TMD Studies: from JLab to EIC
May 7, 2021

Spin-orbit correlations in Monte Carlo simulations

Focus on recent work on the polarized quark fragmentation process

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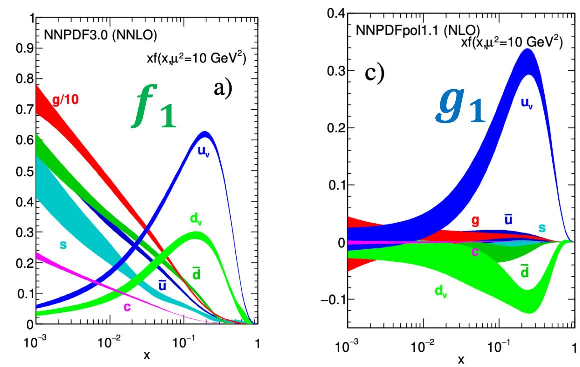
nucleon structure at leading twist

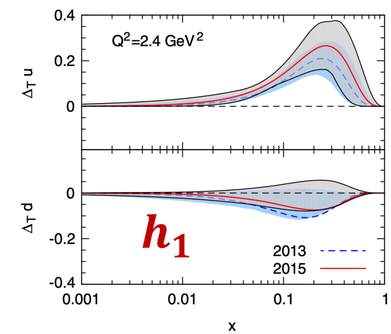
The collinear nucleon structure at leading twist is described by
unpolarised f_1 , helicity g_1, transversity h_1

	nucleon		
quark	**U**	**L**	**T**
U	$f_1(x, k_T^2)$ ***(unpolarized)***		$f_{1T}^{\perp}(x, k_T^2)$ *(Sivers)*
L		$g_1(x, k_T^2)$ ***(helicity)***	$g_{1T}(x, k_T^2)$ *(worm-gear)*
T	$h_1^{\perp}(x, k_T^2)$ *(Boer-Mulders)*	$h_{1L}^{\perp}(x, k_T^2)$ *(worm-gear)*	$h_1(x, k_T^2)$ ***(transversity)*** $h_{1T}^{\perp}(x, k_T^2)$ *(pretzelosity)*

from PDG (2019)



Anselmino et al., PRD 92, 114023 (2015)



transversity is the less known

nucleon structure at leading twist

The collinear nucleon structure at leading twist is described by
unpolarised f_1 , helicity g_1, transversity h_1

quark \ nucleon	U	L	T
U	$f_1(x,k_T^2)$ ***(unpolarized)***		$f_{1T}(x,k_T^2)$ *(Sivers)*
L		$g_1(x,k_T^2)$ ***(helicity)***	$g_{1T}(x,k_T^2)$ *(worm-gear)*
T	$h_1^\perp(x,k_T^2)$ *(Boer-Mulders)*	$h_{1L}^\perp(x,k_T^2)$ *(worm-gear)*	$h_1(x,k_T^2)$ ***(transversity)*** $h_{1T}^\perp(x,k_T^2)$ *(pretzelosity)*

+ 5 other TMD PDFs when the intrinsic k_T is taken into account
→ correlations between the nucleon spin and the spin and k_T of partons
~ basically unknown, but Sivers

In SIDIS some TMDs are coupled to the **unpolarized FF** D_1

$A_{UU}^{\cos\phi_h}$ $\sim f_1 \otimes D_1$ ~ Cahn effect

$A_{UT}^{\sin(\phi_h-\phi_S)}$ $\sim f_{1T} \otimes D_1$ Sivers asymmetry

$A_{LT}^{\cos(\phi_h-\phi_S)}$ $\sim g_{1T} \otimes D_1$ Kotzinian-Mulders

others coupled to the **Collins FF** $H_1^\perp$

$A_{UT}^{\sin(\phi_h+\phi_S-\pi)}$ $\sim h_1 \otimes H_1^\perp$ Collins asymmetry

$A_{UU}^{\cos 2\phi_h}$ $\sim h_1^\perp \otimes H_1^\perp$ ~ Boer-Mulders

$A_{UL}^{\sin(2\phi_h)}$ $\sim h_{1L}^\perp \otimes H_1^\perp$ Kotzinian-Mulders

$A_{UT}^{\sin(3\phi_h-\phi_S)}$ $\sim h_{1T}^\perp \otimes H_1^\perp$ pretzelosity

what about MC simulations of these effects?

MC implementation of spin-orbit effects

Monte Carlo event generators (MCEGs) are important tools
event generation in the full phase space, access to correlations,
multi-dimensional studies, phenomenology

A systematic implementation of all leading order effects related to the intrinsic transverse momentum of quarks and to their spin degree of freedom in complete MCEGs is still missing

Different effects considered separately

- TMD PDFs

$\boldsymbol{k}_T$ dependence in f_1 → «primordial kT» in PYTHIA? (but PDFs in PYTHIA do not depend on $\boldsymbol{k}_T$)
Cahn and Sivers effects implemented in LEPTO *Kotzinian '05*

