International Workshop on Hadron Structure and Spectroscopy - 2022

August 30, 2022
CERN

Spin effects in unpolarized SIDIS using the string + $^3P_0$ model

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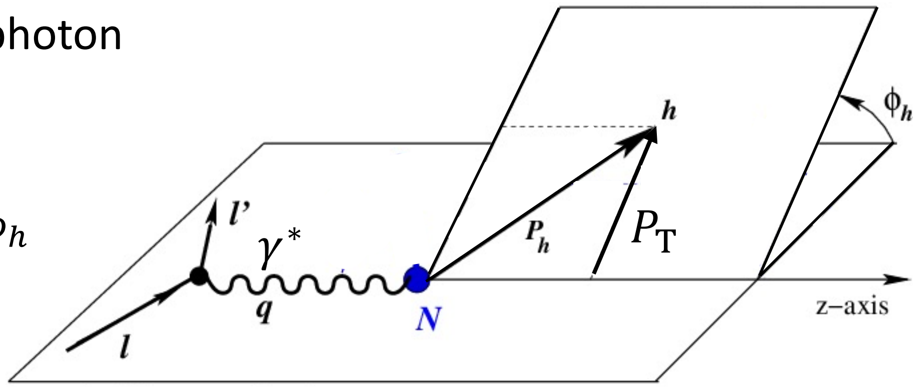
Spin effects in the azimuthal asymmetries in unpolarized SIDIS

Unpolarized SIDIS cross section in the one-photon exchange approximation:

$$\frac{d\sigma}{dxdzdydP_T^2d\phi_h} \propto 1 + \epsilon_1(y) A_{UU}^{\cos\phi_h} \cos\phi_h + \epsilon_2(y)\, A_{UU}^{\cos 2\phi_h} \cos 2\phi_h$$



Partonic content of the azimuthal asymmetries:

Cahn effect *twist 3* — *Boer-Mulders* *twist 3*

$$A_{UU}^{\cos\phi_h} = \frac{2M_N}{Q} C\left[-\frac{\hat{h}\cdot\vec{k}_T}{M_N} f_1^q D_{1q}^h - \frac{(\hat{h}\cdot\vec{p}_\perp)k_T^2}{zM_N^2 M_h} h_1^{\perp q} H_{1q}^{\perp h} + ..\right] / F_{UU}$$

$$A_{UU}^{\cos 2\phi_h} = C\left[2\frac{2\left(\vec{k}_T\cdot\hat{h}\right)^2 - k_T^2}{Q^2} f_1^q D_{1q}^h - \frac{2\left(\vec{k}_T\cdot\hat{h}\right)\left(\vec{p}_\perp\cdot\hat{h}\right) - \vec{k}_T\cdot\vec{p}_\perp}{zM_N M_h} h_1^{\perp q} H_{1q}^{\perp h}\right] / F_{UU}$$

Cahn effect *twist 4* *(the only know term..)* — *Boer-Mulders* *twist 2*

$$F_{UU} = C\left[f_1^q D_1^q\right]$$

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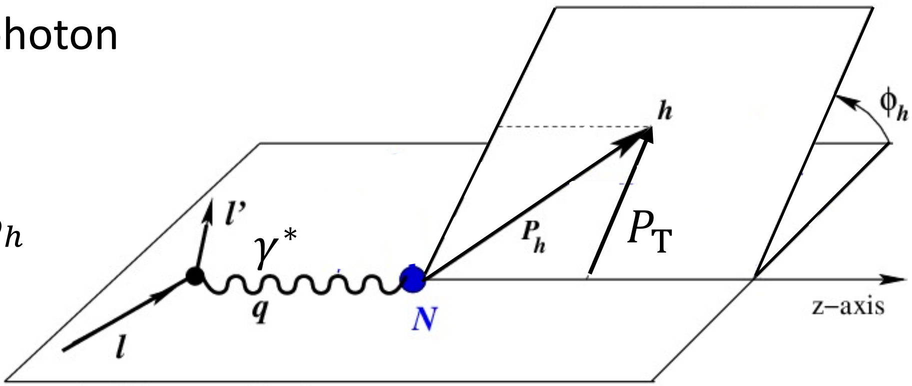

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Cahn effect *twist 4* *(the only know term..)* — *Boer-Mulde* *twist 2*

$$F_{UU} = C\left[f_1^q D_1^q\right]$$

- Important observables, enable access to
  - i. intrinsic $\vec{k}_T$
  - ii. Boer-Mulders TMD

Many data exist:

HERMES	p, d
COMPASS	d, recently p
JLAB	p

large azimuthal asymmetries observed

Spin effects in the azimuthal asymmetries in unpolarized SIDIS

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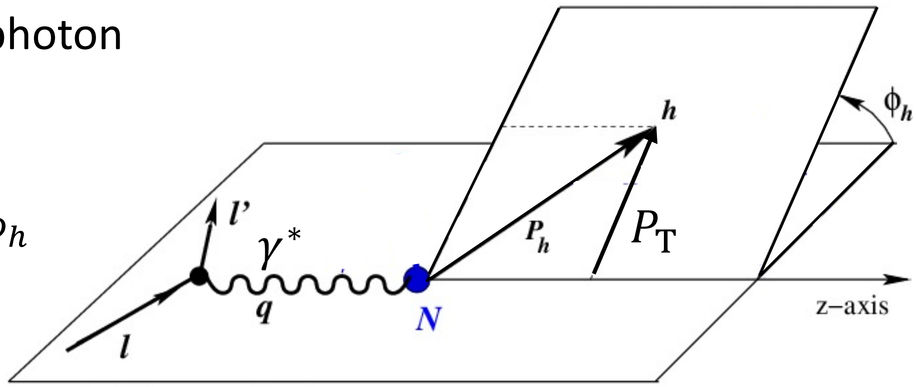

Partonic content of the azimuthal asymmetries:

Cahn effect — twist 3; Boer-Mulders — twist 3

$$A_{UU}^{\cos\phi_h} = \frac{2M_N}{Q} C\left[-\frac{\hat{h}\cdot\vec{k}_T}{M_N} f_1^q D_{1q}^h - \frac{(\hat{h}\cdot\vec{p}_\perp)k_T^2}{zM_N^2M_h} h_1^{\perp q} H_{1q}^{\perp h} + ..\right] / F_{UU}$$

$$A_{UU}^{\cos 2\phi_h} = C\left[2\frac{2\left(\vec{k}_T\cdot\hat{h}\right)^2 - k_T^2}{Q^2} f_1^q D_{1q}^h - \frac{2\left(\vec{k}_T\cdot\hat{h}\right)\left(\vec{p}_\perp\cdot\hat{h}\right) - \vec{k}_T\cdot\vec{p}_\perp}{zM_NM_h} h_1^{\perp q} H_{1q}^{\perp h}\right] / F_{UU}$$

Cahn effect — twist 4 (the only know term..); Boer-Mulders — twist 2

Boer-Mulders TMD: describes transversely polarized quarks in an unpolarized nucleon

