Probing Nucleons and Nuclei in High Energy Collisions INT - October 8th, 2018

Measurements of transverse momentum distributions in semi-inclusive DIS

- from a mainly European perspective -

Gunar.Schnell @ DESY.de


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Euskal Herriko
del País Vasco
                   Unibertsitatea
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The COMPASS experiment @ CERN *NIM A 577(2007) 455* The COMPASS exper

HERMES Experiment (†2007) @ DESY hermes *HERMES at DESY*

2000 Foto: 2000 etc. 27.6 GeV polarized et/et beam scattered off ...

Gunar Schnell INT-18-3, Seattle . **forward-acceptance spectrometer** ⇒ **40mrad**< θ <**220mrad high lepton ID efficiency and purity excellent hadron ID thanks to dual-radiator RICH** polarized (pure) gas targets and allegent and allegent p - unpolarized (H, D, He,…, Xe) - as well as **transversely (H)** and longitudinally (H, D, He)

getting polarized nucleons

- \bullet common polarized targets
	- gas targets -> pure, but lower density
	- solid (e.g. NH3) targets -> high density, but large dilution

getting polarized nucleons

- \bullet common polarized targets
	- gas targets -> pure, but lower density
	- solid (e.g. NH3) targets -> high density, but large dilution
- statistical precision: $\sim \frac{1}{(5.5 \times 10^{-4})^2}$ (f... dilution factor) 1 $fP_{B}P_{T}$ 1 $\overline{}$ *N*
	- solid targets $f \approx 0.2 \rightarrow$ directly scales uncertainties (as do $P_B \& P_T$)
	- dilution also kinematics dependent (partially unknown systematics)

Semi-inclusive DIS

Spin-momentum structure of the nucleon

$$
\frac{1}{2} \text{Tr} \Big[(\gamma^+ + \lambda \gamma^+ \gamma_5) \Phi \Big] = \frac{1}{2} \Big[f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^{\perp} + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \Big]
$$

$$
\frac{1}{2} \text{Tr} \Big[(\gamma^+ - s^j i \sigma^{+j} \gamma_5) \Phi \Big] = \frac{1}{2} \Big[f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^{\perp} + s^i \epsilon^{ij} k^j \frac{1}{m} h_1^{\perp} + s^i S^i h_1 \Big]
$$

$$
+\, s^i(2k^ik^j - {\bm k}^2\delta^{ij})S^j\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\, s^ik^i\frac{1}{m}\,h_{1L}^\perp \Bigg]
$$

 $\begin{array}{c|c|c|c|c} \hline \end{array}$ $\begin{array}{c|c|c} \hline \end{array}$ $\begin{array}{c|c|c} \hline \end{array}$ $\begin{array}{c|c|c} \hline \end{array}$ $\begin{array}{c|c|c} \hline \end{array}$ nucleon pol. nucleon pol. $U \begin{array}{|c|c|c|} \hline f_1 & h_1^{\perp} \ \hline \end{array}$ $L \begin{array}{|c|c|c|} \hline \end{array} \begin{array}{|c|c|c|} \hline g_{1L} & h_{1L}^\perp \end{array}$ $T \mid f_{1T}^{\perp}$ $\frac{1}{1T}$ | g_{1T} | h_1, h_{1T}^\perp

quark pol.

- each TMD describes a particular spinmomentum correlation
- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

Spin-momentum structure of the nucleon

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\frac{1}{2}\text{Tr}\left[\left(\gamma^+ + \lambda\gamma^+\gamma_5\right)\Phi\right] = \frac{1}{2}\left[f_1 + S^i\epsilon^{ij}k^j\frac{1}{m}f_{1T}^{\perp} + \lambda\Lambda g_1 + \lambda S^ik^i\frac{1}{m}g_{1T}\right]
$$
\n
$$
\frac{1}{2}\text{Tr}\left[\left(\gamma^+ - s^j i\sigma^{+j}\gamma_5\right)\Phi\right] = \frac{1}{2}\left[f_1 + S^i\epsilon^{ij}k^j\frac{1}{m}f_{1T}^{\perp} + s^i\epsilon^{ij}k^j\frac{1}{m}h_1^{\perp} + s^iS^ih_1\right]
$$
\n
$$
+ s^i(2k^ik^j - k^2\delta^{ij})S^j\frac{1}{2m^2}h_{1T}^{\perp} + \Lambda s^ik^i\frac{1}{m}h_{1L}^{\perp}\right]
$$

 $U \mid L \mid T$

 $\frac{1}{1T}$ *g*_{1*T*} *h*₁, *h*₁ $\frac{1}{1T}$

transversity

 $U \begin{array}{|c|c|c|} \hline f_1 & h_1^{\perp} \ \hline \end{array}$

 $L \begin{array}{|c|c|c|c|} \hline \end{array} \begin{array}{|c|c|c|c|} \hline g_{1L} & h_{1L}^\perp \end{array}$

Twist-2 Twist-

 $T \mid f_{1T}^{\perp}$

worm-gear

nucleon pol.

nucleon pol.

Sivers

scribes a particular spin-Boer-Mulders relation

functions in black survive integration over transverse momentum

functions in green box are chirally odd pretzelosity

functions in red are naive T-odd

☛ R. Seidl, A. Vossen

☚ relevant for unpolarized final state

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☛ R. Seidl, A. Vossen

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➟ give rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

one-hadron production (ep-rehX) \mathcal{L} ^Q cos ^φ ^dσ⁷ $\frac{1}{\sqrt{2}}$ decreases to $\frac{1}{\sqrt{2}}$ decreases to $\frac{1}{\sqrt{2}}$ decreases to $\frac{1}{\sqrt{2}}$ $\overline{}$

$$
d\sigma = d\sigma_{UU}^{0} + \cos 2\phi \, d\sigma_{UU}^{1} + \frac{1}{Q} \cos \phi \, d\sigma_{UU}^{2} + \lambda_e \frac{1}{Q} \sin \phi \, d\sigma_{LU}^{3}
$$

+
$$
S_L \left\{ \sin 2\phi \, d\sigma_{UL}^{4} + \frac{1}{Q} \sin \phi \, d\sigma_{UL}^{5} + \lambda_e \left[d\sigma_{LL}^{6} + \frac{1}{Q} \cos \phi \, d\sigma_{LL}^{7} \right] \right\}
$$

+
$$
S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^{8} + \sin(\phi + \phi_S) \, d\sigma_{UT}^{9} + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \right\}
$$

$$
\sigma_{XX} + \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma_{UT}^{11} + \sin \phi_S \, d\sigma_{UT}^{12} \right)
$$

Bean Traget
Polarization
+
$$
\lambda_e \left[\cos(\phi - \phi_S) \, d\sigma_{LT}^{13} + \frac{1}{Q} \left(\cos \phi_S \, d\sigma_{LT}^{14} + \cos(2\phi - \phi_S) \, d\sigma_{LT}^{15} \right) \right] \right\}
$$

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-
- $\sum_{}^{p_S}$ ↙ ↘ **Phad Polarization** $\mathcal{X}% _{0}=\mathbb{C}^{2}\times\{N_{0}^{2}$ $\mathcal{Y}% _{M_{1},M_{2}}^{(h,\sigma),(h,\sigma)}(-\varepsilon)$ z ϕ_S ϕ \vec{p}_had \vec{S}_\perp ⃗ \boldsymbol{k} \rightarrow k^{\prime} \mathbf{v}_ℓ

 $\overline{}$

Beam

!

