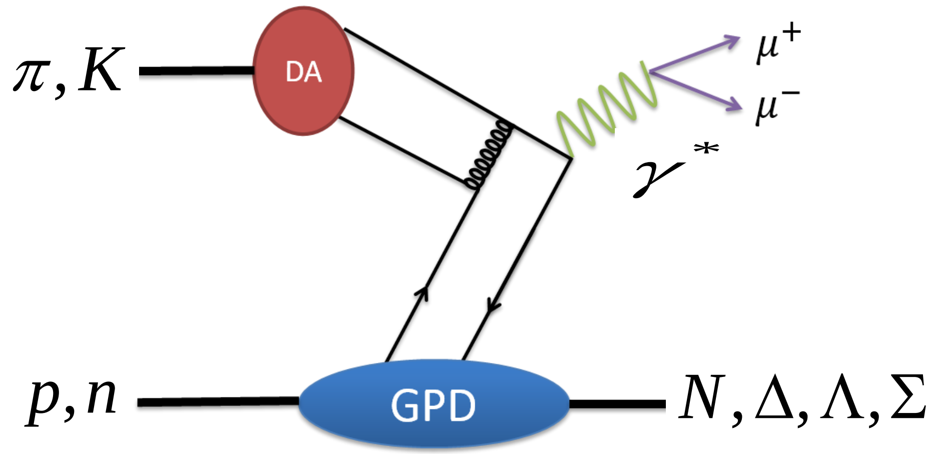


Exclusive Drell-Yan at J-PARC

Wen-Chen Chang 章文箴
Institute of Physics, Academia Sinica

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

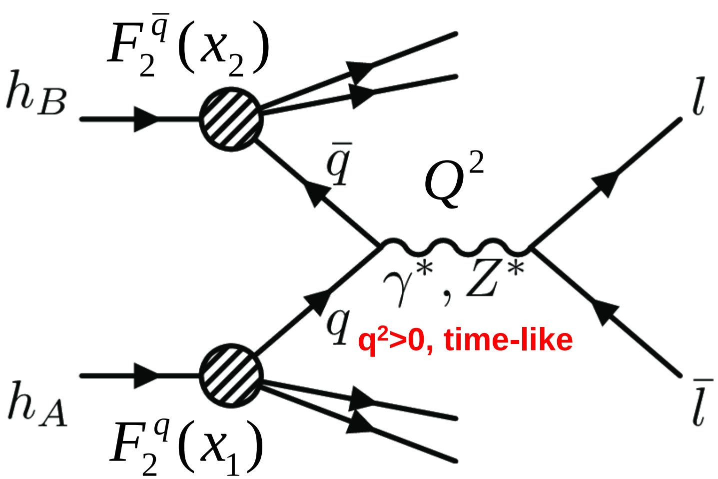
Drell-Yan Process

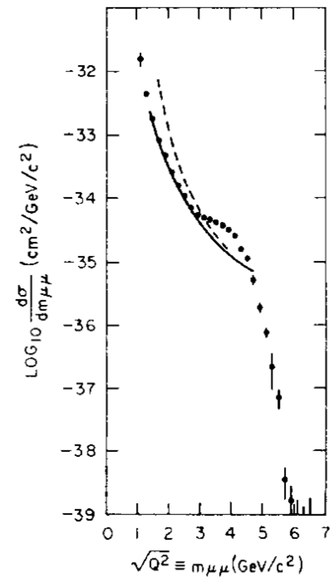
S.D. Drell and T.M. Yan, PRL 25 (1970) 316

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.



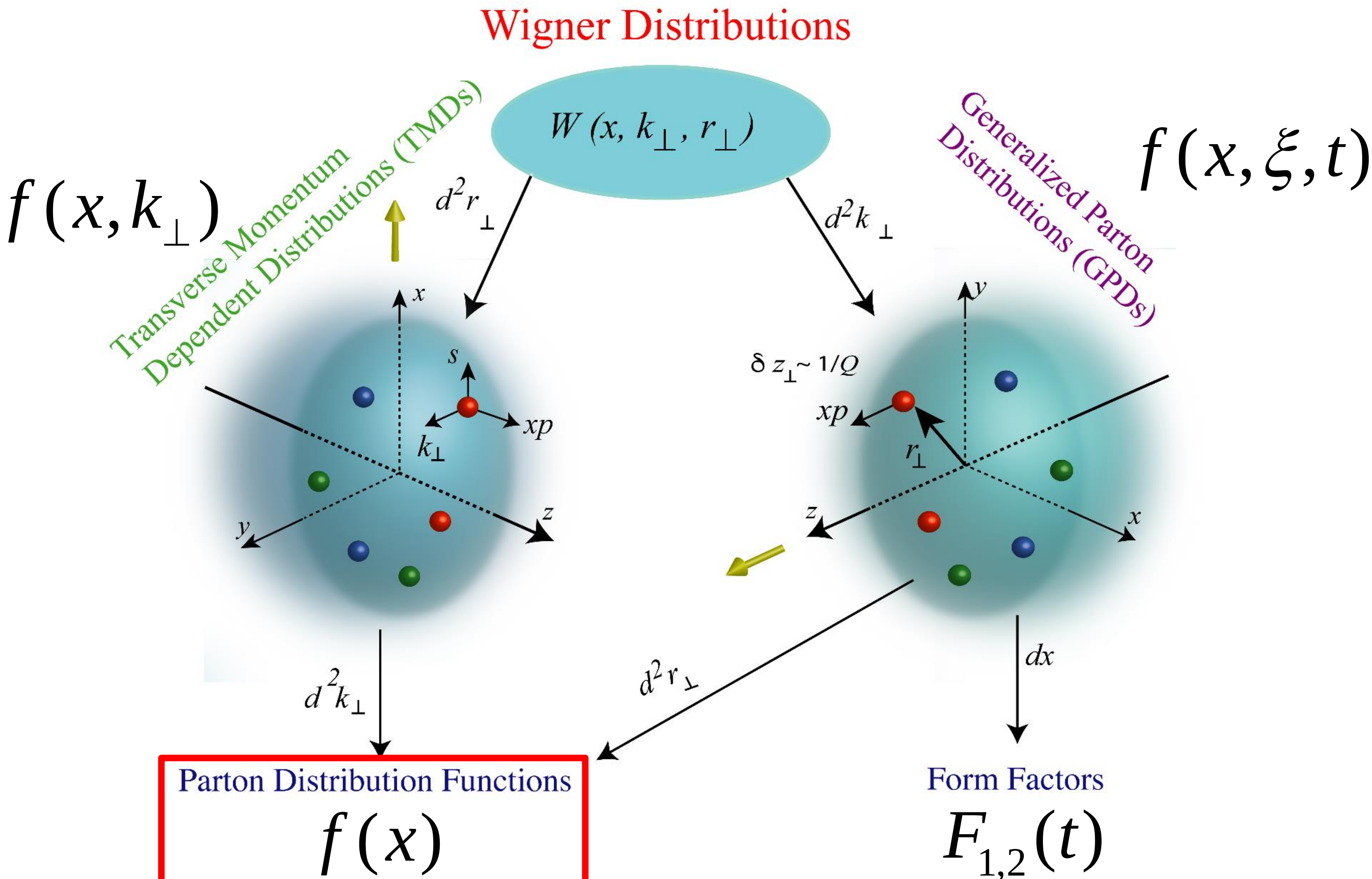


PRL 25 (1970) 1523

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

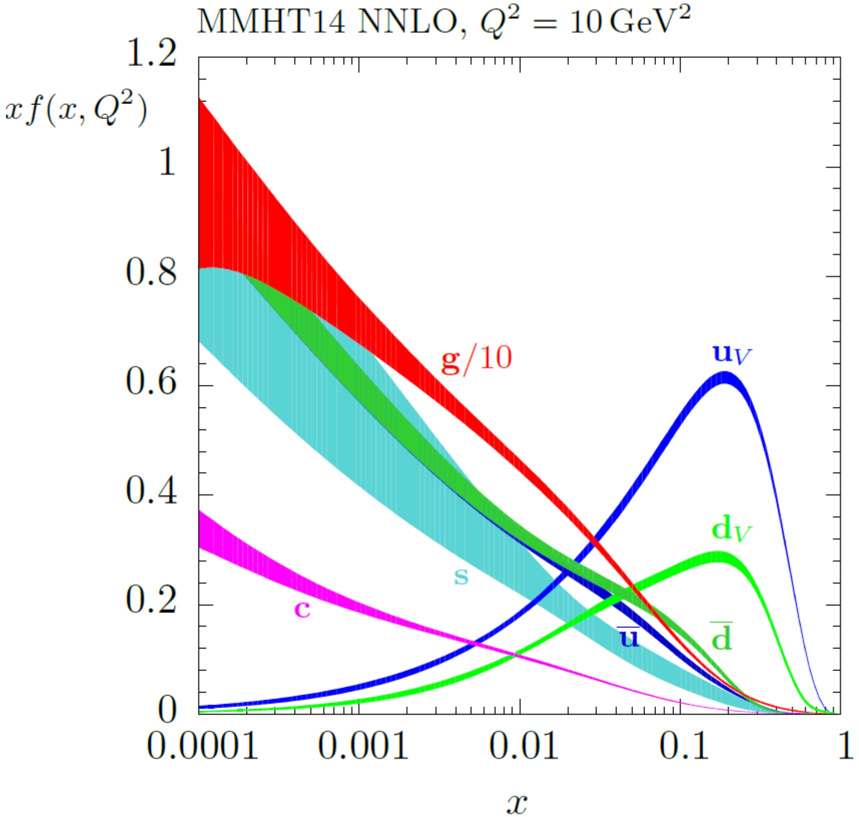
$$\frac{d\sigma}{dQ^2} = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\mathfrak{F}(\tau) = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\int_0^1 dx_1 \int_0^1 dx_2\, \delta(x_1 x_2 - \tau) \sum_a \lambda_a^{-2} F_{2a}(x_1) F_{2\bar{a}}{}'(x_2),$$

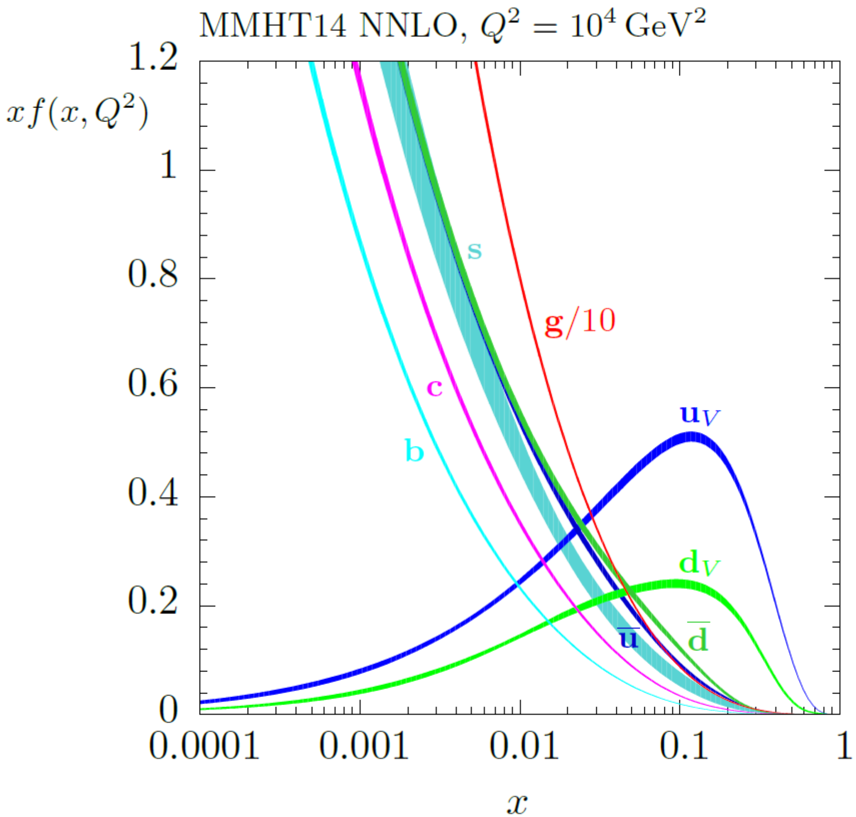
Multi-dimensional Partonic Structures



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

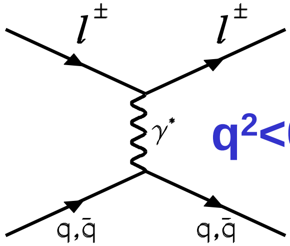
Parton Density Function (PDF)
MMHT 2014

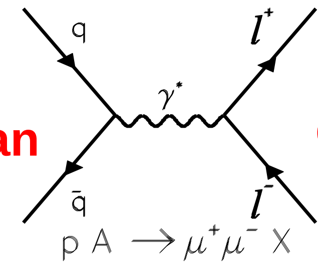


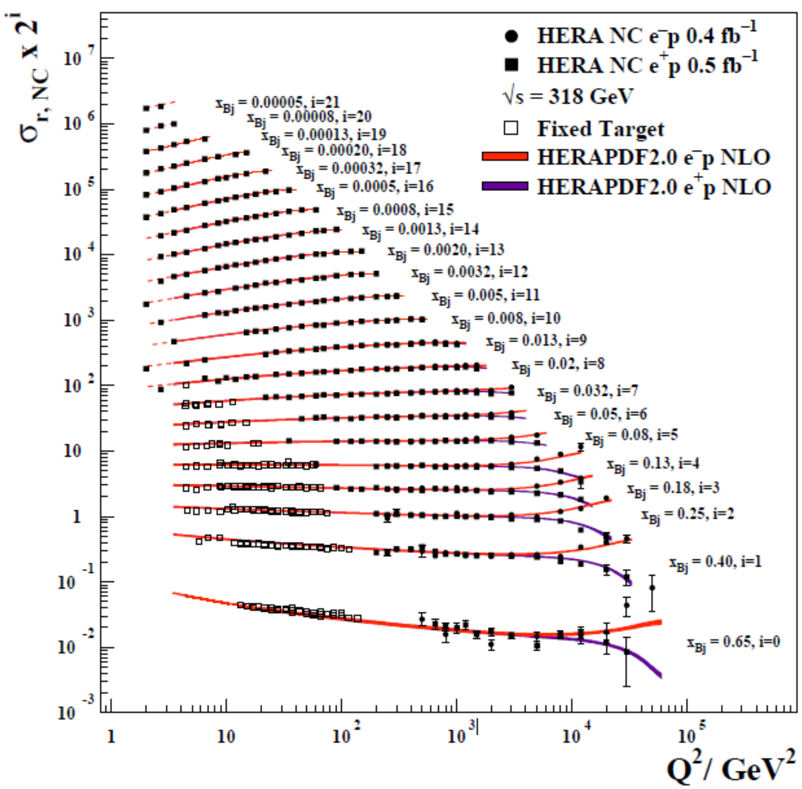


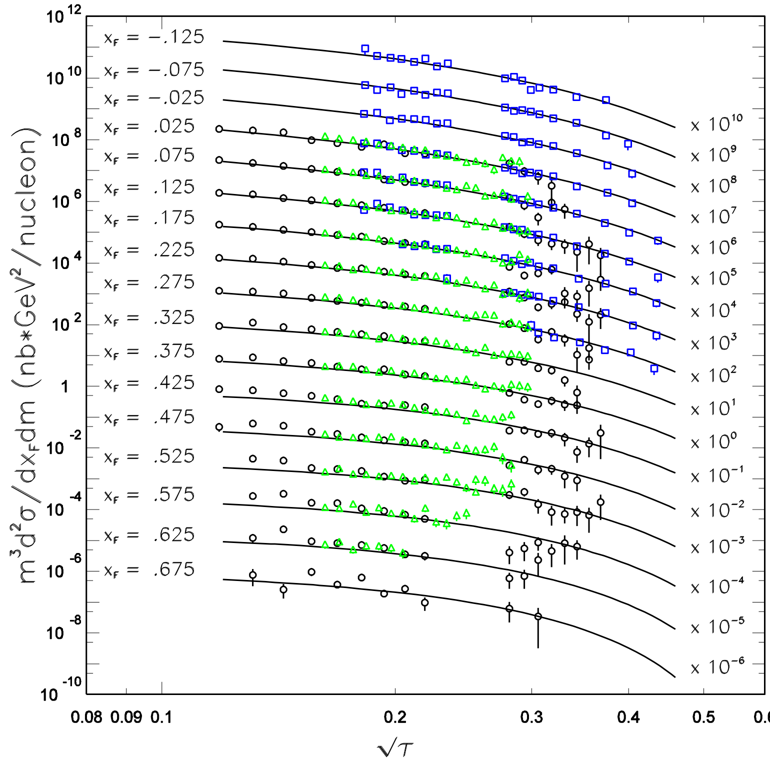
L. A. Harland-Lang, A. D. Martin, P. Motylinski, R.S. Thorne, arXiv:1412.3989

