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“Relativistic Nuclear Physics and Quantum Chromodynamics”
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Particles production in ATROPOS string fragmentation model

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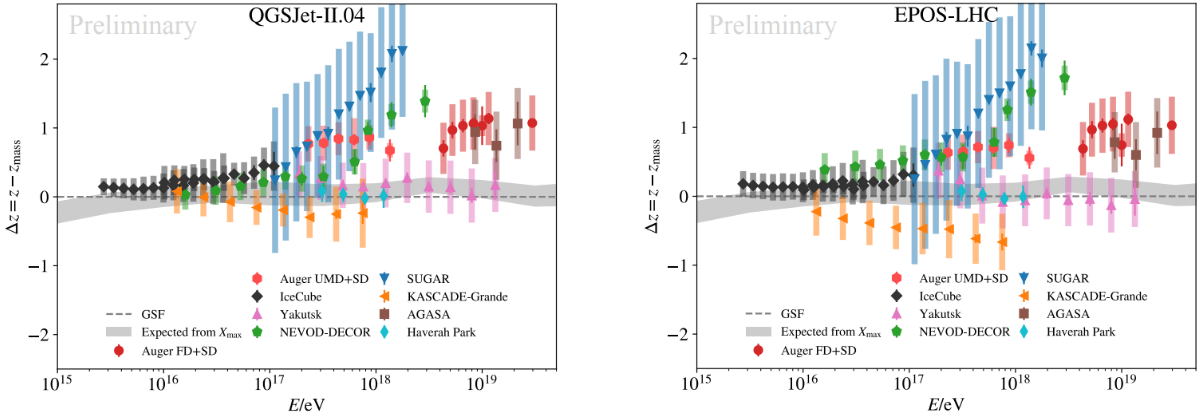
Introduction: a role of hadronization in EAS hadronic interactions physics

The “**Muon Puzzle**”: an excess of muons in EAS induced by UHECR in comparison to predictions from simulations

From J.C. Arteaga-Velázquez, ICRC-2023



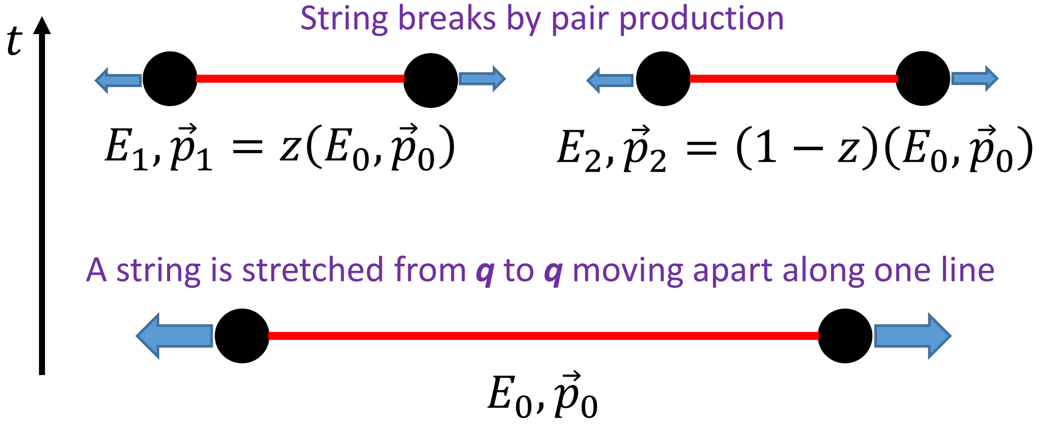
- Need to increase muon number, but not $e^{\pm}$, γ
  - ➢ An important parameter of hadronic interactions:

$$R = \frac{\langle E_{\mathrm{e/m}} \rangle}{\langle E_{\mathrm{hadr}} \rangle}$$

- To decrease R:
  - ➢ Enhance heavier quarks production
  - ➢ Enhance baryon/meson resonances production
  - ➢ Suppress leading π^0 formation

➢ Modify **hadronization** process, but how?

