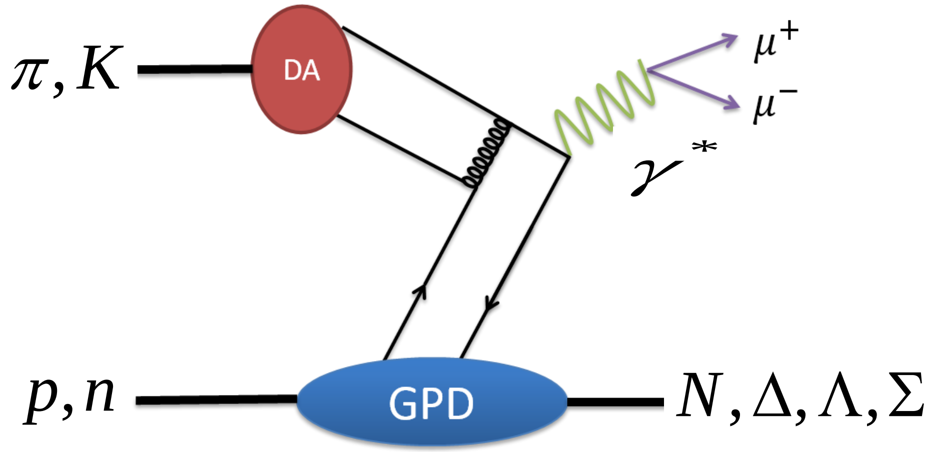
"Towards improved hadron femtography with hard exclusive reactions",
Virginia Tech, Jul 18 – 22, 2022



Exclusive Drell-Yan Process for GPDs at J-PARC E50

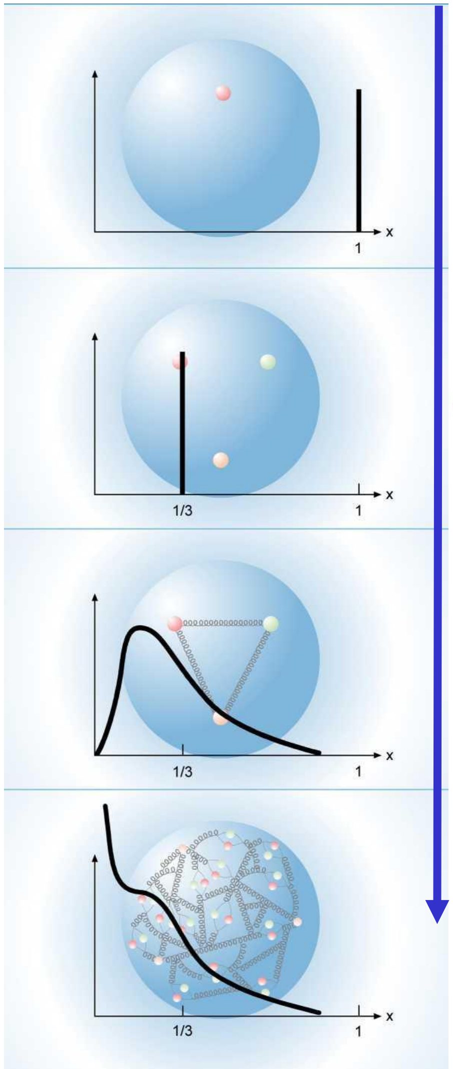
Wen-Chen Chang

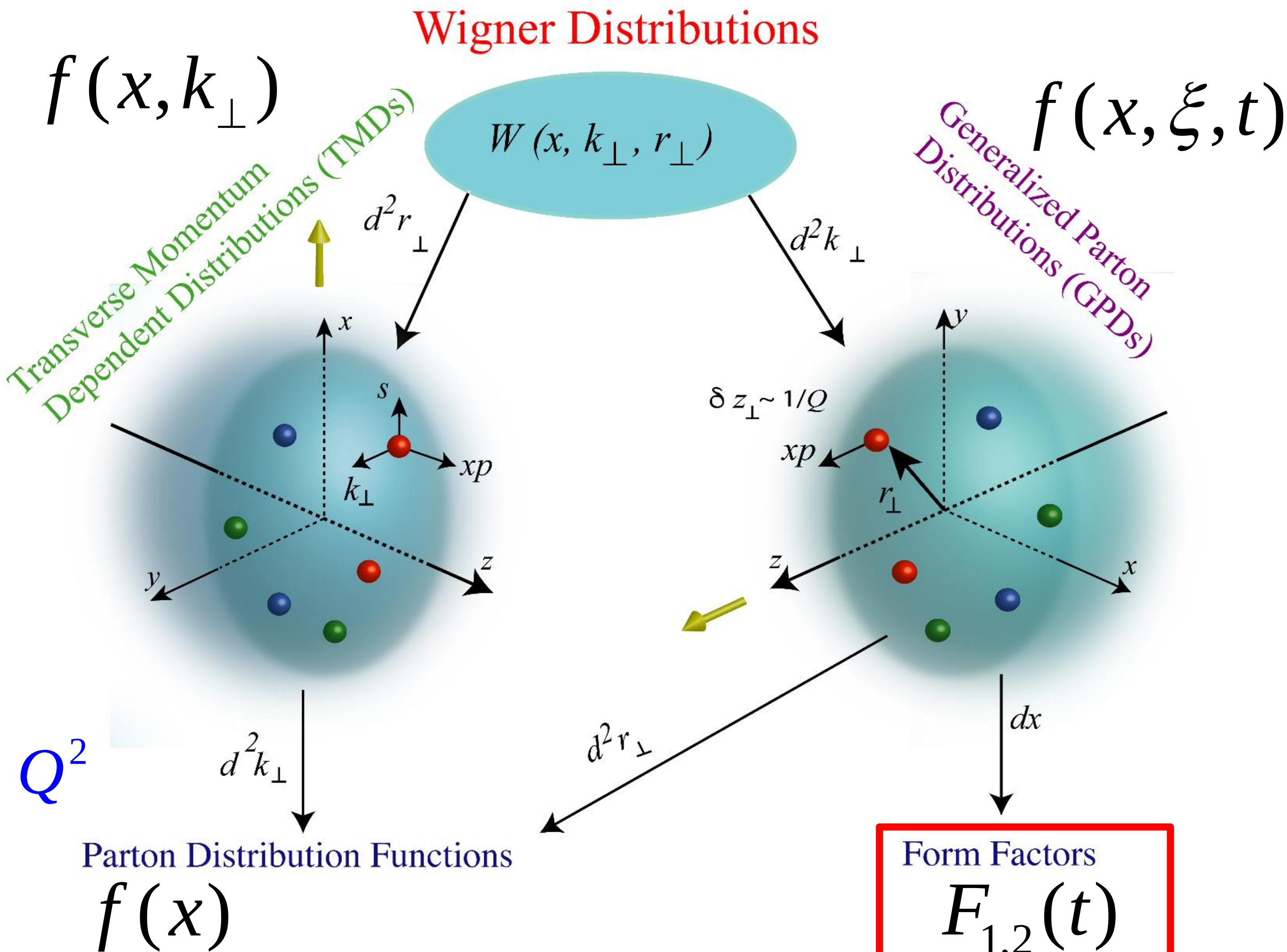
Institute of Physics, Academia Sinica

Outline

- Exclusive Drell-Yan Process:
  measuring GPDs in a *time-like* approach
- Proposal:
  - High-momentum beamline at J-PARC
  - Feasibility study [PRD93 (2016) 114034]
  - Status and prospects
- Summary

