TMD analysis at HERMES using MC

INT Workshop 14-55w Studies of 3D Structure of Nucleon

Universidad del País Vasco

Euskal Herriko Unibertsitatea

Basque Foundation for Science

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Disclaimers

- focus rather on "MC in TMD analyses at HERMES"
- contains a number of trivial, but hopefully still useful, statements
- an not offer a general recipe, though hopefully strained and the set of the set of the set of the set of the s
includence the set of the set of
s can not offer a general recipe, though hopefully some guidance

Some usages for Monte Carlo

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Prelude: role of acceptance in experiments

An unfortunate Lemma

- "No particle-physics experiment has a perfect acceptance!"
	- \bullet obvious for detectors with gaps/holes
	- but also for "4π", especially when looking at complicated final states

An unfortunate Lemma

"No particle-physics experiment has a perfect acceptance!"

HERMES azimuthal acceptance for 2-hadron production

[P. van der Nat, Ph.D. thesis, Vrije Universiteit (2007)]

An unfortunate Lemma 9000 *< 0.77* GeV/c *^h*

"No particle-physics experiment has a perfect acceptance!" *0.64* GeV/c *< p*

An unfortunate Lemma *4.5 Acceptance ^e*ff*ects* **⁷³**

"No particle-physics experiment has a perfect acceptance!"

mass frame and Ph in the γ∗*N center-of-mass frame. In the present work P***¹** *represents the momentum of the positively charged pion, in agreement with Ref. [94].* The partial wave expansion allows to separate different possible contributions to the contributions to the \mathbb{R}^n **distributions even for** and a pion pair in a relative *p*-wave. The expansion is made in terms of the polar angle θ between Γ in the positive hadron in the 4π acceptance **momentum cuts strongly distort kinematic "4**π**" acceptance**

> [P. van der Nat, Ph.D. thesis, **Market Cose (2007)**
Market (2007)] . (2.47)

An unfortunate Lemma

- "No particle-physics experiment has a perfect acceptance!"
	- \bullet obvious for detectors with gaps/holes
	- \bullet but also for " 4π ", especially when looking at complicated final states
- How acceptance effects are handled is one of the
essential questions in experiments!
 $\frac{1}{2}$ essential questions in experiments!

some acceptance effects

acceptance in kinematic variable studied, e.g., azimuthal coverage in extraction of azimuthal moments

acceptance in kinematic variables integrated over, e.g., due to limited statistics not being able to do fully differential analysis

hermes

"acceptance cancels in asymmetries"

$$
A_{UT}(\phi, \Omega) = \frac{\sigma_{UT}(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega)}
$$
\n
$$
\Omega = x, y, z, ...
$$

$$
A_{UT}(\phi, \Omega) = \frac{\sigma_{UT}(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega)} \qquad \qquad \Omega = x, y, z, ...
$$

$$
= \frac{\sigma_{UT}(\phi, \Omega) \epsilon(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega) \epsilon(\phi, \Omega)} \qquad \epsilon : \text{detection efficiency}
$$

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\n
$$
= \frac{\sigma_{UT}(\phi, \Omega) \epsilon(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega) \epsilon(\phi, \Omega)} \qquad \epsilon : \text{detection efficiency}
$$

\n
$$
\neq \frac{\int d\Omega \sigma_{UT}(\phi, \Omega) \epsilon(\phi, \Omega)}{\int d\Omega \sigma_{UU}(\phi, \Omega) \epsilon(\phi, \Omega)}
$$

$$
A_{UT}(\phi, \Omega) = \frac{\sigma_{UT}(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega)} \qquad \Omega = x, y, z, ...
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\n
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= \frac{\sigma_{UT}(\phi, \Omega) \epsilon(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega) \epsilon(\phi, \Omega)} \qquad \epsilon : \text{detection efficiency}
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\n
$$
\neq \frac{\int d\Omega \sigma_{UT}(\phi, \Omega) \epsilon(\phi, \Omega)}{\int d\Omega \sigma_{UU}(\phi, \Omega) \epsilon(\phi, \Omega)} \neq \frac{\int d\Omega \sigma_{UT}(\phi, \Omega)}{\int d\Omega \sigma_{UU}(\phi, \Omega)} \equiv A_{UT}(\phi)
$$

 \bullet "acceptance cancels in asymmetries"

$$
A_{UT}(\phi, \Omega) = \frac{\sigma_{UT}(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega)} \qquad \Omega = x, y, z, ...
$$

\n
$$
= \frac{\sigma_{UT}(\phi, \Omega) \epsilon(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega) \epsilon(\phi, \Omega)} \qquad \epsilon : \text{detection efficiency}
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\n
$$
\neq \frac{\int d\Omega \sigma_{UT}(\phi, \Omega) \epsilon(\phi, \Omega)}{\int d\Omega \sigma_{UU}(\phi, \Omega) \epsilon(\phi, \Omega)} \neq \frac{\int d\Omega \sigma_{UT}(\phi, \Omega)}{\int d\Omega \sigma_{UU}(\phi, \Omega)} \equiv A_{UT}(\phi)
$$

 $\neq \frac{\int dx \, t \, \sigma_{UL}(\phi, \Omega) \, \epsilon(\phi, \Omega)}{\int d\Omega \, \sigma_{UL}(\phi, \Omega) \, \epsilon(\phi, \Omega)} \neq \frac{\int dx \, t \, \sigma_{UL}(\phi, \Omega)}{\int d\Omega \, \sigma_{UL}(\phi, \Omega)} \equiv A_{UL}$
Acceptance does **not cancel** in general when **integrating**
merator and denominator over (large) ranges in ki . Acceptance does not cancel in general when integrating numerator and denominator over (large) ranges in kinematic iuniei utot Acceptance does **not cancel** in general when **integrating** numerator and denominator over (large) ranges in kinematic variables!

