APCTP Focus Program in Nuclear Physics 2022: Hadron Physics Opportunities with JLab Energy and Luminosity Upgrade

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Pohang, Korea

Introduction of quark spin effects in PYTHIA string fragmentation for (un)polarized SIDIS

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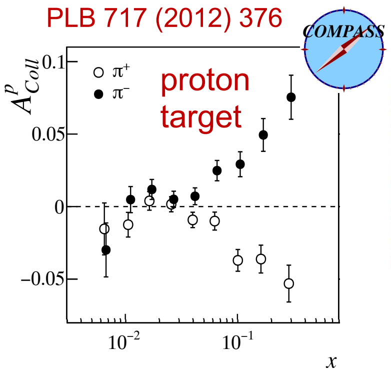
Motivation for spin effects in hadronization

Collins asymmetry *in SIDIS (T pol.)*

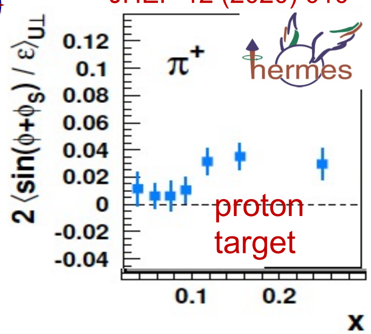
$A_{UT}^{\sin\phi_h+\phi_S-\pi} \sim h_1^q \otimes H_{1q}^{\perp h}$

Transversity *Collins FF*

PLB 717 (2012) 376



JHEP 12 (2020) 010

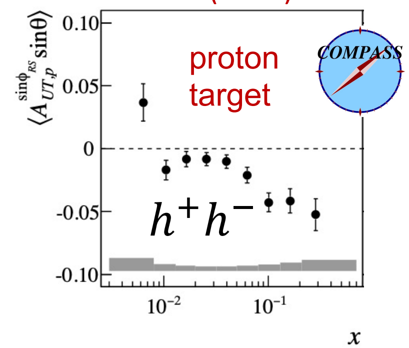


2h asymmetry *in SIDIS (T pol.)*

$\left\langle A_{UT}^{\sin\phi_{RS}} \sin\theta \right\rangle \sim h_1^q \times H_{1q}^{\perp h}$

2h IFF

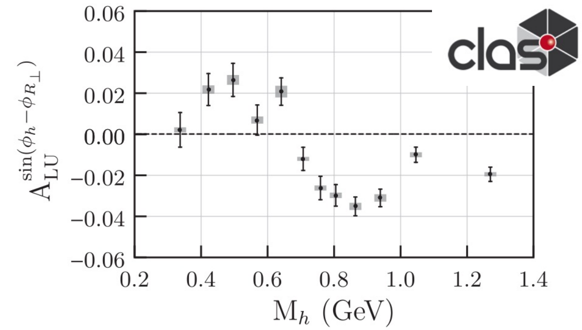
PLB 736 (2014) 124



Jet-handedness *in SIDIS (beam with L pol.)*

$A_{LU}^{\sin\phi_h-\phi_{R_T}} \sim f_1^q \times G_{1q}^{\perp}$

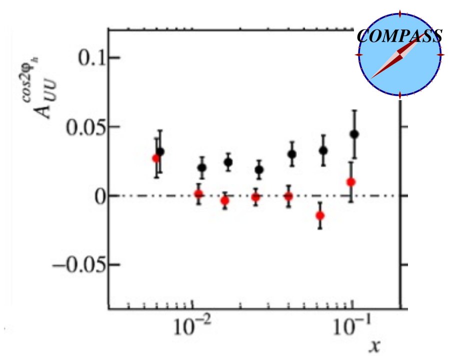
jet-handedness



Azimuthal symmetries in SIDIS (U pol.)

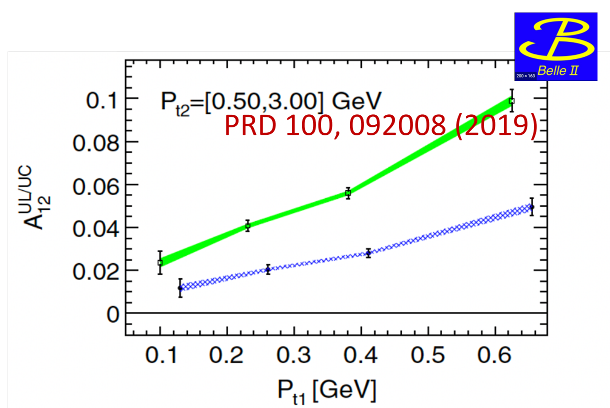
$A_{UU}^{\cos 2\phi_h} \sim h_1^{\perp q} \otimes H_{1q}^{\perp h_1}$

Boer-Mulders



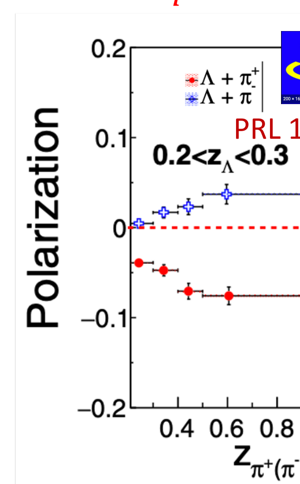
Collins asymmetry in e^+e^-

$A_{12}^{UL} \sim H_{1q}^{\perp h_1} \otimes H_{1q}^{\perp h_2}$



Λ transverse polarization e^+e^-

$P \sim D_{1q}^{\perp\Lambda} \otimes D_{1q}^{\pi}$



Motivation for spin effects in hadronization

***Collins asymmetry** in SIDIS (T pol.)*

***2h asymmetry** in SIDIS (T pol.)*

***Jet-handedness** in SIDIS (beam with L pol.)*

Different measured observables relevant to extract information on the nucleon structure and to study spin-dependence in hadronization

not fully understood, developing models important to get new insights

MCEGs fully implementing spin effects do not exist

recent work on spin effects in parton showers

Richardson, Webster, EPJ, C (2020) 80:83
A. Karlberg et al, EPJC (2021) 81:681
K. Hamilton et al, JHEP03 (2022) 193

still, complete collision events with spin effects can not be treated..

MCEG with spin effects → needed a model for polarized hadronization

recently, string+$^3P_0$ model used to introduce spin effects in PYTHIA string fragmentation for a DIS event with PS and VM production (no parton showers)

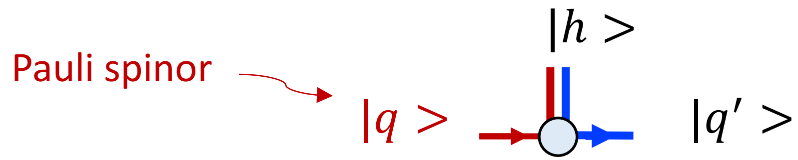
in collaboration with Leif Lönnblad

The string+$^3P_0$ model of hadronization

- Deeply studied by stand alone MC simulations

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

- The building block of the model is the **elementary splitting**



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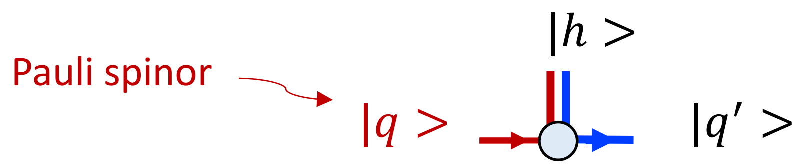
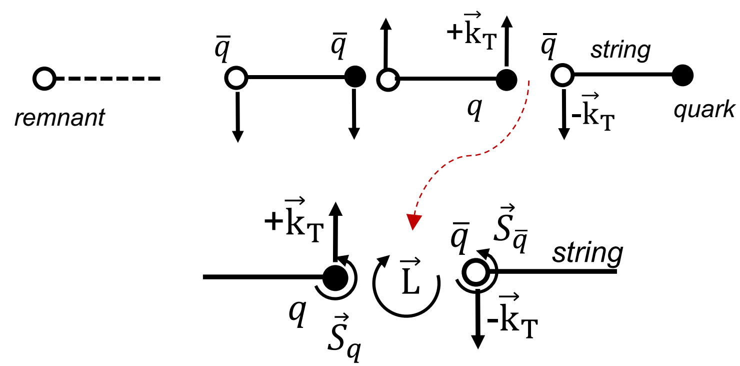


