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Polarized Drell-Yan Program in COMPASS-II at CERN

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Outline:

- Transverse single-spin asymmetry & TMD PDF
- TMD PDF explored by SIDIS & Drell-Yan: Sivers and BM functions
- Polarized DY Experiment in COMPASS-II at CERN
- Summary

History of Transverse Single-Spin Effect

- 1966 Christ and Lee: transverse single-spin asymmetry (SSA), is prohibited by time-reversal invariance of EM and strong interaction in DIS.
- 1975 Large SSA in $p\uparrow p \rightarrow \pi X$
- 1976 Large transverse polarization of Λ in $pp \rightarrow \Lambda X$
- 1978 Kane, Pumplin and Repko: SSAs shall vanish in the massless quark limit.
- 1979 Ralston and Soper: constructed full transverse polarized structure functions and first introduced the "transversity" distributions to be explored by double polarized Drell-Yan process.

History of Transverse Single-Spin Effect

- 1990 Sivers: SSAs originating from the intrinsic transverse motion of quarks in a transversely polarized hadron.
- 1993 Collins: a spin asymmetry in the fragmentation of transversely polarized quarks, correlating with k_T, into an unpolarized hadron, which enables the measurement of SSAs in SIDIS. Sivers SSA should be prohibited due to time-invariance of QCD.
- 1998 Boer and Mulders: SSAs originating from the intrinsic transverse motion of transversely polarized quarks inside an unpolarized hadron.
- 2002 Collins: non-zeroness of Sivers and BM SSAs could be validated by the need of gauge links.

Transverse momentum dependent (TMD) PDF

three distribution functions are necessary to describe the quark structure of the nucleon at LO in the collinear case

taking into account the quark intrinsic transverse momentum k_T,

At leading order 8 PDFs are needed.

T-odd

Sivers function $f_{1T}^{\perp}(x, k_T)$

correlation between the transverse spin of the nucleon and the transverse momentum of the quark

sensitive to orbital angular momentum

Boer-Mulders function $h_1^{\perp}(x, k_T)$

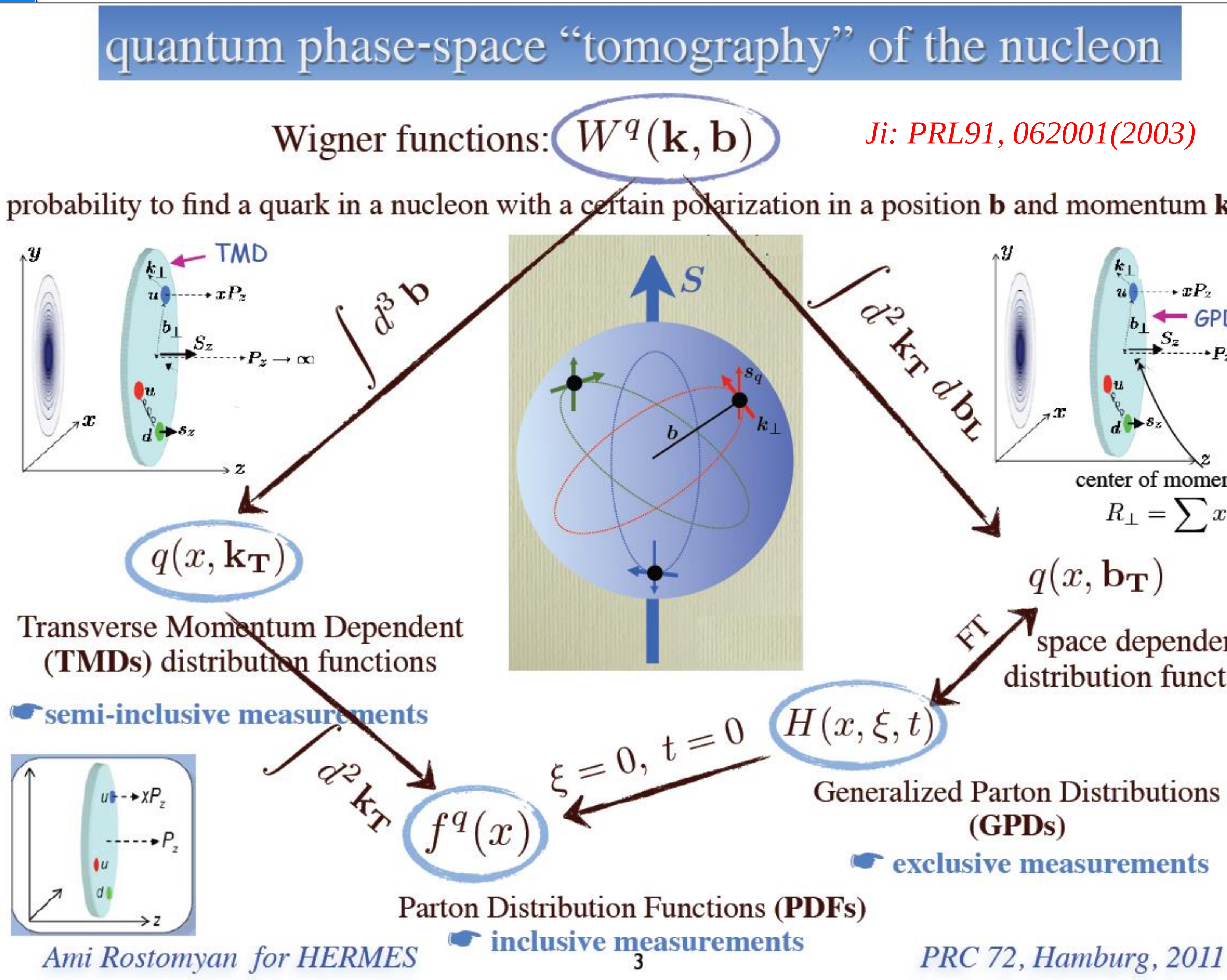
correlation between the transverse spin and the transverse momentum of the quark in unpol nucleons

"TMDs"

nucleon polarization

quark polarization	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ - *Sivers*	$\Delta_0^T q$
L		g_1 - *helicity* Δq	g_{1T} -	
T	$h_1^{\perp}$ - *Boer-Mulders*	$h_{1L}^{\perp}$ -	h_1 - *transversity* $h_{1T}^{\perp}$ - *pretzelosity*	$\Delta_T q$

COMPASS


quantum phase-space "tomography" of the nucleon
Wigner functions: $W^q(\mathbf{k}, \mathbf{b})$
Ji: PRL91, 062001(2003)
probability to find a quark in a nucleon with a certain polarization in a position **b** and momentum **k**
TMD
GPD
$\int d^3\mathbf{b}$
$\int d^2\mathbf{k_T}\, d\mathbf{b_L}$
center of momentum
$R_\perp = \sum x_i r_{\perp_i}$
$q(x, \mathbf{k_T})$
$q(x, \mathbf{b_T})$
Transverse Momentum Dependent (TMDs) distribution functions
semi-inclusive measurements
FT
space dependent distribution functions
$H(x, \xi, t)$
$\xi = 0,\ t = 0$
$\int d^2\mathbf{k_T}$
$f^q(x)$
Generalized Parton Distributions (GPDs)
exclusive measurements
Parton Distribution Functions (PDFs)
inclusive measurements
Ami Rostomyan for HERMES
3
PRC 72, Hamburg, 2011

Constraining OAM by Sivers Functions

A. Bacchetta and M. Radici, Phys. Rev. Lett. 107, 212001 (2011)

$$J^a(Q^2) = \frac{1}{2}\int_0^1 dx\, x[H^a(x,0,0;Q^2) + E^a(x,0,0;Q^2)]. \quad (1)$$

Inspired by results of spectator models [6–10] and theoretical considerations [1], we propose the following simple relation at a specific scale Q_L,

lensing effect

$$f_{1T}^{\perp(0)a}(x;Q_L^2) = -L(x)E^a(x,0,0;Q_L^2), \quad (3)$$

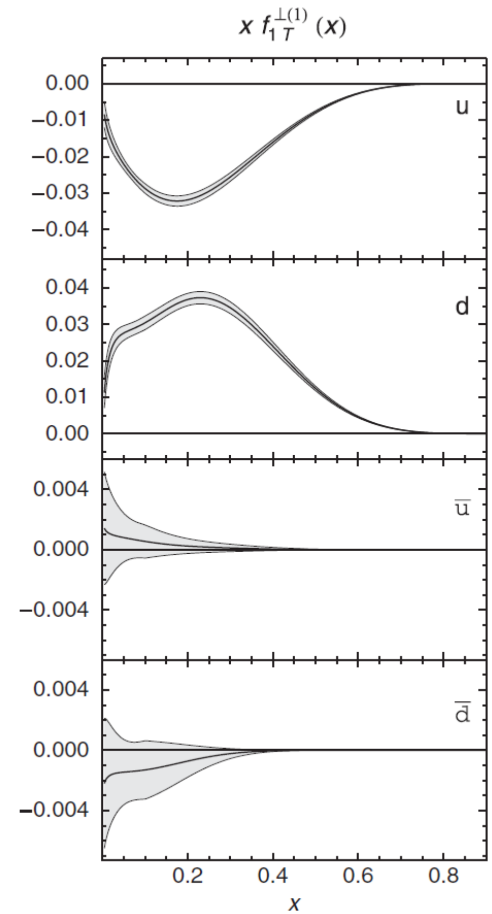
where we define the nth moment of a TMD with respect to its transverse momentum $k_\perp$ as

$$f_{1T}^{\perp(n)a}(x;Q^2) = \int d^2k_\perp \left(\frac{k_\perp^2}{2M^2}\right)^n f_{1T}^{\perp a}(x,k_\perp^2;Q^2), \quad (4)$$

and M is the nucleon mass.

$$f_1^a(x,k_\perp^2;Q_0^2) = \frac{f_1^a(x;Q_0^2)}{\pi\langle k_\perp^2\rangle} e^{-k_\perp^2/\langle k_\perp^2\rangle},$$

$$D_1^a(z,P_\perp^2;Q_0^2) = \frac{D_1^a(z;Q_0^2)}{\pi\langle P_\perp^2\rangle} e^{-P_\perp^2/\langle P_\perp^2\rangle},$$



Constraining OAM by Sivers Functions

A. Bacchetta and M. Radici, Phys. Rev. Lett. 107, 212001 (2011)

equations for the angular momentum (at leading order, with 3 flavors only, and $\Lambda_{QCD} = 257$ MeV), we obtain the following results at $Q^2 = 4$ GeV^2:

$$J^u = 0.229 \pm 0.002^{+0.008}_{-0.012},$$

$$J^{\bar{u}} = 0.015 \pm 0.003^{+0.001}_{-0.000},$$

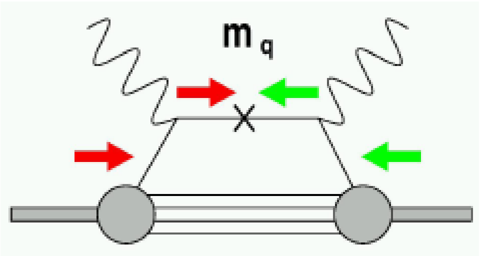
$$J^d = -0.007 \pm 0.003^{+0.020}_{-0.005},$$

$$J^{\bar{d}} = 0.022 \pm 0.005^{+0.001}_{-0.000},$$

$$J^s = 0.006^{+0.002}_{-0.006},$$

$$J^{\bar{s}} = 0.006^{+0.000}_{-0.005}.$$

How to measure SSAs?



Chiral-odd → not accessible in DIS

Require another chiral-odd object

- **Semi-Inclusive DIS**: ambiguity associated with fragmentation process
  - Single-hadron (Collins fragmentation function, $H_1^{\perp}(z)$)
  - Two hadrons (Interference fragmentation function)
  - Vector meson polarization
  - Λ – polarization
- **Drell-Yan**: small cross sections but free from fragmentation
- **Proton-proton collision:** inclusive single-hadron, prompt jet, prompt photon production

High energy spin experiments

C.A. Aidala, S.D. Bass, D. Hasch, G.K. Mallot, Rev. Mod. Phys. 85, 655–691 (2013)

Experiment	Year	Beam	Target	Energy (GeV)	Q^2 (GeV^2)	x
Completed experiments						
SLAC – E80, E130	1976–1983	e^-	H-butanol	$\lesssim$23	1–10	0.1–0.6
SLAC – E142/3	1992–1993	e^-	NH_3, ND_3	$\lesssim$ 30	1–10	0.03–0.8
SLAC – E154/5	1995–1999	e^-	NH_3, ^{6}LiD, ^{3}He	$\lesssim$ 50	1–35	0.01–0.8
CERN – EMC	1985	μ^+	NH_3	100, 190	1–30	0.01–0.5
CERN – SMC	1992–1996	μ^+	H/D-butanol, NH_3	100, 190	1–60	0.004–0.5
FNAL E581/E704	1988–1997	p	p	200	~ 1	$0.1 < x_F < 0.8$
Analyzing and/or Running						
DESY – HERMES	1995–2007	e^+, e^-	H, D, ^{3}He	~ 30	1–15	0.02–0.7
CERN – COMPASS	2002–2012	μ^+	NH_3, ^{6}LiD	160, 200	1–70	0.003–0.6
JLab6 – Hall A	1999–2012	e^-	^{3}He	$\lesssim$ 6	1–2.5	0.1–0.6
JLab6 – Hall B	1999–2012	e^-	NH_3, ND_3	$\lesssim$ 6	1.-5	0.05–0.6
RHIC – BRAHMS	2002–2006	p	p (beam)	2× (31–100)	$\sim$ 1–6	$-0.6 < x_F < 0.6$
RHIC – PHENIX, STAR	2002+	p	p (beam)	2× (31–250)	$\sim$ 1–400	$\sim$ 0.02–0.4
Approved future experiments (in preparation)						
CERN – COMPASS–II	2014+	μ^+, μ^-	unpolarized H_2	160	$\sim$ 1–15	$\sim$ 0.005–0.2
		π^-	NH_3	190		$-0.2 < x_F < 0.8$
JLab12 – HallA/B/C	2014+	e^-	HD, NH_3, ND_3, ^{3}He	$\lesssim$12	$\sim$ 1–10	$\sim$ 0.05–0.8

