COMPASS Spin Physics Program

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

The 25th International Spin Symposium (SPIN 2023)
September 24-30, Duke University, Durham Convention Center, US
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
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• 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 deuterons 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: V. Andrieux, A. Kerbizi, A. Martin, J. Matousek, G. Reicherz, A. Vijayakumar
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 $F_{3\pi}$

28 September 2023

B. Parsamyan
The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

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- Chiral anomaly $F_{3\pi}$
Nucleon 3D structure

- 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
- Measured in exclusive processes:
  - Deeply virtual Compton scattering (DVCS): $\mu + N \rightarrow \mu + \gamma + N$
  - Hard exclusive meson production (HEMP): $\mu + N \rightarrow \mu + VM + N$
  with $VM = \pi^0, \rho(770), \omega(782),...$
COMPASS experimental setup

COmmon 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)
COMPASS experimental setup: Phase II (SIDIS programme)

CERN SPS North Area (building 888)
Two-stage spectrometer LAS+SAS
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- 160 GeV tertiary muon beams
  - $\mu^{+}$ longitudinally polarized

see Gerhard Reicherz’s talk

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COMPASS experimental setup: Phase II (DY programme)

CERN SPS North Area (building 888)
Two-stage spectrometer LAS+SAS
- Large Angle Spectrometer (SM1 magnet)
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  - impinging on Be production target (T6)
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- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

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<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>2002-2004</td>
<td>80% Longitudinal | 20% Transverse SIDIS</td>
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<tr>
<td></td>
<td></td>
<td>2006</td>
<td>Longitudinal SIDIS</td>
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<tr>
<td></td>
<td>Polarized proton ((\text{NH}_3))</td>
<td>2007</td>
<td>50% Longitudinal | 50% Transverse SIDIS</td>
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<tr>
<td>(\pi^- K^+ p)</td>
<td>LH(_2), Ni, Pb, W</td>
<td>2008-2009</td>
<td>Spectroscopy</td>
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<tr>
<td>(\pi^- K^+ p)</td>
<td>Ni</td>
<td>2010-2011</td>
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</tr>
<tr>
<td>(\mu^\pm)</td>
<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>2014-2018</td>
<td>Pilot Drell-Yan</td>
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<tr>
<td>(\mu^\pm)</td>
<td>LH(_2)</td>
<td>2016-2017</td>
<td>Transverse Drell-Yan</td>
</tr>
<tr>
<td>(\mu^+)</td>
<td>Polarized deuteron ((^6\text{LiD}))</td>
<td>2021-2022</td>
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Nucleon spin structure: collinear approach ↔ TMDs

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<td><strong>U</strong></td>
<td>$f_1^q(x)$, number density</td>
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<tr>
<td><strong>L</strong></td>
<td>$g_1^q(x)$, helicity</td>
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<tr>
<td><strong>T</strong></td>
<td>$h_1^q(x)$, transversity</td>
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<tr>
<td><strong>U</strong></td>
<td>$f_1^q(x, k_T^2)$, number density</td>
<td>$h_1^q(x, k_T^2)$, Boer-Mulders</td>
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<td>$g_1^q(x, k_T^2)$, helicity</td>
<td>$h_{1T}^q(x, k_T^2)$, worm-gear L</td>
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<tr>
<td><strong>T</strong></td>
<td>$f_{1T}^q(x, k_T^2)$, Sivers</td>
<td>$g_{1T}^q(x, k_T^2)$, worm-gear T</td>
<td>$h_{1T}^q(x, k_T^2)$, pretzelosity</td>
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</table>

- PDFs – universal (process independent) objects; T-odd PDFs – conditionally universal
Nucleon spin structure: helicity $g_1^q(x)$

- COMPASS contribution: lowest $x$ and highest $Q^2$ regions

COMPASS PLB 769(2017) 34

COMPASS D 2002-2006 data
Nucleon spin structure: helicity $g_{1,p}^q(x)$

- COMPASS contribution: lowest $x$ and highest $Q^2$ regions
- Both deuteron and proton target data