Collins FF: fragmentation of transversely polarized quarks in unpolarized hadrons

$$F_{UU} = C[f_1^q D_1^q]$$

Spin effects in the azimuthal asymmetries in unpolarized SIDIS

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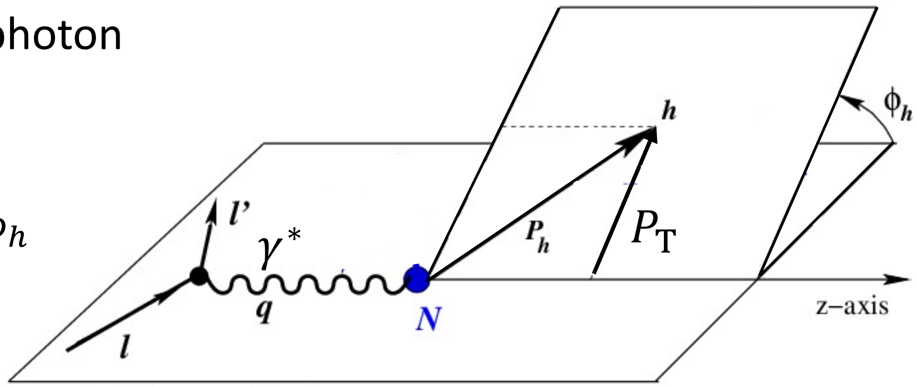

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Boer-Mulders TMD: describes transversely polarized quarks in an unpolarized nucleon

Boer-Mulders

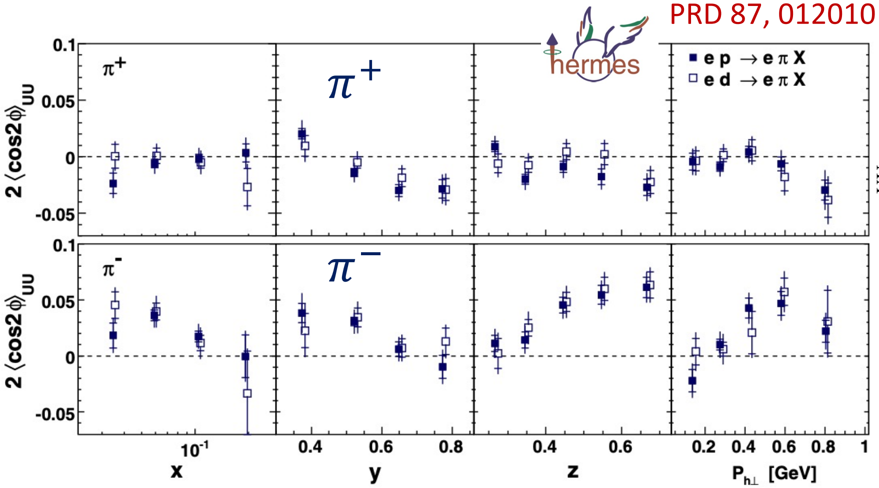
twist 2

Collins FF: fragmentation of transversely polarized quarks in unpolarized hadrons

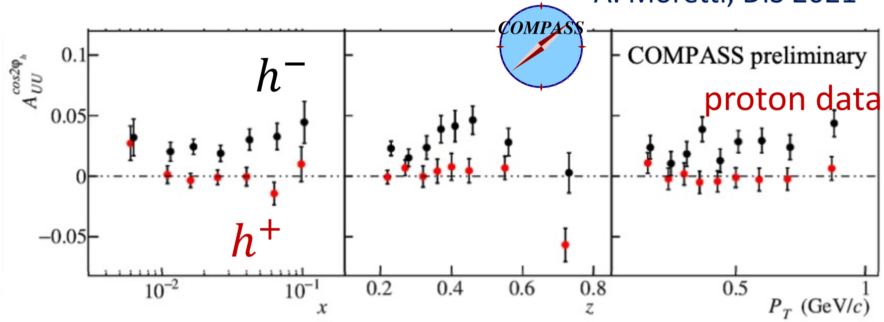
Focus on $A_{UU}^{\cos 2\phi_h}$ in the next slides

Data on the $A_{UU}^{\cos 2\phi_h}$ asymmetry

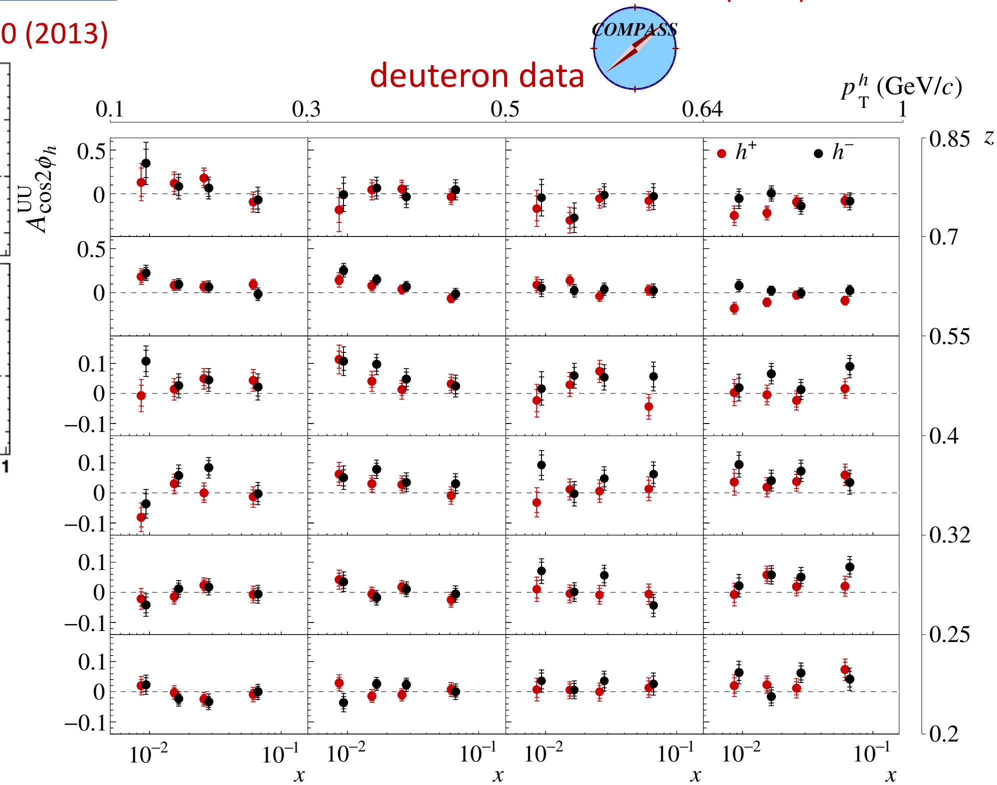
PRD 87, 012010 (2013)



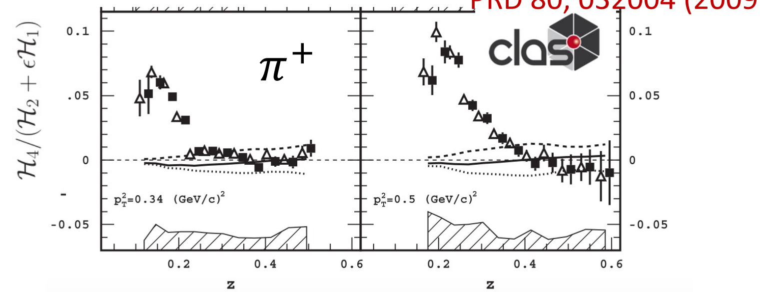
A. Moretti, DIS 2021



NPB 956 (2020) 115039



PRD 80, 032004 (2009)



- phenomenological analyses have been performed
  e.g., Barone et al., PRD91 (2015) 7, 074019

- still no clear interpretation of these asymmetries
  Boer-Mulders function still unknown..

Can we simulate the unpolarized azimuthal asymmetries using event generators?