Factorization of Hard Processes









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

AMBER
: $\pi^{\pm}/ K^{\pm}$ -induced DY/Jpsi

AMBER Apparatus for Meson and Baryon Experimental Research

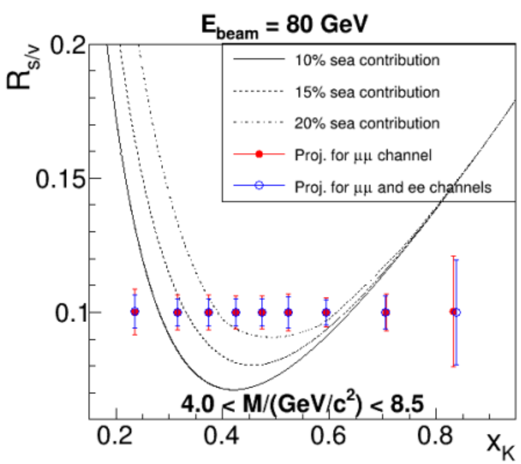
Phase-II: Kaon structure

Oleg's talk

Kaon structure: a window to the region of interference between the Higgs mechanism and the EHM mechanism

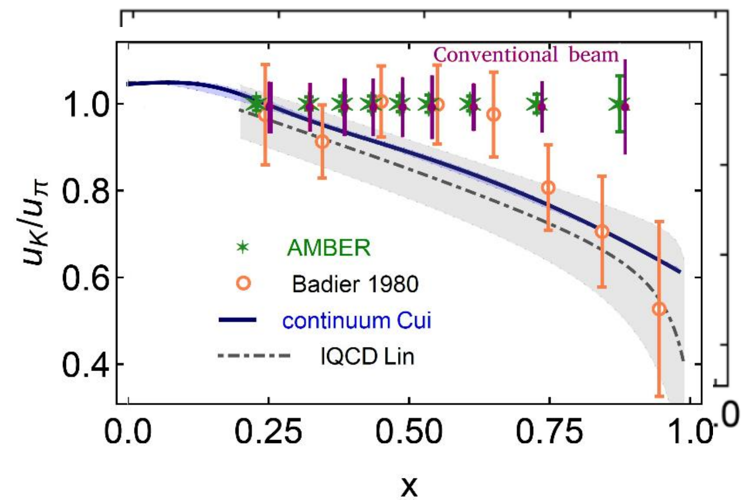
Z-F. Cui, *et al.* EPJC80(2020)1064, H-W. Lin *et al.*, PRD103(2021)014516

The only available experimental data:
NA3 → 200 GeV K⁻ beam on 6 cm Pt target
700 kaon-induced Drell-Yan events



Kaon sea-valence separation using both charges kaon beams:

$$R_{s/v} = \frac{\sigma^{K^+C}}{\sigma^{K^-C} - \sigma^{K^+C}} \propto u_v^K u_v^p$$

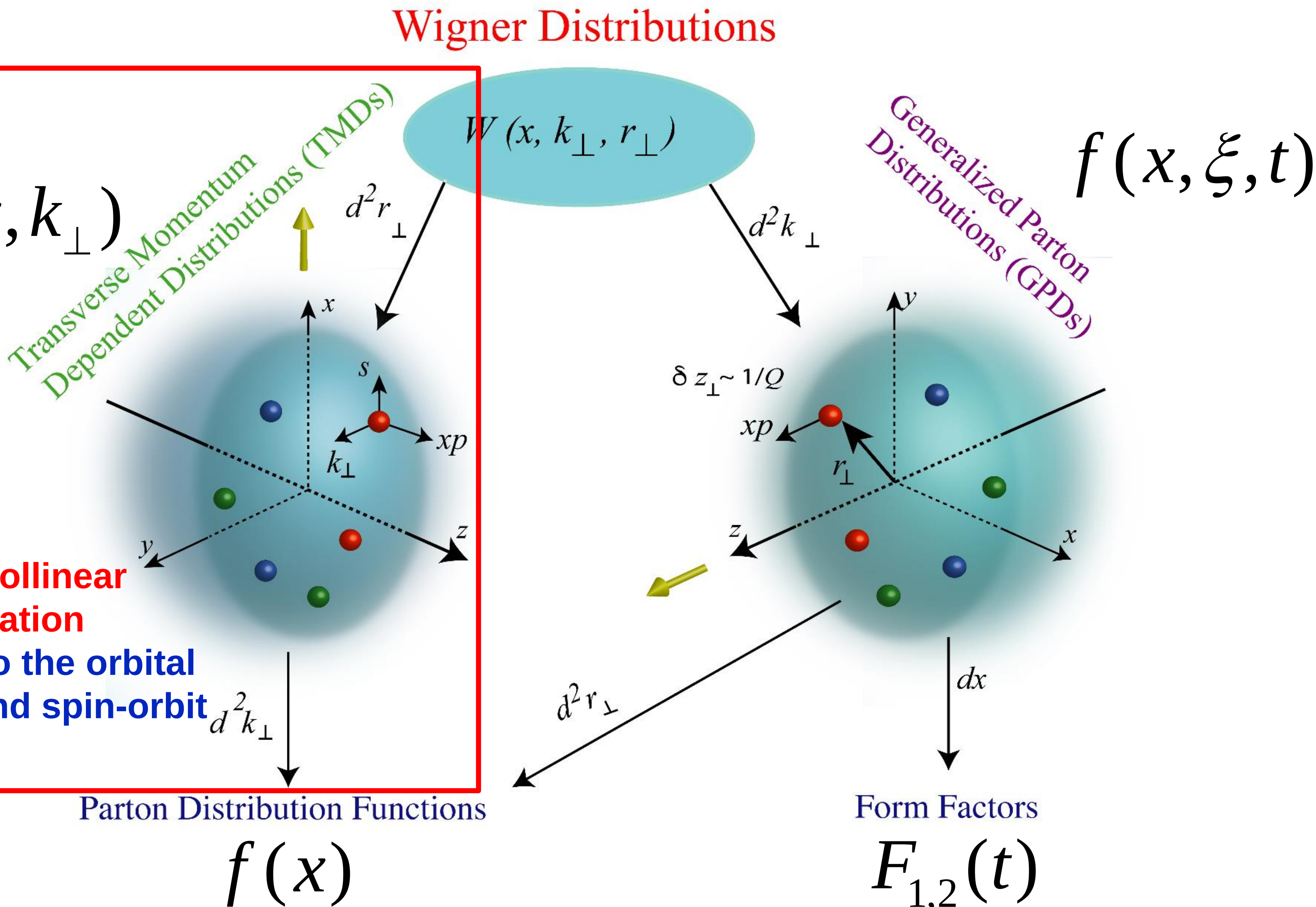


Assumed an RF-separated beam of 2 x 10^7 kaons/second.

16

https://indico.lip.pt/event/1183/contributions/4269/attachments/3462/5360/CQuintans_Jornadas2022.pdf

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

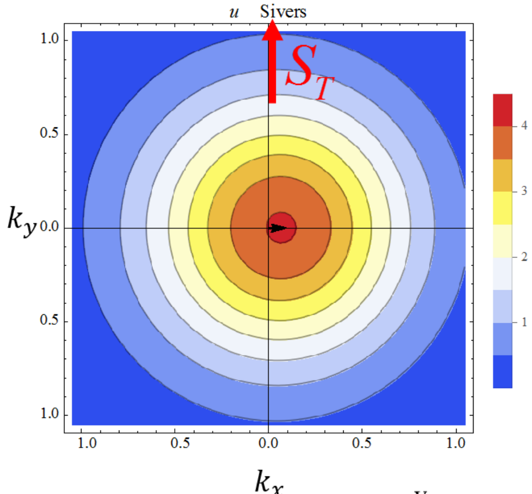
spin of the parton

k_T of the parton

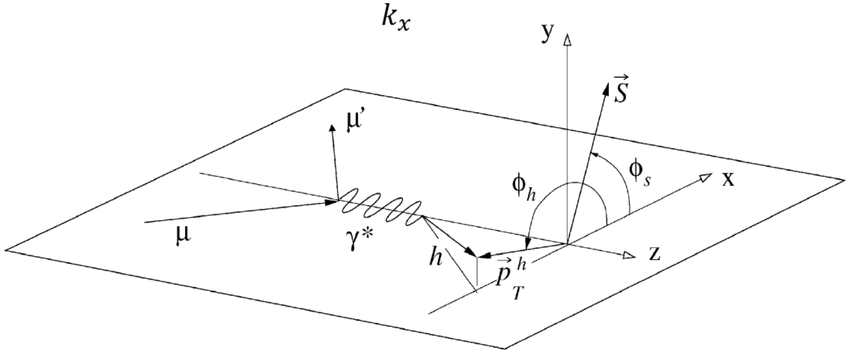
Nucleon \ Quark	U	L	T
U	number density $f_1^{q,g}(x, k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x, k_T^2)$
L		Helicity $g_{1L}^{q,g}(x, k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x, k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x, k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x, k_T^2)$	Transversity $h_1^{q,g}(x,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

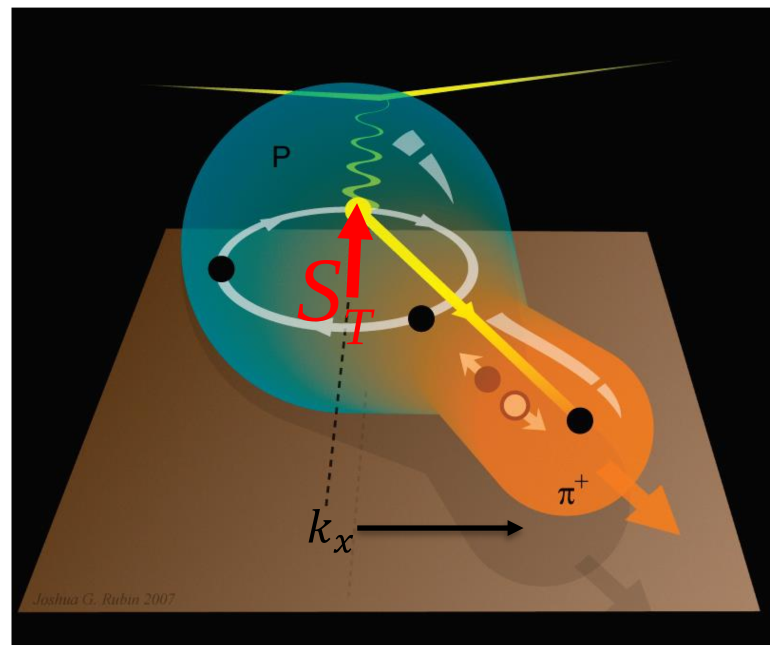
Sivers Asymmetry A_{Siv} in SIDIS (Left-Right Asymmetry w.r.t. S_T)

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



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

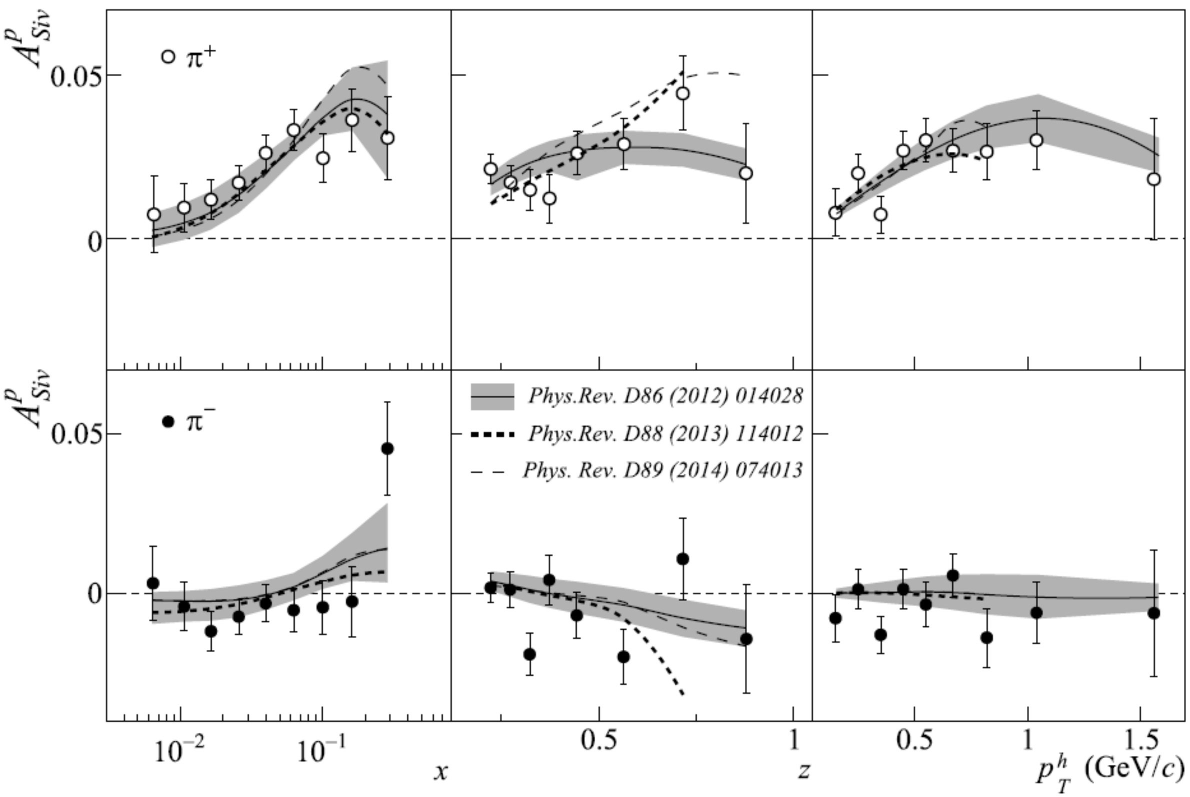


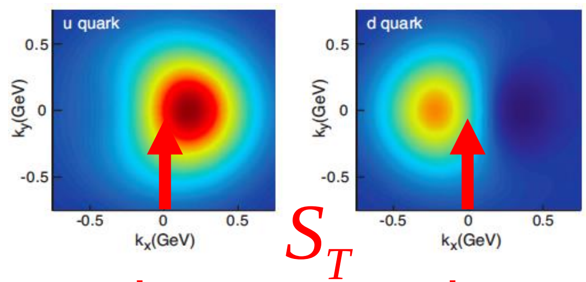


$$A_T^h \equiv \frac{d\sigma(\vec{S}_T) - d\sigma(-\vec{S}_T)}{d\sigma(\vec{S}_T) + d\sigma(-\vec{S}_T)} = \left|\vec{S}_T\right| \cdot \left[D_{NN} \cdot A_{Coll} \cdot \sin(\phi_h + \phi_S - \pi) + A_{Siv} \cdot \sin(\phi_h - \phi_S)\right]$$

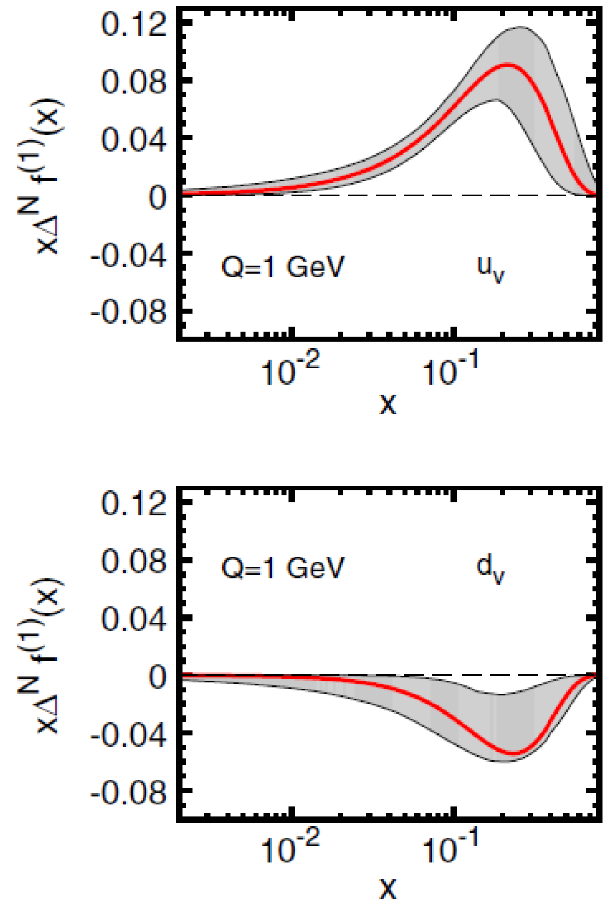
Nonzero Sivers Asymmetries from SIDIS

COMPASS, PLB 744 (2015) 250





Sivers Functions



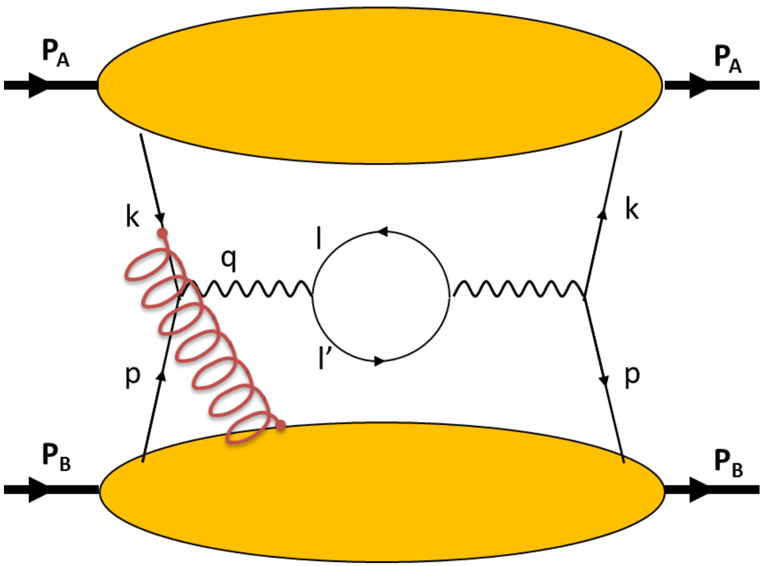
SIDIS $\gamma^*(q^2 < 0)p_\uparrow \to hX$

