May 14, 2021

## QCD Evolution Workshop 2021

# Vector meson production in the polarized quark fragmentation process

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INFN Trieste section

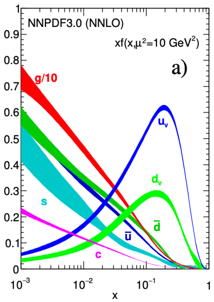
*in collaboration with X. Artru and A. Martin*

# nucleon structure at leading twist

The collinear nucleon structure at leading twist is described by $f_1, g_1, h_1$

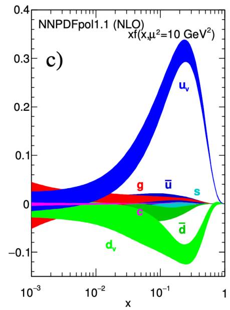
| | nucleon | | |
|---|---|---|---|
| **quark** | **U** | **L** | **T** |
| **U** | $f_1(x, k_T^2)$ ***(unpolarized)*** | | $f_{1T}(x, k_T^2)$ *(Sivers)* |
| **L** | | $g_1(x, k_T^2)$ ***(helicity)*** | $g_{1T}(x, k_T^2)$ *(worm-gear)* |
| **T** | $h_1^\perp(x, k_T^2)$ *(Boer-Mulders)* | $h_{1L}^\perp(x,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

$f_1$



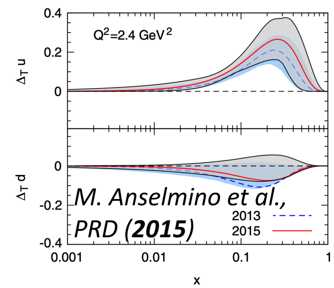

*PDG* (2019)

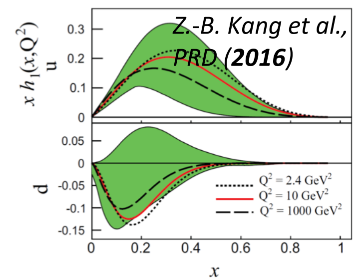
$g_1$

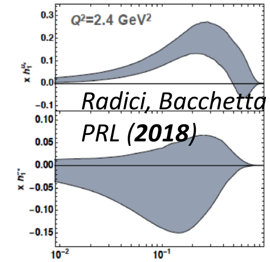



*PDG* (2019)

$h_1$




+ 5 other TMD PDFs when the intrinsic $\boldsymbol{k}_T$ is considered
→ ~ 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 |

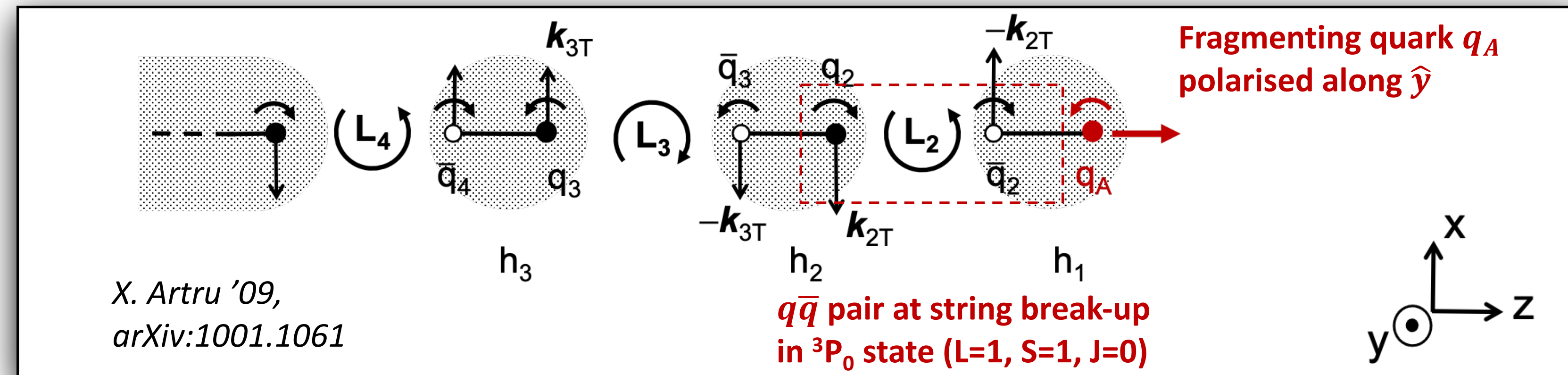
**good understanding of the Collins FF is important**

