May 24, 2022
Pavia, Italy

Adding vector meson production to polarized string fragmentation in PYTHIA

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in collaboration with Leif Lönnblad

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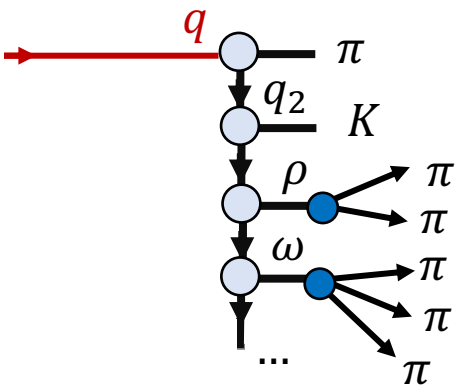
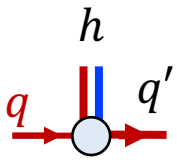
Istituto Nazionale di Fisica Nucleare

Polarized quark fragmentation in PYTHIA



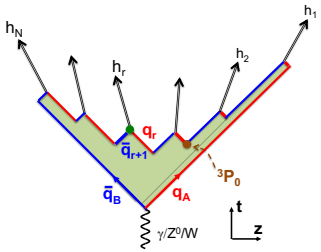
The recursive string+$^3P_0$ model of hadronization



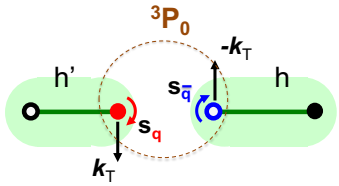
«elementary splitting»

- described by a splitting amplitude
- based on

Lund string model



$^3P_0$ mechanism



- uses the density matrix formalism
- production of

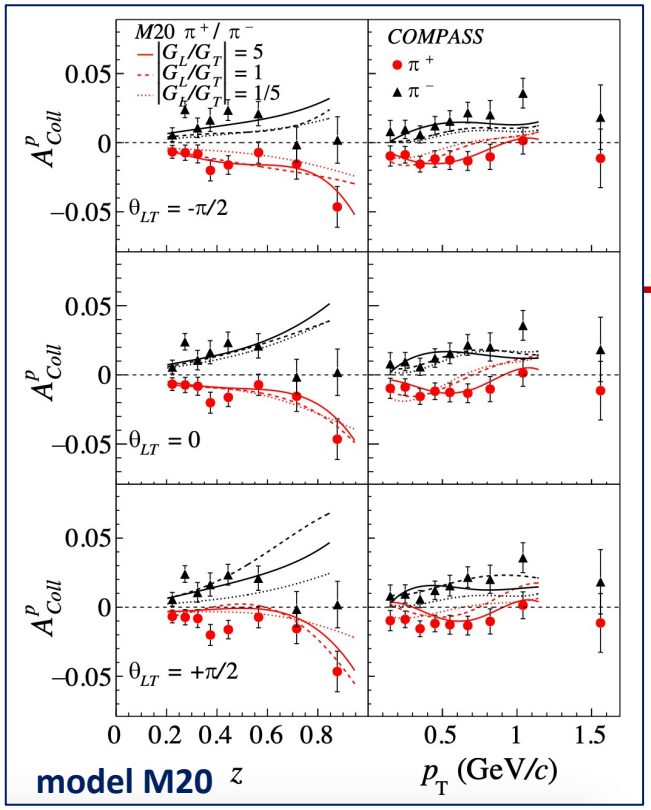
  PS mesons: **model M19**

  AK, Artru, Belghobsi, Martin, Bradamante, PRD100 (2019) no.1, 014003

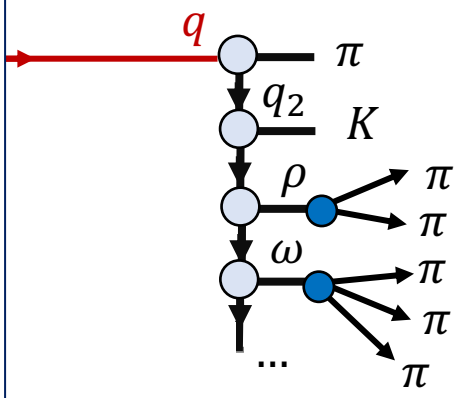
  PS + VM: **model M20** (the most recent)

  AK, Artru, Martin, *PRD104 (2021) 11, 114038*

Polarized quark fragmentation in PYTHIA



Example: *comparison of M20 (rescaled) with Collins asymmetries from COMPASS [Kerbizi, Artru, Martin, PRD104 (2021) 11, 114038]*



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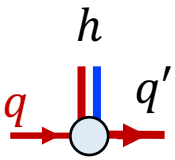

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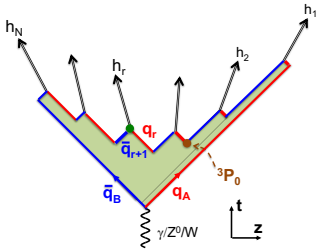

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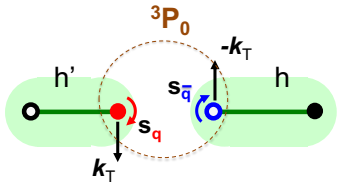

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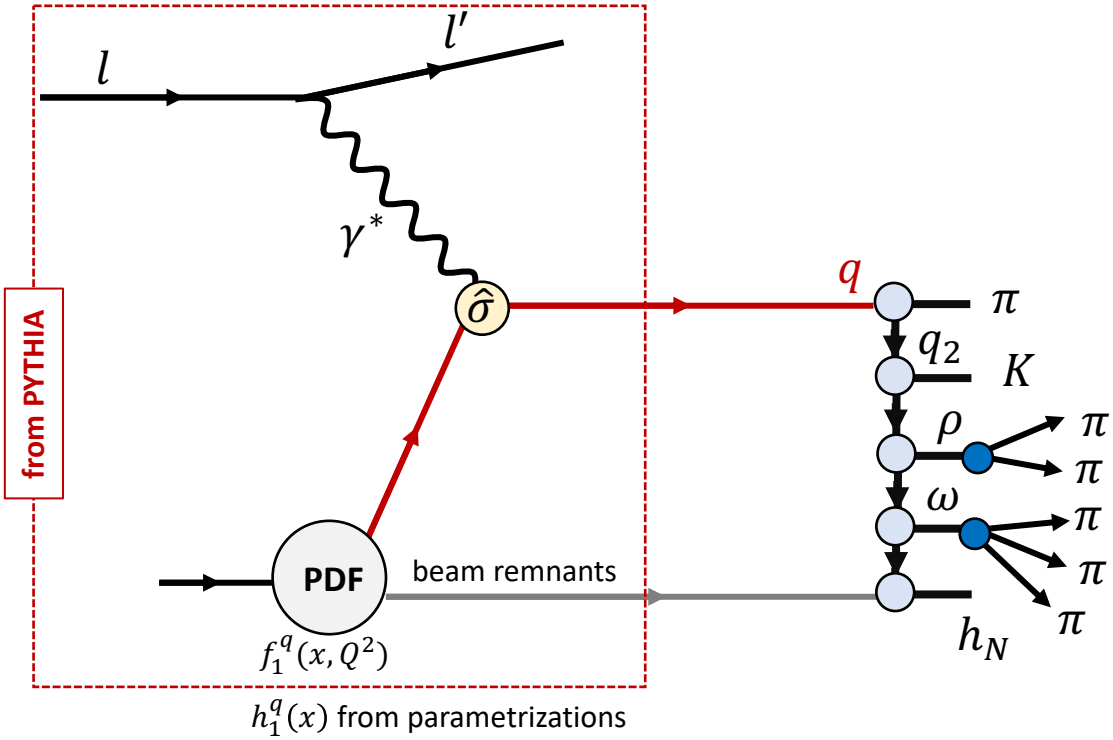
The string+$^3P_0$ model implemented in **stand alone MC** programs used to