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

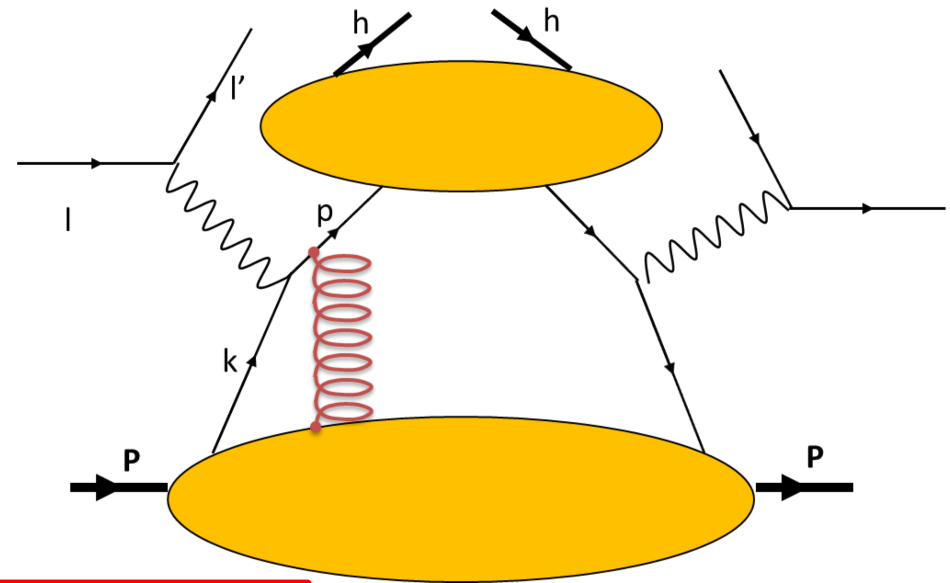
Non-Universality of Sivers Function

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**



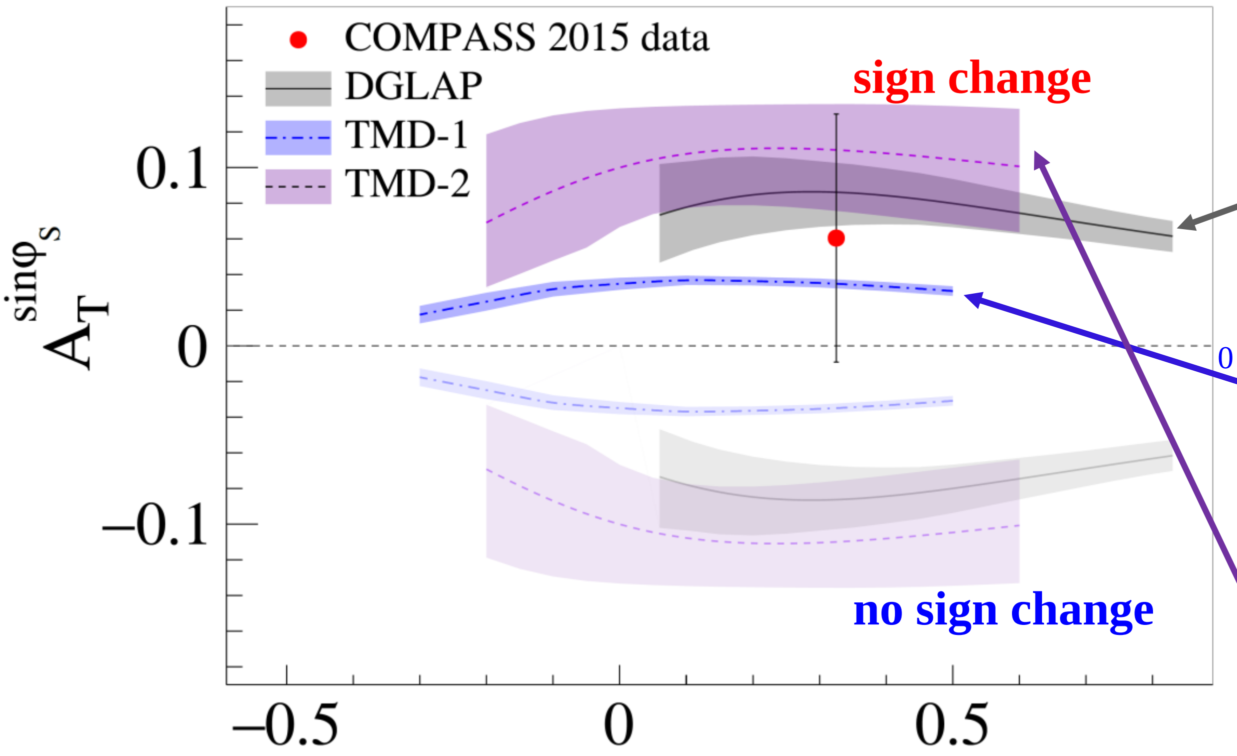
$hp_\uparrow \rightarrow \gamma^*(q^2 > 0)X$ $\boxed{\text{Sivers}\,|_{DY} = -\text{Sivers}\,|_{SIDIS}}$ $\gamma^*(q^2 < 0)p_\uparrow \rightarrow hX$

- 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!

Bakur's talk

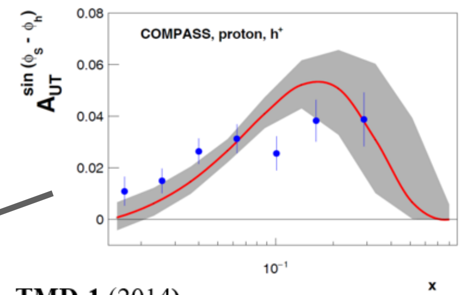
COMPASS, PRL 119 (2017) 112002



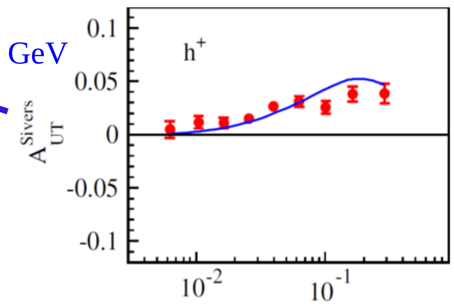
$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

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

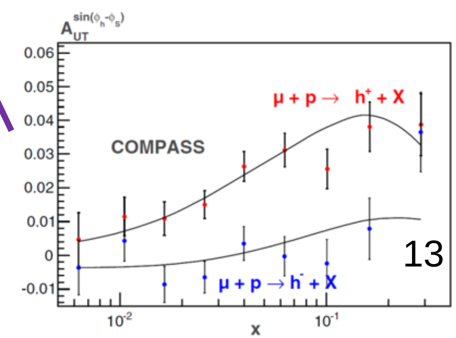
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



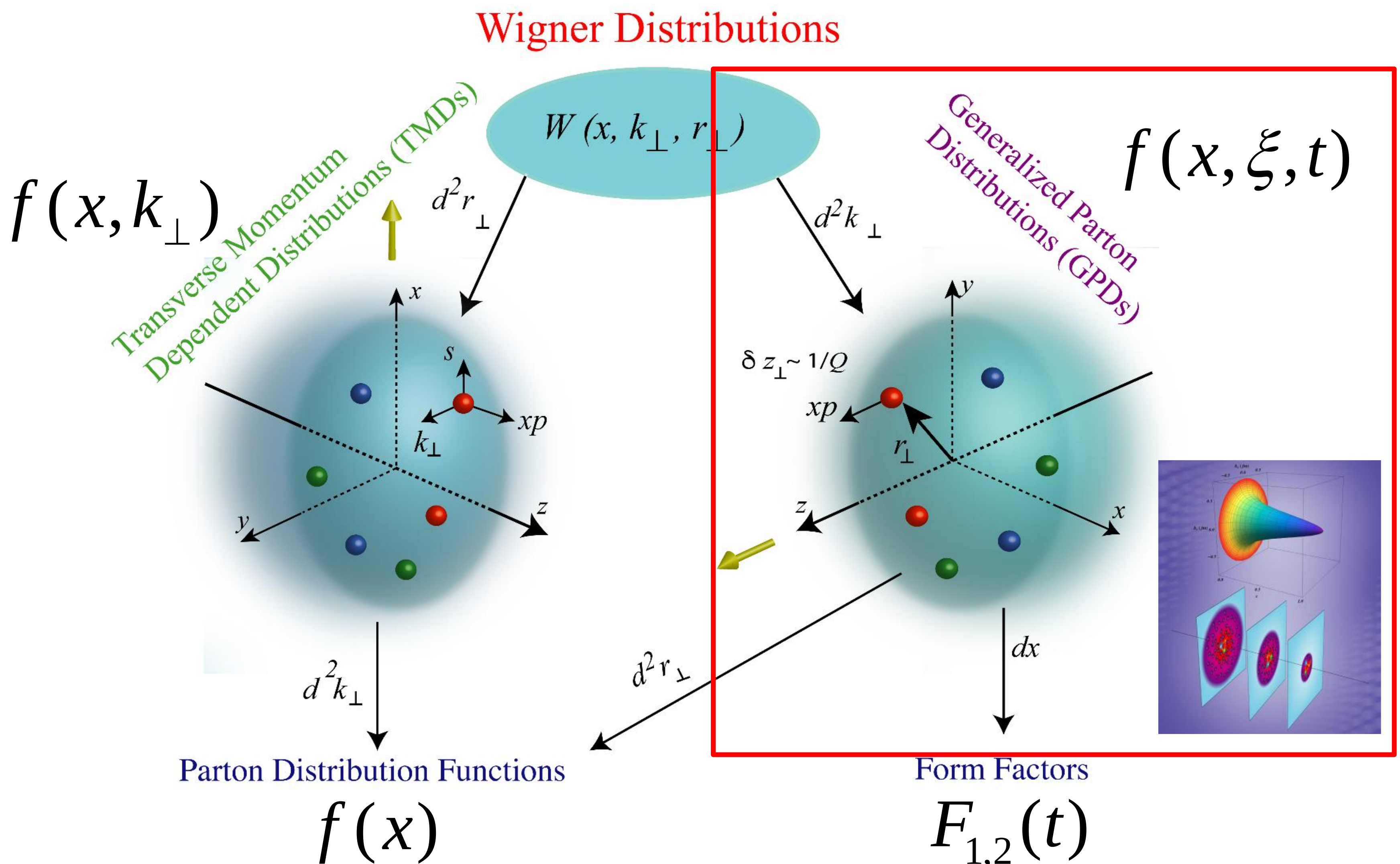
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



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

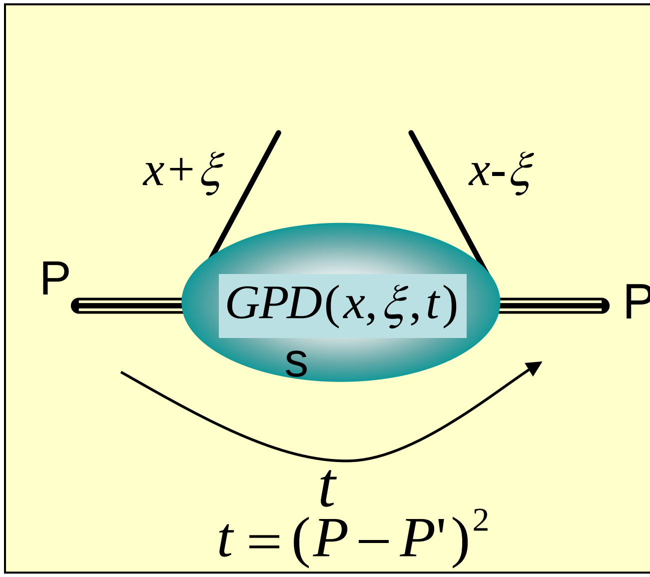


Multi-dimensional Partonic Structures



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

Generalized Parton Distribution (GPD)



$t = \xi = 0$

$$H_f(x,0,0) = q_f(x) = -\bar{q}_f(-x)$$

$$\tilde{H}_f(x,0,0) = \Delta q_f(x) = -\Delta\bar{q}_f(-x)$$

First moment

$$\int_{-1}^{1} dx \sum_f H_f(x,\xi,t) = F_1(-t)$$

Dirac FF

$$\int_{-1}^{1} dx \sum_f E_f(x,\xi,t) = F_2(-t)$$

Pauli FF

$$\int_{-1}^{1} dx \sum_f \tilde{H}_f(x,\xi,t) = g_A(-t)$$

axial FF

$$\int_{-1}^{1} dx \sum_f \tilde{E}_f(x,\xi,t) = g_p(-t)$$

pseudoscalar FF

	γ^μ	$\gamma^\mu\gamma^5$
no spin flip	$H_f(x,\xi,t)$	$\tilde{H}_f(x,\xi,t)$
spin flip	$E_f(x,\xi,t)$	$\tilde{E}_f(x,\xi,t)$

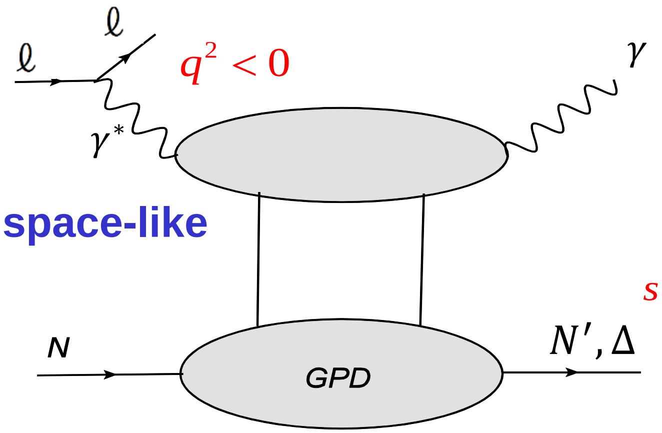
Ji's sum rule

$$J_f = \frac{1}{2}\Delta\Sigma^f + L^f = \frac{1}{2}\int_{-1}^{1} x dx [H_f(x,\xi,0) + E_f(x,\xi,0)]$$

Experimental Approach

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

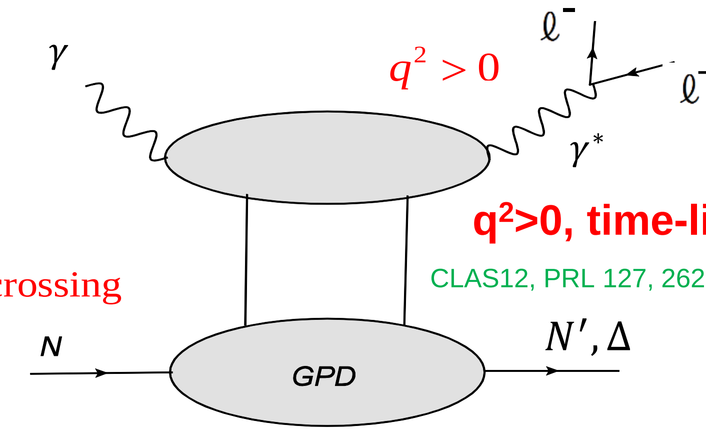
Deeply Virtual Compton Scattering



$q^2<0$, space-like

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

Time-like Compton Scattering



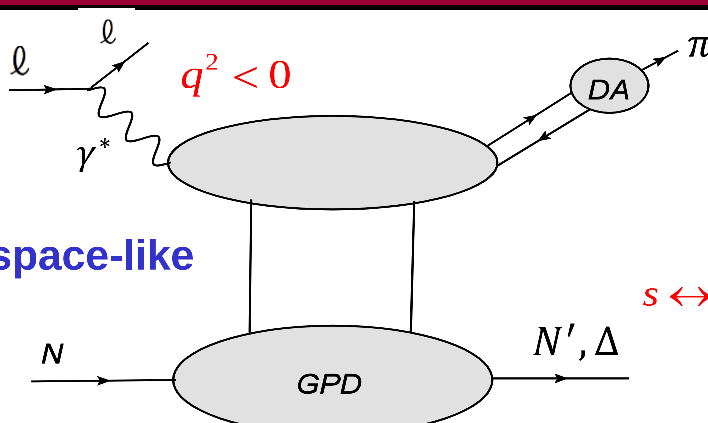
$q^2>0$, time-like

CLAS12, PRL 127, 262501 (2021)

