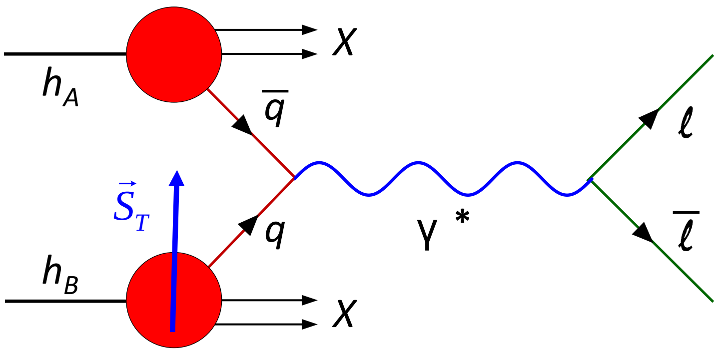
Polarized Drell-Yan measurement at COMPASS-II

Takahiro Sawada, Institute of Physics, Academia Sinica, Taiwan
on behalf of the COMPASS Collaboration



HADRON2013 - Nara (Japan)
Nov 4th - 8th, 2013

Outline

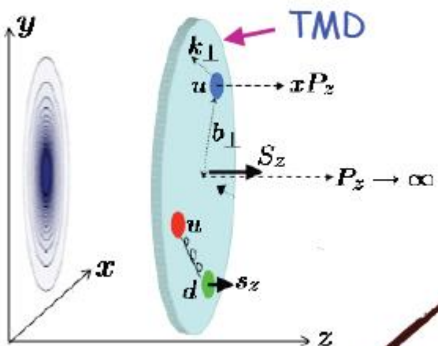
- Brief introduction of TMD PDFs
- Polarized Drell-Yan process
- Polarized Drell-Yan experiment in COMPASS-II
- Beam Test Results
- Expected Precision
- Time Schedule
- Summary

quantum phase-space "tomography" of the nucleon

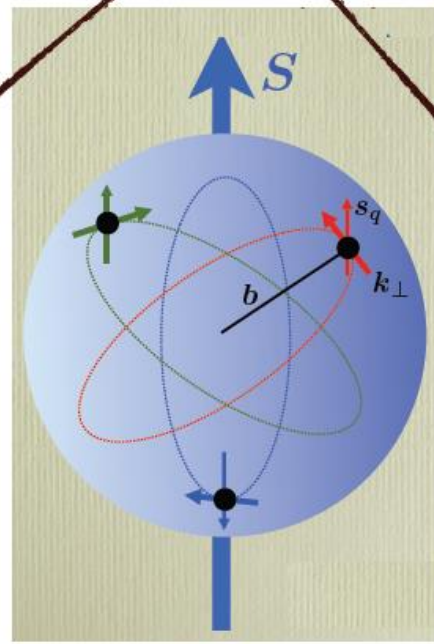
Ji: PRL91, 062001(2003)

Wigner functions: $W^q(\mathbf{k}, \mathbf{b})$

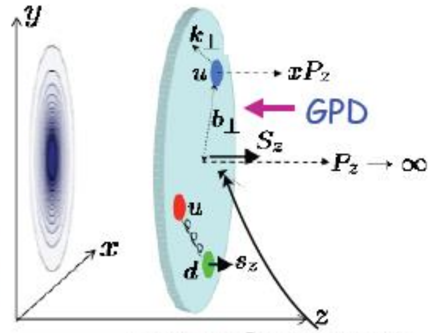
probability to find a quark in a nucleon with a certain polarization in a position **b** and momentum **k**



$\int d^3\mathbf{b}$



$\int d^2\mathbf{k_T}\, d\mathbf{b_L}$



center of momentum

$R_\perp = \sum x_i r_{\perp i}$

$q(x, \mathbf{k_T})$

Transverse Momentum Dependent (**TMDs**) distribution functions

★ Drell-Yan measurements

☛ semi-inclusive measurements

$q(x, \mathbf{b_T})$

FT

space dependent distribution functions

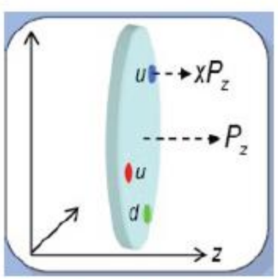
$H(x, \xi, t)$

Generalized Parton Distributions (**GPDs**)

☛ exclusive measurements

$\xi = 0,\ t = 0$

$\int d^2\mathbf{k_T}$



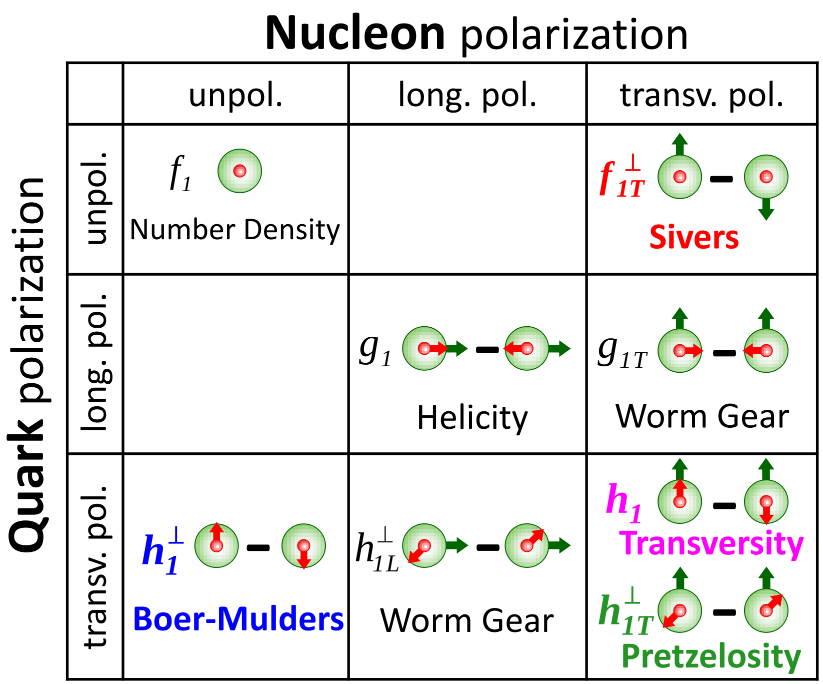
$f^q(x)$

Parton Distribution Functions (**PDFs**)

