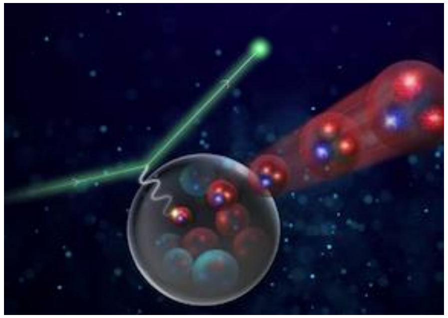
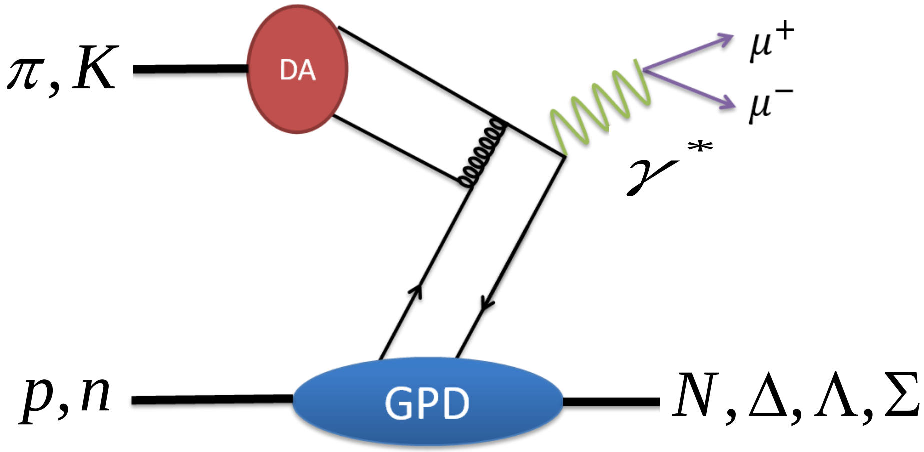


Virtual Workshop of
“The Future of Color Transparency and Hadronization Studies”
June 7-8, 2021



Measuring pion-induced exclusive Drell-Yan process at J-PARC

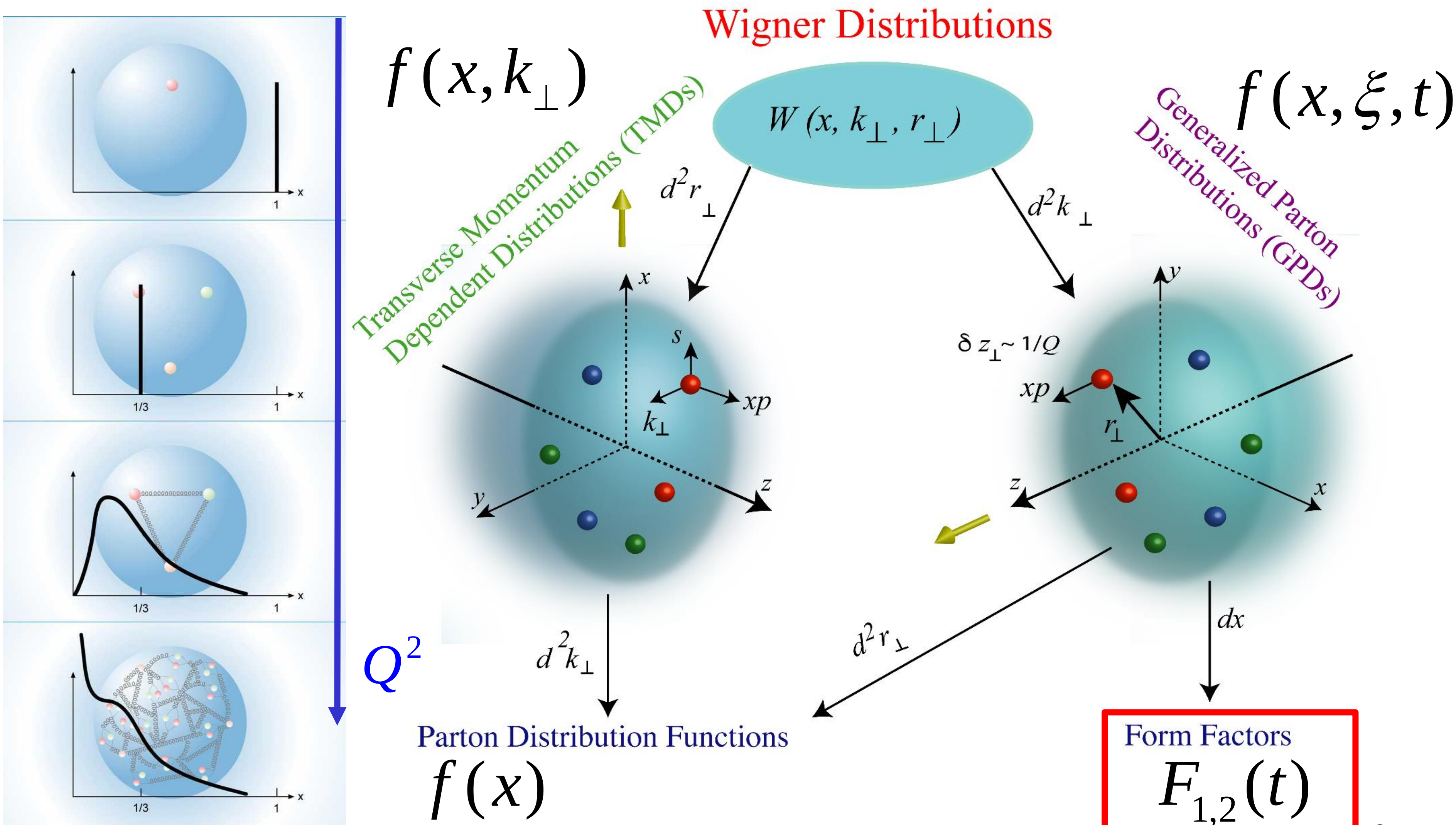
Wen-Chen Chang

Institute of Physics, Academia Sinica, Taiwan

Outline

- Exclusive Drell-Yan Process
  - Measuring GPDs in a time-like approach
  - Connection with color transparency (CT)
- Plan of measurement at J-PARC:
  - High-momentum beamline at J-PARC
  - Feasibility study [PRD93 (2016) 114034]
  - Status and prospects
- Summary

