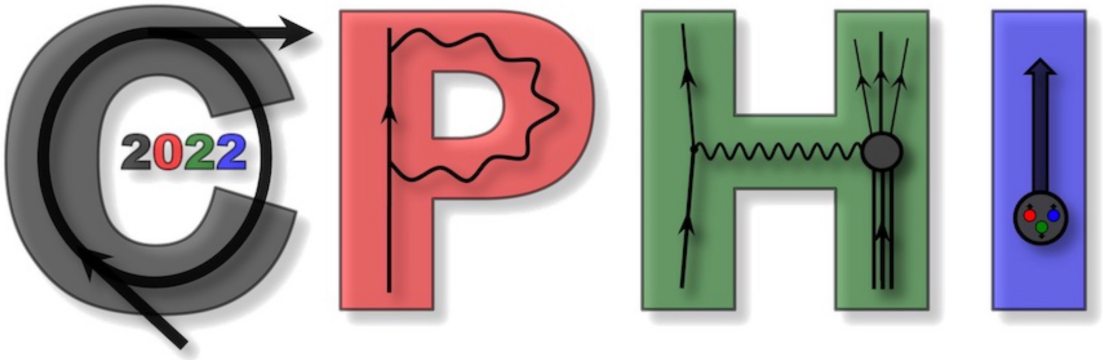


March 9, 2022
Duke University

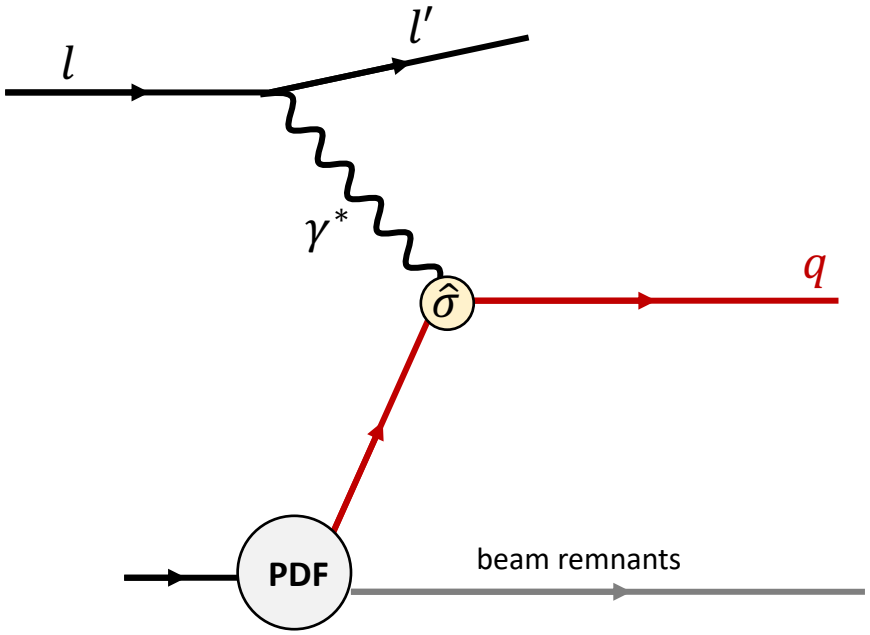
Correlations in Partonic and Hadronic Interactions

Simulation of quark spin effects with Monte Carlo event generators

Albi Kerbizi

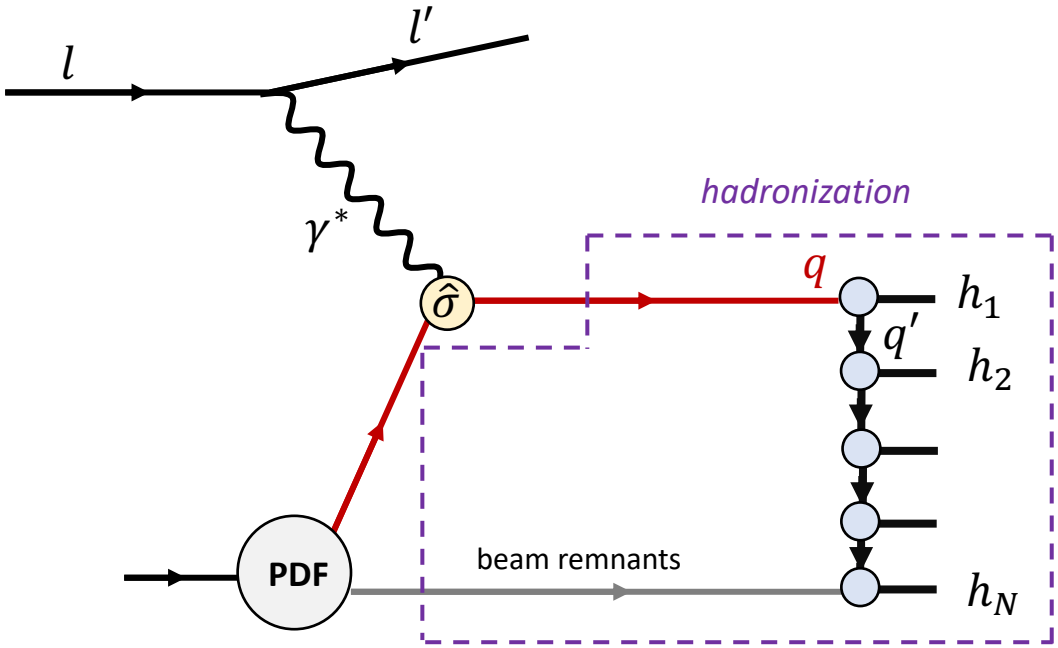
INFN Trieste
Istituto Nazionale di Fisica Nucleare

Polarized SIDIS process in a Monte Carlo Event Generator ~ the goal



PDFs input to the generator

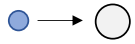
- $f_1^q(x, Q^2)$ used to generation x, Q^2, struck quark flavor
- intrinsic $\vec{k}_T$ treated as part of beam remnants



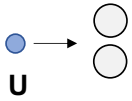
Hadronization

- A model must be utilized
  Lund string Model (Pythia, Lepto,..)
  cluster model (Herwig,..)
  ..
- Can be used to simulate FFs
  1h, 2h or more exclusive final states
- **No spin by default!**

Unpol. FF D_{1q}^{h}



Unpol. DiFF D_{1q}^{hh}



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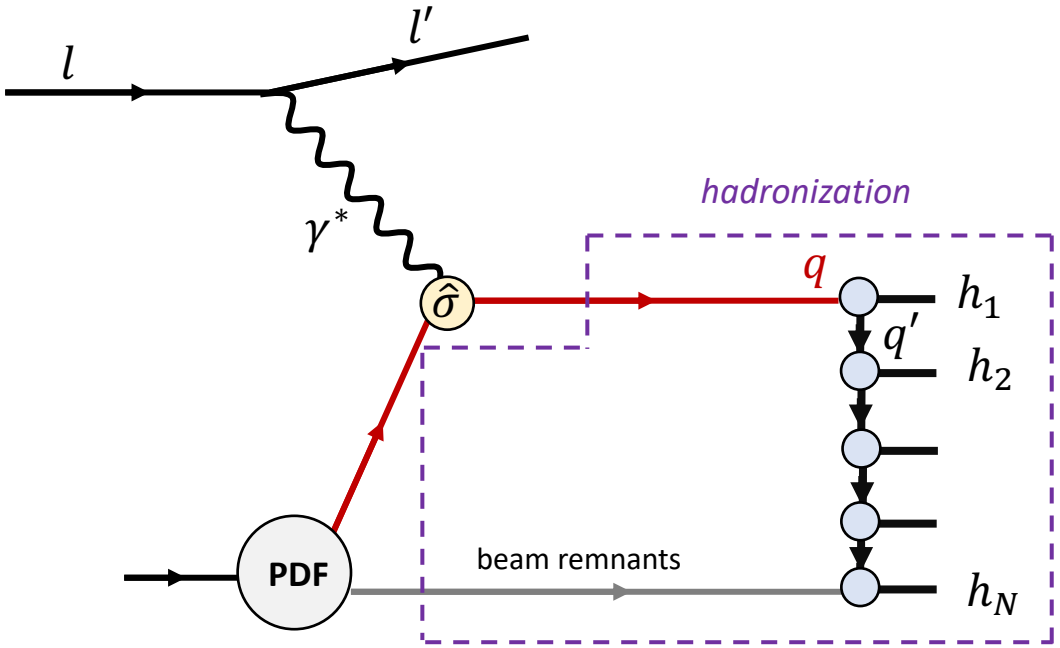

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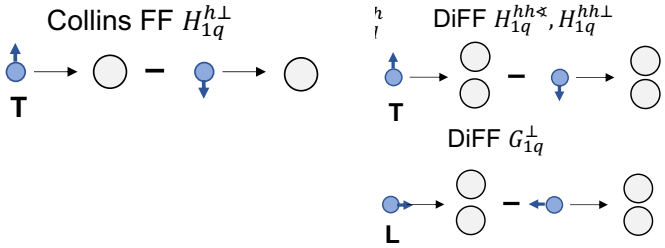
- **Including the spin of q**

Collins FF $H_{1q}^{h\perp}$ DiFF $H_{1q}^{hh\sphericalangle}, H_{1q}^{hh\perp}$ DiFF $G_{1q}^{\perp}$



