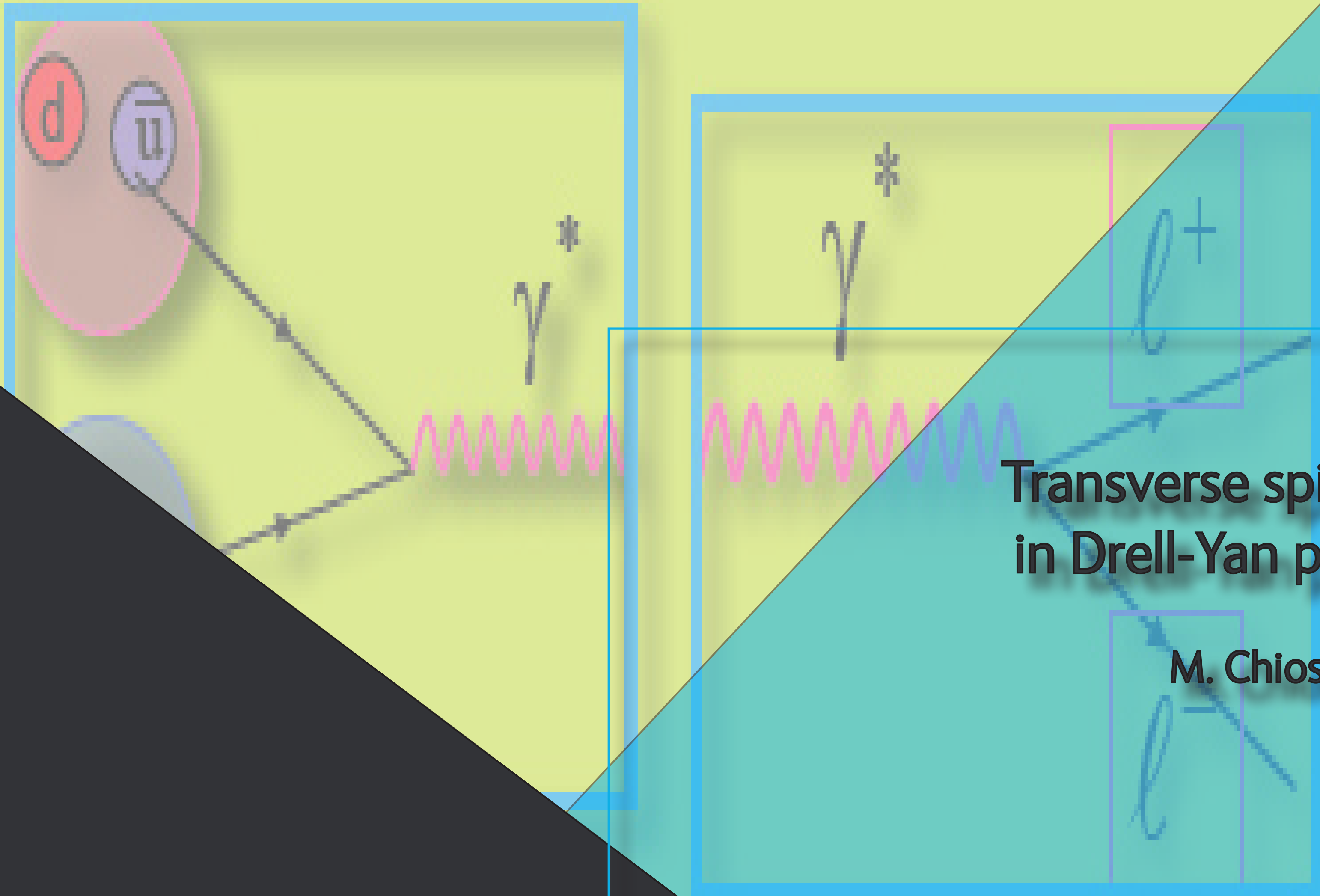


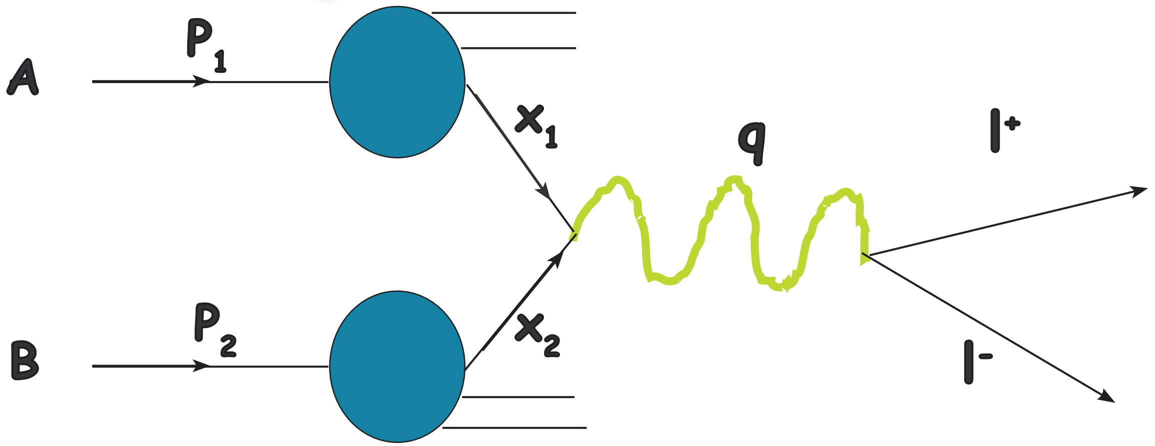
Transverse spin effects in Drell-Yan processes

M. Chiosso

Transversity 2017
Frascati, 11-15 December

Which tool?

Drell-Yan process



Invariants:
$s^2 = (P_1 + P_2)^2$
$x_1 = Q^2/2P_1 \cdot q$
$x_2 = Q^2/2P_2 \cdot q$

$$x_F \approx 2p_L/\sqrt{s} = x_1 - x_2$$
$$M^2_{\mu^+\mu^-} = s x_1 x_2$$

Predictions stated in the original paper

S. D. Drell and T. M. Yan, Phys.Rev. Lett.25, 316 (1970)

The cross section depends only on the scaling variable $\tau = Q^2/s$

The magnitude and shape of the cross section are determined by the parton and antiparton distributions measured in deep inelastic lepton scatterings

If a pion, kaon, or antiproton is used as the projectile, its structure functions can be measured by lepton pair production. This is the only way I know of to study the parton structure of a particle unavailable as a target

Drell-Yan process as a physics tool

The process of lepton pair production is so well understood in perturbative QCD that it has now become an important and powerful tool in search of new physics information"

T-M. Yan, Talk given at the Drell Fest, July 31, 1998, SLAC on the occasion of Prof. Sid Drell's retirement

arXiv:hep-ph/9810268v1 6 Oct 1998

What we want to probe?

Leading twist TMD PDFs

Nucleon Polarization		Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$		$h_1^{\perp}(x,k_T^2)$ *Boer-Mulders*
Nucleon Polarization	L		$g_1(x,k_T^2)$ *Helicity*	$h_{1L}^{\perp}(x,k_T^2)$ *Long-Transversity*
Nucleon Polarization	T	$f_1^{\perp}(x,k_T^2)$ *Sivers*	$g_{1T}(x,k_T^2)$ *Trans-Helicity*	$h_1(x,k_T^2)$ *Transversity* $h_{1T}^{\perp}(x,k_T^2)$ *Pretzelosity*

Leading twist TMD PDFs

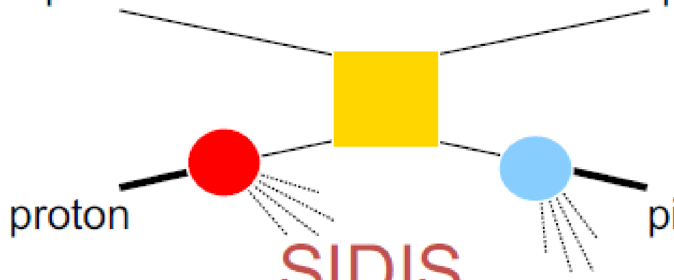
		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$		$h_1^\perp(x,k_T^2)$ Boer-Mulders
	L		$g_1(x,k_T^2)$ Helicity	$h_{1L}^\perp(x,k_T^2)$ Long-Transversity
	T	$f_1^\perp(x,k_T^2)$ Sivers	$g_{1T}(x,k_T^2)$ Trans-Helicity	$h_1(x,k_T^2)$ Transversity $h_{1T}^\perp(x,k_T^2)$ Pretzelosity

Which tools to probe TMDs?

Distribution amplitude

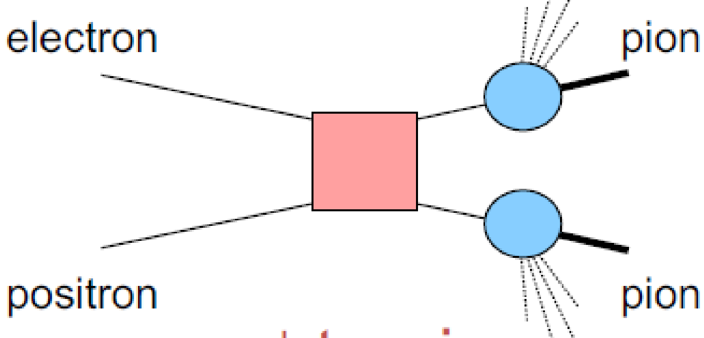
Fragmentation amplitude

DESY COMPASS Jefferson Lab EIC



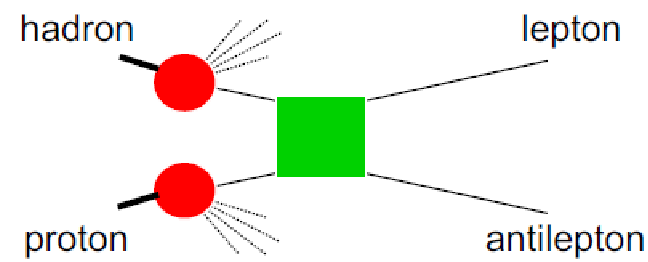
SIDIS

BESIII BELLE CERN BABAR



e⁻e⁺ to pions

COMPASS FNAL BNL JPARC GSI AFTER @ LHC



Drell-Yan

$$p^{\uparrow}p \to W^{\pm}X$$
$$p^{\uparrow}p \to Z^{0}X$$

DY for TMDs

"what can the Drell-Yan experiments offer in probing and understanding the TMDs?"

