**gmc\_trans a Monte Carlo generator for transverse-momentum-dependent distribution and fragmentation functions**

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> > Trento, June 12th 2007

# Outline

- **Motivation & Basics**
- **Details of the MC generator**
	- **Gaussian Ansatz**
	- **Positivity limits**
	- **Event generation**
- **Some results**
	- **Tuning of transverse momentum dependence**
	- **(un)weighted Sivers and Collins amplitudes**
- **Implemented models**

#### Gunar Schnell, Universiteit Gent 2 ECT\* Workshop, June 12, 2007 **Going beyond Collins and Sivers asymmetries** 2

### Motivation

- **Monte Carlo Simulations are a indispensable tool in modern nuclear and particle physics experiments**
- **various "physics generators" exists for the various fields (e.g.,** PYTHIA**,** LEPTO**,** AROMA **etc.)**
- **used for predictions, for the understanding of the experiment, and also for the "correction" of data (e.g., acceptance effects, background processes etc.)**
- **no generator was available for transverse-momentum dependence of distribution and fragmentation functions**

### Initial goals for gmc trans

- **physics generator for SIDIS pion production**
- **include transverse-momentum dependence, in particular simulate Collins and Sivers effects**
- **be fast**
- **allow comparison of input model and reconstructed amplitudes**
- **to be used with standard HERMES Monte Carlo**
- **be extendable (e.g., open for new models)**

# Basic workings

- **use cross section that can (almost) be calculated analytically**
- **start from 1-hadron SIDIS expressions of Mulders & Tangerman (Nucl.Phys.B461:197-237,1996)**
- **use Gaussian Ansatz for all transverse-momentum dependencies of DFs and FFs**
- **unpolarized DFs (as well as helicity distribution) and FFs from fits/parametrizations (e.g., Kretzer FFs etc.)**
- **"polarized" DFs and FFs either related to unpolarized ones (e.g., saturation of Soffer bound for transversity) or some parametrizations used**

# **Caution: Details to follow!**

#### SIDIS Cross Section incl. TMDs **SIDIS Cross Section Including TOIT HIGT. TIMIDS**

 $d\sigma_{UT} \equiv d\sigma^{\rm Collins}_{UT} \cdot \sin(\phi + \phi_S) + d\sigma^{\rm Sivers}_{UT} \cdot \sin(\phi - \phi_S)$ 

$$
\begin{array}{rcl} d\sigma^{\rm Collins}_{UT}(x,y,z,\phi_S,P_{h\perp}) & \equiv & -\dfrac{2\alpha^2}{sxy^2}B(y)\sum_q e_q^2\, \mathcal{I}\left[ \left(\dfrac{k_T\cdot \hat{P}_{h\perp}}{M_h}\right)\cdot h_1^q H_1^{\perp q}\right] \\ & & \\ d\sigma^{\rm Sivers}_{UT}(x,y,z,\phi_S,P_{h\perp}) & \equiv & -\dfrac{2\alpha^2}{sxy^2}A(y)\sum_q e_q^2\, \mathcal{I}\left[ \left(\dfrac{p_T\cdot \hat{P}_{h\perp}}{M_N}\right)\cdot f_{1T}^{\perp q} D_1^q\right] \\ & & \\ d\sigma_{UU}(x,y,z,\phi_S,P_{h\perp}) & \equiv & \dfrac{2\alpha^2}{sxy^2}A(y)\sum_q e_q^2\, \mathcal{I}\left[ f_1^q D_1^q\right] \end{array}
$$

**where**

$$
\mathcal{I}\Big[\mathcal{W}f\,D\Big]=\int d^2p_Td^2k_T\,\delta^{(2)}\left(p_T-\frac{P_{h\perp}}{z}-k_T\right)\Big[\mathcal{W}\,f(x,p_T)\,D(z,k_T)\Big]
$$

0

#### Gaussian Ansatz  $\mathcal{S}$  is the Si $\mathcal{S}$  -c. The Sivers term (and interchanged kT  $\mathcal{S}$  ), i.e., i.e ussian A D STAIL AIRSC "