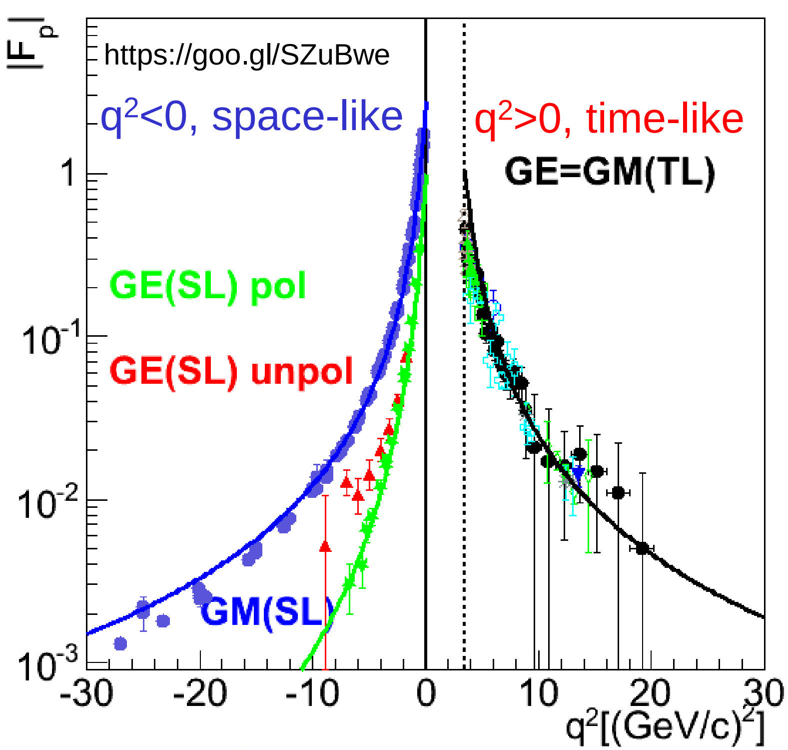
Multi-dimensional Partonic Structures

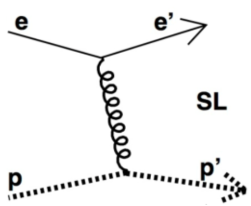


http://www.int.washington.edu/PROGRAMS/17-3/

Electromagnetic Form Factors

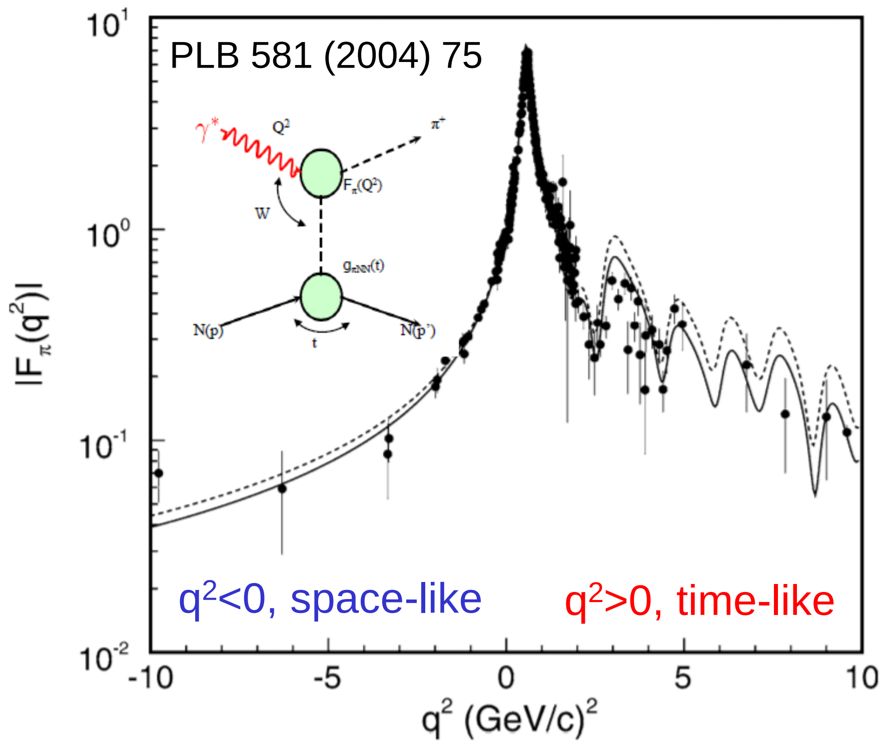
proton

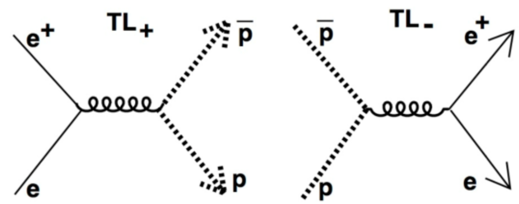




Space-like ($q^2 < 0$):
elastic scattering

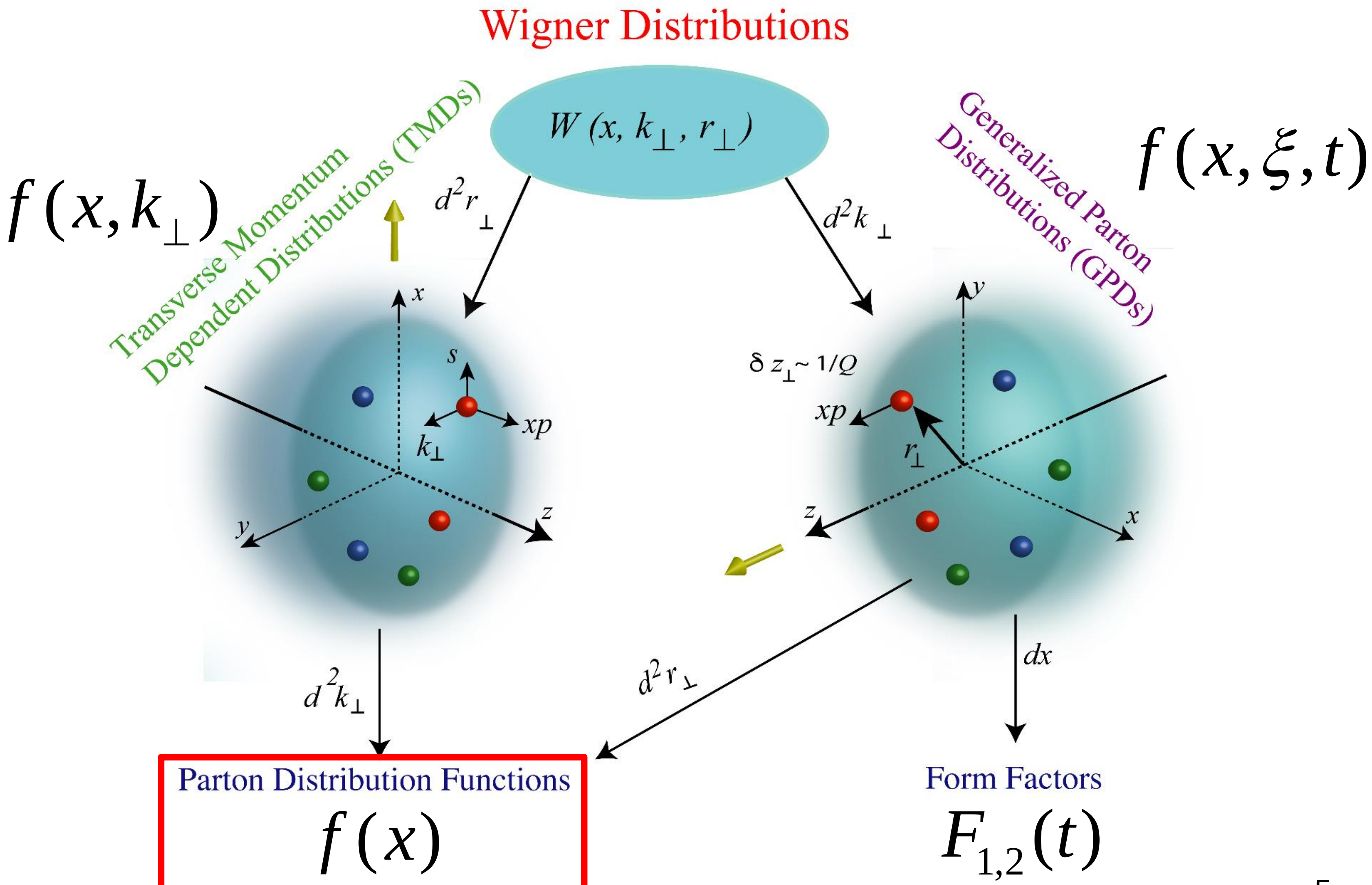
pion





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

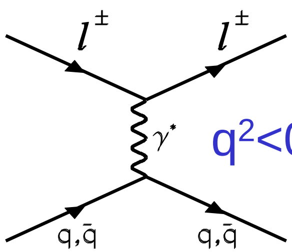
Multi-dimensional Partonic Structures



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

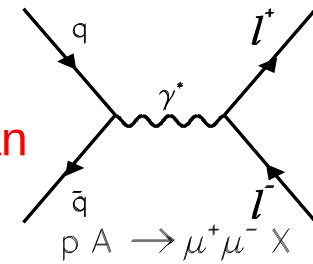
Factorization of Hard Processes

DIS

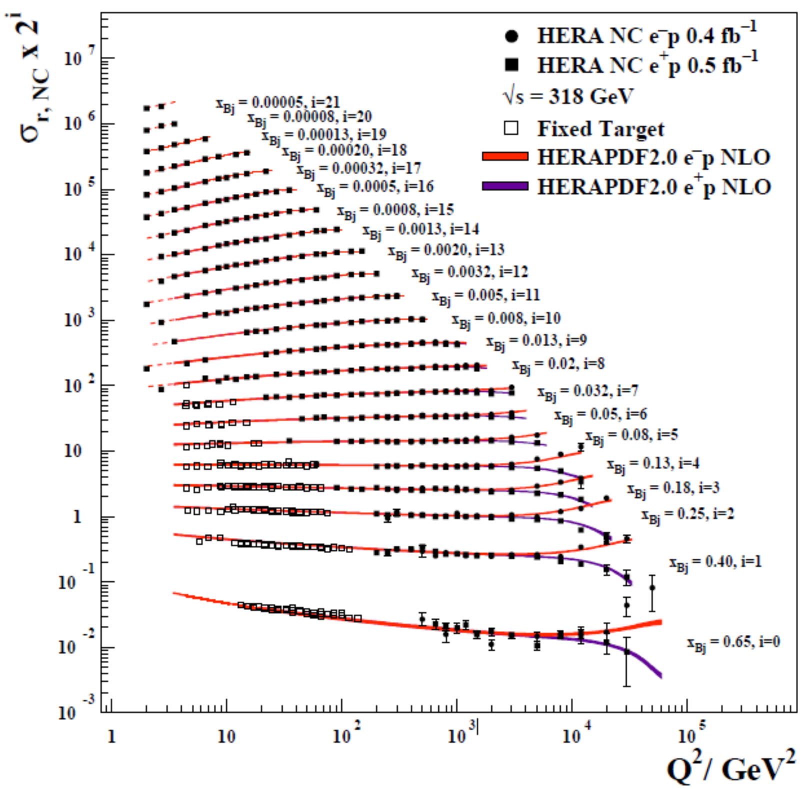


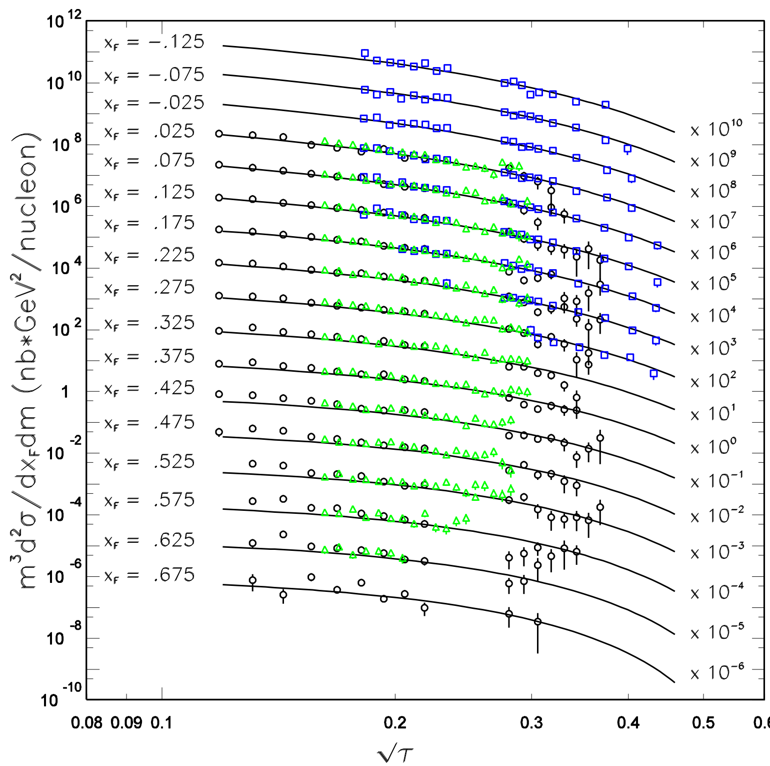
$q^2<0$, space-like

Drell-Yan



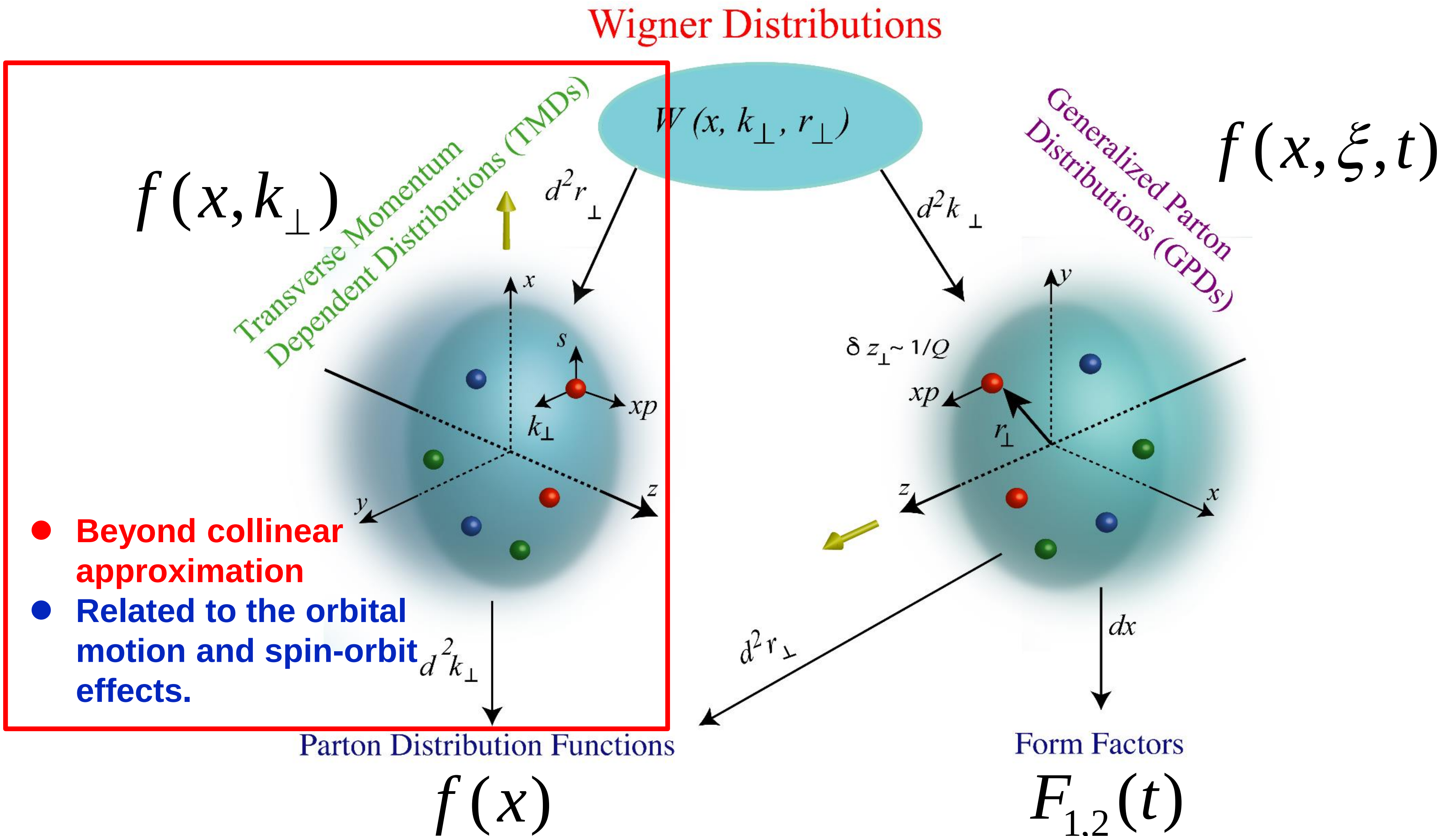
$q^2>0$, time-like





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

Multi-dimensional Partonic Structures



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

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

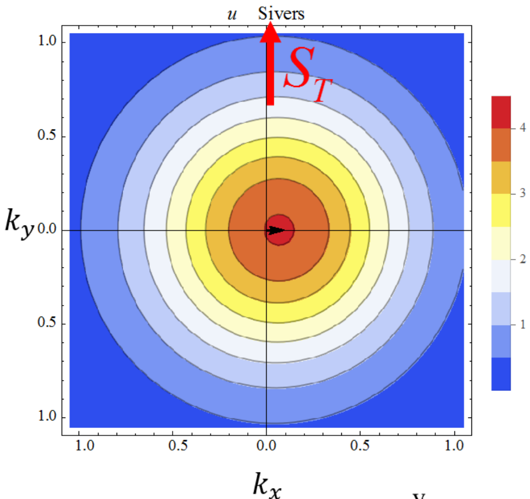
Leading-Twist Transverse-momentum Dependent **Parton Density Function** (TMDs)

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

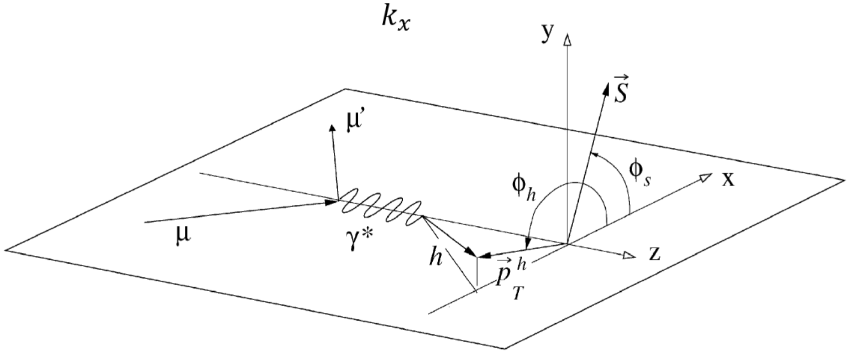
Quark / Nucleon	U	L	T
U	number density $f_1^{q,g}(x, k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x, k_T^2)$
L		Helicity $g_{1L}^{q,g}(x, k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x, k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x, k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x, k_T^2)$	Transversity $h_1^{q,g}(x,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

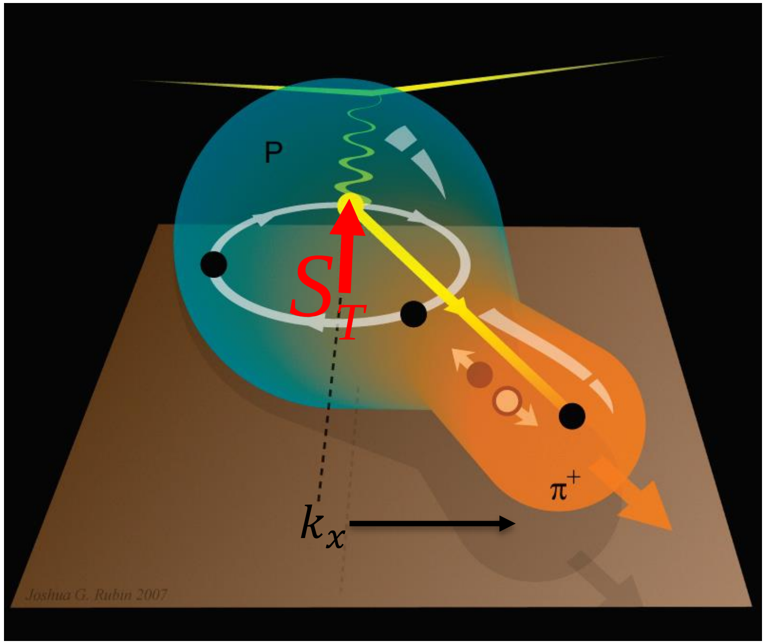
Sivers Asymmetry A_{Siv} in SIDIS (Left-Right Asymmetry w.r.t. S_T)

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



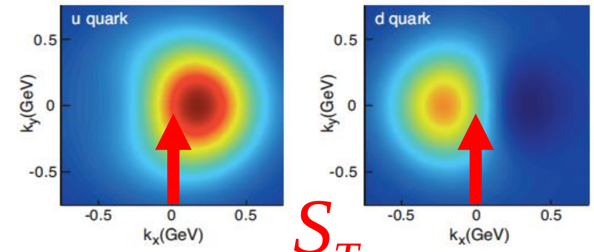
The orbital motion of an u quark inside a proton causes positive-charged pions ($u\bar{d}$) to fly off predominantly to beam-left.





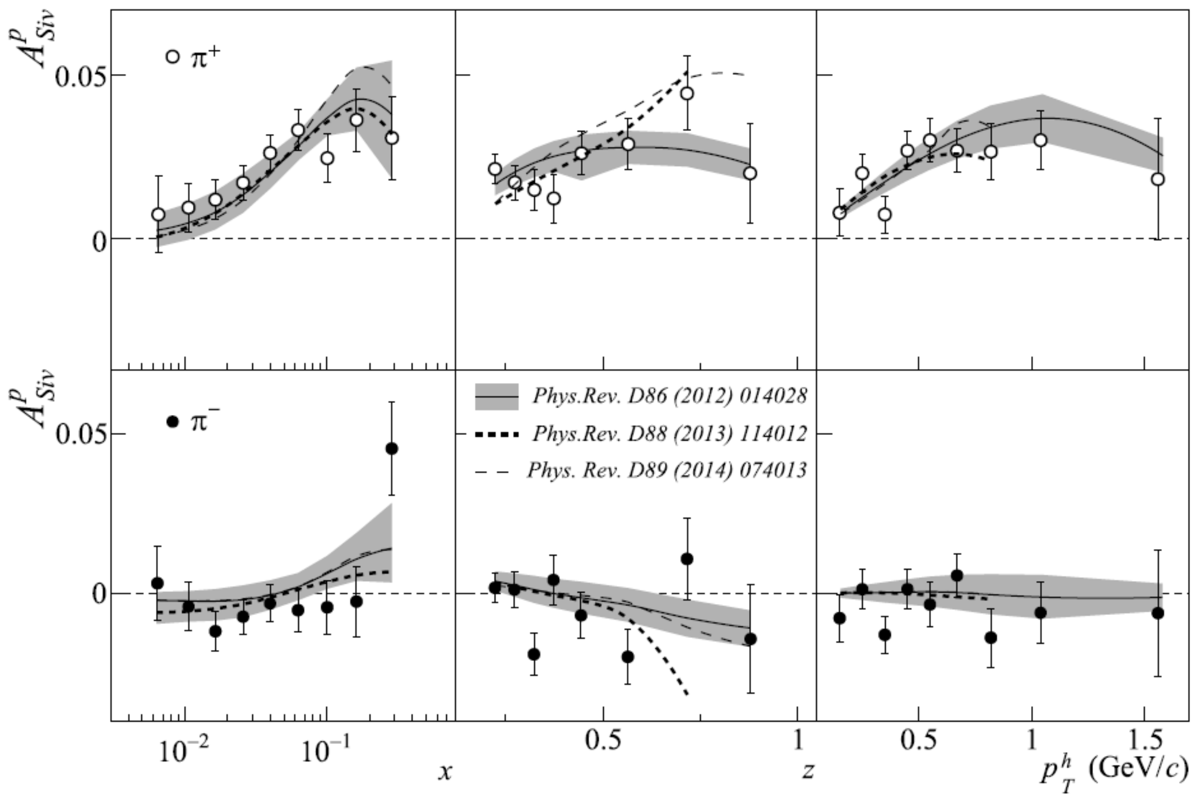
$$A_T^h \equiv \frac{d\sigma(\vec{S}_T) - d\sigma(-\vec{S}_T)}{d\sigma(\vec{S}_T) + d\sigma(-\vec{S}_T)} = \left|\vec{S}_T\right| \cdot [D_{NN} \cdot A_{Coll} \cdot \sin(\phi_h + \phi_S - \pi) + A_{Siv} \cdot \sin(\phi_h - \phi_S)]$$