Convolution of two PDFs

DY

$\text{PDF} \otimes \text{PDF}$

Access to mesons and antiproton TMDs (with mesons and antiproton beam)

Access to sea quarks TMDs of the nucleon

Crucial test of TMD formalism:
experimental confirmation of the sign change prediction of the Sivers and the Boer-Mulders functions between SIDIS and Drell-Yan reactions

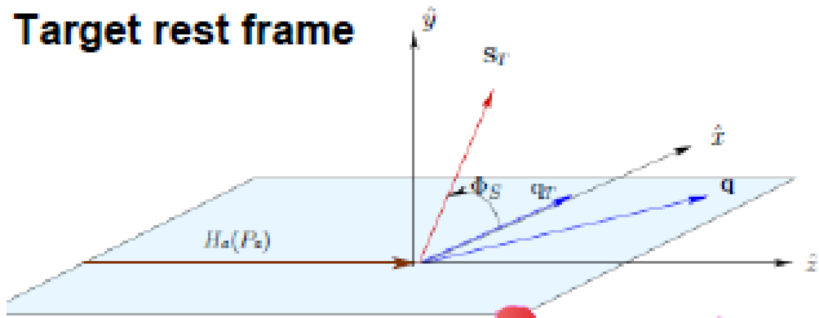
DY for TMDs

Future or planned Drell-Yan experiments: large variety of beam and target and kynematical ranges

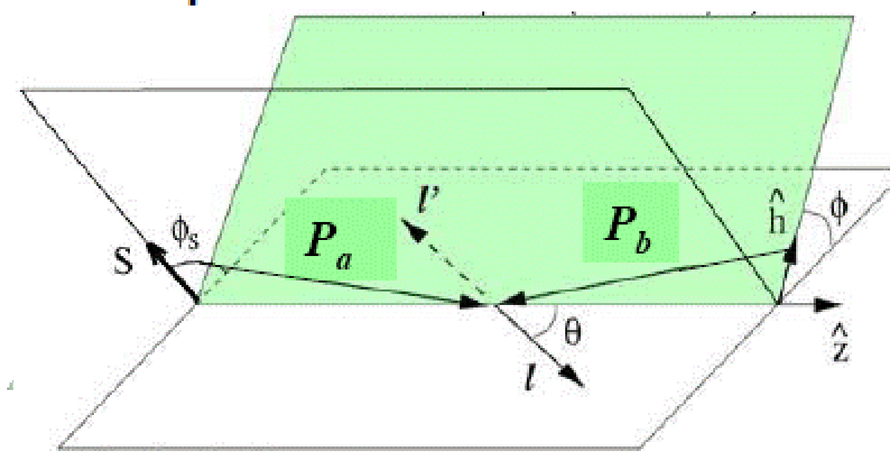
Experiment	particles	beam energy (GeV)	$\sqrt{s}$ (GeV)	$x^{\uparrow}$	$\mathcal{L}$ (cm^{-2}s^{-1})	$\mathcal{P}_{\text{eff}}$	$\mathcal{F}$ (cm^{-2}s^{-1})
AFTER@LHCb	$p + p^{\uparrow}$	7000	115	$0.05 \div 0.95$	$1 \cdot 10^{33}$	80%	$6.4 \cdot 10^{32}$
AFTER@LHCb	$p + {}^{3}\text{He}^{\uparrow}$	7000	115	$0.05 \div 0.95$	$2.5 \cdot 10^{32}$	23%	$1.4 \cdot 10^{31}$
AFTER@ALICE$_{\mu}$	$p + p^{\uparrow}$	7000	115	$0.1 \div 0.3$	$2.5 \cdot 10^{31}$	80%	$1.6 \cdot 10^{31}$
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$ $\bar{p} + p^{\uparrow}$ $K^{\pm} + p^{\uparrow}$	190	19	$0.2 \div 0.3$	$2 \cdot 10^{33}$	18%	$6.5 \cdot 10^{31}$
PHENIX/STAR (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.1$	$2 \cdot 10^{32}$	50%	$5.0 \cdot 10^{31}$
E1039 (FNAL)	$p + p^{\uparrow}$	120	15	$0.1 \div 0.45$	$4 \cdot 10^{35}$	15%	$9.0 \cdot 10^{33}$
E1027 (FNAL)	$p^{\uparrow} + p$	120	15	$0.35 \div 0.9$	$2 \cdot 10^{35}$	60%	$7.2 \cdot 10^{34}$
NICA (JINR)	$p^{\uparrow} + p$	collider	26	$0.1 \div 0.8$	$1 \cdot 10^{32}$	70%	$4.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	200	$0.1 \div 0.5$	$8 \cdot 10^{31}$	60%	$2.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.6$	$6 \cdot 10^{32}$	50%	$1.5 \cdot 10^{32}$
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15	5.5	$0.2 \div 0.4$	$2 \cdot 10^{32}$	20%	$8.0 \cdot 10^{30}$

Single Spin Asymmetries

Target rest frame



Collins-Soper frame



Measure magnitude of azimuthal modulations in cross section: "Single-Spin Asymmetries"

beam PDF ⊗ target PDF

At LO:

$$d\sigma(h^- p^\uparrow \to \mu^+\mu^- X) = 1 + \boxed{\bar{h}_1^\perp} \otimes \boxed{h_1^\perp} \cos(2\phi)$$

$$+ |S_T| \boxed{\bar{f}_1} \otimes \boxed{f_{1T}^\perp} \sin\phi_S$$

$$+ |S_T| \boxed{\bar{h}_1^\perp} \otimes \boxed{h_{1T}^\perp} \sin(2\phi + \phi_S)$$

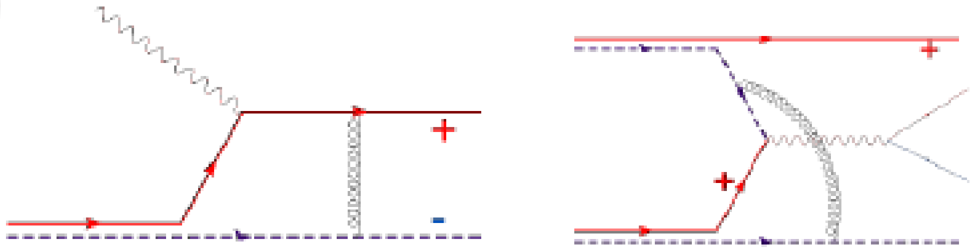
$$+ |S_T| \boxed{\bar{h}_1^\perp} \otimes \boxed{h_1} \sin(2\phi - \phi_S)$$

beam		target
(BM)	⊗	(BM)
(f_1)	⊗	(Sivers)
(BM)	⊗	(Pretzelosity)
(BM)	⊗	(Transversity)

h: multiple hadron species, nucleon & meson beams

Probing the TMD formalism

Sivers and BM functions sign change: first clear-cut check



$$h_1^{q\perp}\Big|_{DY} = -\,h_1^{q\perp}\Big|_{SIDIS}$$

$$f_{1T}^{q\perp}\Big|_{DY} = -f_{1T}^{q\perp}\Big|_{SIDIS}$$

$$\sigma^{\mathrm{DY}} \propto \begin{array}{l} 1 + \bar{h}_1^\perp \otimes h_1^\perp \cos(2\phi) \\ |S_T|\ \bar{f}_1 \otimes \bar{f}_{1T}^\perp \sin\phi_S \end{array}$$

Still needs experimental confirmation

COMPASS at CERN, P-1027 and P-1039 at FERMILAB,
PANDA at FAIR, NICA

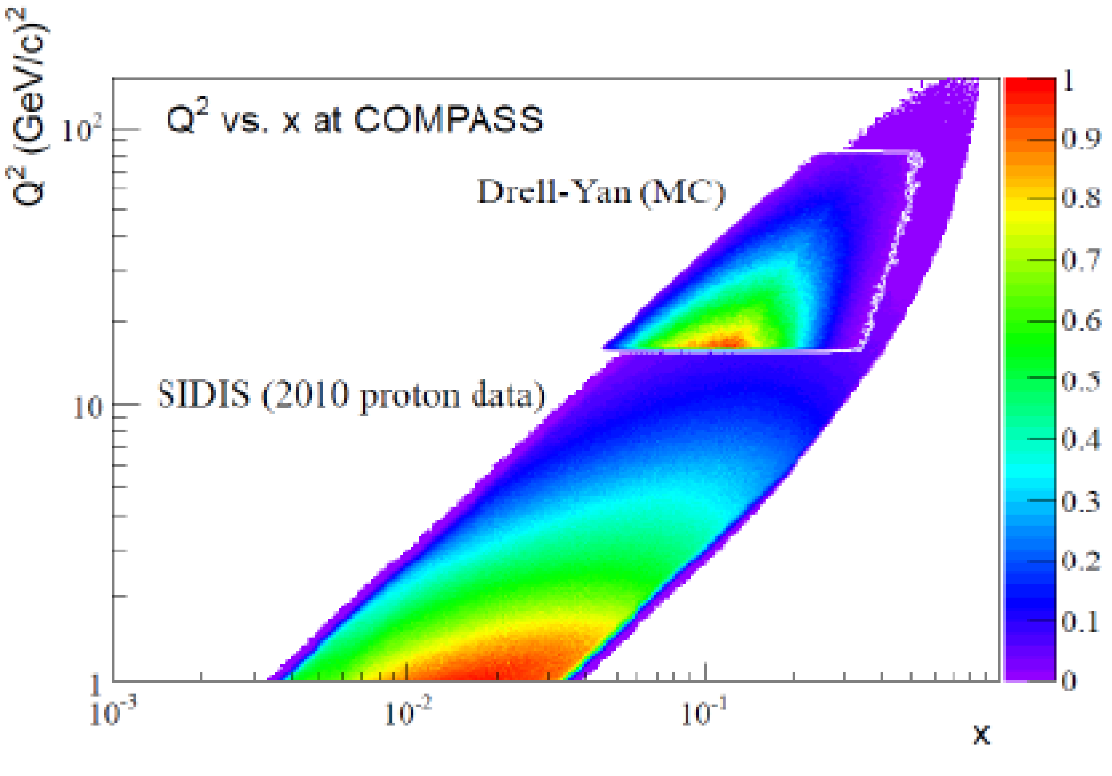
Probing the TMD formalism

COMPASS

$\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X$

2015 DY RUN - first polarized DY data

In the same kinematical region as that for SIDIS extraction



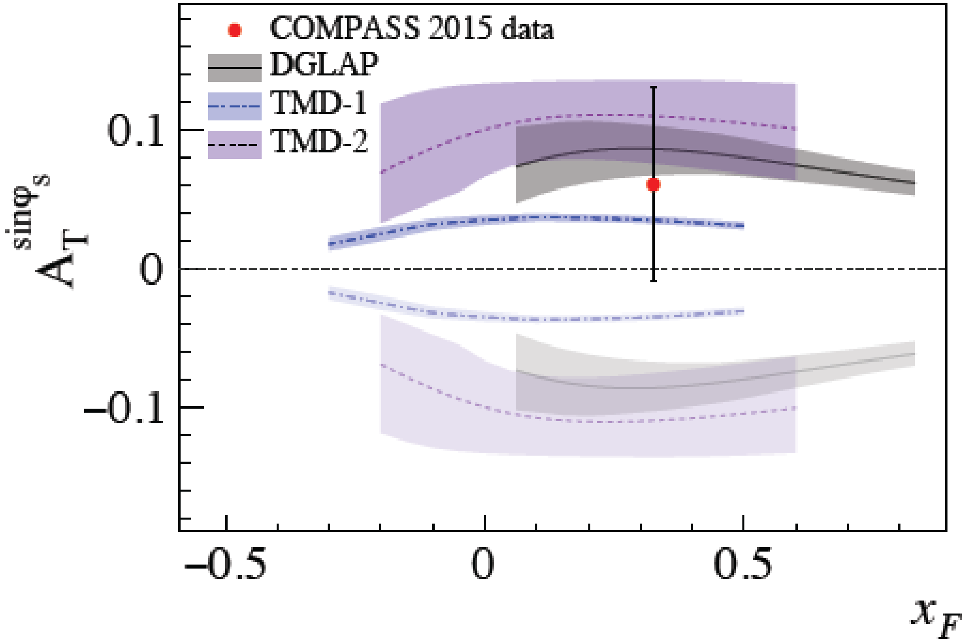
Test of TMD formalism

Probing the TMD formalism

$\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X$

2015 DY RUN - first polarized DY data

In the same kinematical region as that for SIDIS extraction



sign change

no sign change

New data coming in 2018

CERN-EP/2017-059; hep-ex/1704.00488;

