The 12th Circum-Pan-Pacific Symposium on High Energy Spin Physics

# *Exploring nucleon TMDs and GPDs by the Drell-Yan process*

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# Outline

- **Drell-Yan process**: a time-like approach to explore the partonic structures of hadrons
- **TMDs**:
  - Boer-Mulders (BM): $\nu$ (unpolarized), $A_T^{\sin(2\phi_{CS}-\phi_S)}$(polarized)
  - Sivers: $A_T^{\sin(\phi_S)}$(polarized)
- **GPDs**: J-PARC
  - Exclusive pion-induced DY (10-20 $\pi^-$ beam)
  - 2-3 hard hadronic process (30 GeV proton beam)
- **Summary**

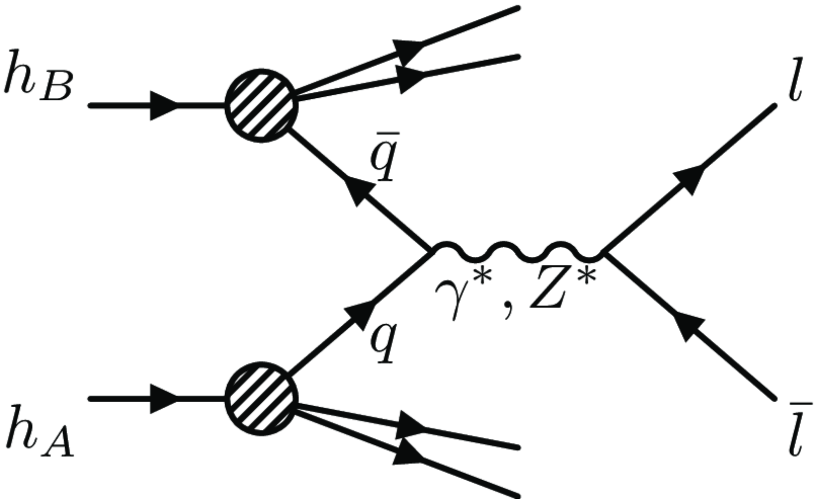
# Drell-Yan Process

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

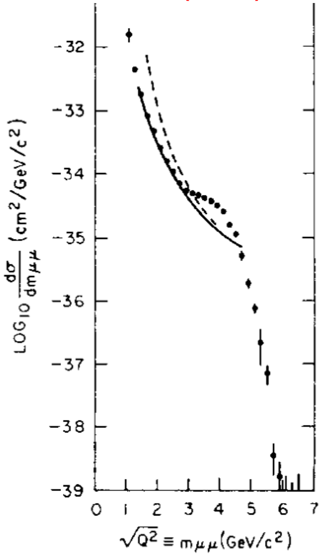
**MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES***

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 $\nu W_2$ near threshold.



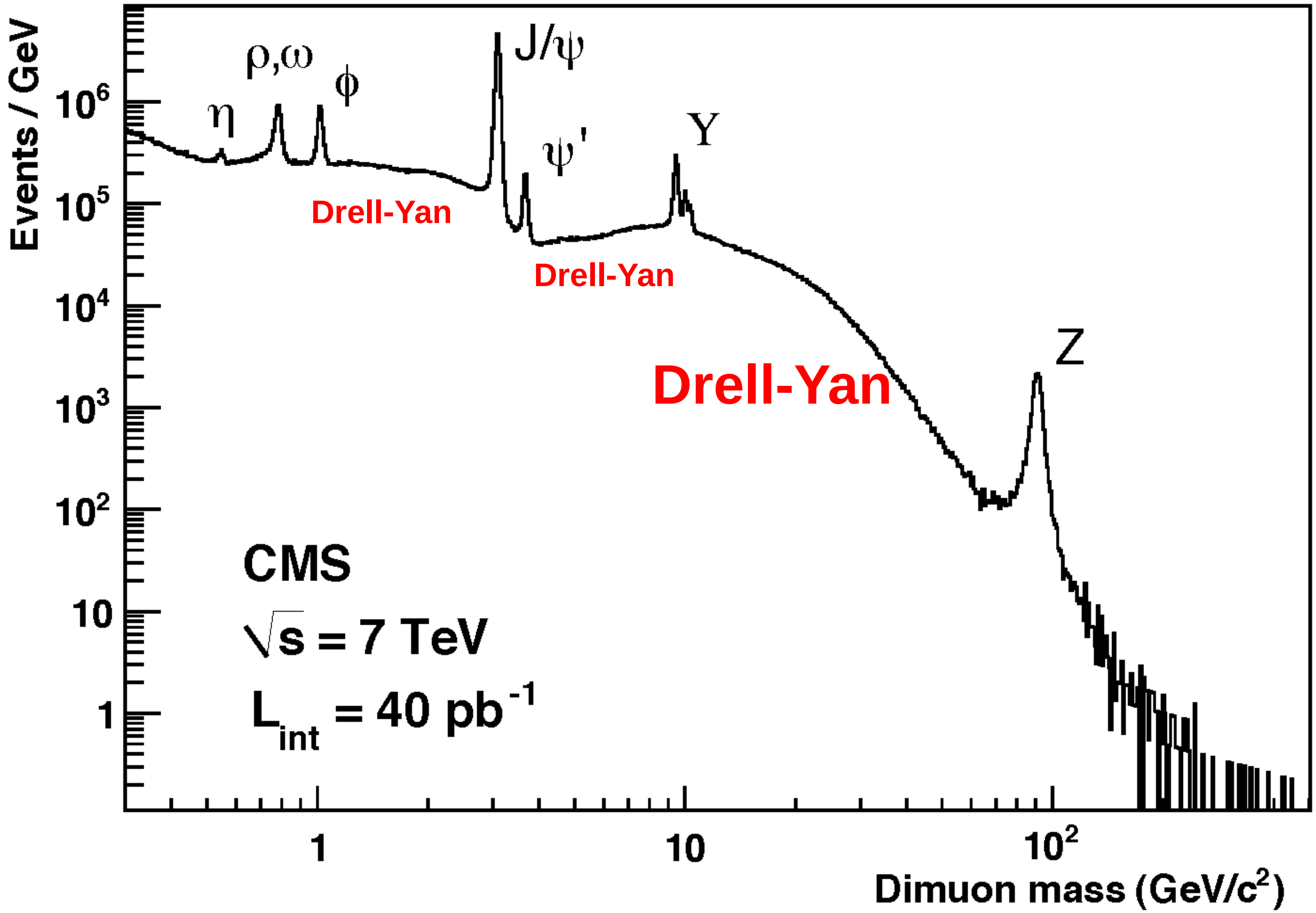

PRL 25 (1970) 1523



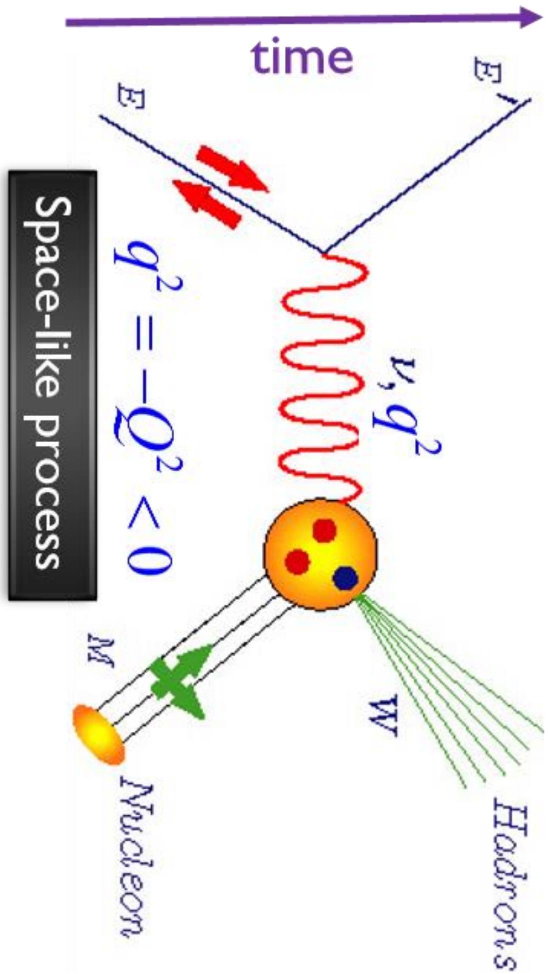

$$\tau = \frac{Q^2}{s} = x_1 x_2$$

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

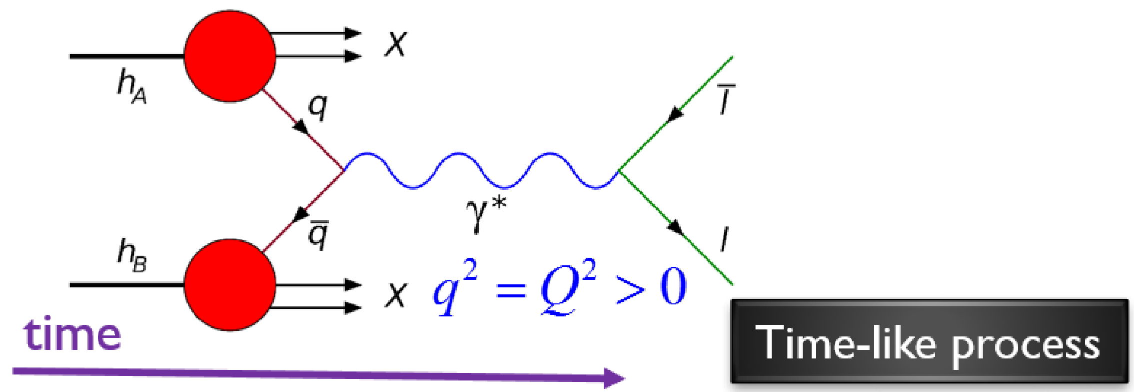
# Dimuon Invariant Mass Spectrum



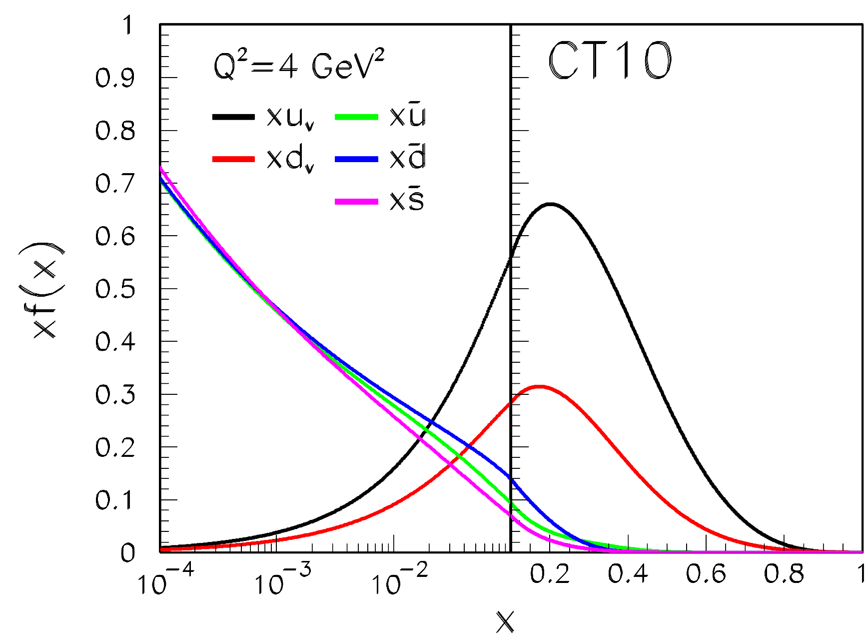
# Proton PDFs



time
E
E'
Space-like process
$q^2 = -Q^2 < 0$
$\nu, q^2$
M
W
Nucleon
Hadrons

$h_A$
$h_B$
X
X
q
$\bar{q}$
$\gamma^*$
$\bar{l}$
$l$
$q^2 = Q^2 > 0$
time
Time-like process

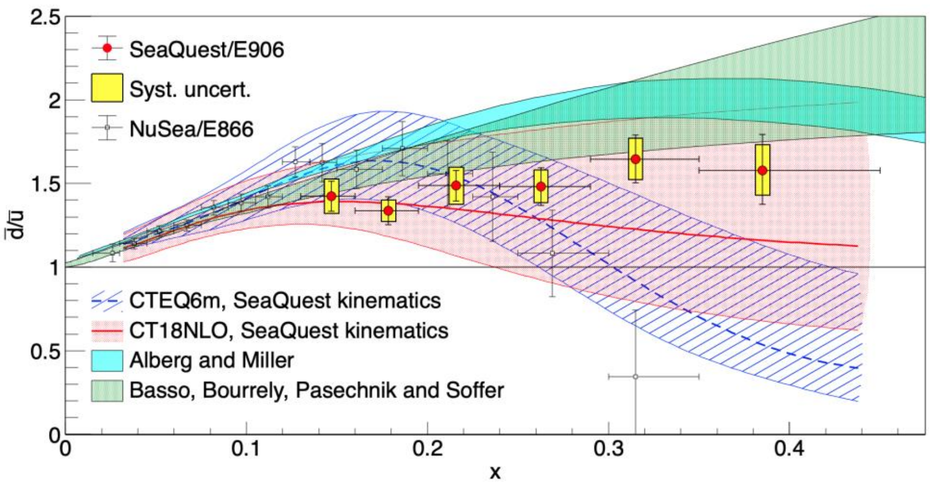



CT10
$Q^2$=4 GeV$^2$
$xu_v$
$xd_v$
$x\bar{u}$
$x\bar{d}$
$x\bar{s}$
xf(x)
x
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$10^{-4}$
$10^{-3}$
$10^{-2}$
0.2
0.4
0.6
0.8
1