COMPASS PLB 753(2016)18

COMPASS p 2007, 2011 data

$g_1^p(x, Q^2) + 12.1 - 0.7 \cdot i$

$g_1^p(x, Q^2)$
Nucleon spin structure: helicity $g_{1,p}^q(x)$

- 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 $g_1^p(x)$
Nucleon spin structure: helicity $g_1^q, d(p)(x)$

- 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 $g_1^p(x)$
- 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)
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

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

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

Cahn effect - R. N. Cahn, PLB 78 (1978)


See L. Gamberg’s talk

The transverse momentum vector $k_T$ is related to the cosine of the azimuthal angles of the partons.

Longitudinal momentum $k^+ = xP^+$

Transverse momentum

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Cahn effect in SIDIS

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

\[
F_{UU}^{\cos\phi_h} = \frac{2M}{Q} \hat{C} \left\{ -\frac{\hat{M}}{M_h} \left( x h_{1q}^\perp + \frac{M_h}{M} f_1 q \frac{D_{q}^{\perp h}}{z} \right) - \frac{\hat{M}}{M} \left( x f_{1q}^\perp D_{1q}^{h} + \frac{M_h}{M} h_{1q}^\perp \frac{H_{q}^{h}}{z} \right) \right\}
\]

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19
Cahn effect in SIDIS

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

Cahn effect

\[ f_1^q(x, k_T^2) \text{ number density} \]

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 clear interpretation

Recent COMPASS results

COMPASS preliminary

see J. Matousek's talk
Cahn effect in SIDIS

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

\[\int_{1}^{q}(x, k_T^2)\text{ number density}\]

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  - A set of complex corrections:
    - Acceptance, diffractively produced VMs, radiative corrections, etc.

Recent COMPASS results

see J. Matousek’s talk
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\]

Cahn effect

\[ f_1^q(x, k_T^2) \]

number density

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- 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 clear interpretation
  - A set of complex corrections:
    - Acceptance, diffractively produced VMs, radiative corrections, etc.
  - Strong \( Q^2 \) dependence – unexplained
    - Do not seem to come from RCs
    - Transition between TMD – collinear regions?

Recent COMPASS results

see J. Matousek’s talk

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Cahn effect in SIDIS

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

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

\( q \) virtual photon
\( k \) scattered quark
\( p \) from fragmentation
\( p_\perp \) outgoing hadron

\( P_T \) - dependent distributions
- Extracted in multi-D kinematic bins
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections, etc.
- Global fits by different groups (SIDIS-DY)
  - Normalization issues
    (See A. Baccehitta’s talk)
- COMPASS measurements
  - Isoscalar target data - published
  - Proton data – ongoing analysis
- COMPASS-2022 data
  - More deuteron data points to be expected

See J. Matousek’s talk

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$\frac{d\sigma}{dx dy dz dp_T^2 d\phi d\phi_S}$ = All measured by COMPASS

\[ \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] \left( F_{UU,T} + \epsilon F_{UU,L} \right) \]

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

\[ \times \]

Quark

<table>
<thead>
<tr>
<th>U</th>
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<tr>
<td>number density</td>
<td>Boer-Mulders</td>
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<tr>
<td>helicity</td>
<td></td>
<td>worm-gear L</td>
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<tr>
<td></td>
<td>Sivers</td>
<td>Kotzinian-Mulders worm-gear T</td>
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<td></td>
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</table>

spin of the nucleon spin of the quark $k_T$
SIDIS: target longitudinal spin dependent asymmetries

\[ \frac{d\sigma}{dxdydzd\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \cdots \right\} \]

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

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

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

\[ F_{UL}^{\sin \phi_h} = \frac{2M}{Q} C \left\{ -\frac{h \cdot p_T}{M} \left( x h_q^q H_{1q}^{1h} + M h_q^q \frac{G_q^q}{z} \right) \right\} \]

\[ + \frac{\hat{h} \cdot k_T}{M} \left\{ x f_{1q}^{\perp q} D_{1q}^h - M h_{1q}^{\perp q} \frac{\tilde{h}_q^h}{z} \right\} \]