- Usually, string fragmentation is seen *universal* for all colliding systems and energies:

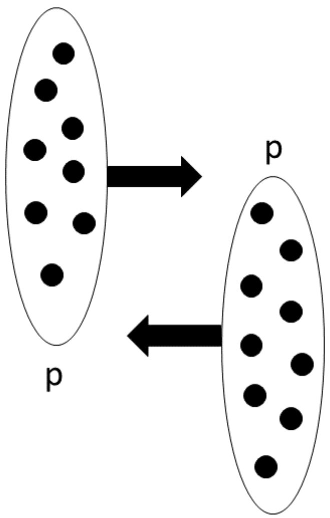


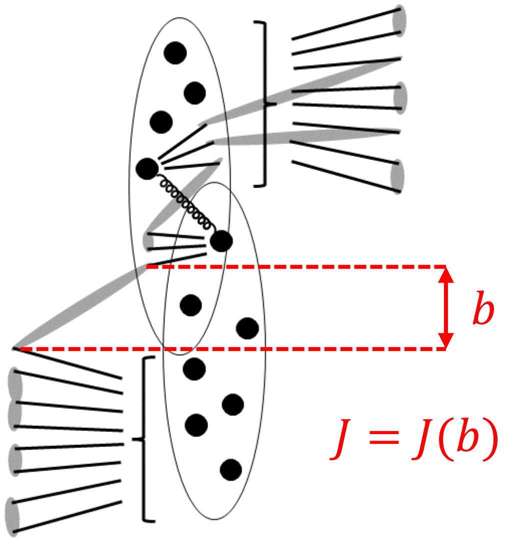
  - ○ z is sampled universally for all collisions

- *Break* string fragmentation universality:
  - ➢ Collective effects (used in EPOS core-corona approach)
  - ➢ Consider **angular momentum** + more general rules for string-to-hadron transition

General idea

- Add angular momentum of the string to account for the impact parameter of color-connected partons



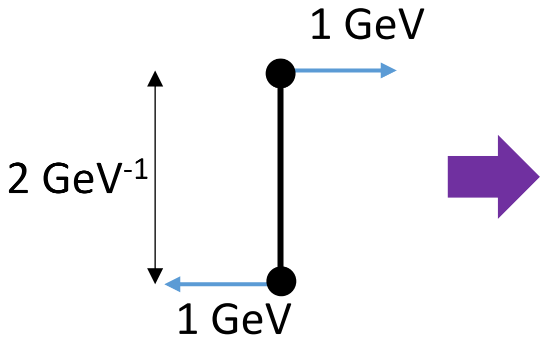


- A difference between colliding systems emerges:

$$J_{e^+e^-} < J_{hh} < J_{hA} < J_{AA}$$

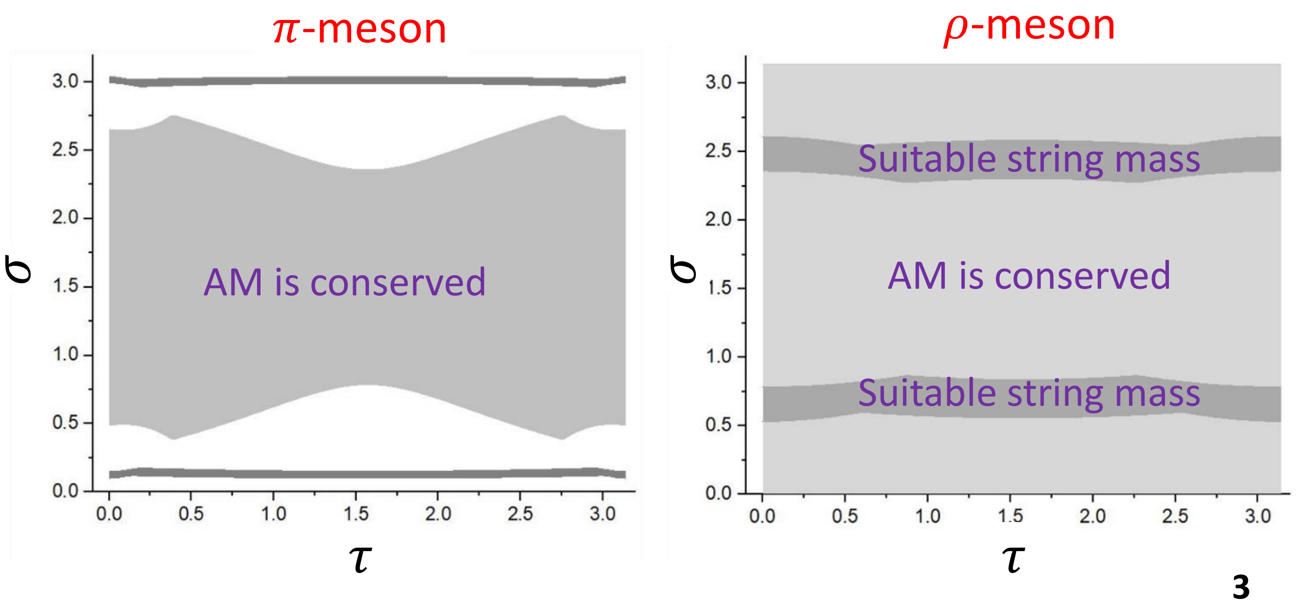
*note that, as only classical string model is used for hadron production, it forces considering angular momentum for *ee* system too