Nonzero Sivers Asymmetries from SIDIS

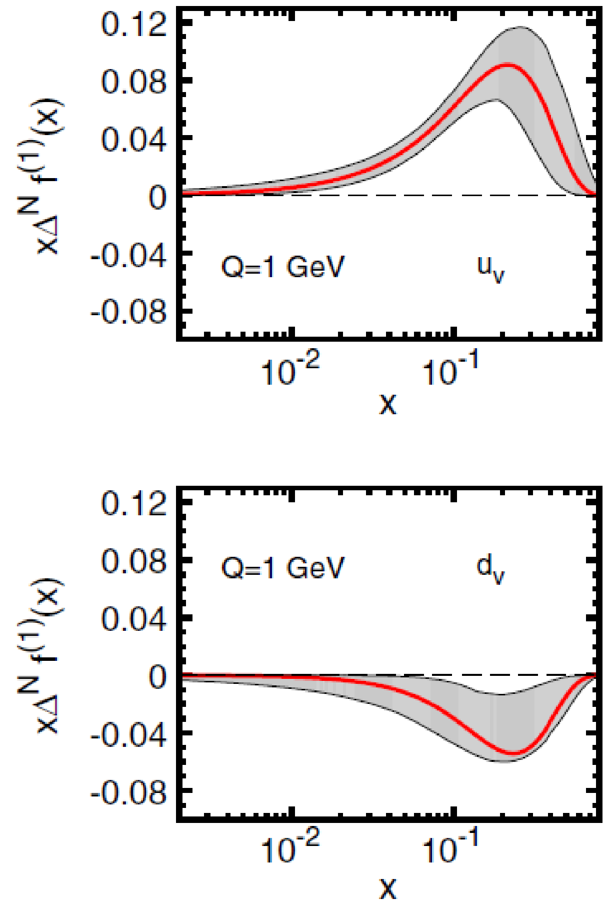


S_T

COMPASS, PLB 744 (2015) 250



Sivers Functions



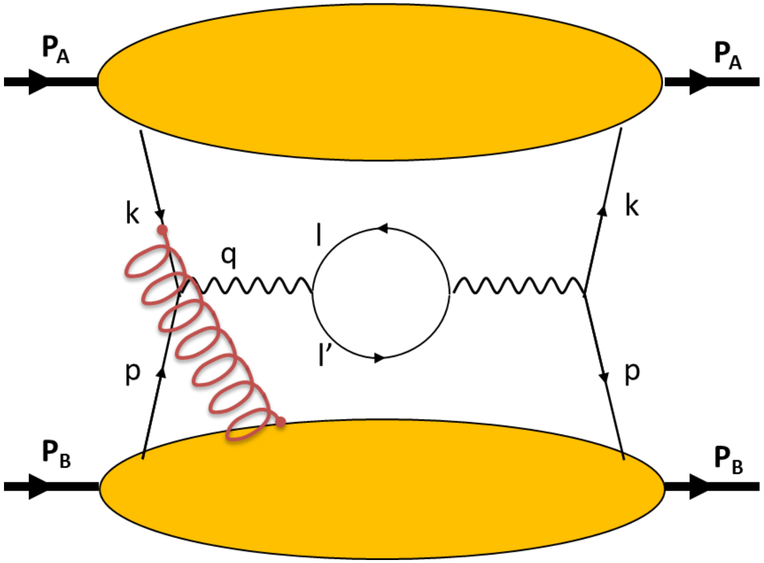
SIDIS $\gamma^*(q^2 < 0)p_\uparrow \to hX$

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

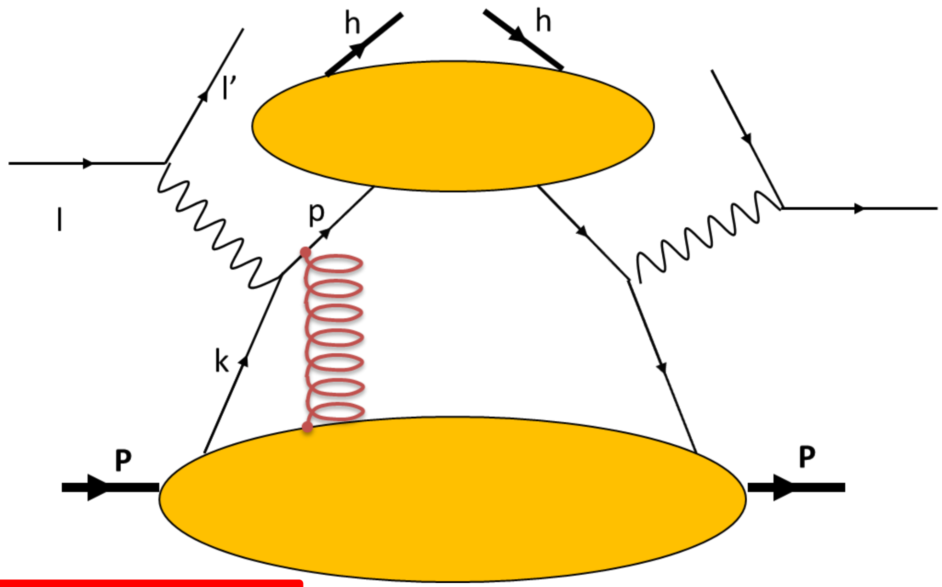
Non-Universality of Sivers Functions

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



SIDIS

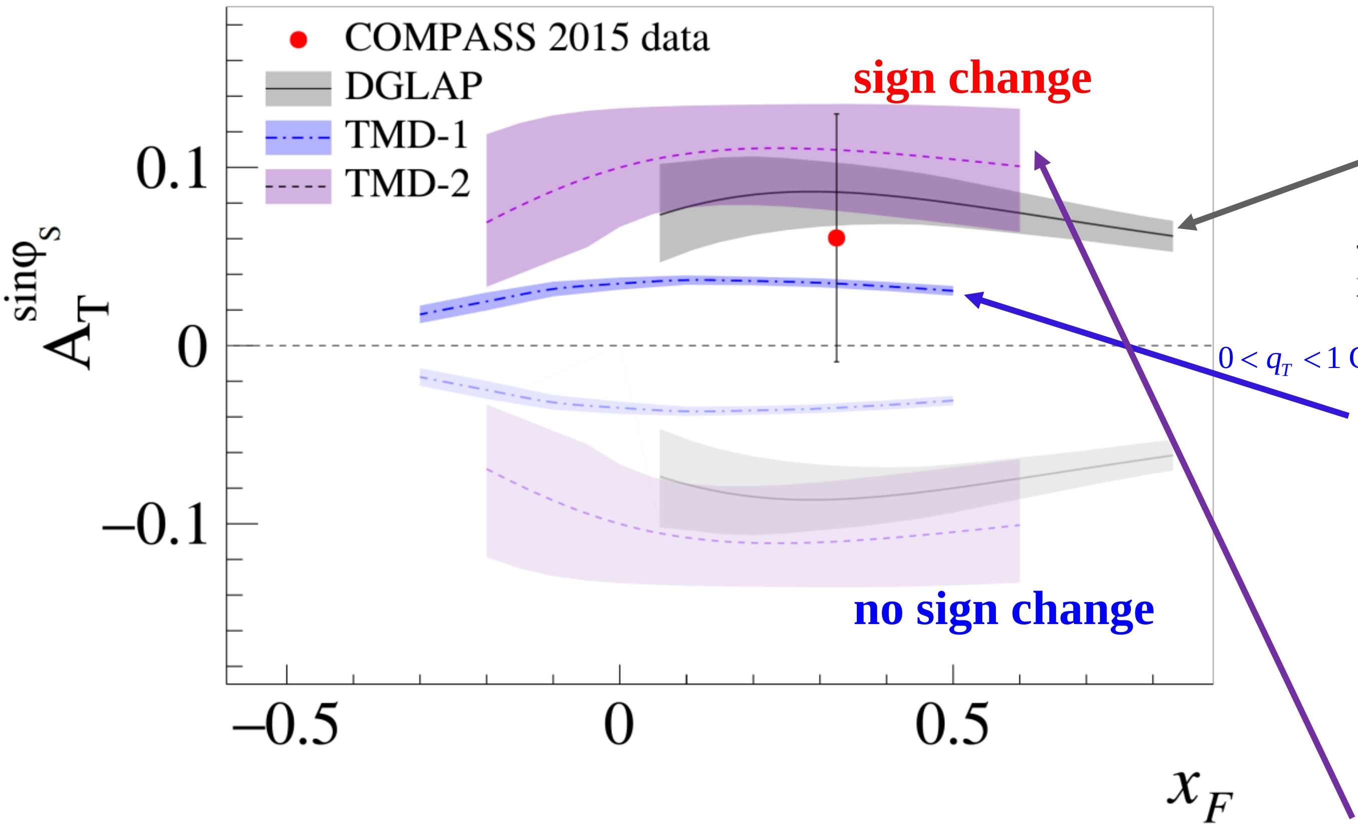


$hp_{\uparrow} \to \gamma^*(q^2 > 0)X$ $\quad \text{Sivers}\,|_{DY} = -\text{Sivers}\,|_{SIDIS}$ $\quad \gamma^*(q^2 < 0)p_{\uparrow} \to hX$

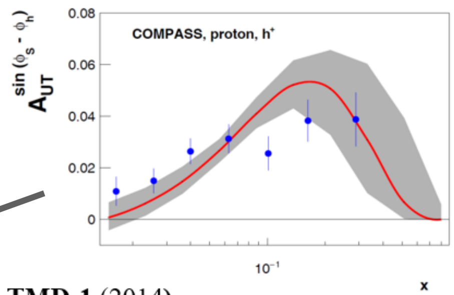
- QCD gluon gauge link (Wilson line) in the initial state (DY) vs. final state interactions (SIDIS).
- ***Fundamental predictions from TMD physics will be tested.***

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

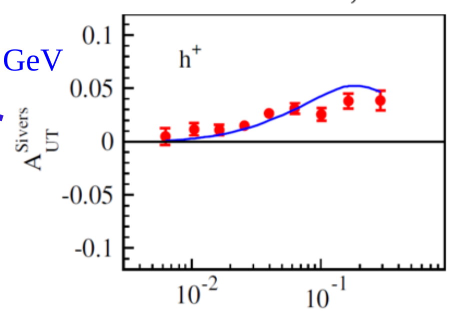
COMPASS, PRL 119 (2017) 112002



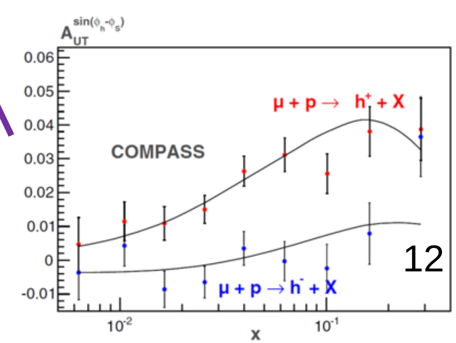
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



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

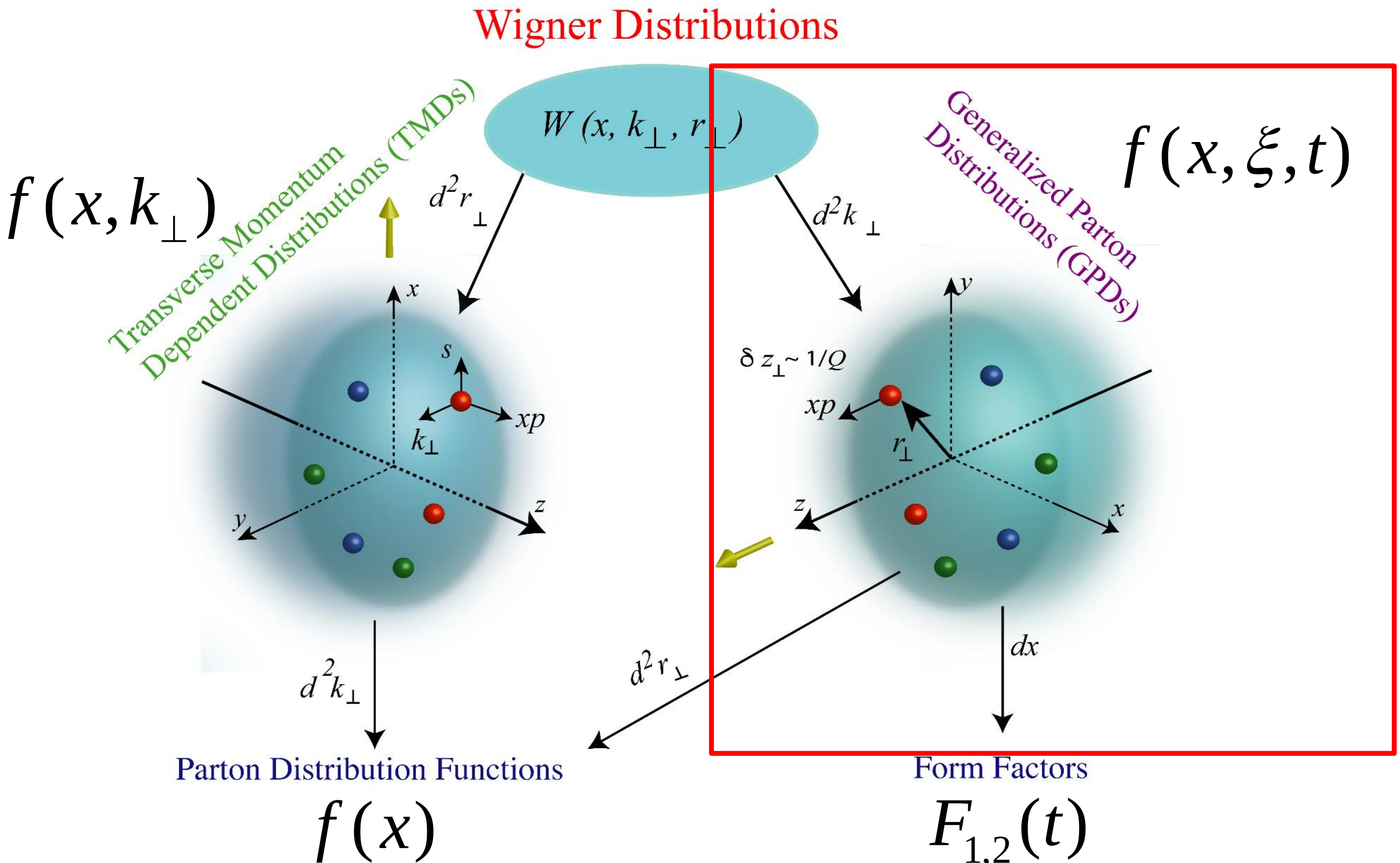


TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



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

Multi-dimensional Partonic Structures

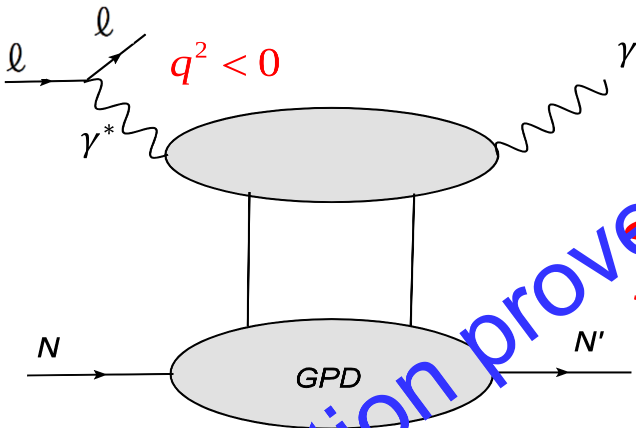


http://www.int.washington.edu/PROGRAMS/17-3/

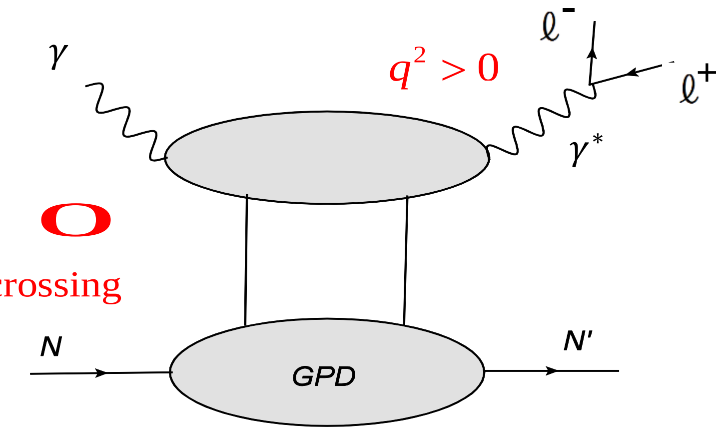
Generalized Parton Distributions

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

Deeply Virtual Compton Scattering



Time-like Compton Scattering



$t < 0$

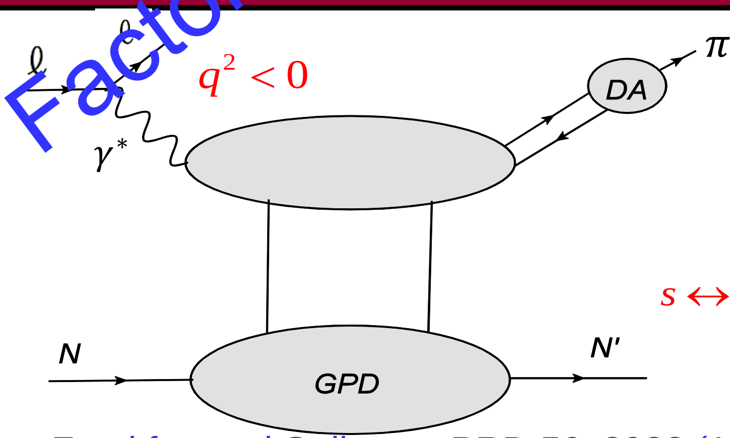
$q^2 > 0$

$s \leftrightarrow u$ channel crossing

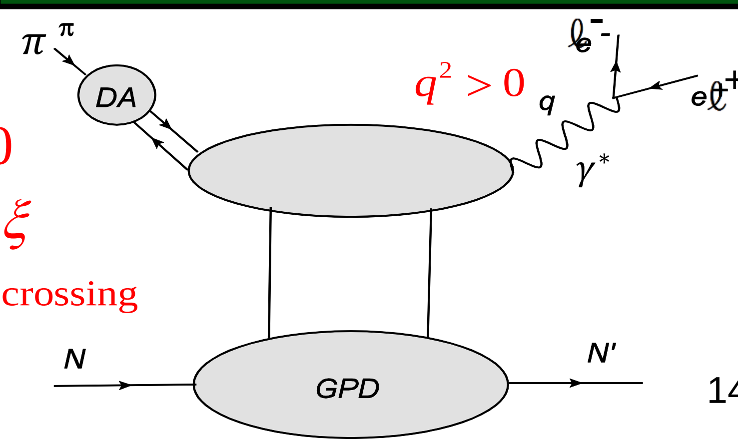
Factorization proved!