- **want to deconvolve convolution integral over transverse momenta**  $\mathbf{r}$ h⊥ M<sup>h</sup> nt to deconvolve convolution integral over trans <u>...</u> The parties of the contract of  $2 \cdot$ **EGAL HITEST AT OVER The convolvement integral for the Collins term can be the convolution integral over transverse** want to deconvolve convolution integral over transverse d-function of the convolution integral, the final de-convolution for the Collins cross section for the opposite de-
- **easy Ansatz: Gaussian dependencies of DFs and FFs on intrinsic (quark) transverse momentum:**  $\overline{\phantom{a}}$ 2M<sup>N</sup> 11  $\overline{a}$ dencie  $1001111210 (940212)$  $1 - \frac{1}{2}$  (z,  $2 \frac{1}{2}$   $\frac{1}{2}$   $\frac{$ 1 sign of the Sivers of the  $-2P_{L}^{2}$

Let us also define following set of constants:

$$
\mathcal{I}[f_1(x, \mathbf{p}_T^2)D_1(z, z^2 \mathbf{k}_T^2)] = f_1(x) \cdot D_1(z) \cdot \frac{R^2}{\pi z^2} \cdot e^{-R^2 \frac{P_{h\perp}^2}{z^2}}
$$
  
with  $f_1(x, p_T^2) = f_1(x) \frac{1}{\pi \langle p_T^2 \rangle} e^{-\frac{p_T^2}{\langle p_T^2 \rangle}} \qquad \frac{1}{R^2} = \langle k_T^2 \rangle + \langle p_T^2 \rangle = \frac{\langle P_{h\perp}^2 \rangle}{z^2}$   
(similar:  $D_1(z, z^2 \mathbf{k}_T^2)$ )

#### Caution: different notations for intrinsic transverse **Caution: different notations for intrinsic transverse** I CAISU.<br>... z<br>2 e−R2P 2 e−R 1 − y2<br>1 + y22  $momentum exist!$ **positivity limit becomes** where the notation of  $[6]$  for the mean values of transverse momenta squared was adopted, i.e. 1.  $\mathbb{R}^n$

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 $\mathbf{P}^{\Omega}$ 

h⊥/z<sup>2</sup>

### Positivity Constraints

- **DFs (FFs) have to fulfill various positivity constraints (resulting cross section must not be negative!)**
- **based on probability considerations can derive positivity limits for leading-twist functions: Bacchetta et al., Phys.Rev.Lett.85:712-715, 2000**
- **Posity: e.g., Soffer bound**
- Sivers and Collins functions: e.g., loose bounds:

$$
\frac{|p_T|}{2M_N} f_{1T}^{\perp}(x, p_T^2) \equiv f_{1T}^{\perp (1/2)}(x, p_T^2) \le \frac{1}{2} f_1(x, p_T^2)
$$
\n
$$
\frac{|k_T|}{2M_h} H_1^{\perp}(z, z^2 k_T^2) \equiv H_1^{\perp (1/2)}(z, z^2 k_T^2) \le \frac{1}{2} D_1(z, z^2 k_T^2)
$$

#### Positivity and the Gaussian Ansatz the Collins Find Collins Fight on the Single  $\mathbf{P}_{\mathbf{C}}$  $f_{\text{1}}(t) = f_{\text{2}}(t)$  $\overline{1}$  $\overline{\phantom{a}}$

$$
\frac{|\bm{p_T}|}{2M_N} f_{1T}^\perp(x,\bm{p_T^2}) \ \leq \ \frac{1}{2} f_1(x,\bm{p_T^2})
$$

$$
\text{with} \quad f_1(x,p_T^2) \;\; = \;\; f_1(x) \frac{1}{\pi \langle p_T^2 \rangle} e^{-\frac{p_T^2}{\langle p_T^2 \rangle}} \\
$$

$$
f_{1T}^{\perp}(x,p_T^2) = f_{1T}^{\perp}(x) \frac{1}{\pi \langle p_T^2 \rangle} e^{-\frac{p_T^2}{\langle p_T^2 \rangle}}
$$

 $\vert$  $|p^{\phantom{+}}_{T}|f^{\perp}_{1T}(x)\leq$  $\leq M_P$  $\mathbf{P}$  $f_1(x)$  $\mathbf{F}$  |r| $\mathbf{$  $|p_T|f_{1T}^{\perp}(x) \leq M_N f_1(x)$ 

