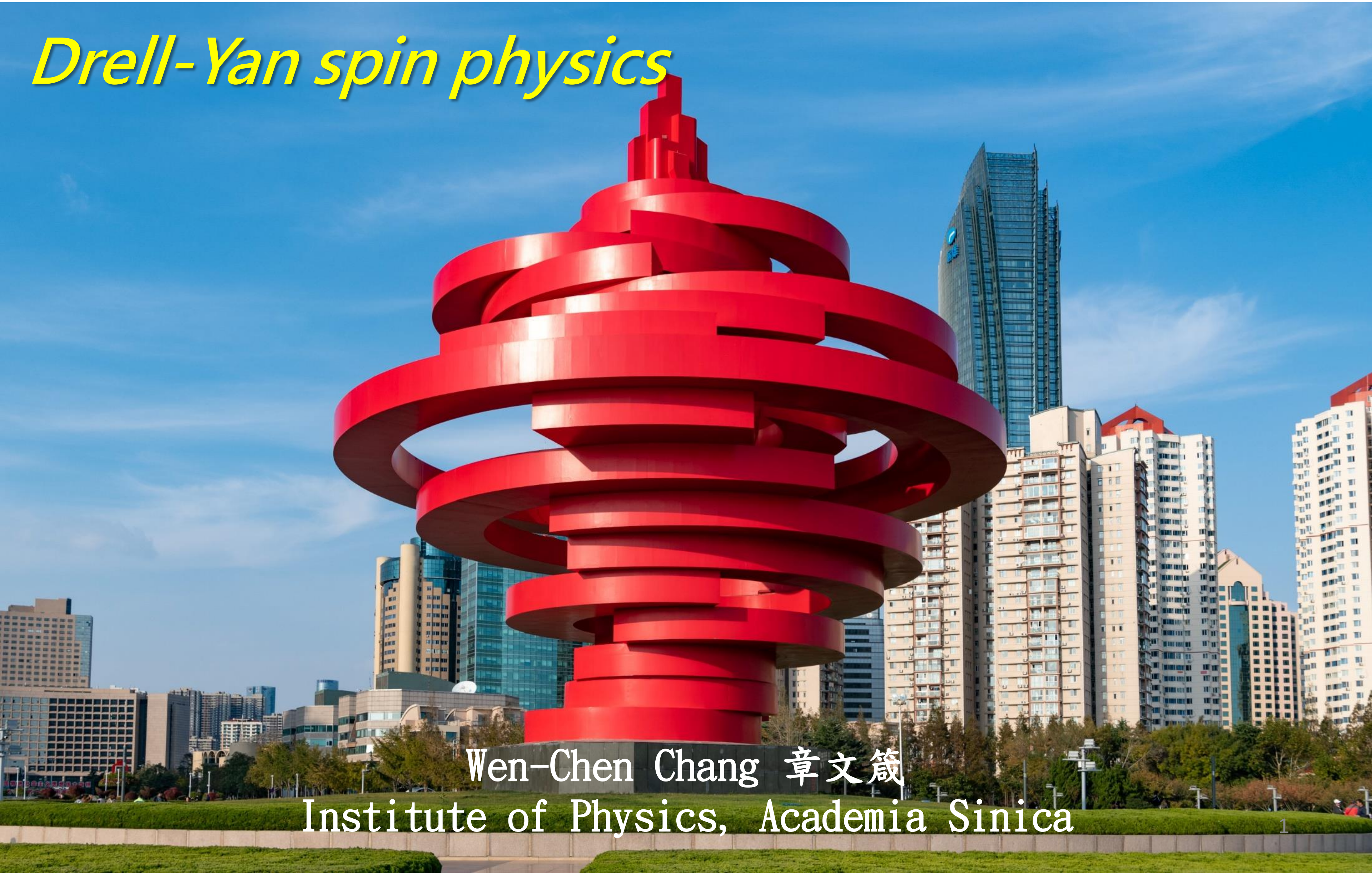
26th International Symposium on Spin Physics

A Century of Spin

Drell-Yan spin physics



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

Outline

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

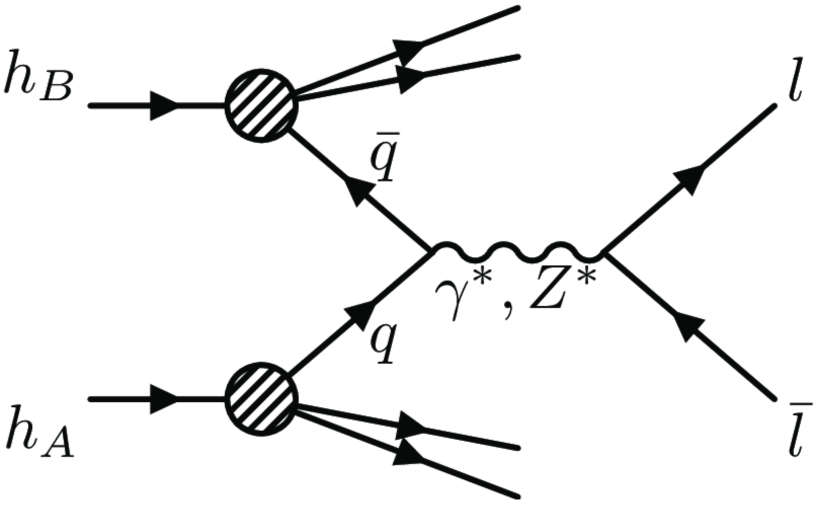
Drell-Yan Process

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

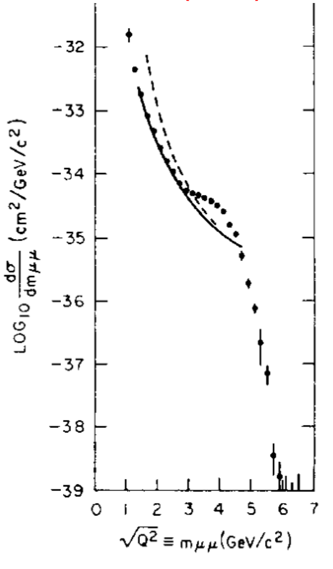
MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan 顏東茂
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.



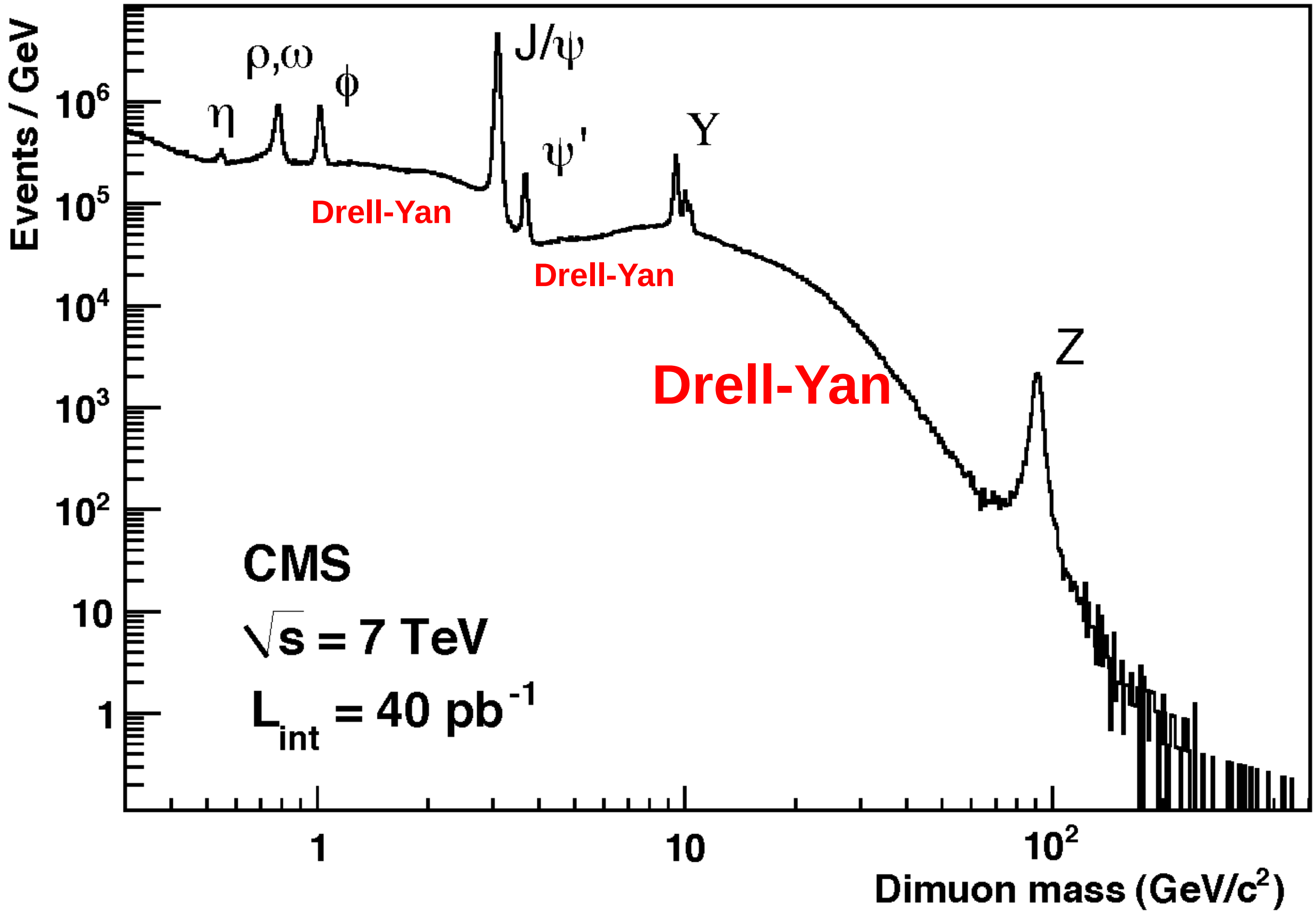
PRL 25 (1970) 1523



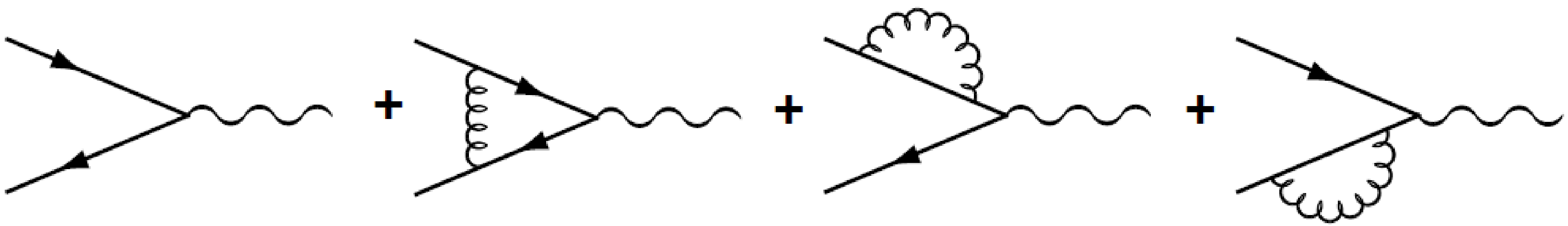
$$\tau = \frac{Q^2}{s} = x_1 x_2$$

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

Dimuon Invariant Mass Spectrum

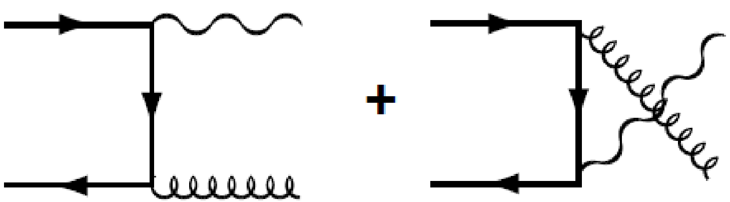


Drell-Yan Process with the $O(\alpha_s^1)$ QCD Effect



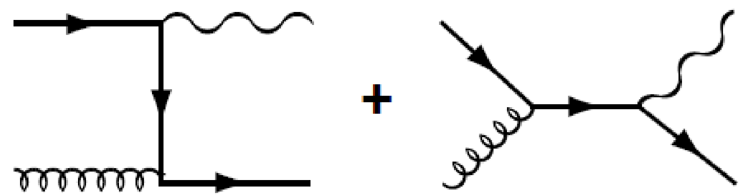
(a)

Quark-antiquark ($q\bar{q}$) annihilation with the virtual gluon correction



(b)

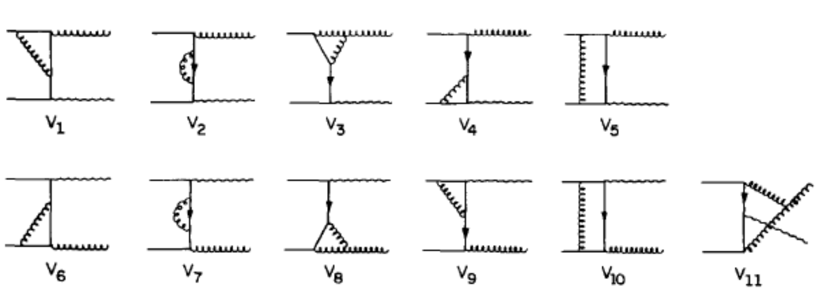
Quark-antiquark ($q\bar{q}$) annihilation with one real gluon



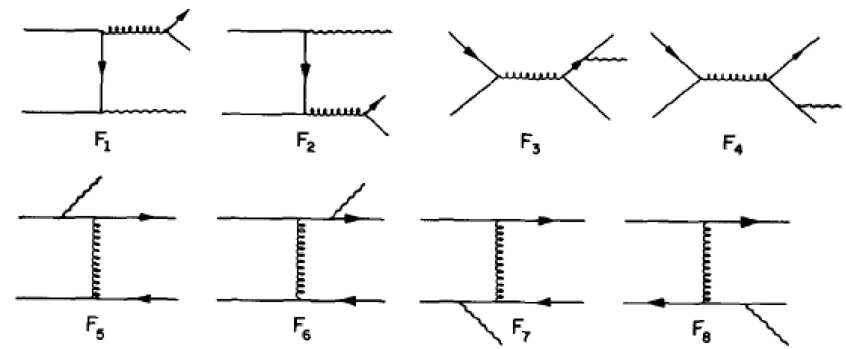
(c)

Quark-gluon (qG) Compton scattering

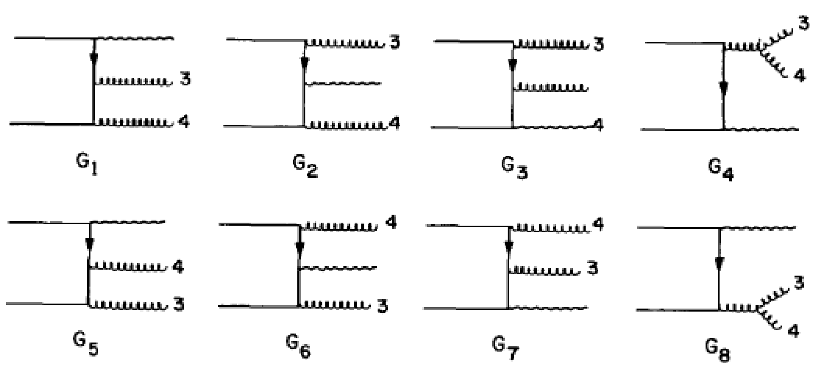
Drell-Yan Process with the $O(\alpha_s^2)$ QCD Effect



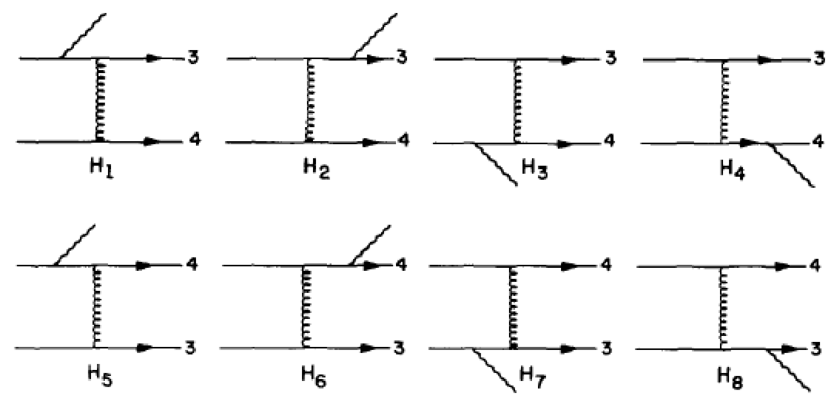
$q\bar{q} \rightarrow G\gamma^*$



$q\bar{q} \rightarrow q\bar{q}\gamma^*$



$q\bar{q} \rightarrow GG\gamma^*$

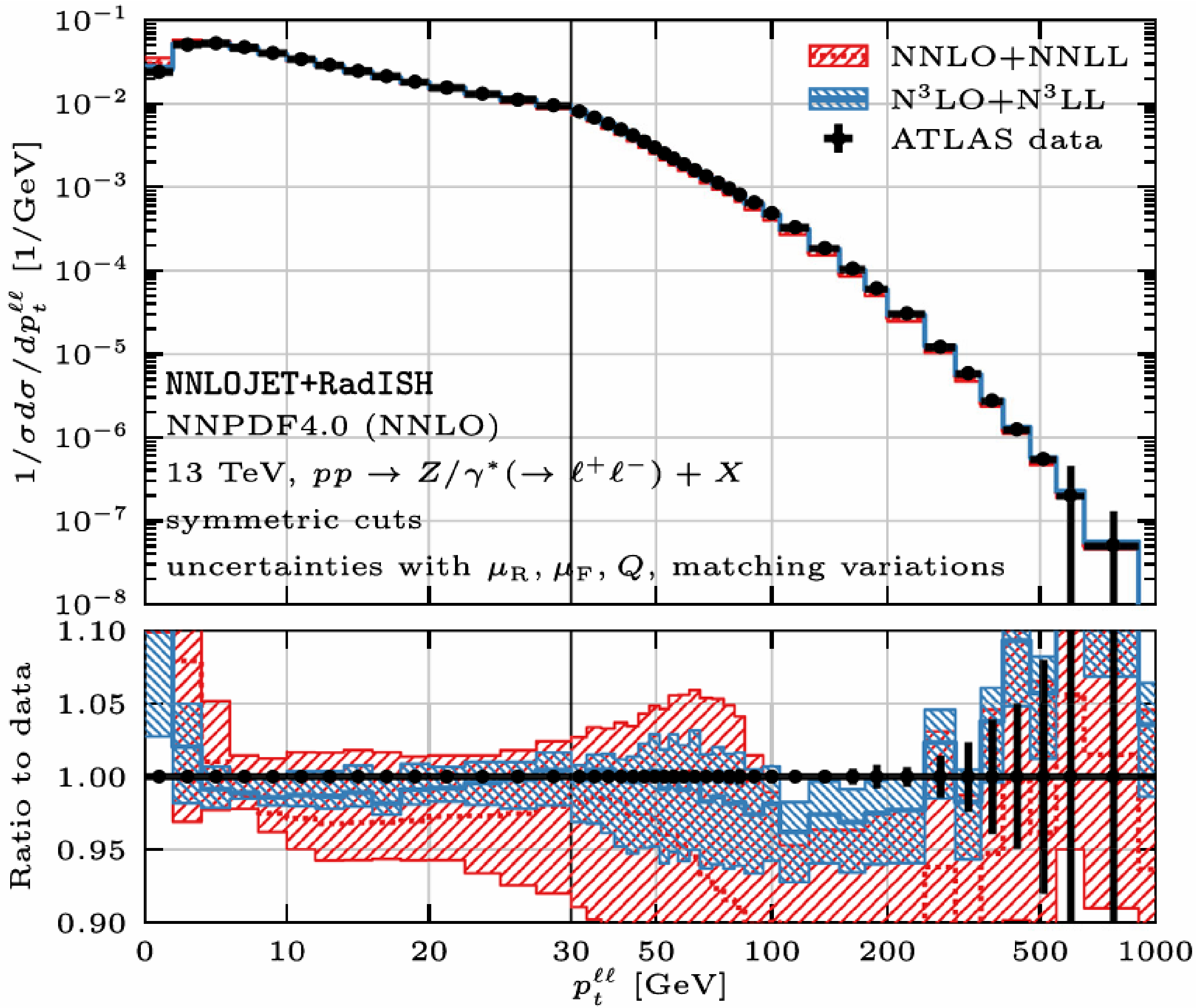


$qq \rightarrow qq\gamma^*$

NPB319 (1989) 37

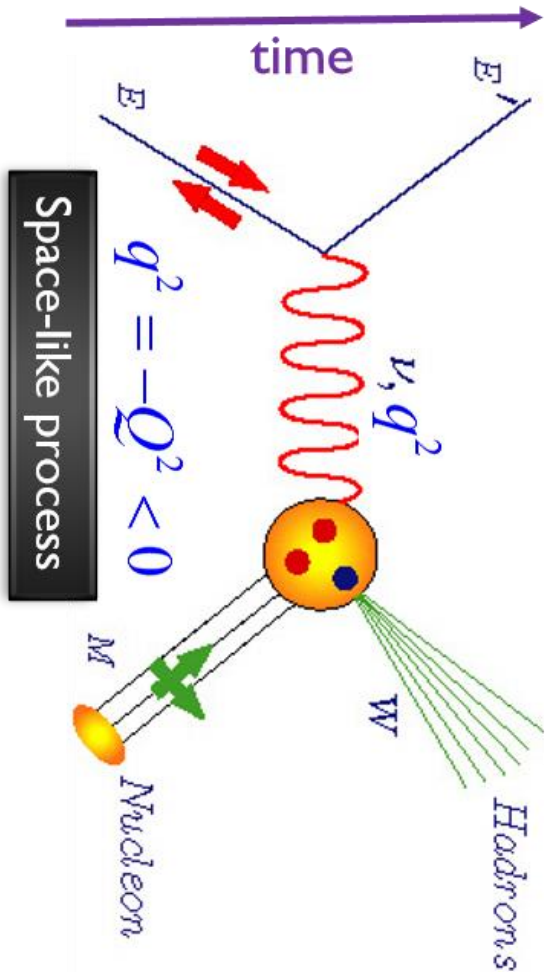
Fixed-order pQCD Calculations

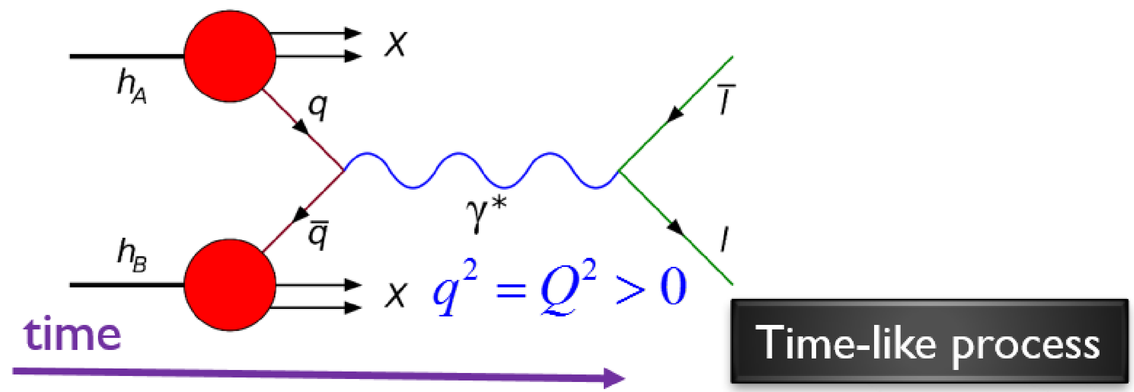
PRL 128, 252001 (2022)