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

Deeply Virtual Meson Production



Exclusive meson-induced DY



$t < 0$

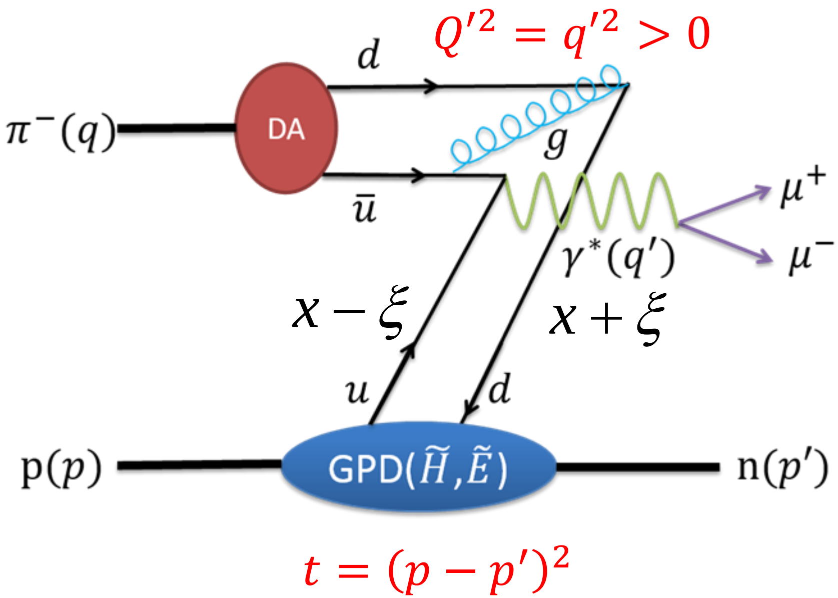
$|x| < \xi$

$s \leftrightarrow u$ channel crossing

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

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

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



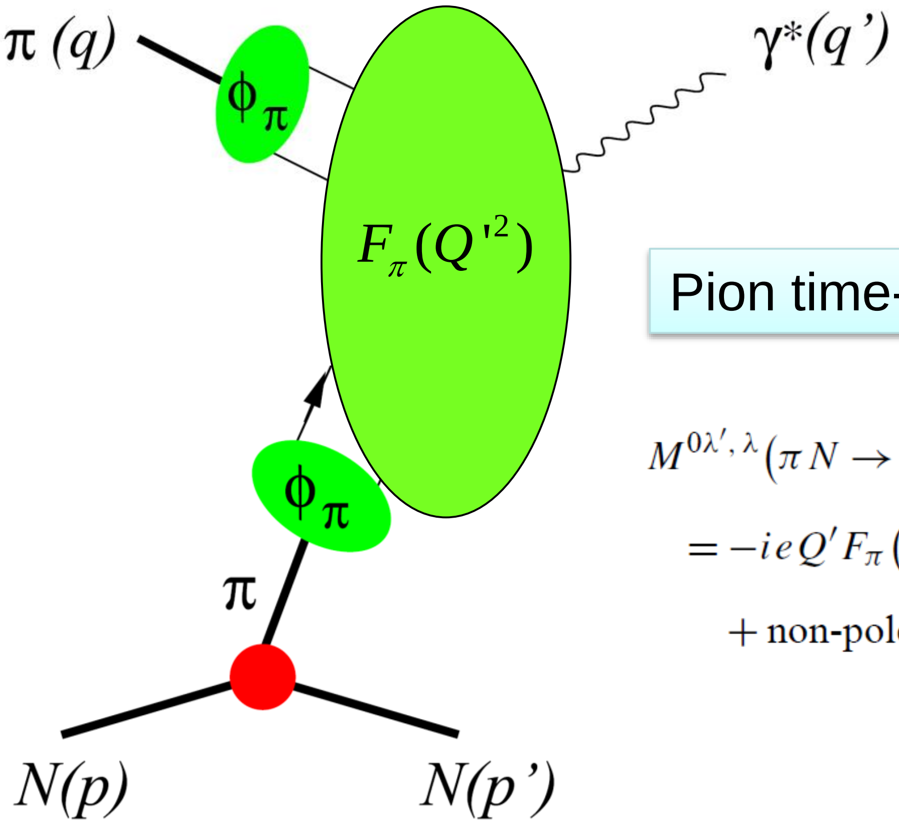
$$\tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s - M_N^2} \qquad \xi = \frac{(p-p')^+}{(p+p')^+} = \frac{\tau}{2-\tau}$$

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

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

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

Pion Timelike FFs



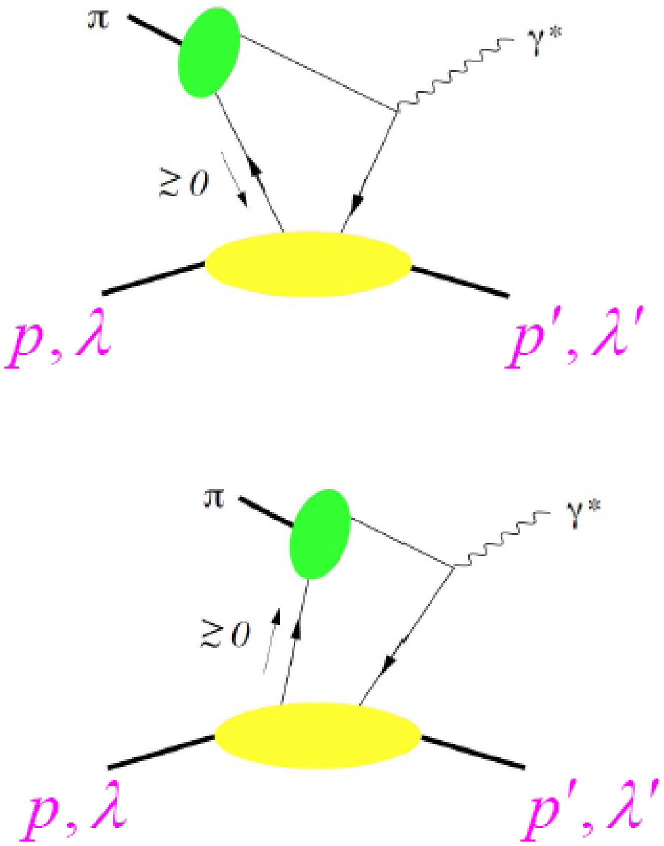
Pion time-like form factors

$$M^{0\lambda',\lambda}(\pi N \to \gamma^* N) = -ieQ' F_\pi(Q'^2)\frac{F_{\text{pole}}(t)}{2Mf_\pi}\bar{u}(p',\lambda')\gamma_5 u(p,\lambda) + \text{non-pole terms.}$$

"…the presence of CT in such models is closely related to the issue of shrinking of $q\bar{q}$ configurations in the pion contributing to the pion form factor in the timelike region. "
Larionov, Strikman and Bleicher, PRC 93, 034618 (2016)

Non-factorizable Contributions

$Q' = 2 - 3\ \mathrm{GeV}$



Light-cone QCD sum rules

$$= g_v^- \int_\eta^{x_0} dx\, e^{-\frac{x-\eta}{x+\eta}\frac{Q'^2}{M_B^2}}\, \tilde{C}_H(x,\eta,Q'^2)$$

$$\times \left[e_u \tilde{H}^{du}(x,\eta,t) - e_d \tilde{H}^{du}(-x,\eta,t) \right]$$

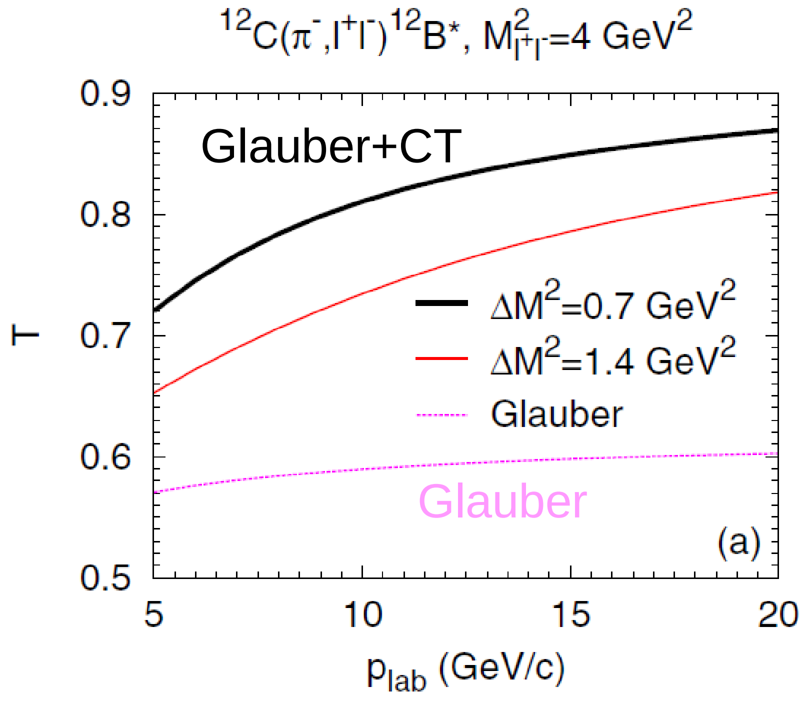
$$\times \overline{u}(p'\lambda')\gamma^+\gamma_5 u(p\lambda) + \cdots$$

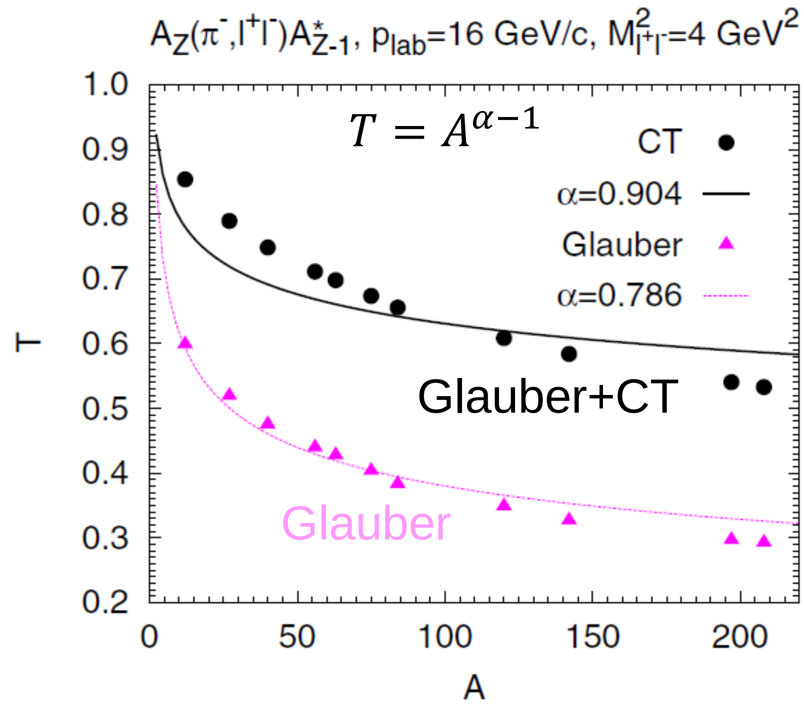
$$\tilde{H}^{du}(x,\eta,t) = \tilde{H}^{u}(x,\eta,t) - \tilde{H}^{d}(x,\eta,t)$$

Kazuhiro Tanaka, arXiv:1703.02190, 1709.01063

Color Transparency in $\pi^- A \rightarrow \gamma^* n(A-1)$

Larionov, Strikman and Bleicher, PRC 93, 034618 (2016)



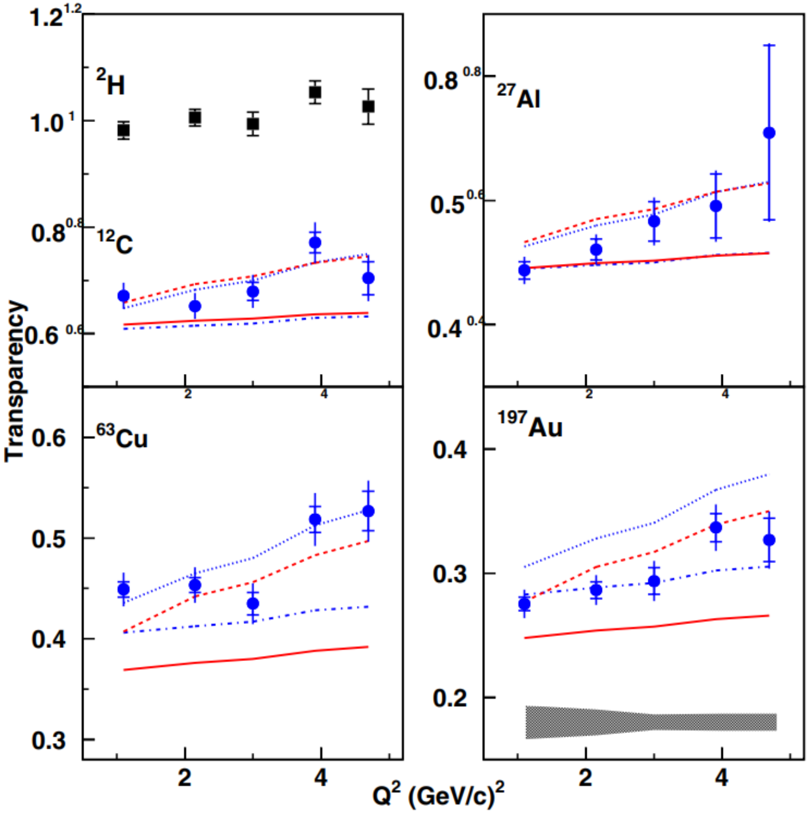


$$T_{l^-l^+} = \frac{d^4\sigma_{\pi^- A \to l^- l^+}/d^4q}{Z d^4\sigma_{\pi^- p \to l^- l^+ n}/d^4q}$$

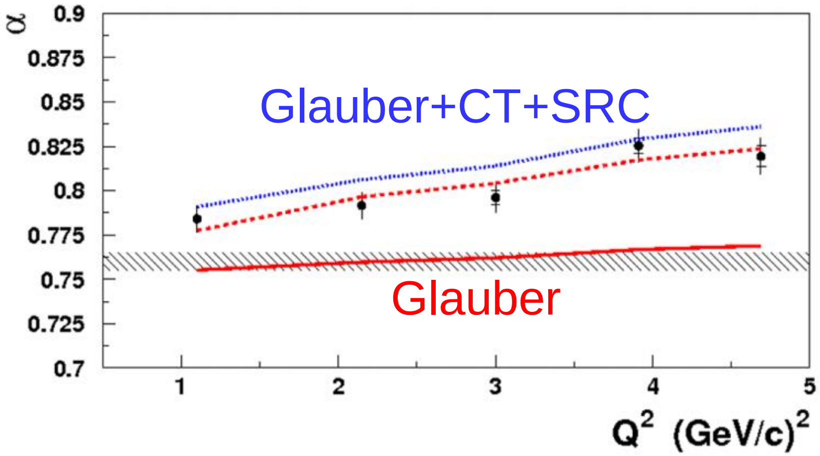
Experimental evidences of CT will be important to support the factorization of $\pi^- p \rightarrow \gamma^* n$ process.

