Nucleon spin and
3D structure studies
at COMPASS

BAKUR PARSAMYAN
AANL, CERN, INFN section of Turin
on behalf of the COMPASS Collaboration

The XXXI International Workshop on
Deep Inelastic Scattering and Related Subjects
April 8 – 12, 2024, Maison MINATEC, Grenoble, France
COMPASS collaboration
Common Muon and Proton Apparatus for Structure and Spectroscopy

25 institutions from 13 countries
– nearly 200 physicists (in 2022)

• CERN SPS north area
• Fixed target experiment
• Approved in 1997 (25 years)
• Taking data since 2002 (20 years)

International Workshop on Hadron Structure and Spectroscopy
IWHSS-2022 workshop (anniversary edition)
CERN Globe, August 29-31, 2022

https://indico.cern.ch/e/IWHSS-2022
COMPASS collaboration
Common Muon and Proton Apparatus for Structure and Spectroscopy

28 institutions from 14 countries – nearly 210 physicists (in 2023: start of the Analysis Phase)

- CERN SPS north area
- Fixed target experiment
- Approved in 1997 (25 years)
- Taking data since 2002 (20 years)

Wide physics program
COMPASS-I
- Data taking 2002-2011
- Muon and hadron beams
- Nucleon spin structure
- Spectroscopy

COMPASS-II
- Data taking 2012-2022
- Primakoff
- DVCS (GPD+SIDIS)
- Polarized Drell-Yan
- Transverse deuteron SIDIS 2022

3 new groups joined the COMPASS collaboration in 2023
UCon (US), AANL (Armenia), NCU (Taiwan)

COMPASS web page: http://wwwcompass.cern.ch

See talks by: S. Asatryan, V. Andrieux, V. Benesova, M. Niemiec, M. Peskova, A. Sandacz, M. Stolarski
**COMPASS experimental setup**

**CCommon Muon Proton Apparatus for Structure and Spectroscopy**

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)

- Primary beam - 400 GeV $p$ from SPS
  - Impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - $h^-$ beam: $97\% \pi^-, 2\% K^-, 1\% p$
  - $h^+$ beam: $75\% \pi^+, 24\% p, 1\% K^+$
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

- Large-acceptance forward spectrometer
  - Precise tracking (350 planes)
    SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon walls
  - PID - CEDARs, RICH, calorimeters, MWs

Various targets:
- Polarized solid-state NH$_3$ or $^6$LiD
- Liquid H$_2$
- Solid-state nuclear targets (e.g. Ni, W, Pb)

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COMPASS experimental setup: Phase II (SIDIS programme)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

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160 GeV tertiary muon beams
- $\mu^+$ longitudinally polarized

- Polarized solid-state NH$_3$ or $^6$LiD
- Two or three oppositely polarized cells
- Longitudinal and transverse polarization
COMPASS experimental setup: Phase II (DY programme)

COmmom Muon Proton Apparatus for Structure and Spectroscopy

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- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized
- Solid-state NH$_3$ material
- Two cells
  - Oppositely polarized
  - Transverse polarization
COMPASS experimental setup: Phase II (DVCS programme)

**COmmon Muon Proton Apparatus for Structure and Spectroscopy**

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- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

- Unpolarized target
- Liquid H$_2$
- Recoil detector “CAMERA”

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COMPASS timeline

- **Phase I**
  - Pilot run
  - SIDIS L/T
  - Spectroscopy

- **COMPASS proposal**

- **CERN experiment brings precision to a cornerstone of particle physics**

- **COMPASS measures the pion polarizability**

- **COMPASS points to triangle singularity**

- **Turning the needle: A snapshot of part of the COMPASS spectrometer. Gauth. F. Druxlik / CERN Photo (using photo)**

- **The COMPASS experiment at CERN has reported the first direct evidence for a long-debated theoretical prediction that tauon decays which can masquerade as a resonance...**

- **25 years 1997 - 2022**

- **9 April 2024**

- **B. Parsamyan**

- **EPJC 77 (2017) 209**
- **PLB 753 (2016) 38**
- **PLB 807 (2020) 135600**
- **PRD 95 (2017) 032004**
- **PLB 744 (2015) 250**
- **PRD 95 (2017) 032004**
The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

**Nucleon structure**
- Hard scattering of $\mu^\pm$ and $\pi^-$ off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions

**Hadron spectroscopy**
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

**Chiral dynamics**
- Test chiral perturbation theory in $\pi(K)\gamma$ reactions
- $\pi^\pm$ and $K^\pm$ polarizabilities
- Chiral anomaly $F_{3\pi}$
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Nucleon 3D structure: GPDs

- Transverse position $\vec{b}_T$ of partons
  - Correlation between $\vec{b}_T$ and $x$
  - Complementary to TMD PDFs
- 8 generalized parton distribution functions (GPDs)
  - Contain information about parton orbital angular momentum
  - Mostly unknown
- COMPASS exclusive process measurements:
  - Deeply virtual Compton scattering (DVCS): $\mu + N \rightarrow \mu + \gamma + N$
  - Hard exclusive meson production (HEMP): $\mu + N \rightarrow \mu + \text{VM} + N$
    with VM = $\pi^0$, $\rho(770)$, $\omega(782)$, ...