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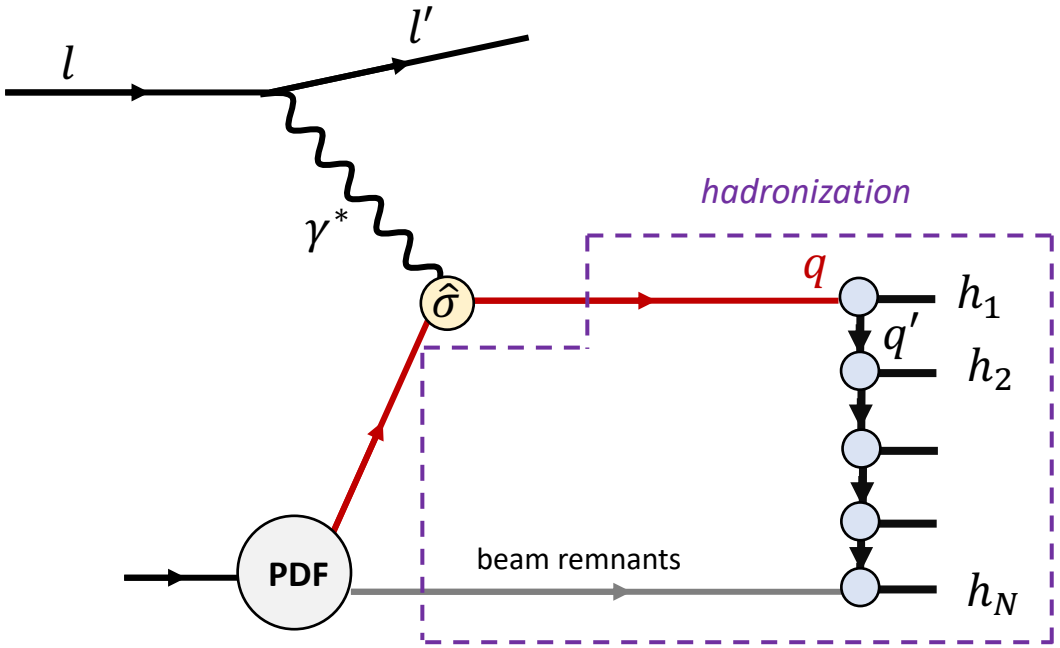

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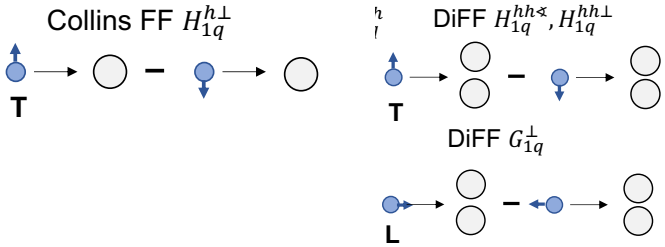

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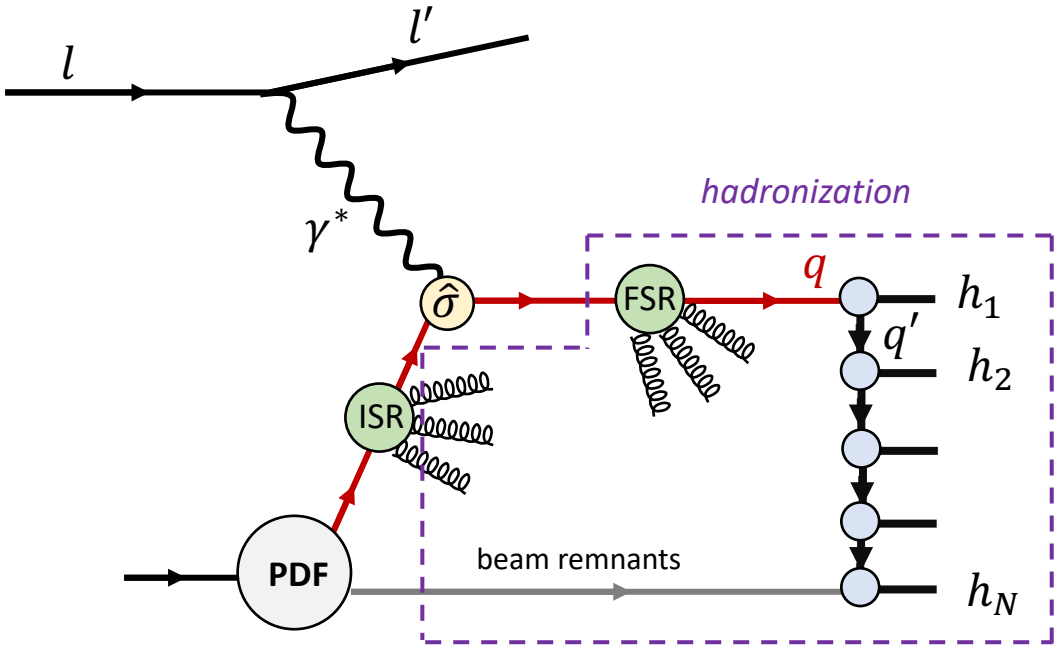
Once spin effects in hadronization are treated correctly
→ other (TMD) PDFs can (in principle) be included
→ possible to simulate the rich structure of azimuthal asymmetries in SIDIS

q\N	U	L	T
U	f_1		f_{1T}
L		g_1	g_{1T}
T	$h_1^\perp$	$h_{1L}^\perp$	$h_1, h_{1T}^\perp$

Polarized SIDIS process in a Monte Carlo Event Generator ~ the goal



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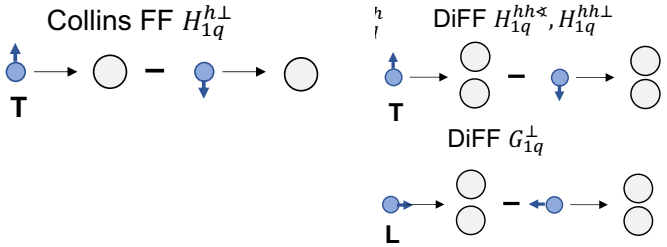

- evolution effects: spin in parton showers
  see e.g. Richardson, Webster, EPJ, C (2020) 80:83

→ **still no match with polarized hadronization**

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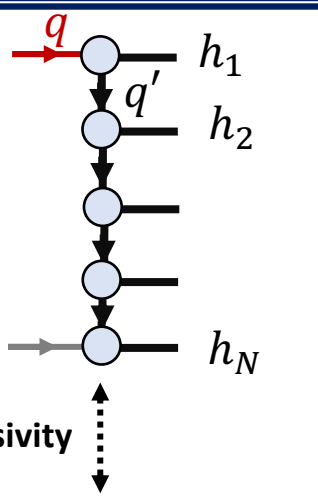
T	$h_1^\perp$	$h_{1L}^\perp$	$h_1, h_{1T}^\perp$

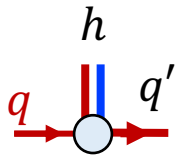
polarized hadronization model is crucial
→ must start from here!
understand hadronization, implement in MCEGs

Current models of polarized hadronization

→ The string+$^3P_0$ model

- **recursive** model





«elementary splitting»

AK, Artru, Belghobsi, Bradamante, Martin, PRD97 (2018) 7, 074010
AK, Artru, Belghobsi, Martin , PRD100 (2019) no.1, 014003
AK, Artru, Martin, PRD104 (2021) 11, 114038

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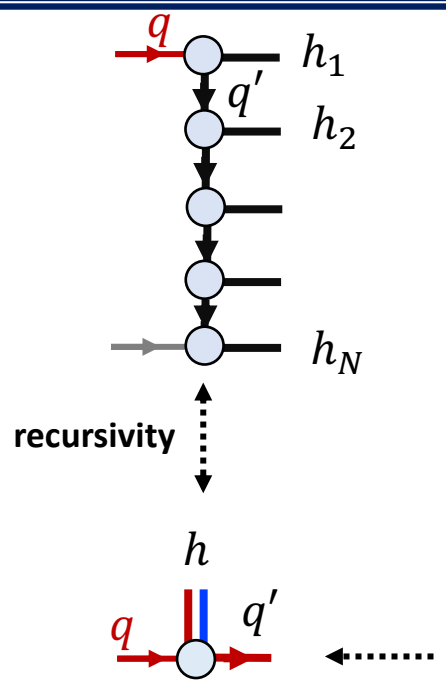

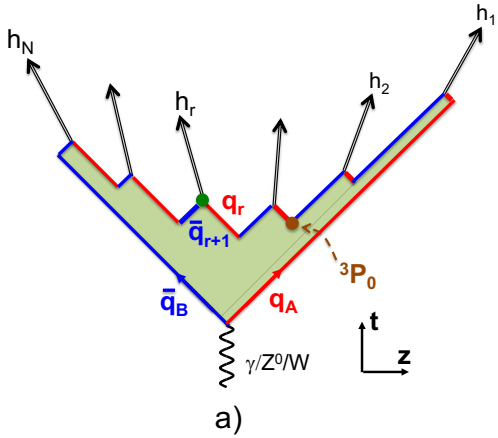

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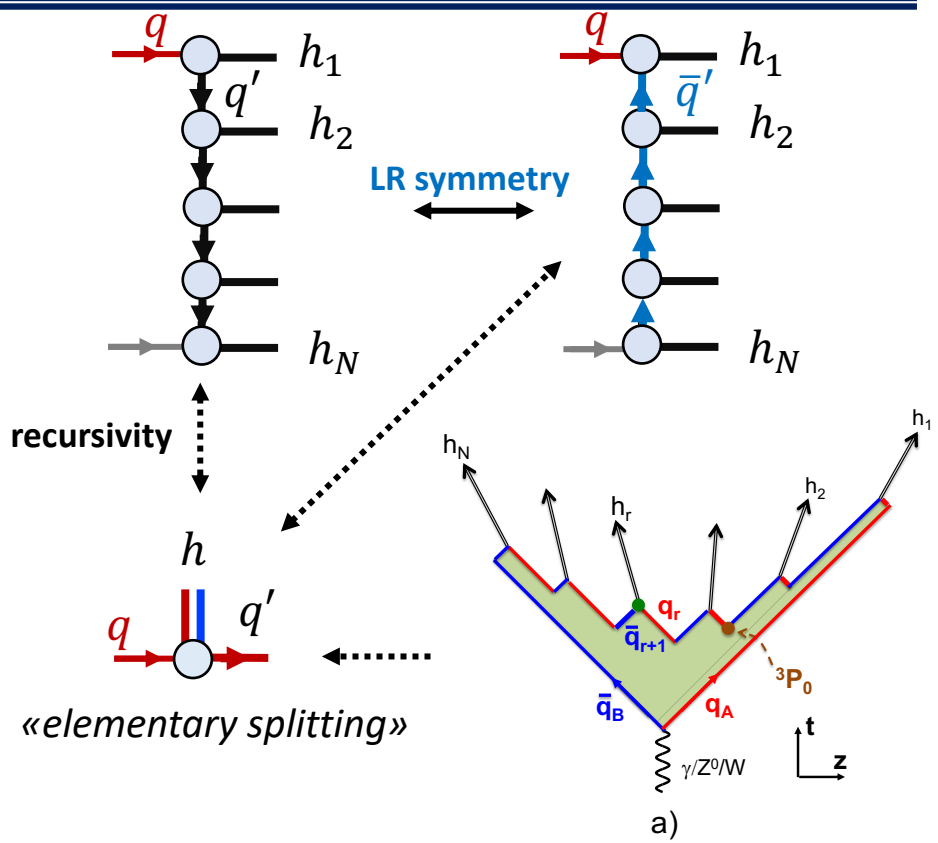