Color Transparency in $\gamma^* A \rightarrow \pi^+ n(A-1)$

JLAB, Hall C, PRL 99, 242502 (2007)



$$T = A^{\alpha-1}$$

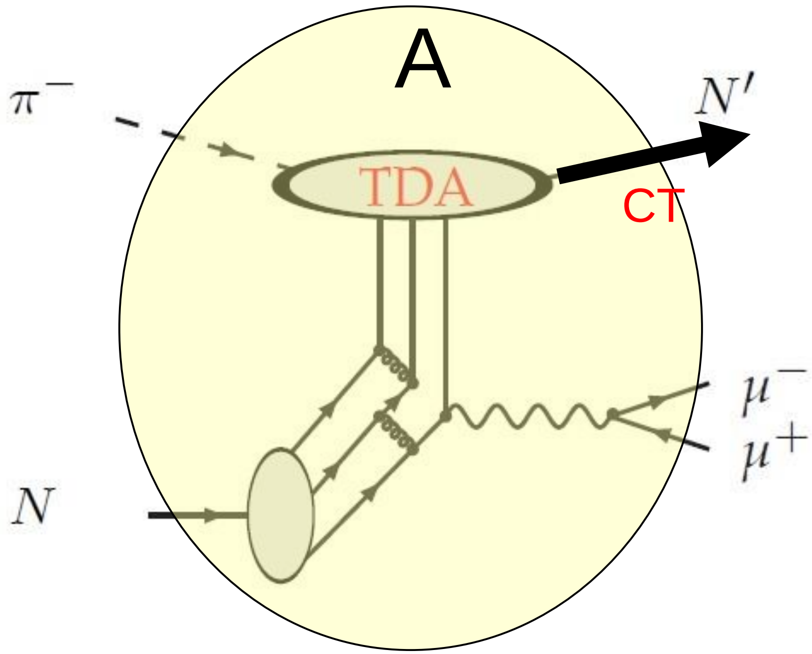


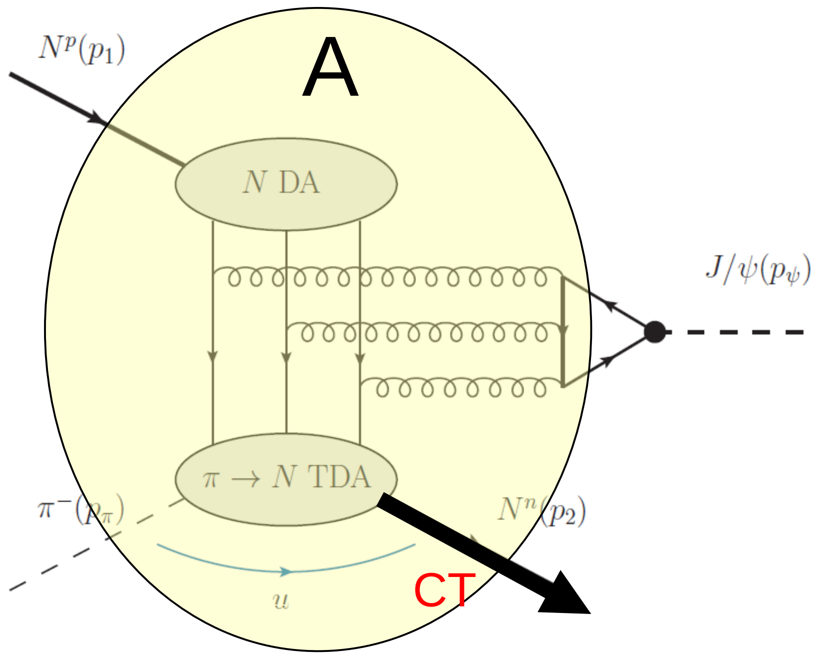
$$T = (\bar{Y}/\bar{Y}_{\mathrm{MC}})_{\mathrm{A}}/(\bar{Y}/\bar{Y}_{\mathrm{MC}})_{\mathrm{H}}$$

u–channel (Backward)

—Transition Distribution Amplitude (TDA)

$\pi^- + \mathrm{p}, \mathrm{A} \rightarrow \gamma^*, \mathrm{J}/\psi + \mathrm{n}$ at large |t|





Bernard Pire , IWHS2011

Pire et al., PRD 95, 034021 (2017)

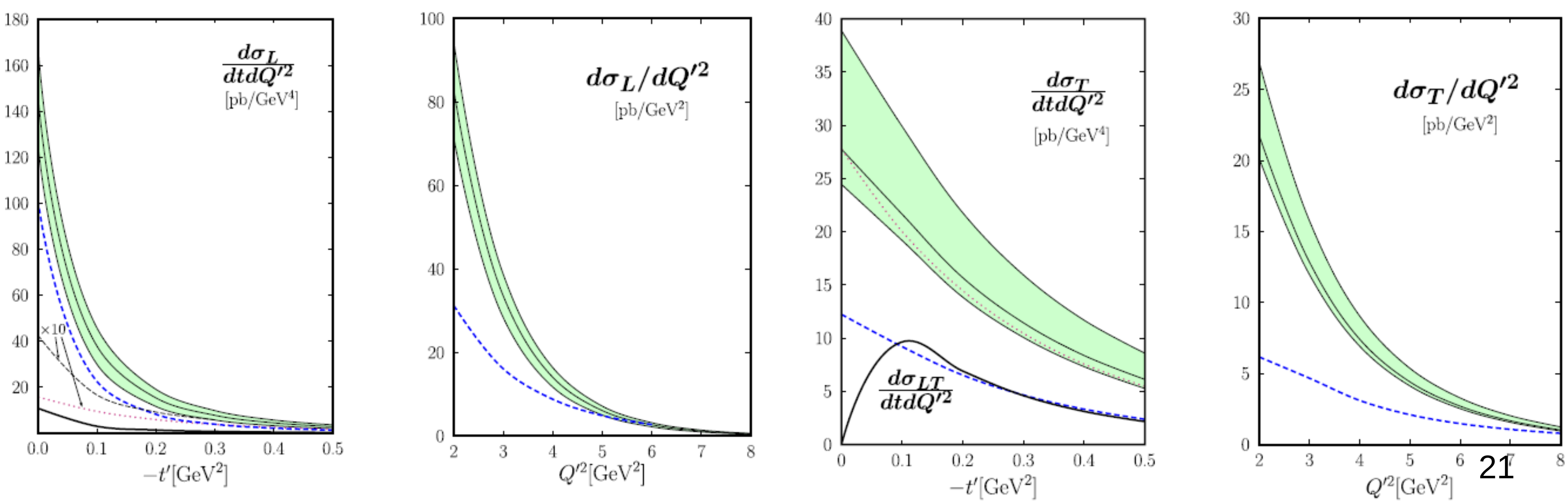
Beyond the Leading Twist

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, $\bar{E}_T$

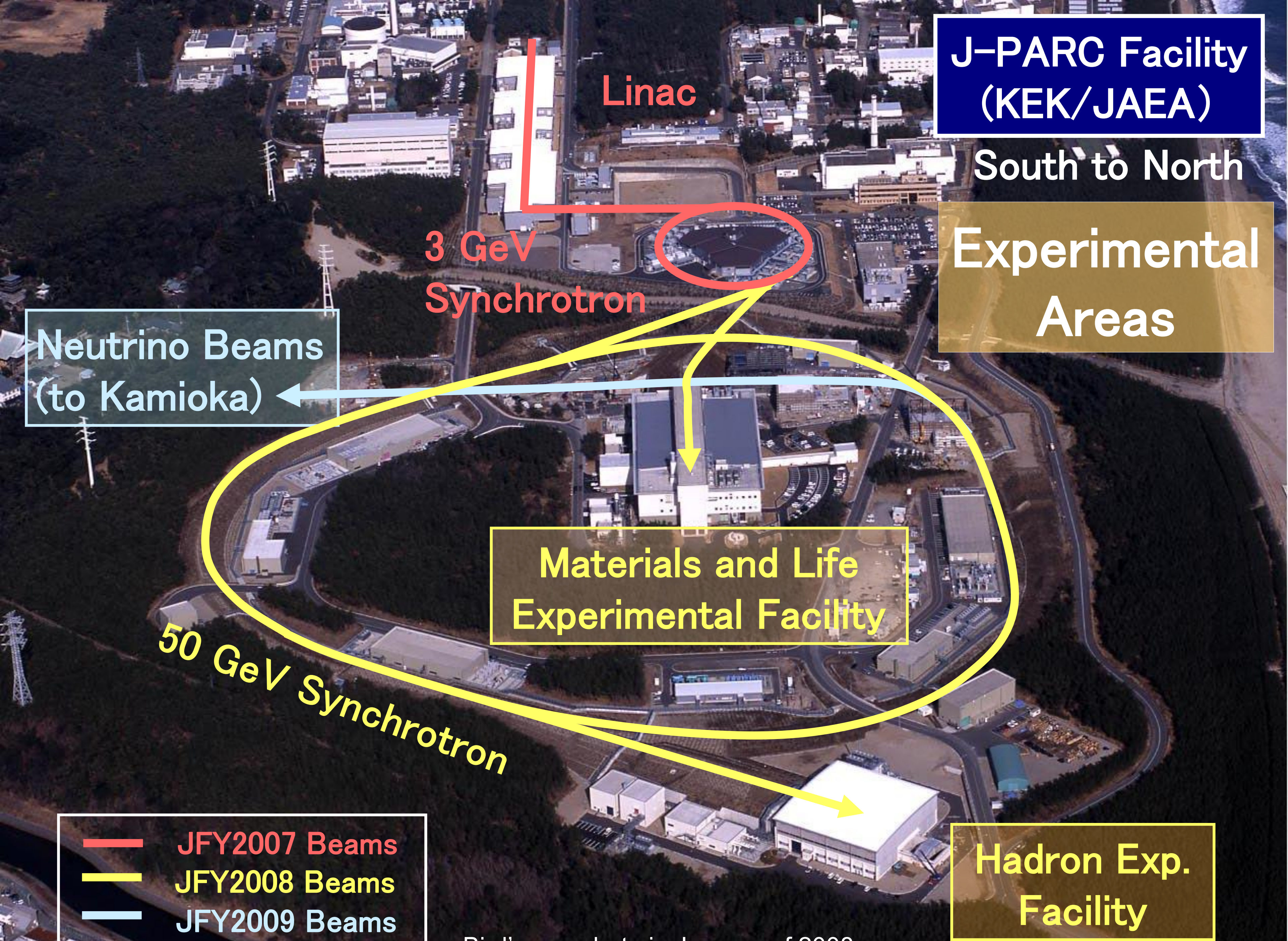
Question: Will the CT effect show dependence of γ^* polarization?



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

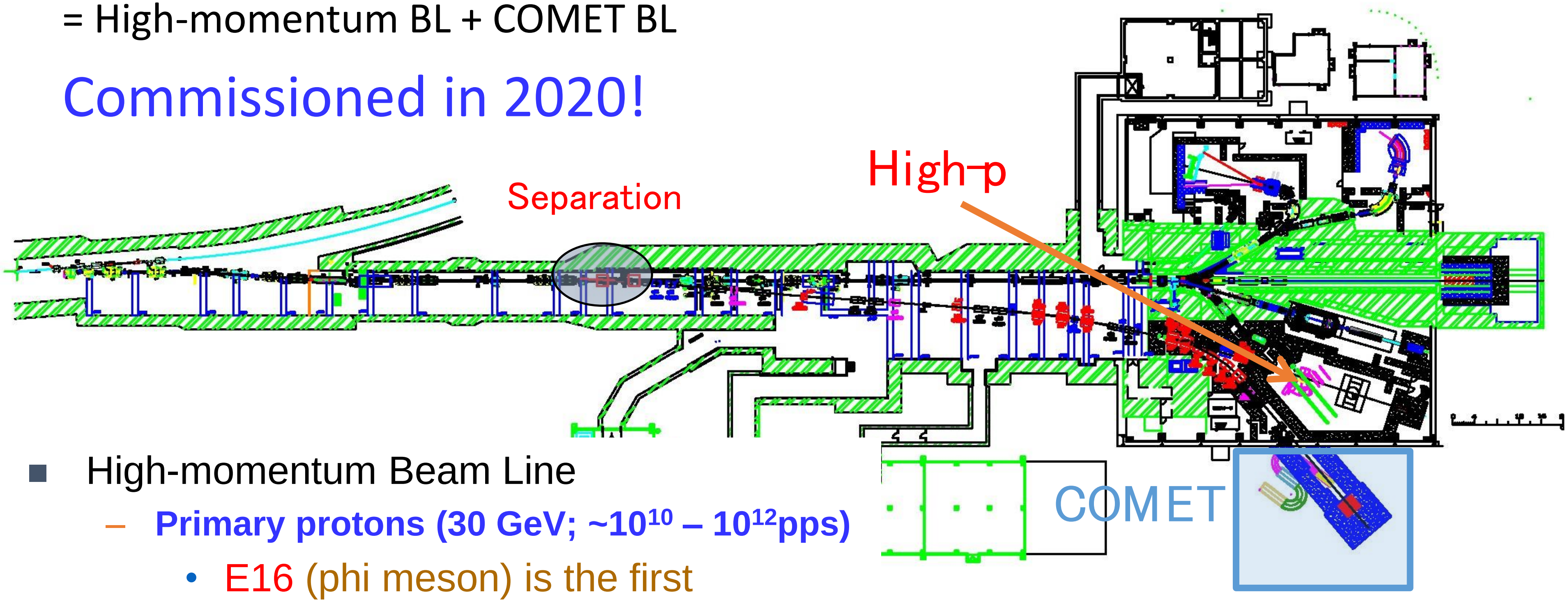


Bird's eye photo in January of 2008

J-PARC High-momentum Beam Line

New primary Proton Beam Line
= High-momentum BL + COMET BL

Commissioned in 2020!

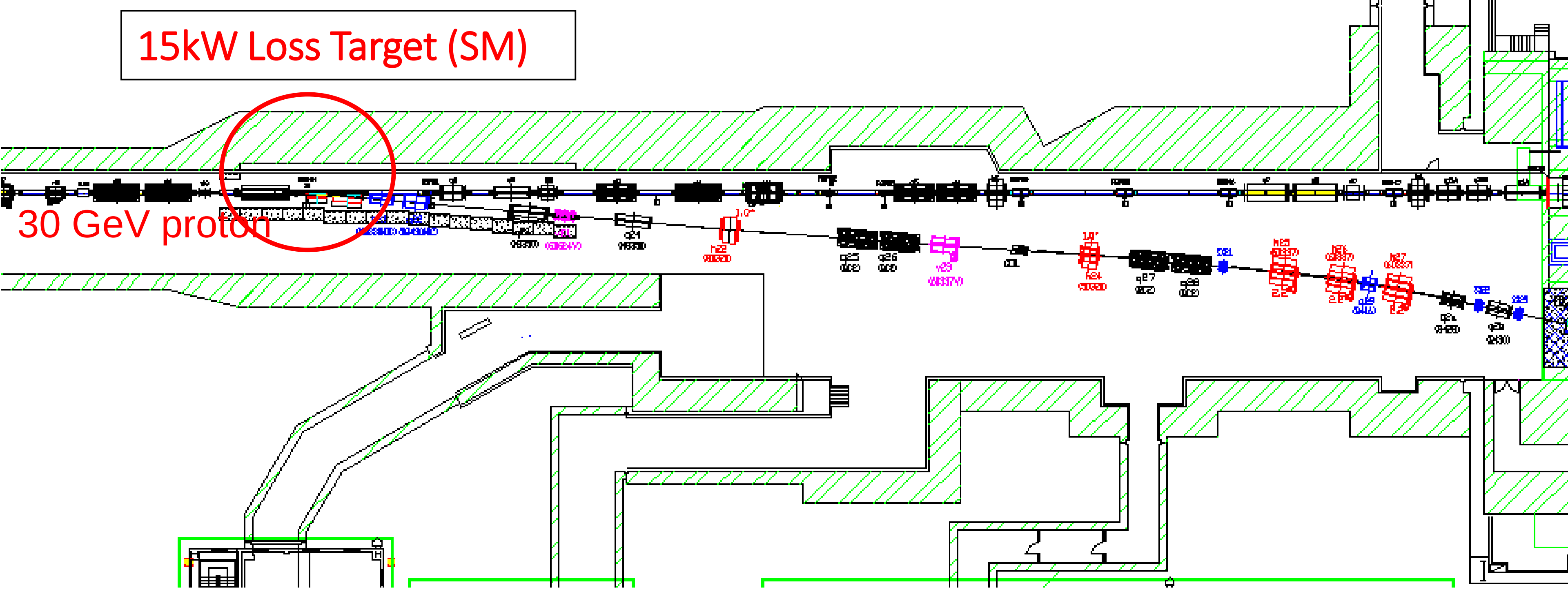


- High-momentum Beam Line
  - **Primary protons (30 GeV; ~10^{10} – 10^{12}pps)**
    - E16 (phi meson) is the first experiment.
  - Unseparated secondary particles (pi, …)
    - High-resolution secondary beam by adding several quadrupole and sextupole magnets.

