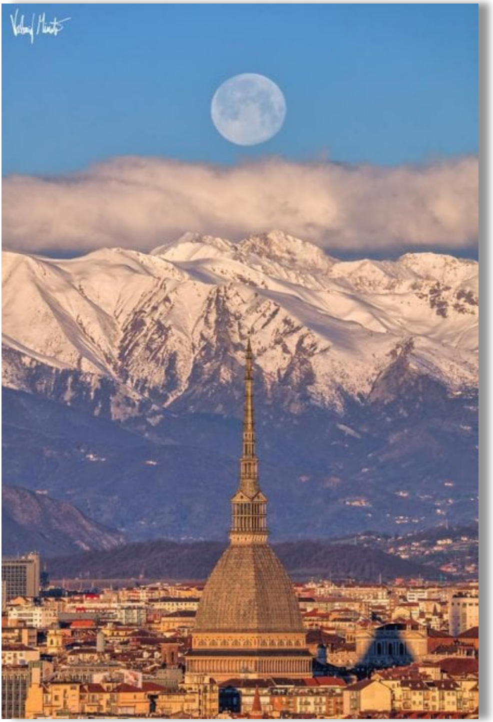
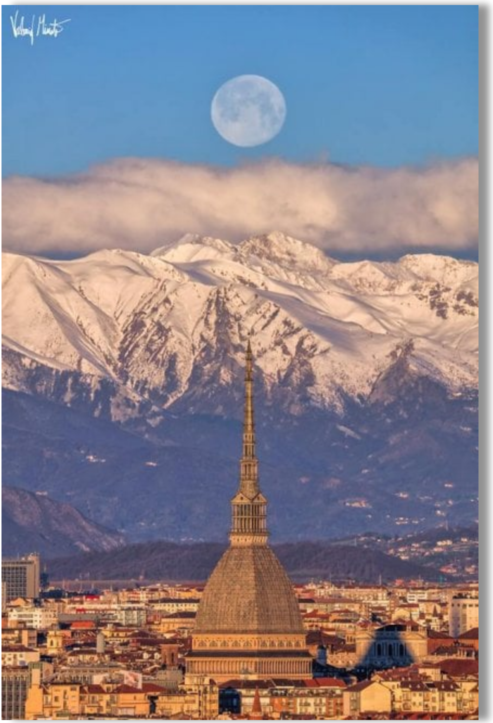


Tuesday 9th April 2019,
DIS 2019, Torino

Inclusion of the $^3P_0$ model in PYTHIA 8

Albi Kerbizi(*) and Leif Lönnblad(**)

(*)University of Trieste and INFN
(**)Lund University



Tuesday 9th April 2019,
DIS 2019, Torino

Inclusion of the $^3P_0$ model in PYTHIA 8

Outlook

String fragmentation and the $^3P_0$ model of polarized fragmentation

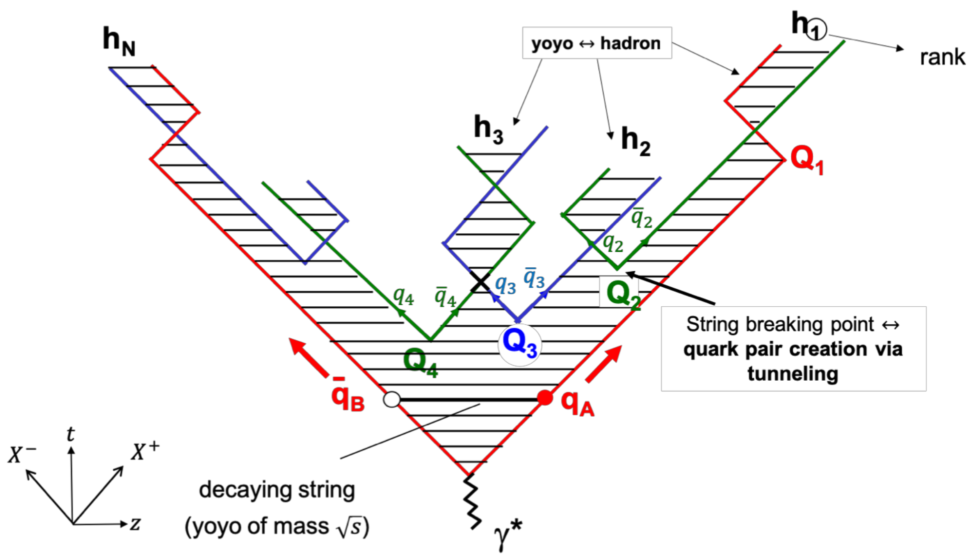
Interface with PYTHIA 8

Comparison with the results from the stand alone $^3P_0$ MC

SIDIS:

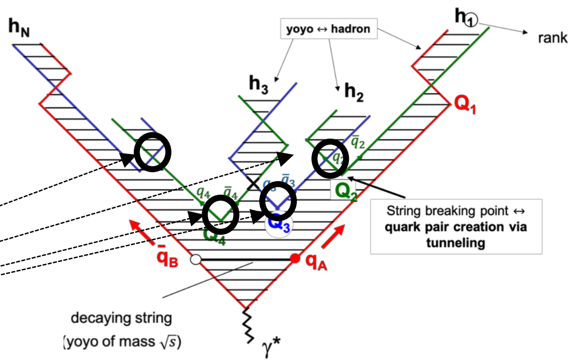
- Implementation of transversity
- Collins asymmetry for p and d

Symmetric Lund Model



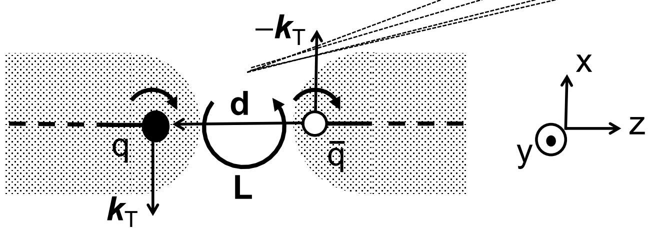
- In the Symmetric Lund Model (SLM) the hadronization process is the left-right symmetric decay of a relativistic string by tunnelling of $q\bar{q}$ pairs
- The string decay is simulated repeating recursively the splitting $q \rightarrow h + q'$
- The hadronization process in PYTHIA is based on this model
- The quark spin is presently neglected in hadronization in PYTHIA and in the other event generators while it is well known that it is at the origin of important effects
- It can be introduced using a model for the fragmentation of a polarized quark

The $^3P_0$ model

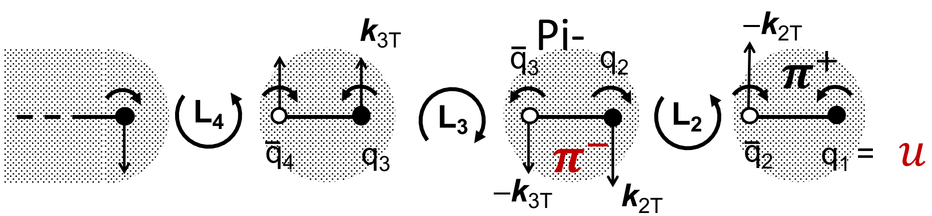


-The $q\bar{q}$ pair at string breaking is produced in the $^3P_0$ state, i.e. L=1, S=1 and J=0

a)



- For an initial quark with transverse polarization, this is **a model for the Collins effect**