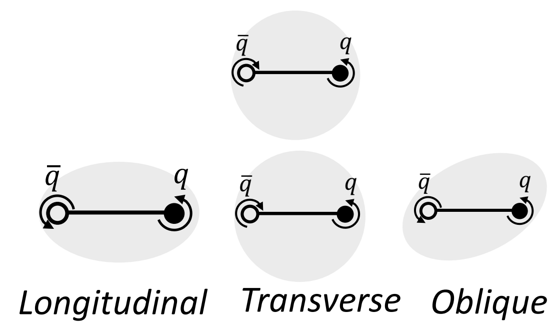
described by the 2×2 quantum mechanical splitting amplitude T

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

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



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



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

- Deeply studied by stand alone MC simulations

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

- The building block of the model is t[h] **elementary splitting**

described by the 2×2 quantum mech[...]

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

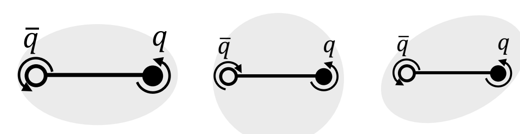
Complex mass μ:
Re μ → longitudinal spin effects *(jet handedness)*
Im μ → transverse spin effects *(Collins, dihadron)*

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

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

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

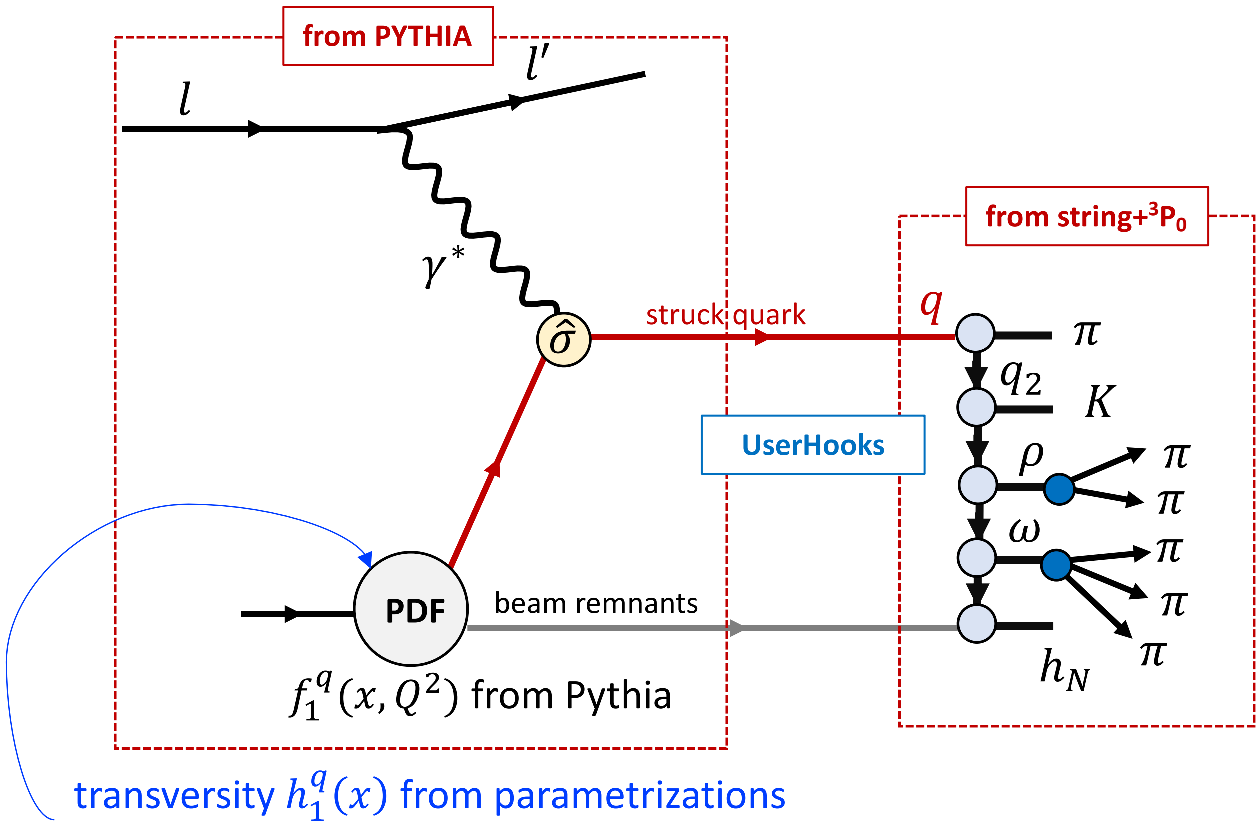
$$\theta_{LT} = \arg\left(\frac{G_L}{G_T}\right)$$ → oblique polarization



Longitudinal *Transverse* *Oblique*

The interface with PYTHIA 8: StringSpinner

The string+$^3P_0$ model has been interfaced to PYTHIA 8 for the DIS process as an external package
→ **StringSpinner** *[AK, L. Lönnblad, CPC 272 (2022) 108234]* *(only PS meson production)*



transversity $h_1^q(x)$ from parametrizations
but other TMDs can be introduced

Implementation of spin effects in PYTHIA

- Polarization $\mathbf{S}_\mathrm{q}$ of the struck quark calculated using h_1^q
- Polarization $\mathbf{S}'_\mathrm{q}$ of the scattered q transformed according to QED

- PYTHIA starts hadronization and emits h_1 = PS
- Accept h_1 with the $^3\mathrm{P}_0$ probability for PS

