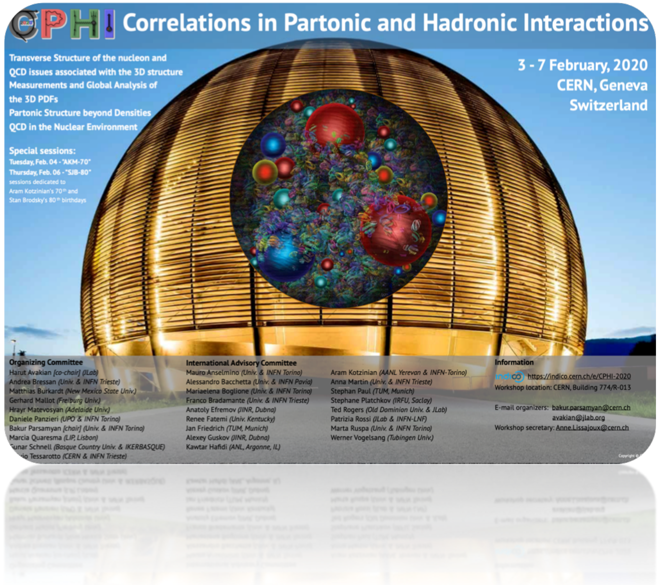

4th February 2020,
CERN

Monte Carlo simulation of polarized quark fragmentation with the string $+^3P_0$ model

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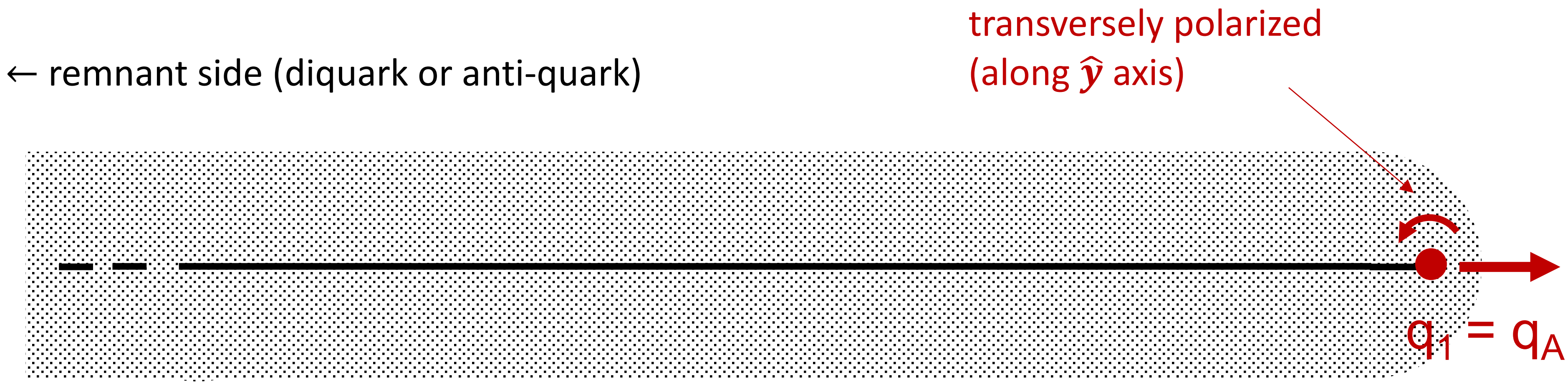
Trieste University and INFN Trieste section

In collaboration with X. ARTRU and A. MARTIN

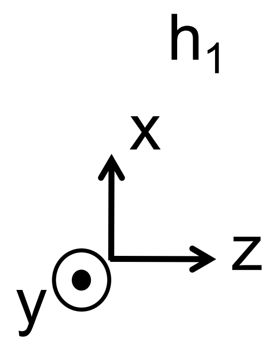
string + $^3P_0$

X. Artru [2009] arXiv:1001.1061

different approach w.r.t Matevosyan, Kotzinian and collaborators PRD95.1 (2017), p. 014021.



string axis defined by the momentum of q_A



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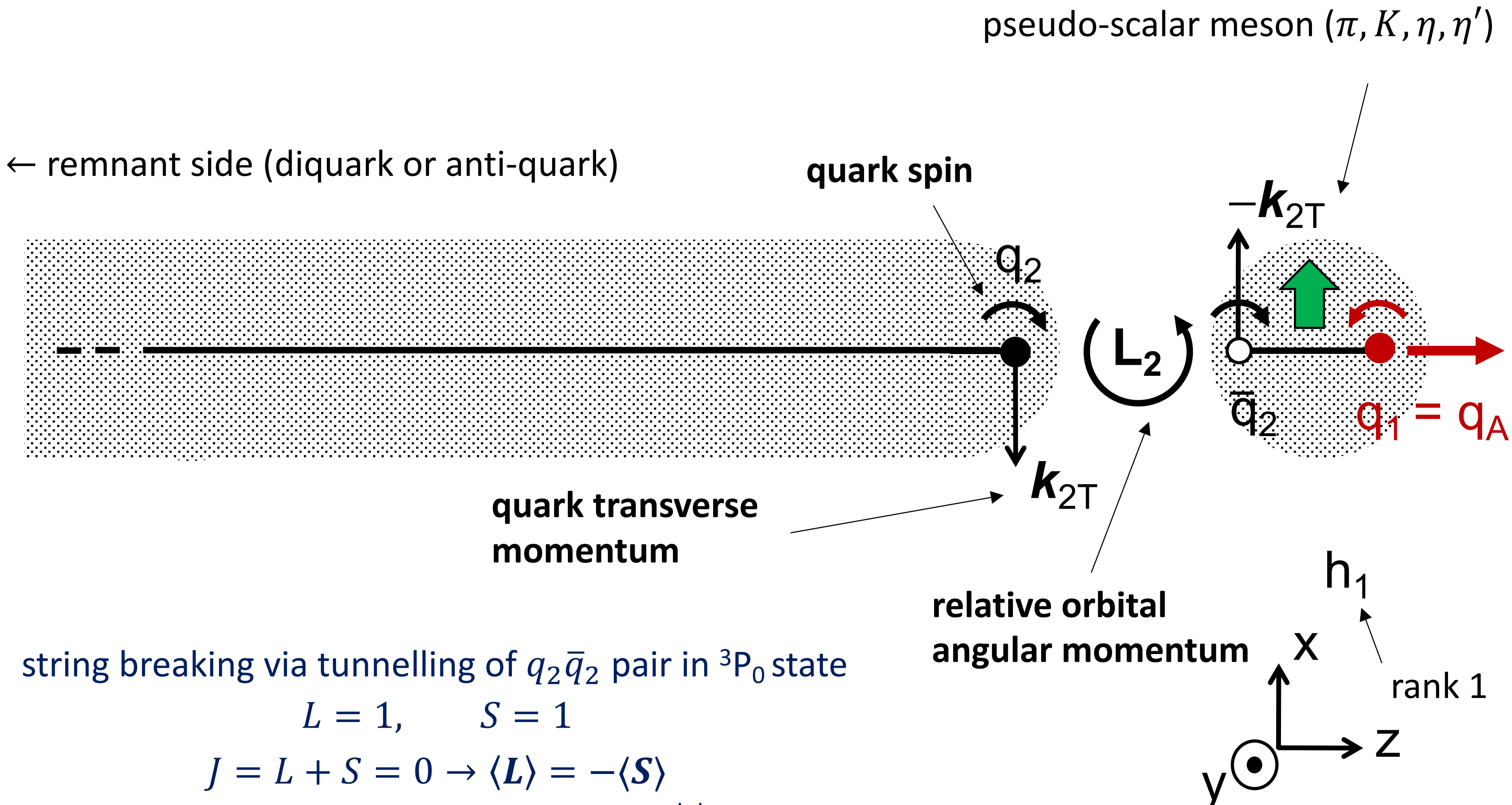

string breaking via tunnelling of $q_2\bar{q}_2$ pair in $^3P_0$ state

$$L = 1, \qquad S = 1$$

$$J = L + S = 0 \rightarrow \langle \boldsymbol{L} \rangle = -\langle \boldsymbol{S} \rangle$$