☛ inclusive measurements

Nucleon Structure at Leading Order (LO)

At LO, the nucleon structure are described by 8 Transverse Momentum Dependent Parton Distribution Functions (TMD PDFs), when the quark intrinsic transverse momentum (k_T) is taken into account.



$f_{1T}^{\perp}(x,k_T^2)$ Sivers function

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

$h_1^{\perp}(x,k_T^2)$ Boer-Mulders function

the correlation between the transverse spin and the transverse momentum of a quark in unpolarized nucleon.

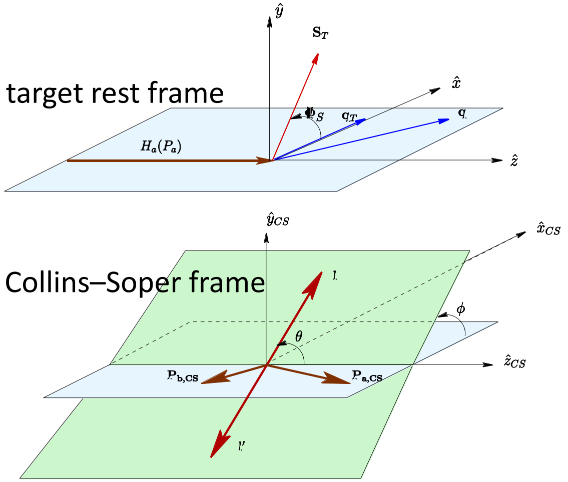
$h_{1T}^{\perp}(x,k_T^2)$ Pretzelosity function

the polarization of a quark along its k_T direction, making accessible to the orbital angular momentum information.

Single transversely-polarized Drell-Yan (DY) cross-section in LO QCD Parton Model

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

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



Clean access to 4 azimuthal modulations (no Fragmentation Functions are involved)

$$A_U^{\cos 2\varphi} \propto \mathrm{BM}(h_1^{\perp})|_{\pi} \otimes \mathrm{BM}(h_1^{\perp})|_{p}$$

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

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

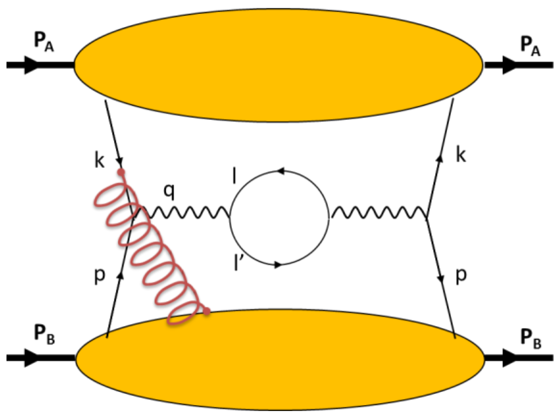
$$A_T^{\sin(2\varphi-\varphi_s)} \propto \mathrm{BM}(h_1^{\perp})|_{\pi} \otimes \mathrm{transversity}(h_1)|_{p}$$

- A : azimuthal asymmetry
- D : depolarization factor
- S_T : transverse target spin
- F : flux of incoming hadrons
- σ_U : cross section surviving integration over φ and φ_S
- φ_S : azimuthal angle of S_T in the target rest frame
- θ, φ : polar and azimuthal angle of the lepton in the Collins-Soper frame

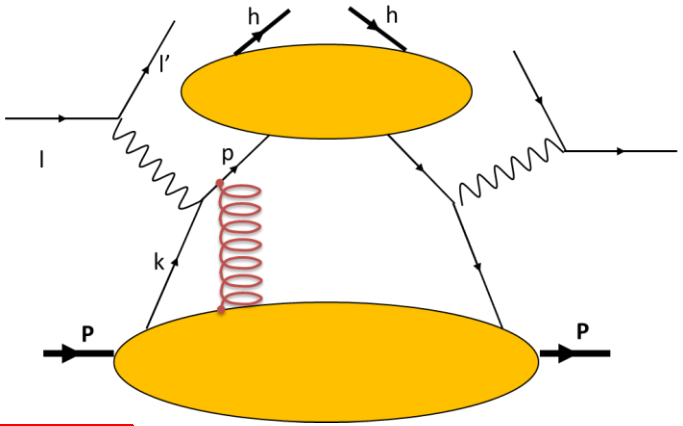
Sign Change of Sivers & Boer-Mulders Functions

J.C. Collins, Phys. Lett. B 536 (2002) 43
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

DY



SIDIS (Semi-Inclusive Deep-Inelastic Scattering)