Test of TMD formalism

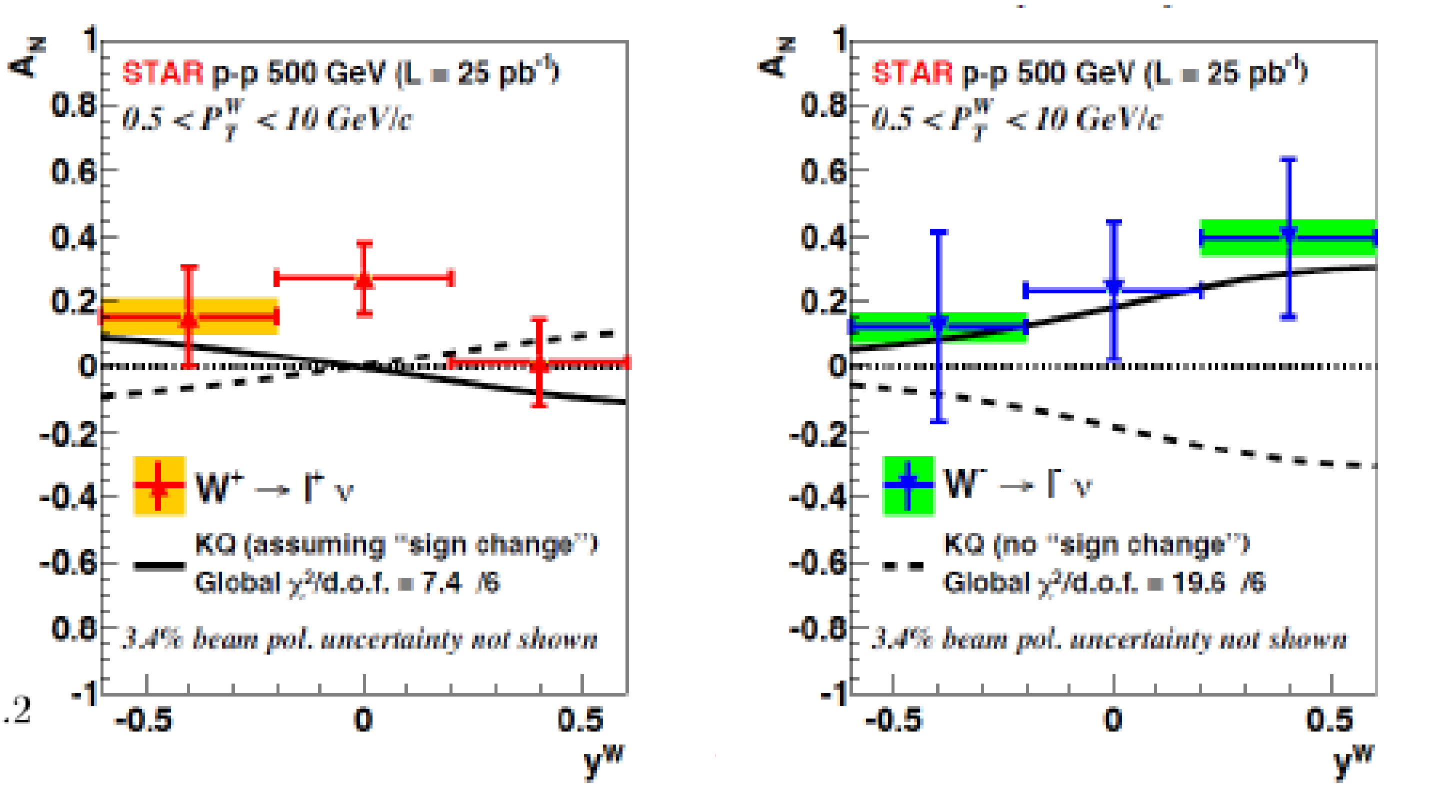
Present

the Sivers function sign change

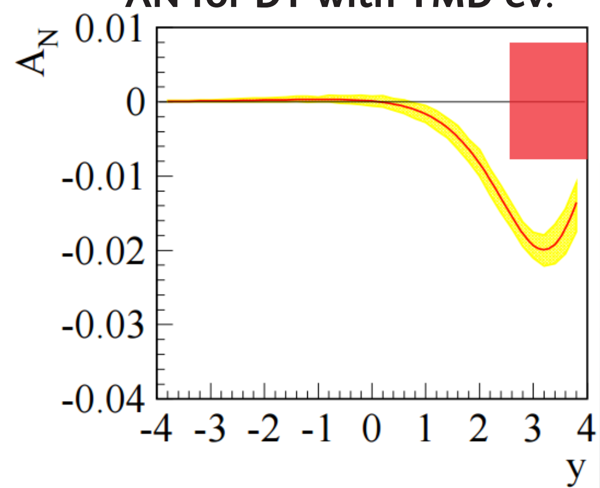
$p^{\uparrow}p \rightarrow W^{\pm}\ X$

STAR Collaboration,
PRL 116 (2016) 132301

- Sign change $\chi^2/d.o.f \sim 1.2$
- No sign change $\chi^2/d.o.f \sim 3.2$



AN for DY with TMD ev.



RUN-17: A goldmine for TMDs@STAR
Collected:
350 pb^{-1} 14 times Run-11 for $-1 < \eta < 1.8$:
AN W+/- & Z0
DY e+e- in $2.5 < \eta < 4.0$ 4.0 GeV < Me+e- < 9.0GeV
AN for DY to +/- 0.008

Test of TMD formalism

Present

the Sivers function

COMPASS

Fermilab

	Beam Pol.	Target Pol.	Favored Quarks	Physics Goal
COMPASS $\pi^- p^\uparrow \to \mu^+ \mu^- X$	✗	✔	Valence quark	Sign change and size of Sivers distribution for valence quark
P-1027 $p^\uparrow p \to \mu^+ \mu^- X$	✔	✗	Valence quark	Sign change and size of Sivers distribution for valence quark
P-1039 $p p^\uparrow \to \mu^+ \mu^- X$	✗	✔	Sea quark	Size and sign of Sivers distribution for Sea quarks, if DY $A_N \neq 0$.

From A. Klein and X. Jiang

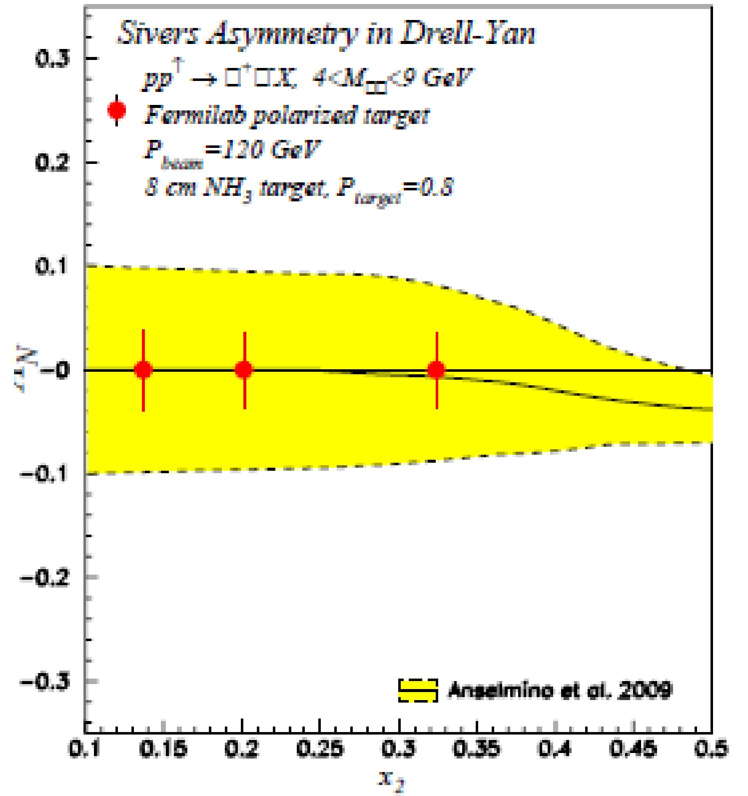
Probing the Sivers function sign change

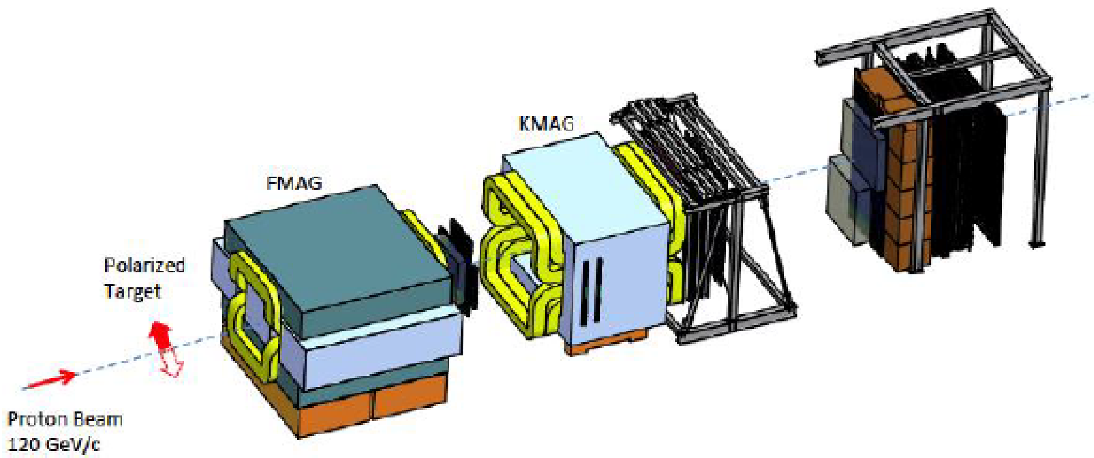
Fermilab P1039

Probing the Sivers function for sea quarks:

What is the sign for Sivers Asymmetry for sea quark?