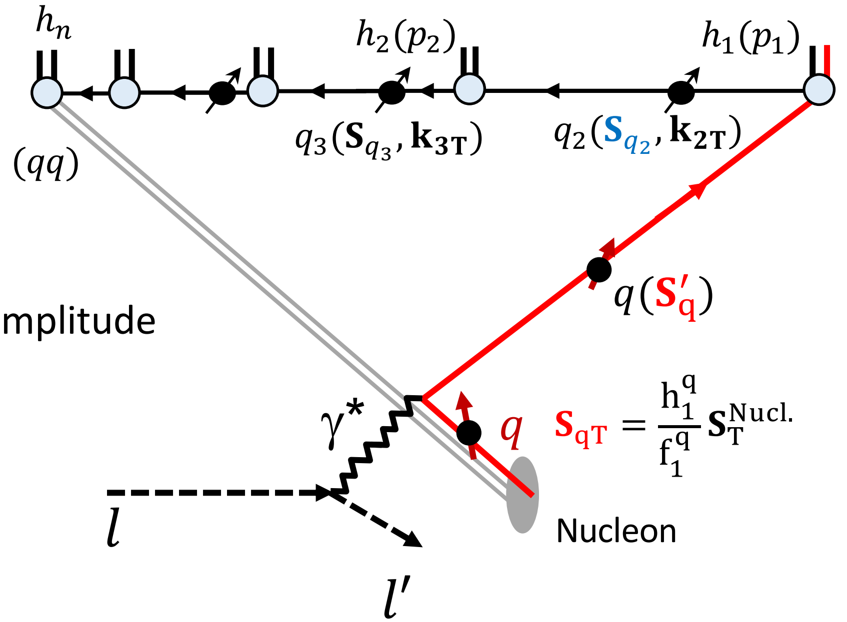
$$w_{\mathrm{PS}} = \left[1 - \hat{a}\ \mathbf{S}_q \cdot (\hat{z}\times\hat{\mathbf{k}}_{2\mathrm{T}})\right]/2$$

$$\hat{a} = \frac{2\mathrm{Im}(\mu)k_{2\mathrm{T}}}{|\mu|^2 + \mathbf{k}_{2\mathrm{T}}^2}$$

- Decay of a PS meson handled by Pythia
- Calculate density matrix $\rho(q_2)$ of q_2 using the splitting amplitude

- PYTHIA emits h_2 = VM
- Accept h_2 with the $^3\mathrm{P}_0$ probability for VM

$$w_{\mathrm{VM}} = \left[1 + f_L\hat{a}\ \mathbf{S}_{q_2} \cdot (\hat{z}\times\mathbf{k}_{3\mathrm{T}})\right]/2$$



Implementation of spin effects in PYTHIA

- Polarization $\mathbf{S}_\mathrm{q}$ of the struck quark calculated using h_1^q
- Polarization $\mathbf{S}'_\mathrm{q}$ of the scattered q transformed according to QED

- PYTHIA starts hadronization and emits h_1 = PS
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$$w_{\mathrm{PS}} = [1 - \hat{a}\,\mathbf{S}_q \cdot (\hat{z}\times\hat{\mathbf{k}}_{2\mathrm{T}})]/2$$

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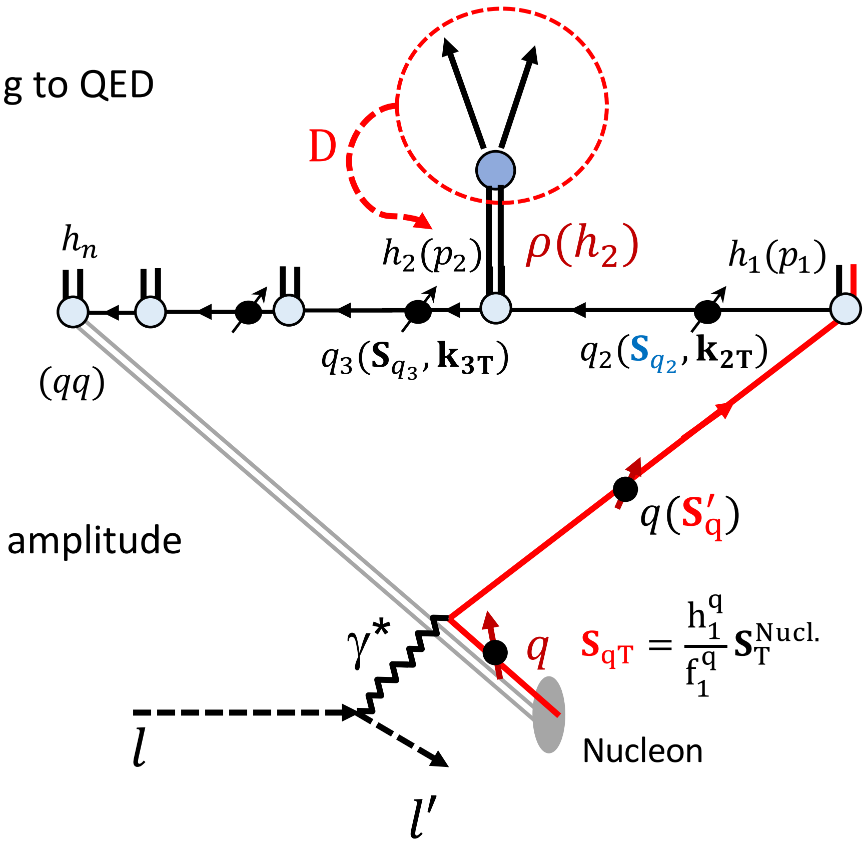
- Decay of a PS meson handled by Pythia
- Calculate density matrix $\rho(q_2)$ of q_2 using the splitting amplitude

- PYTHIA emits h_2 = VM
- Accept h_2 with the $^3P_0$ probability for VM

$$w_{\mathrm{VM}} = [1 + f_L\hat{a}\,\mathbf{S}_{q_2} \cdot (\hat{z}\times\mathbf{k}_{3\mathrm{T}})]/2$$

- **Decay the VM**:
  i. calculate density matrix of VM
  ii. generate the polarized decay
  iii. Return a decay matrix D to the VM production vertex *[Collins '88, Knowles '88]*
  iv. Store decay products and pass them to Pythia at a later stage
  v. calculate density matrix of next quark



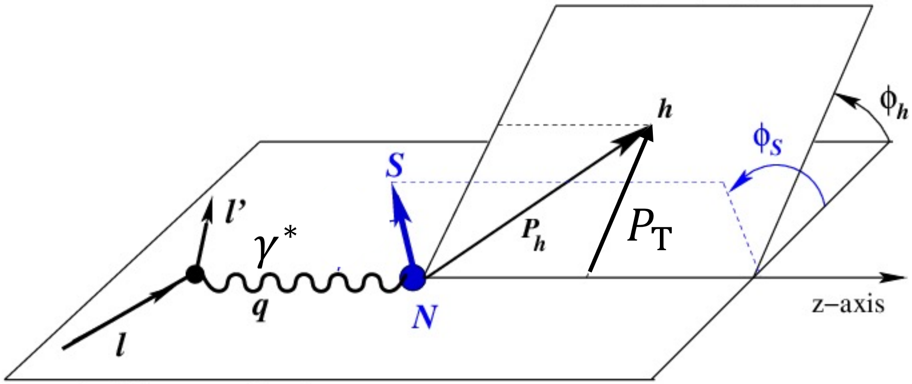
Recipe applied till end of string fragmentation

(selection of)