… geometric acceptance … hermes *Acceptance effects*

extract acceptance from Monte Carlo simulation?

$$
\epsilon(\phi, \Omega) = \frac{\epsilon(\phi, \Omega) \sigma_{UU}(\phi, \Omega)}{\int \sigma_{UU}(\phi, \Omega)}
$$

 $\Omega = x, y, z, \ldots$

 \overline{C} "

simulated cross section

… geometric acceptance … hermes *Acceptance effects*

extract acceptance from Monte Carlo simulation?

$$
\epsilon(\phi, \Omega) = \frac{\epsilon(\phi, \Omega) \sigma_{UU}(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega)}
$$
\n
$$
\neq \frac{\int d\Omega \sigma_{UU}(\phi, \Omega) \epsilon(\phi, \Omega)}{\int d\Omega \sigma_{UU}(\phi, \Omega)}
$$
\n
$$
\neq \int d\Omega \epsilon(\phi, \Omega) \equiv \epsilon(\phi)
$$
\n
$$
\neq \int d\Omega \epsilon(\phi, \Omega) \equiv \epsilon(\phi)
$$
\n
$$
\therefore \text{ Kürzen nur die Dummen."}
$$

$\neq \int dx \, \iota \, e(\varphi, x \iota) = e(\varphi)$
ss-section model does NOT CANCEL in genera
in integrating numerator and denominator over
ge) ranges in kinematic variables! **Cross-section model does NOT CANCEL in general when integrating numerator and denominator over (large) ranges in kinematic variables!** .

"Classique" Example: $\langle cos \phi \rangle$ _{UU} que" Evemple. 1 1 1 *MC MC MC MC MC L n* σ ε ε = 1 *MC*

… averaging ...

 $\langle A(\Omega)\rangle_{\epsilon} \equiv$

Z

often enough one has to average observables over available phase space: properly normalized for

 $d\Omega A(\Omega)\epsilon(\Omega)$

simplicity

… averaging ...

often enough one has to average observables over available phase space:

$$
\langle A(\Omega) \rangle_{\epsilon} \equiv \int d\Omega A(\Omega) \epsilon(\Omega)
$$

$$
\Theta \int d\Omega A(\Omega) \equiv \langle A(\Omega) \rangle \, \omega_{4\pi},
$$

of the experimentalist) simplifies if asymmetries are w
not more than linearly) dependent on kinematics:
 $\langle A(\Omega) \rangle_{\epsilon} = A(\langle \Omega \rangle_{\epsilon})$ for $A(\Omega) = A_0 + A_1 \Omega$ life (of the experimentalist) simplifies if asymmetries are weakly (i.e. not more than linearly) dependent on kinematics:

 $\langle A(\Omega) \rangle_{\epsilon} = A(\langle \Omega \rangle_{\epsilon})$ for $A(\Omega) = A_0 + A_1 \Omega$

The HERMES experiment

(HERMES = HERA Measurement of Spin)

The HERMES Experiment hermes *HERMES at DESY*

The HERMES Experiment hermes *HERMES at DESY*

- pure gas targets
- internal to lepton ring
- unpolarized (¹ H … Xe)
- long. polarized: ¹H, ²H, ³He
- transversely polarized: ¹H

hermes *The HERMES Spectrometer* HERMES (1998-2005) schematically

• Kinematic coverage: 0.02 ≤ x ≤ 0.8 for Q² > 1 GeV² and W > 2 GeV **two (mirror-symmetric) halves** -> no nomogenous azimutnai
- RICH: pion/kaon/proton **-> no homogenous azimuthal coverage**

Particle ID detectors allow for

- lepton/hadron separation
- PID: Cherenkov (RICH after 1997), TRD, Preshower, Calorimeter discrimination 2GeV<p<15GeV

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1-Hadron production (ep->ehX) ^Q sin ^φ ^dσ⁵ ^Q cos ^φ ^dσ⁷ $s = \frac{1}{\sqrt{2\pi}}$ $\frac{1}{100}$ $\frac{1}{100}$ dg $\frac{1}{100}$ dg $\frac{1}{100}$ d $\frac{1}{100}$ $\overline{}$

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

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

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

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

↙ ↘ **Beam Target Polarization**

 σ_{XY}

 $\overline{}$

!

