TMD EFFECTS IN SIDIS @ COMPASS

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(on behalf of the COMPASS Collaboration)

QCD Evolution 2017, Thomas Jefferson National Accelerator Facility
Newport News, VA
Space resolution is function of the distance to the target.
the polarized target system (>2005)

$^3\text{He} - ^4\text{He}$ dilution refrigerator (T~50mK)

- solenoid: 2.5T
- dipole magnet: 0.6T

$^\mu_d$ ($^6\text{LiD}$)
$p$ ($\text{NH}_3$)

polarization:
- $d$ ($^6\text{LiD}$): 50%
- $p$ ($\text{NH}_3$): 90%

dilution factor:
- $d$ ($^6\text{LiD}$): 40%
- $p$ ($\text{NH}_3$): 16%

no evidence for relevant nuclear effects (160 GeV)

opposite polarisation

COMPASS 2007 transverse proton data (part)
## COMPASS data taking

<table>
<thead>
<tr>
<th>muon beam</th>
<th>deuteron ((^6)LiD) PT</th>
<th>2002</th>
<th>80% L/20% T target polarisation</th>
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<tbody>
<tr>
<td></td>
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<td>2003</td>
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<td>2004</td>
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<td>proton (NH(_3)) PT</td>
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<td>2006</td>
<td>L target polarisation</td>
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<tr>
<td>Hadron</td>
<td>LH target</td>
<td>2008</td>
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<td>2009</td>
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<tr>
<td>muon beam</td>
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<td>2010</td>
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<td>2011</td>
<td>L target polarisation</td>
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<tr>
<td>Hadron</td>
<td>Ni target</td>
<td>2012</td>
<td>Primakoff</td>
</tr>
<tr>
<td>muon beam</td>
<td>LH2 target</td>
<td>2012</td>
<td>Pilot DVCS &amp; unpol. SIDIS</td>
</tr>
<tr>
<td>Hadron</td>
<td>Proton (NH3) DT</td>
<td>2014</td>
<td>Pilot DY run</td>
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<tr>
<td></td>
<td>PT</td>
<td>2015</td>
<td>DY run</td>
</tr>
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<td></td>
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<td>2018</td>
<td>2° year of DY run</td>
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<tr>
<td>muon beam</td>
<td>LH2 target</td>
<td>2016</td>
<td>DVCS &amp; unpol. SIDIS</td>
</tr>
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<td>2017</td>
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Measurements with the target transversely polarized:

<table>
<thead>
<tr>
<th>Year</th>
<th>Obs</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>2005</td>
<td>$A_{Siv,d}^h, A_{Col,d}^h$</td>
<td>First $^6$LiD data</td>
</tr>
<tr>
<td>2006</td>
<td>$A_{Siv,d}^h, A_{Col,d}^h$</td>
<td>Full $^6$LiD statistics</td>
</tr>
<tr>
<td>2009</td>
<td>$A_{Siv,d}^{\pi^+,K^+,K_s^0}, A_{Col,d}^{\pi^+,K^+,K_s^0}$</td>
<td>Full $^6$LiD statistics</td>
</tr>
<tr>
<td>2010</td>
<td>$A_{Siv,p}^h, A_{Col,p}^h$</td>
<td>2007 NH$_3$ data</td>
</tr>
<tr>
<td>2012</td>
<td>$A_{UT,d}^{\sin\phi_RS}, A_{UT,p}^{\sin\phi_RS}$</td>
<td>Full $^6$LiD</td>
</tr>
<tr>
<td>2012</td>
<td>$A_{Siv,p}^h, A_{Col,p}^h$</td>
<td>Full NH$_3$ statistics</td>
</tr>
<tr>
<td>2012</td>
<td>$A_{UT,d}^{\sin(\phi_{p}-\phi_S)}, A_{UT,p}^{\sin(\phi_{p}-\phi_S)}$</td>
<td>Exclusive $\rho^0$</td>
</tr>
<tr>
<td>2013</td>
<td>$A_{UT,d}^{(\phi_{p},\phi_S)}, A_{UT,p}^{(\phi_{p},\phi_S)}$</td>
<td>Exclusive $\rho^0$, all asyms.</td>
</tr>
<tr>
<td>2014</td>
<td>$A_{UT,d}^{\sin\phi_RS}, A_{UT,p}^{\sin\phi_RS}$</td>
<td>Full $^6$LiD and NH$_3$</td>
</tr>
<tr>
<td>2014</td>
<td>$A_{Siv,d}^{\pi^+,K^+,K_s^0}, A_{Col,d}^{\pi^+,K^+,K_s^0}$</td>
<td>Full NH$_3$ statistics</td>
</tr>
<tr>
<td>2015</td>
<td>Interplay $A_{UT,p}^{\sin\phi_RS}$ vs $A_{Col,p}^h$</td>
<td>Full NH$_3$ statistics</td>
</tr>
<tr>
<td>2016</td>
<td>$A_{Siv,p}^h$ binned in $Q^2$ to be in DY range</td>
<td>Full NH$_3$ statistics</td>
</tr>
</tbody>
</table>
Accessing TMD PDFs and FFs