Which is the contribution of the sea quark OAM to the proton spin?





E906 spectrometer + polarized target

Future

Test of TMD formalism

Sea-quark OAM contribution to proton spin?

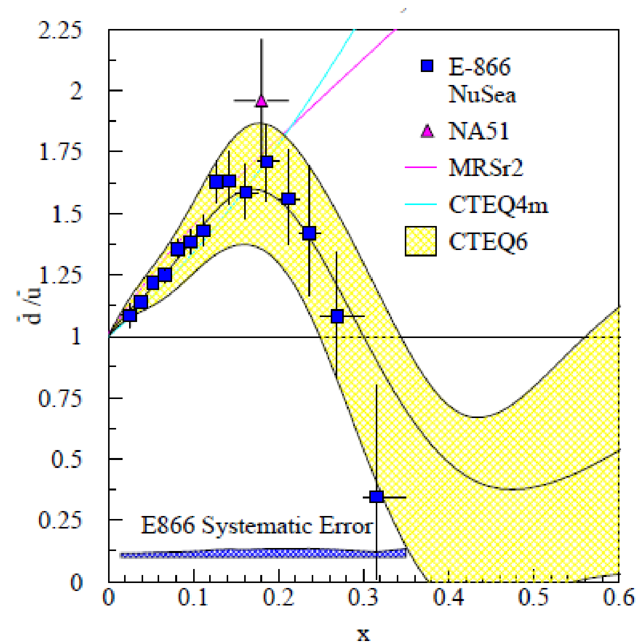
Fermilab **E-866 E906 P1039**

Probing the Sivers function for sea quarks:

If the excess of anti-d quarks is due to a pion cloud around the proton, then the pions (and sea quarks) contribute a significant amount of orbital angular momentum in the x range where significance valence sea quark were measured

Non-zero dbar sea-quark Sivers function is also obtained in order to explain the large Sivers moment observe for K^+ in SIDIS

Sea-quark Sivers investigated in future **SIDIS** experiment at JLAB and EIC



x: 0.1 - 0.5

proton beam on polarized:
NH3 target ubar Sivers
ND3 target: dbar Sivers

With E1027 polarized beam:
access to double spin asymmetry

Sea

landscape

Probing the Sivers function sign change

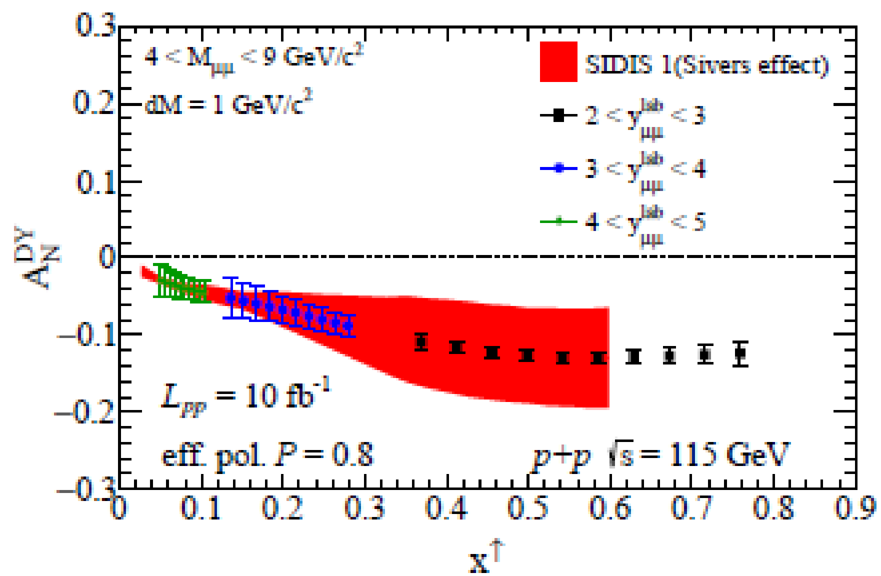
AFTER @ LHC

AFTER@LHC is a complementary facility to further investigate the quark Sivers effect by measuring DY STSAs

Capable of measuring the Drell-Yan A_N in a broad kinematic range with exceptional precision

Accessing the quark Sivers function in a polarised neutron: p+3He collisions

LHCb-like detector



Test of TMD formalism

Future

A clean tool to probe Transversity

1. double polarized Drell-Yan

At LO the double transverse asymmetry is completely determined by the transversity of quarks and antiquarks

$$A_{TT}^{DY} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = a_{TT} \frac{\sum_q e_q^2 \, h_{1q}(x_1, Q^2) \, \bar{h}_{1q}(x_2, Q^2) + [1 \leftrightarrow 2]}{\sum_q e_q^2 \, f_{1q}(x_1, Q^2) \, \bar{f}_{1q}(x_2, Q^2) + [1 \leftrightarrow 2]}$$

$p^{\uparrow} + p^{\uparrow}$ → transversity of sea quarks: NICA

2. single polarized Drell-Yan

$\bar{p} + p^{\uparrow}$ → transversity of valence quarks:

$p + p^{\uparrow}$ → transversity of sea quarks:

COMPASS

PANDA

FAIR

Facility for Antiproton and Ion Research in Europe GmbH

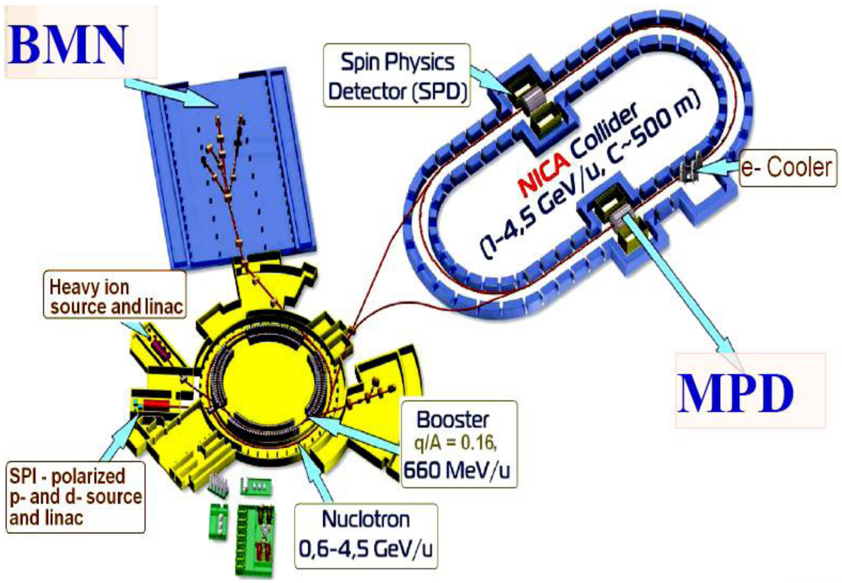
Future

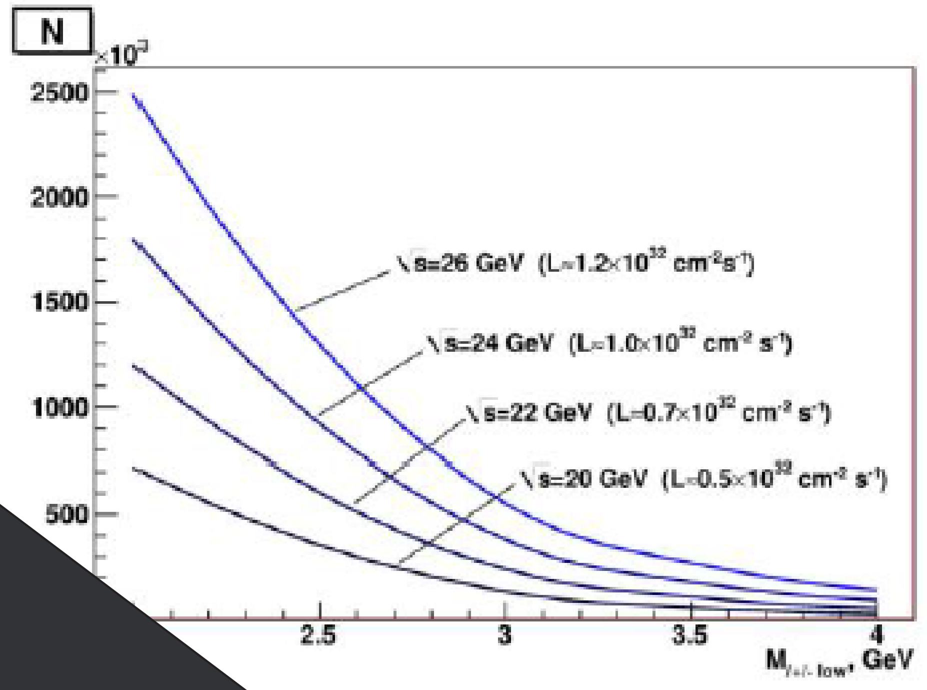
A clean tool to probe Transversity

1. Double spin asymmetries at NICA?

Operation with proton and deuteron beam, all possible polarization combination

First time comprehensive studies of all leading-twist PDFs in single experiment





Experiment	NICA, SPD
mode	*collider*
Beam/target	*pp, pd,dd*
Polarization:b/t	*0.5*
Luminosity	10^{32}
$\sqrt{s}$ *, GeV*	*10-26*
$x_{1(beam)}$ *range*	*0.1-0.8*
q_T*, GeV*	*0.5 -6.0*
Lepton pairs,	$\mu^-\mu^+$, e^+e^-

A clean tool to probe Transversity

Single polarized Drell-Yan

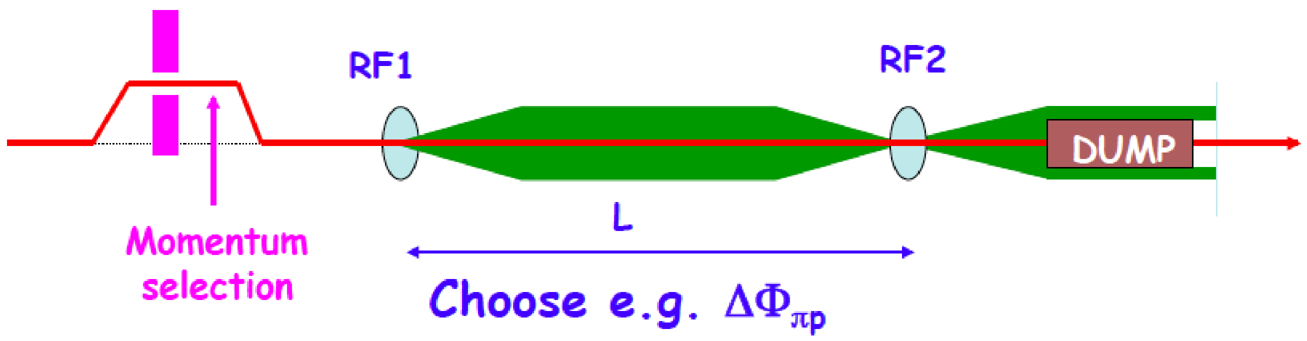
$$\sigma^{\mathrm{DY}} \propto f_{\overline{u}|\bar{p}} \otimes f_{u|p} \longrightarrow$$

beam		target	
(BM)	⊗	(BM)	cos(2ϕ)
(f_1)	⊗	(Sivers)	
(BM)	⊗	(Pretzelosity)	
(BM)	⊗	(Transversity)	sin(2ϕ-ϕ_s)

measurement of transversity entirely free of the uncertainty of fragmentation functions