9 **Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197 Boer and Mulders, Phys. Rev. 2008) 570 Bacchetta et al., Phys. Lett. B 595 (2004)** 3 **Bacchetta et al., JHEP 0702 (2007) 0 "Trento Conventions", Phys. Rev. D 70 (2004) 117504** Trento Conventions", Phys. Rev. D 70 (2004) 117504 \vec{S}_{\perp} Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197 Boer and Mulders, Phys. Rev. D 57 (1998) 5780 Bacchetta et al., Phys. Lett. B 595 (2004) 309 Bacchetta et al., JHEP 0702 (2007) 093

**One-hadron production (ep-
$$
\rightarrow
$$
ehX)
\n
$$
d\sigma = d\sigma_{UU}^0 + \frac{1}{(\cos 2\phi d\sigma_{UU}^1)} + \frac{1}{Q} \cos \phi d\sigma_{UU}^2 + \lambda_e \frac{1}{Q} \sin \phi d\sigma_{LU}^3
$$
\n
$$
+ S_L \left\{ \frac{\sin 2\phi d\sigma_{UL}^4}{\sin 2\phi d\sigma_{UL}^4} + \frac{1}{Q} \sin \phi d\sigma_{UL}^5 + \lambda_e \left[d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi d\sigma_{UL}^7 \right] \right\}
$$
\n
$$
+ S_T \left\{ \frac{\sin(\phi - \phi_S) d\sigma_{UT}^8}{\sin(\phi - \phi_S) d\sigma_{UT}^9} + \frac{\sin(\phi + \phi_S) d\sigma_{UT}^9}{\sin(3\phi - \phi_S) d\sigma_{UT}^{15}} \right\}
$$
\n**Bean-Target**\n**Polarization**\n
$$
+ \lambda_e \left[\frac{\cos(\phi - \phi_S) d\sigma_{LT}^{13}}{\cos(\phi - \phi_S) d\sigma_{LT}^{13}} + \frac{1}{Q} \left(\cos \phi_S d\sigma_{LT}^{14} + \cos(2\phi - \phi_S) d\sigma_{LT}^{15} \right) \right]
$$
\n
$$
= \frac{1}{\sqrt{\frac{\sum_{i=1}^{n} S_i}{n}}}} = \frac{Mulders and Tangerman, Nucl. Phys. B 461 (1996) 197}{\text{Boer and Mulders, Phys. Rev. D 57 (1998) 5780}} = \frac{1}{\sqrt{\frac{\sum_{i=1}^{n} S_i}{n}}}} = \frac{Mulders. Phys. Rev. D 57 (2004) 309}{\text{Bacchet at al., JHEP 0702 (2007) 093}} = \frac{1}{\sqrt{\frac{\sum_{i=1}^{n} S_i}{n}}}
$$
\n
$$
= \frac{1}{\sqrt{\frac{\sum_{i=1}^{n} S_i}{n}}}} = \frac{1}{\sqrt{\frac{\sum_{i=1}^{n} S_i}{n}}}} = \frac{1}{\sqrt{\frac{\sum_{i=1}^{n} S_i}{n}}}} = \frac{1}{\sqrt{\frac{\sum_{i=1}^{n} S_i}{n}}}} = \frac{1
$$**

 \sqrt{x}

⃗ \boldsymbol{k}

 \mathbf{y}

 \sum

one-hadron production (ep-rehX) \mathcal{L} ^Q cos ^φ ^dσ⁷ $\frac{1}{\sqrt{2}}$ decreases to $\frac{1}{\sqrt{2}}$ decreases to $\frac{1}{\sqrt{2}}$ decreases to $\frac{1}{\sqrt{2}}$ $\overline{}$

$$
d\sigma = \left(\frac{d\sigma_{UU}^{0}}{d\sigma_{UU}} + \frac{1}{\omega}\cos\phi \,d\sigma_{UU}^{2} + \lambda_{e}\frac{1}{Q}\sin\phi \,d\sigma_{LU}^{3}
$$

+ $S_{L}\left\{\frac{\sin 2\phi \,d\sigma_{UL}^{4}}{\sin\phi \,d\sigma_{UL}} + \frac{1}{Q}\sin\phi \,d\sigma_{UL}^{5} + \lambda_{e}\left(\frac{d\sigma_{LL}^{6}}{d\sigma_{LL}}\right) + \frac{1}{Q}\cos\phi \,d\sigma_{LL}^{7}\right\}\right\}$
+ $S_{T}\left\{\frac{\sin(\phi - \phi_{S}) \,d\sigma_{UT}^{8}}{\sin(2\phi - \phi_{S}) \,d\sigma_{UT}^{1}} + \frac{\sin(\phi + \phi_{S}) \,d\sigma_{UT}^{9}}{d\sigma_{UT}^{1}} + \frac{\sin(3\phi - \phi_{S}) \,d\sigma_{UT}^{10}}{d\sigma_{UT}^{1}}\right\}$
Bean Target Polarization
+ $\lambda_{e}\left[\cos(\phi - \phi_{S}) \,d\sigma_{LT}^{13}\right] + \frac{1}{Q}\left(\cos\phi_{S} \,d\sigma_{LT}^{14} + \cos(2\phi - \phi_{S}) \,d\sigma_{LT}^{15}\right)\right\}$
Mulders and Tangerman, Nucl. Phys. B 461 (1996) 197
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Bacchetta et al. Phys. Lett. B 595 (2004) 309

Phad

 \vec{p}_had

 $\mathcal{X}% _{0}=\mathbb{C}^{2}\times\{N_{0}^{2}$

⃗ \boldsymbol{k}

 $\mathcal{Y}% _{M_{1},M_{2}}^{(h,\sigma),(h,\sigma)}(-\varepsilon)$

z

!

Polarization

 ϕ

 \mathbf{v}_ℓ

Gunar Schnell INT-18-3, Seattle 9 **Bacchetta et al., Phys. Lett. B 595 (2004)** 3 **Bacchetta et al., JHEP 0702 (2007) 0 "Trento Conventions", Phys. Rev. D 70 (2004) 117504** Trento Conventions", Phys. Rev. D 70 (2004) 117504 Bacchetta et al., Phys. Lett. B 595 (2004) 309 Bacchetta et al., JHEP 0702 (2007) 093

… possible measurements

$$
\frac{d^5\sigma}{dxdydzd\phi_h dP_{h\perp}^2} \propto \left(1 + \frac{\gamma^2}{2x}\right) \{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1 - \epsilon)} F_{UU}^{\cos\phi_h} \cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h\}
$$

normalize to inclusive DIS cross section **hadron multiplicity:**

… possible measurements

$$
\frac{d^5\sigma}{dxdydzd\phi_h dP_{h\perp}^2} \propto \left(1 + \frac{\gamma^2}{2x}\right) \{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1 - \epsilon)} F_{UU}^{\cos\phi_h} \cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h\}
$$

hadron multiplicity:	...	possible	measurable	ments
nonmalize to inclusive DIS	$d^4 \mathcal{M}^h(x, y, z, P_{h\perp}^2) \propto \left(1 + \frac{\gamma^2}{2x}\right) \frac{F_{UU,T} + \epsilon F_{UU,L}}{F_T + \epsilon F_L}$			
$\frac{d^2 \sigma^{incl.DIS}}{dxdy}$	$\propto F_T + \epsilon F_L$			
$\frac{d^5 \sigma}{dxdydz d\phi_h dP_{h\perp}^2} \propto \left(1 + \frac{\gamma^2}{2x}\right) \{F_{UU,T} + \epsilon F_{UU,L}$				
$+ \sqrt{2\epsilon(1-\epsilon)} F_{UU}^{\cos \phi_h} \cos \phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h\}$				

normalize to azimuthindependent cross-section **moments:**

… azimuthal spin asymmetries hermes *Azimuthal Single-Spin Asymmetries*

$$
A_{UT}(\phi, \phi_S) = \frac{1}{\langle |S_\perp|\rangle} \frac{N_h^{\uparrow}(\phi, \phi_S) - N_h^{\downarrow}(\phi, \phi_S)}{N_h^{\uparrow}(\phi, \phi_S) + N_h^{\downarrow}(\phi, \phi_S)}
$$

\$\sim\$ $\sin(\phi + \phi_S) \sum_q e_q^2 \mathcal{I} \left[\frac{k_T \hat{P}_{h\perp}}{M_h} h_1^q(x, p_T^2) H_1^{\perp, q}(z, k_T^2) \right]$
\$\downarrow\$ $\frac{k_f^q}{k}$
\$+\$ $\sin(\phi - \phi_S) \sum_q e_q^2 \mathcal{I} \left[\frac{p_T \hat{P}_{h\perp}}{M} f_{1T}^{\perp, q}(x, p_T^2) D_1^q(z, k_T^2) \right]$
\$+\$ \cdots $\mathcal{I}[\ldots]$: convolution integral over initial (p_T)
and final (k_T) quark transverse momenta

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… azimuthal spin asymmetries hermes *Azimuthal Single-Spin Asymmetries* hermes *Azimuthal Single-Spin Asymmetries*

$$
A_{UT}(\phi, \phi_S) = \frac{1}{\langle |S_\perp|\rangle} \frac{N_h^{\uparrow}(\phi, \phi_S) - N_h^{\downarrow}(\phi, \phi_S)}{N_h^{\uparrow}(\phi, \phi_S) + N_h^{\downarrow}(\phi, \phi_S)}
$$

$$
\sim \sin(\phi + \phi_S) \sum_q e_q^2 \mathcal{I} \left[\frac{k_T \hat{P}_{h\perp}}{M_h} h_1^q(x, p_T^2) H_1^{\perp, q}(z, k_T^2) \right]
$$

$$
+ \sin(\phi - \phi_S) \sum_q e_q^2 \mathcal{I} \left[\frac{p_T \hat{P}_{h\perp}}{M} f_{1T}^{\perp, q}(x, p_T^2) D_1^q(z, k_T^2) \right]
$$

$$
+ \cdots \mathcal{I} [\ldots]
$$
: convolution integral over initial (p_T)
and final (k_T) quark transverse momenta