- TMD FFs

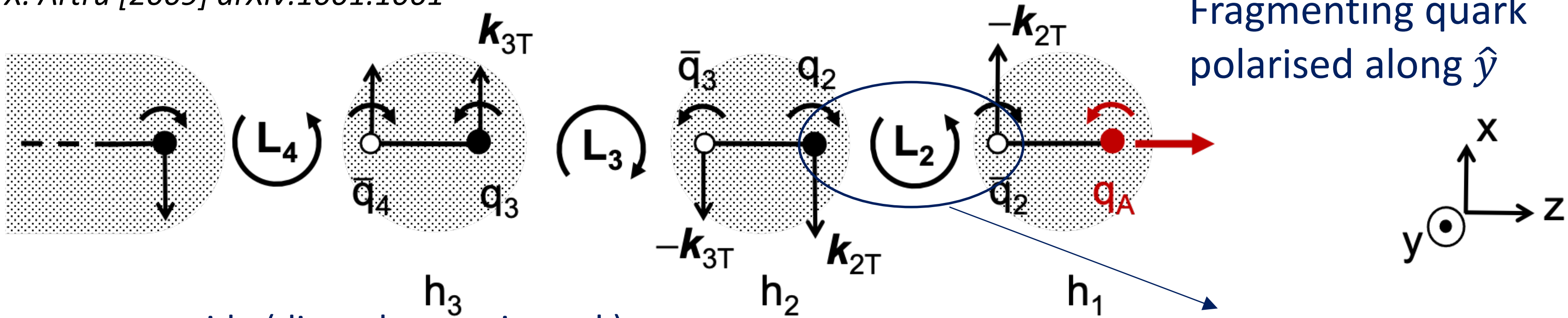
unpolarized quarks, D_1 → Lund String Model, Cluster Model .. (is relation with theory OK?)
polarized quarks → (T) Collins effect $\mathrm{H}_1^{\perp}$, (L) jet handedness
recursive string+3P0 model → **this talk**
stand alone MC *AK et al., PRD 100 (2019) 1, 014003, PRD 97 (2018) 7, 074010*
inclusion in PYTHIA 8.2 *AK and L. Lönnblad, PoS DIS2019 (2019) 179*

extended NJL-jet model
stand alone MC *Matevosyan et al., PRD 95 (2017) 1, 014021*

the classical string + $^3P_0$ model

The string+3P0 model with pseudoscalar (PS) meson production

X. Artru [2009] arXiv:1001.1061

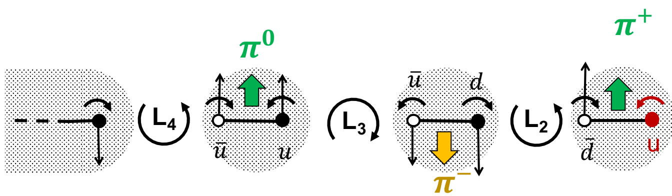


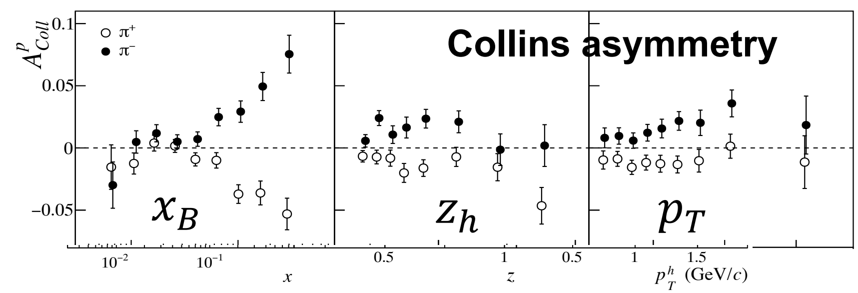
Fragmenting quark polarised along $\hat{y}$

← remnant side (diquark or anti-quark)

$q\bar{q}$ pair at string break-up in $^3P_0$ state (L=1, S=1, J=0)

Assuming e.g. $q_A = u$





COMPASS PLB 717 (2012) 376

π^+ and π^- are emitted on opposite sides

- qualitative agreement with data
- predicts also a di-hadron asymmetry

A quantum mechanical formulation of the string+$^3P_0$ model is used for simulations

elementary splitting: emission of a PS

string decay = recursive repetition of the elementary splitting $q \rightarrow h + q'$

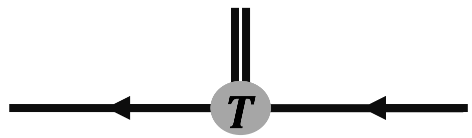
X. Artru, Z. Belghobsi DSPIN-2011, 2013

hadron = {h, — hadron type with transverse mass $\varepsilon_h = \left(m_h^2 + \boldsymbol{p}_T^2\right)^{1/2}$

$Z = p^+/k^+$, — longitudinal momentum fraction

$\boldsymbol{p}_T = \boldsymbol{k}_T - \boldsymbol{k'}_T$} — transverse momentum w.r.t string axis

quark' = {q', k', $\rho(\boldsymbol{S}_{q'})$}



quark = {q, — flavour

k, — 4-momentum

$\rho(\boldsymbol{S}_q)$} — spin density matrix (2x2, Pauli spinors)

Splitting in flavour ⊗ momentum ⊗ spin space

→ Transition Amplitude $\quad T_{q',h,q}(Z, \boldsymbol{p}_T | \boldsymbol{k}_T)$

Splitting Probability

→ Splitting Function $\quad F_{q'hq}(Z, \boldsymbol{p}_T | \boldsymbol{k}_T, \boldsymbol{S}_q) = tr\, T_{q',h,q}\, \rho(\boldsymbol{S}_q)\, T^{\dagger}_{q',h,q}$

Spin transfer to q'

→ spin density matrix of q′ $\quad \rho(\boldsymbol{S}_{q'}) \propto T_{q',h,q}\, \rho(\boldsymbol{S}_q)\, T^{\dagger}_{q',h,q}$

the very basic ingredients for the MC simulations

elementary splitting: emission of a PS

string decay = recursive repetition of the elementary splitting $q \rightarrow h + q'$

X. Artru, Z. Belghobsi DSPIN-2011, 2013

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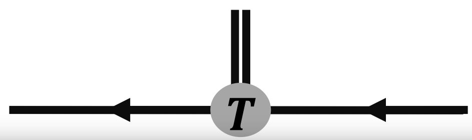


quark = {q, — flavour

k, — 4-momentum

- Expression for the Transition Amplitude

$$T_{q',h,q} = C_{q',h,q} \times \left(\frac{1-Z}{\varepsilon_h^2}\right)^{a/2} e^{-\frac{b_L}{2}\frac{\varepsilon_h^2}{Z}} \times e^{-\frac{b_T}{2}\boldsymbol{k}_T'^2} \times \check{g}\left(\varepsilon_h^2\right) \times [\mu + \sigma_z \sigma \cdot \boldsymbol{k}_T'] \times \sigma_z \times \hat{u}^{-1/2}(\boldsymbol{k}_T)$$

$T_{q',h,q}$ = *Lund String Fragmentation Model* × $^3P_0$ *operator* × *PS coupling* × ..