- COMET
  - Search for μ to e conversion
  - 8 GeV, 50 kW protons
  - Branch from the high-momentum BL
  - Annex building is being built at the south side.

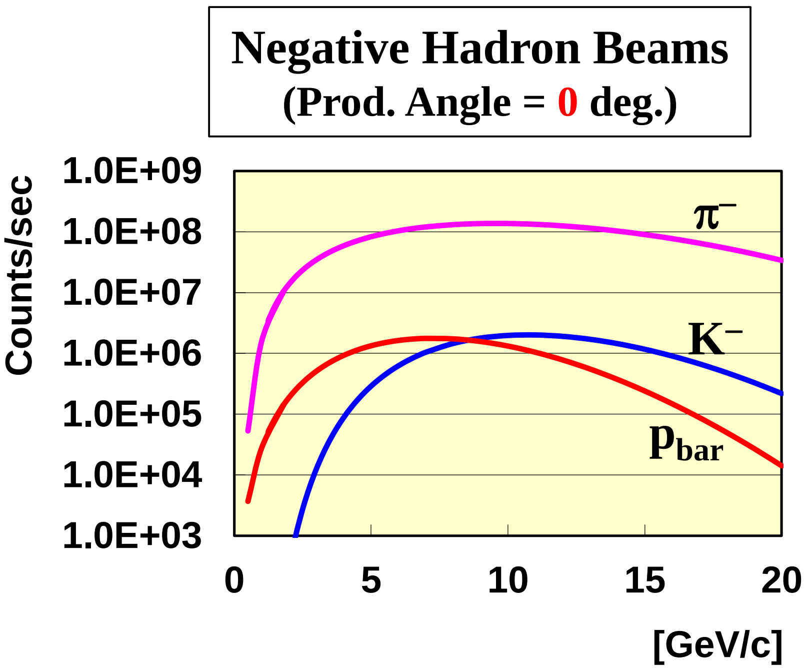
J-PARC High-momentum Beam Line (Hi-P BL)

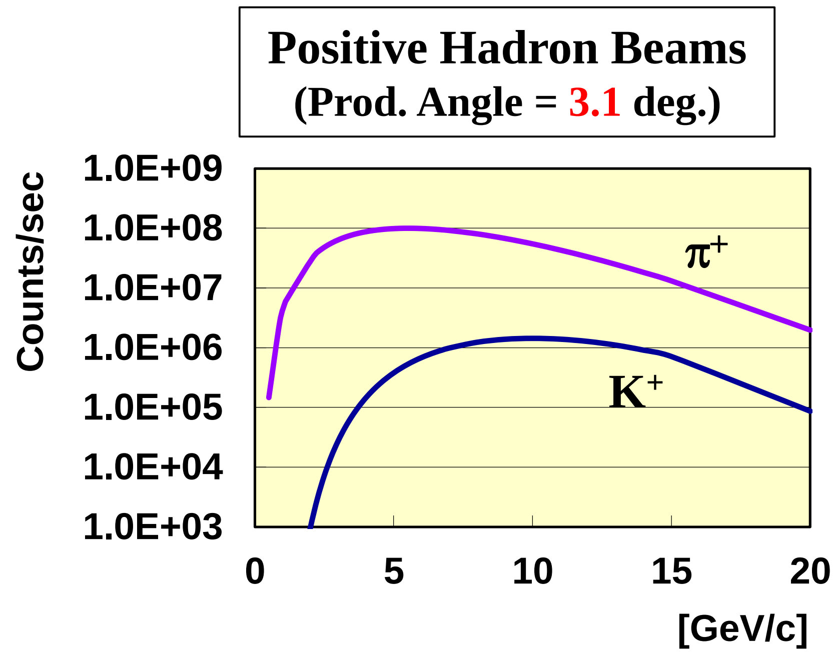
- High-intensity secondary pion beam
- High-resolution beam: Δp/p ~ 0.1%



J-PARC High-momentum Beam Line (Hi-P BL)

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



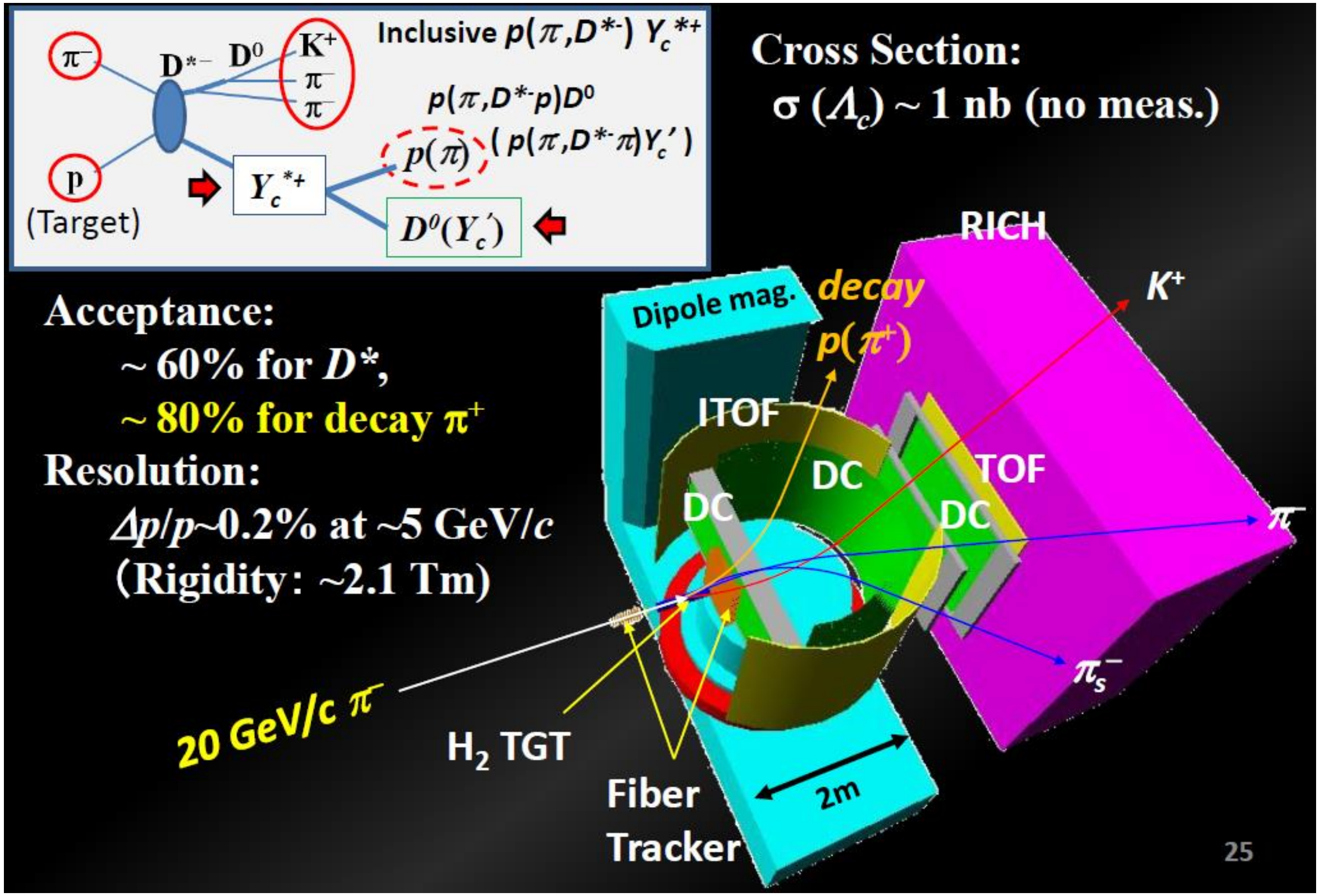


*** Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m**

J-PARC E50 Experiment

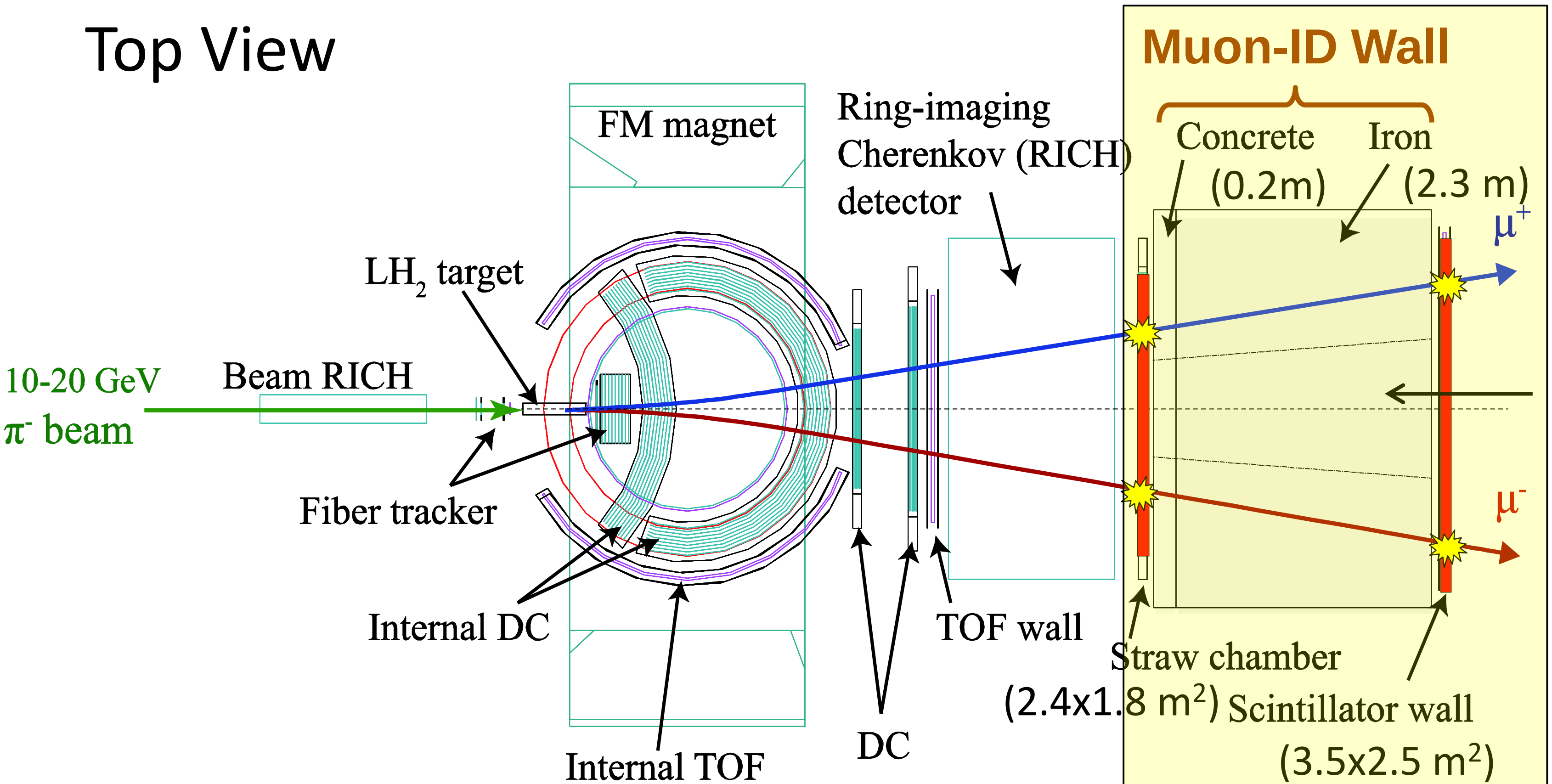
(Charmed Baryon Spectroscopy)

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



H. Noumi, KEK workshop 2015

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



Original Configuration
for Charmed Baryon Spectroscopy

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

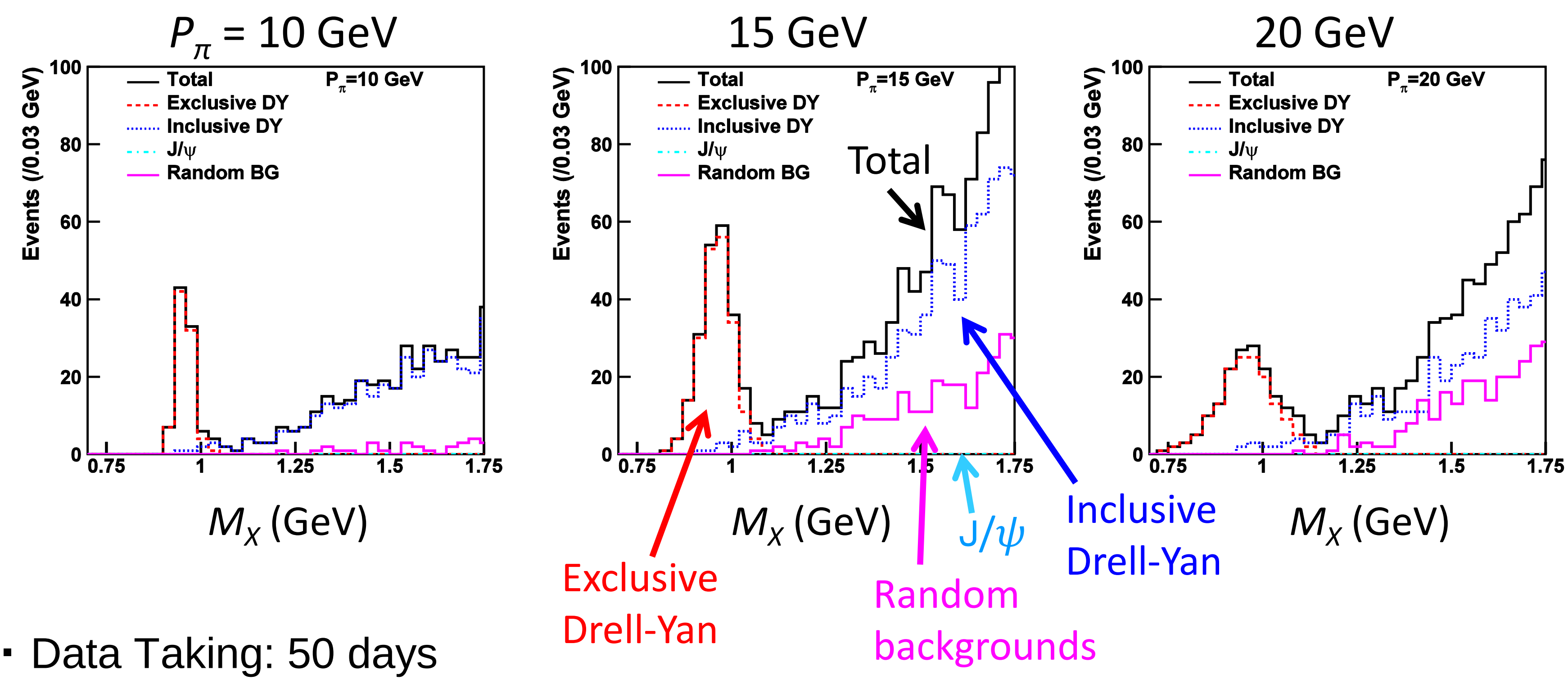
Extension part

Proposal is currently being prepared.