$\bar{p}$ radiofrequency separated beam at M2 CERN beamline

RF Separated Beam (CERN M2 Beam Line)



Deflection with 2 cavities
Relative phase = 0 --> dump
Deflection of wanted particle given by:

$$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1}) \text{ with } \beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$$

To keep good separation, L should increase as p^2 --> limits the beam momentum

Particle type	Fraction at T6	Fraction at COMPASS
pbar	1.6 %	11.3 %
K^-	3.0 %	0 %
π^-	32.4 %	84.3 %
e^-	63.0 %	4.4 %

20 GeV/c

"Normal" h^- beam composition:
97% (π^-) 2.5%(K) 0.5% (pbar)

Transversity & Tensor Charge

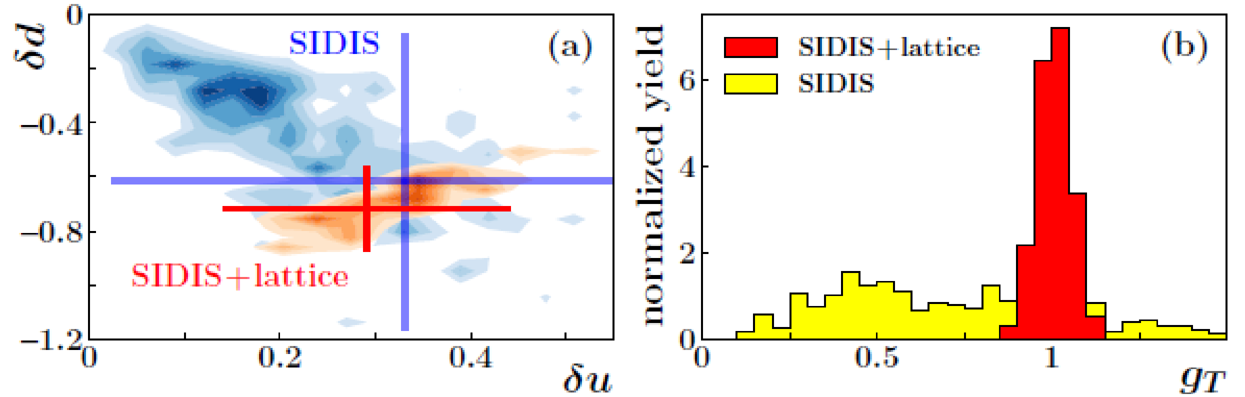
Sea quark transversity not included in the recent extraction of transversity: could it introduce systematic uncertainties in the determination of the tensor charges δu and δd?

huge difference between the accuracy of the extractions from the existing data and from the QCD lattice simulations

h_{1d} extraction affected by large uncertainties

$$g_T = \delta u - \delta d,$$

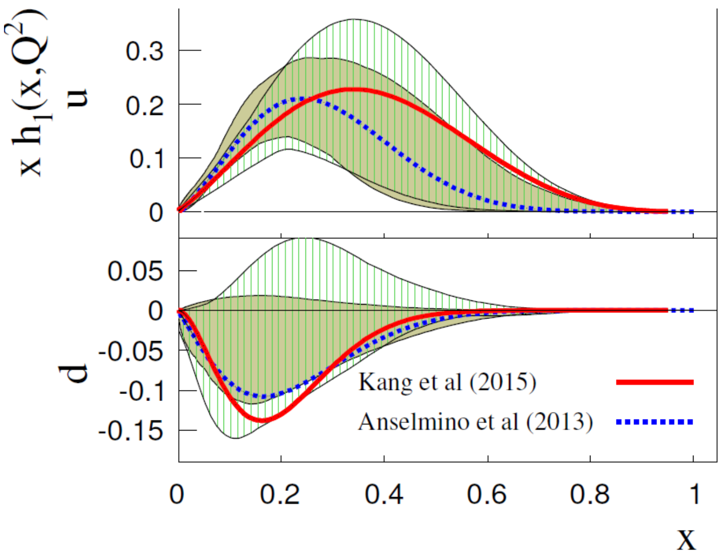
$$\delta q(Q^2) = \int_0^1 dx [h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)]$$



Flavor Separation

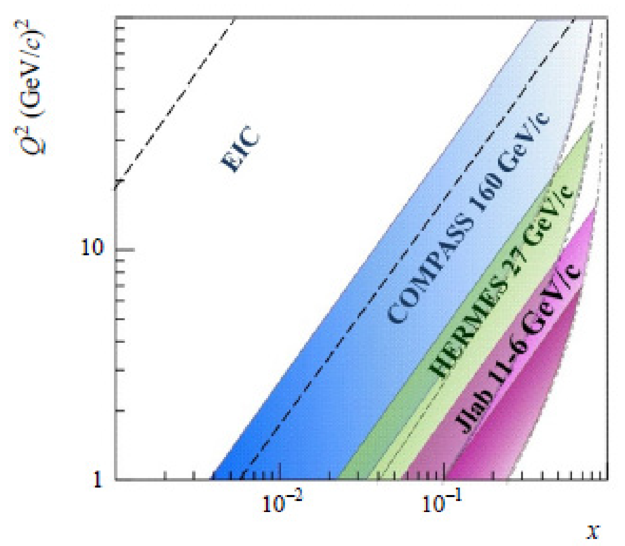
AFTER @ LHC

extract proton transversity using NH3 and 6LiD runs
Provides important cross check for Collins based extraction of proton transversity (magnitude of flavor contributions)



Combine with NH3 measurement to determine flavor dependent Sivers

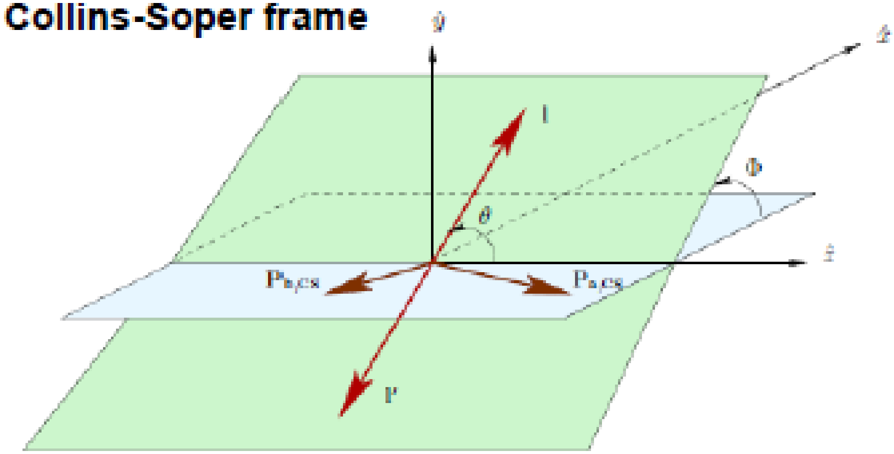
Future SIDIS:
JLab12 with proton and neutron targets
COMPASS with deuteron target
EIC



Unpolarized Drell-Yan

Experimental tool: unpolarized Drell-Yan

Collins-Soper frame



At NLO:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \left\{ (1 + A_U^1 cos^2\theta + \sin(2\theta)\ A_U^{cos\phi} cos\phi + \sin^2\theta\ A_U^{cos2\phi} cos(2\phi)\ \right)$$

$$\lambda = A_U^1;\ \mu = A_U^{\cos\phi};\ \nu = 2A_U^{\cos 2\phi}$$

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$ → pion $(BM)_\pi$ ⊗ proton $(BM)_p$

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

Lam-Tung Relation & Boer-Mulders function

Lam-Tung relation

experimental confirmation of a universal behavior of the valence quark Boer-Mulders functions for pions and nucleons

pion and kaon pdfs

flavor and x dependencies of the Boer-Mulders functions

Boer-Mulder sign change?

Lam-Tung Relation & Boer-Mulders function

$$1 - \lambda = 2\nu$$

- Proton-induced Drell-Yan (E866)
  - consistent with LT-relation
  - no $\cos(2\Phi)$ dependence
  - no p_T dependence

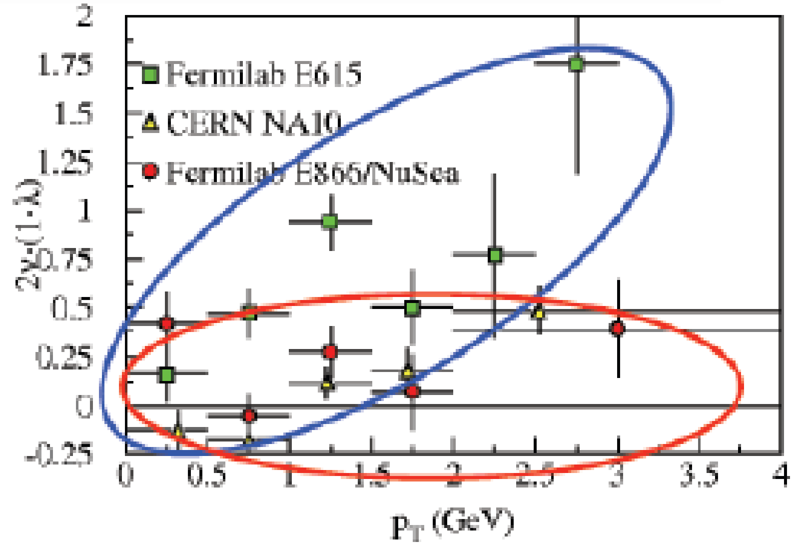
- Pion-induced Drell-Yan (NA10, E615)
  - violates LT-relation
    (independent of nucleus - no nuclear effect)
  - large $\cos(2\Phi)$ dependence
  - strong with p_T