SIDIS x-section

A.Kotzinian, Nucl. Phys. B441, 234 (1995). Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

$$\left\{\begin{array}{l}
1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\varphi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+\lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}+\\
S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h A_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)A_{UL}^{\sin(2\phi_h)}\right]+\\
S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h A_{LL}^{\cos\phi_h}\right]+\\
S_T\left[\begin{array}{l}
\sin\varphi_S\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+\\
\sin(\varphi_h-\varphi_S)\times\left(A_{UT}^{\sin(\varphi_h-\varphi_S)}\right)+\\
\sin(\varphi_h+\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}\right)+\\
\sin(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}\right)+\\
\sin(3\varphi_h-\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)
\end{array}\right]+\\
S_T\lambda\left[\begin{array}{l}
\cos\varphi_S\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}\right)+\\
\cos(\varphi_h-\varphi_S)\times\left(\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\varphi_h-\varphi_S)}\right)+\\
\cos(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)
\end{array}\right]
\end{array}\right\}$$

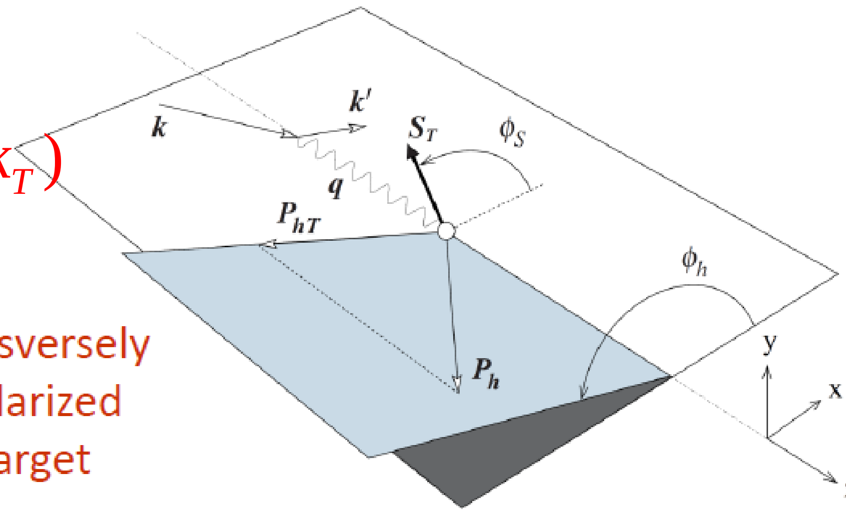
$$A_{U(L),T}^{w(\varphi_h,\varphi_s)} = \frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}, \quad \gamma = \frac{2Mx}{Q}$$

Boer-Mulders $h_1^{\perp}(x,k_T)$

Sivers $f_{1T}^{\perp}(x,k_T)$

transversely polarized target



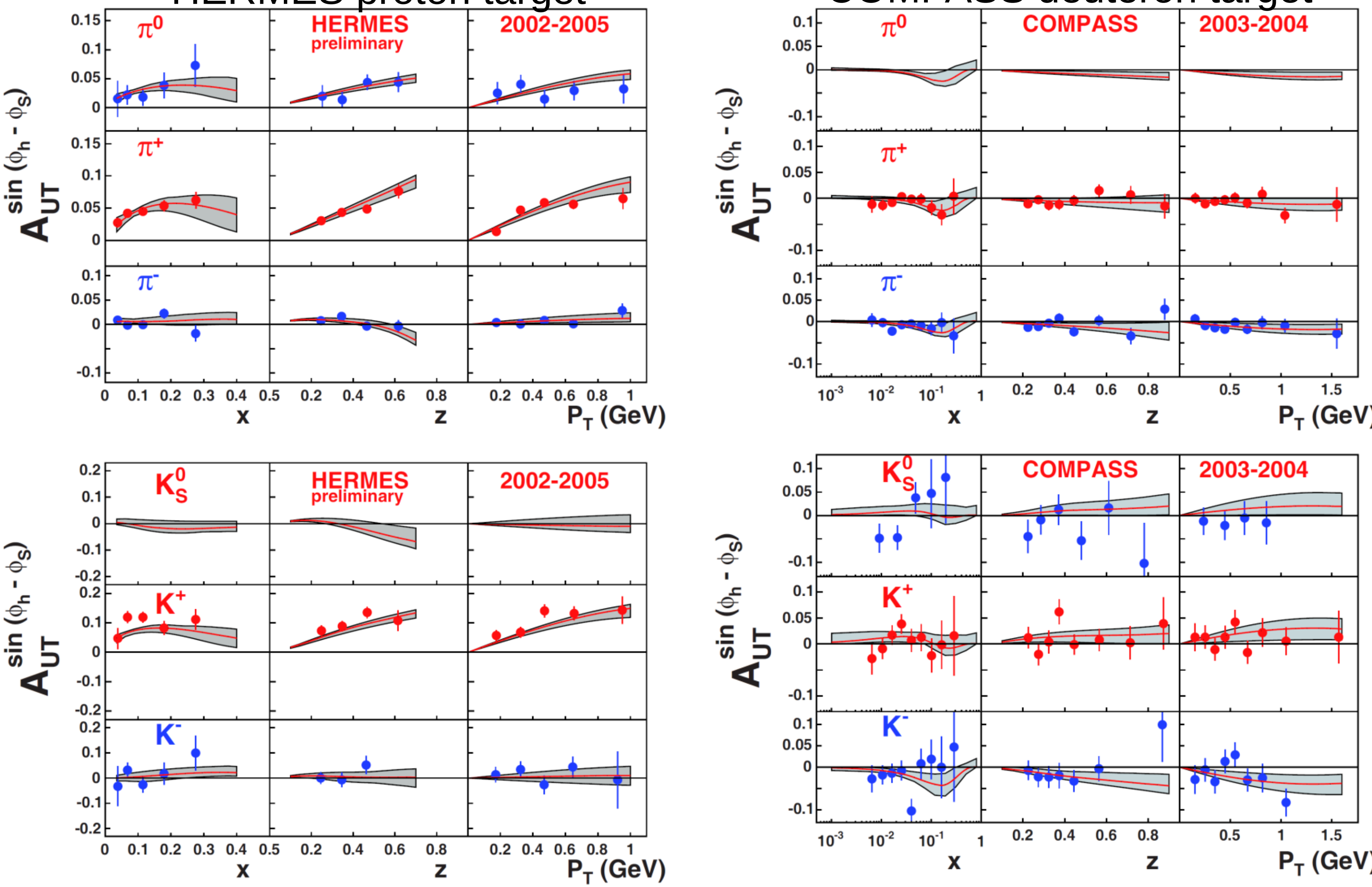
BAKUR PARSAMYAN, DIS2013

Global Analysis of SIDIS from HERMES and COMPASS

M. Anselmino et al., Eur.Phys.J.A39:89-100,2009

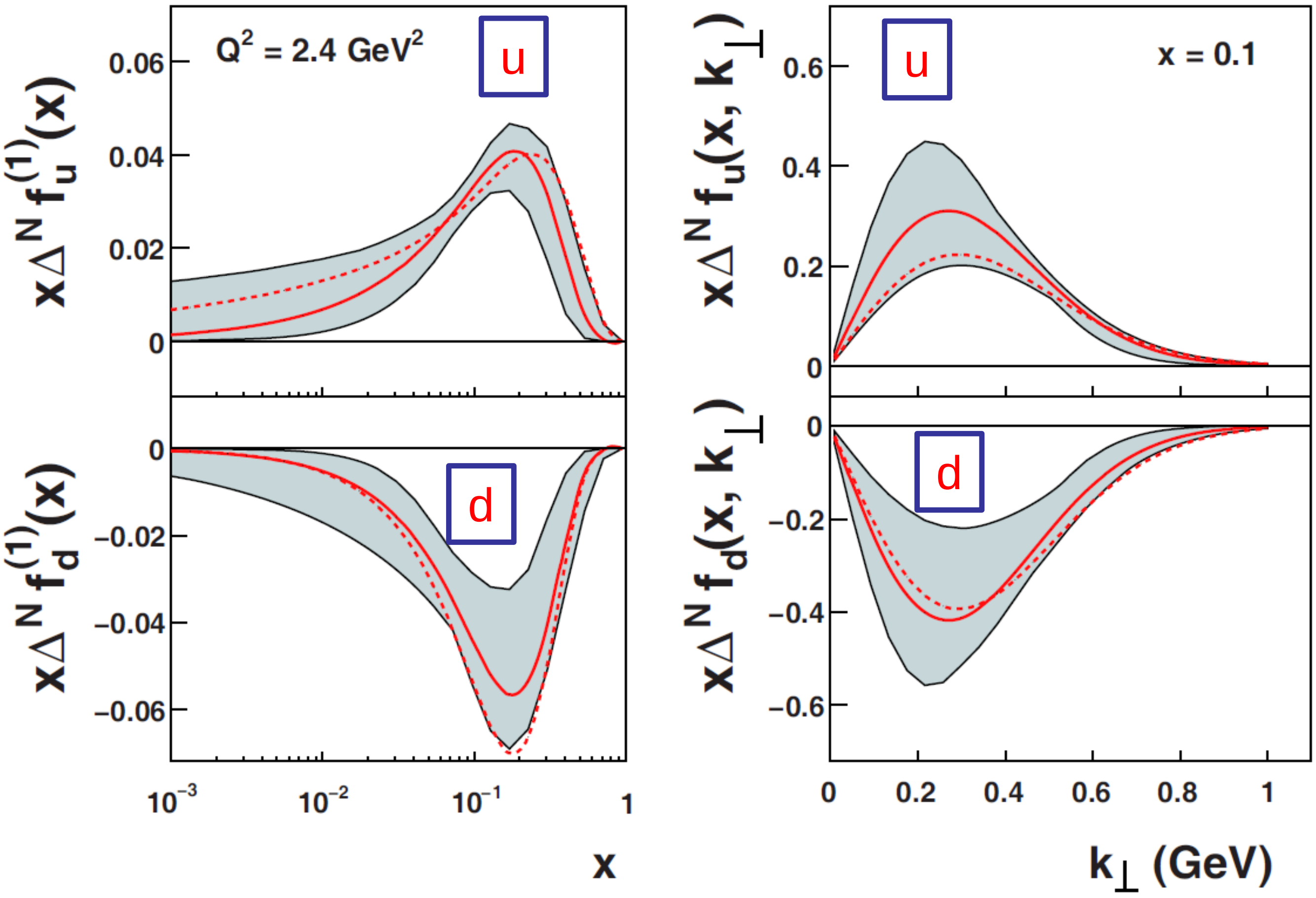
HERMES proton target

COMPASS deuteron target



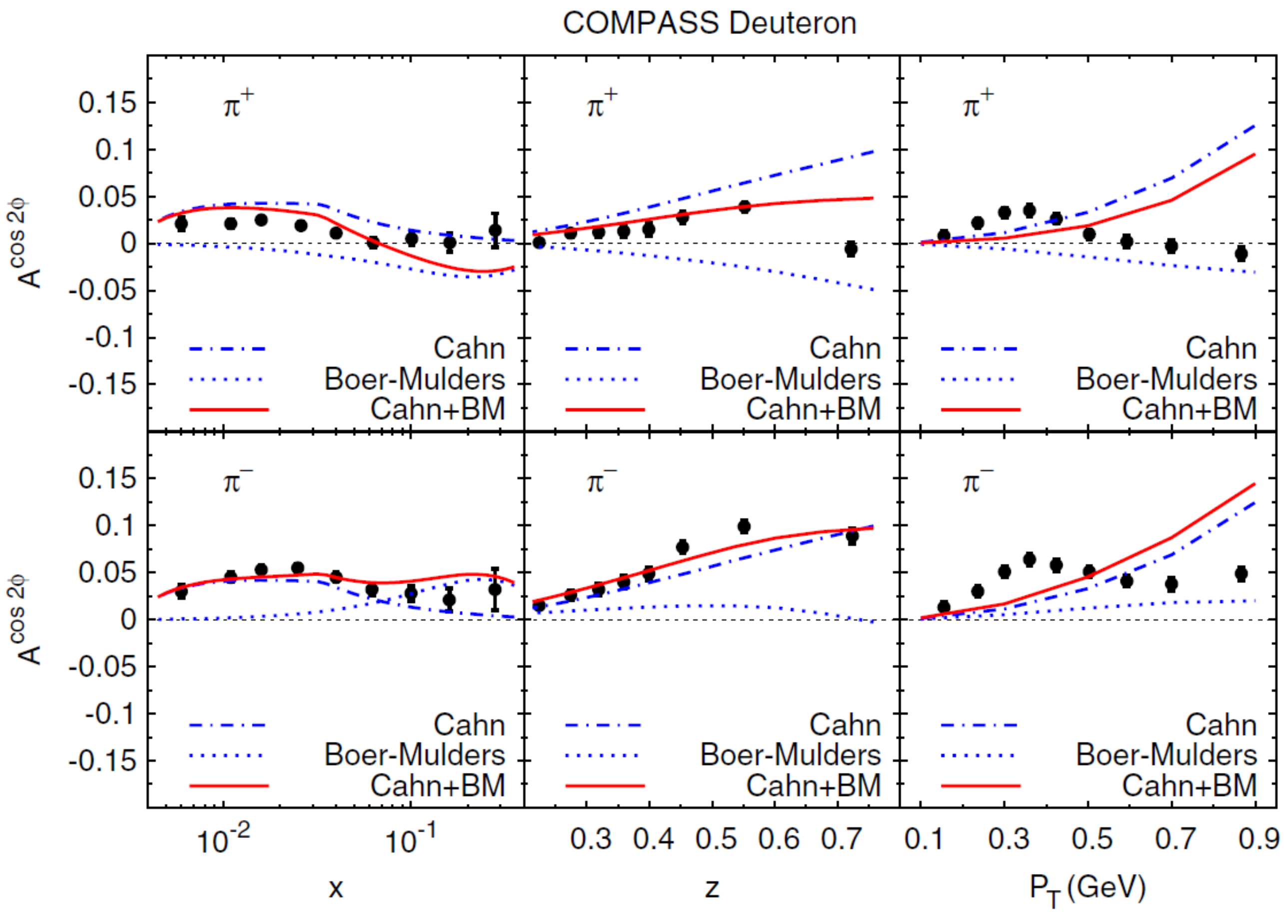
Sivers Functions from SIDIS

M. Anselmino et al., Eur.Phys.J.A39:89-100, 2009



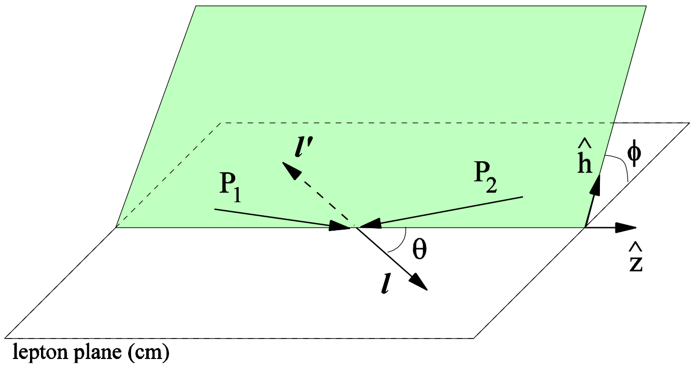
Boer-Mulders Functions from SIDIS

V. Barone et al., PRD 81, 114026 (2010)



The contributions of twist-2 BM functions and twist-4 Cahn term are comparable and hard to be disentangled.