COMPASS 2016 data (2/3)

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**Nucleon spin structure: collinear approach ↔ TMDs**

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• PDFs – universal (process independent) objects; T-odd PDFs – conditionally universal

![Diagram showing quark and parton distributions](image)

**Longitudinal momentum** $k^+ = xP^+$

**Transverse plane**

**Transverse plane**

**Transverse momentum** $k_T$

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Hadron multiplicities; $h^\pm$, $\pi^\pm$ and $K^\pm$ (2016 data) 

A set of complex corrections: 
- Acceptance, rad. corrections, 
- PID, diffractive VMs, etc.

New radiative corrections  
see M. Stolarski’s talk

The article is in a final drafting stage
3D unpolarized Drell-Yan cross section on NH$_3$ and W

- First new results in 30 years!
- Data from light/heavy targets
  - NH$_3$-He, Al, W
- Nuclear dependence
- 1D/2D/3D representations $x_F:q_T:M$
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF

see V. Andrieux’s talk
Nucleon spin structure: collinear approach ↔ TMDs

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- PDFs – universal (process independent) objects; T-odd PDFs – conditionally universal
Nucleon spin structure: helicity $g_{1,d}^q(x)$

- **COMPASS contribution:**
  
  lowest $x$ and highest $Q^2$ regions
Nucleon spin structure: helicity $g^q_{1,p}(x)$

- COMPASS contribution: lowest $x$ and highest $Q^2$ regions
- Both deuteron and proton target data
Nucleon spin structure: helicity $g_{1,q}^p(x)$

- COMPASS contribution: lowest $x$ and highest $Q^2$ regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest $x$ and $Q^2$ – positive signal for $g_{1,p}^p(x)$
Nucleon spin structure: helicity $g_{1,d(p)}^q(x)$

- COMPASS contribution: lowest $x$ and highest $Q^2$ regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest $x$ and $Q^2$ – positive signal for $g_1^p(x)$
- Both inclusive and semi-inclusive measurements – access to flavor
Nucleon spin structure: azimuthal effects

- 1964 Quark model
- 1969 Parton model
- 1973 asymptotic freedom and QCD
- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries
Cahn effect in SIDIS

\[
\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \alpha \frac{y^2}{xyQ^2} \frac{1}{2(1 - \varepsilon)} \left( 1 + \frac{y^2}{2x} \right) \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \times \left( 1 + \sqrt{2\varepsilon(1 + \varepsilon)} A_{UU}^{\cos \phi_h} \cos \phi_h + \ldots \right)
\]

f_1^q (x, k_T^2) number density

The point that there are azimuthal dependences, which arise from the transverse momenta of the partons was clearly stated in this papers: T.P. Cheng and A. Zee, Phys. Rev. D6 (1972) 885; F. Ravndal, Phys. Lett. 43B (1973) 301; R.L. Kingsley, Phys. Rev. D10 (1974) 1580; A.M. Kotsinyan, Teor. Mat. Fiz. 24 (1975) 206;
Cahn effect in SIDIS

\[ \frac{d\sigma}{dxdydzdp_T^2d\phi_Hd\phi_S} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \]

\[ \times \left( 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi} \cos \phi_H + \ldots \right) \]

Cahn effect

As of 1978 – simplistic kinematic effect:
• non-zero \( k_T \) induces an azimuthal modulation

As of 2023 – complex SF (twist-2/3 functions)
• Measurements by different experiments

\[ F_{UU}^{\cos\phi} = \frac{2M}{Q} C \left\{ \hat{h} \cdot p_T \left( xH^{1q}_1 + \frac{M_{h_T}}{M} f_1^q \frac{\tilde{D}^{1q}_{1q}}{z} \right) - \frac{\hat{h} \cdot k_T}{M} \left( xf^{1q}D_{1q}^h + \frac{M_{h_T}}{M} h^{1q}_h \tilde{H}_q \right) \right\} \]

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Cahn effect in SIDIS

\[ \frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[ \frac{y^2}{2(1-\varepsilon)} \right] \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \times \left( 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos \phi_h + \ldots \right) \]

Recent COMPASS results

As of 1978 – simplistic kinematic effect:
- non-zero \( k_T \) induces an azimuthal modulation

As of 2023 – complex SF (twist-2/3 functions)
- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation

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**As of 1978** – simplistic kinematic effect:
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**As of 2023** – complex SF (twist-2/3 functions)
- Measurements by different experiments
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  - So far, no comprehensive interpretation
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.
Cahn effect in SIDIS

\[
d\sigma = \frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \alpha \frac{y^2}{xyQ^2} \frac{1}{2(1-\varepsilon)} \left( 1 + \frac{y^2}{2x} \right) \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \times \left( 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^\cos \cos \phi_h + \ldots \right)
\]

Cahn effect

As of 1978 – simplistic kinematic effect:
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As of 2023 – complex SF (twist-2/3 functions)
- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.
- Strong \( Q^2 \) dependence – unexplained
  - Do not seem to come from RCs
  - Transition between TMD ↔ collinear regions?