- Few free parameters

  a, b_L, b_T → string fragmentation dynamics (Lund Model, e.g. PYTHIA, LEPTO)

  μ **complex mass** from $^3P_0$ mechanism → responible for spin effects ($\mathrm{Im}(\mu)$ → transverse)

- Input function $\check{g}$ → governs spin-independent $\mathbf{k}_T$ - $\mathbf{k'}_T$ correlations

  correlations → Model **M18** — *PRD 97 (**2018**) 7, 074010*

  NO correlations → Model **M19** (much simpler) — *PRD100 (**2019**) no.1, 014003*

Stand alone simulations (M19)

M18 and M19 have been implemented in stand alone MC programs
give very similar results, in spite for M19 being much simpler

Azimuthal spectrum of hadrons
$dN_h \propto 1 + a^{u\uparrow\to h+X}\sin(\phi_h - \phi_{s_u})$
Collins analysing power
$a^{u\uparrow\to h+X} = 2\,\langle\sin(\phi_h - \phi_{s_u})\rangle$

Next slide, simulated Collins analysing power $a^{u\uparrow\to h+X}$ with initial conditions

u quarks fully transversely polarized along $\hat{y}$

Energy calculated from a $\{x_B, Q^2\}$ sample of SIDIS events

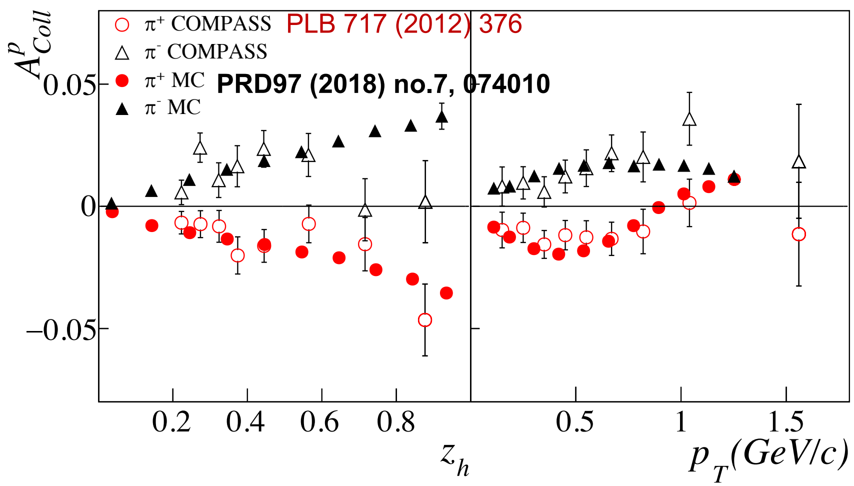
no primordial KT

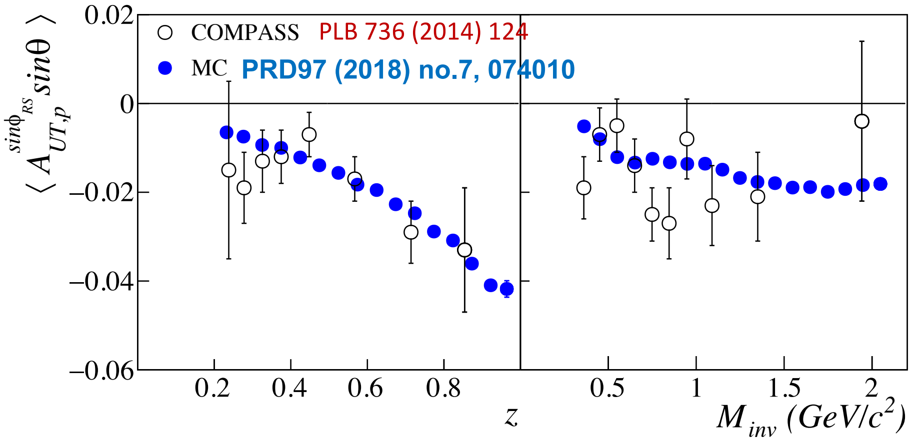
Values of the free parameters

$a = 0.9$
$b_L = 0.5\ (\mathrm{GeV}/c^2)^{-2}$
$b_T = 5.17(\mathrm{GeV}/c)^{-2}$
$\mu = (0.42 + \mathrm{i}0.76)\ \mathrm{GeV/c^2}$

see AK, X. Artru, Z. Belghobsi, F. Bradamante, A. Martin PRD 100 (2019) 1, 014003

Stand alone simulations: comparison with SIDIS data (M19)





Collins asymmetry on protons $A^p_{Coll} \simeq \frac{h_1^u}{f_1^u} a^{u\uparrow\to\pi+X}$

MC → Collins analysing power $a^{u\uparrow\to\pi+X}$
scaled by $\lambda \sim \langle h_1^u / f_1^u \rangle = 0.055 \pm 0.010$

only u quarks fully transversely polarized

λ is estimated by comparison with A^p_{Coll} for π^-

Di-hadron asymmetry for h^+h^- pairs
MC → same scale factor λ

same mechanism as for Collins

the model describes the main properties of data

Improving the model

The model gives already a good description of the main properties of data

few parameters, same mechanism for Collins and dihadron asymmetries, jet handedness (not shown here)