# Collins effect: the string+3P0 model

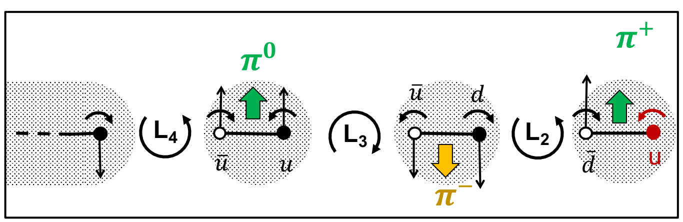
**Collins FF** $H_1^{\perp}$ → fragmentation of a transversely polarised quark into unpolarized hadrons
non perturbative process → can be studied with models

this talk → **string+3P0 model**

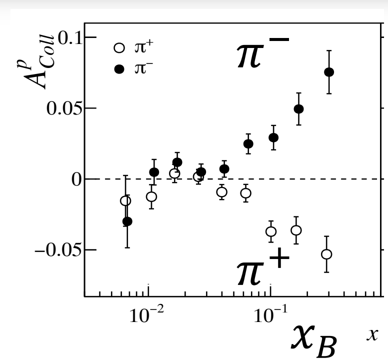
The classical string+3P0 model with pseudoscalar (PS) meson production




Assuming e.g. $q_A = u$




$\pi^+$ and $\pi^-$ are emitted on opposite sides
→ qualitative agreement with data




**Collins asymmetry**

*COMPASS PLB 717 (2012) 376*

**For MC simulations →quantum mechanical model**

# elementary splitting: emission of a PS

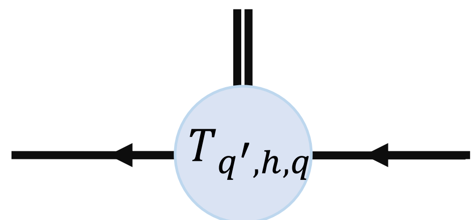
**string decay = recursive repetition of the elementary splitting** $q \to h + q'$

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

$p^+ = Zk^+$
$p^- = \varepsilon_h^2/p^+$
$\boldsymbol{p}_T = \boldsymbol{k}_T - \boldsymbol{k}'_T$

hadron = {h, $p = k - k'$}

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




quark = {$q$, flavour
$k$, 4-momentum
$\rho(\boldsymbol{S}_q)$} spin density matrix (2x2, Pauli spinors)

**Basic ingredients for the MC simulations**

Splitting in flavour ⊗ momentum ⊗ spin space

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

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

Transfer spin information to $q'$ → $\rho(\boldsymbol{S}_{q'}) \propto T_{q',h,q}\, \rho(\boldsymbol{S}_q)\, T^{\dagger}_{q',h,q}$

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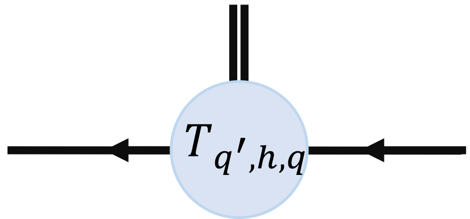



quark = {$q$, flavour
$k$, 4-momentum
$\rho(\boldsymbol{S}_q)$} spin density matrix
(2x2 Pauli spinors)

- Expression for the Transition Amplitude

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

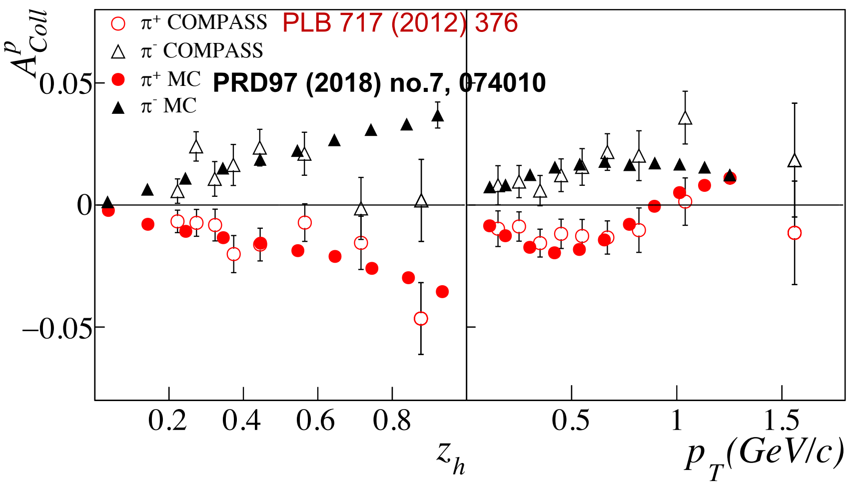
$T_{q',h,q}$ = *Lund String Fragmentation Model* × $^3P_0$ *operator* × *PS coupling* × ..