Recent COMPASS results

see V. Benesova’s talk
Boer-Mulders effect in SIDIS

\[
\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_s} = \\
\left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \\
\times \left( 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos \phi_h} \cos \phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \ldots \right)
\]

Arises due to the correlation between quark transverse spin and intrinsic transverse momentum

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<td>( f_1^q (x, k_T^2) ) number density</td>
<td>( h_1^{\perp q} (x, k_T^2) ) Boer-Mulders</td>
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\[
F_{UU}^{\cos 2\phi_h} = C \left[ -\frac{2(\hat{h} \cdot p_T)(\hat{h} \cdot k_T) - p_T \cdot k_T}{MM_h} \right] h_{1q}^{\perp l} H_{1q}^{\perp l}
\]
Boer-Mulders effect in SIDIS

\[
\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_S} = \\
\left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1+\frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \\
\times (1+\sqrt{2} (1+\varepsilon) A^{\cos\phi_h}_{UU} \cos\phi_h + \varepsilon A^{\cos^2\phi_h}_{UU} \cos^2\phi_h + \ldots)
\]

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\[
F_{UU}^{\cos^2\phi_h} = C \left[ -\frac{2 (\hat{h} \cdot p_T) (\hat{h} \cdot k_T) - p_T \cdot k_T}{M_{h_{1q}}} \frac{h_1^{1q} H_{1q}^{\perp\perp}}{} \right]
\]

- **Collins-like behavior (h^+h^- - mirror symmetry)?**

COMPASS preliminary

2016 proton data

\[
\mu p \rightarrow \mu' h X
\]

• h^-

• h^+

NEW!

see V. Benesova’s talk

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**SIDIS x-section and TMDs at twist-2**

\[
\frac{d\sigma}{dx dy dz dp_t^2 d\phi_h d\phi_S} = \frac{\alpha}{x y Q^2} \left( \frac{y^2}{2(1-\epsilon)} \left( 1 + \frac{y^2}{2x} \right) \right) \left( F_{UU,T} + \epsilon F_{UU,L} \right)
\]

\[
1 + \sqrt{2\epsilon (1+\epsilon)} A_{UU}^{\cos \phi_h} \cos \phi_h + \epsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h
\]

\[
+ \lambda \sqrt{2\epsilon (1-\epsilon)} A_{LU}^{\sin \phi_h} \sin \phi_h
\]

\[
+ S_L \left[ \sqrt{2\epsilon (1+\epsilon)} A_{UL}^{\sin \phi_h} \sin \phi_h + \epsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right]
\]

\[
+ S_L \lambda \left[ \sqrt{1-\epsilon^2} A_{LL} + \sqrt{2\epsilon (1-\epsilon)} A_{LL}^{\cos \phi_h} \cos \phi_h \right]
\]

All measured by COMPASS

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**Quark**

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SIDIS: target longitudinal spin dependent asymmetries

\[
\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \left\{1 + \ldots\right\}
\]

\[
+ S_L \left[\sqrt{2\varepsilon(1 + \varepsilon)} A_{UL}^{\sin \phi_h} \sin \phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h\right]
\]

\[
+ S_L \lambda \left[\sqrt{1 - \varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1 - \varepsilon)} A_{LL}^{\cos \phi_h} \cos \phi_h\right]
\]

\[
F_{\text{LL}}^1 = \mathcal{C} \left\{g_{1L}^q D_{1q}^h\right\}
\]

\[
F_{\sin \phi_h}^{\text{UL}} = \frac{2M}{Q} \mathcal{C} \left\{-\frac{\hat{h} \cdot p_T}{M_h} \left(xh_L^q H_{1q}^{1,h} + \frac{M_h}{M} g_{1L}^q \tilde{G}_{q}^{1,h}\right)\right\}
\]

\[
+ \frac{\hat{h} \cdot k_T}{M} \left(xf_{L}^{1,q} D_{1q}^h - \frac{M_h}{M} h_{1q}^{1,L} \tilde{H}_{q}^{1,h}\right)
\]

\[
F_{\sin 2\phi_h}^{\text{UL}} = \mathcal{C} \left\{-2 \left(\frac{\hat{h} \cdot p_T}{MM_h}\right) \left(\hat{h} \cdot k_T\right) - p_T \cdot k_T \right\} \frac{h_{1q}^{1,L} H_{1q}^{1,h}}{}
\]

\[
F_{\cos \phi_h}^{\text{LL}} = \frac{2M}{Q} \mathcal{C} \left\{-\frac{\hat{h} \cdot p_T}{M_h} \left(xe_L^q H_{1q}^{1,h} + \frac{M_h}{M} g_{1L}^q \tilde{D}_{q}^{1,h}\right)\right\}
\]