Multi-dimensional Partonic Structures

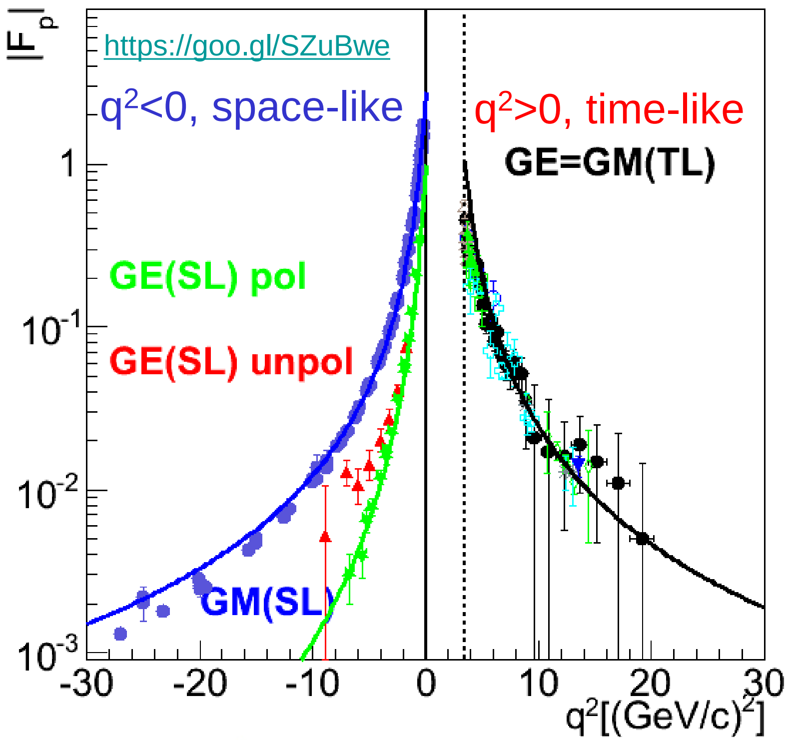


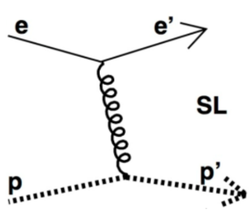


http://www.int.washington.edu/PROGRAMS/17-3/

Electromagnetic Form Factors

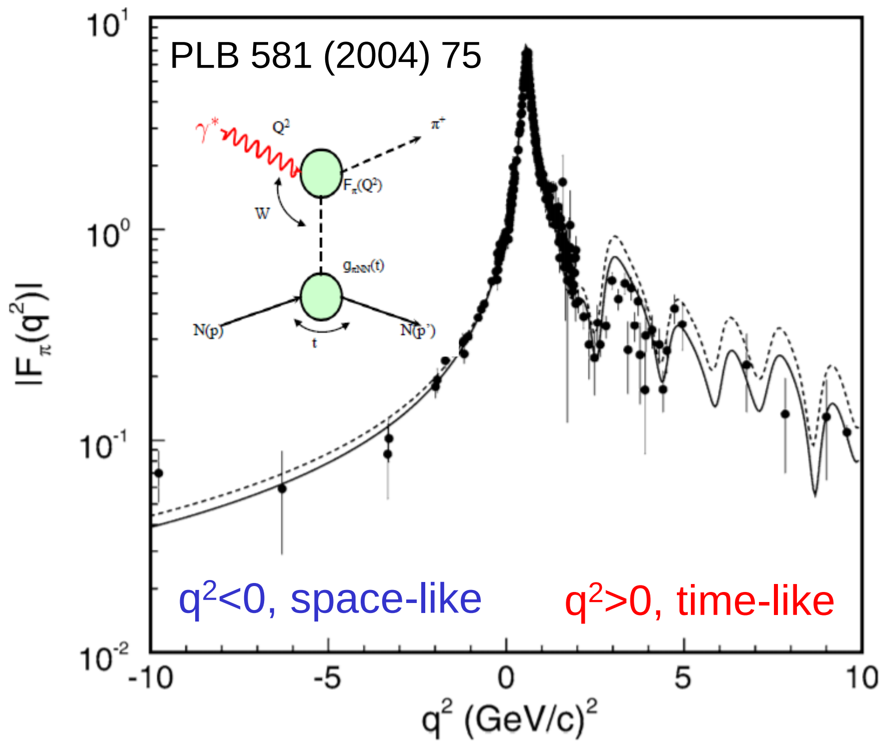
proton

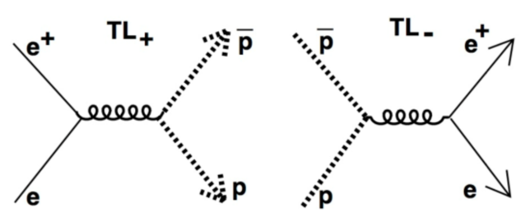




Space-like ($q^2 < 0$): elastic scattering

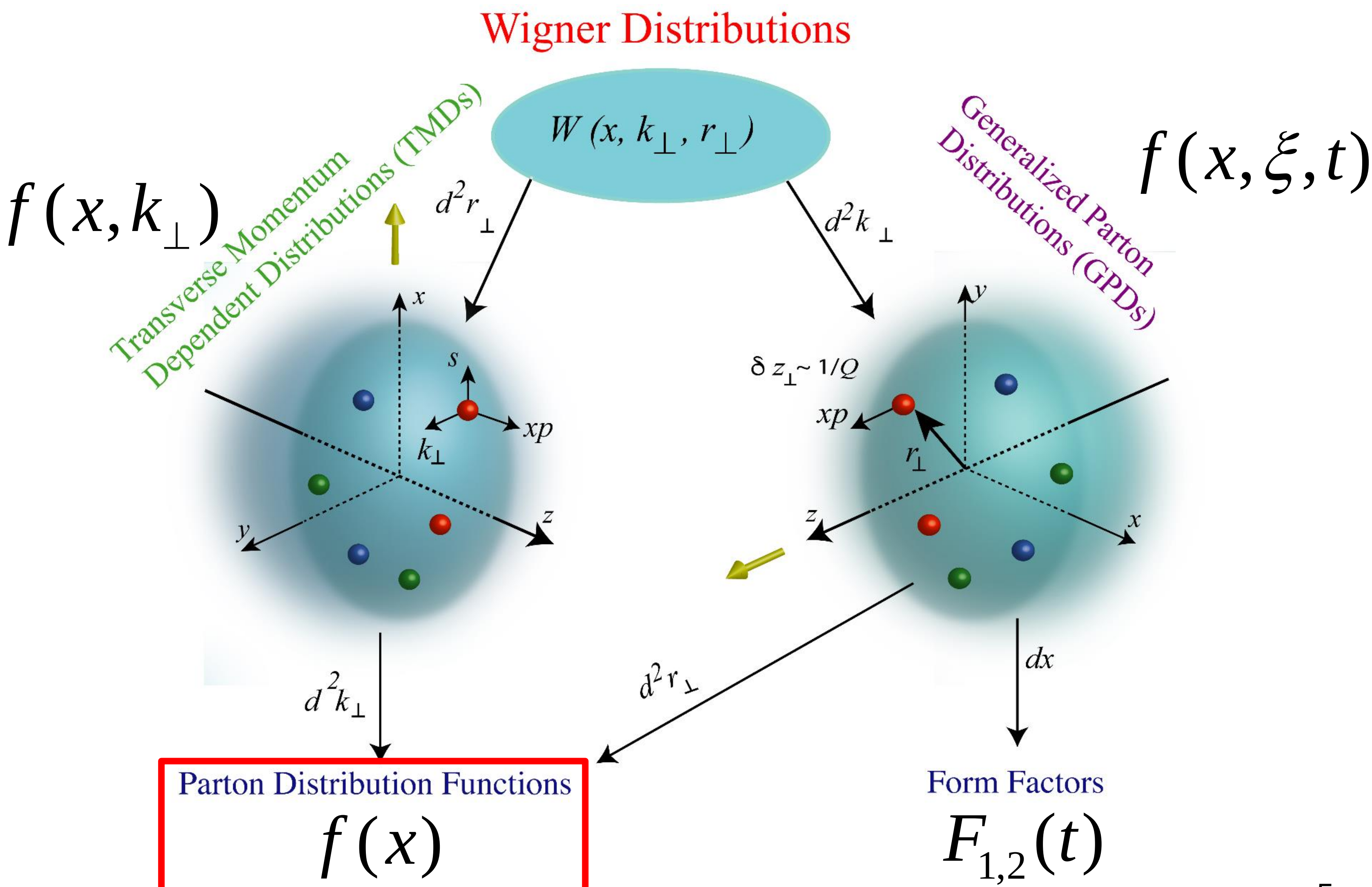
pion





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

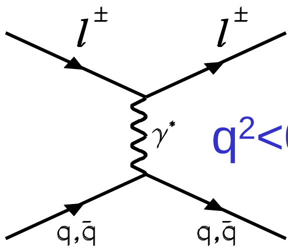
Multi-dimensional Partonic Structures



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

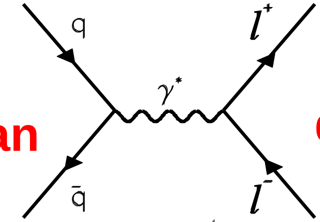
Factorization of Hard Processes

DIS



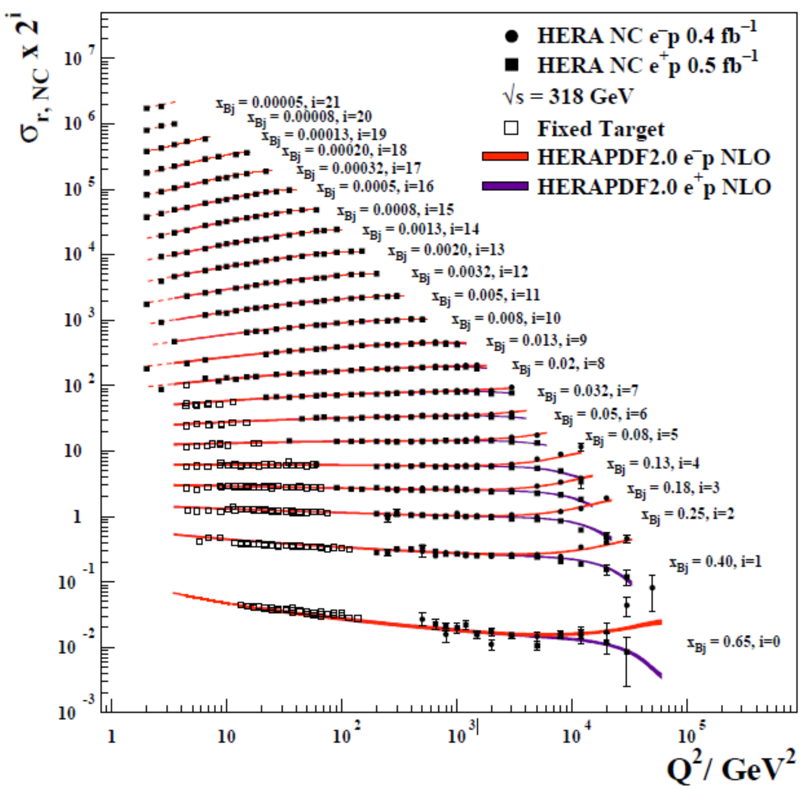
$q^2<0$, space-like

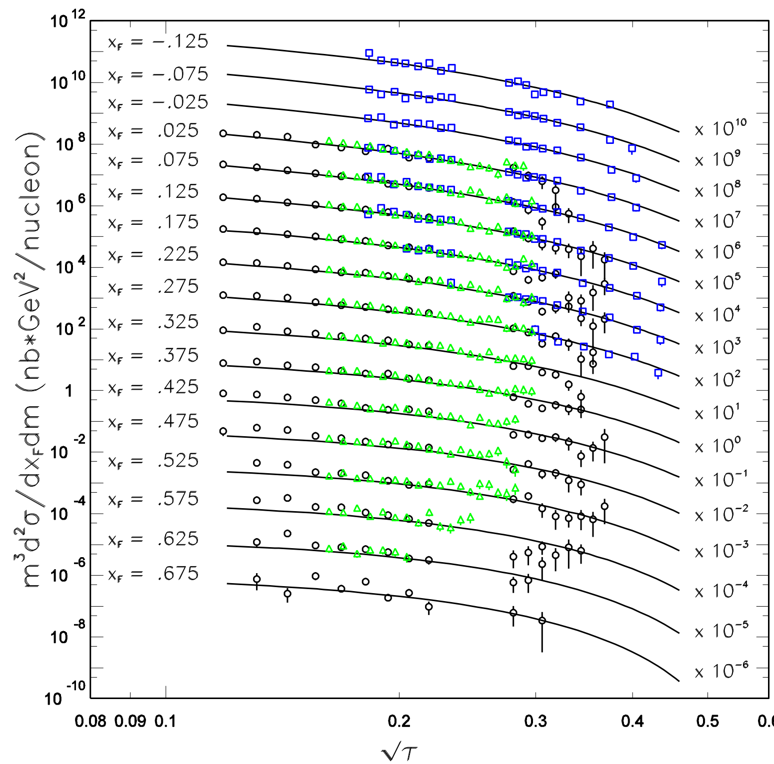
Drell-Yan



$q^2>0$, time-like

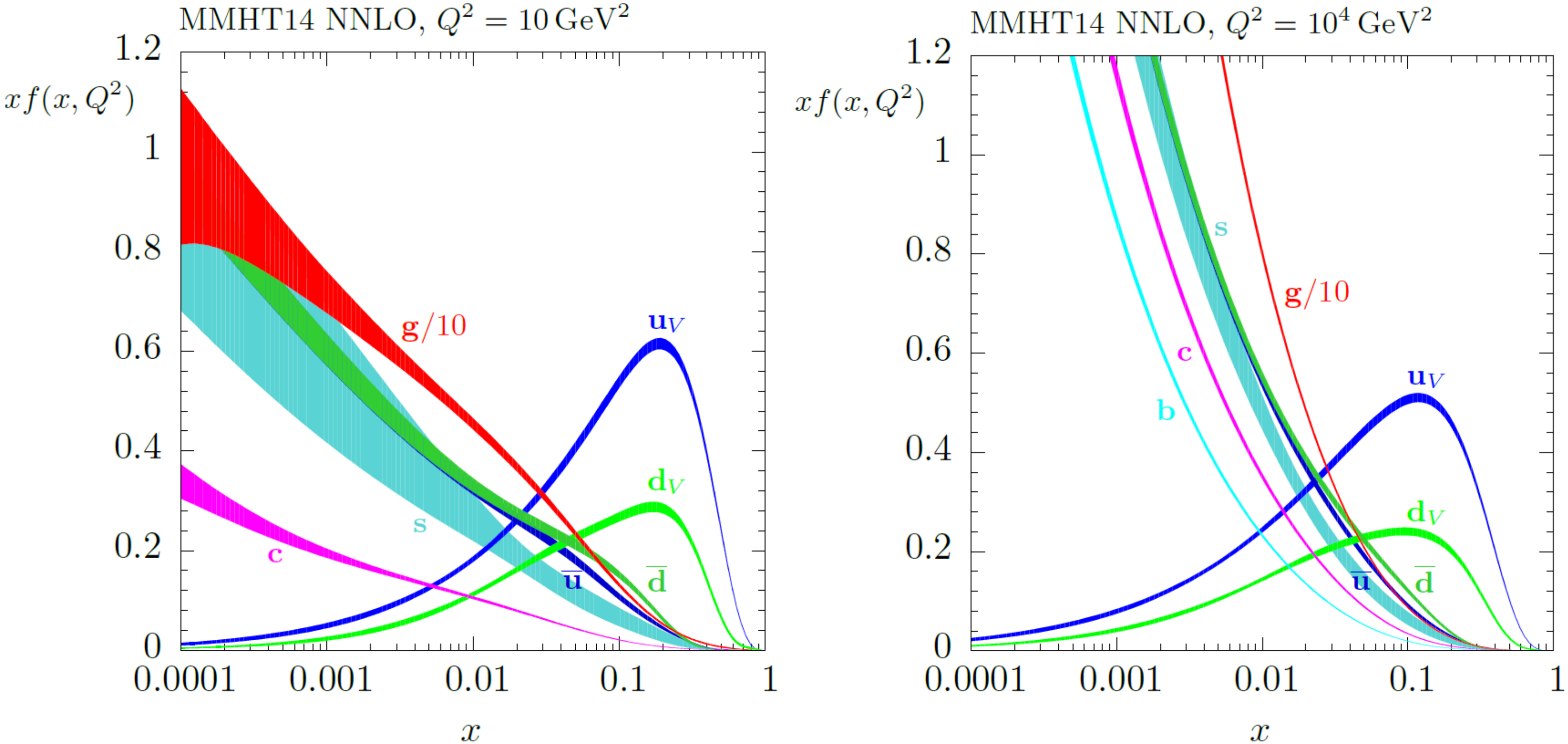
$p\,A \rightarrow \mu^+\mu^- X$





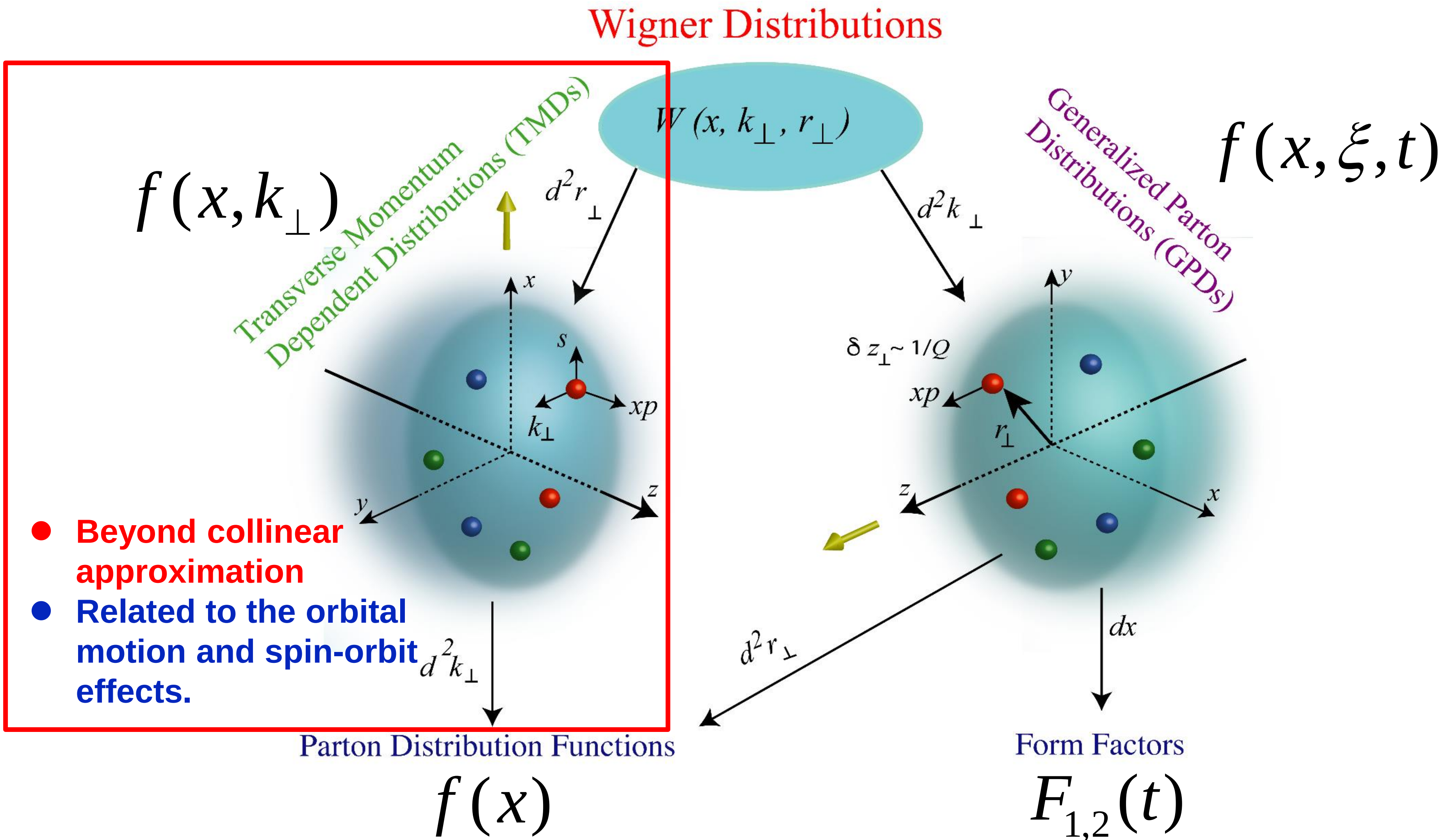
$$\sigma_{proton}(x,Q^2) \sim PDF_{nucleon}(x,Q^2) \otimes \hat{\sigma}_{hard}(Q^2)$$

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)

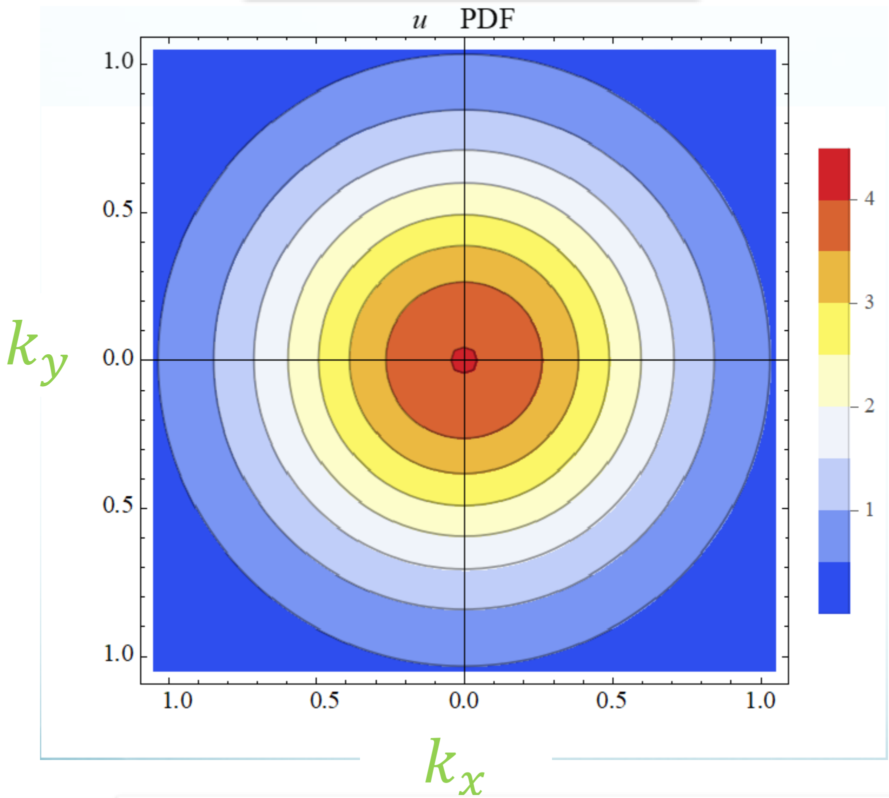
- spin of the nucleon
- spin of the parton
- k_T of the parton

