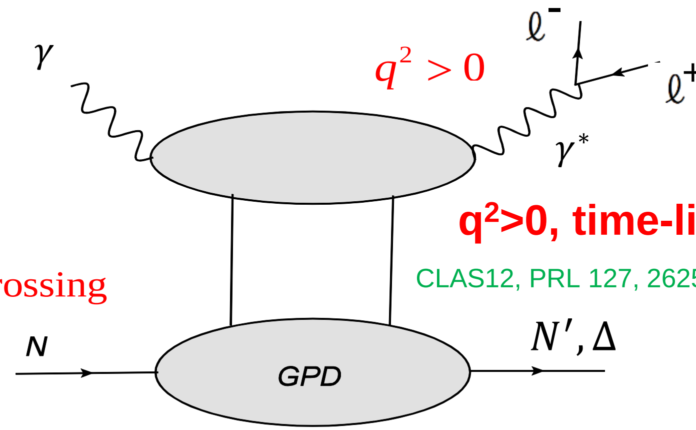


q²<0, space-like

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

$s \leftrightarrow u$ channel crossing

Time-like Compton Scattering

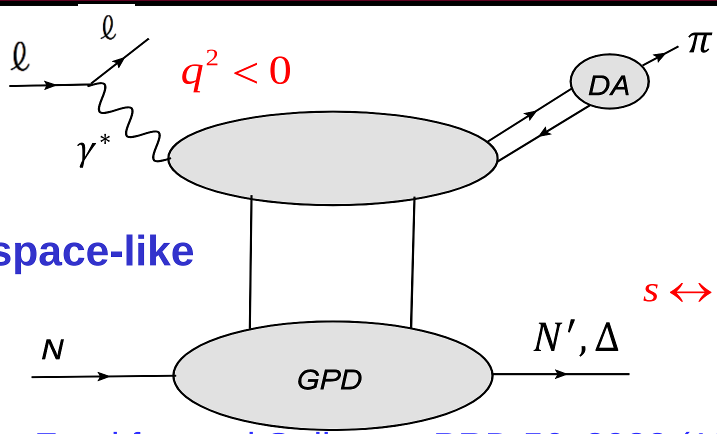


q²>0, time-like

CLAS12, PRL 127, 262501 (2021)

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

Deeply Virtual Meson Production



q²<0, space-like

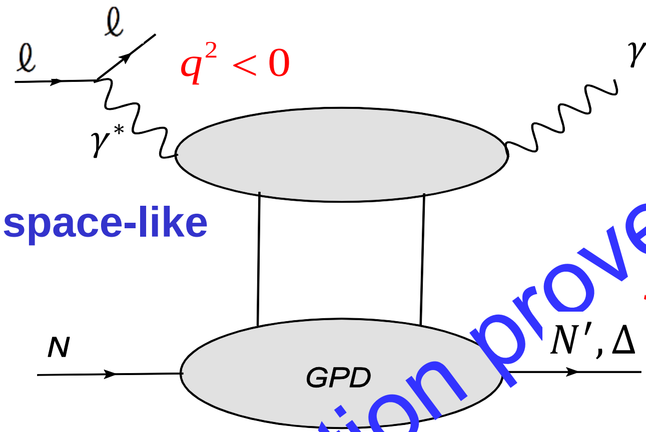
$s \leftrightarrow u$ channel crossing

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

(Transition) GPDs

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

Deeply Virtual Compton Scattering



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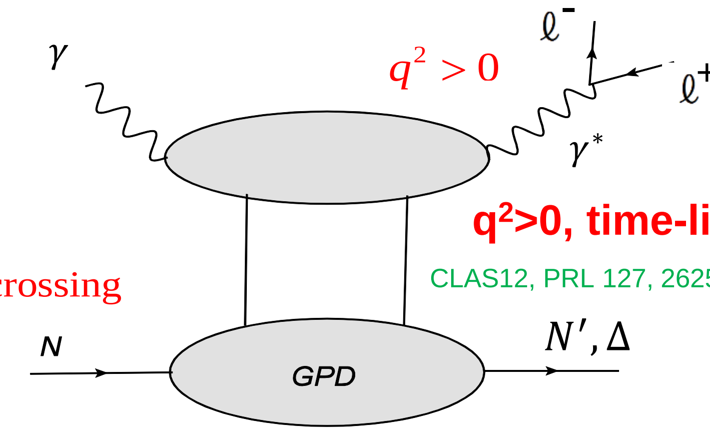
Ji, PRL 78, 610 (1997); Radyushkin, PLB 380, 417 (1996)

Time-like Compton Scattering



q^2>0, time-like

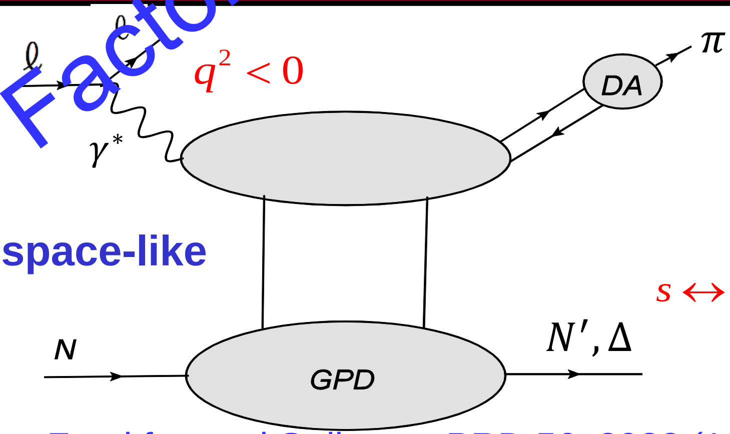
CLAS12, PRL 127, 262501 (2021)

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

$s \leftrightarrow u$ channel crossing

Factorization proved!

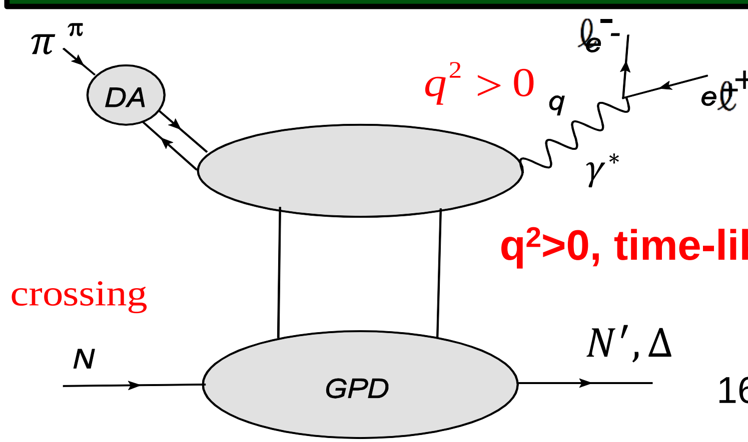
Deeply Virtual Meson Production



q^2<0, space-like

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

Exclusive meson-induced DY

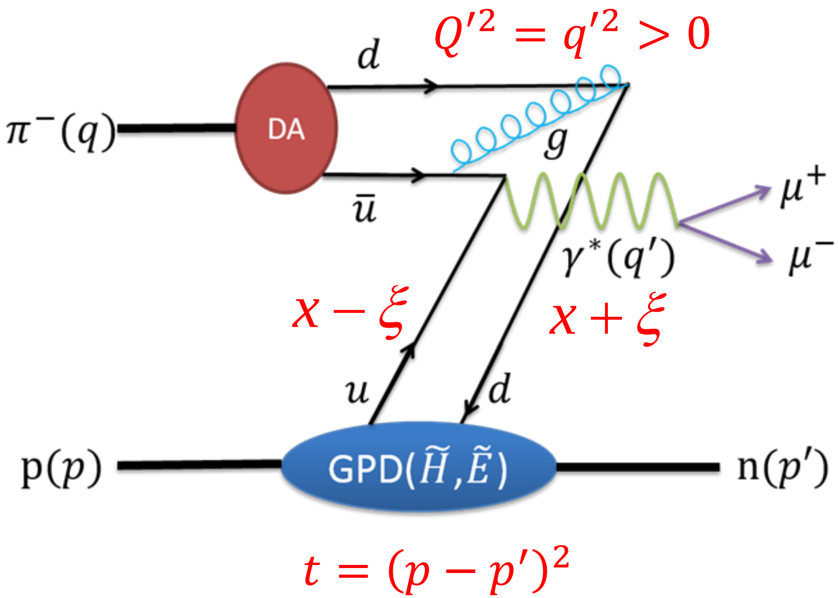


q^2>0, time-like

$s \leftrightarrow u$ channel crossing

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

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



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

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

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

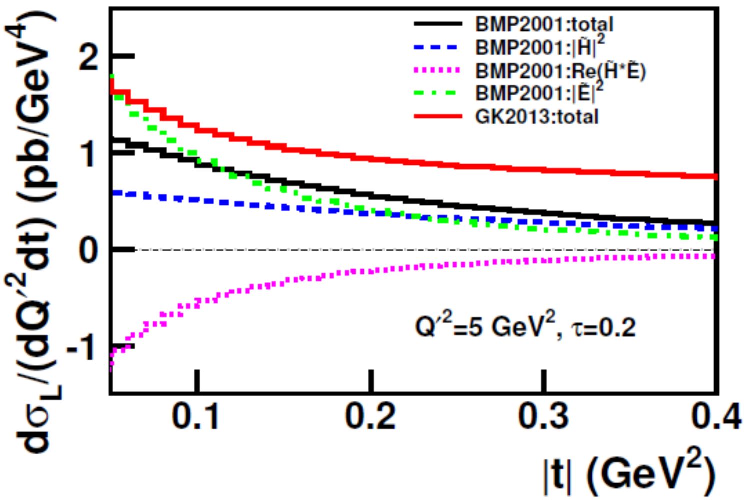
$$\left.\frac{d\sigma_L}{dt dQ'^2}\right|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \Big[(1-\xi^2)|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)|^2 - 2\xi^2 {\rm Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^* \tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2\frac{t}{4m_N^2}|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)|^2\Big],$$