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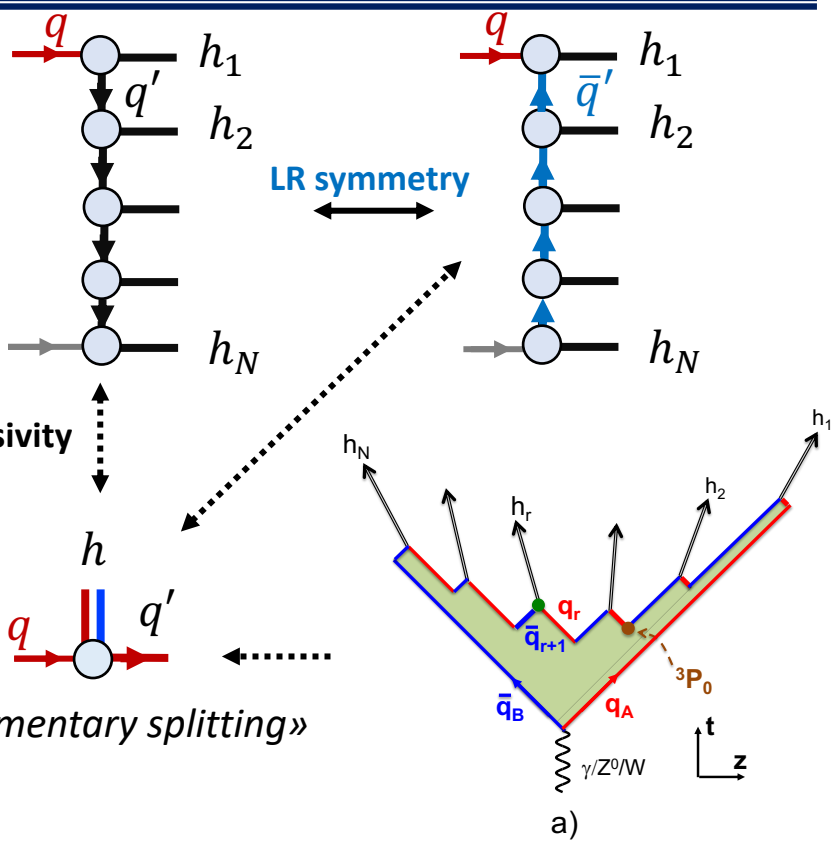

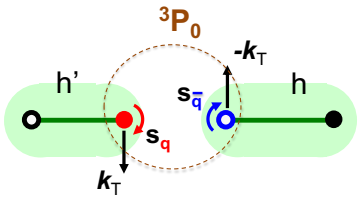

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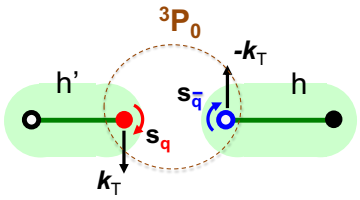

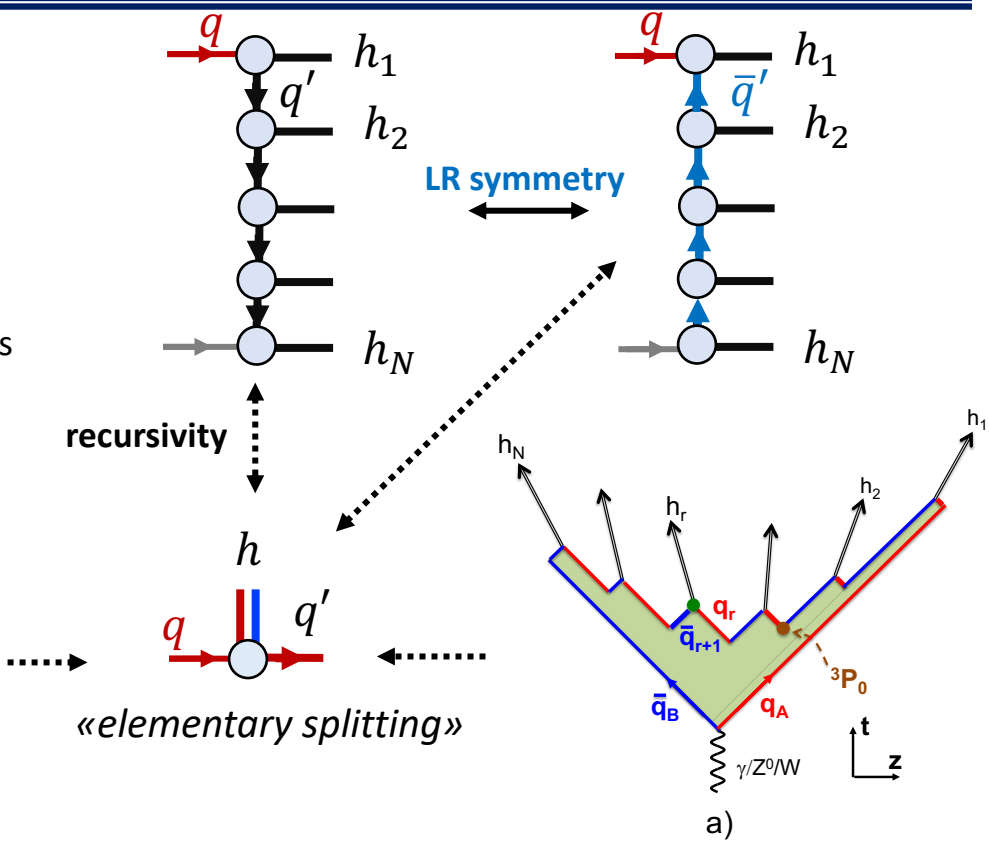

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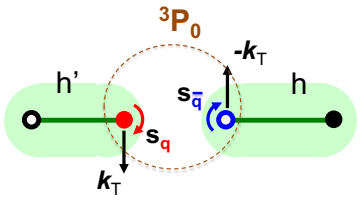

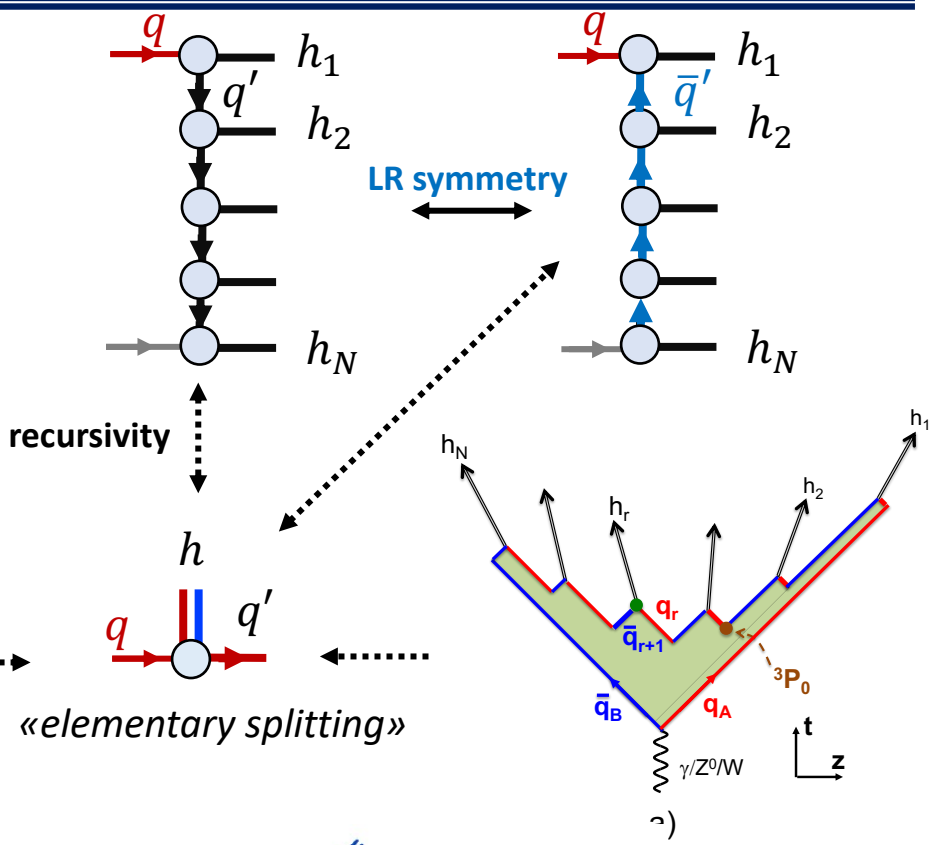

→ The quark-jet model

- recursive model
- generalization of Field-Feyman fragmentation model
- field-theoretic calculation of elementary splitting functions (T-even and T-odd functions treated differently)
- density matrix formalism to propagate spin effects
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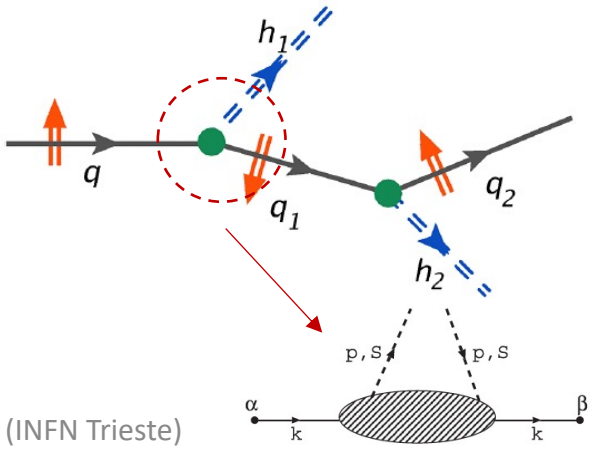
see e.g. Matevosyan, Kotzinian, Thomas, PRD95 (2017) 1, 014021