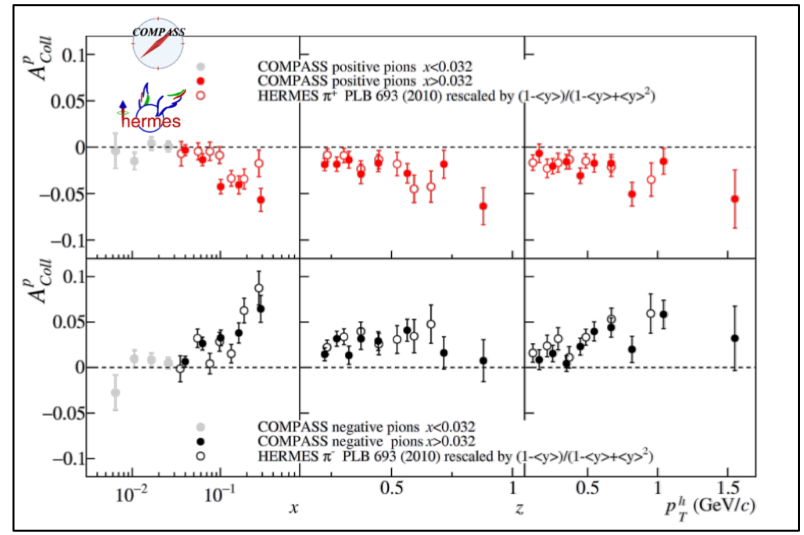
- Few free parameters
  $a, b_L, b_T$ → string fragmentation dynamics (Lund Model, e.g. PYTHIA, LEPTO)
  $\mu$ **complex mass** from $^3P_0$ mechanism → **responible for spin effects** ($\mathrm{Im}(\mu)$ → transverse)
- Input function $\breve{g}$ → governs spin-independent $\mathbf{k}_T$ - $\mathbf{k}'_T$ correlations
  correlations → Model **M18** *PRD 97 (**2018**) 7, 074010*
  NO correlations → Model **M19** (much simpler) *PRD100 (**2019**) no.1, 014003*

# Stand alone simulations (M19): comparison with SIDIS data

M18 and M19 have been implemented in stand alone MC programs
→ give very similar results
→ results from fragmentations of **fully transversely polarized $u$ quarks**

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




Comparison with HERMES also OK
(compatible with COMPASS)

MC → Collins analysing power $a^{u\uparrow\to\pi+X}$
scaled by $\lambda \sim \langle h_1^u/f_1^u\rangle = 0.055 \pm 0.010$
$\lambda$ is estimated by comparison with $A^p_{Coll}$ for $\pi^-$

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

**the model describes the main properties of data**

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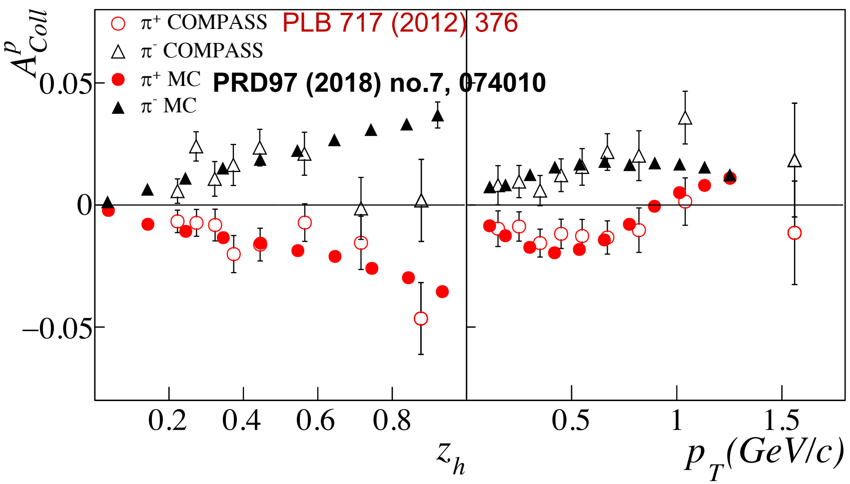
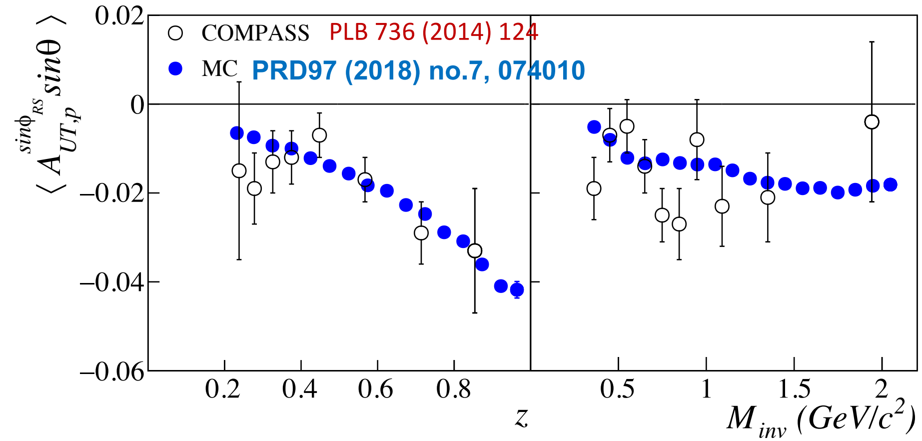



**Dihadron asymmetry** $\langle A^{\sin\phi_{RS}}_{UT,p} \sin\theta\rangle \simeq \frac{h_1^u}{f_1^u} a^{u\uparrow\to\pi+X}$