the pair has vacuum quantum numbers 0^{++}

string + $^3P_0$

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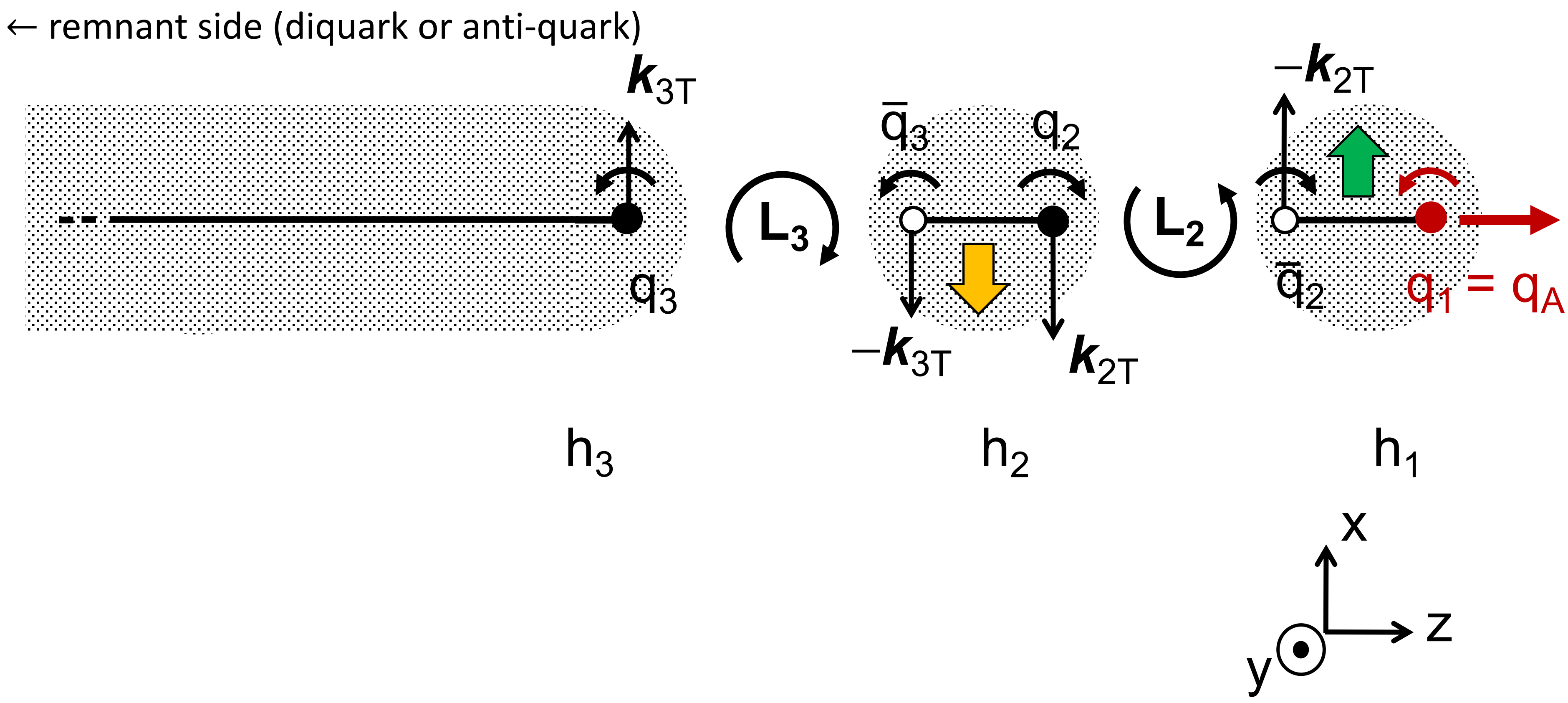
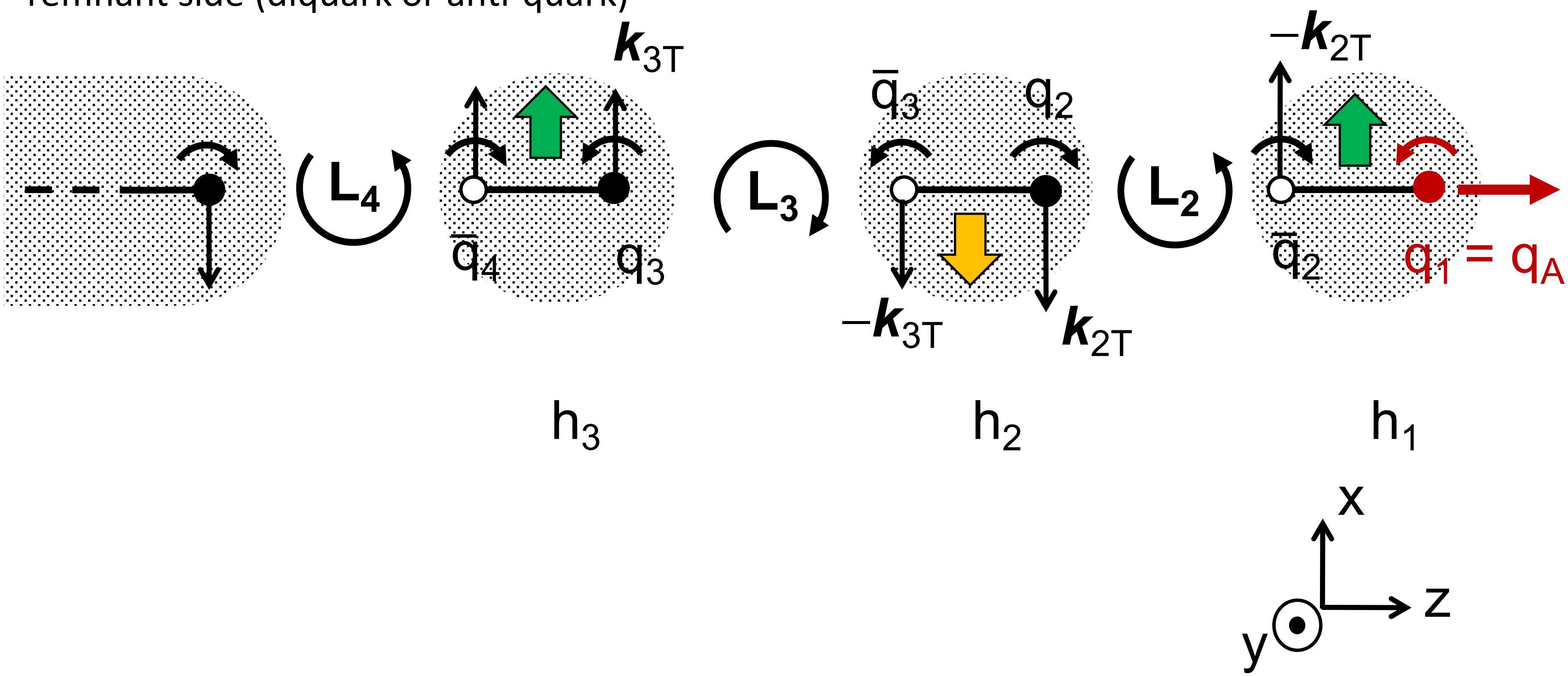


string + $^3P_0$

X. Artru [2009] arXiv:1001.1061

← remnant side (diquark or anti-quark)



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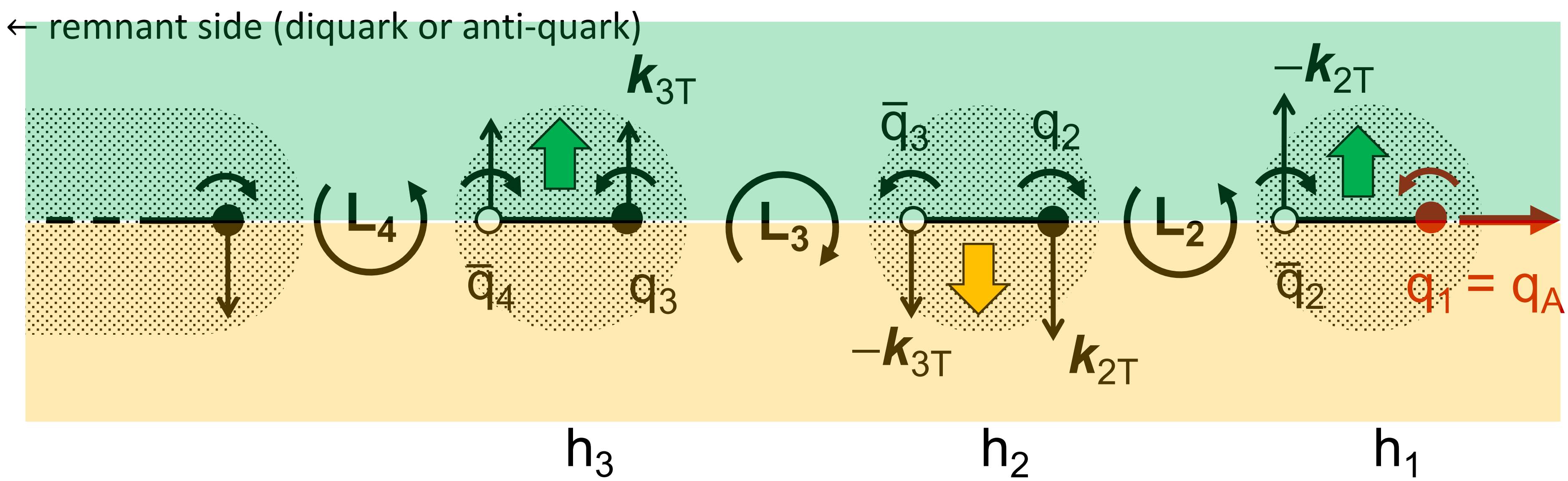
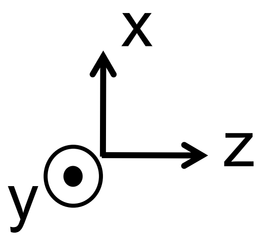
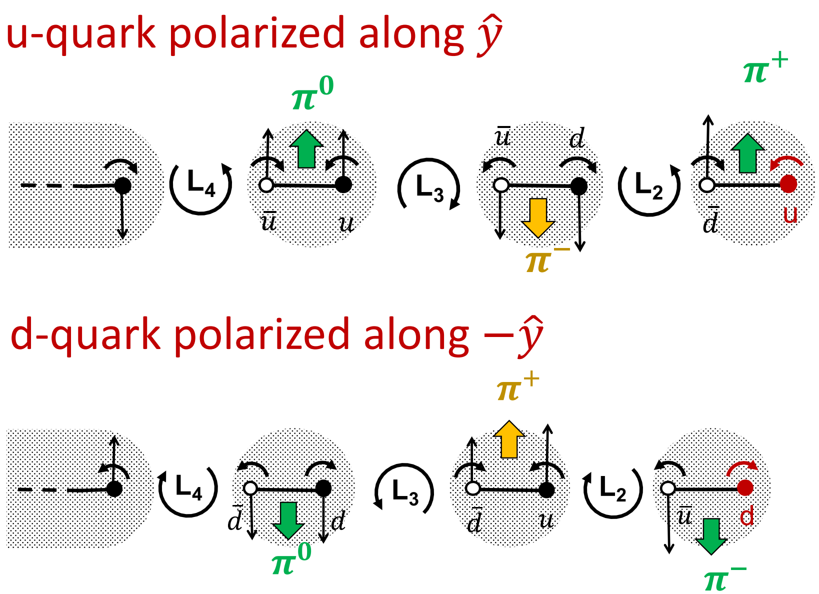


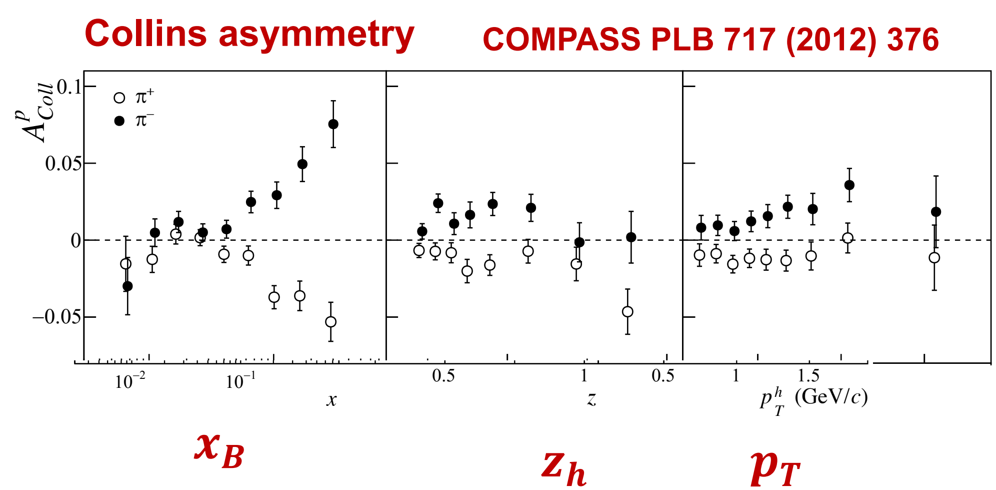
left-right asymmetry with respect to the plane defined by the quark direction of motion and its spin

→ **recursive model for the Collins effect**



string + $^3P_0$





π^+ and π^- are emitted on opposite sides
→ qualitative agreement with experimental data
→ predicts also a di-hadron asymmetry (local compensation of k_T)

- classical picture which gives only qualitative predictions
- MC implementation neccessary: first prototype for $pp^{\uparrow} \to \pi X$ based on probabilities by X. Artru et al.[*], spin effects limited to the leading hadron
- to take into account the **quark spin** → quantum mechanical formulation of the string+ $^3P_0$ model

[*] X. Artru, J. Czyzewski, H. Yabuki arXiv:hep-ph/9508239 [1995]

recursivity: the elementary splitting

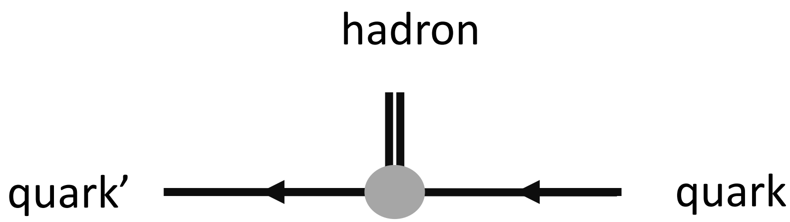
string decay can be viewed as the recursive repetition of the elementary splitting