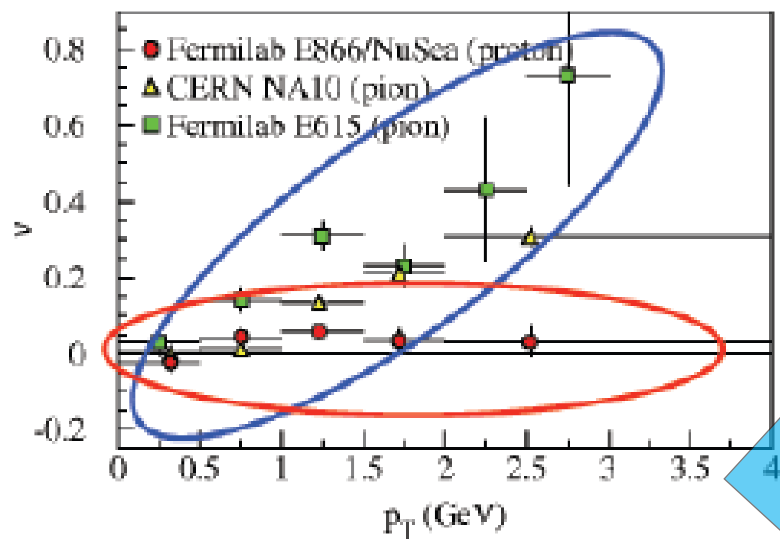
☛ **One candidate to explain LT violation: BM function**

- Pionic DY probes BM (valence), target=proton
  Protonic DY probes BM (sea), target=proton

  BM (sea) $\ll$ BM (valence)

☛ study of spin-orbit correlations





Boer-Mulders function

Obtain BM with kaon beam

$$A_{UU}^{\cos(2\phi)} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{\perp q}$$

$$K^{+}p(x_f) = u^{K}(x_1)\bar{u}^{p}(x_2) + \bar{s}^{K}(x_1)s^{p}(x_2)$$

$$K^{-}p(x_f) = \bar{u}^{K}(x_1)u^{p}(x_2) + s^{K}(x_1)\bar{s}^{p}(x_2)$$

Experiment	Beam type (GeV)	Intensity (/s)	Target	DY events
NA3	K^- (150)	0.25×10^7	Pt	688
	K^- (200)	0.93×10^7		90
	K^+ (200)	0.22×10^7		170
COMPASS++	K^- (80)	1.9×10^7	C	593
	K^- (100)	2.3×10^7		1,800
	K^- (120)	2.5×10^7		3,600
COMPASS++	K^+ (80)	1.7×10^7	C	482
	K^+ (100)	2.1×10^7		1,700
	K^+ (120)	2.3×10^7		3,700

Possibility of Radio-Frequency separated beam pion, kaon and antiproton
increase by a factor of two the maximum kaon/antiproton flux actually achievable
kaon and anti-protons flux possibly reaching 10^7p/s

Future

Boer-Mulders function

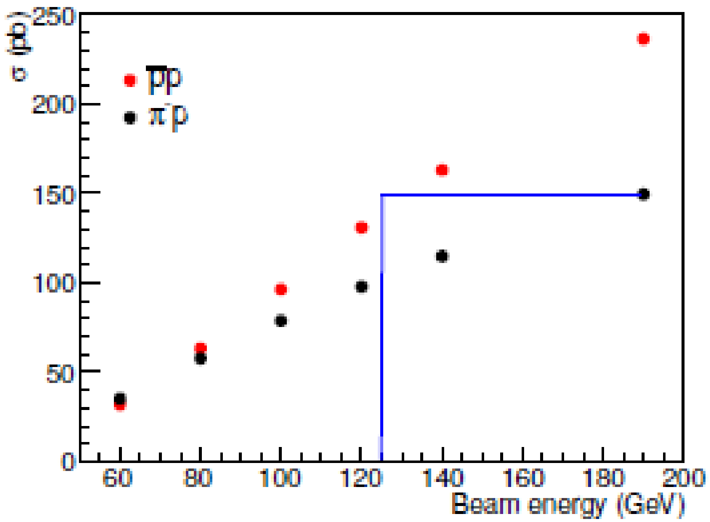
BM with antiproton beam $A_{UU}^{\cos(2\phi)} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{\perp q}$

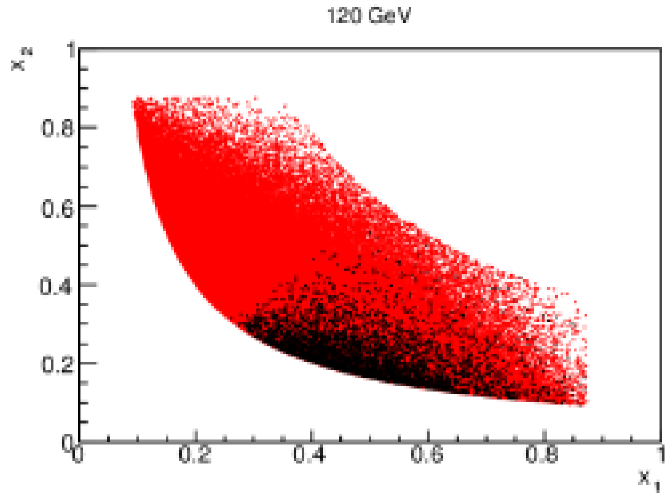
prediction of a universal behavior of the valence quark Boer-Mulders functions for pions and nucleons also awaits experimental confirmation

Combining analysis of DY data with pion and antiproton beam an indipendent extraction of pion BM is achievable

Indipendent extraction of proton BM

opportunity to verify the BM sign-change





Accessing e+e– DY pairs on top of μ+μ– would reinforce the feasibility of polarised measurements

Active absorber

Future

Summary

The Drell-Yan process is a very powerful tool to probe the TMDs

it can definitely help addressing several open challenges:

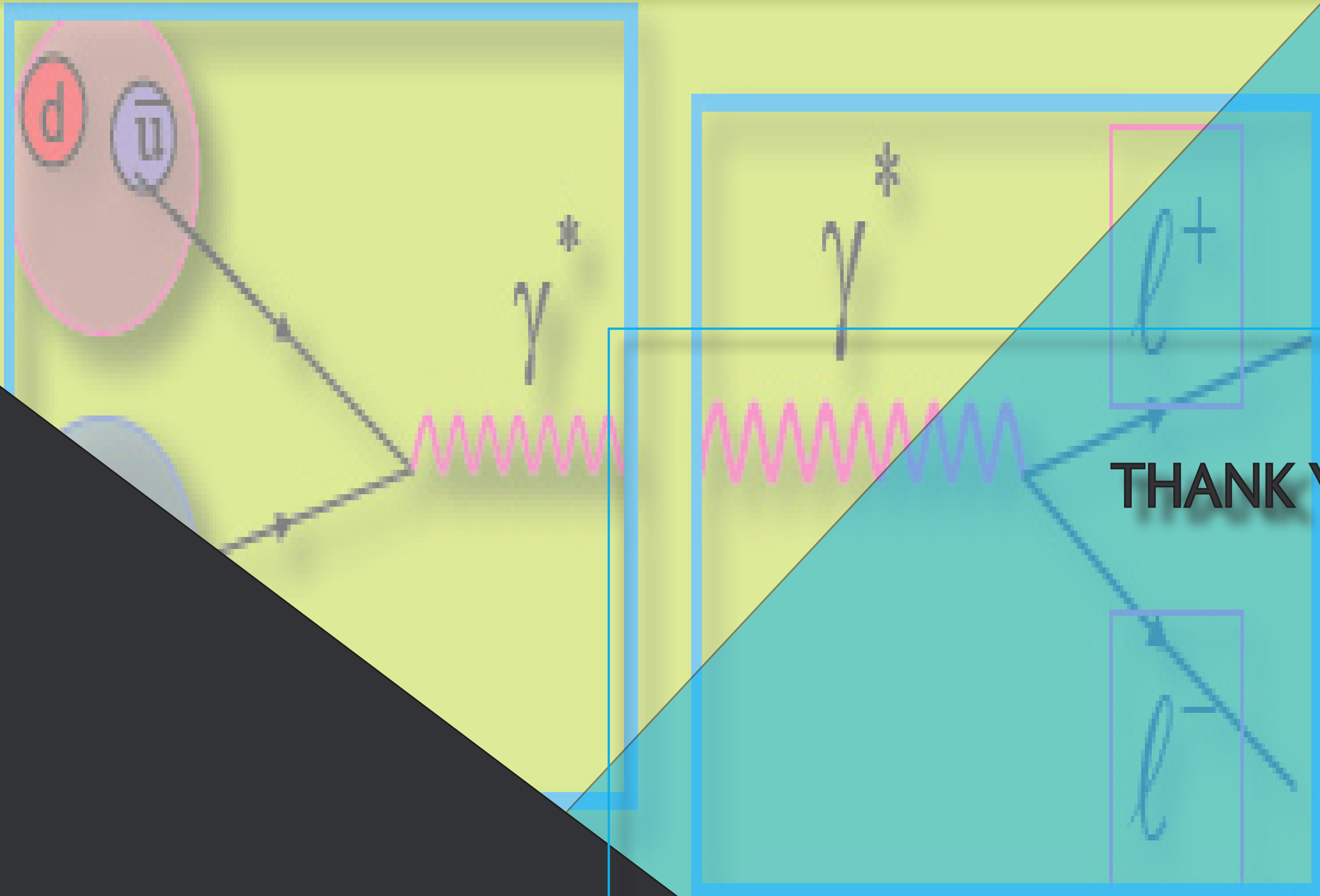
extracting the TMDs in a model indipendent way

check the validity of the TMD factorization formalism

probe the transverse structure of the mesons

easily access the sea-quark PDFs

Growing global interest worlwide, with several ongoing and upcoming experiments at existing or future hadron facilities:
J-PARC
RHIC
GSI – FAIR
CERN (COMPASS and LHC-spin)
NICA
FERMILAB



THANK YOU

Transversity 2017
Frascati, 11-15 December

DY with antiproton beam

http://cds.cern.ch/record/2057587/files/SPSC-P-353.1.pdf

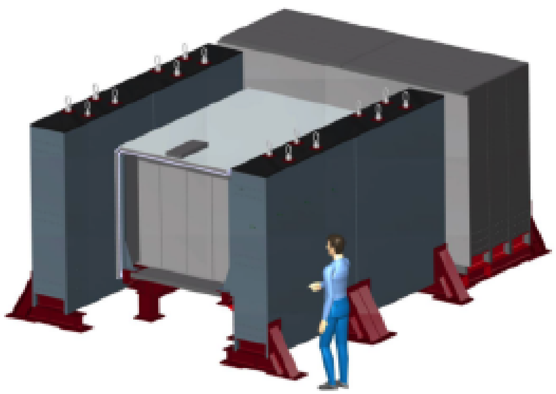


Figure 1: Baby MIND integrated into the WAGASCI experiment.

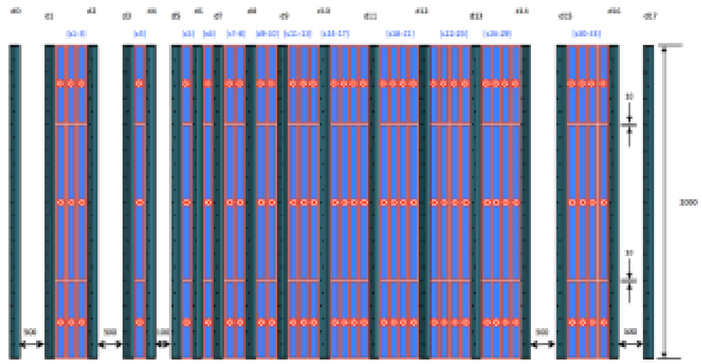


Figure 2: A side view of Baby MIND with scintillator planes (grey) and magnetised iron (blue/red).