Results from simulations of T polarized SIDIS on protons

kinematics of COMPASS and HERMES experiments

no intrinsic $\vec{k}_T$

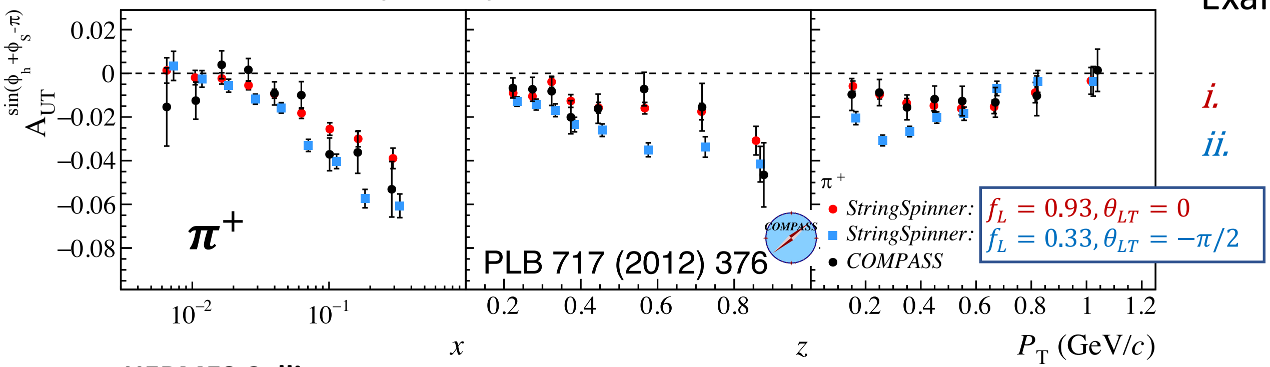


Relevant free parameters for string fragmentation taken from
AK, Artru, Martin, PRD104 (2021) 11, 114038

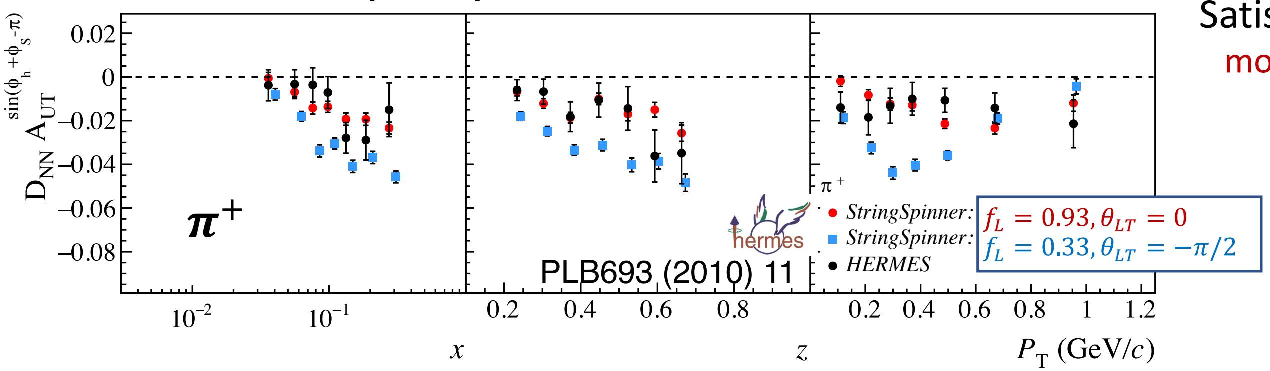
see backup slides

Comparison with SIDIS data on TSA

COMPASS Collins asymmetry



HERMES Collins asymmetry



Example: two choices of parameters

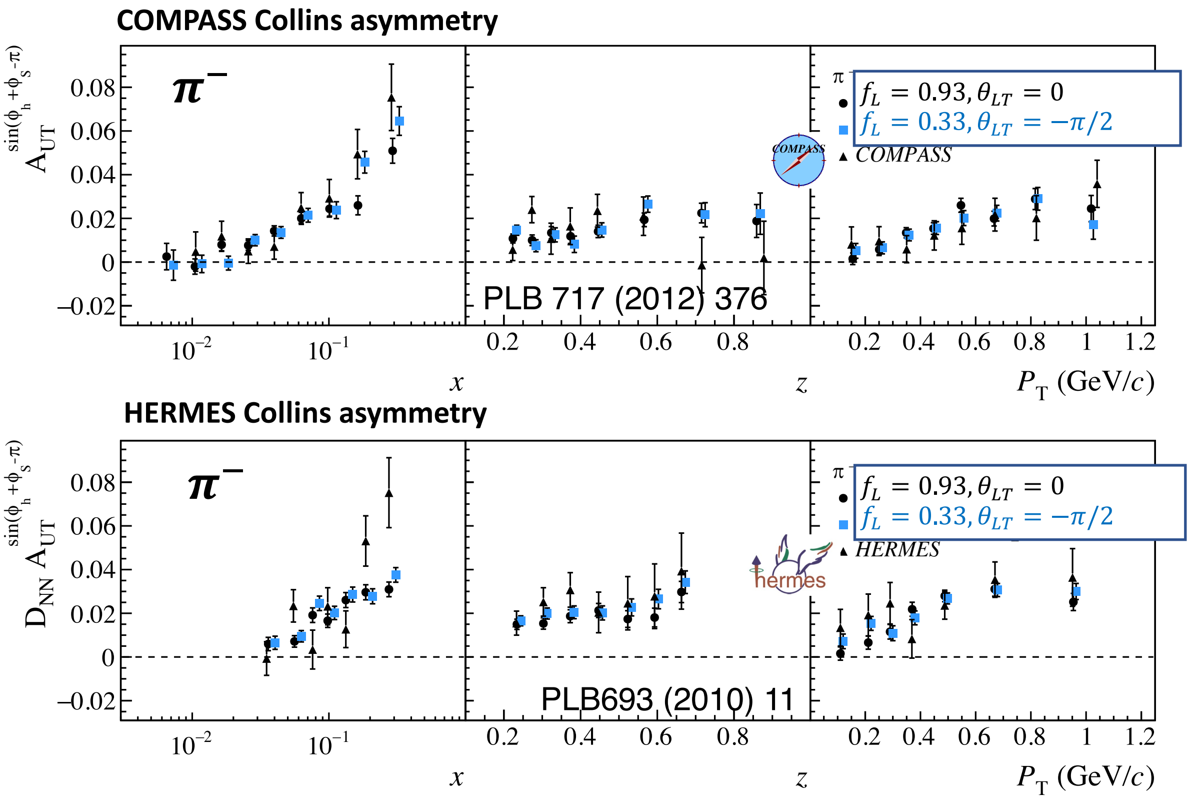
i. $f_L = 0.93,\ \theta_{LT} = 0$ good X^2