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

type $\mathrm{h} = q\bar{q}'$ (ps = pseudo-scalar)
4-momentum $p = k - k'$
no spin information

flavour q'
4-momentum k'
2x2 spin density matrix

$\rho(q')$



flavour q
4-momentum k
2x2 spin density matrix

$\rho(q) = (\mathbf{I} + \boldsymbol{\sigma} \cdot \boldsymbol{S}_q)/2$

polarization vector = $\boldsymbol{S}_q$

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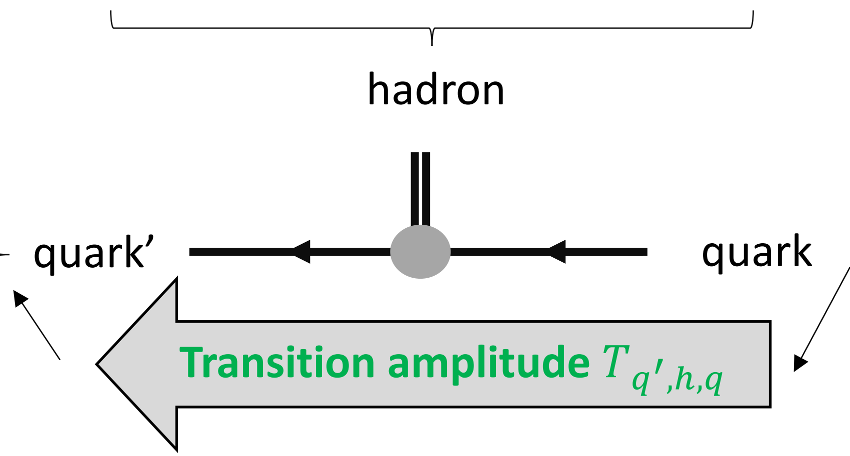

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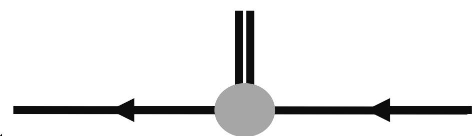
type $\mathrm{h} = q\bar{q}'$ (ps = pseudo-scalar)
4-momentum $p = k - k'$
no spin information

hadron

flavour q'
4-momentum k'
2x2 spin density matrix

$\rho(q') \propto T\rho(q)T^{\dagger}$

quark'



quark

flavour q
4-momentum k
2x2 spin density matrix

$\rho(q) = (\mathbf{I} + \boldsymbol{\sigma}\cdot\boldsymbol{S}_q)/2$

polarization vector = $\boldsymbol{S}_q$

Transition amplitude $T_{q',h,q}$

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

basis for MC simulations

splitting function: probability of emitting h with longitudinal momentum fraction $Z = p^+/k^+$ and transverse momentum $\boldsymbol{p}_T = \boldsymbol{k}_T - \boldsymbol{k}'_T$ from a quark q with polarization $\boldsymbol{S}_q$

recursivity: the elementary splitting

string decay can be viewed as the recursive repetition of the elementary splitting

X. Artru, Z. Belghobsi DSPIN-2011
X. Artru, Z. Belghobsi DSPIN-2013
A. Kerbizi at al, PRD97 (2018) no.7, 074010

type $\mathrm{h} = q\bar{q}'$ (ps = pseudo-scalar)
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flavour q'
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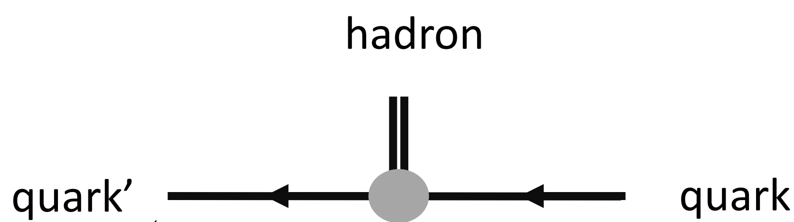


flavour q
4-momentum k
2x2 spin density matrix

$\rho(q') \propto T\rho(q)T^{\dagger}$

Transition amplitude $T_{q',h,q}$

$\rho(q) = (\mathbf{I} + \boldsymbol{\sigma}\cdot\boldsymbol{S}_q)/2$

polarization vector = $\boldsymbol{S}_q$

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

T = flavour × Lund string model × k'_T supp. × input func. × **$^3P_0$ operator** × **ps coupling** × **single quark density**

recursivity: the elementary splitting

the model has:

- 5 free parameters

b_L ~ probability of having a string cutting point

b_T ~ suppression of $\boldsymbol{k}_T$ at string breaking

a ~ suppression of large Z

$\mu \rightarrow$ «complex mass» introduced by the $^3P_0$ mechanism

$\mathrm{Im}(\mu)/|\mu|$ responsible for transverse spin effects

- already in the Lund string Model (PYTHIA, LEPTO,..)
- encode string fragm. dynamics

- **input function**

$\breve{\boldsymbol{g}}(\boldsymbol{\varepsilon}_h^2) \rightarrow$ governs spin-independent $\mathbf{k}_T$ - $\mathbf{k}'_T$ correlations

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

T = flavour × Lund string model × k'_T supp. × input func. × **$^3P_0$ operator × ps coupling ×** **single quark density in $\boldsymbol{k}_T \otimes$ spin space**

possible choices for the input function

more complete $\check{g}$ more simple

$$\check{g}^2(\varepsilon_h^2) = \left(\varepsilon_h^2\right)^a$$

$$\check{g}^2(\varepsilon_h^2) = \left[\int_0^1 dZ Z^{-1} \left(\frac{1-Z}{\varepsilon_h^2}\right)^a e^{-\frac{b_L \varepsilon_h^2}{Z}}\right]^{-1}$$

Model **M18** published in 2018

PRD97 (2018) no.7, 074010

- spin independent $\boldsymbol{k}_T$ -$\boldsymbol{k}'_T$ correlations
- complicates simulations

Model **M19** published in 2019

PRD100 (2019) no.1, 014003

- no spin independent $\boldsymbol{k}_T$ -$\boldsymbol{k}'_T$ correlations
- analytically/numerically simpler
- unpolarized splitting function $\sim$ in PYTHIA

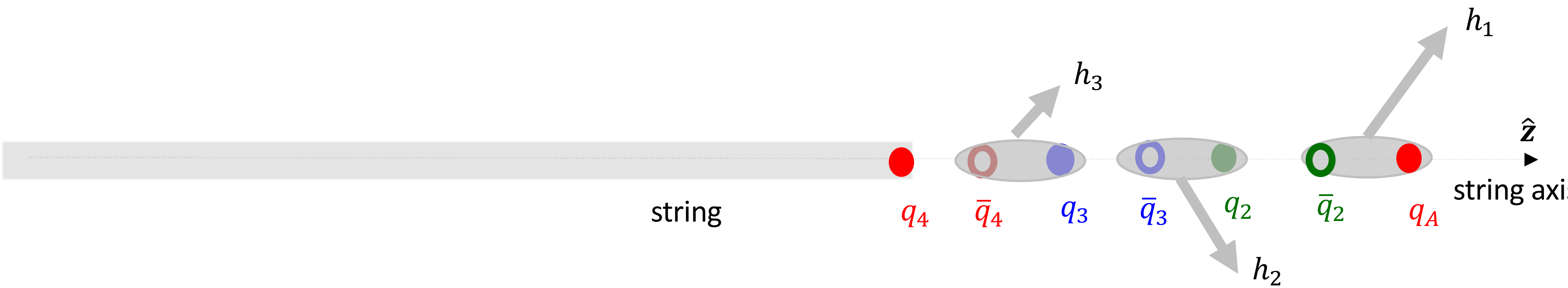
both implemented in a stand alone Monte Carlo programs
both restricted to pseudo-scalar meson emission

General structure of the MC program

- For each event define initial quark $q_A \equiv q_1$ with flavour u, d, s, its energy and its spin density matrix $\rho(q_A)$

1. Generate a $q_2\bar{q}_2$ pair and form the hadron $h_1(q_A\bar{q}_2)$
2. Construct the four-momentum of h_1 by drawing Z_1 and $\boldsymbol{p}_{1T}$ using $F_{q_2 h_1 q_A}$
3. Calculate the spin density matrix of q_2

- Iterate points 1-3 until the exit condition is reached (enough renamining c.m. energy to produce at least one baryonic resonance)



The free parameters of the model

Values of the free parameters in M18 have been fixed in order to have a qualitative agreement between simulation results with

- parameterizations of unpolarized fragmentation functions and experimental data on unpolarized SIDIS
- e^+e^- Collins asymmetries

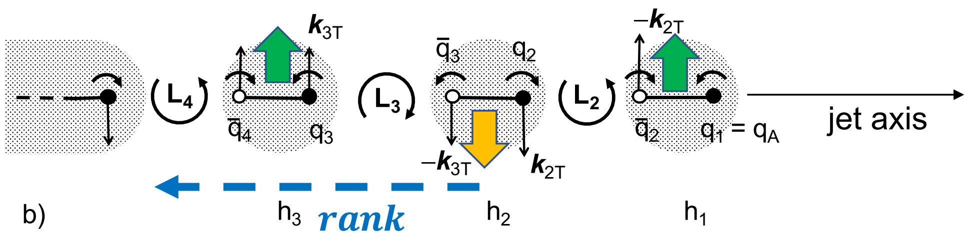
$$b_L = 0.5 \left(\frac{\mathrm{GeV}}{c^2}\right)^{-2}, \qquad b_T = 5.17 \left(\frac{\mathrm{GeV}}{c}\right)^{-2}, \qquad a = 0.9$$

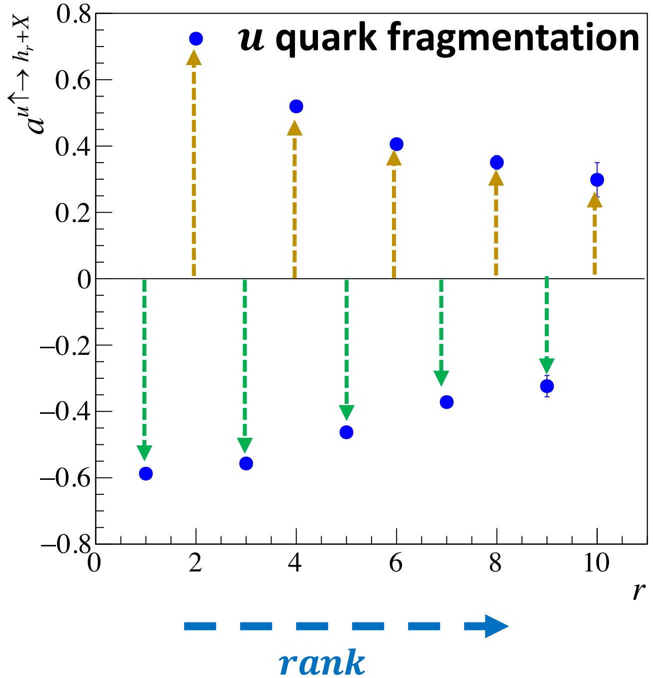
$$\mu = (0.42 + \mathrm{i}0.76)\ \mathrm{GeV/c^2}$$