Drell-Yan 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)

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

NA10 @ CERN: Violation of LT Relation

Z. Phys. 37 (1988) 545

Lam-Tung relation: $1-\lambda-2\nu=0$

π^{-}+W

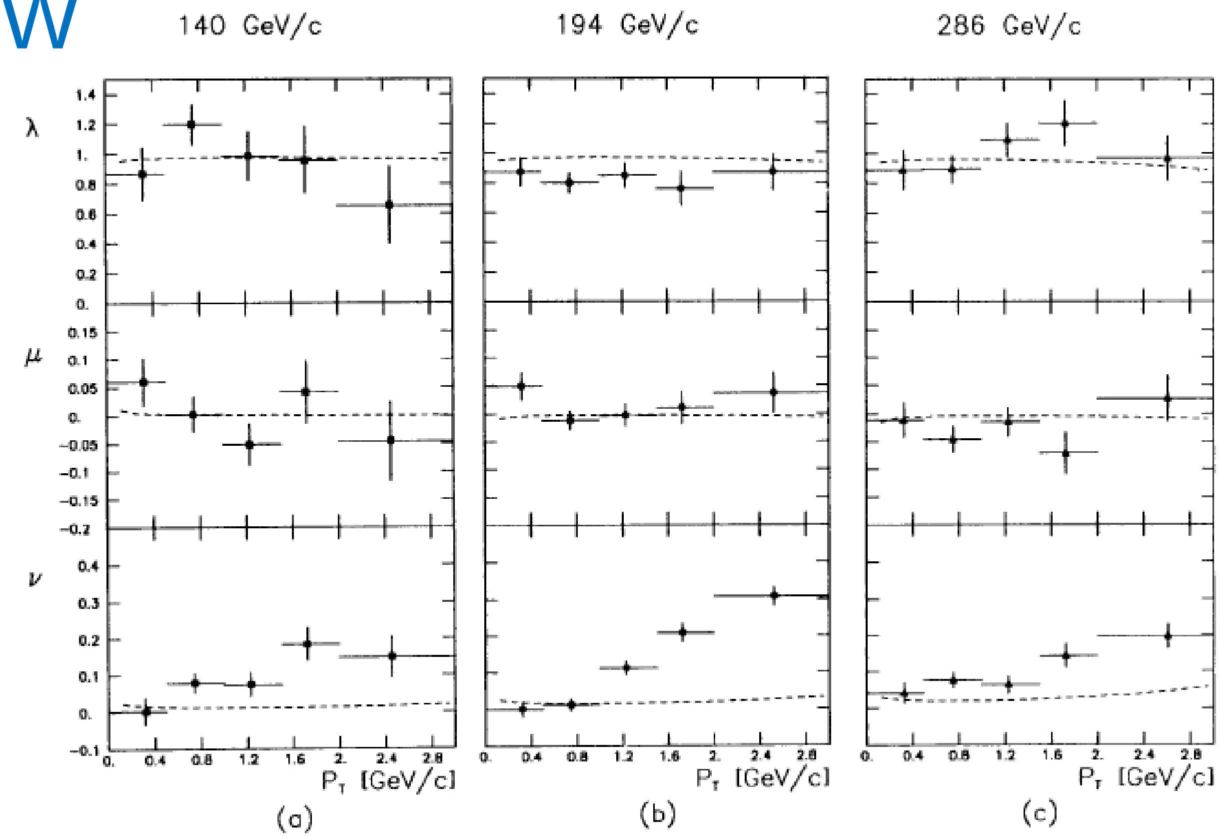


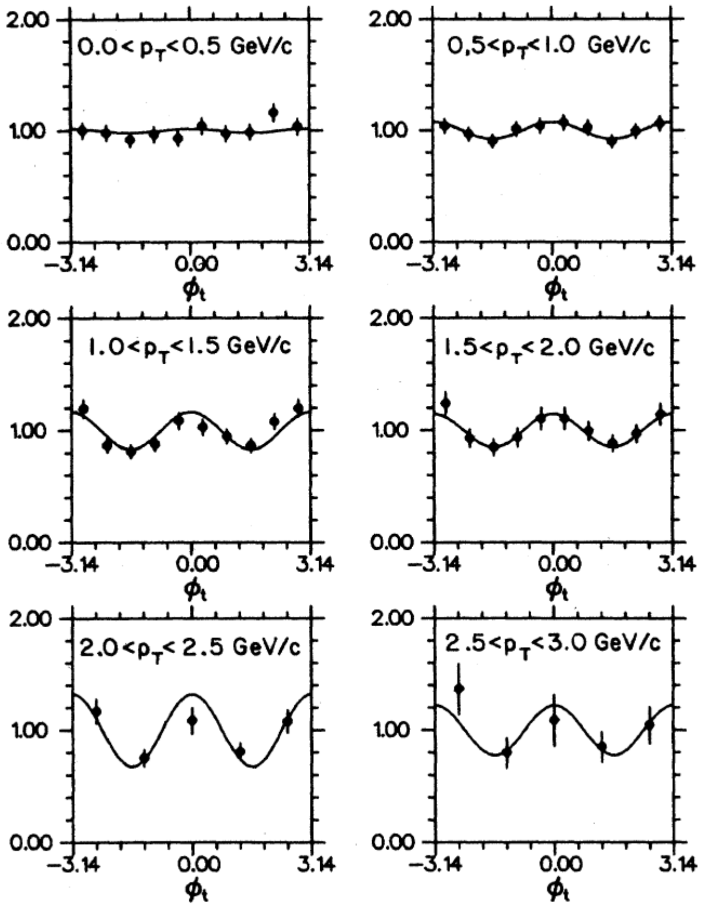
Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. **a** 140 GeV/c; **b** 194 GeV/c; **c** 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

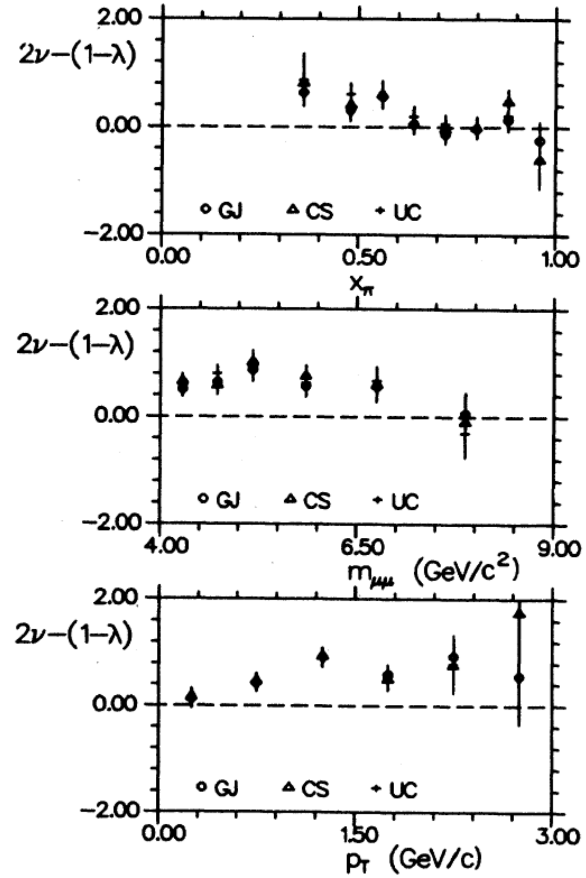
$\nu \neq 0$ and ν increases with p_T

E615 @ FNAL: Violation of LT Relation

PRD 39, 92 (1989)

252-GeV π^{-}+W

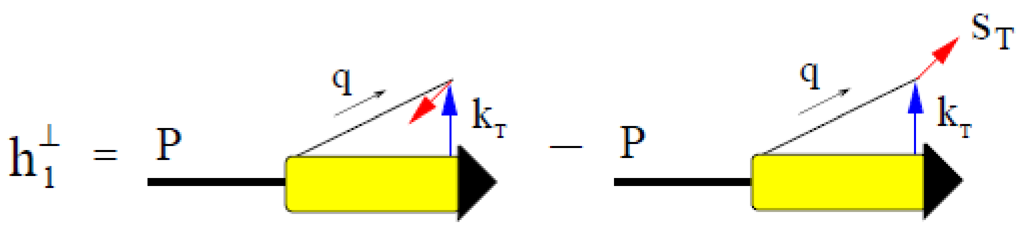




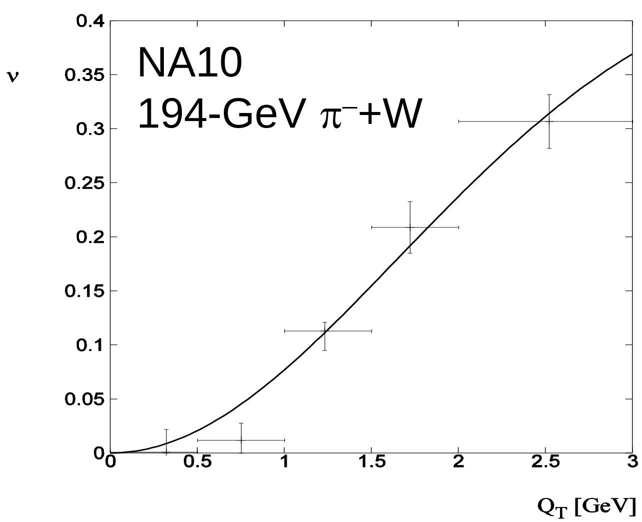
Lam-Tung relation: $1-\lambda-2\nu=0$

Hadronic Effect, Boer-Mulders Functions

D. Boer, PRD 60, 014012 (1999)



- Boer-Mulders Function $h_1^{\perp}$: a correlation between quark's k_T and transverse spin in an unpolarized hadron
- $h_1^{\perp}$ can lead to an azimuthal dependence with $\frac{\nu}{2} \propto h_1^{\perp}(N)\bar{h}_1^{\perp}(\pi)$



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

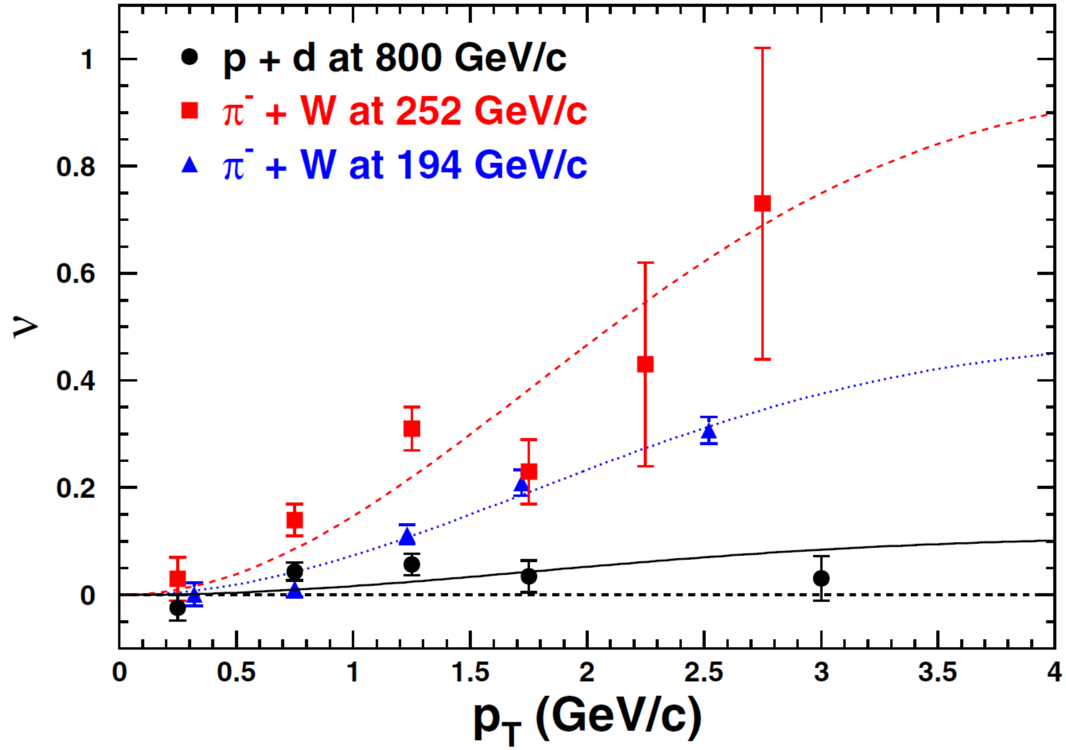
$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}, \qquad \kappa_1 = C_{H_1} C_{H_2}/2$$

$$\kappa = \frac{\nu}{2} \to 0 \text{ for large } |k_T|$$

Consistency of factorization in term of TMDs

Azimuthal cos2ϕ Distribution of DY events in p+d

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 $h_1^{\perp}(p)$]

