The COMPASS Spin Program

Anna Martin
Trieste University and INFN
on behalf of the COMPASS Collaboration
proposed physics programme:

**hadron spectroscopy** \((p, \pi, K)\)
- light mesons, glue-balls, exotic mesons
- polarisability of pion and kaon

**nucleon structure** \((\mu)\)
- longitudinal spin structure
- transverse spin structure

- Drell-Yan \((\pi)\)
- DVCS \((\mu)\)
COMPASS spectrometer

designed to
- use high energy beams
- have large angular acceptance
- cover a broad kinematical range

two stages spectrometer
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

E/HCAL

MuonWall

~ 50 m

calorimetry, \( \mu \text{ID} \)

Polarised Target

SM1

SM2

\( \mu \text{beam} \)

Gent, February 5, 2018

A. Martin
COMPASS spectrometer

two stages spectrometer
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

• use high energy beams
• have large angular acceptance
• cover a broad kinematical range

variety of tracking detectors to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad with a good azimuthal acceptance

MuonWall
E/HCAL
RICH detector

Polarised Target
SM1
SM2

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the polarized target system (>2005)

$^3$He – $^4$He dilution refrigerator (T~50mK)

- solenoid 2.5T
- dipole magnet 0.6T

3 target cells
- 30, 60, and 30 cm long
- opposite polarisation

μ polarization
- d ($^6$LiD) 50%
- p (NH$_3$) 90%

dilution factor
- 40%
- 16%

acceptance > ± 180 mrad

no evidence for relevant nuclear effects (160 GeV)
## COMPASS data taking

<table>
<thead>
<tr>
<th>Year</th>
<th>Muon Beam</th>
<th>Deuterons (LiD) PT</th>
<th>Protons (NH₃) PT</th>
<th>Protons (NH₃) UT</th>
<th>Protons (NH₃) PT</th>
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<tbody>
<tr>
<td>2002-2004</td>
<td>160 GeV</td>
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<td>2005</td>
<td>80% L target polarisation</td>
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<td>2006</td>
<td>acc. shut down / upgrade</td>
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<tr>
<td>2007</td>
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<tr>
<td>2015</td>
<td>100% T, Drell-Yan</td>
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<td>2016-2017</td>
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<td>100% T, Drell-Yan</td>
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### Gent, February 5, 2018
## COMPASS data taking

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<th>Year</th>
<th>Description</th>
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<td>2008</td>
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<td>2009</td>
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<td>2010</td>
<td>100% T</td>
</tr>
<tr>
<td>2011</td>
<td>100% L</td>
</tr>
</tbody>
</table>

### Muon Beam
- **160 GeV**
- Deuteron (\(^6\)LiD) PT

### Proton (NH₃) PT
- **2007**
- 50% L 50% T

### Hadron Beam
- **LH target**
- **2008**
- **2009**

### Muon Beam
- **160,200 GeV**
- Proton (NH₃) PT

### Hadron Beam
- **Ni target**

### Muon Beam
- LH₂ target

### Pion Beam
- Proton (NH₃) UT
- Proton (NH₃) PT

### Muon Beam
- LH₂ target

### Pion Beam
- Proton (NH₃) PT

---

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muon beam program:

LONGITUDINAL SPIN
NUCLEON STRUCTURE
\( \Delta g/g \) from Photon Gluon Fusion

- open charm production
  \( \gamma g \rightarrow c \bar{c} \rightarrow D^0, D^* \)
- high \( p_T \) hadron pairs
  \( \gamma g \rightarrow c \bar{c} \rightarrow 2 \text{ jets or } h^+ h^- \)

\[
\Delta g/g^{LO} = 0.113 \pm 0.038_{\text{stat}} \pm 0.035_{\text{syst}}
\]

- gluon polarisation is much smaller than thought in the 1990s by many theorists
- various methods confirmed by polarised \( pp \) at RHIC
  \[
  \int_{0.05}^{1} \Delta g(x) dx \approx 0.2
  \]
- \( \Delta g \) still can make a substantial contribution to nucleon spin
\[ A_{\text{meas}} = \frac{1}{f_{T}P_{B}} \left( \frac{N^{\text{F}} - N^{\text{F}}}{N^{\text{F}} + N^{\text{F}}} \right) \approx DA_1 = D \frac{g_1(x, Q^2)}{F_1(x, Q^2)} \]