T-odd

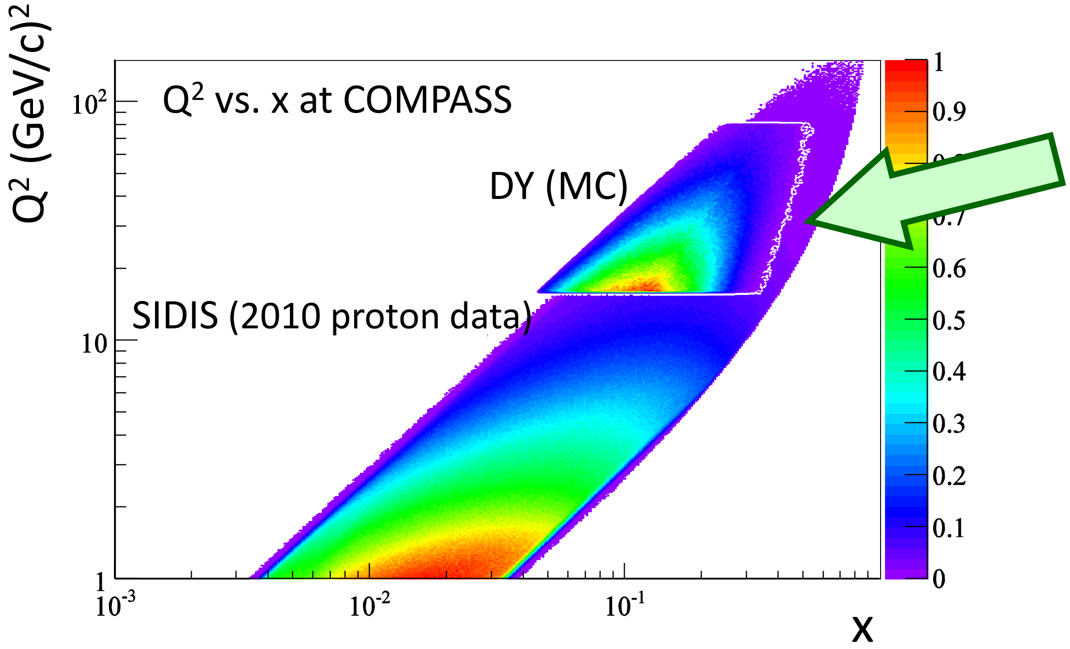
$$f_{1T}^{\perp}|_{\mathrm{DY}} = - f_{1T}^{\perp}|_{\mathrm{SIDIS}}$$ **Sivers**

$$h_{1}^{\perp}|_{\mathrm{DY}} = - h_{1}^{\perp}|_{\mathrm{SIDIS}}$$ **Boer-Mulders**

- QCD gluon gauge link 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.***

DY ⟷ SIDIS at COMPASS

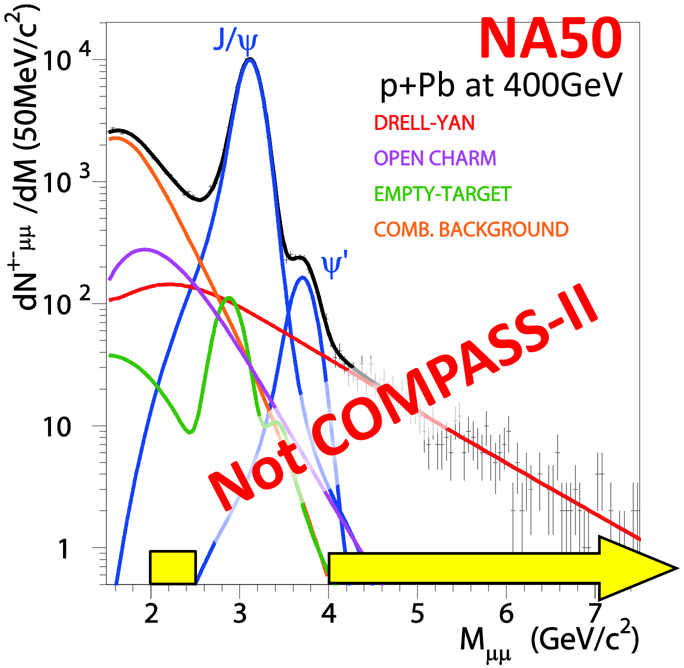
In COMPASS, we have the opportunity to access these TMD PDFs from both DY and SIDIS processes.



There is a phase space overlap between the two measurements.

Kinematics compatibility between DY and SIDIS

DY experiment



* Combinatorial and physics backgrounds are different from COMPASS-II DY.

High Mass Region ($4 \le M_{\mu\mu} \le 9\,\mathrm{GeV/c^2}$)