Cahn effect already implented in LEPTO → simulation of $A_{UU}^{\cos\phi_h}$

[A. Kotzinian, arXiv:0510359]

Boer-Mulders effect never implemented in full event generators

(requires a model for polarized hadronzation)

this work, simulations using :

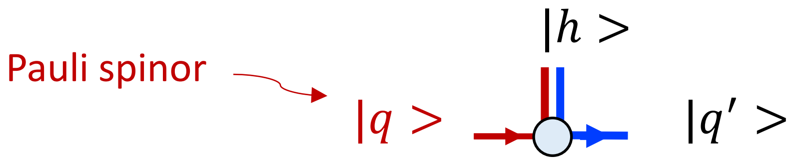
- the string+$^3P_0$ model of hadronization
- the PYTHIA 8 generator

→ simulation of $A_{UU}^{\cos 2\phi_h}$

The string+$^3P_0$ model of hadronization

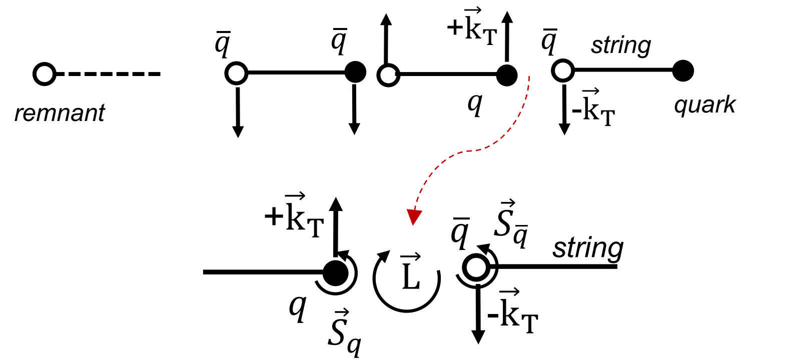
- A quantum mechanical model for the **elementary splitting**

AK, X. Artru, A. Martin, PRD104 (2021) 11, 114038
AK, X. Artru, Z. Belghobsi, A. Martin, PRD 100 (2019) 1, 014003
AK, X. Artru, Z. Belghobsi, F. Bradamante, A. Martin, PRD 97 (2018) 7, 074010



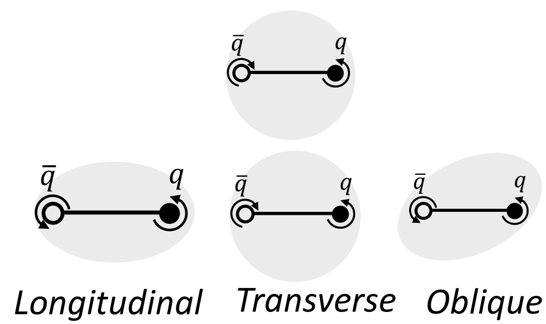
described by the 2×2 splitting amplitude T

T = $(\text{Lund Splitting Function})^{1/2}$ ×



× $^3P_0$ mechanism $\mu + \sigma_z \vec{\sigma}_T \cdot \vec{k}'_T$

× coupling
- PS meson: σ_z
- VM with pol. $\vec{V}$ $G_L V_L^* \mathbf{1} + G_T\, \vec{\sigma}_T \cdot \vec{V}_T^* \sigma_z$



The string+$^3P_0$ model of hadronization: parameters

- A quantum mechanical model for the splitting

AK, X. Artru, A. Martin, PRD104 (2021) 11, 114038
u, Z. Belghobsi, A. Martin, PRD 100 (2019) 1, 014003
u, Z. Belghobsi, F. Bradamante, A. Martin, PRD 97
074010

Complex mass μ:
Re μ → longitudinal spin effects (*jet handedness*)
Im μ → transverse spin effects (*Collins, dihadron*)

desc

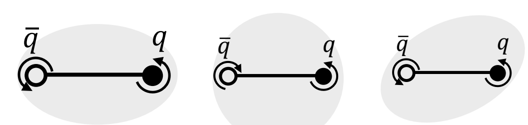
T = (Lund Splitting Function)$^{1/2}$ ×

× $^3P_0$ mechanism $\mu + \sigma_z \vec{\sigma}_T \cdot \vec{k}'_T$

$$f_L = \frac{|G_L/G_T|^2}{2+|G_L/G_T|^2}$$ → fraction of L pol. VMs

$$\theta_{LT} = \arg\left(\frac{G_L}{G_T}\right)$$ → oblique polarization

× coupling
- PS meson: σ_z
- VM with pol. $\vec{V}$ $G_L V_L^* \mathbf{1} + G_T\, \vec{\sigma}_T \cdot \vec{V}_T^* \sigma_z$

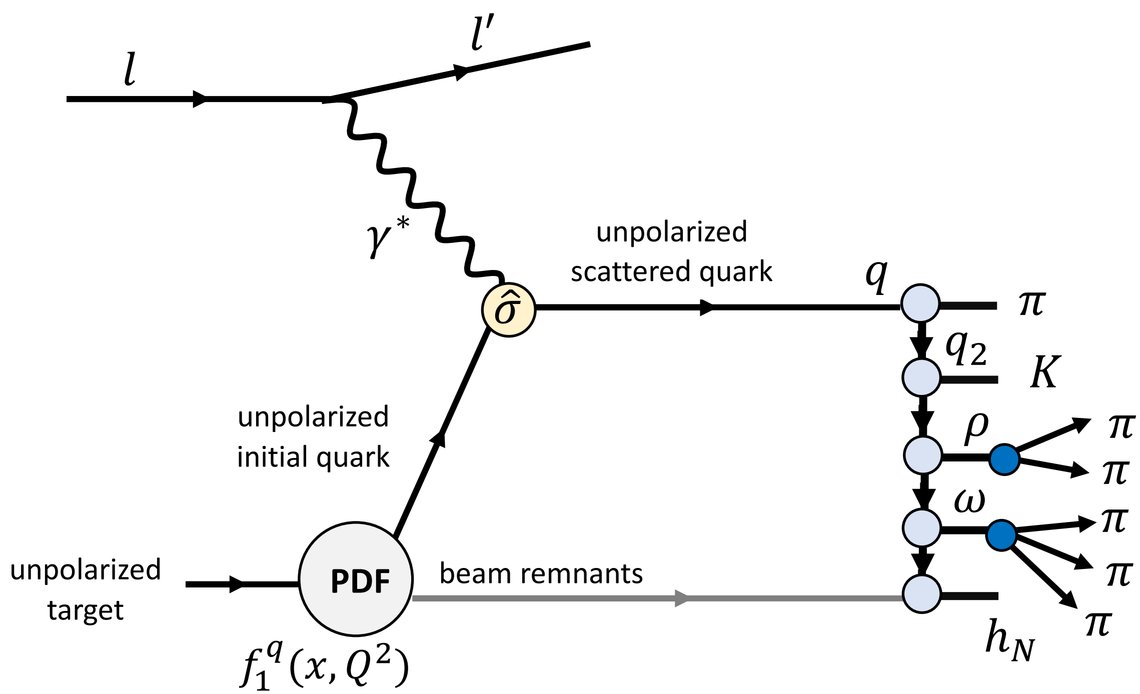


Longitudinal *Transverse* *Oblique*

The interface with PYTHIA 8: StringSpinner

String+$^3P_0$ interfaced to PYTHIA 8 for DIS as an external package → **StringSpinner**

- public version → only PS meson production [AK, L. Lönnblad, CPC 272 (2022) 108234]
- here PS and VM production [AK, talk at ICHEP-2022]