$s \leftrightarrow u$ channel crossing

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

Deeply Virtual Meson Production

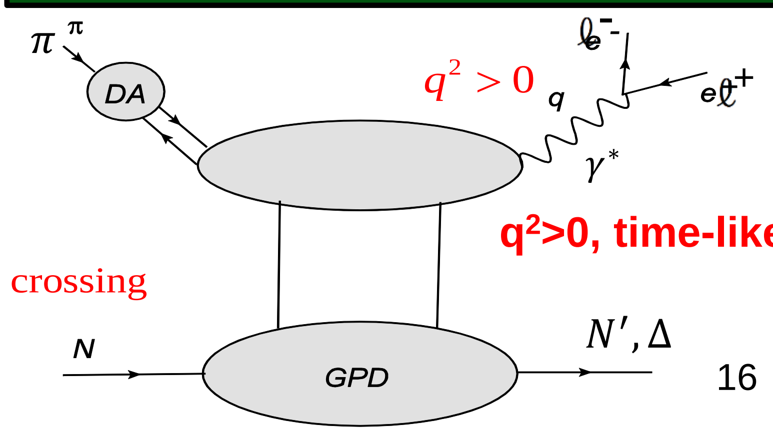


$q^2<0$, space-like

$s \leftrightarrow u$ channel crossing

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

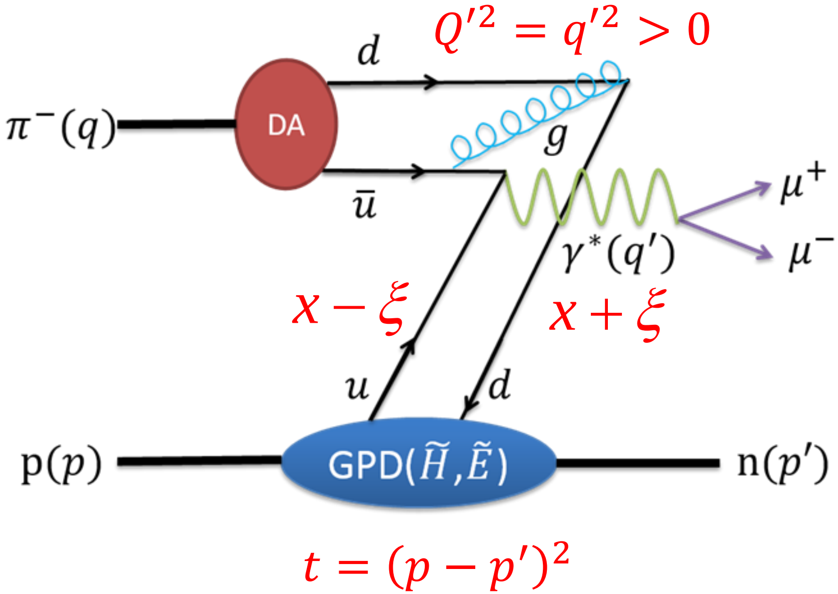
Exclusive meson-induced DY



$q^2>0$, time-like

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

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



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

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

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

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

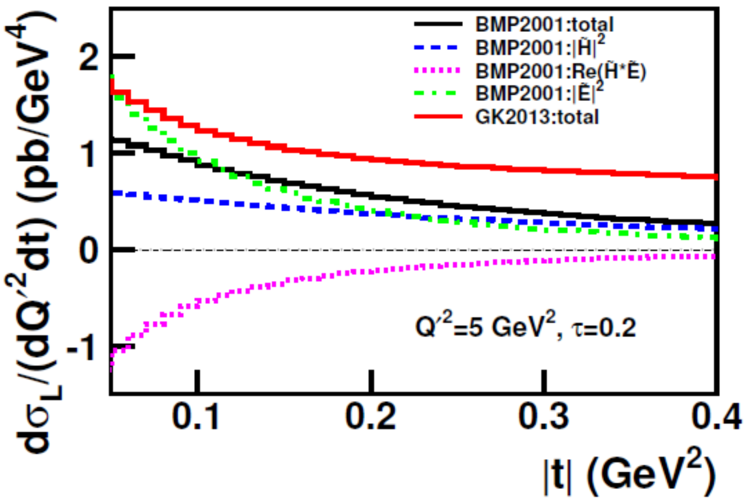
Differential Cross Sections of $\pi N \to l^+ l^- N$

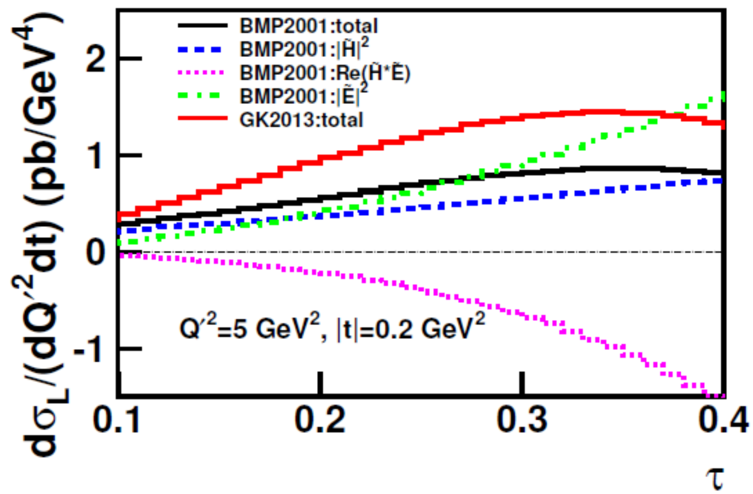
$$\left.\frac{d\sigma_L}{dt\,dQ'^2}\right|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \Big[(1-\xi^2)|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)|^2 - 2\xi^2 \mathrm{Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^* \tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2 \frac{t}{4m_N^2}|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)|^2\Big],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

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

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

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





Production is dominant at forward angles

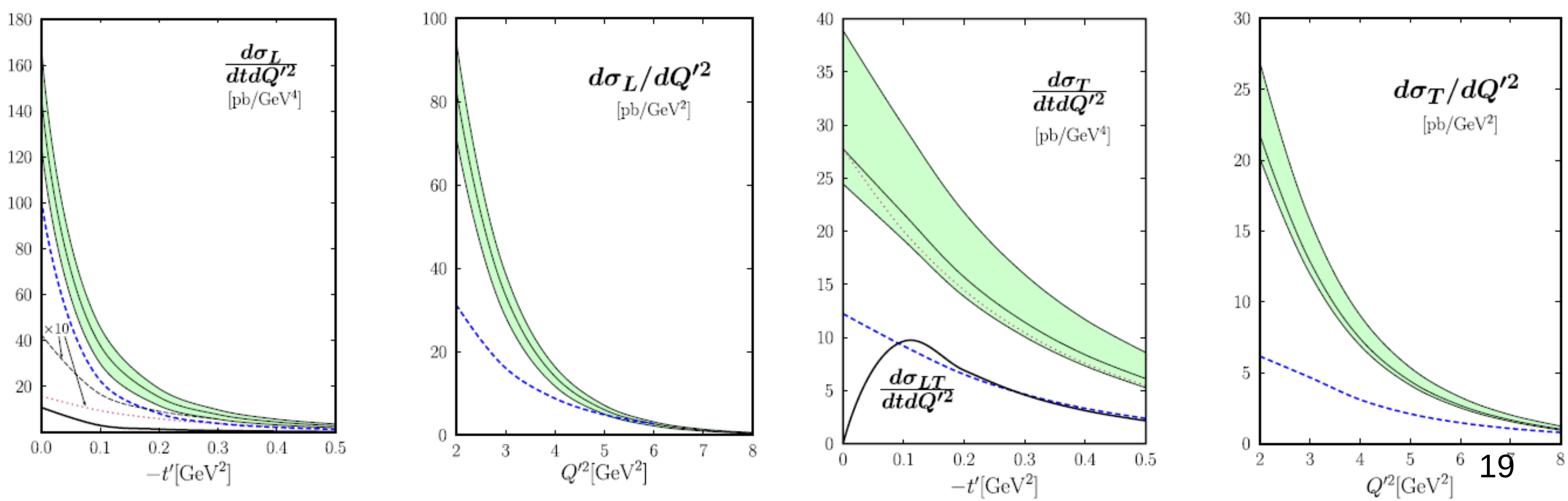
Cross sections increase toward small *s* (→ low beam energy)

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, $\bar{E}_T$



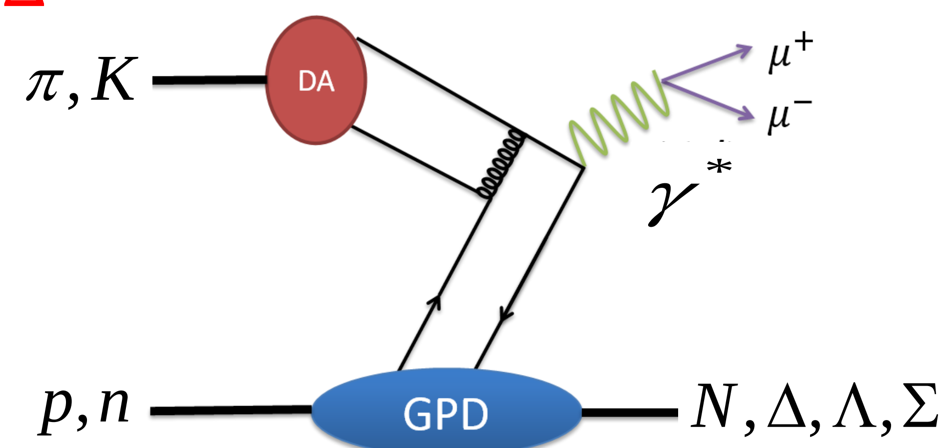
Transition GPDs

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

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

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

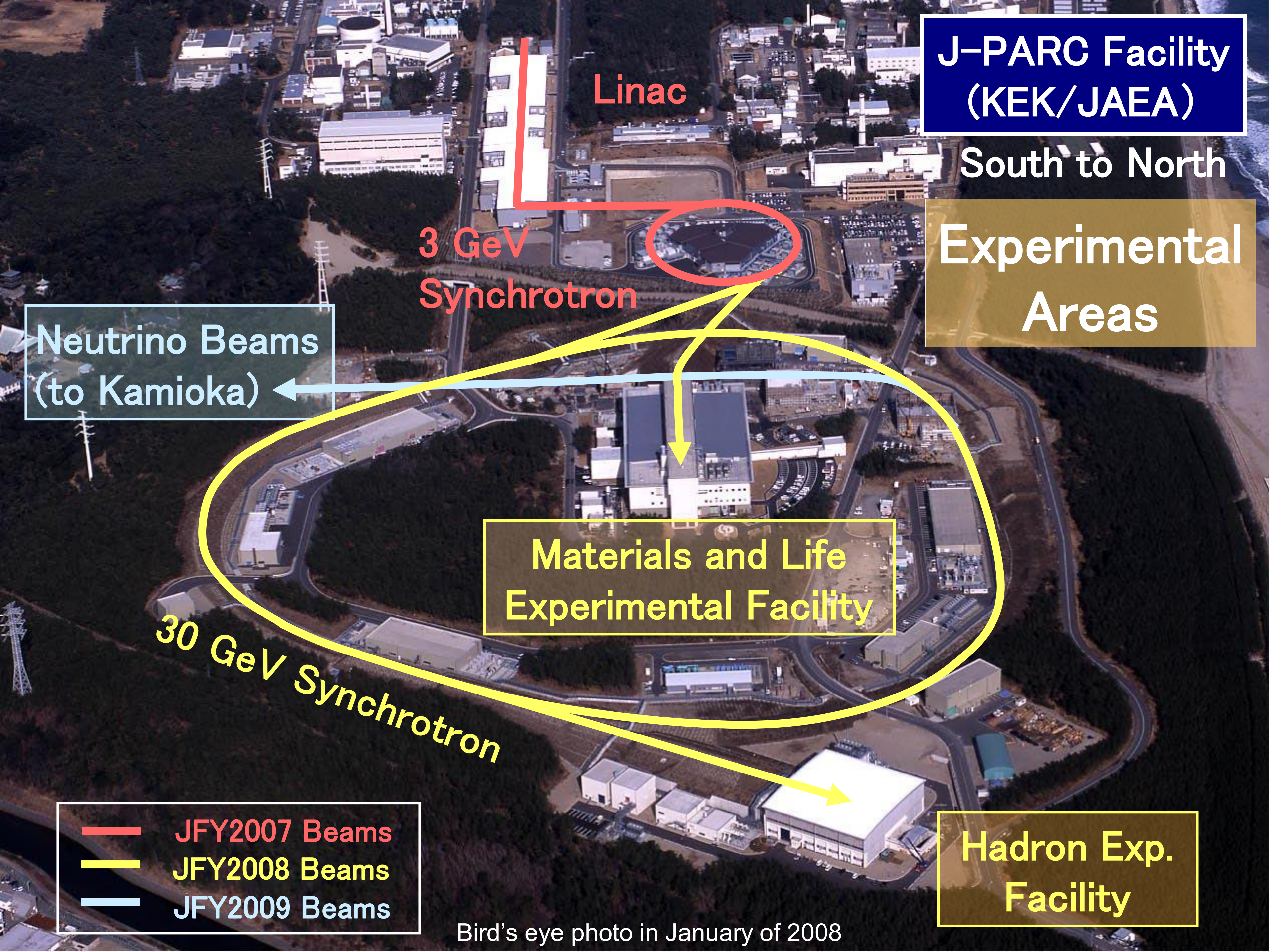
J-PRAC Hadron Hall Extension



Exclusive Drell-Yan Measurement

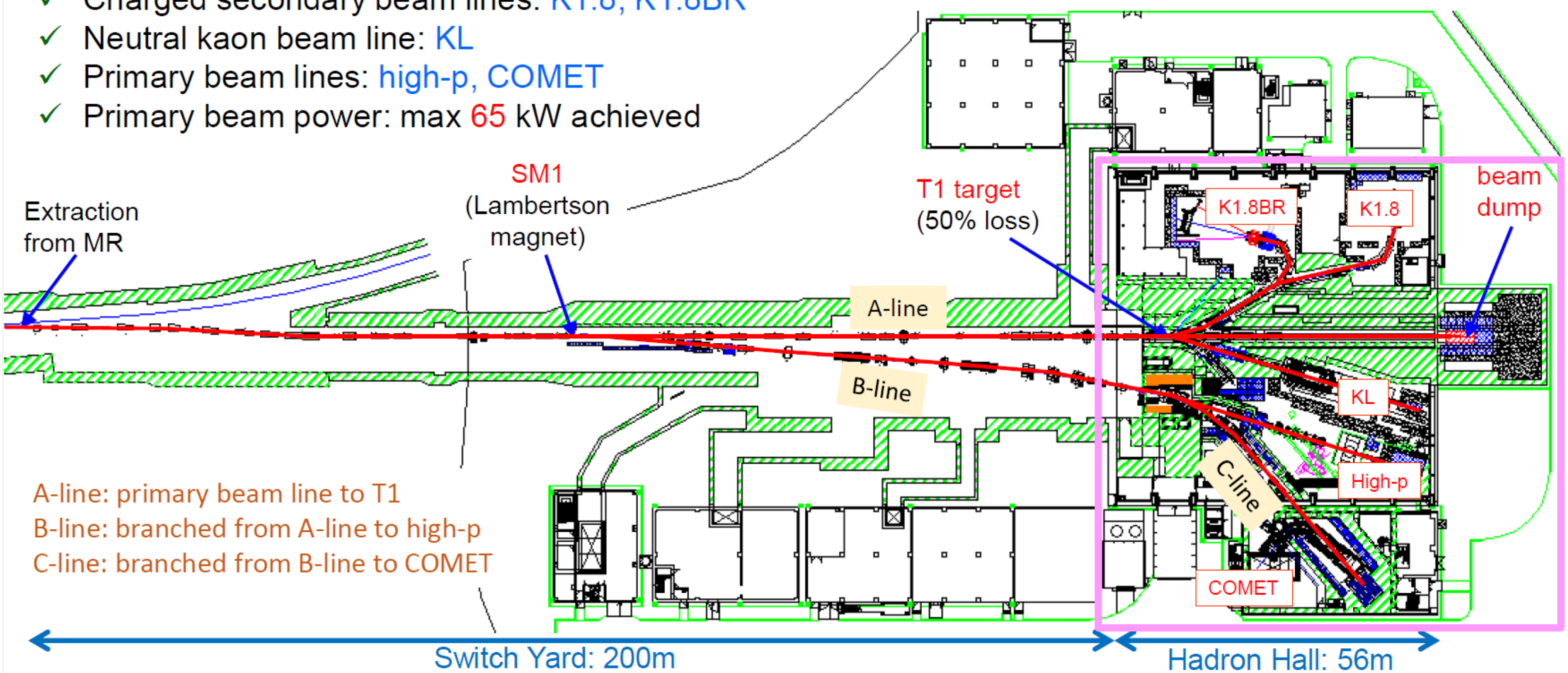
- **Factorization**: $Q^2 \gg 1\ GeV^2$
- **Cross sections**:
  - Cross sections decrease rapidly with an increase of Q^2. $Q^2 < 9\ GeV^2$
  - $\sqrt{s}$ should be small enough to keep $\sqrt{\tau} = \frac{Q}{\sqrt{s}} = \sqrt{x_\pi x_N}$ large enough. Take $Q = 2\ GeV$, $\sqrt{\tau} = \sqrt{0.5 * 0.3} = 0.39$, $\sqrt{s} = 5\ GeV$, 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 ($\sqrt{s} = \mathbf{4} - \mathbf{6}$ GeV) is most appropriate!