- **Clean DY signal**
- Small Production Cross section

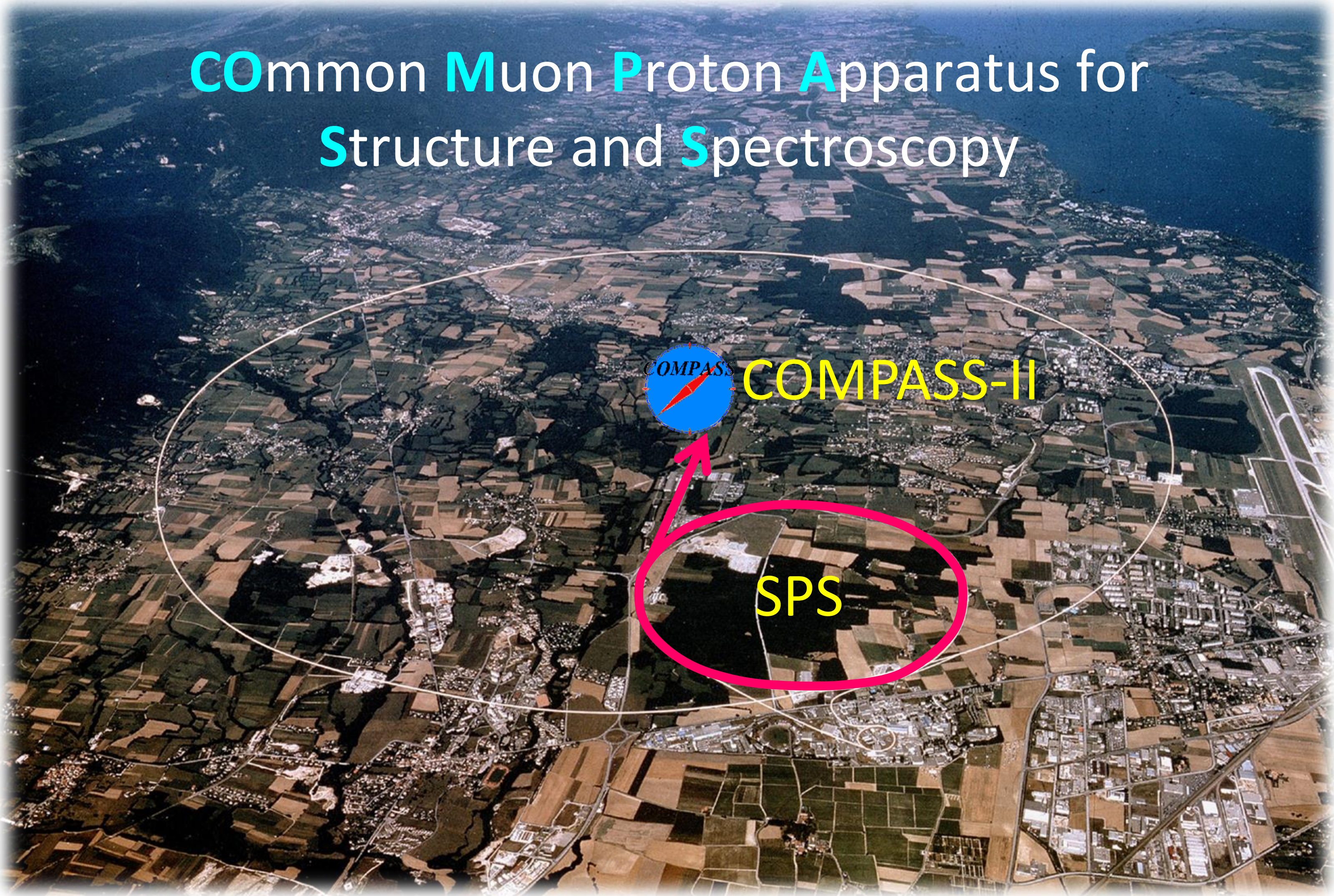
Intermediate Mass Region ($2 \le M_{\mu\mu} \le 2.5\,\mathrm{GeV/c^2}$)

- Combinatorial background

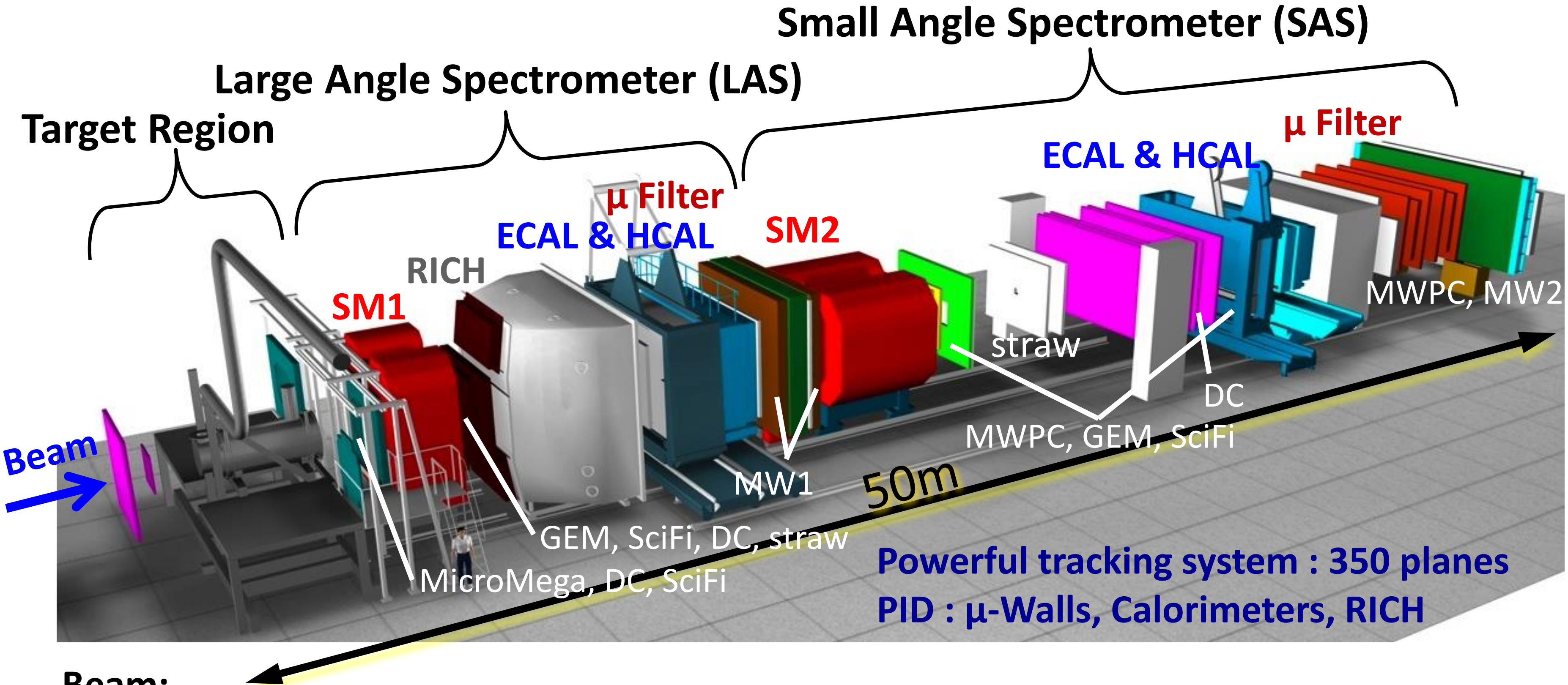
- High intensity beam
  → and also the Detectors and Data Acquisition System (DAQ) designed to stand high particle fluxes.
- Hadron absorber
- Large angular acceptance spectrometer
- Transversely polarized solid state proton target
- Dedicated muon trigger system.