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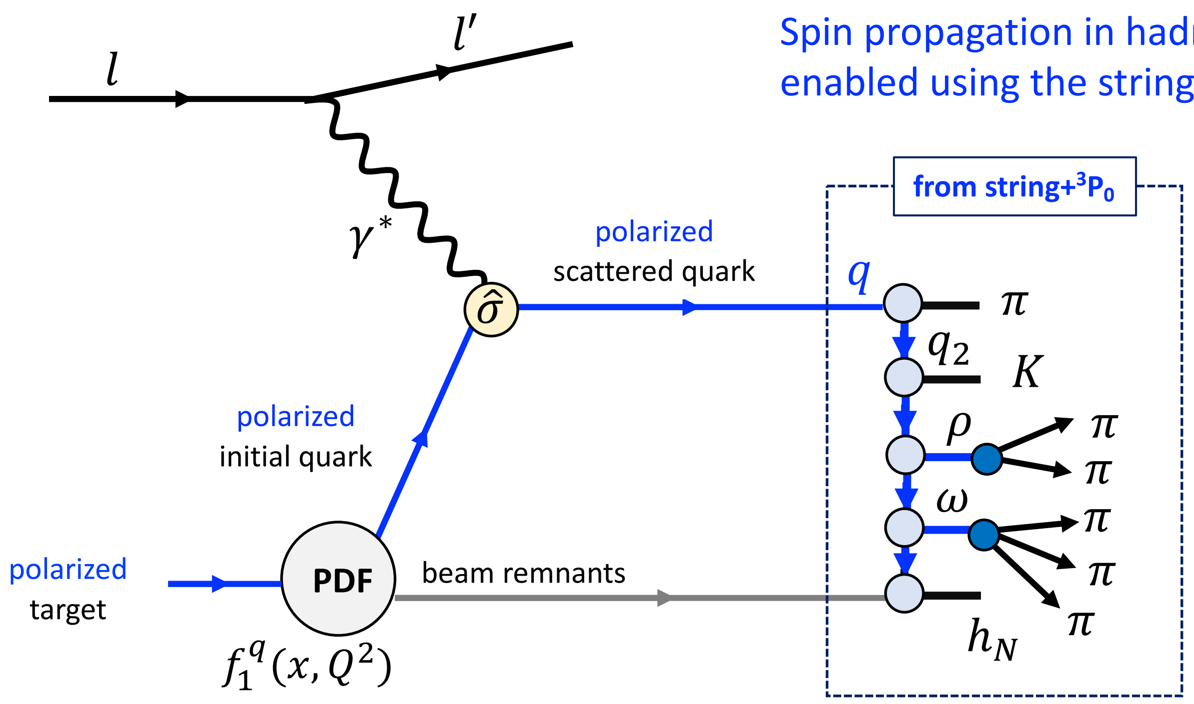

Spin propagation in hadronization enabled using the string+$^3P_0$ model

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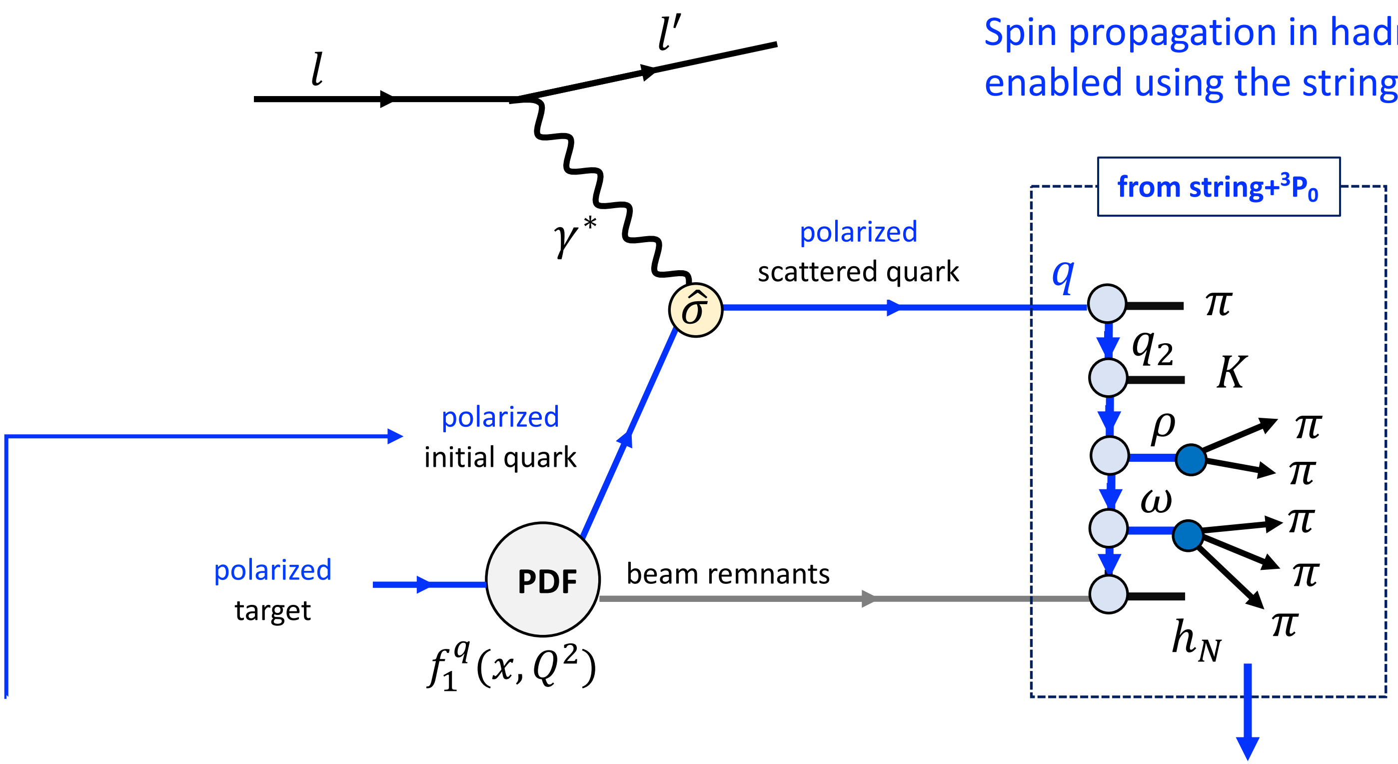