- A simple **example** of hadron production change from angular momentum conservation:



Try to fragment and produce hadron from daughter string

A parameter configuration space of the string break point:



New string hadronization model: ATROPOS

- Use the **Nambu-Goto string** theory:

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

- Main task: find a way to *properly* define the initial conditions …

  $x_\mu(\tau = 0, \sigma) \equiv \rho_\mu(\sigma), \;\; \partial x_\mu / \partial\tau(\tau = 0, \sigma) \equiv v_\mu(\sigma)$
- … and develop a model for fragmenting this string.

➢ Use the **Virasoro** conditions for that

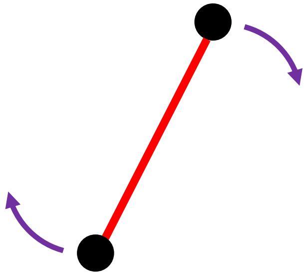
*** Skip the long and boring mathematics ***

For the strict and detailed derivation of the basics of the ATROPOS string model, see

https://doi.org/10.48550/arXiv.2504.08968

Result:

- A string is modeled as a rotating rigid rod

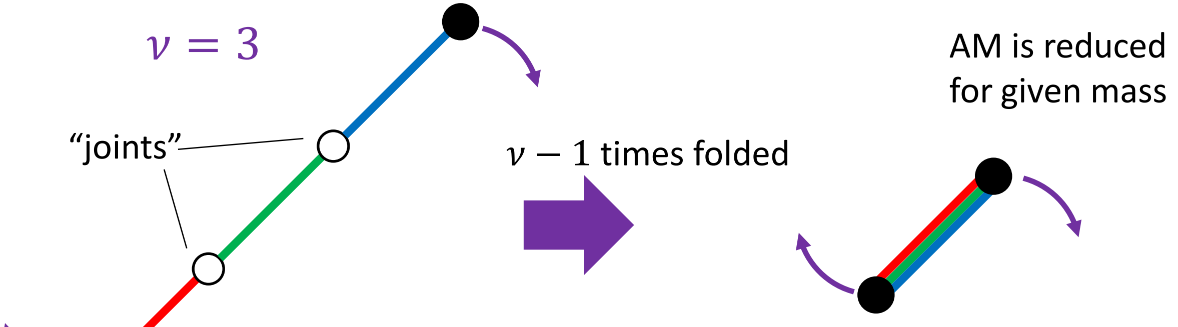


$\rho_\mu(\sigma), v_\mu(\sigma) \sim \cos(\nu\sigma)$

ν: eigenharmonic of the string

$$J = \frac{1}{\nu} \frac{M^2}{2\kappa\pi}$$

- Unable to find other possible configurations!
- Taking $\nu > 1$ can be seen as "folding" of the string:



Parameter ν is used to define AM of the system

* colors are used to highlight different segments of the string; the choice of colors is arbitrary