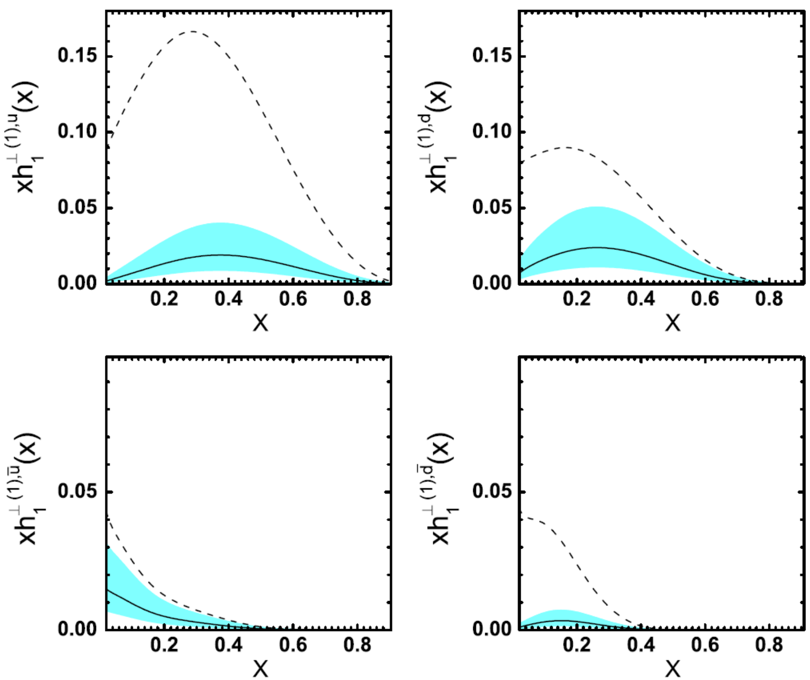
Sea-quark BM functions are much smaller than valence quarks

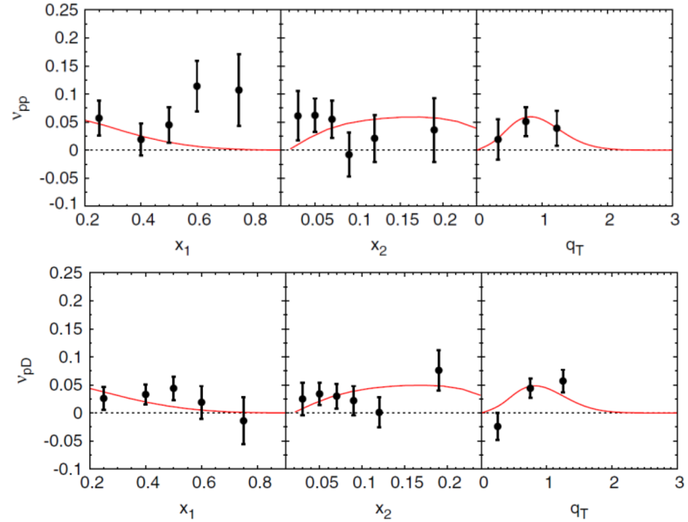
Boer-Mulders functions from unpolarized pd and pp Drell-Yan data

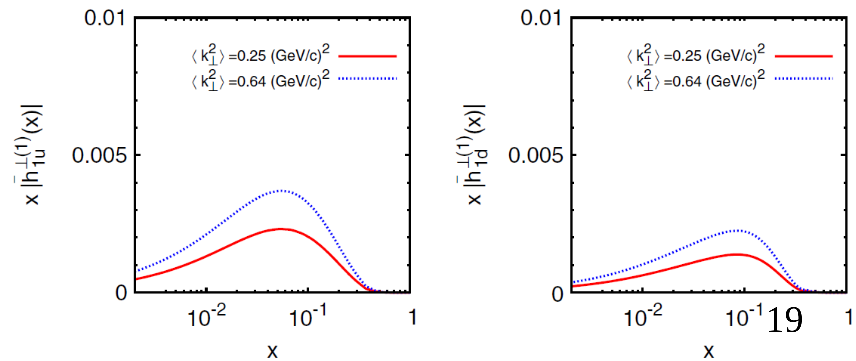
Zhun Lu and I. Schmidt,
PRD 81, 034023 (2010)

V. Barone et al.,
PRD 82, 114025 (2010)

$$h_1^{\perp q}(x, \boldsymbol{p}_T^2) = h_1^{\perp q}(x)\frac{1}{\pi p_{bm}^2}\exp\left(-\frac{\boldsymbol{p}_T^2}{p_{bm}^2}\right).$$

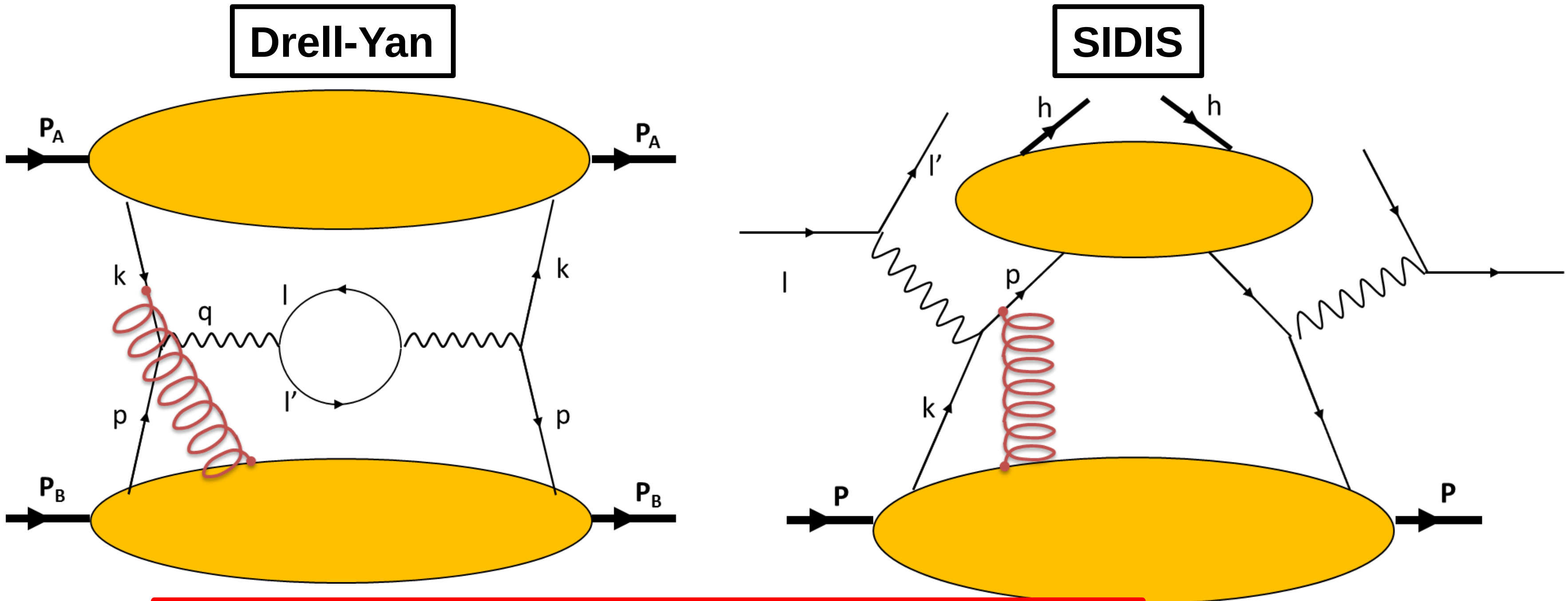






Sign Change of Sivers & Boer-Mulders Functions

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

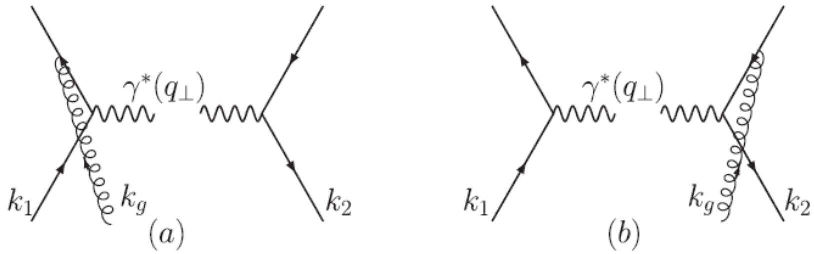


$$\text{Sivers, BM}\,|_{DY} = -\text{Sivers, BM}\,|_{SIDIS}$$

- QCD gluon gauge link (Wilson line) in the initial state (DY) vs. final state interactions (SIDIS).
- ***Experimental confirmation of the sign change will be a crucial test of perturbative QCD and TMD physics.***

“Opposite Sign of SSA for SIDIS and DY” Preserved in NLO QCD

Z-B Kang, B-W Xiao and F. Yuan, PRL 107, 152002 (2011)



- Ji-Ma-Yuan factorization
- Collins-Soper-Sterman resummation

$$\frac{d\Delta\sigma(S_\perp)}{dv\,dQ^2\,d^2q_\perp} = \sigma_0 \epsilon^{\alpha\beta} S_\perp^\alpha W_{UT}^\beta(Q;q_\perp), \qquad (2)$$

b).

$$W_{UT}^\alpha(Q;q_\perp) = \int \frac{d^2b}{(2\pi)^2} e^{i\vec{q}_\perp\cdot\vec{b}} \tilde{W}_{UT}^\alpha(Q;b) + Y_{UT}^\alpha(Q;q_\perp),$$

$q_\perp \ll Q$

$$\tilde{W}_{UT}^\alpha(Q;b) = e^{-\mathcal{S}_{UT}(Q^2,b)} \tilde{W}_{UT}^\alpha(C_1/b, b)$$

$$= (-ib_\perp^\alpha/2) e^{-\mathcal{S}_{UT}(Q^2,b)} \Sigma_{i,j}$$

$$\times \Delta C_{qi}^T \otimes f_{i/A}^{(3)}(z_1', z_1'') C_{\bar{q}j} \otimes f_{j/B}(z_2'), \qquad (9)$$

$$\Delta C_q^T\Big|_{DY} = -\Delta C_q^T\Big|_{SIDIS}$$

Single transversely-polarized DY cross-section in LO QCD Parton Model

S. Arnold, et al., Phys. Rev. D79 (2009) 034005

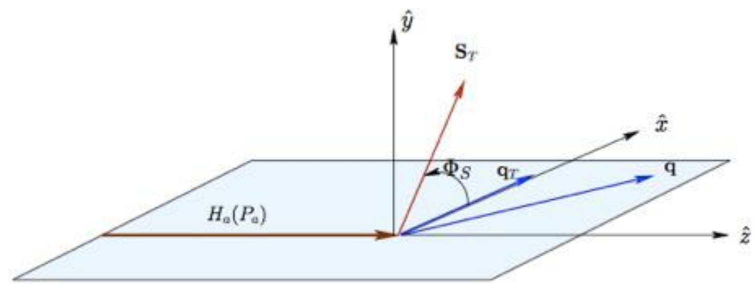
$$\frac{d\sigma^{LO}}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U^{LO}\left\{\left(1 + D_{[\sin^2\theta]}^{LO} A_U^{\cos 2\varphi}\cos 2\varphi\right) + \left|\vec{S}_T\right|\left[A_T^{\sin\varphi_s}\sin\varphi_s\right.\right.$$

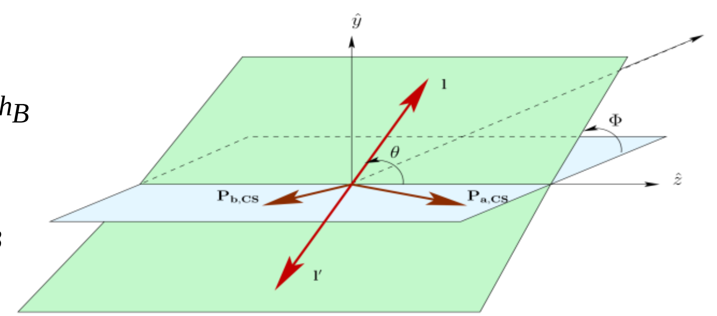
$$A_U^{\cos 2\varphi} \propto \mathrm{BM}(h_1^\perp)\big|_{h_A} \otimes \mathrm{BM}(h_1^\perp)\big|_{h_B}$$

$$A_T^{\sin\varphi_s} \propto \mathrm{Density}(f_1)\big|_{h_A} \otimes \mathrm{Sivers}(f_{1T}^\perp)\big|_{h_B}$$

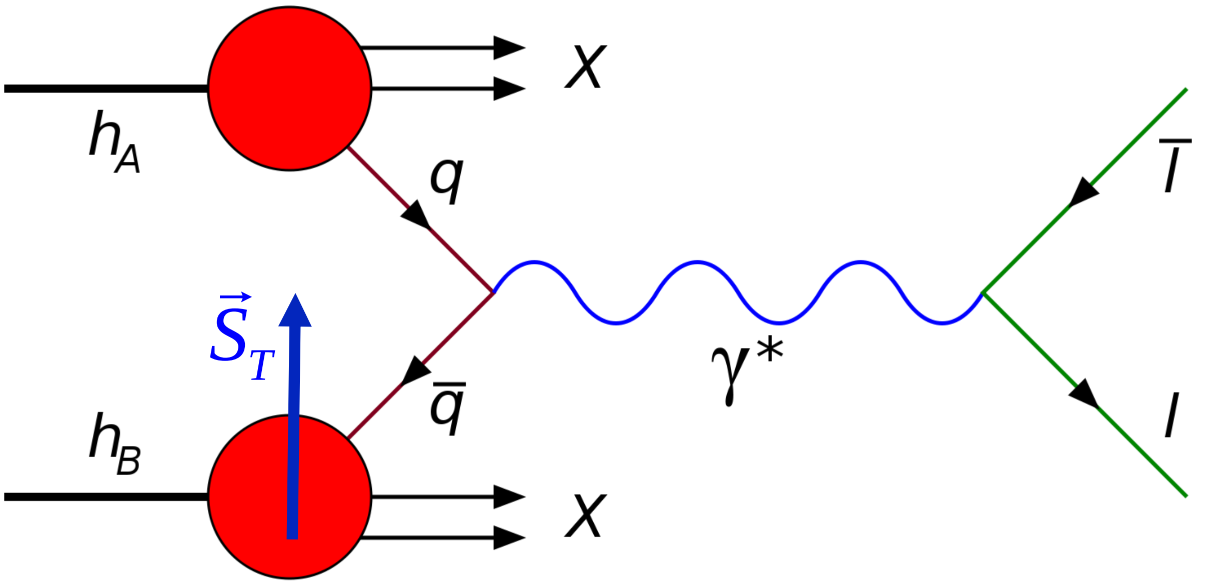
$$A_T^{\sin(2\varphi+\varphi_s)} \propto \mathrm{BM}(h_1^\perp)\big|_{h_A} \otimes \mathrm{pretzelosity}(h_{1T}^\perp)\big|_{h_B}$$

$$A_T^{\sin(2\varphi-\varphi_s)} \propto \mathrm{BM}(h_1^\perp)\big|_{h_A} \otimes \mathrm{transversity}(h_1)\big|_{h_B}$$





We need transversely-polarized Drell-Yan experiments !!!