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 $h_{1T}^{\perp q,g}(x, k_T^2)$

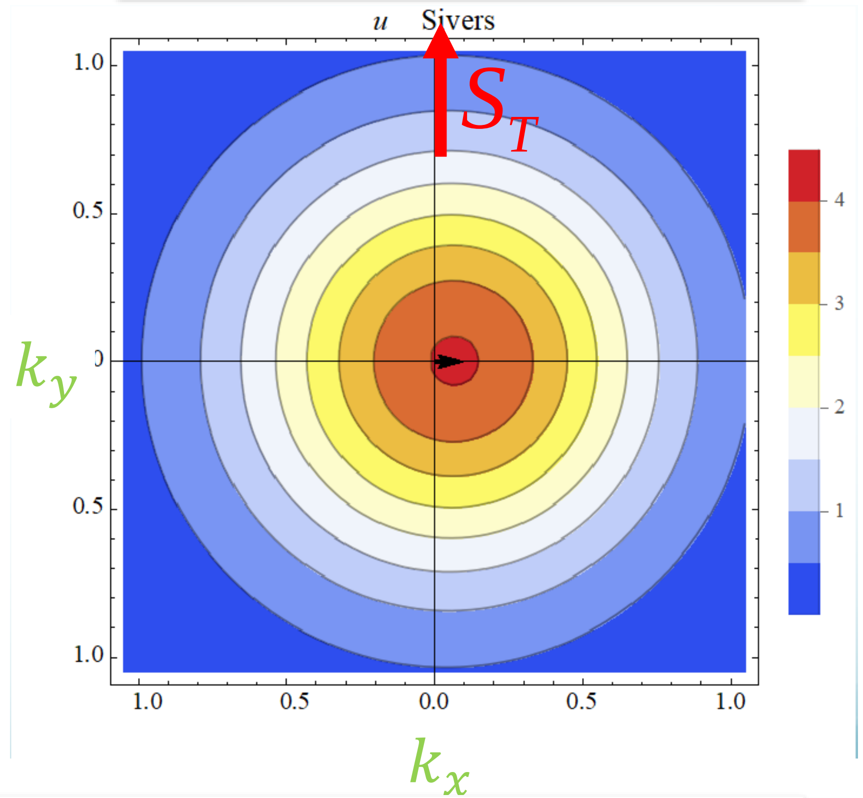
TMD Sivers Function $f_{1T}^{\perp q}$

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

Unpolarized Proton

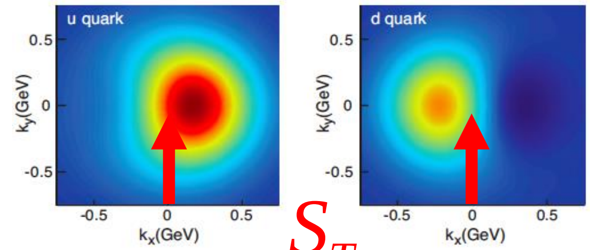


Transversely-polarized Proton



- **A nonzero Sivers function is considered to be strong evidence for the presence of quark orbital angular momentum.**

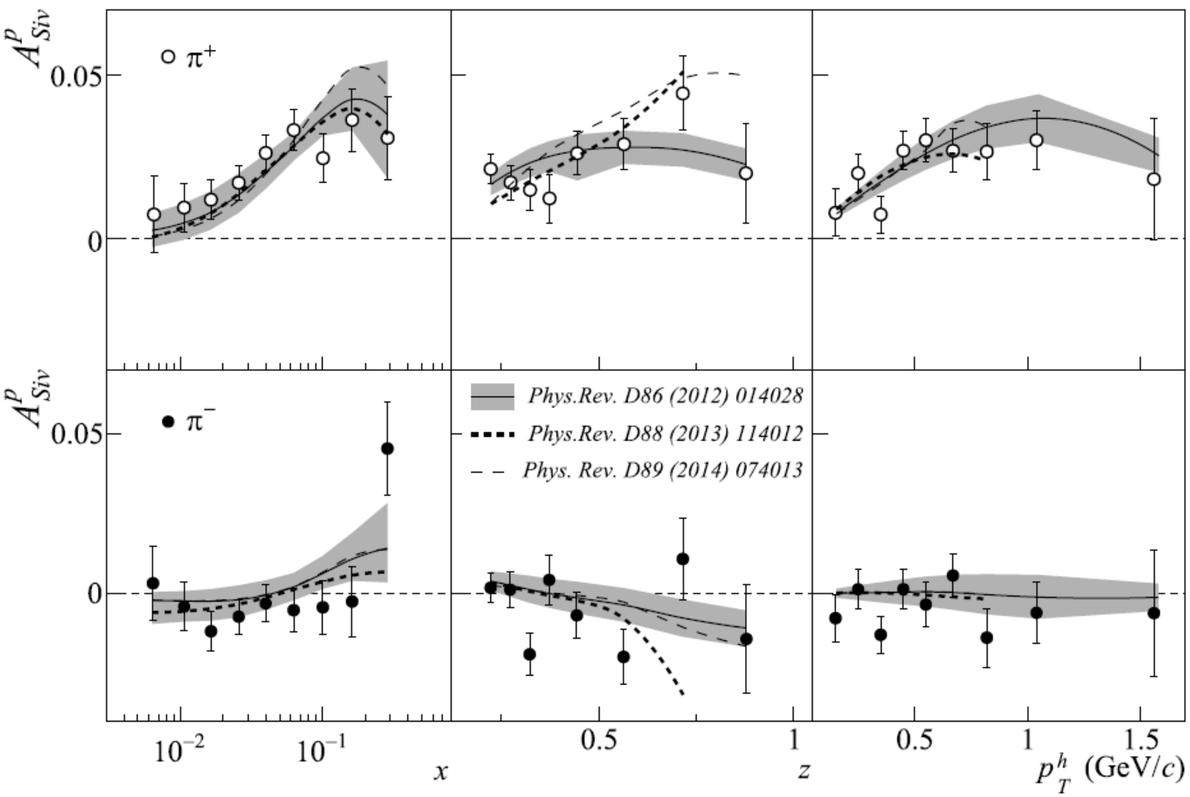
Nonzero Sivers Asymmetries from SIDIS

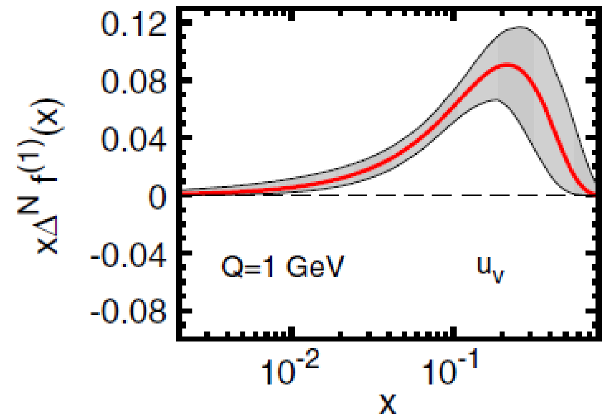


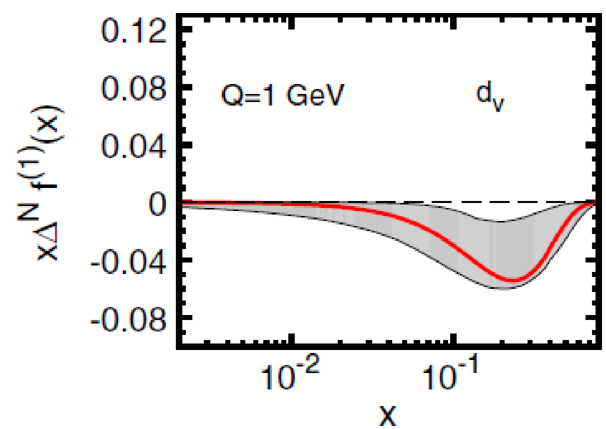
S_T

Sivers Functions

COMPASS, PLB 744 (2015) 250







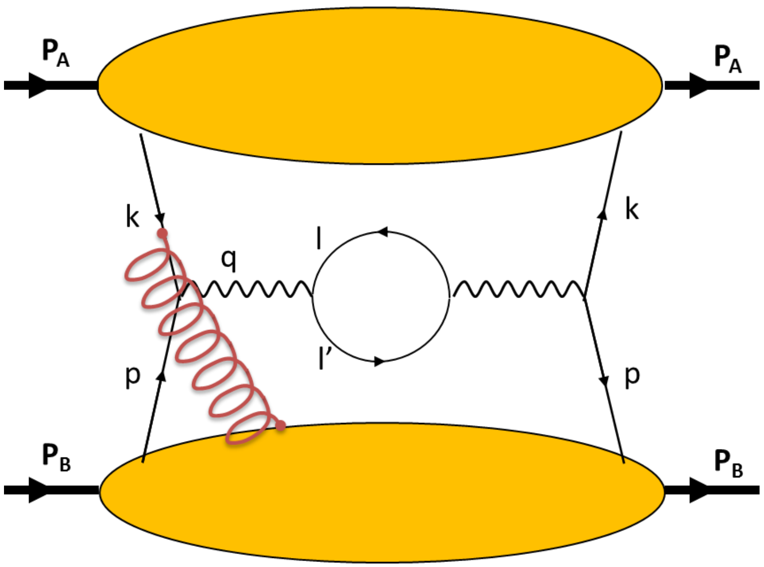
SIDIS $\gamma^*(q^2 < 0)p_\uparrow \to hX$

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

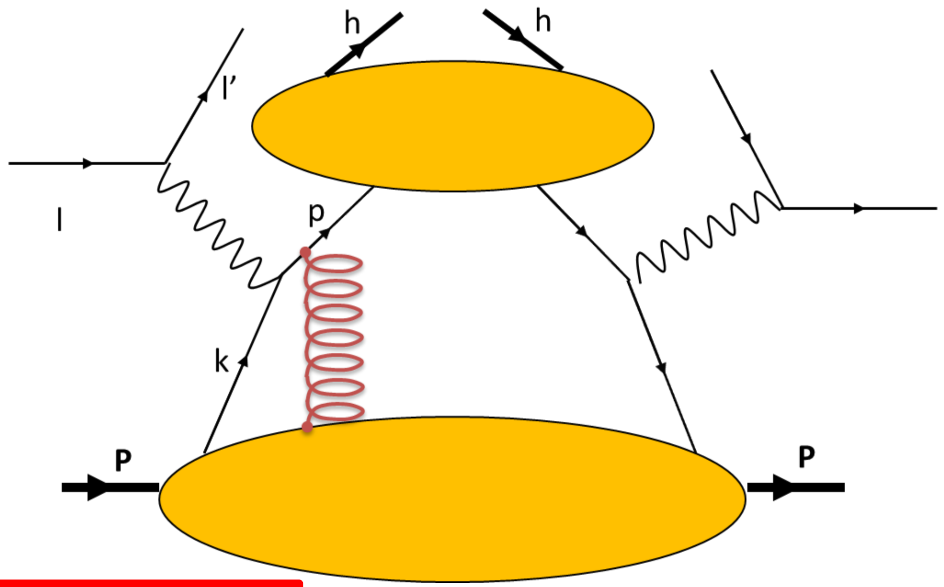
Non-Universality of Sivers Function

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



SIDIS

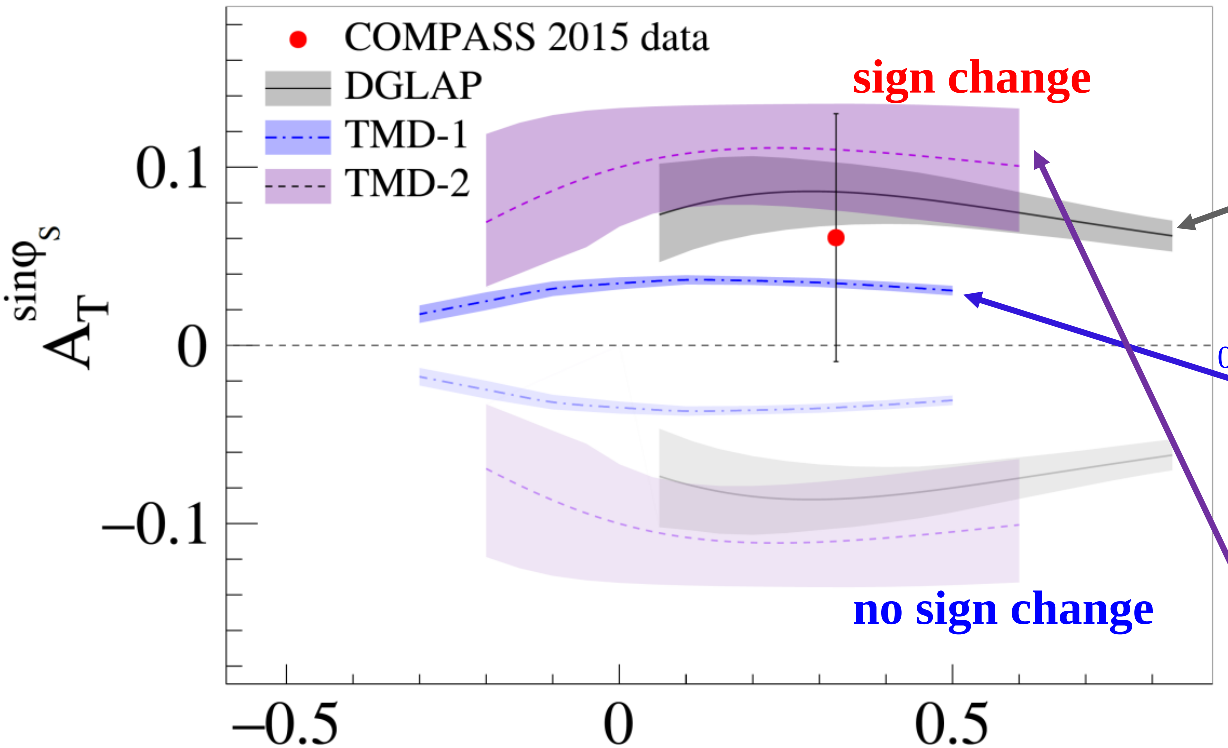


$hp_{\uparrow} \rightarrow \gamma^{*}(q^2 > 0)X$ $\text{Sivers}\,|_{DY} = -\text{Sivers}\,|_{SIDIS}$ $\gamma^{*}(q^2 < 0)p_{\uparrow} \rightarrow hX$

- 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!