String fragmentation

- Daughter strings must satisfy the Virasoro conditions too

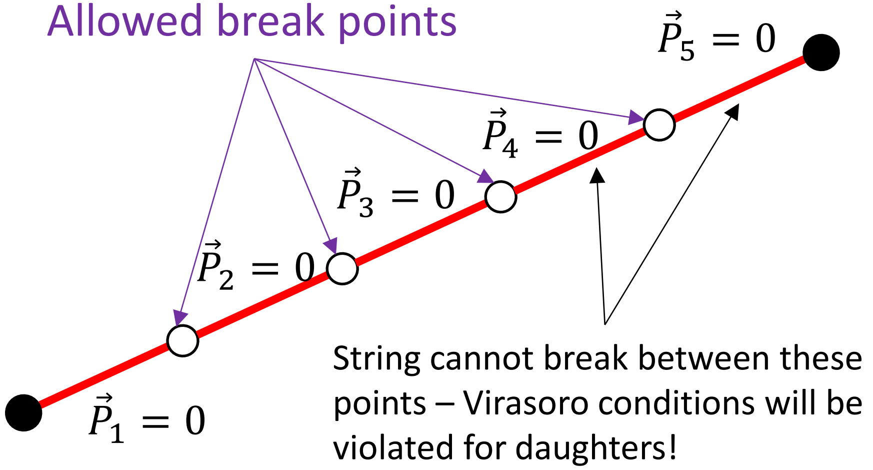
➢ **Countable set of break points!!**

- Since each segment of the string has a total momentum of 0, new strings are produced at rest in the CM system

  ➢ Unrealistic particle production for e^+e^- collisions

  ➢ Need to add energy release to the fragmentation scheme

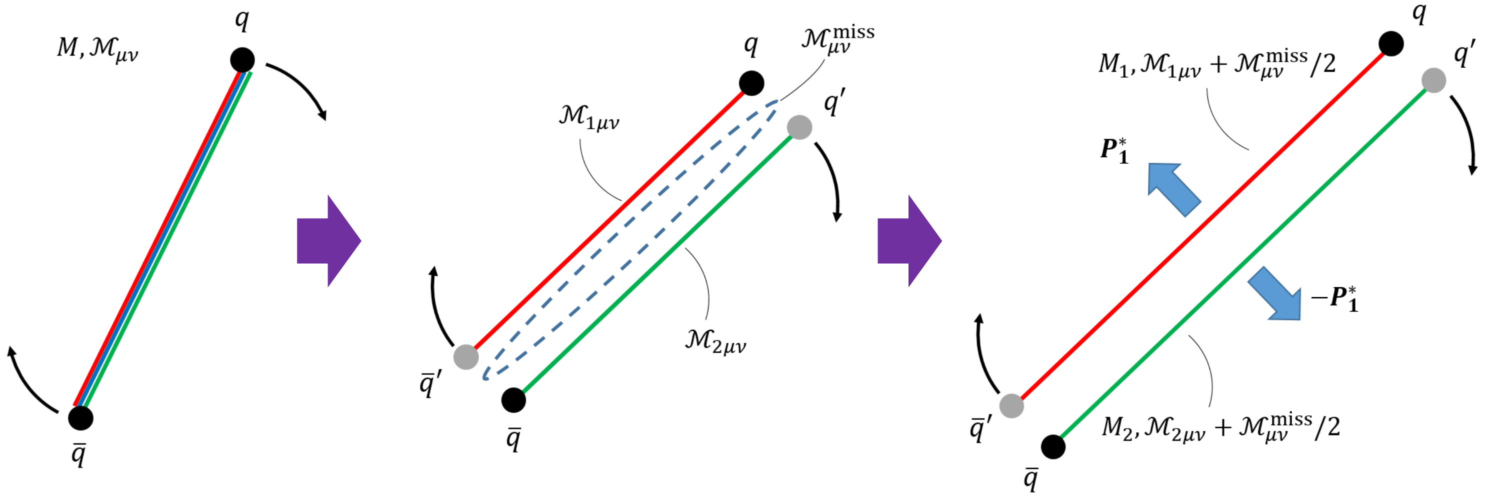
  ➢ Make a chunk of the string disappear and then redistribute energy and momentum between string pieces



$$\sigma_{\text{break}} = \frac{r\pi}{\nu}$$

r is an integer cut factor

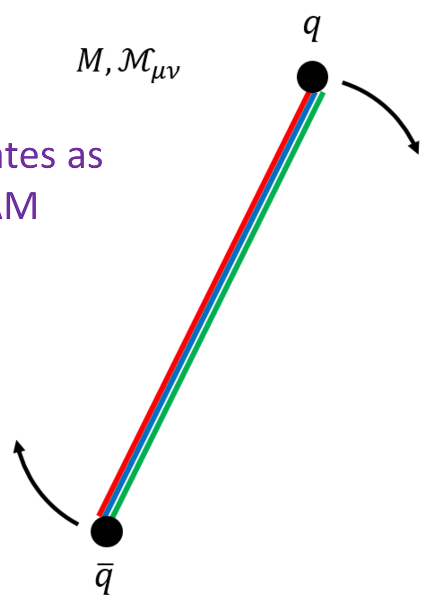
➢ The length of the daughter strings remains the same as those for the mother