We have improved it further following two directions ..

a) Exploit the true predictive power of the model via a more complete simulation of the event

→ interface M19 with PYTHIA 8.2 for SIDIS

→ introduction of transversity PDF

in collaboration with L. Lönnblad

the first step towards a systematic implementation of spin effects in PYTHIA!

b) Improve the description of the polarized fragmentation process

→ extend M19 by introducing vector mesons → **the NEW model M20**

PYTHIA+3P0

M19 is interfaced with PYTHIA 8.2 for the simulation of polarized SIDIS
→ spin effects introduced for the first time in the hadronization part of a complete MCEG
→ parameterizations for u^v and d^v transversity PDFs implemented

→ **PYTHIA+3P0 allows to simulate the Collins and dihadron asymmetries**

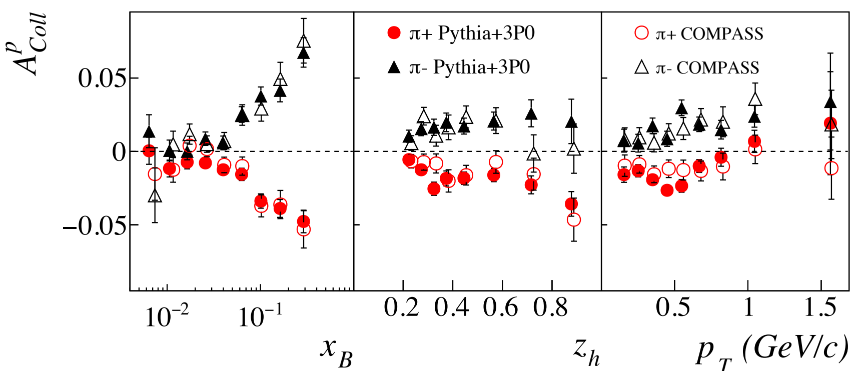
NEW tool!

Simulation of SIDIS off protons @ COMPASS kinematics

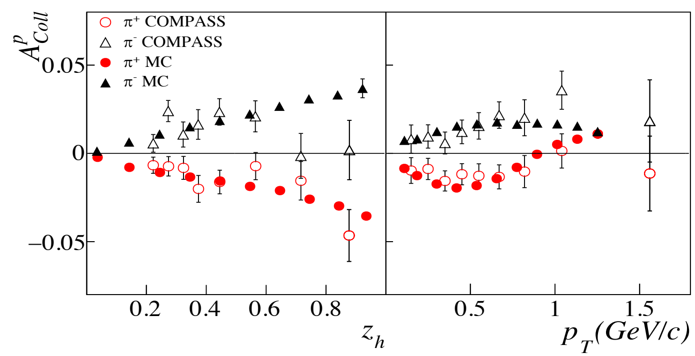
ISR/FSR switched OFF, no intrinsic $\boldsymbol{k}_\perp$

complex mass retuned to $\mu = (0.78 + i0.38)\ \mathrm{GeV/c^2}$

Collins asymmetry PYTHIA+3P0



Collins asymmetry M19



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MC PRD97 (2018) no.7, 074010

Nice description of data!

trend vs z_h is modified in PYTHIA

also good description of di-hadron asymmetries

PYTHIA+3P0 will be available soon!!

AK and L. Lönnblad, in preparation

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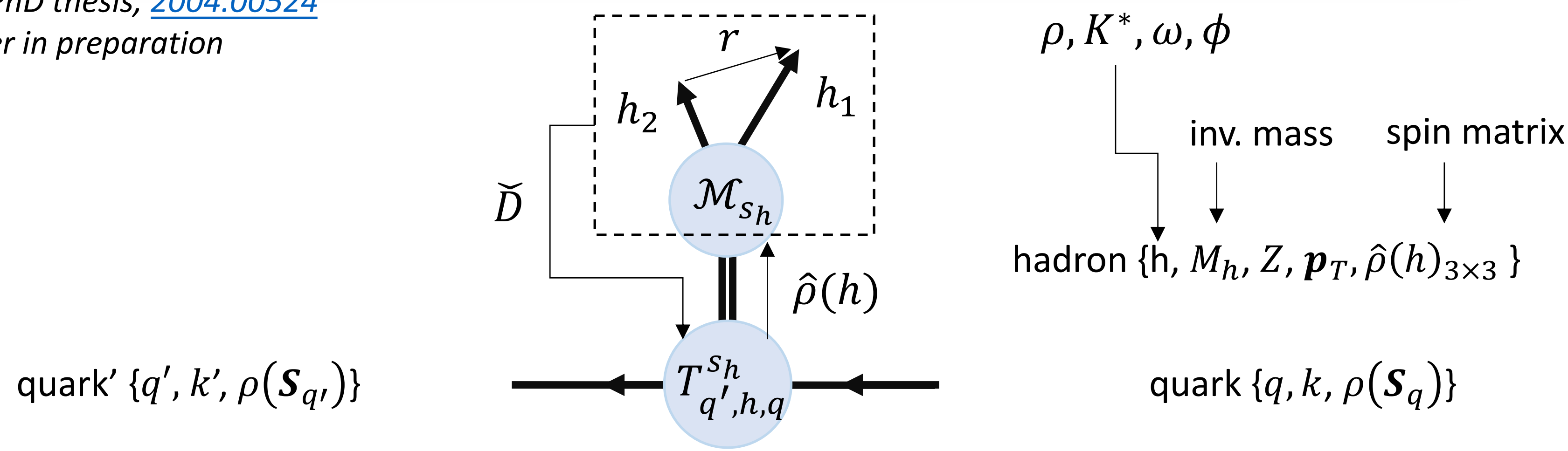
b) Improve the description of the polarized fragmentation process