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

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

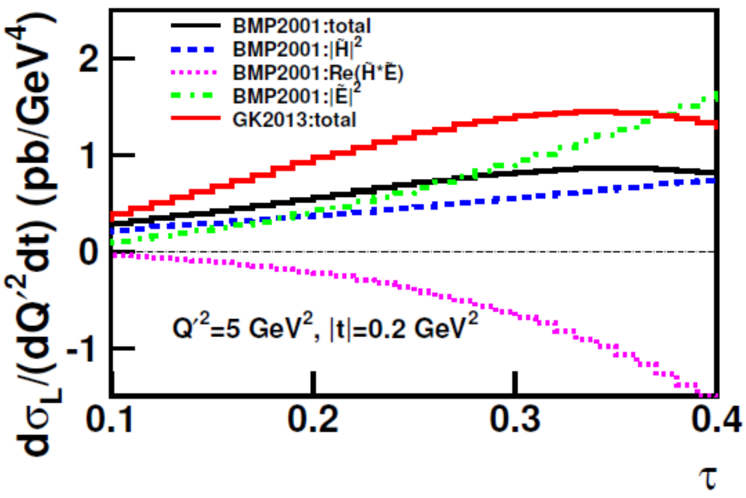
$Q'^2 = q'^2 = 5\ GeV^2$

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



Production is dominant at forward angles

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



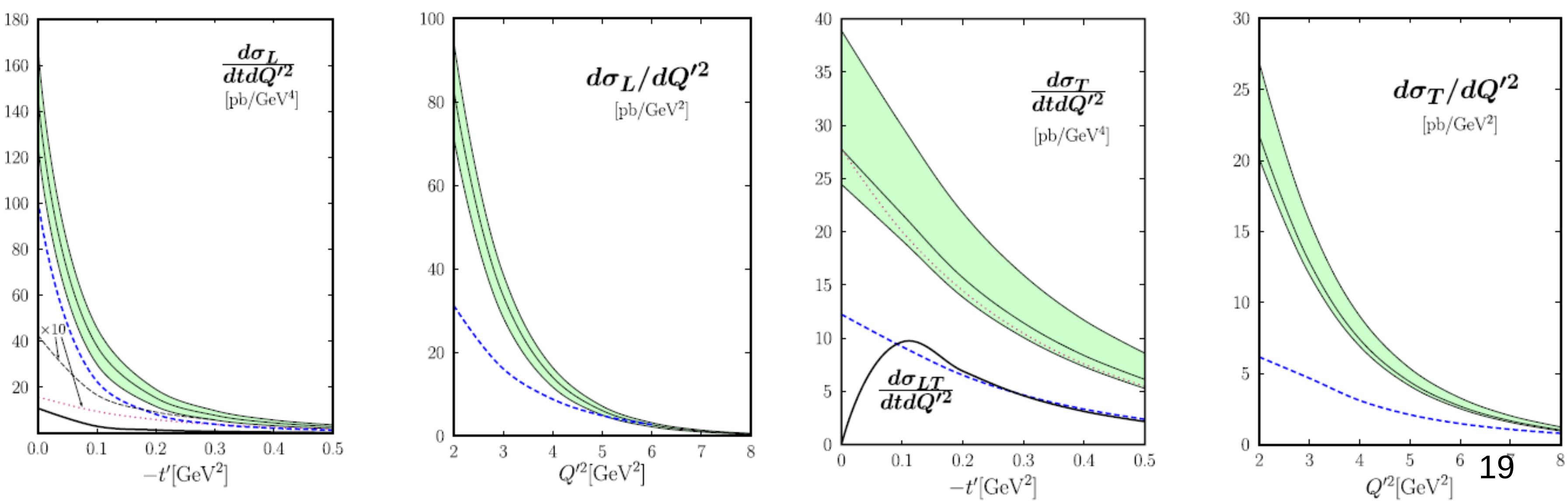
Cross sections increase toward small *s* (→ low beam energy)

Beyond the Leading Twist

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

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

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



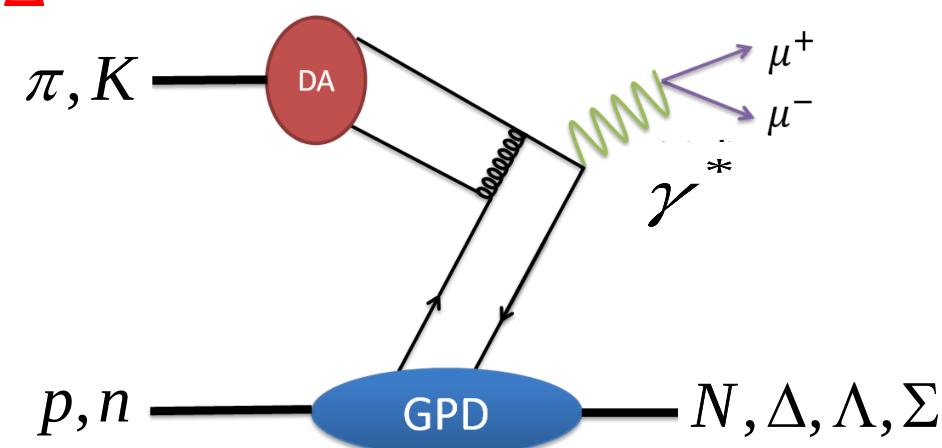
Transition GPDs

"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

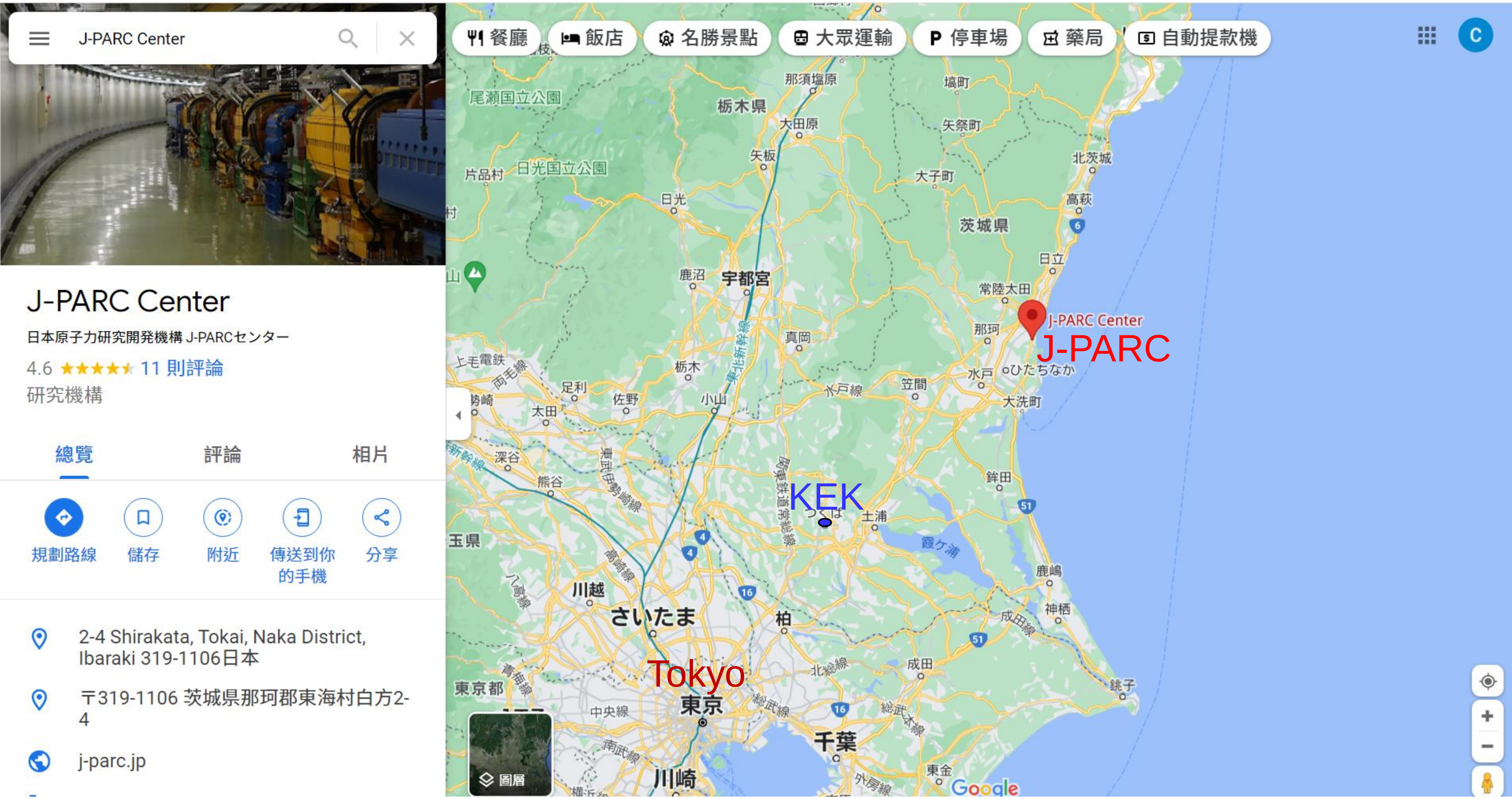


Exclusive Drell-Yan Measurement

- **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 ($\sqrt{s} = \mathbf{4 - 6}$ GeV) is most appropriate!