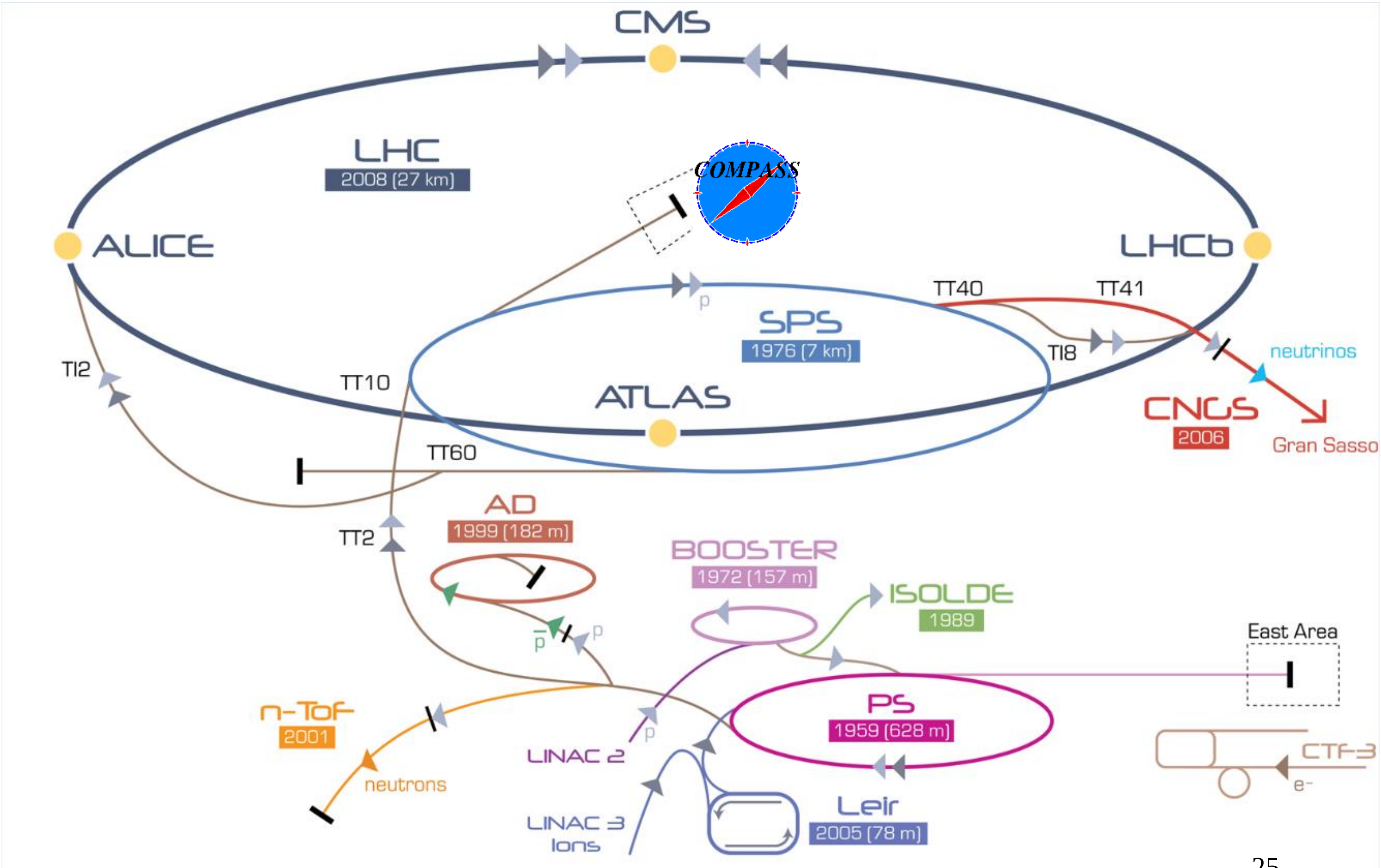


Planned Polarized Drell-Yan Experiments

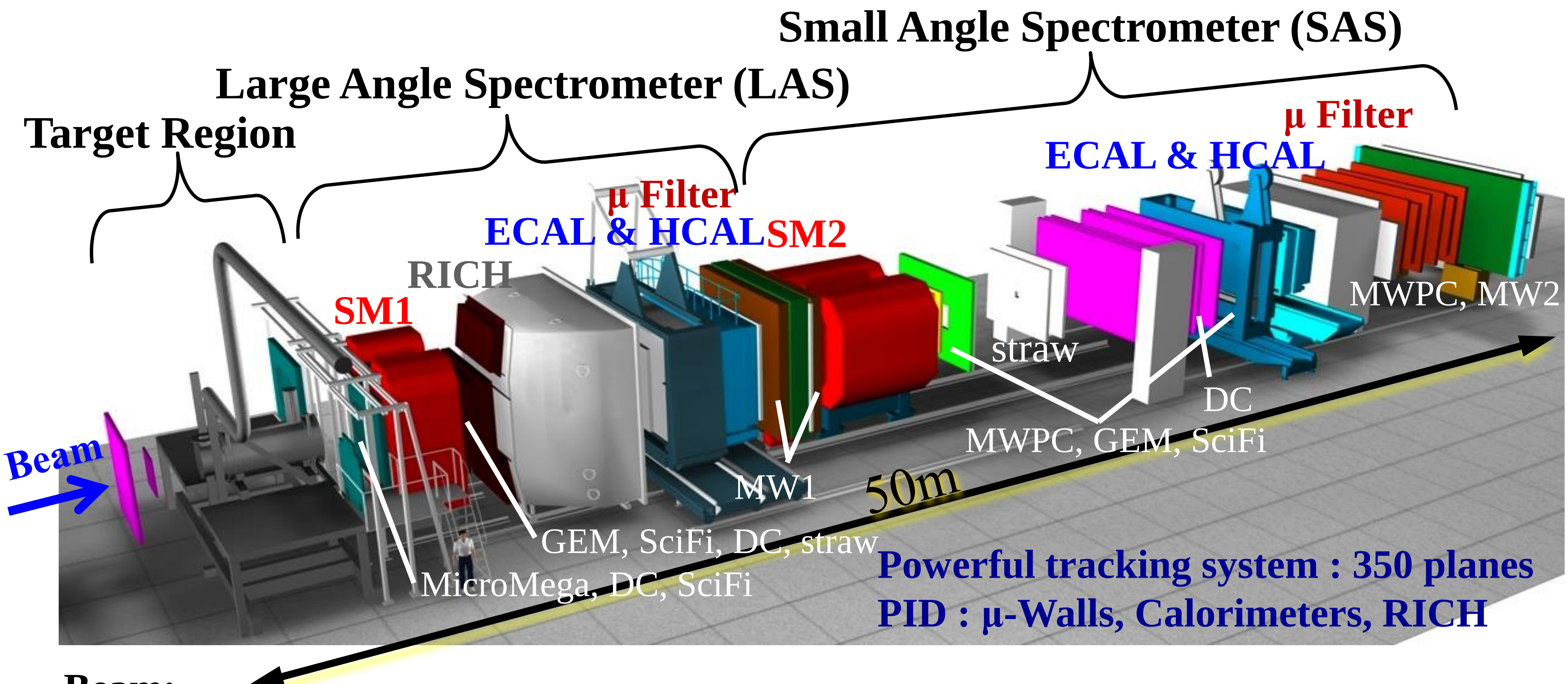
experiment	particles	energy	x_1 or x_2	luminosity	timeline
COMPASS (CERN)	$\pi^{\pm}$ + $p^{\uparrow}$	190 GeV $\sqrt{s}$ = 17.4 GeV	x_2 = 0.2 – 0.3 x_2 ~ 0.05 (low mass)	2 x 10^{33} cm^{-2} s^{-1}	2014
PAX (GSI)	$p^{\uparrow}$ + $\bar{p}$	collider $\sqrt{s}$ = 14 GeV	x_1 = 0.1 – 0.9	2 x 10^{30} cm^{-2} s^{-1}	>2017
PANDA (GSI)	$\bar{p}$ + $p^{\uparrow}$	15 GeV $\sqrt{s}$ = 5.5 GeV	x_2 = 0.2 – 0.4	2 x 10^{32} cm^{-2} s^{-1}	>2016
J-PARC	$p^{\uparrow}$ + p	50 GeV $\sqrt{s}$ = 10 GeV	x_1 = 0.5 – 0.9	1 x 10^{35} cm^{-2} s^{-1}	>2015 ??
NICA (JINR)	$p^{\uparrow}$ + p	collider $\sqrt{s}$ = 20 GeV	x_1 = 0.1 – 0.8	1 x 10^{30} cm^{-2} s^{-1}	>2014
PHENIX (RHIC)	$p^{\uparrow}$ + p	collider $\sqrt{s}$ = 500 GeV	x_1 = 0.05 – 0.1	2 x 10^{32} cm^{-2} s^{-1}	>2018
RHIC internal target phase-1	$p^{\uparrow}$ + p	250 GeV $\sqrt{s}$ = 22 GeV	x_1 = 0.25 – 0.4	2 x 10^{33} cm^{-2} s^{-1}	>2018
RHIC internal target phase-2	$p^{\uparrow}$ + p	250 GeV $\sqrt{s}$ = 22 GeV	x_1 = 0.25 – 0.4	6 x 10^{34} cm^{-2} s^{-1}	>2018
A_nDY RHIC (IP-2)	$p^{\uparrow}$ + p	500 GeV $\sqrt{s}$ = 32 GeV	x_1 = ??	?? cm^{-2} s^{-1}	?
pol. SeaQuest (FNAL)	$p^{\uparrow}$ + p / p + $p^{\uparrow}$	120 GeV $\sqrt{s}$ = 15 GeV	x_1 = 0.3 – 0.9	1 x 10^{36} cm^{-2} s^{-1}	>2014

Wolfgang Lorenzon

COMPASS Facility at CERN (SPS)



COMPASS Setup



Beam:

Polarized lepton beam : μ^+, μ^- 50-280 GeV/c

Hadron beam : π^+, π^+, K^+, K^-, p

Target:

Polarized NH_3 and ^{6}LiD target

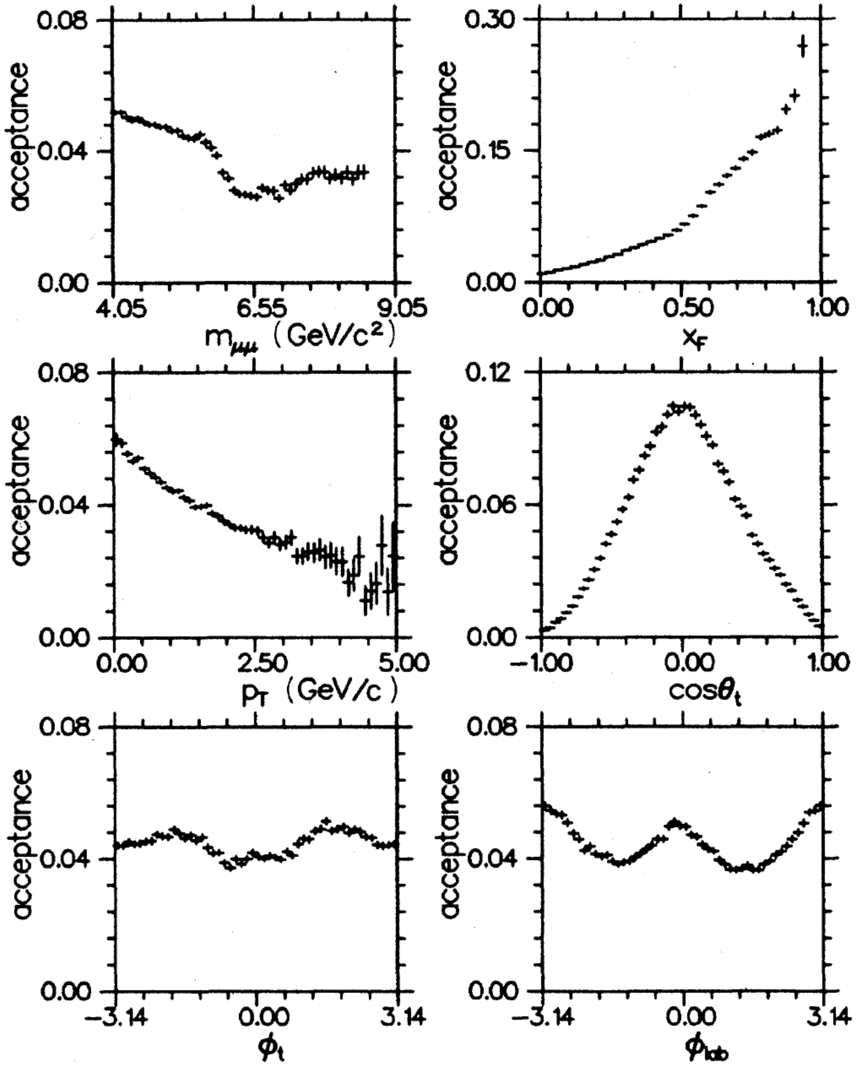
Liquid hydrogen target

Nuclear target

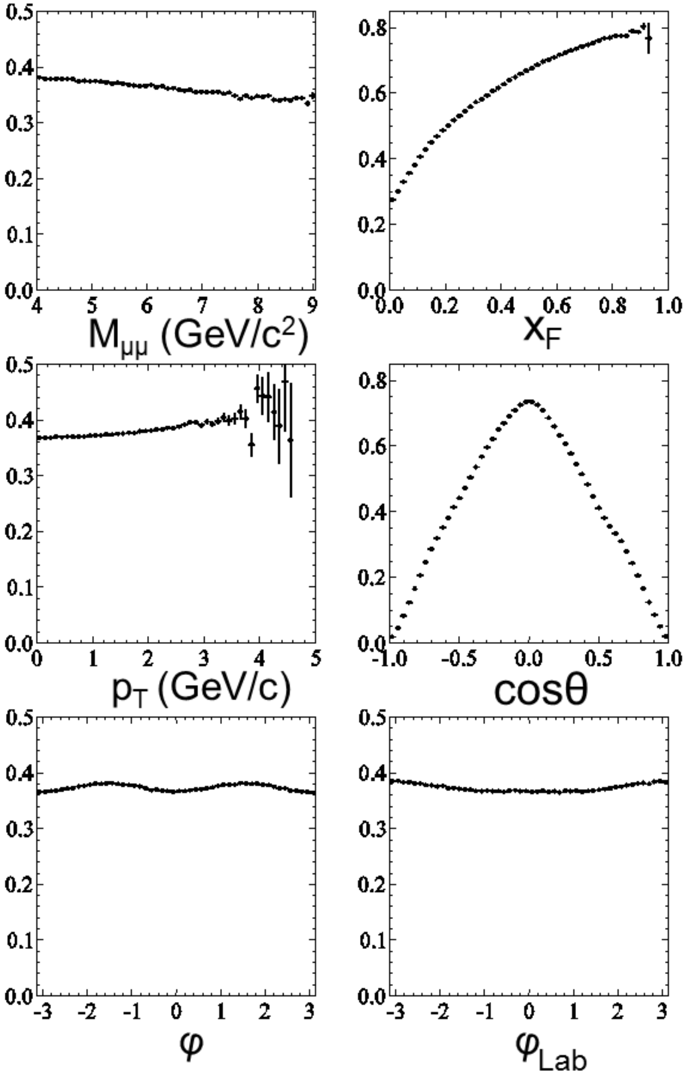
Various Combinations of Beam & Target

Dimuon Acceptance

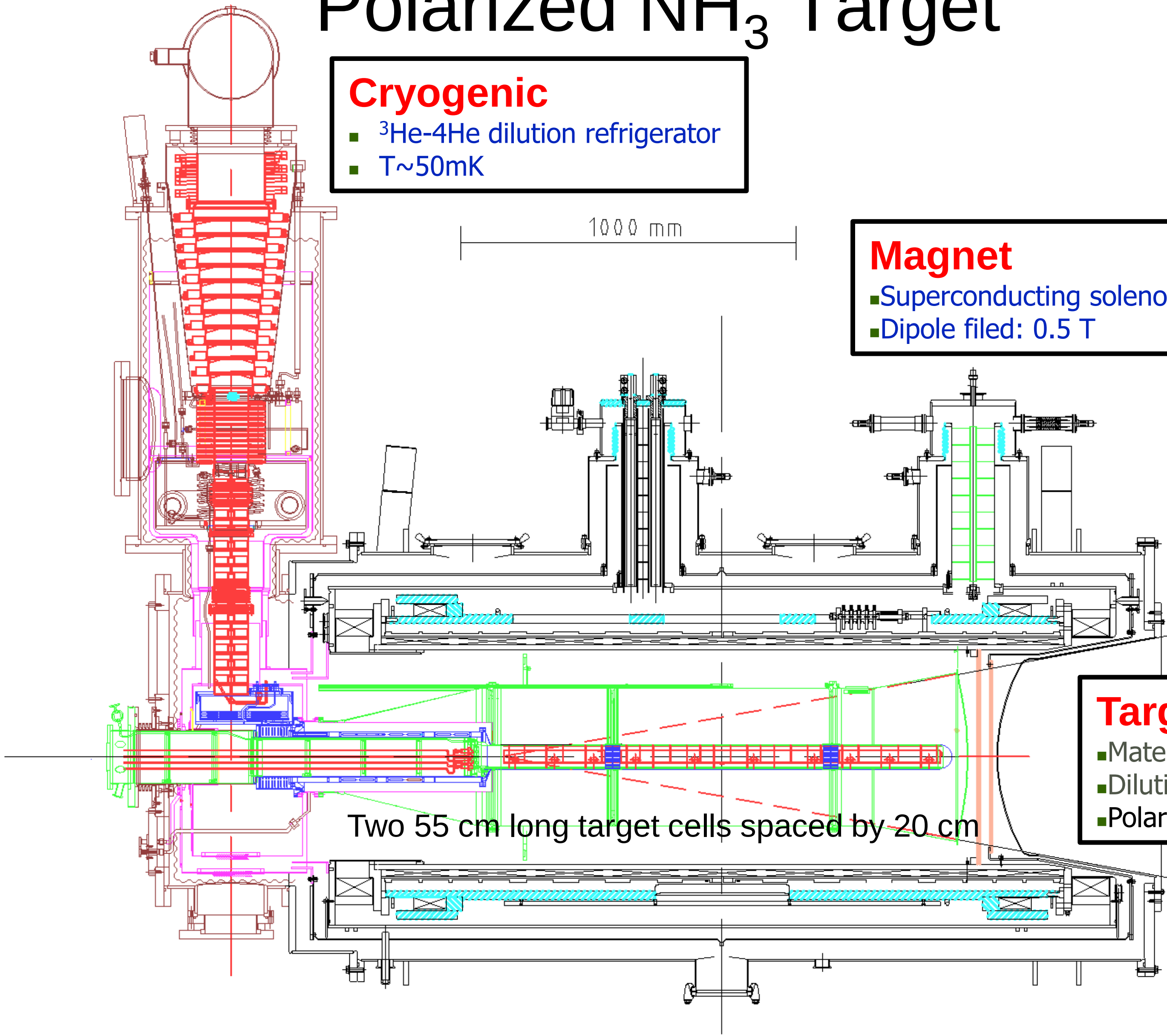
E615 @ FNAL (1989)



COMPASS @ CERN (2014)



Key Elements of Polarized DY Exp. (I): Polarized NH_3 Target



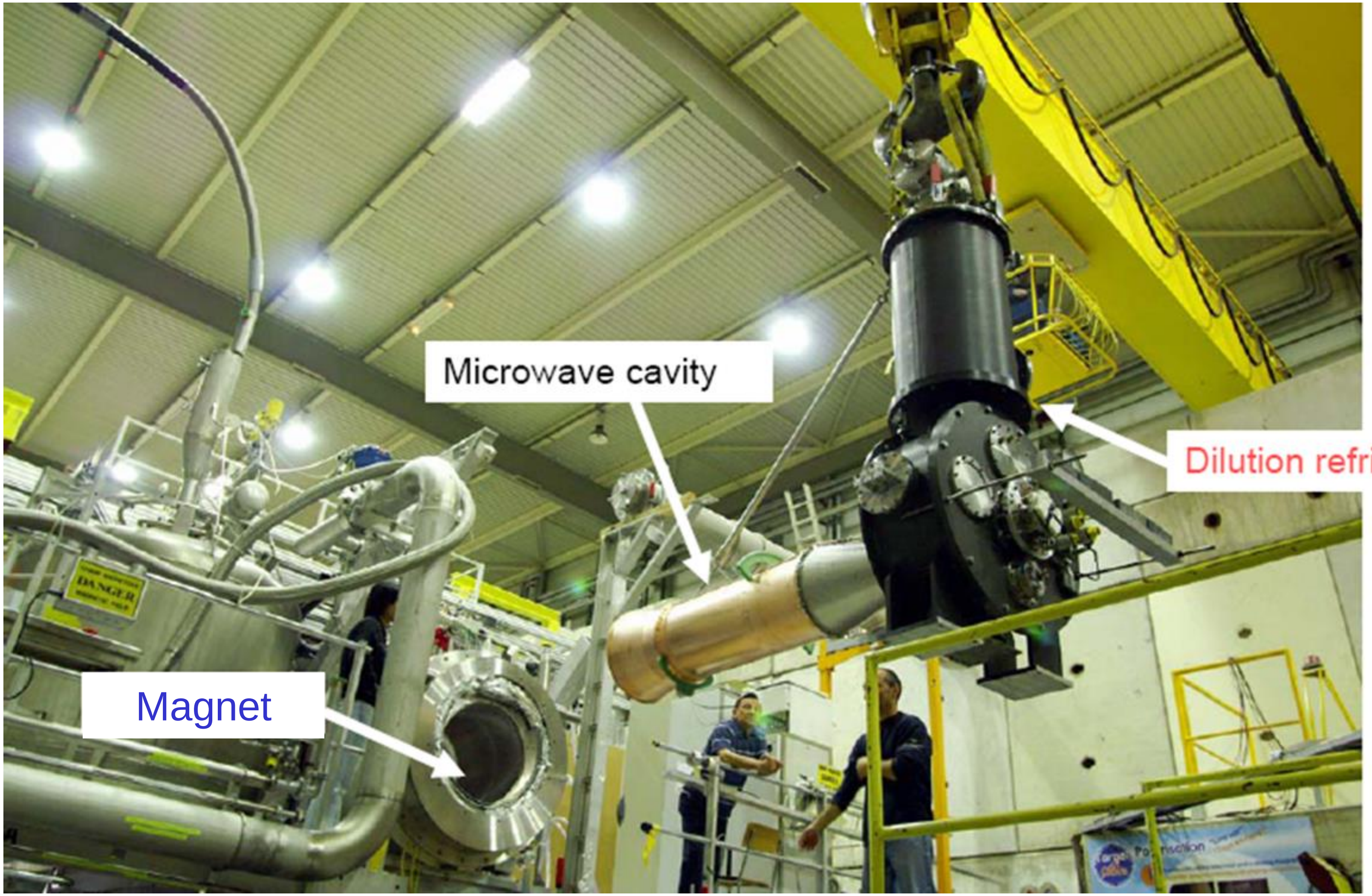
Cryogenic
- ^{3}He-4He dilution refrigerator
- T~50mK

Magnet
- Superconducting solenoid : 2.5 T
- Dipole filed: 0.5 T

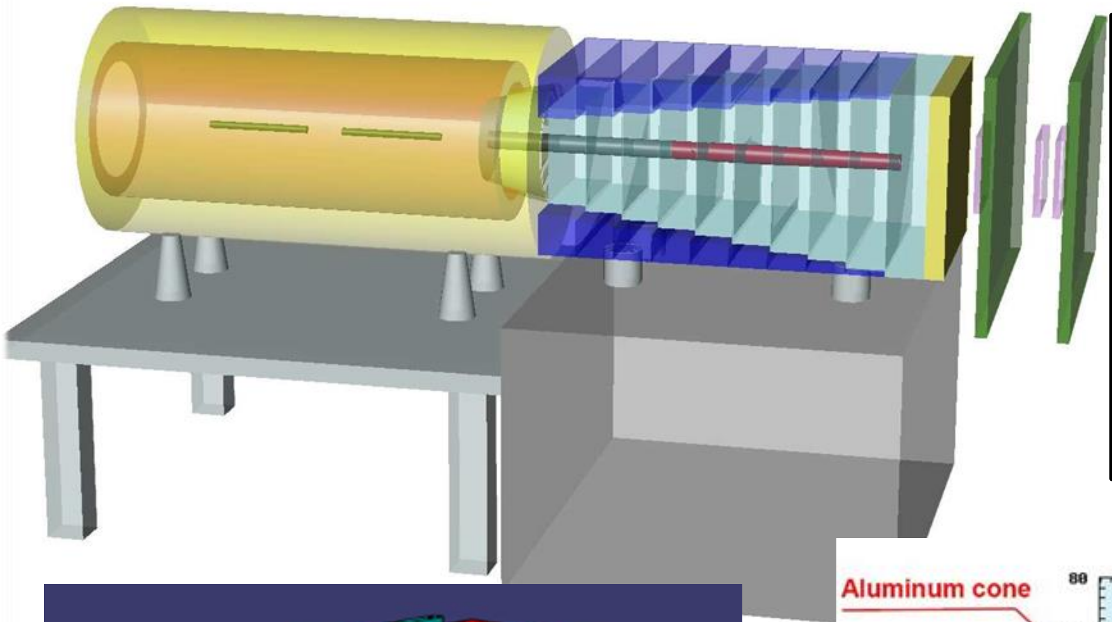
Target
- Materials: p(NH_3)
- Dilution factor: 0.22
- Polarization: >90%

Two 55 cm long target cells spaced by 20 cm

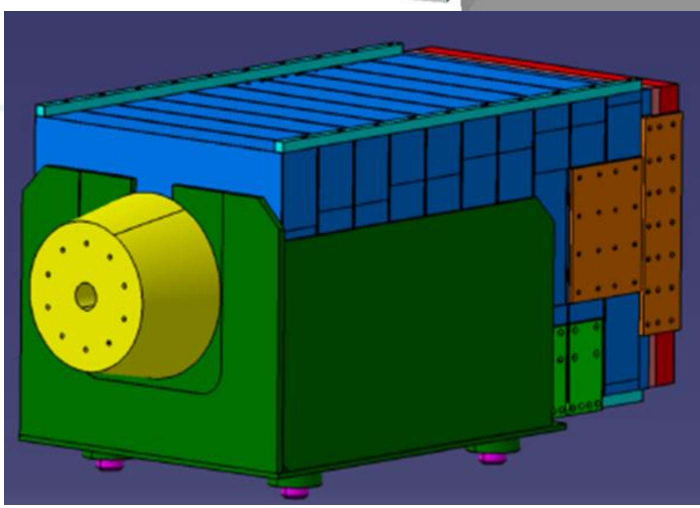
Key Elements of Polarized DY Exp. (I): Polarized NH_3 Target

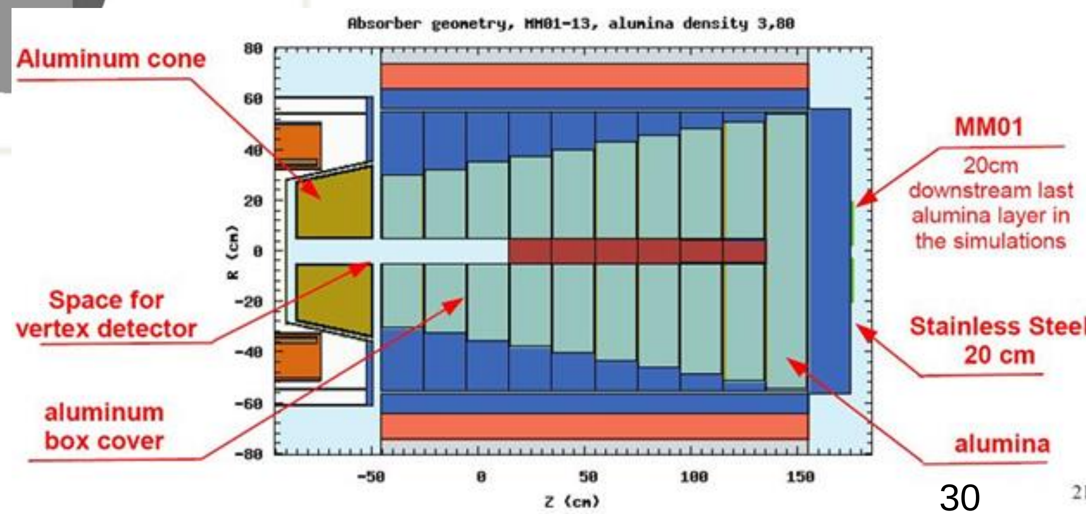


Key Elements of Polarized DY Exp. (II): Hadron Absorber



- Absorber: 236 cm long, made of Al_2O_3.
- Beam plug: 120 cm long, made of tungsten.
- Radiation lengths (multiple scattering for μ): $x/X_0 = 33.53$
- Hadronic interaction lengths (stopping power for π): $x/\lambda_{int} = 7.25$





