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A new String Hadronization Model

Nikolaenko R. V.
National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia
rvnikolaenko@mephi.ru

- **Hadronization** is a process of sequential fragmentation of quark-gluon strings, in which hadrons are born by identifying light strings with them when a number of criteria are met
- Fragmentation of strings is governed by the Artru-Mennesier **Area Decay Law**
- The dynamics of strings is determined by the **Nambu-Goto action** for a relativistic string **with masses at the ends**

The theory of the relativistic string with masses at the ends

The action for a relativistic Nambu-Goto string with masses at the ends is chosen as:

$$S_{\text{string}} = -\gamma \int_{\tau_1}^{\tau_2} d\tau \int_{\sigma_1(\tau)}^{\sigma_2(\tau)} d\sigma \sqrt{(\dot{x}x')^2 - \dot{x}^2 x'^2} - $$

$$-\sum_{i=1}^{2} m_i \int_{\tau_1}^{\tau_2} d\tau \sqrt{\left(\frac{dx_\mu(\tau,\sigma_i(\tau))}{d\tau}\right)^2},$$

where $x_\mu(\tau,\sigma)$ is the parametric definition of the string world surface, $\dot{x}_\mu \equiv \frac{\partial x_\mu}{\partial \tau}$, $x'_\mu \equiv \frac{\partial x_\mu}{\partial \sigma}$, γ is a dimensional parameter of the theory (string tension). When using orthonormal gauge $(\dot{x}_\mu \pm x'_\mu)^2 = 0$, from the action of the string the following equations of motion can be derived:

$$\ddot{x}_\mu - x''_\mu = 0$$

and boundary conditions

$$\mu_1 \frac{d}{d\tau}\left(\frac{\dot{x}_\nu}{\sqrt{\dot{x}^2}}\right) = -x'_\nu(\tau,0),$$

$$\mu_2 \frac{d}{d\tau}\left(\frac{\dot{x}_\nu}{\sqrt{\dot{x}^2}}\right) = x'_\nu(\tau,\pi),$$

where $\mu_1 = m_1/\gamma$, $\mu_2 = m_2/\gamma$.

To get rid of the nonlinearity of boundary conditions, one can restrict the calculations to the type of string motion for which the following condition is satisfied

$$\dot{x}^2(\tau,0) = m_1^{-2}, \qquad \dot{x}^2(\tau,\pi) = m_2^{-2}.$$

Then the boundary conditions take the form:

$$\ddot{x}_\mu(\tau,0) = q_1 x'_\mu(\tau,0), \qquad q_1 = \gamma/m_1^2,$$

$$\ddot{x}_\mu(\tau,\pi) = -q_2 x'_\mu(\tau,\pi), \qquad q_2 = \gamma/m_2^2.$$

The solution to the problem of string motion is represented as a Fourier series

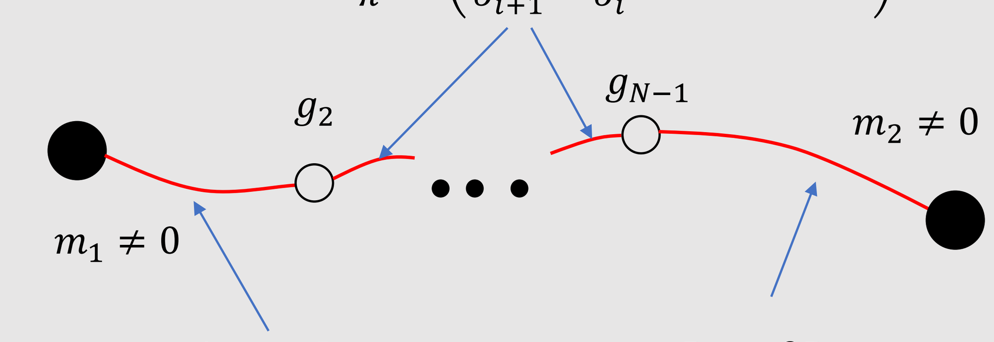
$$x^\mu(\tau,\sigma) = C_0^\mu \tau + D_0^\mu + \sum_{n=1}^{+\infty}\left[C_n^\mu \sin(\omega_n\tau) + D_n^\mu \cos(\omega_n\tau)\right]u_n(\sigma),$$