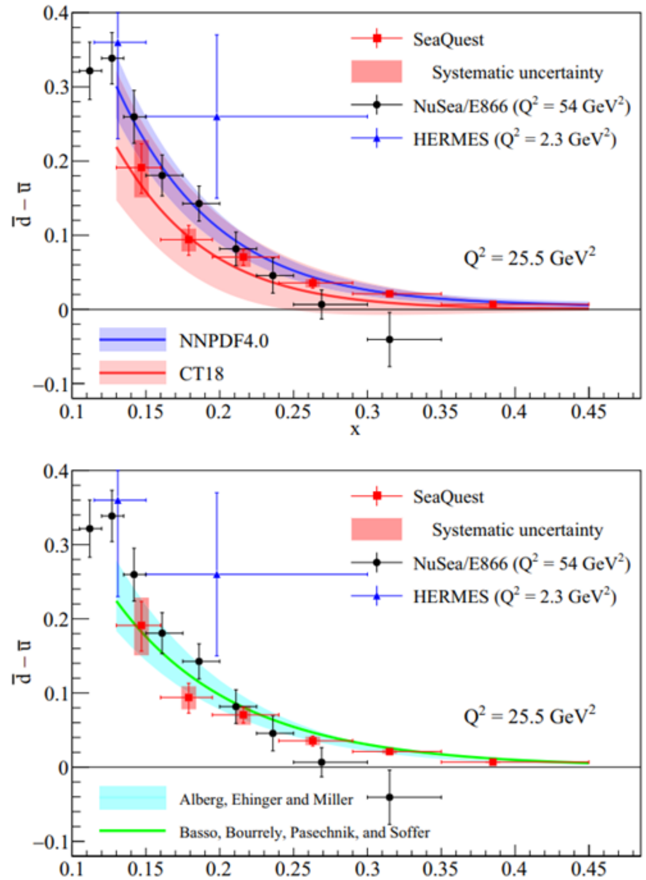
# FNAL SeaQuest: $\bar{d}(x)/\bar{u}(x)$

p+ p,d 120-GeV

Nature 590, 561–565 (2021)

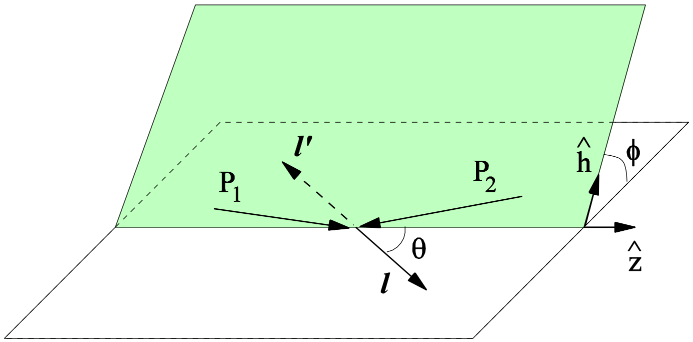



Phys. Rev. C 108, 035202 (2023)




The extracted $\bar{d}/\bar{u}(x)$ are consistent with CT18NLO and predictions of pion-cloud model.

# Decay Angular Distributions




θ and ϕ are the decay polar and azimuthal angles of the $\mu^+$ in the dilepton rest-frame

Collins-Soper frame

$$\frac{d\sigma}{d\Omega} \propto (1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi)$$

$$\propto (W_T (1 + \cos^2\theta) + W_L (1 - \cos^2\theta) + W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta} \sin^2\theta \cos 2\phi)$$

$q\bar{q}$ annilation parton model:

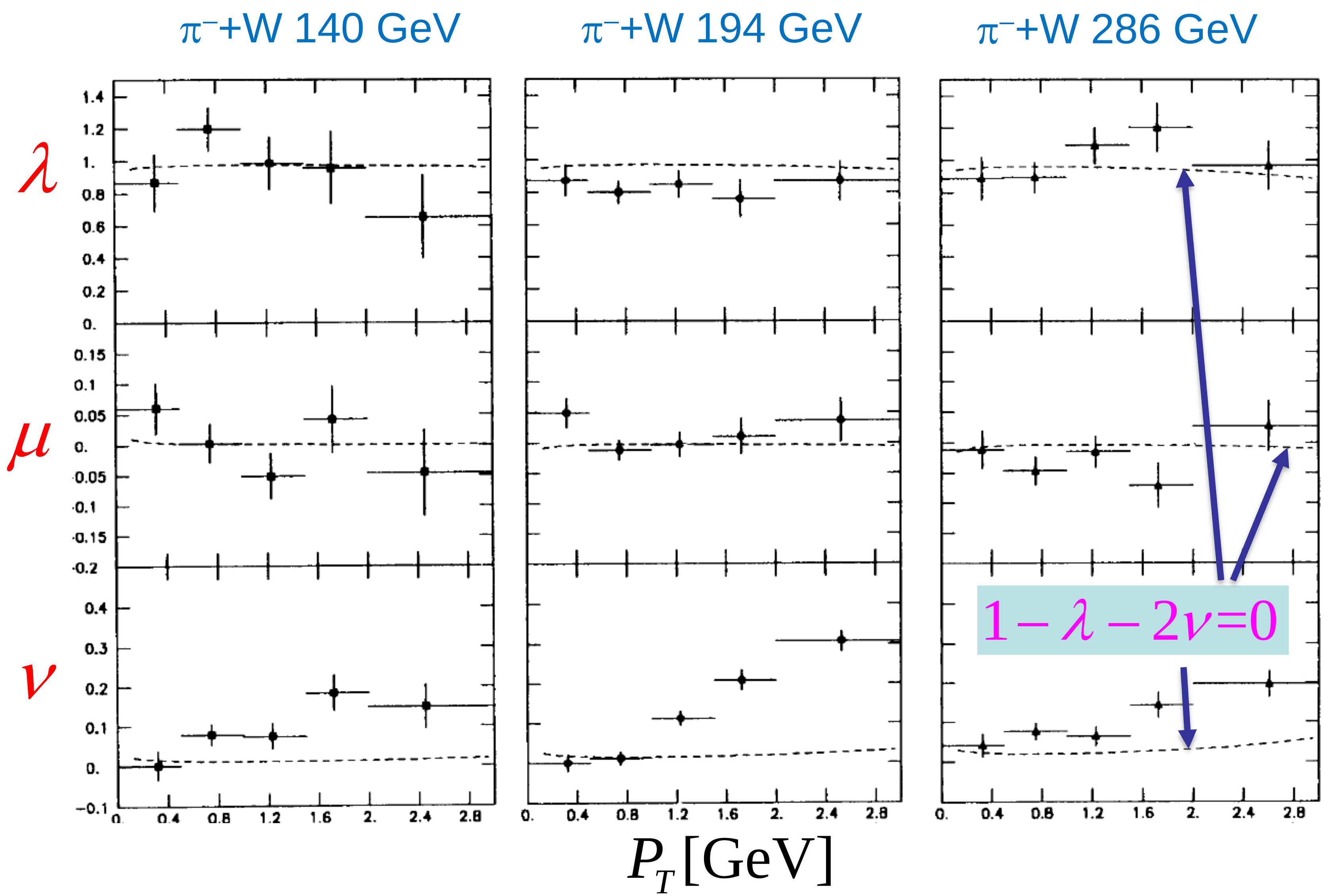
$O(\alpha_s^0)$ $\lambda$=1, $\mu = \nu$=0; $W_T = 1, W_L = 0$

Lam-Tung relation (1978)

Collinear pQCD: $O(\alpha_s^1)$, $W_L = 2W_{\Delta\Delta}$; $1 - \lambda - 2\nu = 0$

# NA10 @ CERN: Violation of LT

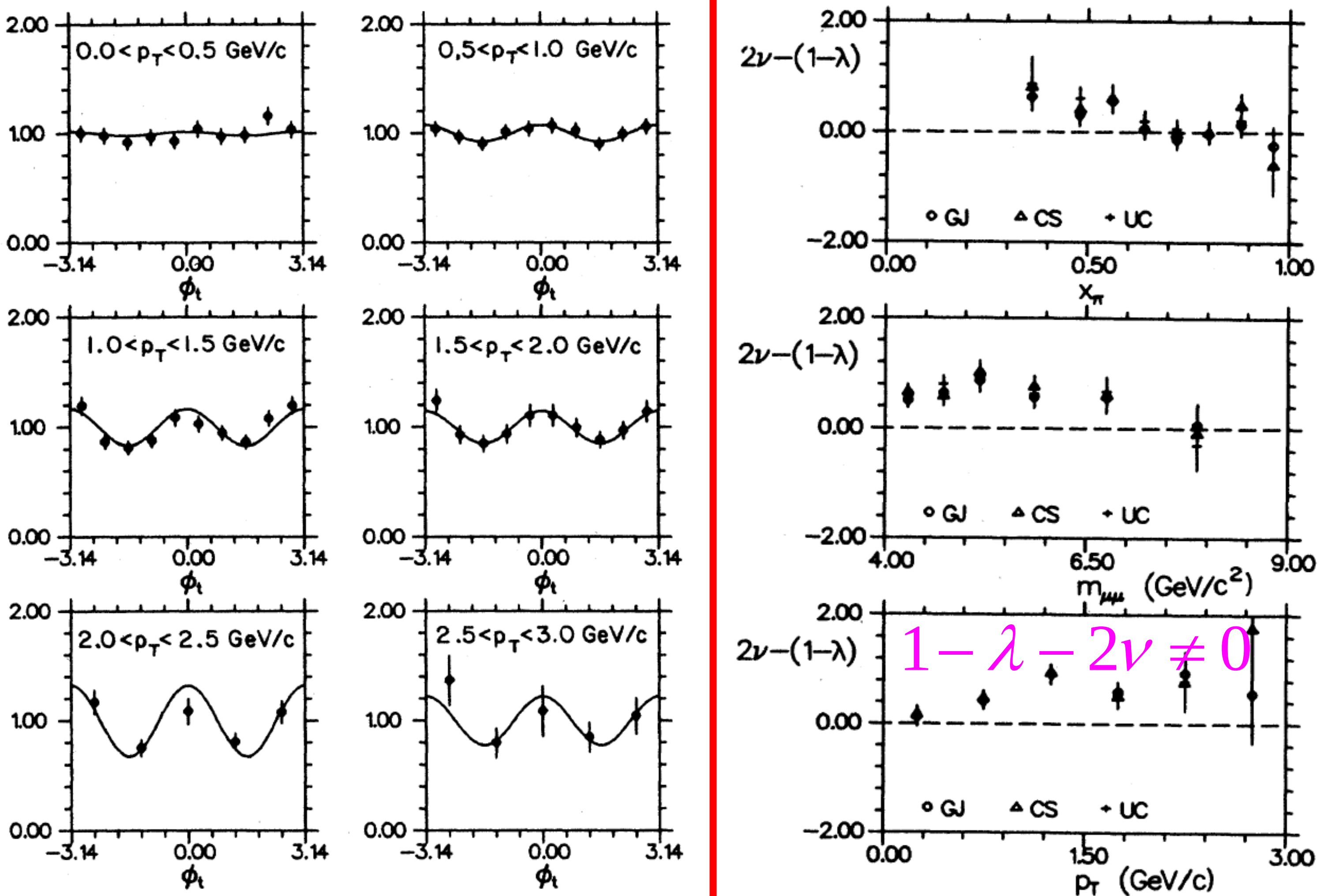
*Z. Phys. 37 (1988) 545*



# E615 @ FNAL: Violation of LT

*PRD 39, 92 (1989)*

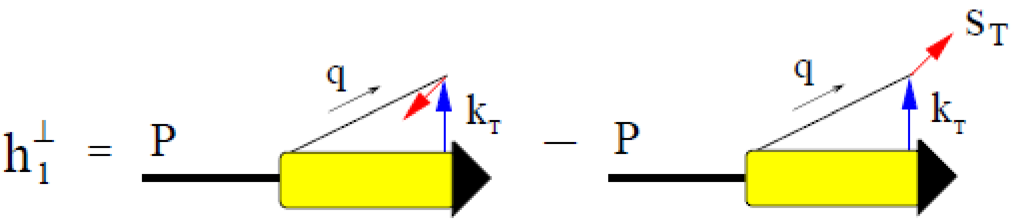
$\pi^-$+W 252-GeV

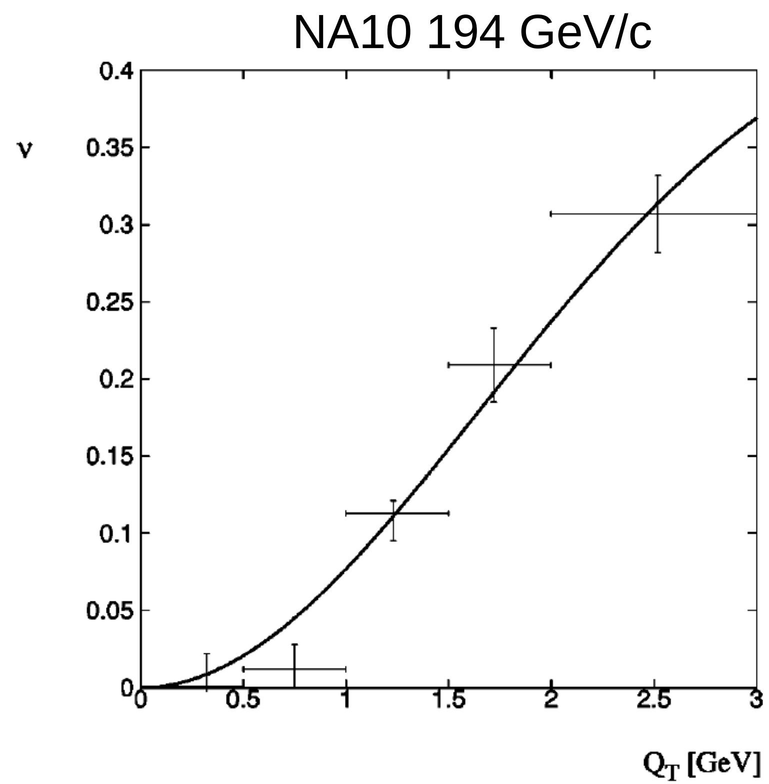



$\cos 2\phi$ modulation at large $p_T$

# TMD Boer-Mulders Effect ($h_1^\perp$)

Boer, PRD 60, 014012 (1999)