Transversity PDF h_1^q

Collins/dihadron asymmetry

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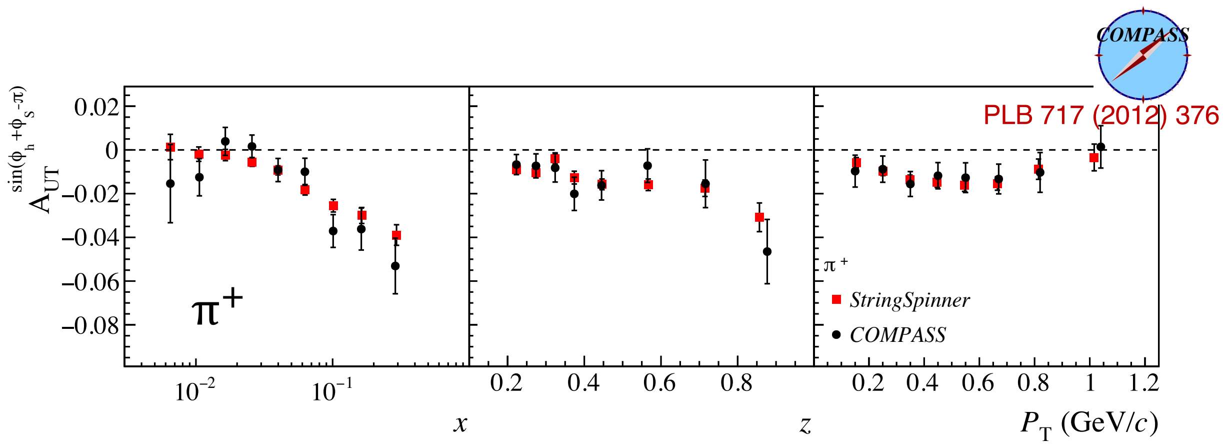
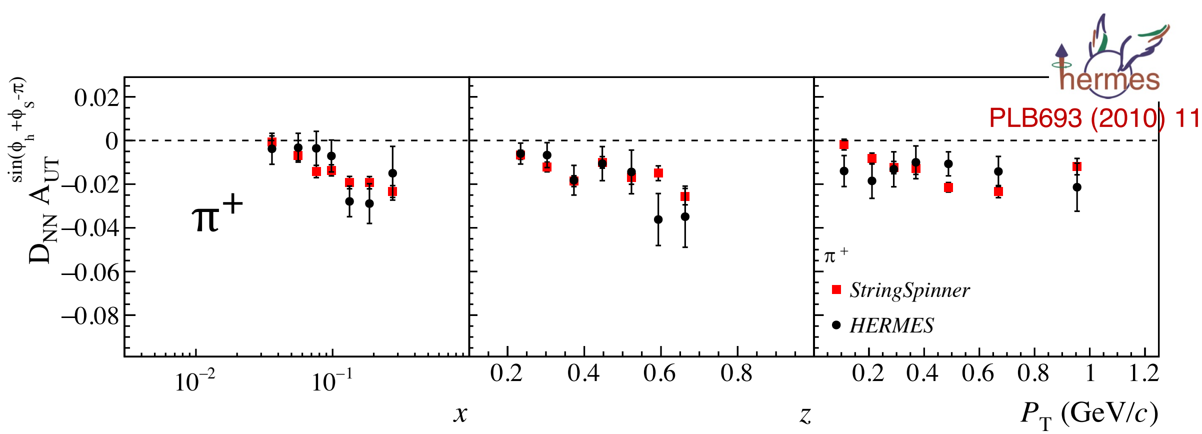
Example: Comparison with Collins asymmetries in SIDIS





Parameters for spin effects

$\mu = (0.42 + i\,0.76)$ GeV/c^2

$f_L = 0.93, \ \theta_{LT} = 0$

Satisfactory description also for π^-

Other sets of parameters also possible

The interface with PYTHIA 8: StringSpinner

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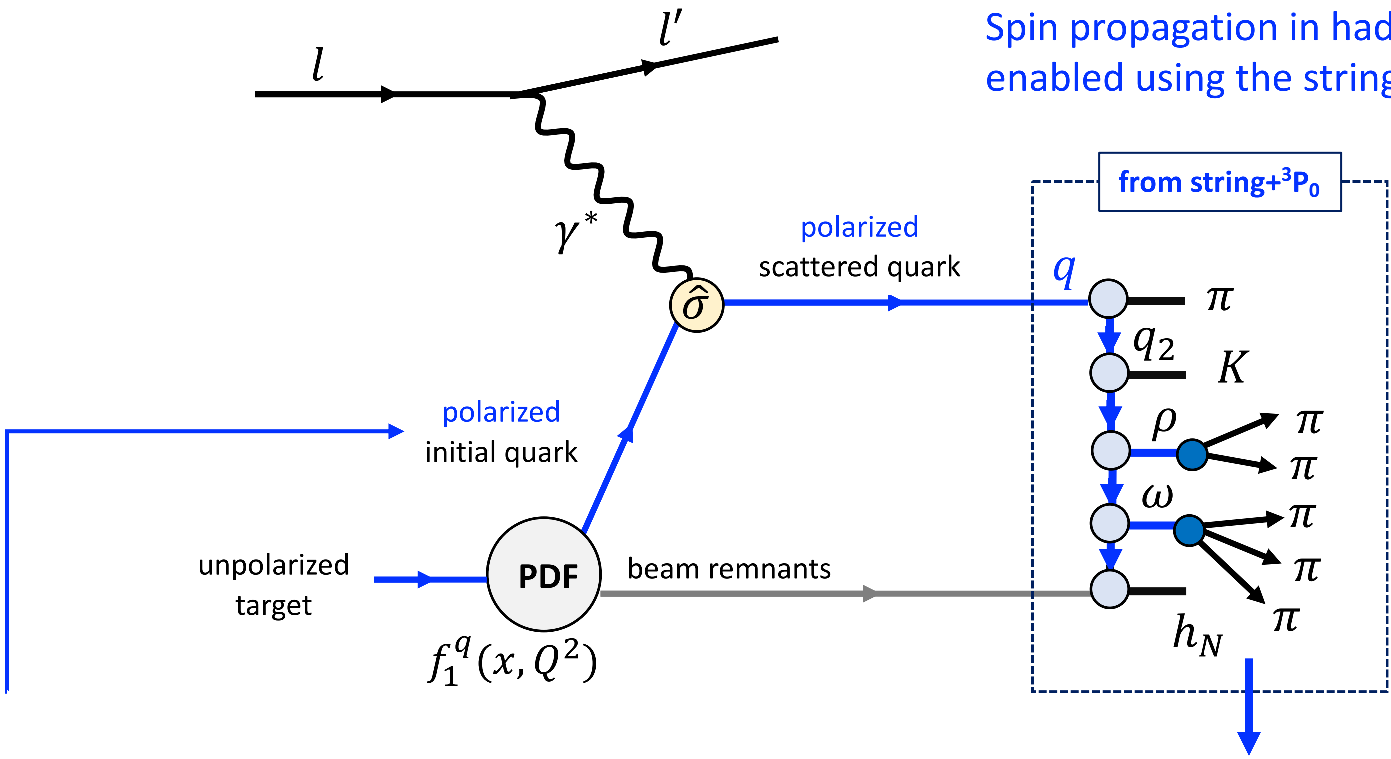


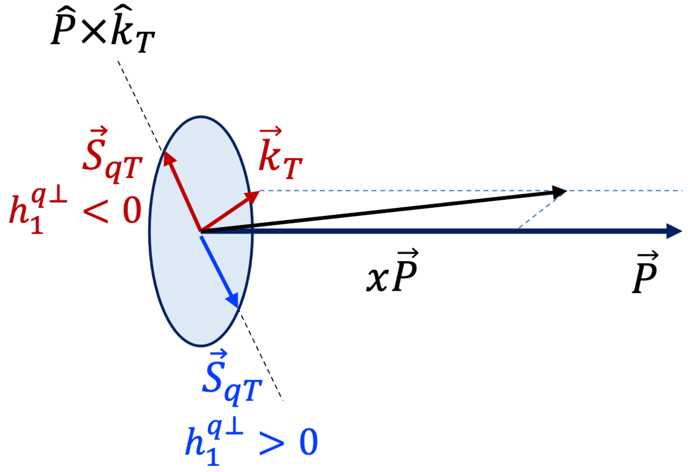
Transversity PDF h_1^q

Boer-Mulders TMD PDF $h_1^{\perp q}$ (new)

Collins/dihadron asymmetry

$A_{UU}^{\cos 2\phi_h}$ asymmetry (new)

Recall on the Boer-Mulders effect



Quark transverse polarization due to the Boer-Mulders function

[Boer,Mulders, PRD57 (1998) 5780]

$$\vec{S}_{qT} = \frac{k_T}{M_N}\frac{h_1^{\perp q}}{f_1^q}\left(-\hat{P}\times\hat{k}_T\right)$$