J-PARC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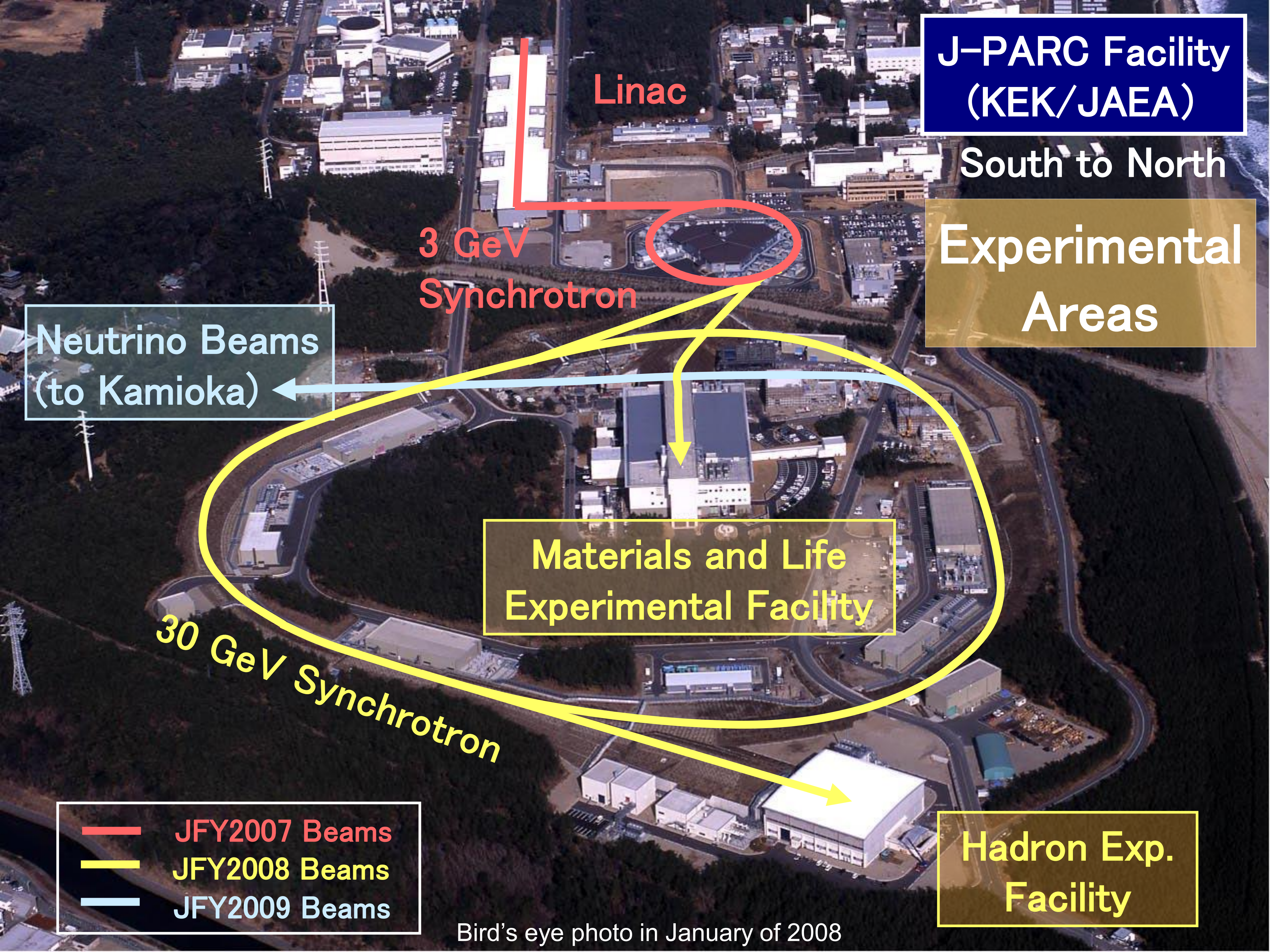
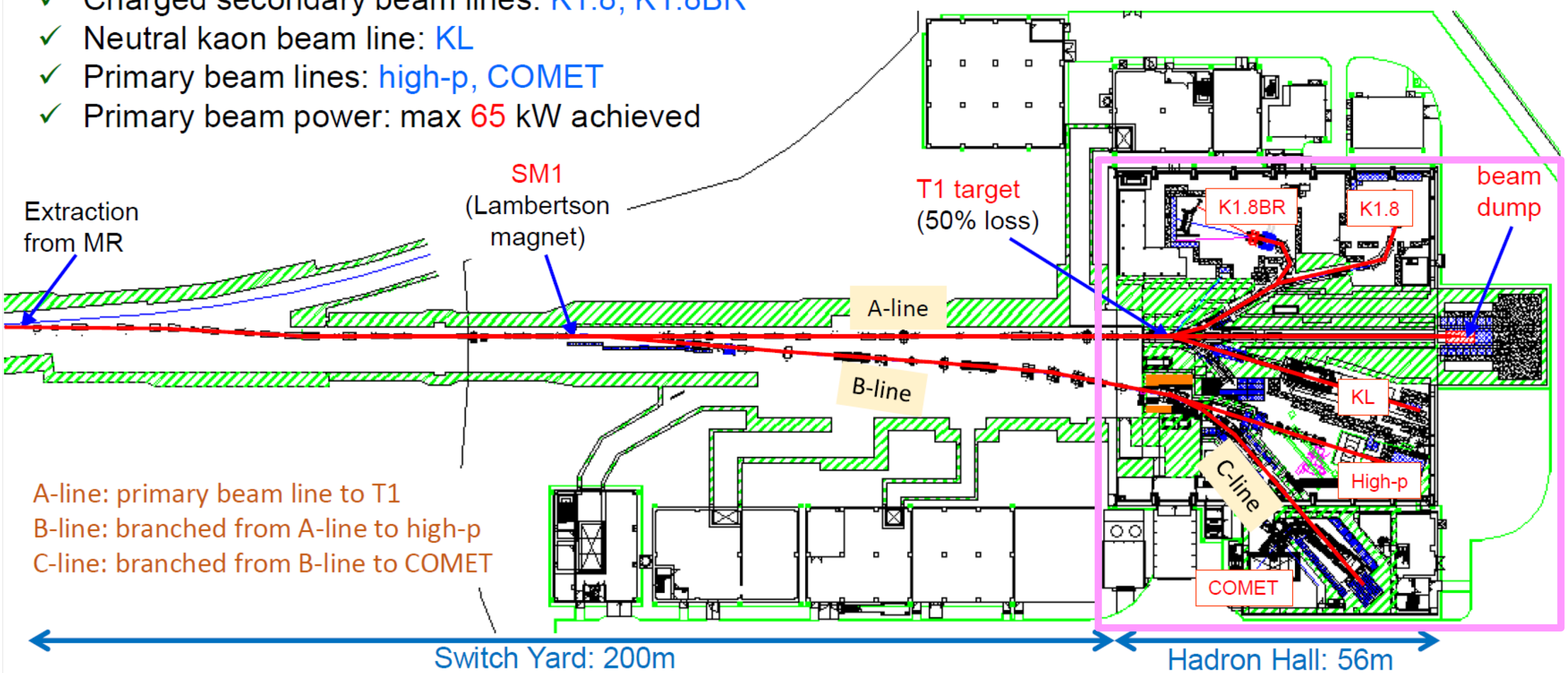

J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV Synchrotron
Experimental Areas
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
30 GeV Synchrotron
Hadron Exp.
Facility
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

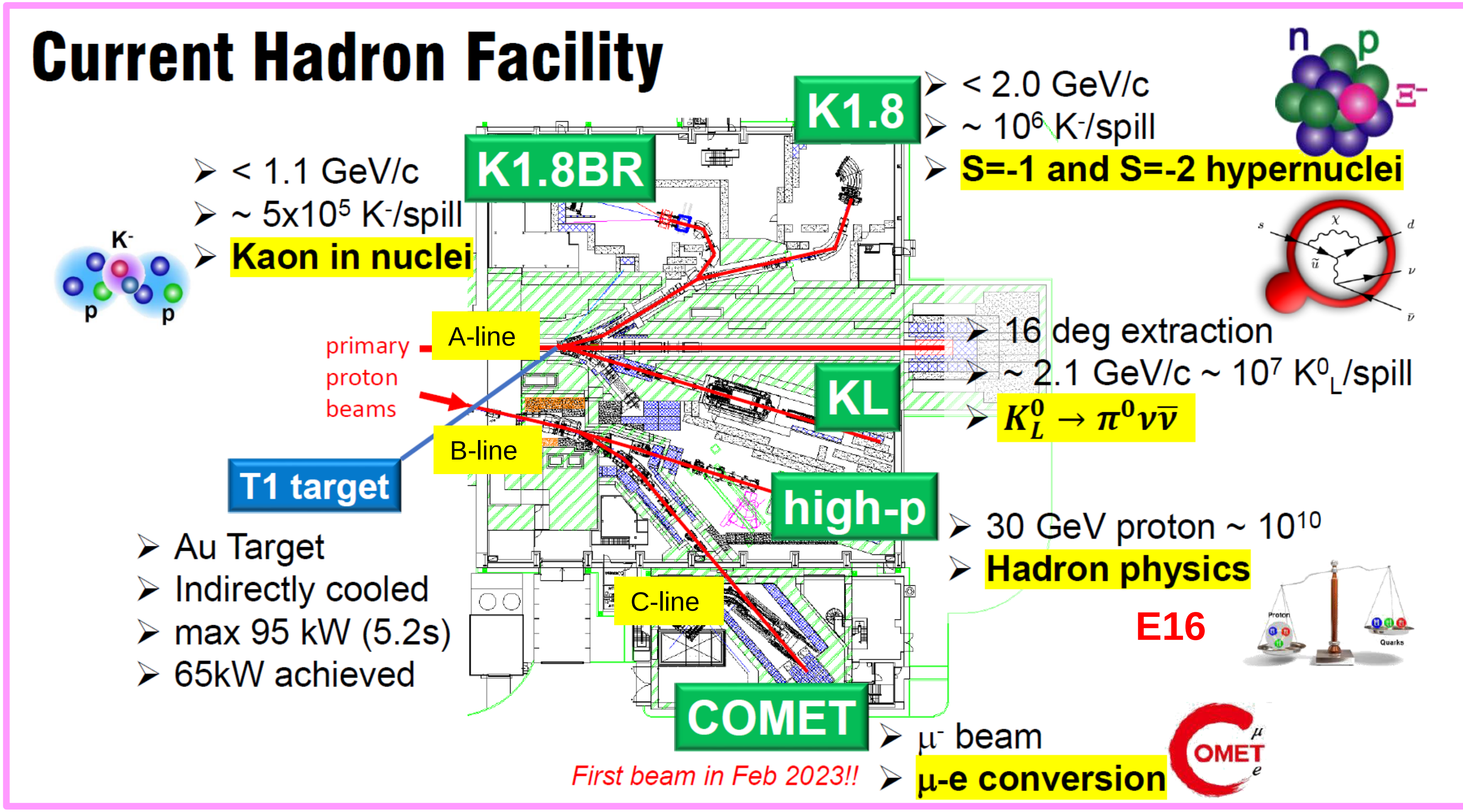
J-PARC Hadron Hall (Current Status)

- ✓ 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

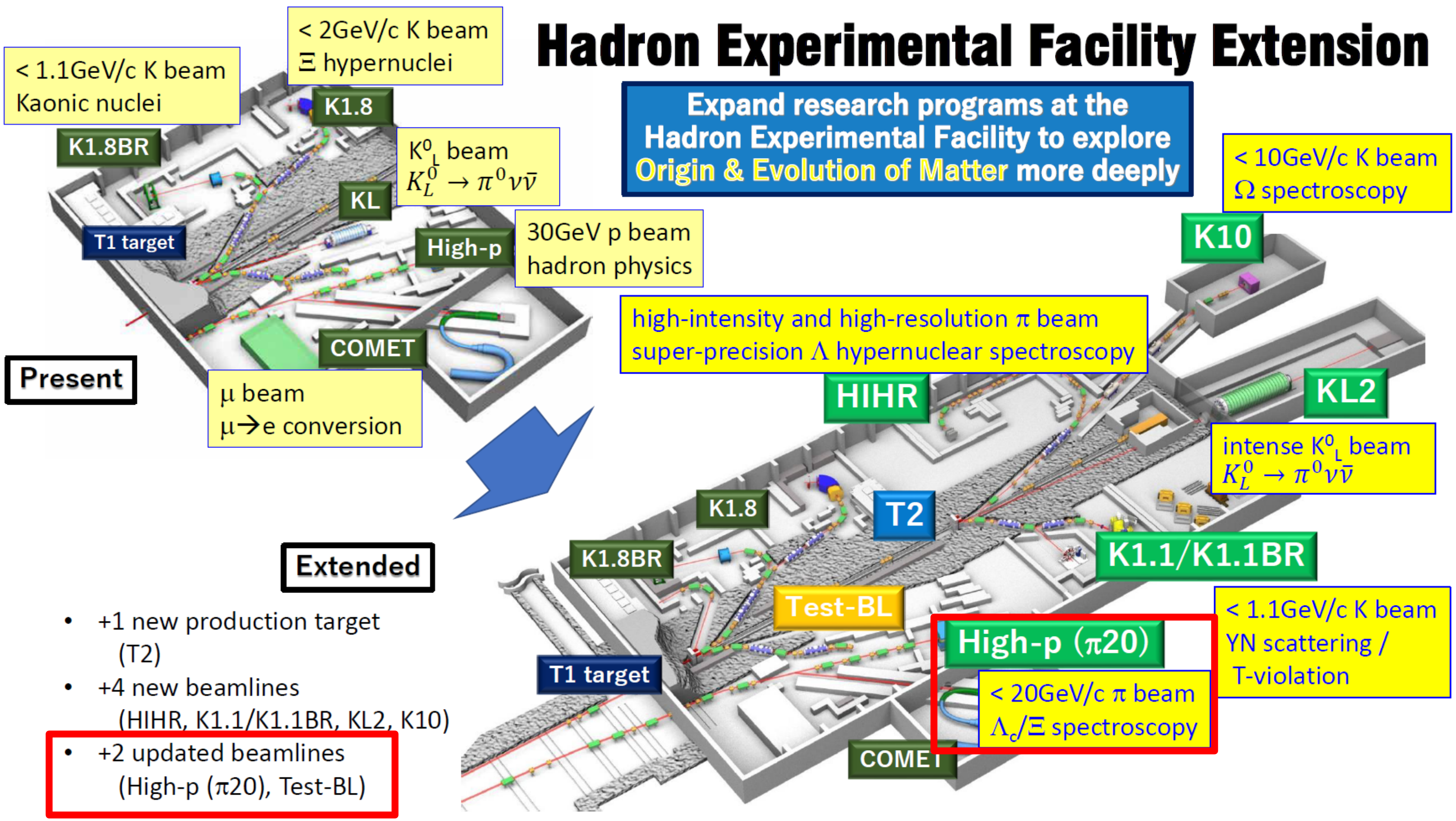
J-PARC Hadron Hall (Current Status)



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)!