→ extend M19 by introducing vector mesons → **the NEW model M20**

spin effects with PS and VM production are treated systematically, for the first time

elementary splitting: emission of a VM

AK, PhD thesis, 2004.00524
paper in preparation



NEW Transition Amplitude	$T^{s_h}_{q',h,q}(M, Z, \boldsymbol{p}_T, s_h \vert \boldsymbol{k}_T)$
Splitting Probability	
→ **NEW Splitting Function**	$F_{q'hq}(M, Z, \boldsymbol{p}_T \vert \boldsymbol{k}_T, \boldsymbol{S}_q) = tr\, T^{s_h}_{q',h,q}\rho(\boldsymbol{S}_q)T^{s_h\,\dagger}_{q',h,q}$
Spin transfer to h	
→ spin density matrix of h	$\hat{\rho}_{s_h s_h'}(h) \propto tr\, T^{s_h}_{q',h,q}\, \rho(\boldsymbol{S}_q)\, \mathrm{T}^{s_h'\dagger}_{q',h,q}$
Decay (e.g. VM→ $h_1 h_2$)	
→ angular distribution	$dN/d\Omega \propto \mathcal{M}_{s_h}\, \hat{\rho}_{s_h s_h'} \mathcal{M}^\dagger_{s_h'}$
Bring decay information back to q'	
→ decay matrix	$\breve{D}_{s_h' s_h} = \mathcal{M}^\dagger_{s_h'} \mathcal{M}_{s_h}$
Transfer spin information to q'	
→ spin density matrix of q'	$\rho(\boldsymbol{S}_{q'}) = \breve{D}_{s_h s_h'}\, T^{s_h'}_{q',h,q}\rho(\boldsymbol{S}_q)\mathrm{T}^{s_h\dagger}_{q',h,q}$

elementary splitting: emission of a VM

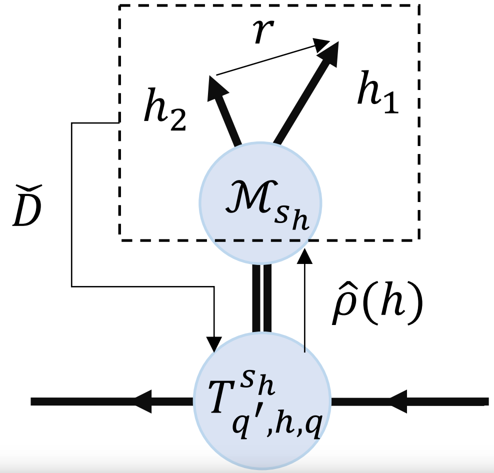
AK, PhD thesis, [2004.00524]
paper in preparation

ρ, K^*, ω, ϕ

inv. mass   spin matrix

hadron {h, M_h, Z, $\boldsymbol{p}_T$, $\hat{\rho}(h)_{3\times3}$ }

quark' {q', k', $\rho(\boldsymbol{S}_{q'})$}



quark {q, k, $\rho(\boldsymbol{S}_q)$}

Complicated recipe!

respects entanglement $q' \leftrightarrow$ momenta of decay hadrons *(Collins '88, Knowles '88)*

Form of the NEW splitting amplitude

$T^{s_h}_{q',h,q}$ = relativistic BW × *Lund String Fragmentation Model* × $^3P_0$ *operator* × *VM coupling* × ..

VM coupling → complex free parameters

G_L → coupling of q to VM with linear L polarisation along the string axis

G_T → coupling of q to VM with linear T polarisation w.r.t the string axis

Only two new parameters in the model

$|G_L|/|G_T|$ → global Collins effect of the VM (depends on VM polarisation!)

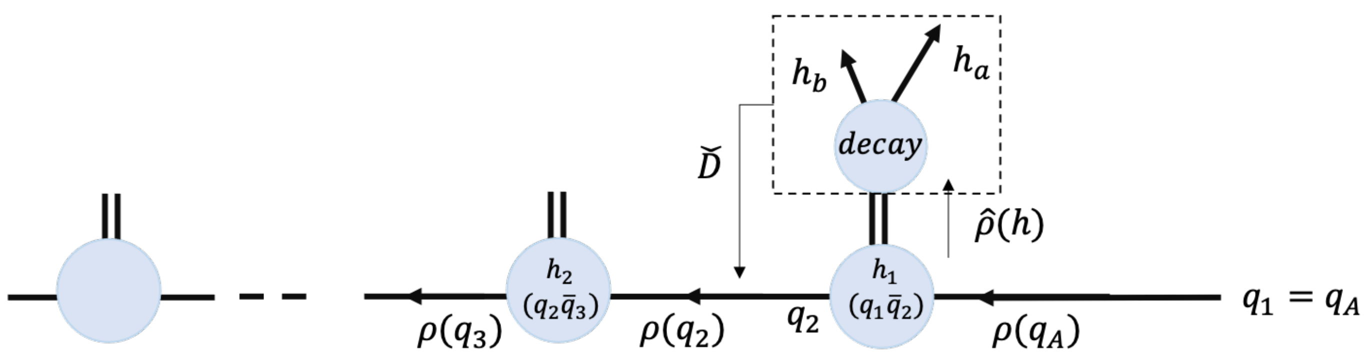
$\theta_{LT} = \arg(G_L/G_T)$ → oblique polarisation (LT)

Stand alone MC implementation of M20

For each event define initial quark $q_A \equiv q_1$, i.e. flavour (u, d, s), momentum, density matrix $\rho(q_A)$