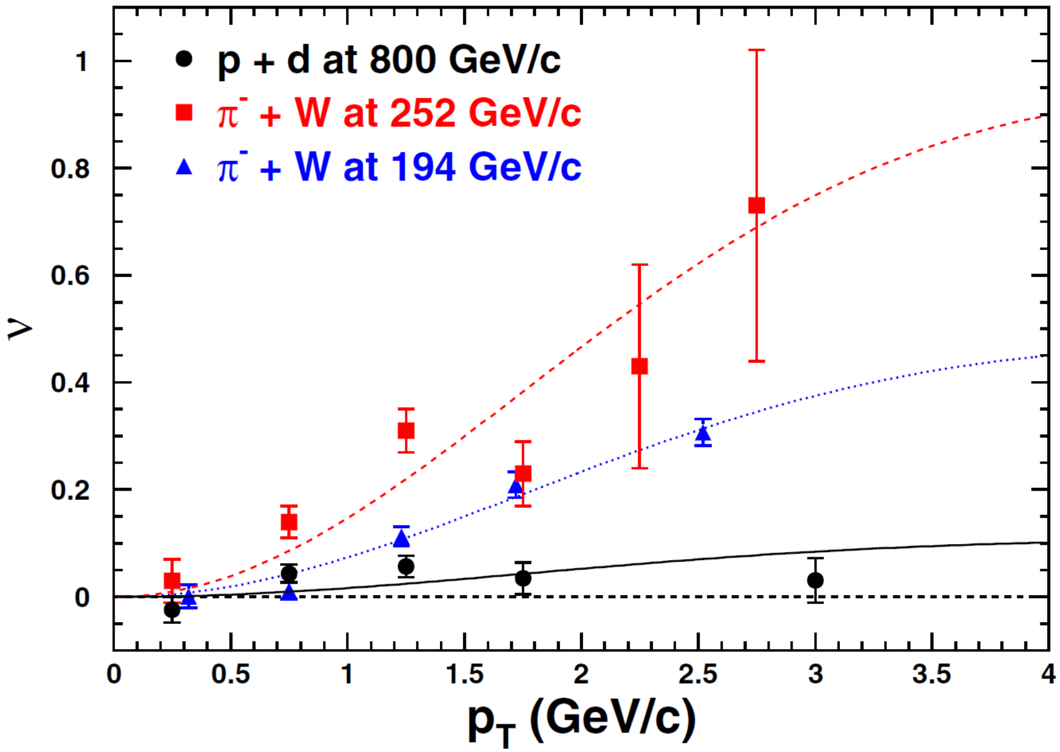



- $h_1^\perp$ represents a correlation between quark's $k_T$ and transverse spin $S_T$ in an unpolarized hadron.
- $h_1^\perp$ could lead to an azimuthal dependence with $\frac{\nu}{2} \propto h_1^\perp(\pi) h_1^\perp(N)$

# Azimuthal cos2ϕ Distribution in proton-induced DY

*E866, PRL 99, 082301 (2007)*




$$h_1^{\perp}(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x),$$

$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2},$$

$$\kappa_1 = C_{H_1} C_{H_2}/2$$

$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

$\nu(pd \rightarrow \mu+\mu- X) \sim$ [valence $h_1^{\perp}(p)$] * [sea $h_1^{\perp}(p)$]

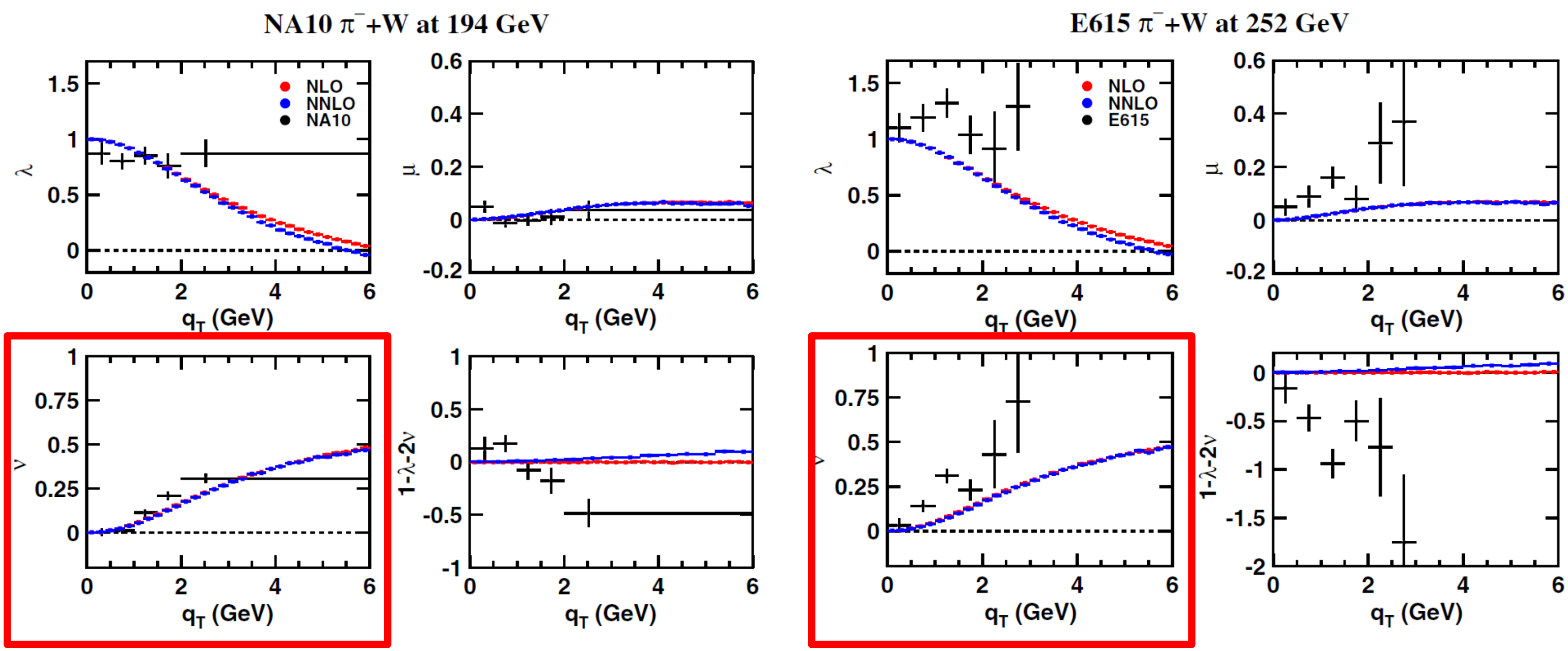
$h_1^{\perp}(\pi)$ and $h_1^{\perp}(p)$ are of the same sign.

- J.C. Peng, Transversity 2014

Sea-quark BM functions are much smaller than valence quarks

# Fixed-order pQCD Contribution

W.C. Chang, R.E. McClellan, J.C. Peng, O. Teryaev, PRD 99, 014032 (2019)

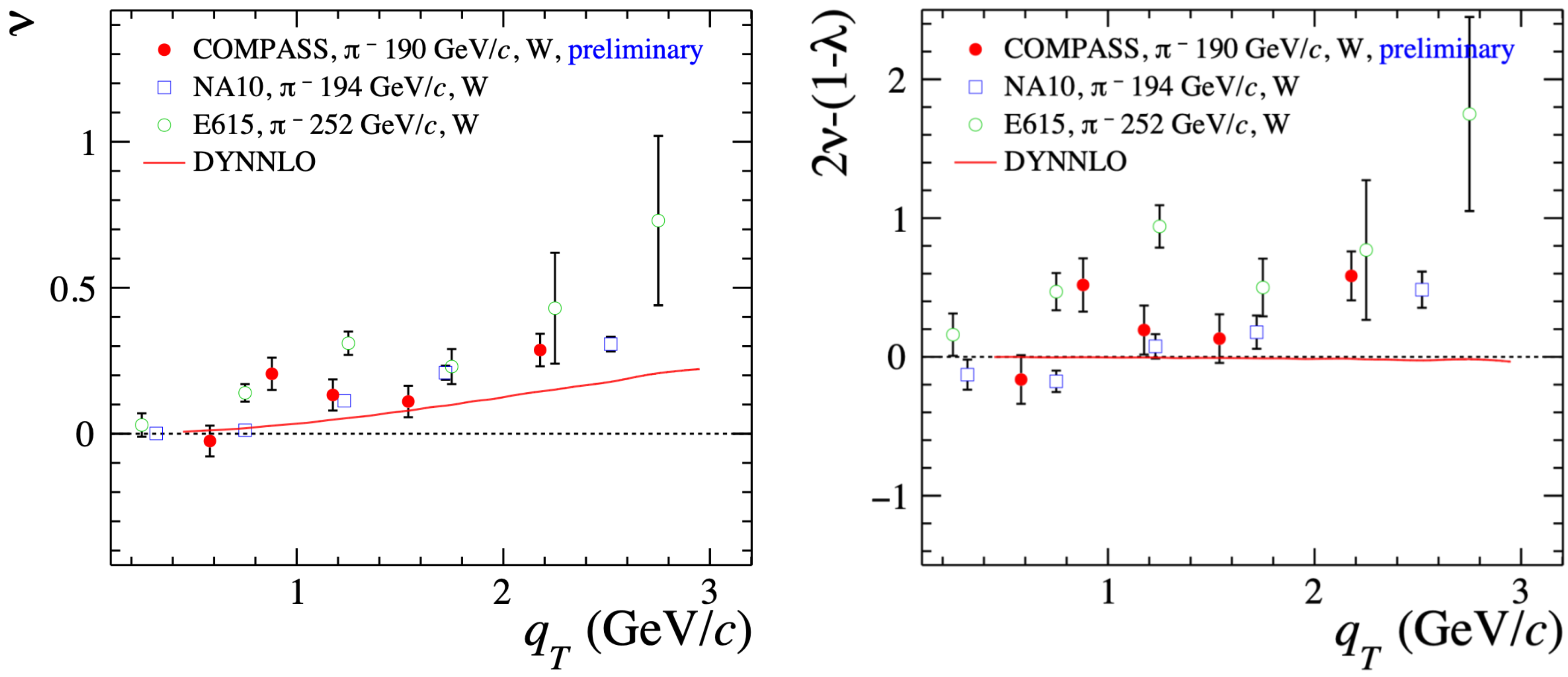



The pQCD contribution accounts for the majority of non-zero $\nu$!

$NLO : O(\alpha_s^1); NNLO : O(\alpha_s^2)$

# COMPASS @ CERN: Violation of LT

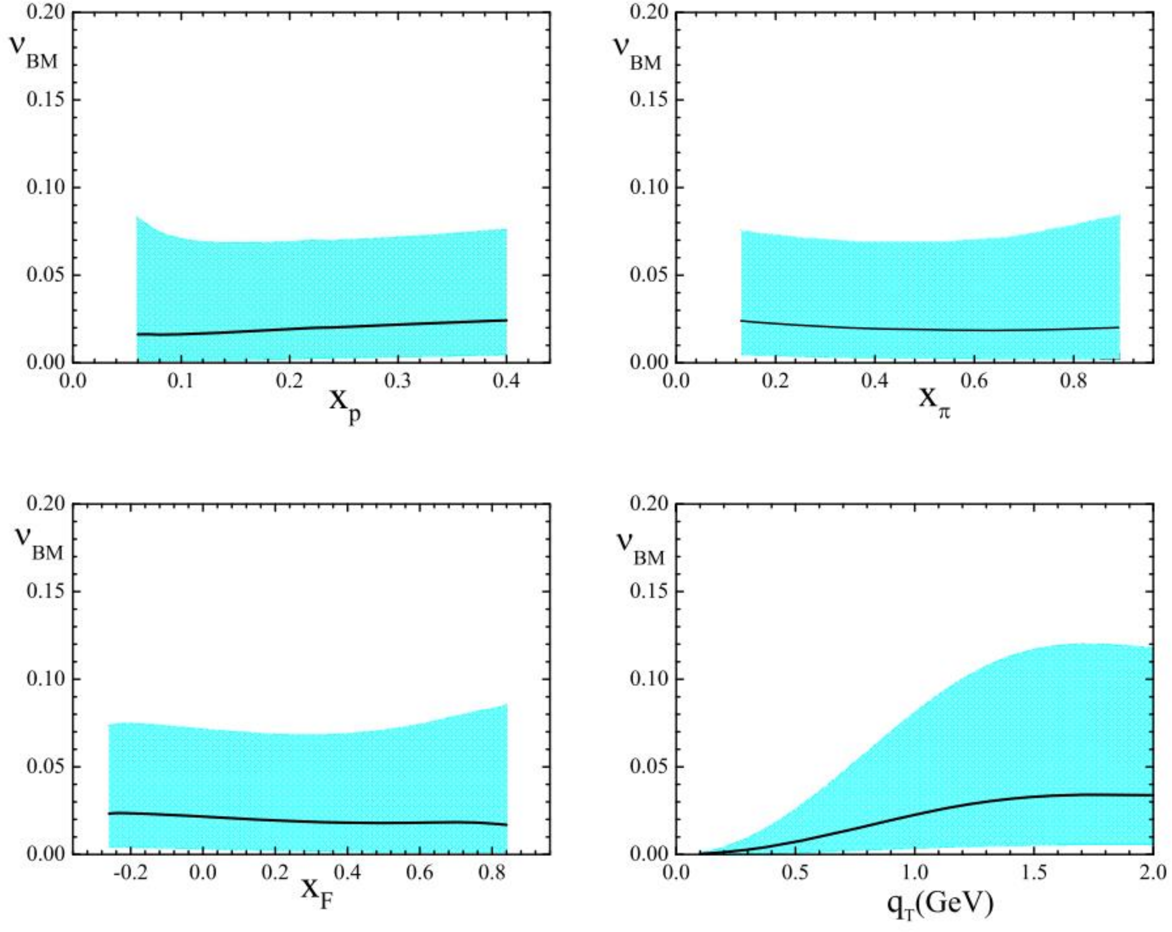
$\pi^{-}$+W 190-GeV




[DIS 2021 proceedings, Y.H. Lien]