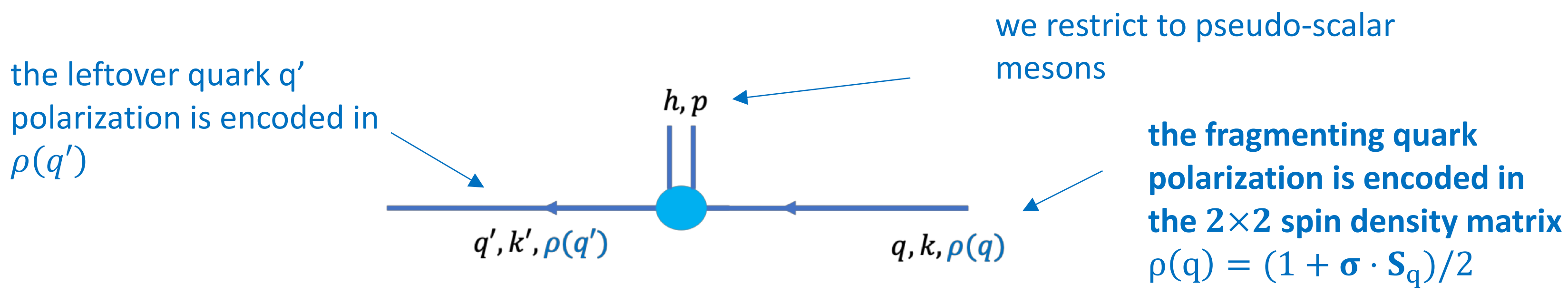
b) h3 h2 h1

The $^3P_0$ model

The quantum mechanical formalism has been explicitly written down and implemented in a stand alone Monte Carlo one year ago

AK, X. Artru, Z. Belghobsi, F. Bradamante and A. Martin, PRD97 (2018) no.7, 074010
AK, X. Artru, Z. Belghobsi and A. Martin, arXiv:1903.01736

The polarized splitting in the $^3P_0$ model



- Each polarized splitting is described by a polarized splitting function $F_{q'hq}(Z, \boldsymbol{p}_T; \boldsymbol{S}_q)$ which gives the probability that h is emitted with longitudinal momentum fraction $Z = p^+/k^+$ and transverse momentum $\boldsymbol{p}_T$ (referred to the string axis)

- The polarized splitting function is derived by a left-right symmetric $^3P_0$ splitting matrix $T_{q'hq}$ as

$$F_{q'hq}(Z, \mathbf{p}_T; \mathbf{S}_q) = \mathrm{tr}\left(T_{q'hq}\rho(q)T^\dagger_{q'hq}\right)$$
$$\mathbf{p}_T = \mathbf{k}_T - \mathbf{k}'_T$$

- The spin density matrix of q' is

$$\rho(q') = \frac{T_{q'hq}\rho(q)T^\dagger_{q'hq}}{\mathrm{tr}\left(T_{q'hq}\rho(q)T^\dagger_{q'hq}\right)}$$

The polarized splitting function in the $^3P_0$ model

The polarized splitting function is

$$F_{q',h,q} = \left|C_{q'hq}\right|^2 \left(\frac{1-Z}{\varepsilon_h^2}\right)^a \frac{e^{-b_L\varepsilon_h^2/Z}}{N_a(\varepsilon_h^2)} \frac{b_T^2}{\pi} \frac{e^{-b_T \mathbf{k}_T'^2}}{1+b_T|\mu|^2} \left[|\mu|^2 + \mathbf{k'}_T^2 - 2Im(\mu)\, \boldsymbol{S}\cdot(\hat{\mathbf{z}}\times\mathbf{k}'_T)\right]$$

as in the Lund Model implemented in PYTHIA

term arising from the $^3P_0$ mechanism
→ the spin effects are parametrized by **one complex parameter → $\boldsymbol{\mu}$**
(plays the role of a complex mass)

The free parameters of the model are:

- $b_L = 0.5\ GeV^{-2}$: linked to the probability of having a string cutting point
- $b_T = 5.17\ GeV^{-2}$: suppression of $q\bar{q}$ transverse momentum
- $a = 0.9$: suppression of large Z

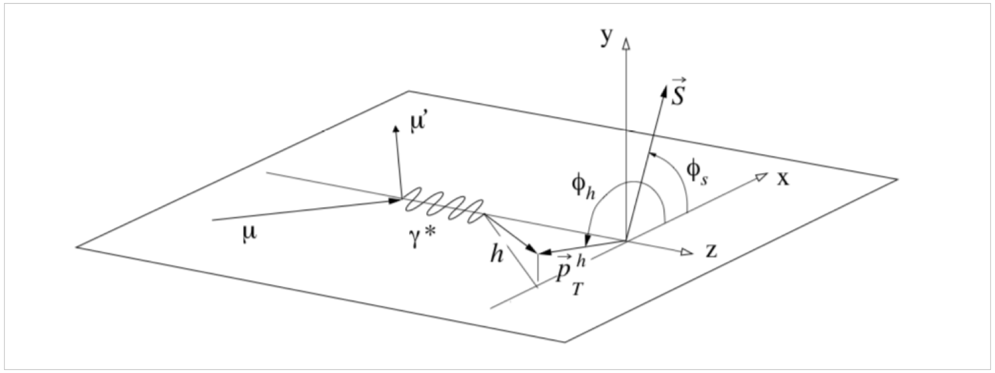
→ fixed comparing the stand alone simulation results with p_T^2 distributions from COMPASS and with unpolarized FFs extracted from global fits

- $\mu = (0.42 + i0.76)$GeV: complex mass responsible for the Collins effect

→ $Im(\mu)/|\mu|$ **fixed from comparison with e^+e^- Collins asymmetries**
→ $|\mu|^2$determined from the slope of the unpolarized p_T^2 distributions for $p_T^2 \to 0$

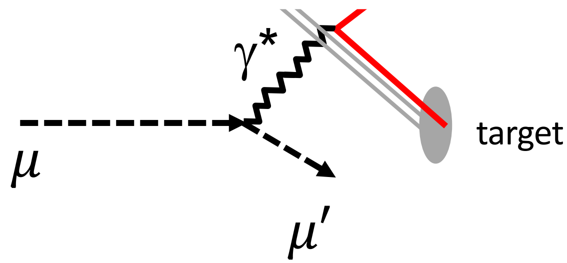
Details and results in arXiv:1903.01736

Interface of the $^3P_0$ model with PYTHIA 8



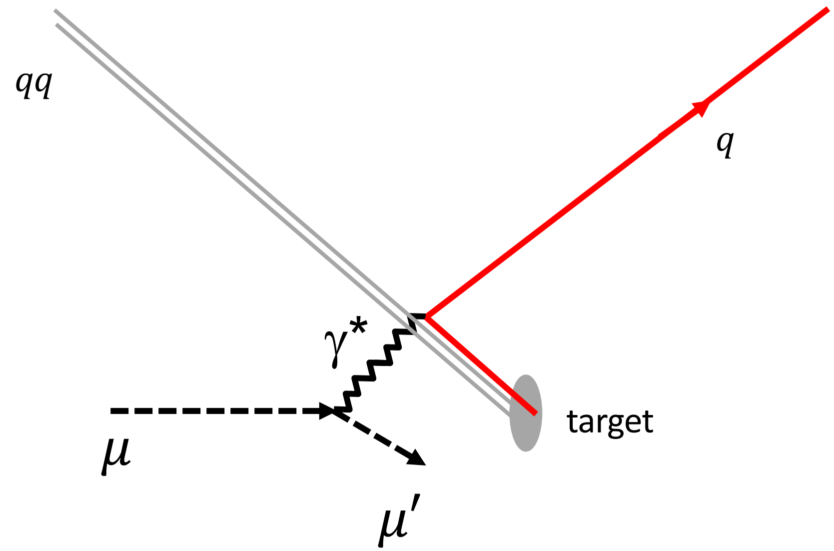
- The $^3P_0$ model has been interfaced for the first time with PYTHIA
- The interface consists of a C++ header file and of a Fortran module
- **It is implemented for DIS processes**
- Presently
    - parton showers and multiple interactions are switched off
    - primordial $\mathbf{k}_T$ is switched off
    - only pseudoscalar mesons are produced (the only spiecies currently treated according to the $^3P_0$ mechanism)