$\pi^- N \to l^+ l^- X$ 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

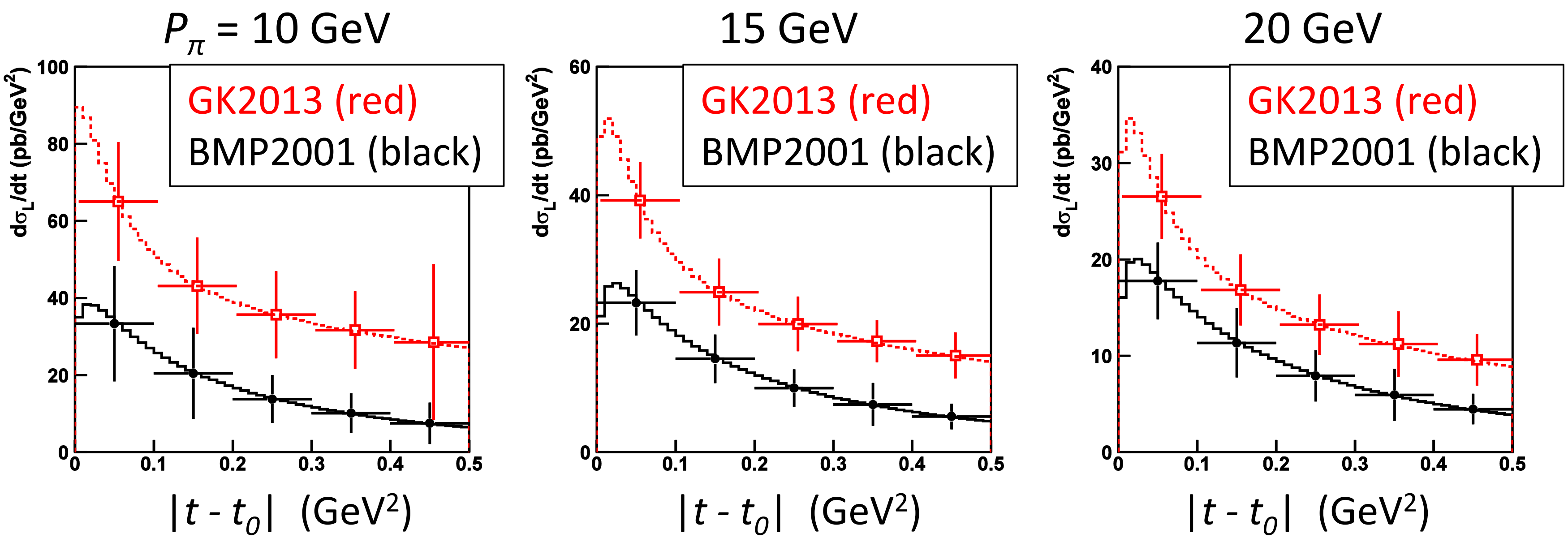


- Data Taking: 50 days
- $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV
- $|t - t_0| < 0.5$ GeV^2
- "GK2013" GPDs

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

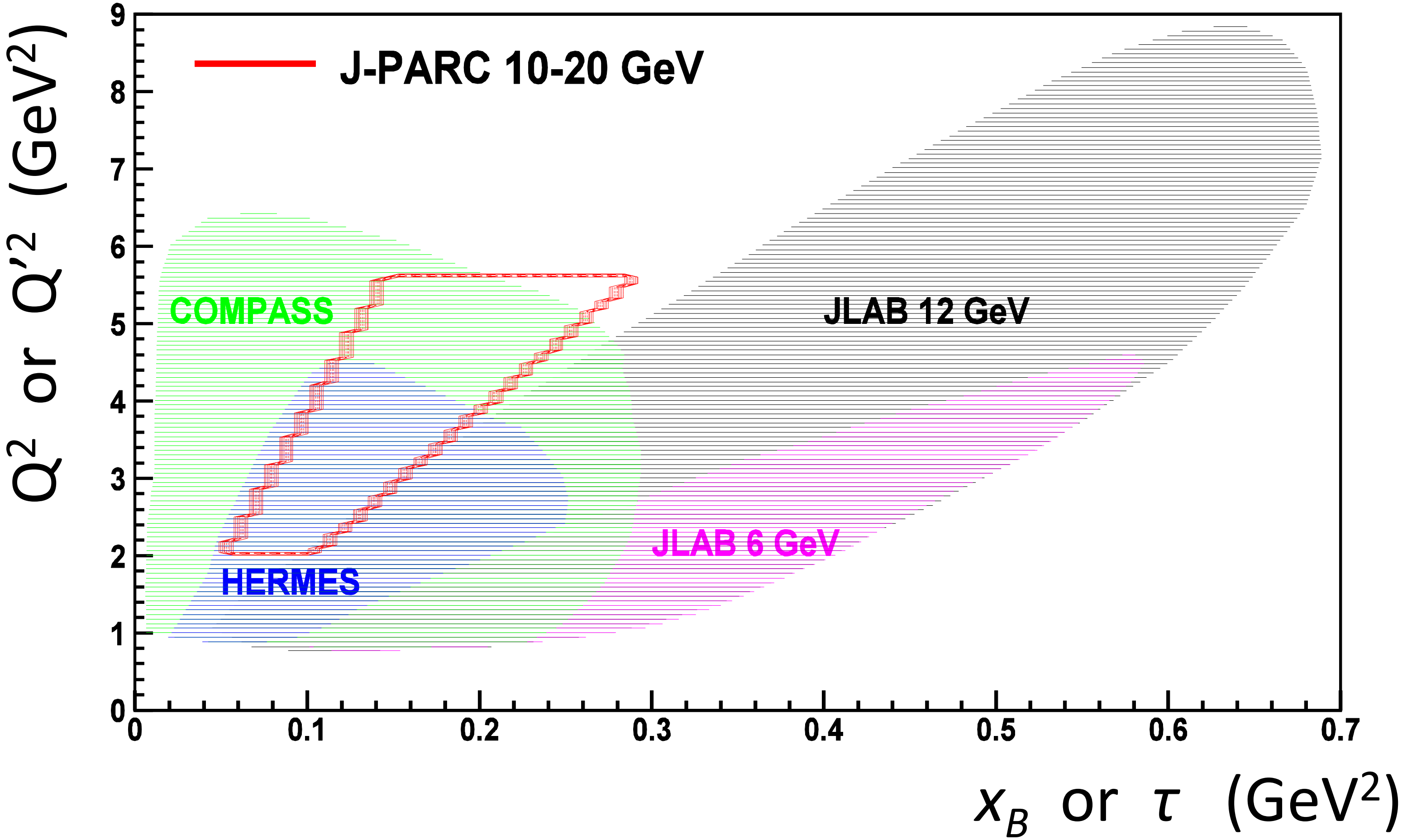
π^- Beam Momentum



- 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.

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

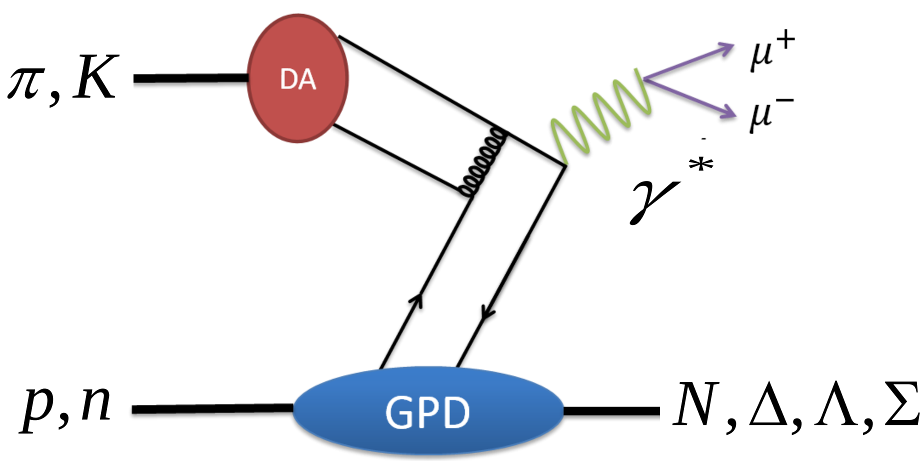


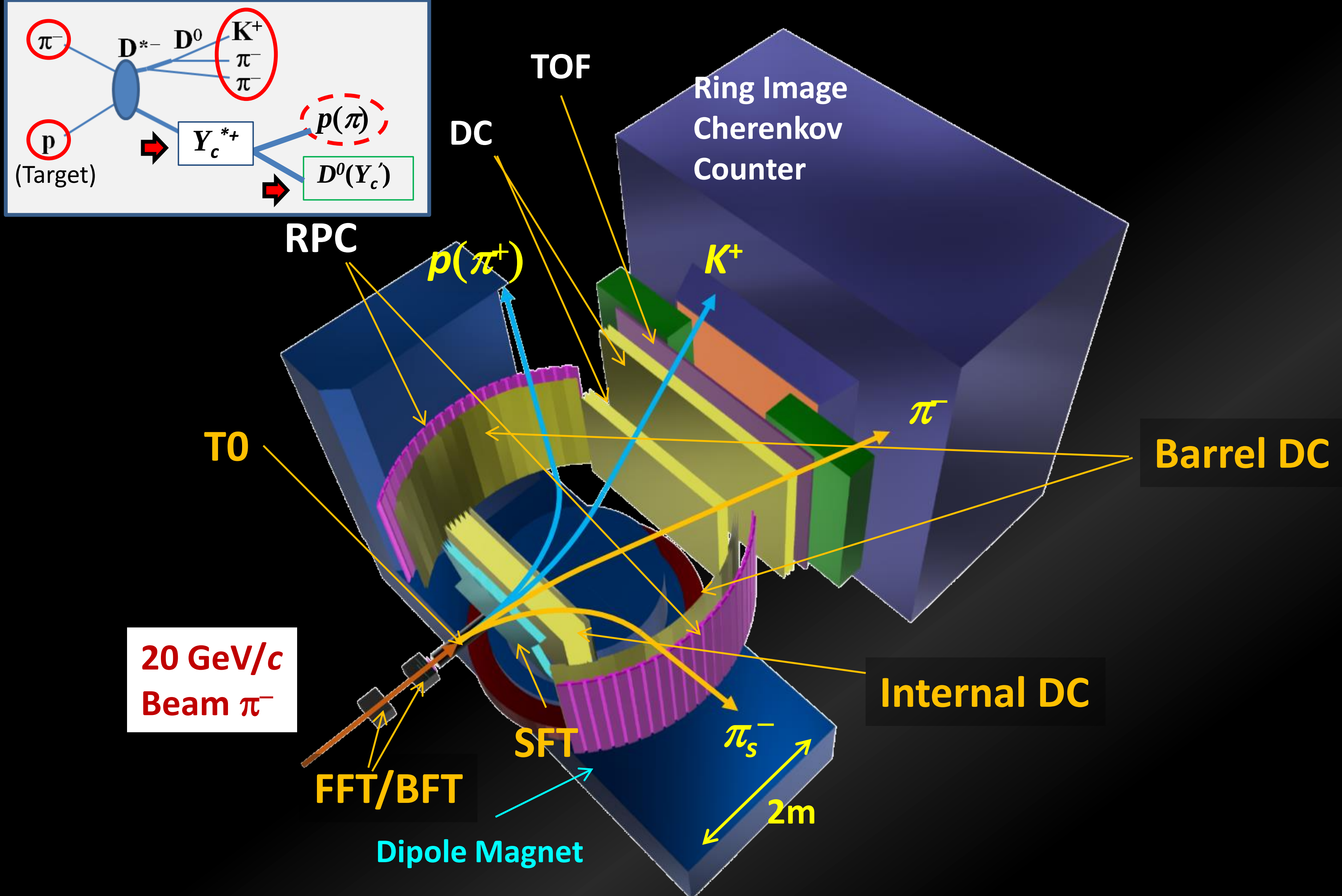
- JLAB, HERMES, COMPASS → Space-like approach
- J-PARC → **Time-like** approach

"GPD" and "Transition GPD"

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

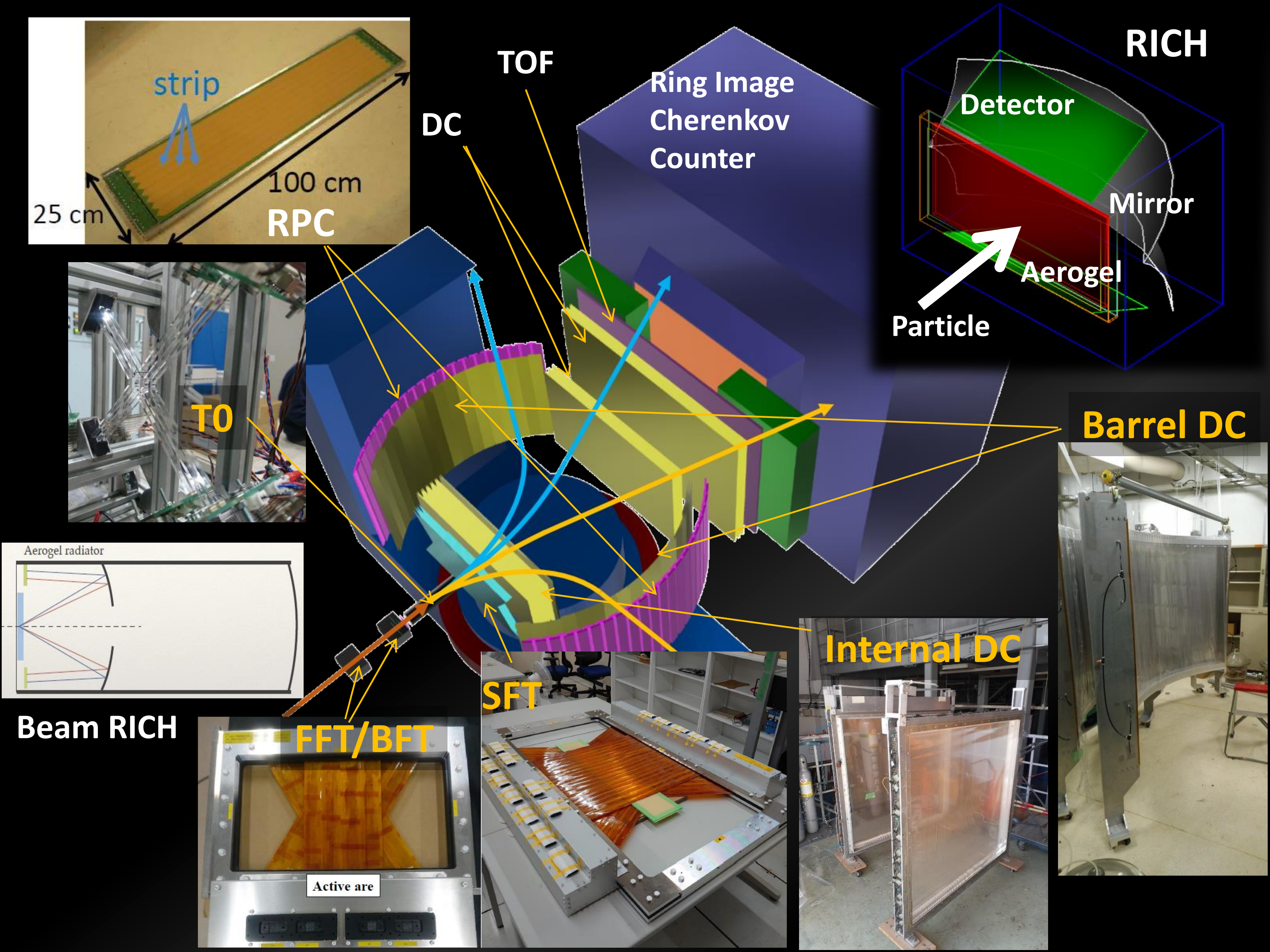
- $\pi^- \mathrm{p} \to \gamma^* n$
- $\pi^- \mathrm{p} \to \gamma^* \Delta^0$
- $\pi^- \mathrm{n} \to \gamma^* \Delta^-$
- $\pi^+ \mathrm{n} \to \gamma^* \mathrm{p}$
- $\pi^+ \mathrm{p} \to \gamma^* \Delta^{++}$
- $\pi^+ \mathrm{n} \to \gamma^* \Delta^+$
- $K^- \mathrm{p} \to \gamma^* \Lambda$
- $K^- \mathrm{p} \to \gamma^* \Lambda(1405)$
- $K^- \mathrm{p} \to \gamma^* \Lambda(1520)$
- $K^- \mathrm{n} \to \gamma^* \Sigma^-$
- $K^+ \mathrm{n} \to \gamma^* \Theta^+$