. it azimuthal modulations, e.g., using maximum-likelihood method π azimuthal modulations, e.g., using maximum-likelihood method fit azimuthal modulations, e.g., using maximum-likelihood method

 $PDF(2/\sin(\phi + \phi_{\alpha}))_{UFT}$, $\phi(\phi_{\alpha}) = \frac{1}{4} [1 + P_{\pi}(2/\sin(\phi + \phi_{\alpha}))_{UFT} \sin(\phi + \phi_{\alpha}) + 1]$ 1 . $PDF(2\langle\sin(\phi\pm\phi_S)\rangle_{UT},\ldots,\phi,\phi_S) = \frac{1}{2}\{1+P_T(2\langle\sin(\phi\pm\phi_S)\rangle_{UT}\sin(\phi\pm\phi_s)+\ldots)\}$

"Qual der Wahl"

- SIDIS structure functions come with various kinematic prefactors
	- include in definition of asymmetries ("cross-section asym.") M.L. pdf $\propto [1 + \mathcal{A}^{\sin(\phi + \phi_s)}(x, y, z, P_{h\perp}) + ...]$
	- factor out from asymmetries ("structure-fct. asym.") $M.L. \text{ pdf } \propto [1 + D(y)A^{\sin(\phi + \phi_s)}(x, y, z, P_{h\perp}) + ...]$

"Qual der Wahl"

- SIDIS structure functions come with various kinematic prefactors
	- include in definition of asymmetries ("cross-section asym.") M.L. pdf $\propto [1 + \mathcal{A}^{\sin(\phi + \phi_s)}(x, y, z, P_{h\perp}) + ...]$
	- factor out from asymmetries ("structure-fct. asym.") $M.L. \text{ pdf } \propto [1 + D(y)A^{\sin(\phi + \phi_s)}(x, y, z, P_{h\perp}) + ...]$
- **latter facilitates comparisons between experiments and** simplifies kinematic dependences by removing known dependences
	- but what about twist suppression, also factor out?
	- and what about other kinematically suppressed contributions?

… other complications

- **theory done w.r.t. virtual-photon direction**
- experiments use targets polarized w.r.t. lepton-beam direction _ገ
 ⎛ c c \overline{c} \overline{c} \overline{c} \overline{c} \overline{c} \overline{c} \overline{c}

 \mathscr{L}

S

 θ_{γ^*}

S⊥

l ′

 $\widetilde{\mathbf{q}}$

 \mathbf{P}_h

 $\mathbf{P}_{h\perp}$

z

 $y¹$

l

… other complications $\sqrt{\frac{1}{\log \theta_{\gamma^{*}}}}$

- theory done w.r.t. virtual-photon direction λ \int_{x}^{y}
- experiments use targets polarized w.r.t. lepton-beam direction _ገ
 ⎛ ients use targets poiarized w.r.t. lepton-beam direction **Theory: Polarization along virtual photon direction (q)**

 \ddot{x}

S

 θ_{γ^*}

 ${\bf S}_\perp$

l ′

 $\widetilde{\mathbf{q}}$

 \mathbf{P}_h

 $\mathbf{P}_{h\perp}$

z

 \hat{y}

l

➡ mixing of longitudinal and transverse polarization effects [Diehl & Sapeta, EPJ C 41 (2005) 515], e.g., 2
ا(oolarization $\mathsf{e}\mathsf{f}$ f $2C$ |
|ts cos di x no of longitudingl and transverse polarization effects **asymmetries via:** [**Diehl and Sapeta, Eur. Phys. J. C41 (2005)**]

$$
\begin{pmatrix}\n\left\langle \sin \phi \right\rangle_{UL}^{1} \\
\left\langle \sin(\phi - \phi_{S}) \right\rangle_{UT}^{1} \\
\left\langle \sin(\phi + \phi_{S}) \right\rangle_{UT}^{1}\n\end{pmatrix} = \begin{pmatrix}\n\cos \theta_{\gamma^{*}} & -\sin \theta_{\gamma^{*}} & -\sin \theta_{\gamma^{*}} \\
\frac{1}{2} \sin \theta_{\gamma^{*}} & \cos \theta_{\gamma^{*}} & 0 \\
\frac{1}{2} \sin \theta_{\gamma^{*}} & 0 & \cos \theta_{\gamma^{*}}\n\end{pmatrix}\n\begin{pmatrix}\n\left\langle \sin \phi \right\rangle_{UL}^{q} \\
\left\langle \sin(\phi - \phi_{S}) \right\rangle_{UT} \\
\left\langle \sin(\phi + \phi_{S}) \right\rangle_{UT}\n\end{pmatrix}
$$

 $(\cos \theta_{\gamma^*} \simeq 1$, $\sin \theta_{\gamma^*}$ up to 15% at HERMES energies)

… other complications $\sqrt{\frac{1}{\log \theta_{\gamma^{*}}}}$

- theory done w.r.t. virtual-photon direction λ \int_{x}^{y}
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 ⎛ ients use targets poiarized w.r.t. lepton-beam direction **Theory: Polarization along virtual photon direction (q)**

 \ddot{x}

S

 θ_{γ^*}

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l ′

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 \mathbf{P}_h

 ${\bf P}_{h\perp}$

z

 \hat{y}

l

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\frac{1}{2} \sin \theta_{\gamma^{*}} & 0 & \cos \theta_{\gamma^{*}}\n\end{pmatrix}\n\begin{pmatrix}\n\left\langle \sin \phi \right\rangle_{UL}^{q} \\
\left\langle \sin(\phi - \phi_{S}) \right\rangle_{UT} \\
\left\langle \sin(\phi + \phi_{S}) \right\rangle_{UT}\n\end{pmatrix}
$$

(a) and on sume target for both poiarizain ■ need data on same target for both polarization orientations! … results ...

multiplicities @ HERMES

- extensive data set on pure proton and deuteron targets for identified charged mesons
	- access to flavor dependence of fragmentation through different mesons and targets
- input to fragmentation function analyses
- extracted in a multi-dimensional unfolding procedure:
	- \bullet $(x, z, P_{h\perp})$
	- \odot (Q², z, P_{h⊥})

 $\langle \mathcal{M}(Q^2) \rangle_{Q^2} \neq \mathcal{M}(\langle Q^2 \rangle)$ (0.102) **0 0.2 0.3**

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even though having similar average kinematics, multiplicities **0.3** in the two projections are different in the two projections and diffe **proton deuteron** $\frac{1}{2}$ **O** even though having similar average kinematics, multiplicities **0.6** in the two projections are different
$\langle \mathcal{M}(Q^2) \rangle_{Q^2} \neq \mathcal{M}(\langle Q^2 \rangle)$

the average along the valley will be smaller than the average along the gradient

 $\langle \mathcal{M}(Q^2) \rangle_{Q^2} \neq \mathcal{M}(\langle Q^2 \rangle)$

- **•** the average along the valley will be smaller than the average along the gradient
- still the **average kinematics** can be the same

 $\langle \mathcal{M}(Q^2) \rangle_{Q^2} \neq \mathcal{M}(\langle Q^2 \rangle)$

- **the average along the valley will** be smaller than the average along the gradient
- still the **average kinematics** can be the same

take-away messages: (when told so) integrate your cross section over the kinematic ranges dictated by the experiment (e.g., do not simply evaluate it at the average kinematics)

To experiments: fully differential analyses!

integrating vs. using average kinematics

10 -1 1 10 -1 1 10 -1 1 10 -1 1 1 and Q^2 10 +0.02 +0.07 $\frac{z}{2}$: $\frac{0.21}{z}$ +0.27 0.2-0.3 0.3-0.4 $0.4 - 0.6$ $0.6 - 0.8$ HERMES $z-Q^2$ K^+ - d $-$ DSS07 +0.02 +0.04 +0.09 +0.29 z : 0.2-0.3 $0.3 - 0.4$ $0.4 - 0.6$ $0.6 - 0.8$ HERMES z-x (not included in the fit) K^{\dagger} - d $+0.03$ $4+0.08$ \blacktriangle +0.18 $+0.38$ K^- d +0.03 +0.08 \blacktriangle +0.18 +0.38 $K-d$ K^+ - p $+0.02$ +0.07 +0.27 $K^{\text{+}}$ - p +0.02 +0.04 \triangle _{+0.09} +0.29 K- - p $+0.03$ $+0.08$ $+0.18$ $+0.38$ Q^2 K- - p +0.03 \blacktriangle +0.08 \triangle +0.18 +0.38 $10 \quad x$ -1 (by now old) **DSS07** FF fit to $z-Q^2$ projection [R. Sassot, private communication]