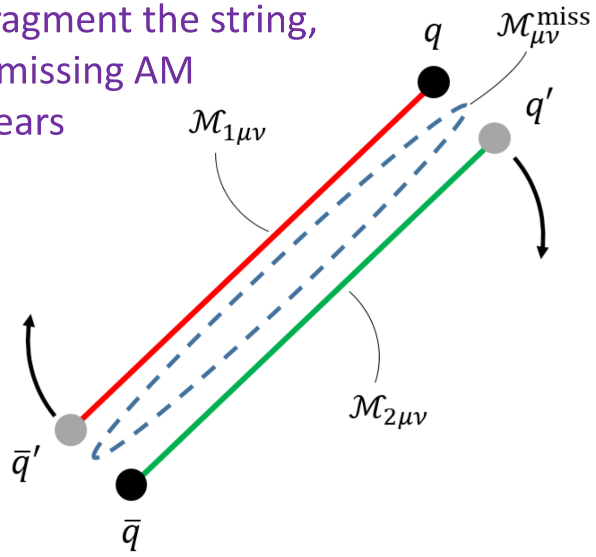
- Note that eigenharmonic ν is inherited by the daughters!

Angular momentum conservation

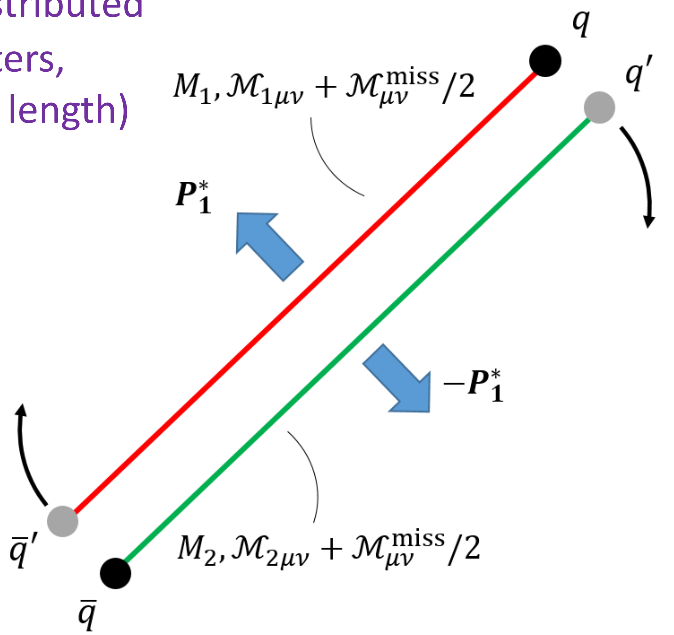
A string rotates as a rod with AM tensor $\mathcal{M}_{\mu\nu}$



The chunk is deleted to fragment the string, the missing AM appears



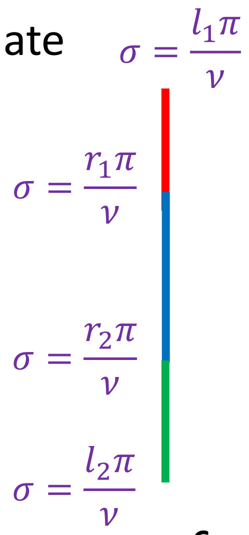
$\mathcal{M}_{\mu\nu}^{\text{miss}}$ is redistributed among daughters, their mass (=> length) is adjusted



- For a string of arbitrary generation, the angular momentum is defined by its mass: $J = M^2/(2\kappa\nu\Delta\sigma)$
- The missing chunk of the string carries AM $J^{\text{miss}} = M^2/(2\kappa\nu[\sigma_{\text{br2}} - \sigma_{\text{br1}}])$, where $\sigma_{\text{br1,2}}$ are sampled break points
- J^{miss} redistributes between string fragments: their masses M_1, M_2 are adjusted to match the total AM