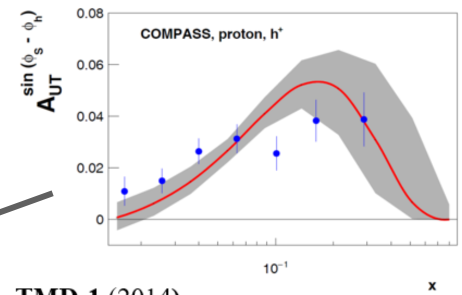
COMPASS, PRL 119 (2017) 112002



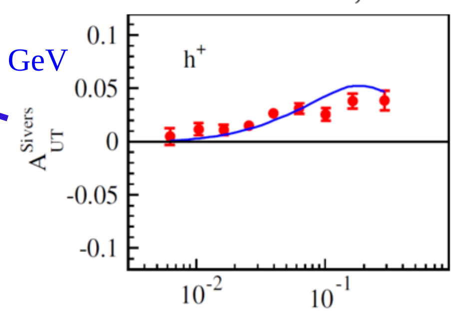
$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

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

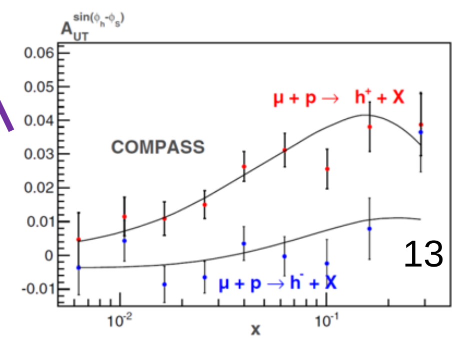
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



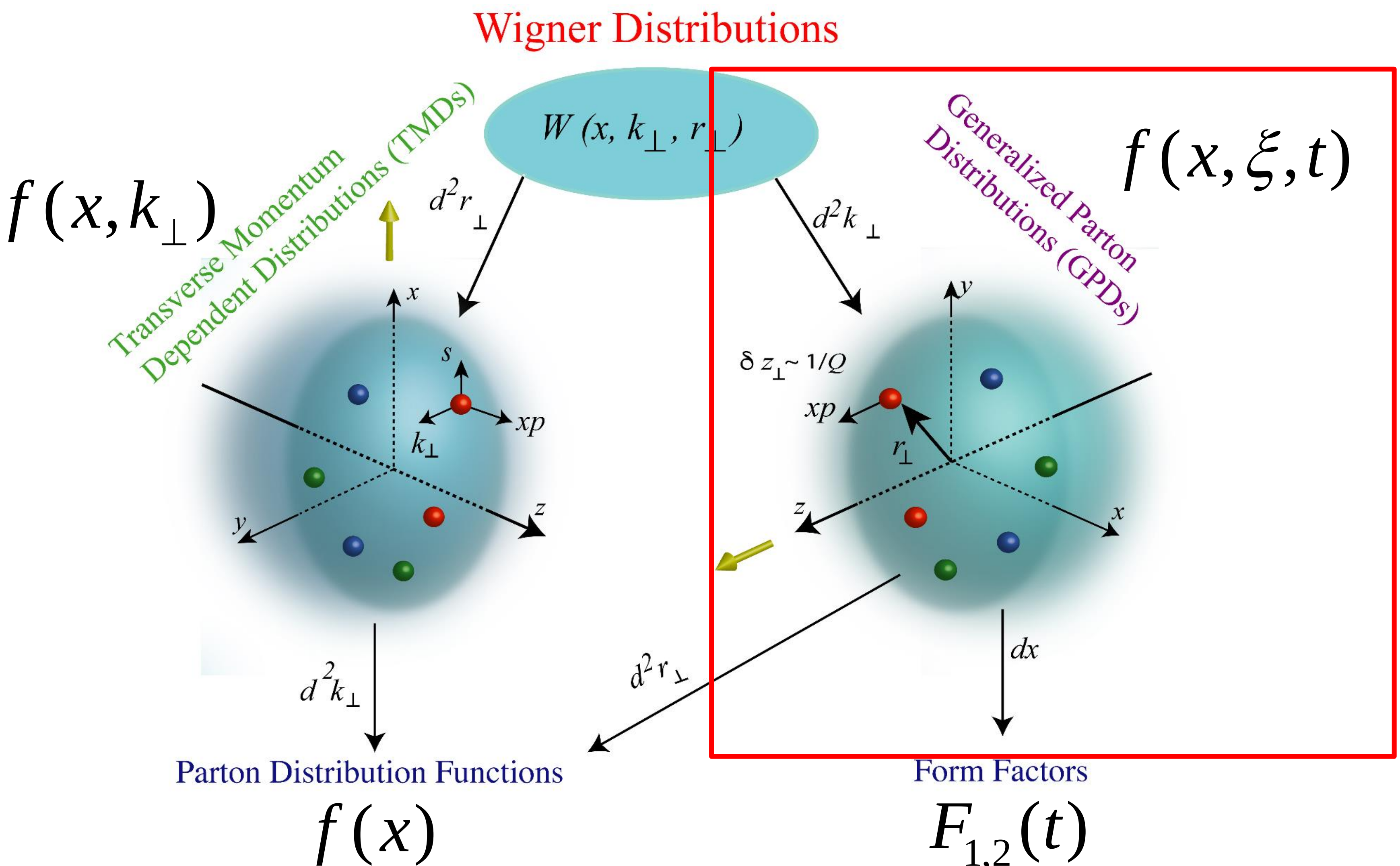
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



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



Multi-dimensional Partonic Structures

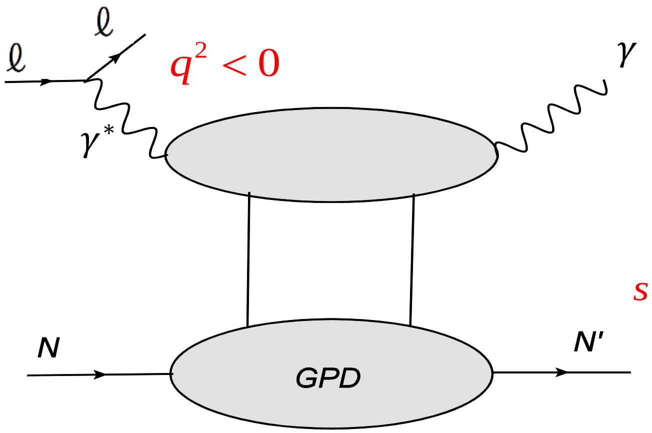


http://www.int.washington.edu/PROGRAMS/17-3/

Generalized Parton Distributions

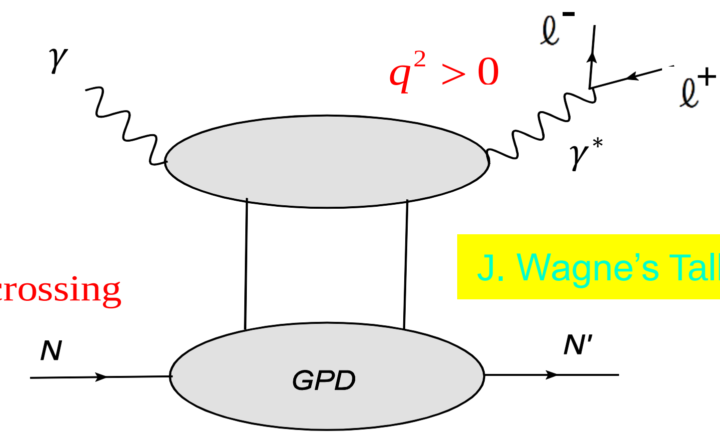
Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering



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

Time-like Compton Scattering

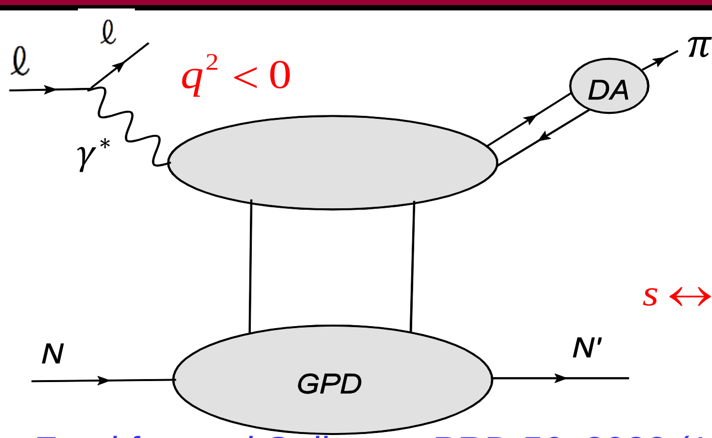


J. Wagne's Talk

$s \leftrightarrow u$ channel crossing

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

Deeply Virtual Meson Production



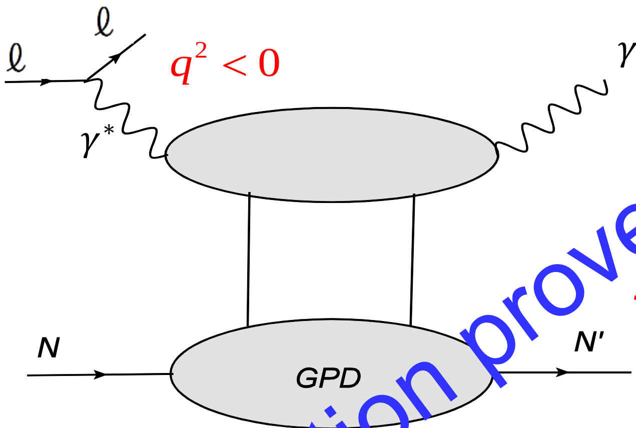
$s \leftrightarrow u$ channel crossing

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

Generalized Parton Distributions

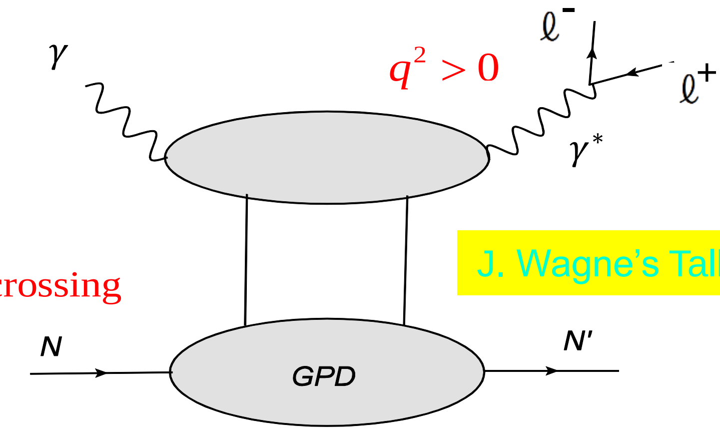
Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering



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

Time-like Compton Scattering



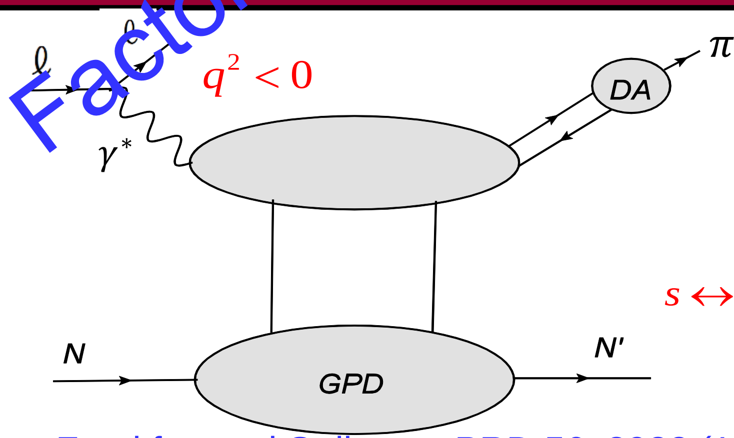
J. Wagne's Talk

$s \leftrightarrow u$ channel crossing

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

Factorization proved!

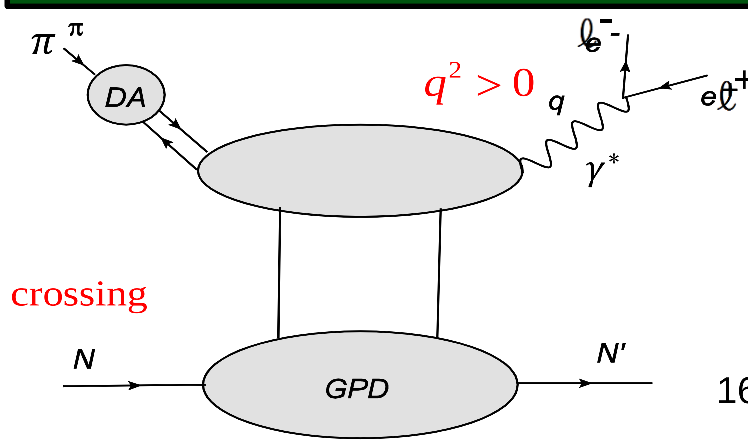
Deeply Virtual Meson Production



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

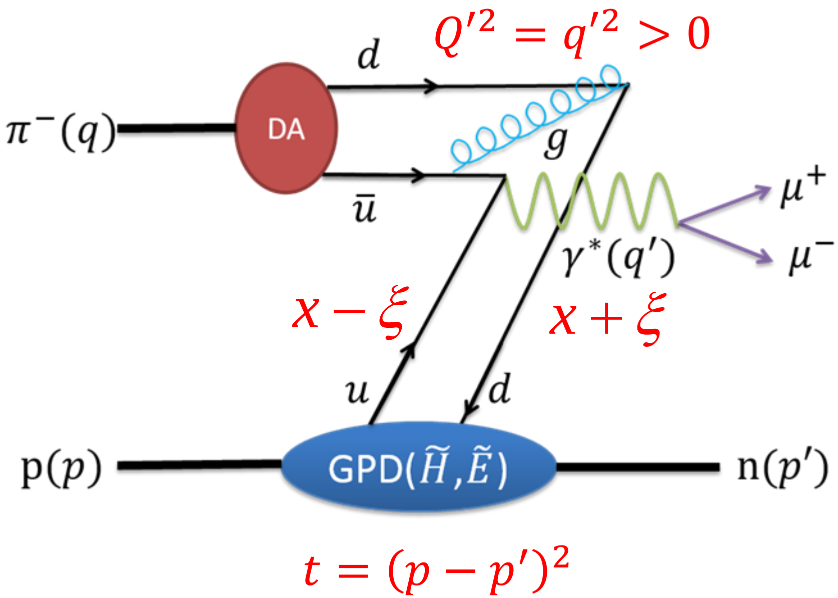
$s \leftrightarrow u$ channel crossing

Exclusive meson-induced DY



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

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



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

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

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

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

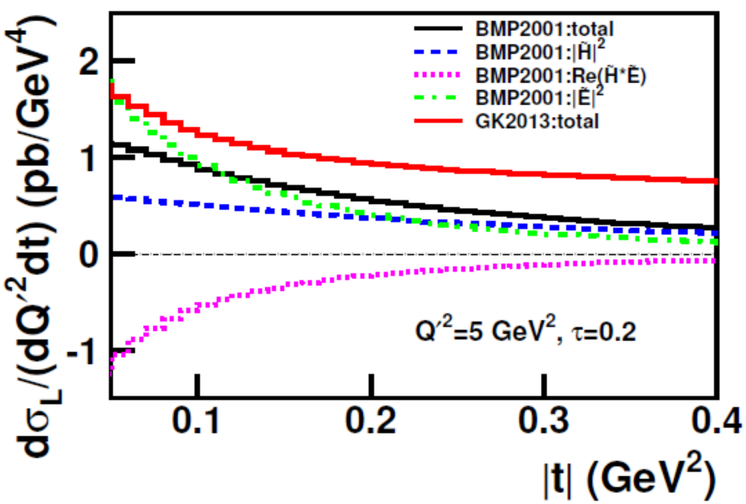
Differential Cross Sections of $\pi N \to l^+ l^- N$