- study the model predictions
- compare with data (SIDIS and e^+e^-) → needs rescaling

(no transversity PDF for SIDIS)

Polarized quark fragmentation in PYTHIA



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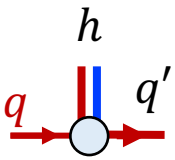

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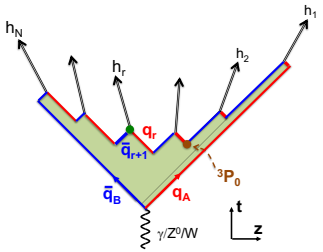

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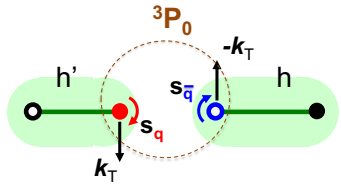

M19 implemented in PYTHIA 8.2 for the SIDIS process
→ **StringSpinner** *[Kerbizi, Lönnblad, CPC 272 (2022) 108234]*
- spin effects for PS meson production
- parametrizations of transversity PDFs

this talk: first interface of M20 with PYTHIA 8
(tested with version 8.244)

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Implementation of spin effects in PYTHIA

- PYTHIA generates a DIS event → we go in the GNS
- A string is stretched between struck q and remnant
- The polarization vector $\mathbf{S}_{\mathrm{qT}}$ is calculated using the parametrizations of transversity h_1^q for u^{val} and d^{val}
- The polarization $\mathbf{S}'_{\mathrm{q}}$ of scattered q is reduced and reflected according to QED
- PYTHIA starts hadronization and emits e.g. h_1 = PS
- Accept h_1 with the $^3P_0$ weight

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

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

μ = complex mass
$\mathrm{Im}(\mu) \neq 0$ for T spin effects
$\mathrm{Re}(\mu) \neq 0$ for L spin effects

- Calculate density matrix $\rho(q_2)$ of q_2 by using string+$^3P_0$
- PYTHIA emits e.g. h_2 = VM
- Accept h_2 with the $^3P_0$ weight

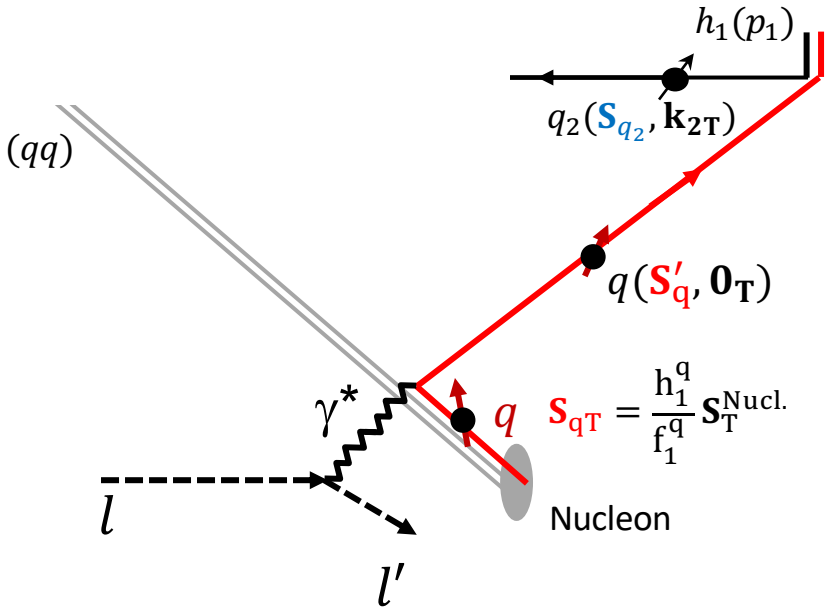
$$w_{\mathrm{VM}} = \left[1 + f_L \hat{a}\ \mathbf{S}_{q_2} \cdot \left(\hat{z}\times\mathbf{k}_{3\mathrm{T}}\right)\right]/2$$

$$f_{\mathrm{L}} = \frac{\left|{}^{G_L}/_{G_T}\right|^2}{2+\left|{}^{G_L}/_{G_T}\right|^2}$$

G_L = coupling of q to VM with L pol. (w.r.t string axis $\hat{z}$)
G_T = coupling of q to VM with T pol. (w.r.t string axis)
$f_{\mathrm{L}} \simeq$ fraction of VMs with L pol.

- The hadronization chain continued till the exit condition is called by PYTHIA

Spin effects are activated for the production of all VMs and PS



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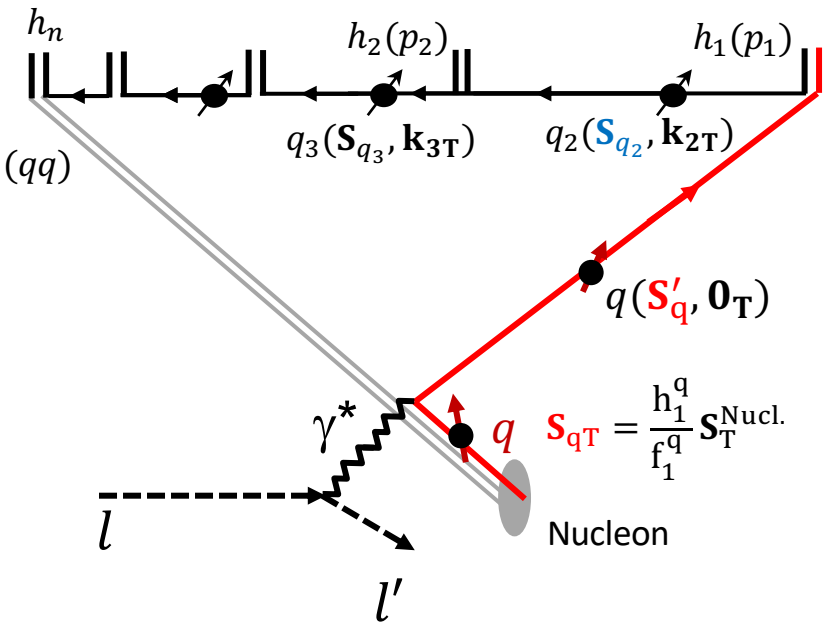

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Implementation of spin effects in PYTHIA: DECAYS

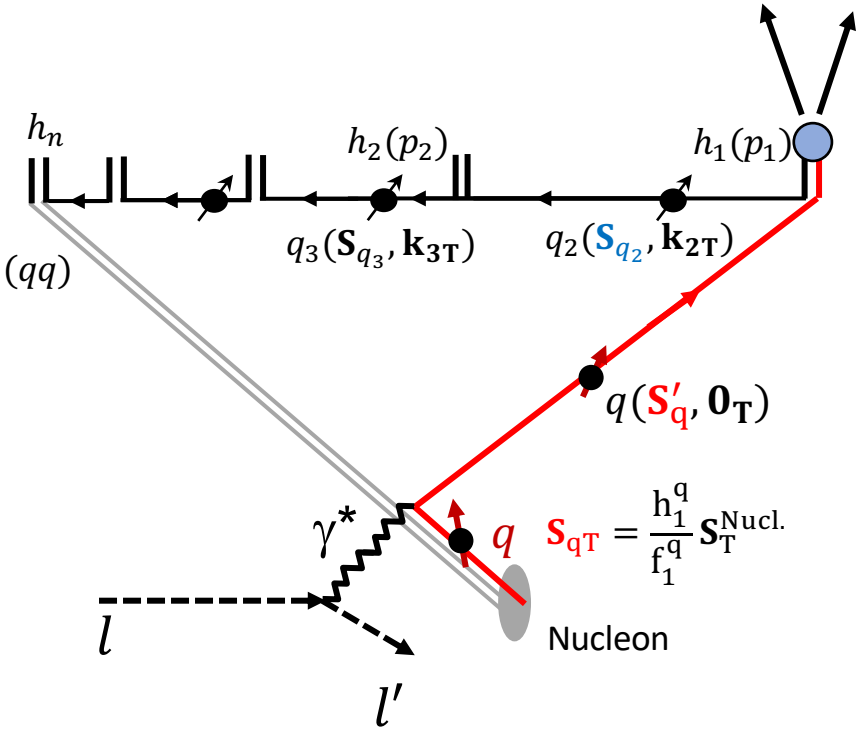
- After completion of string fragmentation PYTHIA starts decays
- If a PS meson is to be decayed, e.g. h_1 →let PYTHIA handle it
- If a VM is to be decayed, e.g. h_2

i. calculate the spin density matrix of q_2
ii. calculate the density matrix of the VM
iii. generate the polarized decay following string+$^3P_0$ and pass the information to PYTHIA