where $u_n(\sigma)$ are the eigenfunctions of the Sturm-Liouville problem, and the coefficients C_n^μ, D_n^μ are determined from the initial data $p_\mu\gamma\dot{x}_\mu(0,\sigma)$, $\rho_\mu(\sigma) = x_\mu(0,\sigma)$.

- Existing models use the initially point-like string approximation with a piecewise constant distributed momentum function.

The generalized form of initial conditions:

$$p_i^\mu(\sigma) = \frac{(N-1)}{\pi}\left(\frac{p_{i+1}^\mu - p_i^\mu}{\sigma_{i+1} - \sigma_i}(\sigma - \sigma_i) + p_i^\mu\right)$$



$$A_\mu = \alpha P_\mu \qquad B_\mu = \beta P_\mu$$

$$B_\mu = \frac{P_\mu}{b}(1 - a\alpha) \qquad A_\mu = \frac{P_\mu}{a}(1 - b\beta)$$

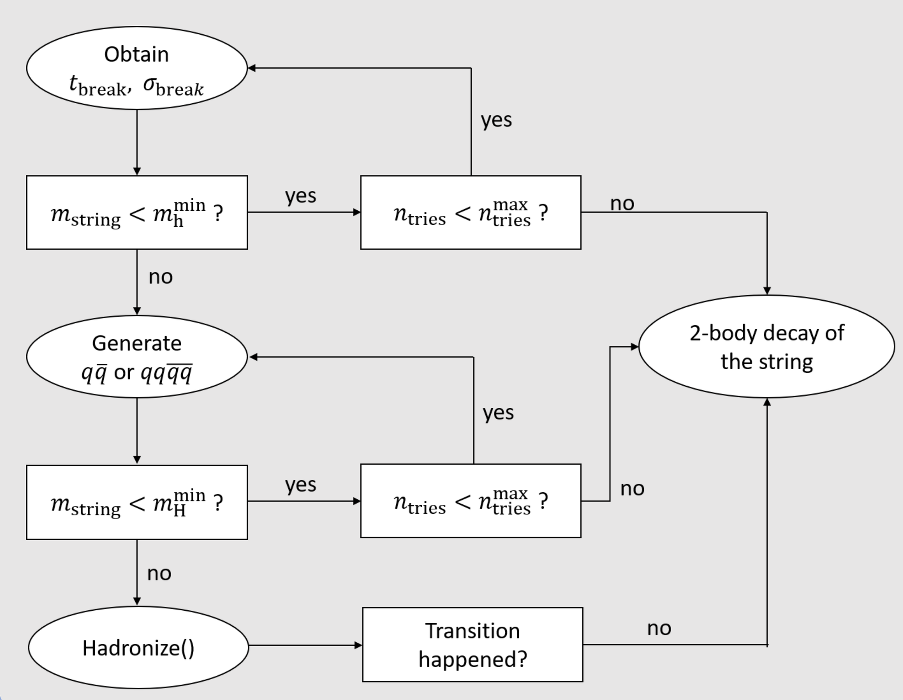
$$\alpha = \frac{1}{a}\left(1 - \frac{\kappa b}{m_1 M}\right) \qquad \beta = \frac{1}{b}\left(1 - \frac{\kappa a}{m_2 M_{N-1}}\right)$$

$$a = \frac{\pi}{2}, \quad b = \frac{\pi}{2} + \frac{1}{q_1} \qquad a = \frac{\pi}{2} + \frac{1}{q_2}, \quad b = \frac{\pi}{2}$$

- For the first time the strings with massive quarks at the ends can be defined in the model of fragmentation thanks to the generalized form of the initial conditions.