Bjorken sum rule verified to 9%
Helicity

\[ A_1^d, A_1^{K^\pm}, A_1^{\pi^\pm} \]
\[ A_1^p, A_1^{K^\pm}, A_1^{\pi^\pm} \]
\[ \Delta u, \Delta \bar{u}, \Delta d, \Delta \bar{d}, \Delta s = \Delta \bar{s} \]

\( \Delta s > 0 ? \)

results for \( \Delta s \) depend very much on the strange quark FFs used

input:
unpol PDFs (MRST04),
LO FFs (DSS)
curves:DSSV param.
unpolarised SIDIS

factorisation ansatz

\[ \sigma^h \sim \sum \sigma_{\text{hard}} \otimes \text{PDF} \otimes FF \]

\[ q(x, Q^2) \quad D^h_q(z, Q^2) \]

hadron multiplicities

\[ \frac{dM^h(x, z, Q^2)}{dz} = \frac{d\sigma^h(x, z, Q^2)/dx dz dQ^2}{d\sigma^{DIS}(x, Q^2)/dx dQ^2} \]

at LO pQCD

\[ \frac{dM^h(x, z, Q^2)}{dz} = \frac{\sum_q e_q^2 q(x, Q^2) D^h_q(z, Q^2)}{\sum_q e_q^2 q(x, Q^2)} \]
charged pion multiplicities

160 GeV $\mu$, unpolarised $^6$LiD

$1 \text{ (GeV/c)}^2 < Q^2 < 60 \text{ (GeV/c)}^2$, $0.004 < x < 0.4$, $0.1 < y < 0.7$, $W > 5 \text{ GeV/c}^2$, $0.20 < z < 0.85$

317 $(x,y,z)$ kinematic bins

strong $z$ dependence, $\sim$ no dependence on $y$
charged kaon multiplicities

160 GeV \mu,\ \text{unpolarised} \ ^6\text{LiD} \quad 1 (\text{GeV/c})^2 < Q^2 < 60 (\text{GeV/c})^2, \quad 0.004 < x < 0.4, \quad 0.1 < y < 0.7, \quad W > 5 \text{ GeV/c}^2, \quad 0.20 < z < 0.85

more than 620 data points

strong $z$ dependence, week $x$ dependence

PLB 767 (2017) 133
MUON beam PROGRAM:

TRANSVERSITY and TMD PDFs
the structure of the nucleon

taking into account the quark intrinsic transverse momentum $k_T$,
at leading order other 6 TMD PDFs are needed for a full description
of the nucleon structure

transversity PDF

correlation between the transverse polarisation of the nucleon and the transverse polarisation of the quark

collinear

chiral odd

<table>
<thead>
<tr>
<th>nucleon polarisation</th>
<th>U</th>
<th>L</th>
<th>T</th>
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<tbody>
<tr>
<td>U</td>
<td>$f_1$</td>
<td>$f_{1T}$</td>
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<tr>
<td>L</td>
<td>$g_1$</td>
<td>$g_{1T}$</td>
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<tr>
<td>T</td>
<td>$h_1$</td>
<td>$h_{1L}$</td>
<td>$h_{1T}$</td>
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<tr>
<td>Boer Mulders</td>
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<td>transversity $\Delta T q$</td>
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<tr>
<td>$\Delta_0 T q$</td>
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</table>

Sivers PDF
sensitive to orbital angular momentum

Boer-Mulders PDF

T-odd
change of sign

SIDIS gives access to all of them
Semi-Inclusive Deep Inelastic Scattering

hard interaction of a lepton with a nucleon via virtual photon exchange

\[ \sigma^{lN\rightarrow lhX} \sim \sum_q \sigma^{lq\rightarrow lq} \otimes f(x) \otimes D_q^h(z) \]

\[ x = \frac{Q^2}{2P \cdot q} \quad y = \frac{P \cdot q}{P \cdot \ell} = _{LAB} \frac{E - E'}{E} \]

\[ Q^2 = -q^2 \quad W^2 = (P + q)^2 \]

\[ z = \frac{P \cdot P_h}{P \cdot q} = _{LAB} \frac{E_h}{E - E'} \]

\[ p_T^h, \phi_h \]
Semi-Inclusive Deep Inelastic Scattering

\[
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP^2_{h\perp}} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right. \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos2\phi_h} + \lambda_c \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h} \\
+ S_{||} \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin2\phi_h} \right\} + S_{||} \lambda_c \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right]
\]