How the interface works



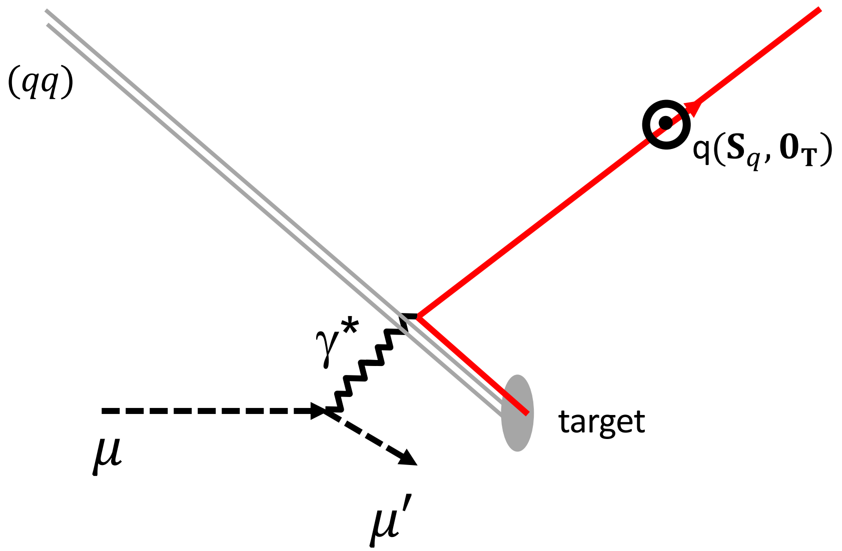
- PYTHIA generates a DIS event

How the interface works



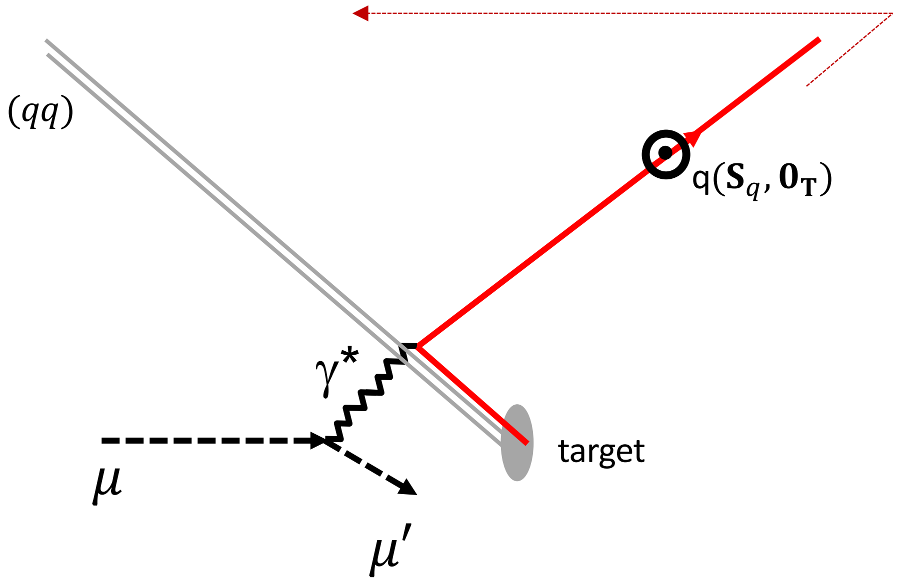
- PYTHIA sets up a string between the struck quark q and the remnant qq
- We boost the system in the string rest frame

How the interface works



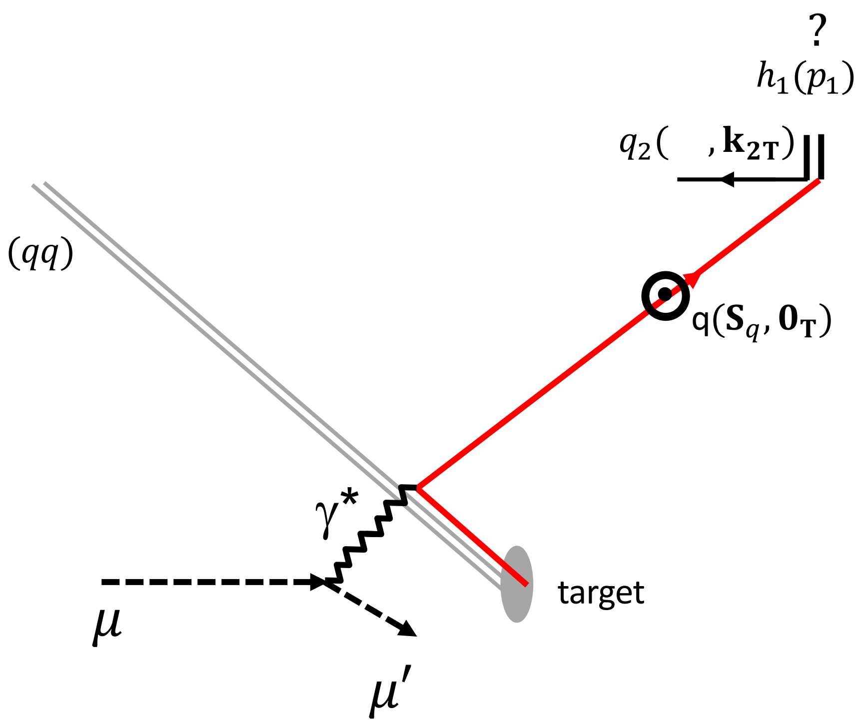
- PYTHIA sets up a string between the struck quark q and the remnant qq
- We boost the system in the string rest frame
- We choose the polarization of the active quark $\mathbf{S}_{\mathrm{q}}$

How the interface works



We force hadronization to evolve from the quark side to the remnant side

How the interface works

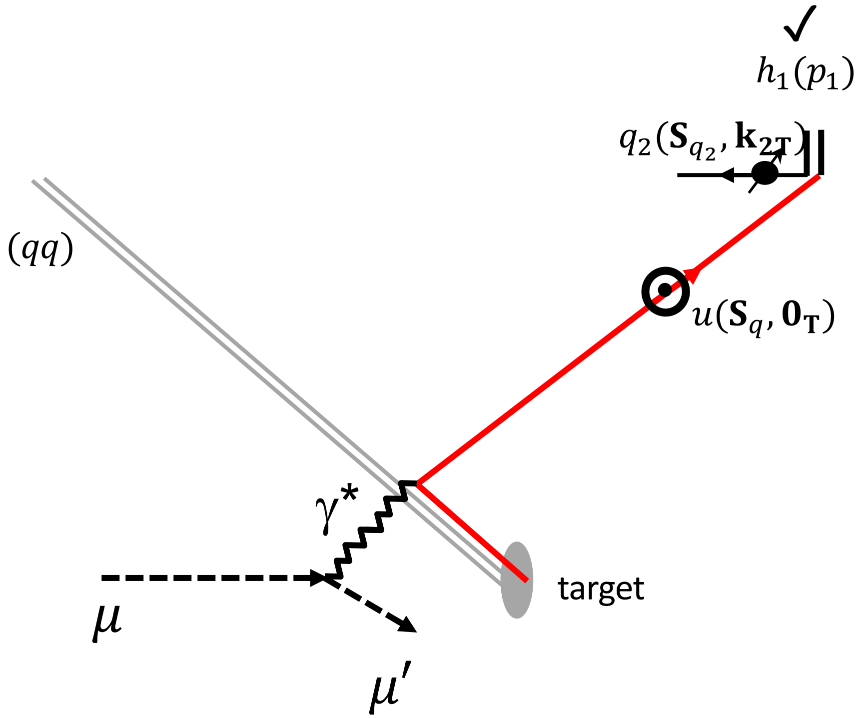


- PYTHIA emits a first hadron h_1 by generating a $q_2\bar{q}_2$ pair → from p_1 we calculate the momentum of q_2
- We accept the hadron according to the $^3P_0$ weight