Hadronization generator ATROPOS

Fragmentation cycle

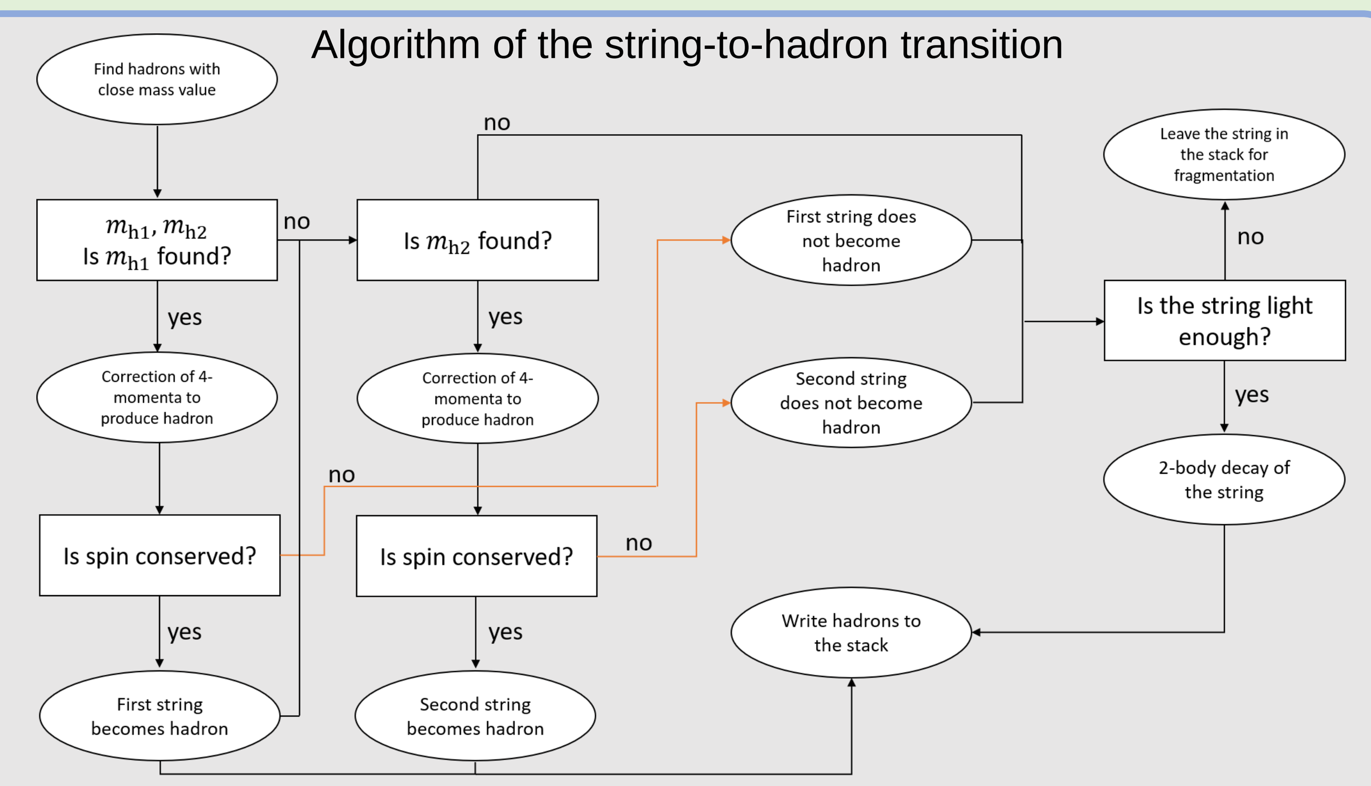


- Software solution based on the C++ language using the CERN ROOT package.
- The strings between a of quark-antiquark or (anti)quark-(anti)diquark pair with an arbitrary number of gluons between them are considered.
- Area Decay Law:

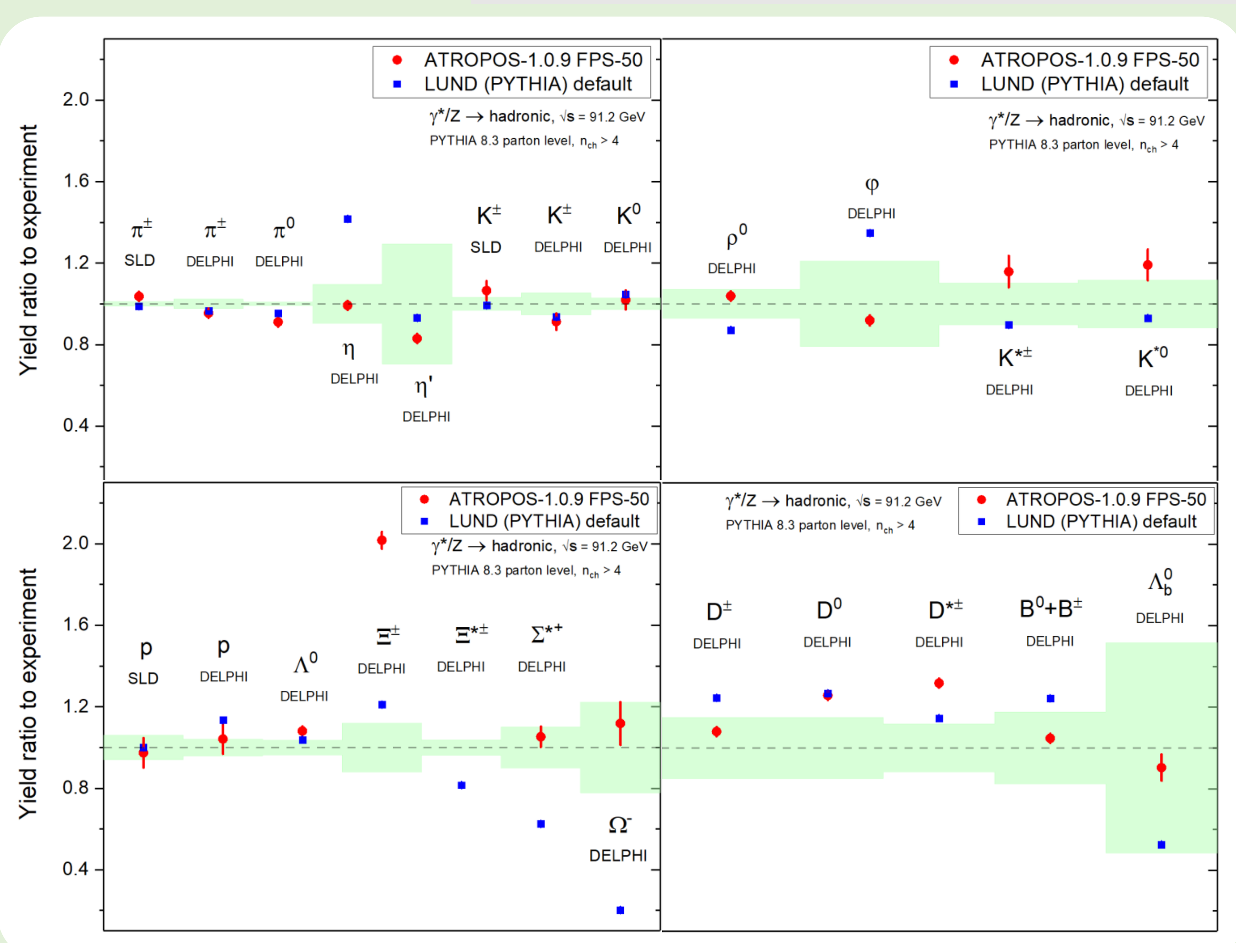
$$\frac{dP}{dA} = const \equiv P_0, \qquad P_{\text{alive}}(\tau) = e^{-P_0 A(\tau)}$$

- A generalized form of initial conditions is used.
- It is assumed that one set of parameters will be used for all types of interactions and particles.