Current models of polarized hadronization

→ The string+$^3P_0$ model ⇨ next slides

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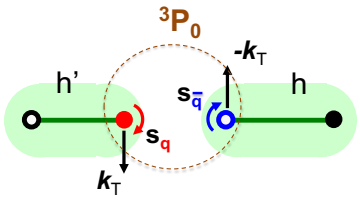

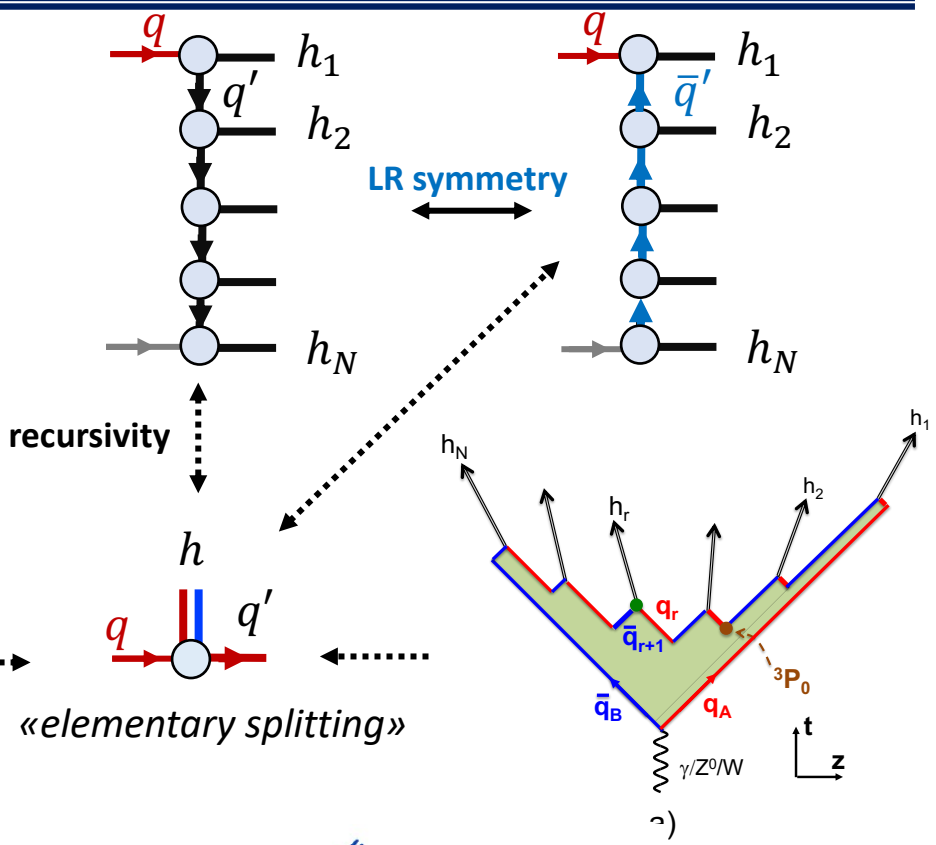

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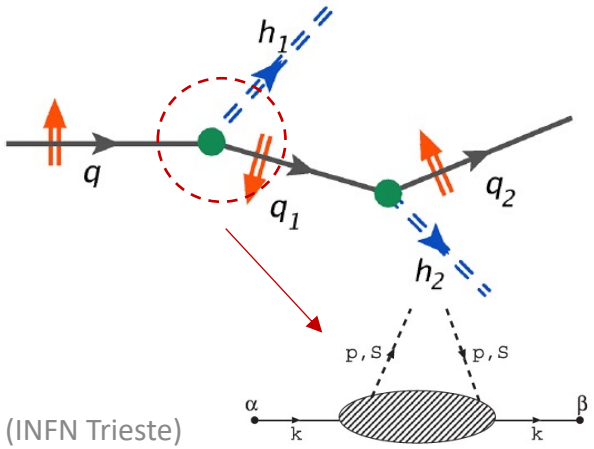
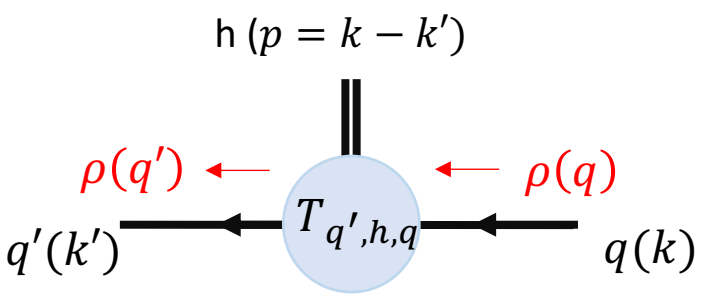


Elementary splitting in the string+$^3P_0$ model



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

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

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

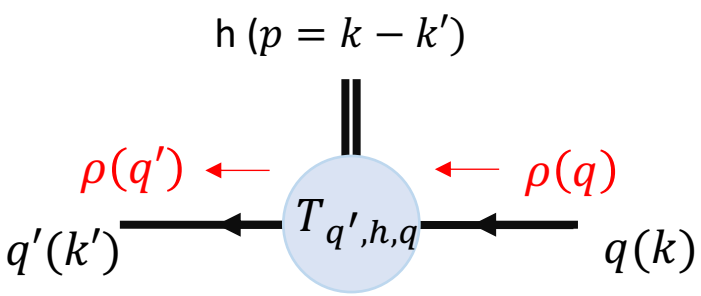
iii) Calculate the density matrix of q'

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

Couplings:

$\Gamma_h = \sigma_z$ → PS meson

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



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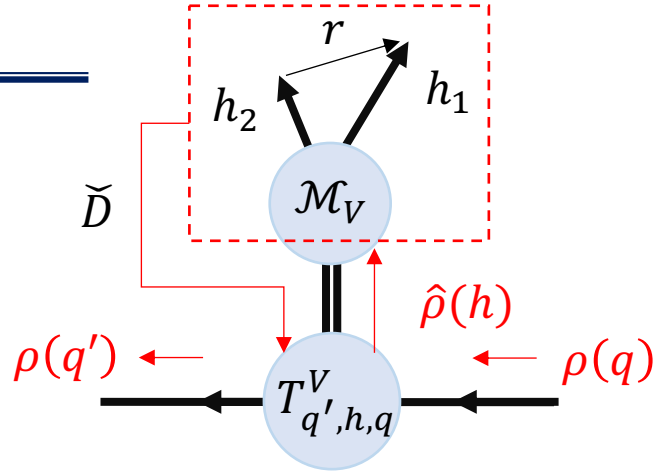

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Couplings:

$\Gamma_h = \sigma_z$ → PS meson

$\Gamma_{h,\boldsymbol{V}} = G_L V_L^* \mathbf{1} + G_T \boldsymbol{V}^*_{\boldsymbol{T}} \cdot \boldsymbol{\sigma}_{\boldsymbol{T}} \sigma_z$ → 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'

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

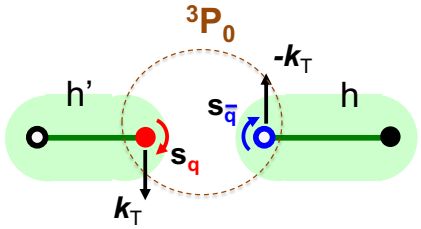
The free parameters of the string+$^3P_0$ model

Spin effects

complex mass μ from $^3P_0$ wave function

$Im(\mu) \rightarrow$ T spin effects (Collins, dihadron)

$Re(\mu) \rightarrow$ L spin effects (jet-handedness)



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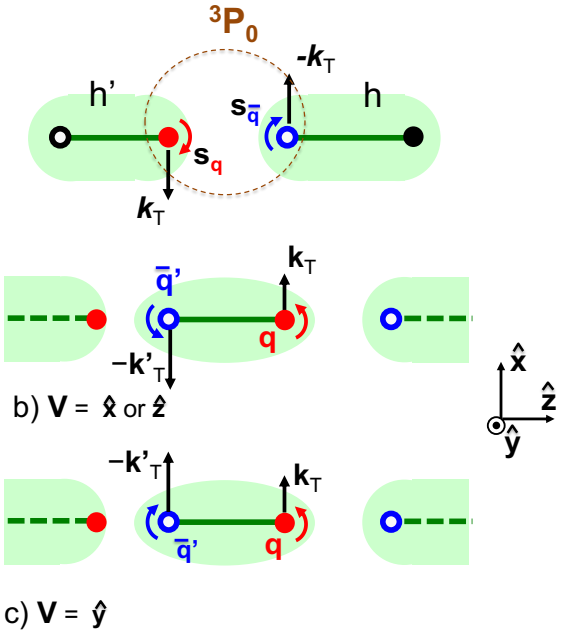
Coupling to VM

$G_L \rightarrow$ VM with L pol. along the string axis

$G_T \rightarrow$ VM with T pol. w.r.t the string axis



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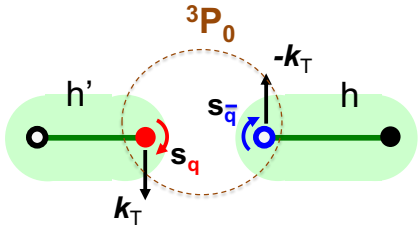