The initial conditions in simulations

- **Fragmentation chains of transversely and fully polarized u quarks** with initial spin density matrix $\rho(q_A) = (1 + \sigma_y)/2$
- Energy of fragmenting quark calculated from a $\{x_B, Q^2\}$ sample of SIDIS events

Collins analysing power as function of rank





- Azimuthal spectrum of hadrons

$$N_h(\phi_C) = N_U\left[1 + a^{u\uparrow\to h+X}\sin\phi_C\right]$$

$$\phi_C = \phi_h - \phi_{s_u}$$

- Analysing power calculated as

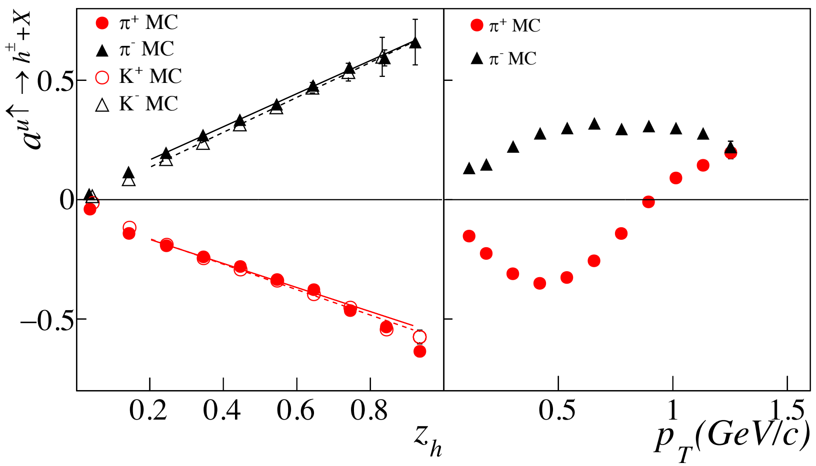
$$a^{u\uparrow\to h+X} = 2\langle\sin\phi_C\rangle$$

- classical picture reproduced
- the quark spin information decays along the fragmentation chain

Collins analysing power as function of z_h and p_T

PRD97 (2018) no.7, 074010

u quark fragmentation

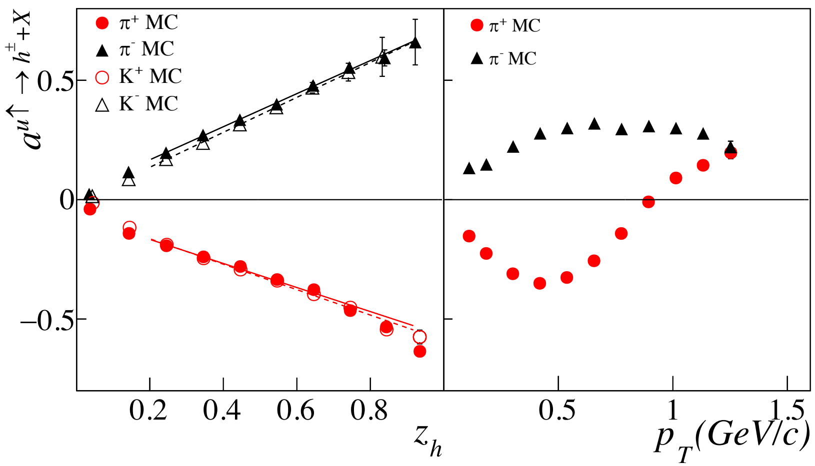


- mirror symmetry for opposite charges
- decreases with $z_h = E_h/E_{frag.\,quark}$
- change of sign of $a^{u\uparrow\to h+X}(p_T)$ due to a second rank π^+ produced after a first rank π^0

Collins analysing power as function of z_h and p_T

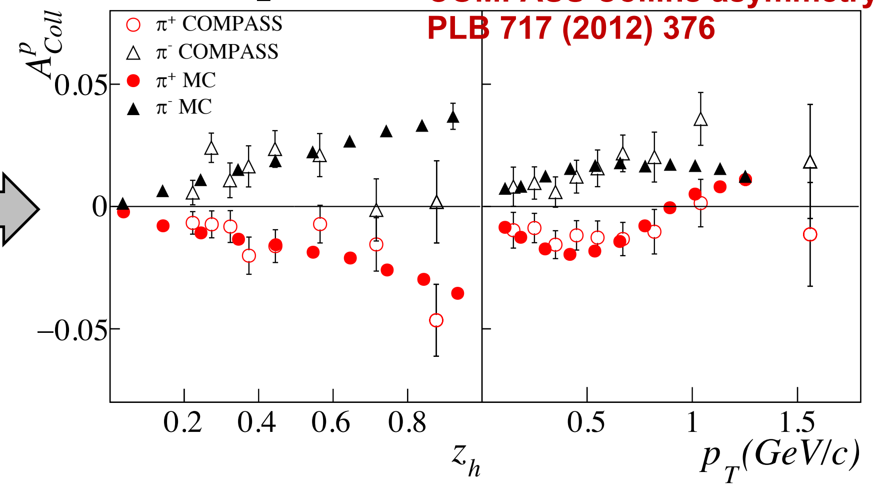
PRD97 (2018) no.7, 074010

u quark fragmentation



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

COMPASS Collins asymmetry
PLB 717 (2012) 376



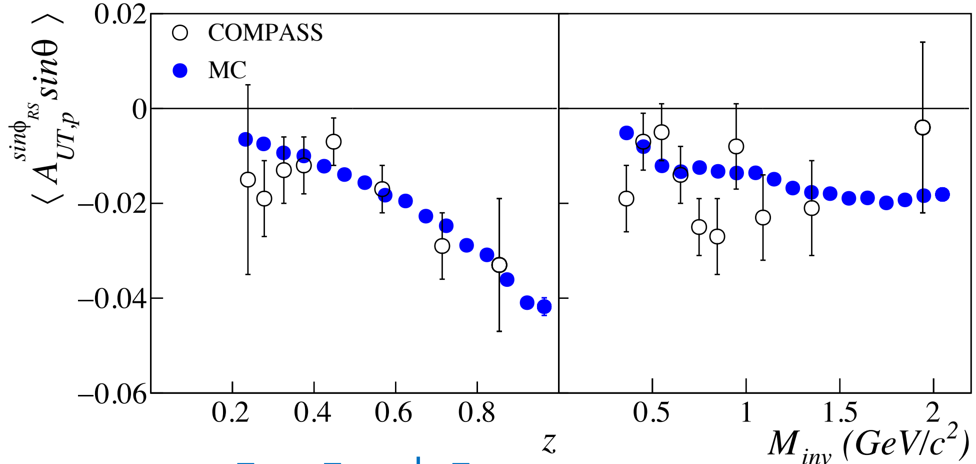
- mirror symmetry for opposite charges
- decreases with $z_h = E_h/E_{frag.\,quark}$
- change of sign of $a^{u\uparrow\to h+X}(p_T)$ due to a second rank π^+ produced after a first rank π^0

- MC scaled by $\lambda \sim \langle h_1^u/f_1^u \rangle = 0.055 \pm 0.010$ because in reality quarks are partially polarized
- λ is estimated by comparison with the COMPASS (proton) asymmetries

dihadron asymmetry

PRD97 (2018) no.7, 074010

COMPASS PLB 736 (2014) 124



$z = z_{h^+} + z_{h^-}$

Asymmetry of oppositely charged hadron pairs in the same jet

- MC points scaled by the same factor $\lambda \sim \langle h_1^u / f_1^u \rangle = 0.055 \pm 0.010$

possible choices for the input function

$\check{g}$

more complete

more simple

$$\check{g}^2(\varepsilon_h^2) = (\varepsilon_h^2)^a$$

Model **M18** published in 2018

PRD97 (2018) no.7, 074010

- spin independent $\boldsymbol{k}_T$ -$\boldsymbol{k}'_T$ correlations
- complicates simulations

$$\check{g}^2(\varepsilon_h^2) = \left[\int_0^1 dZ Z^{-1}\left(\frac{1-Z}{\varepsilon_h^2}\right)^a e^{-\frac{b_L \varepsilon_h^2}{Z}}\right]^{-1}$$

Model **M19** published in 2019

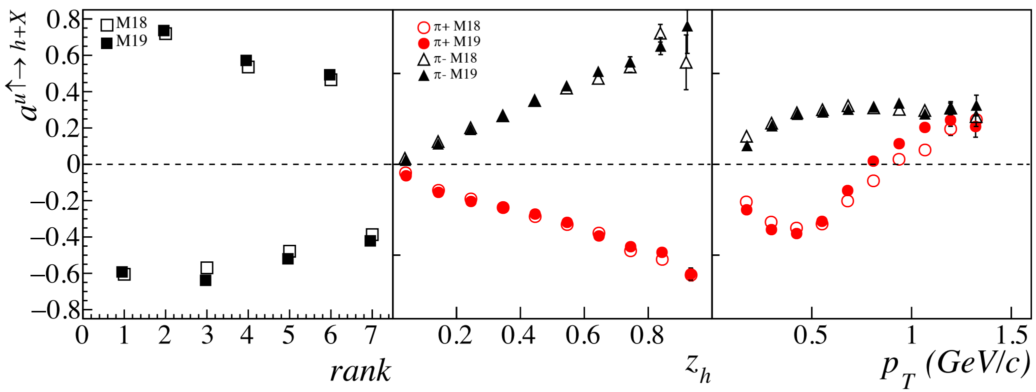
PRD100 (2019) no.1, 014003

- no spin independent $\boldsymbol{k}_T$ -$\boldsymbol{k}'_T$ correlations
- analytically/numerically simpler
- unpolarized splitting function ~ in PYTHIA

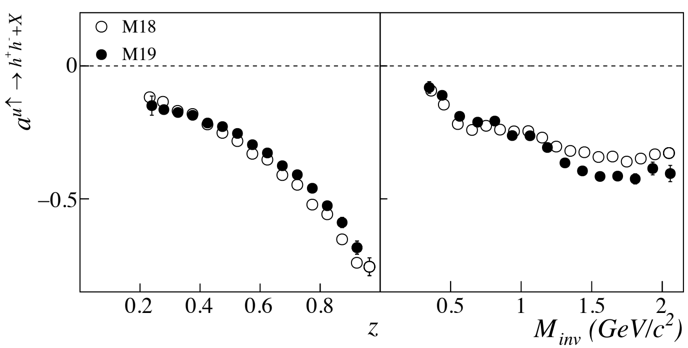
both implemented in a stand alone Monte Carlo programs
both restricted to pseudo-scalar meson emission

Comparison between M19 and M18

re-tuning $(b_T)_{M19} = 1.63\times(b_T)_{M20}$ to have same p_T^2 distributions



PRD100 (2019) no.1, 014003



Very similar:

1. kinematical distributions
2. Collins analysing power as function of rank, z_h and p_T
3. dihadron analysing power

Conclusion:

M19 gives the same results as M18

in spite of being by far simpler

vector meson production

a very recent development using M19 (*) → model **M20**

(*) A. Kerbizi, PhD thesis, XXXII cycle, Trieste University [2020]

necessary
- in fragmentation vm are produced roughly as many as pseudo-scalar mesons
- decay products contribute to the final hadrons

non - trivial task
- spin 1 → 3x3 spin density matrix → non isotropic decay distributions
- spin of vm correlated in an entangled way with spin of q' → different spin transfer mechanism from q to q'

what exists
- a prototype of MC code for $pp^{\uparrow} \rightarrow \rho + X$ based on probabilities, spin effects limited to the first rank hadron -> Czyzewski (*)
- coupling $q' - vm - q$ → two new complex coupling constants -> Artru (**)
- recipe for propagation of spin correlations in simulations which take into account entanglement -> Collins, Knowles (***)

in the following slides
- **systematic account of vector mesons in the simulation of a polarized quark fragmentation chain in a way which is consistent with quantum mechanics**