# Boer-Mulders in the unpolarized Drell–Yan at COMPASS

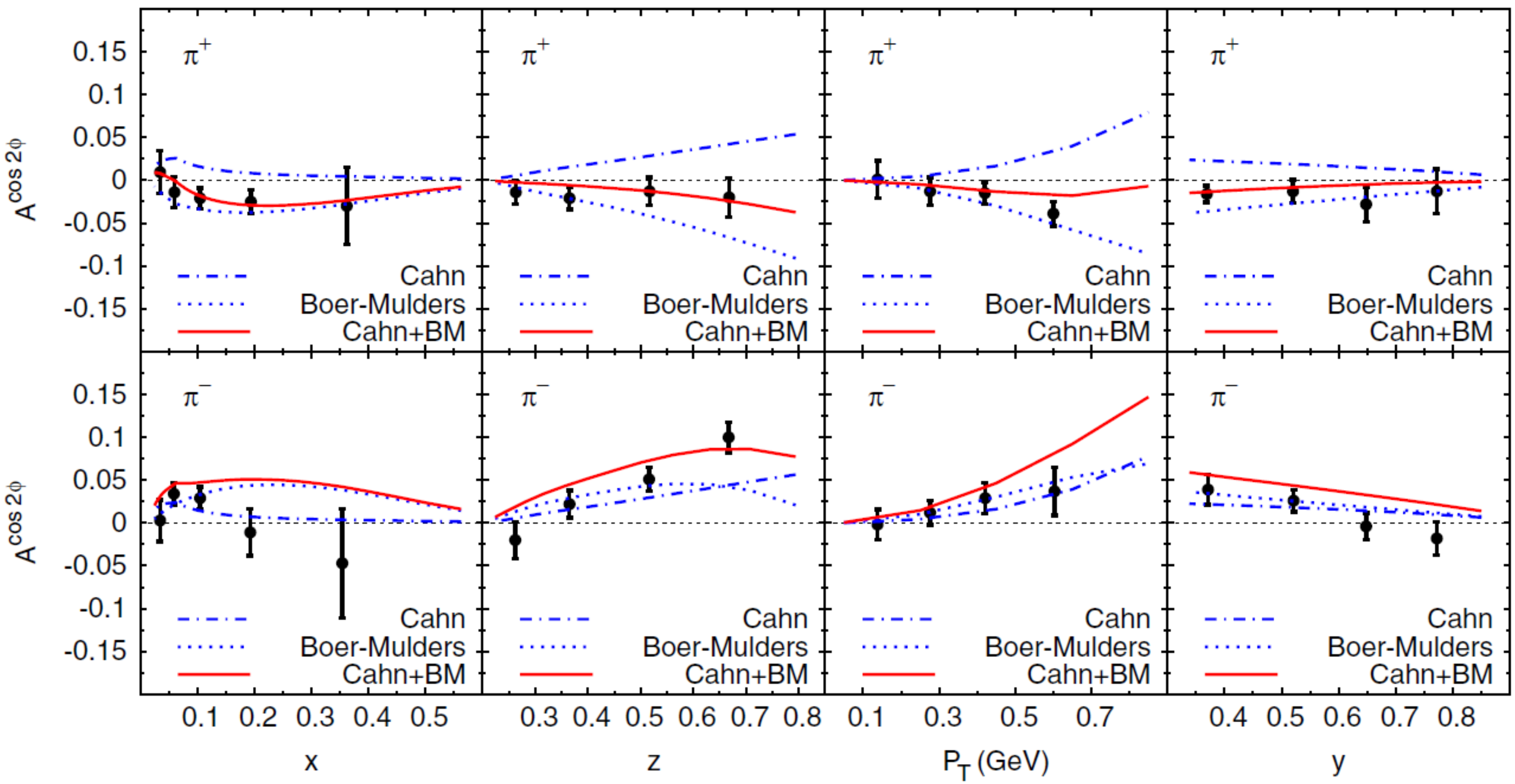
X. Wang, W. Mao, and Z. Lu, Eur. Phys. J. C 78 643 (2018)



Andrea Bressan’s talk

# Boer-Mulders in SIDIS

HERMES Proton    HERMES, AIP Conf. Proc. 1149, 423 (2009).

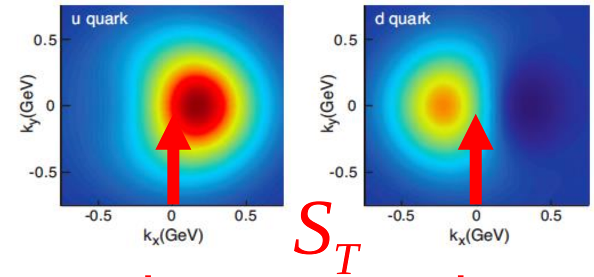




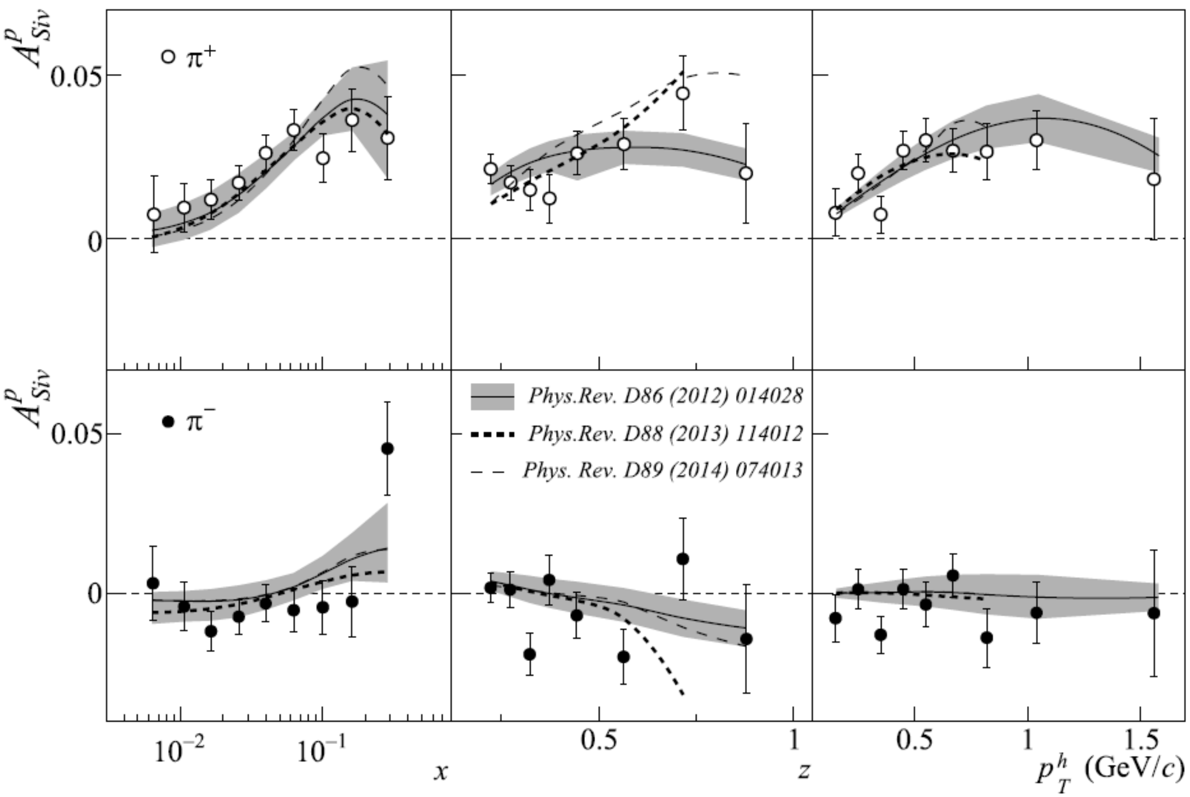

Barone et al., PRD 81, 114026 (2010) [arXiv:0912.5194]

Andrea Bressan's talk

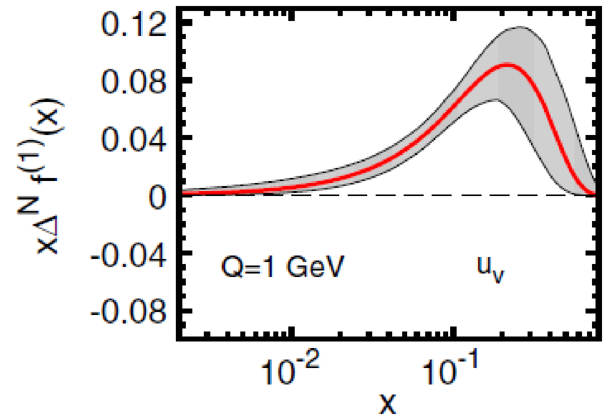
# Nonzero Sivers Asymmetries in SIDIS

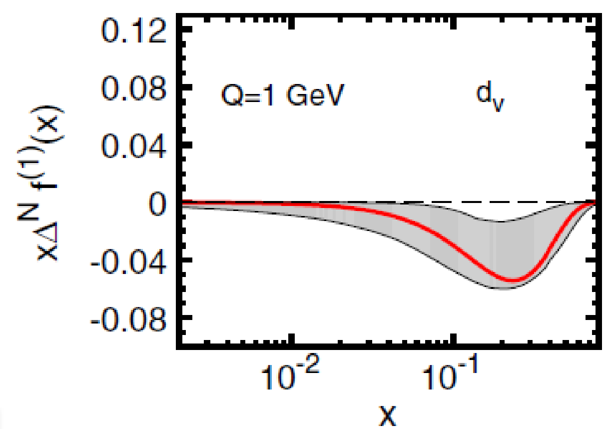



COMPASS, PLB 744 (2015) 250




Sivers Functions




Signals of flavor-dependent Sivers functions in SIDIS

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

# SIDIS vs. Drell-Yan

## Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \\ + S_T \left[ \begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \end{array} \right] \\ + S_T \lambda \left[ \sqrt{\left(1-\varepsilon^2\right)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \right] \end{array} \right\}$$

**SIDIS-DY bridge**

## Drell–Yan process (DY)

$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[ \begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left( \begin{array}{l} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS}\right)$

| SIDIS | | DY |
|---|---|---|
| $A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots$ | Boer-Mulders | $A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$ |
| $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$ | Sivers | $A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$ |
| $A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$ | Transversity | $A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$ |
| $A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$ | Pretzelosity | $A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$ |
| $A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$ | Worm-gear L | $A_L^{\sin 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1L,p}^{\perp q}$ |
| $A_{LL} \propto g_{1L}^q \otimes D_{1q}^h,\ A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$ | | Double polarized DY only |



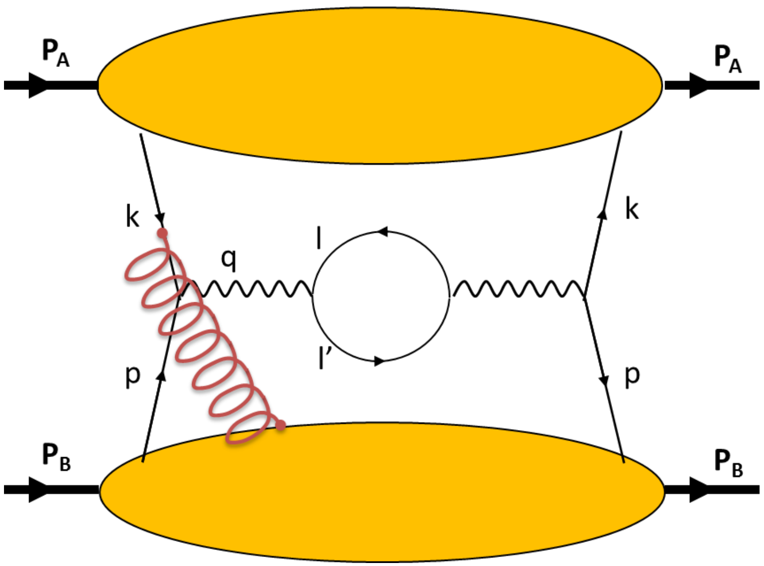
DIS 2021, Y.H. Lien

Stephen Pate's talk

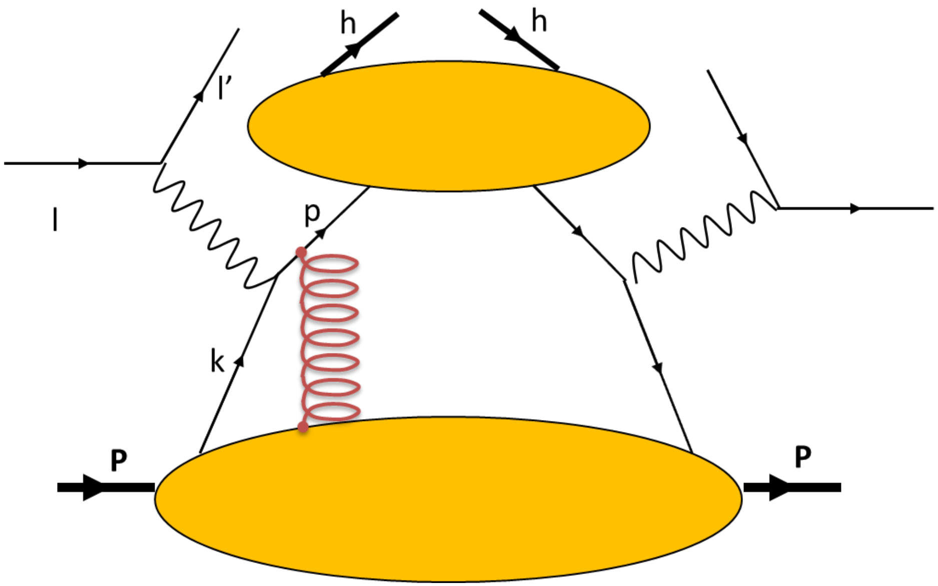
# Sign Change of T-odd Sivers/BM Functions