\[
+ \frac{\hat{h} \cdot k_T}{M} \left(xg_{L}^{1,q} D_{1q}^h - \frac{M_h}{M} h_{1q}^{1,L} \tilde{E}_{q}^{1,h}\right)
\]
SIDIS: target longitudinal spin dependent asymmetries

\[
\frac{d\sigma}{dxdydzdp_T^2d\phi_s d\phi}\propto \left( F_{U,U,T} + \varepsilon F_{U,U,L} \right) \left( 1 + \ldots \right)
\]

\[
+ S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin2\phi_h} \sin2\phi_h \right]
\]

\[
+ S_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL}^{\cos\phi_h} \cos\phi_h + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right]
\]

COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

- \( A_{UL}^{\sin\phi_h} \)
  - Q-suppression, Various different “twist” ingredients
  - Sizable TSA-mixing
  - Significant \( h^+ \) asymmetry, clear \( z \)-dependence
  - \( h^- \) compatible with zero

- \( A_{UL}^{\sin2\phi_h} \)
  - Only “twist-2” ingredients
  - Additional \( p_T \)-suppression
  - Compatible with zero, in agreement with models
  - Collins-like behavior?

- \( A_{LL}^{\cos\phi_h} \)
  - Q-suppression, Various different “twist” ingredients
  - Compatible with zero, in agreement with models
SIDIS: target longitudinal spin dependent asymmetries

\[
\frac{d\sigma}{dx dy dz dp_T^2 d\phi_T d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \ldots + S_L \sqrt{1 - \varepsilon^2} A_{LL} + \ldots \right\}
\]

\[ F_{LL}^1 = \mathcal{C} \left\{ \frac{g_q}{\bar{q}_L} D_{1q}^h \right\} \]

- Measurement of (semi-)inclusive \( A_1(A_{LL}) \) is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No \( P_T \)-dependence observed

**HERMES: PRD 99, 112001 (2019)**

**COMPASS Proton-2007, -2011 kinematics**
SIDIS: target longitudinal spin dependent asymmetries

\[
\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_s} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \ldots + S_L \lambda \sqrt{2\varepsilon (1-\varepsilon)} A_{LL}^{\cos \phi_h} \cos \phi_s + \ldots \right\}
\]

\[
F_{LL}^{\cos \phi_h} = \frac{2M}{Q} C \left\{ -\frac{\hat{h} \cdot p_T}{M} \left( x e_L^q H_{1q}^\perp + \frac{M}{M} g_{1L}^q \tilde{D}_{q}^\perp \right) \right\} + \frac{\hat{h} \cdot k_T}{M} \left( x g_L^q D_{1q}^h - \frac{M}{M} h_{1q}^l \tilde{E}_{q}^h \right) \]

- Q-suppression, various different “twist” ingredients
- Measured to be non zero at CLAS6, what about CLAS12?
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions
SIDIS: target longitudinal spin dependent asymmetries

\[
\frac{d\sigma}{dx dy dz dp_T^2 d\phi_T d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \ldots + S_L \sqrt{2\varepsilon (1 + \varepsilon)} A_{UL}^{\sin \phi_h} \sin \phi_h + \ldots \right\}
\]

where

\[
F_{UL}^{\sin \phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ \hat{h} \cdot p_T \left( x h_L^q H_{1q}^h + \frac{M_h}{M} g_{1L}^q \tilde{G}_{q}^{\perp h} \right) \right. \\
+ \left. \frac{\hat{h} \cdot k_T}{M} \left( x f_L^q D_{1q}^h - \frac{M_h}{M} h_{1L}^q \tilde{H}_{q}^{\perp h} \right) \right\}
\]


- Q-suppression, various different “twist” ingredients
- Measured to be non-zero COMPASS and HERMES
- Non-zero trend for $h^+$, $h^-$ compatible with zero, clear $z$-dependence
SIDIS x-section and TMDs at twist-2: TSAs

\[
\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_S} = \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{y^2}{2x} \right) \left( F_{UU,T} + \varepsilon F_{UU,L} \right)
\]

\[
1 + \sqrt{2\varepsilon (1+\varepsilon) A_{UU}^{\cos\phi_h} \cos \phi_h + \varepsilon A_{UU}^{2\cos\phi_h} \cos 2\phi_h}
+ \lambda \sqrt{2\varepsilon (1-\varepsilon) A_{LU}^{\sin\phi_h} \sin \phi_h}
+ S_L \left[ \sqrt{2\varepsilon (1+\varepsilon) A_{UL}^{\sin\phi_h} \sin \phi_h + \varepsilon A_{UL}^{2\sin\phi_h} \sin 2\phi_h} \right]
+ S_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL}^{\cos\phi_h} \cos \phi_h + \sqrt{2\varepsilon (1-\varepsilon) A_{LL}^{\cos\phi_h} \cos \phi_h} \right]
\]

\[
\times \left[ A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S)
+ \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S)
+ \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S)
+ \sqrt{2\varepsilon (1+\varepsilon) A_{UT}^{\sin\phi_h} \sin \phi_h}
+ \sqrt{2\varepsilon (1+\varepsilon) A_{UT}^{2\sin\phi_h} \sin(2\phi_h - \phi_S)} \right]
\]