$$w(\mathbf{S}_q, \mathbf{k}_{2\mathrm{T}}) = \frac{1}{2}\left[1 - \frac{2\,\mathrm{Im}(\mu)\mathbf{S}_q \cdot (\hat{z}\times\mathbf{k}_{2\mathrm{T}})}{|\mu|^2 + \mathbf{k}_{2\mathrm{T}}^2}\right]$$

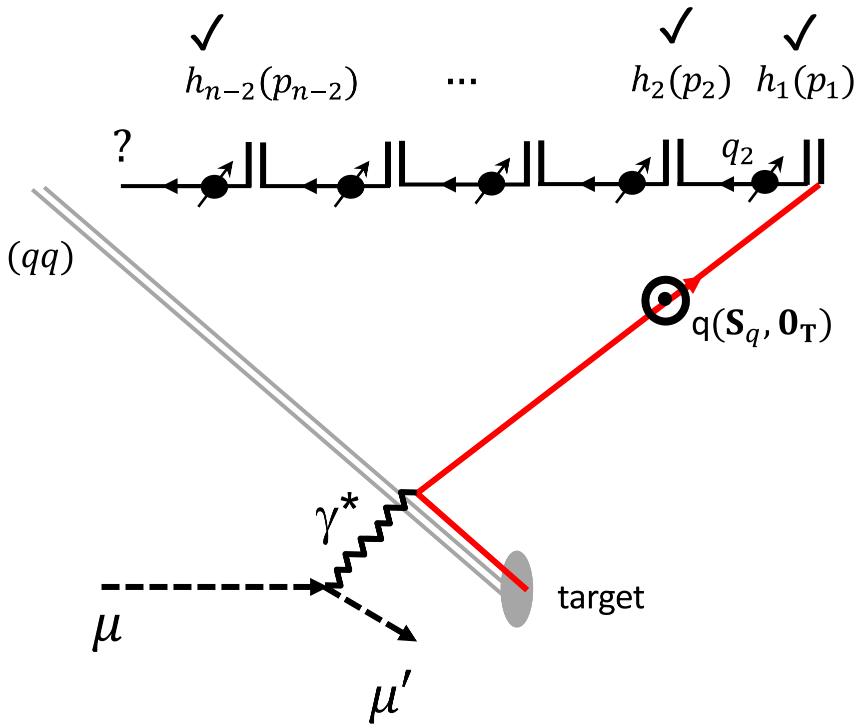
- $\mathrm{w} \simeq \mathrm{Prob}(^3\mathrm{P}_0 \text{ spin effects.})/\mathrm{Prob}(\text{no spin effects.})$

How the interface works



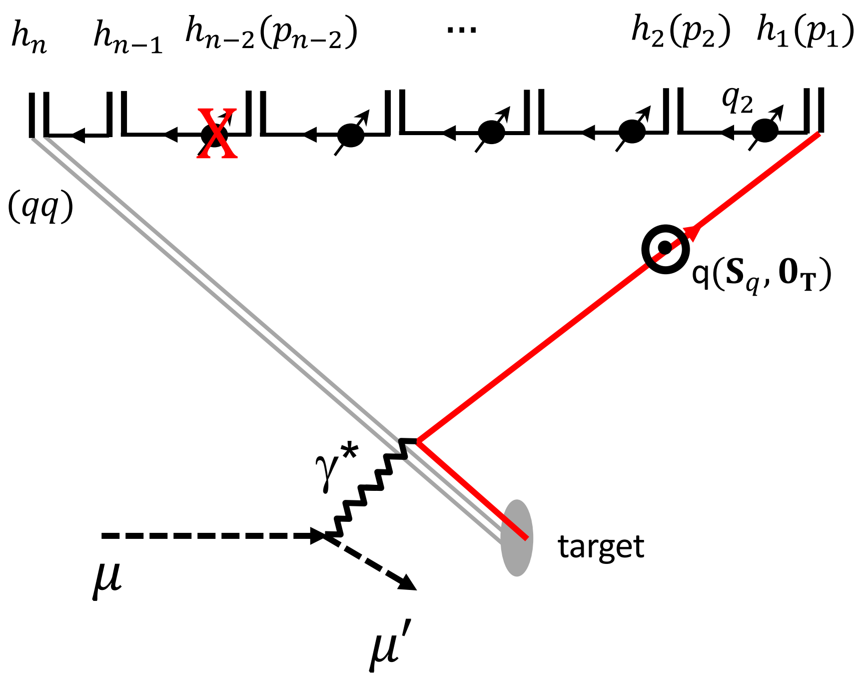
- If accepted, h_1 is stored in the event record otherwise a new h_1 is tried
- The spin density matrix of q_2 is calculated according to the $^3P_0$ rules

How the interface works



- The hadronization chain continues with the emission of further hadrons until the energy of the remaining string piece is sufficient to produce only the last two hadrons that join the quark jet with the remant jet

How the interface works



- The hadronization chain continues with the emission of further hadrons until the energy of the remaining string piece is sufficient to produce only the last two hadrons that join the quark jet with the remant jet
- The exit condition is handled by PYTHIA without calling the $^3P_0$ mechanism → the last two hadrons are generated **«unpolarized»**

Results from simulations

- **We generate DIS events with**

  $160\ \mathrm{GeV}/c$ muons off a p or n target at rest → COMPASS kinematics

$^3P_0$ settings:

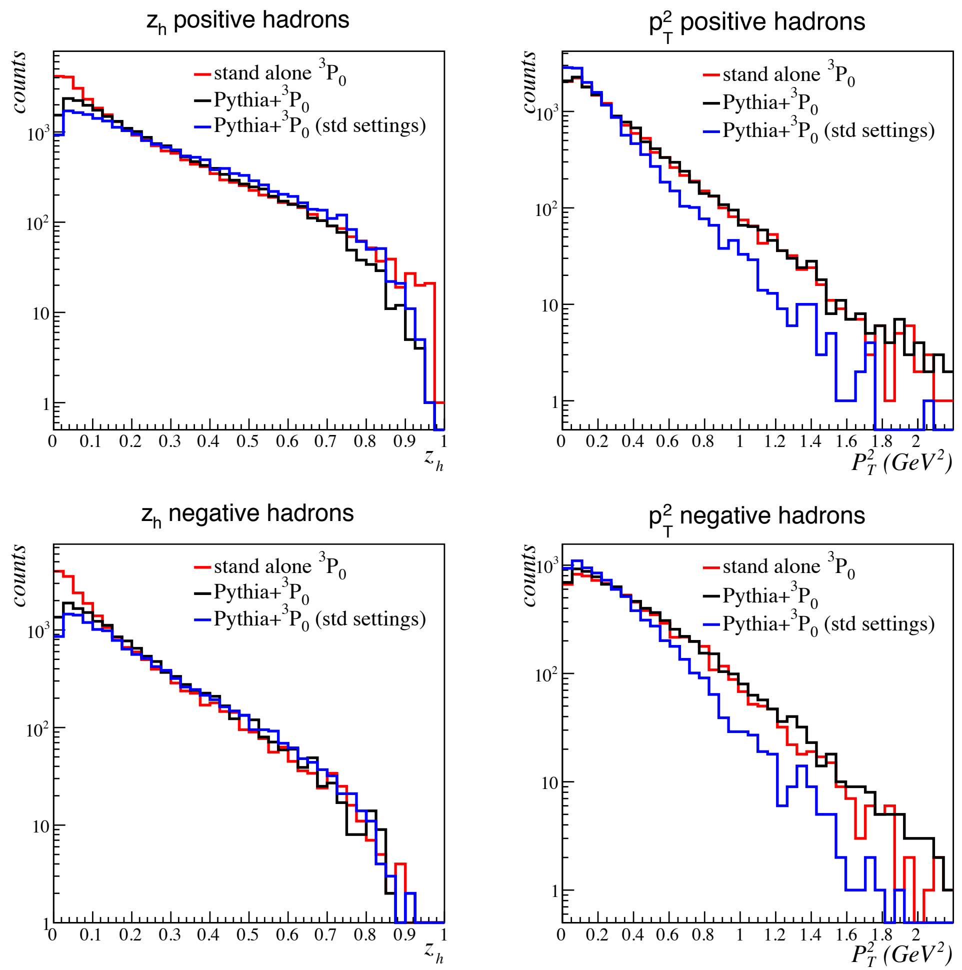
$$\mathrm{StringZ{:}\,aLund} = 0.9, \qquad \mathrm{StringZ{:}\,bLund} = 0.5\ \mathrm{GeV}^{-2},$$
$$\mathrm{StringPT{:}\,sigma} = 0.38\ \mathrm{GeV}^{-1}, \qquad \mu = (0.42 + \mathrm{i}0.76)\ \mathrm{GeV}$$

Cuts on events:

$$W > 5.0\ \mathrm{GeV}, \qquad 0.2 < \mathrm{y} < 0.9, \qquad \mathrm{Q}^2 > 1.0\ \mathrm{GeV}^2$$

Comparison between Pythia + $^3P_0$ and stand alone $^3P_0$: z_h and $\mathbf{p_T^2}$ distributions

For comparison with the stand alone MC only $(ud)_0$---u strings In PYTHIA



$p_T > 0.1\ GeV/c$

$z_h > 0.2$

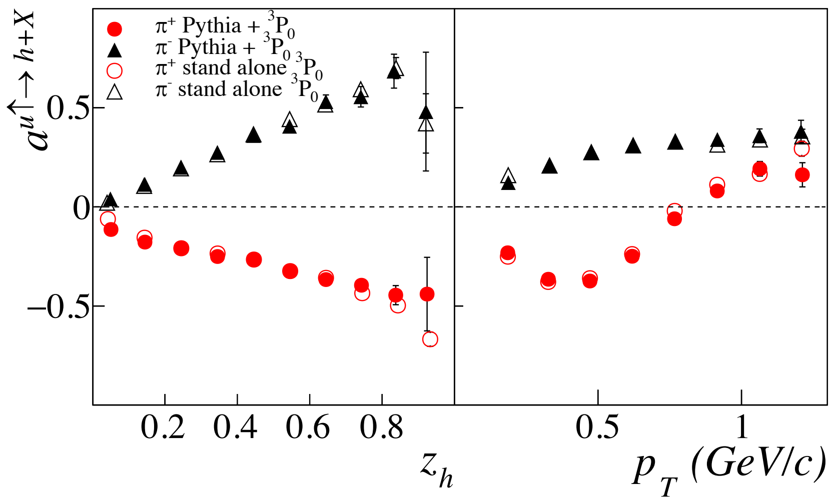
stand alone MC: u jets

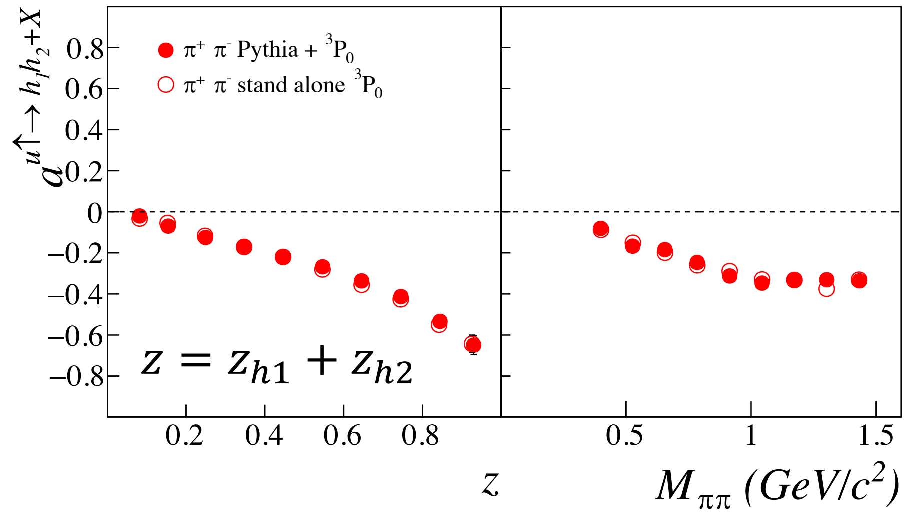
PYTHIA + $^3P_0$ with $^3P_0$ setting

PYTHIA + $^3P_0$ with default setting

- **Same distributions in stand alone $^3P_0$ MC and Pythia + $^3P_0$** apart from some differences at small z_h due to the different exit conditions
- $\langle p_T^2 \rangle$ is slightly smaller for PYTHIA with default setting

Comparison between Pythia + $^3P_0$ and stand alone $^3P_0$: Collins and di-hadron analysing powers





$p_T > 0.1\ GeV/c$ $\qquad$ $z_h > 0.2$

$z_{hi} > 0.1,$ $\qquad$ $R_T > 0.07\ (\frac{GeV}{c})$

Collins analysing power defined as

$$a^{u\uparrow\rightarrow h+X} = 2\langle \sin \phi_C \rangle$$
$$\phi_C = \phi_h - \phi_{s_u}$$

- Only transversely polarized u quarks
- **Same spin effects!!**

di-hadron analysing power defined as

$$a^{u\uparrow\rightarrow h_1 h_2+X} = 2\langle \sin(\phi_{\mathbf{R_T}} - \phi_{\mathbf{s}_u}) \rangle$$
$$\mathbf{R}_T = (z_2 p_{1T} - z_1 p_{2T})/z$$

The interface has been validated → the $^3P_0$ model is correctly implemented in PYTHIA for DIS