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

Mulders and Tangermann, Nucl. Phys. B 461 (1998)

Boer and Mulders, Phys. Rev. D 57 (1998) 5780

Bacchetta et al., Phys. Lett. B 595 (2004) 309

B qunar.schnell @ destate the 2014 and 25 and 25 and 2014 and 2014 and 2014 25 **Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197 Boer and Mulders, Phys. Rev. 2008) 570 Bacchetta et al., Phys. Lett. B 595 (2004) 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

1-Hadron production (ep-
$$
\rightarrow
$$
ehX)
\n
$$
d\sigma = \boxed{d\sigma_{UU}^0 + \frac{1}{\cos 2\phi} \frac{d\sigma_{UU}^1}{d\phi_{UU}} + \frac{1}{Q} \cos \phi \frac{d\sigma_{UU}^2}{d\phi_{UL}} + \lambda_e \frac{1}{Q} \sin \phi \frac{d\sigma_{UU}^3}{d\phi_{UL}}}
$$
\n+ S_L $\left\{ \sin 2\phi \frac{d\sigma_{UL}^4}{d\phi_{UL}} + \frac{1}{Q} \sin \phi \frac{d\sigma_{UL}^5}{d\phi_{UL}} + \lambda_e \left[d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi \frac{d\sigma_{UL}^7}{d\phi_{UL}} \right] \right\}$
\n+ S_T $\left\{ \frac{\sin(\phi - \phi_S) \frac{d\sigma_{UT}^8}{d\phi_{UL}} + \frac{\sin(\phi + \phi_S) \frac{d\sigma_{UT}^9}{d\phi_{UT}}}{d\phi_{UT}} + \sin \phi_S \frac{d\sigma_{UT}^{12}}{d\phi_{UT}^7} \right\}$
\nBean Target
\nPolarization $+ \lambda_e \left[\cos(\phi - \phi_S) \frac{d\sigma_{LT}^{13}}{d\phi_{LT}} + \frac{1}{Q} \left(\cos \phi_S \frac{d\sigma_{LT}^{14}}{d\phi_{UL}} + \cos(2\phi - \phi_S) \frac{d\sigma_{LT}^{15}}{d\phi_{LT}} \right) \right]$
\nMulders and Tangerman, Nucl. Phys. B 461 (1996) 197
\nBocchetta et al., Phys. Lett. B 595 (2004) 309
\nBacchetta et al., JHEP 0702 (2007) 093

Bacchetta et al., JHEP 0702 (2007) 0 Bacchetta et al., Phys. Lett. B 595 (2004) 309 Bacchetta et al., JHEP 0702 (2007) 093

"Trento Conventions", Phys. Rev. D 70 (2004) 117504 Trento Conventions", Phys. Rev. D 70 (2004) 117504

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Phad

 \bar{p}_ha

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

⃗ \boldsymbol{k}

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

z

Polarization

 ϕ

 \mathbf{v}_ℓ

Measuring azimuthal SSA

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

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

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

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

\n
$$
\Rightarrow 2D \text{ Max.Likelihd. fit of to get Collins and Sivers amplitudes:}
$$

\n
$$
PDF(2\langle \sin(\phi \pm \phi_S) \rangle_{UT}, \ldots, \phi, \phi_S) = \frac{1}{2} \{1 + P_T(2\langle \sin(\phi \pm \phi_S) \rangle_{UT} \sin(\phi \pm \phi_s) + \ldots \}
$$

 \Rightarrow 2D Max.Likelihd. fit of to get Collins and Sivers amplitudes:

. $PDF(2\langle\sin(\phi\pm\phi_S)\rangle_{UT},\dots,\phi,\phi_S)=\frac{1}{2}\{1+P_T(2\langle\sin(\phi\pm\phi_S)\rangle_{UT}\sin(\phi\pm\phi_s)+\ldots)\}$

1D vs. 2D fitting

 \bullet limited acceptance introduces correlations to originally orthogonal azimuthal Fourier amplitudes

1D vs. 2D fitting

 \bullet limited acceptance introduces correlations to originally orthogonal azimuthal Fourier amplitudes

choice of models

 \bullet linear dependence kind of trivial to reproduce (see earlier slide)

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gu

GMCTRANS ingredients

Initial goals

- 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) to be used with standard HERMES Monte Carlo
- be extendable (e.g., open for new models)
Basic workings

- use cross section that can be calculated analytically
- do not simulate full event
- start from 1-hadron SIDIS expressions of Mulders & Tangerman (Nucl.Phys.B461:197-237,1996) and others
- use Gaussian Ansatz for all transverse-momentum dependences of DFs and FFs
- unpolarized DFs (as well as helicity distribution) and FFs from fits/parametrizations (e.g., Kretzer FFs etc.)
- inpolarized DFs (as well as helicity distribution) and FF:
its/parametrizations (e.g., Kretzer FFs etc.)
polarized" DFs and FFs either related to unpolarized of
e.g., saturation of Soffer bound for transversity)or sol
para "polarized" DFs and FFs either related to unpolarized ones (e.g., saturation of Soffer bound for transversity)or some parametrizations used