All measured by COMPASS
SIDIS TSAs: Collins and Sivers effects (deuteron)

\[
\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \cdots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \right\}
\]

\[
F_{UT}^{\sin(\phi_h - \phi_S)} = C \left[ -\frac{\hat{h} \cdot p_T}{M_h} h^i \right] \]

\[
F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[ -\frac{\hat{h} \cdot k_T}{M} f_T^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0
\]

COMPASS PLB 673 (2009) 127

- 1st COMPASS deuteron measurements
- Collins and Sivers asymmetries compatible with zero within uncertainties.

9 April 2024

B. Parsamyan
SIDIS TSAs: Collins effect and Transversity

\[
\frac{d\sigma}{dx dy dz dp^+_T d\phi_h d\phi_S} \propto \left( F_{UU,T} + \epsilon F_{UU,L} \right) \left\{ 1 + \ldots + S_T \epsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \ldots \right\}
\]

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?
SIDIS TSAs: Collins effect and Transversity

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_T d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \cdots + S_T \varepsilon A_{UT}^{\sin(\phi_T + \phi_S)} \sin(\phi_T + \phi_S) + \cdots \right\}$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

COMPASS, PBL 770 (2017) 138

HERMES, JHEP 12 (2020) 010
SIDIS TSAs: Collins effect and Transversity

\[
\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_S} \propto \left( F_{UU,T} + \epsilon F_{UU,L} \right) \left\{ 1 + \ldots + S_T \epsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \ldots \right\}
\]

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?
- Extensive phenomenological studies and various global fits by different groups

Anselmino et al.
PRD92 (2015) 114023

M. Radici and A. Bacchetta
PRL 120 (2018) no.19, 192001

JAM Collaboration,
PRD 106 (2022) 3, 034014

9 April 2024
SIDIS TSAs: Collins effect and Transversity

\[
\frac{d\sigma}{dxdydzdp^2} \propto \left( F_{UU,T} + \epsilon F_{UU,L} \right) \left\{ 1 + \ldots + S T \epsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) + \ldots \right\}
\]

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?
- Extensive phenomenological studies and various global fits by different groups

[Addendum to the COMPASS-II Proposal]
Projected uncertainties for Collins asymmetry

COMPASS-II (2022)
- 2nd COMPASS deuteron measurements performed
- Crucial to constrain the transversity TMD PDF for the d-quark
SIDIS TSAs: Collins effect and Transversity

$$\frac{d\sigma}{dx dy dz dp_T d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \{1 + \ldots + S_T \varepsilon A^{\sin(\phi_h + \phi_S)}_{UT} \sin(\phi_h + \phi_S) + \ldots\}$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES
  
  (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?
- Extensive phenomenological studies and various global fits by different groups

Total protons delivered on the production target: \(~5.95 \times 10^{18}\) (98% of the request) in \(~150\) days

- COMPASS 2022 run
  - SPS efficiency: \(~73\%\)
  - Spectrometer efficiency: \(~90\%\)
  - Physics data collection efficiency: \(~75\%\)

Highly successful Run in 2022!
SIDIS TSAs: Collins effect and Transversity

\[ \frac{d\sigma}{dxdydzdp_1d\phi_hd\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \{ 1 + \cdots + S_T \varepsilon A^\sin(\phi_h+\phi_S) \sin(\phi_h+\phi_S) + \cdots \} \]

- Measured on P/D in SIDIS and dihadron SIDIS
- Extensive phenomenological studies and various global fits by different groups
- New deuteron data crucial to constrain $d$-quark transversity

\[ F^\sin(\phi_h+\phi_S)_{UT} = C \left( \hat{h} \cdot p_T \frac{\hat{h}^qH_{1q}}{M_h} \right) \]

COMPASS 2022 run – highly successful data-taking!
- 2\textsuperscript{nd} COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades

See S. Asatryan’s slides
Dihadron Collins effect and Transversity

\[ \frac{d^7 \sigma}{d \cos \theta \, d M_{hh} \, d \phi_R \, dz \, dx \, dy \, d \phi_S} = \]

\[ \alpha^2 \frac{2\pi}{2\pi Q^2 y} \left( 1 - y + \frac{y^2}{2} \right) \sum_q e_q^2 \, f_1^q(x) \, D_{1,q}(z, M_{hh}^2, \cos \theta) + \]

\[ S_\perp (1 - y) \sum_q e_q^2 \frac{|p_1 - p_2|}{2M_{hh}} \sin \theta \sin \phi_{RS} \, h_1^q(x) \, H_{1,q}(z, M_{hh}^2, \cos \theta) \]

\[ A_{UT}^{\sin \phi_{RS}} = \frac{|p_1 - p_2|}{2M_{hh}} \sum_q e_q^2 \, h_1^q(x) \, H_{1,q}(z, M_{hh}^2, \cos \theta) \]

COMPASS 2022 run – highly successful data-taking!