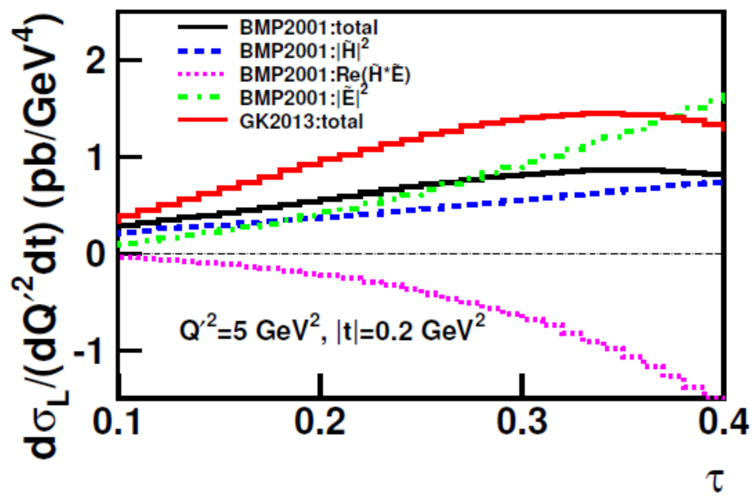
$$\left.\frac{d\sigma_L}{dt dQ'^2}\right|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \Big[(1-\xi^2)|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)|^2 - 2\xi^2 {\rm Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^* \tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2 \frac{t}{4m_N^2}|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)|^2\Big],$$

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

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

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





Production is dominant at forward angles

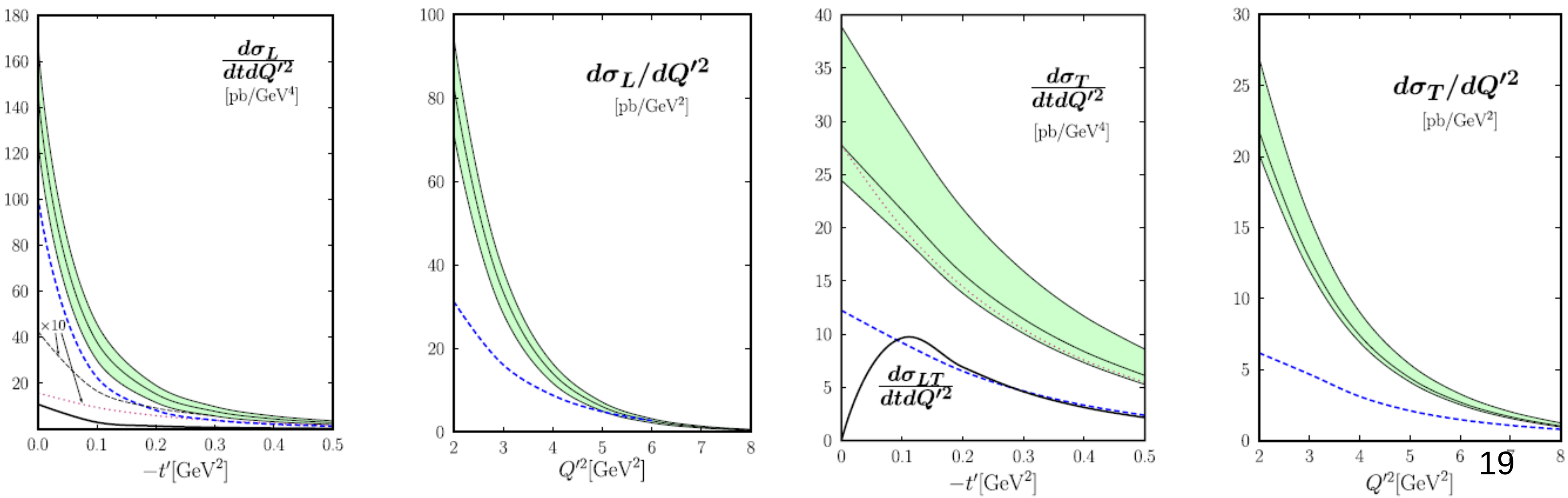
Cross sections increase toward small *s* (→ low beam energy)

Beyond the Leading Twist

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

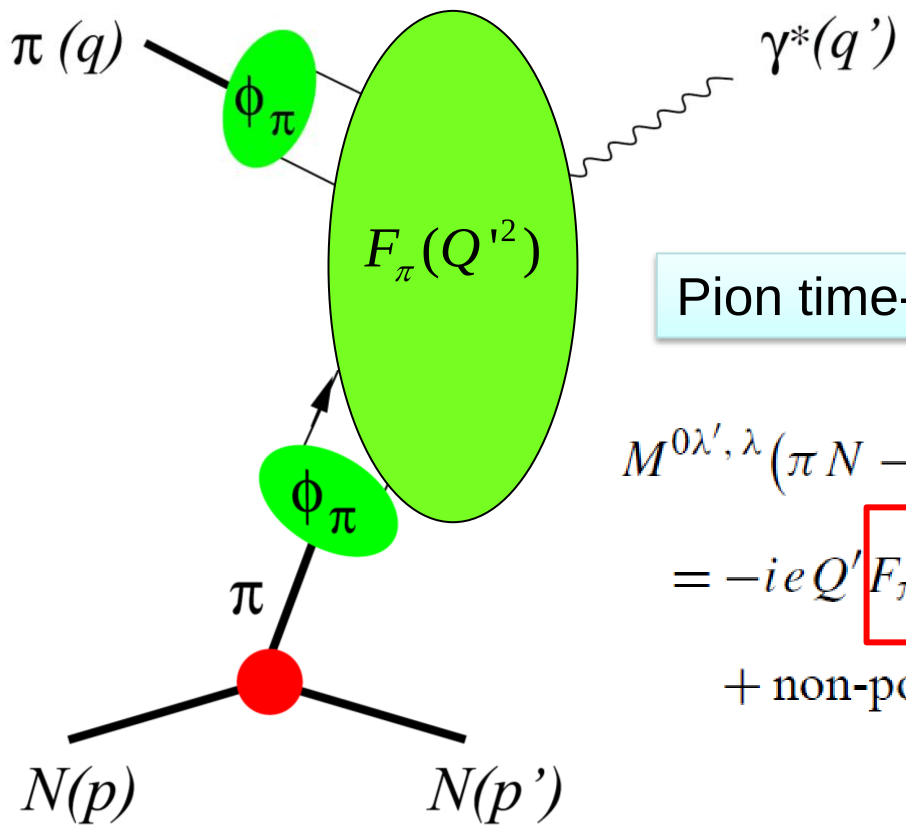
$$\frac{d\sigma}{dt\,dQ'^2\,d\cos\theta\,d\varphi} = \frac{3}{8\pi}\left(\sin^2\theta\,\frac{d\sigma_L}{dt\,dQ'^2} + \frac{1+\cos^2\theta}{2}\,\frac{d\sigma_T}{dt\,dQ'^2} + \frac{\sin 2\theta\cos\varphi}{\sqrt{2}}\,\frac{d\sigma_{LT}}{dt\,dQ'^2} + \sin^2\theta\cos 2\varphi\,\frac{d\sigma_{TT}}{dt\,dQ'^2}\right)$$

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



Pion Timelike FFs

D. Gaskell's Talk



Pion time-like form factors

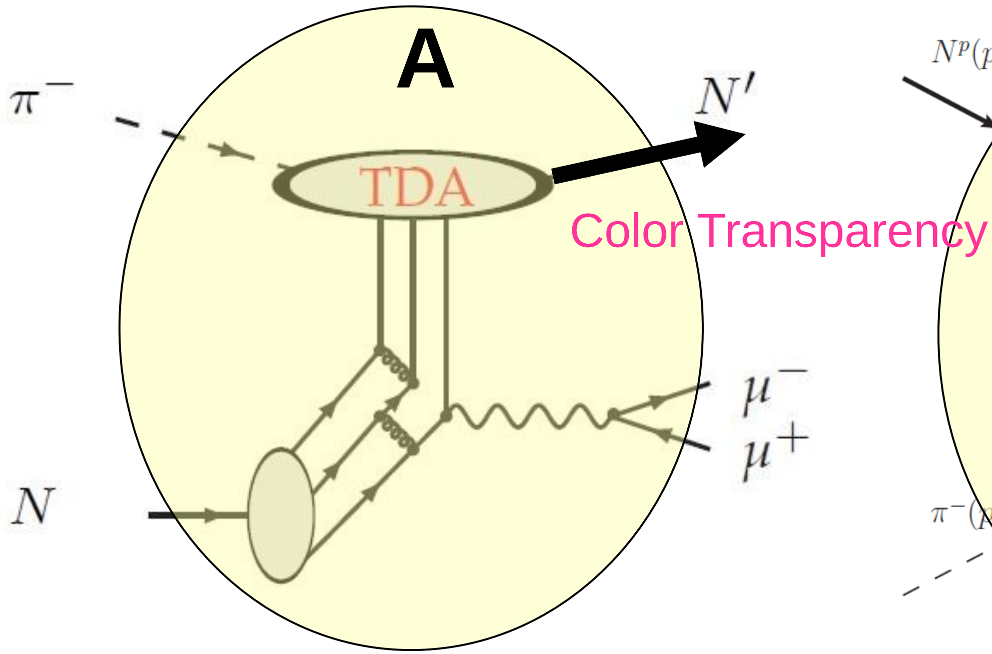
$$M^{0\lambda',\lambda}(\pi N \to \gamma^* N)$$
$$= -ieQ' F_\pi(Q'^2) \frac{F_{\text{pole}}(t)}{2Mf_\pi} \bar{u}(p',\lambda')\gamma_5 u(p,\lambda)$$
$$+ \text{non-pole terms.}$$

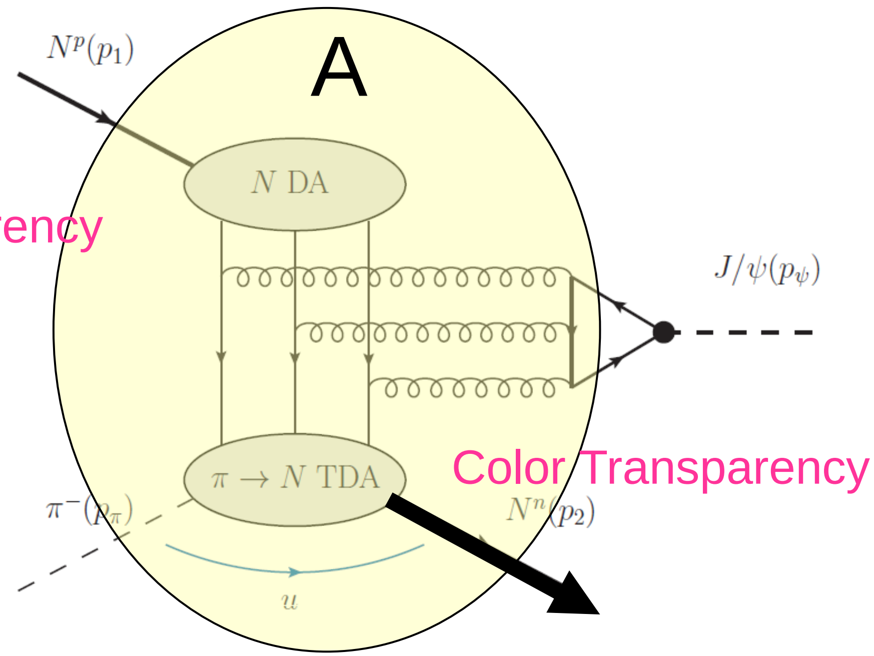
pion pole approximation

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)

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

Exclusive Diphoton Process

J. Qiu's Talk

PREPARED FOR SUBMISSION TO JHEP JLAB-THY-22-3617, MSUHEP-22-018

https://arxiv.org/abs/2205.07846

Exclusive production of a pair of high transverse momentum photons in pion-nucleon collisions for extracting generalized parton distributions

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Jian-Wei Qiu[a,b] **Zhite Yu**[c]

[a] *Theory Center, Jefferson Lab, Newport News, Virginia 23606, USA*

[b] *Department of Physics, William & Mary, Williamsburg, Virginia 23187, USA*

[c] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*

E-mail: jqiu@jlab.org, yuzhite@msu.edu

ABSTRACT: We show that exclusive production of a pair of high transverse momentum photons in pion-nucleon collisions can be systematically studied in QCD factorization approach if the photon's transverse momentum q_T with respect to the colliding pion is much

Exclusive Diphoton Process

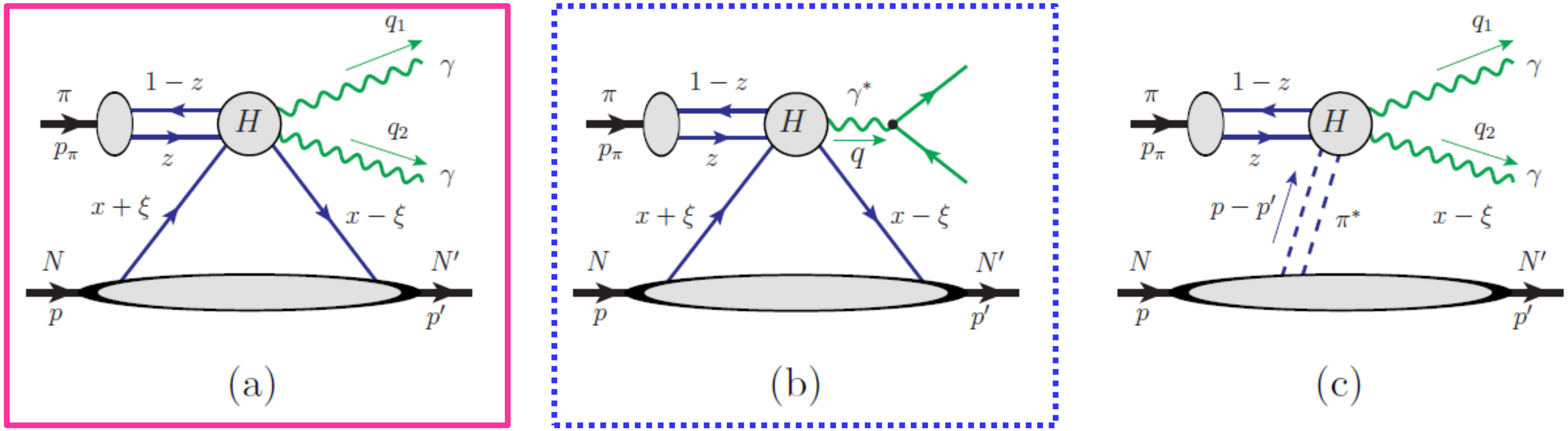
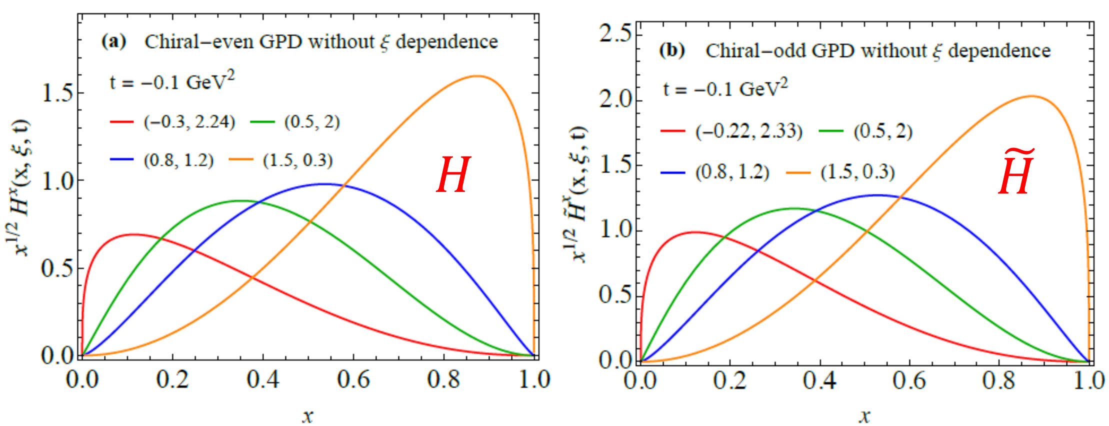


figure 2: Exclusive massive photon-pair (a) and lepton-pair (b) production in pion-nucleon collision, and (c) the photon-pair productions when $|t| \equiv |(p-p')^2| \to 0$.