- The density matrix of the VM (hence the decay) depends on

$$\left|{}^{G_L}/_{G_T}\right|, \qquad \theta_{LT} = \arg\left(\frac{G_L}{G_T}\right)$$

θ_{LT} = **oblique (LT) polarization**



Spin effects in decays are activated for the hadronic decays of ρ, K*, ω, ϕ

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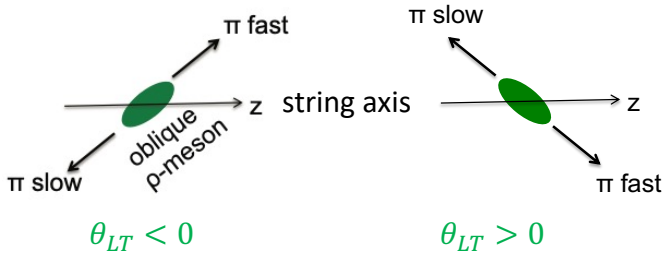
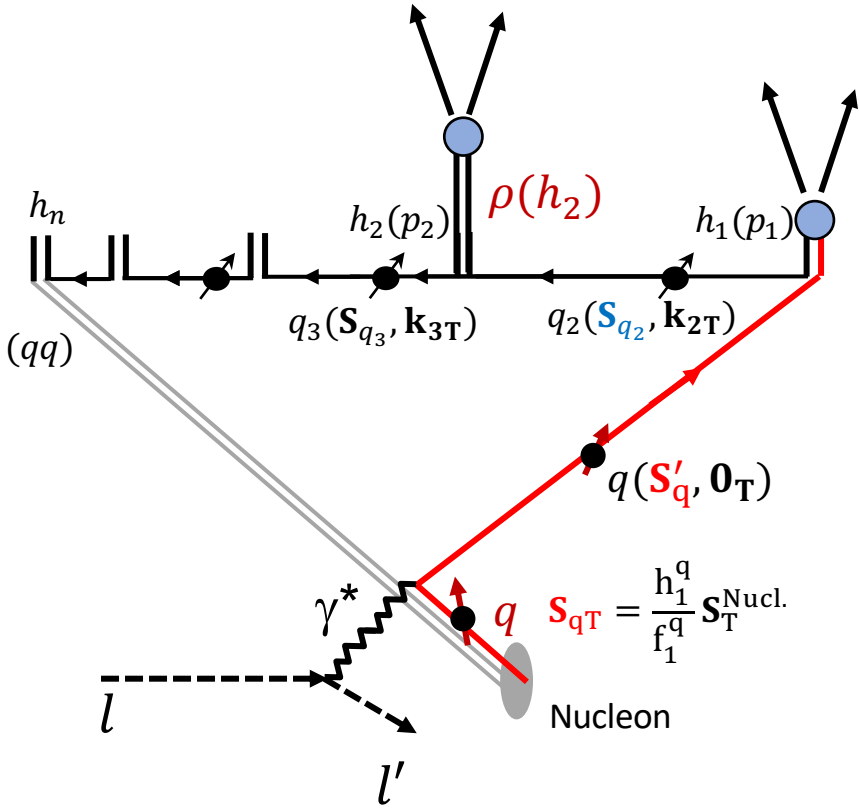


$\theta_{LT} < 0$ $\theta_{LT} > 0$



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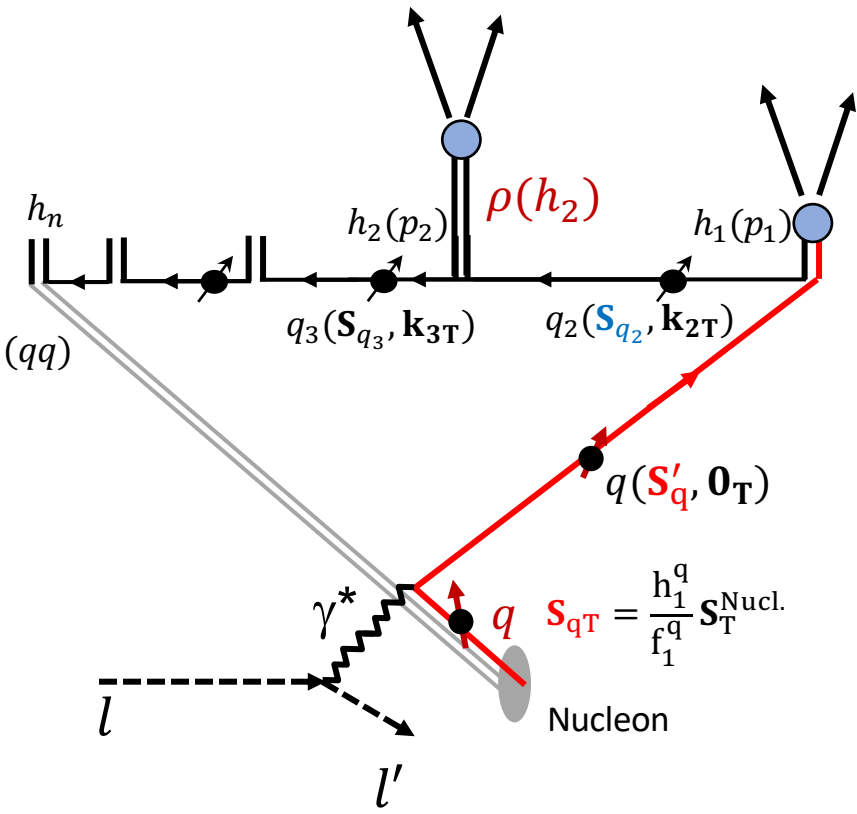


This recipe is at variance with M20:
the decay of the VM must be simulated right after its production

(Collins '88, Knowles '88)

Here → approximated recipe (technical reason), but the Collins-Knowles recipe

- does not affect the spin transfer along the quark chain *(see arxiv: 2004.00524)*
- has a negligible effect on TSA *(verified with M20)*