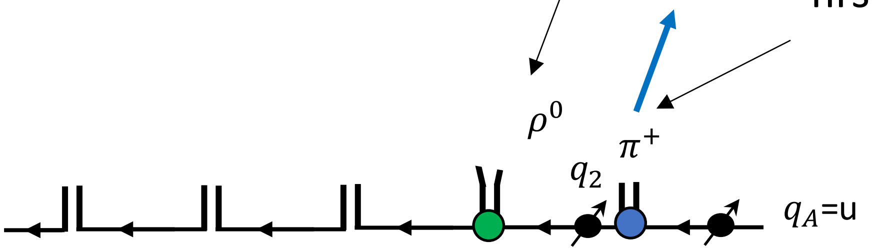
(*) Acta Phys.Polon. 27 (1996) 1759-1766
(**) arXiv:1001.1061, 2009
(***) Collins, Nucl.Phys. B304 (1988), Knowles, Nucl.Phys. B310 (1988)

Introduction of vector mesons

Suppose this is a ρ^0 with prob. $\frac{f_{vm}}{f_{vm}+f_{ps}}$

f_v/f_{ps} taken as in PYTHIA 8 = 0.62 (u,d), 0.725 (s)

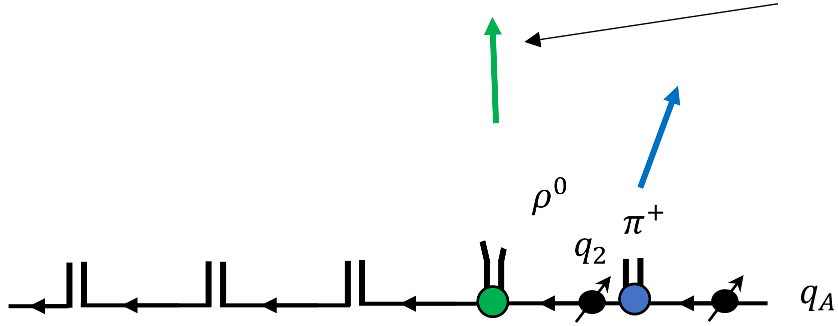
first rank -> π^+



calculate the spin density matrix of q_2

Introduction of vector mesons

generate mass and momentum of ρ^0



relativistic Breit-Wigner

splitting function for vm production

$$F_{q',h,q} = \sum_{\alpha=L,T} tr\, T^{\alpha}_{q',h,q}\,\rho(q)\,T^{\alpha\dagger}_{q',h,q}$$

depends on $|G_L|/|G_T|$
- regulates the strength of the Collins effect for the vector meson
1^{st} new free param.

T^{α} = mass distrib × .. same as ps .. × **vm coupling** × single quark density in $k_T \otimes$ spin space

$$(^*)\ \Gamma^{\alpha}_{h} = \begin{cases} G_T \times \sigma_z \boldsymbol{\sigma}_T \\ G_L \times \boldsymbol{I}_{2\times 2} \end{cases}$$

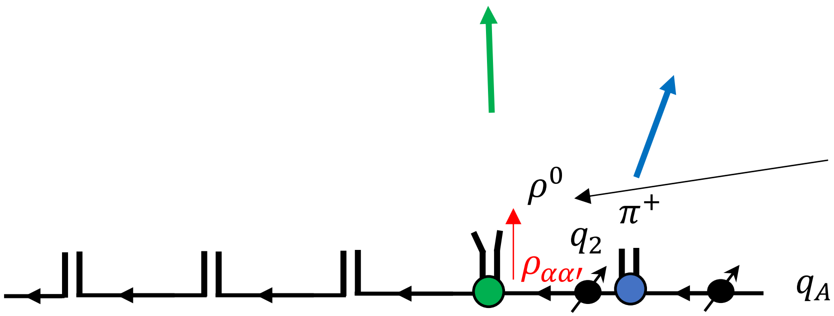
-> G_T coupling with transversely polarized vm

-> G_L coupling with longitudinally polarized vm

G_L and G_T complex free parameters

(*) X. Artru [arXiv:1001.1061, 2009]

Introduction of vector mesons



calculate spin density matrix $\rho_{\alpha\alpha'}$ of ρ^0

in the vector meson rest frame

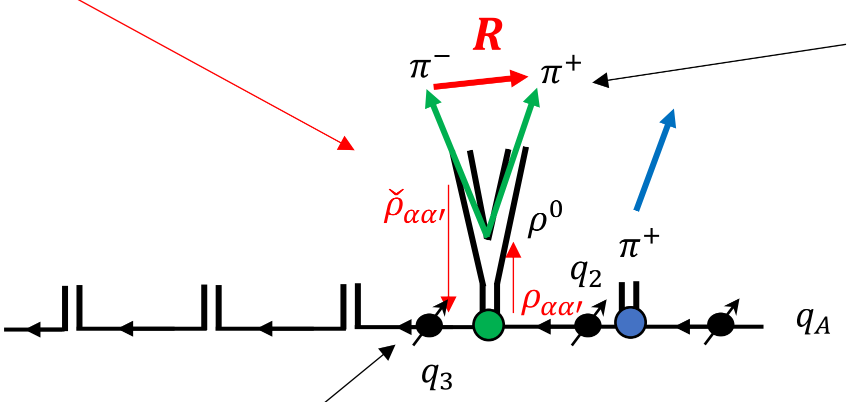
$$\hat{\rho}_{\alpha\alpha'}(vm) \propto tr\, T^{\alpha}_{q',h,q}\rho(q)\mathrm{T}^{\alpha'\dagger}_{q',h,q}$$

depends on |GL|/GT| and $\theta = \arg(G_L/G_T)$
→ 2^{nd} new free parameter
→ gives an oblique linear polarization which can enhance or reduce the Collins effect of the decay products

Introduction of vector mesons

come back with a
«decay matrix» $\check{\rho}_{\alpha\alpha'}$

$\check{\rho}_{\alpha\alpha'} = \widehat{\boldsymbol{R}}_{\alpha}\widehat{\boldsymbol{R}}_{\alpha'}$



Simulate the decay of the ρ^0 in its rest frame and then boost to the string rest frame

angular distribution in the ρ^0 rest frame

$$\frac{dN}{d\Omega} = \frac{3}{4\pi}\rho_{\alpha\alpha'}\widehat{\boldsymbol{R}}_{\alpha}\widehat{\boldsymbol{R}}_{\alpha'}$$

Finally calculate the spin density matrix of q_3

$$\rho(q_3) = \check{\rho}_{\alpha\alpha'} tr\, T^{\alpha}_{q',h,q}\rho(q)\mathrm{T}^{\alpha'\dagger}_{q',h,q}$$

- Collins-Knowles recipe
→ takes into account entangled spin-correlations between ρ^0 and q_3

- this mechanism is repeated until the end of the chain
ρ, K^*, ω, ϕ included

Simulations with M20

- Fragmentations of **fully transversely polarized $\boldsymbol{u}$** quarks
- No tuning of $|G_L|/|G_T|$ and θ_{LT}
- Model by Czyzewski [*] based on the non relativistic quark model gives

$$\left.\frac{a_p^{u\uparrow\to\rho^+ + X}}{a_p^{u\uparrow\to\pi^+ + X}}\right|_{rank\ 1} = -\frac{1}{3}$$

- M20 gives

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

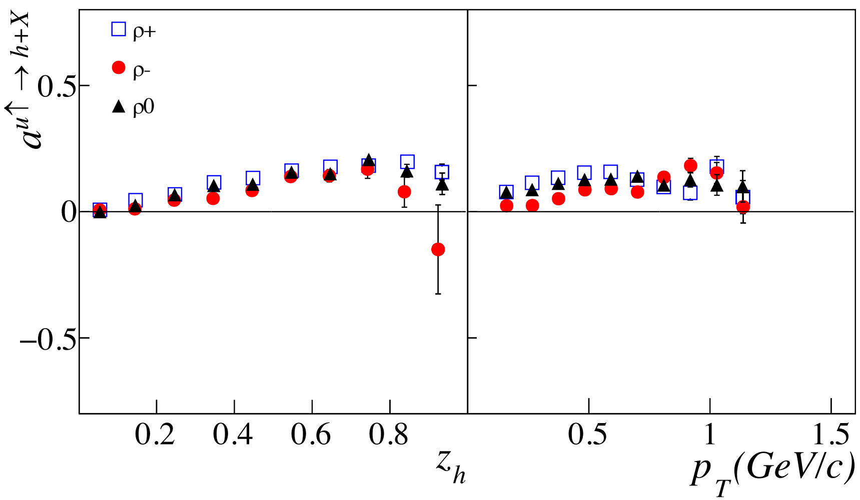
→ current choice of free parameters $\frac{|G_L|}{|G_T|} = 1$ and $\theta_{LT} = 0$

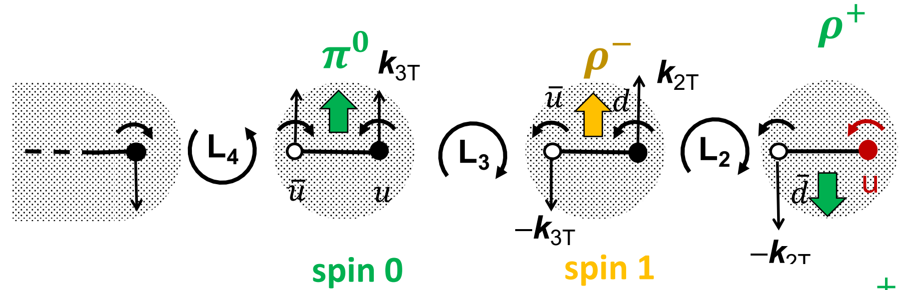
however $|G_L|/|G_T|$=1 and θ_{LT}=0

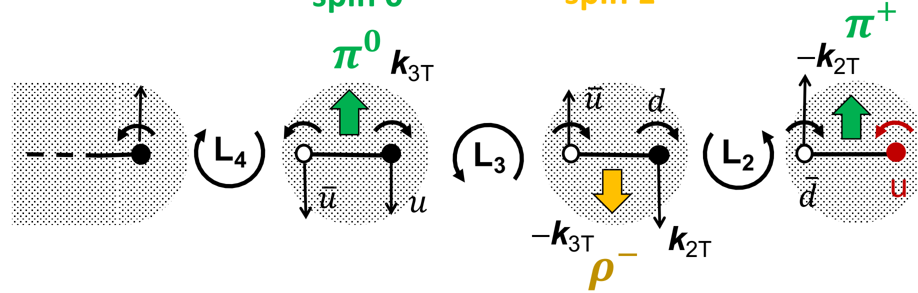
need not be necessarily true!