*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**



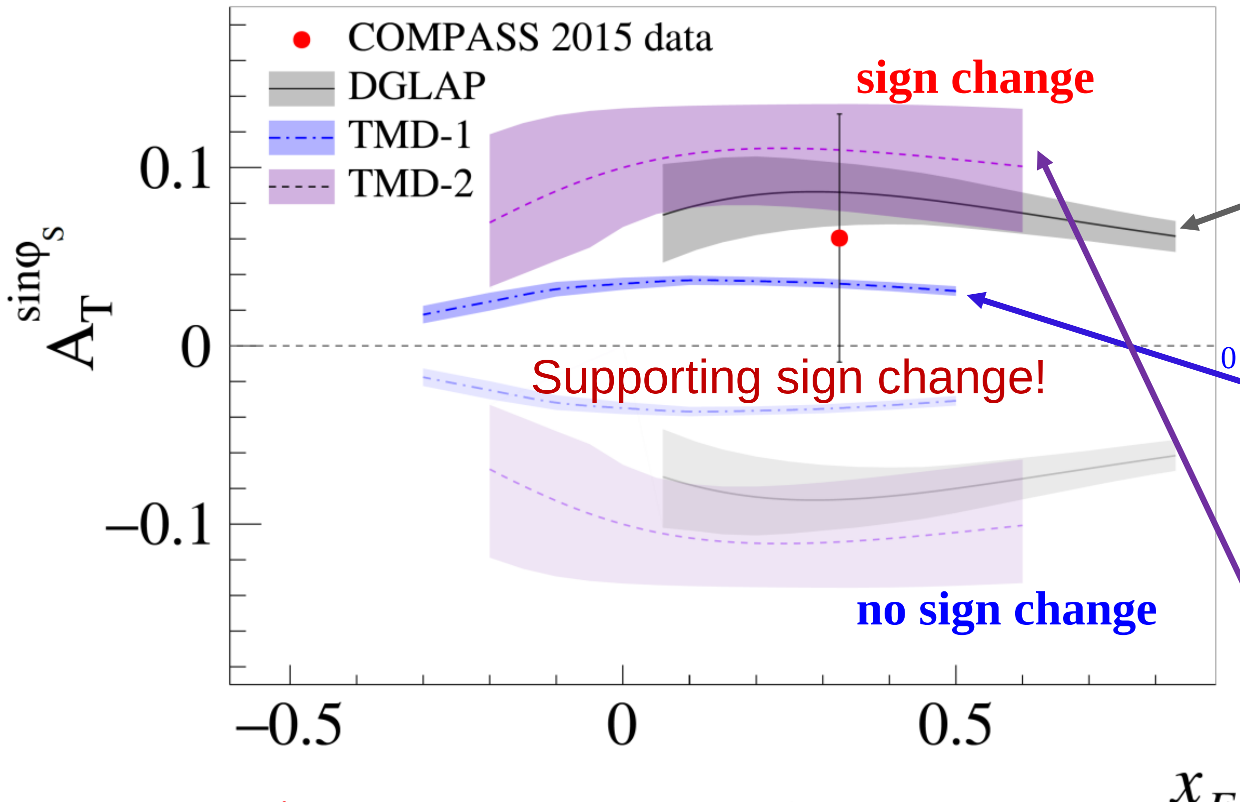

$$\text{Sivers/BM}\,|_{DY} = -1 * \text{Sivers/BM}\,|_{SIDIS}$$

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

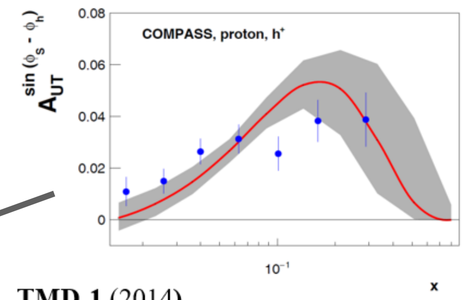
# Sivers in Polarized Drell-Yan

2015 runs

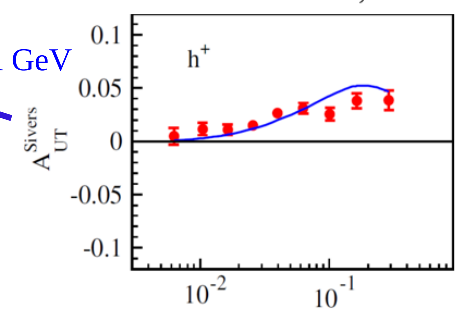
**COMPASS, PRL 119 (2017) 112002**



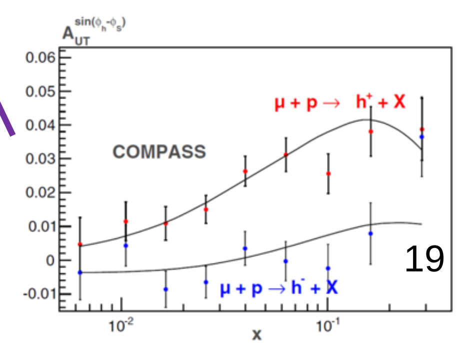

**DGLAP** (2016)
M. Anselmino et al., **arXiv:1612.06413**




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




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



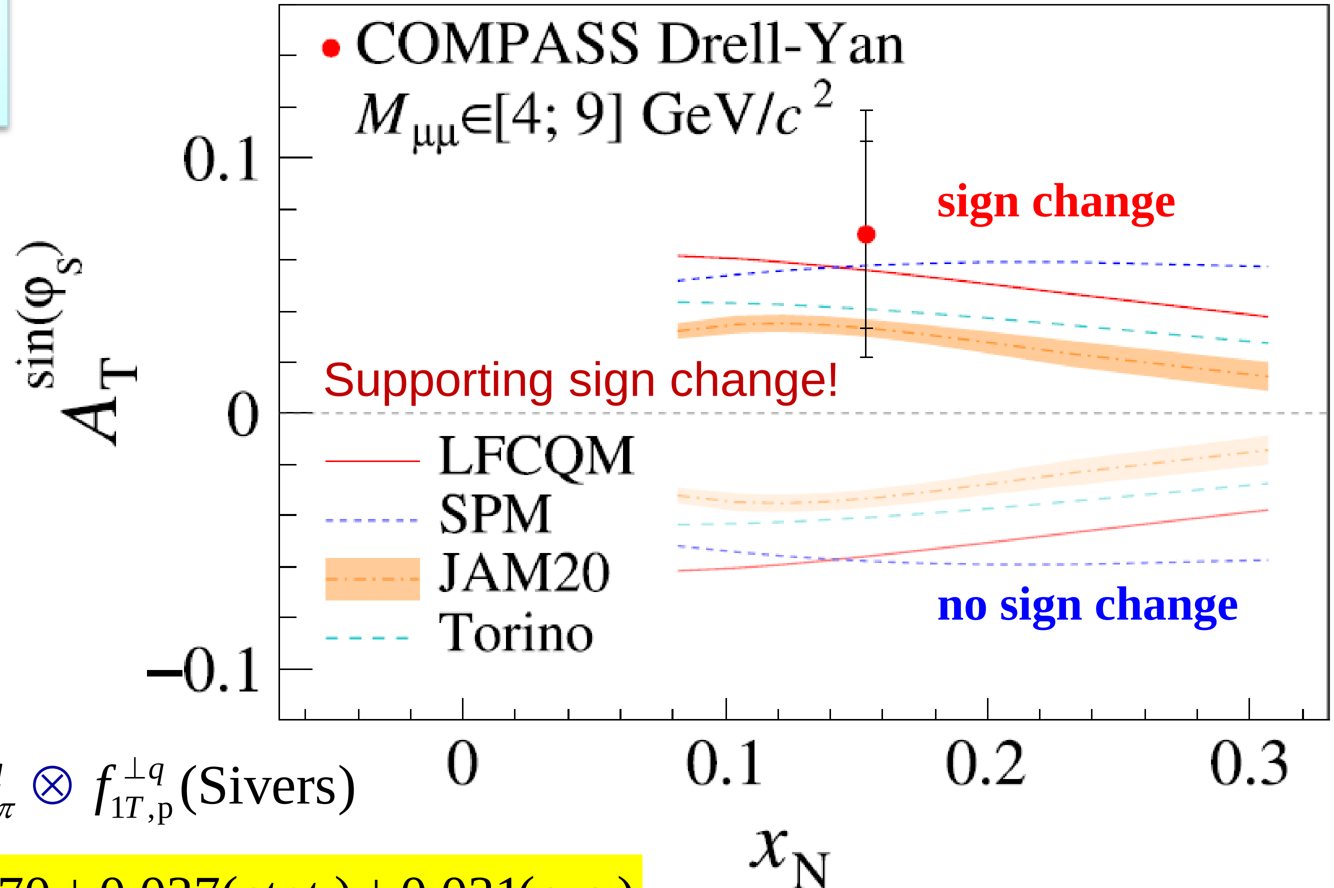

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}(\text{Sivers})$$

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

# Sivers in Polarized Drell-Yan

Statistics:
2015: 35K
2018: 37K

**COMPASS, PRL 133, 071902 (2024)**




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

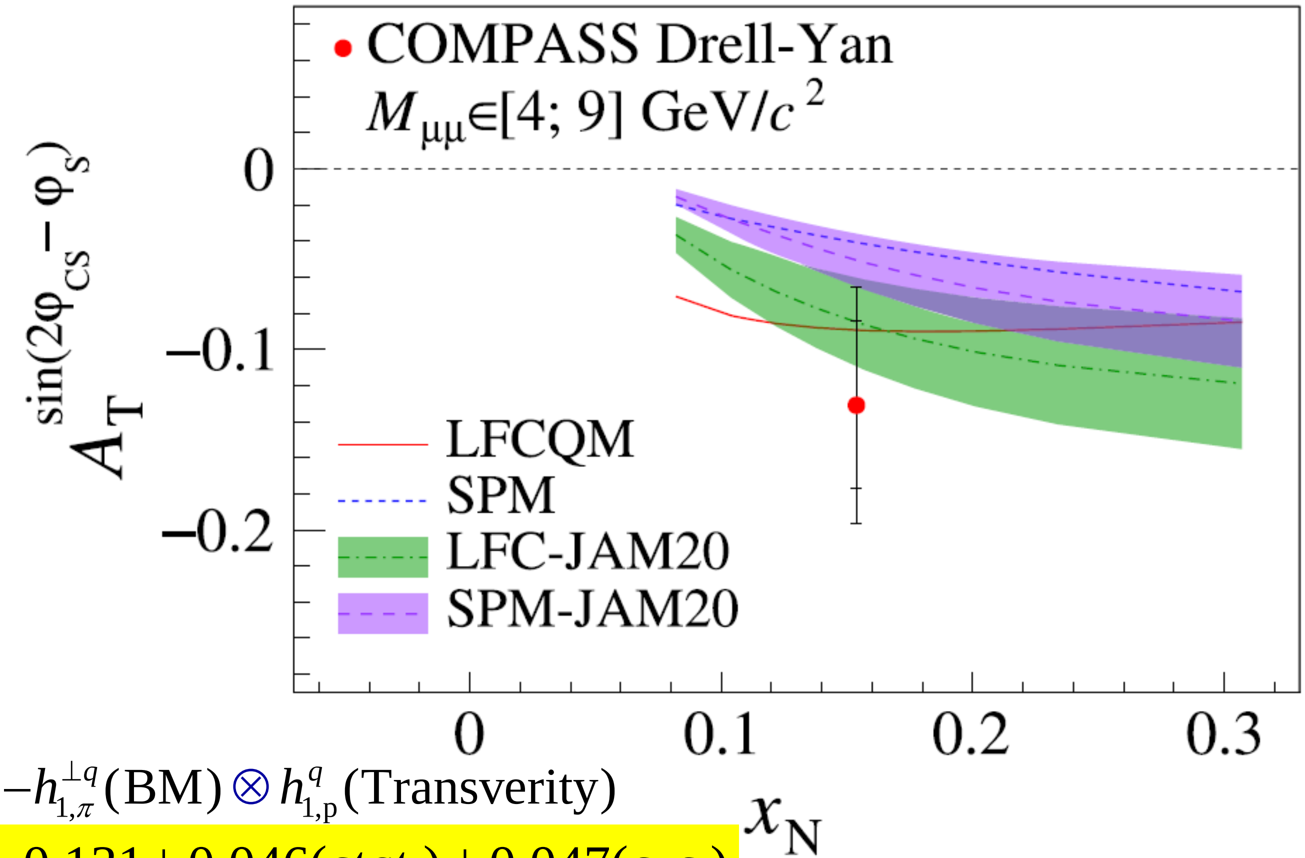
$A_T^{\sin\varphi_s} = 0.070 \pm 0.037(stat.) \pm 0.031(sys.)$

Agreeing with the sign-change of Sivers function!

# Transversity in Polarized Drell-Yan

Statistics:
2015: 35K
2018: 37K

**COMPASS, PRL 133, 071902 (2024)**




$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto -h_{1,\pi}^{\perp q}(\mathrm{BM}) \otimes h_{1,\mathrm{p}}^{q}(\mathrm{Transverity})$

$A_T^{\sin(2\varphi_{cs}-\varphi_s)} = -0.131 \pm 0.046(stat.) \pm 0.047(sys.)$

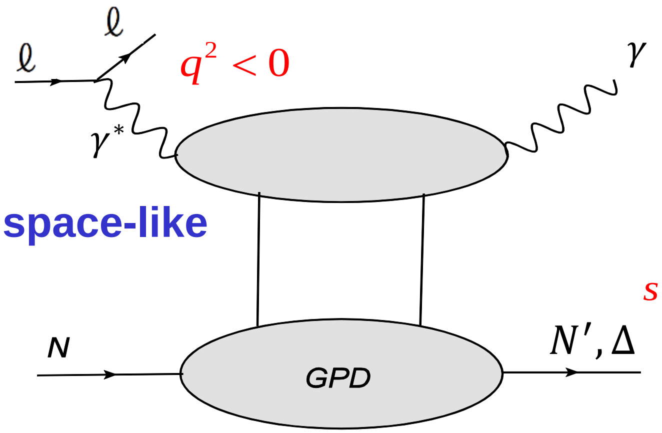
$h_{1,\mathrm{p}}^{q}(+) \rightarrow h_{1,\pi}^{\perp q}(\mathrm{DY},+) \xrightarrow{\nu_{\pi p}>0} h_{1,p}^{\perp q}(\mathrm{DY},+) \Leftrightarrow h_{1,p}^{\perp q}(\mathrm{SIDIS},-)$

Agreeing with sign-change of proton u BM functions between DY and SIDIS!