Algorithm of the string-to-hadron transition

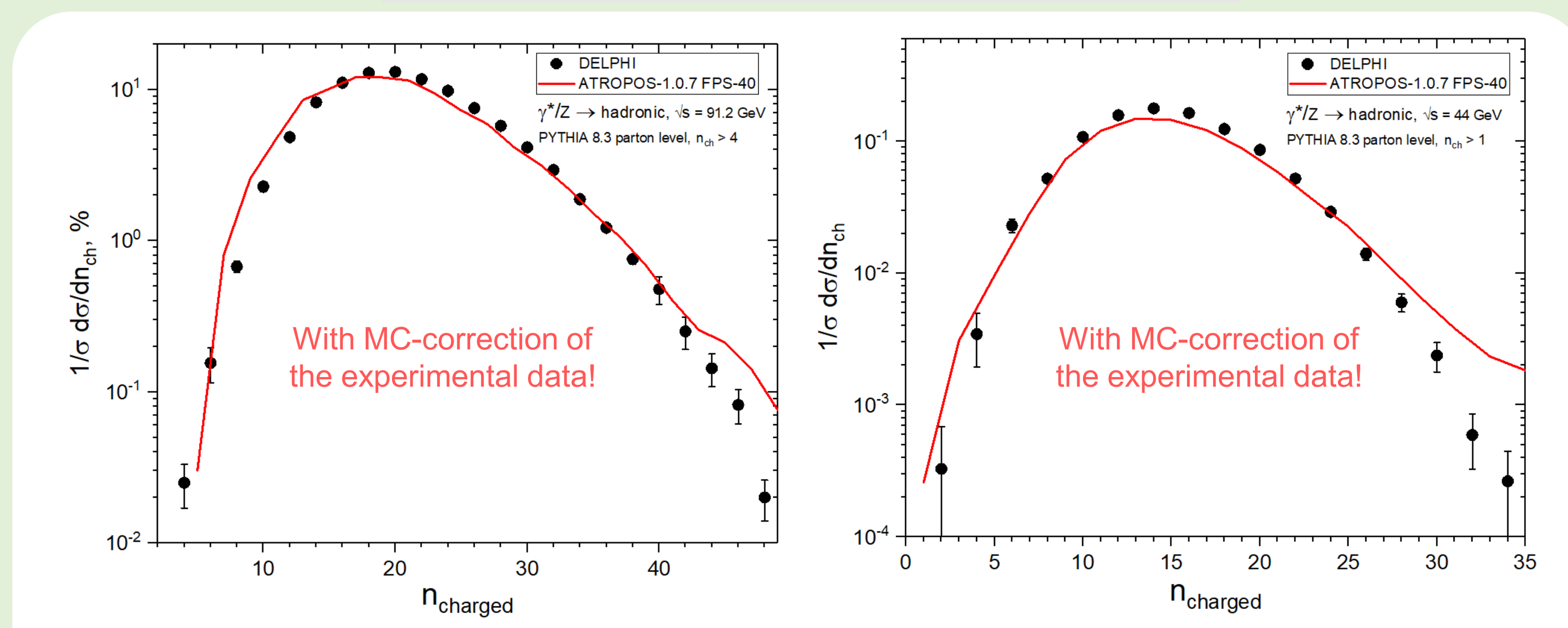


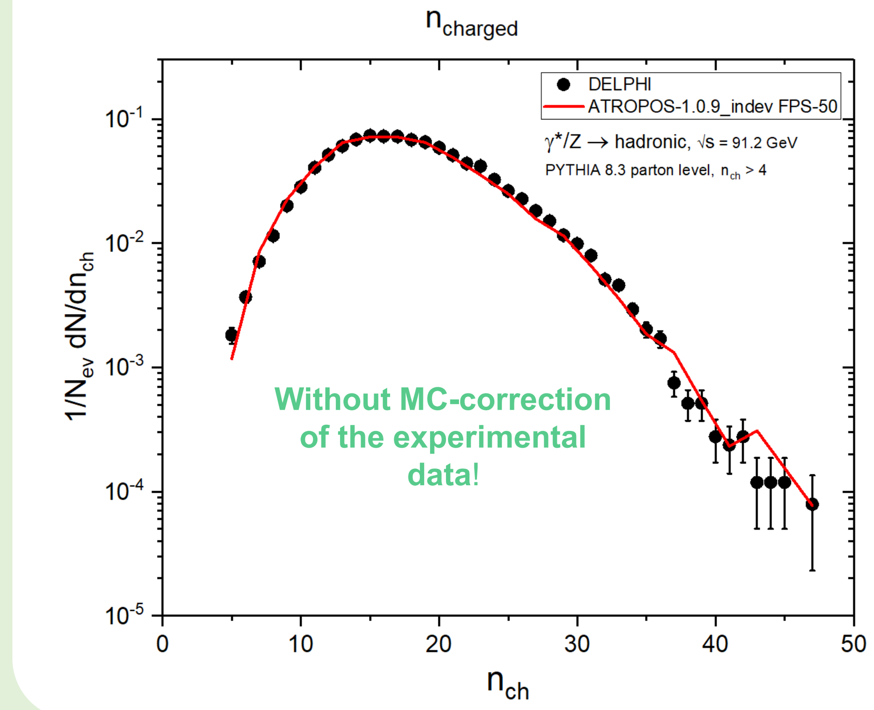
Comparison of the particles yields



- Yield of η-mesons is well described.
- The yield of light vector mesons and Σ-, Ω-hyperons is described better then in PYTHIA.
- Good agreement on the multiplicity of c- and b-particles.
- Few problems: too many Ξ-hyperons and some vector resonances.