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

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

$$
d\sigma_{UT}^{\text{Collins}}(x, y, z, \phi_S, P_{h\perp}) = -\frac{2\alpha^2}{sxy^2} B(y) \sum_q e_q^2 \mathcal{I} \left[\left(\frac{k_T \cdot \hat{P}_{h\perp}}{M_h} \right) \cdot h_1^q H_1^{\perp q} \right]
$$

$$
d\sigma_{UT}^{\text{Sivers}}(x, y, z, \phi_S, P_{h\perp}) = -\frac{2\alpha^2}{sxy^2} A(y) \sum_q e_q^2 \mathcal{I} \left[\left(\frac{p_T \cdot \hat{P}_{h\perp}}{M_N} \right) \cdot f_{1T}^{\perp q} D_1^q \right]
$$

$$
d\sigma_{UU}(x, y, z, \phi_S, P_{h\perp}) = \frac{2\alpha^2}{sxy^2} A(y) \sum_q e_q^2 \mathcal{I} \left[f_1^q D_1^q \right]
$$

where

$$
d\sigma_{UU}(x, y, z, \varphi_S, F_{h\perp}) = \frac{1}{sxy^2} A(y) \sum_{q} e_q L \left[J_1 D_1 \right]
$$

where

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

Gaussian Ansatz $\mathbf{r} = \mathbf{r}$ \overline{A} is a compact \overline{A} "

- want to deconvolve convolution integral over transverse momenta k^T · P ˆ but want to deconvolve convolution integral over transverse momenta ver *Positivity Limits & Failure of Gaussian Ansatz* ^M^N ^πz³ · (1 [−] ^C)⟨p² a want to deconvolve convolution integra $momenta$ in the convolution integral and because of the fact that k^T comes with the opposite sign compared to p^T in the
- **easy Ansatz: Gaussian dependences of DFs and FFs on** intrinsic (quark) transverse momentum: For cappelling completences we will also give the result for the unit for the cross section using the easy Ansatz: Gaussian depenc $\overline{}$ nces of ²) [≡] ^H[⊥](1/2) $\overline{}$ **O** ensy Ansatz: Gaussian dependences of DFs and FFs on sign of the Sign o

$$
\mathcal{I}[f_1(x, \mathbf{p}_T^2)D_1(z, z^2 \mathbf{k}_T^2)] = f_1(x) \cdot D_1(z) \cdot \frac{R^2}{\pi z^2} \cdot e^{-R^2 \frac{P_{h\perp}^2}{z^2}}
$$

with $f_1(x, p_T^2) = f_1(x) \frac{1}{\pi \langle p_T^2 \rangle} e^{-\frac{p_T^2}{\langle p_T^2 \rangle}} \frac{1}{R^2} = \langle k_T^2 \rangle + \langle p_T^2 \rangle = \frac{\langle P_{h\perp}^2 \rangle}{z^2}$

(similar: $D_1(z,z^2\bm{k_T^{\,2}})$) $\binom{2}{1}$)

th $f_1(x,p_T^2) = f_1(x) \frac{1}{\pi \langle p_T^2 \rangle} e^{-\frac{1}{\langle p_T^2 \rangle}} \qquad \frac{1}{R^2} \equiv \langle k_T^2 \rangle + \langle p_T^2 \rangle = \frac{\langle P_{h\perp}^2 \rangle}{z^2}$
similar: $D_1(z,z^2k_T^2)$)
aution: different notations for intrinsic transver
momenta exist! (Here: "Amsterdam notati Caution. Official notations for intrinsic fransverse S Then one gets even more compact versions. R^2 R^2 **z**
33 Caution: different notations for intrinsic transverse . momenta exist! (Here: "Amsterdam notation") momenta exist! (F

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Positivity Constraints

- DFs (FFs) have to fulfill various positivity constraints (resulting cross section has to be positive!)
- based on probability considerations one can derive positivity limits for leading-twist functions: Bacchetta et al., Phys. Rev. Lett. 85 (2000) 712-715
- **Posity:** e.g., Soffer bound
- Sivers and Collins functions: e.g., loose bounds:

Sivers and Collins functions: e.g., loose bounds:
\n
$$
\frac{|p_T|}{2M_N} f_{1T}^{\perp}(x, p_T^2) \equiv f_{1T}^{\perp (1/2)}(x, p_T^2) \le \frac{1}{2} f_1(x, p_T^2)
$$
\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 bitrary in size but have to function \mathbb{R}^n . Specifically, if one looks at a two-dimensional subspace of the two-dimensional subspace of the two-dimensional subspace of the two-dimensional subspace of the two-dimensi POSITIVITY and the Gaussian Ansatz Positivity and the Ga 1 $\overline{}$ ssian ,

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

Positivity and the Gaussian Ansatz bitrary in size but have to function \mathbb{R}^n . Specifically, if one looks at a two-dimensional subspace of the two-dimensional subspace of the two-dimensional subspace of the two-dimensional subspace of the two-dimensi POSITIVITY and the Gaussian Ansatz Positivity and the Ga 1 $\overline{}$ ssian ,

$$
\frac{|p_T|}{2M_N} f_{1T}^{\perp}(x, p_T^2) \leq \frac{1}{2} f_1(x, p_T^2)
$$
\nwith $f_1(x, p_T^2) = f_1(x) \frac{1}{\pi \langle p_T^2 \rangle} e^{-\frac{p_T^2}{\langle p_T^2 \rangle}}$
\n $f_{1T}^{\perp}(x, p_T^2) = f_{1T}^{\perp}(x) \frac{1}{\pi \langle p_T^2 \rangle} e^{-\frac{p_T^2}{\langle p_T^2 \rangle}}$
\n
$$
\frac{|p_T|}{f_{1T}^{\perp}(x)} \leq M_N f_1(x)
$$
\nNo (useful) solution for non-zero Sivers function!