COMPASS-II fulfills all the conditions.

COMPASS-II facility at CERN



COMPASS-II facility



Beam:

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

Hadron beam : π^+, π^-, K^+, K^-, p

Target:

Polarized proton and deuteron target

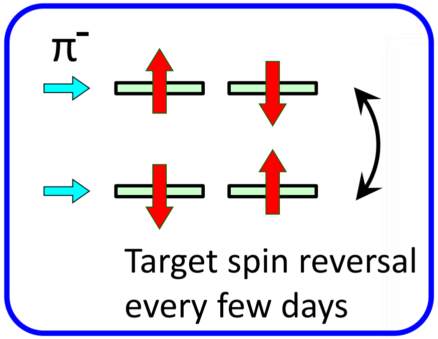
Liquid hydrogen target

Nuclear target

Various Combinations of Beam & Target

Key Elements in DY@COMPASS-II

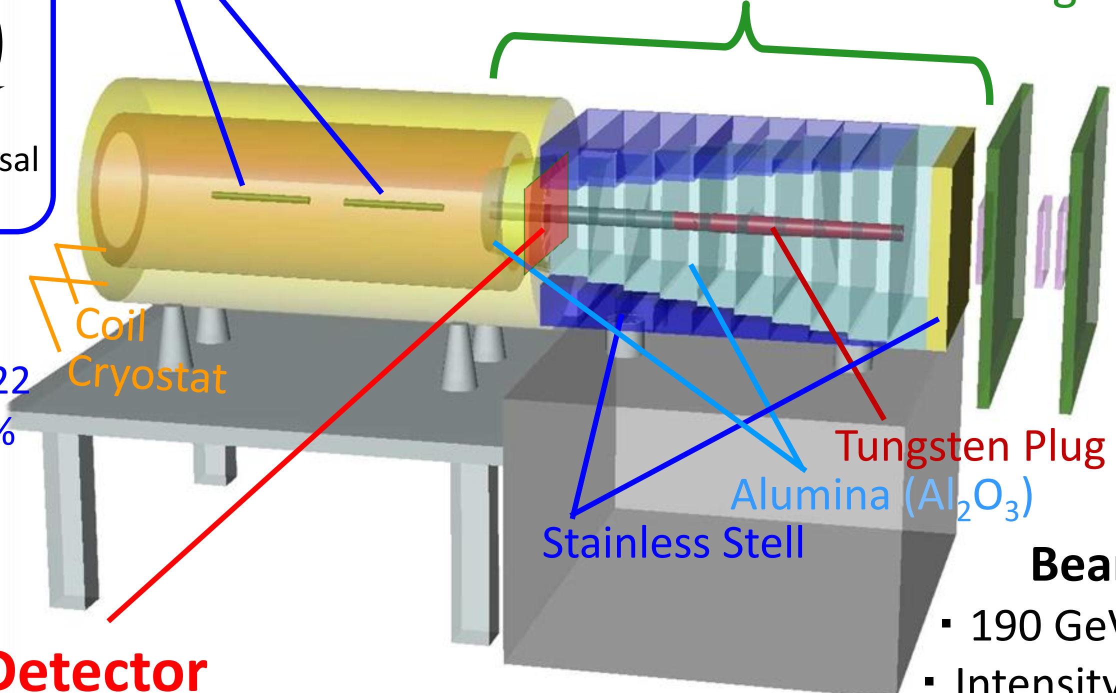
Polarized NH_3 target



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

Magnet
- Solenoid : 2.5 T
- Dipole : 0.5 T

Hadron Absorber
- Large Stopping Power for hadrons
- Small Multiple Scattering for leptons
- Radiation Shielding



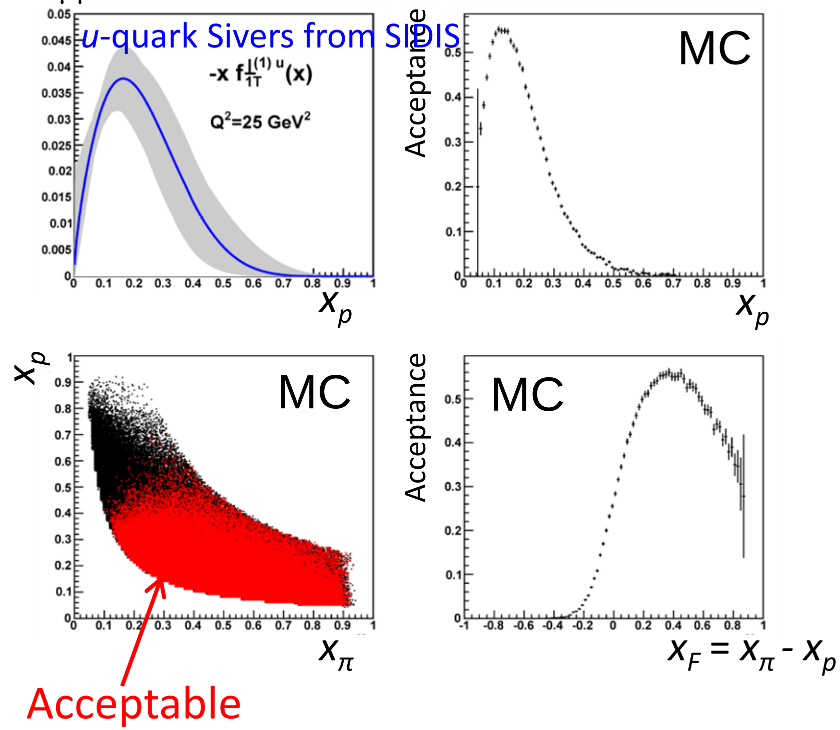
Beam
- 190 GeV/c π-
- Intensity: 10^8 particles/s
- Spill extraction length: 9.6 sec
- SPS cycle: 33.6 sec