ii. $f_L = 0.33,\ \theta_{LT} = -\frac{\pi}{2}$ bad X^2

Satisfactory description of SIDIS data

more precise SIDIS data would be useful

Comparison with SIDIS data on TSA



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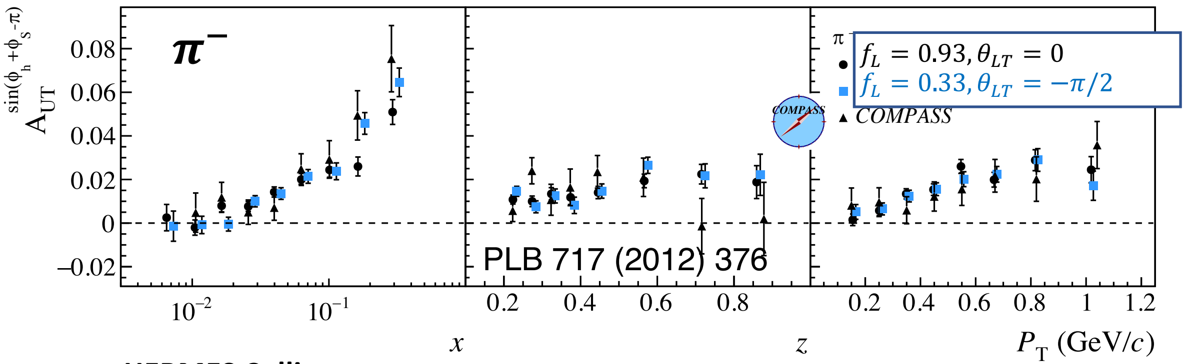
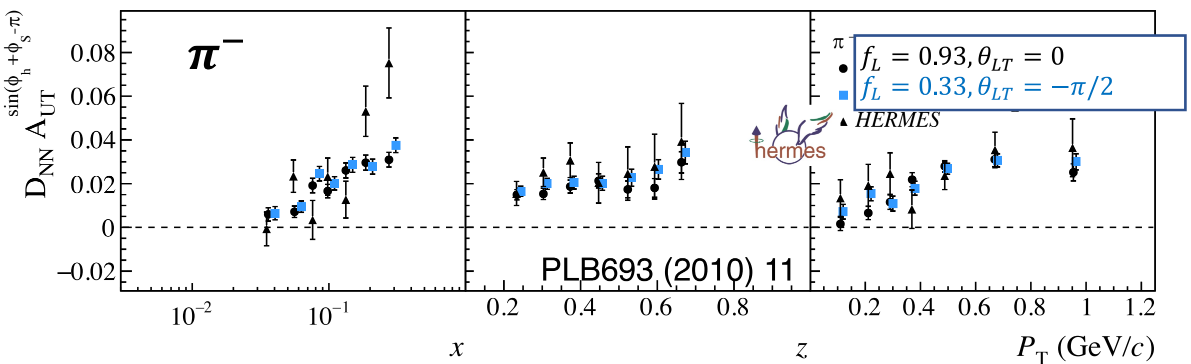
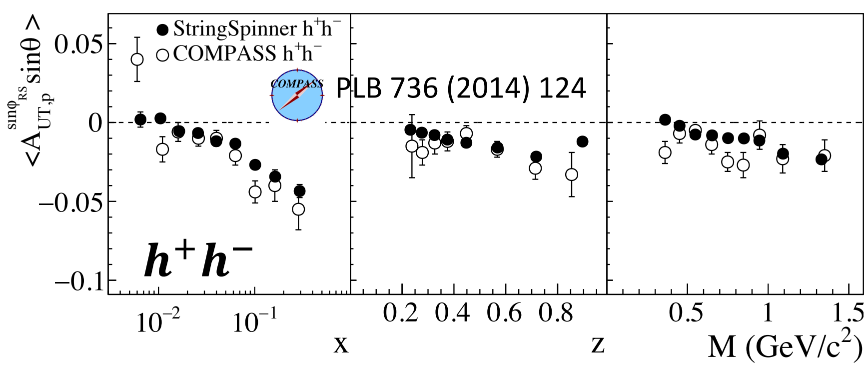


HERMES Collins asymmetry



COMPASS 2h asymmetry



Example: two choices of parameters

i. $f_L = 0.93, \ \theta_{LT} = 0$ good X^2

ii. $f_L = 0.33, \ \theta_{LT} = -\frac{\pi}{2}$ bad X^2

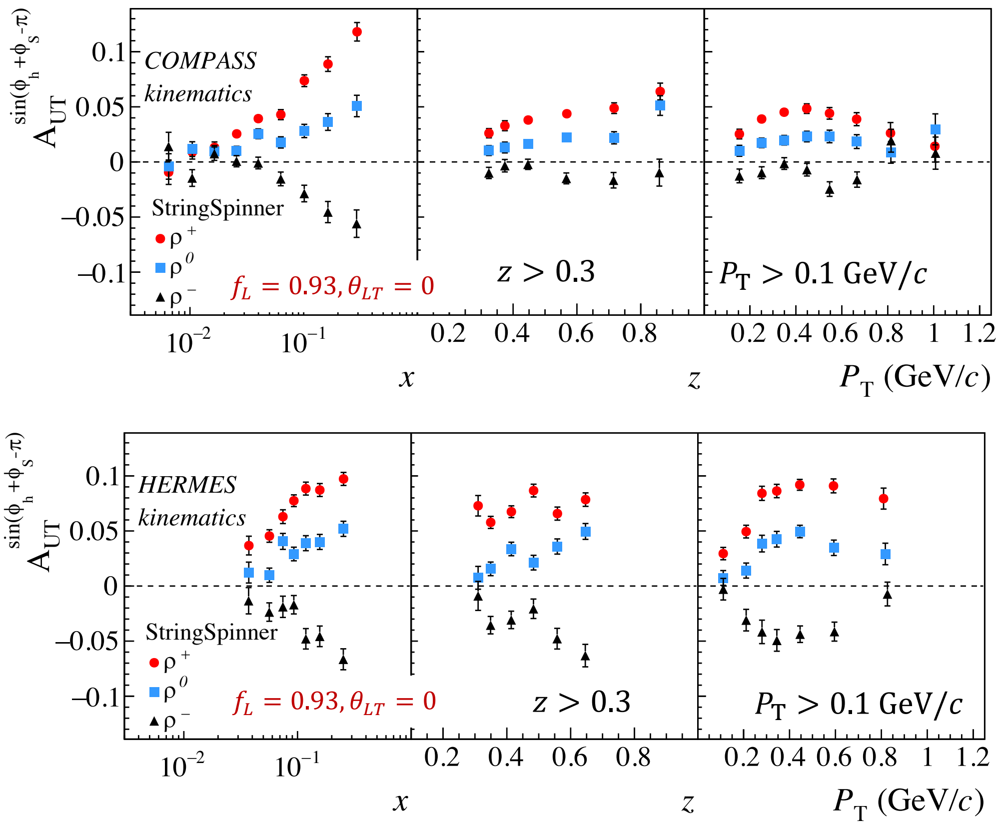
Satisfactory description of SIDIS data

more precise SIDIS data would be useful

Good description of 2h asymmetry

weak depenence on f_L and θ_{LT}

Collins asymmetries for ρ mesons in SIDIS



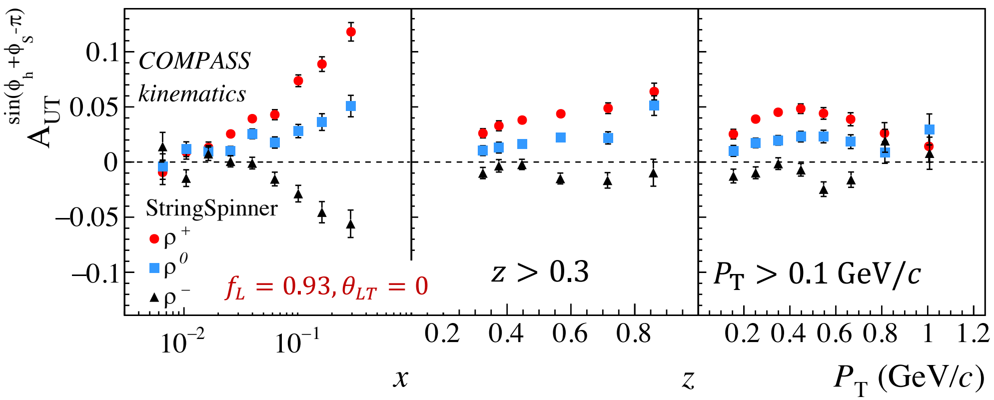
Large effects for large f_L

the asymmetry vanishes as $f_L \to 0$ (not shown here)