No (useful) solution for non-zero Sivers function!

Modify Gaussian width

Skewed Gaussian Ansatz

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

:y limit:

⇒ **positivity limit:** f[⊥] ¹^T (x, p^T

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

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

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

 \sum \boldsymbol{q} $e_{\bm{q}}^{\bm{2}}$ 4π α^2 $\frac{1}{(MExyz)^2} \left[X_{UU} + |\mathrm{S}_T| X_{SIV} \sin(\phi_h - \phi_s) + |\mathrm{S}_T| X_{COL} \sin(\phi_h + \phi_s) \right]$ \mathbf{r}

where the cross section expressions are (using the skewed Gaussian Ansatz): using Gaussian Ansatz for transverse-momentum ndence of DFs an dependence of DFs and FFs: $\mathbf \ell$ \mathbf{F}

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

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

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

$$
M_{\pi}z \left[\langle p_T^2 \rangle + (1 - C) \langle k_T^2 \rangle \right] \qquad \text{L} \quad \langle p_T \rangle + (1 - C) \langle k_T \rangle \right]
$$
\n
$$
\times \quad (1 - y) \cdot h_1(x) \cdot H_1^{\perp}(z)
$$
\n
$$
X_{\text{SIV}} = -\frac{|P_{h\perp}|}{M_{p}z} \frac{(1 - C') \langle p_T^2 \rangle}{\left[\langle k_T^2 \rangle + (1 - C') \langle p_T^2 \rangle \right]^2} \exp\left[-\frac{P_{h\perp}^2/z^2}{\langle k_T^2 \rangle + (1 - C') \langle p_T^2 \rangle} \right]
$$
\n
$$
\times \quad \left(1 - y + \frac{y^2}{2} \right) f_{1T}^{\perp}(x) \cdot D_1(z)
$$
\ngauge, shell @ desv.de

\n
$$
N_{\text{SIV}} = -\frac{1}{2} \left[\frac{1}{2} \int_{0}^{1} f_{1T}^2(z) \cdot D_1(z) \right]
$$
\nand

Example: Sivers (azimuthal) moments *Single Spin Asymmetries (using skewed Gaussian Ansatz) Single Spin Asymmetries (using skewed Gaussian Ansatz)*

 $\mathop{\varepsilon\mathsf{r}}$ oss section expressions to evaluate azin $\mathop{\varepsilon\mathsf{r}}$ moments: *Single Spin Asymmetries (using skewed Gaussian Ansatz)* use cross section expressions to evaluate use cross section expressions to evaluate azimuthal

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

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

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

model-dependence on transverse momenta
"swallowed" by p_T^2 - moment of Sivers fet.: $f_{1T}^{\perp (1)}$

Gunar Schnell HERMES Analysis Week, Sept. ²⁹th, ²⁰⁰⁴ – p. 9/10 |Ph[⊥]| zM^N ndel-denendence on transverse! Ice on transverse Gwundweu Dy p_T municin of orers for \mathcal{G} model-denendence on transverse momenta endence on trar model-dependence on transverse momenta $\mathbf{M}_{\mathbf{q}}$ $\frac{1}{2}$ $-$ moment of Sivers fct.: model-dependence on transverse momenta "swallowed" by p_T^2 - moment of Sivers fct.: $f_{1T}^{\perp(1)}$ 2 *T*

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|
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Selected Results

Tuning the Gaussians in gmc_trans

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

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0 0.5 1 1.5

Tuning the Gaussians in gmc_trans

ころい

Ulrike Elschenbroich, Makins Relation, Collaboration Meeting, March 2006 – p.9

Tuning the Gaussians in gmc_trans

ノスツ

Ulrike Elschenbroich, Makins Relation, Collaboration Meeting, March 2006 – p.10

Some rather simple models for Transversity & friends $\begin{array}{lllll} \mathbf{r} & \mathbf{r} & \mathbf{r} & \mathbf{r} & \mathbf{r} & \mathbf{r} & \mathbf{r} \end{array}$ functions are proportional to the helicity DF: $\mathcal{L} = \mathcal{L} \mathcal{L} = \mathcal{L$ ome rather simple models for Transvorsity & friends \sim 0.9 \sim 0.0 \sim Some rather simple de models tor The parametrisation of the unpolarised FFs fulfil isospin and charge conjugation symmetry

$$
\delta u(x) = 0.7 \cdot \Delta u(x) \qquad f_{1T}^{\perp u}(x) = -0.3 \cdot u(x)
$$

\n
$$
\delta d(x) = 0.7 \cdot \Delta d(x) \qquad f_{1T}^{\perp d}(x) = 0.9 \cdot d(x)
$$