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Di-hadron asymmetry for $h^+h^-$ pairs
MC → same scale factor $\lambda$

**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**

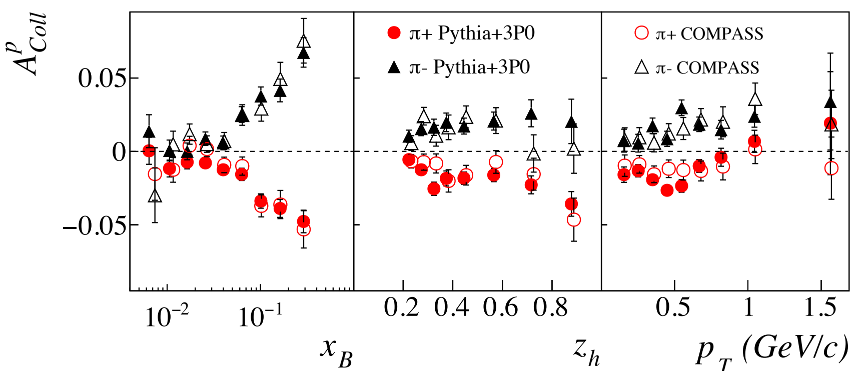
# PYTHIA+3P0

M19 is interfaced with PYTHIA 8.2 for SIDIS
→ spin effects in the hadronization part introduced for the first time
→ parameterizations for $u^v$ and $d^v$ transversity PDFs implemented
→ **PYTHIA+3P0 allows to simulate the Collins and dihadron asymmetries**

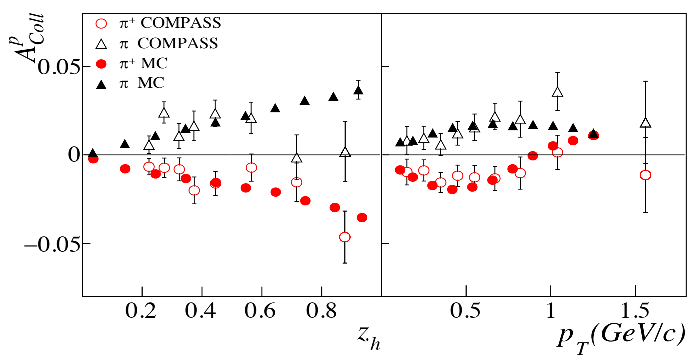
NEW tool!

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**




COMPASS PLB 717 (2012) 376
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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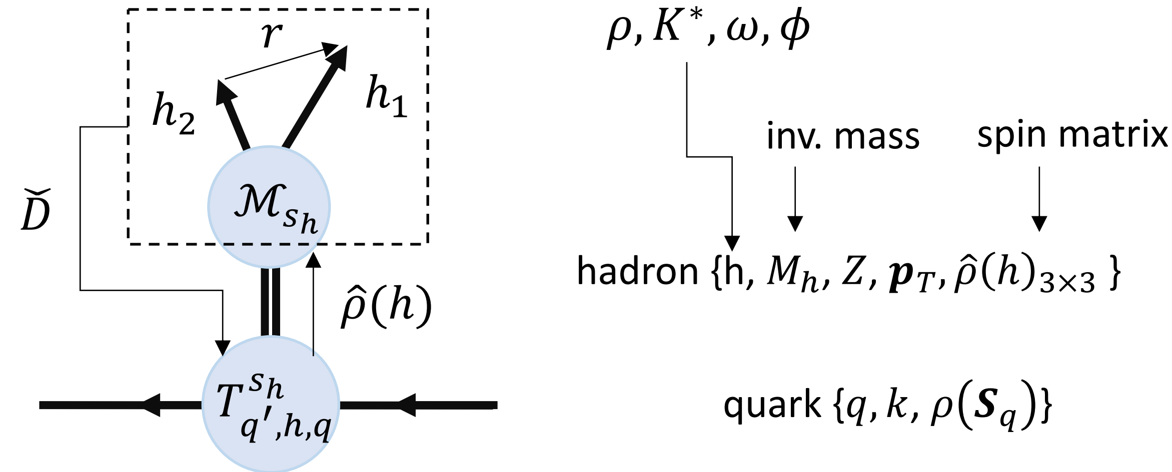
**spin effects with PS and VM production are treated systematically, for the first time**

# elementary splitting: emission of a VM

*AK, PhD thesis, [2004.00524]()*
*paper in preparation*




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

**NEW recipe** *details in backup*

**Introduce NEW Transition Amplitude** $T^{s_h}_{q',h,q}(M_h, Z, \boldsymbol{p}_T, s_h|\boldsymbol{k}_T)$

→ Generate $h$ using the NEW Splitting Function
→ Transfer spin information to $h$ [density matrix $\hat{\rho}(h)$]
→ Decay of h (e.g. VM→ $h_1h_2$, VM→ $h_1h_2h_3$) [use $\hat{\rho}(h)$ ]
→ Bring decay information back to $q'$ [ decay matrix $\check{D}$]
→ Transfer spin information to $q'$ [ density matrix $\rho(\boldsymbol{S}_{q'})$]