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integrating vs. using average kinematics

(by now old) **DSS07** FF fit to $z-Q^2$ projection

z-x "prediction" reasonable well when using **integration** over phase-space limits (red lines)

integrating vs. using average kinematics

(by now old) **DSS07** FF fit to $z-Q^2$ projection

z-x "prediction" reasonable well when using **integration** over phase-space limits (red lines)

significant changes when using **average kinematics**

Ph⊥ dependence

- multi-dimensional analysis allows going beyond collinear factorization
- flavor information on transverse momenta via target variation and hadron ID e.g. [A. Signori et al., JHEP 11(2013)194]

$\begin{array}{|c|c|c|c|c|}\n\hline\nh_1 & \hline\nh_2 & \hline\n\end{array}$ momentum-dependent hadron multiplicities [15] and Ph⊥-multiplicity landscape

- [11] J. Ashman et al. (EMC), Z. Phys.C 52, 361 (1991).
- \overline{a} [15] A. Airapetian et al. (HERMES), Phys. Rev. D87, 074029 (2013).
- [16] C. Adolph et al. (COMPASS), Eur. Phys. J. C73, 2531 (2013); 75, 94(E) (2015).
- [31] R. Asaturyan et al., Phys. Rev. C 85, 015202 (2012).
- ["This paper"] M. Aghasyan et al. (COMPASS), Phys. Rev. D 97, 032006 (2018).

… as well as more limited measurements by H1 and Zeus

$\begin{array}{|c|c|c|c|c|}\n\hline\nh_1 & \hline\nh_2 & \hline\n\end{array}$ momentum-dependent hadron multiplicities [15] and Ph⊥-multiplicity landscape

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… as well as more limited measurements by H1 and Zeus

- data on LiD target
- \bullet differential in x , $z, Q^2, P_{h\perp}^2$
- **O** one example (lowest z bin)
- **•** high statistical precision allows detailed studies

Gunar Schnell INT-18-3, Seattle \mathbf{F}_{1} and negatively (full squares) and negatively (full circles) charged hadrons as a function of P2

<u>Metal et al.</u> Ph⊥ dependence

 $E(N)$ 10 0, ocaling

 W_2 according to the binning given in Ref. [11]. The EMC in Ref. [11]. The EMC in E

differences between h⁺ and h⁻ increase with z

COMPASS vs. JLab & HERMES \mathbf{r} ranges. The comparison shown in Fig. 12, where the compa Γ \cap Λ \cap Λ \cap Λ \subset \subset Λ \subset Γ \subset P2 hT in four W² bins in the range 0.2 <z< 0.4, demon- \mathbf{h} are compared in the four bins of \mathbf{h} x_{i} lied and ς GUILNIVILU

 $\left(\mathrm{GeV}/c \right)^2$

 $\rm \frac{5}{2}$

 P^+

2 *M* d 1

 10^{-1}

fitting the Ph⊥ dependence TTING THE Ph₁ depend denote the normalization coefficients, α $d^2M h(x, \Omega^2, z)$ M $\frac{u_{M}(x, y, z, z)}{u_{M}(x, z)} = \frac{18}{100} \exp \left(-\frac{z}{x} \right)$ $0.3 < z < 0.4$ 10^{-1} $\begin{array}{ccc} 0.5 & 0.7 & 0.6 \\ 0.4 & 0.4 & 0.6 \end{array}$ $0.6 < z < 0.8$ $\langle Q^2 \rangle$ = 1.25 (GeV/*c*)² $\langle x \rangle = 0.006$ *c* (GeV/ *p* -1 0.3 < *z* < 0.4 0.4 < *z* < 0.6 0.6 < *z* < 0.8 ² 〉 = 4.65 (GeV/*c*) ² 〈*Q* $0.008 < x < 0.013$ \overline{T} of small \overline{C} and \overline{C} \overline{r} fitting the P_1 hti significantly increases with $\frac{1}{2}$ n_{1L} $\frac{1}{1}$, h_{1T}^{\perp} $d^2M h(r, \Omega^2, z)$ $\mathbf{d}^{\mathsf{T}}M^{\mathsf{T}}(X, \mathcal{Q}^{\mathsf{T}}; Z)$ $\frac{1}{\omega^2}$ confirms the one may be one may be ω donomica uepenuence $\sqrt{2}$ \mathcal{U} and \mathcal{U} \mathcal{F}_{hT} $\tau_{\overline{D2}}$ $\overline{\Delta P}$ $\overline{\Delta P}$ $\overline{\Delta 2}$ $\rm _{hT}^{\rm 2}\rangle\,(GeV/c)^{\rm 2}$ $P = \begin{bmatrix} 2 & 1 & 0 \\ 0 & 0.4 & 0 \end{bmatrix}$ in Eq. (8), and the exponent in Eq. (8), 0.2 0.6 0.003 < *x* < 0.008 where the normalization coefficient N and the average $1 < Q^2/(GeV/c)^2 < 1.7$ Δ 3 < $Q^2/(GeV/c)^2 < 7$ **a** $1 < Q^2/(GeV/c)^2 < 1.7$ $4/3 < Q^2/(GeV/c)^2 < 7$
 a $1.7 < Q^2/(GeV/c)^2 < 3$ **7** $2Q^2/(GeV/c)^2 < 16$ $\overline{0.2}$ 0.4 0.6 0.2 0.4 λ 0.6 0.032 < *x* < 0.055 | 0.055 < *x* < 0.1 | 0.1 < *x* < 0.21 | 0.21 < *x* < 0.4 0.2 0.4 0.6 $0.055 < x < 0.1$ $0.013 < x < 0.02$ $16 < Q^2/(GeV/c)^2 < 81$ 0.2 0.4 0.6 $0.1 < x < 0.21$ $0.02 < x < 0.032$ 2 *z* 0.2 0.4 0.6 $0.21 < x < 0.4$ $\begin{cases} \frac{C}{2} \\ \frac{C}{2} \end{cases}$ \ $\langle Q^2 \rangle = 1.25$ $\begin{picture}(180,10) \put(150,10){\line(1,0){15}} \put(150,1$ $\mathbb{R} \setminus \mathbb{R}$ difference the set \mathbb{R} . Despite the \mathbb{R} $\begin{bmatrix} \overline{a} & \overline{b} & \overline{c} & \overline{c} & \overline{d} \ \overline{c} & \overline{d} & \overline{d} & \overline{d} \end{bmatrix}$ ht.
HT. Most likely due to the top the top the top stress of the top that the top that the top the top the top the
HT. Most likely due to the top the differences in the agreement between $\mathcal{L}_{\mathbf{e}}$ the two sets is rather modest, and the data sets is \mathcal{C}_t $\begin{bmatrix} 1 & 0 & 0.6 < z < 0.8 \end{bmatrix}$ hT [∼] ⁰.⁰⁵ ^ðGeV=cÞ². This dip, which is not fitting the D. denendence TITTING THE Ph₁ dependence $d^2M^h(x, Q^2; z)$ $dzdP_{hT}$ \equiv N $\langle P_{\rm hT}^2 \rangle$ $\exp\left(-\frac{P_{\rm h}^2}{\sqrt{R_{\rm B}^2}}\right)$ hT $\langle P_{\rm hT}^2 \rangle$ " $\begin{bmatrix} 7 & 7 & 16 & 2^2/(GeV/c)^2 < 81 \\ 16 & 4 & 4 \end{bmatrix}$ Q² and z. $\begin{bmatrix} 0.2 \end{bmatrix}$ either the z or the quark flavor dependence of TMD-FFs. Recent semi-inclusive measurements of transverse- \mathbf{P}_{\bullet} and $\mathbf{P}_{\mathbf{A}}$ and \mathbf{P}_{\bullet} $\begin{bmatrix} 1 \ 0.2 \end{bmatrix}$ and $\begin{bmatrix} 0.2 \ 0.2 \ 0.4 \ 0.6 \end{bmatrix}$ and $\begin{bmatrix} 0 \ 0.2 \ 0.4 \ 0.6 \end{bmatrix}$ and $\begin{bmatrix} 0 \ 0.2 \ 0.4 \ 0.6 \end{bmatrix}$ and $\begin{bmatrix} 0 \ 0.2 \ 0.4 \ 0.6 \end{bmatrix}$

 $\sqrt{r^2}$ $\langle P_{h\perp}^z(z)\rangle = z^2\,\langle p_T^z\rangle + \langle K_T^z\rangle$ does not work! shown as a function of z². The eight panels correspond to the eight x-bins as indicated, where in each panel data points from all five Q² $\sum_{i=1}^n \sum_{i=1}^n \binom{n}{i}$ $\langle P_{h\perp}^2(z)\rangle = z^2 \langle p_T^2$ $\rangle + \langle K_T^2$ ⇥ does not work!