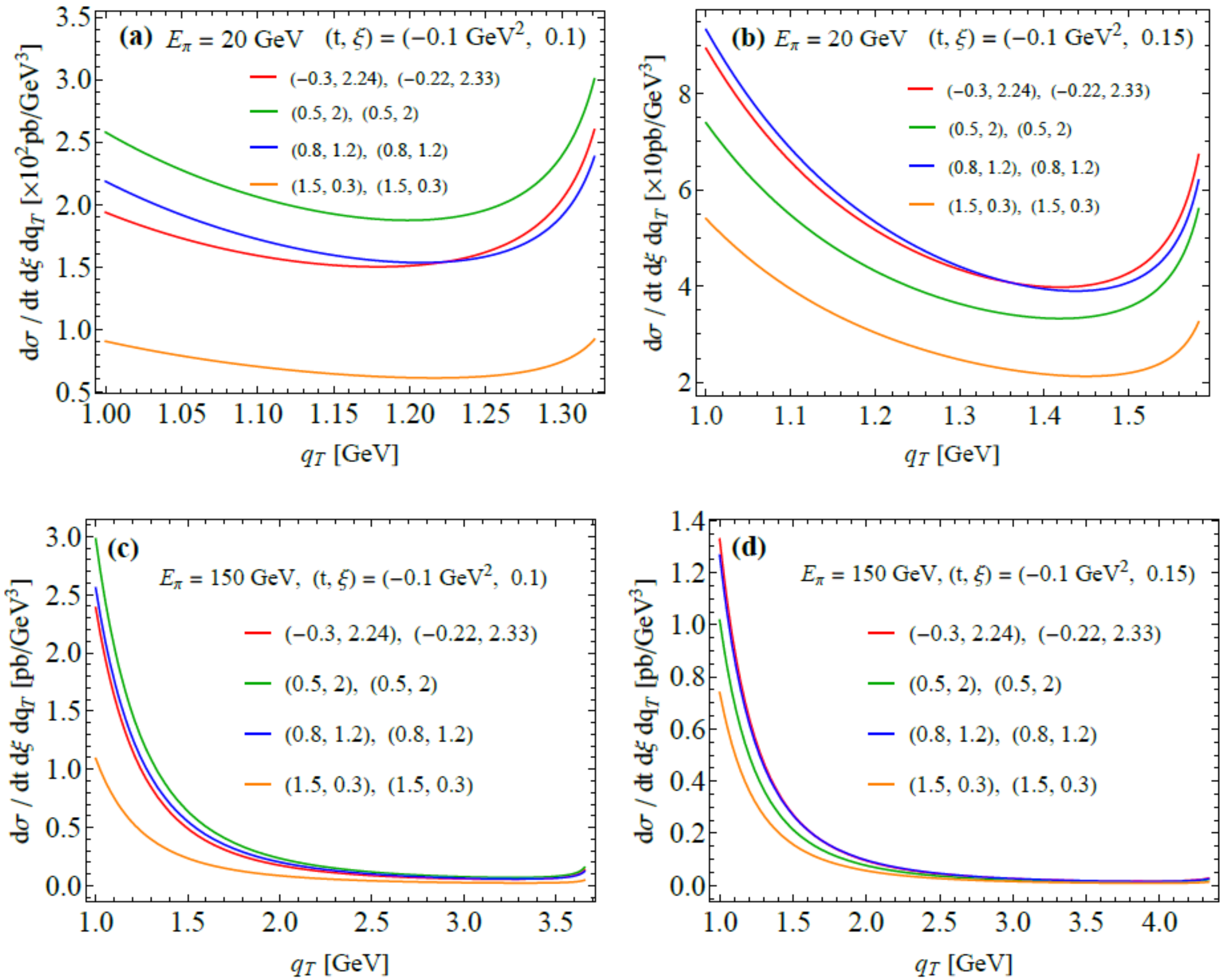


Exclusive Diphoton Process

qT spectrum: sensitive to the x-dependence of H and $\widetilde{H}$

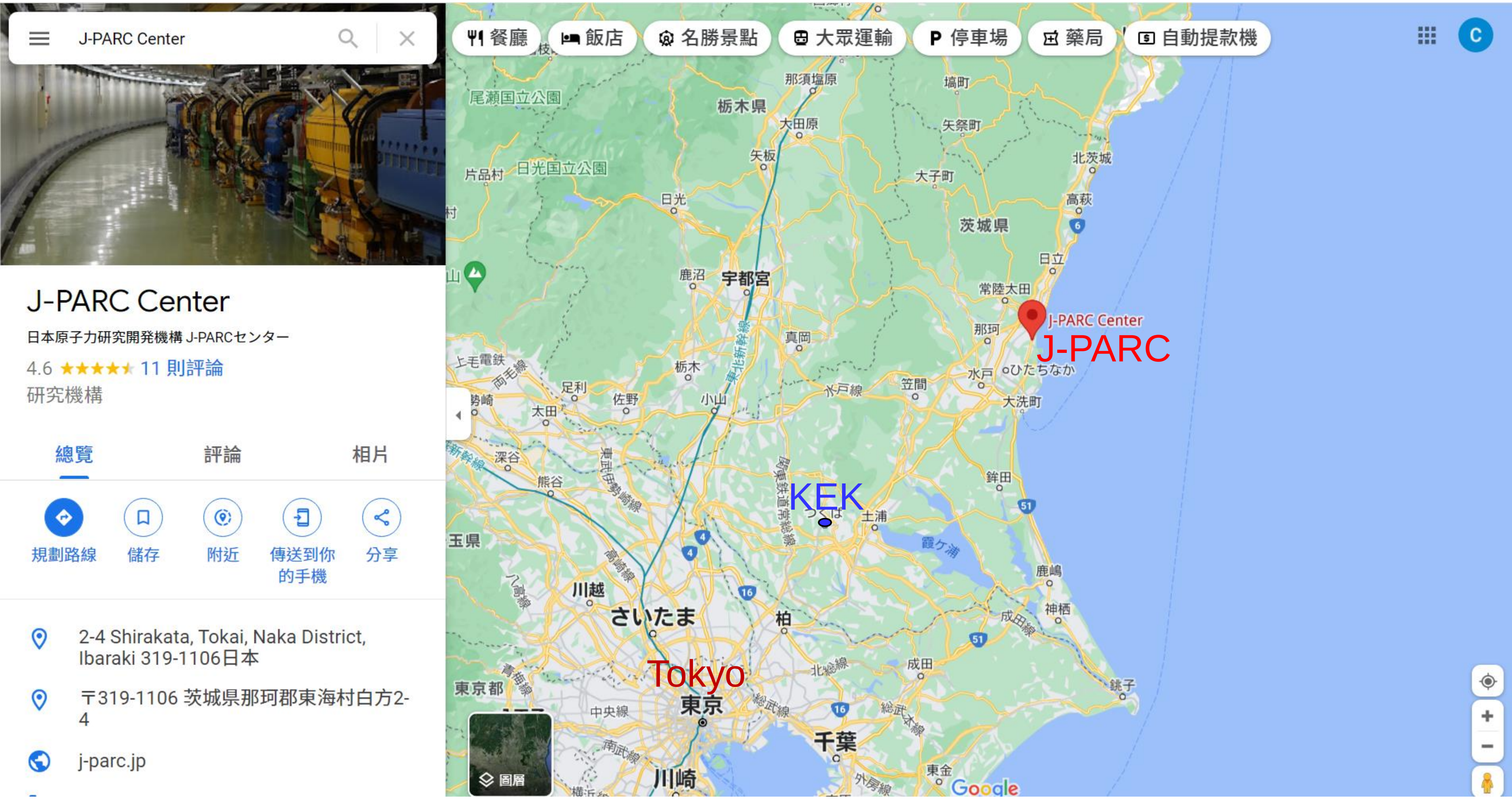
J-PARC
$E_\pi = 20\ GeV$

CERN AMBER
$E_\pi = 150\ GeV$



$$\sigma(E_\pi = 20\ \text{GeV}) \approx 100 \times \sigma(E_\pi = 150\ \text{GeV})$$

J-PARC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4.6 ★★★★★ 11 則評論
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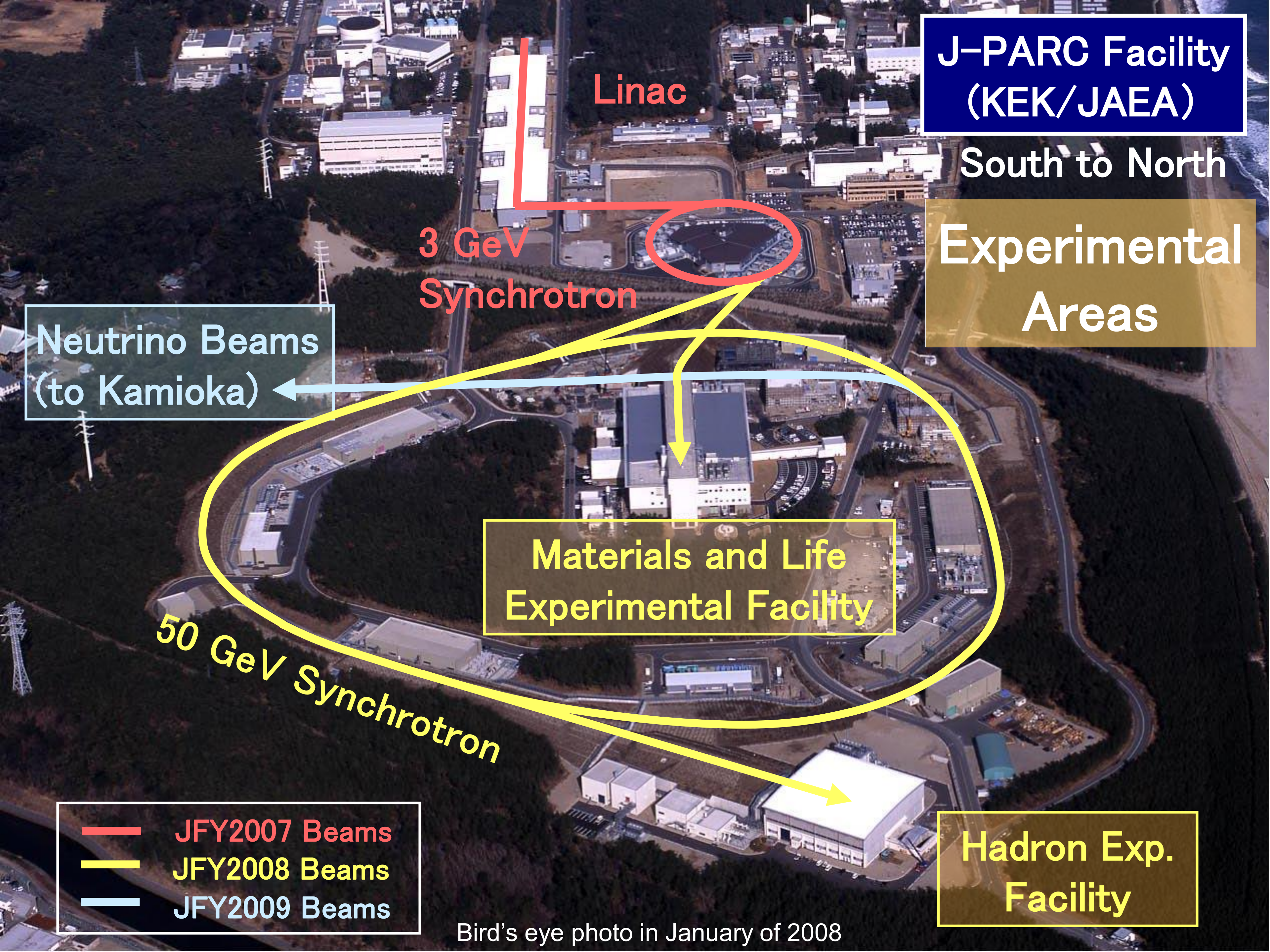
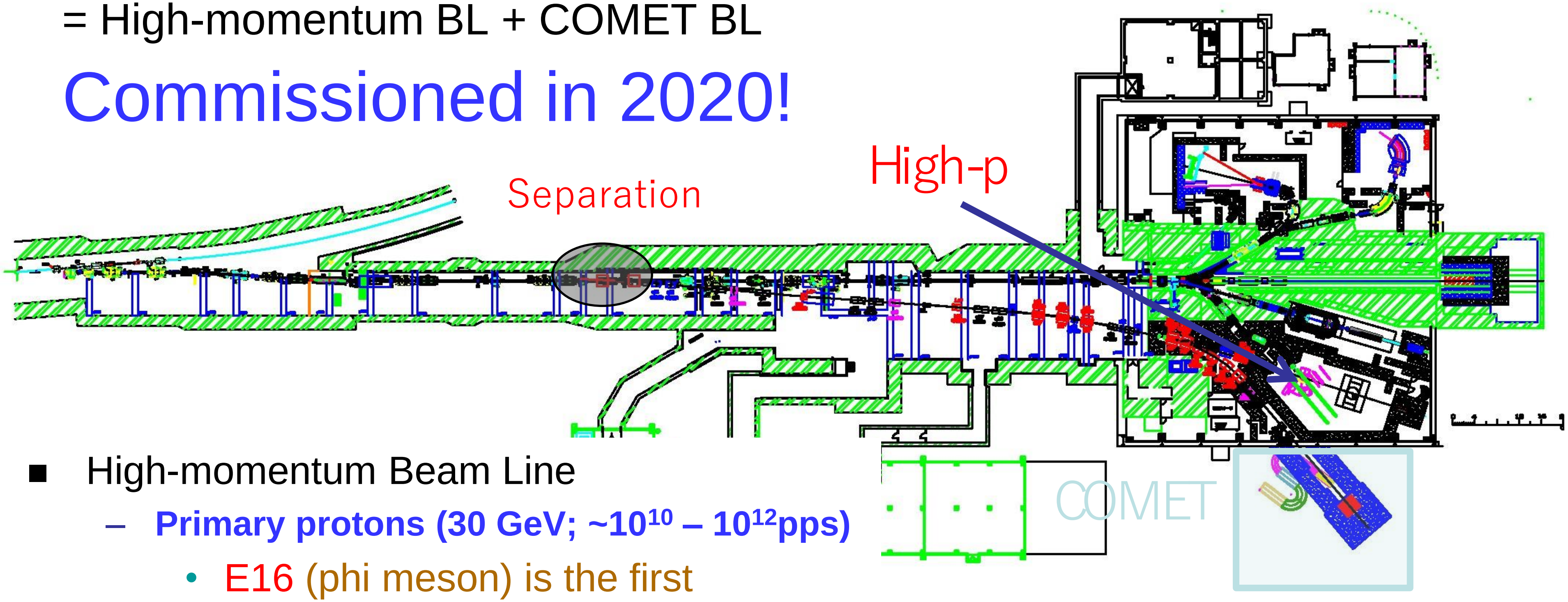