Vertex Detector
Improvement of
- Mass/Angle Resolution of the virtual photon
- Vertex Position Resolution

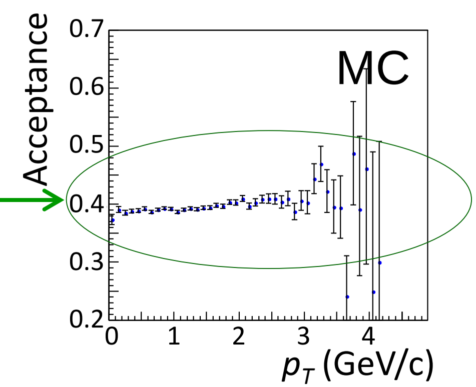
Kinematics/Acceptance

$\pi^- p \rightarrow \mu^+ \mu^- X \quad 4 \leq M_{\mu\mu} \leq 9\,\mathrm{GeV/c^2}$

- The COMPASS acceptance covers the **valence quark region**
- $<P_T>$ ~ 1GeV – TMDs induced effects expected to be dominant with respect to the higher QCD corrections



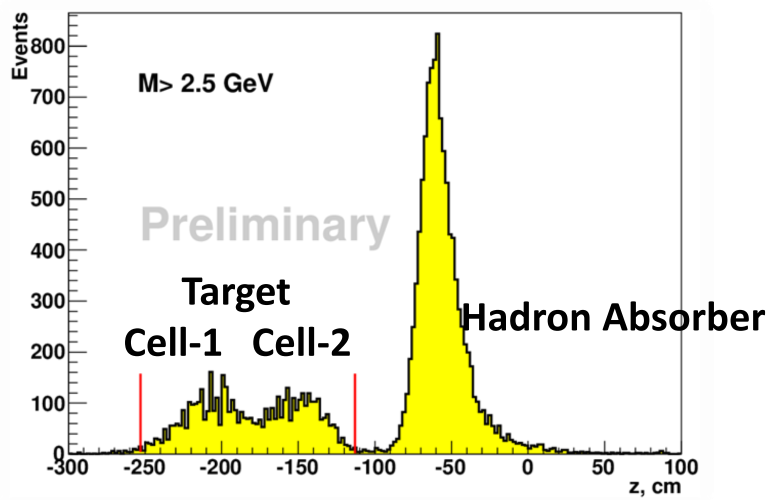
Large angular acceptance spectrometer (approx. 10 times larger acceptance compare to the typical past DY experiments) provides a "flat" acceptance for p_T



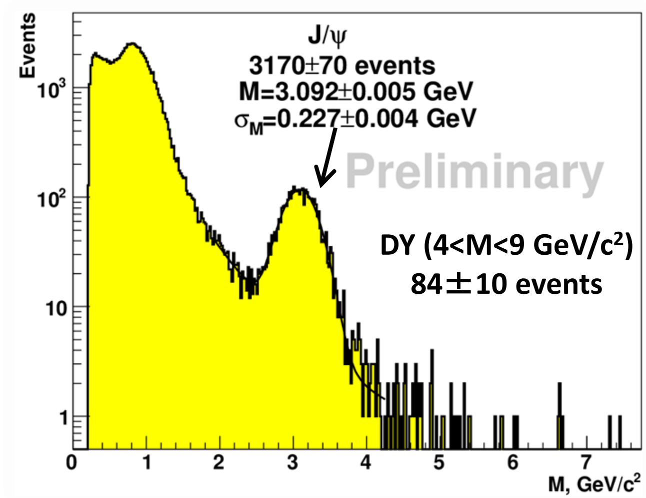
M. Anselmino et al., Eur. Phys. J. A39 (2009) 89

Beam Test 2009

- 160 GeV/c π- beam
- 2 cells polyethylene target
- Hadron Absorber and Beam Plug (not final ver.)
- 3 days of data taking



z-vertex position of $\mu^+ \mu^-$ pairs



Invariant mass spectrum of $\mu^+ \mu^-$ pairs

Reasonable Z-vertex separation, allowing
to distinguish the 2 target cells and the absorber.