# elementary splitting: emission of a VM

*AK, PhD thesis, [2004.00524]*
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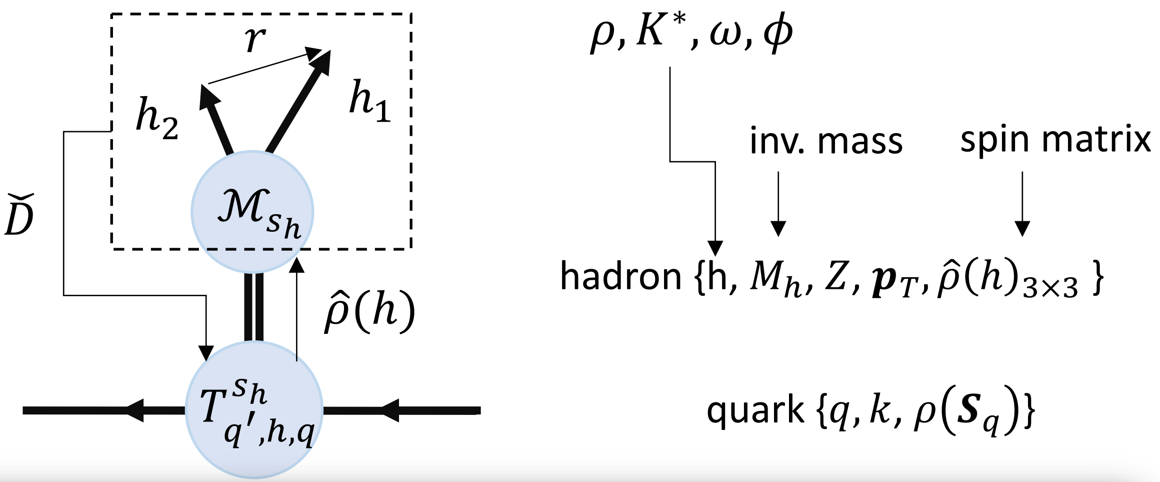



**Complicated recipe!**

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* × $^3$P$_0$ *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!)

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

# Stand alone simulations with M20

M20 has been implemented in a stand alone MC program

Values of the free parameters

all mesons — as in model M19

$a = 0.9$
$b_L = 0.5\ (\mathrm{GeV}/c^2)^{-2}$
$b_T = 8.43(\mathrm{GeV}/c)^{-2}$
$\mu = (0.42 + \mathrm{i}0.76)\ \mathrm{GeV/c^2}$

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

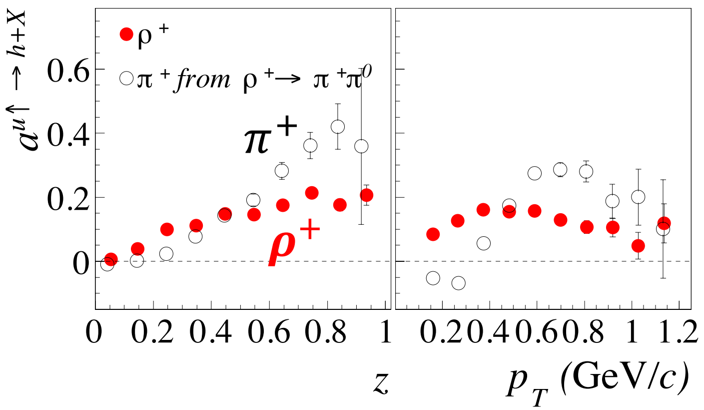
Next slides, initial conditions

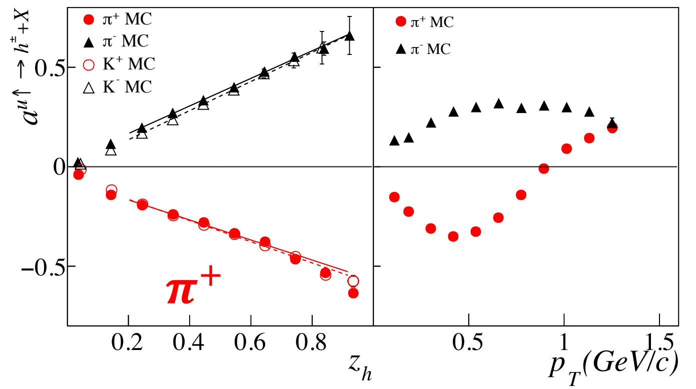
$u$ quarks fully transversely polarized along $\hat{y}$