+ \left| S_{\perp} \right| \left\{ \frac{f_{II} D_I}{\sin(\phi_h - \phi_S)} (F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)}) \\
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \right\}
\]

+ \left| S_{\perp} \right| \lambda_c \left\{ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \\
+ \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right\}
\]
Semi-Inclusive Deep Inelastic Scattering

\[
\frac{d\sigma}{dx dy d\psi d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xy Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} \vphantom{1+\varepsilon} \right. \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_c \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right. \\
+ S_{||} \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \vphantom{1+\varepsilon} \right. \\
+ \left. S_{||} \lambda_c \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right\}
\]

14 independent azimuthal modulations

- amplitudes of the modulations → transversity and TMD PDFs

SIDIS
- allows to disentangle the effects related to the different TMD PDFs and to access all of them
- by identifying the final state hadrons and using different targets allows for flavour separation → very powerful tool

all the amplitudes (AA) have been measured in COMPASS on p and d
unpolarised SIDIS

relevance for TMDs:

- the cross-section depends on $P_{hT}$ comes from:
  - intrinsic $k_T$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
    \[ \langle P_{hT}^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_T^2 \rangle \]
- the azimuthal modulations in the unpolarized cross-sections comes from:
  - intrinsic $k_T$ of the quarks
  - Boer-Mulders PDF

combined analysis should allow to disentangle the different effects phenomenological work is ongoing the Boer-Mulders PDF is still unknown

COMPASS has published results on
- azimuthal asymmetries and $P_{hT}$ distributions from 2004 $^6LiD$ data
- $P_{hT}$ distributions from 2006 $^6LiD$ data NEW and more results will come from 2016/17 data on $LH_2$
unpolarised SIDIS – $P_{hT}$ distributions

$Q^2 \, (GeV/c)^2$

$0.3 < z < 0.4$

$\langle P_{hT}^2 \rangle = \langle p_T^2 \rangle + z^2 \langle k_T^2 \rangle$

NEW:
2006 data
hep-ex/1709.0737
acc. PRD

A. Martin
unpolarised SIDIS – $P_{hT}$ distributions

$\langle P_{hT}^2 \rangle = \langle p_{\perp}^2 \rangle + z^2 \langle k_T^2 \rangle$

NEW:
2006 data
hep-ex/1709.0737
acc. PRD

total:
4918 data points
some results from
SIDIS off transversely polarised targets

TRANSVERSITY and TMD PDFs
MAJOR RESULT:
since 2004 two of these new PDF's have been measured
and shown to be different from zero
by COMPASS and HERMES

the transversity PDF  amplitude of the sine modulation in $\phi_h + \phi_s - \pi$
Collins asymmetry $\sim h_i \otimes H^\perp_i$

the Sivers PDF  amplitude of the sine modulation in $\phi_h - \phi_s$
Sivers asymmetry $\sim f_{IT}^\perp \otimes D_I$

A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON
TRANSVERSITY PDFs
Collins asymmetry $\sim h_{I} \otimes H_{I}^{\perp}$

2004: first evidence for non-zero Collins asymmetry on p from HERMES

COMPASS results

PRL94 2005
NPB765 2007
PLB673 2009

Hall A PRL107, 2011

Gent, February 5, 2018

A. Martin
Collins asymmetry

\[ \sim h_i \otimes H_i^\perp \]

2004: first evidence for non-zero Collins asymmetry on p from HERMES COMPASS results

- **Deuteron** (2002-2004)
  - \( A_{Coll}^d \)

- **Proton** (2007-2010)
  - \( A_{Coll}^p \)

- **K^+**
  - \( A_{Coll}^d \)