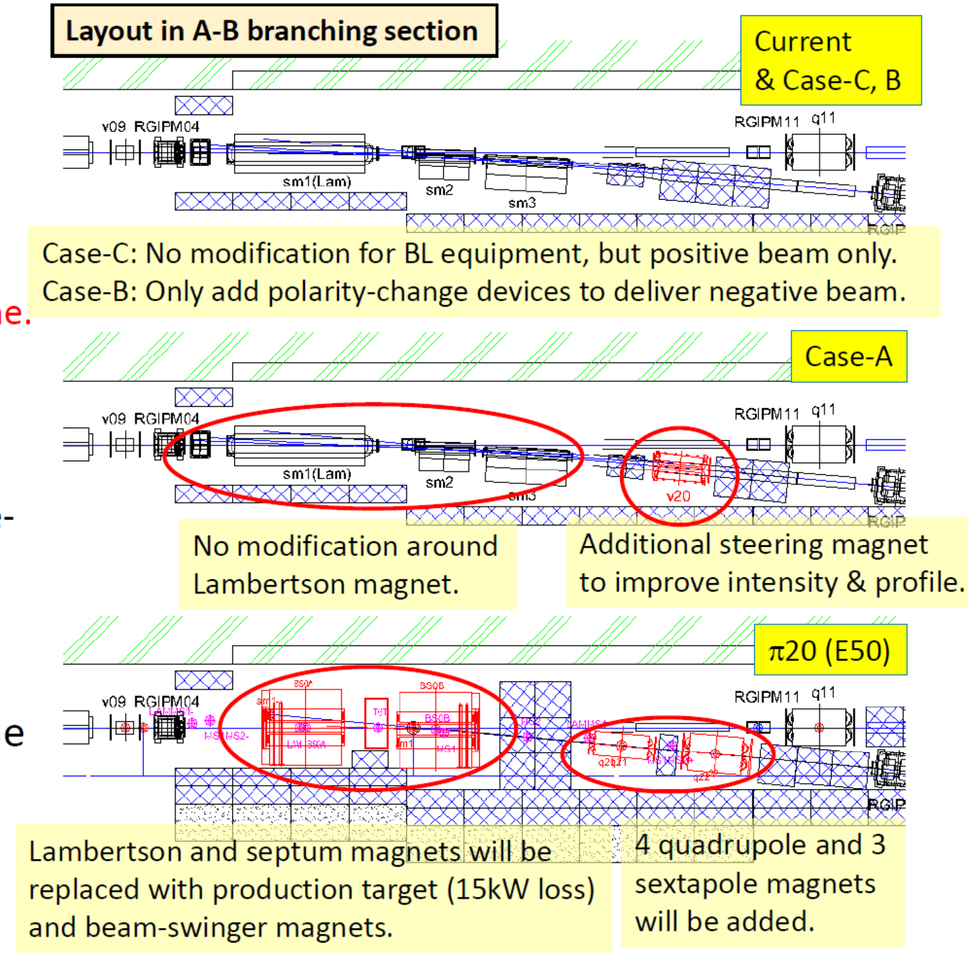
https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html
https://arxiv.org/abs/2110.04462

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.

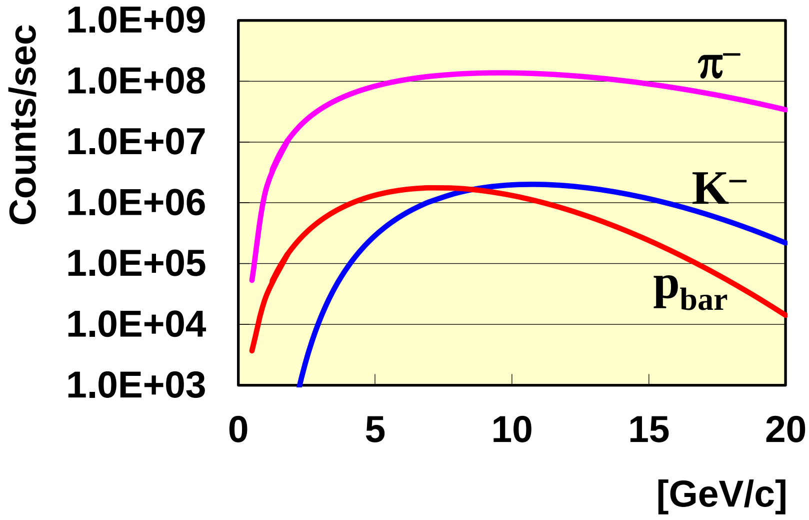


https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html
https://arxiv.org/abs/2110.04462

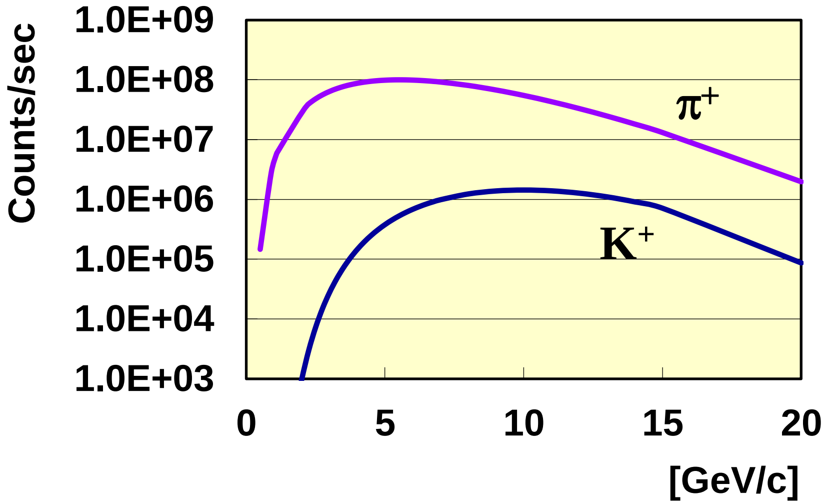
Hadron Experimental Facility
π20 Beam Line

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

Negative Hadron Beams
(Prod. Angle = 0 deg.)



Positive Hadron Beams
(Prod. Angle = 3.1 deg.)

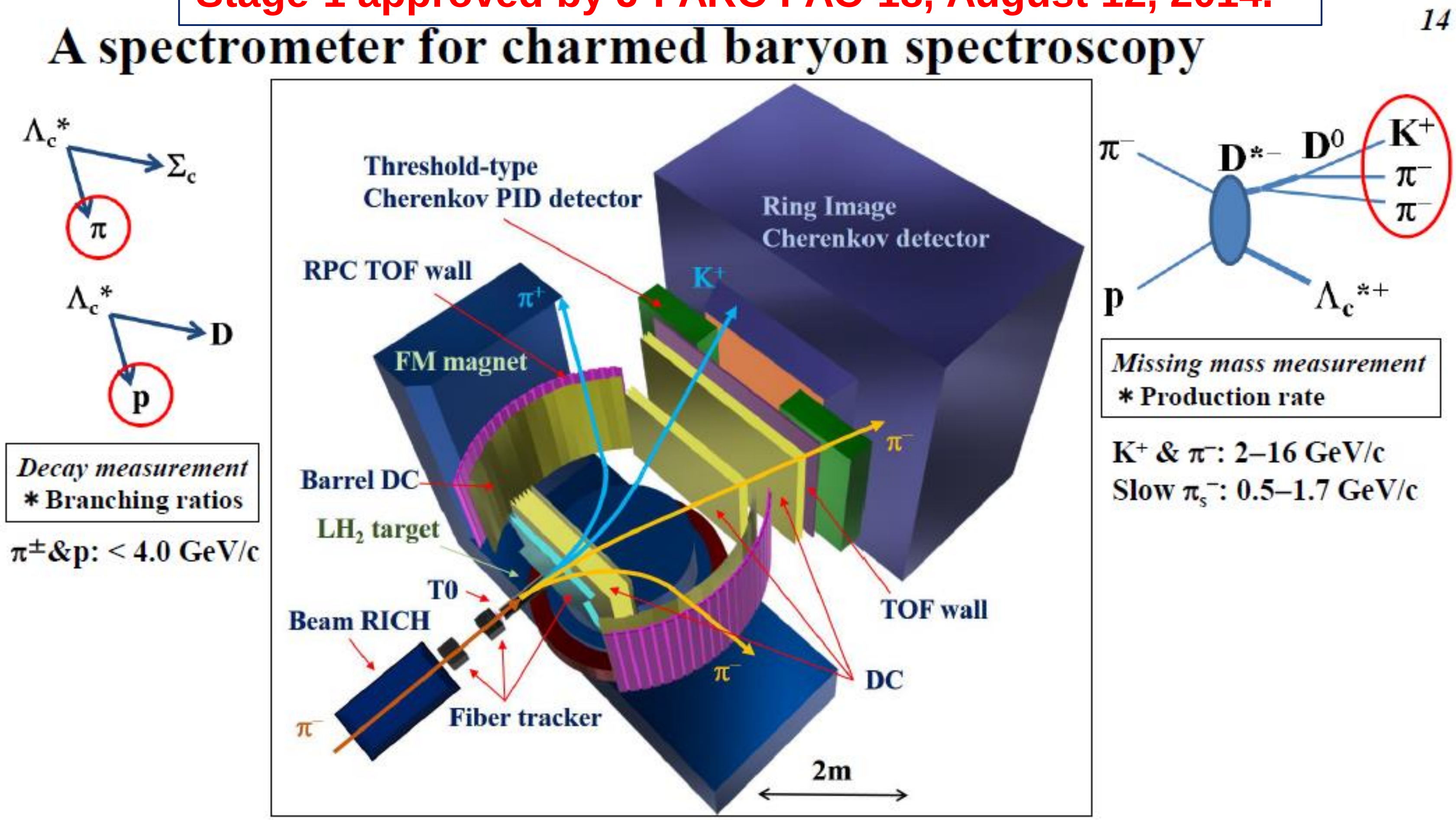


*** Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m**

J-PARC E50 Experiment

(Charmed Baryon Spectroscopy)

Stage-1 approved by J-PARC PAC-18, August 12, 2014.