The interface has been validated → the $^3P_0$ model is correctly implemented in PYTHIA for DIS

as first exercise → implementation of transversity

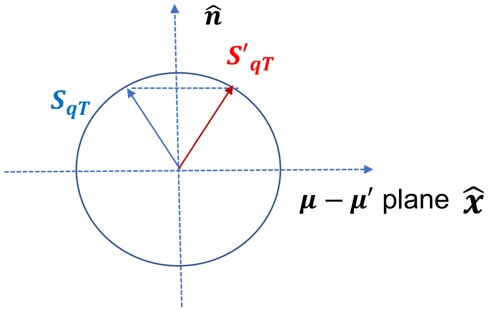
Implementation of transversity

To implement the effects of the transversity PDF $\mathrm{h}_1^{\mathrm{q}}$

a. calculate the polarization of the active quark q = u,d before hard scattering

$$\mathbf{S}_{\mathrm{qT}} = \frac{\mathrm{h}_1^{\mathrm{q}}}{\mathrm{f}_1^{\mathrm{q}}} \mathbf{S}_{\mathrm{T}}^{N}$$

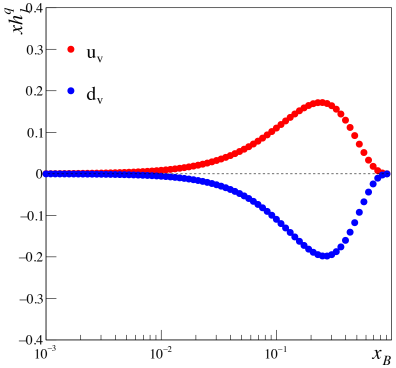
$\mathbf{S}_{\mathrm{T}}^{N}$ is the polarization vector of the nucleon in the GNS



$$x h_1^u(x) = 3.2\, x^{1.3}(1-x)^4$$

b. assign to the fragmenting quark the polarization vector

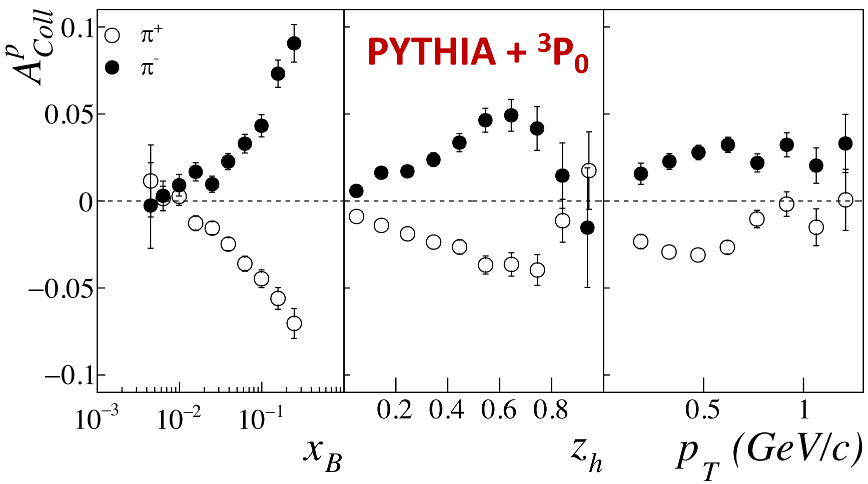
$$\mathbf{S}'_{\mathrm{qT}} = \mathrm{D_{NN}}\ [\mathbf{S}_{\mathrm{qT}} - 2\,(\mathbf{S}_{\mathrm{qT}} \cdot \hat{\boldsymbol{x}})\hat{\boldsymbol{x}}]$$
$$\mathrm{D_{NN}} = (1-\mathrm{y})/(1-\mathrm{y}+\mathrm{y}^2/2)$$



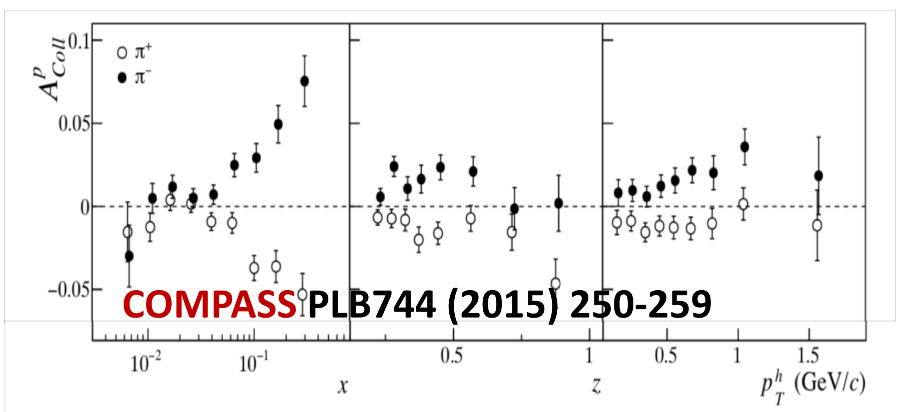
$$x h_1^d(x) = -4.6\, x^{1.44}(1-x)^4$$

- **For this exercise parametrization $\mathbf{h}_1^{\mathbf{q}}$** → from A. Martin et al, PRD91 (2015) no.1, 014034
- Parametrization of $\mathrm{f}_1^{\mathrm{q}}$ → CTEQ5L LO (default in PYTHIA)

Collins asymmetry for proton from Pythia + $^3P_0$



$p_T > 0.1\ GeV/c \quad z_h > 0.2$



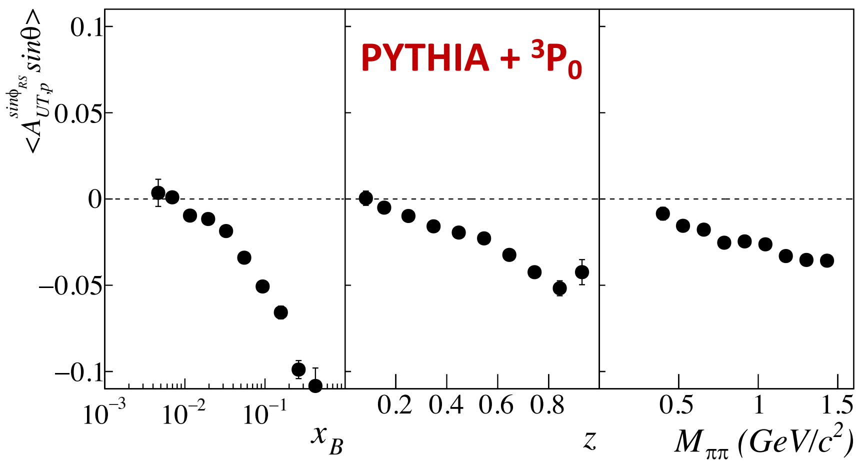
COMPASS PLB744 (2015) 250-259

Collins asymmetry in SIDIS for a proton target:

$$A^p_{Coll} = \frac{\sum_{q=u,d} e_q^2\, x h_1^q\, H_{1q}^h}{\sum_q e_q^2\, x f_1^q\, D_{1q}^h}$$