- **K^-**
  - \( A_{Coll}^d \)

PRL94 2005
NPB765 2007
PLB673 2009
PLB693 2010
PLB744 2015

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transversity from SIDIS


fit to HERMES p, COMPASS d, Belle e+e- data

M. Anselmino et al., PRD 2015
transversity from SIDIS


fit to HERMES p, COMPASS d, Belle e-

M. Anselmino et al., PRD 2015

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Transversity from Collins and di-hadron asymmetries

point by point extraction

one can use directly the COMPASS p and d asymmetries, and the Belle data to evaluate the analysing power (with some “reasonable” assumption)

*advantage*: no Monte Carlo nor parametrisation is needed

open points: dihadron
closed points: Collins

A.M., F. Bradamante, V. Barone
PRD 2015
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A.M., F. Bradamante, V. Barone
PRD 2015
Sivers function
Sivers asymmetry

\[ A_{Siv} \sim \frac{\sum_q e_q^2 f_{1T}^{\perp q} \otimes D_{1q}}{\sum_q e_q^2 f_1^{q} \cdot D_{1q}} \]

deuteron

\[ A_{Siv}^{d} \]

\( h^+ \)

\( h^- \)

2002-2004 data
NPB765 2007, PLB673 2009

proton

\[ A_{Siv}^{p} \]

\( \pi^+ \)

\( \pi^- \)

\( K^+ \)

\( K^- \)

clearly positive for \( \pi^+ \) down to \( x \sim 10^{-2} \)
slightly lower than HERMES results

PLB 2010, 2012
Sivers function

\[ A_{Siv} \sim \frac{\sum_q e_q^2 f_{1T}^q \otimes D_{1q}}{\sum_q e_q^2 f_1^q \cdot D_{1q}} \]

fits to COMPASS and HERMES data since 2005

Anselmino et al., JHEP04 2017

Sun and Yuan
PRD88 2013

large uncertainties, in particular for the d-quark
Sivers asymmetry on proton

Drell-Yan $Q^2$ range at COMPASS
no evolution SIDIS $\rightarrow$ DY

clearly positive test of change of sign feasible
the weighted Sivers asymmetry

\[ A_{Siv} \propto \frac{\sum_q e_q^2 \cdot f_{1T}^{\perp q} \otimes D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h} \]

\[ w = P_T/zM \]

\[ A_{Siv}^w = \frac{\sigma_S^w}{\sigma_U} = 2 \frac{\sum_q e_q^2 \cdot f_{1T}^{\perp (1)q} \cdot D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h} \]

\[ \rightarrow \text{non negligible uncertainties in extractions} \]

\[ \vec{k}_T ! \]

a possible way out: use of the \( P_T \) weighted asymmetries

obtained by weighting the spin dependent part of the cross-section

\[ w = \frac{P_T}{zM} \]

proposed a long time ago …

reconsidered recently

J. C. Collins et al. PRD 73 (2006) 014021

preliminary results by HERMES in 2005
the weighted Sivers asymmetry

\[ A_{Siv}^w(x) = 2 \frac{\sum_q e_q^2 x f_{1T}^{1(1)q}(x) \int D_{1q}(z) dz}{\sum_q e_q^2 x f_1^q(x) \int D_{1q}(z) dz} \]

\[ w = P_T/zM \]

u-dominance:

\[ A_{Siv}^w \sim 2 f_{1T}^{1(1)u}(x)/f_1^u(x) \]
the weighted Sivers asymmetry

\[ A_{Siv}^w(x) = 2 \frac{\sum_q e_q^2 x f_{1T}^{(1)q}(x) \int D_{1q}(z) dz}{\sum_q e_q^2 x f_1^q(x) \int D_{1q}(z) dz} \]
\[ w = P_T/zM \]

\[ u\text{-dominance: } A_{Siv}^w \sim 2 f_{1T}^{(1)u}(x)/f_1^u(x) \]

\[ A_{Siv}^w \text{ SPIN2016, arXiv:1702.00621} \]
\[ A_{Siv} \text{ PLB717 (2012) 383} \]
other SIDIS results