from Monte-Carlo simulation:
expected J/Ψ : 3600±600
expected DY : 110± 22

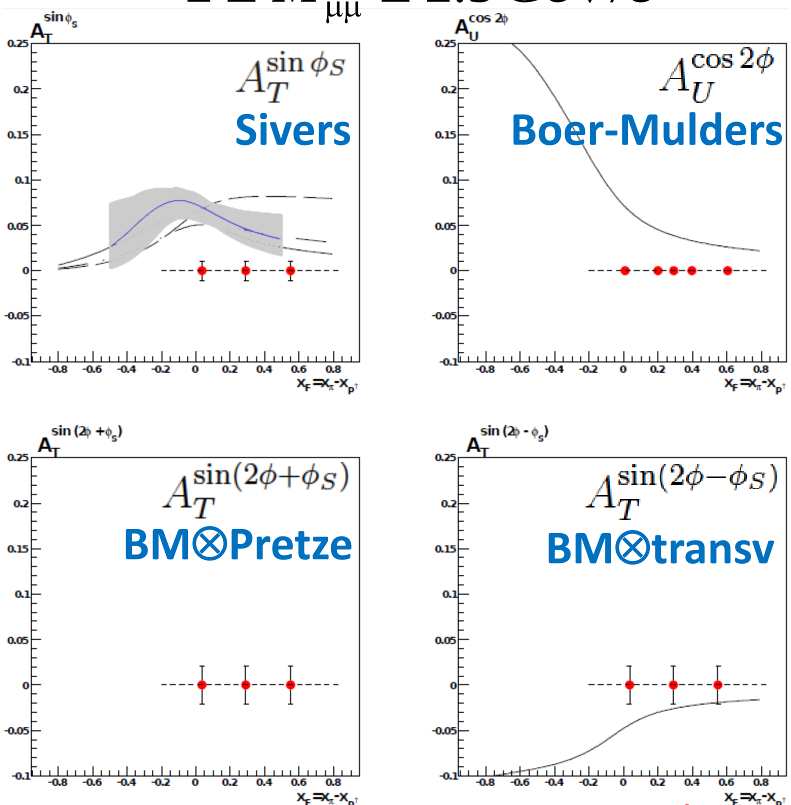
Theoretical Predictions vs. Expected Precision

Luminosity: $1.2 \times 10^{32}\, cm^{-2}s^{-1}$ (Beam Intensity: $6 \times 10^{7}\, particles/sec$)

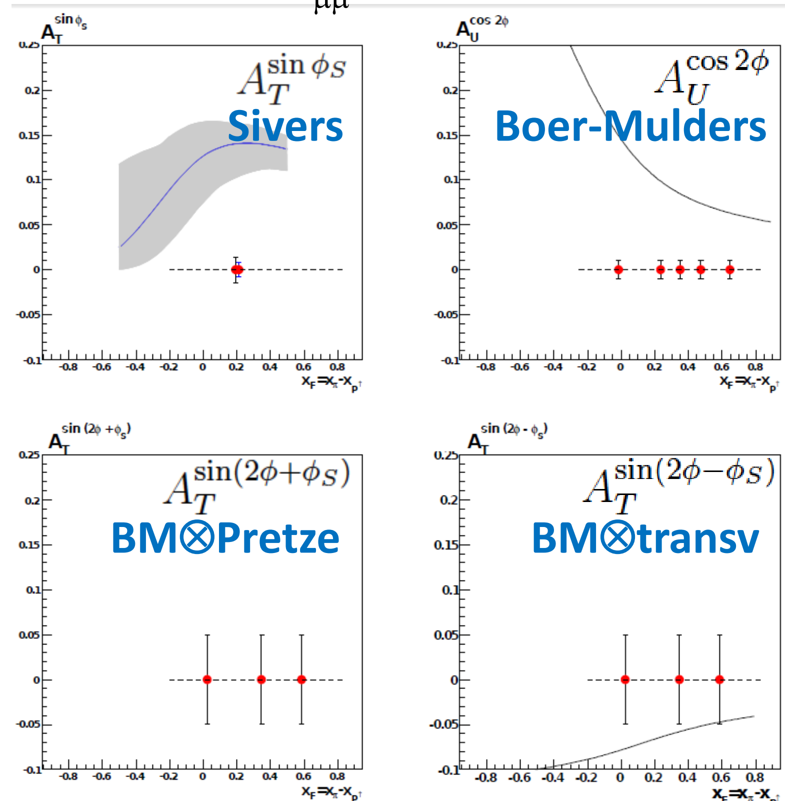
280 days of data-taking → 2.5×10^5 DY events in $4 \le M_{\mu\mu} \le 9\,\mathrm{GeV/c^2}$ region

1.4×10^6 DY events in $2 \le M_{\mu\mu} \le 2.5\,\mathrm{GeV/c^2}$ region

$2 \le M_{\mu\mu} \le 2.5\,\mathrm{GeV/c^2}$



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



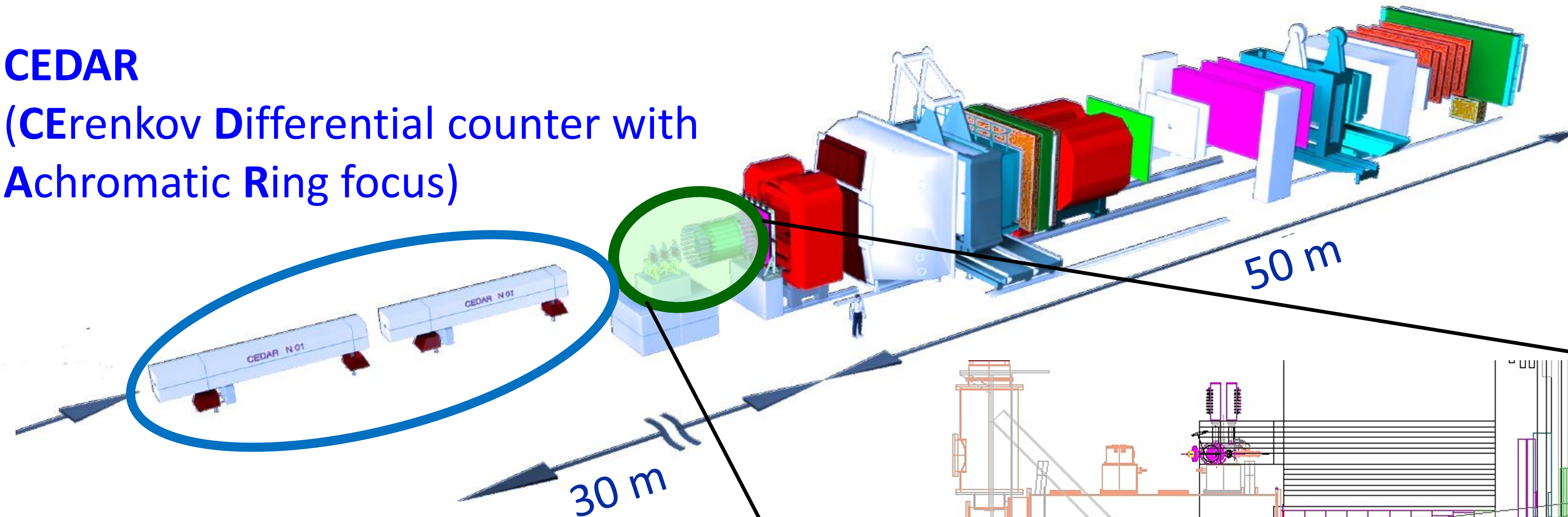
M. Anselmino et. Al, Eur.Phys.J.A39:89-100,2009.