#### Positivity and the Gaussian Ansatz the Collins Find Collins Fight on the Single  $\mathbf{P}_{\mathbf{C}}$  $f_{\text{1}}(t) = f_{\text{2}}(t)$  $\overline{1}$  $\overline{\phantom{a}}$

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$$

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f_{1T}^{\perp}(x,p_T^2) = f_{1T}^{\perp}(x) \frac{1}{\pi \langle p_T^2 \rangle} e^{-\frac{p_T^2}{\langle p_T^2 \rangle}}
$$

 $\vert$  $|p^{\phantom{+}}_{T}|f^{\perp}_{1T}(x)\leq$  $\leq M_P$  $\mathbf{P}$  $f_1(x)$  $\mathbf{F}$  |r| $\mathbf{$  $|p_T|f_{1T}^{\perp}(x) \leq M_N f_1(x)$ 

### **Problem for non-zero Sivers function! Problem for non-zero Sivers function!**

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#### Modify Gaussian width **Skewed Gaussian Ansatz Skewed Gaussian Ansatz**

$$
f_{1T}^\perp(x,p_T^2) = f_{1T}^\perp(x) \, \frac{1}{(1-C)\pi\langle p_T^2\rangle} \, e^{-\frac{p_T^2}{(1-C)\langle p_T^2\rangle}}
$$

⇒ **positivity limit:** ⇒ **positivity limit:**

$$
f_{1T}^\perp(x) \, \frac{|p_T|}{2 M_N} \frac{1}{\pi (1-C) \langle p_T^2 \rangle} \, e^{- \frac{p_T^2}{(1-C) \langle p_T^2 \rangle}} \;\; \leq \;\; 1/2 \, f_1(x) \, \frac{1}{\pi \langle p_T^2 \rangle} \, e^{- \frac{p_T^2}{\langle p_T^2 \rangle}}
$$

$$
\frac{|p_T|}{1-C} e^{-\frac{C}{1-C} \frac{p_T^2}{\langle p_T^2 \rangle}} \leq M_N \frac{f_1(x)}{f_{1T}^{\perp}(x)}
$$



#### **SIDIS Cross Section incl. TMDs Transverse Momentum Section incl TMDs**

 $\sum$  $\boldsymbol{q}$  $e_{\bm{q}}^{\bm{2}}$  $4\pi$  $\alpha^2$  $\sum_{a} \frac{q}{4\pi} \frac{1}{(MExyz)^2} \left[ X_{UU} + |S_T| X_{SIV} \sin(\phi_h - \phi_s) + |S_T| X_{COL} \sin(\phi_h + \phi_s) \right]$  $\frac{q}{4\pi} \frac{1}{(M)^2}$  $\frac{q}{\pi}$  $(\mathcal{M} Exyz)^2$  [XUU +  $(\mathcal{M} Exyz)^2$ ]

using Gaussian Ansatz for transverse-momentum dependence of DFs and FFs: asing Caassian impact for cransverse momentum expensence of 213

$$
X_{UU} = R^2 e^{-R^2 P_{h\perp}^2/z^2} \left(1 - y + \frac{y^2}{2}\right) f_1(x) \cdot D_1(z)
$$
  

$$
X_{COL} = + \frac{|P_{h\perp}|}{M_{\pi}z} \frac{(1 - C)\langle k_T^2 \rangle}{\left[\langle p_T^2 \rangle + (1 - C)\langle k_T^2 \rangle\right]^2} \exp\left[-\frac{P_{h\perp}^2/z^2}{\langle p_T^2 \rangle + (1 - C)\langle k_T^2 \rangle}\right]
$$
  

$$
\times (1 - y) \cdot h_1(x) \cdot H_1^{\perp}(z)
$$

$$
X_{SIV} = -\frac{|P_{h\perp}|}{M_p z} \frac{(1-C')\langle p_T^2 \rangle}{\left[\langle k_T^2 \rangle + (1-C')\langle p_T^2 \rangle\right]^2} \exp\left[-\frac{P_{h\perp}^2/z^2}{\langle k_T^2 \rangle + (1-C')\langle p_T^2 \rangle}\right]
$$
  