- Basically combined tracking+SM1+calorimeter
- Instead of scintillators → High granularity detectors
- Can be placed between target and SM1
- Additional absorber in SM1 with beam dump?
- Could in principle allow also for e^+e^- detection?

Boer-Mulders function - sign change

1) From SIDIS data, one deduces that the proton B-M functions are negative for both u and d quarks:

$$h_{1,u}^{\perp,DIS}(p) < 0\ ;\ \ h_{1,d}^{\perp,DIS}(p) < 0$$

2) From NA10 pion Drell-Yan data, one deduces that the product of the pion valence quark B-M function and the proton valence quark B-M function is positive. Using u-quark dominance, we have:

$$h_{1,u}^{\perp,DY}(p) * h_{1,u}^{\perp,DY}(\pi) > 0$$

Therefore, either a) $h_{1,u}^{\perp,DY}(p) > 0;\ h_{1,u}^{\perp,DY}(\pi) > 0$ $(sign-change)$

or b) $h_{1,u}^{\perp,DY}(p) < 0;\ h_{1,u}^{\perp,DY}(\pi) < 0$ $(no\ sign-change)$

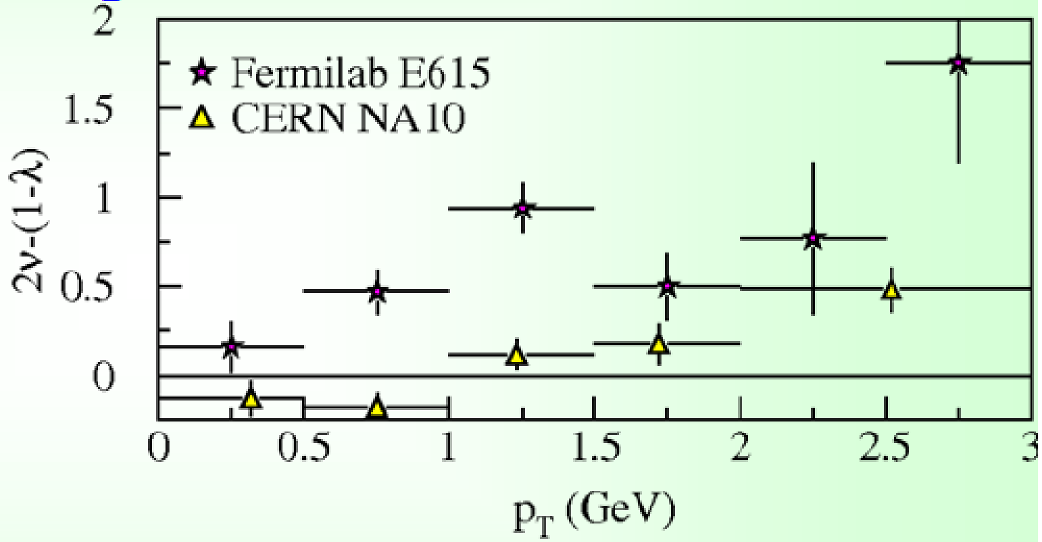
3) The crucial measurement is to determine the sign of the pion B-M function in polarized $\pi - p$ D-Y, since the $\sin(\phi + \phi_S)$ modulation is sensitive to the sign of $h_{1,u}^{\perp,DY}(\pi)$.

Lam-Tung relation

Lam-Tung Relation is theoretically robust

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

- Pionic Drell-Yan experiments see a violation which grows as a function of p_T. (Esp. NA10);
- Significant non-zero ν ($\cos 2\phi$) term



- Possible explanations?
  - Nuclear effects
  - Higher-Twist effects from quark-antiquark binding in pion
  - Factorization breaking QCD Vacuum
  - k_T dependent transverse momentum distribution (Boer Mulders $h_1^\perp$)

A clean tool to probe Transversity

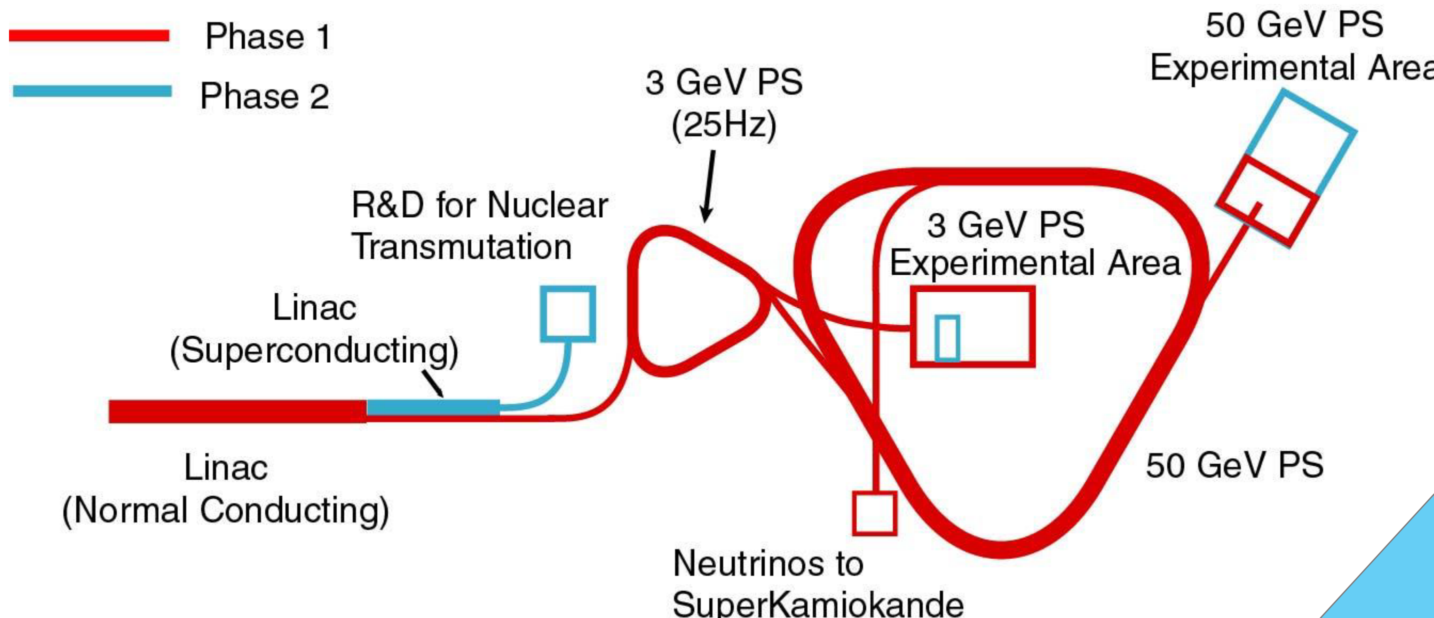
1. Double spin asymmetries at J-PARC?

Drell-Yan measurements using polarized proton beam on polarized target at the 50-GeV PS will provide determination of the spin-dependent antiquark distribution at an x region not accessible in the RHIC-spin program.

Polarized H^- source

RF dipole at 3 GeV RCS

Two 30% partial snakes at 50 GeV Main Ring

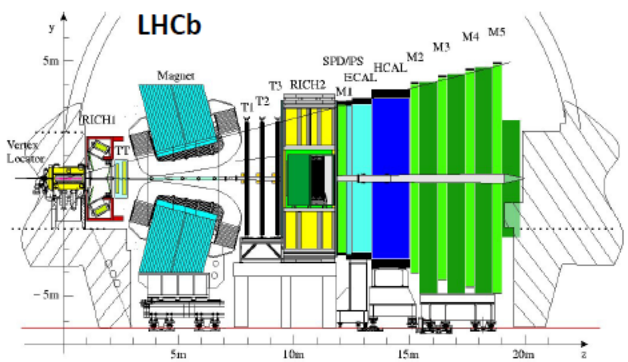


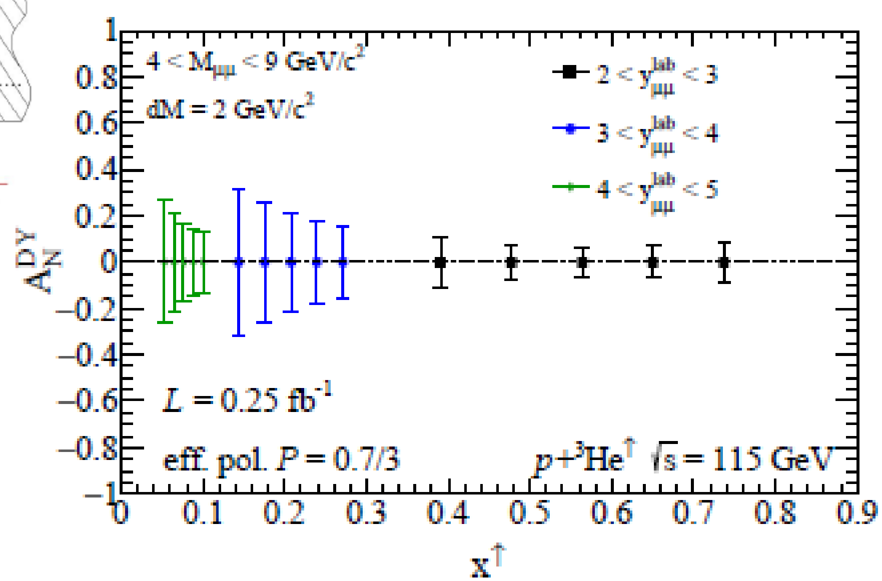
Probing the Sivers function sign change

AFTER @ LHC

Accessing the quark Sivers function in a polarised neutron: $p+3He^{\uparrow}$ collisions

Access to polarised neutrons and thus to the Sivers functions in a neutron which can shed some light on its isospin dependence





Lam-Tung Relation & Boer-Mulders function

origin of the Lam-Tung relation violation
Measurements with different beams over wide kinematical ranges would help differentiating the origin of Lam-Tung violation