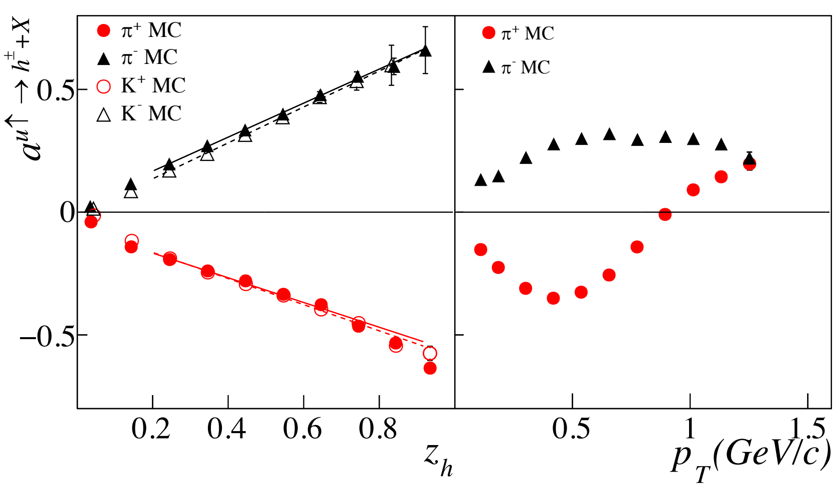
[*]Acta Phys.Polon. 27 (1996) 17591766

Collins analysig power of $\rho^{\pm}, \rho^{0}$

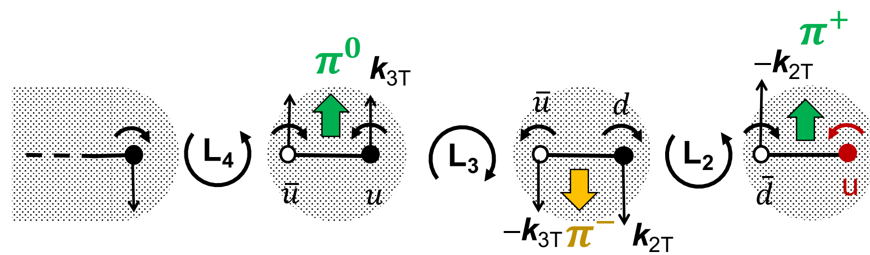






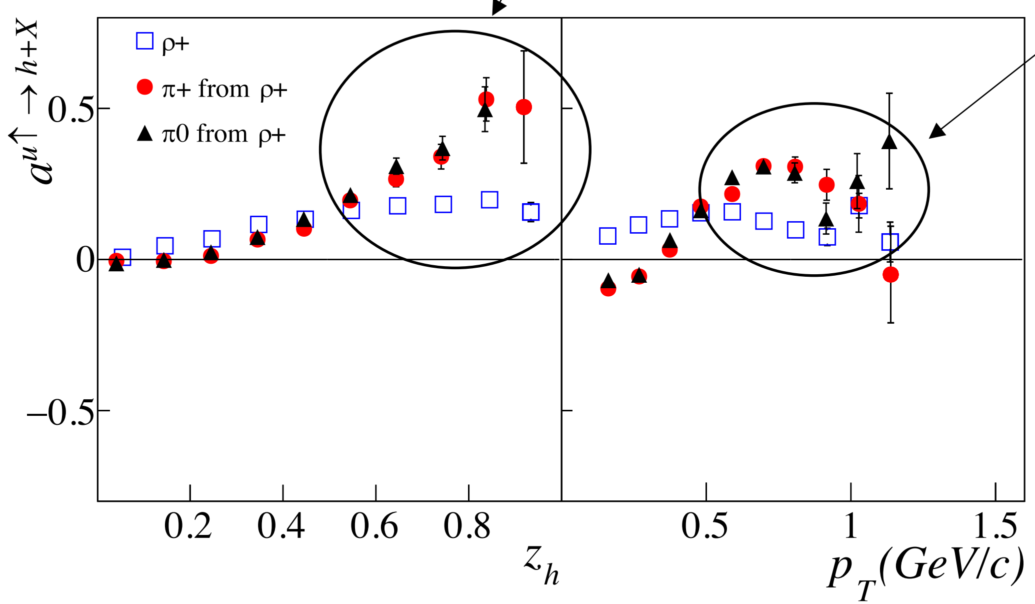


- **opposite sign of Collins analysing power for ρ^+ and π^+**
- $a^{u\uparrow\to\rho^-+X} \sim a^{u\uparrow\to\rho^++X}$ by chance, not true for $\frac{|G_L|}{|G_T|} \neq 1$



Collins analysig power of pions from ρ^+ decay

pions with large z_h come preferentially from decay of rank 1 ρ^+ linearly polarized along $\hat{\boldsymbol{z}}$ for which $a^{u\uparrow\to\rho_L^+ + X} \sim 3a^{u\uparrow\to\rho^+_{unpol.}+X}$



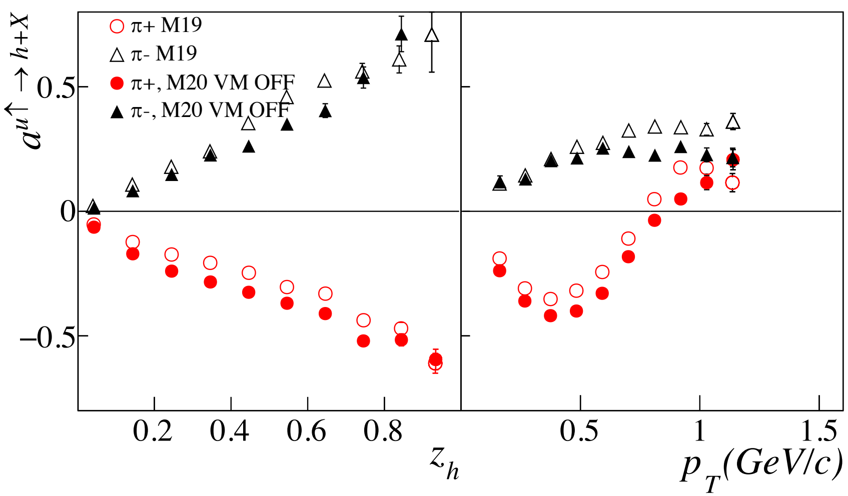
pions from
- rank 1 ρ^+ linearly pol. along $\boldsymbol{p}_T(\rho^+)$
- ρ^+ linearly pol. along $\hat{\boldsymbol{z}}\times\boldsymbol{p}_T(\rho^+)$

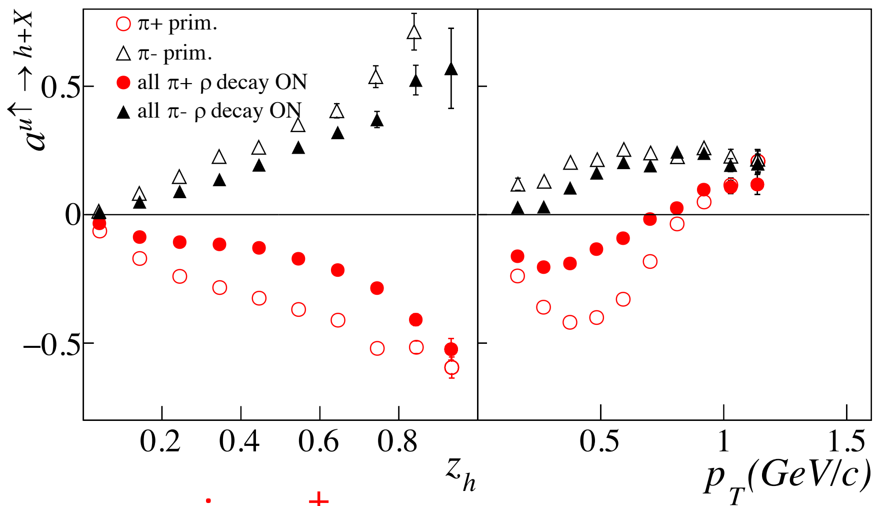
in both cases

$$a^{u\uparrow\to\rho_T^+ + X} \sim 3a^{u\uparrow\to\rho^+_{unpol.}+X}$$

- same analysing power for π^+ and π^0 -> decay process invariant under parity

Collins analysig power for pions from M20





○ π^+ from M19
△ π^- from M19

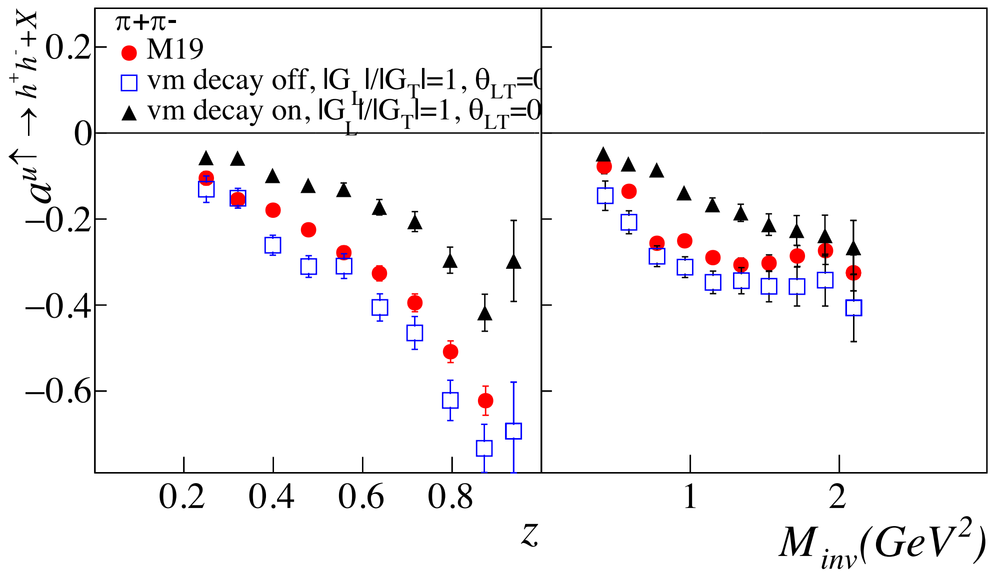
● prim. π^+ from M20
▲ prim. π^- from M20

○ prim. π^+
△ prim. π^-

● π^+ prim + π^+ from ρ decay
▲ π^- prim + π^- from ρ decay

- **analysing power of primary pions reduced by a factor of 2** as a consequence of ρ meson decay!
- K^*, ω, ϕ contribute less to the pion analysing power
- the trend as function of z_h for π^+ is no more linear