\n
$$
\delta q(x) = 0.3 \cdot \Delta q(x) \qquad f_{1T}^{\perp q}(x) = 0.0 \qquad q = \bar{u}, d, s, \bar{s}
$$

$$
H_{1,\text{fav}}^{\perp(1)}(z) = 0.65 \cdot D_{1,\text{fav}}(z)
$$

\n
$$
H_{1,\text{dis}}^{\perp(1)}(z) = -1.30 \cdot D_{1,\text{dis}}(z)
$$

\n**GRSV for PDFs and Kretzer FF for D**1

 $O₁$

Generated vs. extracted amplitudes 5.2.1 Unweighted Asymmetry Amplitudes 101 5.2.1 Unweighted Asymmetry Amplitudes In the Monte Carlo generator gmc_trans, leading order parametrisations of the unpo-5.2.1 Unweighted Asymmetry Amplitudes 99 Cononated ye ovtrocted amplitudes to world data, are implemented as functions of x and z. Different models for the x and z $\mathcal{L} = \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \$ xtracted amplitudes

Generated vs. extracted amplitudes

Extraction of weighted moments

$\sqrt{2}$ ⊥/zM·sin(φ-φ S)〉UT π + **D.05** $\frac{1}{2}$ $\overline{}$ Not so good news for weighted moments!

SCI

 $\frac{1}{\sqrt{2}}$

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further improvement of the models

DSS FFs and modified Anselmino et al. Sivers fit: *5.1. The estimate of the systematic uncertainty*

further improvement of the models

DSS FFs and modified Anselmino et al. Sivers fit: *5.1. The estimate of the systematic uncertainty*

missing items in gmc_trans

- not so good model for transversity & Collins FF
- missing models for other single- and double-spin asymmetries
- no azimuthal modulations of unpolarized cross section
- **•** no radiative corrections
- orrelations etc.) no full event generation (missing track multiplicities and correlations etc.)

"reshuffling" PYTHIA events Uffling" PYTHTA events

- use model for azimuthal distribution to introduce spin dependence in PYTHIA \blacksquare \blacksquare as a simuthal distribution to introduce spin(for a sin(for \blacksquare where we will dependence with virtuality the asymmetry model for the estimate of systematic uncertainties on the estimate of systematic uncertainties on the estimate of systematic uncertainties on the estimate of systemati
- throw random number ρ and assign spin state up if, e.g., ϵ the column and ϵ is given. For each scattering event, the approximated cross section \bullet in ow rundom number ρ and assign spin state ap it, e.g.,

$$
\rho < \frac{1}{2}(1+\sin{(\phi-\phi_S)}\Xi_{11}^{\sin{(\phi-\phi_S)},h} + \sin{(\phi+\phi_S)}\Xi_{11}^{\sin{(\phi+\phi_S)},h} + \sin{(\phi_S)}\Xi_{11}^{\sin{(\phi_S)},h})
$$

then target spin orientation " ("+") is assigned. The sequence of random numbers is fixed to random numbers is

repeat systematic studies using an identical distribution of transverse target spin states. Thereby, no

parametrization of azimuthal dependences
(extracted, e.g., from real data) ing influence of the systematic uncertainties on the systematic uncertainties was found with a manufacture within with a manufacture with with a manufacture with with with a manufacture with with the SSA amplitudes with wi the statistical accuracy of the simulated data. (extracted, e.g., from real data) parametrization of azimuthal dependences

Parametrization of azimuthal dependence only the Collins and Sivers mechanism. In the fully differential maximum likelihood fit a probability differen
In the fully differential maximum likelihood fit a probability differential maximum likelihood fit a probabili model [Mil06] optimised for the description of a GMC_TRANS Monte Carlo simulation including only the Collins and Sivers meaning. In the full method fit a probability of the full may be fit a probability

• fully differential model extracted in M.L. fit to data with PDF *P* ⇣ α *lifferential model extracted*

$$
P(x, Q2, z, |\mathbf{P}_{h\perp}|, \phi, \phi_S; \Xi_{22}^{\sin(\phi-\phi_S),h}, \Xi_{22}^{\sin(\phi+\phi_S),h})
$$

= 1 + S_⊥ (sin($\phi - \phi_S$) $\Xi_{22}^{\sin(\phi-\phi_S),h}$ + sin($\phi + \phi_S$) $\Xi_{22}^{\sin(\phi+\phi_S),h}$)

$$
\Xi_{22}^{\sin(\phi \pm \phi_S),h} = \Xi_{22,1}^{\sin(\phi \pm \phi_S),h} \mathbf{Q}^{2'} + \Xi_{22,2}^{\sin(\phi \pm \phi_S),h} \mathbf{X}' + \Xi_{22,4}^{\sin(\phi \pm \phi_S),h} \mathbf{Z}^{2'} + \Xi_{22,4}^{\sin(\phi \pm \phi_S),h} \mathbf{X}^{2'} + \Xi_{22,5}^{\sin(\phi \pm \phi_S),h} \mathbf{Z}^{2'} + \Xi_{22,6}^{\sin(\phi \pm \phi_S),h} \mathbf{X}^{2'} + \Xi_{22,6}^{\sin(\phi \pm \phi_S),h} \mathbf{X}^{2'} + \Xi_{22,6}^{\sin(\phi \pm \phi_S),h} \mathbf{X}^{2'} + \Xi_{22,8}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,1}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,1}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,1}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,12}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,13}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,14}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,16}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,18}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,18}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,18}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,22}^{\sin(\phi \pm \phi_S),h} \mathbf{X}'^{2'} + \Xi_{22,22}^{\sin(\phi \pm \phi_S
$$