- SIDIS off polarized p, d, n targets
  
  \[ \sigma_{\ell p \to \ell' h X} \sim f_{q,p}(x, k_{\perp}^2) \otimes \sigma_{\ell q \to q} \otimes D_{1q}^h(z, p_{\perp}^2) \]

- hard polarised pp scattering

- polarised Drell-Yan

- future: eN colliders

\[ \sigma_{\ell p \to \ell' h X} \sim f_{q,h}(x_1, k_{\perp}^2) \otimes f_{q,p}(x_2, k_{\perp}^2) \otimes \hat{\sigma}_{q \to \mu \mu}(\hat{s}) \]

- future: FAIR, JPark, NICA

\[ \sigma_{e^+ e^- \to h_1 h_2} \sim \hat{\sigma}_{\ell\ell \to \bar{q}q}(\hat{s}) \otimes D_{q_1}^{h_1}(z_1, p_{\perp}^2) \otimes D_{q_2}^{h_2}(z_2, p_{\perp}^2) \]
hard interaction of a lepton with a nucleon via virtual photon exchange

\[ Q^2 = -q^2 \]

\[ x = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{2M_p \nu} \]

\[ y = \frac{P \cdot q}{P \cdot \ell} = \frac{E - E'}{E} \]

\[ W^2 = (P + q)^2 = M_P^2 - Q^2 + 2M_p \nu \]

\[ z = \frac{P \cdot P_h}{P \cdot q} = \frac{E_h}{\nu} \]
Kinematic coverage
Kinematic coverage

COMPASS
HERMES
JLAB12

$Q^2 (\text{GeV}/c^2)$

$W^2 = 100 (\text{GeV}/c^2)^2$
$W^2 = 25 (\text{GeV}/c^2)^2$
$W^2 = 5 (\text{GeV}/c^2)^2$

$y = 0.9$
$y = 0.1$

$x$

$10^{-2}$
$10^{-1}$

$1$

$10$
$100$
$1000$

$dN/dW^2$

$W^2 (\text{GeV}/c^2)^2$

COMPASS 2007 transverse proton data (part)
SIDIS access to TMDs

\[ \sigma_{\ell p \rightarrow \ell' h X} \sim f_{q,p}(x, k_{\perp}^2) \otimes \sigma_{q \rightarrow q} \otimes D_{1q}^h(z, p_{\perp}^2) \]

TMDs \((x, k_{\perp})\)

**TMDs**

- **FFs** \((z, p_{\perp})\)