- **PYTHIA +$^3P_0$ reproduces the trends of the Collins asymmetry seen in data as function of x_B and p_T**
- As function of z_h the trends are different at mid z_h → **remainder: only pseudoscalar mesons!!**

di-hadron asymmetry for proton from Pythia + $^3P_0$



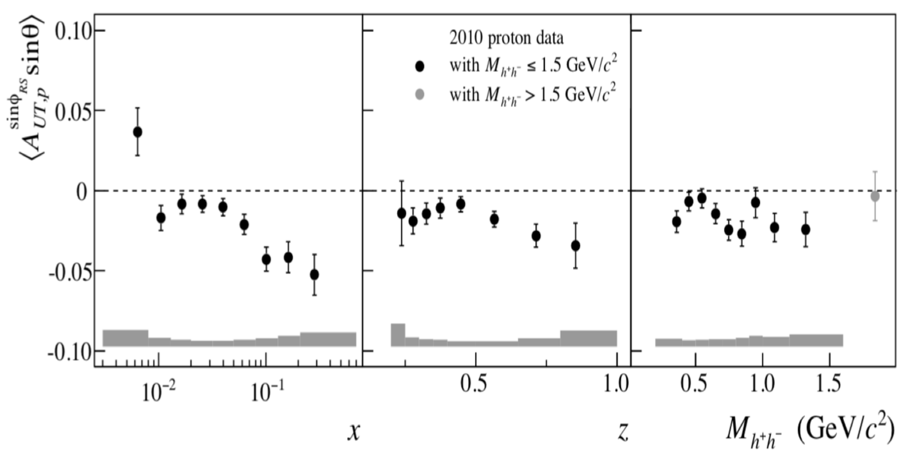
di-hadron asymmetry in SIDIS for a proton target:

$$A_{2h}^{p} = \frac{\sum_{q=u,d} e_q^2\, h_1^q\, H_{1q}^{h_1 h_2}}{\sum_q e_q^2\, f_1^q\, D_{1q}^{h_1 h_2}}$$

Similar trends as the measured asymmetry

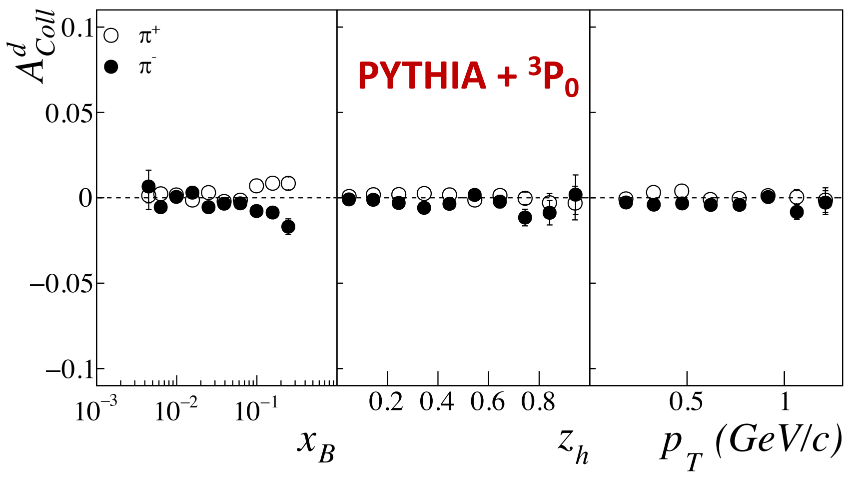
→ again: only pseudoscalar mesons here!!

COMPASS PLB 736 (2014) 124-131



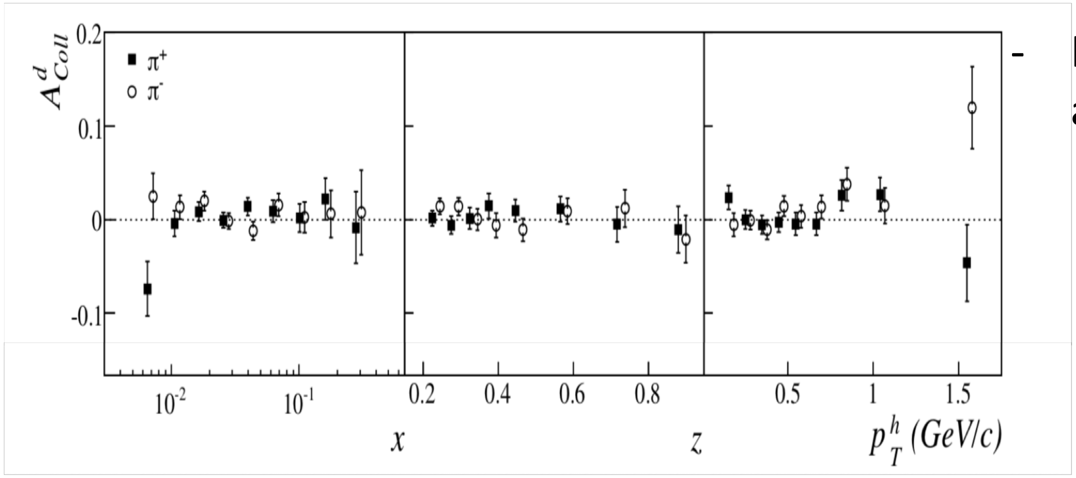
$$z_{hi} > 0.1, \qquad R_T > 0.07\ \left(\frac{GeV}{c}\right)$$

Collins asymmetry for deuteron from Pythia + $^3P_0$



$p_T > 0.1\ GeV/c \quad z_h > 0.2$

COMPASS PLB673 (2009) 127-135

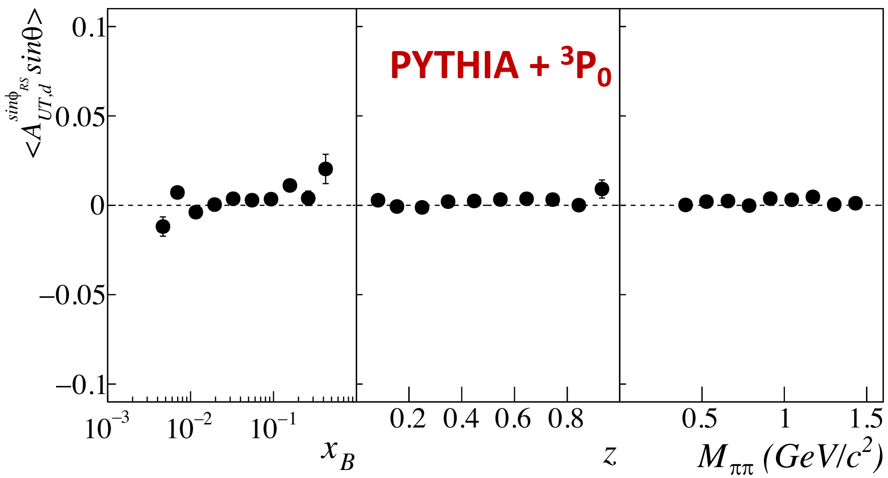


Collins asymmetry in SIDIS for d=p+n target:

$$A^d_{Coll} \simeq \frac{h_1^u + h_1^d}{f_1^q + f_1^d} \frac{4H_{1u}^{\perp\pi} + H_{1d}^{\perp\pi}}{4D_{1q}^{\pi} + D_{1q}^{\pi}}$$