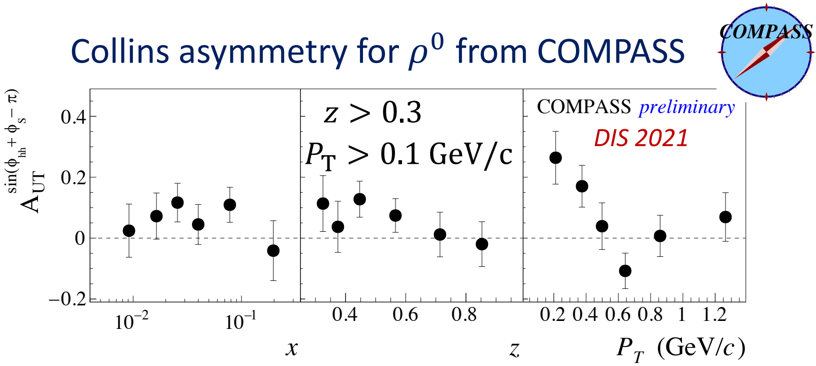
Strong dependence on f_L

a precise measurement of the asymmetry would help to fix the parameter

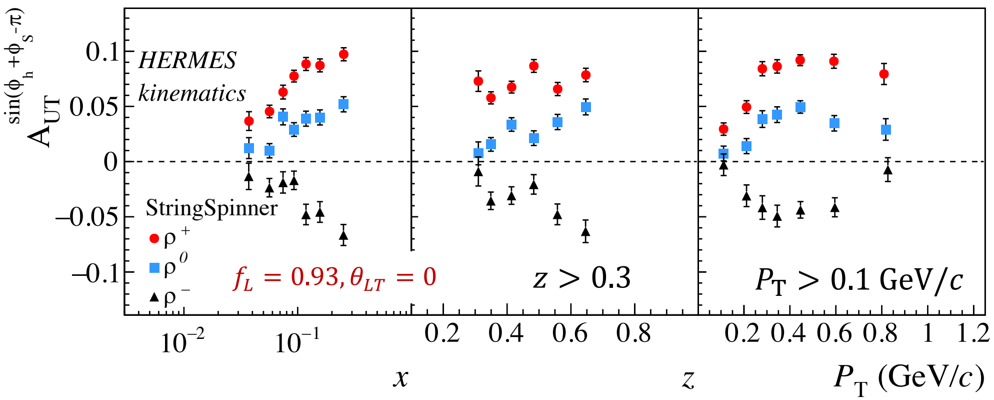
Collins asymmetries for ρ mesons in SIDIS



Collins asymmetry for ρ^0 from COMPASS



interesting result,
same sign as simulations and similar average value



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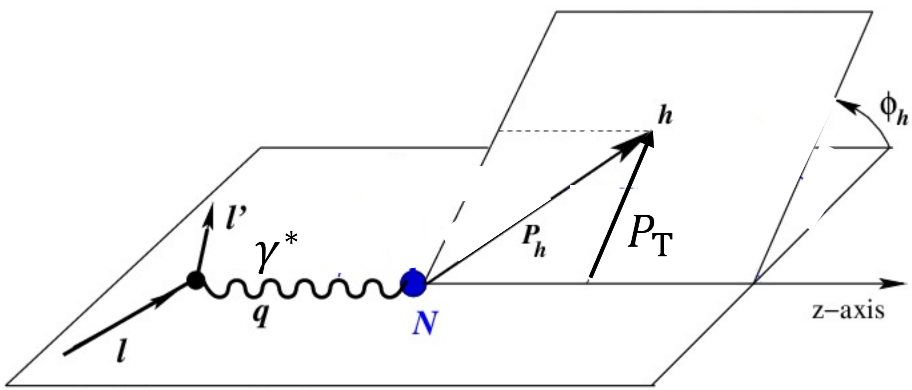
the asymmetry vanishes as $f_L \to 0$ (not shown here)

Strong dependence on f_L

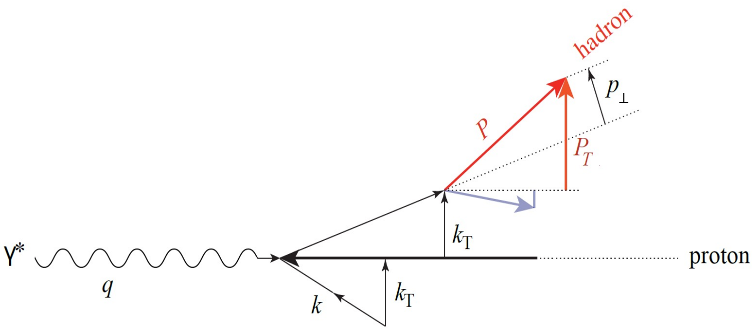
a precise measurement of the asymmetry would help to fix the parameter

Till now SIDIS with a T polarized target, **but spin effects also in unpolarized SIDIS**



Azimuthal asymmetries in unpolarized SIDIS

- Allow to access intrinsic $\vec{k}_T$ and Boer-Mulders TMD



kinematics of the hard scattering

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

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

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

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

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

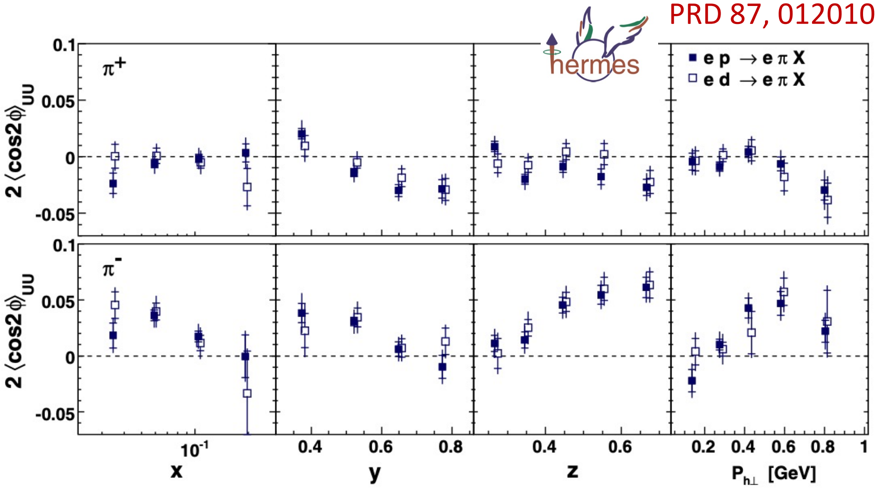
- Interplay of contributions at different twists

- Many data exist, large azimuthal asymmetries observed

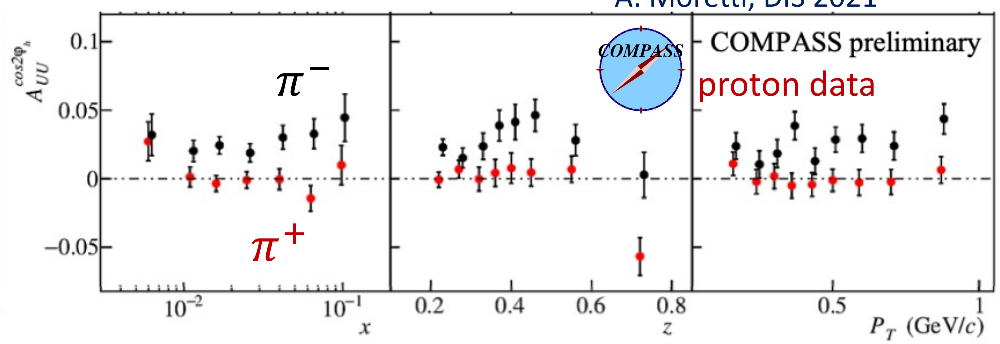
HERMES	p, d
COMPASS	d, recently p
JLAB	p