Description of data

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5. The analysis of the measured SSA Evaluation of detector effects

Figure 5.6.: Estimate of the systematic uncertainty of the reconstruction of the Sivers amplitudes: From the reconstruction of the rec events, the Pythia Monte Carlo simulation Sivers and Sivers and Sivers and Sivers and Sivers and Sivers and Si differences include effects from internal and external radiative effects, acceptance, PID, (mis)alignment etc.

qunar.schnell @ desy.de 2014 perfection of a perfection of the perfection of the person ideas of the person of the problem of the problem of (right properties to the employment parallel model evaluated at the mean reconstructed at the mean reconstruct
The mean reconstruction of the mean reconstruction of the mean reconstruction of the mean reconstruction of th king solid line is assigned as systematic uncertainty representation is assigned as systematic uncertainty representation of the difference is assigned as systematic uncertainty representation of the systematic uncertainty in further step "smoothed" to reduce statistical fluctuations 54

some Pro&Cons of "reshuffling"

- whole event topology and correlations available
- **•** flexible
- applicable also to cases where no guidance from theory available on shape/magnitude of modulations

some Pro&Cons of "reshuffling"

- whole event topology and correlations available
- **•** flexible
- applicable also to cases where no guidance from theory available on shape/magnitude of modulations
- **•** need parametrization if from real data, where to stop Taylor (or other) expansion?
- eed parametrization
f from real data, where to stop Taylor (or other) expan
arge uncertainties on (some) parameters can introduce
purious effects in systematics calculation
elies on good description of unpolarized cross se large uncertainties on (some) parameters can introduce large spurious effects in systematics calculation

• relies on good description of unpolarized cross section

Another example: Aut in inclusive hadron production $\mathsf{f}\mathsf{n}\mathsf{p}\mathsf{r}$ a $\mathsf{f}\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}$ and $\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}$ twist Collins fragmentation function can be mapped onto one another [53]. For *P* ² *^T* ∼ *^Q* ² one cannot make any quantitative theoretical statement about their connection.

Another example: Aut in inclusive hadron production $\mathsf{f}\mathsf{n}\mathsf{p}\mathsf{r}$ a $\mathsf{f}\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}$ and $\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}$ twist Collins fragmentation function can be mapped onto one another [53]. For *P* ² *^T* ∼ *^Q* ² one cannot make any quantitative theoretical statement about their connection.

Another example: Aut in inclusive hadron production $\mathsf{f}\mathsf{n}\mathsf{p}\mathsf{r}$ a $\mathsf{f}\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}$ and $\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}$ twist Collins fragmentation function can be mapped onto one another [53]. For *P* ² *^T* ∼ *^Q* ² one cannot make any quantitative theoretical statement about their connection.

 α and leptons by using a transition-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-ra

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Figure E.6. The *^A*sin *UT* fit function (with squares) evaluated at the average bin Another example: A_{UT} in of *x^F* in four di0erent slices of *p^T* . See Section 5.3.1. inclusive hadron production $\mathsf{f}\mathsf{n}\mathsf{p}\mathsf{r}$ a $\mathsf{f}\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}$ and $\mathsf{n}\mathsf{n}\mathsf{n}\mathsf{n}$ twist Collins fragmentation function can be mapped onto one another [53]. For *P* ² *^T* ∼ *^Q* ² one cannot make any quantitative theoretical statement about their connection. A substantial number of theoretical predictions (see, e.g.,

 α and leptons by using a transition-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-radiation-ra

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0.1 0.2 0.3 0.4 0.5 F x 0.1 0.2 0.3 0.4 0.5 Another example: Aut in *UT* fit function (with squares) evaluated at the average bin kinematics ^h*x^F* ⁱ, plotted together with the *^A*sin inclusive hadron production **0.5 1 1.5 2** \blacksquare **0.5 1 1.5 2** Figure E.2. The *^A*sin *UT* fit function (with squares) evaluated at the average bin kinematics ^h*p^T* ⁱ, plotted together with the *^A*sin *UT* amplitudes as a function $\mathsf{P}\mathsf{I}\mathsf{I}\mathsf{I}\mathsf{C}\mathsf{I}\mathsf{V}\mathsf{I}\mathsf{O}\mathsf{I}$

similar problematics: di-hadron AUT

• many kinematic variables needed to describe process

 $N^{\uparrow (\downarrow)}(\phi_{R\perp},\phi_S,\theta,M_{\pi\pi}) \,\propto\,$:
|-
| 1 $\mathrm{d} x\, \mathrm{d} y\, \mathrm{d} z\, \mathrm{d}^2\textit{\textbf{P}}_{\textit{\textbf{h}}\bot}\, \epsilon(x,y,z,\textit{\textbf{P}}_{\textit{\textbf{h}}\bot},\phi_{R\bot},\phi_S,\theta,M_{\pi\pi}) \ \times$ $\times \sigma_{U\uparrow(\downarrow)}(x,y,z,\textbf{\textit{P}}_{\textit{h}\perp},\phi_{R\perp},\phi_S,\theta,M_{\pi\pi}),$