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

\[ F_{LL}^{\cos \phi_h} = \frac{2M}{Q} C \left\{ -\frac{h \cdot p_T}{M} \left( x e_{1q}^q H_{1q}^{1h} + M h_q^q \frac{\tilde{D}_q^q}{z} \right) \right\} \]

\[ + \frac{\hat{h} \cdot k_T}{M} \left\{ x g_{1q}^{\perp q} D_{1q}^h - M h_{1q}^{\perp q} \frac{\tilde{E}_q^h}{z} \right\} \]

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SIDIS: target longitudinal spin dependent asymmetries

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

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

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

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

B. Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex]

2007, 2011 data preliminary
SIDIS: target longitudinal spin dependent asymmetries

\[ \frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \{1 + \ldots + S_L \lambda \sqrt{2\varepsilon (1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos \phi_h + \ldots \} \]

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

B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]

- 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
Selected results for di-hadron LSAs

COMPASS (NH₃) 2007+2011 data: preliminary

- Alternative way to access various twist-2/-3 distributions
- Non-zero signal for $A_{UL}^{\sin\phi_R}$ and $A_{LL}^1$
- CLAS-COMPASS: different behavior for $A_{UL}^{\sin2\phi_R}$ at large $x$?

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\[
\frac{d\sigma}{dx dy dz d\phi_L d\phi_S} = \text{All measured by COMPASS}
\]

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

\[
1 + 2\varepsilon (1 + \varepsilon) A_{UU}^{\cos \phi_L} \cos \phi_h + \varepsilon A_{UU}^{\cos 2\phi_L} \cos 2\phi_h
\]

\[
+ \lambda \sqrt{2\varepsilon (1 - \varepsilon)} A_{UL}^{\sin \phi_L} \sin \phi_h
\]

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

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

\[
A_{UT}^{\sin (\phi_h - \phi_s)} \times \sin (\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{UT}^{\sin (\phi_h + \phi_s)} \sin (\phi_h + \phi_s)
\]

\[
+ \varepsilon A_{UT}^{\sin (3\phi_h - \phi_s)} \sin (3\phi_h - \phi_s)
\]

\[
+ \sqrt{2\varepsilon (1 + \varepsilon)} A_{UT}^{\sin \phi_L} \sin \phi_s
\]

\[
+ \sqrt{2\varepsilon (1 - \varepsilon)} A_{UT}^{\sin (2\phi_h - \phi_s)} \sin (2\phi_h - \phi_s)
\]

\[
A_{UT}^{\cos (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos \phi_L} \cos \phi_s
\]

\[
+ \varepsilon A_{LT}^{\cos (2\phi_h - \phi_s)} \cos (2\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
A_{UT}^{\sin (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
A_{UT}^{\sin (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
A_{UT}^{\sin (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
A_{UT}^{\sin (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
A_{UT}^{\sin (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h - \phi_s)} \cos (\phi_h - \phi_s)
\]

\[
A_{UT}^{\sin (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (\phi_h + \phi_s)} \cos (\phi_h + \phi_s)
\]

\[
A_{UT}^{\sin (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]

\[
+ \varepsilon A_{LT}^{\cos (3\phi_h - \phi_s)} \cos (3\phi_h - \phi_s)
\]
SIDIS TSAs: Collins and Sivers effects (deuteron)

\[
\frac{d\sigma}{dxdydzed\phi_d d\phi_s} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + ... + S_T A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) ... \right\}
\]

\[
F_{UT}^{\sin(\phi_h + \phi_s)} = C \left[ -\frac{\hat{h} \cdot \vec{p}_T}{M_h} h_1^q H_{1q}^{1h} \right]
\]

\[
F_{UT,T}^{\sin(\phi_h - \phi_s)} = C \left[ -\frac{\hat{h} \cdot \vec{k}_T}{M} f_{1q} \tilde{D}_1 \right], F_{UT,L}^{\sin(\phi_h - \phi_s)} = 0
\]