Validation of StringSpinner + M20 - setup

Simulations of DIS events of 160 GeV/c μ^- on p target

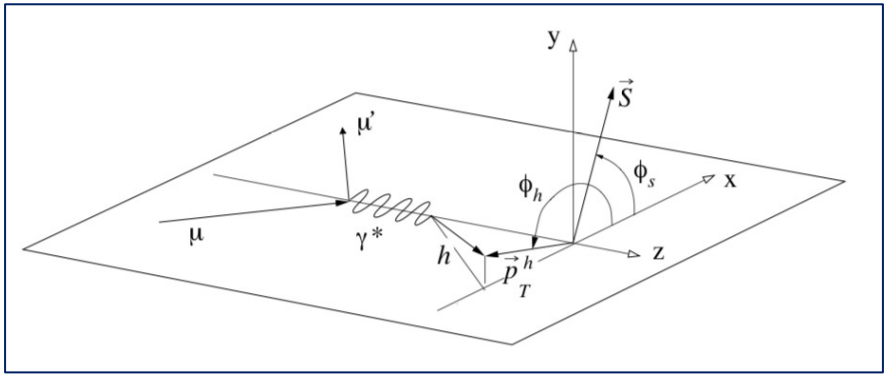
parton showers switched OFF

intrinsic $\vec{k}_{\mathrm{T}}$ swtiched OFF

To compare with M20 select

$(\mathrm{ud})_0 \;\!-\!\!-\!\!-\!\!- -u^{\uparrow}$ strings

u fully transversely polarized

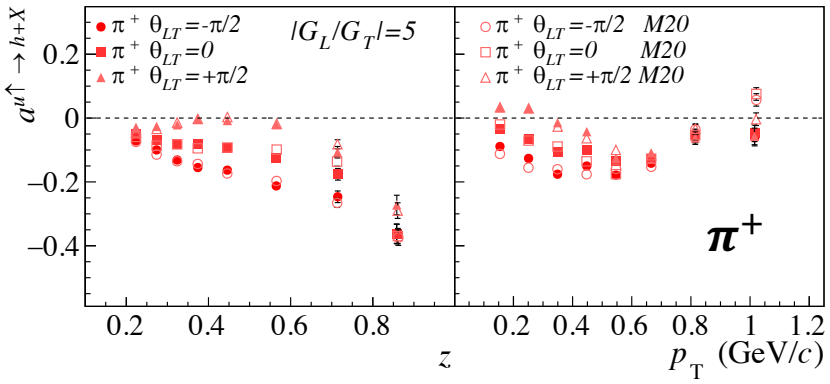


Relevant free parameters for string fragmentation

M20 setting, as in *Kerbizi, Artru, Martin, PRD104 (2021) 11, 114038*

StringZ:aLund	0.9	standard PYTHIA parameters
StringZ:bLund	0.5 $(\mathrm{GeV/c^2})^{-2}$	
StringPT:sigma	0.37 $\mathrm{GeV/c}$	
StringPT:enhancedFraction	0.0	
StringPT:enhancedWidth	0.0 $\mathrm{GeV/c}$	
$\mathrm{Re}(\mu)$	0.42 $\mathrm{GeV/c^2}$	**spin effects**
$\mathrm{Im}(\mu)$	0.76 $\mathrm{GeV/c^2}$	
$\lvert G_L/G_T \rvert$	5, 1, 1/5	
θ_{LT}	$-\pi/2$, 0, $+\pi/2$	

Validation of transverse spin effects in StringSpinner + M20

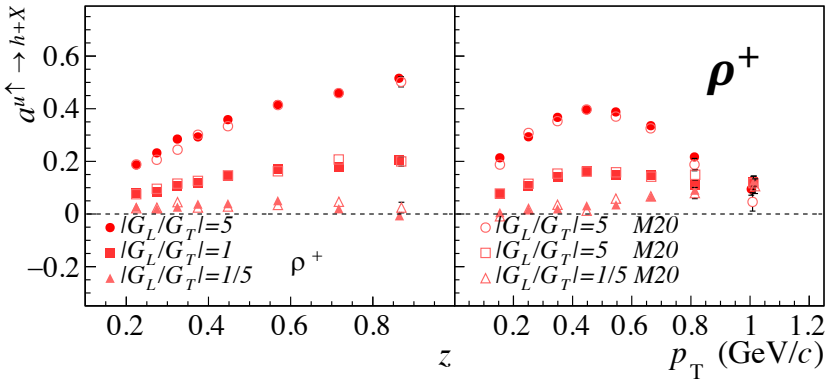


Collins analysing power for π^+ ok

same analysing power

same dependence on free parameters

ok also π^-



Collins analysing power for ρ^+ ok

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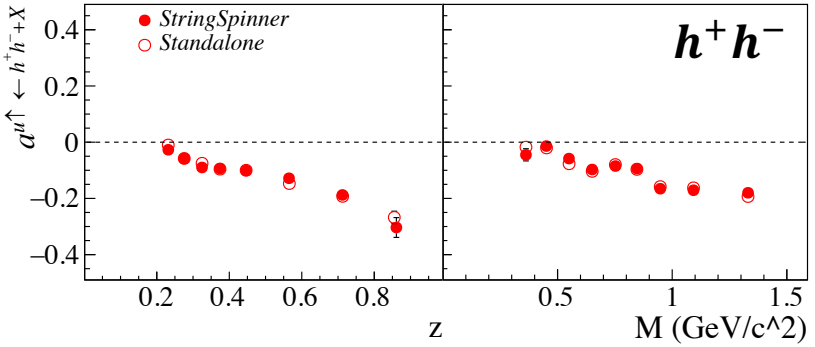
ok also ρ^0, ρ^-



Dihadron analysing power for h^+h^- ok

same analysing power

same spin effects as M20!

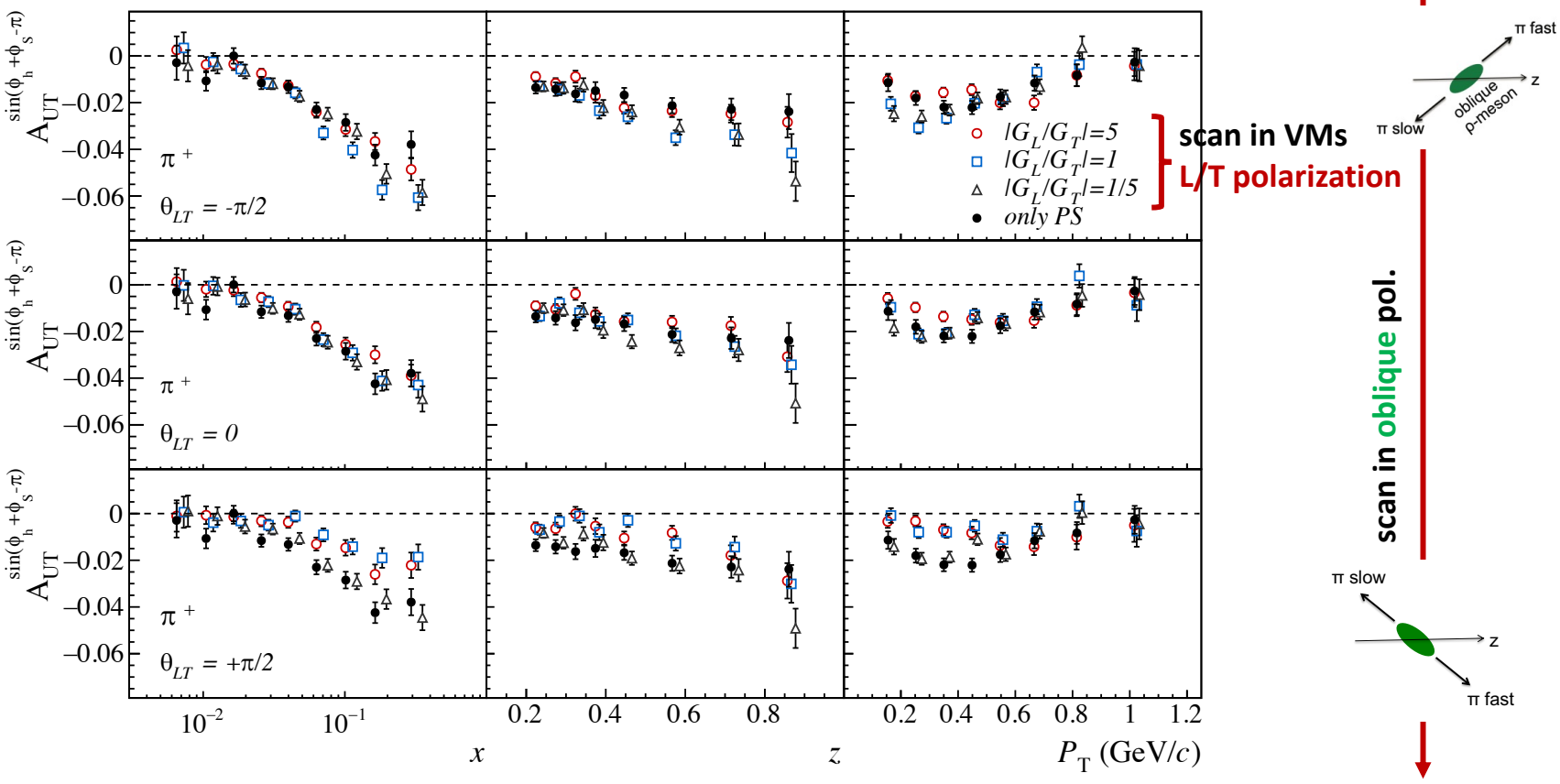
also same kinematic distributions (not shown)