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

no primordial KT

# Collins analysing power for $\rho$ and decay $\pi$




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

model M19 → only PS

$\rho^+$ analysing power
- opposite to $\pi^+$
- ~ 3 times smaller than $\pi^+$

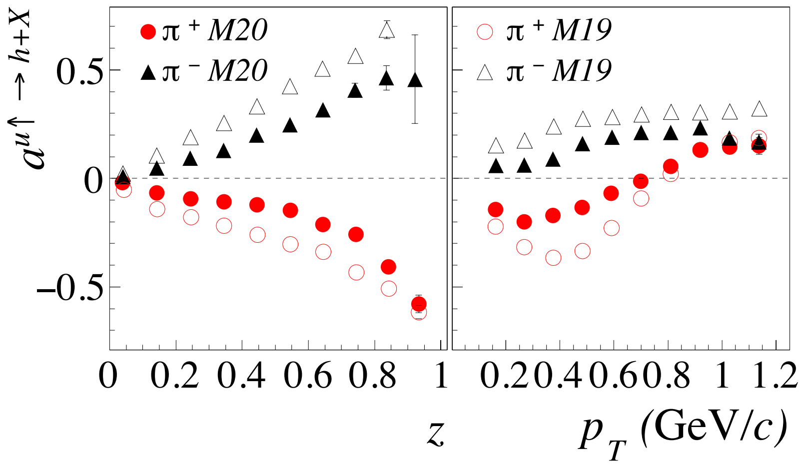
as expected from the M20 prediction

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

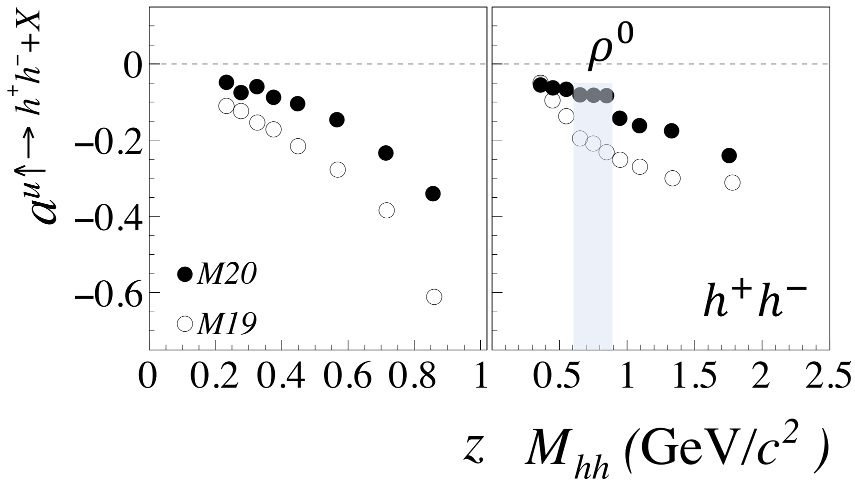
decay $\pi^+ \to$ larger analysing power w.r.t $\rho^+$ at large $z_h$
different trend as function of $p_T$

# 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%

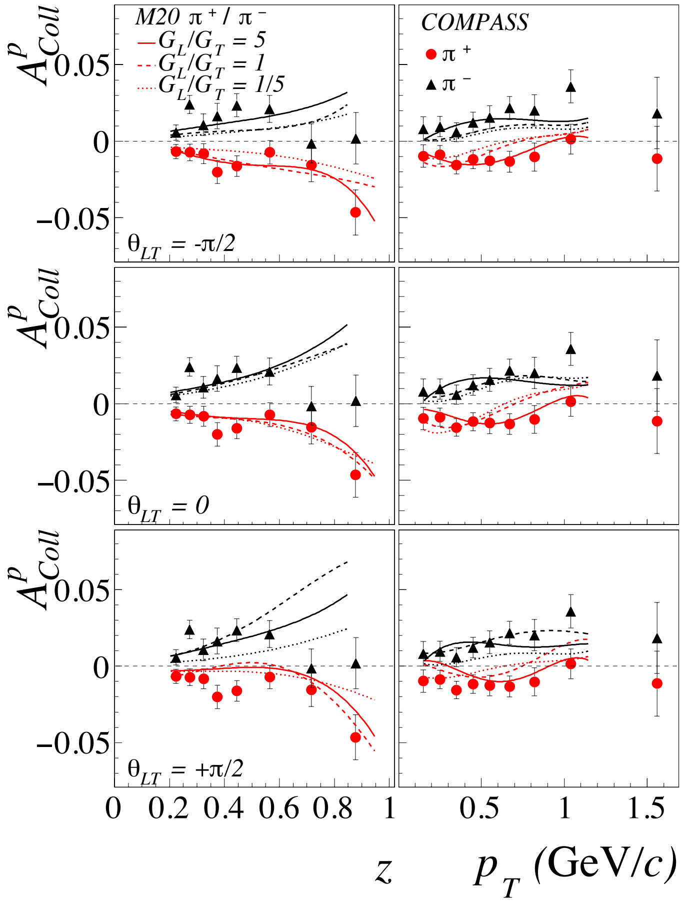
di-hadron analysing power calculated using the relative transverse momentum