 
$$
\times \left(1-y+\frac{y^2}{2}\right) f_{1T}^{\perp}(x) \cdot D_1(z)
$$
  
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XUU = R2e−R2P 2005

#### Sivers (azimuthal) moments  $\liminf_{\Omega} \ln \min_{\Omega}$ e cross section expressions to evaluate with extracted as y concern compare **Single Spin Asymmetries (using constanged constanged constanged constangular expressions to evaluate**  $\frac{1}{2}$  (azimuthal) momen use cross section expressions to evaluate **azimuthal moments:**

$$
-\langle \sin(\phi-\phi_s) \rangle_{UT}=\frac{\sqrt{(1-C)\langle p_T^2\rangle}}{\sqrt{(1-C)\langle p_T^2\rangle+\langle k_T^2\rangle}}\frac{A(y)\frac{1}{xy^2}\sum e_q^2f_{1T}^{\perp(1/2)}(x)D_1(z)}{A(y)\frac{1}{xy^2}\sum e_q^2f_1(x)D_1(z)}\\-\langle \sin(\phi-\phi_s)\rangle_{UT}=\frac{M_N\sqrt{\pi}}{2\sqrt{(1-C)\langle p_T^2\rangle+\langle k_T^2\rangle}}\frac{A(y)\frac{1}{xy^2}\sum e_q^2f_{1T}^{\perp(1)}(x)D_1(z)}{A(y)\frac{1}{xy^2}\sum e_q^2f_1(x)D_1(z)}
$$

$$
-\langle \frac{|P_{h\perp}|}{zM_N} \sin(\phi - \phi_s) \rangle_{UT} = \frac{2\sqrt{(1-C)\langle p_T^2 \rangle}}{M_N \sqrt{\pi}} \frac{A(y) \frac{1}{xy^2} \sum e_q^2 f_{1T}^{\perp(1/2)}(x) D_1(z)}{A(y) \frac{1}{xy^2} \sum e_q^2 f_1(x) D_1(z)} - \langle \frac{|P_{h\perp}|}{zM_N} \sin(\phi - \phi_s) \rangle_{UT} = \frac{A(y) \frac{1}{xy^2} \sum e_q^2 f_{1T}^{\perp(1)}(x) D_1(z)}{A(y) \frac{1}{xy^2} \sum e_q^2 f_1(x) D_1(z)}
$$

**z** odel-depend nce on transverse  $\mathcal{L}_{\text{GUT}}$  ,  $\mathcal{L}_{\text{GUT}}$  , model-dependence on transverse momenta endence on trai model-dependence on transverse momenta ||Ph⊥||<br>|-<br>|Ph⊥||Ph zmena  $s$  and  $\frac{1}{\sqrt{2}}$ <sup>T</sup> #  $v_T^2$ - n xy<sup>2</sup> "swallowed" by  $p_T^2$ - moment of Sivers fct.:  $f_{1T}^{\perp(1)}$ 

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#### Sivers (azimuthal) moments  $\liminf_{\Omega} \ln \min_{\Omega}$ e cross section expressions to evaluate with extracted as y concern compare **Single Spin Asymmetries (using constanged constanged constanged constangular expressions to evaluate**  $\frac{1}{2}$  (azimuthal) momen use cross section expressions to evaluate **azimuthal moments:**

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$$

$$
-\langle \frac{|P_{h\perp}|}{zM_N} \sin(\phi-\phi_s) \rangle_{UT} = \frac{2\sqrt{(1-C)\langle p_T^2 \rangle}}{M_N \sqrt{\pi}} \frac{A(y) \frac{1}{xy^2} \sum e_q^2 f_{1T}^{\perp(1/2)}(x) D_1(z)}{A(y) \frac{1}{xy^2} \sum e_q^2 f_1(x) D_1(z)} \\ -\langle \frac{|P_{h\perp}|}{zM_N} \sin(\phi-\phi_s) \rangle_{UT} = \frac{A(y) \frac{1}{xy^2} \sum e_q^2 f_{1T}^{\perp(1)}(x) D_1(z)}{A(y) \frac{1}{xy^2} \sum e_q^2 f_1(x) D_1(z)}
$$