(selection of)

Results from simulations of T polarized SIDIS on protons

COMPASS and HERMES kinematics
parton showers switched OFF
intrinsic $\vec{k}_{\mathrm{T}}$ swtiched OFF

Sensitivity of TSA to free parameters: Collins asymmetry



Simulations of the Collins asymmetry for π^+ in the COMPASS kinematics

- **stable results** against changes of parameters
- similarities with StringSpinner+M19 for some choices of the parameters

Caveat:

StringSpinner + M19: $\mu = (0.78 + \mathrm{i}0.38)\ \mathrm{GeV/c^2}$

StringSpinner + M20: $\mu = (0.42 + \mathrm{i}0.76)\ \mathrm{GeV/c^2}$

$\mathrm{Im}(\mu)$ differs by a factor of 2

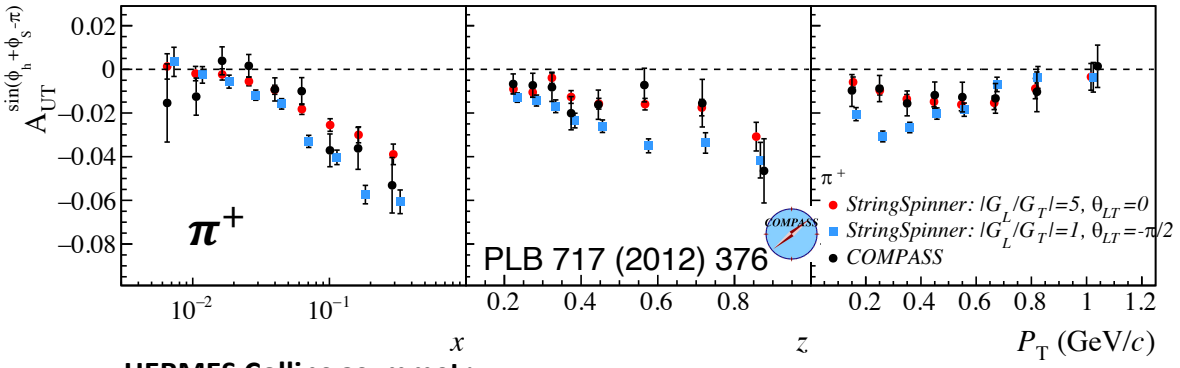
each tuned to reproduce the measured TSA

which value?

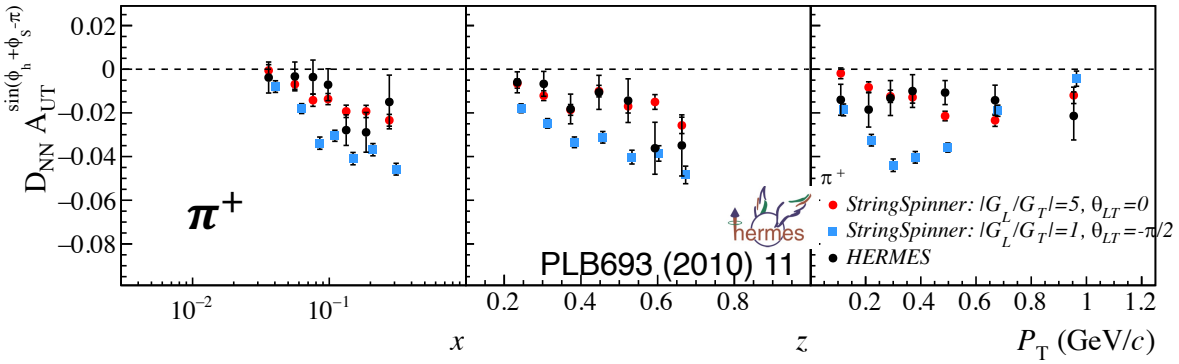
→ e^+e^- data **and e^+e^- simulations!**

Comparison with SIDIS data on TSA

COMPASS Collins asymmetry



HERMES Collins asymmetry



Examples with two choices of free parameters

i. $\left|\frac{G_L}{G_T}\right| = 5, \theta_{LT} = 0 \rightarrow$ gives a good X^2

ii. $\left|\frac{G_L}{G_T}\right| = 1, \theta_{LT} = -\frac{\pi}{2} \rightarrow$ gives a bad X^2