Dihadron analysing power

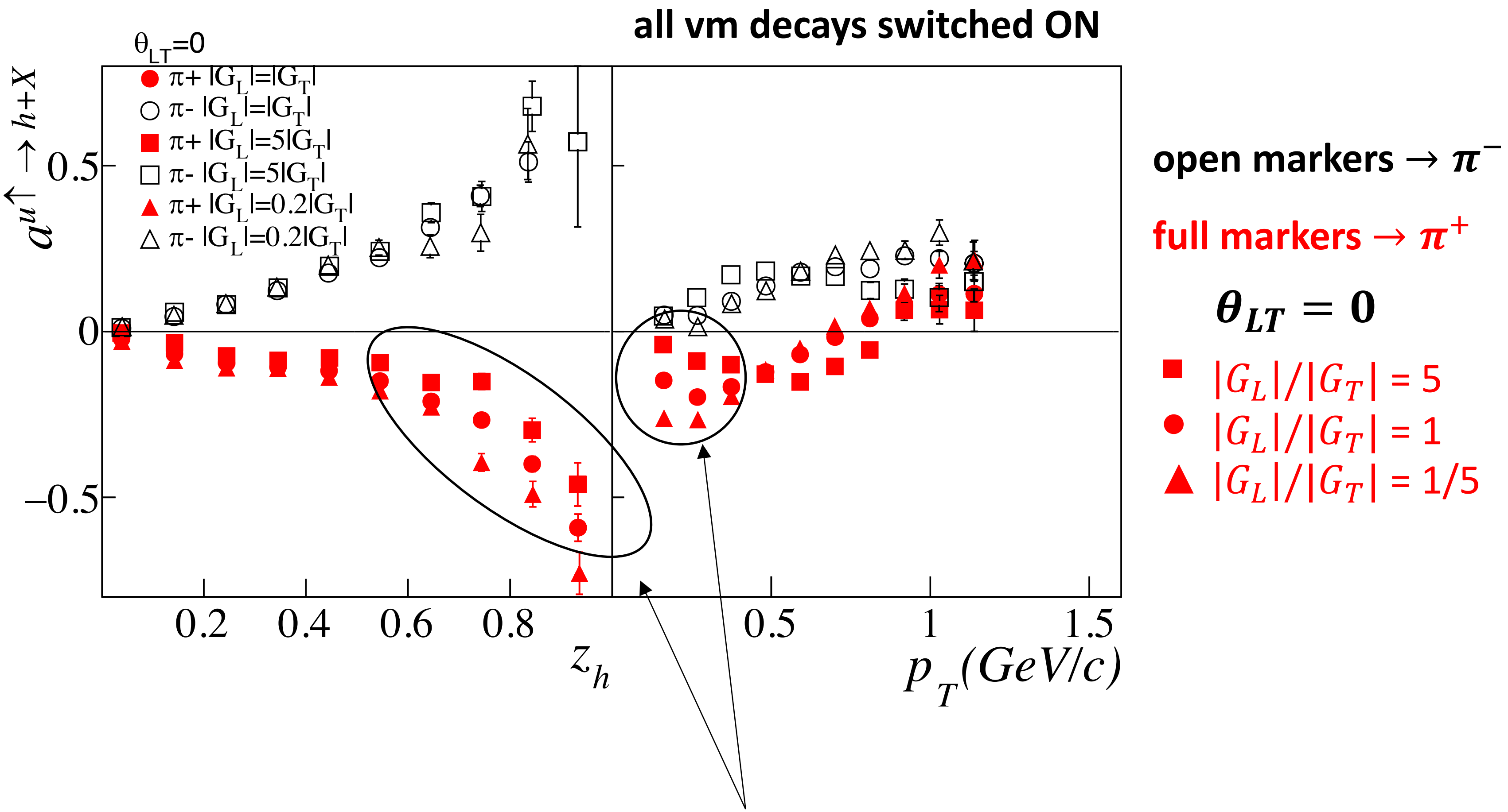


$|G_L|/|G_T| = 1$
$\theta_{LT} = 0$

□ VM decay OFF
● M19
▲ VM decay ON

- large effect on the dihadron analysing power, decreased by a factor of 2!

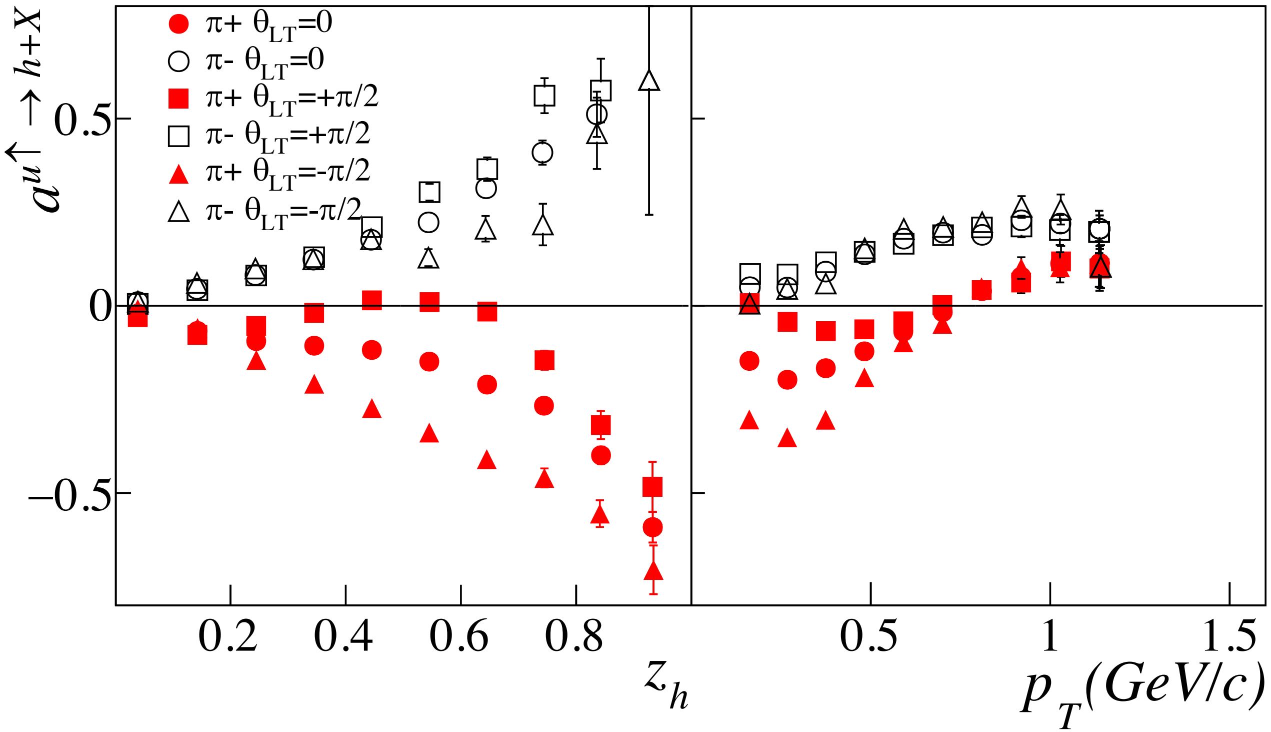
Sensitivity to $|G_L|/|G_T|$



- sensible variations at large z_h and at small p_T
- small effect on dihadron analysing power

Sensitivity to θ_{LT}

all vm decays switched ON



open markers → π^-

full markers → π^+

$|G_L|/|G_T|$ = 1

$\theta_{LT} = +\pi/2$

$\theta_{LT} = 0$

$\theta_{LT} = -\pi/2$

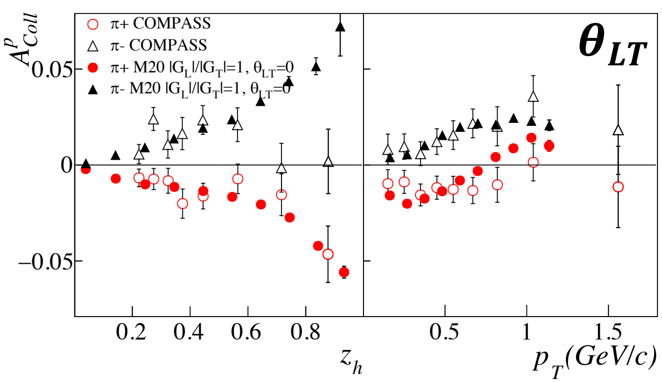
- **θ_{LT} can enhance ore reduce the Collins analysing power of final adrons** -> oblique polarization of the vm
- large effect for all z_h and $p_T < 0.5$ (GeV/c)
- small effect on dihadron analysing power

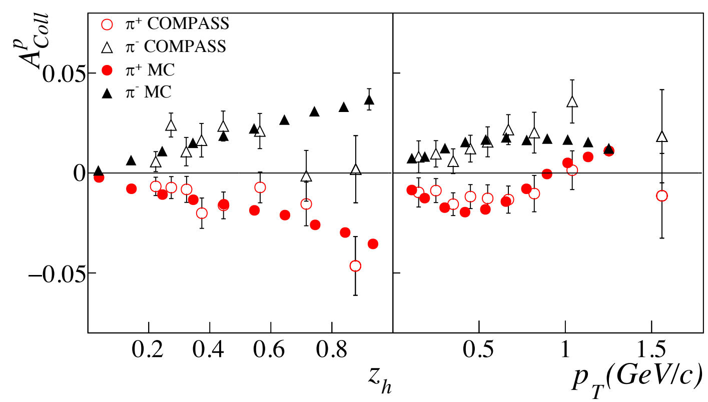
Comparison with COMPASS asymmetries

full points -> MC **open points -> COMPASS PLB 717 (2012) 376**

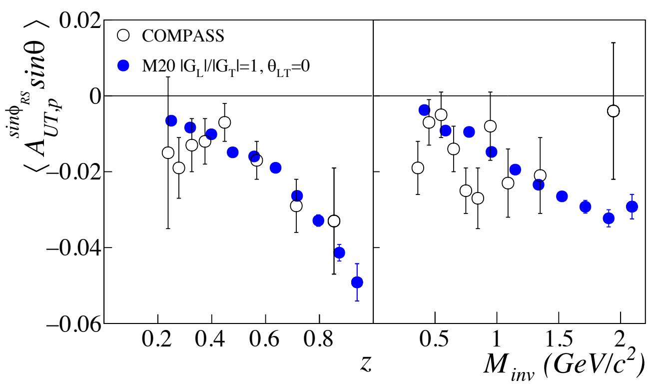
with vector mesons $|G_L|/|G_T|$ = 1 **only pseudoscalar mesons**

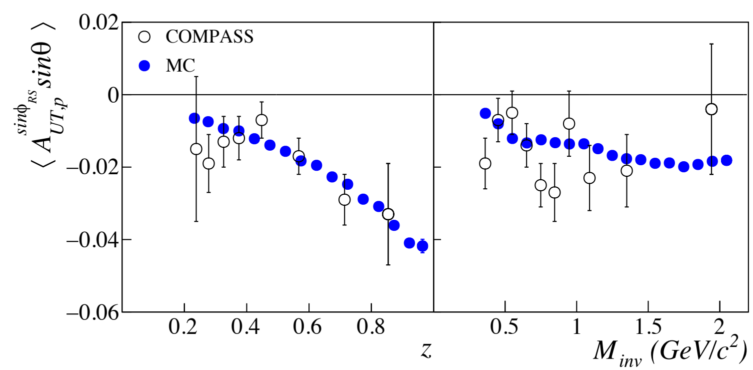
$\theta_{LT} = 0$





$\lambda' \sim 0.11 \pm 0.02$ $\lambda \sim 0.055 \pm 0.010$





- MC points scaled by the factors λ' and λ
- M20 promising but tuning of parameters is necessary
- different trends as function of z_h for π^-?