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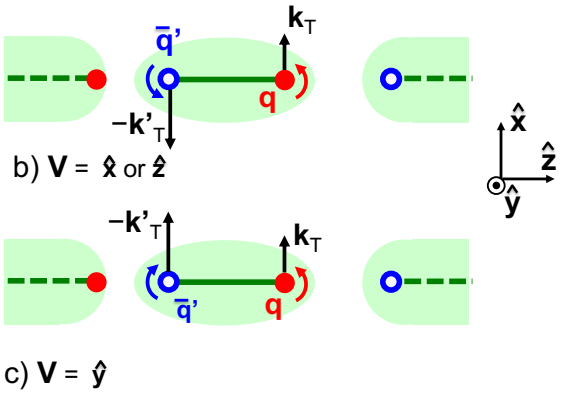
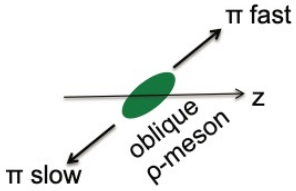


Effective parameters for VM production

$$|G_L|^2 + 2|G_T|^2 = \frac{VM}{PS} = \begin{cases} 0.62 \text{ light mesons.} \\ 0.725 \text{ strange mesons} \end{cases}$$ → as in Pythia 8

$|G_L/G_T|$ → spin alignment, Collins effect of the VM

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



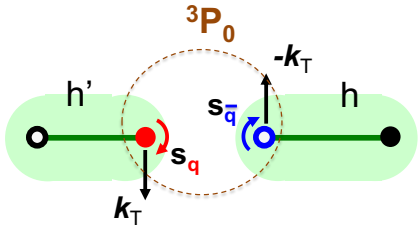
The free parameters of the string+$^3P_0$ model

Spin effects

complex mass μ from $^3P_0$ wave function

$Im(\mu) \rightarrow$ T spin effects (Collins, dihadron)

$Re(\mu) \rightarrow$ L spin effects (jet-handedness)



Coupling to VM

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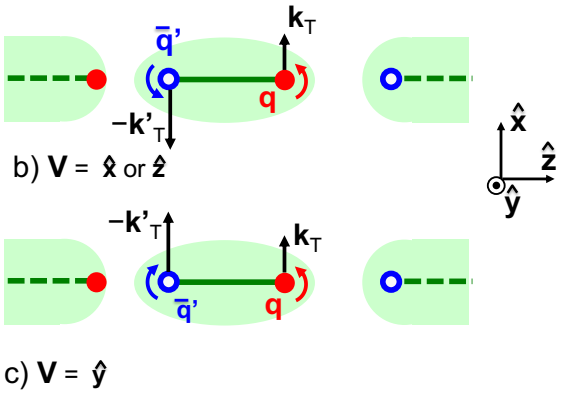

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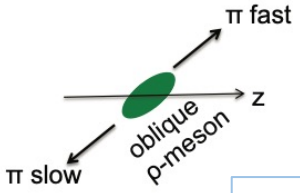


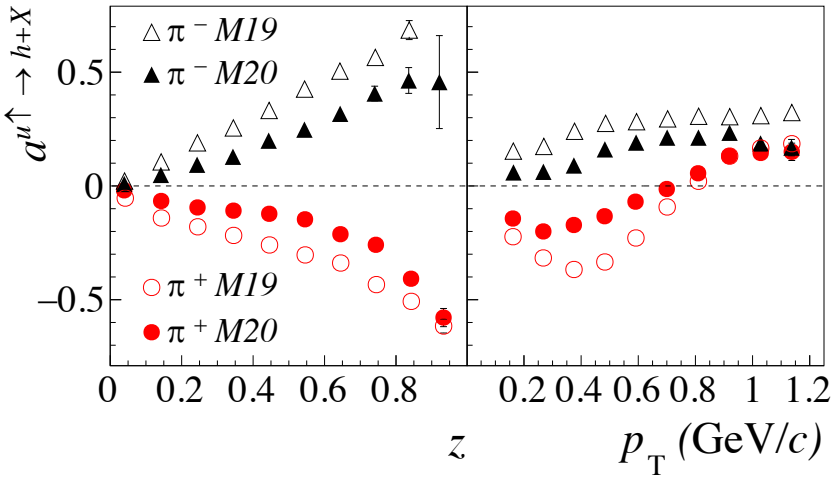
+ Parameters for spin-less Lund splitting Function
→parametrize the string decay process (*see backup slides)*

Following slides, simulations with
u quarks with full T pol. along $\hat{y}$
no primordial $\vec{k}_T$

Effect of VM production on TSA

M19 = only PS
M20 = PS, VM

Collins analysing power



Different trends as compared to M19
Dilution of about 50%

Large effect on Collins
→ VM important to understand how the observed asymmetries arise

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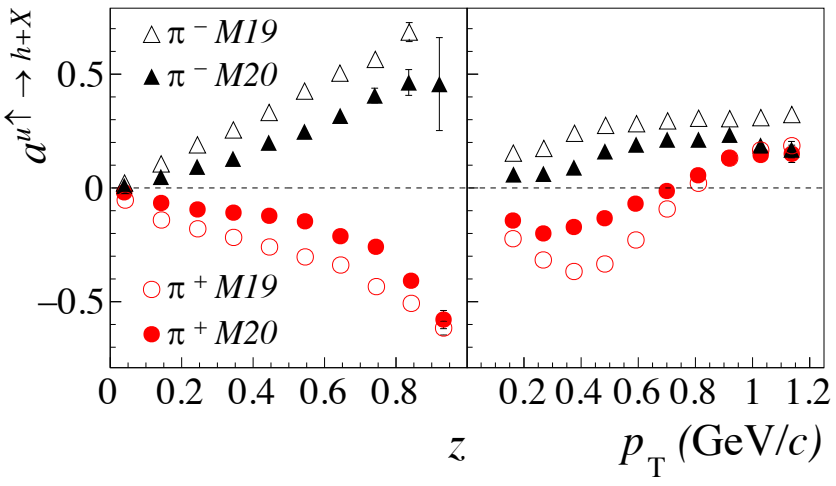
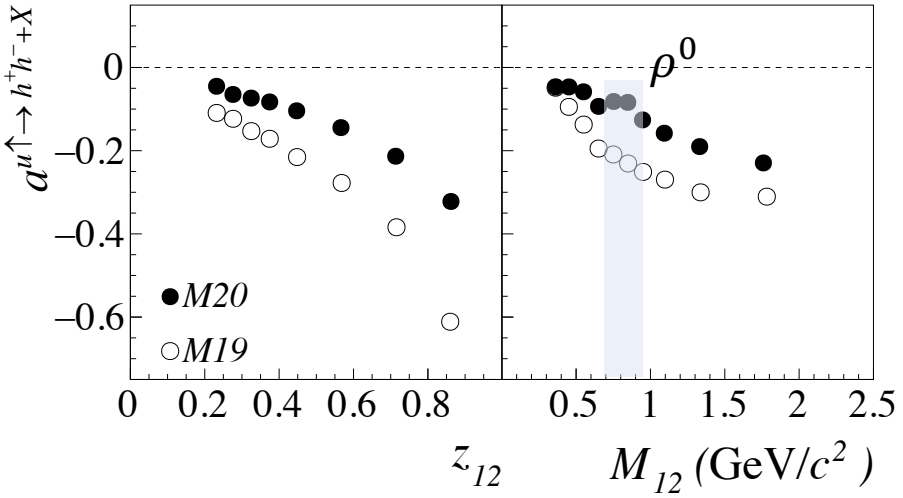


Different trends as compared to M19
Dilution of about 50%

Di-hadron analysing power



VM decays do not contribute to the 2h asymmetry
(decay symmetric w.r.t $\boldsymbol{R} \leftrightarrow -\boldsymbol{R}$)
50% dilution w.r.t M19
→ stronger dilution around ρ^0

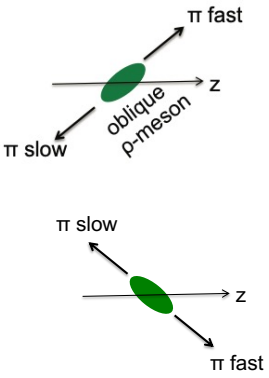
Large effect on Collins and dihadron analysing powers
→ VM important to understand how the observed asymmetries arise

Comparison with SIDIS data

Different combinations of free parameters

$$\left|\frac{G_L}{G_T}\right| = \begin{cases} 5 & \text{L pol. VM} \\ 1 & \text{T, L pol. VM} \\ 1/5 & \text{T pol. VM} \end{cases}$$

$$\theta_{LT} = \begin{cases} -\frac{\pi}{2} & \text{VM with oblique pol.} \\ 0 & \text{VM with no oblique pol.} \\ +\frac{\pi}{2} & \text{VM with oblique pol.} \end{cases}$$



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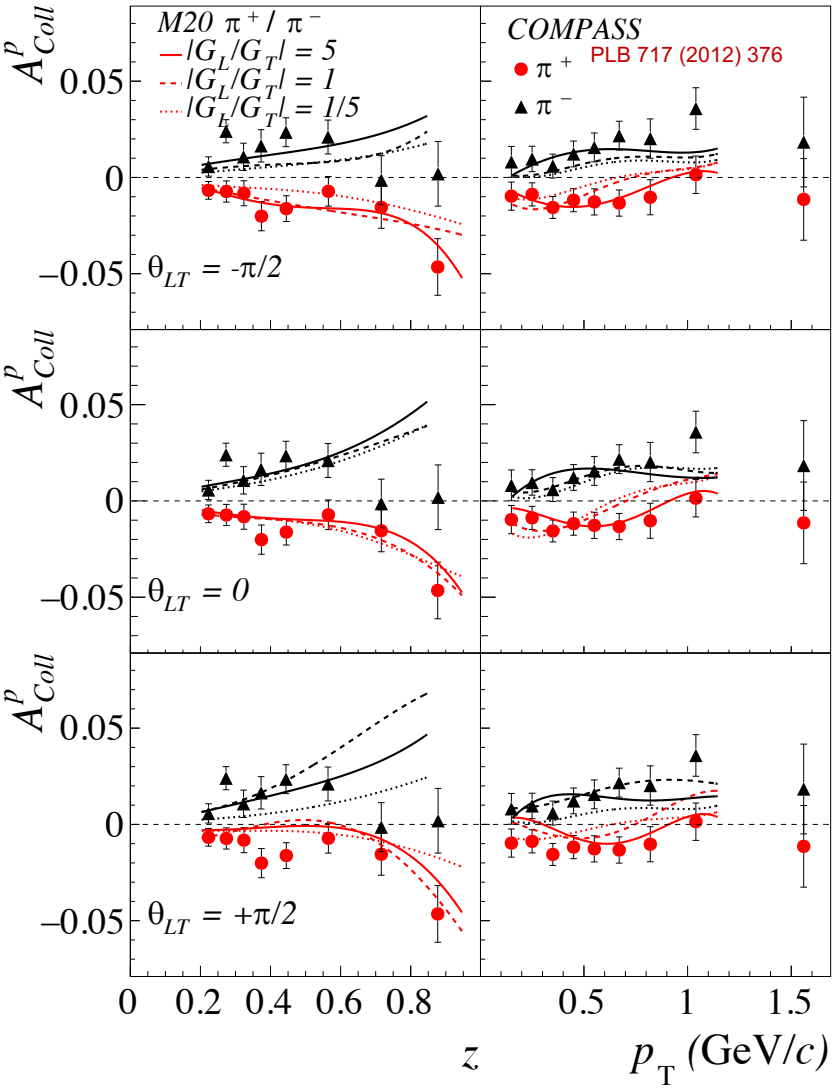