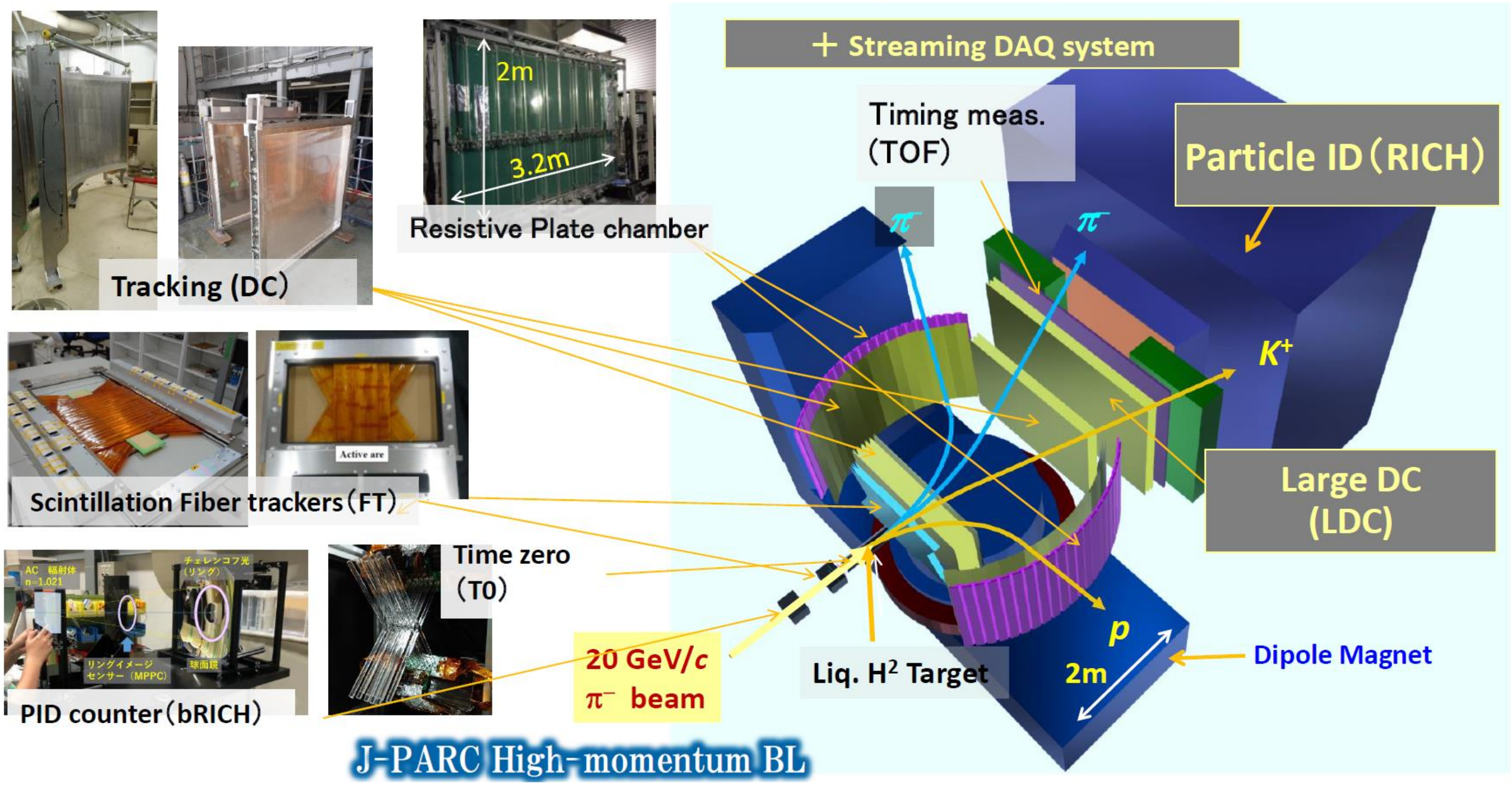


K. Shirotori, J-PARC workshop

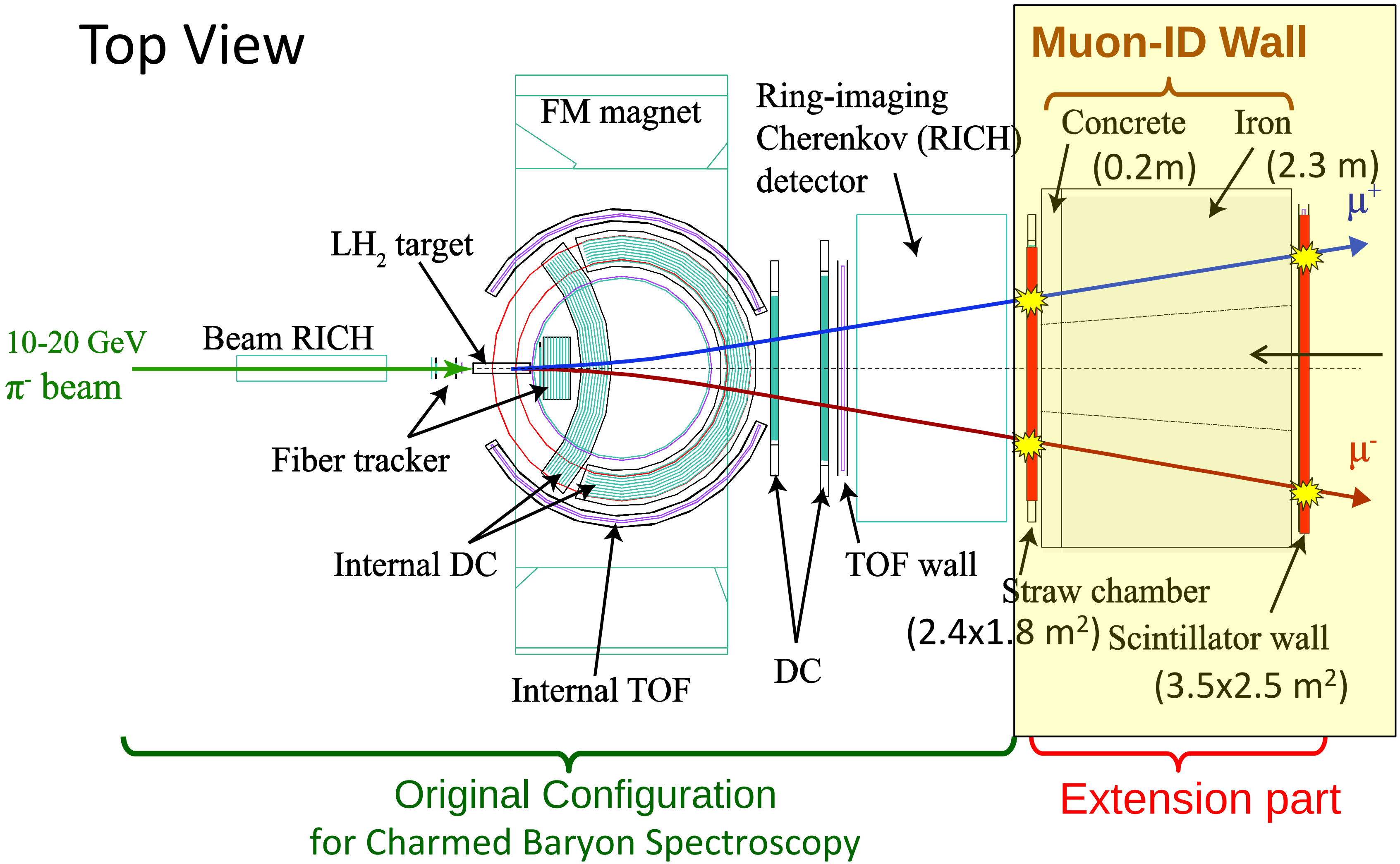
J-PARC E50 Experiment

(Charmed Baryon Spectroscopy)

Spectrometer : Large Solid Angle、PID system、high-resolution[11]