Positivity condition, *assuming* $h_{1L}^{\perp}=0$

[Bacchetta et al,PRL 85 (2000) 712-715]

$$\frac{k_T}{M_N}\frac{\left|h_1^{\perp q}\right|}{f_1^q} \leq 1$$

Inclusion of the Boer-Mulders effect in StringSpinner

Consider fully polarized quarks, i.e.

$$\vec{S}_{qT} = \text{sign}(\mathrm{h}_1^{\perp q})\ \hat{q} \times \hat{k}_T$$

saturation of positivity condition,

only the sign of $\mathrm{h}_1^{\perp q}$ is relevant

Scattered quark depolarized and reflected

$$\vec{S}'_{\mathrm{qT}} = D_{\mathrm{NN}} \times (\vec{S}_{qT} - 2\, \vec{S}_{qT} \cdot \hat{l}_T)$$

Intrinsic $\vec{k}_T$ generated from Pythia according to the distribution

$$dk_T^2\, e^{-k_T^2/\langle k_T^2 \rangle} \times d\phi_{k_T}/2\pi$$

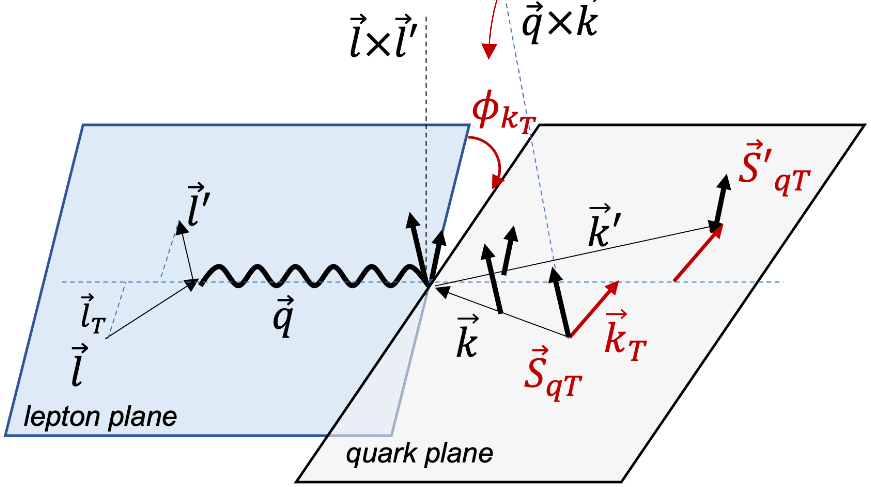
We take

$$\langle k_T^2 \rangle = 0.1 \left(\frac{\text{GeV}}{c}\right)^2$$

no flavor dependence

no kinematic dependence

flat because no Cahn effect



Lepton-quark hard scattering in the GNS.

(selection of) Preliminary results on $A_{UU}^{\cos 2\phi_h}$

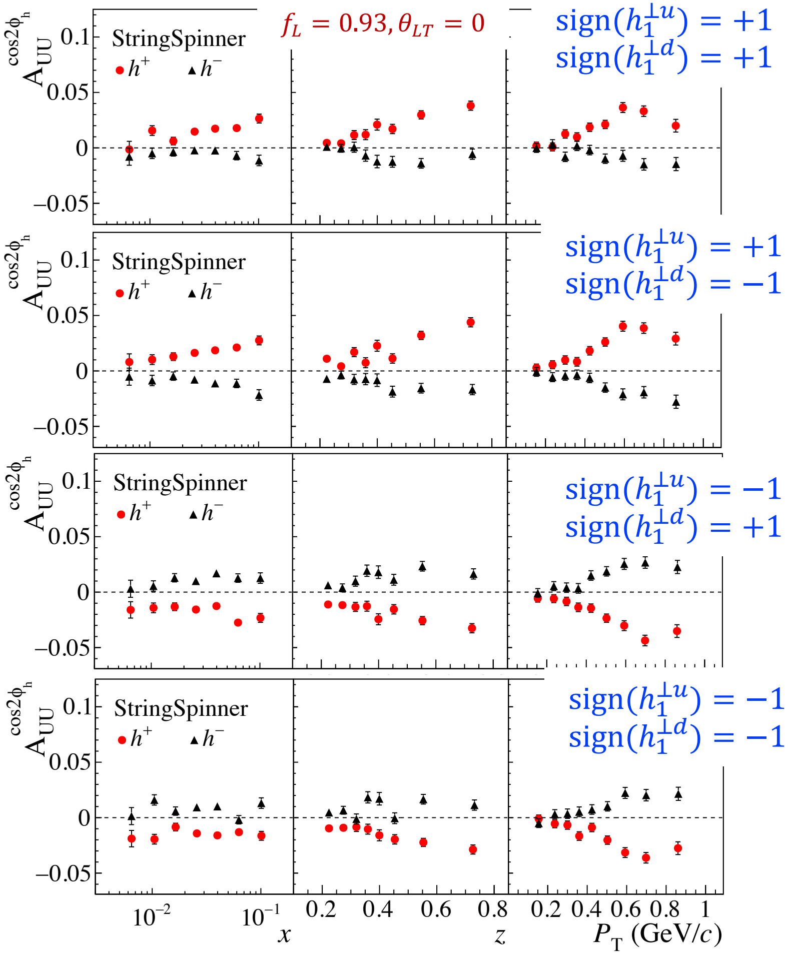
simulations of SIDIS off unpolarized protons in the COMPASS kinematics