1. Generate a $q_2\bar{q}_2$ pair and form the hadron $h_1(q_A\bar{q}_2)$, VM with prob. $\frac{f_{VM}}{f_{VM}+f_{PS}}$
2. Generate M_{h_1} (if VM), $\boldsymbol{k}_{2T}$, Z_1, using $F_{q_2 h_1 q_A}$ $\rightarrow$ construct p_1
3. If $h_1 =$ PS go to 4.
   If $h_1 =$ VM $\rightarrow$ calculate $\hat{\rho}(h)$
   a) generate decay hadrons in VM rest frame and boost to string frame
   b) construct the decay matrix $\breve{D}$
4. Calculate the spin density matrix of q_2

- Iterate points 1-4 until the exit condition (enough renamining mass to produce at least one baryonic resonance)



Stand alone simulations with M20

Values of the free parameters used in simulations

all mesons

$a = 0.9$

$b_L = 0.5\ (\mathrm{GeV}/c^2)^{-2}$ as in model M19

$b_T = 8.43(\mathrm{GeV}/c)^{-2}$

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

VM production

$f_{VM}/f_{PS} = 0.62\ (0.725)$ for u,d (s) as in PYTHIA 8

$|G_L|/|G_T| = 1$

$\theta_{LT} = 0$

→ following the NR quark model *Czyzewski '96*

sensitivity to parameters values also explored

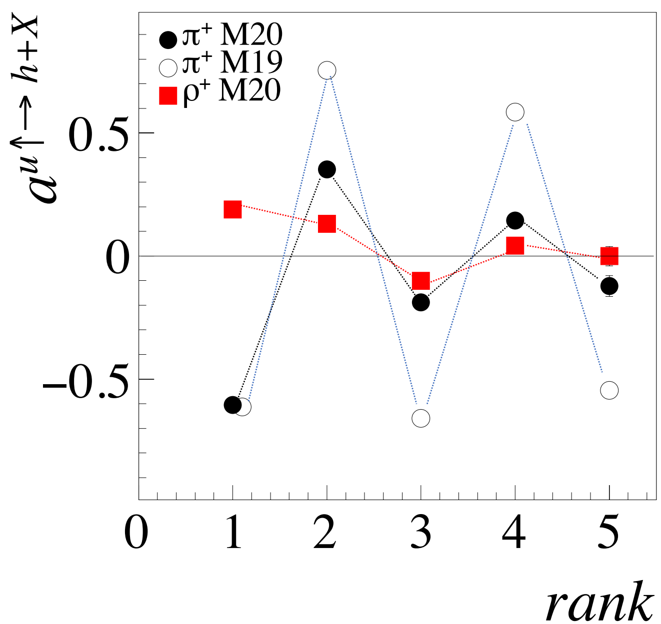
Initial conditions

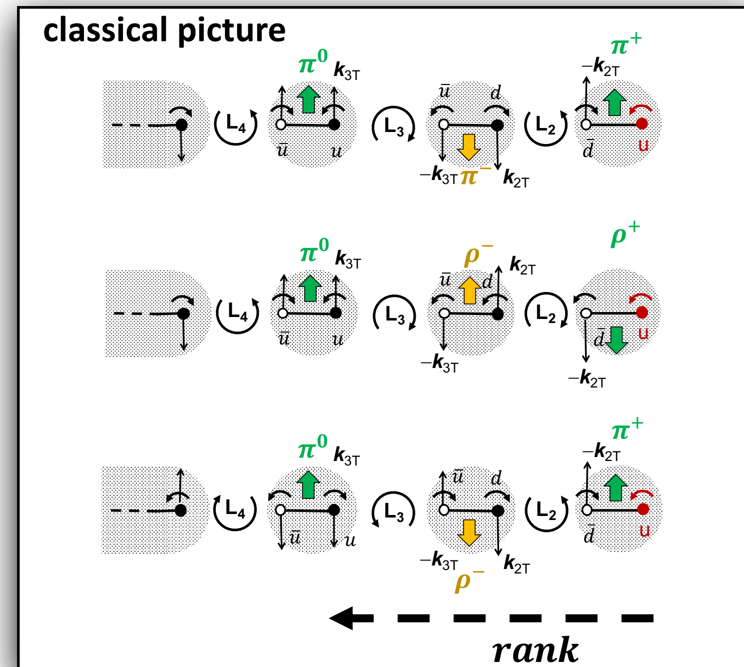
u quarks fully transversely polarized along $\hat{y}$

Energy calculated from a $\{x_B, Q^2\}$ sample of SIDIS events

no primordial KT

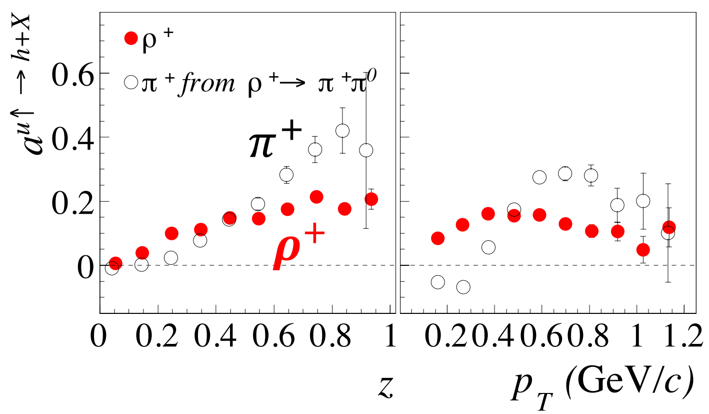
Collins analysing power as function of rank