- **PYTHIA+$^3P_0$ predicts a very small Collins asymmetry for deuteron as in the data (some effects at large x_B)**
- It is due to cancellations between h_1^u and h_1^d in the asymmetry

di-hadron asymmetry for deuteron from Pythia + $^3P_0$

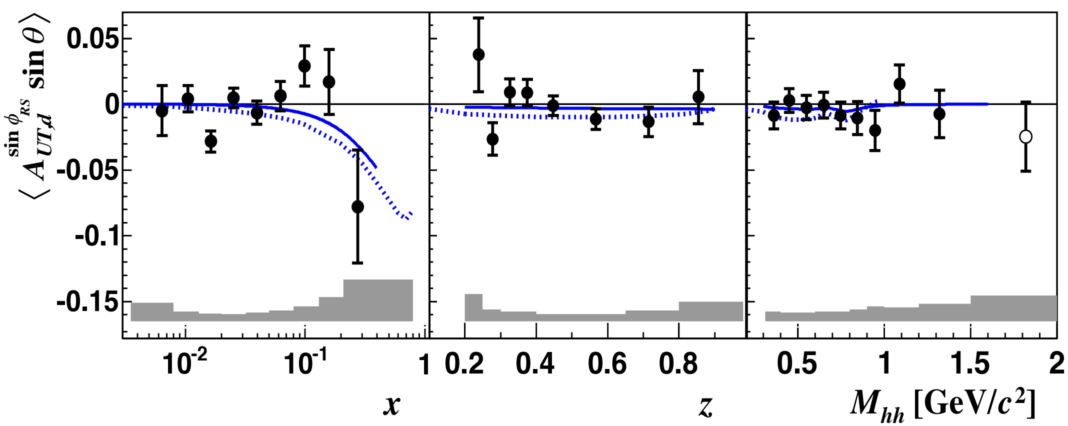


The di-hadron asymmetry in SIDIS for a d target is

$$A_{2h}^{d} = \frac{h_1^u + h_1^d}{f_1^q + f_1^d} \frac{4H_{1u}^{h_1h_2} + H_{1d}^{h_1h_2}}{4D_{1q}^{h_1h_2} + D_{1q}^{h_1h_2}}$$

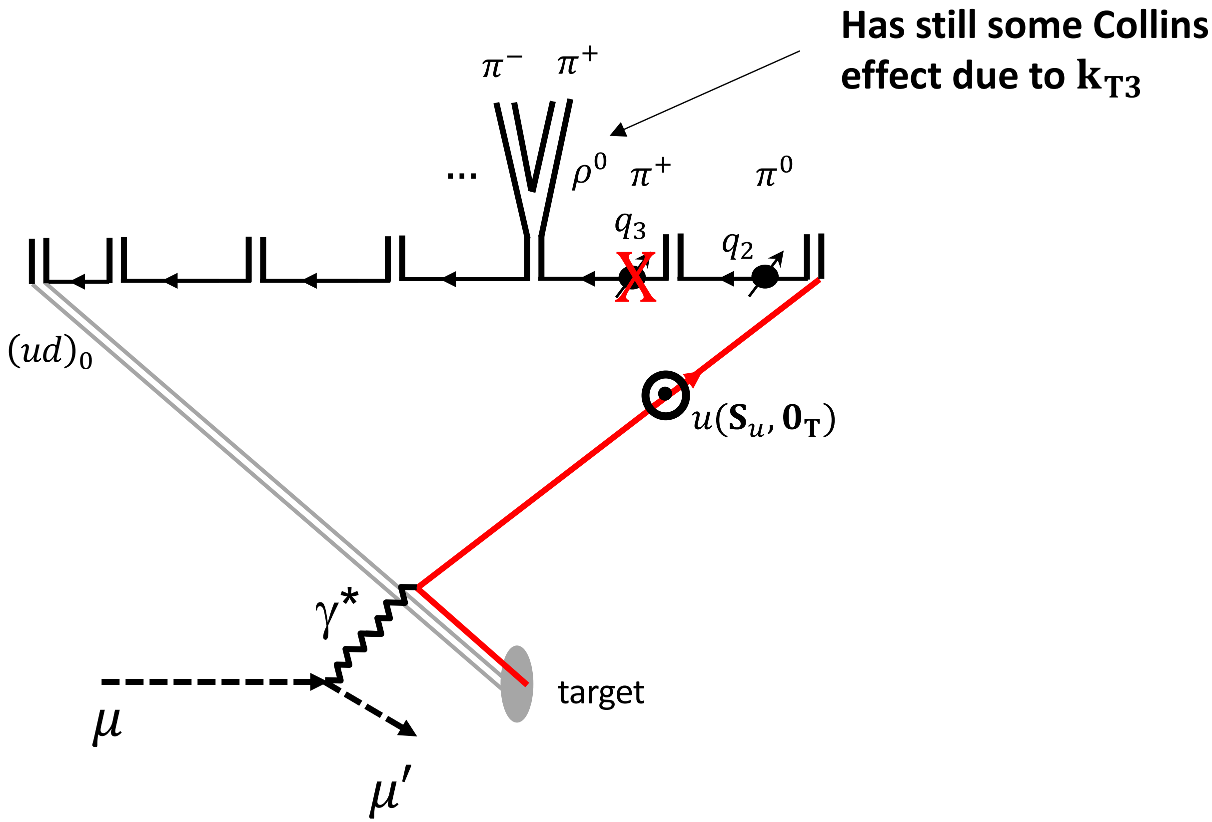
- **Very small asymmetry as in data (some effect at large x_B)**

COMPASS PLB 713 (2012) 10-16



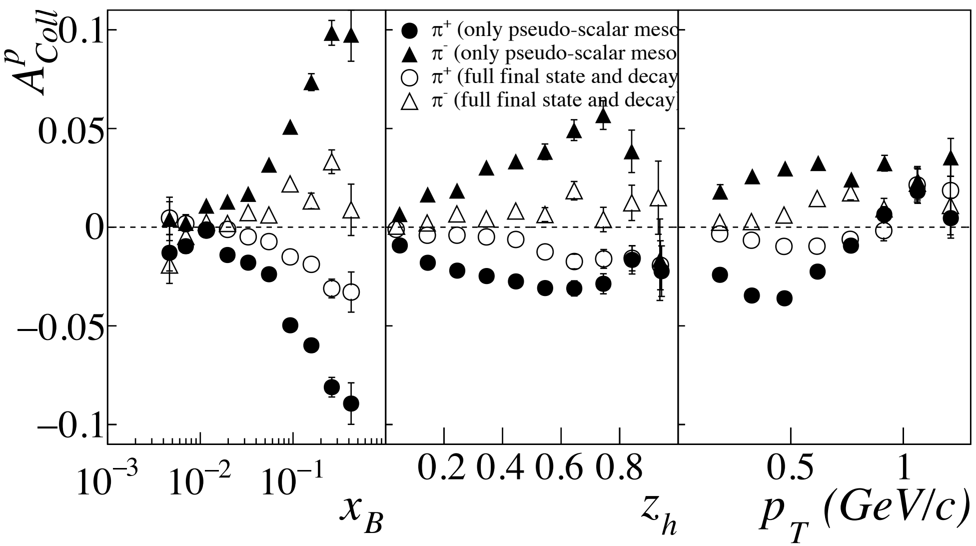
$z_{hi} > 0.1, \qquad R_T > 0.07 \left(\frac{GeV}{c}\right)$

A different option for the final state in PYTHIA + $^3P_0$



An other possible option is to allow PYTHIA **generate all hadron types** (vector mesons, baryons,..) but **disabling spin effects when the first non pseudo-scalar hadron produced**

A different option for the final state in PYTHIA + $^3P_0$



- **Strong effect on the Collins asymmetry**

- **A retuning of the complex mass μ seems to be needed**

An other possible option is to allow PYTHIA **generate all hadron types** (vector mesons, baryons,..) but **disabling spin effects when the first non pseudo-scalar hadron produced**

Conclusions

- **For the first time the quark spin has been implemented in the hadronization in PYTHIA by interfacing the $^3P_0$ model with PYTHIA 8**
- The results are very promising!
- Already now it is possible to perform multi dimensional studies, compare with data and make predictions for future measurements, …

A write-up is in preparation and PYTHIA + $^3P_0$ model will be available soon

... and of course this is not the end of the story!!

This work was supported by the LDRD project «Phenomenological study of hadronization in nuclear and high-energy physics experiments».