- 2nd COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades
- New results – dihedron Collins-like asymmetries
- Access to collinear transversity PDF; Non-zero trend at large \( x \)
- Precision comparable with proton results

See S. Asatryan’s slides
SIDIS TSAs: Sivers effect

\[
\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \ldots \right\}
\]

- COMPASS-HERMES discrepancy
- T-oddness: sign-change (SIDIS ↔ Drell-Yan)
  - Explored by COMPASS
- New precise deuteron data from COMPASS
  - Unique input to constrain Sivers PDF

New!

- COMPASS-HERMES discrepancy
- T-oddness: sign-change (SIDIS ↔ Drell-Yan)
  - Explored by COMPASS
- New precise deuteron data from COMPASS
  - Unique input to constrain Sivers PDF
SIDIS TSAs: Kotzinian-Mulders asymmetry

\[ \frac{d\sigma}{dxdydzdpd\phi_d d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \ldots + \lambda S_T \sqrt{1 - \varepsilon^2} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) + \ldots \right\} \]

\[ F_{LT}^{\cos(\phi_h - \phi_S)} = C\left[ \frac{\hat{h} \cdot \mathbf{k}_T}{M^2} g_{1T} h D_{1q} \right] \]

COMPASS/HERMES/CLAS6 results

- Only “twist-2” ingredients
- Sizable non-zero effect for \( h^+ \)
- Similar effect at HERMES


See also, PRD 107, (2023) 034016 – global fit by: M. Horstmann, A. Schafer and A. Vladimirov

9 April 2024

B. Parsamyan
COMPASS 2022 run: new unique deuteron data

Pavia group fits

analysis of statistical error with replica method (200) 68% confidence level

$Q^2 \geq 1.4 \text{ GeV}^2$, $0.2 \leq z \leq 0.7$
$P_{ht} < \min[0.2Q, 0.7Qz] + 0.5 \text{ GeV}$

300 data points $\rightarrow$ 118 data fitted
14 free parameters
$\chi^2/\text{d.o.f.} = 1.06 \pm 0.10$

JAM Collaboration, PRD 106 (2022) 3, 034014

S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D. Pitonyak
PRD 105 (2022) 3, 034007

Bacchetta, Delcarro, Pisano, Radici, in preparation

Bacchetta & Radici, PRL 107 (11)
Echevarria et al., PRR 139 (14)
TC
Boglione et al., JHEP 1007 (18)
PV11
PV19

Same kinematic cuts applied to unpolarized

$P_{ht}$, $P_{L}$ selected data projections
SIDIS and single-polarized DY x-sections at twist-2 (LO)

\[ \frac{d\sigma^{LO}}{dxdydzp^2d\phi_n d\phi_S} \propto F_{UU,T}^{\perp} + \varepsilon F_{UU,L}^{\perp} \]

\[ \times \left\{ \begin{align*}
  1 & + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\
  + S_L & \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \\
  + S_T & \varepsilon A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\
  + S_T & \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\
  + S_T & \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \\
  + S_T & \lambda \left[ \sqrt{1 - \varepsilon^2} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \right]
\end{align*} \right\} \]

\[ \frac{d\sigma^{LO}}{d\mathbf{q}^4d\Omega} \propto F_U^T \left( 1 + \cos^2 \theta_{CS} \right) \]

\[ \times \left\{ \begin{align*}
  1 & + \mathbf{D}_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \\
  + S_L & \sin^2 \theta_{CS} A_L^{\sin 2\phi_{CS}} \sin 2\phi_{CS} \\
  + S_T & \varepsilon A_T^{\sin \phi_S} \sin \phi_S \\
  + S_T & \varepsilon A_T^{\sin(2\phi_{CS} - \phi_s)} \sin(2\phi_{CS} - \phi_s) \\
  + S_T & \varepsilon A_T^{\sin(2\phi_{CS} + \phi_s)} \sin(2\phi_{CS} + \phi_s) \\
\end{align*} \right\} \]

where \( \mathbf{D}_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} \left( 1 + \cos^2 \theta_{CS} \right) \)

See M. Niemiec’s talk
Single-polarized Drell-Yan cross-section at twist-2 (LO)

\[
\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left( 1 + \cos^2 \theta_{CS} \right) \\
+ \left[ D_{\sin^2 \theta_{CS}} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \right. \\
+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\
\left. \times \right] \\
\begin{bmatrix}
A_T^{\sin \varphi_S} \sin \varphi_S \\
+ S_T \\
+ D_{\sin^2 \theta_{CS}} \left( A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right. \\
+ A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \\
\end{bmatrix}
\]

COMPASS phase-II proposal submitted in 2010 (Drell-Yan, DVCS,...)

Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS → sign change test

9 April 2024

B. Parsamyan
Drell-Yan TSAs – Sivers effect

\[
\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[ A_T^{\sin \varphi_S} \sin \varphi_S + \ldots \right]
\]

Sivers DY TSA

\[
A_T^{\sin \varphi_S} \propto f_{1,q}^T \otimes f_{1T,q}^T
\]

See M. Niemiec’s talk

Sivers SIDIS TSA

\[
A_{UT}^{\sin (\phi_h - \phi_s)} \propto f_{1T,q}^{1q} \otimes D_{1q}^h
\]

COMPASS proton Sivers measurements

- Clear signal in the matching $Q^2$ ranges

COMPASS 2015 data

COMPASS proton SIDIS measurements

• Clear signal in the matching $Q^2$ ranges

9 April 2024
Drell-Yan TSAs – Sivers effect

\[ \frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[ A_T^{\sin \varphi_S} \sin \varphi_S + \ldots \right] \]

COMPASS

Drell-Yan, NH\textsubscript{3}

2015+2018 data

4.3 < M_{\mu \mu}/(\text{GeV}/c^2) < 8.5

DY

COMPASS

\( \pi^+ + p^\perp \rightarrow \mu^+ + \mu^- + X \)

2015+2018 data

J/\psi

COMPASS proton Sivers measurements

• Clear signal in the matching \( Q^2 \) ranges

Sivers SIDIS TSA

\[ A_{UT}^{\sin (\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h \]

Sivers DY TSA

\[ A_T^{\sin \varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,\perp}^{q} \]

See M. Niemiec’s talk

\[ \text{COMPASS} \]

PLB 770 (2017) 138
Drell-Yan TSAs – Transversity

\[
\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[ D_{\sin^2 \theta_{CS}} A_T \sin(2\varphi_{CS} - \varphi_S) \sin(2\varphi_{CS} - \varphi_S) + \ldots \right]
\]

Transversity DY TSA

\[ A_T \sin(2\varphi_{CS} - \varphi_S) \propto h_{1,\pi}^q \otimes h_{1,p}^q \]

See M. Niemiec’s talk

Collins SIDIS TSA

\[ A_{UT} \sin(\phi_h + \phi_s) \propto h_{1,\pi}^q \otimes H_{1,q}^{1,\pi} \]

COMPASS proton Collins measurements

- Clear signal in the matching \( Q^2 \) ranges

9 April 2024

B. Parsamyan

COMPASS

New!

COMPASS

Drell-Yan, NH\(_3\) 2015+2018 data

4.3 < \( M_{\mu\mu} / (\text{GeV}/c^2) \) < 8.5

\( \pi^- + p^\uparrow \rightarrow \mu^+ + \mu^- + X \)

2.85 < \( M_{\mu\mu} / (\text{GeV}/c^2) \) < 3.4

COMPASS 2015 data
Transverse-spin asymmetries in $\pi^- p^\uparrow$ scattering

Theory curves based on S. Bastami et al. JHEP 02, (2021),166

See M. Niemiec’s talk

<table>
<thead>
<tr>
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<th>COMPASS</th>
<th>Drell-Yan data</th>
<th>$M_{\mu\mu}$$\in$[4; 9] GeV/c$^2$</th>
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<td>\includegraphics[width=0.3\textwidth]{sivers_pdfs.png}</td>
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<td>\includegraphics[width=0.3\textwidth]{compass_sivers.png}</td>
</tr>
</tbody>
</table>

### Drell-Yan measurements

- Ruled out predictions for large asymmetries
- General agreement with currently available model calculations
- COMPASS data favors the sign-change hypothesis for the Sivers TMD PDF
- COMPASS data also favors pion Boer-Mulders TMD PDF sign-change (model-based)

### J/$\psi$ production channel

- All TSAs are small and compatible with zero
- Hint that J/$\psi$ production might go via gluon-gluon fusion in COMPASS
- Access to small gluon TMDs?

9 April 2024

B. Parsamyan
Conclusions

• Importance of careful understanding and confrontation of experimental data from different experiments
  o Different kinematic domains and phase-space limitations
  o Experiments employ complex analysis techniques, Monte-Carlo simulations, and sophisticated corrections (acceptance, VMs, radiative corrections)

• Close collaboration between different experiments → general benefit for the field
  o Knowledge transfer, comparison of the analysis techniques, tools, and methodology, cross-analyses between different experiments

• Close collaboration between experiment and phenomenology/theory
  o Flexibility in adapting on the analysis side to the choice of the observables, phase-space selections, etc. (before publishing the data)
  o Different possibilities for common paper projects, external membership

• Possibility to organize effective and fruitful collaborative work
Conclusions

• COMPASS holds the record for the longest-running CERN experiment (20 years of data-taking)

• Series of successful and important measurements addressing nucleon spin-structure
  o Inclusive measurements, unpolarized and polarized SIDIS (longitudinal/transverse)
  o First-ever polarized Drell-Yan measurements

• A wealth of (SI)DIS, Drell-Yan, DVCS, HEMP data collected across the years
  o Petabytes of data available for analysis

• Wide and unique kinematic domain accessing low $x$ and large $Q^2$
  o Will remain unique for at least another decade

• World-unique SIDIS deuteron data collected in 2022
  o Highly successful run, promising preliminary results

• Since 2023 the experiment entered the Analysis Phase
  o The spectrometer has been transferred to the COMPASS successor in the M2 beamline – the AMBER collaboration
  o 3 new groups joined COMPASS in the course of 2023 for the Analysis Phase
  o If you are interested – don’t hesitate to get in touch!