# Processes for Measuring GPDs

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

## Deeply Virtual Compton Scattering

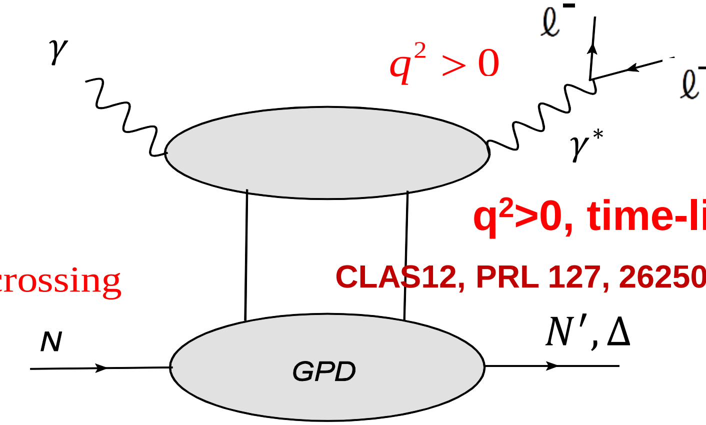



**$q^2$<0, space-like**

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

$s \leftrightarrow u$ channel crossing

## Time-like Compton Scattering

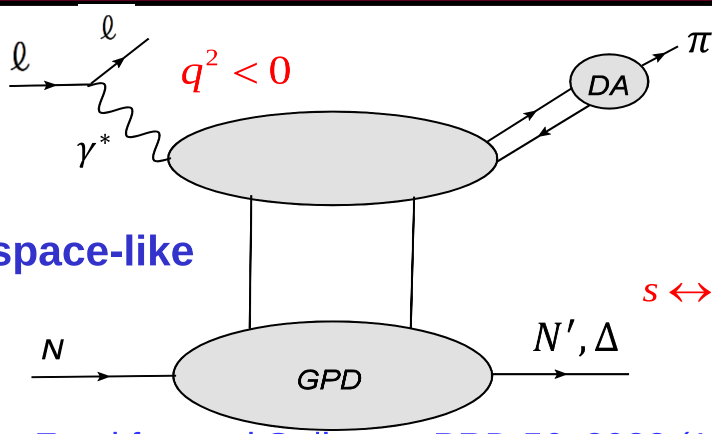



**$q^2$>0, time-like**

**CLAS12, PRL 127, 262501 (2021)**

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

## Deeply Virtual Meson Production

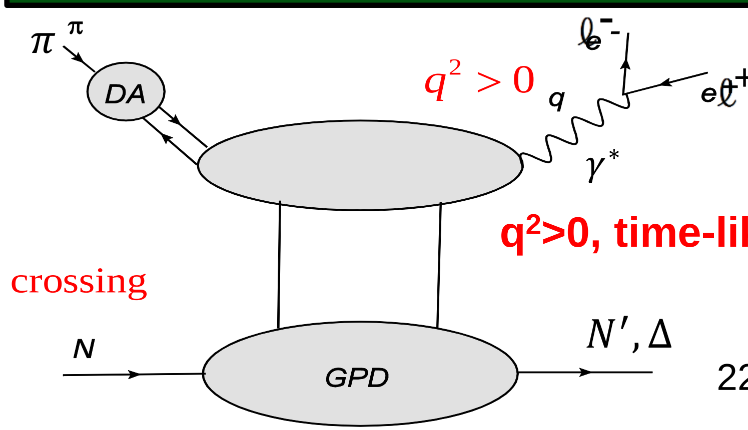



**$q^2$<0, space-like**

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

$s \leftrightarrow u$ channel crossing

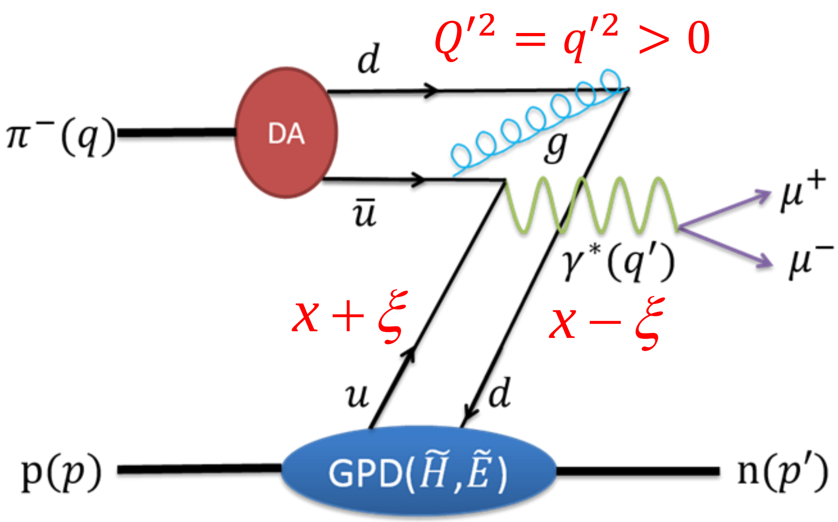
## Exclusive meson-induced DY




**$q^2$>0, time-like**

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

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

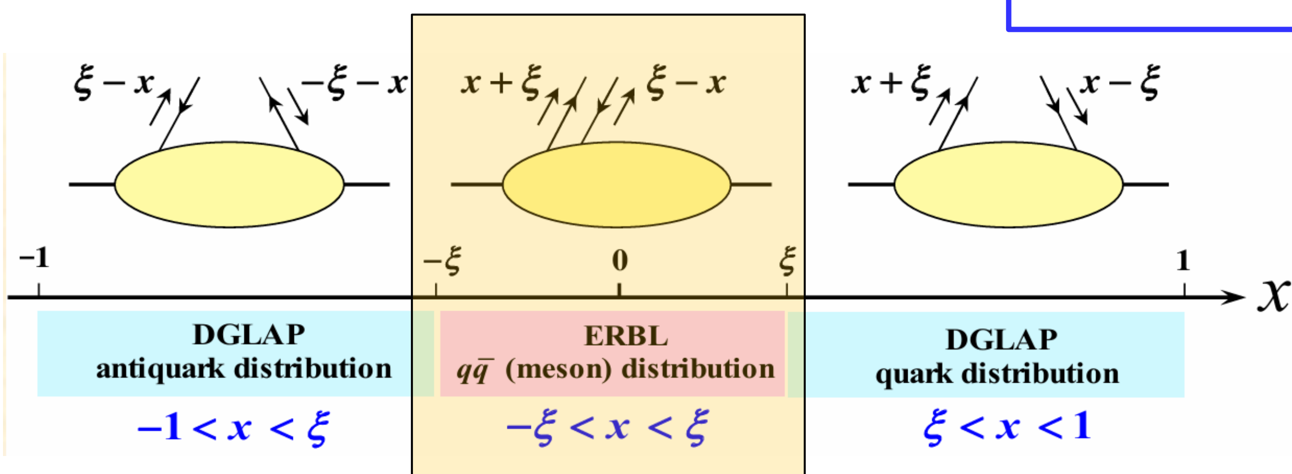



$t = (p - p')^2$

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

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

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



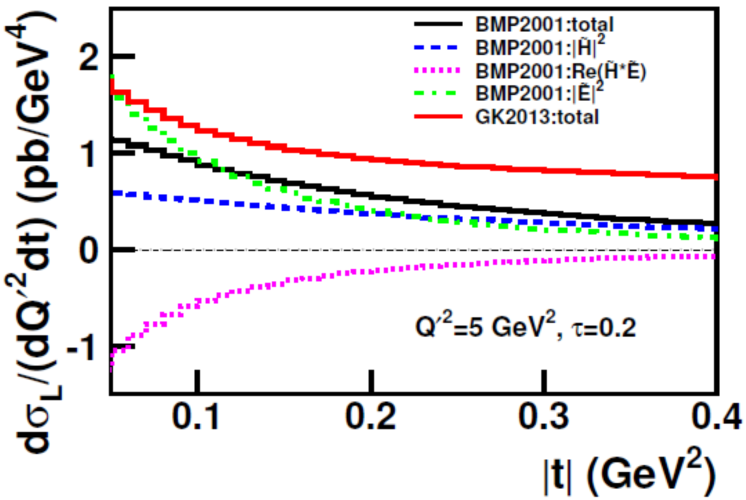
# Differential Cross Sections of $\pi N \rightarrow l^+ l^- N$

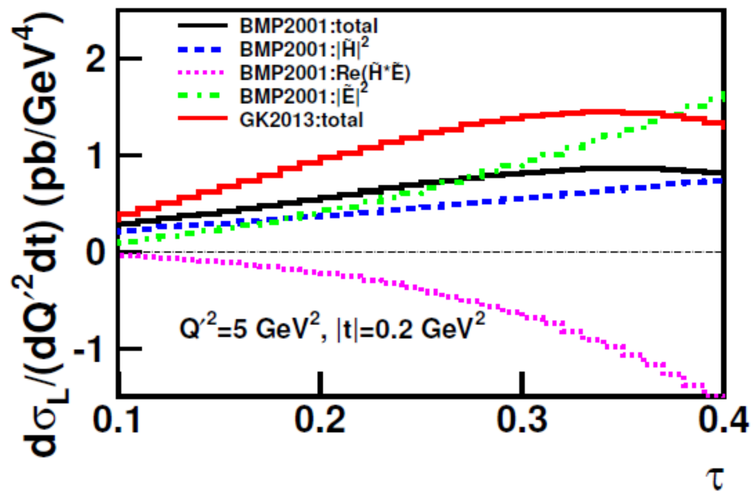
$$\frac{d\sigma_L}{dt\,dQ'^2}\bigg|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8}f_\pi^2\left[(1-\xi^2)|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)|^2 - 2\xi^2{\rm Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^*\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2\frac{t}{4m_N^2}|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)|^2\right],$$

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

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

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




Production is dominant at forward angles

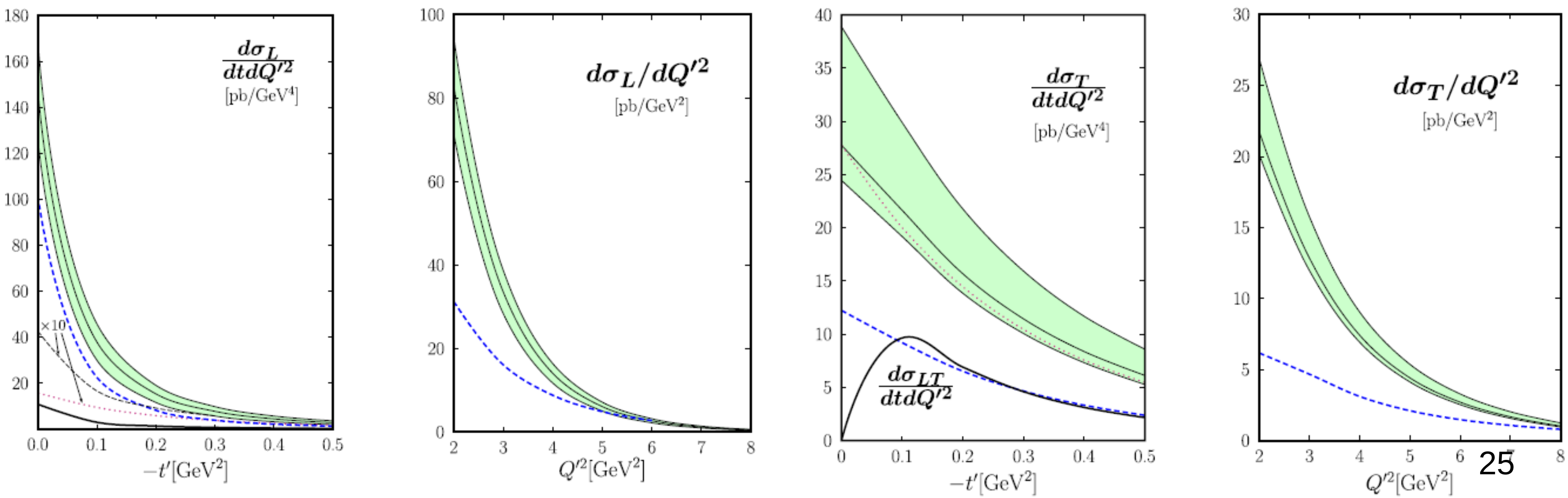
Cross sections increase toward small *s* (→ low beam energy)

# Beyond the Leading Twist

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

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

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



# Exclusive Drell-Yan Measurement

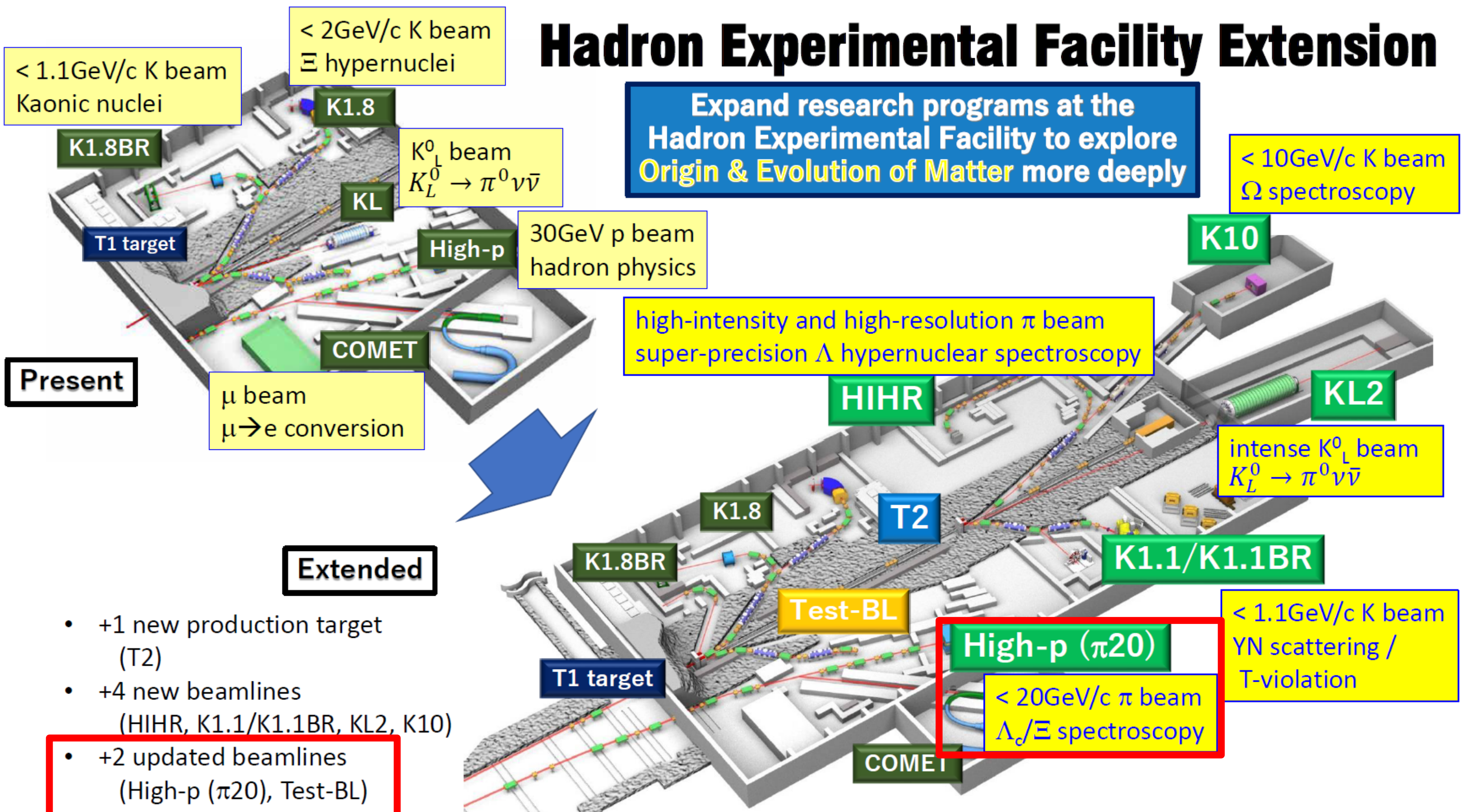
- **Factorization**: $Q^2 \gg 1\ GeV^2$
- **Cross sections**:
  - Cross sections decrease rapidly with an increase of $Q^2$. $Q^2 < 9\ GeV^2$
  - $\sqrt{s}$ should be small enough to keep $\sqrt{\tau} = \frac{Q}{\sqrt{s}} = \sqrt{x_\pi x_N}$ large enough. Take $Q = 2\ GeV$, $\sqrt{\tau} = \sqrt{0.5 *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