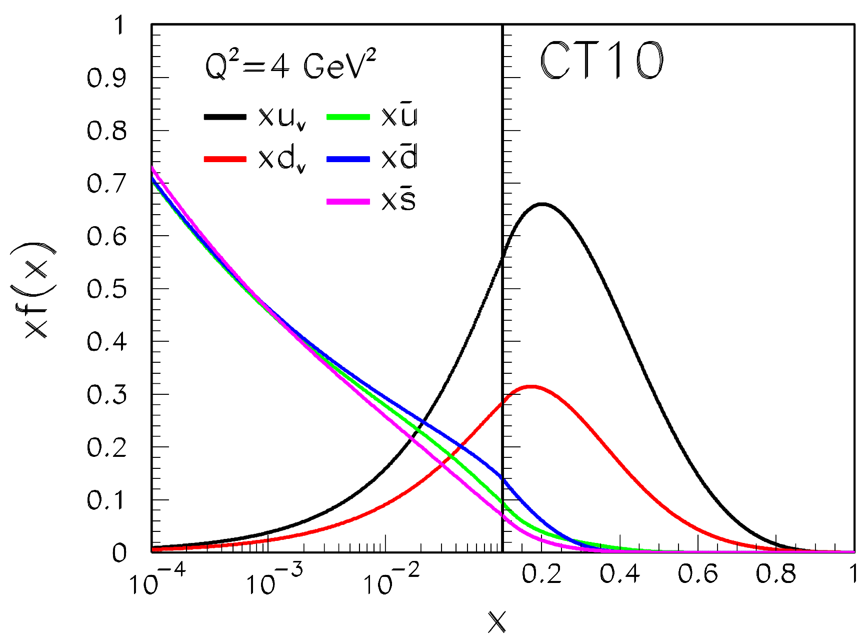


5-10% accuracy

Proton PDFs


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


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


Q^2=4 GeV^2
CT10
xu_v
xd_v
$x\bar{u}$
$x\bar{d}$
$x\bar{s}$
xf(x)
x

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

SIDIS vs. Drell-Yan

Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

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

SIDIS-DY bridge

Drell–Yan process (DY)

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

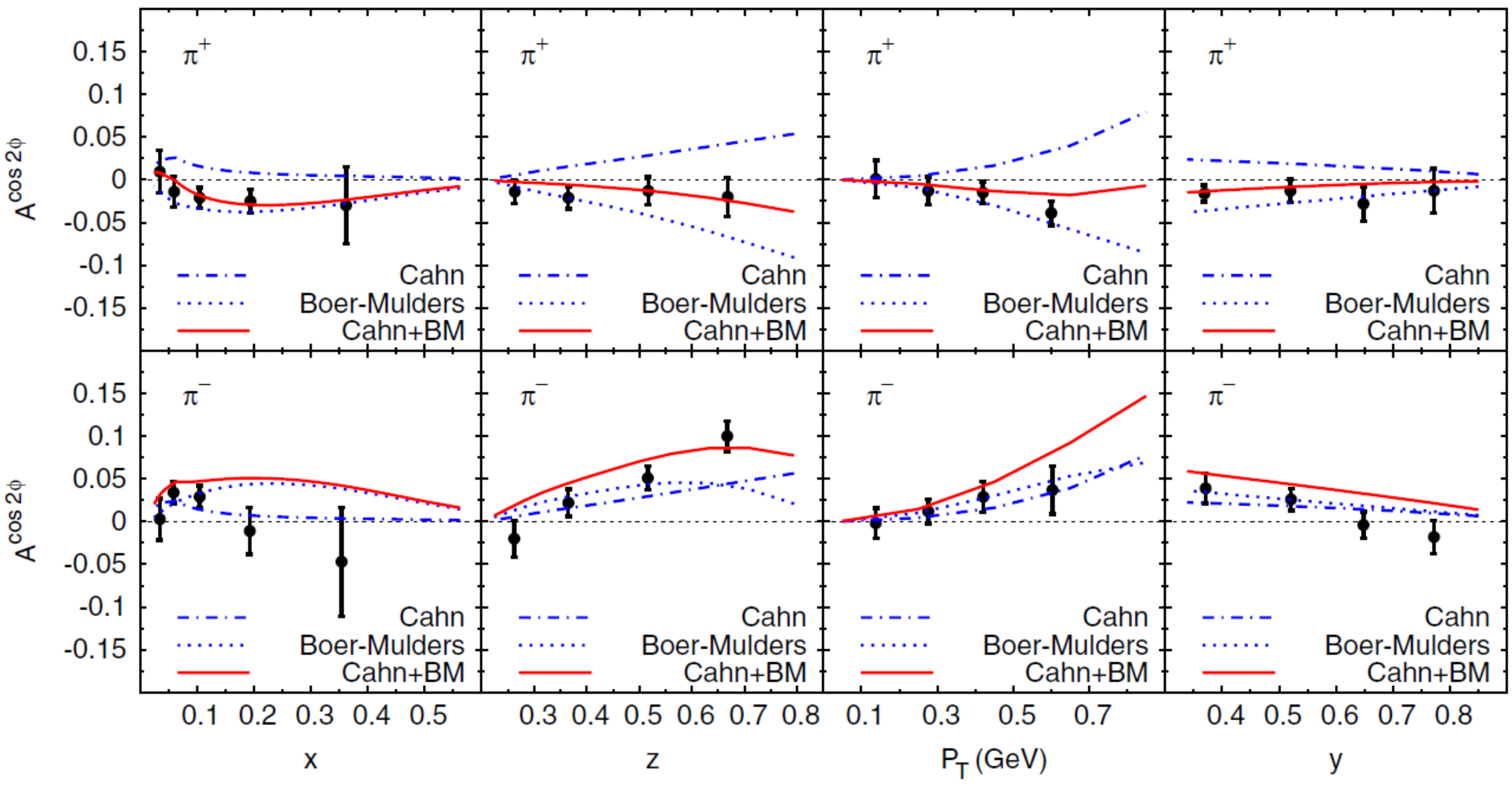
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

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

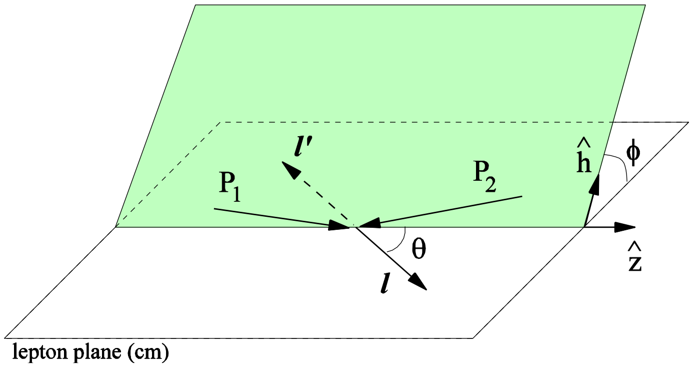
Boer-Mulders Effect ($h_1^{\perp}$) in SIDIS

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



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

Decay Angular Distributions



θ and ϕ are the decay polar and azimuthal angles of the μ^+ 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:

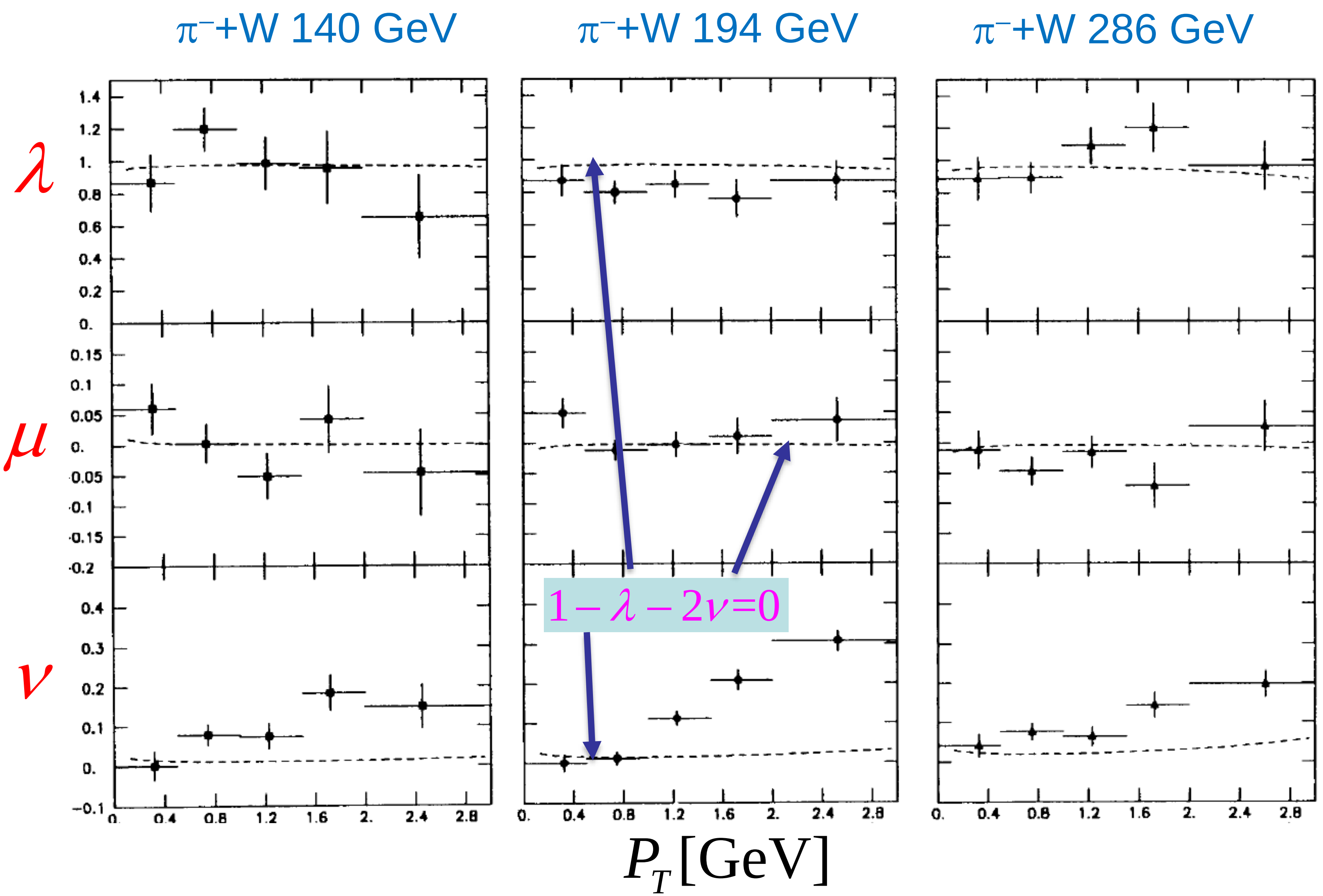
$O(\alpha_s^0)$ $\lambda=1$, $\mu=\nu=0$; $W_T=1, W_L=0$

Lam-Tung relation (1978)

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

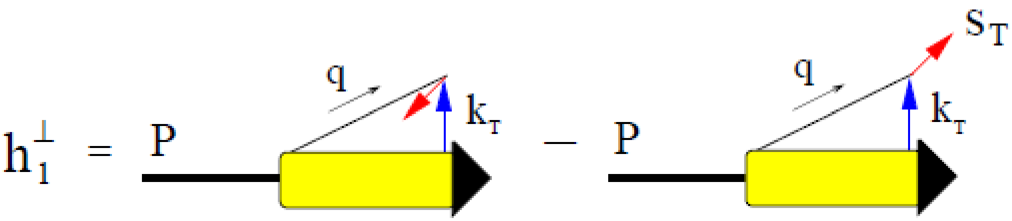
NA10 @ CERN: Violation of LT

Z. Phys. 37 (1988) 545



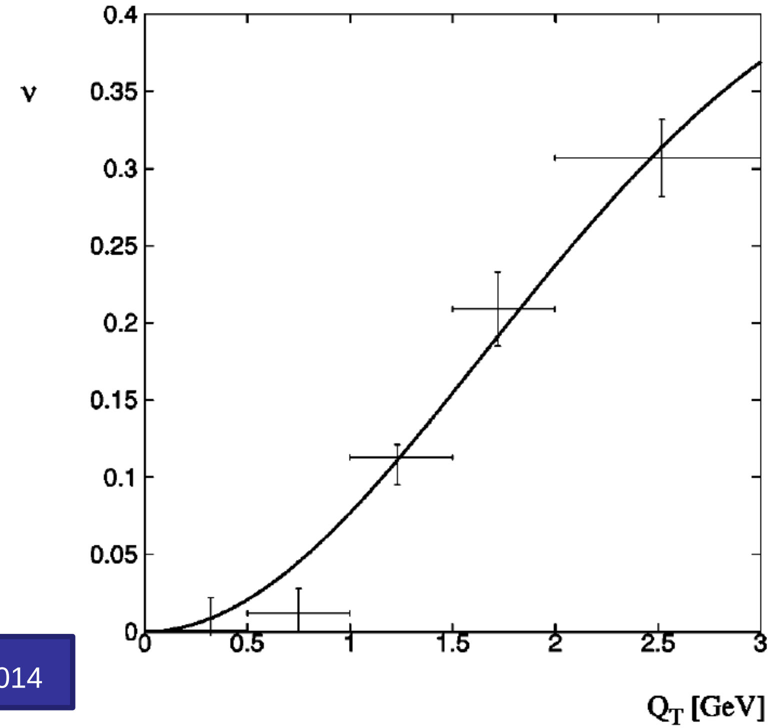
Boer-Mulders Effect ($h_1^\perp$) in Drell-Yan

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 $\frac{\nu}{2} \propto h_1^\perp(\pi) h_1^\perp(N)$

NA10 194 GeV/c



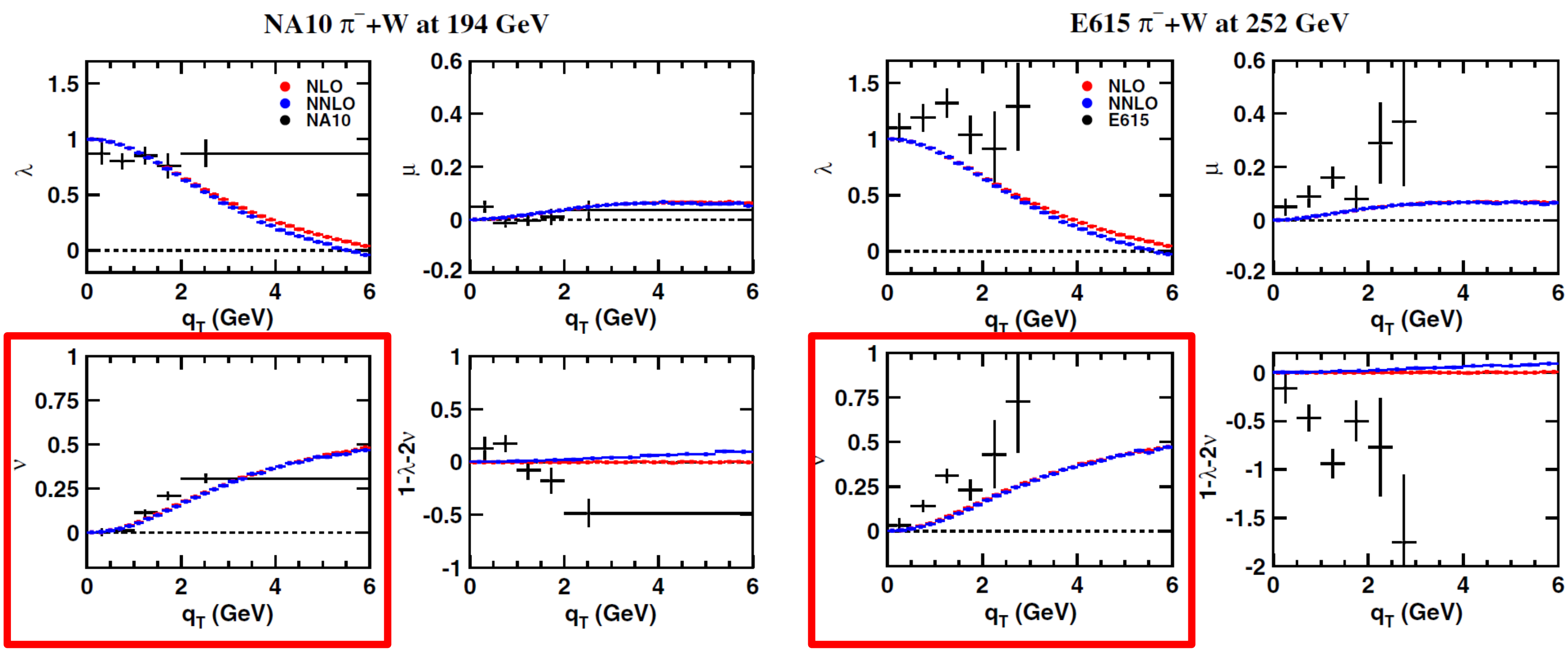
$h_1^\perp(\pi)$ and $h_1^\perp(p)$ are of the same sign. - J.C. Peng, Transversity 2014

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

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

Fixed-order pQCD Contribution

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



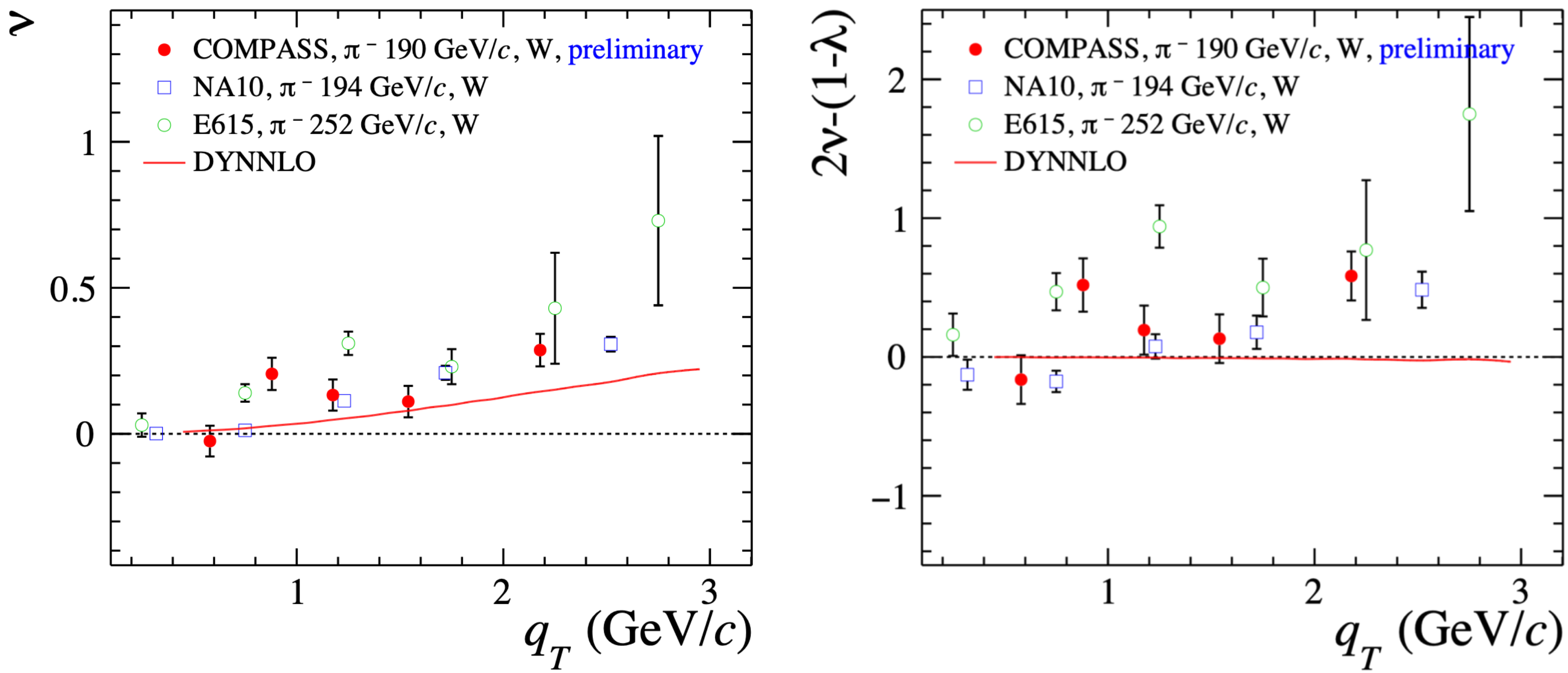
The pQCD contribution accounts for the majority of non-zero ν!