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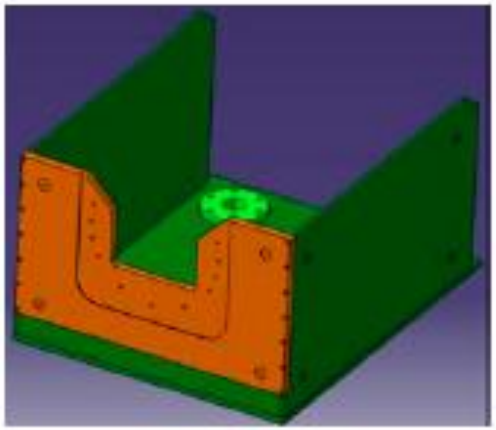
Key Elements of Polarized DY Exp. (II): Hadron Absorber

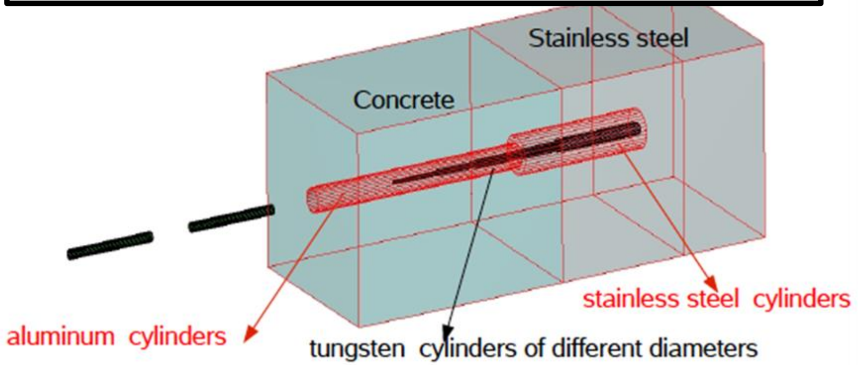
Cradle of the absorber



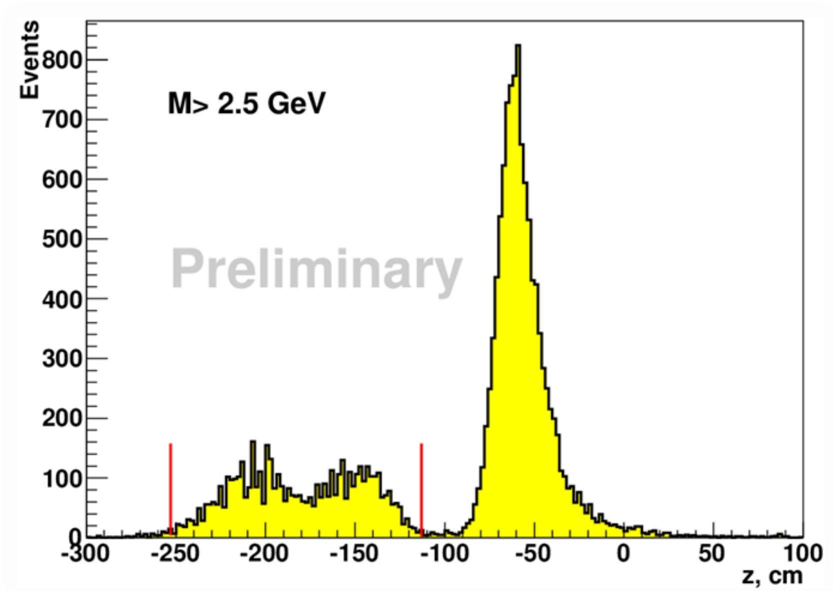
Un-magnetic stainless frame

DY Feasibility @COMPASS: Beam Test 2009

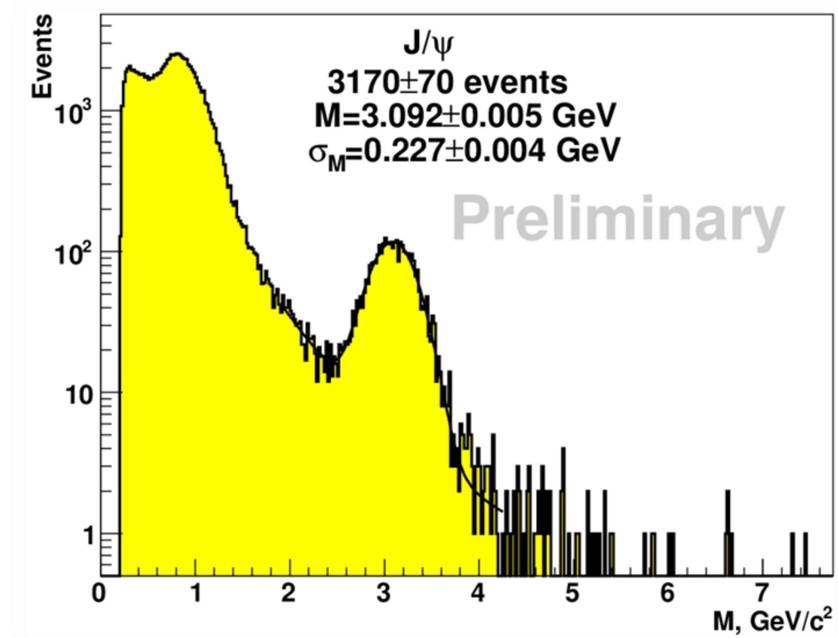
- 160 GeV/c π- beam
- 2 cells polyethylene target
- Prototype hadron absorber and beam plug
- 3 days of data taking



DY Feasibility @COMPASS: Beam Test 2009



z-vertex position of dimuon pairs



Invariant mass spectrum of dimuon pairs

$3.7\text{x}10^{11}$ 190-GeV π^- beam

	Expected	Found
J/ψ	3600±600	3170±70
DY M>4 GeV	110±22	84±10

Expected Statistical Precision

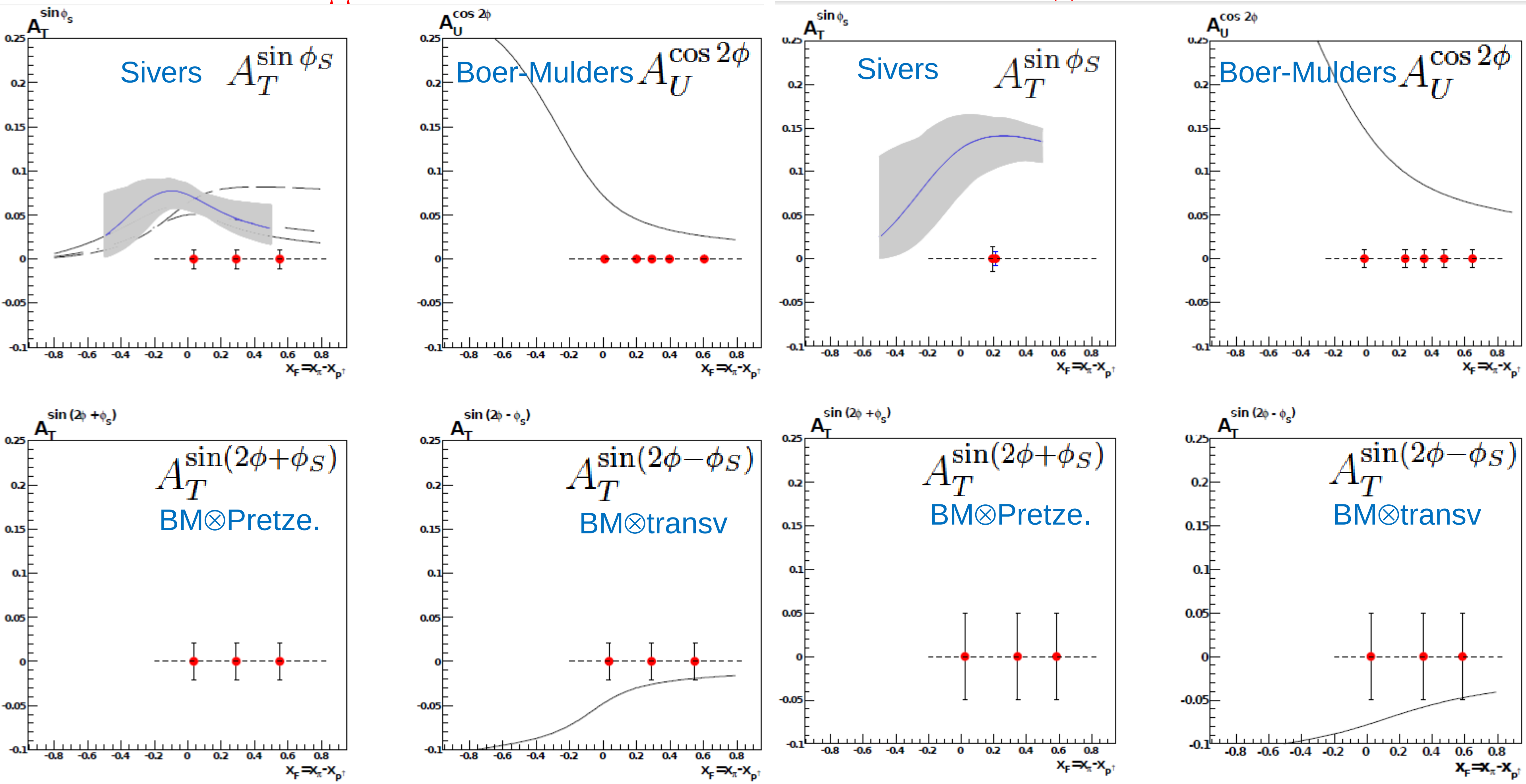
With a beam intensity $I_{beam} = 6 \times 10^7$ particles/second,
a luminosity of $L = 1.7 \times 10^{33}\ cm^{-2} s^{-1}$ can be obtained.

$\hookrightarrow$ Assuming 2 years of data-taking, one can collect > 200000 DY events in the region $4 < M_{\mu\mu} < 9.$ GeV/c^2.

Asymmetry	Dimuon mass (GeV/c^2)		
	$2 < M_{\mu\mu} < 2.5$	J/ψ region	$4 < M_{\mu\mu} < 9$
$\delta\ A_U^{\cos 2\phi}$	0.0020	0.0013	0.0045
$\delta\ A_T^{\sin \phi_S}$	0.0062	0.0040	0.0142
$\delta\ A_T^{\sin(2\phi+\phi_S)}$	0.0123	0.008	0.0285
$\delta\ A_T^{\sin(2\phi-\phi_S)}$	0.0123	0.008	0.0285

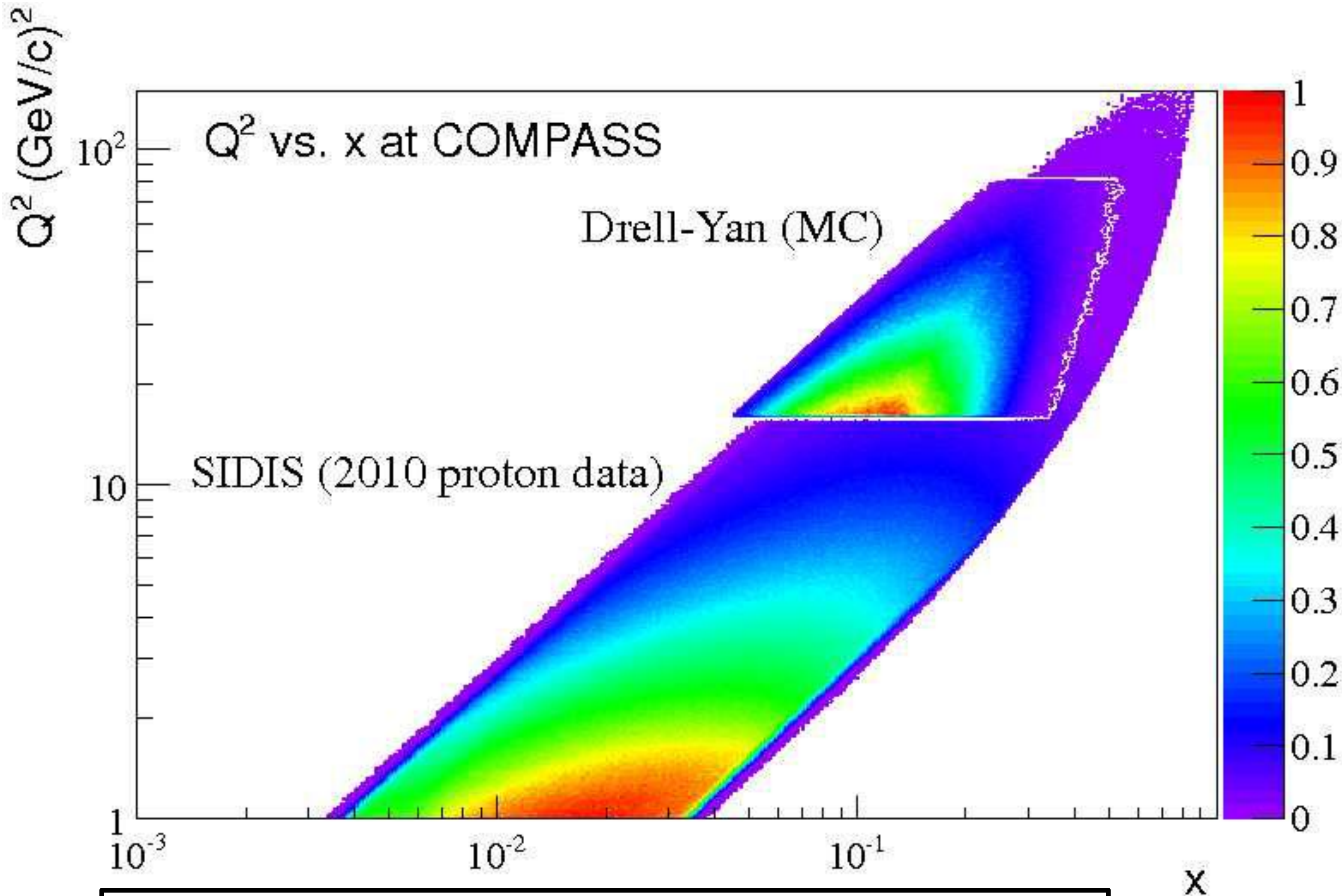
Theoretical Predictions vs. Expected Precision