**Nucleon polarization**

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<thead>
<tr>
<th></th>
<th>U</th>
<th>T</th>
<th>L</th>
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<tr>
<td><strong>U</strong></td>
<td>(f_1)</td>
<td>(f_{1T}^\perp)</td>
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<tr>
<td><strong>T</strong></td>
<td>(h_{1T}^\perp)</td>
<td>(h_1, h_{1T}^\perp)</td>
<td>(h_{1L}^\perp)</td>
</tr>
<tr>
<td><strong>L</strong></td>
<td>(g_{1T}^\perp)</td>
<td></td>
<td>(g_{1L}^\perp)</td>
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**Hadron polarization**

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<td><strong>L</strong></td>
<td>(G_{1T}^\perp)</td>
<td></td>
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**T odd**  **chiral odd**

Factorisation (Collins & Soper, Ji, Ma, Yuan, Qiu & Vogelsang, Collins & Metz...)

JLab 22/05/2017
The cross-section dependence from $P_{hT}$ results from:

- intrinsic $k_\perp$ of the quarks
- $p_\perp$ generated in the quark fragmentation
- A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to

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

The azimuthal modulations in the unpolarised cross sections comes from:

- Intrinsic $k_\perp$ of the quarks
- The Boer-Mulders PDF
- Difficult measurements were one has to correct for the apparatus acceptance

COMPASS and HERMES have

- results on $^6\text{LiD (}\sim d\text{)}$ and $d$ and on $p$ (Hermes only)
- No COMPASS measurements on $p$ since on $N\text{H}_3 (\sim p)$ nuclear effects may be important

⇒COMPASS-II, measurements on LH$_2$ in parallel with DVCS
The full cross section for the unpolarised case is written as:

\[
\frac{d\sigma}{dx \, dy \, dz \, dP_{hT}^2 \, d\phi_h \, d\psi} = \left[ \frac{\alpha^2 \, y^2}{xyQ^2 \, 2(1 - \epsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \epsilon F_{UU,L}) \left\{ 1 + \cos \phi_h \sqrt{2\epsilon(1 + \epsilon)} A_{UU}^{\cos \phi_h} \right\}
\]

\[
A_{UU}^x(x, z, dP_{hT}^2, Q^2) = \frac{F_{UU}^x}{F_{UU,T} + \epsilon F_{UU,L}}
\]

\[
\epsilon = \frac{1 - y - \frac{1}{4} y^2 \gamma^2}{1 - y + \frac{1}{2} y^2 + \frac{1}{4} y^2 \gamma^2} \quad \text{and} \quad \gamma = \frac{2xM}{Q}
\]

\[
F_{UU} = C [f_1 D_1] = x \sum_q e_q^2 \int d\vec{p}_\perp d\vec{k}_\perp \delta^2 (z\vec{k}_\perp + \vec{p}_\perp - \vec{P}_{hT}) f_1^q (x, k_{\perp}^2, Q^2) D_{1,q}^h (z, p_{\perp}^2, Q^2)
\]
When looking at the content of the structure functions/modulations in terms of TMD PDFs for the $\cos \phi_h$ and $\cos 2\phi_h$ we can write:

$$F_{UUU}^{\cos \phi_h} = -\frac{2M}{Q} C \left[ \frac{\hat{h} \cdot \vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M} \vec{P}_{hT} - z(\hat{h} \cdot \vec{k}_\perp) \frac{h_1^\perp H_1^\perp}{zM_h M} \right] + \text{twists} > 3$$

$$F_{UUU}^{\cos 2\phi_h} = C \left[ \frac{(\hat{h} \cdot \vec{k}_\perp)(\hat{h} \cdot \vec{p}_\perp) - \vec{p}_\perp \cdot \vec{k}_\perp}{MM_h} h_1^\perp H_1^\perp \right] + \text{twists} > 3$$