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

COMPASS @ CERN: Violation of LT

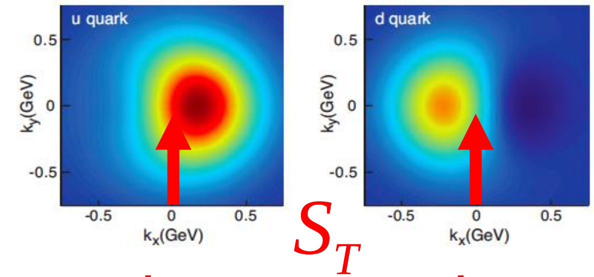
2015 runs

π^-+W 190-GeV

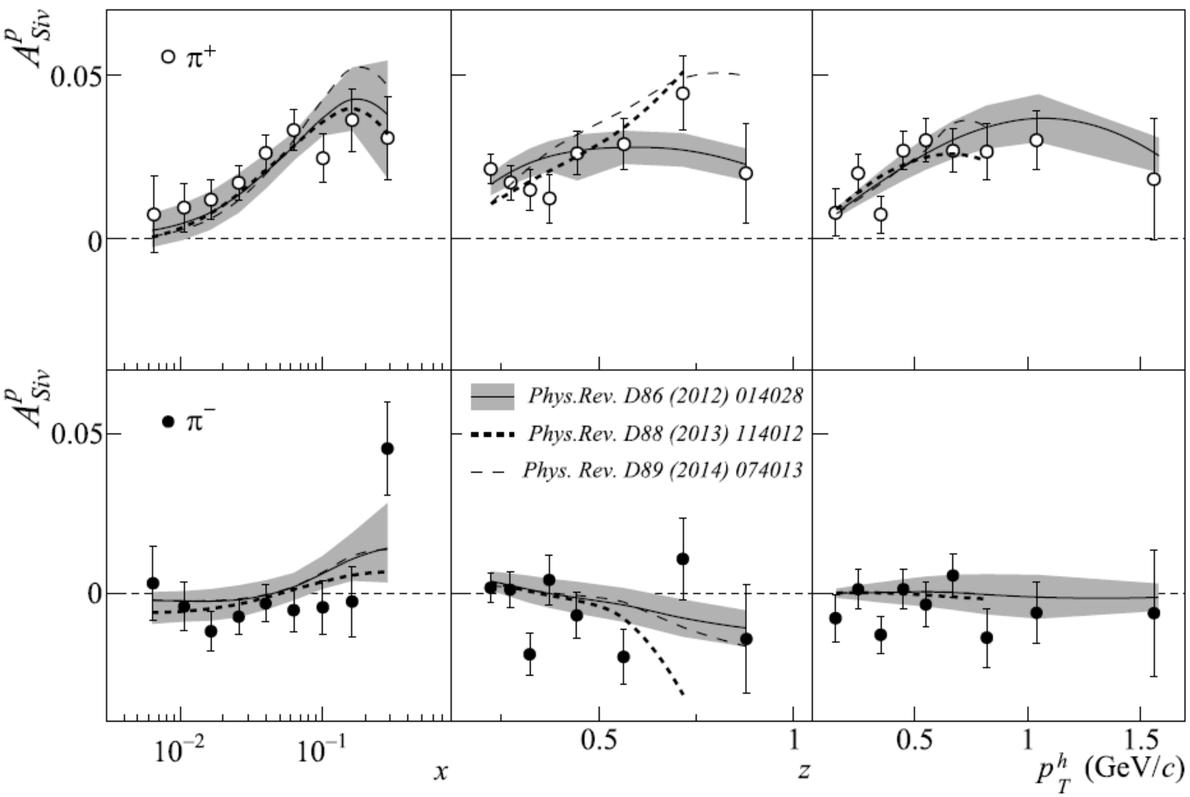


DIS 2021 proceedings, Y.H. Lien

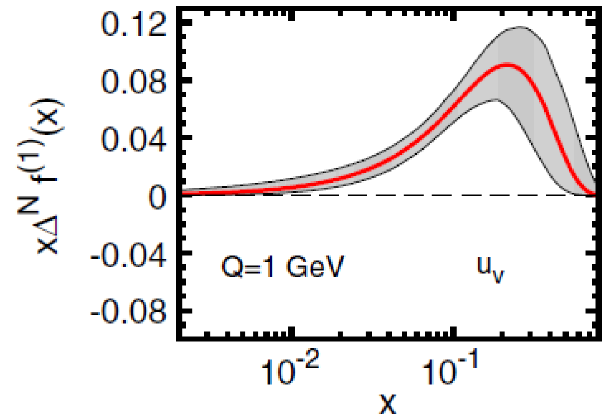
Nonzero Sivers Asymmetries in SIDIS

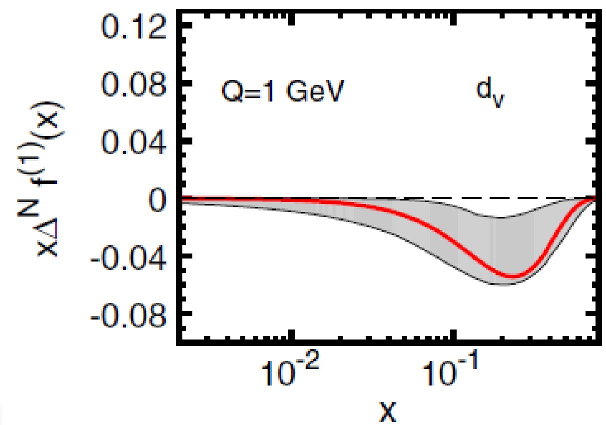


COMPASS, PLB 744 (2015) 250



Sivers Functions





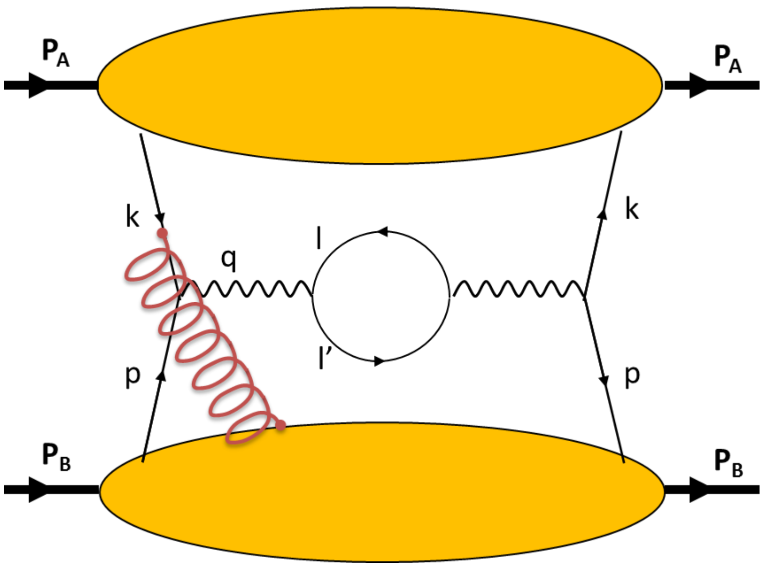
Signals of flavor-dependent Sivers functions in SIDIS

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

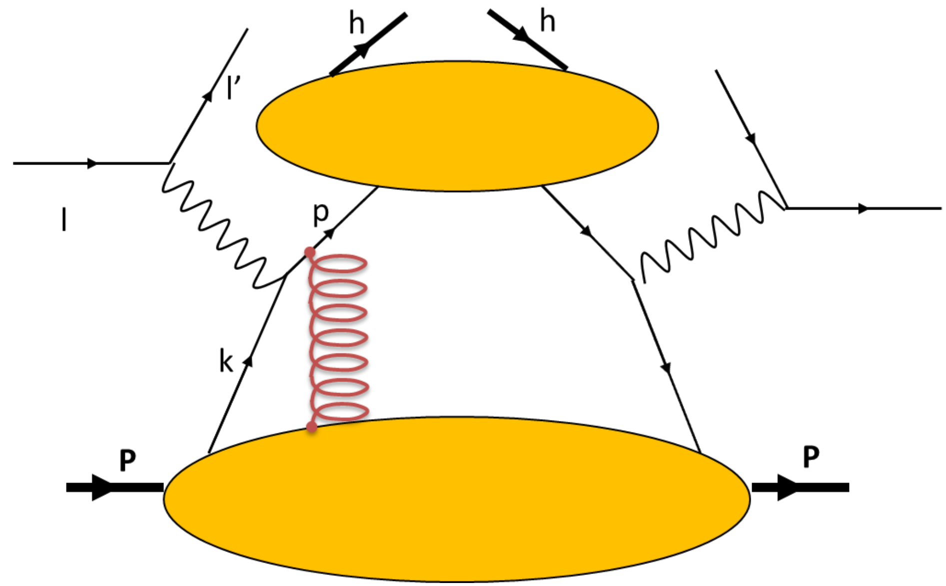
Sign Change of T-odd Sivers/BM Functions

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



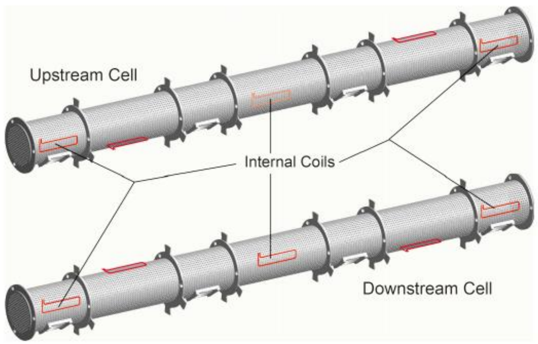
SIDIS

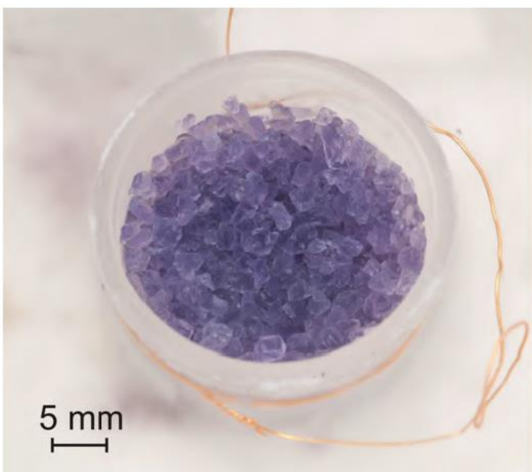


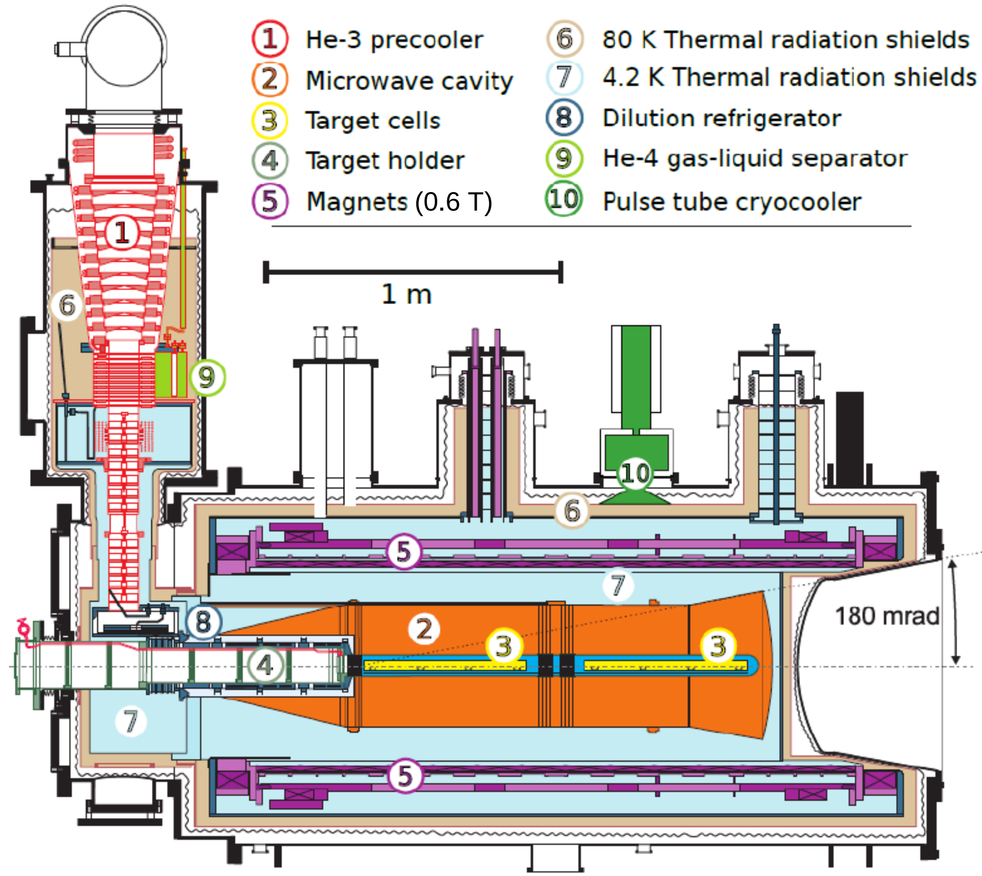
$$\text{Sivers/BM}\,|_{DY} = -1 * \text{Sivers/BM}\,|_{SIDIS}$$

- 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.***

COMPASS Polarized NH_3 Target



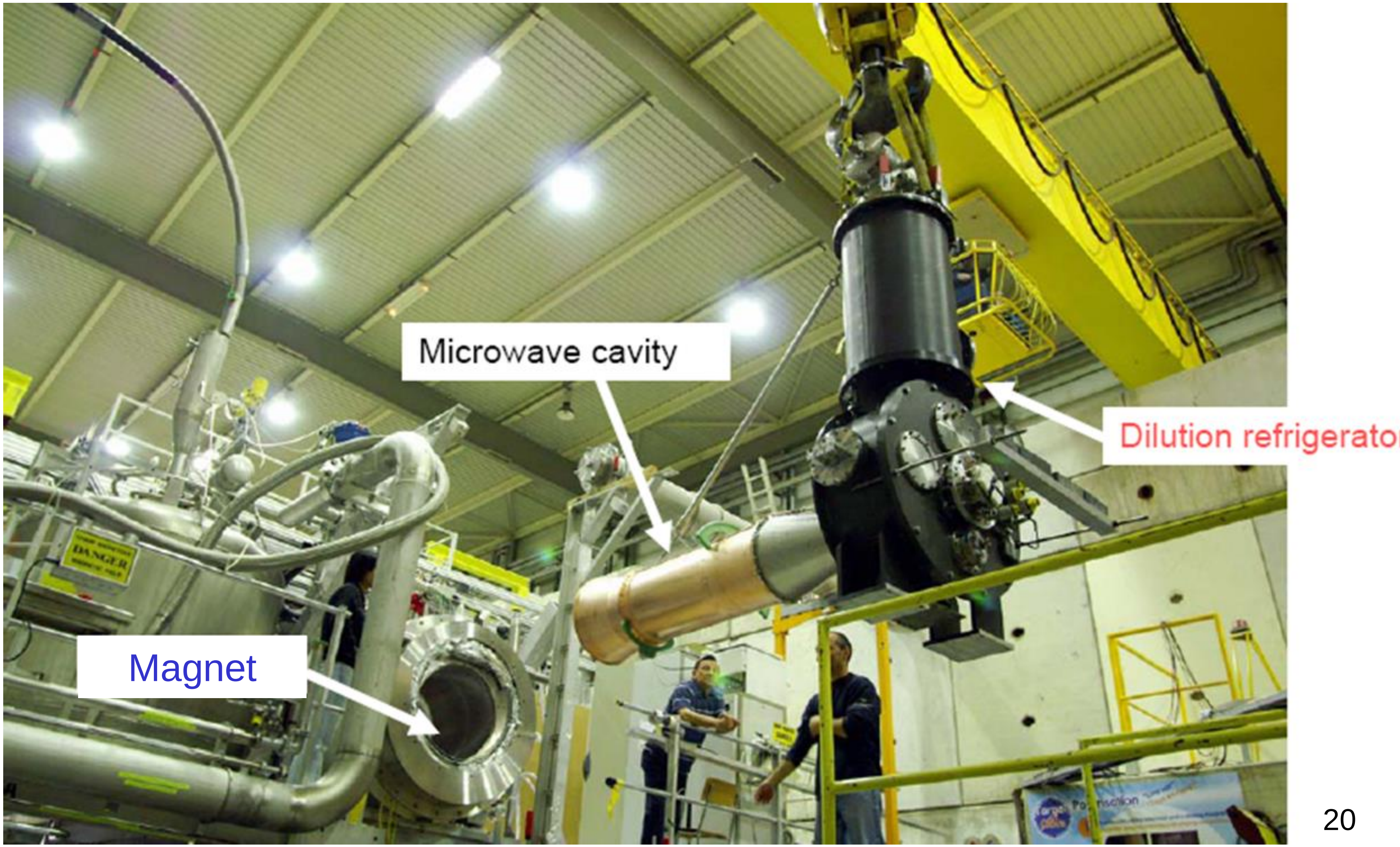




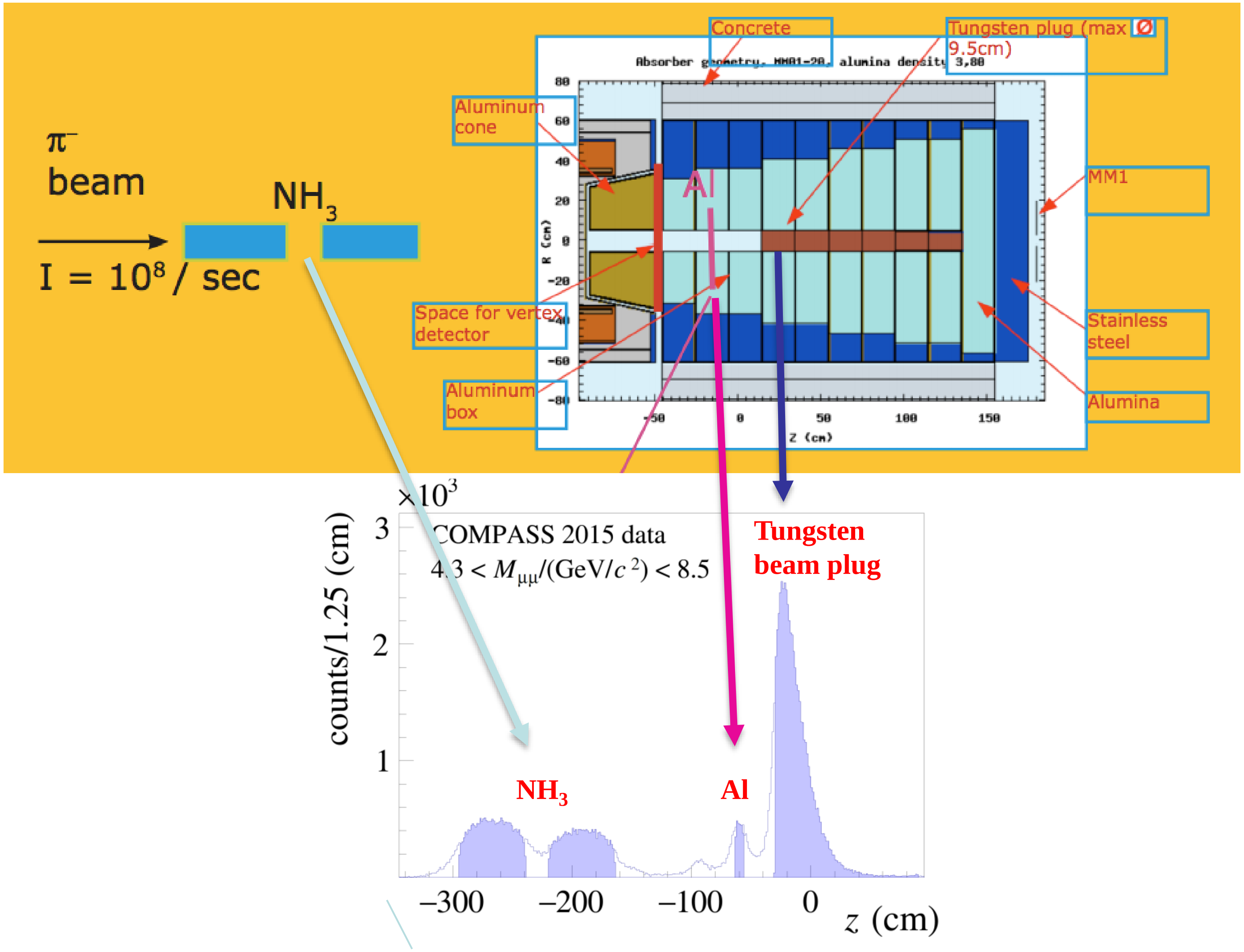
Polarization: 70%
Relaxation time: 1000 hrs

Target cell: 55 cm (L) * 4 cm (R)

COMPASS Polarized NH_3 Target

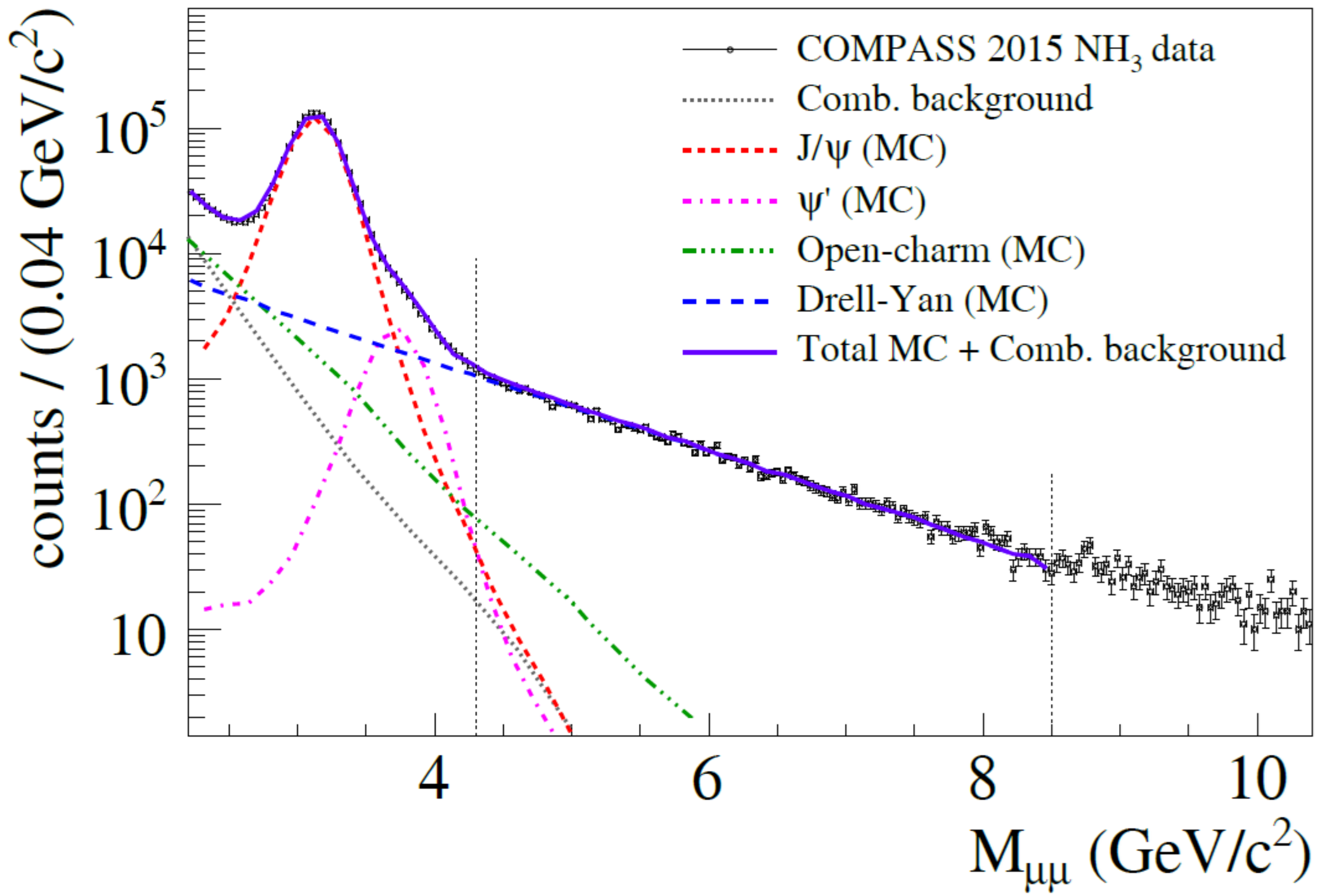


COMPASS 2015 Transversely Polarized Drell-Yan Run



COMPASS, PRL 119 (2017) 112002

Dimuon Invariant-mass Distributions (2015 Trans.-pol. Drell-Yan Runs)