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

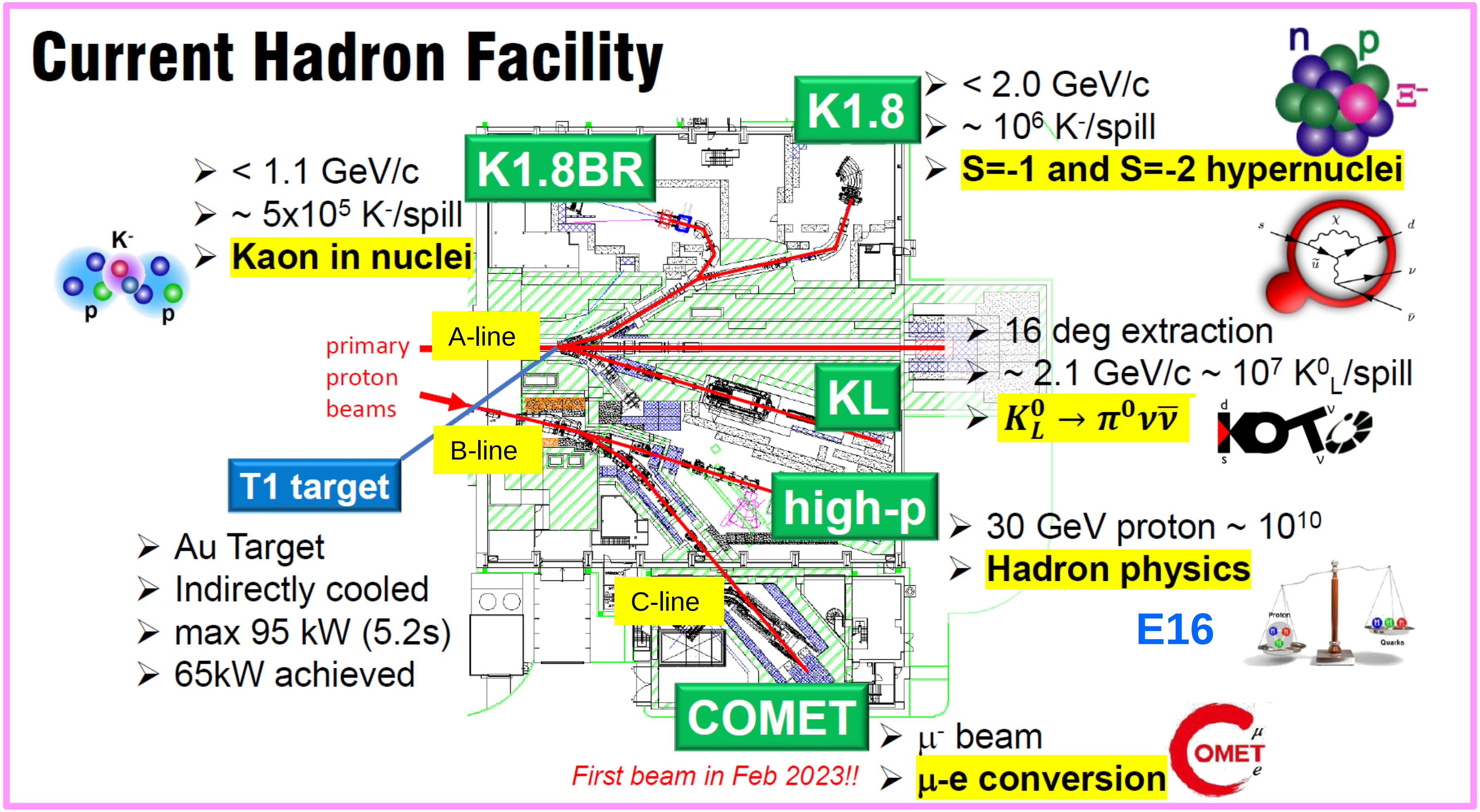
J-PARC Hadron Hall (Current Status)

- ✓ 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

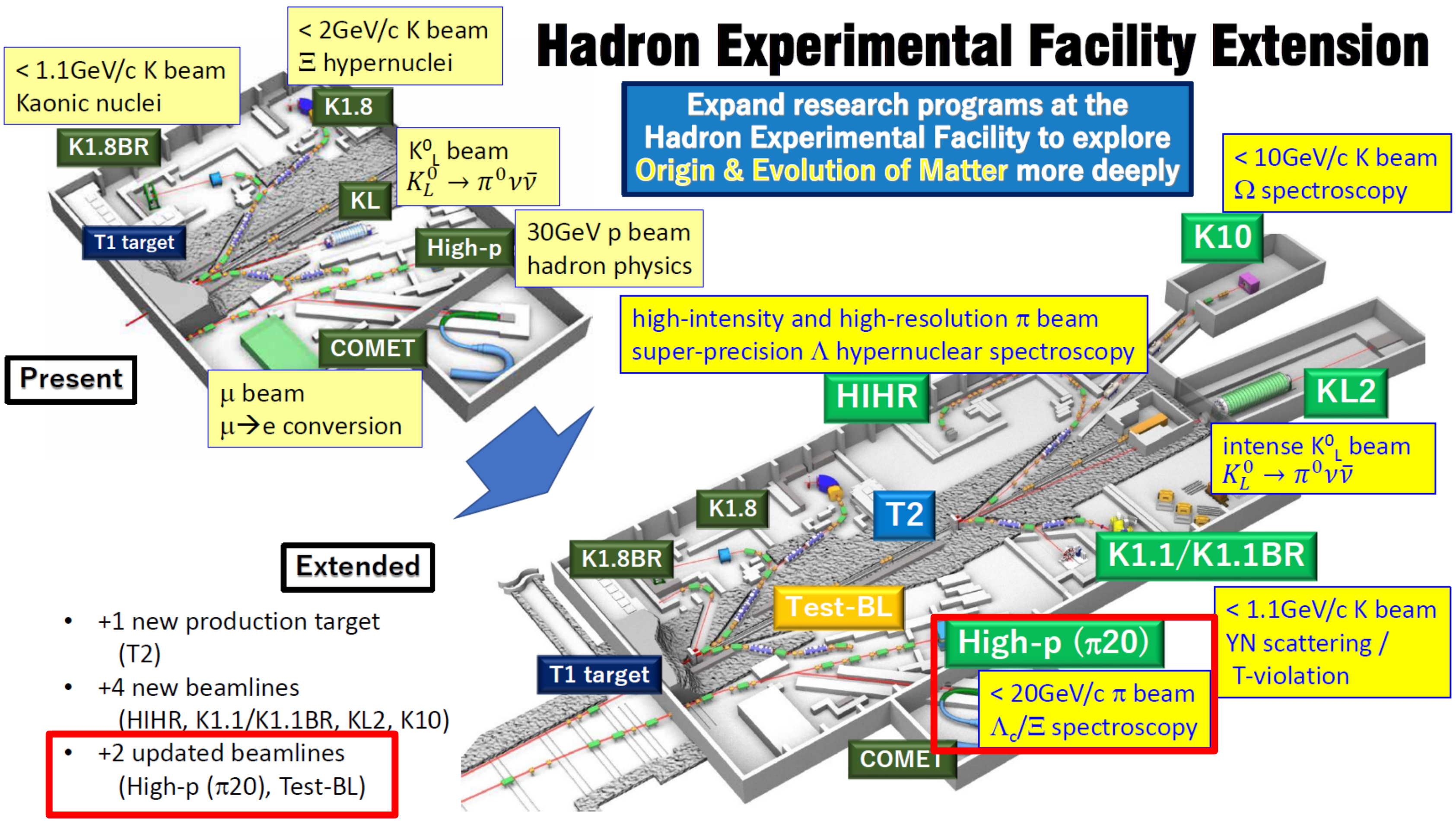
J-PARC Hadron Hall (Current Status)



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)!



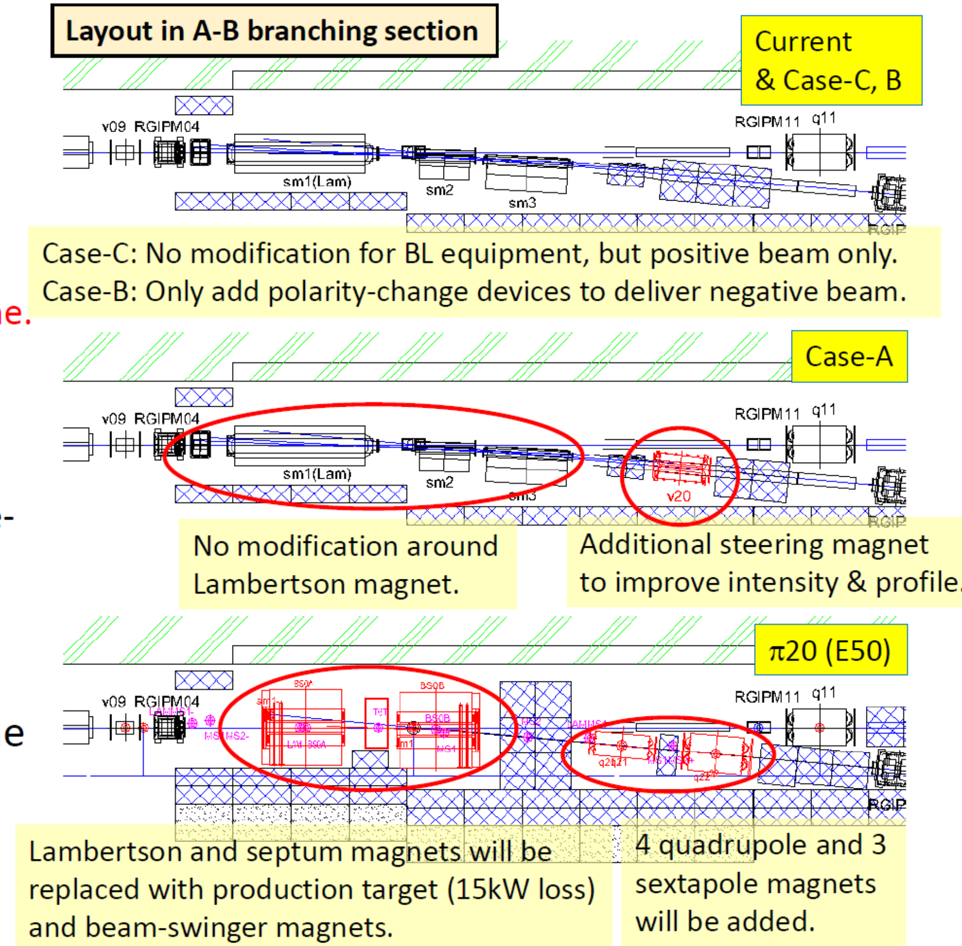
https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html
https://arxiv.org/abs/2110.04462

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.

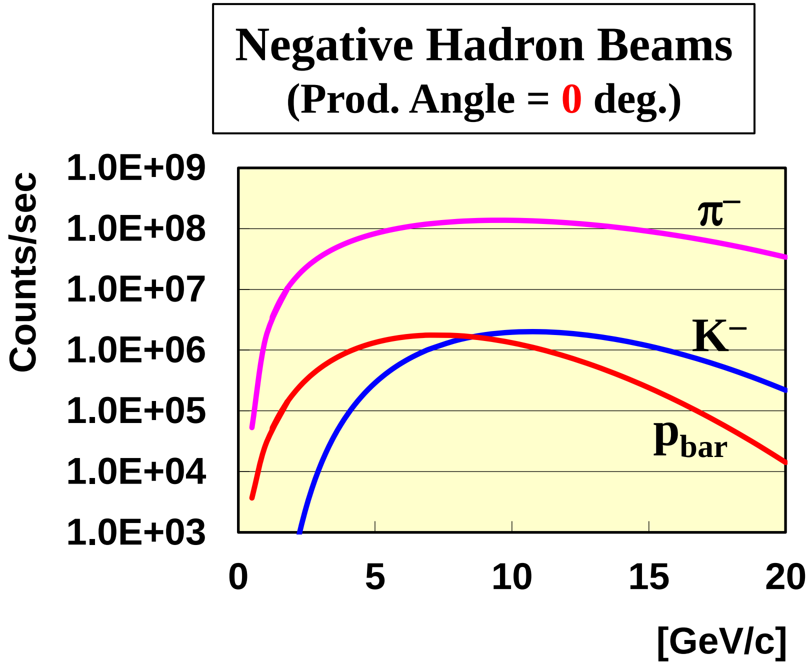


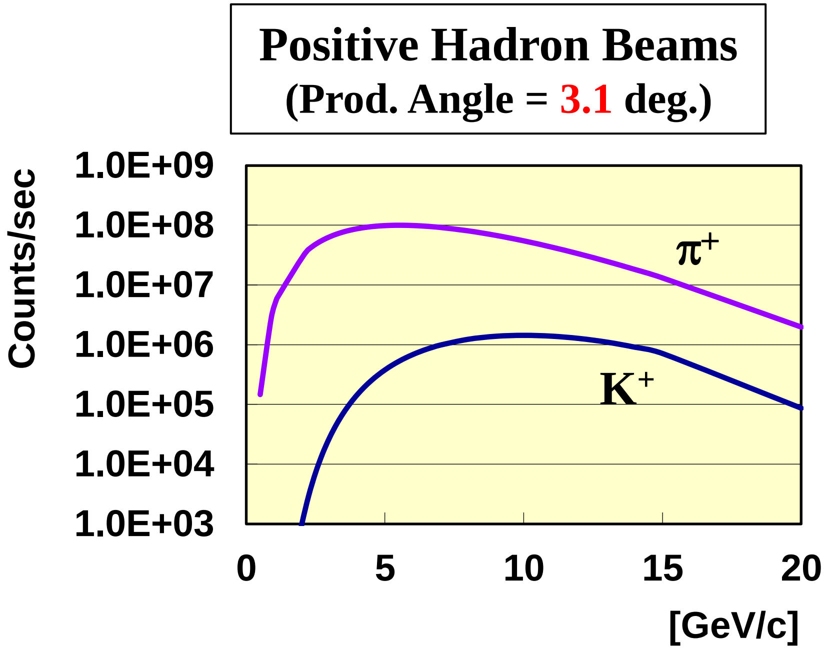
https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html
https://arxiv.org/abs/2110.04462

Hadron Experimental Facility

π20 Beam Line

- High-intensity secondary pion beam
- High-resolution beam: $\Delta p/p \sim 0.1\%$