In the $\cos 2\phi_h$ Cahn effects enters only at twist4

$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C \left[ \{2(\hat{h} \cdot \vec{k}_\perp)^2 - k_\perp^2 \} f_1 D_1 \right]$$
Importance of unpolarised SIDIS

\[ F^h_{UU}(x, z, P^2_{hT}; Q^2) = x \sum_q e_q^2 \int d^2 \vec{k}_\perp \, d^2 \vec{p}_\perp \, \delta(\vec{p}_\perp - z \vec{k}_\perp) \]

\[ M^h(x, z, P^2_{hT}; Q^2) = \frac{d^5 \sigma^h / dx dQ^2 dz d^2 \vec{p}_T}{d^2 \sigma^{DIS} / dx dQ^2} \sim \frac{F^h_{UU}(x, z, P^2_{hT}; Q^2)}{F_{UU,T} + \varepsilon F_{UU,L}} \]
Importance of unpolarised SIDIS
Boer-Mulders in $\cos 2\phi$

\[ F_{UU}^{\cos 2\phi}(x, z, P_{h_T}^2; Q^2) = -x \sum_q e_q^2 \int d^2 \vec{k}_\perp d^2 \vec{p}_\perp \frac{2(\hat{h} \cdot \vec{k}_\perp)(\hat{h} \cdot \vec{k}_\perp) - \vec{k}_\perp \cdot \vec{p}_\perp}{Mm_h} h_{1,q}^\perp(x, k'^2; Q^2)H_{1,q}^\perp(z, p'^2; Q^2) \]
Boer-Mulders in $\cos 2\phi$ and in $\cos \phi$
Sivers Asymmetry

- **Sivers**: correlates nucleon spin & **quark transverse momentum** $k_T$ / T-ODD: at LO for $\mu p^\uparrow \rightarrow \mu X h^\pm$

- \[ A_{Siv}(x, z) = \frac{F_{UT}^{\sin \Phi_{Siv}}(x, z)}{F_{UU}(x, z)} = \frac{\sum_q e_q^2 x f_{1T}^q(x, k_T^2) \otimes D_h^1(z, p_T^2)}{\sum_q e_q^2 x f_1^q(x, k_T^2) \otimes D_h^1(z, p_T^2)} \]

- To evaluate it we need to solve the convolutions (i.e. make hypothesis on the transverse momenta dependences of the TMDs)

- Gaussian ansatz:
  \[ f_{1T}^q(x) e^{-\frac{k_T^2}{\langle k_T^2 \rangle_S}} \quad D_h^1(z) e^{-\frac{p_T^2}{\langle p_T^2 \rangle}} \]

- Leading to:
  \[ A_{Siv, G}(x, z) = \frac{\sqrt{\pi M}}{\sqrt{z^2 \langle k_T^2 \rangle_S + (p_T^2)}} \frac{\sum_q e_q^2 x f_{1T}^{q(1)}(x) z D_h^1(z)}{\sum_q e_q^2 x f_1^q(x) D_h^1(z)} \]

- with $f_{1T}^{q(1)}(x) = \int d^2 k_T \frac{k_T^2}{2M^2} f_{1T}^q(x, k_T^2)$
Sivers asymmetry on $p$ charged pions (and kaons), HERMES and COMPASS

![Graph showing Sivers asymmetry](image-url)
If we weight the spin dependent part of the cross-section

\[ F_{UT}^{\sin \Phi_{Siv}}(x, z) = \sum_q e_q^2 \int d^2 \vec{p}_T P_T F_q(x, z, P_T^2) \]

with \( w = \frac{P_T}{zM} \), i.e.