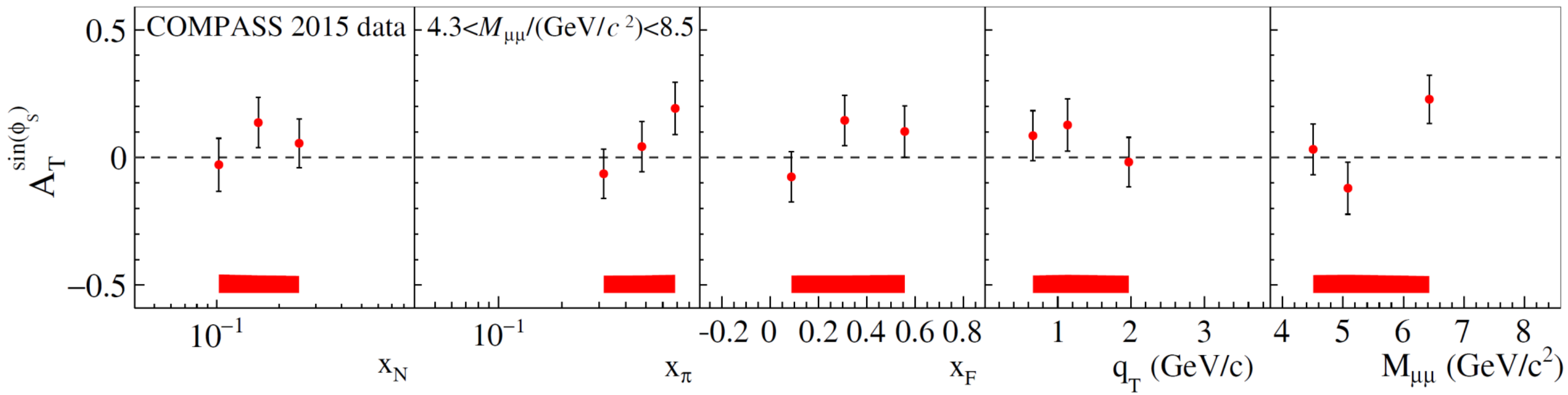
COMPASS, PRL 119 (2017) 112002

Transverse Spin Asymmetries in Trans.-pol. Drell-Yan: Sivers

$$A_T^{\sin\phi_s} \propto \text{Density } f_1\,|_\pi \otimes \text{Sivers } f_{1T}^{\perp}\,|_p$$

$$\frac{d\sigma^{LO}}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U^{LO}$$

$$\left\{ \left(1 + D_{[\sin^2\theta]}^{LO} A_U^{\cos 2\varphi} \cos 2\varphi\right) + \left|\vec{S}_T\right| \left[\boxed{A_T^{\sin\varphi_S}} \sin\varphi_S + D_{[\sin^2\theta]}^{LO} \left(A_T^{\sin(2\varphi-\varphi_S)} \sin(2\varphi-\varphi_S) + A_T^{\sin(2\varphi+\varphi_S)} \sin(2\varphi+\varphi_S) \right) \right] \right\}$$

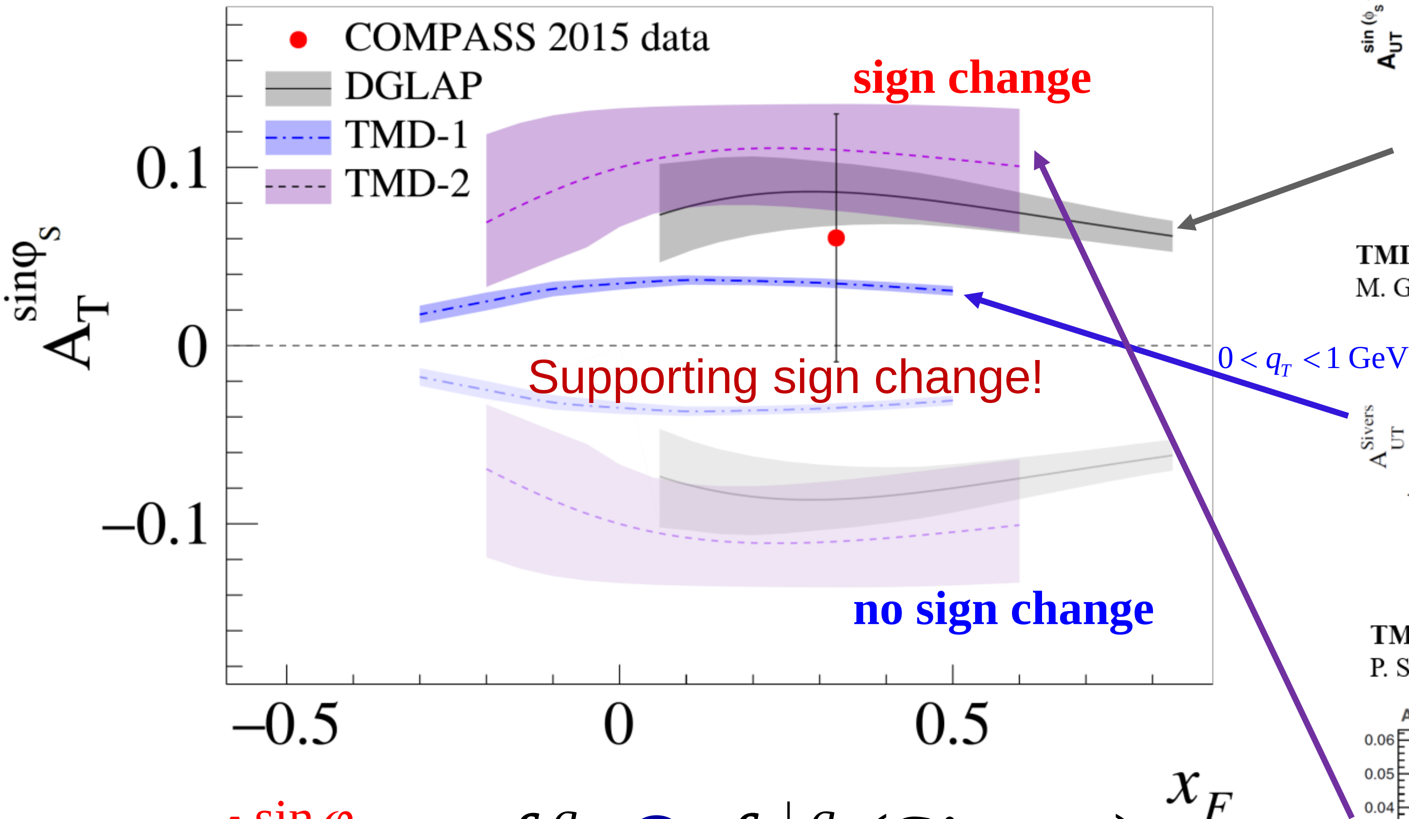


COMPASS, PRL 119 (2017) 112002

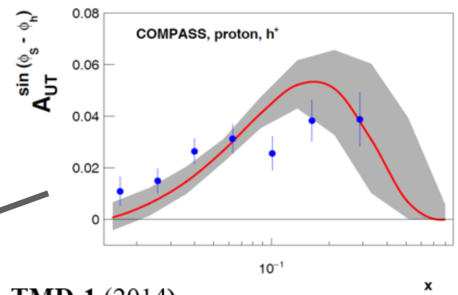
Sivers in Polarized Drell-Yan

2015 runs

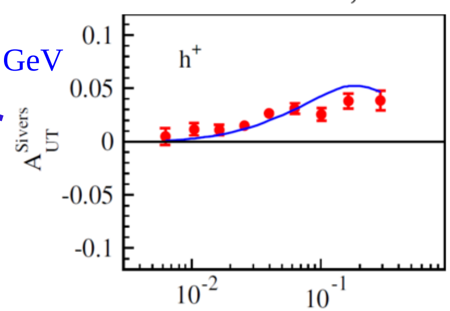
COMPASS, PRL 119 (2017) 112002



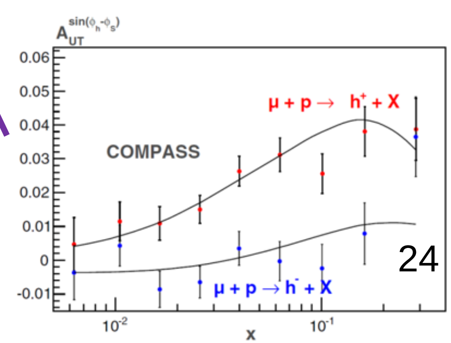
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



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



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

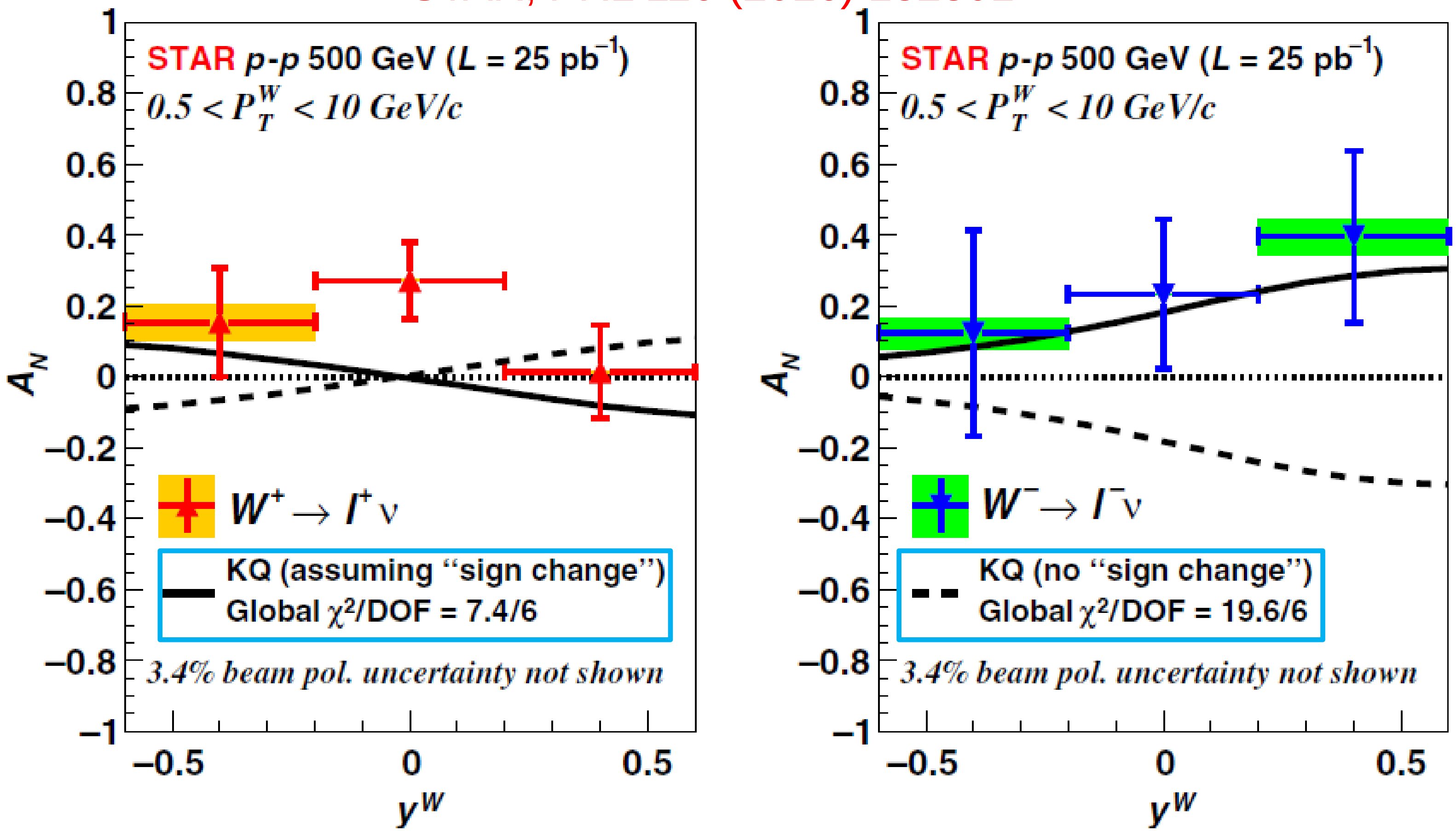


$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q} \text{(Sivers)}$$

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

Transverse SSA of W production in polarized pp collisions at RHIC

STAR, PRL 116 (2016) 132301



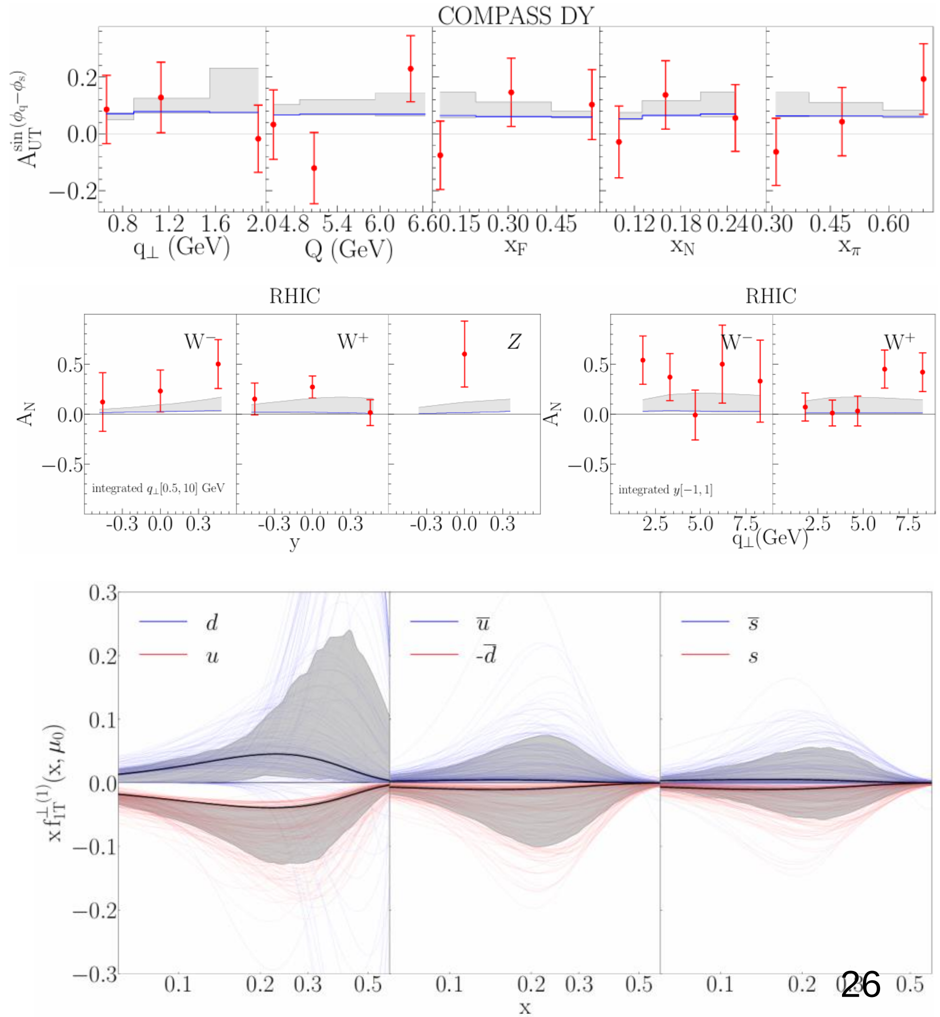
$$A_N = \frac{1}{\langle P \rangle} \frac{\sqrt{N_\uparrow(\phi) N_\downarrow(\phi+\pi)} - \sqrt{N_\uparrow(\phi+\pi) N_\downarrow(\phi)}}{\sqrt{N_\uparrow(\phi) N_\downarrow(\phi+\pi)} + \sqrt{N_\uparrow(\phi+\pi) N_\downarrow(\phi)}},$$

Global Analysis of Sivers Functions

M. G. Echevarria, Z.-B. Kang, and J. Terry, JHEP01(2021)126, arXiv: 2009.10710

$$f_{1T}^{\perp}(x,k_T)_{[\text{SIDIS}]} = -f_{1T}^{\perp}(x,k_T)_{[\text{DY}]}$$

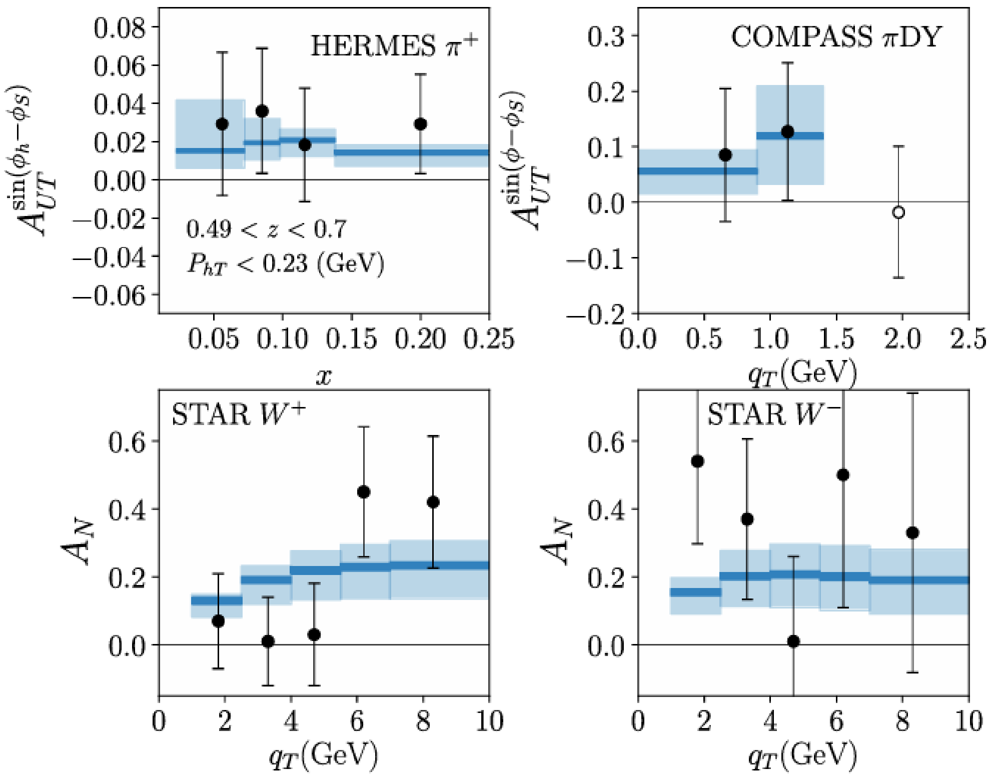
Collab	Ref	Process	Q_{avg}	N_{data}	χ^2/N_{data}
COMPASS	[44]	$ld \to lK^0X$	2.52	7	0.770
		$ld \to lK^-X$	2.80	11	1.325
		$ld \to lK^+X$	1.73	13	0.749
		$ld \to l\pi^-X$	2.50	11	0.719
		$ld \to l\pi^+X$	1.69	12	0.578
	[43]	$lp \to lh^-X$	4.02	31	1.055
		$lp \to lh^+X$	3.93	34	0.898
	[46]	$\pi^-p \to \gamma^*X$	5.34	15	0.658
HERMES	[41]	$lp \to lK^-X$	1.70	14	0.376
		$lp \to lK^+X$	1.73	14	1.339
		$lp \to l\pi^0X$	1.76	13	0.997
		$lp \to l(\pi^+ - \pi^-)X$	1.73	15	1.252
		$lp \to l\pi^-X$	1.67	14	1.498
		$lp \to l\pi^+X$	1.69	14	1.697
JLAB	[45]	$lN \to l\pi^+X$	1.41	4	0.508
		$lN \to l\pi^-X$	1.69	4	1.048
RHIC	[47]	$pp \to W^+X$	M_W	8	2.189
		$pp \to W^-X$	M_W	8	1.684
		$pp \to Z^0X$	M_Z	1	3.270
Total				226	0.989

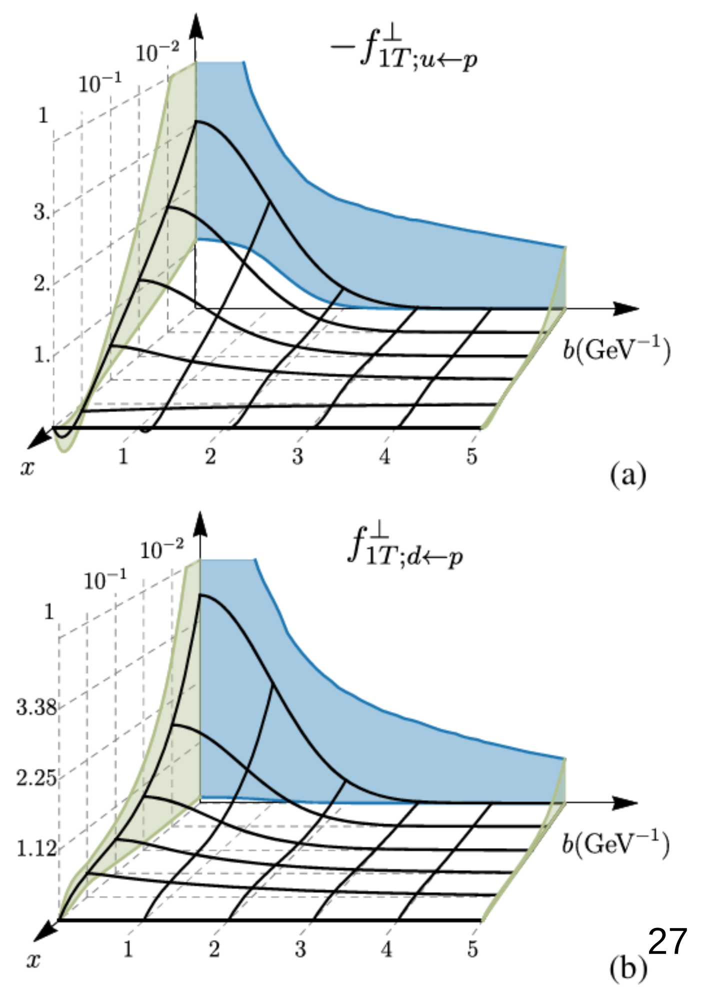


Global Analysis of Sivers Functions

M. Bury, A. Prokudin, and A. Vladimirov, PRL 126, 112002 (2021), arXiv: 2012.05135

$$f_{1T}^{\perp}(x, k_T)_{[\text{SIDIS}]} = -f_{1T}^{\perp}(x, k_T)_{[\text{DY}]}$$