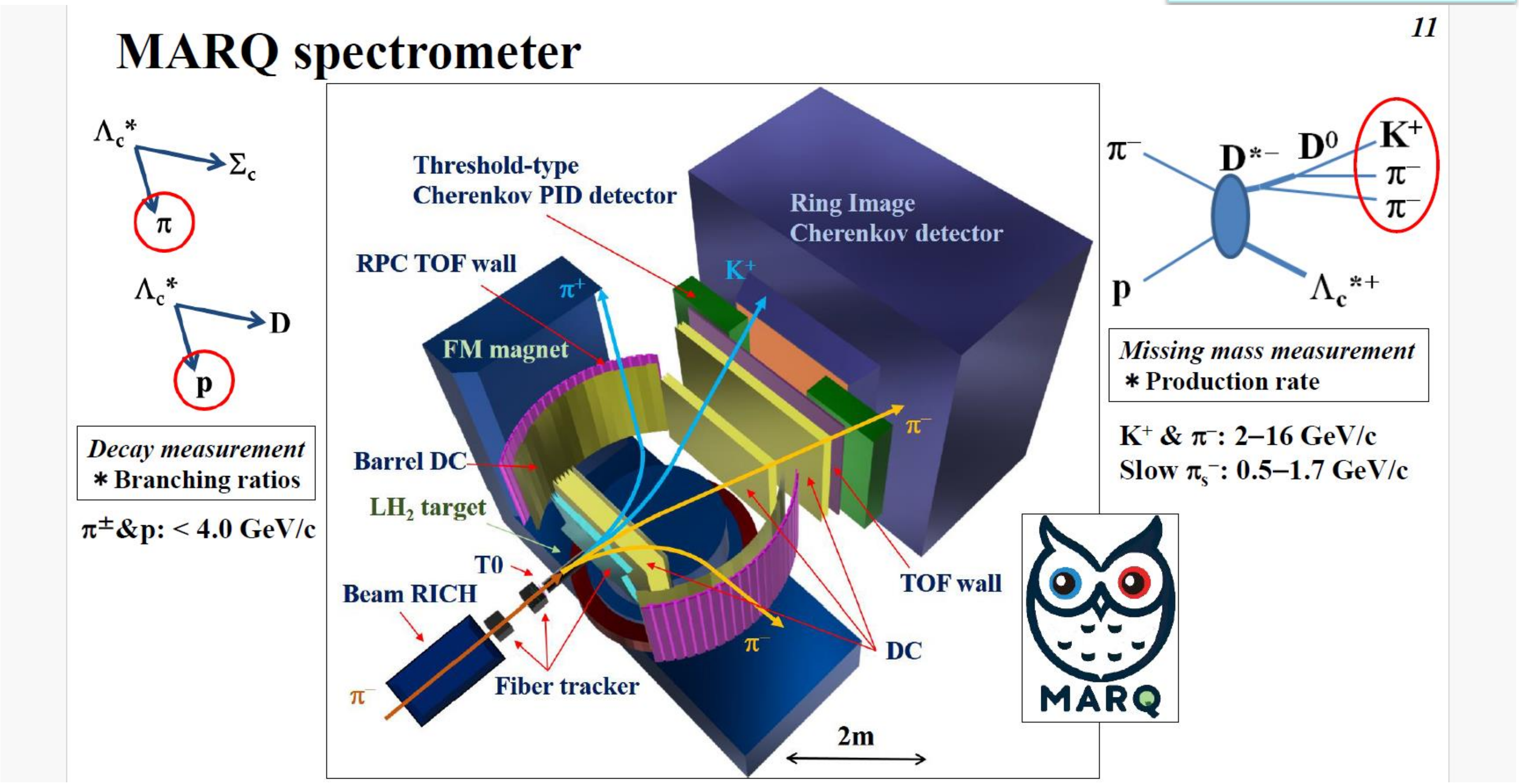


*** Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m**

J-PARC E50/MARQ Experiment

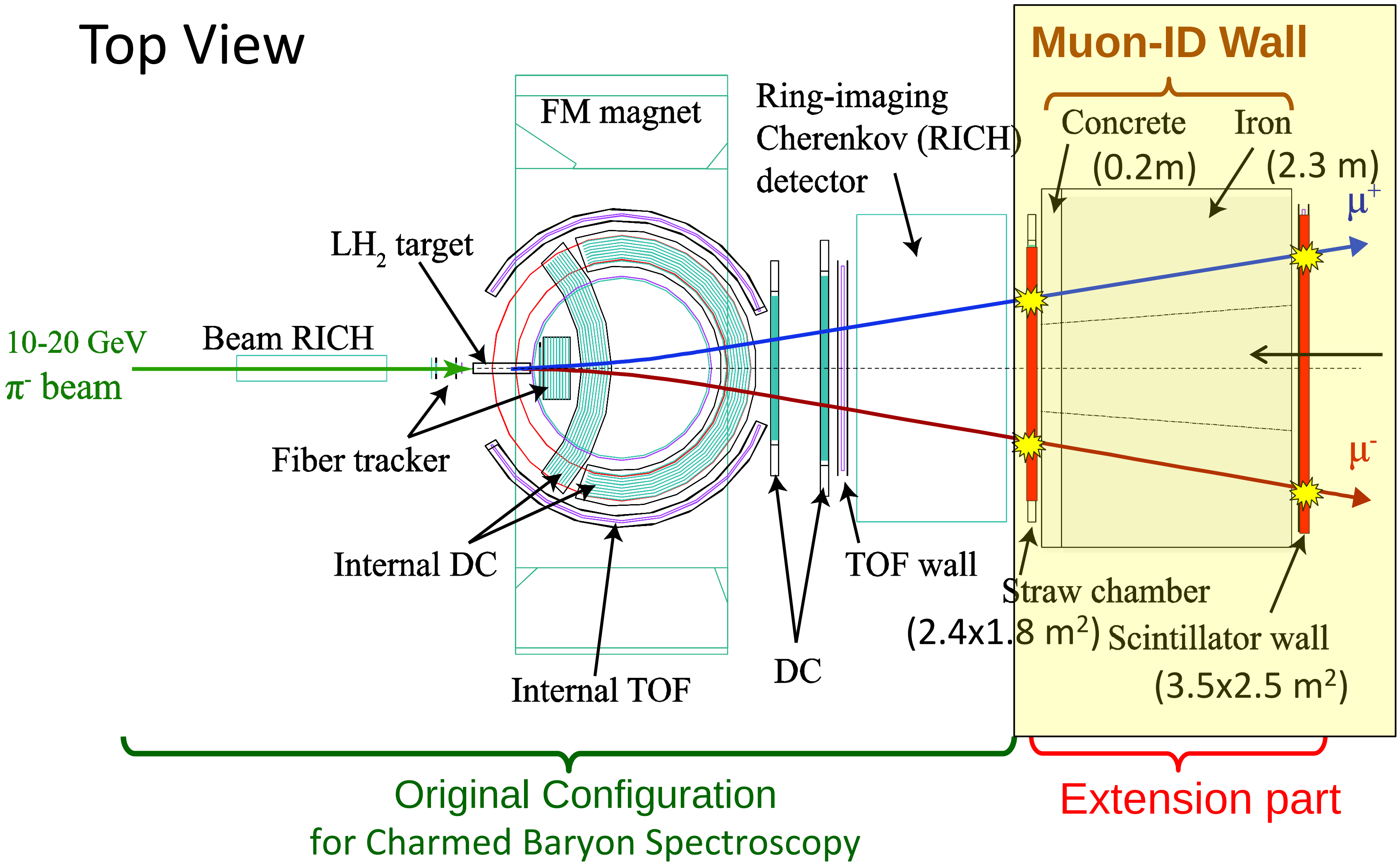
(Charmed Baryon Spectroscopy)

K. Shirotori's talk



Large acceptance, PID, good momentum resolution

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

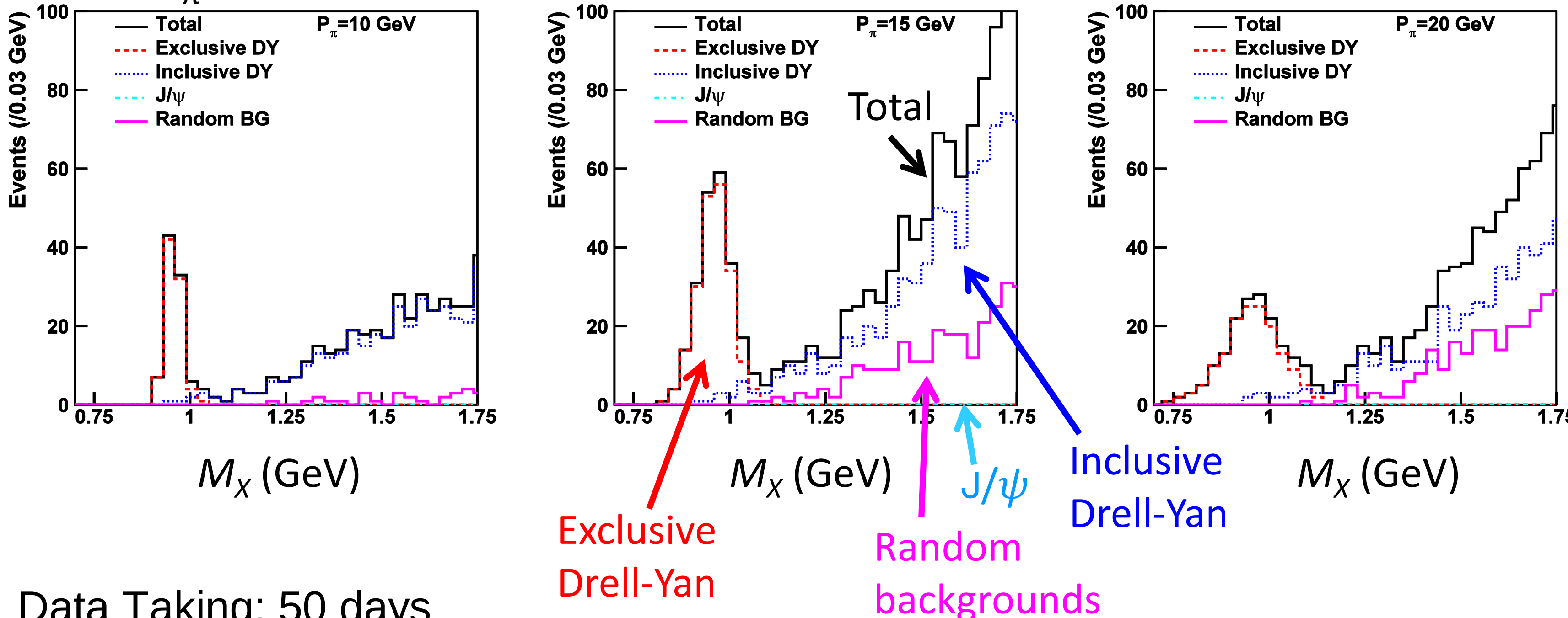


$\pi^- N \to \mu^+\mu^- X$ Missing-mass M_X

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



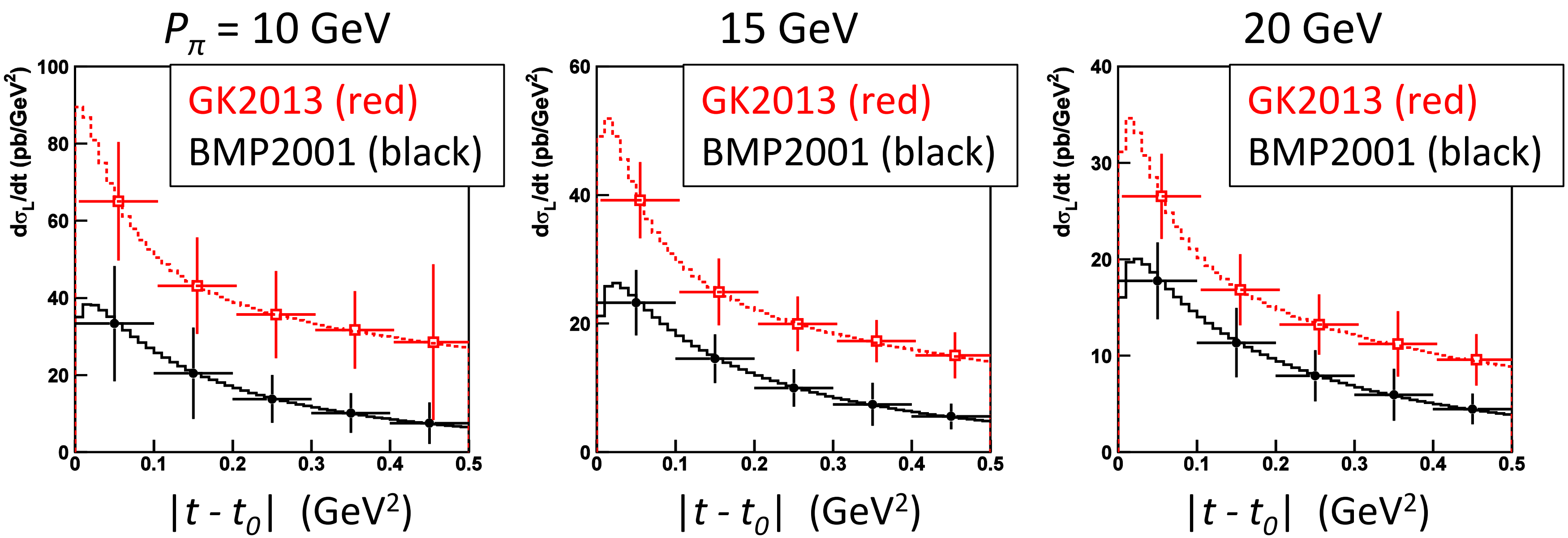
- Data Taking: 50 days
- $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV
- $|t - t_0| < 0.5$ GeV^2
- "GK2013" GPDs

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

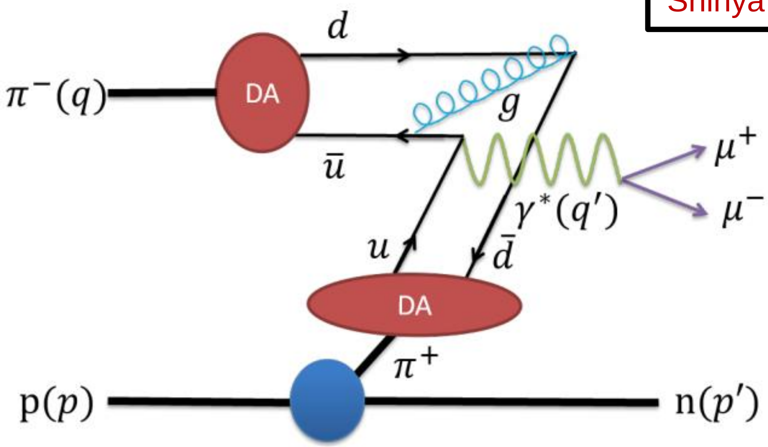


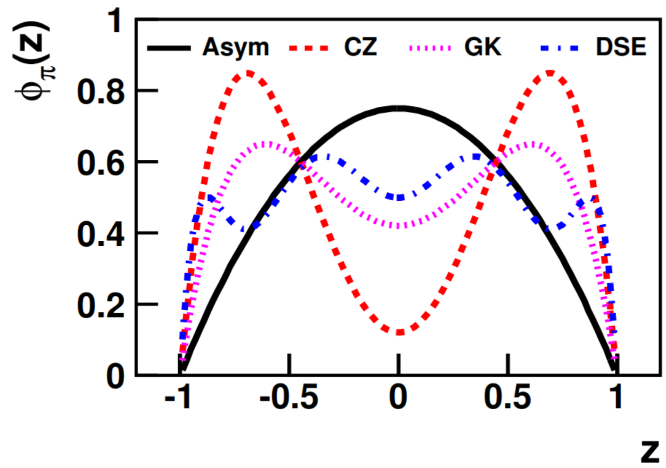
- Data Taking: 50 days
- $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV
- $|t - t_0| < 0.5$ GeV^2

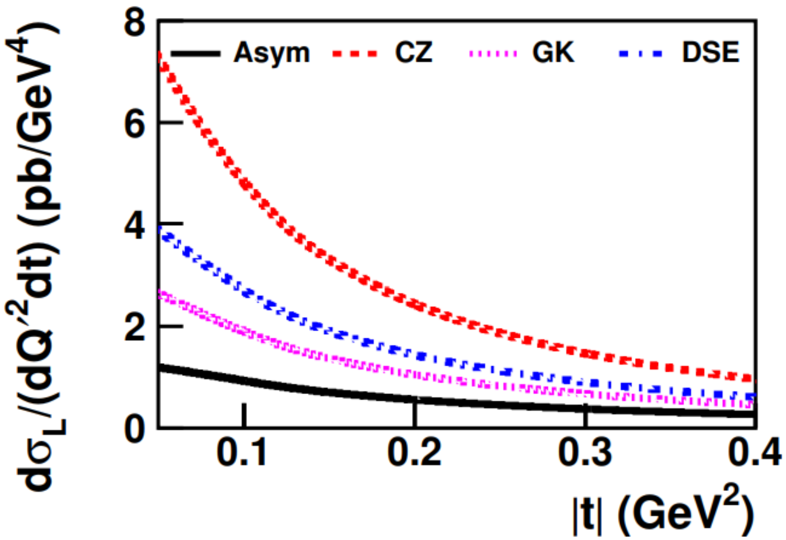
The statistics sensitivity is good enough for discriminating the predictions from two current GPD models.