\[ F_{UT}^{\sin \Phi_{Siv,w}}(x, z) = \sum_q e_q^2 \int d^2 \vec{p}_T \frac{P_T^2}{zM} F_q(x, z, P_T^2) = 2 \sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) D_{1q}^h(z) \]

and

\[ F_q(x, z, P_T^2) = \int d^2 \vec{k}_T \int d^2 \vec{p}_T \delta^2(\vec{P}_T - z\vec{k}_T - \vec{p}_T) \frac{\vec{p}_T \cdot \vec{k}_T}{M_P^2} x f_{1T}^{\perp q}(x, k_T^2) D_{1q}(z, p_T^2) \]

we have no longer a convolution but a product of two integrals and we can write

\[ A_{Siv}^w(x, z) = \frac{F_{UT}^{\sin \Phi_{Siv,w}}(x, z)}{F_{UU}(x, z)} = 2 \frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) D_{1q}^h(z)}{\sum_q e_q^2 x f_1^q(x) D_{1q}^h(z)} \]

with \( f_{1T}^{\perp(1)q}(x) = \int d^2 \vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x, k_T^2) \)
The weighted Sivers asymmetry

- In one dimension: for $x$

\[
A_{Siv}^w(x) = 2 \frac{\sum_q e_q^2 x f_{1T}^{(1)q}(x) \int D_1^h(z) dz}{\sum_q e_q^2 x f_1^q(x) \int D_1^h(z) dz}
\]

and for $z$

\[
A_{Siv}^w(z) = 2 \frac{\sum_q e_q^2 D_1^h(z) \int C(x) x f_{1T}^{(1)q}(x) dx}{\sum_q e_q^2 D_1^h(z) \int C(x) x f_1^q(x) dx}
\]

with $C(x) = \int_{\Omega_y} dy \frac{1-y+y^2/2}{x^2 y^2}$

- Note that assuming $u$-dominance at large $x$ for positive hadrons:

\[
A_{Siv}^{w,h^+}(x) \approx 2 \frac{f_{1T}^{(1)u}(x)}{f_1^u(x)} \quad \text{and} \quad A_{Siv}^{w,h^+}(z) = 2 \frac{\int C(x) x f_{1T}^{(1)u}(x) dx}{\int C(x) x f_1^u(x) dx}
\]
The weighted Sivers asymmetry

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

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

standard cuts

\[ z > 0.2 \]

\[ \sim 2 \frac{f_{1T}^{(1)u}(x)}{f_1^u(x)} \]

both \( f_{1T}^{(1)u} \) and \( f_{1T}^{(1)d} \) contribute
The weighted Sivers asymmetry

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

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

standard cuts
\[ z > 0.2 \]

The weighted Sivers asymmetry

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

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

standard cuts
\[ z > 0.2 \]

The ratio between weighted and unweighted Sivers asymmetries follows the average of \( \left\langle \frac{P_{hT}}{z_M} \right\rangle \) of the unpolarised sample.
The weighted Sivers asymmetry

1. weight $\mathbf{w} = \frac{P_T}{zM}$  

$A_{Siv}^{w}(z)$  

$0.1 < z < 1.0$

\[
2 \frac{\int C(x) x f_{1T}^{(1)u}(x) dx}{\int C(x) x f_{1}^{u}(x) dx}
\]
The weighted Sivers asymmetry

1. weight $w = \frac{P_T}{zM}$

$A_{Siv}^w(z)$

$0.1 < z < 1.0$

The ratio between weighted and unweighted Sivers asymmetries follows the average of $\left< \frac{P_{hT}}{zM} \right>$ of the unpolarised sample.
The weighted Sivers asymmetry

1. weight \( w = \frac{P_T}{zM} \) \( A_{Siv}^w(z) \) \( 0.1 < z < 1.0 \)

For \( 0.1 < z < 0.2 \) the asymmetries for \( h^+ \) and \( h^- \) show the same behavior
Interplay among dihadron and single hadron asymmetries

- Collins asymmetry for h+ and for h- "mirror symmetry"
- dihadron asymmetry *only somewhat larger than h+ Collins*

hints for a common origin of the Collins FF and DiFF

Como 2013, DSpin2013, PLB736 (2014) 124

look at

the $\Delta \phi = \phi_1 - \phi_2$

dependence of the asymmetries
Interplay among dihadron and single hadron asymmetries