#### sin $\mathbb{Z}$   $\$ (cimilar for Colling)  $\lim_{x \to 0} \mathbf{moment}$  $\sim$  (SII)  $i$ lar for  $\bigcap$ π τοι alline momente) 111110 1110111011100) (similar for Collins moments)

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### Monte Carlo event generation

- **need to generate events according to cross section:**
	- **throw flavor of struck quark according to integrated (unpolarized) cross section for each quark flavor**
	- *throw*  $(x, Q^2, z)$  *according to unpolarized cross* **section**
	- throw pion's transverse momentum  $P_h^2$  according to **Gaussian Ansatz** *h*⊥
	- generate azimuthal angles  $(\phi, \phi_S)$  according to **polarized cross section**
- **cross section should be positive automatically if positivity constraints on DFs and FFs are fulfilled, but better check again**   $(x, Q^2, z)$  accordin<br>
bion's transverse n<br>
an Ansatz<br>
te azimuthal angle<br>
ed cross section<br>
ion should be posi<br>
constraints on DF<br>
r check again

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# Some (more) details

- **event generation by accept-or-reject method:**
	- first throw flat in  $(x, Q^2, z)$ , e.g., get value r1
	- **second random number r2 determines accept/reject status: r2 above curve: reject r2 below curve: accept**  $(x, Q^2,$ <br> **18 (***x***)**<br> **18 (***x***)**<br> **18 (***x***)<br>
	<b>18 (***x***)**<br> **18 (***x***)<br>
	<b>18**<br> **18**<br> **18** 0.75 1 r2a  $r1 = v$
- $\bullet$  have to know maxim **of f(x), i.e., of the cross section (checked at beginning)** f(x)



can gain some speed by not throwing flat in, e.g.,  $Q^2$ , **but according to global behaviour**

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### **Some Results**

### Tuning the Gaussians in gmc\_trans Ph⊥

**0.025**

**0.08**



**constant Gaussian widths, i.e., no dependence on x or z:**

**0 0.5 1 1.5**  $\langle K_T \rangle$  = 0.44  $\langle p_T \rangle$  = 0.44

**tune to data integrated over whole kinematic range**

#### Tuning the Gaussians in gmc\_trans Ph⊥<br>Ph⊥<br>Ph⊥ Ph⊥ Ph⊥ Ph⊥ Ph⊥ Ph⊥ Ph⊥ **3500 x 10 <sup>2</sup> reconstructed events events** π **+/- 0.225 rec/gen 1200 e**<br>**e**<br>**e** 1200 **x 10 <sup>2</sup> reconstructed events** π **+/-**

**generated events**



**0.025 200**

**0.1 600**

**400**

**0.125 800**

**0.15 1000**

**02c0 (scaled)**

**generated events**

 $\left\langle \cdot \right\rangle =$  $\frac{1}{\sqrt{2}}$ **0**  $\ell$   $\gamma$ **0.05 0 0.5 1 1.5 0.35 rec/gen**  $\langle p_T \rangle = 0.38$  $\langle K_T \rangle$  = 0.38

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**500**

**1000**

**1500**

**2000**

**2500**

**3000**

21

# Comparison Data-MC: *P<sup>h</sup>*<sup>⊥</sup>  $\mathbf{a}$



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Tuning the Gaussians in gmc\_trans  $\left\langle P_{h\perp}^2(x,z)\right\rangle =\ \left\langle P_{h\perp}^2(z)\right\rangle =\ \begin{array}{c} \circ\ \mathbf{c}\ \$  $P_{h\perp}^2(x,z)$  $\rangle = z^2 \langle p_T^2(x)$  $\rangle + \langle K_T^2(z)$  $\left\langle \right\rangle$ **in general: so far:**  $\langle P_{h\perp}^2(z)$  $\rangle = z^2 \langle p_T^2$  $\rangle + \langle K_T^2$  $\left\langle \right\rangle$ 

### **constant!**

#### Tuning the Gaussians in gmc\_trans **so far:**  $\langle P_{h\perp}^2(z)$  $\rangle = z^2 \langle p_T^2 \rangle$  $\rangle + \langle K_T^2$ so far:  $\langle P_h^2 \rangle(z) \rangle = z^2 \langle p_T^2 \rangle + \langle K_T^2 \rangle$