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

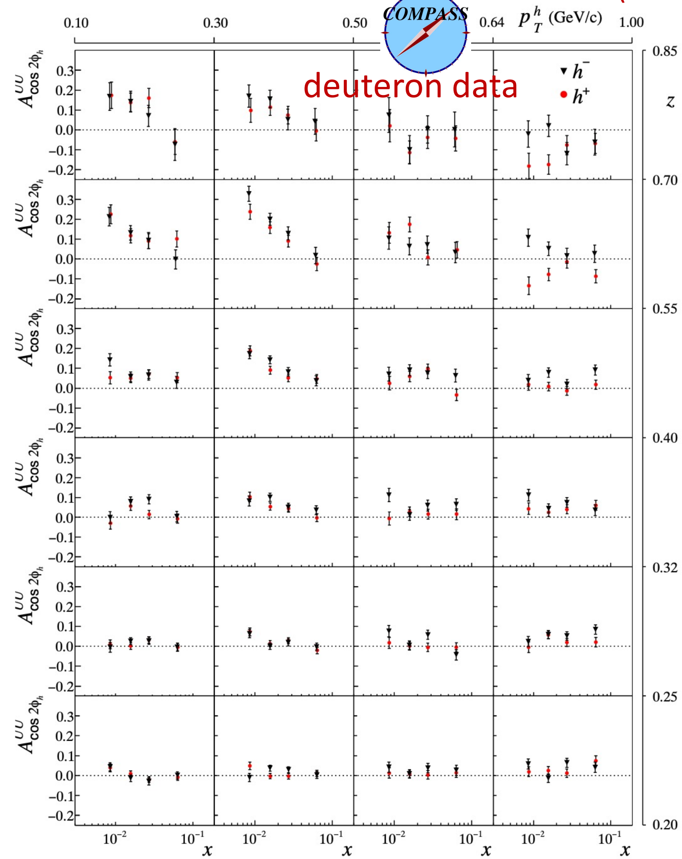
PRD 87, 012010 (2013)



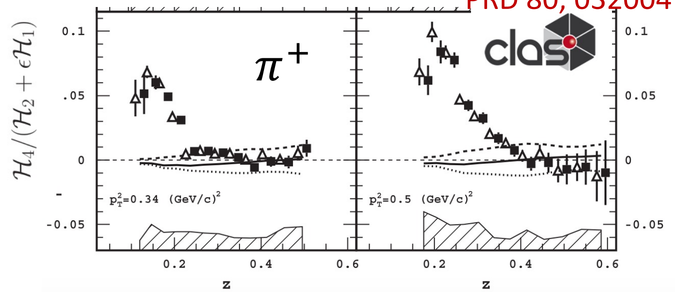
A. Moretti, DIS 2021



NPB 886 (2014) 1046



PRD 80, 032004 (2009)



- many phenomenological analyses
- still no understanding of these asymmetries,

  Boer-Mulders function still unknown..

can we simulate $A_{UU}^{\cos\phi_h}$ and $A_{UU}^{\cos 2\phi_h}$ *asymmetries?*

Cahn effect already implented in LEPTO — A. Kotzinian, arXiv:0510359

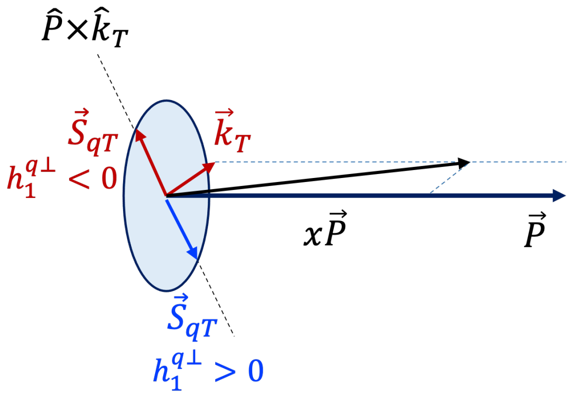
Boer-Mulders effect not fully included in simulations

requires polarized hadronzation — *AK, Artru, Belghobsi, Bradamante, Martin, JPCS* 938 (2017) 1, 012051

→ we start from here (*ongoing work in Trieste)*

Setting up the simulation of the Boer-Mulders effect

Recall on the Boer-Mulders TMD
[Boer,Mulders, PRD57 (1998) 5780]



Quark transverse polarization induced by the Boer-Mulders function

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

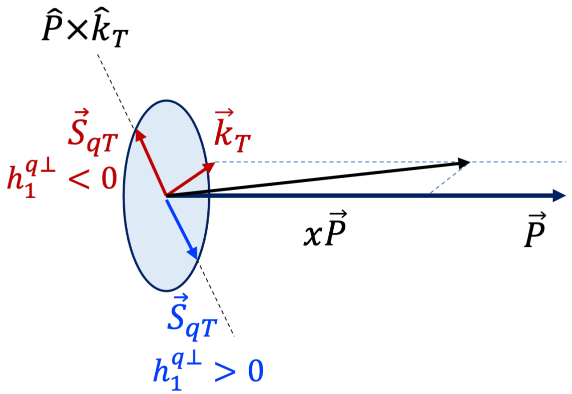
Positivity condition, *assuming* $h_{1L}^{\perp} = 0$
Bacchetta et al,PRL 85 (2000) 712-715

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

Setting up the simulation of the Boer-Mulders effect

Recall on the Boer-Mulders TMD

[Boer,Mulders, PRD57 (1998) 5780]



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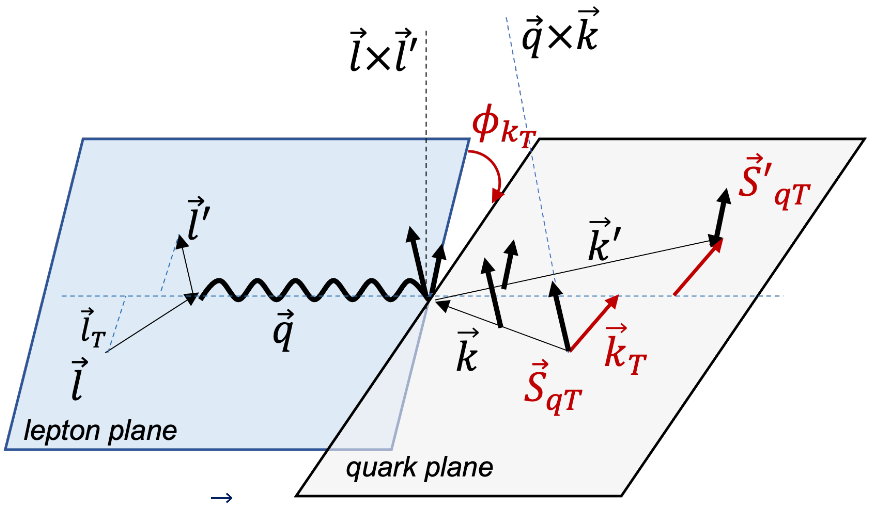
$$\frac{k_T}{M_N}\frac{\left|h_1^{q\perp}\right|}{f_1^q} \leq 1$$