Theoretical Interpretations of Lam-Tung Violation in pion-induced DY

	Boer-Mulders Function	QCD chromo-magnetic effect	Glauber gluon
Origin of effect	Hadron	QCD vacuum	Pion specific
Quark-flavor dependence	Yes	No	No
Hadron dependence	Yes	No	Yes
Large P_T limit	0	Nonzero	0
Violation for πp	Yes (valence quarks involved)	Yes	Yes
Violation for Kp	Yes (valence quarks involved)	Yes	Yes/No
Violation for $\bar{p}p$	Yes (valence quarks involved)	Yes	No
Violation for pp	No (sea quarks involved)	Yes	No
References	PRD 60, 014012 (1999)	Z. Phy. C 60,697 (1993)	PLB 726, 262 (2013)

the Sivers function sign change

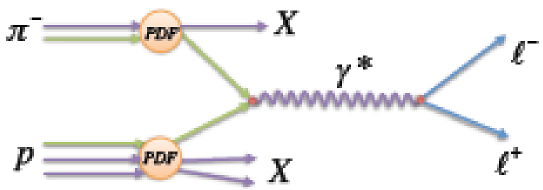
COMPASS

$\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X$

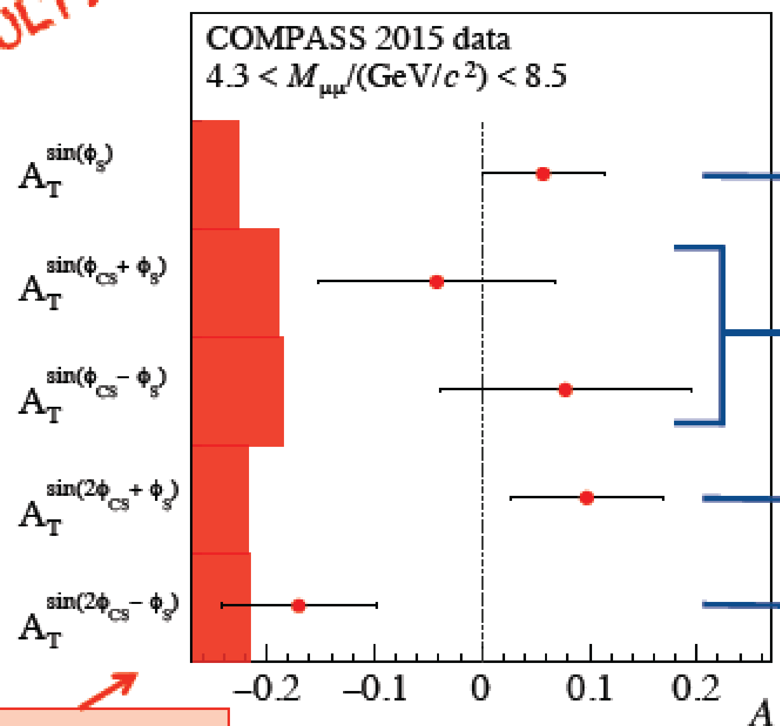
2015 DY RUN - first polarized DY data

TSAs

NEW RESULTS



$$d\sigma^{DY} \propto 1 + D_{[\sin 2\theta]} A_{UU}^{\cos\phi} \cos\phi + D_{[\sin^2\theta]} A_{UU}^{\cos 2\phi} \cos 2\phi$$
$$+ S_T \Big[D_{[1+\cos^2\theta]} A_{UT}^{\sin\phi_S} \sin\phi_S$$
$$+ D_{[\sin^2\theta]} \left(A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) + A_{UT}^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) \right)$$
$$+ D_{[\sin 2\theta]} \left(A_{UT}^{\sin(\phi-\phi_S)} \sin(\phi-\phi_S) + A_{UT}^{\sin(\phi+\phi_S)} \sin(\phi+\phi_S) \right) \Big]$$



$\sigma_{syst} = 0.7\ \sigma_{stat}$

- Unpolarised PDF (π) $\otimes$ Sivers (p)
- higher twist asymmetries
- Boer-Mulders (π) $\otimes$ pretzelosity (p)
- Boer-Mulders (π) $\otimes$ transversity (p)

Preprint: CERN-EP-2017-059
arXiv: 1704.00488

Test of TMD formalism

Drell-Yan process as a physics tool

arXiv:hep-ph/9810268v1 6 Oct 1998

1. It played a crucial role in the design of the experiments at CERN which discovered the W and Z bosons

2. For the first time we have gotten a glimpse for how the quarks and antiquarks are distributed inside the unstable particles pion and kaon

3. By combining proton and antiproton data, it is possible to separate the valence and sea distributions inside a proton and an antiproton

4. Lepton pair production data have become an integral component of the global fits together with the deep inelastic lepton scatterings in determining the parton distributions inside a nucleon

5. Lepton pair production with a polarized target/beam has been suggested as a tool to pin down the spin-dependent parton distributions in a nucleon, especially for the sea quarks

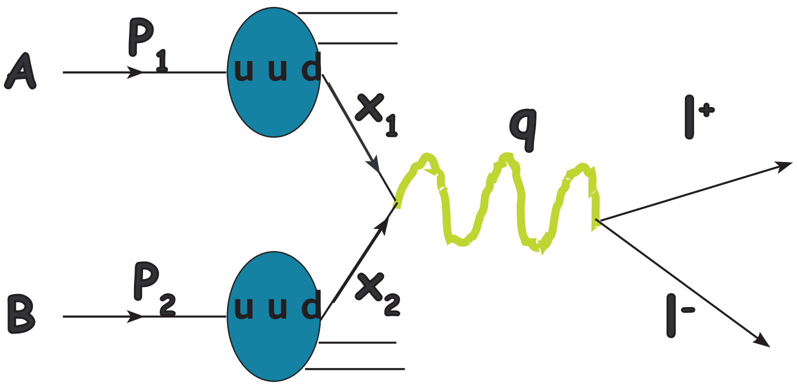
Fermilab Proton induced DY scattering

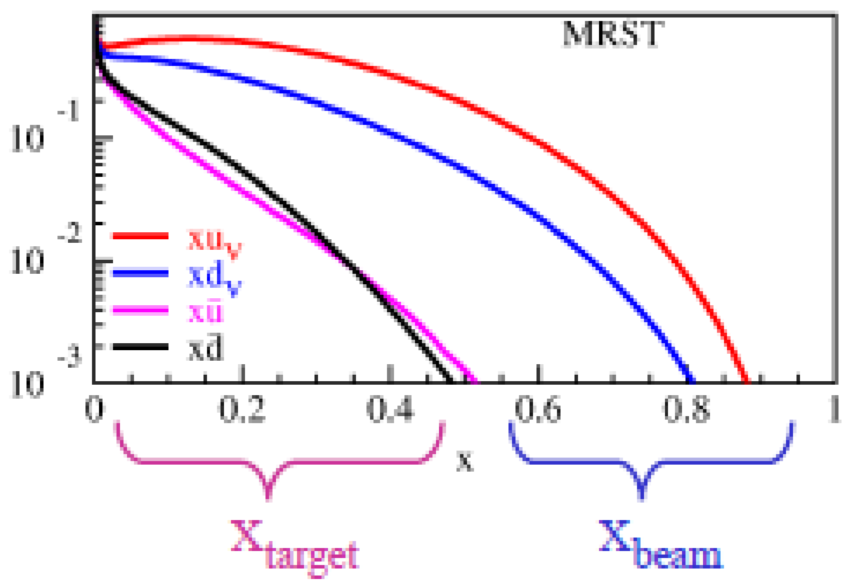
Detector acceptance chooses range in x_{target} and x_{beam}

$x_F = x_{beam} - x_{target} > 0$

high-x: valence beam quarks

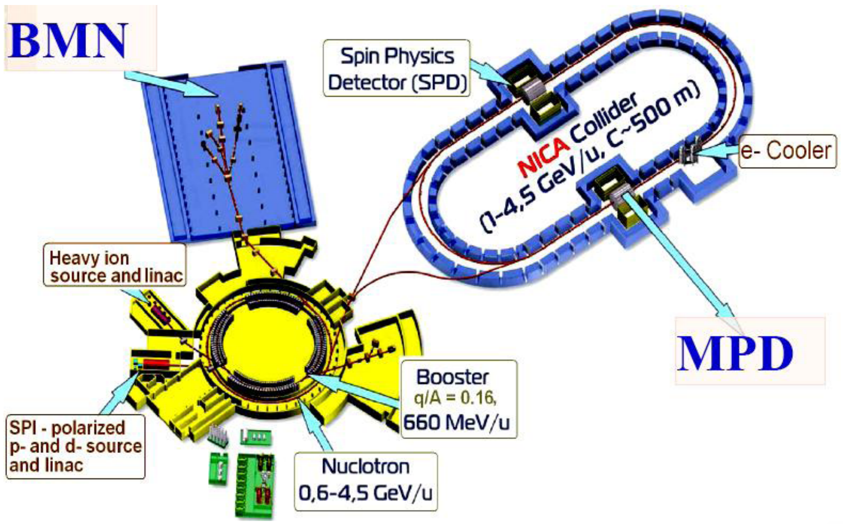
Low/interm.-x: sea target quarks





A clean tool to probe Transversity

1. Double spin asymmetries at NICA?

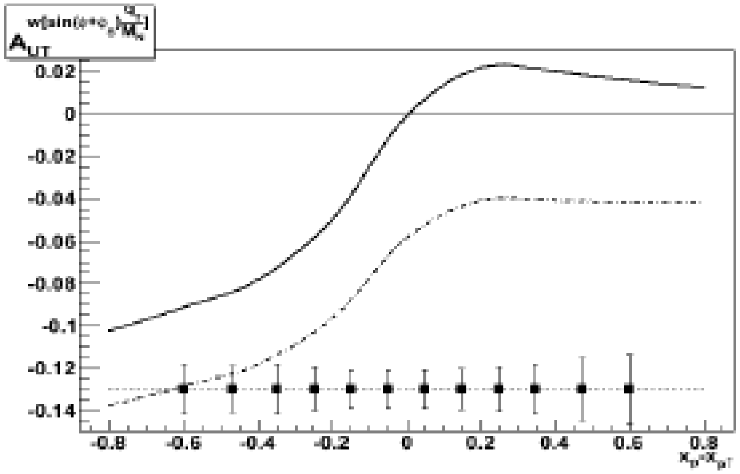


Operation with proton and deuteron beam, all possible polarization combination

First time comprehensive studies of all leading-twist PDFs in single experiment

estimations of Boer-Mulders asymmetry
statisitical error with 100k events
two versions of the evolution model for the transversity are considered

$\sqrt{s} = 26\ GeV\ with\ Q^2 = 15$



Experiment	NICA, SPD
mode	*collider*
Beam/target	*pp, pd,dd*
Polarization:b/t	*0.5*
Luminosity	10^{32}
√s , GeV	*10-26*
$x_{1(beam)}$ *range*	*0.1-0.8*
q_T*, GeV*	*0.5 -6.0*
Lepton pairs,	$\mu^-\mu^+$, e^+e^-

Future

Drell-Yan for transverse spin effects

already played a key role in the study of transverse spin and TMDs

- Ralston & Soper (1979) introduced the transversity distribution h_1 in the context of transversely polarized DY. The same process was studied in the 90s by Artru & Mekhfi, Jaffe & Ji, Cortes, Pire & Ralston

- The first phenomenological indication of the possible existence of a T-odd TMD, the Boer-Mulders function came from Boer's (1999) study of the $\cos 2\phi$ asymmetry in DY