 \bullet at least for one of them strong dependence expected:

60

 $\overline{}$

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Asin(

)

define your measurement wisely

- data point interpreted as asymmetry
	- **at the average kinematics given**
	- \bullet integrated over kinematic ranges
- results in different systematics -> select the one with smallest systematics?
back to di-hadron production

asymmetries at average kinematics -> large effects with strong model dependence

sin(2φ*^h* − φ*^R* − φ*^S*) = sin(2φ*h*) cos(φ*^R* + φ*^S*) − cos(2φ*h*)sin(φ*^R* + φ*^S*). (4.22)

back to di-hadron production

asymmetries at average kinematics -> large effects with strong model dependence

integrated over kinematic range -> still large effects but less model dependent mc

Unpolarized SIDIS

SIDIS cross section

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

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the detector smearing effects. Note this result is independent of the QED rent mi … event migration ...

… event migration ...

аń,

 $t \hbox{ }$ h bins in the 12 h bins in the same kinematical bins in the same ki

200

180

160

140

120

 $\mathcal{Y}^{\mathrm{exp}}(\Omega_i) \propto \sum$ *N j*=1 S_{ij} *j* $d\Omega d\sigma(\Omega) + \mathcal{B}(\Omega_i)$

$$
\mathcal{Y}^{\text{exp}}(\Omega_i) \propto \sum_{j=1}^N S_i \left(\int_j d\Omega \, d\sigma(\Omega) \right) + \mathcal{B}(\Omega_i)
$$

experimental yield in ith bin depends on all Born bins j ...

$$
\mathcal{Y}^{\text{exp}}(\Omega_i) \propto \sum_{j=1}^N S_{ij} \int_j d\Omega \, d\sigma(\Omega) + \left(\mathcal{B}(\Omega_i)\right)^2
$$

- experimental yield in ith bin depends on all Born bins j ...
- … and on BG entering kinematic range from outside region

$$
\mathcal{Y}^{\mathrm{exp}}(\Omega_i) \propto \sum_{j=1}^N S_{ij} \int_j d\Omega \, d\sigma(\Omega) + \mathcal{B}(\Omega_i)
$$

- **•** experimental yield in ith bin depends on all Born bins j ...
- … and on BG entering kinematic range from outside region
- smearing matrix **Sij** embeds information on migration
	- determined from Monte Carlo independent of physics model in limit of infinitesimally small bins and/or flat acceptance/crosssection in every bin
	- limit of infinitesimally small bins and/or flat acceptance/d
section in every bin
in real life: dependence on BG and physics model due to fi
bin sizes in real life: dependence on BG and physics model due to finite bin sizes

$$
\mathcal{Y}^{\mathrm{exp}}(\Omega_i) \propto \sum_{j=1}^N S_{ij} \int_j d\Omega \, d\sigma(\Omega) + \mathcal{B}(\Omega_i)
$$

- experimental yield in ith bin depends on all Born bins j ...
- … and on BG entering kinematic range from outside region
- smearing matrix **Sij** embeds information on migration
	- determined from Monte Carlo independent of physics model in limit of infinitesimally small bins and/or flat acceptance/crosssection in every bin
	- limit of infinitesimally small bins and/or flat acceptance/
section in every bin
in real life: dependence on BG and physics model due to fi
bin sizes
version of relation gives Born cross section from measured in real life: dependence on BG and physics model due to finite bin sizes
- inversion of relation gives Born cross section from measured yields

Multi-D vs. 1D unfolding at work

Neglecting to unfold in z changes x dependence dramatically ➡ 1D unfolding clearly insufficient

dimensional extraction (blue). This illustrates the large systematic uncertainty in t order the proper kinematic dependencies during the analysis during the analys

Multi-D vs. 1D unfolding at work

Neglecting to unfold in z changes x dependence dramatically ➡ 1D unfolding clearly insufficient

even though only interested in collinear observable, need to carefully consider transverse d.o.f.

summary

- acceptance plays crucial part, especially in analysis of multi-particle final states, and that even for asymmetries
- acceptance studies and/or corrections (e.g., unfolding) require realistic Monte Carlo simulation of underlying physics
- gmc_trans provides reasonably realistic Collins and Sivers amplitudes for pions and kaons based on Gaussian Ansatz
- reshuffling PYTHIA events, guided by, e.g., real data, provides a powerful tool to study systematics
	- still relies on good description of unpolarized cross section
- still relies on good description of unpolarized cross section

Nake a careful choice of how data points are to be interpreted (at a

inematics or average over kinematic range)

evaluate systematics accordingly make a careful choice of how data points are to be interpreted (at average kinematics or average over kinematic range)
	- evaluate systematics accordingly

gunar.schnell @ desy.de 2014 fully differential analyses clearly preferred, though more challenging 69