To exploit the true predictive power of the model,
M19 has been interfaced with PYTHIA 8 for SIDIS processes
introducing for the first time spin effects for pseudoscalar mesons in a complete event generator

a parameterization for the transversity PDF for valence u and d quarks is implemented
→ **allows to simulate the Collins and dihadron asymmetries**

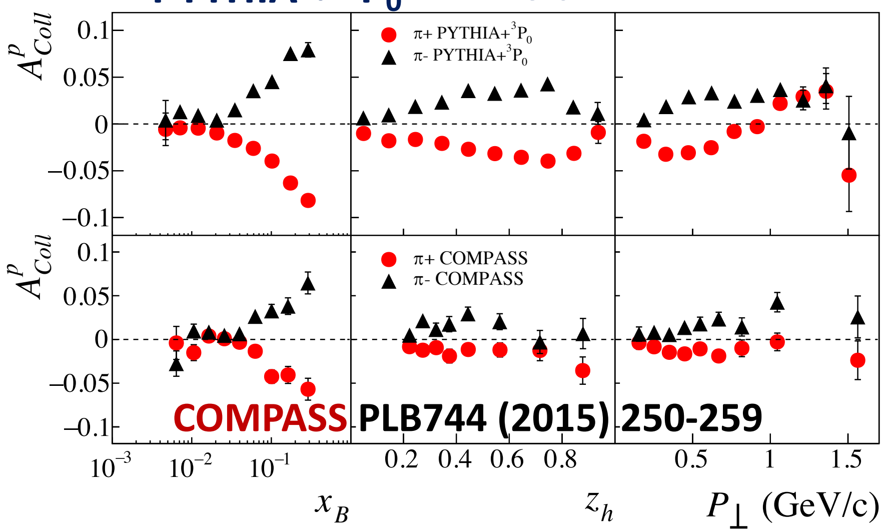
for the description of the interface see

A. Kerbizi and L. Lönnblad, **PoS DIS2019 (2019) 179**

a write-up is in preparation [A. Kerbizi and L. Lönnblad]

Collins and dihadron asymmetries on proton from PYTHIA+$^3P_0$

PYTHIA + $^3P_0$ only pseudo-scalar mesons

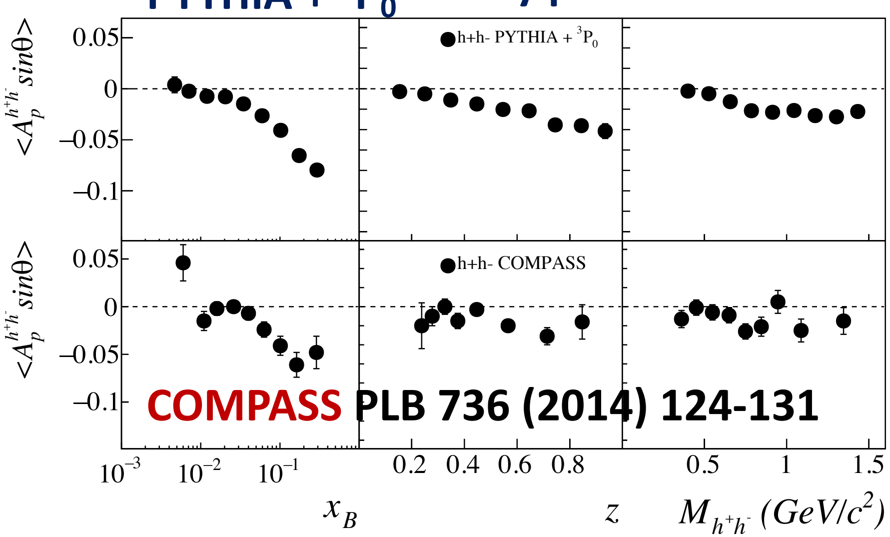


Collins asymmetry for charged pions

-similar trends as the Collins asymmetry seen in data as function of x_B and p_T
-different z_h trends -> no vector mesons

very promising results!

PYTHIA + $^3P_0$ only pseudo-scalar mesons



dihadron asymmetry for h+h- pairs

similar trends as the measured asymmetry

conclusions

- **The fragmentation process of polarized quarks with pseudoscalar and vector meson emission within the quantum mechanical formulation of the string+3P0 model has been simulated for the first time**

- The results of the stand alone MC are in good qualitative agreement with the present data

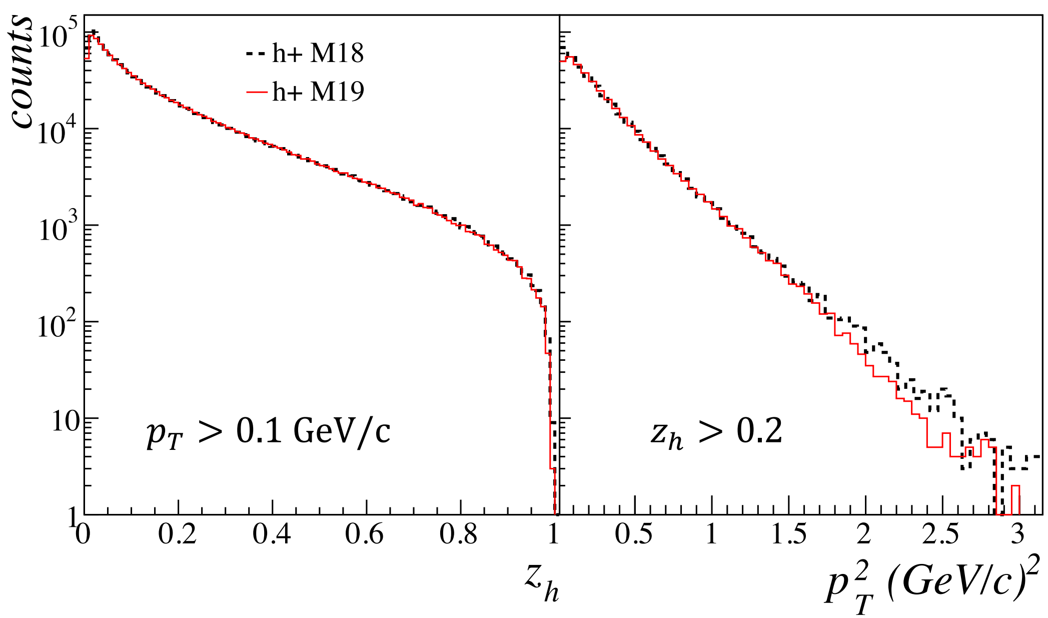
- **the interface with Pythia 8 for pseudo-scalar meson production has been developed** and will be public soon

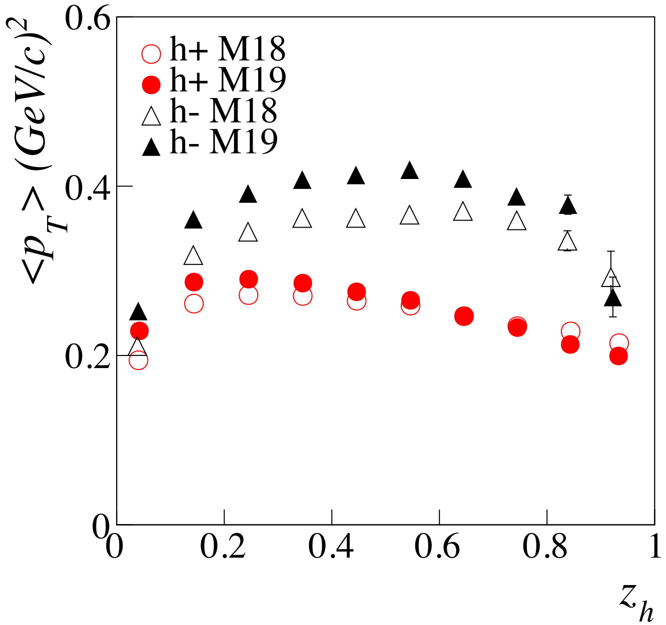
- The first step is done.. but this is not the end of the story

    - better tuning of parameters
    - study of e+e- annihilation
    - …

backup slides

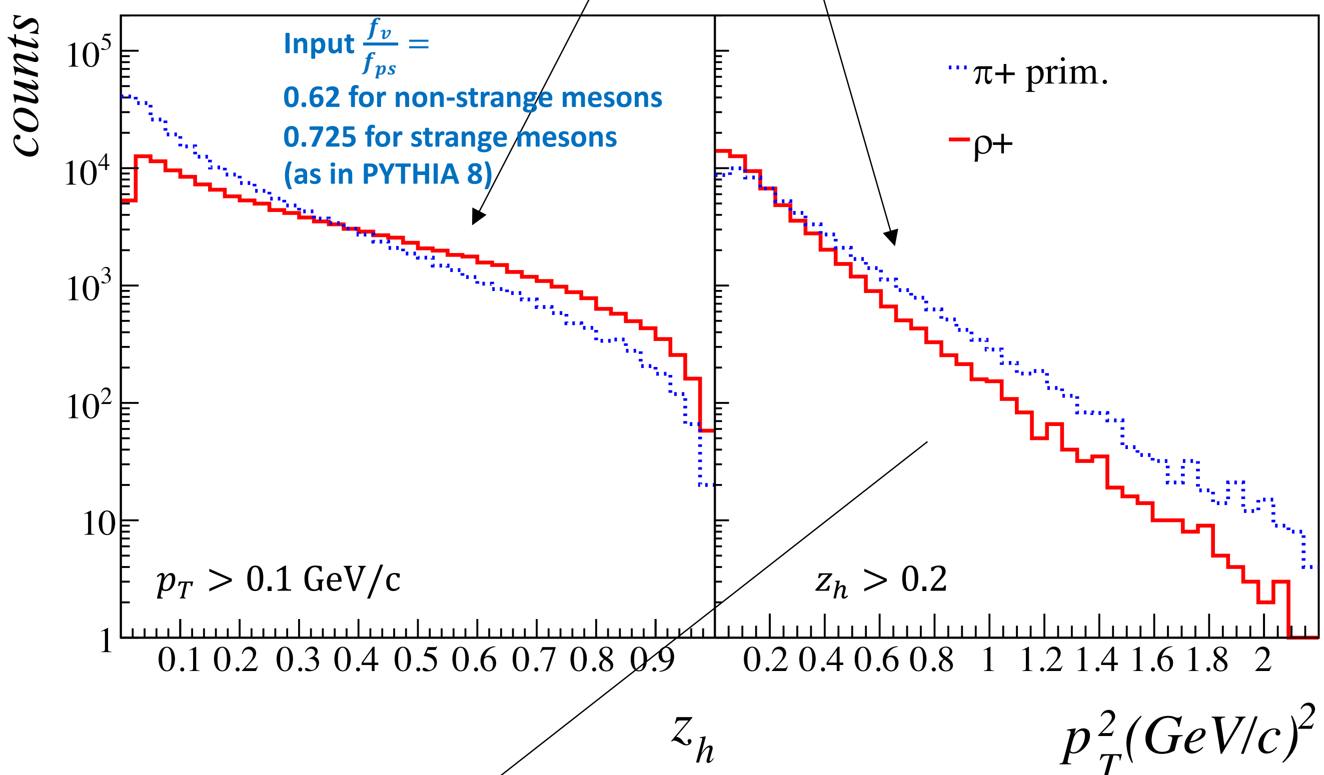
Kinematic distributions: comparison between M18 and M19





M20: kinematic distributions for primary π^+ and ρ^+

fraction vm/ps depends on the kinematics



- **Prediction of the string+$^3P_0$ model with vector meson production:**

$$\langle p_T^2 \rangle(\rho^+) < \langle p_T^2 \rangle(\mathrm{prim.}\,\pi^+)$$

This is at variance with PYTHIA!

- already expected in X. Artru and Z. Belghobsi DSPIN2011