J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Experimental
Areas
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
50 GeV Synchrotron
Hadron Exp.
Facility
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

J-PARC High-momentum Beam Line

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

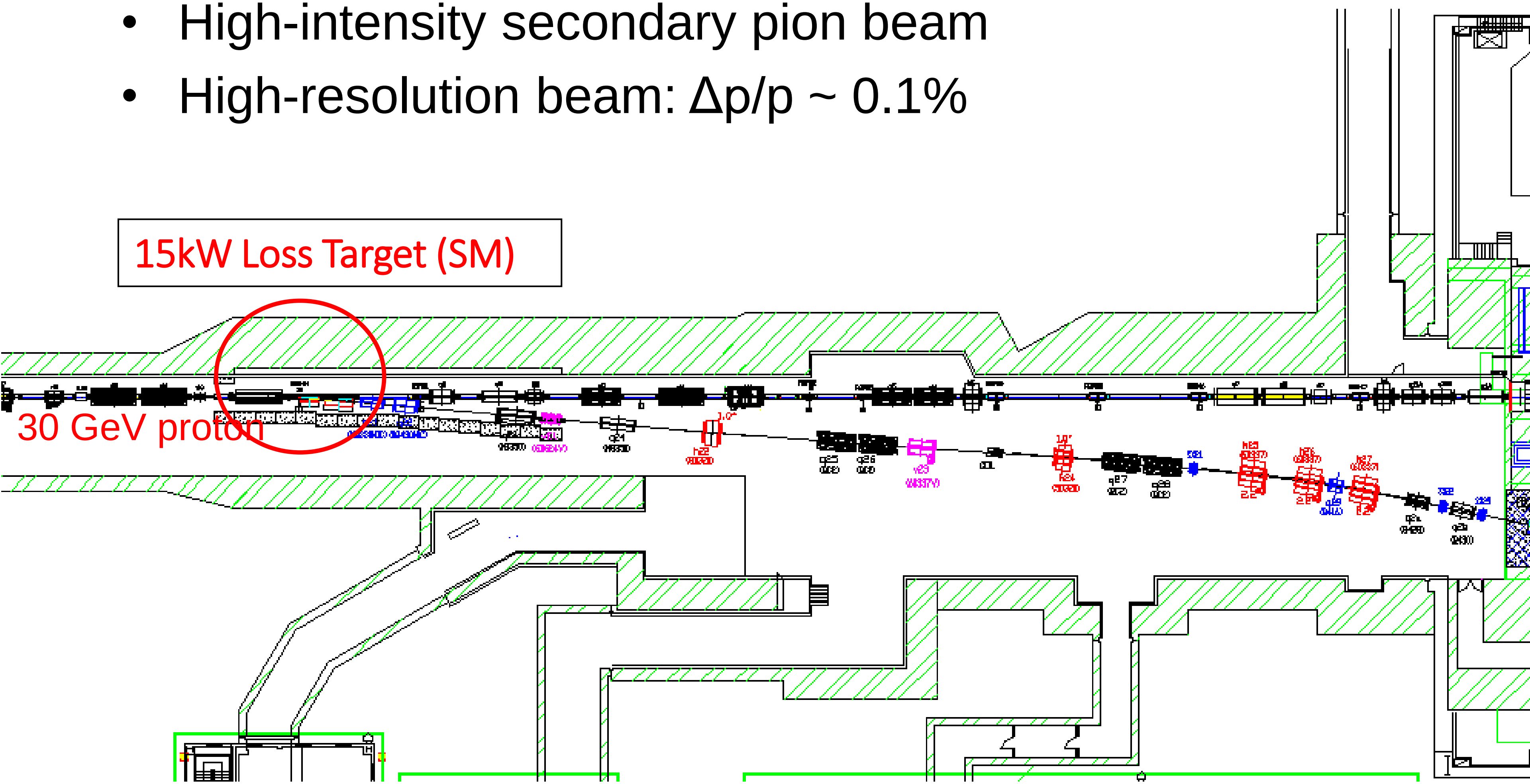
Commissioned in 2020!



- 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)

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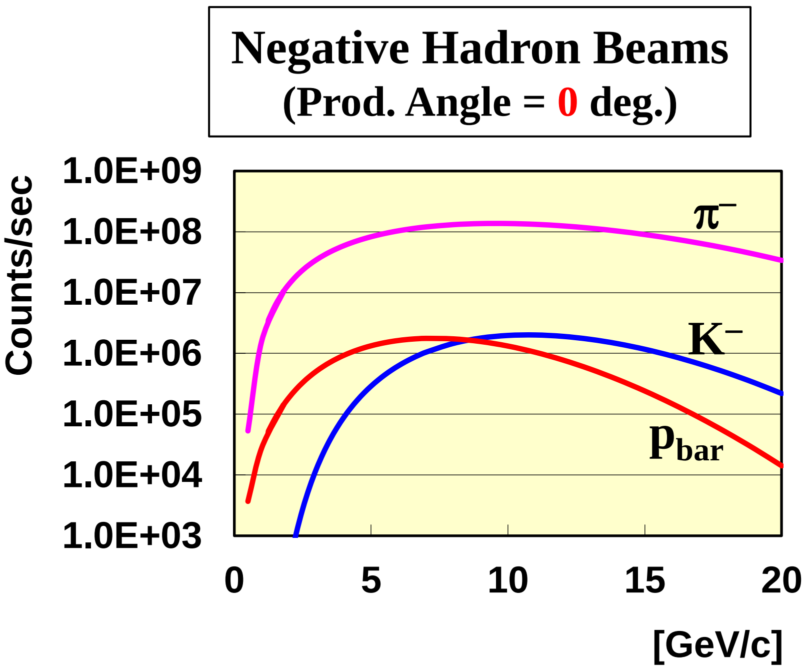
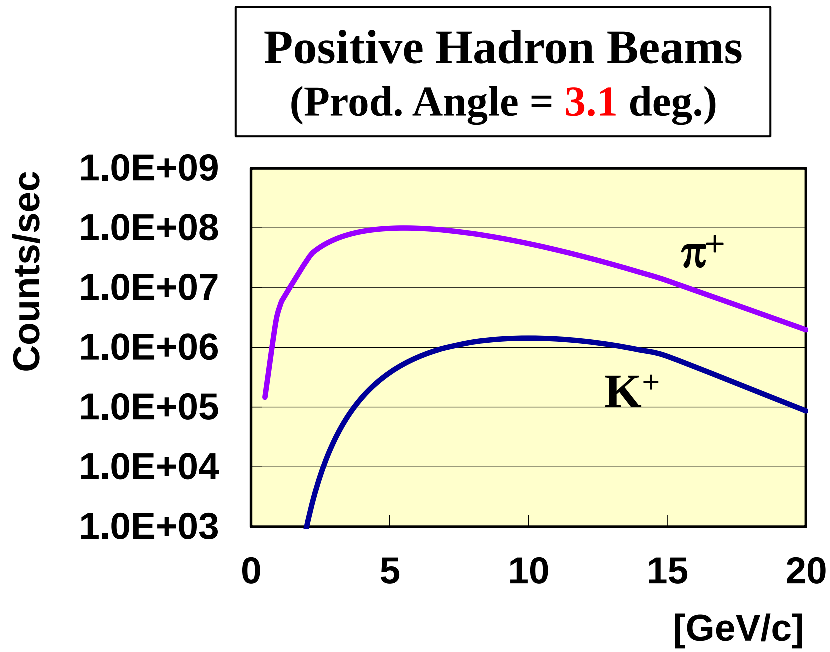




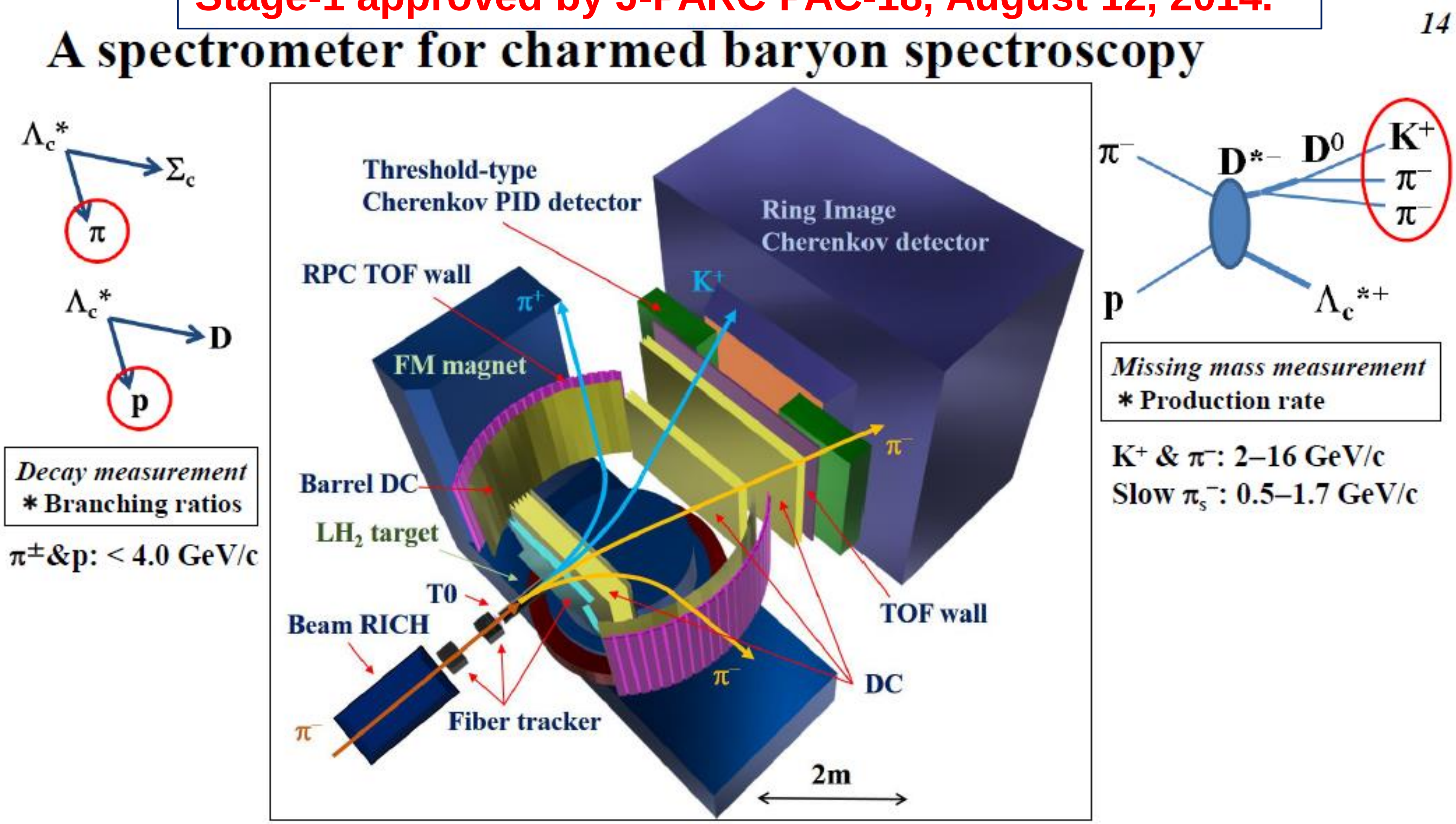
*** Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m**

J-PARC E50 Experiment

N. Tomida's Talk

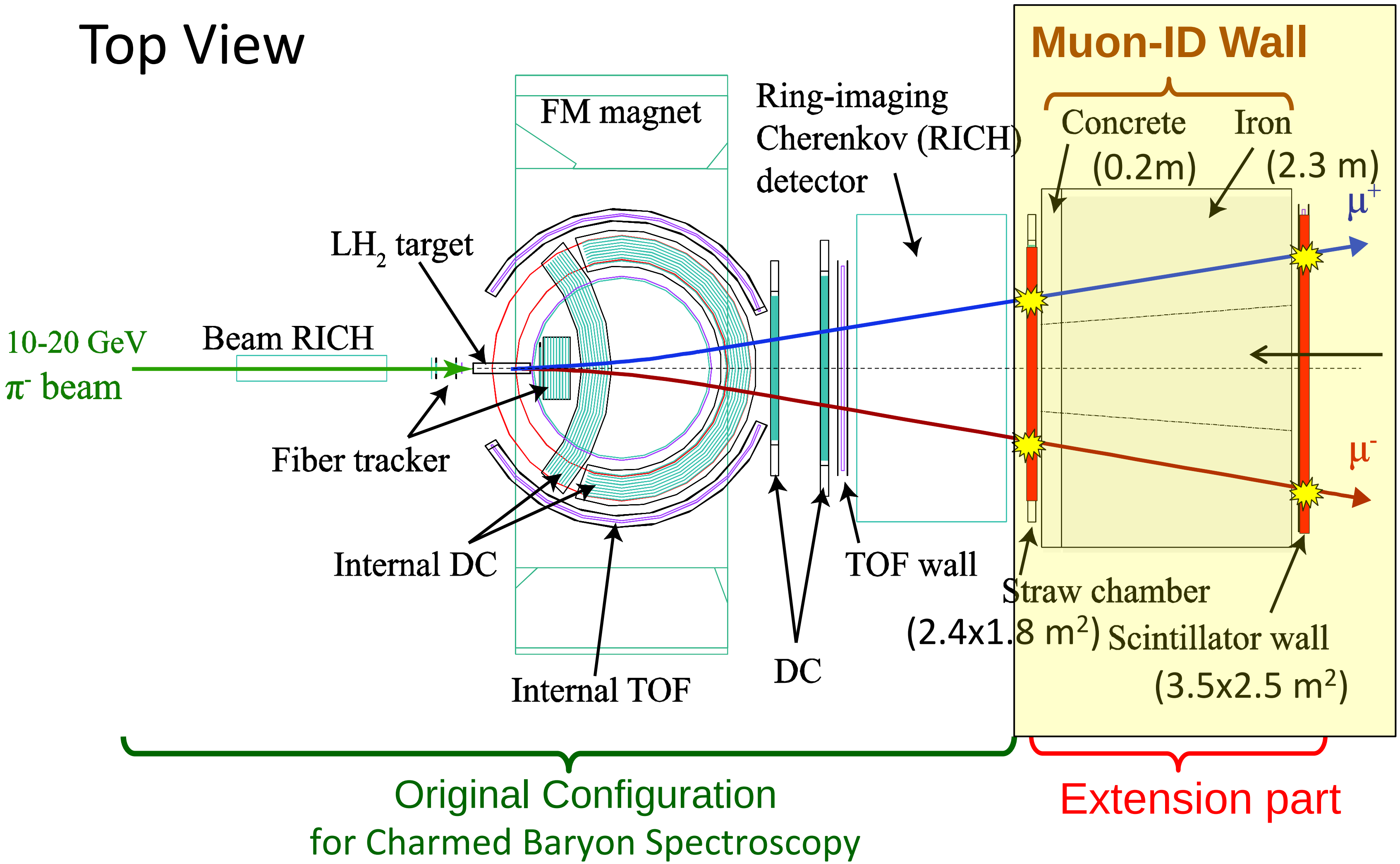
(Charmed Baryon Spectroscopy)