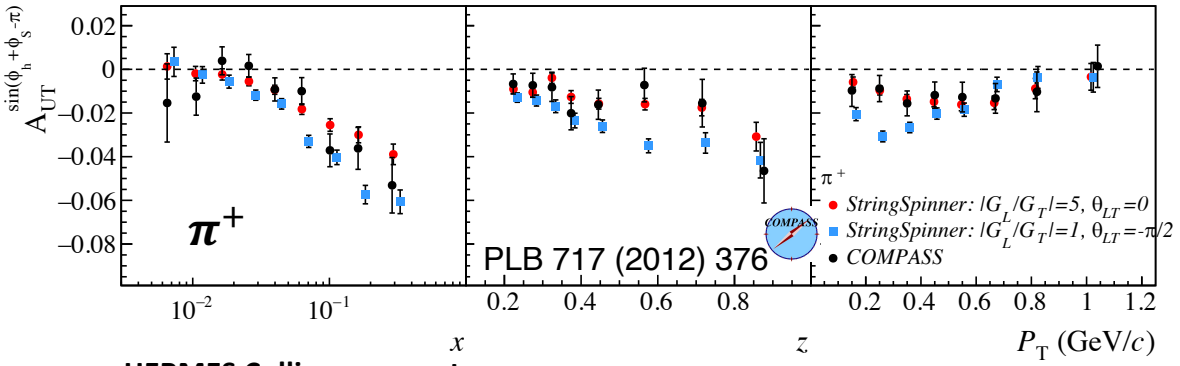
Satisfactory description of SIDIS data

also for other values of $\left|\frac{G_L}{G_T}\right|$ and θ_{LT}

→ more precise SIDIS data would be needed to fix them

Comparison with SIDIS data on TSA

COMPASS Collins asymmetry



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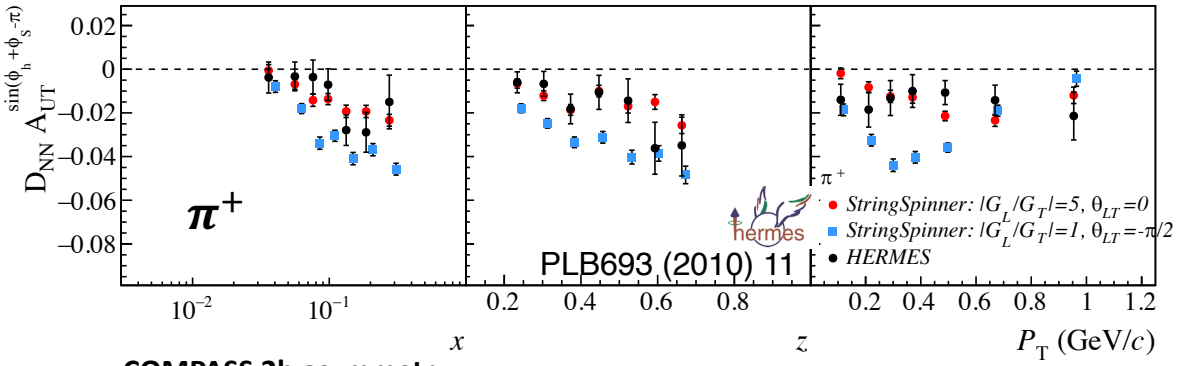
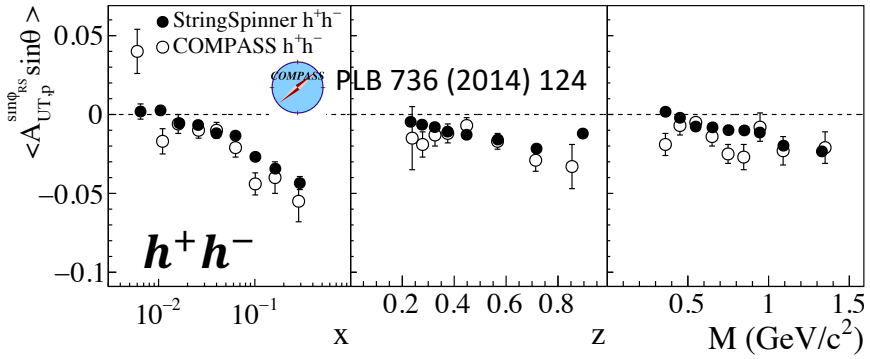


COMPASS 2h asymmetry



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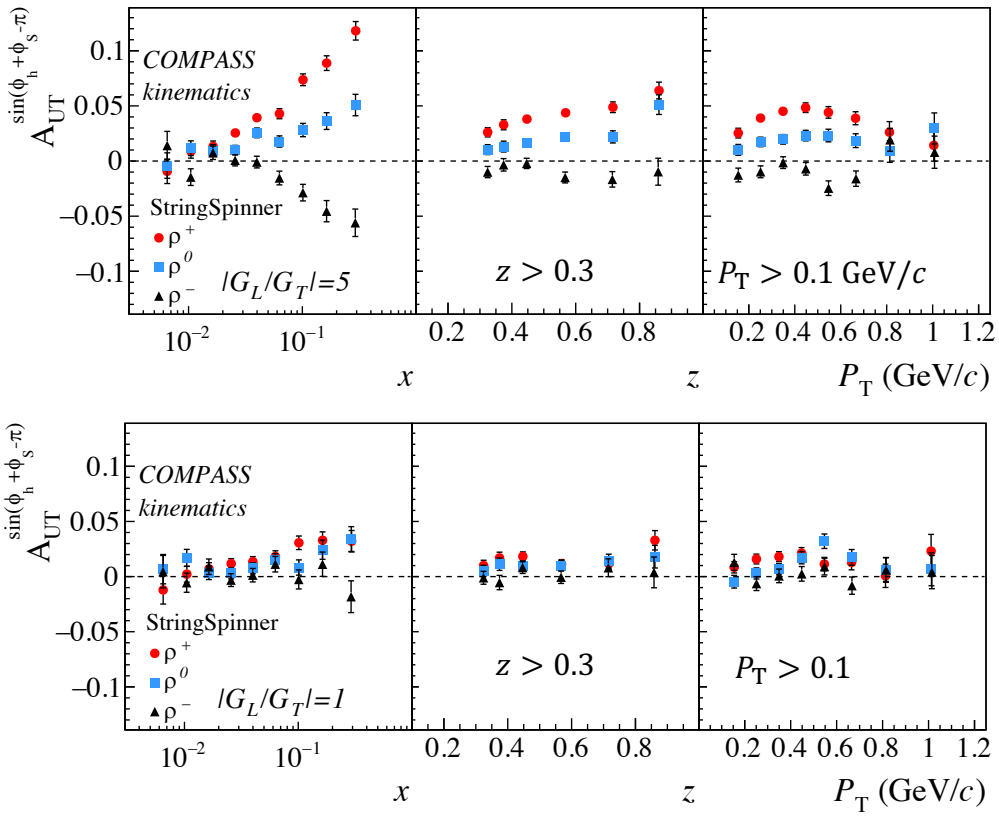
Good description of 2h asymmetry

weak depenence on $\left|\frac{G_L}{G_T}\right|$ and θ_{LT}

Collins asymmetries for inclusive ρ mesons in SIDIS



Strong dependence on $|G_L/G_T|$!

Large asymmetries when VM production with L polarization is favoured!

up to 10% at large x for ρ^+

For VM with T polarization → vanishing asymmetry (not shown here)

large variations with $|G_L/G_T|$

→ a precise measurement would help to fix the parameter

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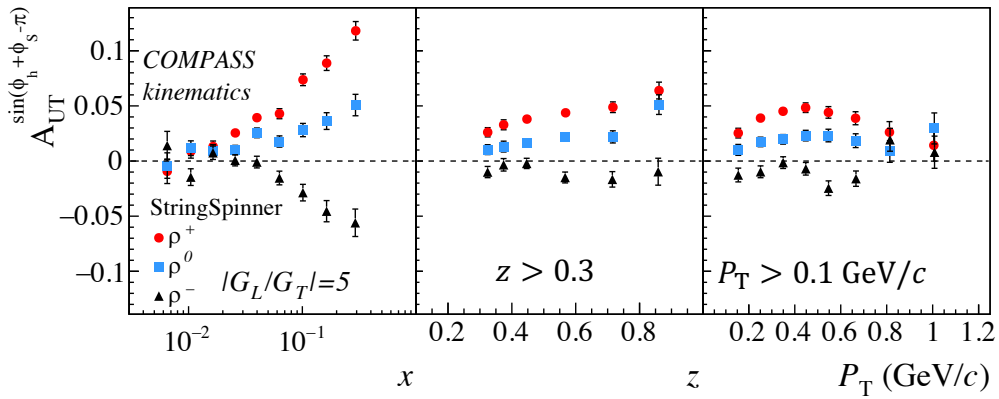
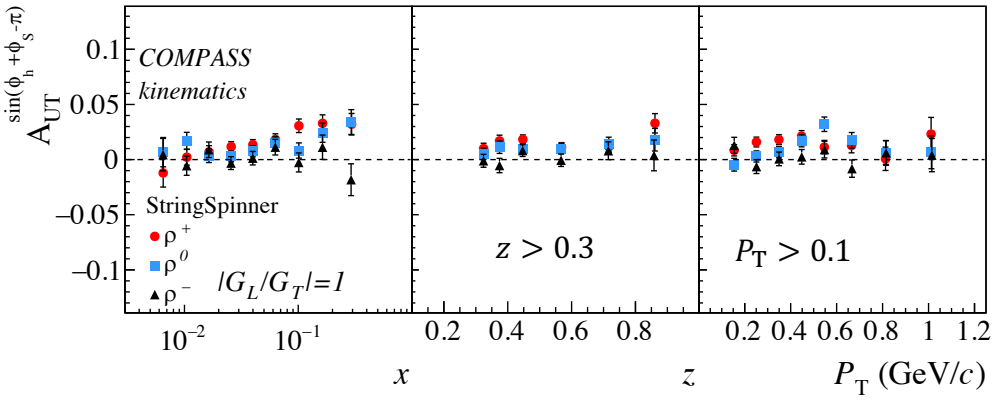
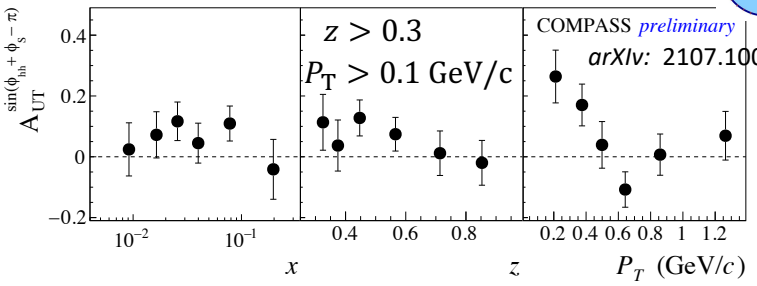