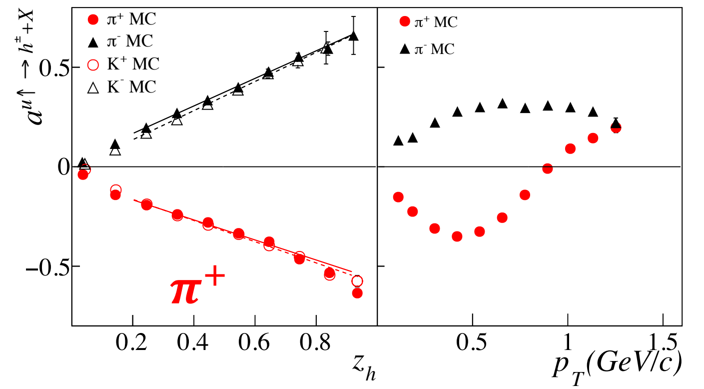




- classical picture reproduced
  ρ^+ have opposite effect w.r.t π^+
- quark spin information decays along the chain
  faster decay in M20

Collins analysing power for ρ and decay π





AK et al., PRD 100 (2019) 1, 014003,

model M19 → only PS

ρ^+ analysing power

- opposite to π^+
- ~ 3 times smaller than π^+
- as expected from the M20 prediction

$$\left.\frac{a^{u\uparrow\to\rho+X}}{a^{u\uparrow\to\pi+X}}\right|_{rank=1} = -\frac{|G_L|^2}{2|G_T|^2+|G_L|^2}$$

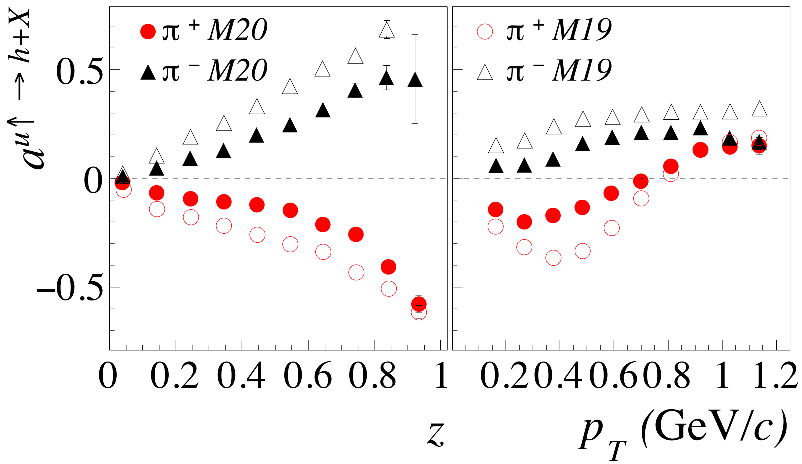
ρ^- , ρ^0 ~ to ρ^+ for $|G_L|/|G_T| = 1$

decay π^+ → larger analysing power at large z_h and large p_T w.r.t ρ^+

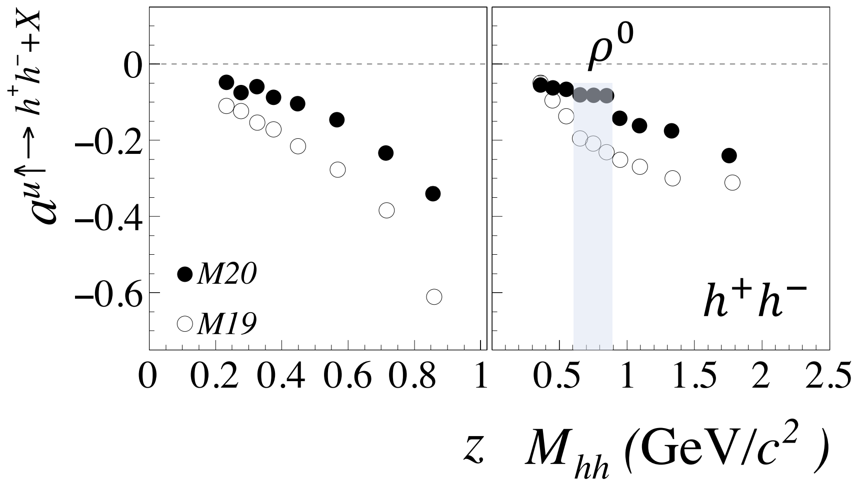
- large z_h → π^+ emitted along $\hat{z}$ from longitudinally polarized ρ^+
- large p_T → π^+ emitted along $\vec{p}_T^{\,\rho}$ from rank 1 ρ^+
  emitted along $\hat{z}\times\vec{p}_T^{\,\rho}$ from rank 2 ρ^+
- small p_T → π^+ emitted along $-\vec{p}_T^{\,\rho}$ from rank 1 ρ^+

Effect of VM decays on transverse spin asymmetries

Collins analysing power



Di-hadron analysing power



Large effect on Collins analysing power w.r.t M19

- different trends
- average analysing power diluted by 50%

di-hadron analysing power calculated using the relative transverse momentum

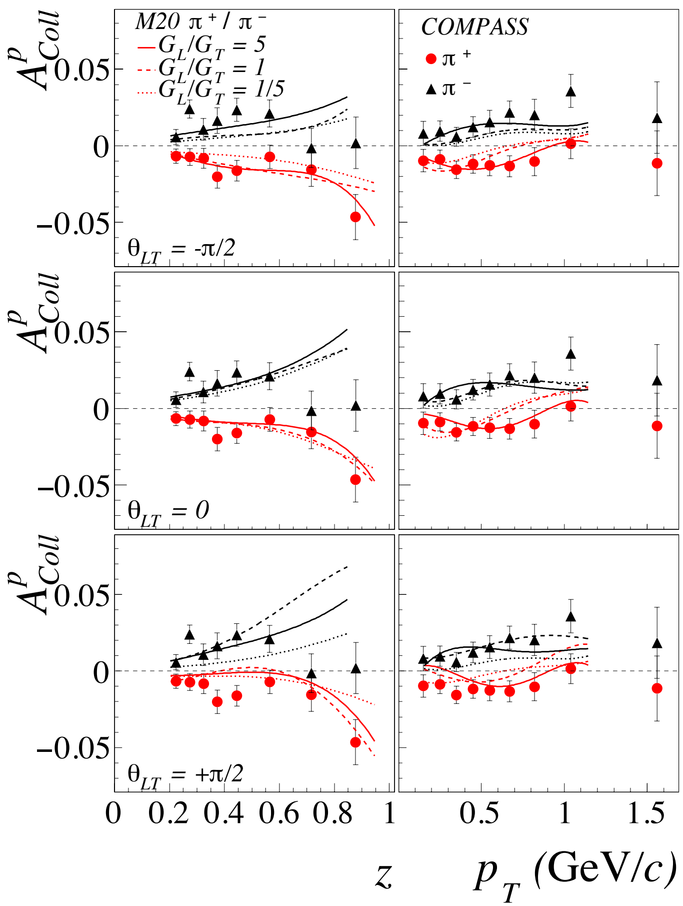
$$\boldsymbol{R}_T = z_2 \boldsymbol{p}_{1T}/z - z_1 \boldsymbol{p}_{2T}/z$$