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



K. Shirotori, J-PARC workshop

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

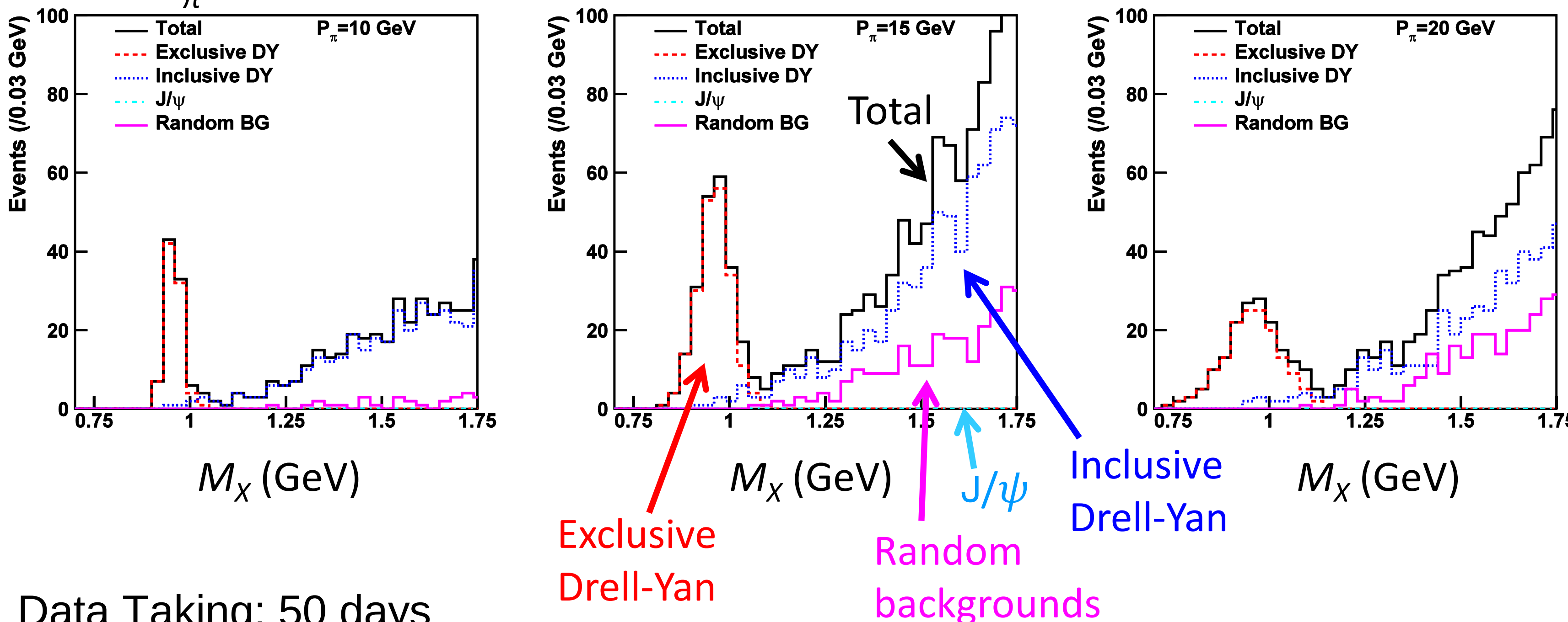


$\pi^- N \rightarrow l^+ l^- X$ Missing-mass M_X

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

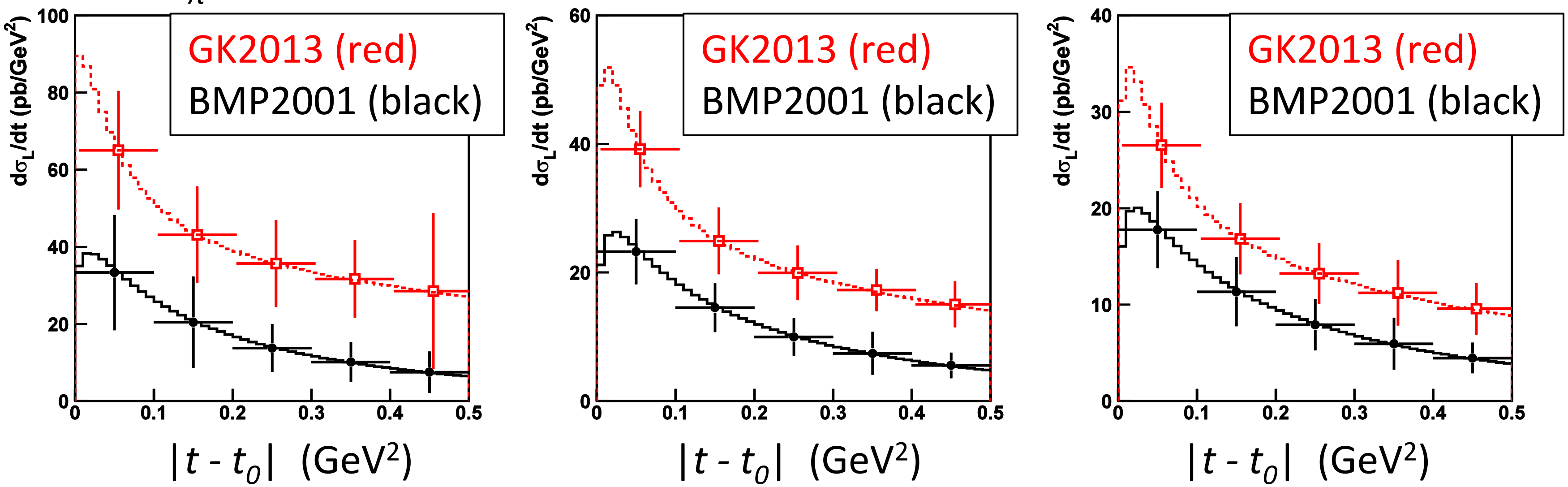
The exclusive Drell-Yan events could be identified by the signature peak at the nucleon mass in the missing-mass spectrum for all three pion beam momenta.

Expected Statistical Sensitivity

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

π^- Beam Momentum

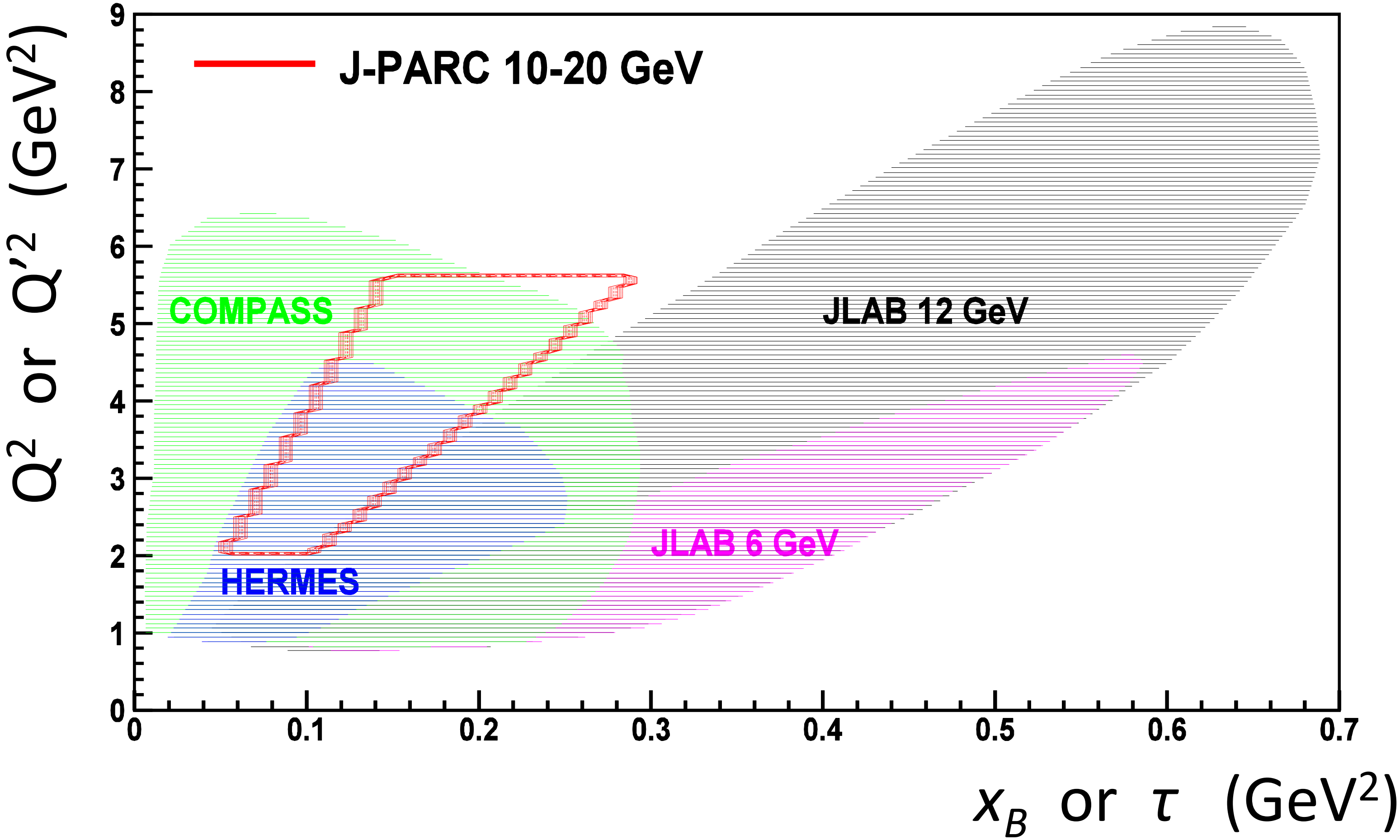
P_π = 10 GeV 15 GeV 20 GeV



- 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

C. Weiss's Talk

"GPD" and "Transition GPD"

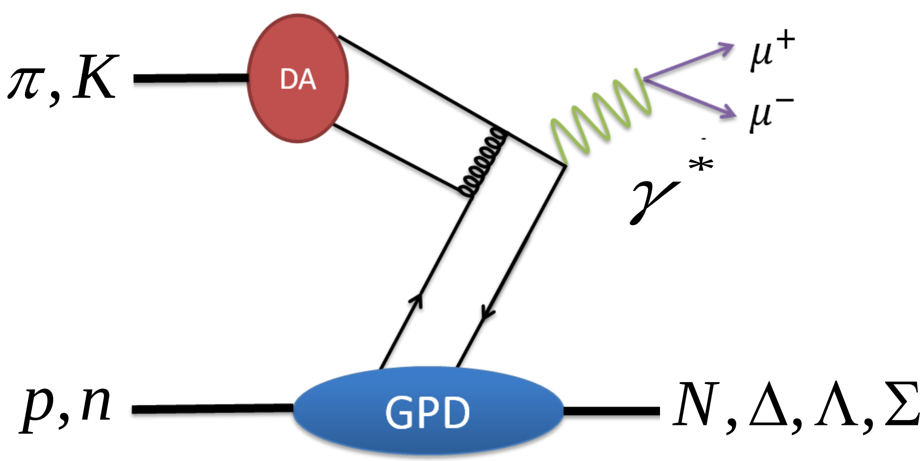
"Transition GPD": L. L. Frankfurt et al., PRD 60, 014010 (1999)

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

R. Trotta's Talk

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

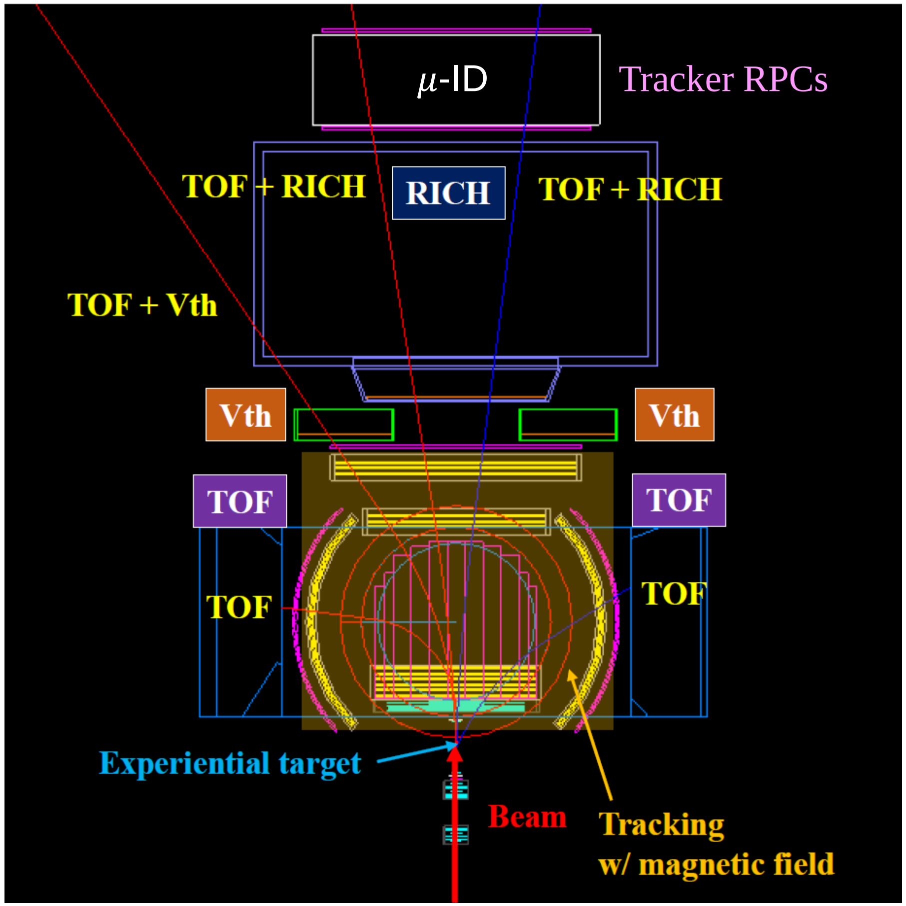
J-PRAC Hadron Hall Extension



Timeline

- 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
  - Commission: 2025 (expected)

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 (***Osaka Metropolitan University),
Chia-Yu Hsieh, Po-Ju Lin, Wen-Chen Chang (Academia Sinica)

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 is a novel approach of measuring GPDs and will bring important understandings on:
  - (Universality of) nucleon GPDs
  - DA and timelike FFs of pions
  - Color-transparency (with nuclei targets)
  - TDA …