 $\langle p_T \rangle$  = 0.38  $\langle K_T \rangle$  = 0.38

 $\langle p_T^2 \rangle \simeq 0.185$  $\langle K_T^2 \rangle \simeq 0.185$ 

#### Tuning the Gaussians in gmc\_trans **now:**  $\langle P_{h\perp}^2(z)$  $\rangle = z^2 \langle p_T^2 \rangle$  $\rangle + \langle K_T^2(z)$  $\setminus$



**z-dependent! tuned to HERMES data in acceptance "Hashi set"**

 $U$ ulrike Elschenbroich, Makins Relation,  $\Delta$ 006 – p.88  $\Delta$ 006 – p.88

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#### Tuning the Gaussians in gmc\_trans z en la provincia de la provincia de  $\langle P_{h\perp}^2(z)$  $\rangle = z^2 \langle p_T^2 \rangle$  $\rangle + \langle K_T^2(z)$  $\setminus$



### **z-dependent!**

**"Hashi set"**

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#### Generated vs. extracted amplitudes **Generated Vs. Extracted annontudes** 101 100 5.2 The Monte Carlo Generator Generator Generator Generator Generator Generator Generator Generator Genera  $\mathbf{1}$ . 1 Unweighted Asymmetry Amplitudes Asymmetry Asymmetry Asymmetry Amplitudes Asymmetry Amplitudes Asymmetry Amplitudes Amplitudes Asymmetry Amplitudes Amplitudes Amplitudes Amplitudes Amplitudes Amplitudes Amplitu In the Monte Carlo generation generator group or gaining order parameters of the unpo-5.2.1 Unweighted Asymmetry Amplitudes 99 **in the analysis of the Carlo production**  $\sum_{n=1}^{\infty}$ In the Monte Carlo generator gmathematic gratic gratic gratic gratic gratic  $\mathcal{H}$  . The unportant parametrisations of the unportant parametrisations of the unportant parametrisations of the unportant parameters  $\mathcal{H}$  $\cot \theta$   $\sin \theta$ icteu amphituues



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# Comparison for weighted moments



#### No.  $\overline{\mathbf{v}}$ Not so good news for weighted moments

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# **Where to go from here?**

# Models for integrated DFs and FF

- **"usual PDFs" from** PEPSI **library**  $f_1, g_1$  from Pl<br> **P** or Kretzer<br> **d**<br> **umetrization**<br>
<sup>30</sup>
- $D_1$  from KKP or Kretzer
- $h_1$  can be
	- $\bullet = g_1$
	- **Soffer bound**
	- **Leader parametrization**

# Models for Sivers and Collins Fcts

- **Sivers function**  $f_{1T}^{\perp}$ 
	- $\bullet$   $f_{1T}^{\perp}(x) \sim f_1(x)$
	- $f_{1T}^{\perp}(x) \sim g_1(x)$
	- Boglione-Mulders parametrization  $\begin{split} &f_{1T}^\perp(x) \sim f_1(x)\ &f_{1T}^\perp(x) \sim g_1(x)\ \text{Boglione-Mulders parameter} \ &f_{1T}^{\perp(1)}(x) \sim f_1(x)\ \text{ollins function: } H_1^\perp \ &H_1^\perp(z) \sim D_1(z)\ \text{Boglione-Mulders} \ &\text{Leader} \ &H_1^{\perp(1)}(z) \sim D_1(z)\ &\text{L, Universiteit Gent}} \end{split}$  $f_{1T}^{\perp (1)}$  $f_1(T^{(1)}(x) \sim f_1(x)$
- **Collins function:** *H*<sup>⊥</sup> 1
	- $H_1^{\perp}(z) \sim D_1(z)$
	- Boglione-Mulders
	- **•** Leader

$$
\bullet \ \ H_1^{\perp(1)}(z) \sim D_1(z)
$$

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# Models for Sivers and Collins Fcts