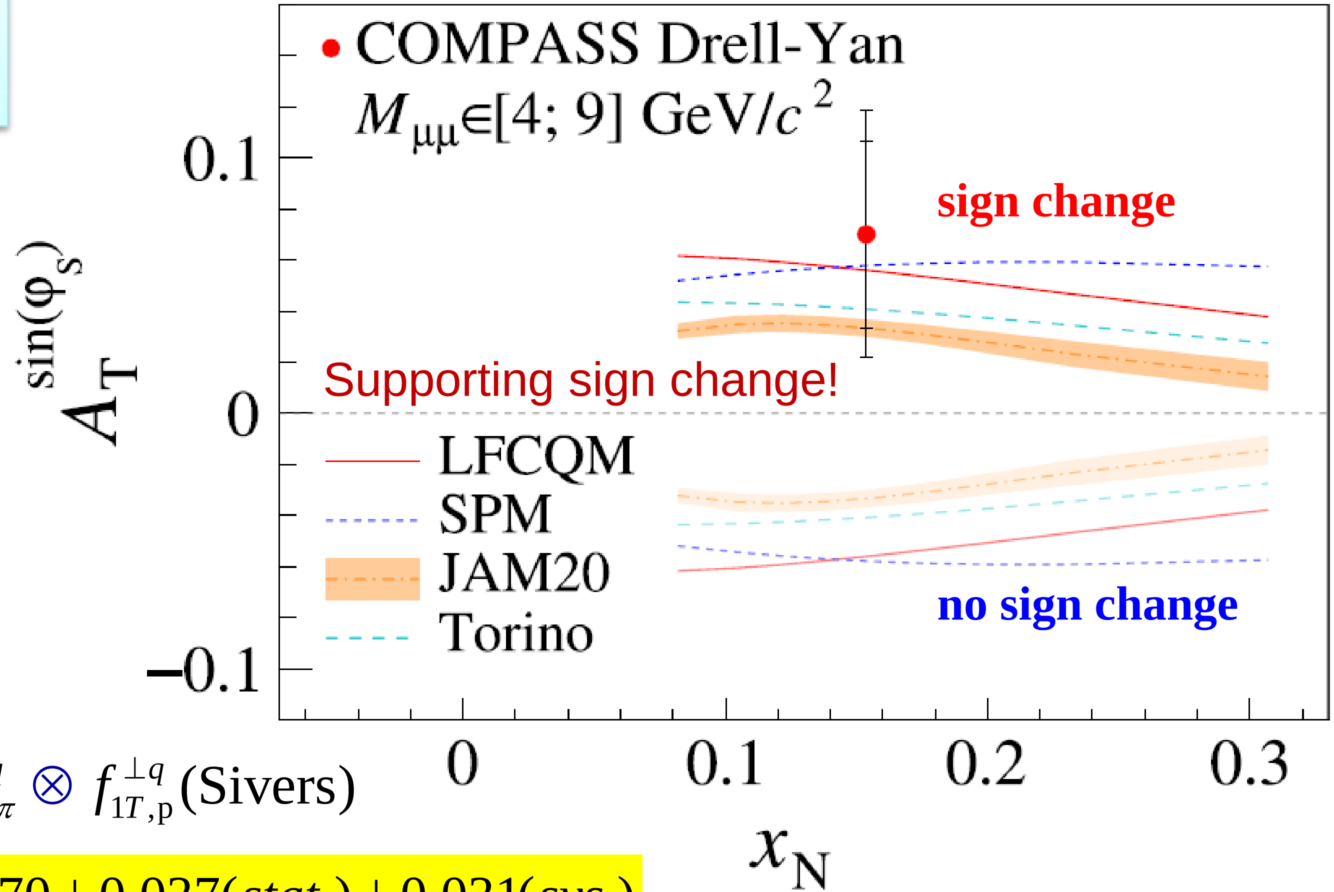




Sivers in Polarized Drell-Yan

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)

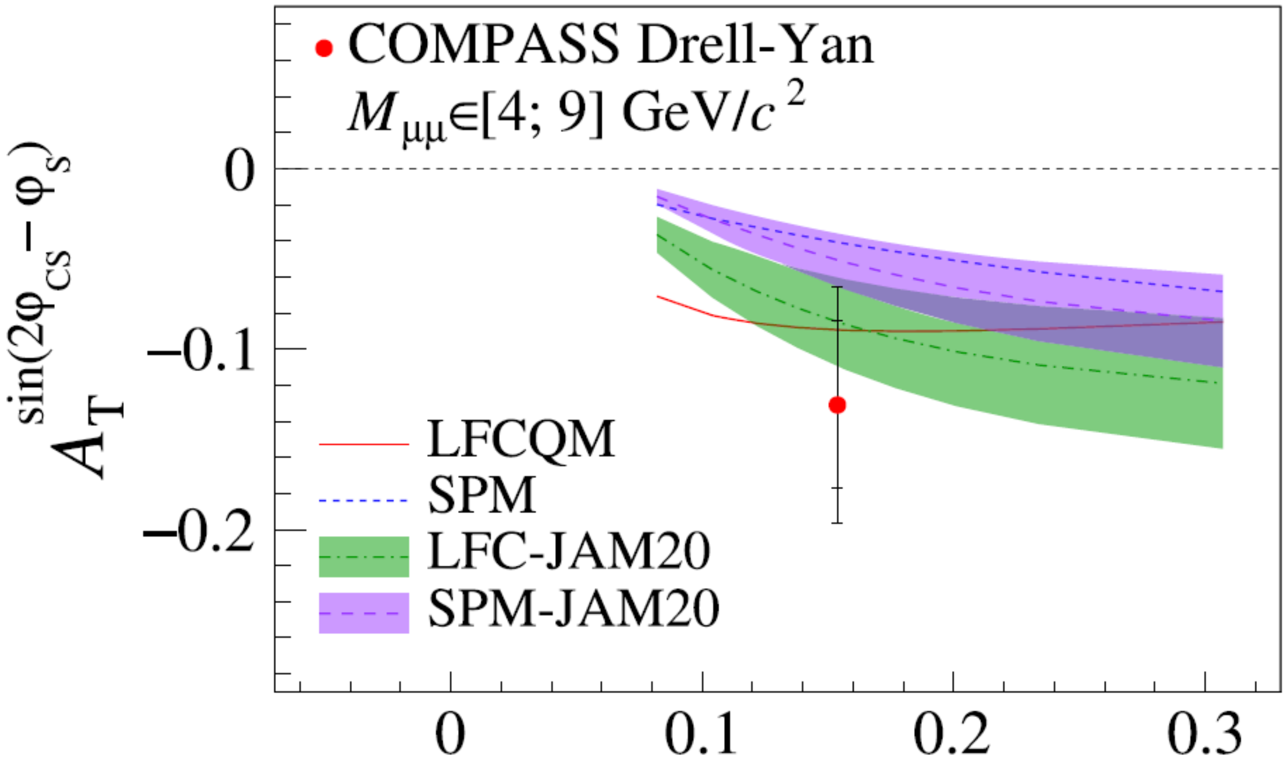
$A_T^{\sin\varphi_s} = 0.070 \pm 0.037(stat.) \pm 0.031(sys.)$

Agreeing with the sign-change of Sivers function!

Transversity in Polarized Drell-Yan

Statistics:
2015: 35K
2018: 37K

COMPASS, PRL 133, 071902 (2024)



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

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

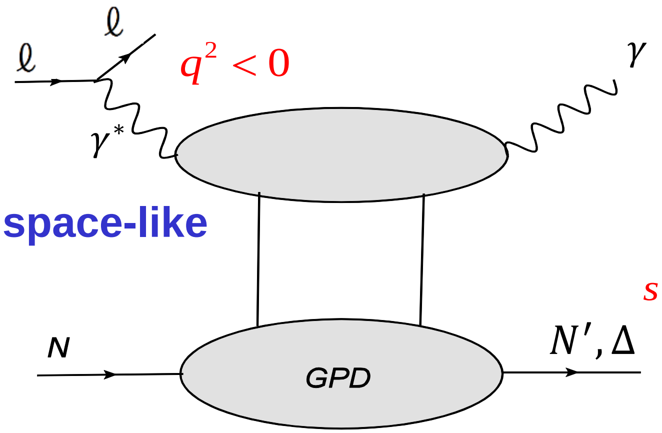
$h_{1,\mathrm{p}}^{q}(+) \rightarrow h_{1,\pi}^{\perp q}(\mathrm{DY},+) \xrightarrow{\nu_{\pi p}>0} h_{1,p}^{\perp q}(\mathrm{DY},+) \Leftrightarrow h_{1,p}^{\perp q}(\mathrm{SIDIS},-)$

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

Experimental Approach

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

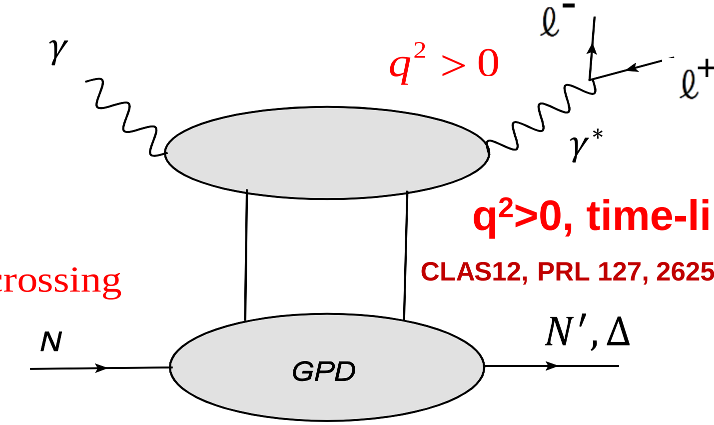
Deeply Virtual Compton Scattering



q^2<0, space-like

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

Time-like Compton Scattering



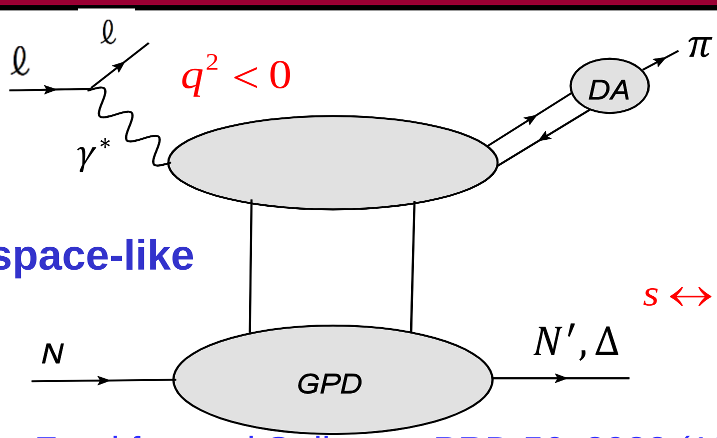
q^2>0, time-like

CLAS12, PRL 127, 262501 (2021)

$s \leftrightarrow u$ channel crossing

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

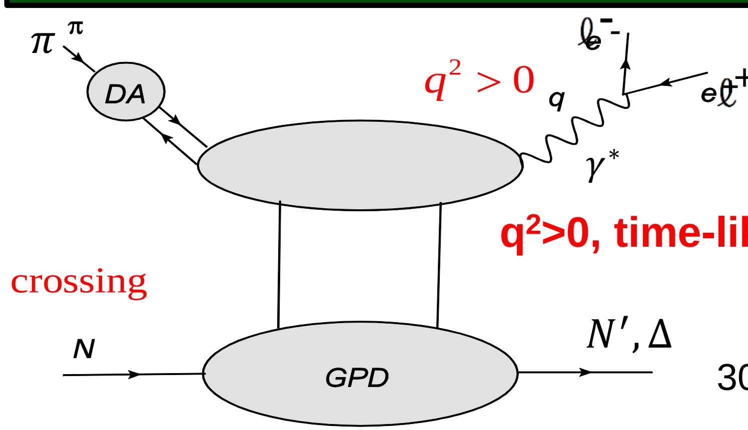
Deeply Virtual Meson Production



q^2<0, space-like

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

Exclusive meson-induced DY

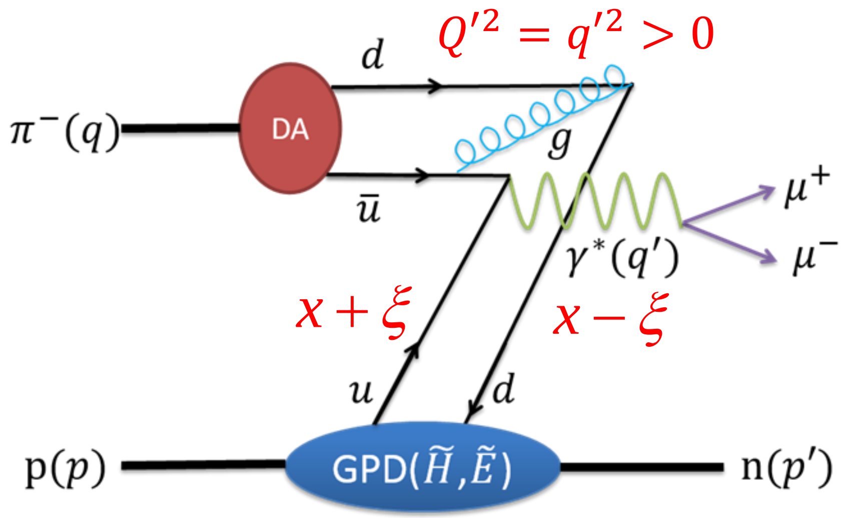


q^2>0, time-like

$s \leftrightarrow u$ channel crossing

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

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

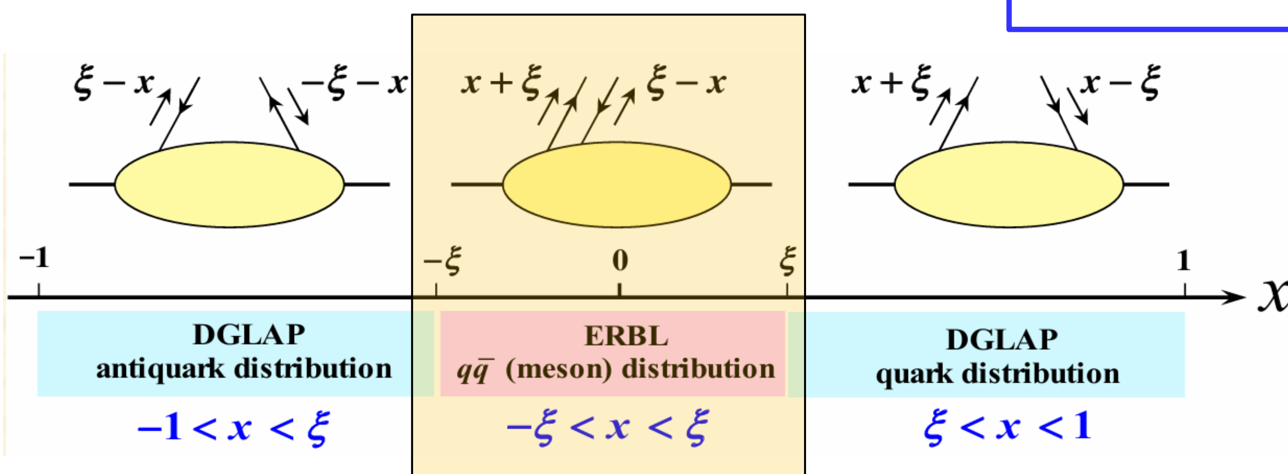


$$t = (p - p')^2$$

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

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

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



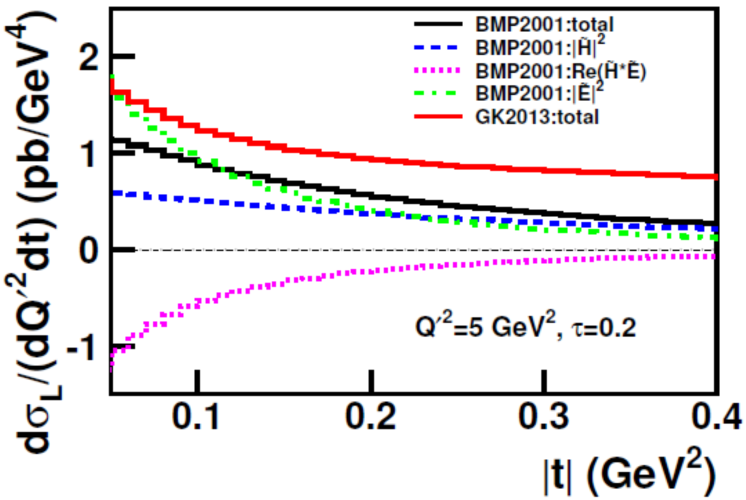
Differential Cross Sections of $\pi N \to l^+ l^- N$

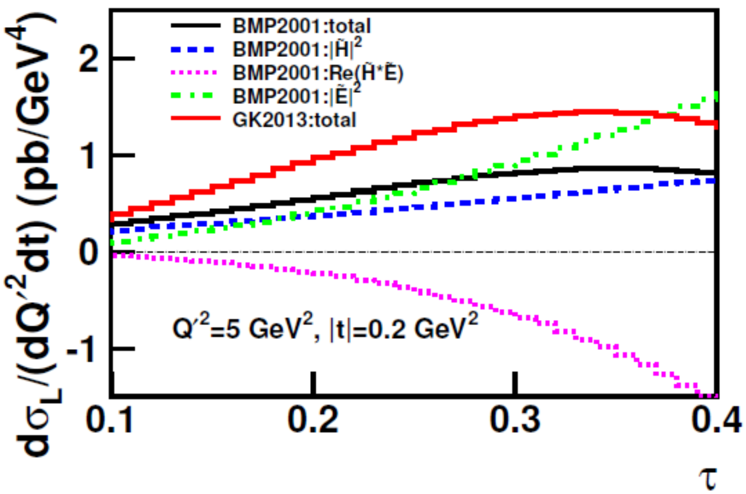
$$\left.\frac{d\sigma_L}{dt\,dQ'^2}\right|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \Big[(1-\xi^2)|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)|^2 - 2\xi^2 {\rm Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^* \tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2 \frac{t}{4m_N^2}|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)|^2\Big],$$

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

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

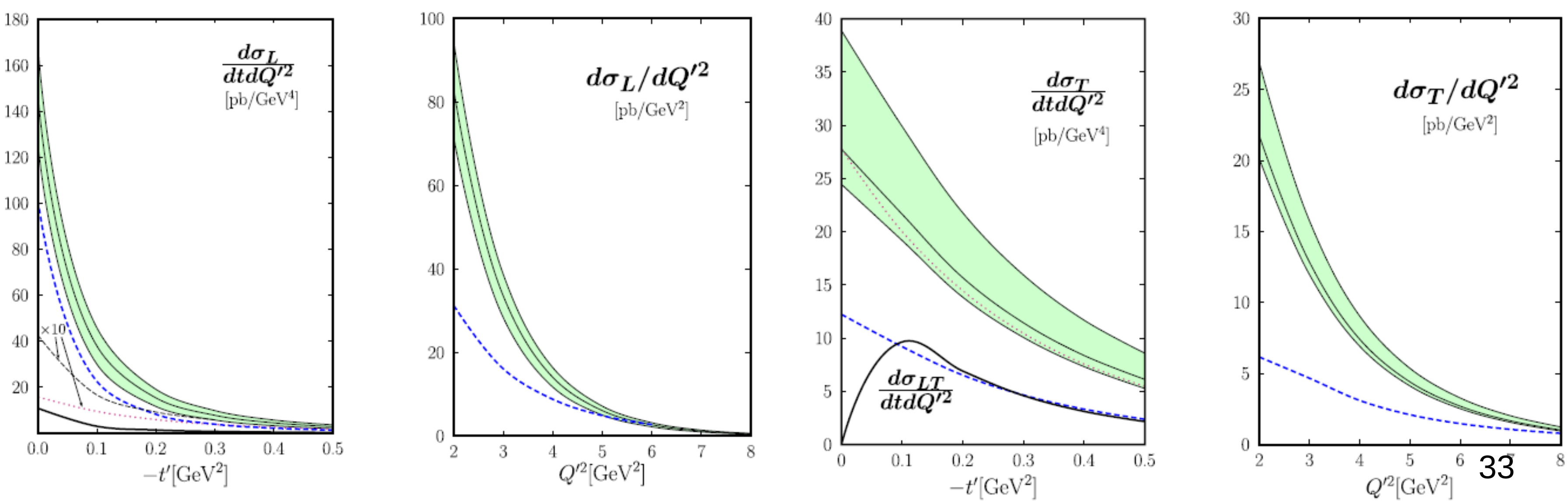
Cross sections increase toward small *s* (→ low beam energy)