Collins asymmetry for ρ^0 from COMPASS



talk of F. Bradamante

interesting result,
same sign as simulations and similar average value

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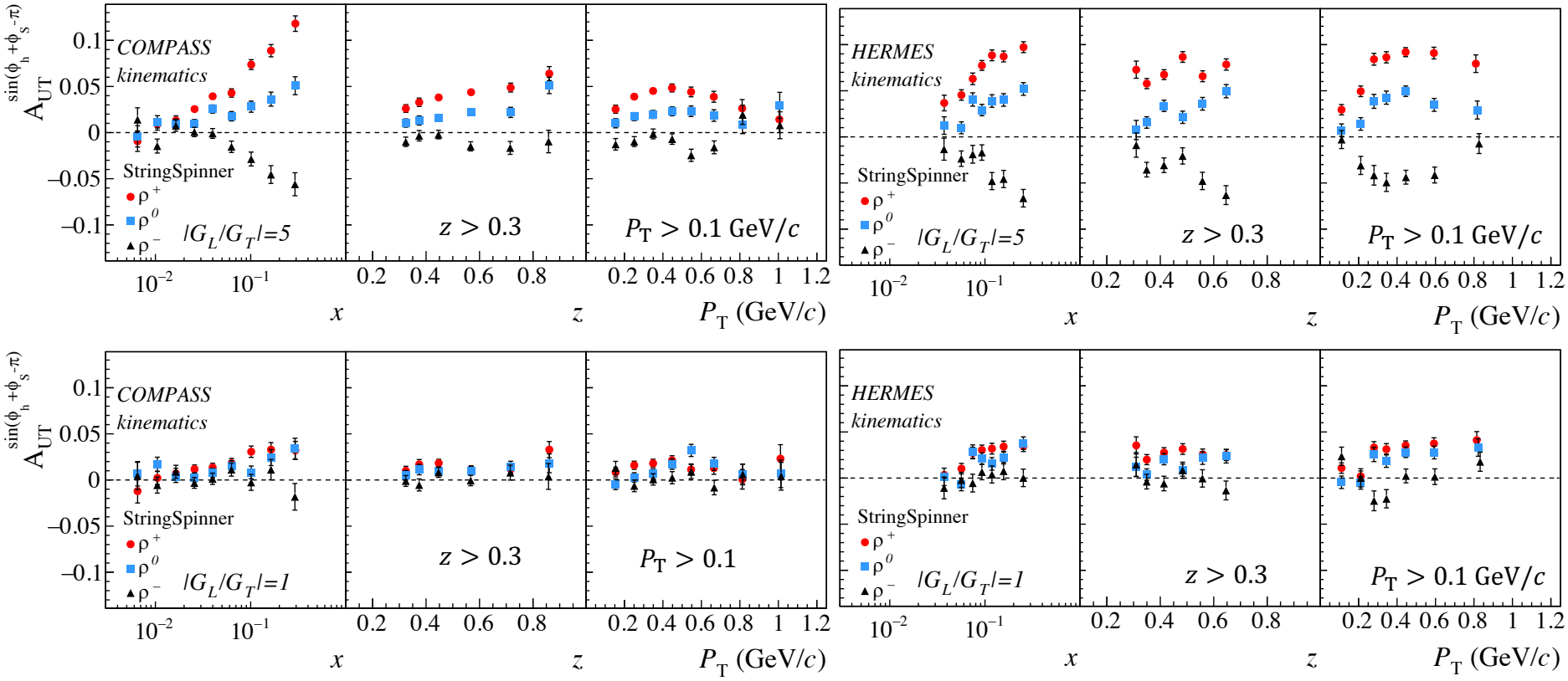
→ a precise measurement would help to fix the parameter

Collins asymmetries for inclusive ρ mesons in SIDIS



Strong dependence on $|G_L/G_T|$!

Large asymmetries when VM production with L polarization is favoured!

up to 10% at large x for ρ^+

For VM with T polarization → vanishing asymmetry (not shown here)

large variations with $|G_L/G_T|$

→ a precise measurement would help to fix the parameter

Conclusions

- The work on the systematic introduction of spin effects in the hadronization part of PYTHIA 8 is being continued

- A first major extension of StringSpinner for SIDIS: introduction of VM production in polarized string fragmentation by using the string+$^3P_0$ model

→ it gives promising results

hopefully, will be published soon..

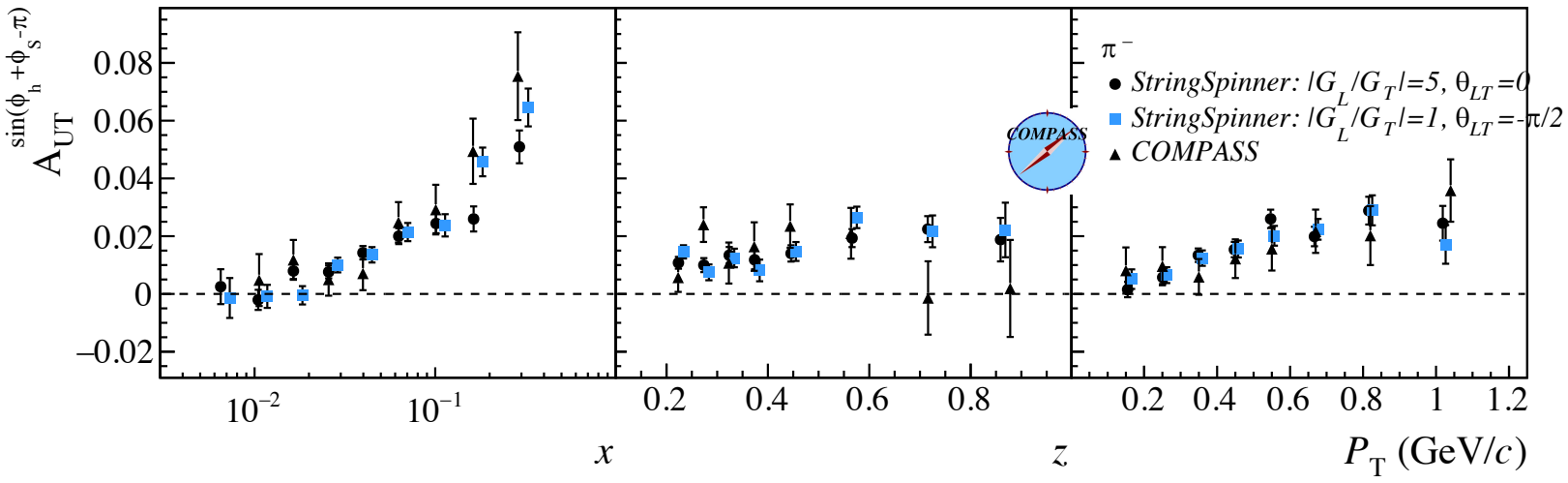
- The introduction of spin effects for the e^+e^- annihilation to hadrons is an important and essential next step to take