Multiplicity of charged particles

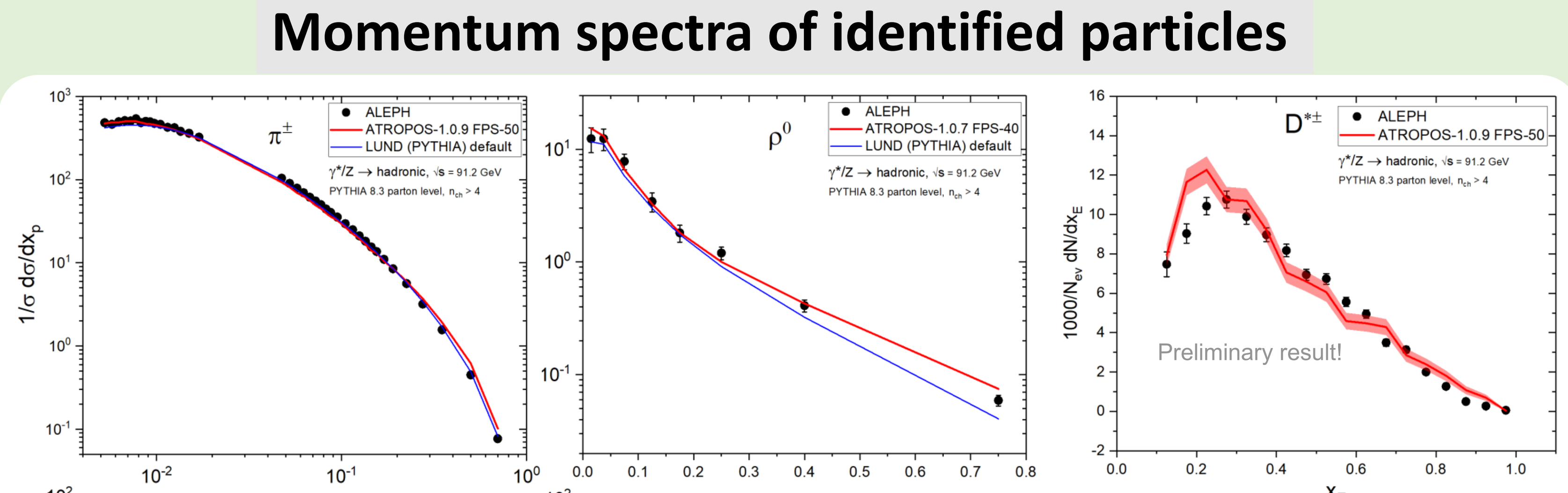


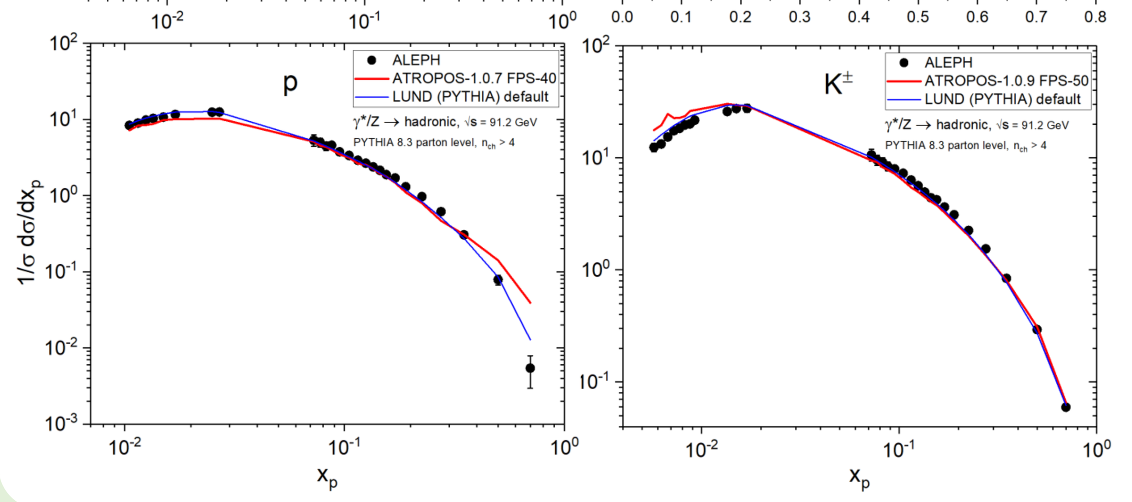


Criteria for selecting particles and events:

1. Polar angle of a particle track $25° < \theta < 155°$
2. Particle momentum $p > 0.1$ GeV
3. At least five charged particles in the event
4. At least five “hadrons” with momentum $p > 0.2$ GeV
5. Total energy of charged particles $E > 15$ GeV
6. Polar angle of the sphericity axis $50° < \theta_S < 130°$

Momentum spectra of identified particles





- $\pi^\pm$-mesons and $K^\pm$-mesons spectra are well reproduced
- The spectrum of ρ^0-mesons is in better agreement then in PYTHIA
- Proton spectrum too high at large momenta: need further tuning

Conclusion

- The initial conditions were derived for a string consisting of an arbitrary number of partons and with heavy quarks at the ends.
- ATROPOS has become the first hadronization model in which the production of heavy c- and b-hadrons is described based on the first principles of the theory.
- The mathematical apparatus of the model describes the fragmentation of strings with heavy and light quarks in the same way.
- The results obtained using the ATROPOS generator indicate that the yield of vector and heavy particles can be increased within the framework of the non-collective hadronization model by introducing new mechanisms through the mathematical apparatus of quark-gluon string fragmentation.