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

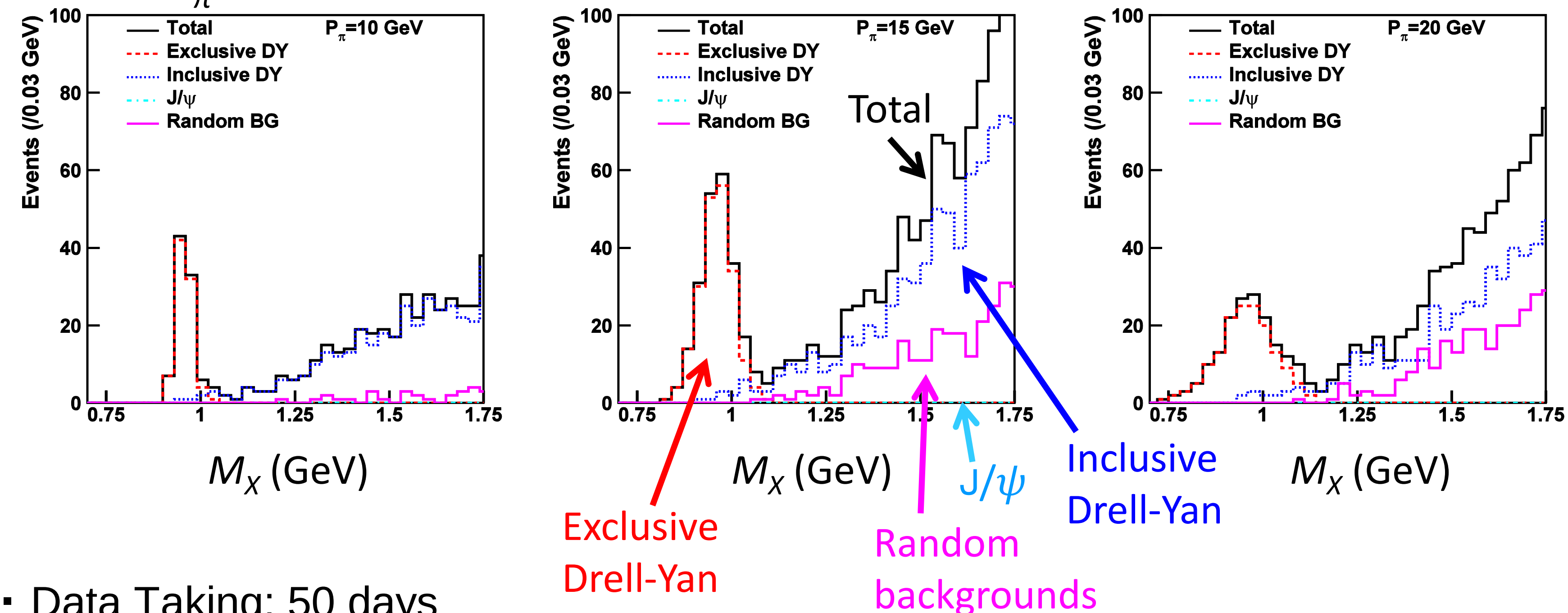


$\pi^- N \rightarrow l^+ l^- X$ Missing-mass M_X

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



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

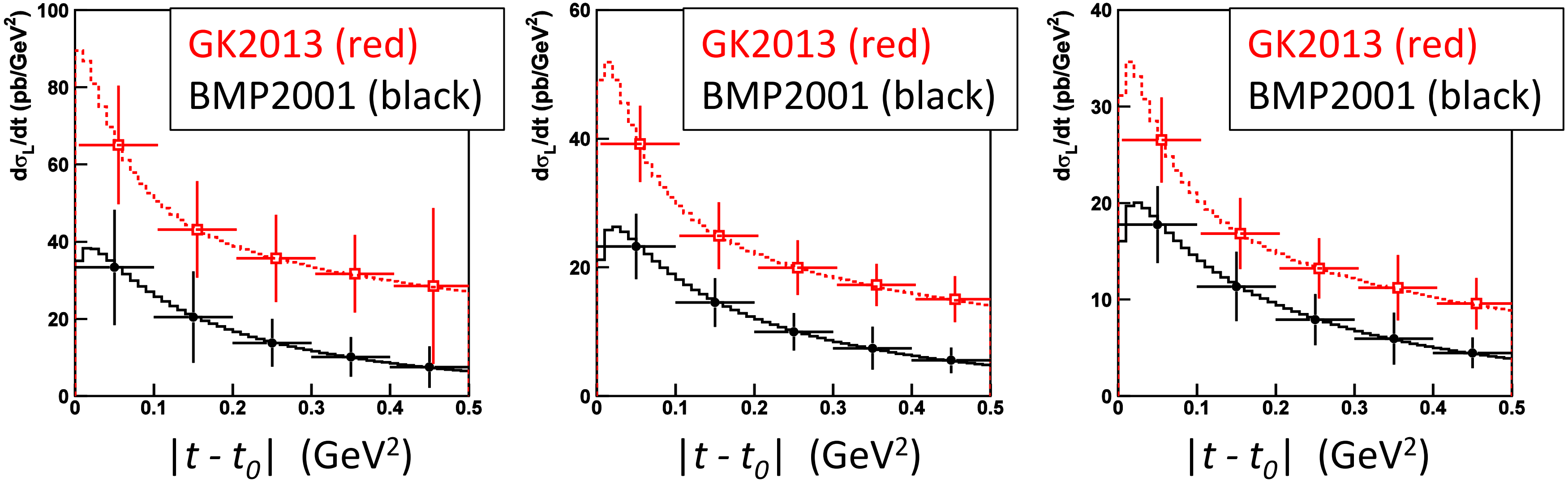
The exclusive Drell-Yan events could be identified by the signature peak at the nucleon mass in the missing-mass spectrum for all three pion beam momenta.

Expected Statistical Sensitivity

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

π^- Beam Momentum

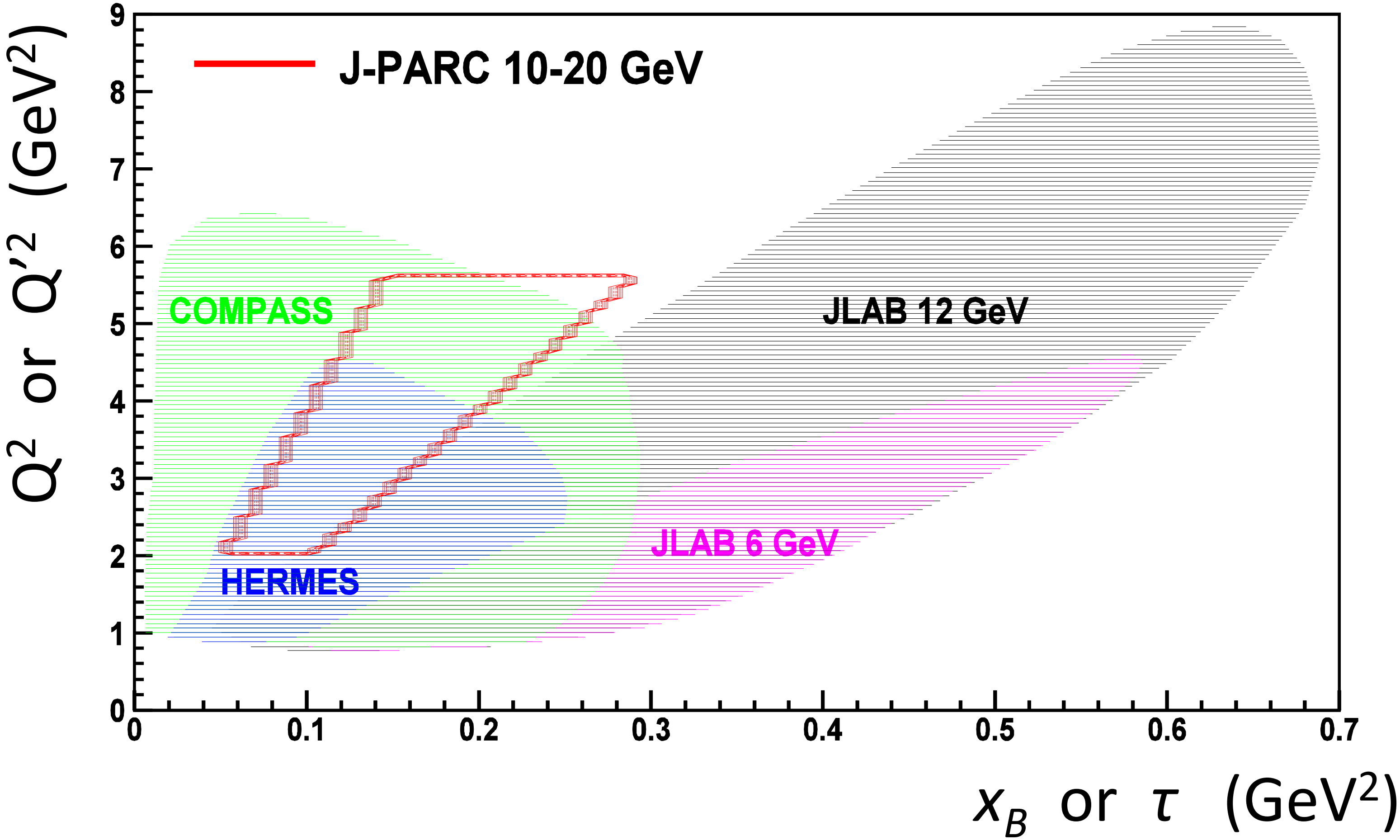
P_π = 10 GeV   15 GeV   20 GeV



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

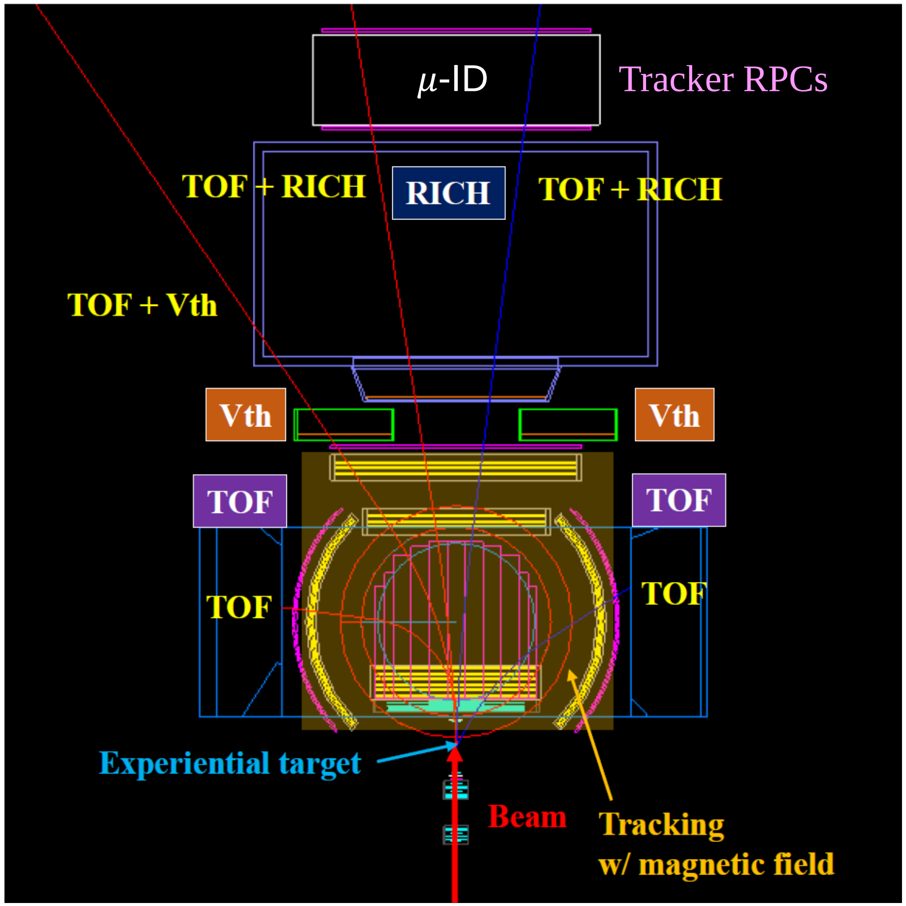
The statistics sensitivity is good enough for discriminating the predictions from two current GPD models.

Kinematic regions of GPDs explored by space-like and time-like processes



- JLAB, HERMES, COMPASS → Space-like approach
- J-PARC (KEKB) → **Time-like** approach

Proposal to complete…



- The μ-ID system:
  - Tracker RPCs: rejection of muons from the decay-in-flight pions and kaons.
  - Material of hadron absorber: concrete and steel
- Updating the GPD modeling.
- Simulate the expected signal-to-background and yields of exclusive DY events.
- Optimize the design of μ-ID system and dimuon trigger.