[COMPASS, PRD 97 (2018) 032006]

 10^{-1}

fit

Gunar Schnell Gunar Schnell $P_{\rm hT}^2 \left({\rm GeV}/c \right)^2$

Helicity density φ **(deg)** $\frac{1}{2}$. Azimuthal modulation of the target single spin asymmetric single spin asymmetric single spin asymmetric spin asym metry AUL for pions integrated over the full kinematics. Only

CLAS data hints at width μ 2 of \bm{g}_1 $v_{\rm L}$, integrated over all kinematical variathat is less than the width μ_0 of f. that is less than the width μ_0 of f_1

$$
f_1^q(x, k_T) = f_1(x) \frac{1}{\pi \mu_0^2} \exp\left(-\frac{k_T^2}{\mu_0^2}\right)
$$

$$
g_1^q(x, k_T) = g_1(x) \frac{1}{\pi \mu_2^2} \exp\left(-\frac{k_T^2}{\mu_2^2}\right)
$$

 $\frac{1}{2}$ … also suggested by lattice QCD $\Lambda \sim \alpha$ / Γ for and d n_1 \sim 911 101 σ 91 σ tribution due to differences between the true luminosity \mathbf{r} $A_1 \approx g_1/F_1$ for eg1-dvcs

CLAS data hints at width μ 2 of \bm{g}_1 $v_{\rm L}$, integrated over all kinematical variathat is less than the width μ_0 of f. *n*idth

$$
f_1^q(x, k_T) = f_1(x) \frac{1}{\pi \mu_0^2} \exp\left(-\frac{k_T^2}{\mu_0^2}\right)
$$

$$
g_1^q(x, k_T) = g_1(x) \frac{1}{\pi \mu_2^2} \exp\left(-\frac{k_T^2}{\mu_2^2}\right)
$$

for the asymmetries *A*p*[±]*

also suggested by lattice QCD HERMES and COMPASS and 2002–2008–2008–2009 MERMES $t_n = \text{diam}(f_{i,n} + p_n)$ dependenced 100 no significant $P_{h\perp}$ dependences seen on D at HERMES and *COMPASS* vored Collins functions are roughly equal and have opposin3 the assumption of $P_{h\perp}$ dependences seen on D at

Gunar Schnell INT-18-3, Seattle

CLAS data hints at width μ 2 of \bm{g}_1 $v_{\rm L}$, integrated over all kinematical variathat is less than the width μ_0 of f. that is less than the width μ_0 of $\bm{\mathsf{f}}_1$

$$
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$$

$$
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$$

ess than the width μ_0 of f , and perhans a hint an protons at COMPASS? values of y are expected to be negligible to be negligible \mathcal{A} (but opposite trend than at CLAS) perhaps a hint on protons at COMPASS?

tribution due to differences between the true luminosity \mathbf{r}

... also suggested by lattice QCD HERMES and COMPASS $t_n = \text{diam}(f_{i,n} + p_n)$ dependenced 100 no significant P $_{\mathsf{h}\perp}$ dependences seen on D at HERMES and COMPASS vored Collins functions are roughly equal and have oppo-

The quest for transversity

Transversity (Collins fragmentation)

- **•** significant in size and opposite in sign for charged pions
- **disfavored** Collins FF **large** and **opposite in sign** to favored one

 \bullet leads to various cancellations in SSA observables

2005: First evidence from HERMES SIDIS on proton

> **Non-zero transversity Non-zero Collins function**

- \bullet since those early days, a wealth of new results:
	- **COMPASS** [PLB 692 (2010) 240, PLB 717 (2012) 376, PLB 744 (2015) 250]

HERMES [PLB 693 (2010) 11]

 $\mathsf{Jefferson}$ Lab [PRL 107 (2011) 072003]

FIG. 2 (color online). The extracted neutron Collins and Sivers *Gunar Schnell*

- \bullet since those early days, a wealth of new results:
	- **COMPASS** [PLB 692 (2010) 240, PLB 717 (2012) 376, PLB 744 (2015) 250]
	- **HERMES** [PLB 693 (2010) 11]
	- Jefferson Lab [PRL 107 (2011) 072003]

• **No Q2-evolution? Intriguing result!**nt emplitudes s Collins amplitudes

- excellent agreement of various proton data, also with neutron results
- no indication of strong evolution effects

Collins amplitudes *x x* Fig. 5: Left: comparison between the Collins asymmetries for pions as a function of *x*, extracted from 2007 and 2010 data taking. Right: the same comparison for the Sivers asymmetries. The Sivers asymmetries as σ

 10^{-2} 10⁻¹

 10^{-2} 10⁻¹

− 0.0€

• since those early days, a wealth of new results:

COMPASS

[PLB 692 (2010) 240, PLB 717 (2012) 376, PLB 744 (2015) 250]

HERMES

[PLB 693 (2010) 11]

Jefferson Lab \bullet [PRL 107 (2011) 072003]

(GeV/*c*) *^h*

COMPASS

(GeV/*c*) *^h*

 $\frac{1}{2}$

 p_T^h (GeV/*c*)

-0.05

0.05

0.1

-0.1

-0.05

0

 $\overline{\mathbf{Q}}$

!**sin(**

 \bullet **+** Φ <u>ທ</u>

) # **K UT**

0.05

0.1

0.15

0

Collins amplitudes *x x* Fig. 5: Left: comparison between the Collins asymmetries for pions as a function of *x*, extracted from 2007 and 2010 data taking. Right: the same comparison for the Sivers asymmetries. The Sivers asymmetries as σ

 10^{-2} 10⁻¹

 10^{-2} 10⁻¹

− 0.0€

(GeV/*c*) *^h*

COMPASS

(GeV/*c*) *^h*

 \oint

 p_T^h (GeV/*c*)

Collins amplitudes Fig. 5: Left: comparison between the Collins asymmetries for pions as a function of *x*, extracted from 2007 and 2010 data taking. Right: the same comparison for the Sivers asymmetries. The Sivers asymmetries as σ ng amh

 $\overline{}$

 $\ddot{}$

0

−0.1

0

 $\ddot{}$

−0.1

z

0.1

0.1

0.1

0.1

 0.4

0.5 1 p_T^h (GeV/*c*)

 $0.5 \t1 \t1.5$

[PRC90 (2014).055201]

COMPASS

0.5 1 1.5

 $\overline{0.2}$ 0.3

(GeV/*c*) *^h*

(GeV/*c*) *^h*

the "Collins trap"

$$
H_{1,\text{fav}}^{\perp} \simeq -H_{1,\text{dis}}^{\perp}
$$

thus

$$
\langle \sin(\phi + \phi_S) \rangle_{UT}^{\pi^+} \sim (4h_1^u - h_1^d) H_{1, \text{fav}}^{\perp}
$$

$$
\langle \sin(\phi + \phi_S) \rangle_{UT}^{\pi^-} \sim - (4h_1^u - h_1^d) H_{1, \text{fav}}^{\perp}
$$

"impossible" to disentangle u/d transversity -> current limits driven mainly by Soffer bound?