Lepton-quark hard scattering in GNS



Intrinsic $\vec{k}_T$ from Pythia, following the distribution

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

$$\langle k_T^2\rangle = 0.1\left(\frac{\text{GeV}}{c}\right)^2$$ (const., flavor independent)

Consider fully polarized (valence)quarks

saturation of positivity condition

$$\vec{S}_{qT} = \pm\,\hat{q}\times\hat{k}_T$$

→ allows to study the maximum expected effect

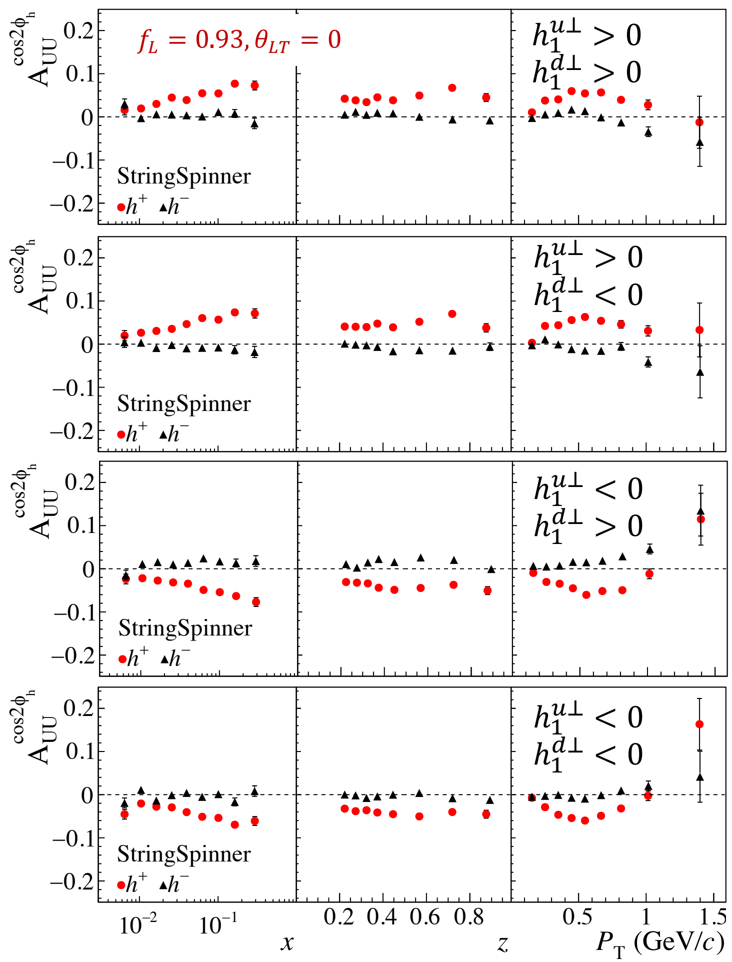
Scattered quark depolarized and reflected

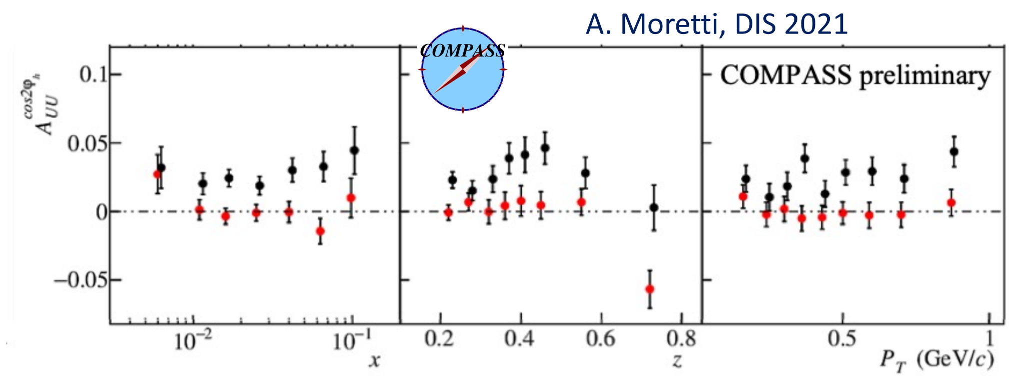
$$\vec{S}'_{\text{qT}} = D_{\text{NN}} \times (\vec{S}_{qT} - 2\,\vec{S}_{qT}\cdot\hat{l}_T)$$

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 saturating BM TMD, sea quarks unpolarized





difficult to describe the data taking into account only valence quarks

need also sea quarks and interplay with Cahn effect

Conclusions

- Using the string+$^3P_0$ model, we have started a systematic introduction of spin effects in Pythia 8 hadronization for DIS → StringSpinner
  the most recent version with PS and VM production
  to be published soon

- Good description of available data on TSA
  remarkable TSA for ρ mesons in DIS predicted

- Inclusion of the Boer-Mulders effect in StringSpinner
  ongoing work on simulation of unpolarized azimuthal asymmetries in SIDIS

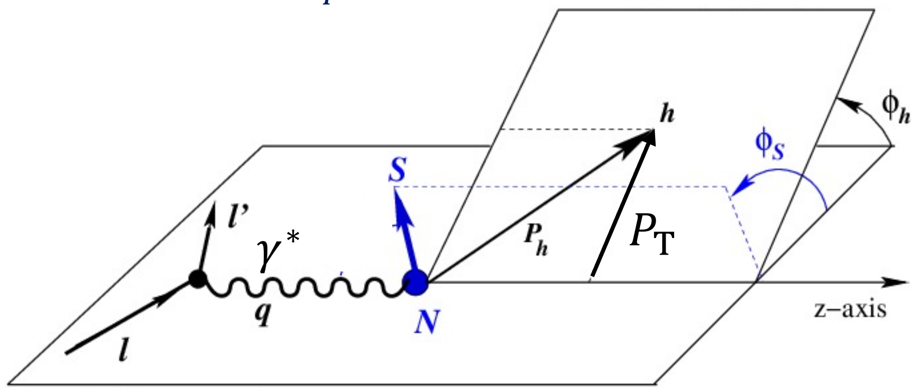
Backup

(selection of)

Results from simulations of T polarized SIDIS on protons

kinematics of COMPASS and HERMES experiments

no intrinsic $\vec{k}_T$



Relevant hadronic variables

Bjorken x

fractional energy $z = E_h/E_{\gamma^*}|_{TRF}$

transverse momentum P_T

Relevant free parameters for string fragmentation

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

Pythia parameters:

StringZ:aLund	0.9	
StringZ:bLund	0.5	$(\mathrm{GeV}/c^2)^{-2}$
StringPT:sigma	0.37	GeV/c
StringPT:enhancedFraction	0.0	
StringPT:enhancedWidth	0.0	GeV/c

String+3P0 parameters

$\mathrm{Re}(\mu)$	0.42	GeV/c^2
$\mathrm{Im}(\mu)$	0.76	GeV/c^2
f_L	0.93, 0.33, 0.02	No unique setting
θ_{LT}	$-\pi/2$, 0, $+\pi/2$	No unique setting