- 2h TSAs
- interplay Collins asymmetry – 2h asymmetry
- multidimensional analysis of p TSAs
- transversity induced $\Lambda$ polarisation
- gluon Sivers asymmetries
- LSAs
Drell-Yan at COMPASS
DRELL-YAN PROCESS

COMPLEMENTARY APPROACH TO SIDIS

COMPASS is measuring for the FIRST TIME
the Drell-Yan process \( \pi^- p \rightarrow \mu^+ \mu^- X \)
with a transversely polarized proton target

aim: test the fundamental prediction the change of sign
of the Sivers function from SIDIS to Drell-Yan
DRELL-YAN PROCESS

COMPLEMENTARY APPROACH TO SIDIS

COMPASS is measuring for the FIRST TIME the Drell-Yan process $\pi^- p \rightarrow \mu^+ \mu^- X$ with a transversely polarized proton target.

aim: test the fundamental prediction change of sign of the Sivers function from SIDIS to Drell-Yan.

$$\frac{d \sigma^{LO}}{d^4q d\Omega} = \frac{\alpha^2_{em}}{F q^2} \hat{\sigma}_U \left\{ \left( 1 + D_{[\sin^2 \theta]}^{LO} A_u^{\cos 2\phi} \cos 2\phi \right) + S_L D_{[\sin^2 \theta]}^{LO} A_L^{\sin 2\phi} \sin 2\phi + \hat{S}_T \left[ A_T^{\sin \phi} \sin \phi_S + D_{[\sin^2 \theta]}^{LO} (A_T^{\sin (2\phi + \phi_S)} \sin (2\phi + \phi_S) + A_T^{\sin (2\phi - \phi_S)} \sin (2\phi - \phi_S)) \right] \right\}.$$
Drell-Yan

190 GeV $\pi^-$ beam, transversely polarised proton (NH$_3$) target

2015 run:

thick hadron absorber
Drell-Yan

190 GeV $\pi^-$ beam, transversely polarised proton target

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Drell-Yan

190 GeV $\pi^-$ beam, transversely polarised proton target

$q_T$ weighted Sivers asymmetry

$$A_T^w \sim \frac{f_{1T}^{(1)u}}{f_1^u}$$

PRL 119 (2017)

change of sign

same sign

convolution

evolution

pion PDFs
future
future

Lol is open for new ideas/proponents

A.) RF separated kaon and anti-proton beam:
- 1. Hadron spectroscopy ✔
- 2. Drell-Yan physics ✔
- 3. Primakoff with kaon beam
- 4. Direct Photons with kaon ✔
- 5. RF separated beam

B.) Standard muon beam:
- 1. DVCS with trans. polarised proton target
- 2. Elastic muon proton scattering ✔

C.) Standard hadron beam:
- 1. Polarised/Unpolarised DY with various targets ✔
- 2. Absolute cross-section measurements p + He -> pbar X ✔
- 3. Hadron spectroscopy with antiprotons

D.) Spectrometer upgrades – hardware

For the moment it is ~50 pages long document

12/12/2017

Oleg Denisov
near future

Proposal for

**One year of run with 160 GeV muons to measure SIDIS off transversely polarised $d$**

the missing piece of information to complete our programme

with these data, the $d$ asymmetries would have a statistical uncertainty

$$\sigma_d \approx 0.6 \sigma_p$$
or smaller

an example

Collins asymmetry

transversity from COMPASS $p$ and $d$ data

$\rightarrow$ tensor charge

we will gain knowledge in a kinematic range that only COMPASS can cover,
as long as EIC will not start
Conclusions

SIDIS gave and is giving fundamental contributions to the study of the spin structure of the nucleon
  helicity
  Sivers PDF, transversity, Collins FFs different from zero

to progress further
  • comparison with different processes, e+e-, Drell-Yan, pp hard scattering
  • more from SIDIS
    • precision measurements at new facilities with different energies
      JLab12, EIC
    • COMPASS can still do a lot in the “consolidation” phase from existing data
      Λ polarisation, weighted asymmetries, … new ideas and tests and with new data
      LH₂, the future d↑ run

still a long way, a lot to be learned, and a lot of fun!
Thank you!