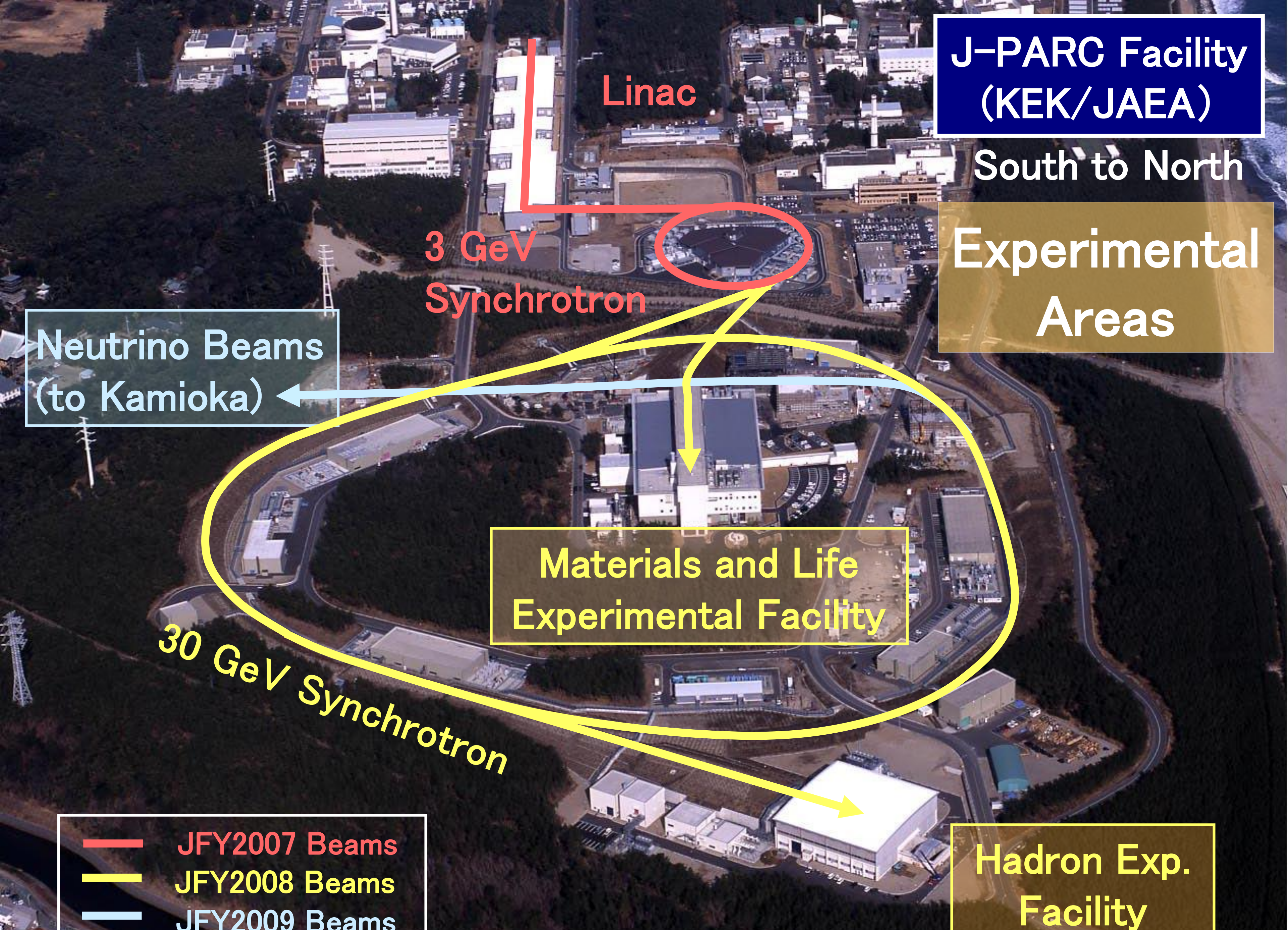
Beyond the Leading Twist

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

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

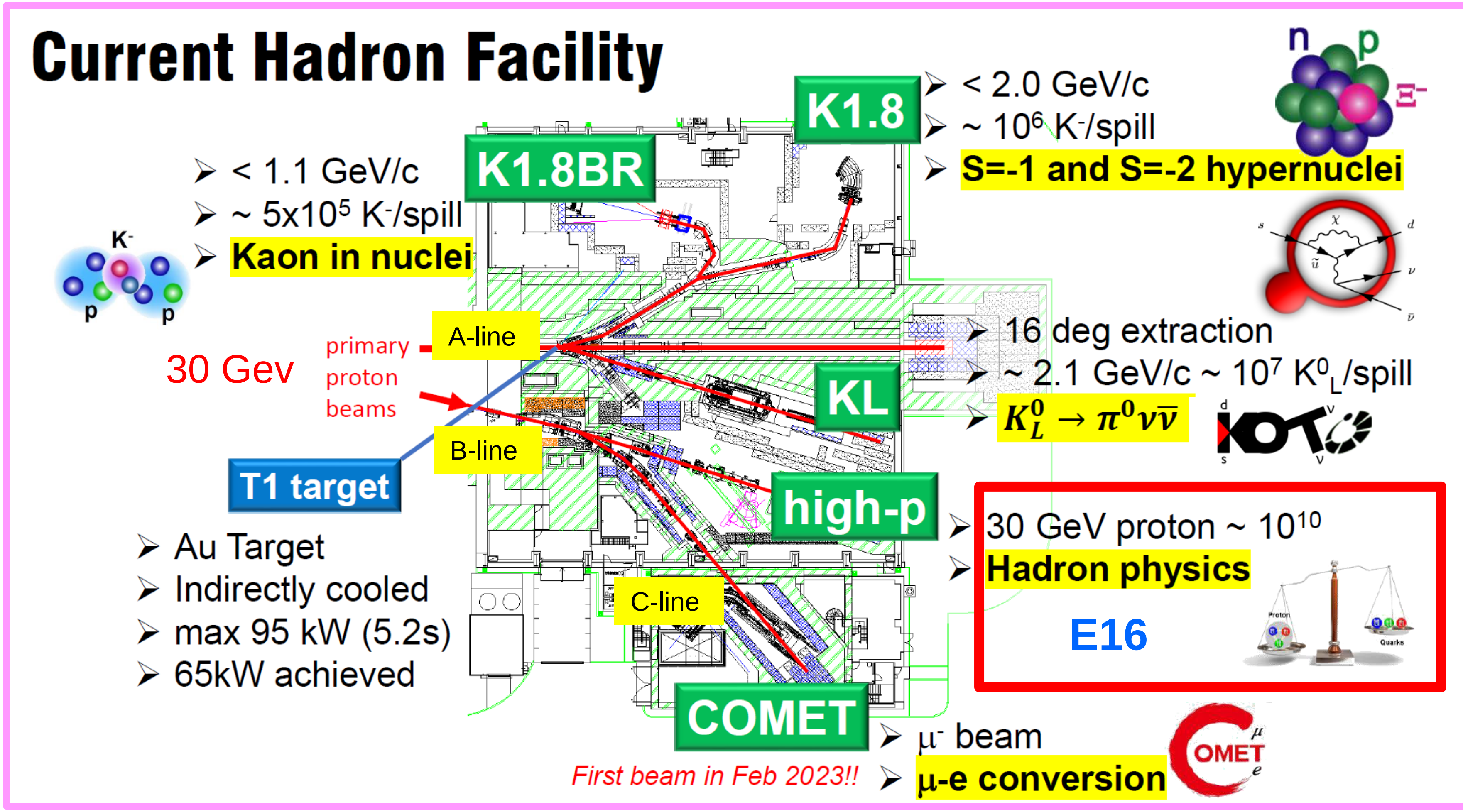
Transversity GPDs: H_T, $\bar{E}_T$





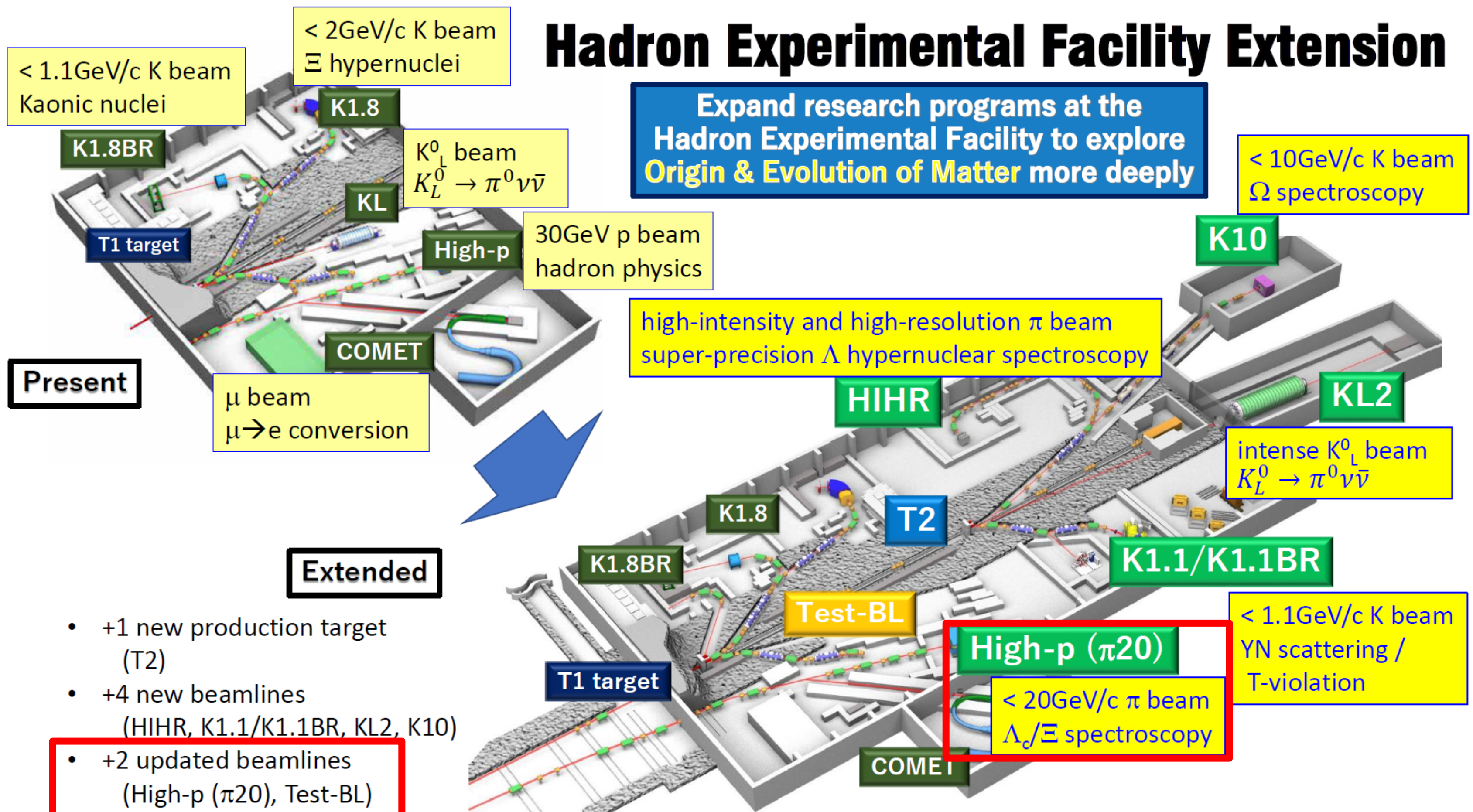
Bird's eye photo in January of 2008

J-PARC Hadron Hall (Current Status)



Hadron Hall Extension

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

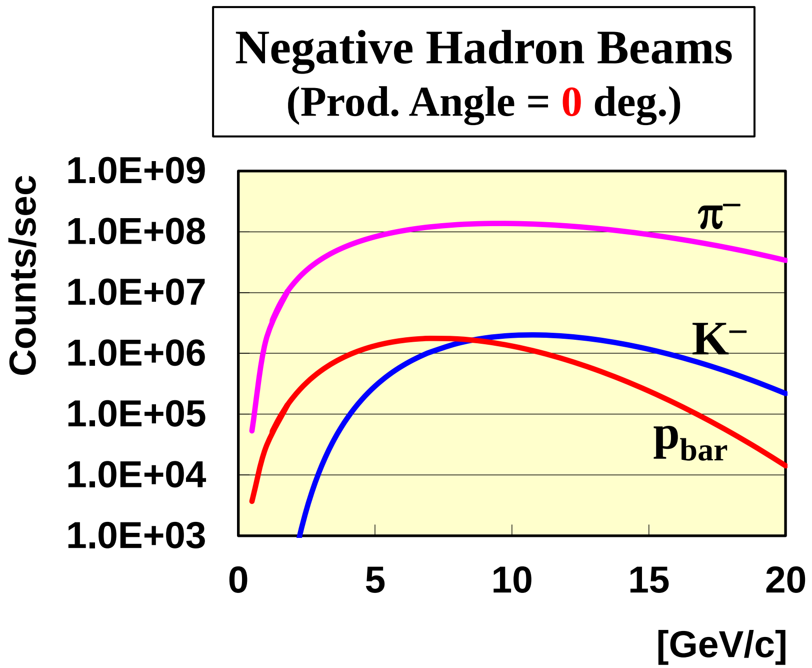


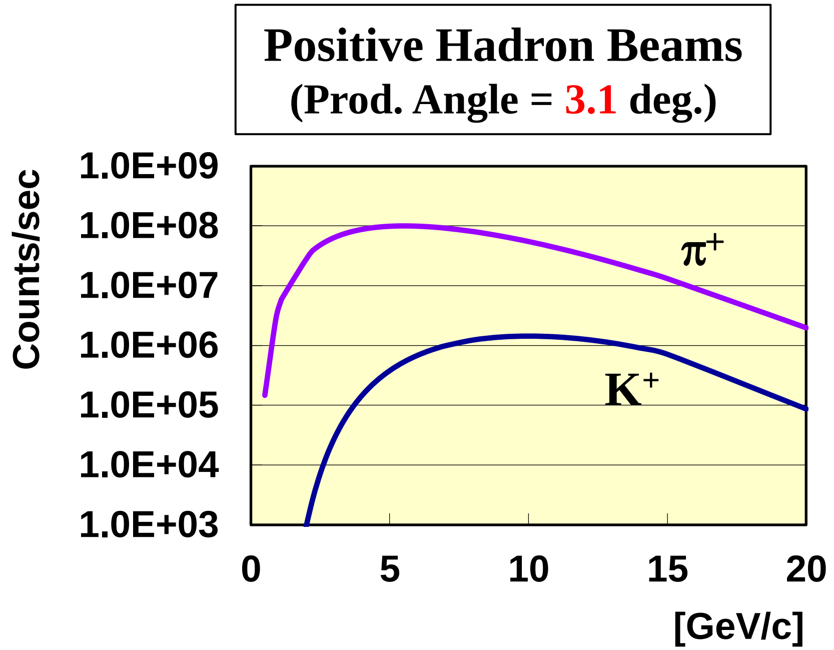
- +1 new production target (T2)
- +4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10)
- +2 updated beamlines (High-p (π20), Test-BL)

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%

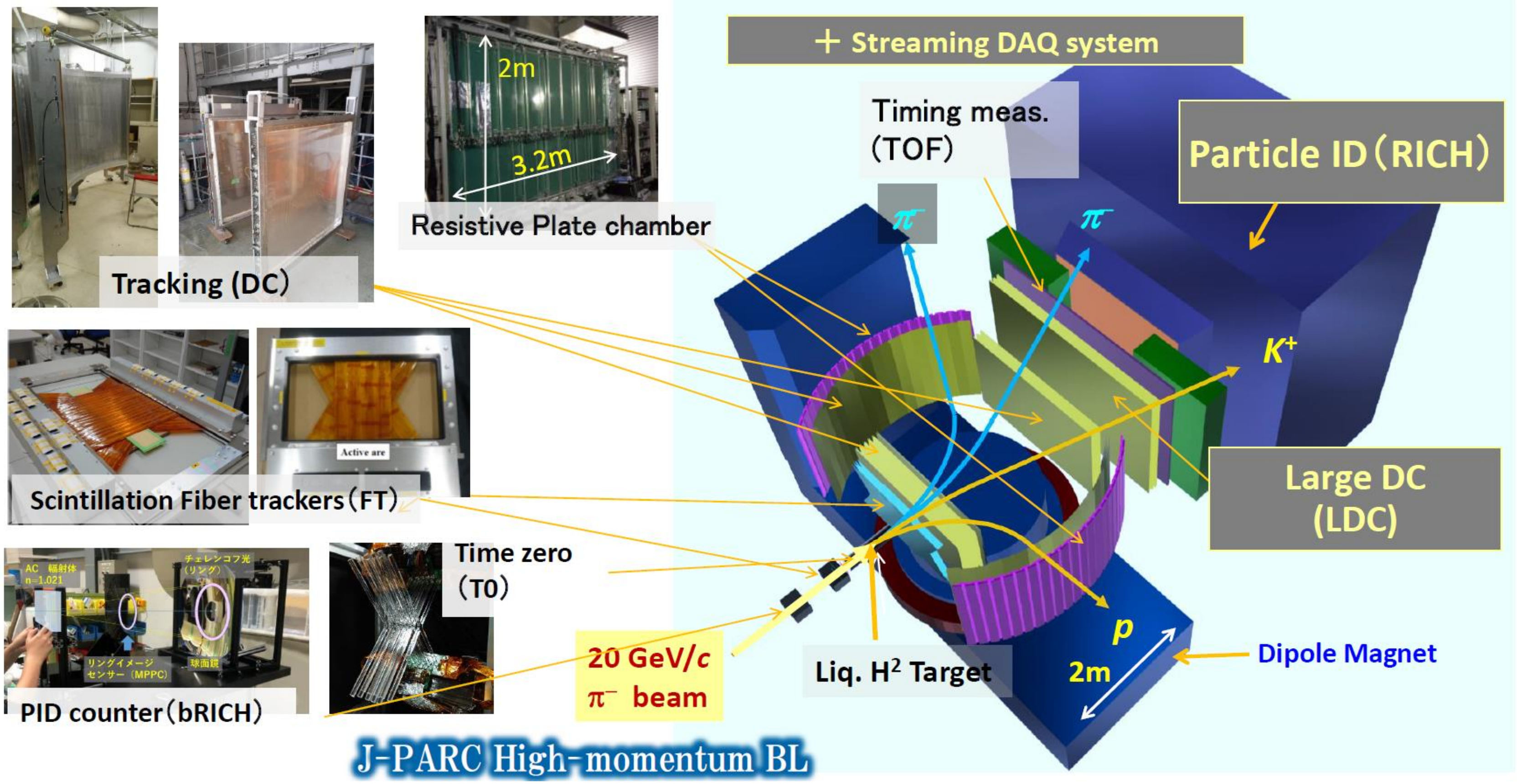




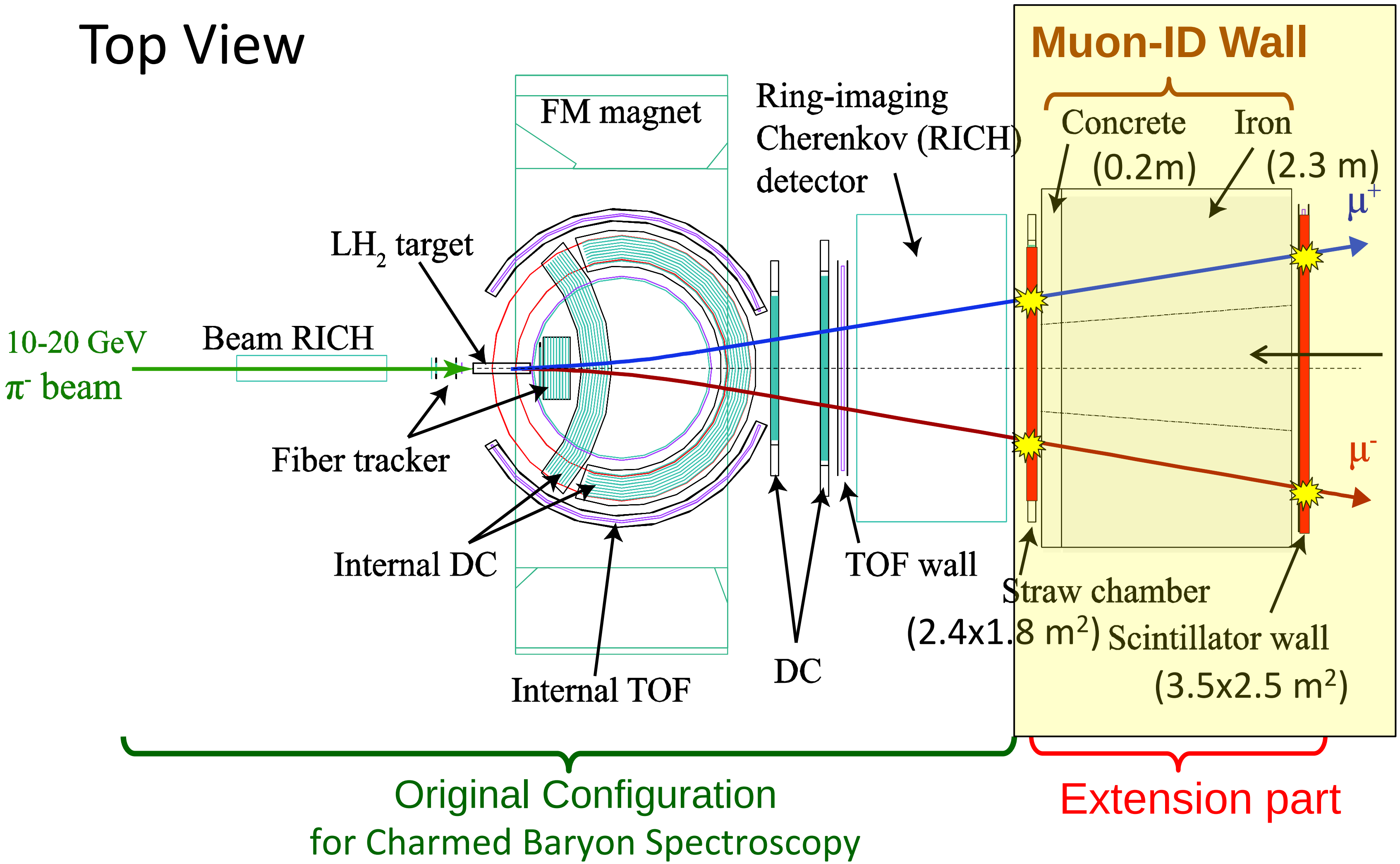
*** Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m**

J-PARC E50/MARQ Experiment
(Charmed Baryon Spectroscopy)

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



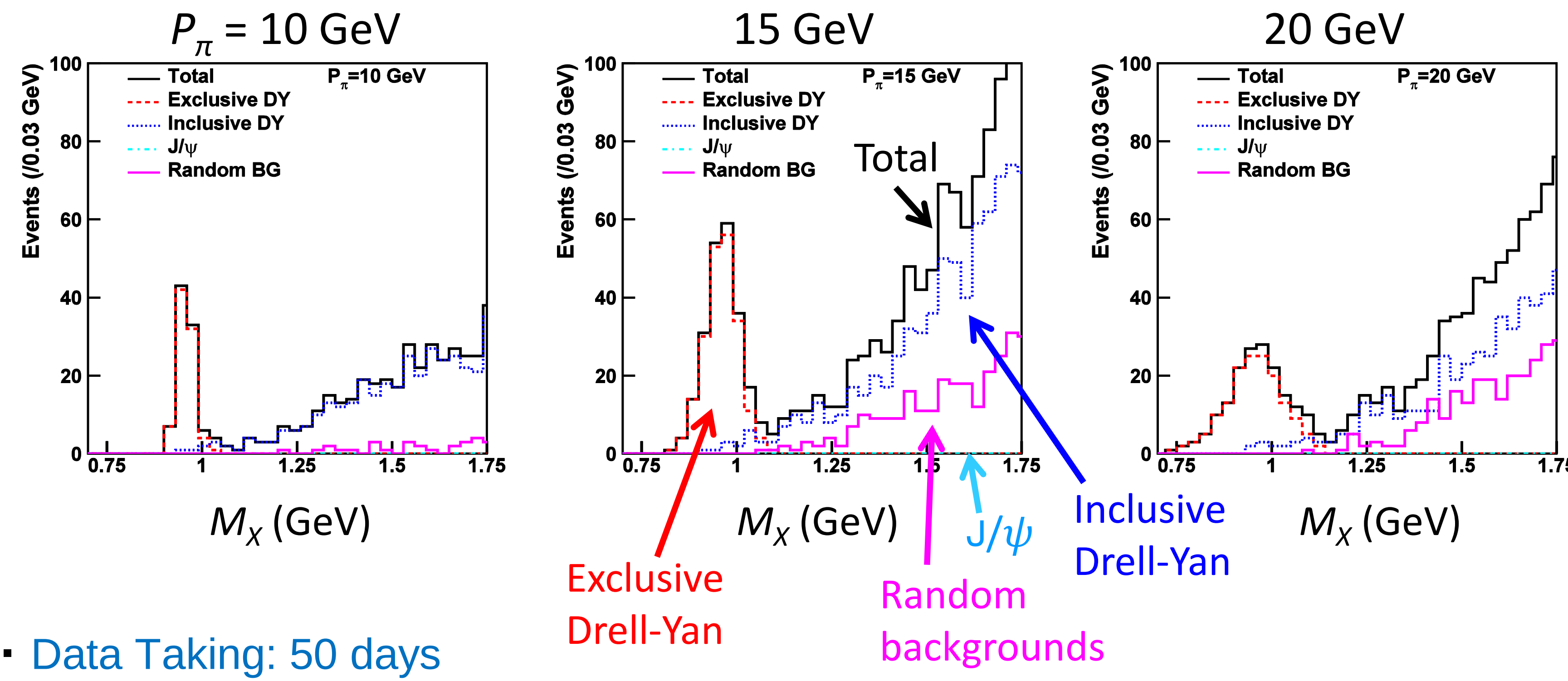
J-PARC E50/MARQ Experiment for Drell-Yan measurement



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

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

π^- Beam Momentum



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

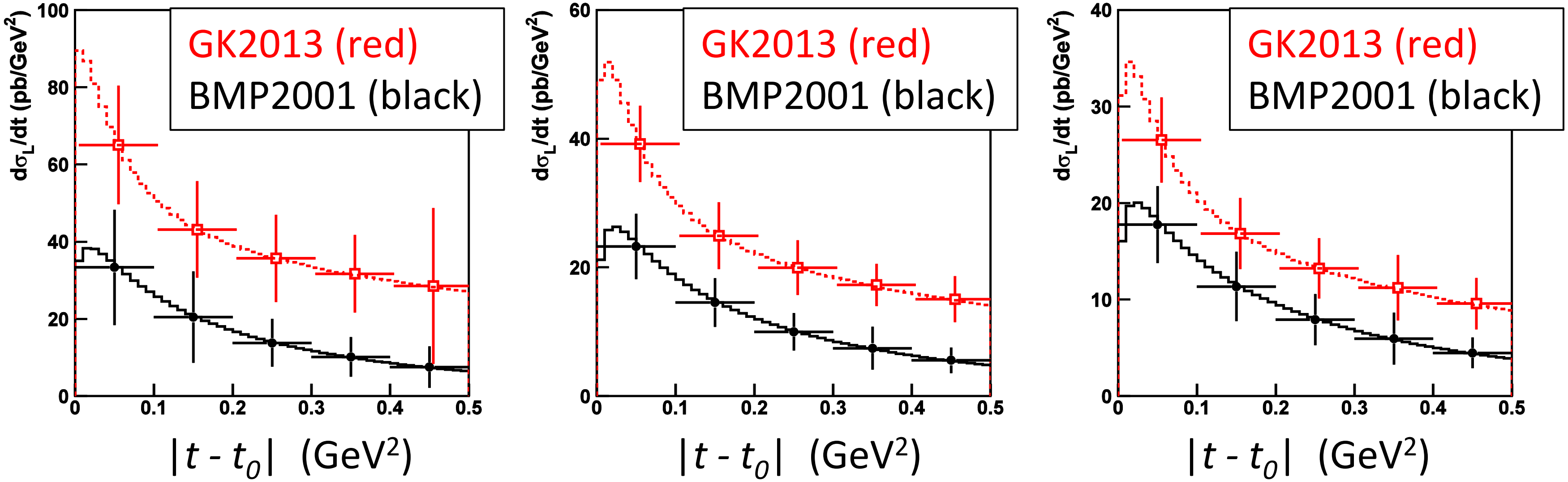
The exclusive Drell-Yan events could be identified by the signature peak at the nucleon mass in the missing-mass spectrum for all three pion beam momenta.