Natsuki Tomida (Kyoto University), ***Takahiro Sawada (***ICRR, University of Tokyo), ***Chia-Yu Hsieh, Po-Ju Lin, Po-Hung Wang, Wen-Chen Chang (***Academia Sinica)

Hadron Hall Extension

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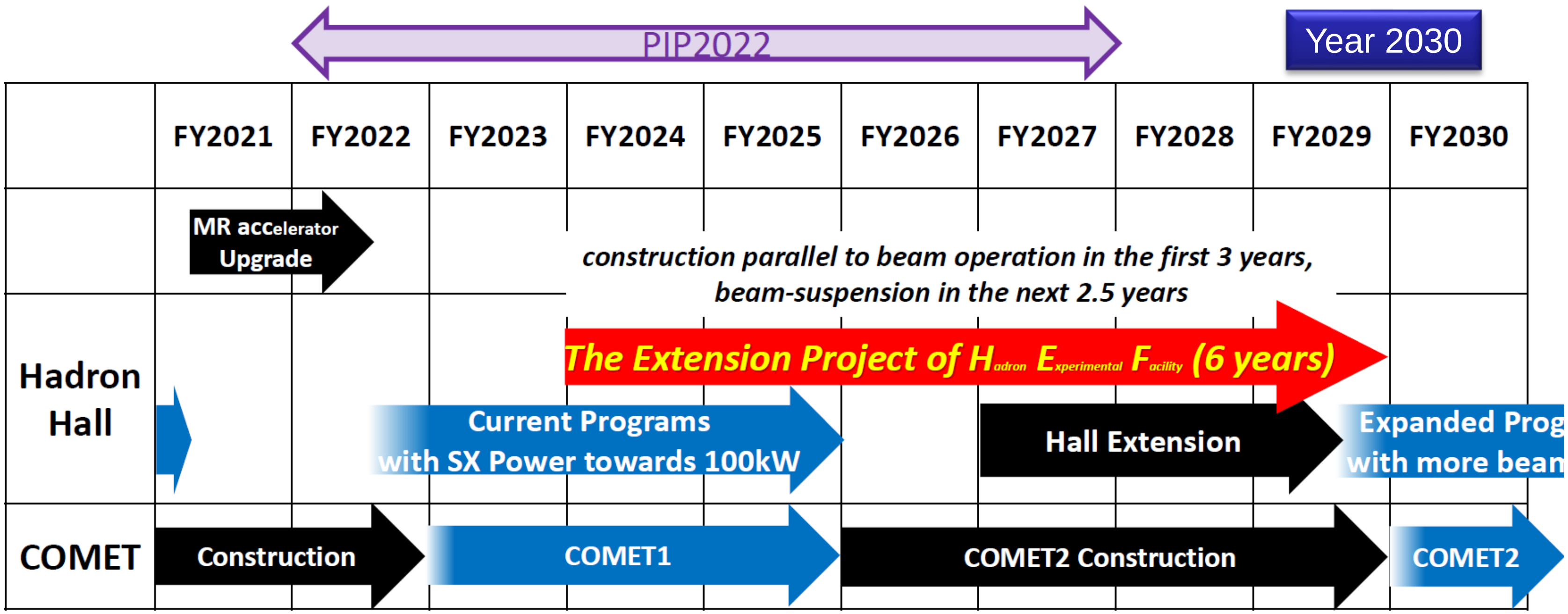
Timeline of the HEF-ex Project



We would like to start the project in PIP2022

→ We are working on getting the timeline consistent with current programs

Given the earliest availability of pion beams in 2030, is there any possibility of measuring GPDs with the 30-GeV proton beam?

Transition GPDs with Proton Beams

Kumano's talk

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]

[1]*Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), 1-1, Ooho, Tsukuba, Ibaraki, 305-0801, Japan*

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

[3]*Department of Physics, Pennsylvania State University, University Park, Pennsylvania 16802, USA*

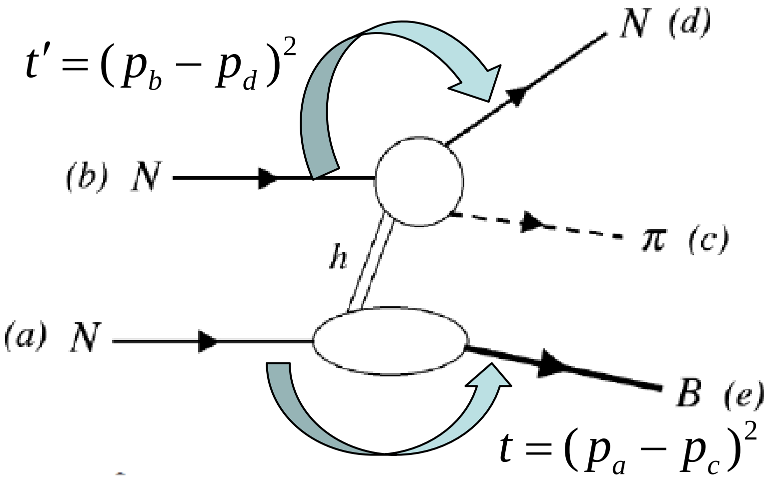
[4]*Nishogakusha University, 6-16, Sanbancho, Chiyoda, Tokyo, 102-8336, Japan*

(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

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



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 $a + b \to c + d + e$, 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: $p_T^{(c)} \approx -p_T^{(d)}$.

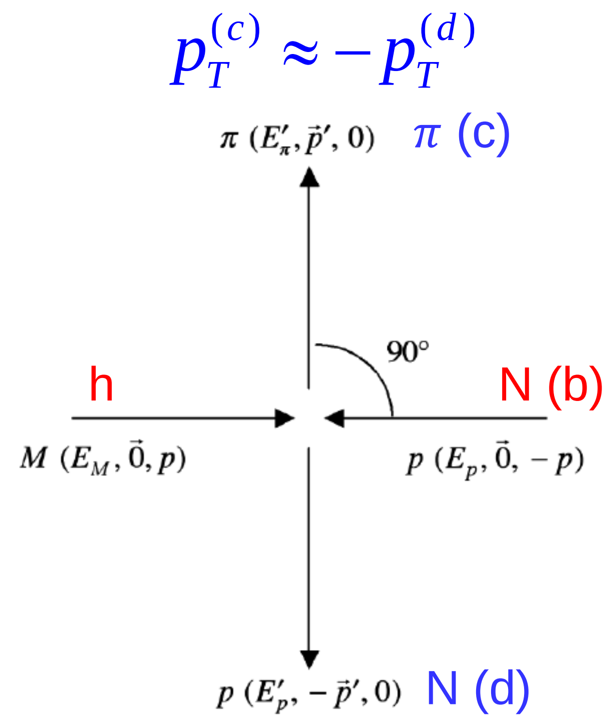
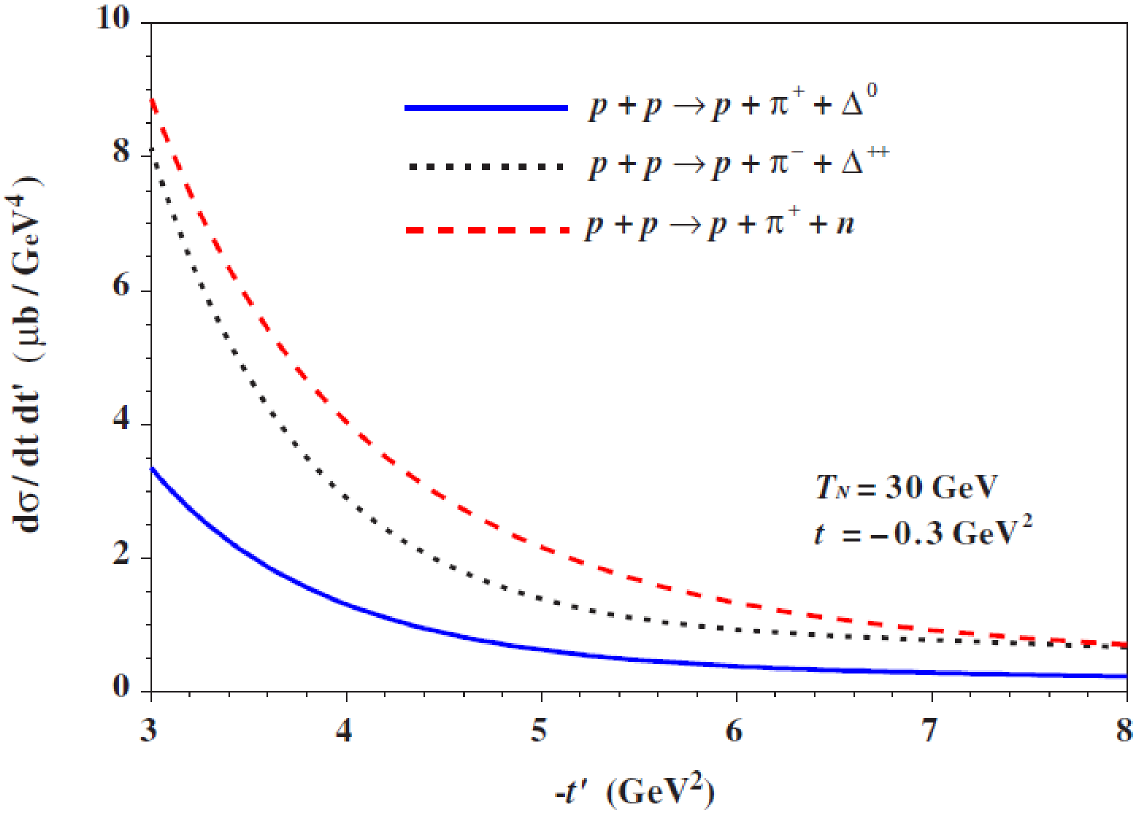


FIG. 8. $Mp \to \pi p$ elastic scattering at $\theta_{\rm c.m.} = 90°$.

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

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

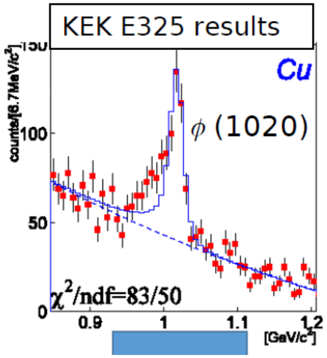


The measurement of –t' (~ qT of forward-moving N) dependence could be used to explore the x-dependence of GPDs.
Qiu & Yu, JHEP 08 (2022) 103, PRD 107 (2023) 014007, arXiv:2305.15397

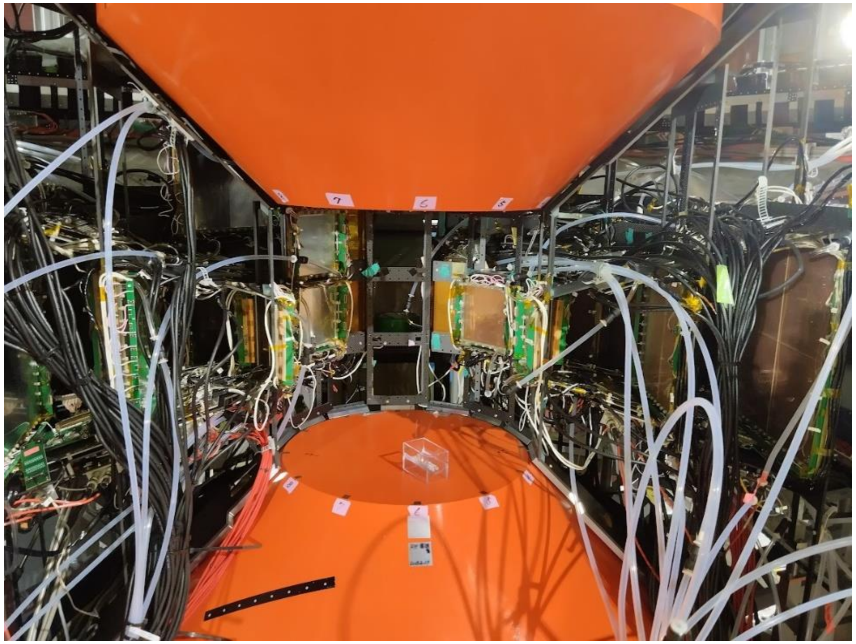
Kumano, Strikman, and Sudoh, PRD 80, 074003 (2009)