- **Sivers function**   $f_{1T}^{\perp}$ 
	-
	- $f_{1T}^{\perp}(x) \sim g_1(x)$
	- Boglione-Mulders parametrization 32 *f* ⊥ <sup>1</sup>*<sup>T</sup>* (*x*) ∼ *f*1(*x*)  $f_{1T}^{\perp (1)}$  $f_1(T^{(1)}(x) \sim f_1(x)$ •  $f_{1T}^{\perp}(x) \sim f_1(x)$ <br>
	•  $f_{1T}^{\perp}(x) \sim g_1(x)$ <br>
	• Boglione-Mulders parametrizations<br>
	•  $f_{1T}^{\perp(1)}(x) \sim f_1(x)$ <br> **Collins function intervals of the state of the state**

H<sub>o</sub>

Collins functio

Bogliothe-Mulders *H*<sup>⊥</sup> (2) ∴ 20(2)

Leader

# Beyond Collins and Sivers

- **certainly would like to model all TMDs, e.g., Boer-Mulders function, to get full cross section**
- **even go to subleading-twist, e.g., Cahn effect**
- **first attempts to implement those have been made**
- **leading twist -- "straight forward" (just a few more convolution integrals)**
- **subleading twist -- "hmmmm..."**
	- **biggest problem there: positivity limits don't exist on DF and FF level**

### Status of unpolarized cross section

- **almost implemented:**
	- **Boer-Mulders effect**
	- **Cahn effect**
		- **can adjust Gaussian width, kinematic dependencies and normalization**
		- **generated values (cross-section and unweighted moments) are available for end-user, however, weighted moments not available**

### Status of polarized cross section

- **hardly implemented:**
	- $\bullet$  twist-3 AUT  $\sin \phi_S$  term (involves transversity)
		- **can partially adjust Gaussian width (involves 2 terms - only the one involving the Collins function is adjustable), kinematic dependencies and normalization**  $\sin \phi_S$  term<br>lly adjust G:<br>ly the one in<br>le), kinema<br>tion<br>values: cros<br>ver, momen
		- **generated values: cross-section is available for enduser, however, moments are not available**

### $\sin \phi_S$  - term in A\_UT a2 + b2 ∞ H b2 ⇒ c2 ⊗ H b2 ⇒ c2 ⊚ H b2



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### - term in A\_UT sinφ*S*\$

#### $2(2-y)\sqrt{1-y}\frac{M}{Q}\mathcal{I}$  $\left[\frac{\mathbf{k_T}\cdot\mathbf{p_T}}{2MM_h}[2h_1+x(\tilde{h}_T^{\perp}-\tilde{h}_T)]H_1^{\perp}-\frac{M_h}{zM}h_1\tilde{H}\right]$

### convolution integral and DF & FF known/implemented

twist-3 FF (Koike?) (turned off in gmc\_trans)

### Cahn Effect

- **similar to twist-3 AUT term**
- **reduced to product of f1 and D1**
- **neglect any interaction-dependent terms**
- **get f1 and D1 from PDF/FF library**
- **however,** 
	- **need additional scaling factor, and**
	- **need different Gaussian width than normal f1 and D1**

### The Twist-3 Problems

- **need scaling factors, even though Mulders&Tangerman etc. would suggest a normalization that is fixed by involved PDFs and FFs**
- **same is true for Gaussian widths: need different ones than for "normal" f1 and D1 (or transversity and Collins FF)**
- **therefore: intrinsicly inconsistent treatment failure of Gaussian Ansatz?**
- **in general: encountered severe positivity violations (in particular with Cahn effect)**

### Summary

- **gmc\_trans is a working MC generator for TMDs in SIDIS (pion production)**
- **based on Gaussian Ansatz for transverse momentum dependencies**
- **Collins and Sivers effect implemented**
- **z-dependence of Gaussian widths tuned to HERMES data**
- **implementation of other (partially subleading-twist) terms not straight-forward**

### Outlook / Wishlist

- **finish Boer-Mulders implemention**
- **implement newest results from fits and model calculations on transversity, Sivers & Collins functions**
- **implement Kaons and neutron target**
	- ➡ **comparison with HERMES and COMPASS data possible**
- **add radiative corrections (**RADGEN**)**
- **solve twist-3 problems**
- **gmc\_trans for 2-hadron production**

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