31

[Z.B. Kang et al. PRD93 (2016) 014009]

the "Collins trap"

$$
H_{1,\text{fav}}^{\perp} \simeq -H_{1,\text{dis}}^{\perp}
$$

thus

 $\langle \sin(\phi + \phi_S) \rangle$ $\frac{\pi^+}{UT}\sim \left(4h^u_1-h^d_1\right)$ $\overline{ }$ $H_{1,\text{fav}}^\perp$ $\langle \sin(\phi + \phi_S) \rangle_{UT}^{\pi^-} \sim -\left(4h_1^u - h_1^d\right)$ $\overline{)}$ $H_{1,\text{fav}}^\perp$

"impossible" to disentangle u/d transversity -> current limits driven mainly by Soffer bound?

clearly need precise data from "neutron" target(s), e.g., COMPASS d, and later JLab12 & EIC

(valid for all chiral-odd TMDs)

d-transversity running at COMPASS

currently much more p than $d_{\vec{a}}$ of **add another year of d running** large impact on d-transvers **•** reduced correlations betwe (note, correlations important in tensor-charge calculation) *x* 10^{-2} 10⁻¹ $\frac{1}{6}$ 0.4 −0.4 −0.2 0.0 0.2 $x h_1^{u_v}$ 10^{-2} 10⁻¹ 0.4 0.2 0.0 0.2 0.4 $x h_1^{d_v}$ ¹ (right) extracted from the 2010 proton data and gain in h₁ precision

Transversity's friends

- Twist-2 TMDs chiral-odd ➥ needs Collins FF (or similar)
- ¹H, ²H & ³He data consistently small
- cancelations? pretzelosity=zero? or just the additional suppression by two powers of Ph[⊥] **POWEr'S OT Ph⊥**

 $\mathbf{\Theta}$

Worm-Gear I \sim from pions coming from pions computed from \sim

again: chiral-odd

- evidence from CLAS?
- consistent with zero at COMPASS and HERMES

Sivers amplitudes for pions

 $\sum_q e_q^2 f_{1\rm T}^{\perp, q}(x, p_T^2) \otimes_{\cal W} D_1^q(z, k_T^2)$

 $\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)$

Sivers amplitudes for pions

 $2\langle\sin\left(\phi-\phi_{S}\right)\rangle_{\text{UT}}=-$

 π^* dominated by u-quark scattering:

$$
\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes \mathcal{W} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}
$$

 $\sum_q e_q^2 f_{1\rm T}^{\perp, q}(x, p_T^2) \otimes_{\cal W} D_1^q(z, k_T^2)$

 $\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)$

☛ u-quark Sivers DF < 0

Sivers amplitudes for pions

 $2\langle\sin\left(\phi-\phi_{S}\right)\rangle_{\text{UT}}= \sum_q e_q^2 f_{1\rm T}^{\perp, q}(x, p_T^2) \otimes_{\cal W} D_1^q(z, k_T^2)$ $\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)$

 π^* dominated by u-quark scattering:

 $\approx -\frac{f_{1T}^{\perp,u}(x,p_T^2) \otimes W D_1^{u\to\pi^+}(z,k_T^2)}{f^u(x,p^2) \otimes D^{u\to\pi^+}(z,k_T^2)}$ $f_1^u(x, p_T^2) \otimes D_1^{u \to \pi^+}(z, k_T^2)$

☛ u-quark Sivers DF < 0

☛ d-quark Sivers DF > 0 (cancelation for π)

 k_y (GeV)

Sivers amplitudes

cancelation for D target r D target \bullet supports opposite signs of up and down Sivers

 \mathcal{A} i, as in figuration-averaged distribution-averaged distributions, as in figurations, as in figurati symmetric. But when the spin of the spin of the spin of the nucleon is taken into account (indicated α [A. Bacchetta et al.] \blacksquare symmetric. But when the spin of the nucleon is taken into account (indicated

- **-0.4** 〈 **2** by the white arrow in the plots), the distribution can be distorted. These r D taraet voor downby the white arrow in the plots), the distribution can be distributed. Th cancelation for D target *p Siv* Ω *p Siv* supports opposite signs of up and down Sivers
- \bullet using 3He target and from COMPASS for proton target (also multi-d)

38

 $\frac{0.1}{38}$ U.Equity and the contract of the $\overline{3}$ A. A. A. A. B. Lett. B 693, 11 (2010).

 \mathcal{A} i, as in figuration-averaged distribution-averaged distributions, as in figurations, as in figurati symmetric. But when the spin of the spin of the spin of the nucleon is taken into account (indicated α [A. Bacchetta et al.] \blacksquare symmetric. But when the spin of the nucleon is taken into account (indicated

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- newer results from JLab using 3He target and from COMPASS for proton target (also multi-d)
- hint of Q^2 dependence \bullet from COMPASS vs. **HERMES** Gunar Schnell INT-18-3, Seattle Collins or Sivers moments from Refs. [41–43], are shown [7] V. Barone et al., Prog. Part. Nucl. Phys. 65, 267 and included in the Fit systematic uncertainty. The neutron [4] M. Alekseev et al., Phys. Lett. B 673, 127 (2009). Fig. 11: The Sivers asymmetries for positive pions (top) and kaons (bottom) on proton as a function of *x*, *z* and

 \mathcal{A} included in the Fit systematic uncertainty. The neutron in the

38

Sivers amplitudes pions vs. kaons

Sivers amplitudes pions vs. kaons

 $\overline{}$

Sivers amplitudes pions vs. kaons

-0.1 π**-** \overline{L} \vec{Z}_1 **0.1** 〉**UT** 〉**UT)** $\mathbf{0.2} \Big[\mathsf{K^+}$ **+ 0.05** π somewhat unexpected if hermes $\begin{bmatrix} -1 \\ 1 \end{bmatrix}$ hermes **)))S S0.1** <u>(၇</u> Δ $\overline{}$ dominated by scattering off **- - 0.1** \blacktriangle **0.05** $\overline{}$ 〈**sin(0** 〈**sin(** u-quarks: $\alpha\simeq-\frac{\mathbf{f_{1T}^{\perp,u}}(\mathbf{x},\mathbf{p_T^2})\otimes_{\mathcal{W}}\mathbf{D}_1^{\mathbf{u}\rightarrow\pi^+/\mathbf{K}^+}(\mathbf{z},\mathbf{k_T^2})}{\mathbf{f_{1L}(\mathbf{x},\mathbf{p_2^2})}\otimes\mathbf{D}^{\mathbf{u}\rightarrow\pi^+/\mathbf{K}^+}(\mathbf{z},\mathbf{k_T^2})},$ **0 2 0** $\overline{\mathbf{Q}}$ 0.2 **⁺ ^K** 0.2 **- K -0.05** Collins ${\bf f^{u}_1(x,p^{2}_{T})\; \otimes D_1^{u \to \pi^{+}/K^{+}}(z,k^{2}_{T})})$ **-1** 〉**UT -1 0.4 0.6 0.5 1 10 10** Ph
Ph⊥
Phr **z P**
P
E
⊥∂ **x x** *p Siv* π ≤ 0.1 $0.2^{\frac{2}{3}}$ Phenomenological Fit 0.1 0.2 0.3 0.4 φ Sivers [PRC90 (2014).055201]〈**sin(** \circ π^+ 〈**sin(0** 0 **0** 0 K^+ -0.2 0.05 **2** Exp. -0.4 Fit $\overline{\varphi}$ 0.1 0.2 0.3 0.2 0.3 0.4 **-0.1** $\mathsf{\dot{X}}_{\mathsf{bj}}$ X_{bj} π**-**〉**UT 0.4 0.6 0.5 1** 0 **10 0.05**
Cunnicipaly lange V⁻ covements: for ³¹-**)**surprisingly large K² asymmetry for ³He [PLB 744 (2015) 250] target (but zero for K+?!) −0.05 **0** 10^{-2} 10⁻¹ Gunar Schnell and 39 are shown to 39 and 39 and

Gunar Schnell $\begin{array}{ccc} x & 39 & 10 \end{array}$ $\begin{array}{ccc} 1 & 1 & 1 \end{array}$ **Gunar Schnell** α nd systematic error bands for both K α

interlude: dealing with multi-d dependences

- TMD cross sections differential in at least 5 variables
	- some easily parametrized (e.g., azimuthal dependences)
	- others mostly unknown

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	- some easily parametrized (e.g., azimuthal dependences)
	- others mostly unknown
- **•** one-dimensional binning provide only glimpse of true physics
	- even different kinematic bins can't disentangle underlying physics dependences
	- e.g., binning in x involves [incomplete] integration(s) over $P_{h\perp}$