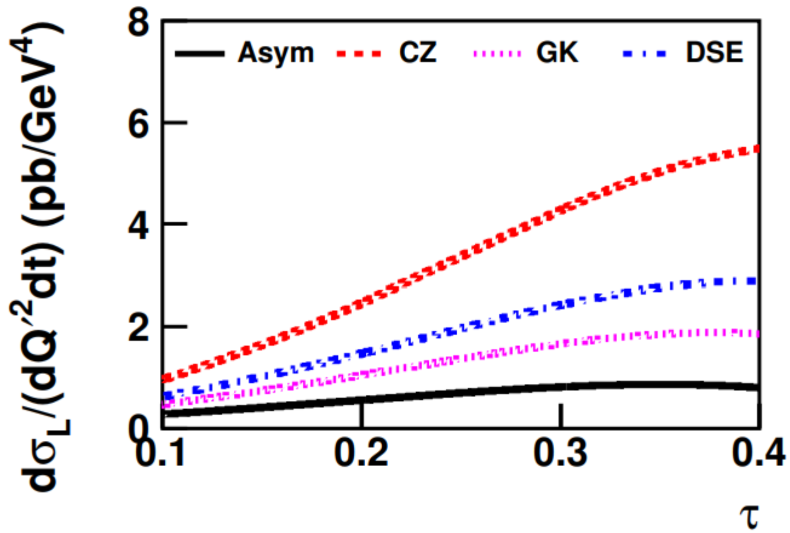
Sensitivity to π DAs

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

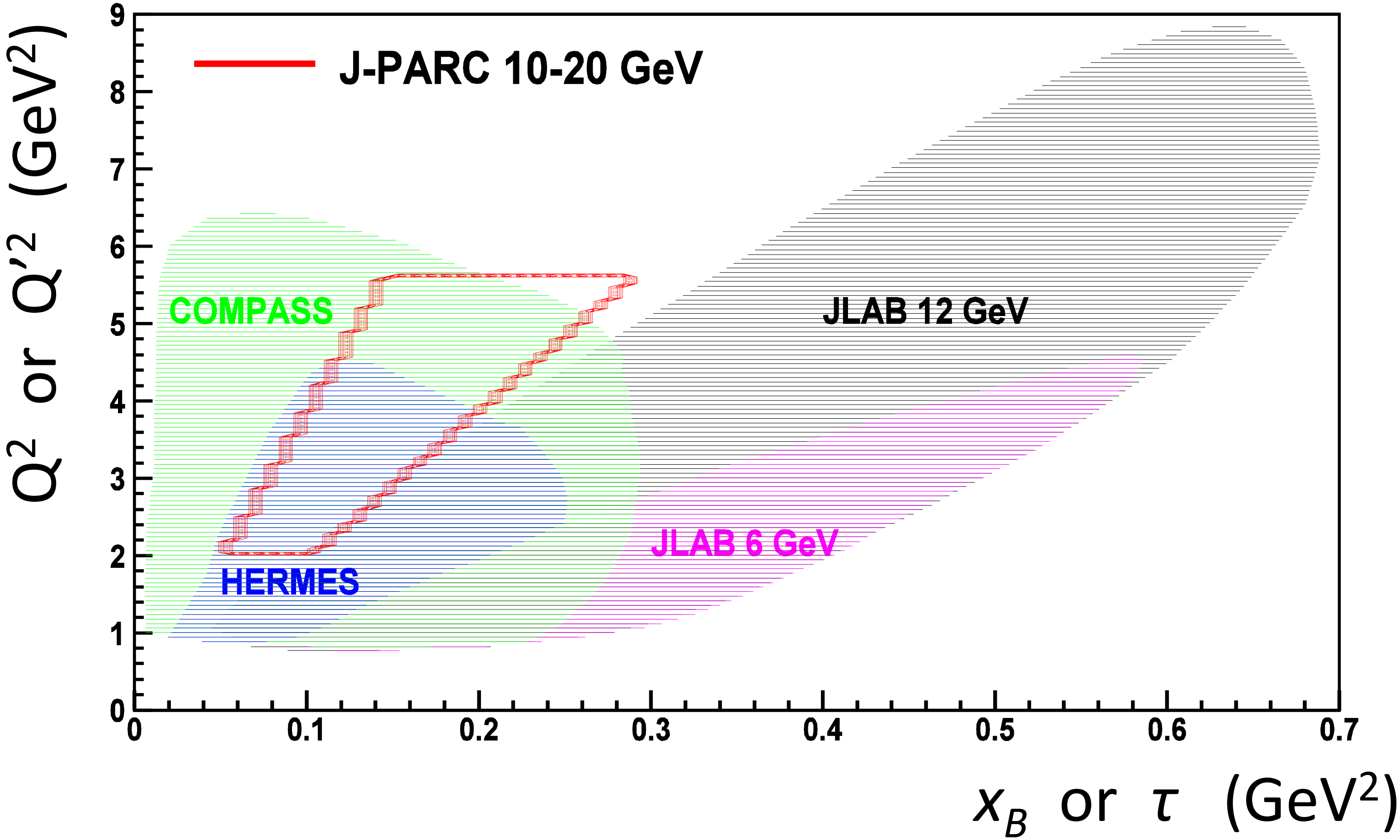






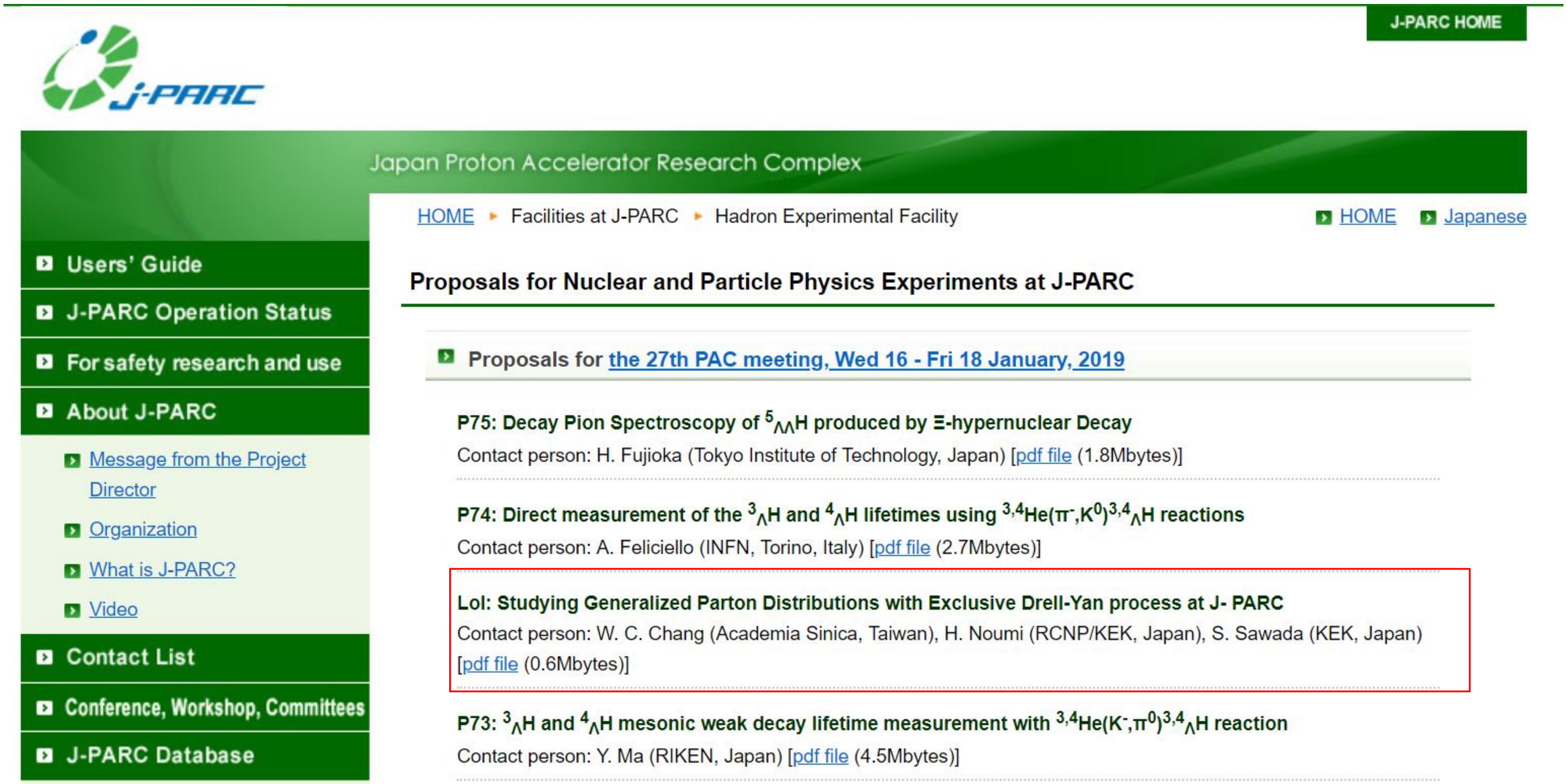


Universality of GPDs



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

J-PARC LoI (2019)



J-PARC HOME

J-PARC

Japan Proton Accelerator Research Complex

HOME ▸ Facilities at J-PARC ▸ Hadron Experimental Facility

HOME Japanese

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- J-PARC Operation Status
- For safety research and use
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- Contact List
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- J-PARC Database

Proposals for Nuclear and Particle Physics Experiments at J-PARC

Proposals for the 27th PAC meeting, Wed 16 - Fri 18 January, 2019

P75: Decay Pion Spectroscopy of $^{5}_{\Lambda\Lambda}$H produced by Ξ-hypernuclear Decay
Contact person: H. Fujioka (Tokyo Institute of Technology, Japan) [pdf file (1.8Mbytes)]

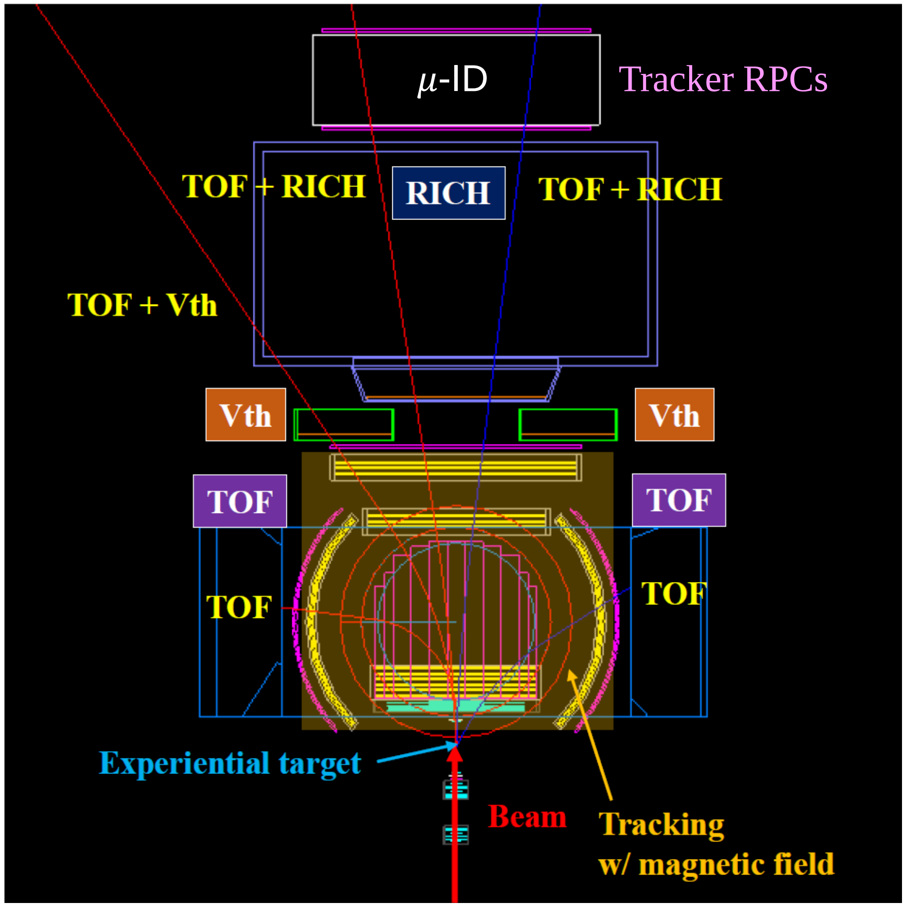
P74: Direct measurement of the $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H lifetimes using ^{3,4}He(π^-,K^0)$^{3,4}_{\Lambda}$H reactions
Contact person: A. Feliciello (INFN, Torino, Italy) [pdf file (2.7Mbytes)]

LoI: Studying Generalized Parton Distributions with Exclusive Drell-Yan process at J- PARC
Contact person: W. C. Chang (Academia Sinica, Taiwan), H. Noumi (RCNP/KEK, Japan), S. Sawada (KEK, Japan) [pdf file (0.6Mbytes)]

P73: $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H mesonic weak decay lifetime measurement with ^{3,4}He(K$^-$,π^0)$^{3,4}_{\Lambda}$H reaction
Contact person: Y. Ma (RIKEN, Japan) [pdf file (4.5Mbytes)]

A total of 23 collaborators from Japan, Korea, U.S. and Taiwan

Proposal to complete…



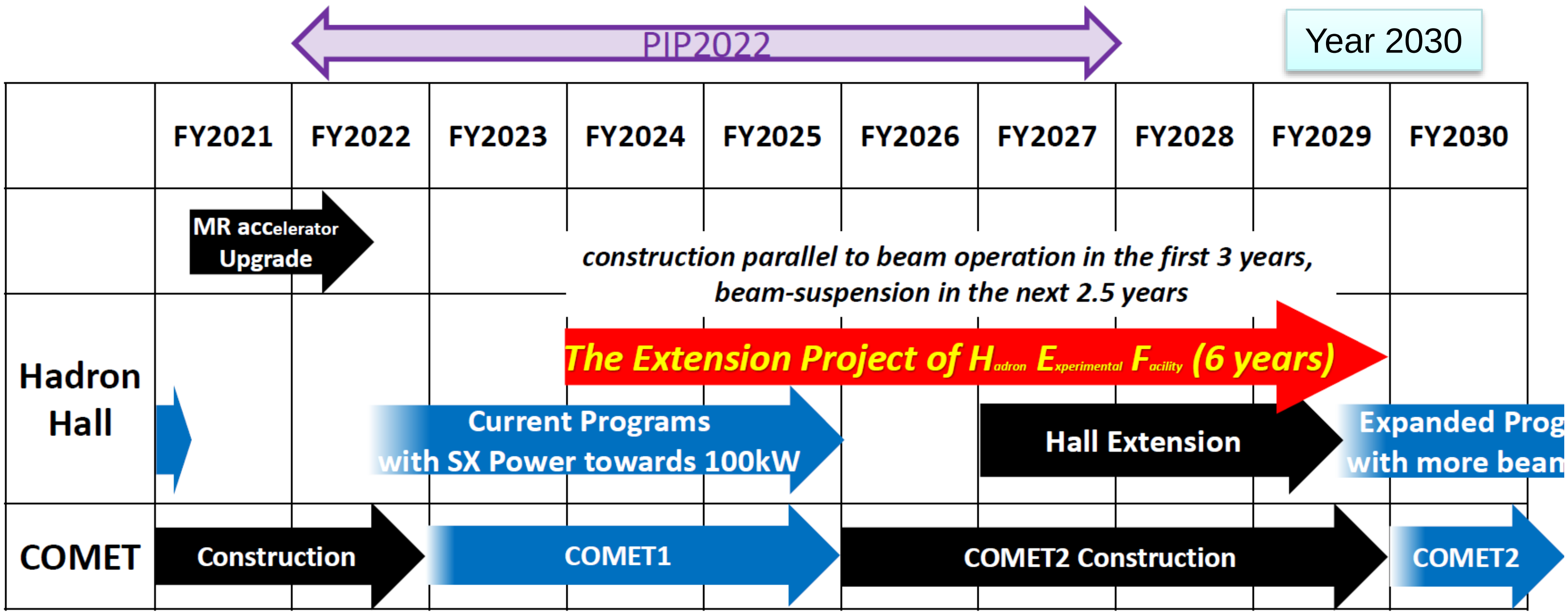
- The μ-ID system:
  - Tracker RPCs: rejection of muons from the decay-in-flight pions and kaons.
  - Material of hadron absorber: concrete and steel
- Updating the GPD modeling.
- Simulate the expected signal-to-background and yields of exclusive DY events.
- Optimize the design of μ-ID system and dimuon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

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

Hadron Hall Extension

15

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?