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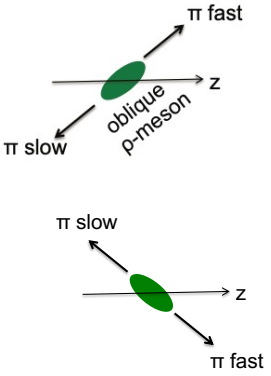


MC scaled by a constant for each combination

Large variations for different values of $|G_L|/|G_T|$ and θ_{LT}

→ **both parameters important**

hint for $|G_L/G_T| = 5, \theta_{LT} = -\pi/2$

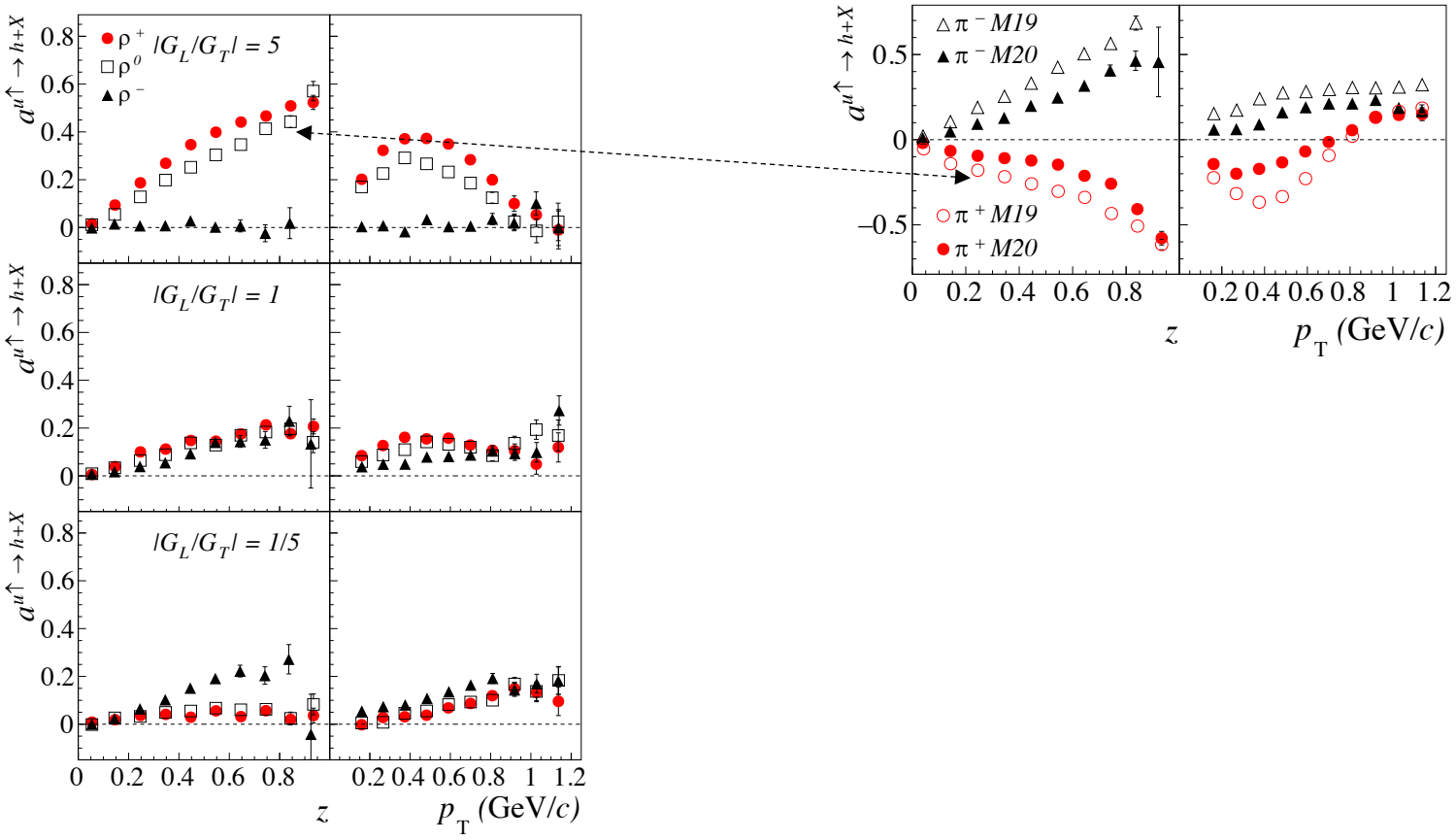
or $|G_L/G_T| = 1, \theta_{LT} = 0$

→ more precise data needed to fix the free parameters

comparison with 2h asymmetry OK

less sensitive to $|G_L G_T|$ and θ_{LT}

Collins effect for ρ mesons



→ Opposite sign w.r.t π^+
(in agreement with Czyzewski '96)

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

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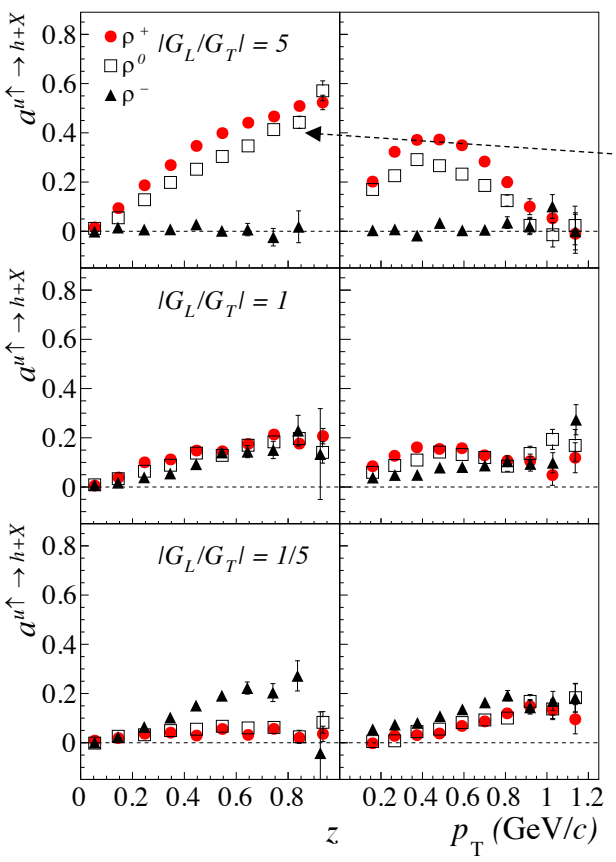

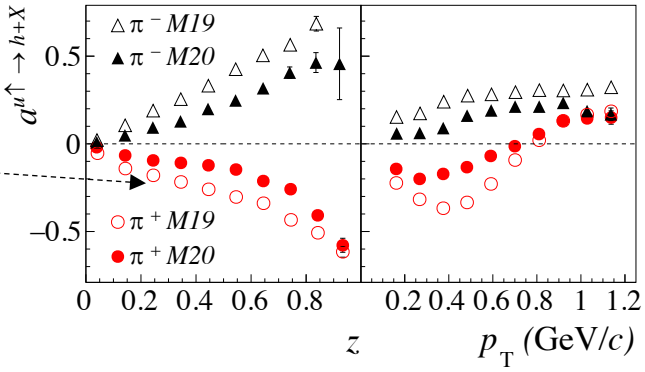

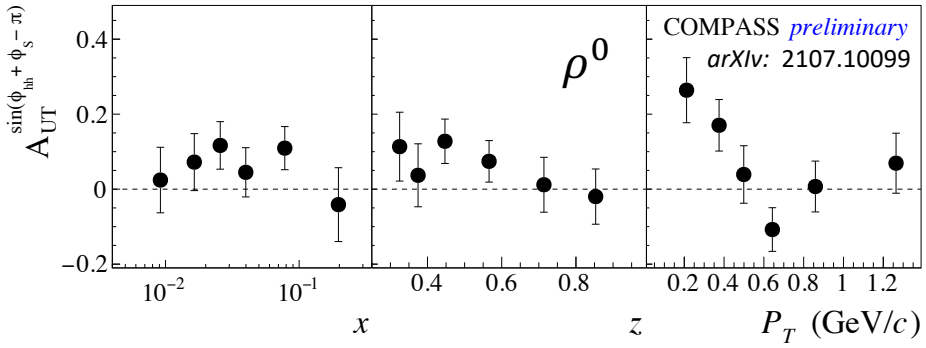

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First measurement by COMPASS

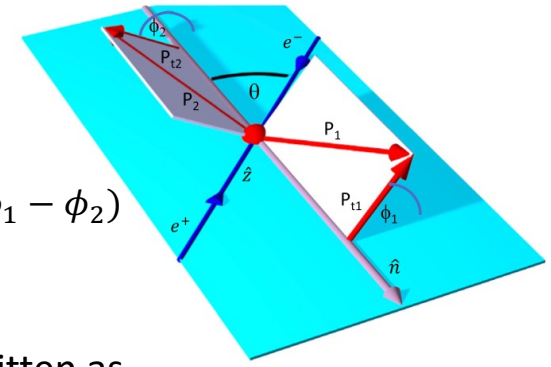
→ **Hint for $\frac{|G_L|}{|G_T|} > 1$?**

→ Measurements feasible
more precise data are needed,
e^+e^- data would be wellcome!