- TMD cross sections differential in at least 5 variables
	- some easily parametrized (e.g., azimuthal dependences)
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- **•** one-dimensional binning provide only glimpse of true physics
	- even different kinematic bins can't disentangle underlying physics dependences
	- e.g., binning in x involves [incomplete] integration(s) over $P_{h\perp}$
- further complication: physics (cross sections) folded with acceptance
	- NO experiment has flat acceptance in full multi-d kinematic space

$$
\frac{N^+(x) - N^-(x)}{N^+(x) - N^-(x)} = \frac{\int d\omega \,\epsilon(x,\omega) \,\Delta\sigma(x,\omega)}{\int d\omega \,\epsilon(x,\omega) \,\sigma(x,\omega)}
$$

measured cross sections / asymmetries often contain "remnants" of experimental acceptance ε

$$
\frac{N^+(x) - N^-(x)}{N^+(x) - N^-(x)} = \frac{\int d\omega \,\epsilon(x,\omega) \,\Delta\sigma(x,\omega)}{\int d\omega \,\epsilon(x,\omega) \,\sigma(x,\omega)} \neq \frac{\int d\omega \,\Delta\sigma(x,\omega)}{\int d\omega \,\sigma(x,\omega)}
$$

measured cross sections / asymmetries often contain "remnants" of experimental acceptance ε

$$
\frac{N^+(x) - N^-(x)}{N^+(x) - N^-(x)} = \frac{\int d\omega \,\epsilon(x,\omega) \,\Delta\sigma(x,\omega)}{\int d\omega \,\epsilon(x,\omega) \,\sigma(x,\omega)} \neq A(x,\langle \omega \rangle)
$$

- measured cross sections / asymmetries often contain "remnants" of experimental acceptance ϵ
- difficult to evaluate precisely in absence of good physics model
	- general challenge to statistically precise data sets
	- avoid 1d binning/presentation of data
	- **•** theorist: watch out for precise definition (if given!) of experimental results reported … and try not to treat data points of different projections as independent

clear left-right asymmetries for pions and positive kaons

into the plane

[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]**UT** ψ **sin** clear left-right asymmetries $\frac{\bullet}{\circ} \pi^+$ $\overline{\mathsf{C}}$ $\overline{\mathsf{K}}$ **A 0.1 0.1** for pions and positive kaons -0000000 $-0.0C$ **0 0 •** increasing with x_F (as in pp) **-0.1 -0.1 8.8% scale uncertainty** π^- **0 0.2 0.4 [GeV]** 〉 **TP** 〈**0.2 0.4 0.8 0.8** COOOOOOO **0.6 0.6 0.4** \bullet *e p* **0 0.2 0.4 0.2 0.4** $\frac{\mathsf{x}_\mathsf{F}}{A}$ **UT** ψ **sin** π^+ $\frac{\bullet}{\circ}$ π⁺ **e** K⁺
 \overline{C} K⁺ **A 0.1 0.1** initially increasing with P_T **0 0** with a fall-off at larger P_T **-0.1 -0.1 8.8% scale uncertainty 0.3 0.5 1 1.5 2** 〉 **F x** 〈**0.30 0.5 1 1.5 2 0.2 0.2** coopoo **0.1 0.1 0.5 1 1.5 2 0 0.5 1 1.5 2 P_T** [GeV]

- clear left-right asymmetries for pions and positive kaons
- \bullet increasing with x_F (as in pp)

e p

 π^+

 π^-

 \bullet x_F and P_T correlated ➥ look at 2D dependences

back to SIDIS

Gunar Schnell INT-18-3, Seattle

3d analysis: 4x4x4 bins in \bullet

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- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength

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- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations

[Adolph et al., Phys. Lett. B 770, 138-145 (2017)]

PUTION OCTIVIERS

2d analysis to match Q² range probed in Drell-Yan

- 2d analysis to match Q² range probed in Drell-Yan
- allows also more detailed evolution studies

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h S I I aes - Dreil s i s in \mathbb{Z} S sin 2 $\overline{}$ \boldsymbol{U} l *C*₂ **T C C C C** *CS S A* \blacksquare M M UUES - UIEI nlitudes - Drell. PINUUCS - UI EN- $\overline{\P}$ ° Sivers amplitudes - Drell-Yan \overline{U} $\overline{f_1}$ $\overline{h_1^{\perp}}$ Sivers amb

h S I I JUES - UTEII in \mathbb{Z} S sin 2 $\overline{}$ \boldsymbol{U} l *C*₂ **T C C C C** *CS S A* \blacksquare M M plitudes - Drell-PINUUCS - UI EN- $\overline{\P}$ ° Sivers amplitudes - Drell-Yan \overline{U} $\overline{f_1}$ $\overline{h_1^{\perp}}$ Sivers amb pion Boer-Mulders PDFs, the obtained results may be used rs amplitudes - Drell-Yan

- $\blacksquare^{0.9}$ \odot \blacksquare (slight) preference for sign change
- $\frac{1}{2}$ $\frac{3}{2}$ \bullet some model curves move around when properly adjusted to exp.'s kinematics $\frac{1}{2}$ $\frac{1}{2}$ when properly adjusted to evalue $\begin{array}{ccc} \n\begin{array}{ccc}\n1 & 0.4 & 1.6 \\
0.2 & 1.8 & 0.6\n\end{array}\n\end{array}$
	- more data currently taken

Sivers amplitudes - weighted

- $\begin{array}{c|c} \hline h_{1T}^{\perp} & \bullet & \mathsf{P}_{\mathsf{h}\perp} \; \mathsf{weighting}, \; \hbox{in principle, resolves convolutions} \ \hline \end{array}$ and P. Mulders. PLB 406 (1997) 373)1 ${\sf P}_{\sf h\perp}$ weighting, in principle, resolves convolutions [A. Kotzinian and P. Mulders, PLB 406 (1997) 373)]
- General formalism was first introduced in 1997 (A. Kotzinian and P. Mulders, **PLB 406 (1997) 373**) requires excellent control of detector efficiencies
	- **P.** often no full integral (low, and high ary 1702.006 pm often no full integral (low- and high- $\mathsf{P}_{\mathsf{h}\perp}$ missing)

modulations in spin-independent SIDIS cross section

=

$$
\frac{\mathrm{d}^5 \sigma}{\mathrm{d}z \,\mathrm{d}\phi_h \,\mathrm{d}P_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \left(1 + \frac{\gamma^2}{2x}\right) \{A(y) F_{\text{UU,T}} + B(y) F_{\text{UU,L}} + C(y) \cos \phi_h F_{\text{UU}}^{\cos \phi_h} + B(y) \cos 2\phi_h F_{\text{UU}}^{\cos 2\phi_h}\}
$$

(Implicit sum over quark flavours)

not zero! \bullet

[Airapetian et al., PRD 87 (2013) 012010]

- opposite sign for charged pions with larger magnitude for π^-
	- -> same-sign BM-function for valence quarks?

- not zero!
- **•** opposite sign for charged pions with larger magnitude for π^- -> same-sign BM-function for valence quarks?
- intriguing behavior for kaons

- not zero!
- **•** opposite sign for charged pions with larger magnitude for π^- -> same-sign BM-function for valence quarks?
- intriguing behavior for kaons
- available in multidimensional binning both from HERMES and from COMPASS

signs of Boer-Mulders *8 CONCLUSIONS* 17

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signs of Boer-Mulders \bullet Projected uncertainties for 2017 sample are \bullet times smaller compared to published asymmetries smaller compared to published as \bullet errors is stated to be considered to be a

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in 2016/17 extensive $\frac{1}{3}$ data set collected on liquid-H target (DVCS program)

signs of Boer-Mulders \bullet Projected uncertainties for 2017 sample are \bullet times smaller compared to published asymmetries smaller compared to published as \bullet errors is stated to be considered to be a

- in 2016/17 extensive $\frac{1}{3}$ data set collected on liquid-H target (DVCS program)
- will allow precision studies of multiplicities and AUU & ALU modulations

non-vanishing twist-3

subleading twist **I** - <sin(φ)>_{UL} *Longitudinally Polarized Targets?* $\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$ $\langle \sin \phi \rangle$ q $_{UL}$ = $\langle \sin \phi \rangle$ _i l U_L + sin θ_{γ^*} $\sqrt{ }$ $\langle \sin(\phi + \phi_S) \rangle$ l U_T + $\langle \sin(\phi - \phi_S) \rangle$ l \emph{UT} "

- experimental A_{UL} dominated by twist-3 contribution the set of th $m+3$ contribution
	- correction for A_{UT} contribution increases purely longitudinal asymmetry for positive pions positive pions on longitudinalized polarized polarized polarized polarized polarized polarized polarized polarized polarized
Internal polarization polarized polarized polarized polarized polarized polarized polarized polarized polarize orrectior
.. s is the contract of $\frac{1}{s}$ and $\frac{1}{s}$ nej
nsi:
	- consistent with zero for π**-**π⁺ α nsistent with zero for π^{-}

subleading twist **I** - <sin(φ)>_{UL} $\langle \sin \phi \rangle$ q $_{UL}$ = $\langle \sin \phi \rangle$ _i l U_L + sin θ_{γ^*} $\sqrt{ }$ $\langle \sin(\phi + \phi_S) \rangle$ l U_T + $\langle \sin(\phi - \phi_S) \rangle$ l \emph{UT} " *Longitudinally Polarized Targets?* $\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

subleading twist II - <sin(φ)>LU

opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed

Gunar Schnell INT-18-3, Seattle 58 CLAS more sensitive to e(x)Collins term due to higher x probed?