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.
- Run 0-d: Dec/2023 (earliest case) or Feb, Mar/2024 (more likely)

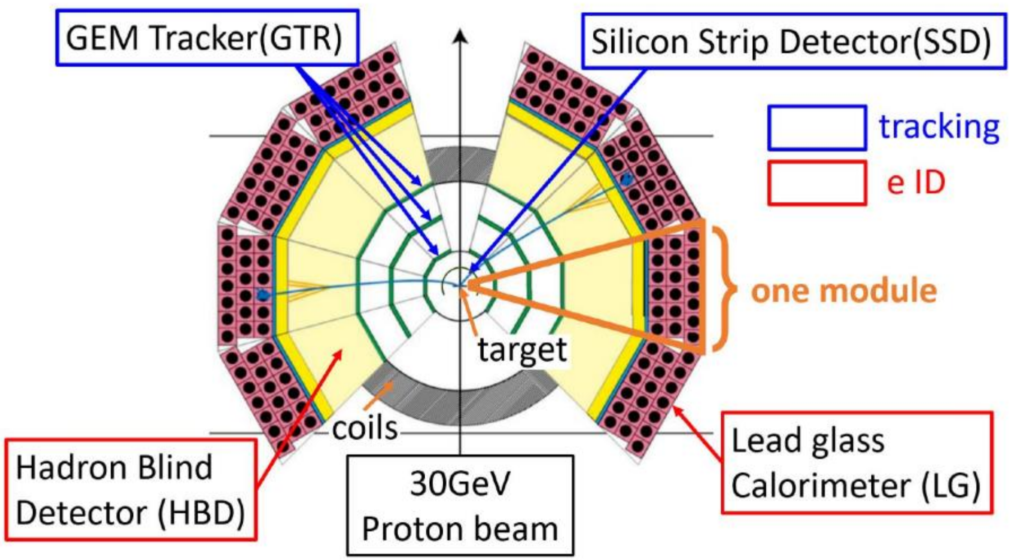


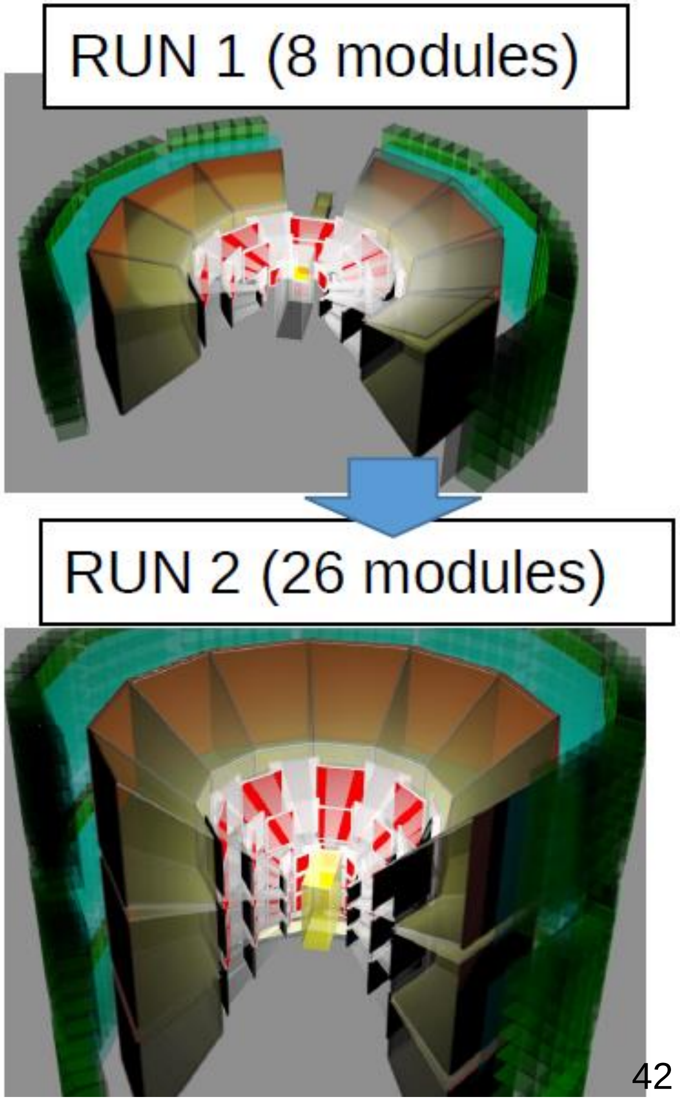
E16 Experiment at J-PARC



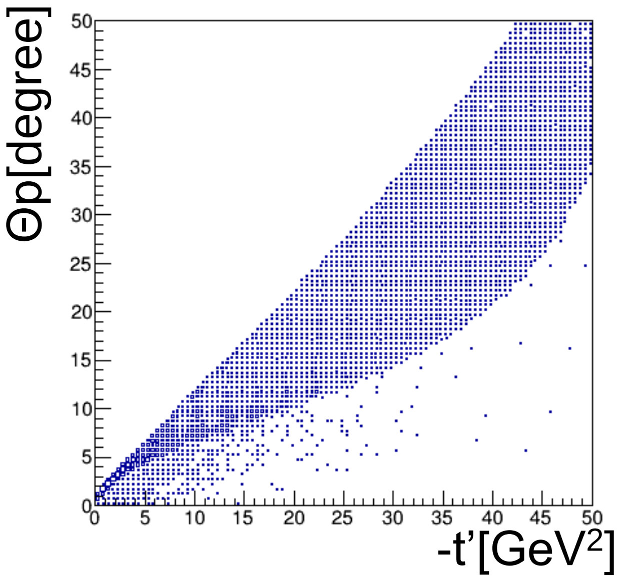
E16 Acceptance/PID Performance

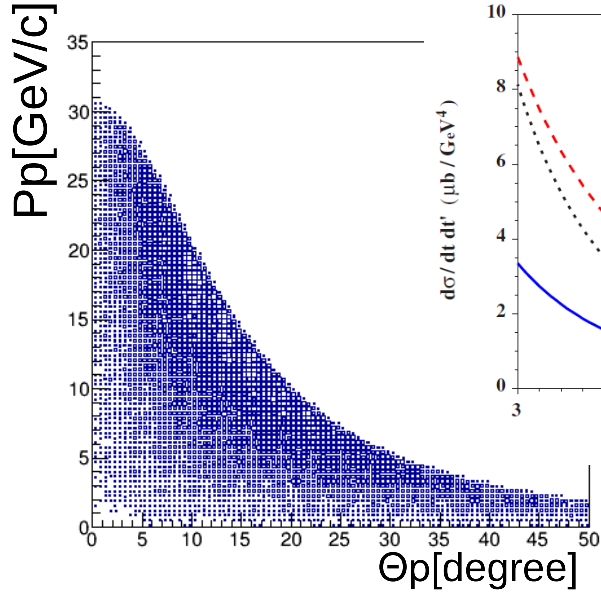
$\theta_{p,\pi} > 15\,\mathrm{deg}$

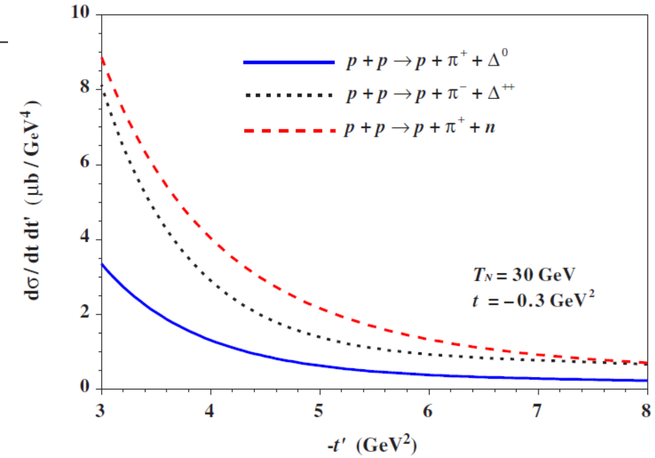




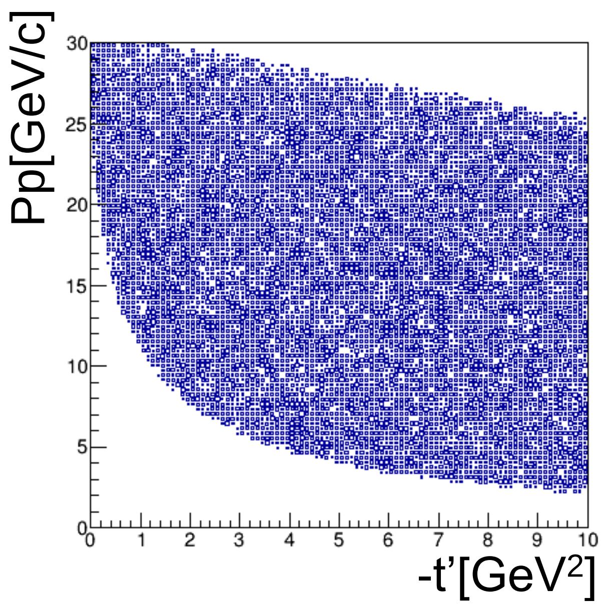
p(30 GeV)p→pπ⁺n

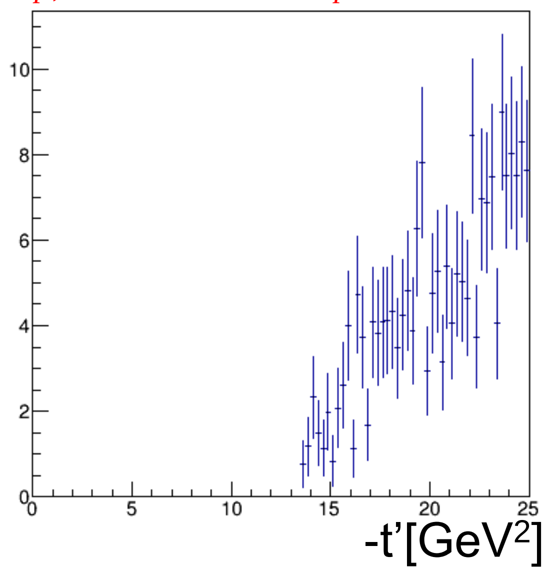






$\theta_{p,\pi} > 15$ deg, $\phi_{p-\pi} > 160$ deg





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

Summary

- Hadron structures are explored by both space-like and time-like approaches: FFs, PDFs, TMDs and GPDs.
- Planned measurements of exclusive π-induced Drell-Yan process in E50 will a novel approach of measuring GPDs and will bring important understandings on:
  - (Universality of) transition 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 two-to-three hard processes within E16 experiment is investigated.

Collaborators

Po-Ju Lin (National Central Univ.)
Chia-Yu Hsieh (Academia Sinica)
Shunzo Kumano (Japan Women's Univ.; KEK)
Jen-Chieh Peng (UIUC)
Shinya Sawada (KEK)
Takahiro Sawada (ICRR, Univ. of Tokyo)
Kazuhiro Tanaka (Juntendo Univ.)
Natsuki Tomida (Kyoto Univ.)
Po-Hung Wang (Academia Sinica)