Comparison with e^+e^- data

Comparison with Collins asymmetries for back-to-back pions measured recently by BELLE

BELLE, PRD 100, 092008 (2019)



$$R_{12}^{UL} = \frac{N_{\pi^+\pi^-} + N_{\pi^-\pi^+}}{N_{\pi^+\pi^+} + N_{\pi^-\pi^-}} \approx 1 + A_{12}^{UL}\cos(\phi_1 - \phi_2)$$

The $A_{12}^{UL}(z, p_T)$ asymmetry can be written as

$$A_{12}^{UL}(z, p_T) = \left\langle \frac{\sin^2\theta}{1+\cos^2\theta} \right\rangle \times \left|a^{fav}(z, p_T)\right|^2 \times \left(\frac{5 + 5\alpha^2 + 2\alpha'^2}{5 + 5\beta^2 + 2\beta'^2} - \frac{5\alpha + \alpha'^2}{5\beta + \beta'^2}\right)$$

$z_1 = z_2 \equiv z$
$p_{1T} = p_{2T} \equiv p_T$

$\left\langle \frac{\sin^2\theta}{1+\cos^2\theta} \right\rangle$: 0.91

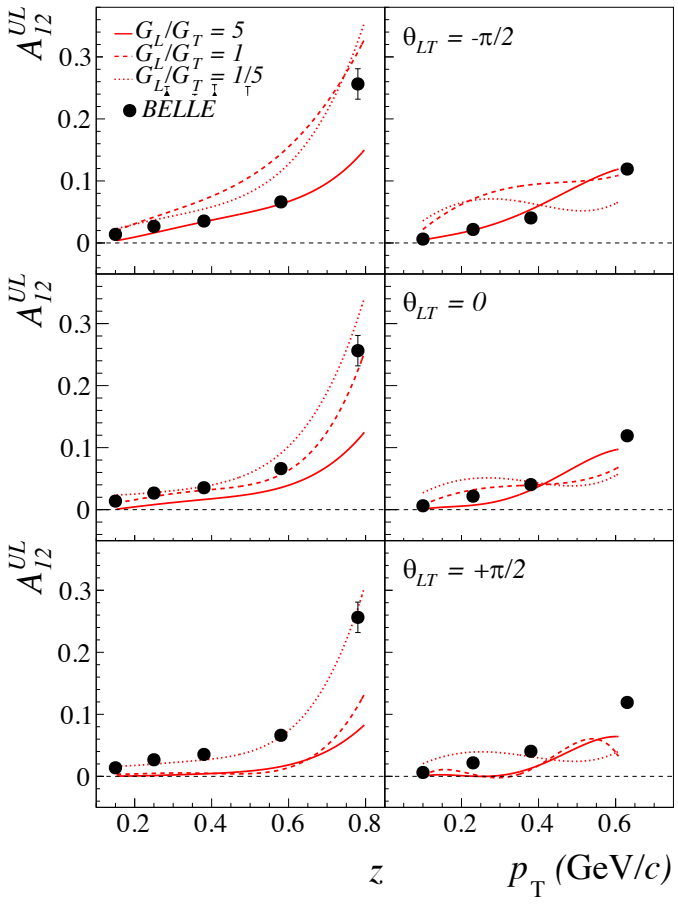
$\left|a^{fav}(z, p_T)\right|^2$: Collins analyzing power for fav. fragmentation

$\left(\frac{5 + 5\alpha^2 + 2\alpha'^2}{5 + 5\beta^2 + 2\beta'^2} - \frac{5\alpha + \alpha'^2}{5\beta + \beta'^2}\right)$: isospin + charge congj.

$\alpha = H_1^{fav}/H_1^{unfav}$ $\alpha' = H_{1,s}^{unfav}/H_1^{unfav}$
$\beta = D_1^{fav}/D_1^{unfav}$ $\beta' = D_{1,s}^{unfav}/D_1^{unfav}$

Belle data corrected for charm production
A_{12}^{UL} has been **evaluated** using M20 (cuts as in data, MC not rescaled)

Comparison with e^+e^- data



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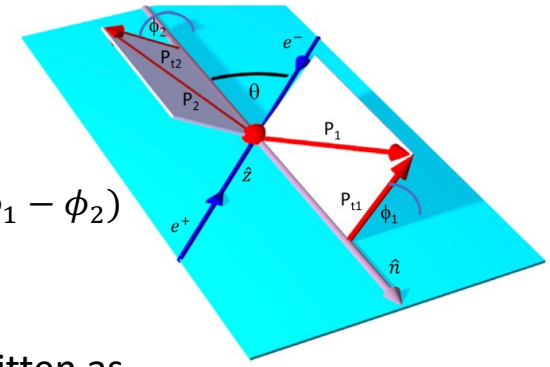

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→ satisfactory description for $\left|\frac{G_L}{G_T}\right| = 5, \theta_{LT} = -\frac{\pi}{2}$ and $\left|\frac{G_L}{G_T}\right| = 1, \theta_{LT} = 0$ as for SIDIS data

A new di-hadron asymmetry

VMs do not contribute to the standard dihadron asymmetry

They contribute to the z-ordered di-hadron asymmetry, namely

$$a^{u\uparrow\to h_1 h_2+X} = 2\langle \sin(\phi_R - \phi_{S_u})\rangle \,,\; \boldsymbol{R}_T = z_2\boldsymbol{p}_{1T}/z - z_1\boldsymbol{p}_{2T}/z, \quad z_1 > z_2 \text{ (z-ordering)}$$

→ Due to the oblique polarization which depends on θ_{LT}

z-ordered 2h analysing power in the decay $\boldsymbol{\rho^0 \to \pi^+\pi^-}$

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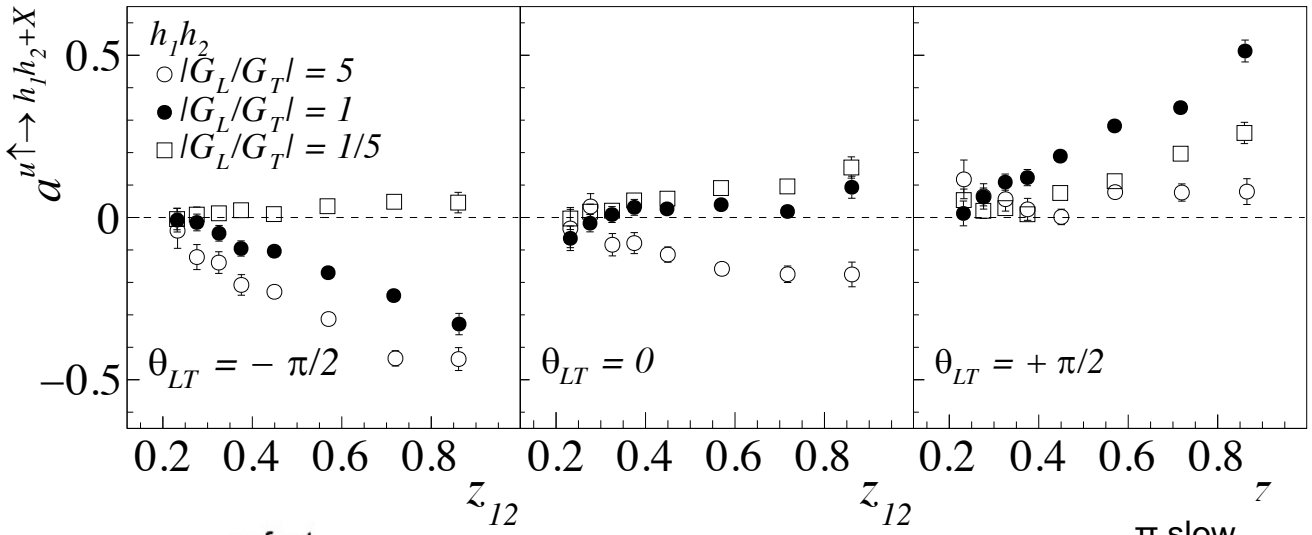

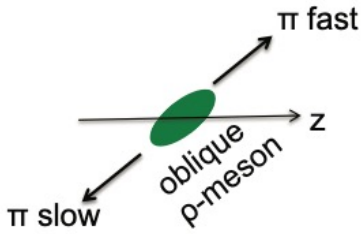

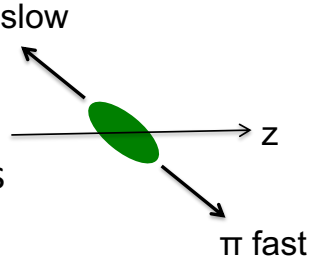

Relevant to study the oblique polarization of VMs

→ asymmetry still large below the ρ^0 region

→ interesting measurement in SIDIS and e^+e^-

Interface of the string+$^3P_0$ model to PYTHIA hadronization

The simulation of complete scattering events requires many physics ingredients
(PDF, hard scattering, parton showers, hadronization, decays ..)