Acceptance: ~ 60% for D^*, ~ 80% for decay π^+

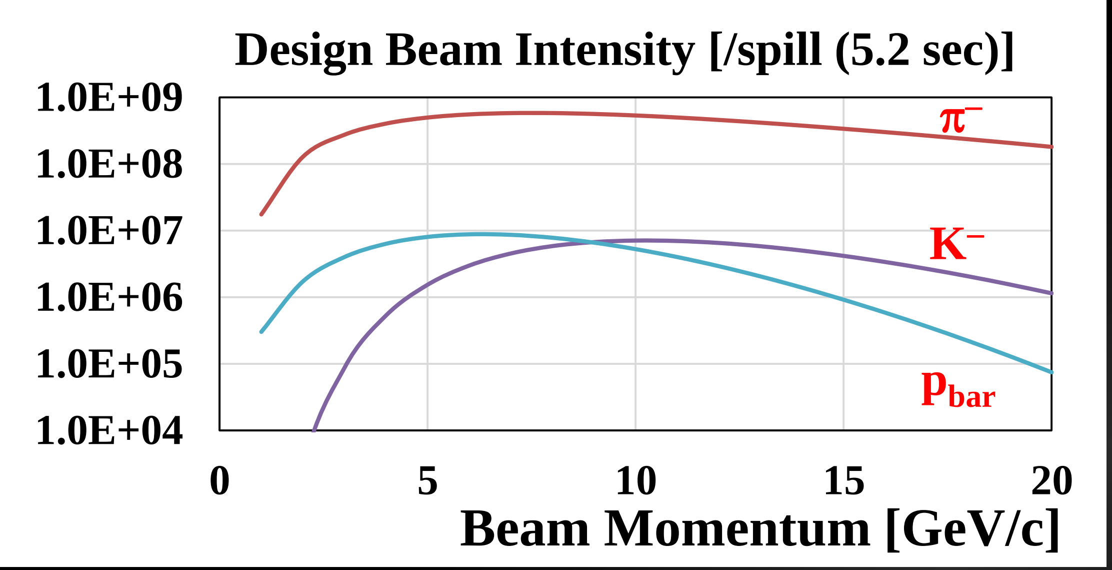
Resolution: $\Delta p/p$~0.2% at ~5 GeV/c（Rigidity：~2.1 Tm)

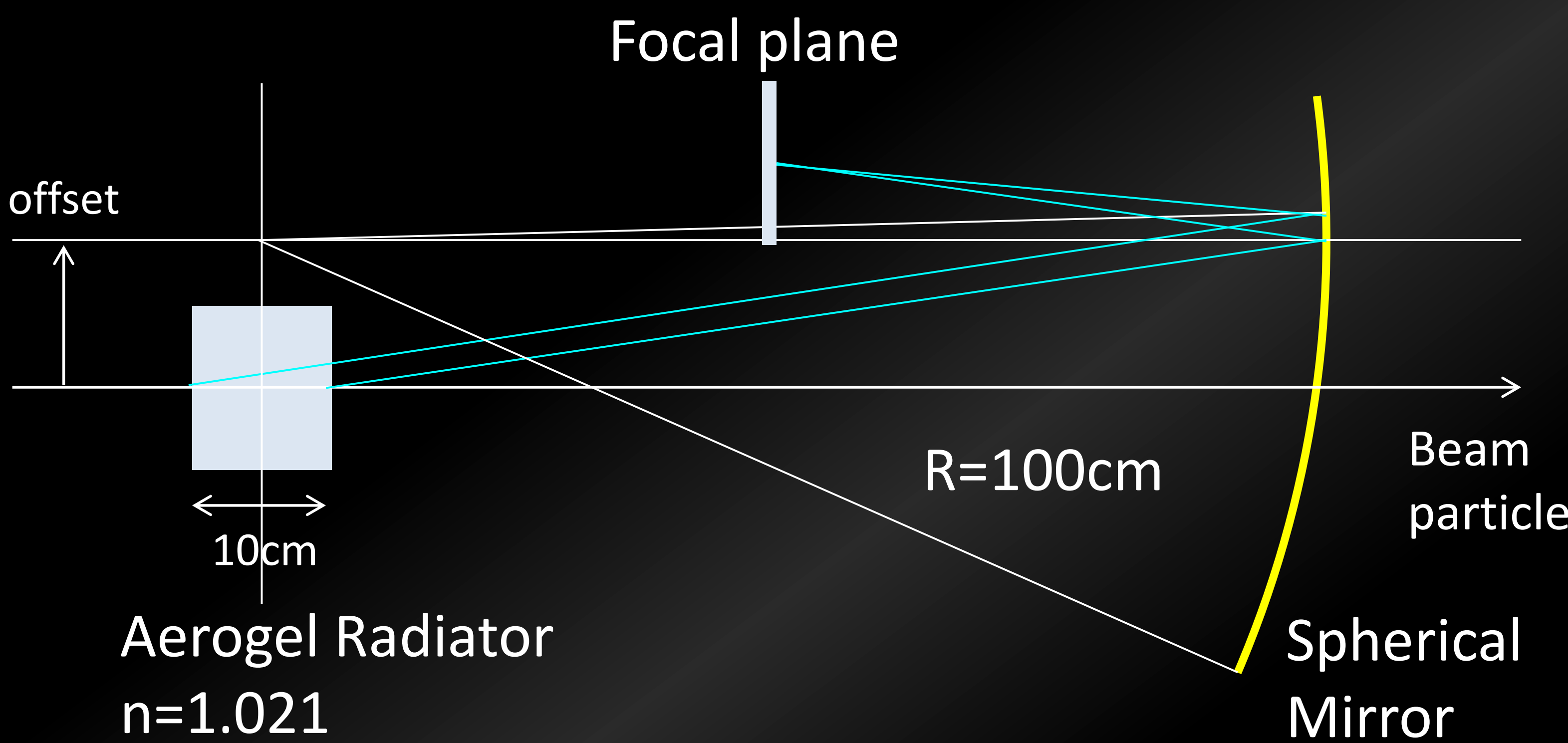


strip
100 cm
25 cm
RPC
TOF
DC
Ring Image
Cherenkov
Counter
RICH
Detector
Mirror
Aerogel
Particle
T0
Barrel DC
Aerogel radiator
Beam RICH
FFT/BFT
SFT
Internal DC
Active are

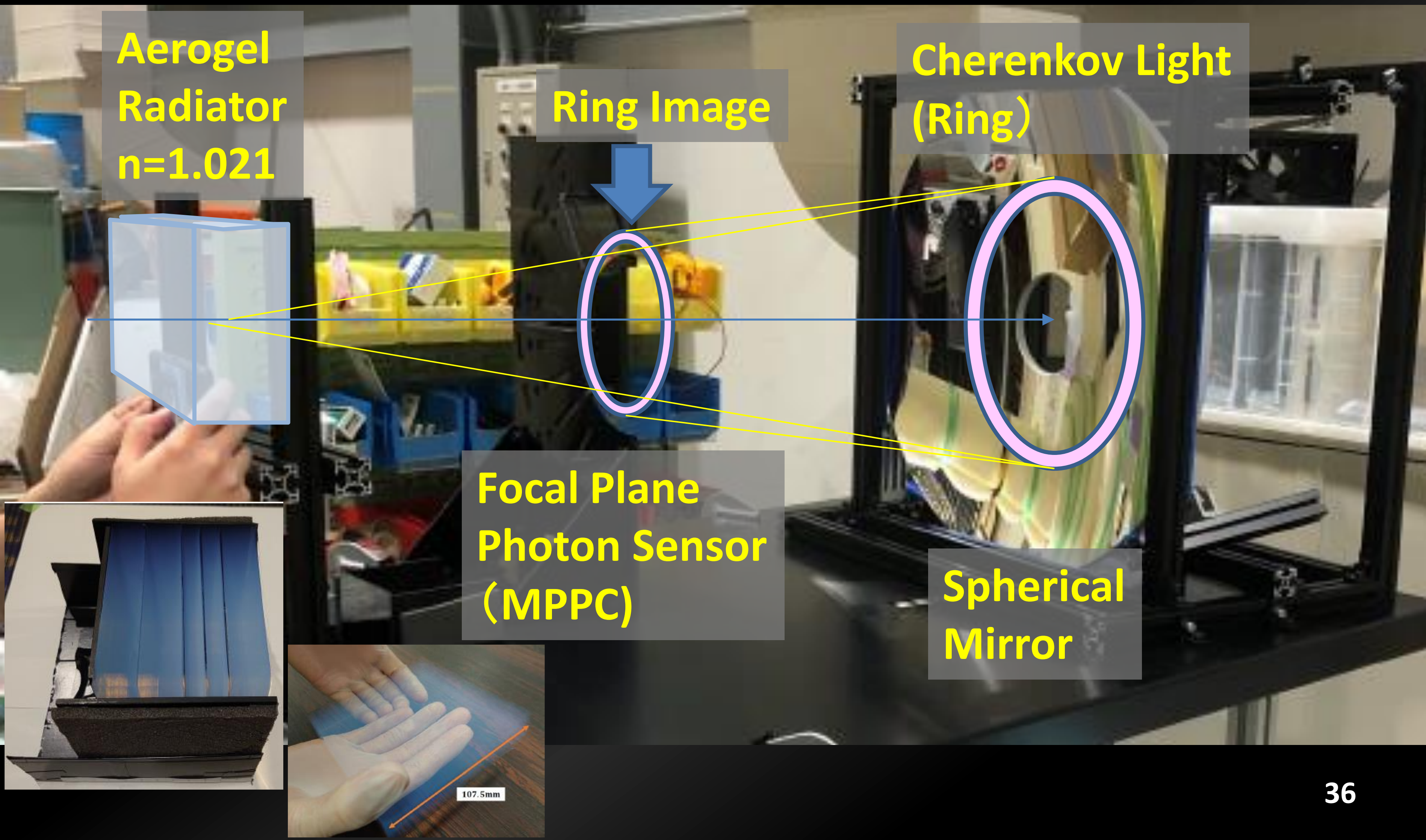
Beam RICH

S. Kajikawa
Master Thesis
2021 Tohoku Univ.





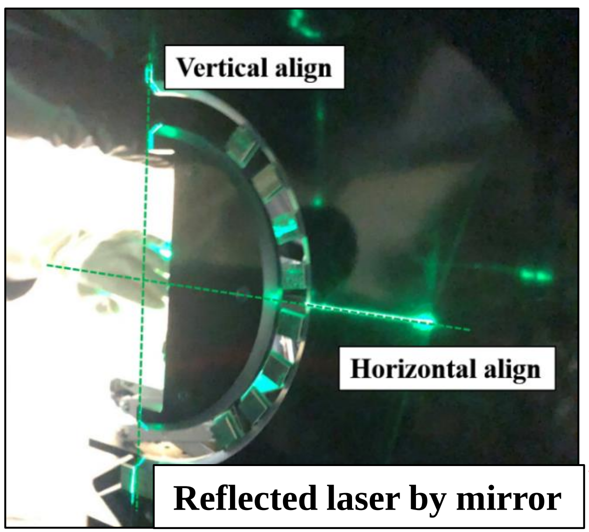
Beam RICH: test w/ electron@LEPS

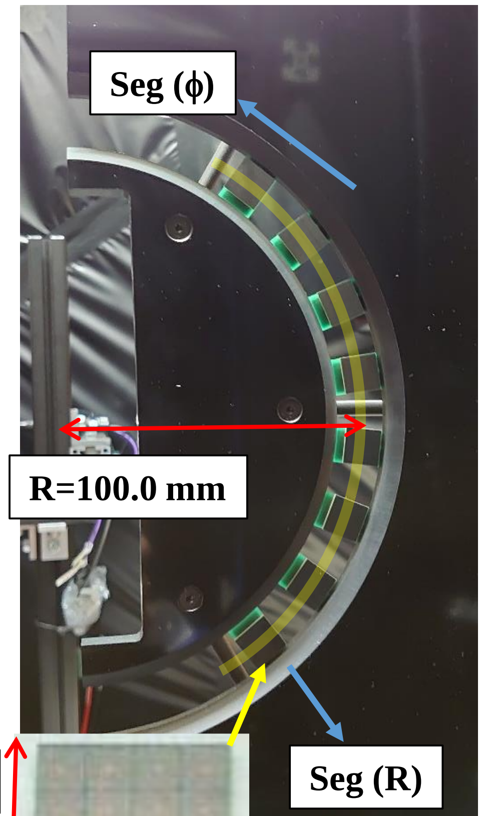


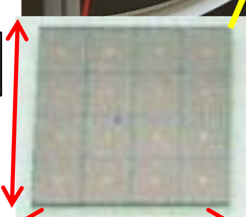
Hit pattern on detector plane

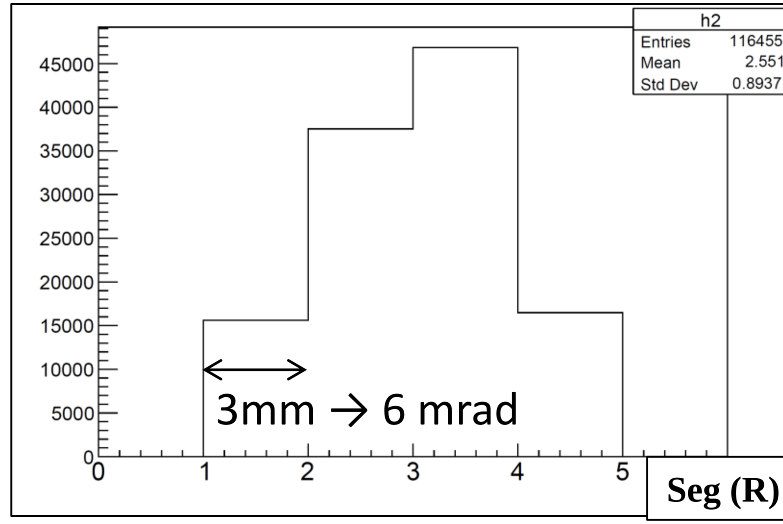
- **Multi-Pixel Photon Counter (MPPC) (3-mm 4×4 array, 8 sets)**
  - **Seg(R): 1–4 seg**
  - **Seg(ϕ): 1–32 seg**

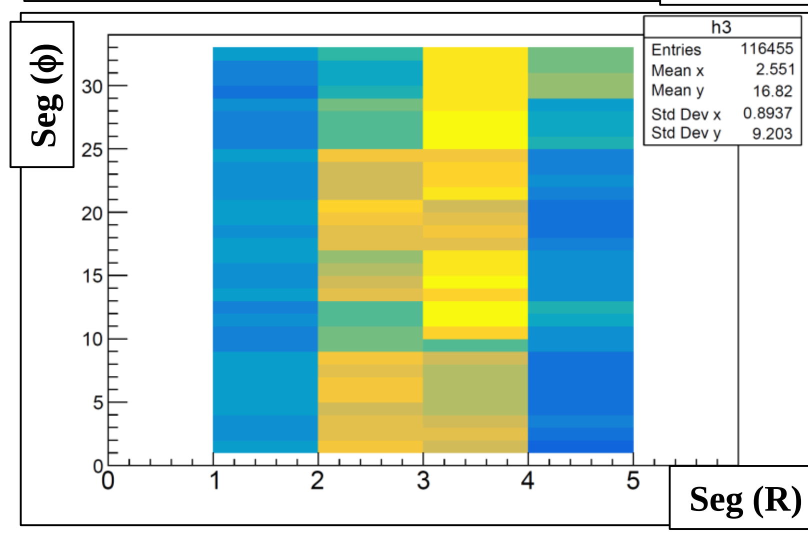
  (half a full space)
- **Clear hit pattern**
  - **Alignment: OK**











MPPC S13361-3050: 3-mm 4x4 array

Timeline of E50

- Beamline:
  - High-P beamline: 2020 (30-GeV proton beam)
  - Secondary meson beams: 2025 (expected)
- Studies of nucleon structures in E50:
  - Letter of intent: summited in December, 2018
  - Proposal: plan to submit by 2022
    (CT study can be incorporated)
  - Commission: 2025 (expected)

Summary

- Nucleon structures are explored by the space-like and time-like approaches: FFs, PDFs, TMDs and GPDs.
- Planned measurements of exclusive π-induced Drell-Yan process at J-PARC will bring important understandings on:
  - (Universality of) nucleon GPDs
  - Pion DAs, timelike FFs,…
- Timelike CT measurements with nuclear targets are important to validate the fundamental factorization assumption and can be accommodated in the proposal.