$$a^{u\uparrow \to h^+h^-+X} = 2\langle \sin(\phi_R - \phi_{S_A}) \rangle$$

50% dilution w.r.t M19

- effect at ρ^0 peak due to $\rho^0 \to \pi^+\pi^-$ symmetric w.r.t $\boldsymbol{R}_T \leftrightarrow -\boldsymbol{R}_T$

Comparison with SIDIS data



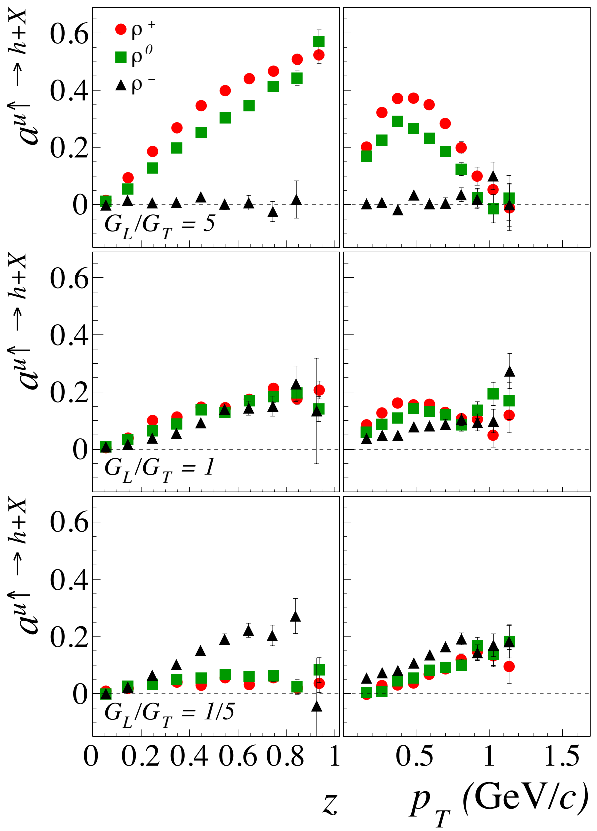
MC scaled by a factor λ depending on $|G_L|/|G_T|$ and θ_{LT}

Large variations for π^+ due to different values of $|G_L|/|G_T|$ and θ_{LT}
somewhat smaller for π^-
→ both parameters are important

hint for $\frac{|G_L|}{|G_T|} > 1, \theta_{LT} < 0$?

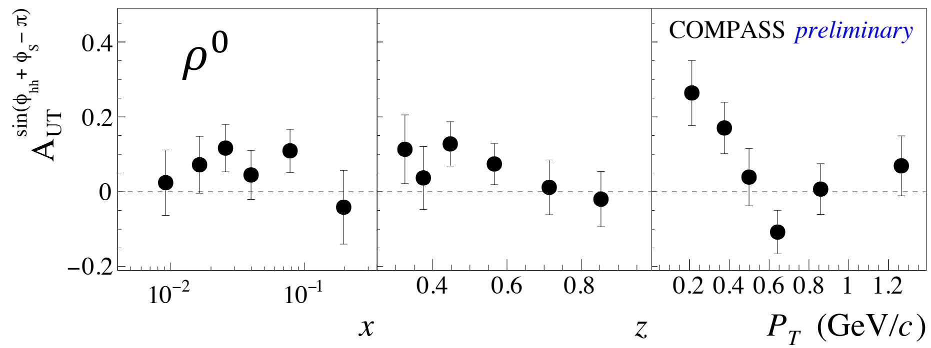
more precise data would help to fix the free parameters

Sensitivity to free parameters: Collins effect for ρ mesons



Strong dependence on $|G_L|/|G_T|$
both size and shapes change

from *AK talk at DIS-2021*



COMPASS results: NEW! Measurements feasible

they could be used to fix the parameters

Hint for $\frac{|G_L|}{|G_T|} > 1$ (in particular from p_T)

Conclusions

The string+3P0 model with PS meson emission (M18, M19) implemented in a stand alone MC

→ describes the main features of Collins and di-hadron asymmetries!

M19 has been interfaced to PYTHIA 8

→ parameterisations for the transversity PDF implemented

→ more complete description of TSA

the code will available very soon *(AK and L. Lönnblad, in preparation)*

For the first time implementation of the string+3P0 model with PS and VM production (M20) in a stand alone MC *(paper in preparation)*

→ detailed study of Collins effect for VM

→ only 4 free parameters for spin effects, to be fixed from comparison with data

μ OK, hints for $|G_L|/|G_L| > 1$ and $\theta_{LT} < 0$

more precise data would help (COMPASS 2021-2022 d run, JLab12 ..)

ongoing work, promising results …