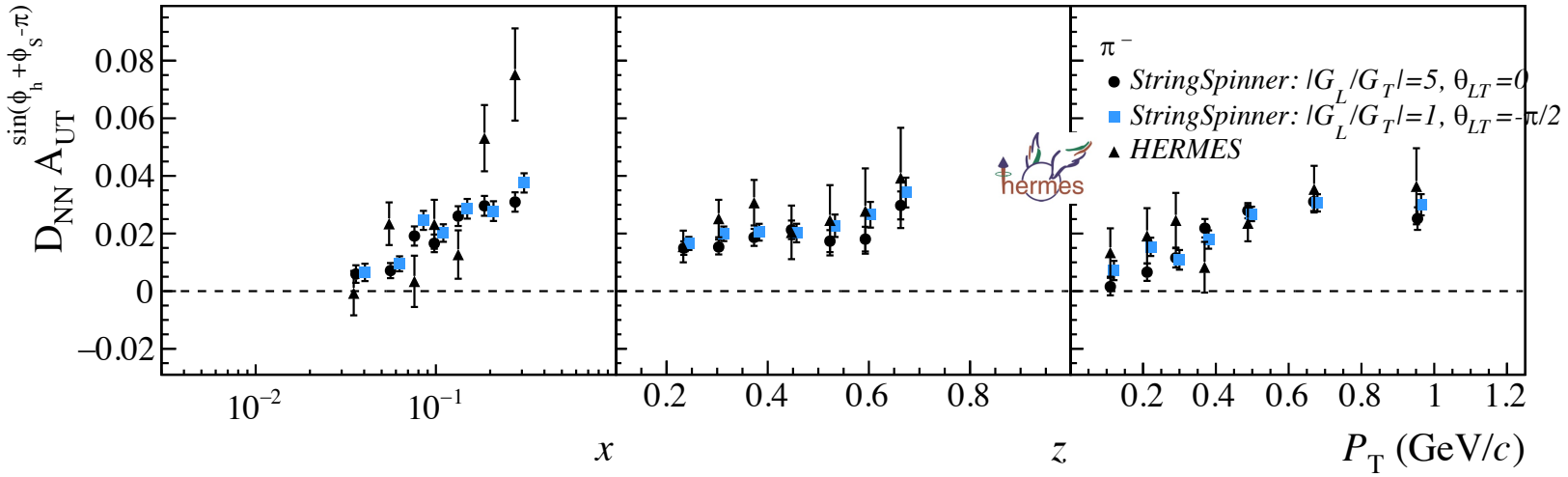
→ it would allow to better tune the free parameters of the string+$^3P_0$ model

many ideas and tools are already there..

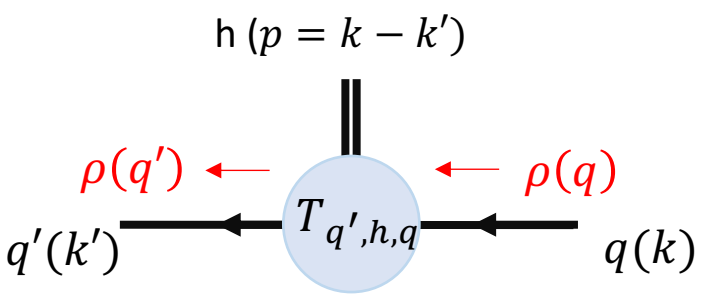
Backup

Comparison of Collins asymmetries for π^- with SIDIS data

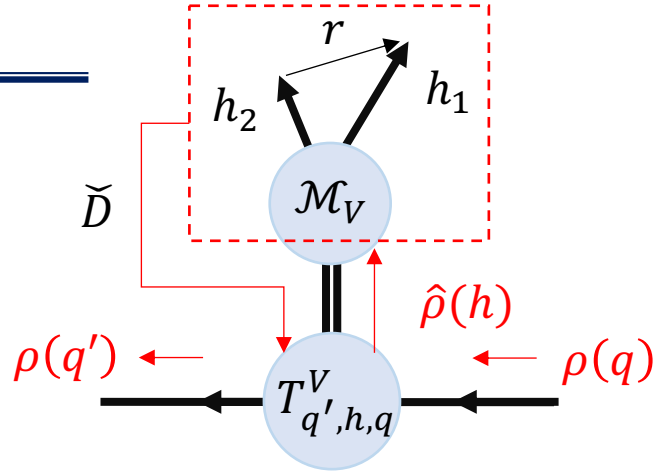




Elementary splitting in the string+$^3P_0$ model



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



M19: Emission of a PS meson (π, K, η, η')

AK, Artru, Belghobsi, Martin , PRD100 (2019) no.1, 014003

i) Introduce the Splitting Amplitude (2×2 matrix)

$$T_{q',h,q}(Z, \boldsymbol{p}_T|\boldsymbol{k}_T) = \mathrm{F}^{1/2}_{\mathrm{Lund}} \times \Gamma_h \times (\mu + \sigma_z \boldsymbol{\sigma} \cdot \boldsymbol{k}'_T)$$

coupling $^3P_0$ wave func.

ii) Generate h according to the Splitting Function

$$F_{q'hq}(Z, \boldsymbol{p}_T|\boldsymbol{k}_T, \boldsymbol{S}_q) = \mathrm{tr}\, T_{q',h,q}\, \rho(q)\, T^\dagger_{q',h,q}$$

iii) Calculate the density matrix of q'

$$\rho(q') \propto T_{q',h,q}\, \rho(q)\, T^\dagger_{q',h,q}$$

Couplings:

$\Gamma_h = \sigma_z$ → PS meson

$\Gamma_{h,\boldsymbol{V}} = G_L V_L^* \mathbf{1} + G_T \boldsymbol{V}_T^* \cdot \boldsymbol{\sigma}_T \sigma_z$ → VM with pol. $\boldsymbol{V}$

M20: Emission of a VM $(\rho, K^*, \omega, \phi)$

AK, Artru, Martin, PRD104 (2021) 11, 114038

i) Introduce the Splitting Amplitude (2×2 matrix)

$$T^V_{q',h,q}(M, Z, \boldsymbol{p}_T, s_h|\boldsymbol{k}_T) = \mathrm{F}^{1/2}_{\mathrm{Lund}} \times \Gamma_{h,V}\, (\mu + \sigma_z \boldsymbol{\sigma} \cdot \boldsymbol{k}'_T)$$

use the recipe of Collins '88 and Knowles '88 to

ii) Generate h according to the Splitting Function

$$F_{q'hq}(M, Z, \boldsymbol{p}_T\, |\boldsymbol{k}_T, \boldsymbol{S}_q) = tr\, T^V_{q',h,q} \rho(q) T^{V\,\dagger}_{q',h,q}$$

iii) Calculate density matrix of h

$$\hat{\rho}_{VV'}(h) \propto tr\, T^V_{q',h,q}\, \rho(q)\, \mathrm{T}^{V'\dagger}_{q',h,q}$$

iv) Simulate the polarized decay

$$dN/d\Omega \propto \mathcal{M}_V\, \hat{\rho}_{VV'} \mathcal{M}^\dagger_{V'}$$

v) Bring decay information back to q'

$$\breve{D}_{V'V} = \mathcal{M}^\dagger_{V'} \mathcal{M}_V$$

vi) Calculate density matrix of q'

$$\rho(q') = \breve{D}_{VV'}\, T^{V'}_{q',h,q} \rho(q) \mathrm{T}^{V\dagger}_{q',h,q}$$

List of free parameters in the string+$^3P_0$ model

Spin effects

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

Spinless Lund splitting Function

Elementary splitting

$$q(k) \rightarrow h(p) + q'(k')$$

Spinless Splitting Function

$$F_{\mathrm{Lund}}^{1/2}(Z, \boldsymbol{p}_T) = C_{q',h,q}^{1/2}(1-Z)^{a/2} \exp\left(-\frac{b_L \varepsilon_h^2}{2Z}\right) \exp -b_T\, \boldsymbol{k}_T'^{\,2}$$

$$\varepsilon_h^2 = m_h^2 + \boldsymbol{p}_T^2, \qquad \boldsymbol{p}_T = \boldsymbol{k}_T - \boldsymbol{k}_T', \qquad Z = p^+/k^+$$

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

Vector Meson production

$$2|G_T|^2 + |G_L|^2 = \begin{cases} 0.62 & \text{light mesons} \\ 0.725 & \text{strange mesons} \end{cases}$$

$|G_L/G_T| = 5{,}1{,}1/5$
$\theta_{LT} = -\frac{\pi}{2}, 0, +\frac{\pi}{2}$