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

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*

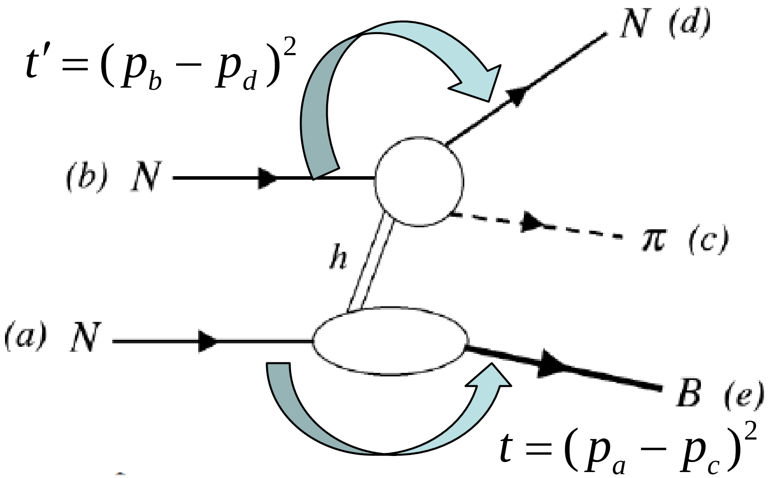
(Received 10 May 2009; published 2 October 2009)

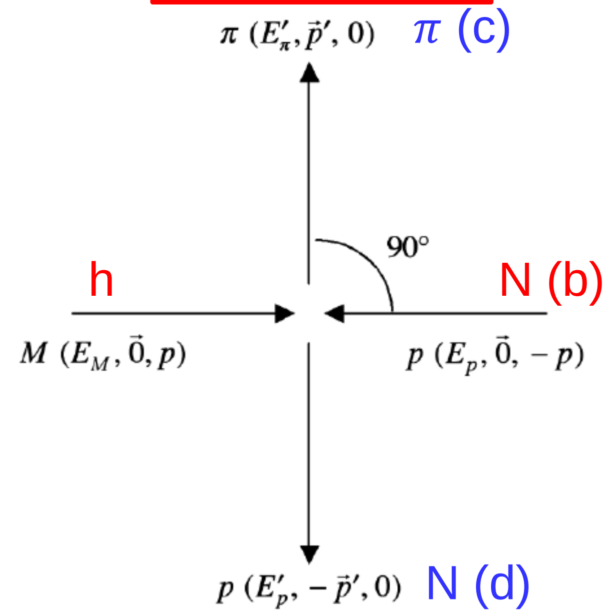
We consider a novel class of hard branching hadronic processes $a + b \to c + d + e$, where hadrons c and d have large and nearly opposite transverse momenta and large invariant energy, which is a finite fraction of the total invariant energy. We use color transparency logic to argue that these processes 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

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

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



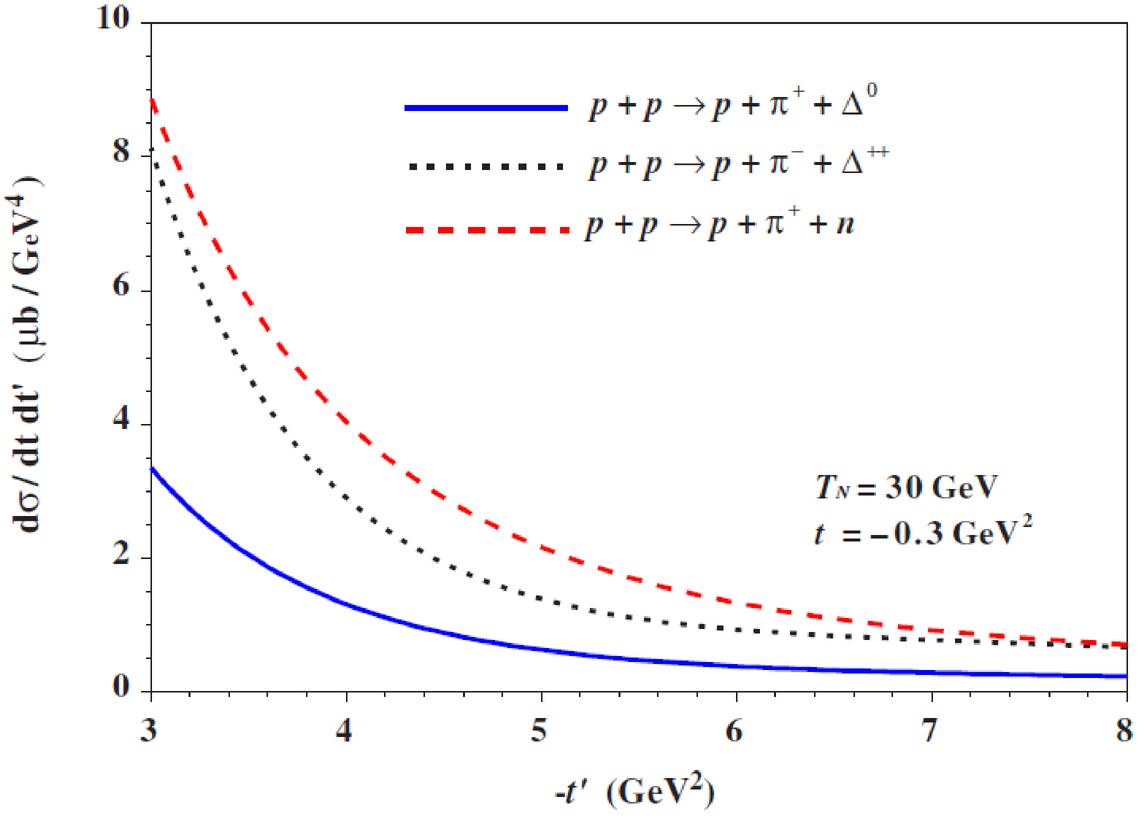


It was suggested in Refs. [25,26] that one can investigate the presence of small-size color singlet $q\bar{q}$ and qqq clusters in hadrons using large-angle branching hadronic processes $a + b \rightarrow c + d + e$, where the hadron e is produced in the fragmentation of b with fixed Feynman x_F and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

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

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

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



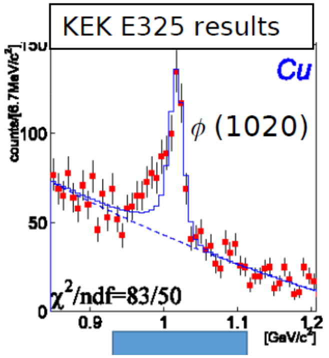
The measurement of –t' (~ qT of forward-moving N) dependence could be used to explore the x-dependence of GPDs.

Qiu & Yu, JHEP 08 (2022) 103, PRD 107 (2023) 014007, arXiv:2305.15397

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

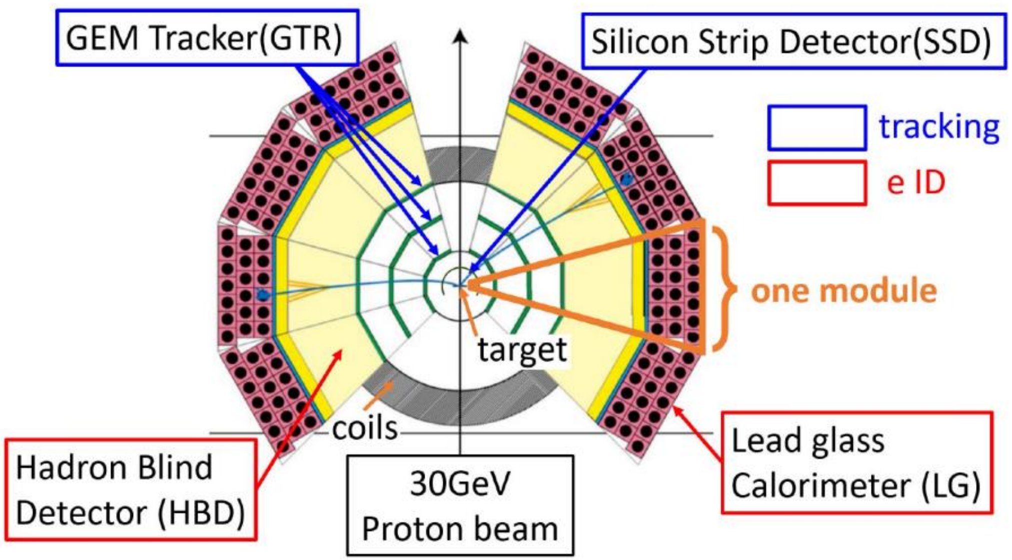
E16 Experiment at J-PARC

- 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): 2020,2021,2023,2024.
- Run 1: Nov/2024

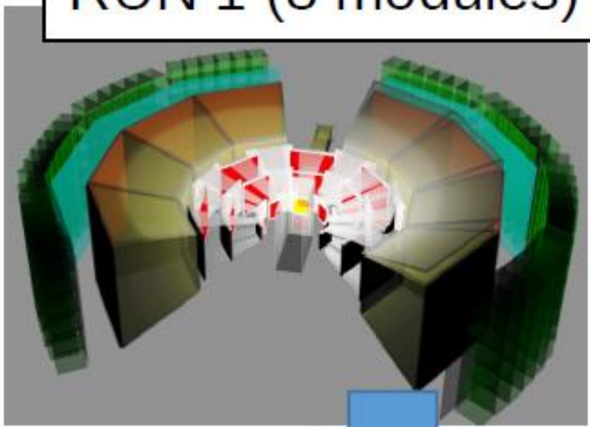


E16 Acceptance/PID Performance

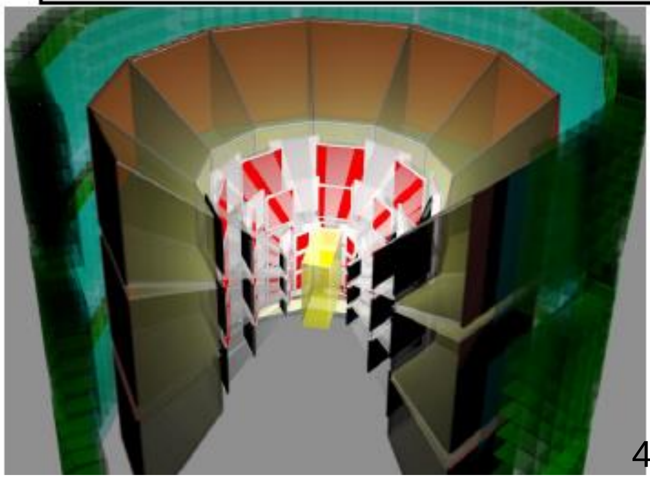
$$\theta_{p,\pi} > 15\mathrm{deg}$$



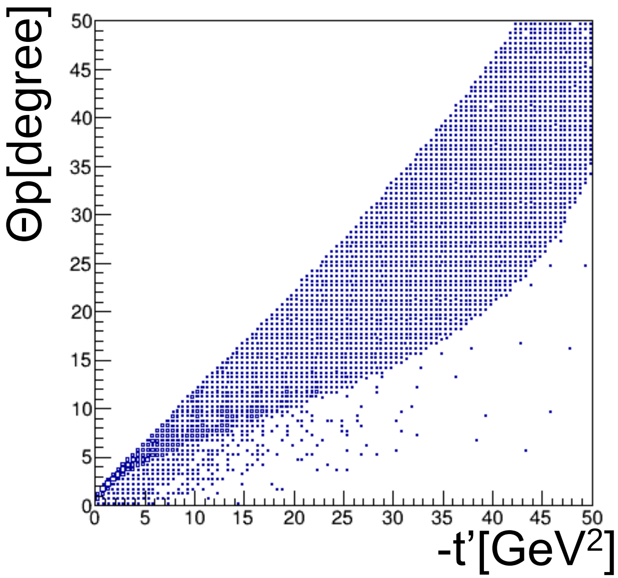
RUN 1 (8 modules)

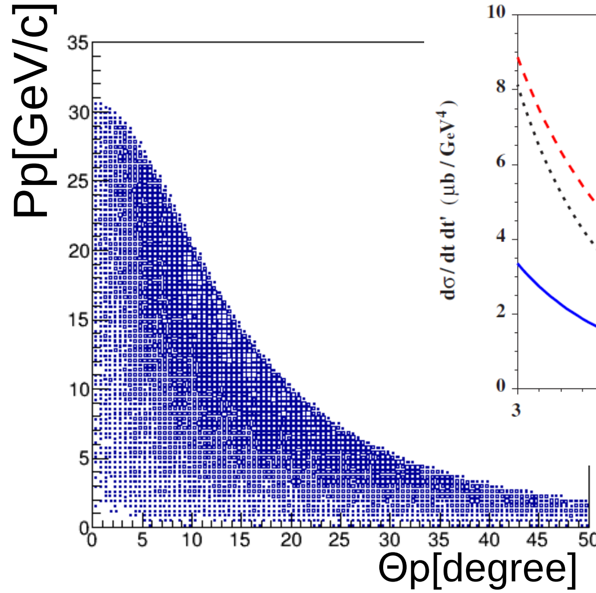


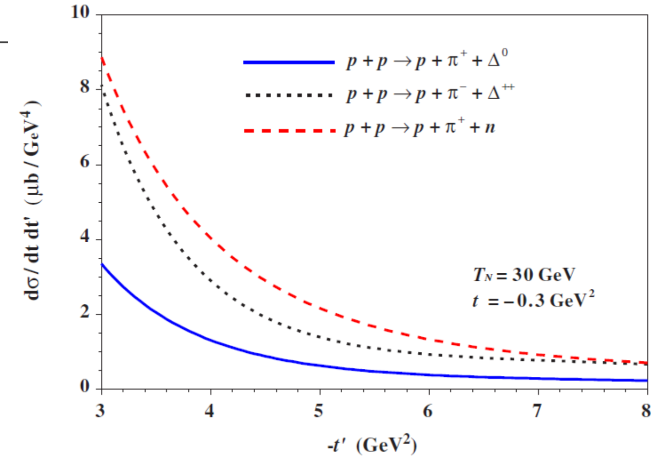
RUN 2 (26 modules)

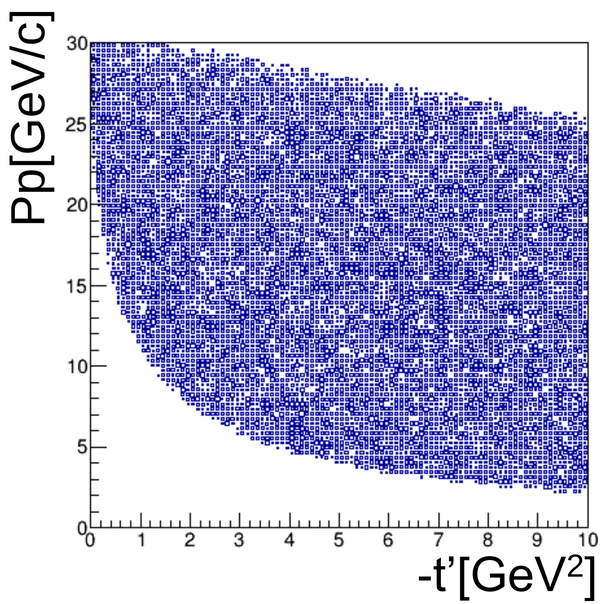


p(30 GeV)p→pπ⁺n

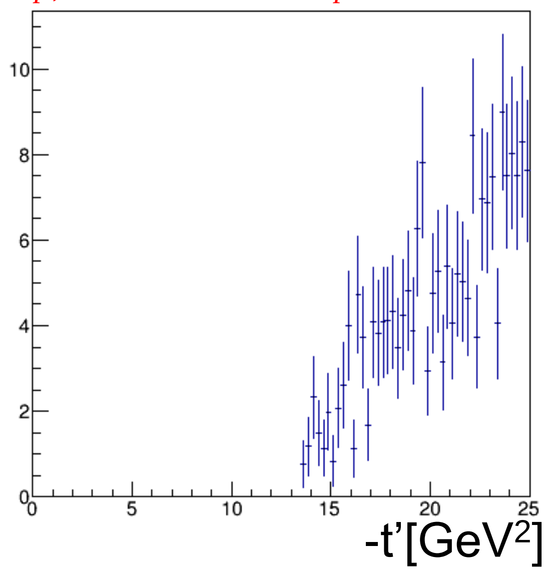








$\theta_{p,\pi} > 15$ deg, $\phi_{p-\pi} > 160$ deg



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.
- Exclusive π-induced Drell-Yan process will a novel approach of measuring GPDs and the measurements 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 two-to-three hard processes within E16 experiment is investigated.