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

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

50% dilution w.r.t M19
- effect at $\rho^0$ peak due to $\rho^0 \to \pi^+\pi^-$ symmetric w.r.t $\boldsymbol{R}_T \leftrightarrow -\boldsymbol{R}_T$

# Comparison with SIDIS data



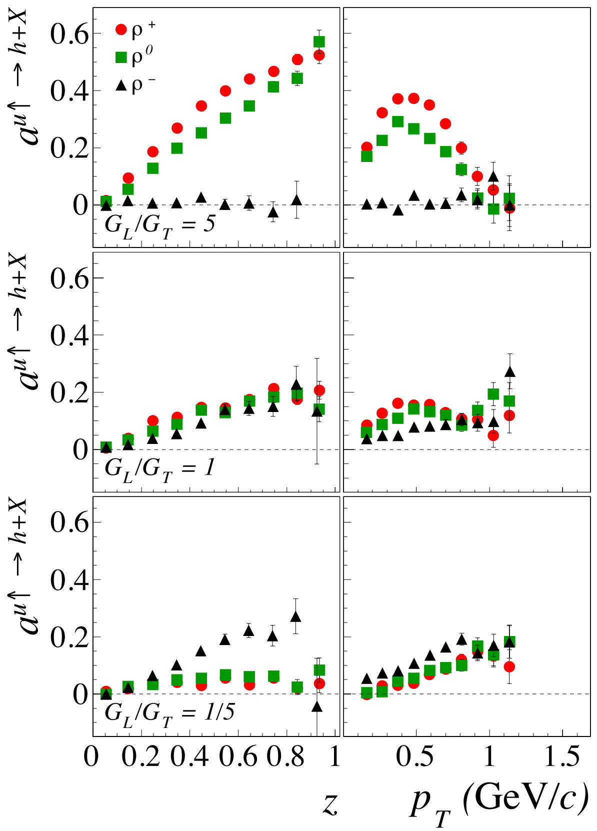

MC scaled by a factor $\lambda$ depending on $|G_L|/|G_T|$ and $\theta_{LT}$

Large variations due to different values of $|G_L|/|G_T|$ and $\theta_{LT}$
→ both parameters are important

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

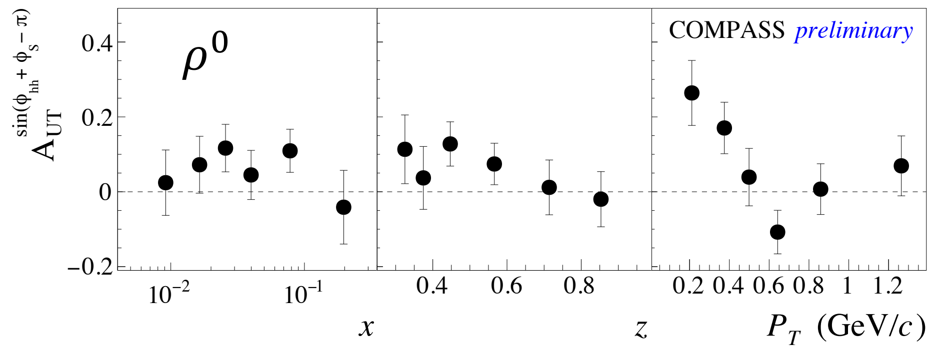
more precise data would help to fix the free parameters

# Sensitivity to free parameters: Collins effect for $\rho$ mesons




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

*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)

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

M19 has been interfaced to PYTHIA 8.2

→ parameterisations for transversity PDFs

→ 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

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

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

promising results … work ongoing

# backup

# Stand alone simulations (M19)

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give very similar results

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

Azimuthal spectrum of hadrons
$dN_h \propto 1 + a^{u\uparrow\to h+X} \sin(\phi_h - \phi_{s_u})$
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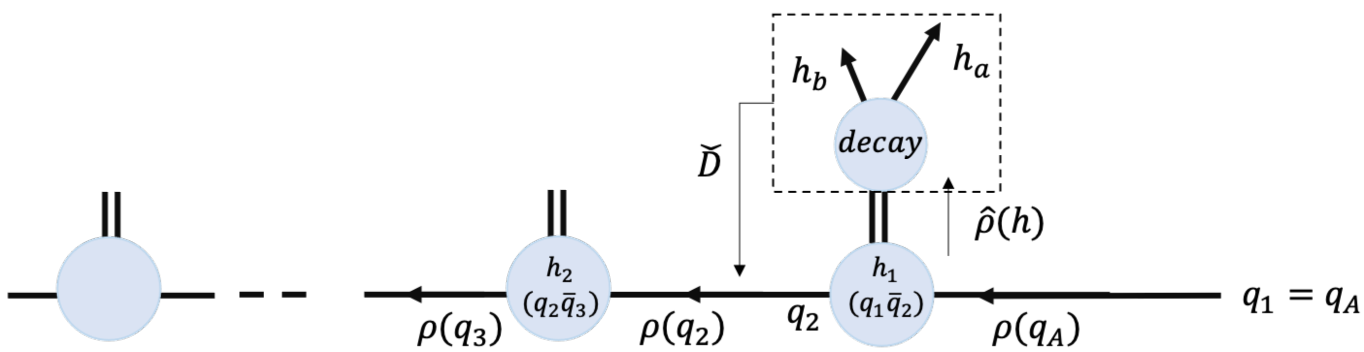
*see AK, X. Artru, Z. Belghobsi, F. Bradamante, A. Martin PRD 100 (2019) 1, 014003*