$2 \leq M_{\mu\mu} \leq 2.5\,\mathrm{GeV/c^2}$ $4 \leq M_{\mu\mu} \leq 9\,\mathrm{GeV/c^2}$



M. Anselmino et. Al, Eur.Phys.J.A39:89-100,2009.
V. Barone et al., Phys. Rept. 359 (2002) 1.
B. Zhang et al., Phys. Rev. D77 (2008) 054011,

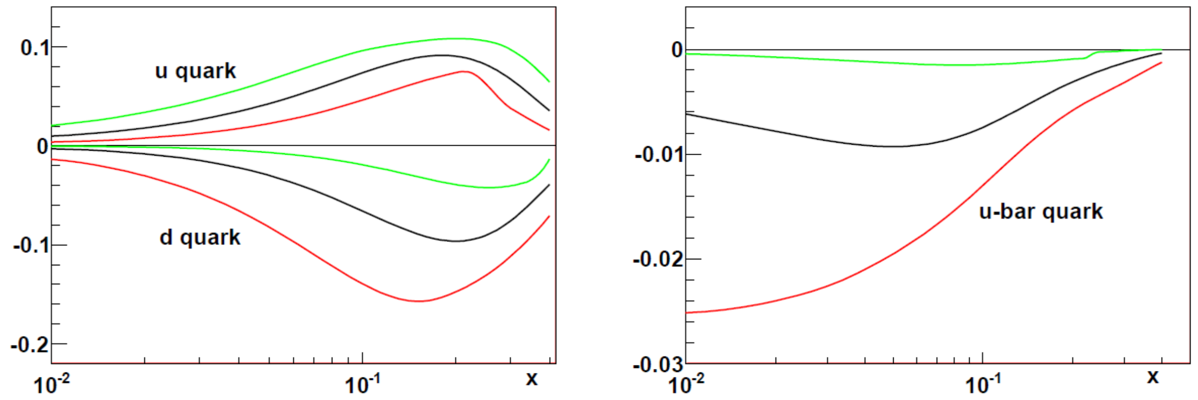
Overlapping Kinematic Region

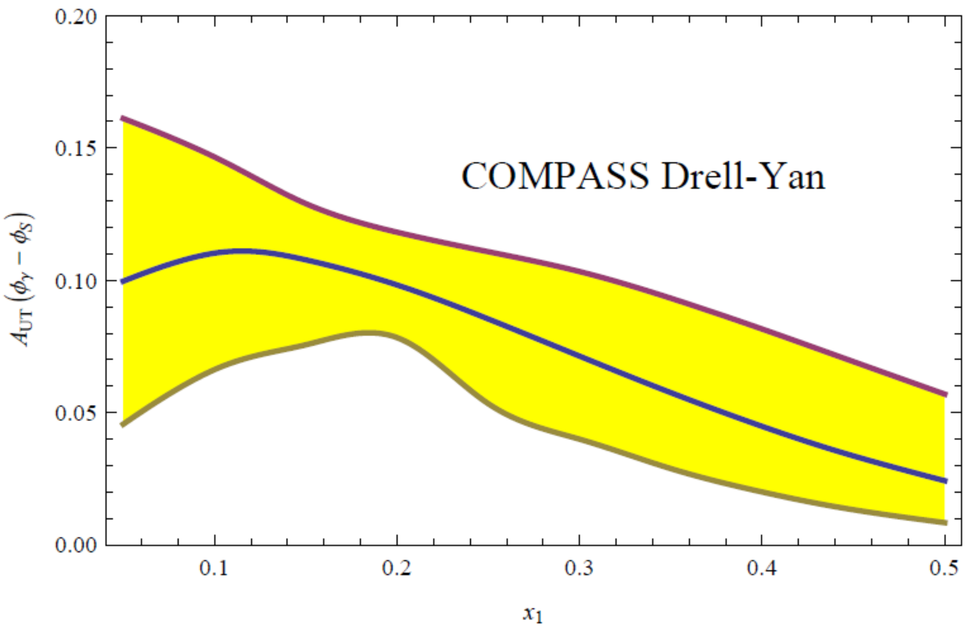


SIDIS and DY have overlapping acceptance at COMPASS
➔ Consistent extraction of TMD PDFs in the same region.

Sivers Functions with TMD Evolution

P. Sun and F. Yang, arXiv: 1308.5003

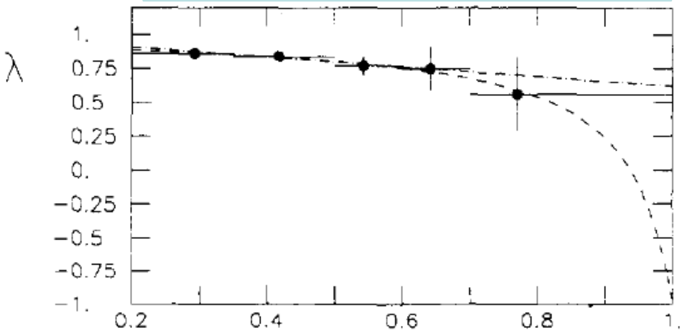




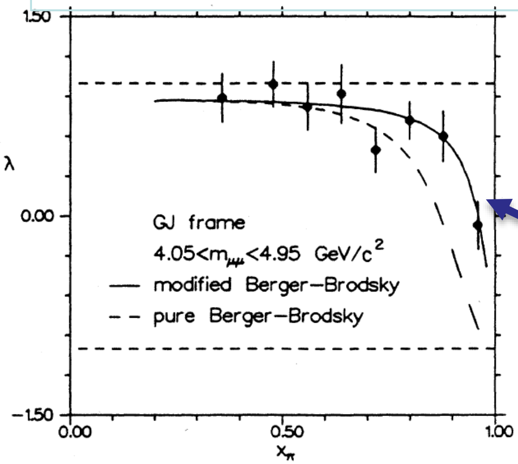
Interesting Physics to be studied in unpolarized Pion-induced DY: Nuclei Targets?

Higher-Twist Effect?

NA10 @ CERN (1988)



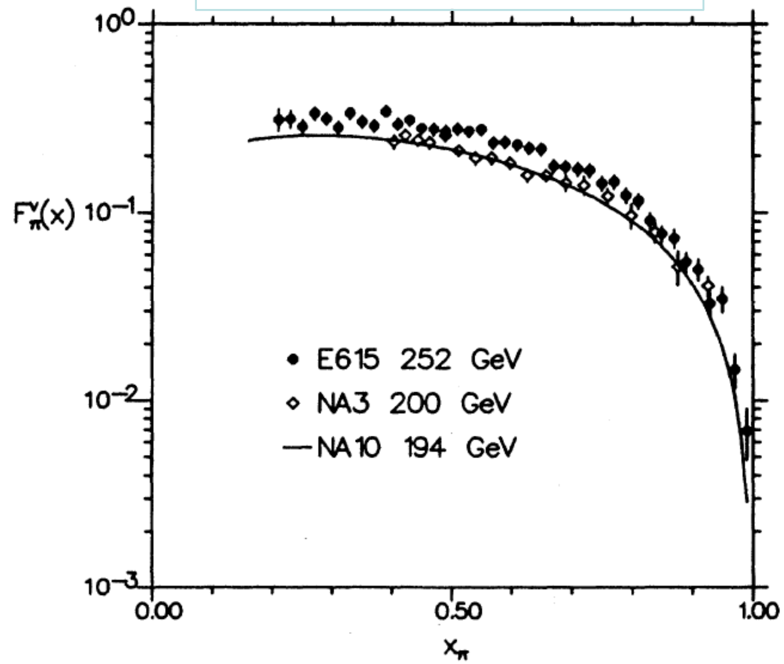
E615 @ FNAL (1989)



Transversely-polarized
→ Longitudinally polarized

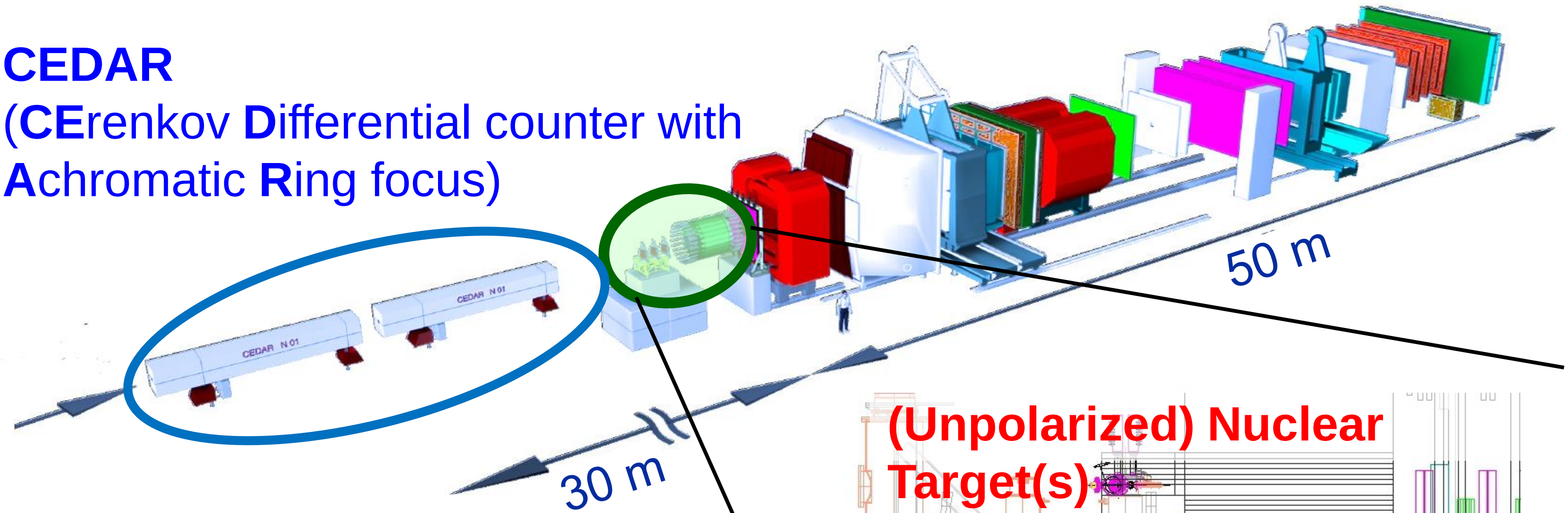
Pion PDF

E615 @ FNAL (1988)



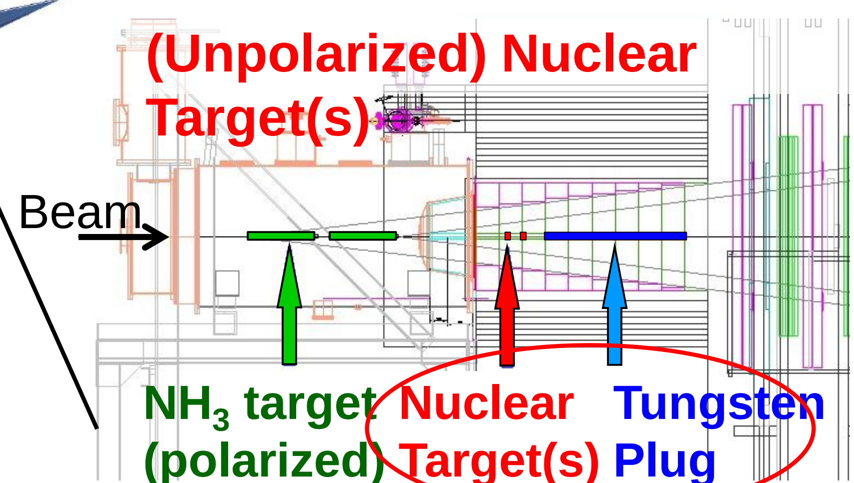
Possibility of *extended* setup

CEDAR
(**CE**renkov **D**ifferential counter with **A**chromatic **R**ing focus)



h^+ beam: p (75%) / π^+ (24%)
h^- beam: π^- (97%) / K^- (2.4%)

→ **Beam Particle Identification**



In parallel with the "*normal*" DY exp.

- **Flavor dependency of EMC effect**
- **Partonic structure of π and *K***
- **Strange quark in nucleon**

COMPASS-II Drell-Yan Program

- **2014-2018 short-term plan (partially approved):**
  - The polarized Drell-Yan measurement will start in mid-October 2014, with a short beam test.
  - Physics data taking will take place over the whole 2015.
  - A second year of DY data-taking is planned, in case of LS2 delay, in 2018.
- **2020-2024 medium-term plan (not approved yet) :**
  - Polarized ^{6}LiD target: full flavor separation of TMD SSAs.
  - Long LH_2 and nuclei targets: unpolarized pion-induced DY.
- **>2025 long-term plan (not approved yet) :**
  - Extracted high intensity RF separated antiproton/kaon beam: (un)polarized antiproton/kaon-induced DY.

Summary

- Transverse single-spin effect has triggered the investigation of k_T-dependence (TMD) PDFs via SIDIS and Drell-Yan processes.
- The effect of Sivers function in SIDIS is clearly observed.
- The Drell-Yan process offers a clean testing ground for extracting the Boer-Mulders and Sivers functions without the complication of fragmentation.
- A successful measurement of Sivers and Boer-Mulders functions in the coming polarized COMPASS-II DY experiment, will mark a milestone of perturbative QCD and TMD physics.