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

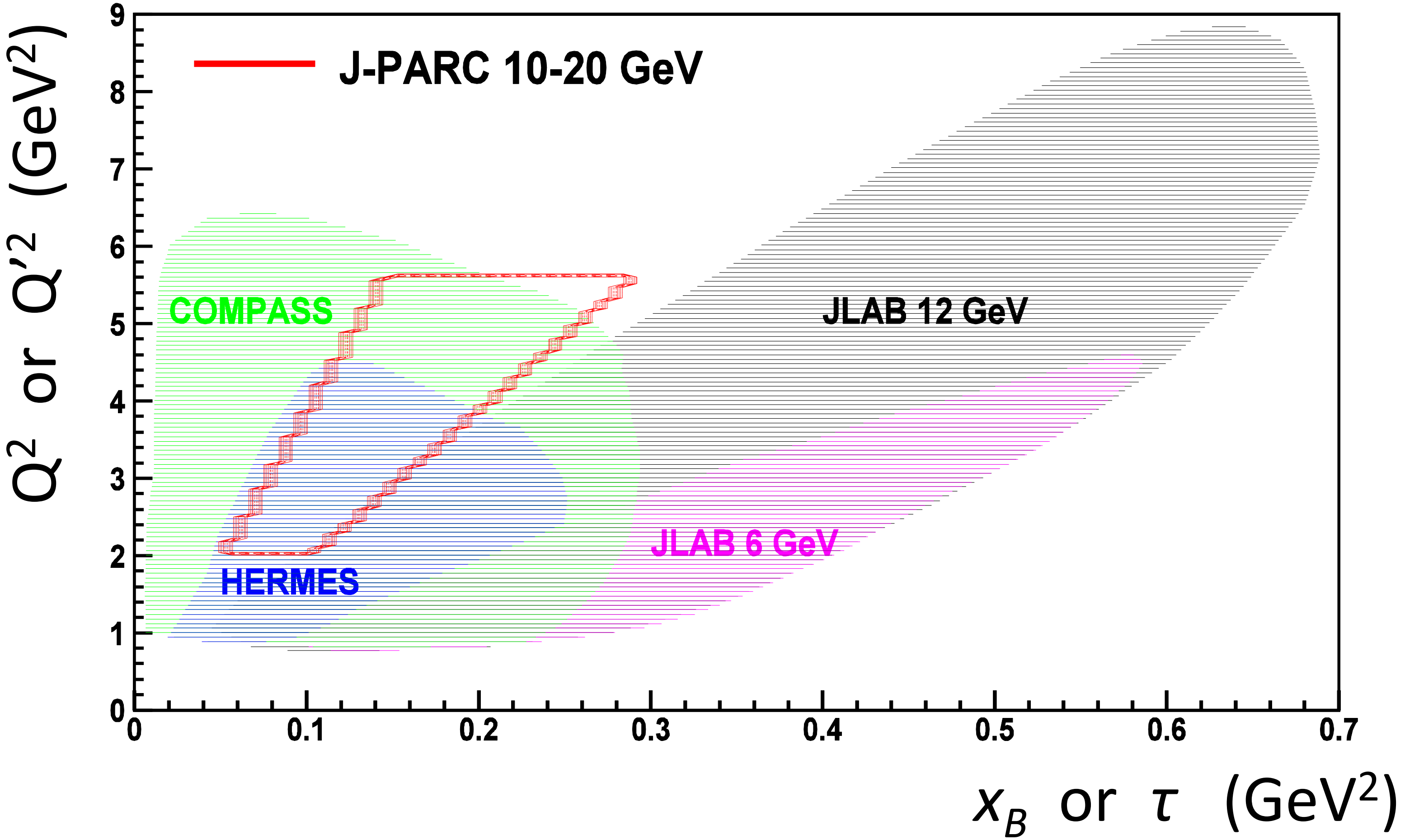
P_π = 10 GeV　　15 GeV　　20 GeV



- 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.

Universality of GPDs

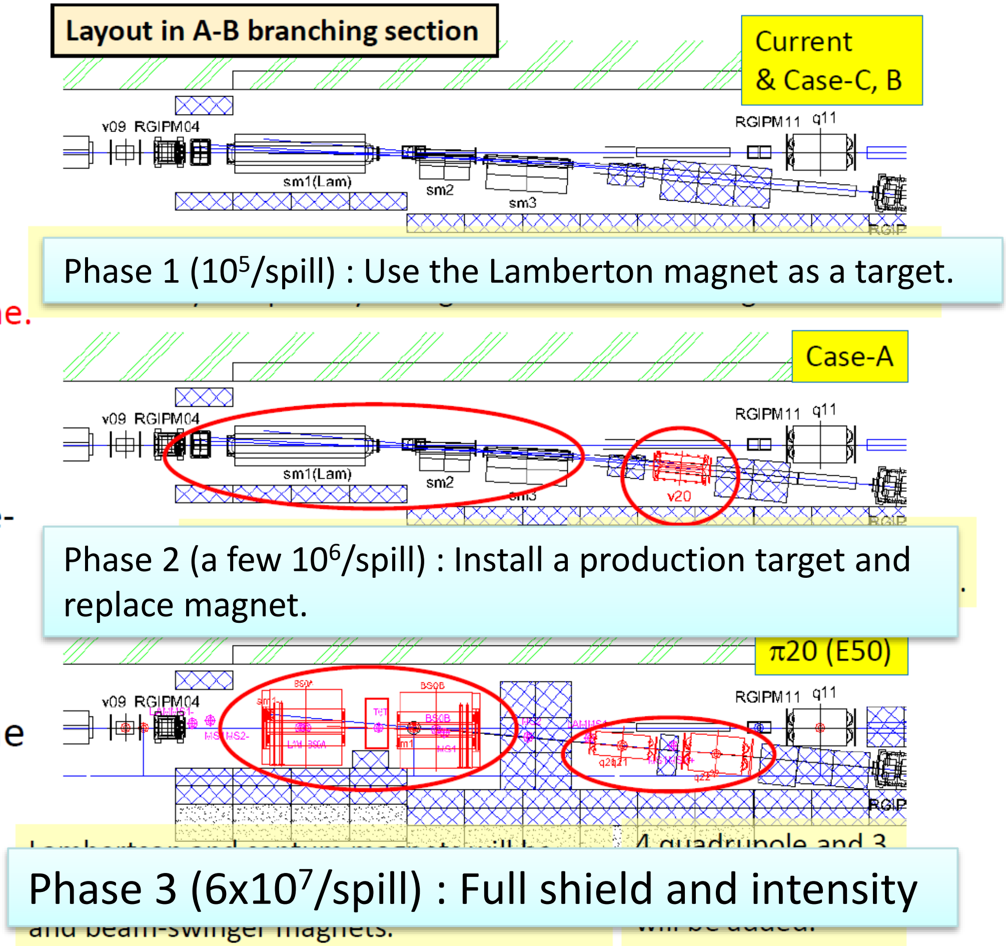


- JLAB, HERMES, COMPASS → Space-like approach
- J-PARC → Time-like approach

Staging Plan of **π20 Beamline**

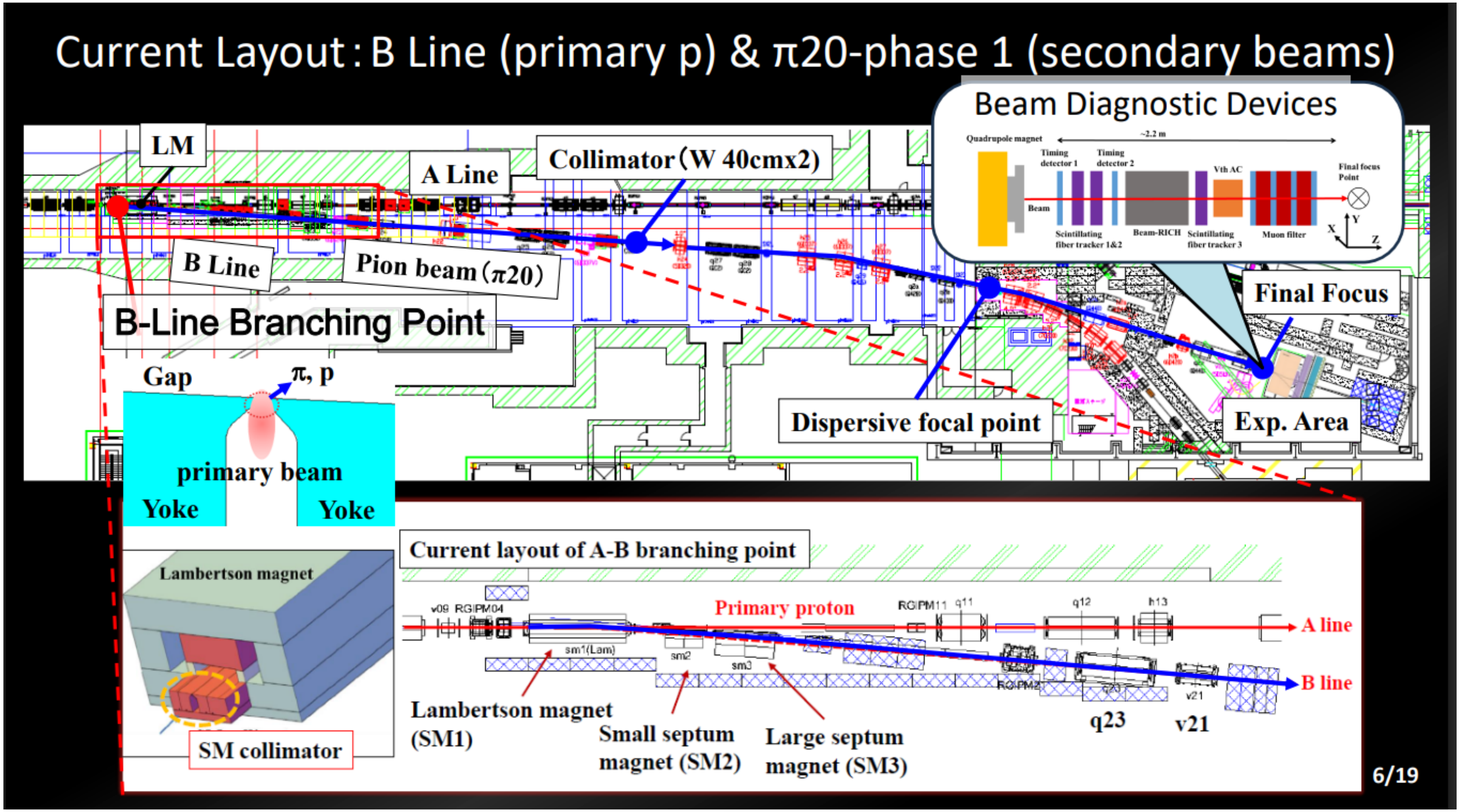
Toward π20

- 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.



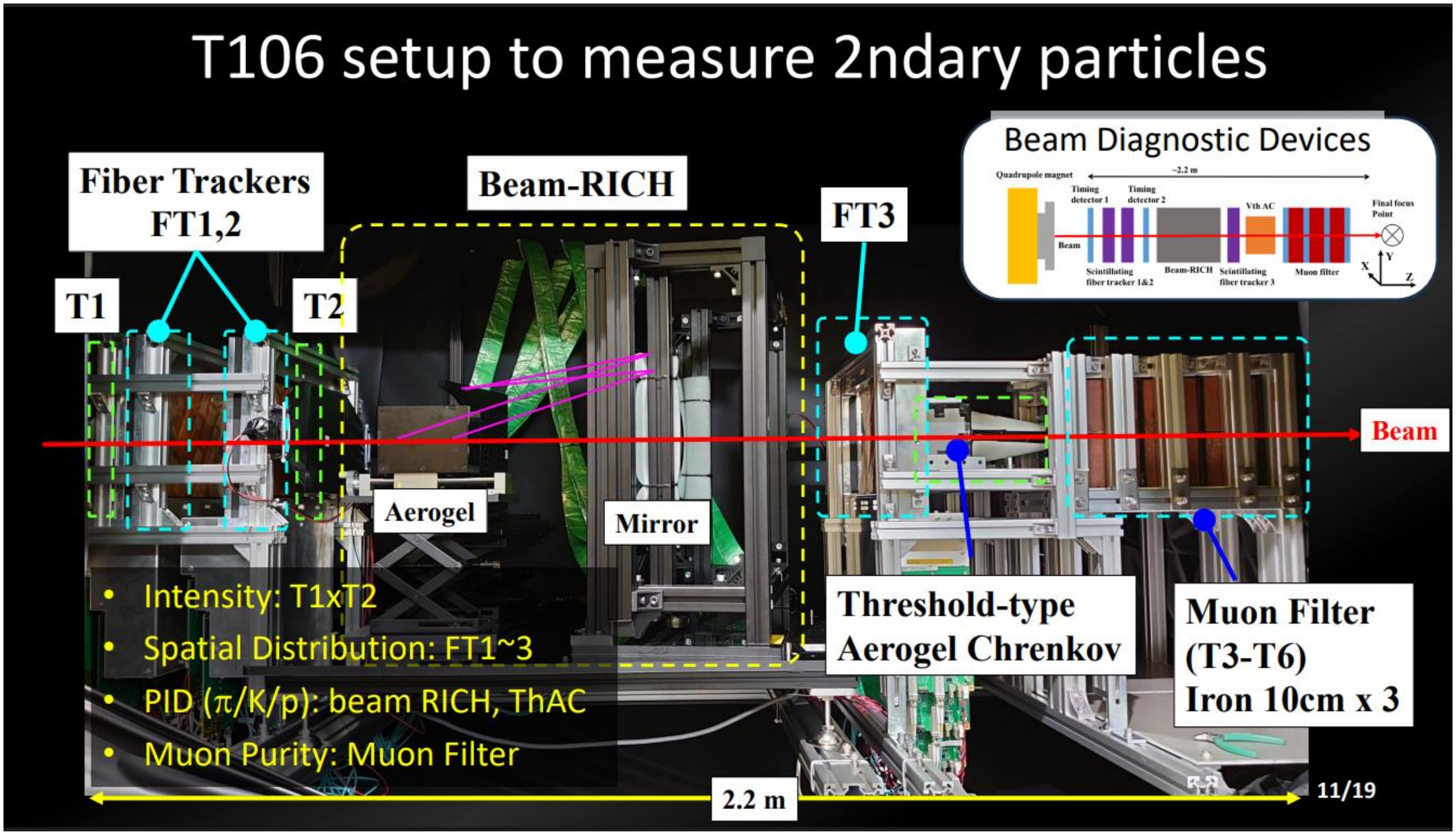
https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html
https://arxiv.org/abs/2110.04462

T106: First Measurement of Secondary Beams at the J-PARC High-Momentum Beam Line (Jan. 2025)



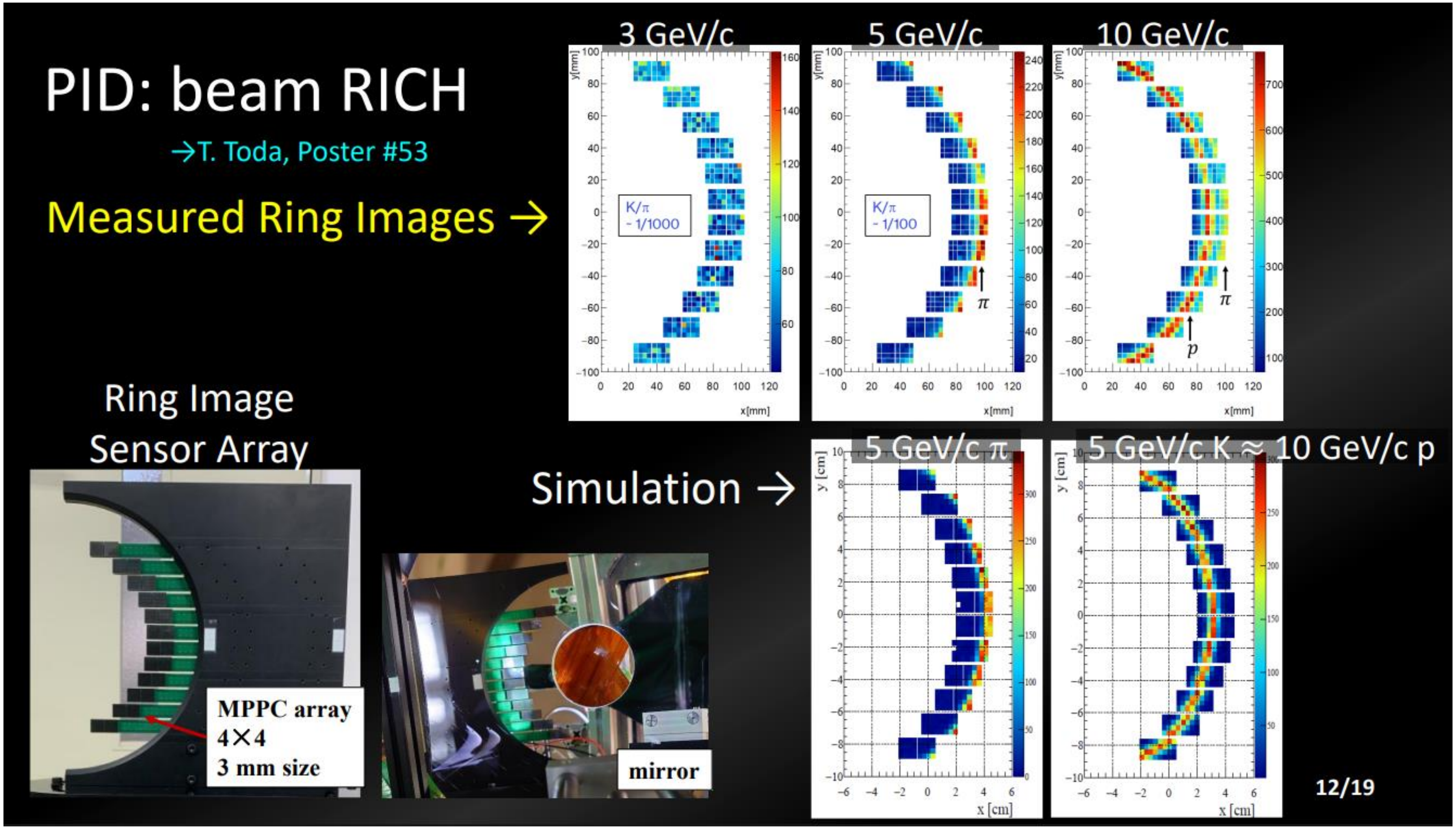
Hadron 2025, H. Noumi

T106: First Measurement of Secondary Beams at the J-PARC High-Momentum Beam Line (Jan. 2025)



[Hadron 2025, H. Noumi]

T106: First Measurement of Secondary Beams at the J-PARC High-Momentum Beam Line (Jan. 2025)



Hadron 2025, H. Noumi

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]

[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*

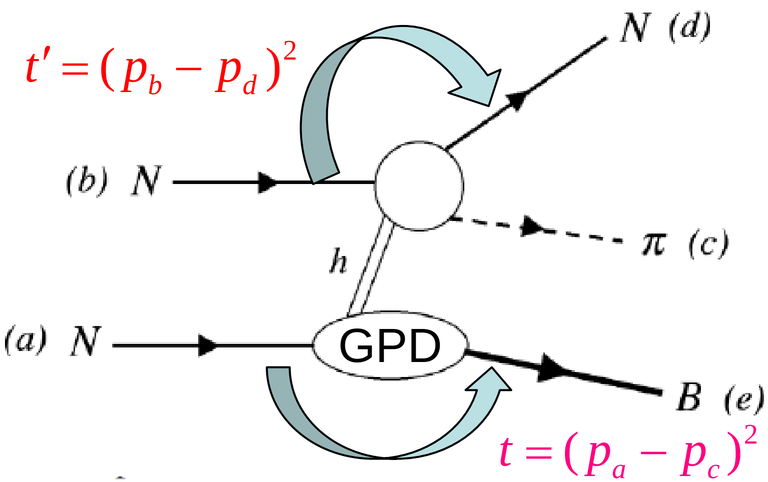
[4]*Nishogakusha University, 6-16, Sanbancho, Chiyoda, Tokyo, 102-8336, Japan*

(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

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

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



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

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

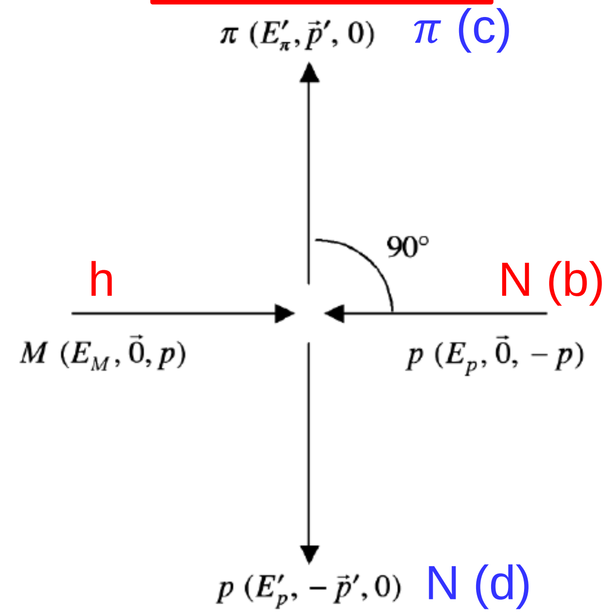
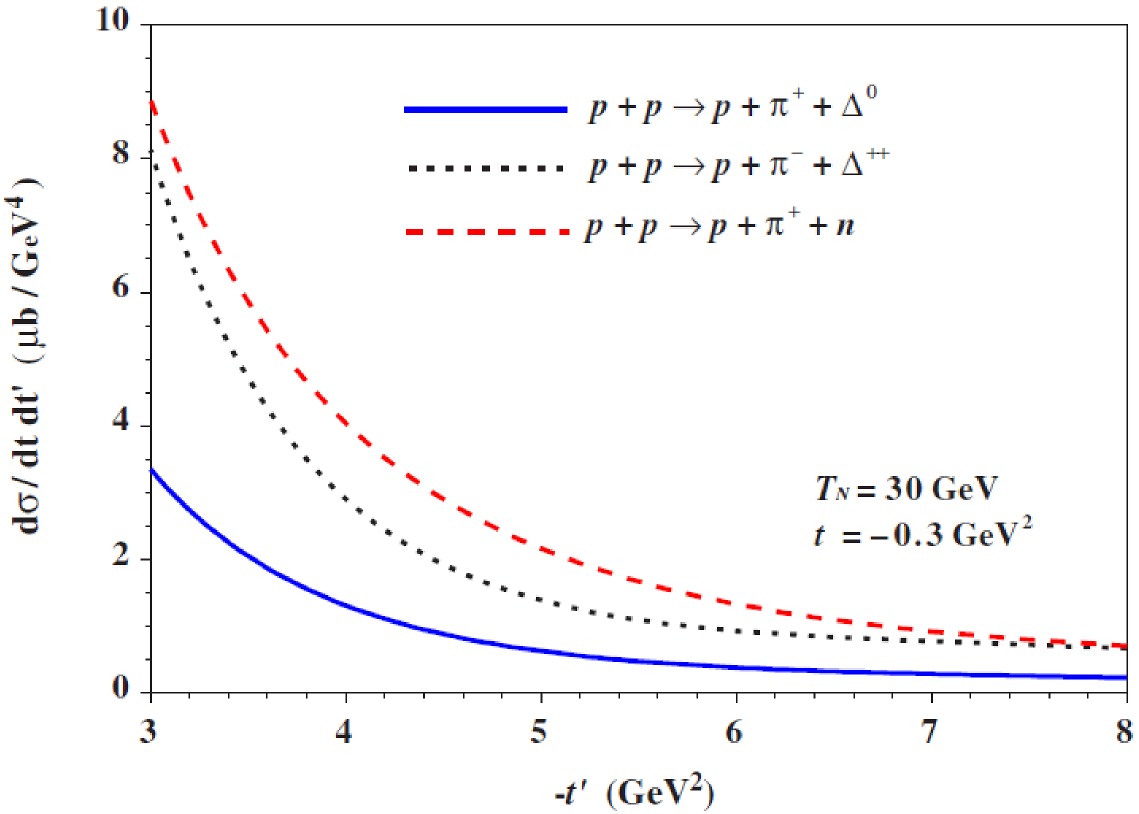


FIG. 8. $Mp \rightarrow \pi p$ elastic scattering at $\theta_{\rm c.m.} = 90°$.