Shinya Sawada's talk

# Hadron Hall Extension

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

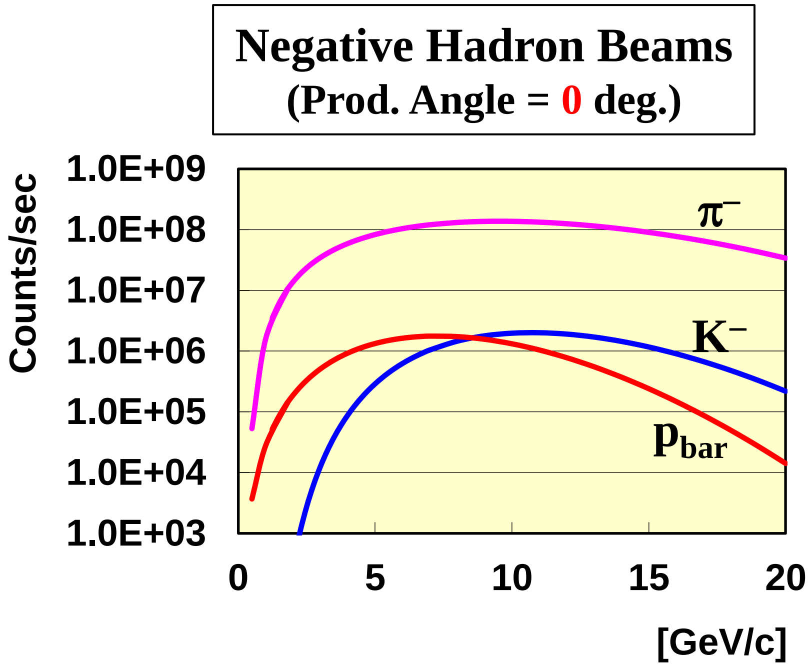


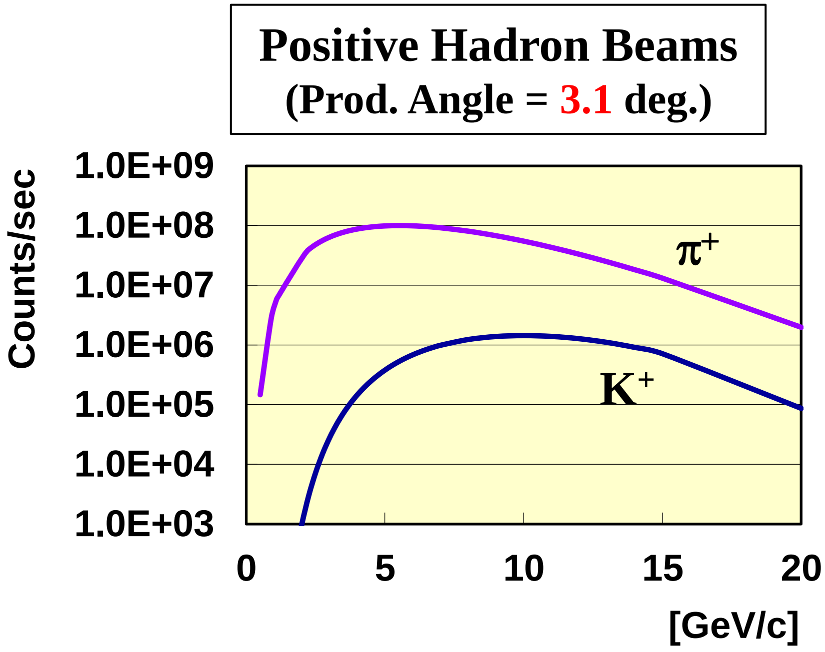

- +1 new production target (T2)
- +4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10)
- +2 updated beamlines (High-p (π20), Test-BL)