COMPASS PLB 673 (2009) 127

- 1st COMPASS deuteron measurements
- Collins and Sivers asymmetries compatible with zero within uncertainties.
SIDIS TSAs: Collins and Sivers effects (proton)

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

\[
F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[ \frac{\hat{h} \cdot p_T}{M_h} h_1^g H_{1q}^{\perp} \right]
\]

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

COMPASS PLB 744(2015)250

- 1st COMPASS deuteron measurements – Collins and Sivers asymmetries compatible with zero
- COMPASS proton measurements – clear non-zero signal for both asymmetries
SIDIS TSAs: Collins effect and Transversity

\[
\left. \frac{d\sigma}{dx dy dz dp_T^2 d\phi_d d\phi_s} \right| \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \ldots + S_T \varepsilon A_{UT}^{\sin(\phi_T + \phi_s)} \sin(\phi_T + \phi_s) + \ldots \right\}
\]

\[
F_{UT}^{\sin(\phi_T + \phi_s)} = C \left[ \frac{\hat{h} \cdot p_T}{M_h} h_i^q H_{1q}^{\perp L} \right]
\]

- 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

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

- 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?
SIDIS TSAs: Collins effect and Transversity

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

- 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?

\[ F_{UT}^{\sin(\phi_h + \phi_s)} = C \left[ \frac{\hat{h} \cdot p_T}{M_h} h_q^1 H_{iq}^{1,1h} \right] \]

PLB 824 (2022) 136834

Inclusive \( \rho^0 \) Collins asymmetry

- PLB 843 (2023) 137950

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

[B. Parsamyan]
SIDIS TSAs: Collins effect and Transversity

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

- 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
SIDIS TSAs: Collins effect and Transversity

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

- 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**

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

- 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?
- 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!**

28 September 2023

B. Parsamyan
SIDIS TSAs: Collins effect and Transversity

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

- 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

COMPASS-II (2022)
- 2nd COMPASS deuteron measurements performed
- Crucial to constrain the transversity TMD PDF for the d-quark

See A. Martin’s slides
SIDIS TSAs: Collins effect and Transversity

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

- 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

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

\( z > 0.1, W > 10 \text{ GeV}/c^2 \)

New!

COMPASS-II (2022)
- 2nd COMPASS deuteron measurements performed
- Crucial to constrain the transversity TMD PDF for the d-quark

28 September 2023
B. Parsamyan
COMPASS 2022 run: new unique deuteron data

Pavia group fits

Bacchetta, Delcaro, Pisano, Radici, in preparation

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

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

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

COMPASS 2022 deuteron run
SIDIS TSAs: Kotzian-Mulders asymmetry

\[ \frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \ldots + \lambda \mathcal{S}_T \sqrt{1 - \varepsilon^2} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) + \ldots \right\} \]

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

COMPASS/HERMES/CLAS6 results

\( A_{LT}^{\cos(\phi_h - \phi_S)} \)

- 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

28 September 2023

B. Parsamyan
SIDIS TSAs: Sivers effect

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

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

- COMPASS-HERMES discrepancy
  - Q^2-evolution?
- T-odd TMD PDF: Expected to change sign between SIDIS and Drell-Yan
- New precise deuteron data
SIDIS Sivers TSA in COMPASS Drell-Yan $Q^2$-ranges

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

\[ F_{UT,T}^{\sin(\phi_h - \phi_s)} = C \left[ -\frac{\hat{h} \cdot \hat{k}_T}{M} f_{UT}^{1g} D^{h}_{1q} \right], \quad F_{UT,L}^{\sin(\phi_h - \phi_s)} = 0 \]

**COMPASS PRELIMINARY**

SIDIS 2010 NH$_3$ proton data

1st COMPASS multi-D fit done for all eight TSAs

28 September 2023

B. Parsamyan
COMPASS Multi-D TSA analyses

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

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

\[ F_{UT}^{\sin(\phi_T + \phi_S)} = C \left[ -\frac{\hat{h} \cdot p_T}{M_h} h_{tq}^{\parallel h} h_{tq}^{\perp q} \right] \]