Thank You!
Joint XX-th International Workshop on Hadron Structure and Spectroscopy and 5-th Workshop on Correlations in Partonic and Hadronic Interactions

Yerevan, Armenia
30 September – 4 October, 2024
https://indico.cern.ch/e/IWHSS-CPHI-2024
• **Spare slides**
# COMPASS data taking campaigns

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target</th>
<th>year</th>
<th>Physics programme</th>
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<tbody>
<tr>
<td>$\mu^+$</td>
<td>Polarized deuteron ($^6\text{LiD}$)</td>
<td>2002, 2003, 2004</td>
<td>80% Longitudinal</td>
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<tr>
<td></td>
<td></td>
<td>2006</td>
<td>Longitudinal SIDIS</td>
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<tr>
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<td>Polarized proton ($\text{NH}_3$)</td>
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<td>$\pi^-</td>
<td>K^-</td>
<td>p$</td>
<td>LH$_2$, Ni, Pb, W</td>
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<tr>
<td>$\mu^+$</td>
<td>Polarized proton ($\text{NH}_3$)</td>
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<td>Transverse SIDIS</td>
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<tr>
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<td>LH$_2$</td>
<td>2012</td>
<td>Pilot DVCS &amp; HEMP &amp; unpolarized SIDIS</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>Polarized proton ($\text{NH}_3$)</td>
<td>2014</td>
<td>Pilot Drell-Yan</td>
</tr>
<tr>
<td>$\mu^+$</td>
<td>LH$_2$</td>
<td>2015, 2018</td>
<td>Transverse Drell-Yan</td>
</tr>
<tr>
<td>$\mu^+$</td>
<td>Polarized deuteron ($^6\text{LiD}$)</td>
<td>2016, 2017</td>
<td>DVCS &amp; HEMP &amp; unpolarized SIDIS</td>
</tr>
<tr>
<td>$\mu^+$</td>
<td>Polarized deuteron ($^6\text{LiD}$)</td>
<td>2021, 2022</td>
<td>Transverse SIDIS</td>
</tr>
</tbody>
</table>
Selected results for di-hadron LSAs

COMPASS (NH$_3$) 2007+2011 data: preliminary

- Alternative way to access various twist-2/-3 distributions
- Non-zero signal for $A_{UL}^{s \sin \phi_R}$ and $A_{LL}^1$
- CLAS-COMPASS: different behavior for $A_{UL}^{s \sin 2 \phi_R}$ at large x?
Nucleon spin structure: helicity $g_{1,d(p)}^q(x)$

- COMPASS contribution: lowest $x$ and highest $Q^2$ regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest $x$ and $Q^2$ – positive signal for $g_1^p(x)$
- Gluon polarization measurements via open charm and SIDIS
- COMPASS - first to rule out a large gluon polarization in the nucleon!
  Precise test of Bjorken sum rule (9% level)
SIDIS TSAs: Collins and Sivers effects (proton)

\[ \frac{d\sigma}{dx dy dz dp_T d\phi_h d\phi_S} \propto \left( F_{U,U,T} + \epsilon F_{U,U,L} \right) \left\{ 1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + S_T \epsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \right\} \]

\[ F_{UT}^{\sin(\phi_h - \phi_S)} = C \left[ \frac{\hat{h} \cdot p_T}{M_h} h^{\perp}_{1q} H_{1q}^{\perp h} \right] \]

\[ F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[ \frac{\hat{h} \cdot k_T}{M} f_{1T}^{\perp q} D_{1q}^{h} \right], \quad F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0 \]

COMPASS PLB 744(2015)250

- 1\textsuperscript{st} COMPASS deuteron measurements – Collins and Sivers asymmetries compatible with zero
- COMPASS proton measurements – clear non-zero signal for both asymmetries

9 April 2024

B. Parsamyan
SIDIS TSAs: Collins effect and Transversity

\[
\frac{d\sigma}{dx dy dz dp_\perp d\phi_h d\phi_S} \propto \left( F_{UU,T} + \epsilon F_{UL,L} \right) \left\{ 1 + \ldots + S_T \epsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \ldots \right\}
\]

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

Inclusive \( \rho^0 \) Collins asymmetry

- indication for a positive asymmetry
- opposite to \( \pi^+ \) and \( \pi^0 \) as predicted by the models
- Large effect at small \( P_T \)