V. Barone et al., Phys. Rept. 359 (2002) 1.

B. Zhang et al., Phys. Rev. D77 (2008) 054011,

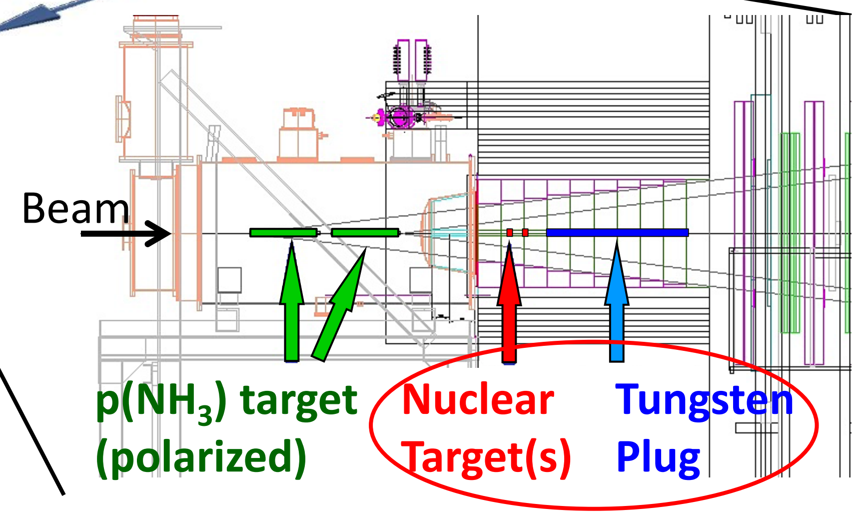
Possibility of *extended* setup

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



(Unpolarized)
Nuclear Target(s)

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

- **Flavor dependency of EMC effect**
- **Structure of the π and *K***
- **Strange quark in nucleon**

Time Schedule

- The first-ever polarised DY experiment will be started in the 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.

- Medium term future program (^{6}LiD and LH_2 targets):
  2020-2024 ?
- Long term future program (Kaon & Anti-proton high intensity):
  2025- ?

A lots of new unique data is just behind the corner !!

Summary

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

backup

Planned Polarized Drell-Yan Experiments

Experiment	Particles	Energy	x_1 or x_2	Luminosity	Timeline
COMPASS (CERN)	$\pi^{\pm}$ + $p^{\uparrow}$	190 GeV $\sqrt{s}$ = 19 GeV	x_2 = 0.2 – 0.3 x_2 ~ 0.05 (low mass)	2 x 10^{33} cm^{-2} s^{-1}	2014
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
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
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 ?
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
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
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}	?

Sivers Functions with TMD Evolution

P. Sun and F. Yang, arXiv: 1308.5003

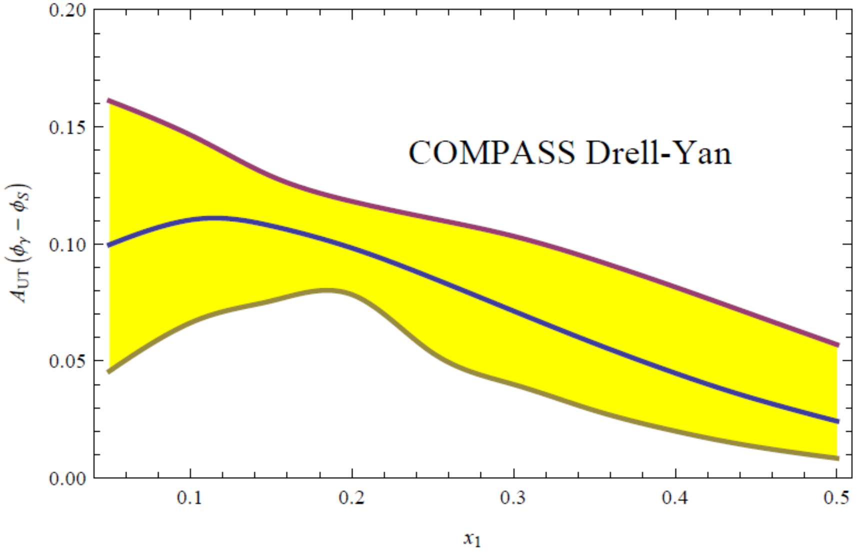


FIG. 12: Predictions for the Sivers single spin asymmetry for the Drell-Yan process at COMPASS, with π^- beam of 190GeV, as function of x_p. We have chosen the average $x_\pi \approx 0.55$ and integrate transverse momentum up to 2GeV.