3D x:Q^2:z or x:Q^2:p_T x:z:p_T

- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

SIDIS and single-polarized DY $x$-sections at twist-2 (LO)

$$\frac{d\sigma^{LO}}{dx dy dz dp_t^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\times \left\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h 
+ S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \\
+ S_T \varepsilon A_{UT}^{\sin (\phi_h - \phi_S)} \sin (\phi_h - \phi_S) \\
+ S_T \lambda \sqrt{1 - \varepsilon^2} A_{LT}^{\cos (\phi_h - \phi_S)} \cos (\phi_h - \phi_S) \right\}$$

$$\times \left\{ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} 
+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\
+ S_T \left[ A_T^{\sin \varphi_S} \sin \varphi_S \\
+ D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin (2\varphi_{CS} - \varphi_S)} \sin (2\varphi_{CS} - \varphi_S) \\
+ A_T^{\sin (2\varphi_{CS} + \varphi_S)} \sin (2\varphi_{CS} + \varphi_S) \right) \right] \right\}$$

where $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$
SIDIS and single-polarized DY x-sections at twist-2 (LO)

\[
\frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right)
\]

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

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

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

\[
+ S_T \lambda \sqrt{1 - \varepsilon^2} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S)
\]

\[
\times \left\{ 1 + D_{\sin^2 \theta_{CS}}^{\sin^2 \theta_{CS}} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS}
+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\phi_{CS}} \sin 2\phi_{CS} \right\}
\]

\[
\text{where } D_{\sin^2 \theta_{CS}} = \sin^2 \theta_{CS} \frac{1}{1 + \cos^2 \theta_{CS}}
\]

- Sign-change of T-odd Sivers and Boer-Mulders TMD PDFs;
- Multiple access to Collins FF $H_{1q}^{1h}$ and pion Boer-Mulders PDF $h_{1,\pi}^{1q}$

28 September 2023
B. Parsamyan
SIDIS and single-polarized DY $x$-sections at twist-2 (LO)

- $2.5 < M/(\text{GeV}/c^2) < 4.3$ “Charmonia mass”
  - Strong $J/\psi$-signal → study of $J/\psi$ physics
  - Good signal/background
- $4.3 < M/(\text{GeV}/c^2) < 8.5$ “High mass”
  - Low DY cross-section
  - Beyond charmonium region, background < 3%
  - Valence region → largest asymmetries

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

\[
D_{\sin^2 \theta_{CS}} \left[ A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \right] \times \left[ \begin{array}{c} A_T^{\sin \varphi_S} \sin \varphi_S \\ -A_T^{\sin (2\varphi_{CS} - \varphi_S)} \sin (2\varphi_{CS} - \varphi_S) \\ + A_T^{\sin (2\varphi_{CS} + \varphi_S)} \sin (2\varphi_{CS} + \varphi_S) \end{array} \right]
\]

\[
D_{\sin^2 \theta_{CS}} = \sin^2 \theta_{CS} / \left(1 + \cos^2 \theta_{CS}\right)
\]
Single-polarized DY measurements at COMPASS

COMPASS preliminary
Drell-Yan NH₃ data
4.3 < M_{μμ}/(GeV/c²) < 8.5

\[ \langle x_π \rangle = 0.50 \]
\[ \langle x_N \rangle = 0.17 \]

\[
\frac{dσ^{LO}}{dq^4dΩ} \propto F_U^1 \left( 1 + \cos^2 θ_{cs} \right)
\]

\[
x + S_L \sin^2 θ_{cs} A_L \cos 2θ_{cs} \sin 2φ_{cs}
\]

\[
\times \left\{ D_{\sin^2 θ_{cs}} A_U \cos 2φ_{cs} \cos 2φ_{cs}
\right\}
\]

\[
+ S_T \sin θ_{cs} A_T \sin 2φ_{cs} \sin 2φ_{cs}
\]

\[
+ D_{\sin^2 θ_{cs}} A_T \sin 2φ_{cs} \left( \sin \left( 2φ_{cs} - φ_S \right) + \sin \left( 2φ_{cs} + φ_S \right) \right)
\]

\[
D_{\sin^2 θ_{cs}} = \sin^2 θ_{cs} / \left( 1 + \cos^2 θ_{cs} \right)
\]