subleading twist II - <sin(φ)>LU M_h M_h

consistent behavior for charged pions / hadrons at HERMES / COMPASS for isoscalar targets

$subleading$ twist $III - \langle sin(\phi_s)\rangle_{UT}$

- significant non-zero signal observed for negatively charged **UT 0.03 X-** " **e** # **p- e 2 < 1GeV ² Q** mesons $\frac{1}{2}$
- vanishes in inclusive limit, e.g. **0** after integration over Ph⊥ and z, **-0.01** and summation over all hadrons **9.3% scale uncertainty**

$subleading twist III - ssin(\phi_s)$

- significant non-zero signal \bullet observed for negatively charged mesons
- vanishes in inclusive limit, e.g. \bullet after integration over Ph⊥ and z, and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

$$
\begin{aligned}\left(x f_T^\perp D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z}\right)\\-\ \mathcal{W}(p_T,k_T,P_{h\perp})\left[\left(x h_T H_1^\perp + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^\perp}{z}\right) \right.\\ \left.-\left(x h_T^\perp H_1^\perp - \frac{M_h}{M} f_{1T}^\perp \frac{\tilde{D}^\perp}{z}\right)\right]\end{aligned}
$$

$subleading$ twist $III - \langle sin(\phi_s)\rangle_{UT}$

conclusions

- **1st round of SIDIS measurements coming to an end**
- various indications of flavor-& spin-dependent transverse momentum
- transversity is non-zero and quite sizable
	- d-quark transversity difficult to access with only proton targets
- Sivers and chiral-even worm-gear function also clearly non-zero
- various sizable twist-3 effects
- **•** highlights still to come
	- **HERMES transverse-target, ALU & ALL asymmetries**
	- COMPASS transverse d; high-statistics data set on unpol. pure H; multi-d asymmetries
- precision measurements needed to fully map TMD landscape (fully differential!)
- need also program with polarized D and 3He

backup

hermes *Interference Fragmentation – Models* **Transversity** (2-hadron fragmentation)

$$
A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin \theta h_1 H_1^{\triangleleft}
$$

predictions and HERMES COMPASS 2007: [C. Adolph et al., Phys. Lett. B713 (2012) 10] [A. Airapetian et al., JHEP 06 (2008) 017] COMPASS 2010: [C. Braun et al., Nuovo Cimento C 035 (2012) 02]

NEW: Accompany of the Comparison of the Company of the Company of the Company of the Company of TV (2-hadron fragmentation)

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Transversity

NEW: Accompany of the Comparison of the Company of the Company of the Company of the Company of TV (2-hadron fragmentation)

HERMES, COMPASS: for comparison scaled HERMES data by depolarization factor and changed sign

²H results consistent with

zero $\overline{[A, Vq]}$ sen et al. PRL 10⁷ (2011) 072004] **0.3** $0.27 < z$, < 0.33 $0.33 < z$, < 0.40 **0.2** $0.50 < z < 0.60$ 佳
* m_q [GeV/c²] ≈ 0.02

0.70 $< z_1 \le 0.80$ **0.80 0.80** $< z_1 \le 1.00$

x

m, $[{\rm GeV/c}^2]$

 m_a [GeV/c²]

PRL 107 (2011) 1201 (2012) 1202 (2012) 1202 (2012) 1202 (2012) 1202 (2012) 1202 (2012) 1202 (2012) 1202 (2012)

predictions and HERMES COMPASS 2007: [C. Adolph et al., Phys. Lett. B713 (2012) 10] *COMPASS 2007/2010 proton data* [A. Airapetian et al., JHEP 06 (2008) 017] COMPASS 2010: [C. Braun et al., Nuovo Cimento C 035 (2012) 02]

data from e⁺e⁻ by BELLE ϵ \rightarrow ϵ \sim ϵ \sim ϵ \sim ϵ \sim ϵ I Trom e e Dy BELLE

Gunar Schnell **INT-18-3, Seattle**

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 $\overline{00}$

[10] J. C. Collins and D. E. Soper, Nucl. Phys. B193, 381 The district of the light of the Magnetic COMP $\frac{2}{3}$ updated analysis available (incl. COMPASS) 66

 $\rlap{\,/}^{\rlap{\hspace{0.02cm}/}{\prime}}\rlap{\,/}^{}=\varphi_{\rlap{\hspace{0.02cm}/}{\prime}}$

 $P_{h1} + P_{h2}$ $\vec{\text{P}}_{\text{h1}} + \vec{\text{P}}$

 P_{h1} .
ቮ

$\overline{P_{n2}}$

suggested common origin of Collins and di-hadron FF in PLB 736 (2014) 124 \overline{a} evaluate the Collins asymmetry, which all the combinations of \overline{a} all the combinations of \overline{a} positive and negative hadrons with *z >* 0*.*1 are used in the case of similarity between the two different asymmetries stays the same \bullet suggested common opiqin of \circ multi-hadrons fragmentation of the struck quark azimuthal angles di-hadron FF in PLB 736 (2014) 124 **Fig. 8.** Comparison between the dihadron asymmetry (black points) and the Collinslike asymmetry for the dihadron (open blue points) as a function of *x* for the 2010

when measuring the asymmetries for the common hadron sample, and when a transverse \mathcal{L}

68

 68

overselv polarised that when a transversely polarised that when the fragmentation \mathcal{L} p -wave components of the p

asymmetries are very similar? This assembly as a subleading twist-

 $1, q$ are the interference H , and in the interference H , and in the inte

 $U \mid L \mid T$

 $\frac{d^2\perp}{dt^2}\parallel g_{1T}\parallel h_1, h_{1T}^\perp$

 $U \begin{array}{|c|c|c|} \hline f_1 & h_1^{\perp} \end{array}$

 $L \begin{array}{|c|c|c|} \hline g_{1L} & h_{1L}^{\perp} \ \hline \end{array}$

 $T \mid f_{1T}^{\perp}$

FF TMD flavor dependence

• fit to HERMES multiplicity data:

$$
m_N^h(x,z,\boldsymbol{P}_{hT}^2;Q^2) = \frac{\pi}{\sum_q e_q^2\,f_1^q(x;Q^2)}\,\sum_q e_q^2\,f_1^q(x;Q^2)\,D_1^{q\to h}(z;Q^2)\,\frac{e^{-\boldsymbol{P}_{hT}^2/\langle \boldsymbol{P}_{hT,q}^2 \rangle}}{\pi\,\langle \boldsymbol{P}_{hT,q}^2 \rangle}
$$

FF TMD flavor dependence

 $q \rightarrow \pi$ favored width < unfavored

FF TMD flavor dependence [GeV2] [GeV−2] [GeV2] All replicas 0*.*21 *±* 0*.*02 1*.*65 *±* 0*.*49 2*.*28 *±* 0*.*46 0*.*14 *±* 0*.*07 5*.*50 *±* 1*.*23 0*.*13 *±* 0*.*01

O fit to SIDIS, DY & Z boson production: JHEP 06 (2017) 081 ● fit to SIDIS, DY & Z boson production: JHEP 06 (2017) 081

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1903.219
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RMES,
MPASS
401.50 � Bacchetta, Delcarro, Pisano, Radici, Signori, in preparation (Q = 1 GeV) � Signori, Bacchetta, Radici, Schnell arXiv:1309.3507 � Schweitzer, Teckentrup, Metz, arXiv:1003.2190 Anselmino et al. arXiv:1312.6261 [HERMES] Anselmino et al. arXiv:1312.6261 [HERMES, high z] Anselmino et al. arXiv:1312.6261 [COMPASS, norm.] � Anselmino et al. arXiv:1312.6261 [COMPASS, high z, norm.] Echevarria, Idilbi, Kang, Vitev arXiv:1401.5078 ($Q = 1.5$ GeV)

fit to ete⁻ data: PLB 772 (2017) 78-86 ■ fit to e^te⁻ data: PLR 772 (2017) 78-86 ■ 111 IV did extractions. In the square values of the square square square square square square square square s
■ 111 IV did did under the square squar - - - - - - c duru.

O new data: COMPASS arXiv:1709.07374 data: COMPASS a <u>in post</u>

data, (7) results from ref. *at high zonar Schnell* \sim 71