# 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)



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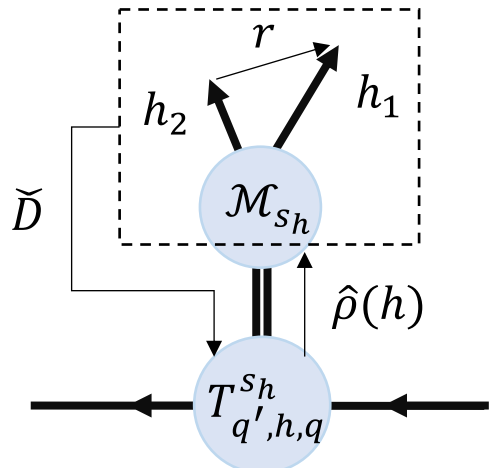



$\rho, K^*, \omega, \phi$

inv. mass

spin matrix

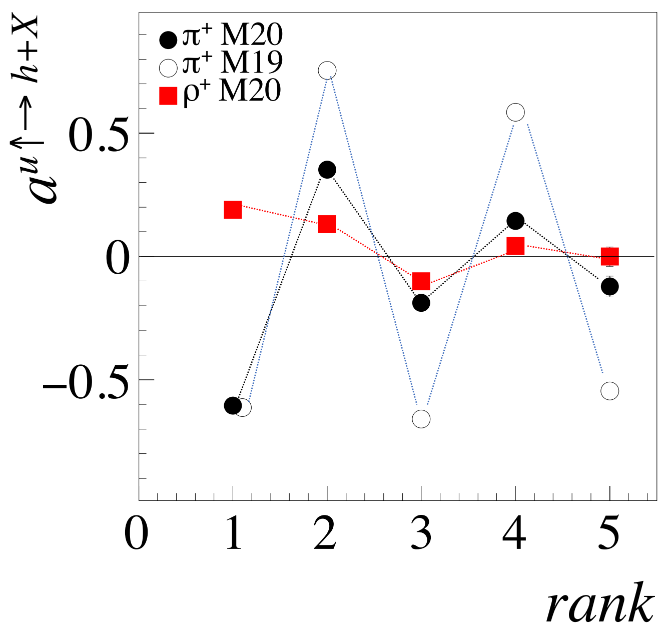
hadron {h, $M_h$, $Z$, $\boldsymbol{p}_T$, $\hat{\rho}(h)_{3\times 3}$ }

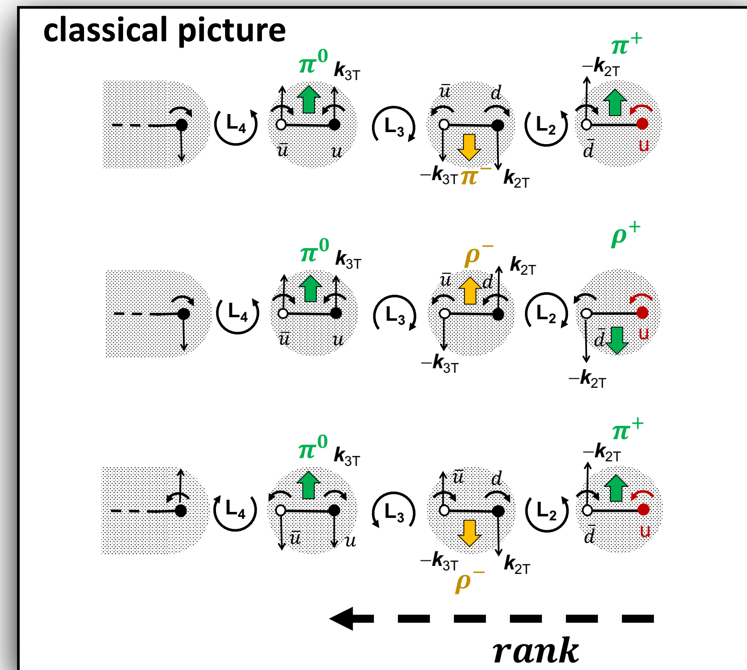
quark' $\{q', k', \rho(\boldsymbol{S}_{q'})\}$

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

| | |
|---|---|
| **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 $q'$ | $\rho(\boldsymbol{S}_{q'}) = \breve{D}_{s_h s_h'}\, T^{s_h'}_{q',h,q}\rho(\boldsymbol{S}_q)\mathrm{T}^{s_h\dagger}_{q',h,q}$ |

# Collins analysing power as function of rank




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