Existing general purpose event generators include all these effects (for spin-less processes)

→ **introducing spin effects on top of them as an external additional feature is very convenient**

decoupled from new releases of the generator
must be done systematically, and with compromises

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StringSpinner:

an external «plug-in» which interfaces string+$^3P_0$ with PYTHIA 8.2 for SIDIS

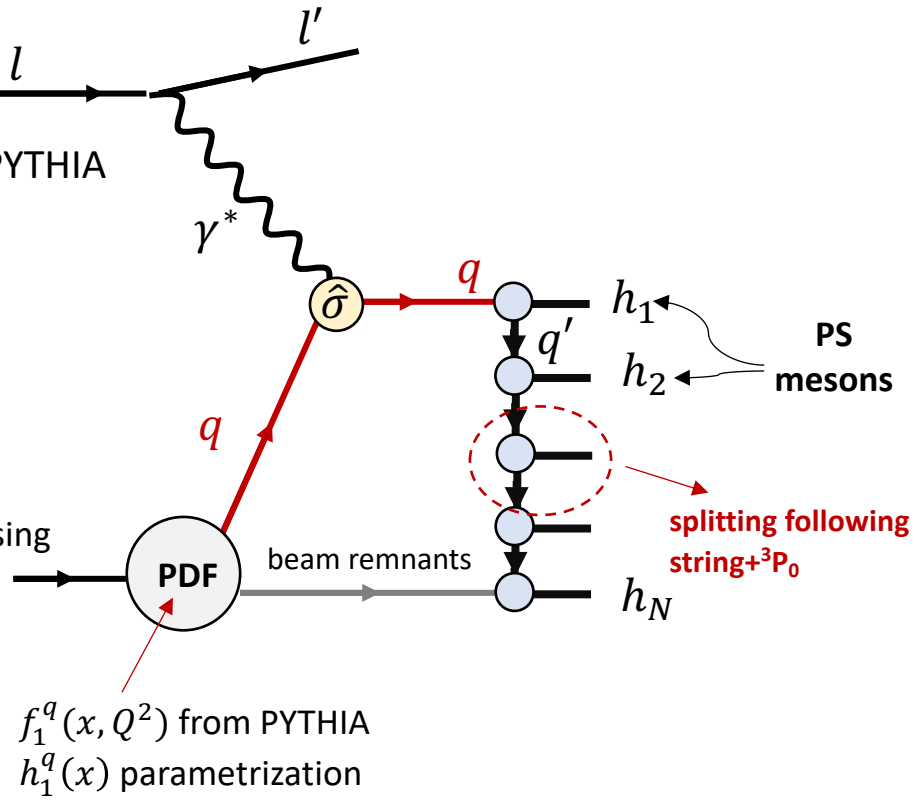
AK, L. Lönnblad, CPC 272 (2022) 108234

→ ISR/FSR switched OFF

→ spin effects in string fragmentation to PS mesons

→ parametrizations of transversity PDFs introduced (for u^v and d^v, can be changed by the user)

→ also possible to chose the quark polarization by hand (analysing power)



Transverse spin asymmetries from StringSpinner

Simulations of SIDIS off protons in the COMPASS kinematics
(no intrinsic $\vec{k}_T$, $\mu = (0.78 + i0.38)\ \mathrm{GeV/c^2}$)

Code of StringSpinner available in
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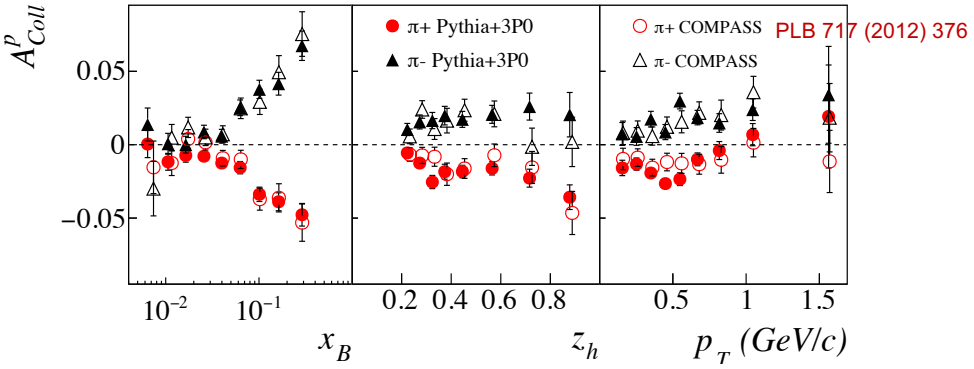
Collins asymmetry from StringSpinner



- Satisfactory description of TSA
  .. promising tool!

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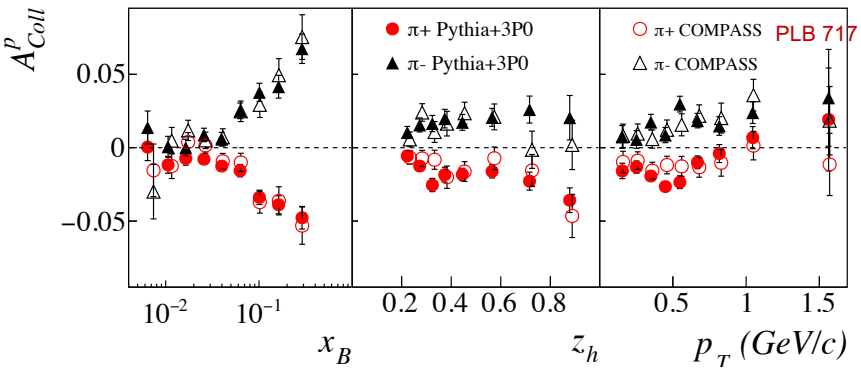
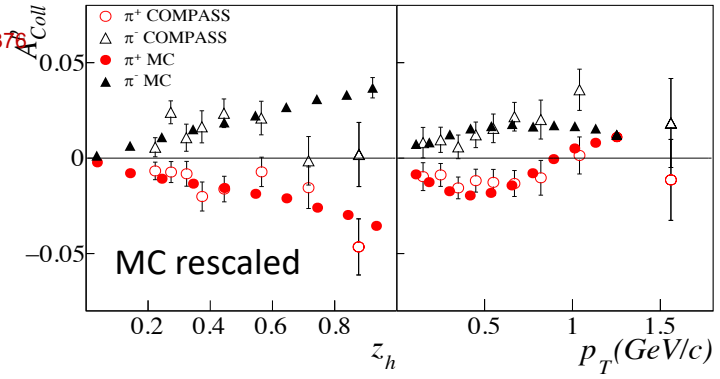


from **Standalone MC**



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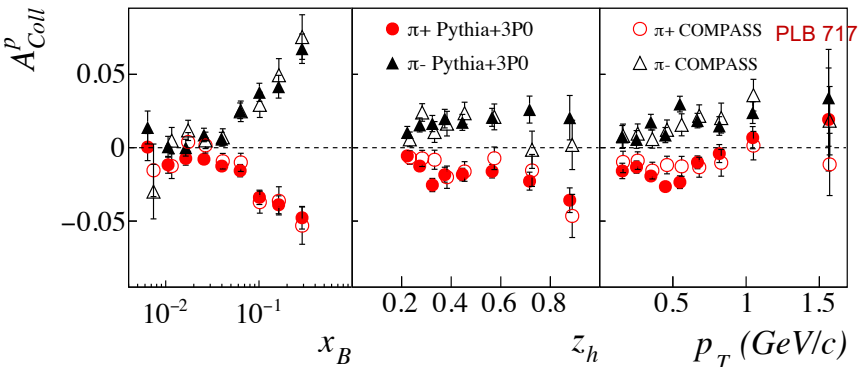

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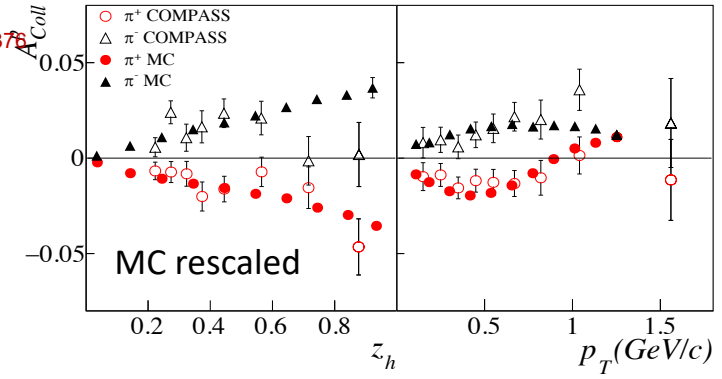
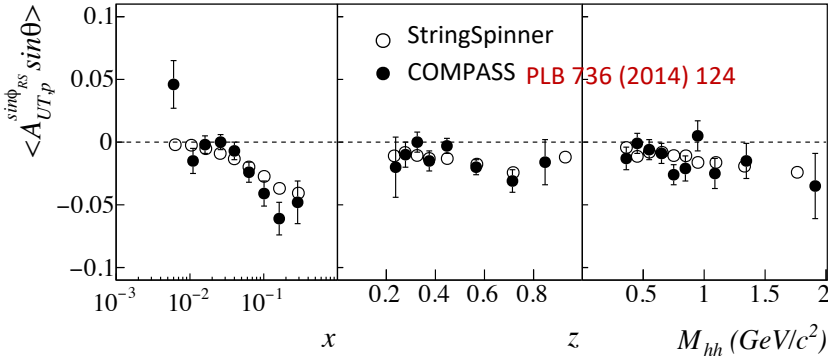


Dihadron asymmetry from StringSpinner



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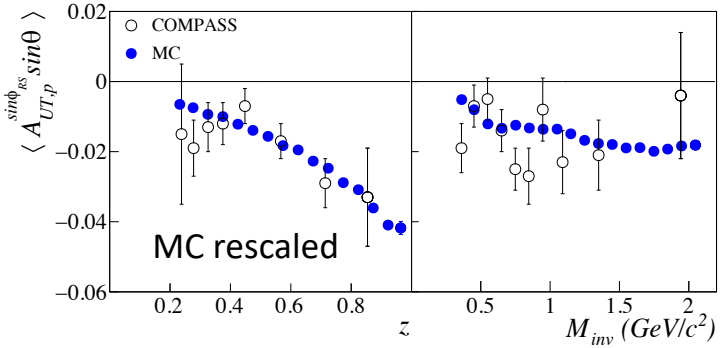

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Conclusions

The string+$^3P_0$ model includes PS meson and VM emission and has been studied in detail

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

→ hints for values of the free parameters related to VM

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

and also new measurements, e.g. Collins asymmetries for ρ mesons,

z-ordered 2h asymmetry in e^+e^- annihilation!

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.. the base for the systematic inclusion of spin effects in a MCEG has been laid!

now is time to move on!

include VM production in StringSpinner

apply the string+$^3P_0$ model to the e^+e^- annihilation event

…

backup

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

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

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