Analytically

\[ A_{CL1}^{\sin \Phi_C} = a_1 + a_2 \cos \Delta \phi \]

\[ A_{CL2}^{\sin \Phi_C} = a_2 + a_1 \cos \Delta \phi \]

Agreement with data if \( a_1 = -a_2 = a \)

\[ A_{CL\ 2h}^{\sin \Phi_{2h,s}} = a \sqrt{2(1 - \cos \Delta \phi)} \]

Ratio of the \( \Delta \phi \) integrated 2h and 1h asymmetries: \( 4/\pi \)

*slightly larger than \( h^+ \)*
Interplay among dihadron and single hadron asymmetries

analyitically

\[ A_{\text{CL}1}^{\sin \Phi} = a_1 + a_2 \cos \Delta \phi \]
\[ A_{\text{CL}2}^{\sin \Phi} = a_2 + a_1 \cos \Delta \phi \]

mirror symmetry

agreement with data if

\[ A_{\text{CL}2h}^{\sin \Phi_{2h,s}} = a \sqrt{2 (1 - \cos \Delta \phi)} \]

agreement with data

a very simple relationships among the asymmetries in the “2h sample”

they are driven by the same elementary mechanism.

ratio of the \( \Delta \phi \) integrated 2h and 1h asymmetries: \( 4/\pi \)

slightly larger than \( h^+ \)
From Collins asymmetries to transversity

- Following Physical Review D 91, 014034 (2015), in the valence region

\[ xh_1^u = \frac{1}{5} \frac{1}{\tilde{a}_p^h (1 - \tilde{\alpha})} \left[ (xf_p^+ A_p^+ - xf_p^- A_p^-) + \frac{1}{3} (xf_d^+ A_d^+ - xf_d^- A_d^-) \right] \]

\[ xh_1^d = \frac{1}{5} \frac{1}{\tilde{a}_p^h (1 - \tilde{\alpha})} \left[ \frac{4}{3} (xf_d^+ A_d^+ - xf_d^- A_d^-) - (xf_p^+ A_p^+ - xf_p^- A_p^-) \right] \]

With \( \tilde{a}_p^h \) and \( \tilde{\alpha} \) constants
New deuteron data

- Benchmark: extraction from Collins asymmetries

![Graph showing Collins asymmetries](image)
New deuteron data

- 1 full year (same as 2010). We also gain from $\frac{f_P P_{PT}}{f_D P_{DT}} = \frac{0.155 \times 0.8}{0.40 \times 0.5} = 0.6$

THIS IS A KEY MEASUREMENT THAT WILL IMPACT OUR KNOWLEDGE,
Conclusions

- The study of TMDs has entered the phase of multidimensional analysis
- An important step in this direction is the large sample of precise unpolarised data, both as multiplicities and as azimuthal modulations
- In the next years more of such data will be available both from COMPASS and from JLab12
- One year of deuteron data (something that COMPASS can do after 2020) will strongly impact our knowledge of $h_1^d$!
- Waiting for the EIC to extend the accessible phase space, the description of such data is a mandatory task for the theory of TMDs
Thank you
and see you all in Trieste for the EICUG meeting (July 18-22, 2017)
eicug2017.ts.infn.it
The CM Energy vs Luminosity Landscape

CEIC1 = Chinese version of Electron-Ion Collider ("A dilution-free mini-COMPASS")

MEIC1 = EIC@Jlab

eRHIC = EIC@BNL

LHeC = ep/eA collider @ CERN

CEIC2

MEIC2

HL-eRHIC

FCC-he
SIDIS Experiment must:

- Have large acceptances on all the relevant variables $x, Q^2, z, P_{hT}, \phi$
- Use different targets (p, d, n) and identify hadrons to allow flavor separation
- Be ad different energies for to cover PDFs from the valence region down to small-$x$
- Large luminosity to allow multidimensional results needed by the complexity of TMDs

The polarized lepton-nucleon collider will be a mandatory tool to reach the level of ordinary PDF