HM events are in the valence quark range

4.3 < M/(GeV/c²) < 8.5 “High mass” range
Beyond charmonium region, background < 3%
Valence region → largest asymmetries

\[ \langle M \rangle = 5.3 \text{ GeV/c}^2 \]

28 September 2023
Drell-Yan TSAs – Transversity

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

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

COMPASS

Drell-Yan, NH\textsubscript{3}

15+2018 data

4.3 < \mu^2/(GeV/c^2) < 8.5

Collins SIDIS TSA

\[A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^q \otimes H_{1q}^h\]

16 < Q^2/(GeV/c)^2 < 81

COMPASS

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

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

Transversity DY TSA

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

COMPASS

28 Years

1997–2022

COMPASS

Drell-Yan, NH₃

2015+2018 data

\[ \sin(2\varphi_{CS}-\varphi_S) \]

DY

\[ A_T \]

\[ x_N \]

\[ x_{\pi} \]

\[ x_F \]

\[ q_T \mathrm{(GeV/c)} \]

\[ M_{\mu\mu} \mathrm{(GeV/c^2)} \]

\[ 4 \leq M_{\mu\mu}/(\mathrm{GeV/c^2}) \leq 8.5 \]

\[ 2.85 \leq M_{\mu\mu}/(\mathrm{GeV/c^2}) \leq 3.4 \]

COMPASS

\[ \pi^- + p^+ \rightarrow \mu^+ + \mu^- + X \]

2015+2018 data

\[ \sin(2\varphi_{CS}-\varphi_S) \]

J/ψ

Collins SIDIS TSA

\[ A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^q \otimes H_{1\perp q} \]

\[ 4 \leq Q^2/(\mathrm{GeV/c^2}) \leq 6.25 \]

COMPASS

PLB 770 (2017) 138

28 September 2023

B. Parsamyan
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

\[ A_T^\text{sin}\varphi_S \propto f_{1T,\perp}^q \otimes f_1^{\perp q} \]

Sivers SIDIS TSA

\[ A_{UT}^\text{sin}(\phi_h - \phi_s) \propto f_{1T}^{\perp q} \otimes D_{1q}^h \]
DY TSAs at COMPASS (high-mass range)

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

- General agreement with available theory predictions
3D unpolarized Drell-Yan cross section on NH$_3$ and W

- Data from light and heavy targets
- 3D representation
- Larger systematics for tungsten

28 September 2023

B. Parsamyan

See V. Andrieux’s slides
Conclusions

- Importance of careful understanding and confrontation of experimental data from different experiments
  - Different kinematic domains and phase-space limitations
  - 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
  - Knowledge transfer, comparison of the analysis techniques, tools, and methodology, cross-analyses between different experiments
- Close collaboration between experiment and phenomenology/theory
  - Flexibility in adapting on the analysis side to the choice of the observables, phase-space selections, etc. (before publishing the data)
  - 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
  - Inclusive measurements, unpolarized and polarized SIDIS (longitudinal/transverse)
  - First-ever polarized Drell-Yan measurements
- A wealth of (SI)DIS, Drell-Yan, DVCS, HEMP data collected across the years
  - Petabytes of data available for analysis
- Wide and unique kinematic domain accessing low $x$ and large $Q^2$
  - Will remain unique for at least another decade
- World-unique SIDIS deuteron data collected in 2022
  - Highly successful run, promising preliminary results
- Since 2023 the experiment entered the Analysis Phase
  - The spectrometer has been transferred to the COMPASS successor in the M2 beamline – the AMBER collaboration
  - 3 new groups joined COMPASS in the course of 2023 for the Analysis Phase
  - If you are interested – don’t hesitate to get in touch!

Thank You!
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