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

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

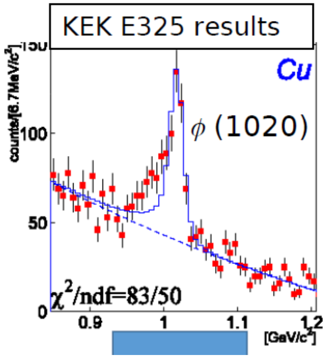
Kumano, Strikman, and Sudoh, PRD 80, 074003 (2009)



- 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]

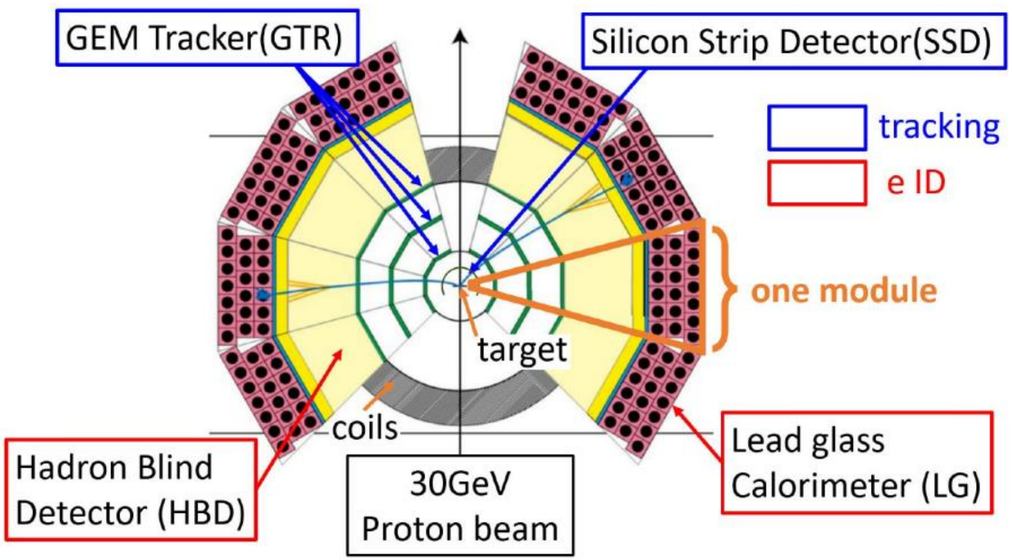
E16 Experiment at J-PARC

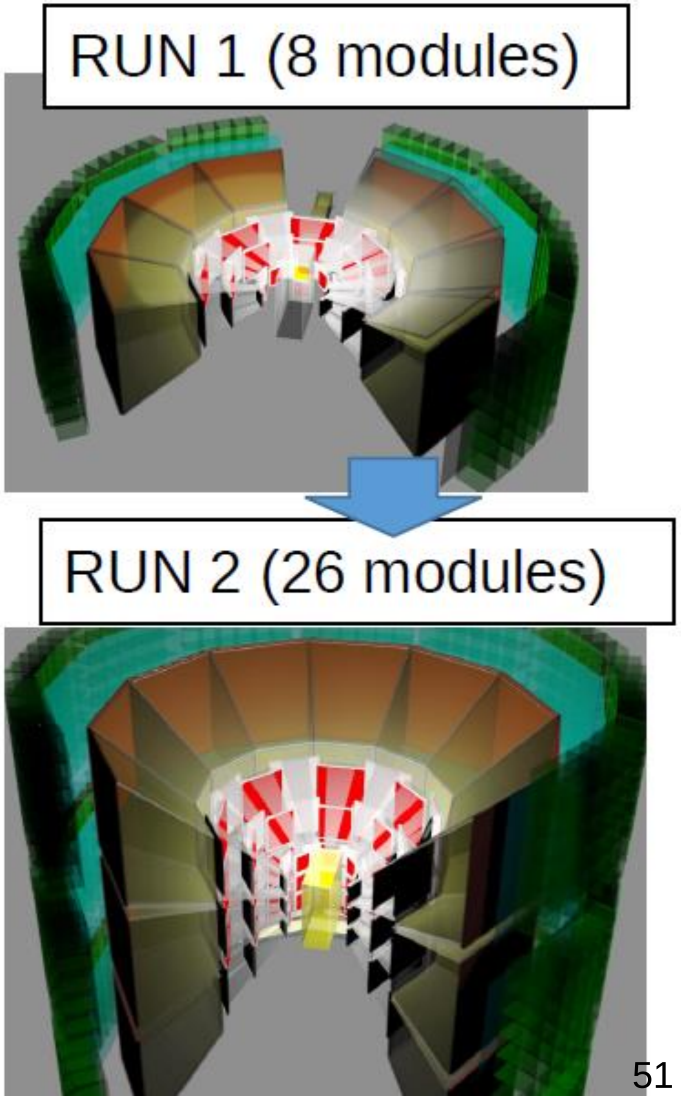
- E16 will measure the e+e- decay of ρ, ω, ϕ mesons produced in 30-GeV p+A (C, Cu, Pb, etc.) reactions.
- Modification of line shapes in nuclear matter as the evidence of chiral symmetry restoration.
- Commission runs (Run 0): 2020,2021,2023,2024.
- Run 1: Nov/2025



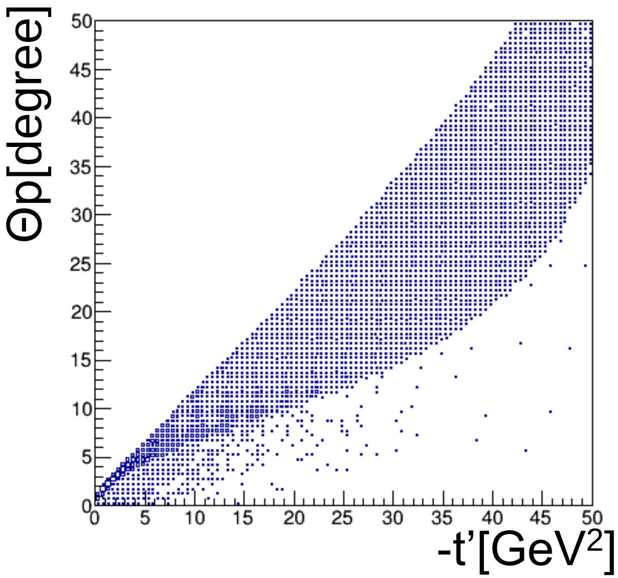
E16 Acceptance/PID Performance

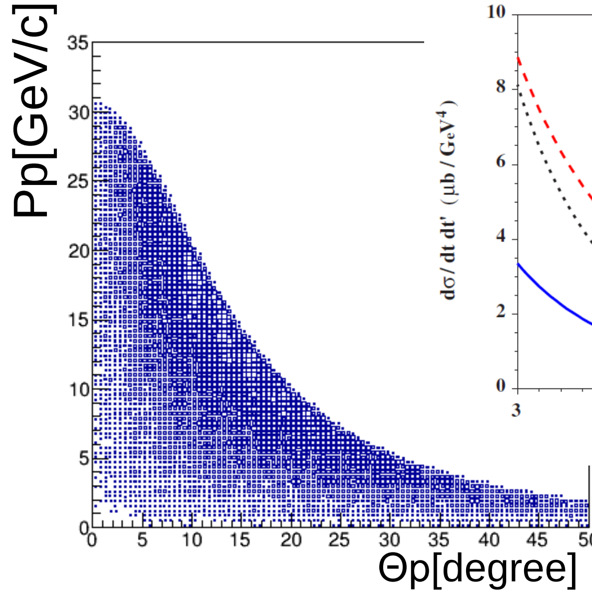
$\theta_{p,\pi} > 15\,\mathrm{deg}$

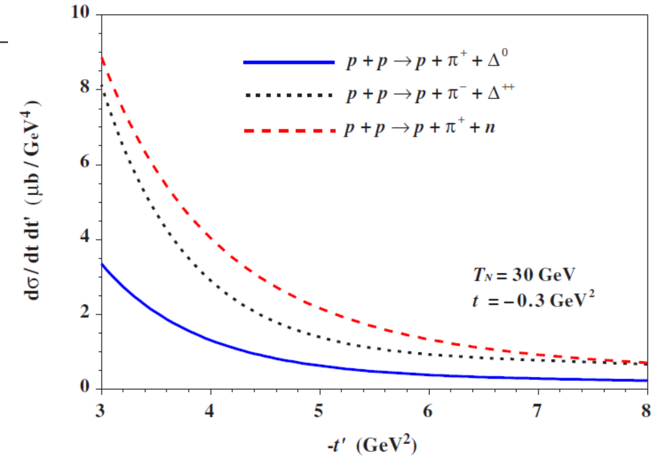




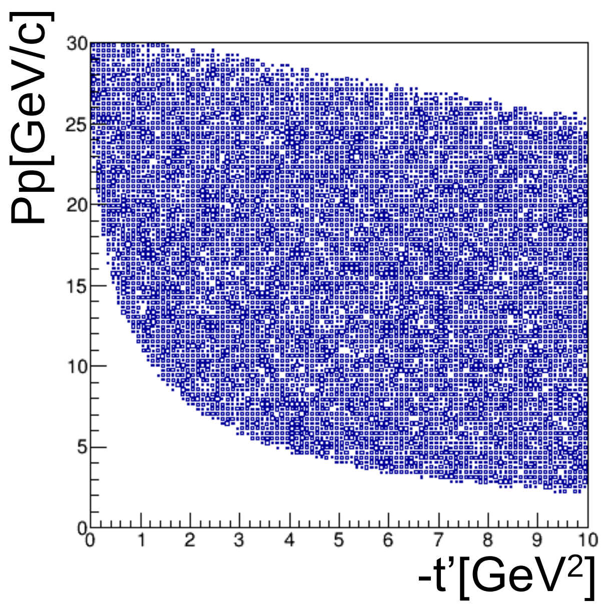
E16: p(30 GeV)p→pπ$^+$n

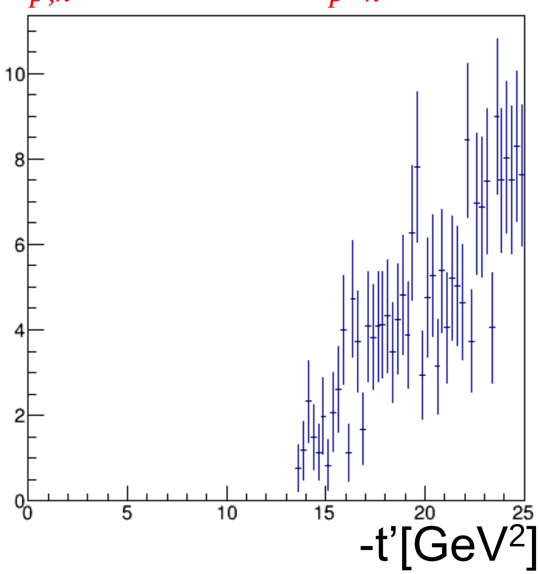






$\theta_{p,\pi} > 15$ deg, $\phi_{p-\pi} > 160$ deg





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

"Mini-MARQ": p(30 GeV)p→pπ$^+$n

Experimental conditions

		Primary (original plan)	Secondary (phase-1)
Beam	Intensity	10^{10} / spill (2 s)	10^6 / spill
	particle	30 GeV protons	10-20 GeV/c p/π unseparated
	measurement	×	**O (PID/ Intensity / Momentum)**
Detector geometry		**Avoid around beam (radiation control)**	**Can be installed in the beam axis**

"mini-MARQ spectrometer"

- FM magnet + Trackers (ready)

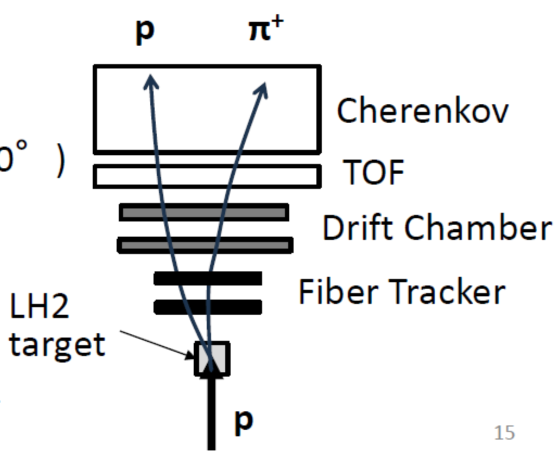
$p + p \rightarrow p + \pi^+ + n$

- Forward PID detectors (p, π^+ in $\Theta<10^\circ$)
- Missing Mass : $p+p \rightarrow p+\pi^+ + X$

$p + p \rightarrow p + \pi^+ + \Delta^0$

$p + p \rightarrow p + \pi^- + \Delta^{++}$

- Side PID detectors
- Invariant mass : $\Delta^0 \rightarrow p+\pi^-, \Delta^{++} \rightarrow p+\pi^+$



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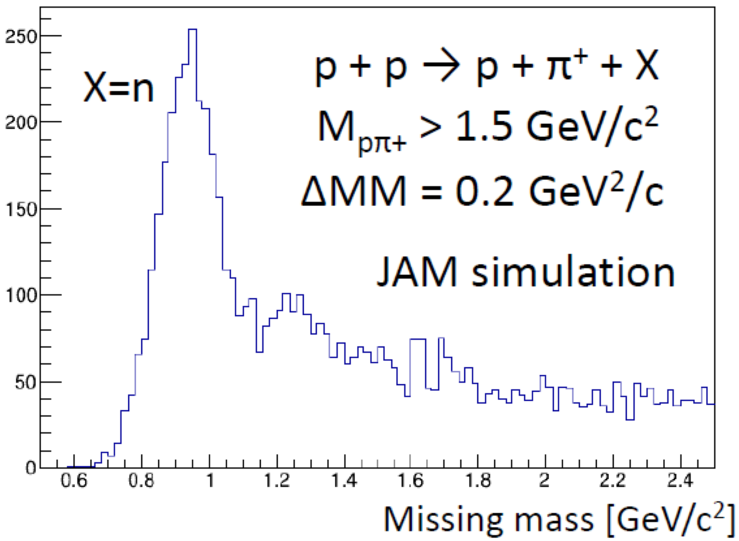
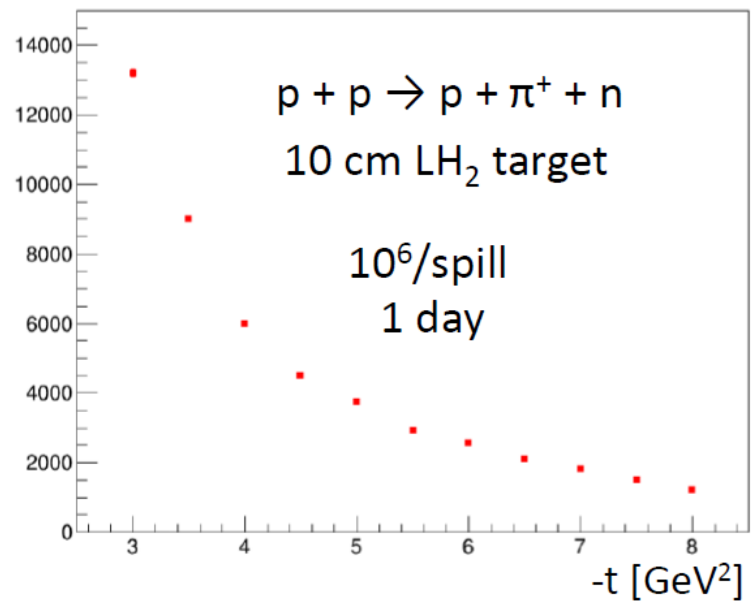
“Mini-MARQ”: $p(30\ \mathrm{GeV})p \rightarrow p\pi^+n$

Experimental expectation

Missing mass



Yield



Promising !

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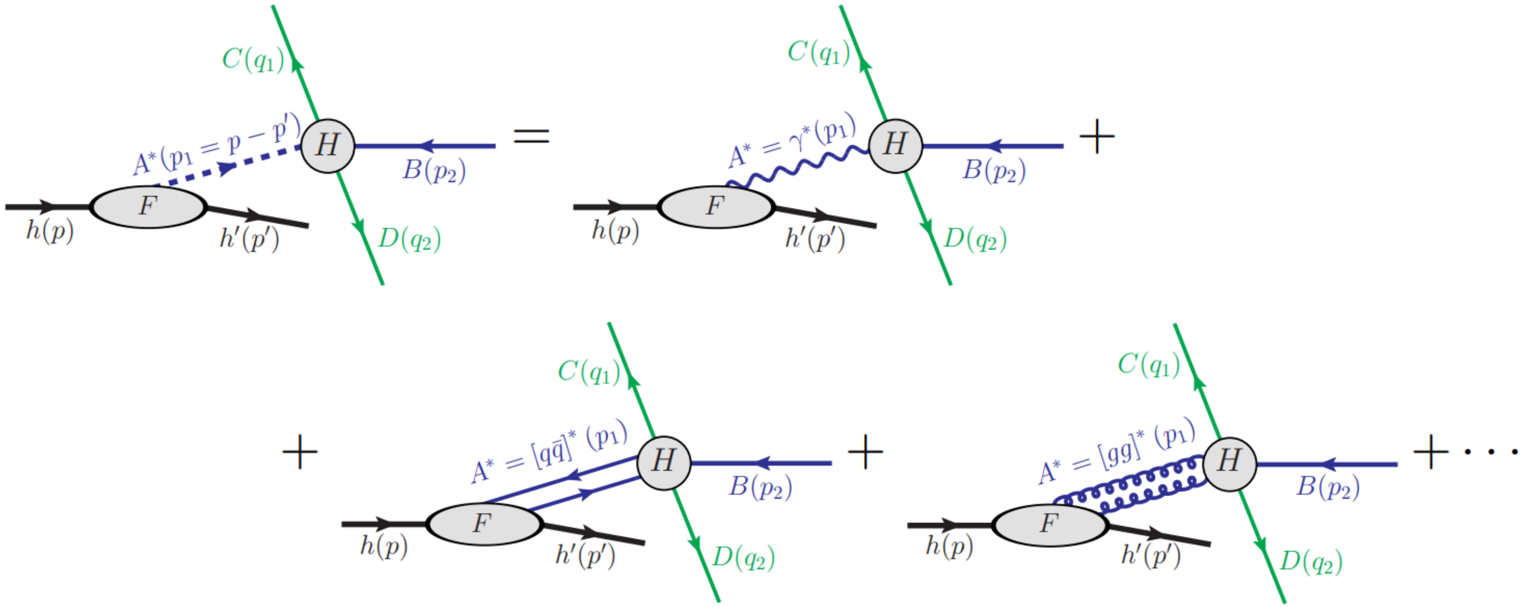
Single Diffractive Hard 2-to-3 Processes

$$B(p_2) + h(p) \to C(q_1) + D(q_2) + h'(p')$$



The x-dependence of GPDs can be extracted in these processes!

Jian-Wei Qiu and Zhite Yu

JHEP 08 (2022) 103; PRD 107 (2023) 014007; PRL 131 (2023) 161902

Single Diffractive Hard 2-to-3 Process

$$B(p_2) + h(p) \to C(q_1) + D(q_2) + h'(p')$$

B	h	C	D	Process
γ^*	N	γ		DVCS
γ^*	N	$\pi, \phi, J/\psi$		DVMP
γ^*	N	l^+	l^-	DDVCS
γ	N	l^+	l^-	TCS
γ	N	γ	$\pi, \phi, J/\psi$	
γ	N	γ	γ	
γ	N	$\pi, \phi, J/\psi$	$\pi, \phi, J/\psi$	
π	N	l^+	l^-	Exclusive Drell-Yan
π	N	γ	$\pi, \phi, J/\psi$	
π	N	γ	γ	
π	N	γ	$\pi, \phi, J/\psi$	
N	N	meson	Baryon	S. Kumano et al., PRD 80 (2009) 074003

Summary

- Drell-Yan process, complementary to DIS, SIDIS ,DVCS, and DVMP, is a time-like approach to explore PDFs, TMDs and GPDs.
- **TMDs**:
  - Unpolarized Drell-Yan: the $\cos 2\phi$ angular distribution can be used for extraction of BM.
  - Polarized Drell-Yan: COMPASS TSAs support the predicted sign change of Sivers as well as BM.
- **GPDs**:
  - Universality of GPDs could be checked with the exclusive Drell-Yan process and 2-3 hard process with the pion/proton beams at J-PARC.

Thank you and Prof. T.M. Yan