Contribution of the Boer-Mulders TMD to $A_{UU}^{\cos 2\phi_h}$

DIS in the COMPASS kinematics with a proton target

valence u and d quarks polarized

sea quarks unpolarized



kinematic cuts as in data

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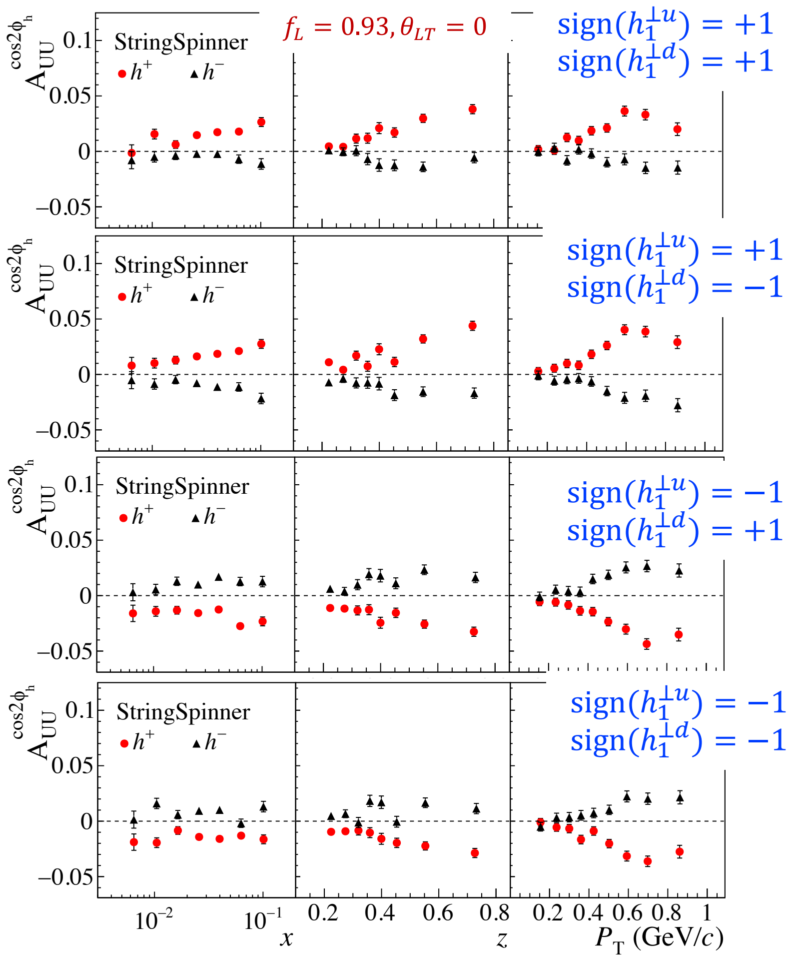
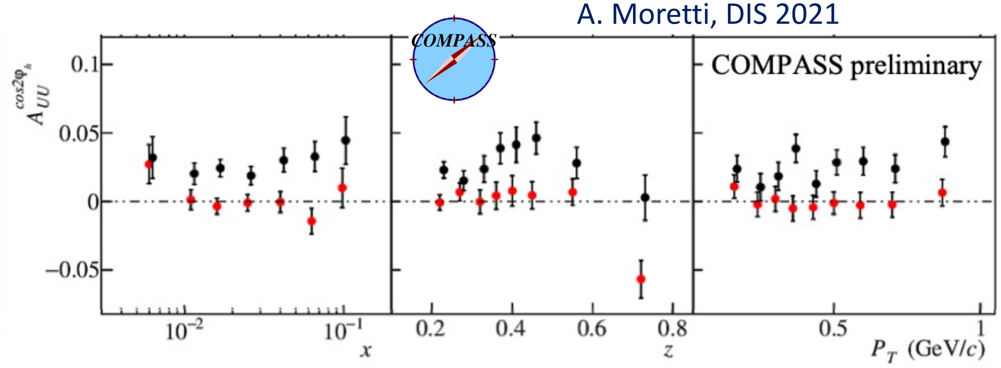


kinematic cuts as in data

A. Moretti, DIS 2021



difficult to describe the data taking into account only valence quarks

→ compensate by chosing appropriately the sing of the Boer-Mulders TMD for sea quarks?

Note:

- same sign of the asymmetry for leading hadrons as the Boer-Mulders TMD
- smaller effect for subleading hadrons

Contribution of the Boer-Mulders TMD to $A_{UU}^{\cos 2\phi_h}$

DIS in the COMPASS kinematics with a proton target

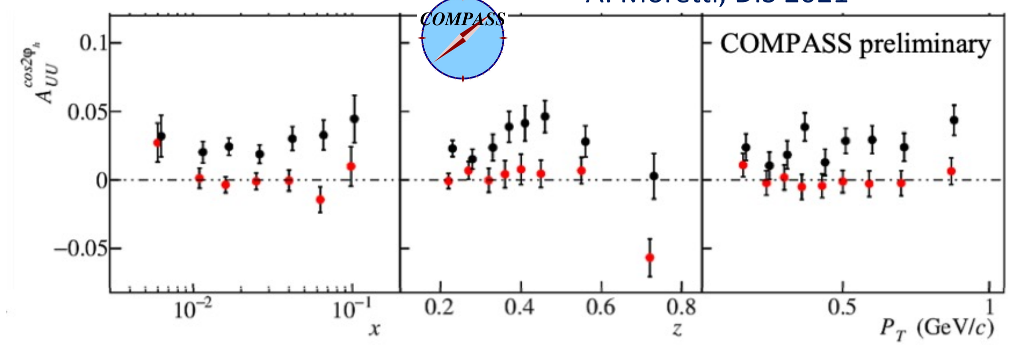
valence u and d quarks polarized

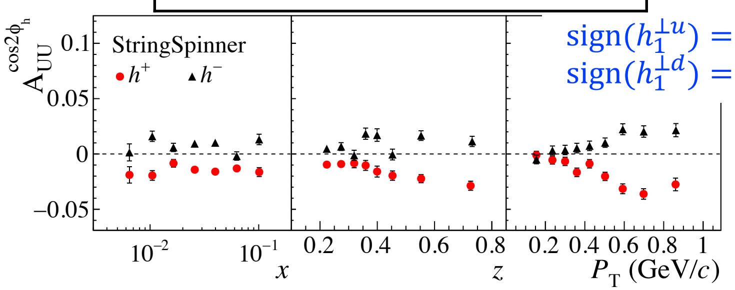
u/d sea quarks polarized

π^+	$A_{UU}^{\cos 2\phi_h}$	sign($h_1^{\perp q}$)
Data	~0	
u^{val}	-	-
$\bar{d}$	+	+
u^{sea}	+	+

π^-	$A_{UU}^{\cos 2\phi_h}$	sign($h_1^{\perp q}$)
Data	+	
u^{val}	~0	-
$\bar{u}$	+	+
d^{sea}	+	+