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

# J-PARC Hadron Hall
# π20 Beam Line

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



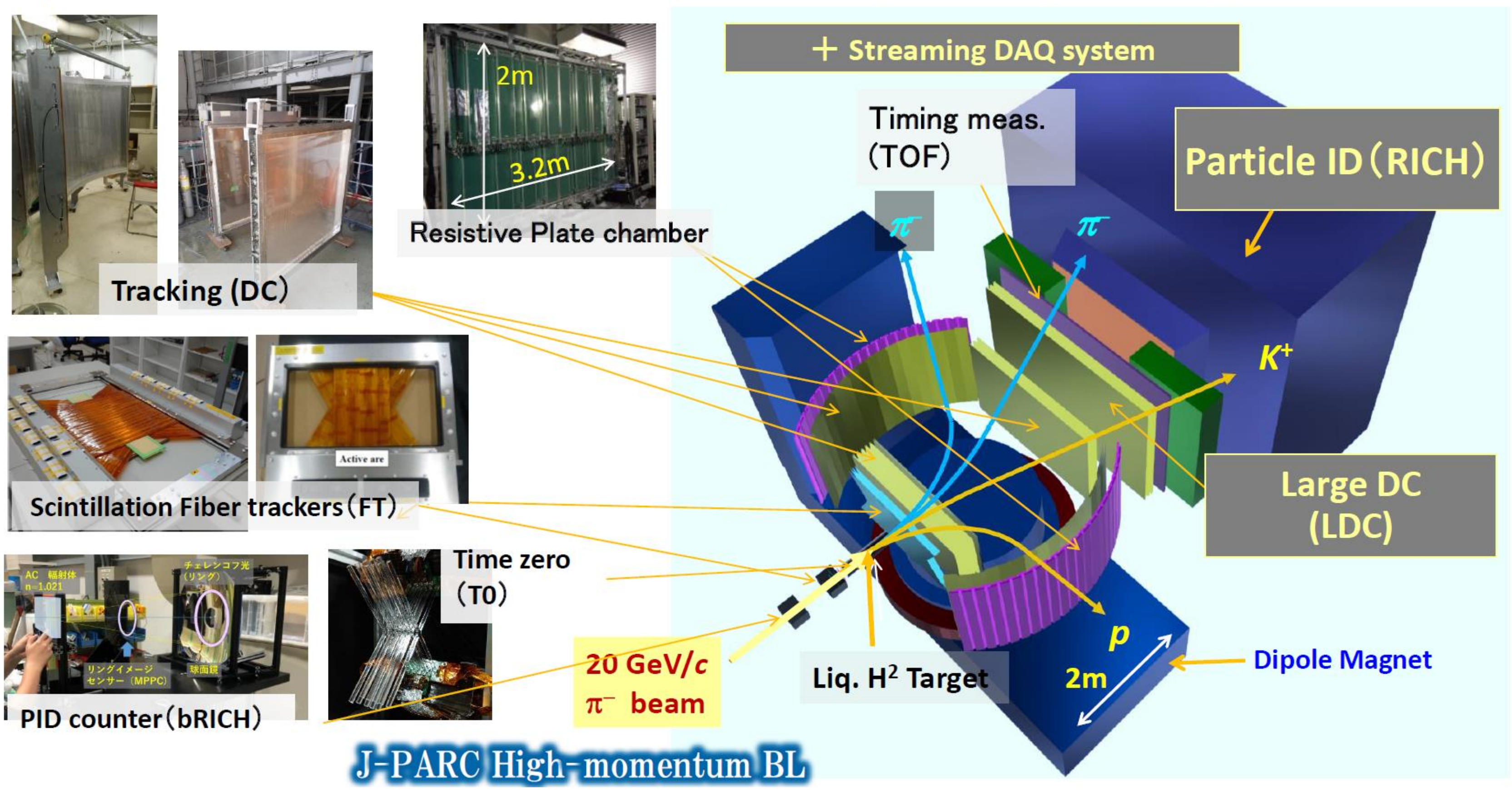




*** Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m**

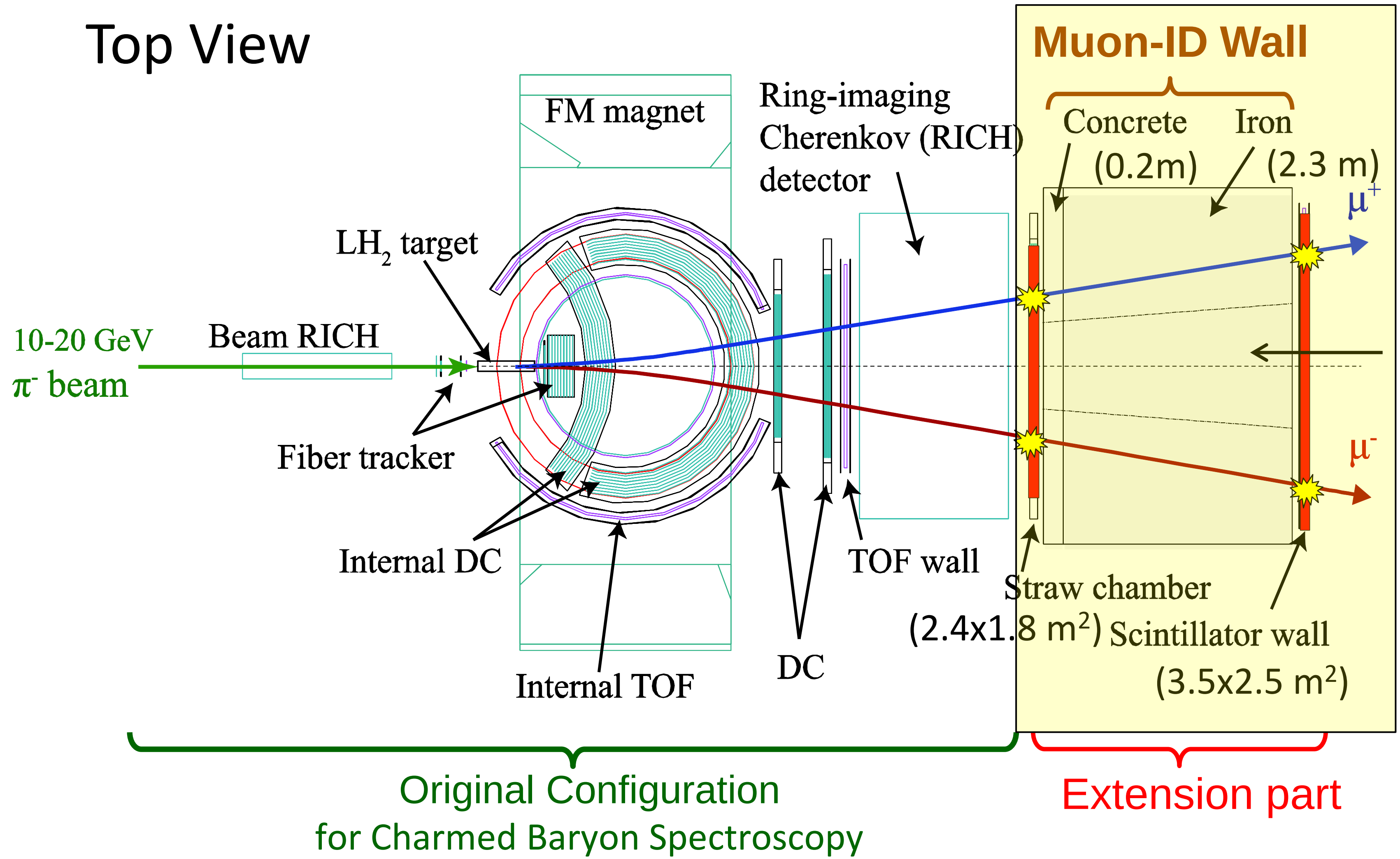
# J-PARC E50/MARQ Experiment

## (Charmed Baryon Spectroscopy)

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



# J-PARC E50/MARQ Experiment for Drell-Yan measurement

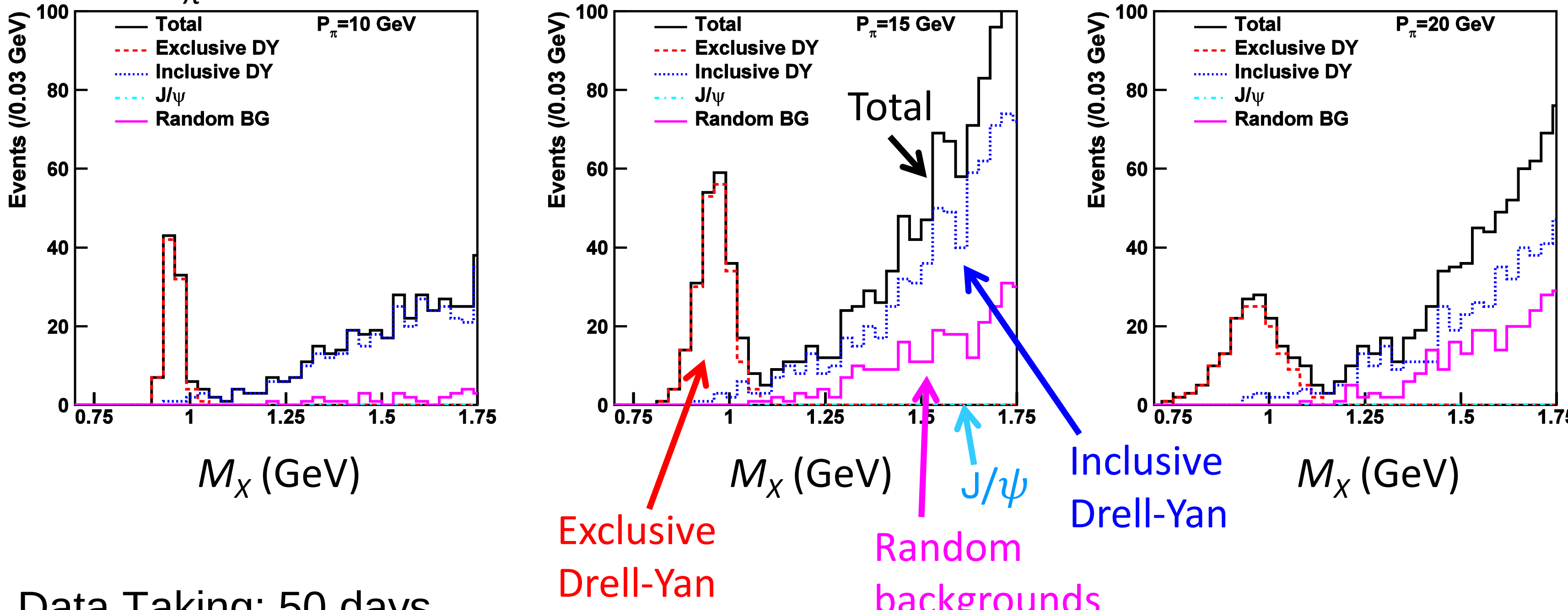


# $\pi^- N \to \mu^+ \mu^- X$ Missing-mass $M_X$

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

$\pi^-$ Beam Momentum

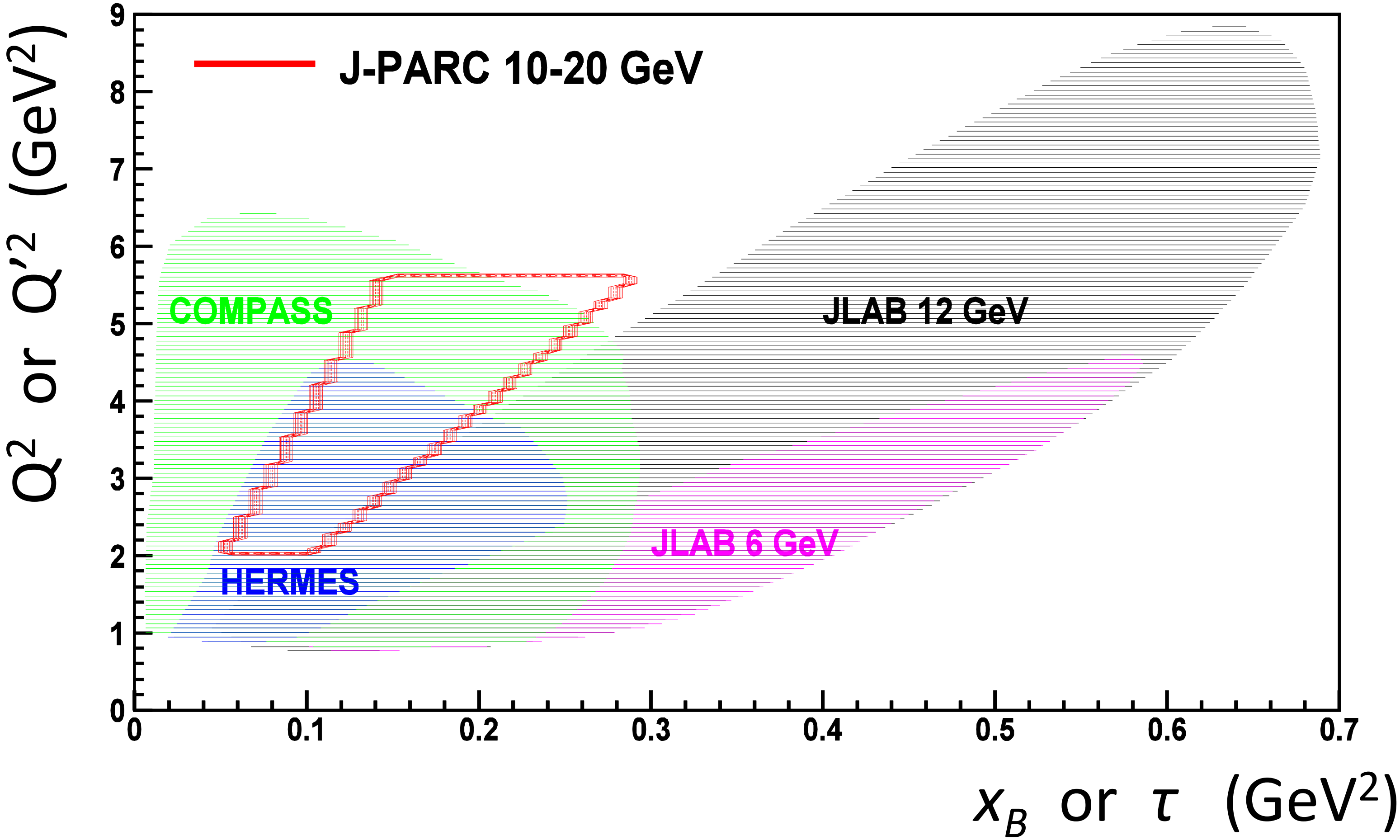
$P_\pi$ = 10 GeV | 15 GeV | 20 GeV




- 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.

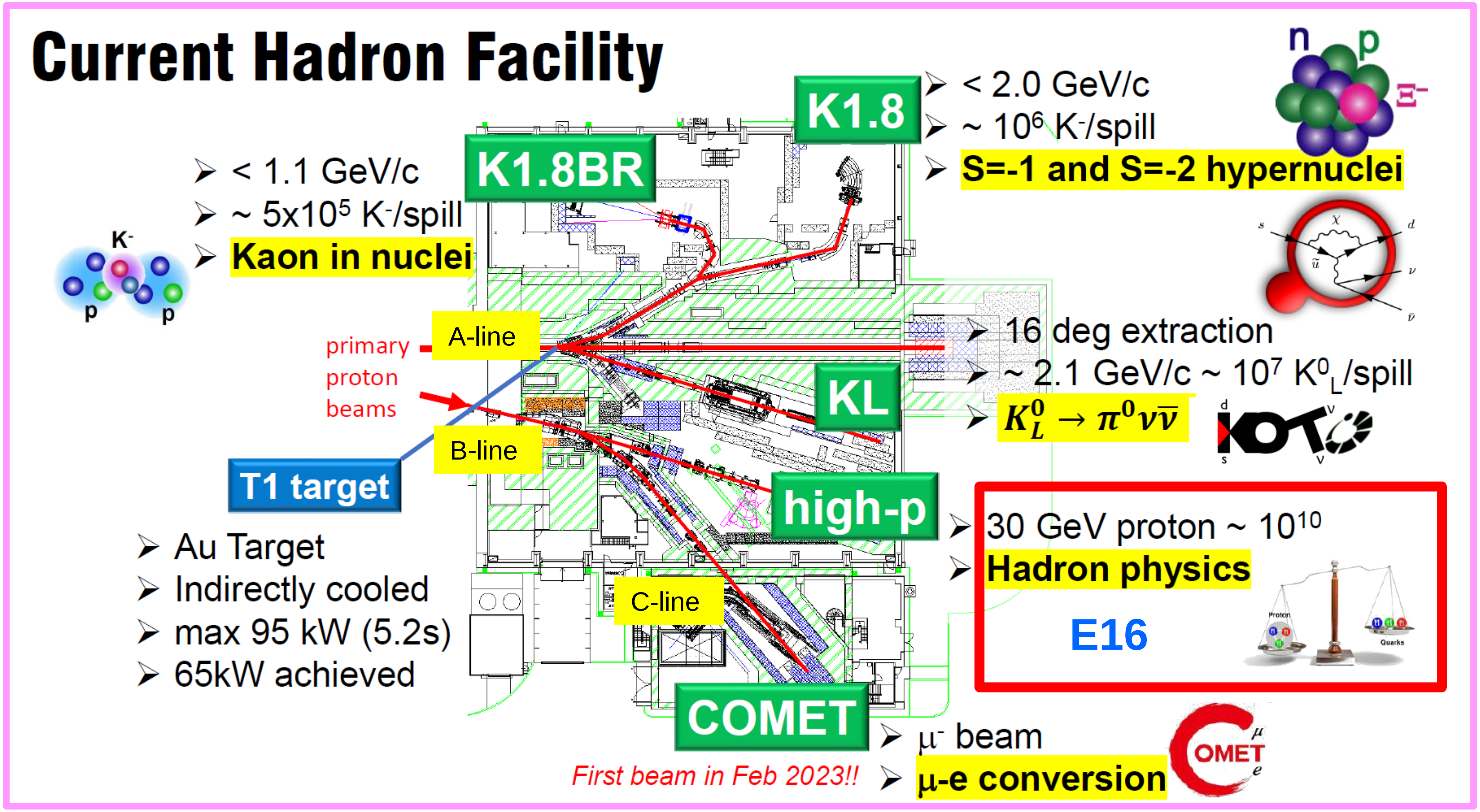
# Universality of GPDs




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

Shinya Sawada's talk

# J-PARC Hadron Hall (Current Status)




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

# GPDs with Proton Beams: 2-to-3 Hard Process

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]

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[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*

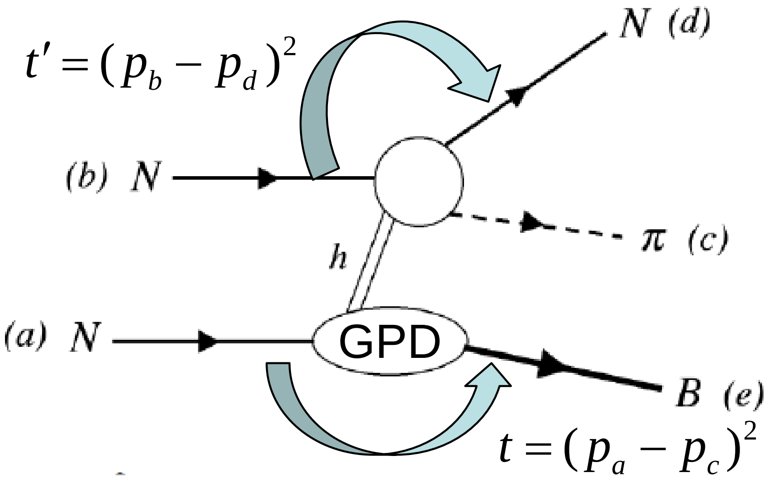
[4]*Nishogakusha University, 6-16, Sanbancho, Chiyoda, Tokyo, 102-8336, Japan*

(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 $N$, $\pi$, and $B$ are a nucleon, a pion, and a baryon (nucleon or $\Delta$), respectively, with a large momentum transfer between $B$ (or $\pi$) 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 $\pi N$ 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

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

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




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

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

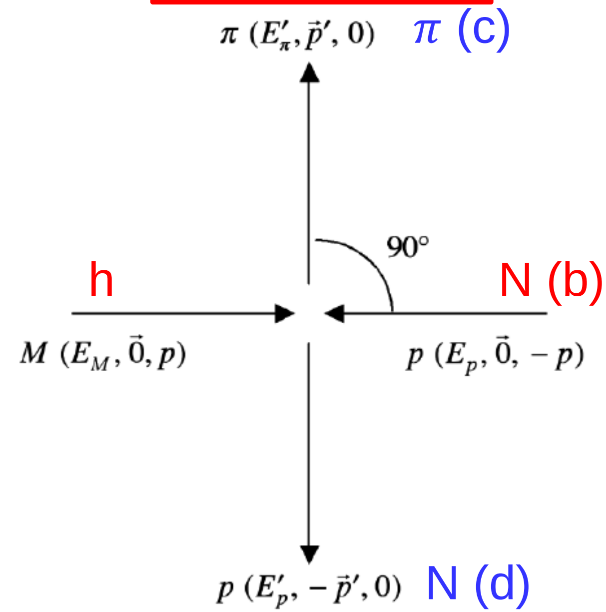
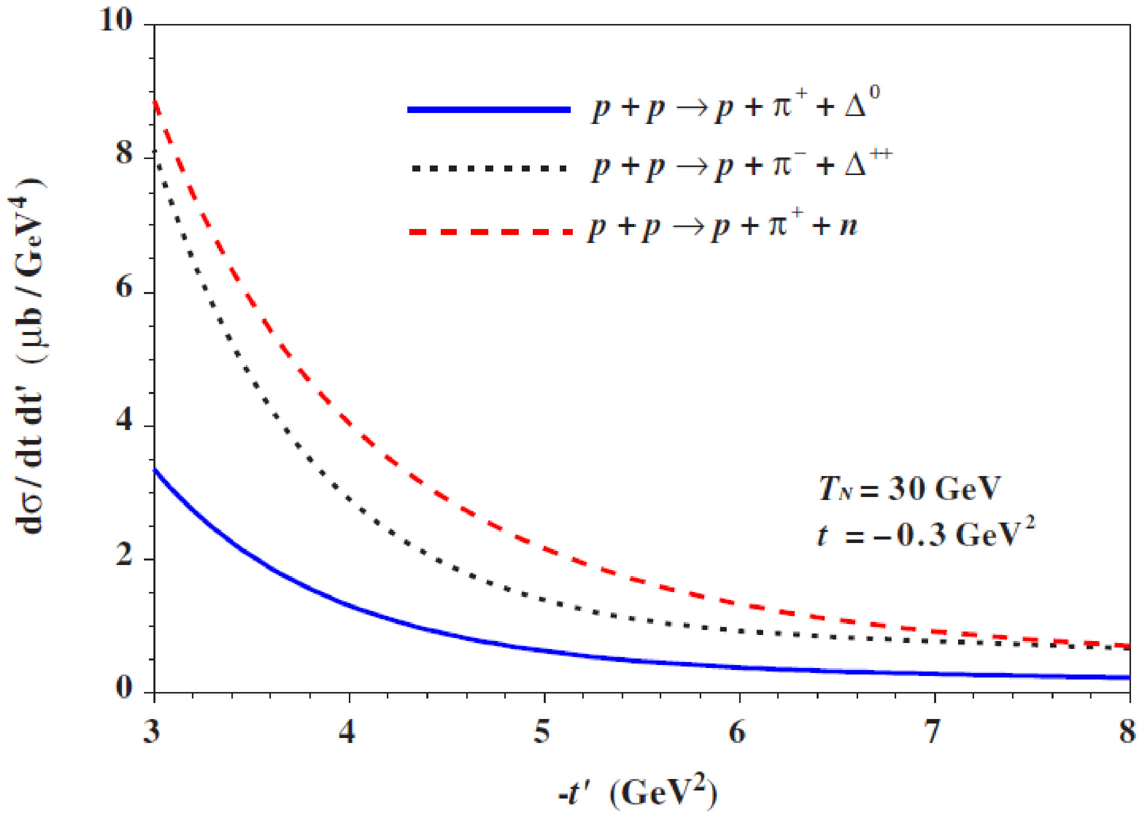



FIG. 8. $Mp \to \pi p$ elastic scattering at $\theta_{\mathrm{c.m.}} = 90°$.

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

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

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




- Possible measurement within the on-going J-PARC E16 experiment is considered. [N. Tomida]
- The –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]

# Summary

- Drell-Yan process, complementary to DIS, SIDIS ,DVCS, and DVMP, is unique in validating the universality properties of PDFs, TMDs and GPDs.
- COMPASS TSAs support the predicted sign change of Sivers as well as BM functions.
- It will be very interesting to carry out the GPDs measurement with the hadron beams at J-PARC.

# Thank you! Prof. T.M. Yan