A. Moretti, DIS 2021





$\text{sign}(h_1^{\perp u}) = -1$

$\text{sign}(h_1^{\perp d}) = -1$

kinematic cuts as in data

Contribution of the Boer-Mulders TMD to $A_{UU}^{\cos 2\phi_h}$

DIS in the COMPASS kinematics with a proton target

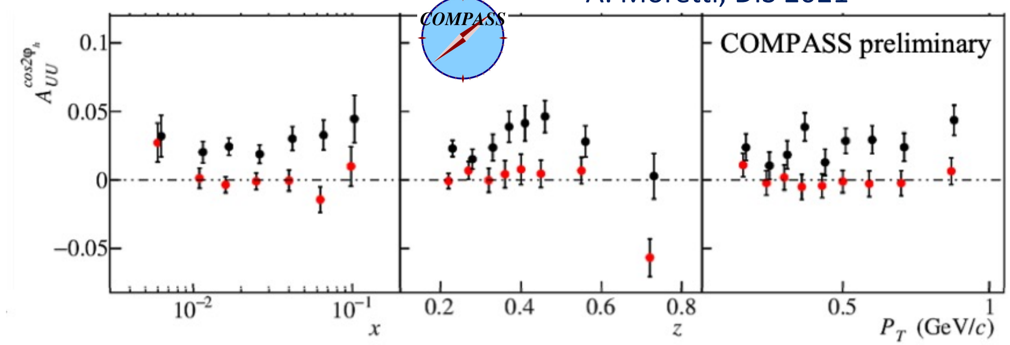
valence u and d quarks polarized,

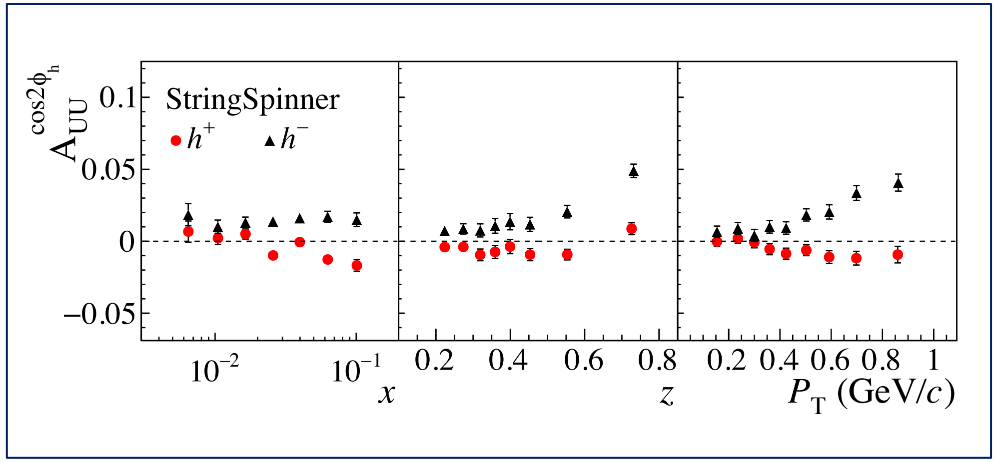
u/d sea quarks polarized

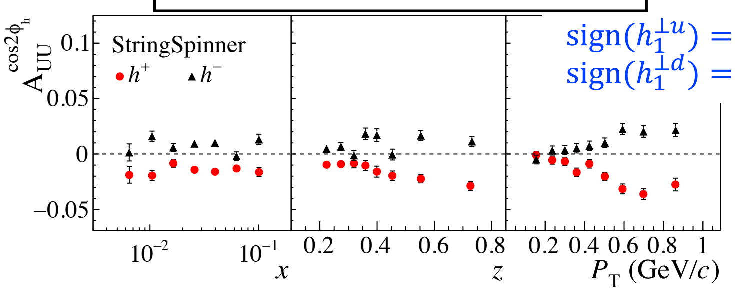
π^+	$A_{UU}^{\cos 2\phi_h}$	$\mathrm{sign}(h_1^{\perp q})$
Data	~0	
u^{val}	-	-
$\bar{d}$	+	+
u^{sea}	+	+

π^-	$A_{UU}^{\cos 2\phi_h}$	$\mathrm{sign}(h_1^{\perp q})$
Data	+	
u^{val}	~0	-
$\bar{u}$	+	+
d^{sea}	+	+

A. Moretti, DIS 2021







$\mathrm{sign}(h_1^{\perp u}) = -1$
$\mathrm{sign}(h_1^{\perp d}) = -1$

kinematic cuts as in data

- Better comparison with data
- still non vanishing asymmetry for h+ (large xB)
- different trends at large z_h

Conclusions

- We have introduced spin effects in PYTHIA 8 hadronization for SIDIS with PS and VM production by using the string+$^3P_0$ model → StringSpinner

the *most recent version to be published soon*

- Good description of available data on TSA

- Introduction of spin effects for unpolarised SIDIS in StringSpinner ongoing

  Boer-Mulders effect included → preliminary results on $A_{UU}^{\cos 2\phi_h}$

  next step, addition of the Cahn effect

Backup

Relevant free parameters for string fragmentation

see Kerbizi, Artru, Martin, PRD104 (2021) 11, 114038

Pythia parameters:

StringZ:aLund	0.90
StringZ:bLund	0.50 $(\mathrm{GeV/c^2})^{-2}$
StringPT:sigma	0.37 $\mathrm{GeV/c}$
StringPT:enhancedFraction	0.00
StringPT:enhancedWidth	0.00 $\mathrm{GeV/c}$
BeamRemnants:primordialKTremnant	0.00
BeamRemnants:halfScaleForKT	0.00
BeamRemnants:halfMassForKT	0.00
BeamRemnants:primordialKThard	0.50

String+$^3P_0$ parameters

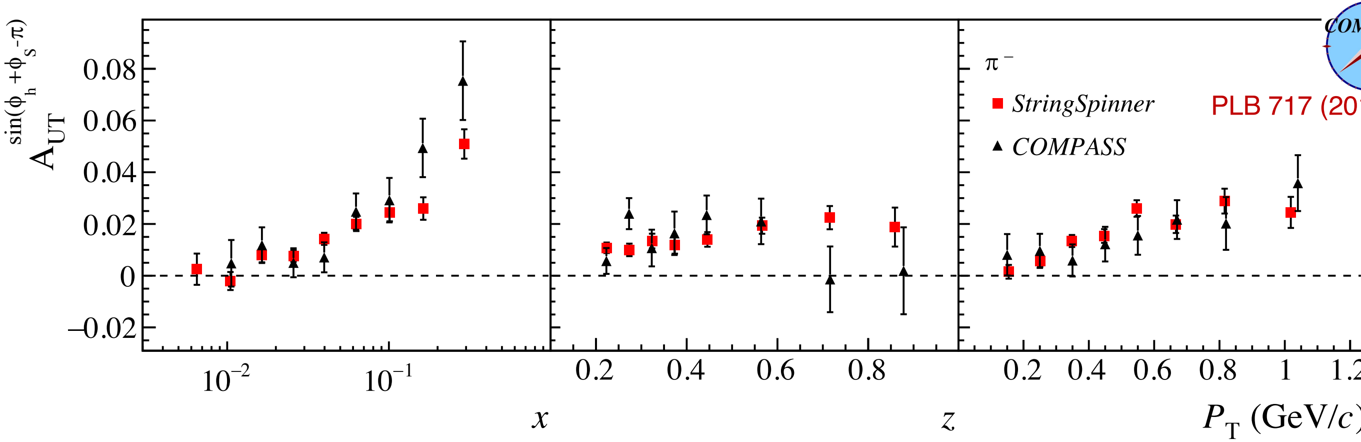
$\mathrm{Re}(\mu)$	0.42 $\mathrm{GeV/c^2}$
$\mathrm{Im}(\mu)$	0.76 $\mathrm{GeV/c^2}$
f_L	*0.93*
θ_{LT}	0.00

Comparison with Collins asymmetries in SIDIS for π^-

Parameters for spin effects

$\mu = (0.42 + i\,0.76)\ \mathrm{GeV/c^2}$

$f_L = 0.93,\ \theta_{LT} = 0$



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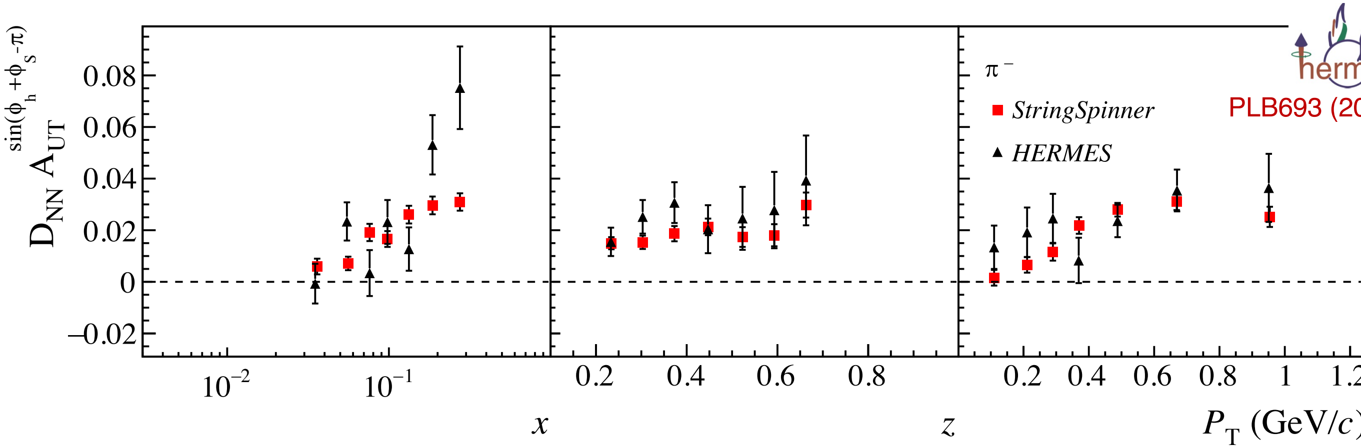

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