- Different proportion laws may be proposed to calculate the fraction of J^{miss} taken by each fragment
- For $J \propto M^2$:

$$M_1 = \frac{r_1 - l_1}{\sqrt{(l_2 - l_1)(l_2 - l_1 - r_2 + r_1)}} M,$$
$$M_2 = \frac{l_2 - r_2}{\sqrt{(l_2 - l_1)(l_2 - l_1 - r_2 + r_1)}} M.$$



String-to-hadron transition

We adopt the following rules to model the transition from string to hadron:

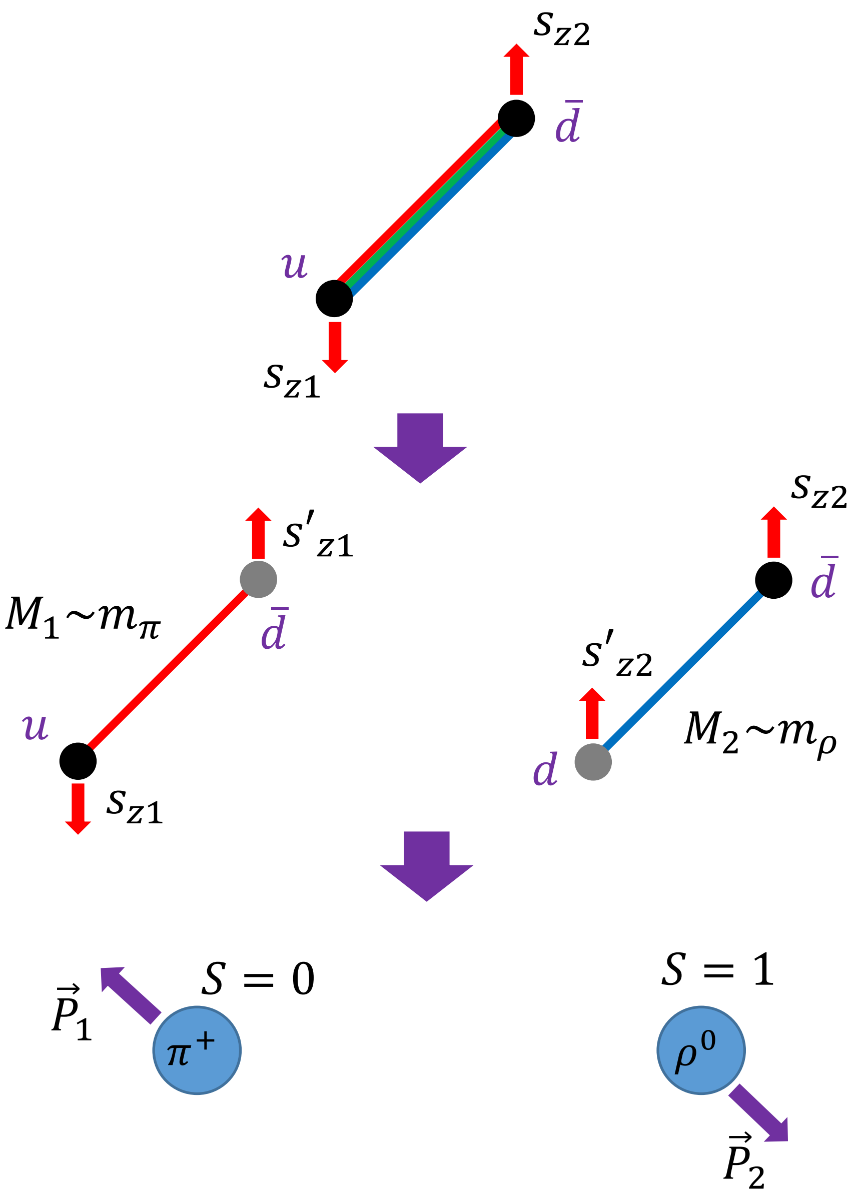
1. **The string may or may not become hadron after it is produced**

2. **The string must have the same flavor content as a potential hadron**
    - The type of the parton pair produced in the break point is sampled after the coordinates of the break point are selected according to Area Law
    - Each pair type is assigned a relative probability of production

3. **The end-point partons of the string must have the spin projection values that combine to the total spin of the hadron**
    - The spin projections for partons are sampled after the flavor
    - The free parameter is used to define the relative probability for possible spin states

4. **The value of the string mass must be close enough to the mass of hadron**
    - Another parameter is used to define the allowed relative difference
    - To produce hadrons on-shell, the inter-string interaction is used to redistribute energy and momentum

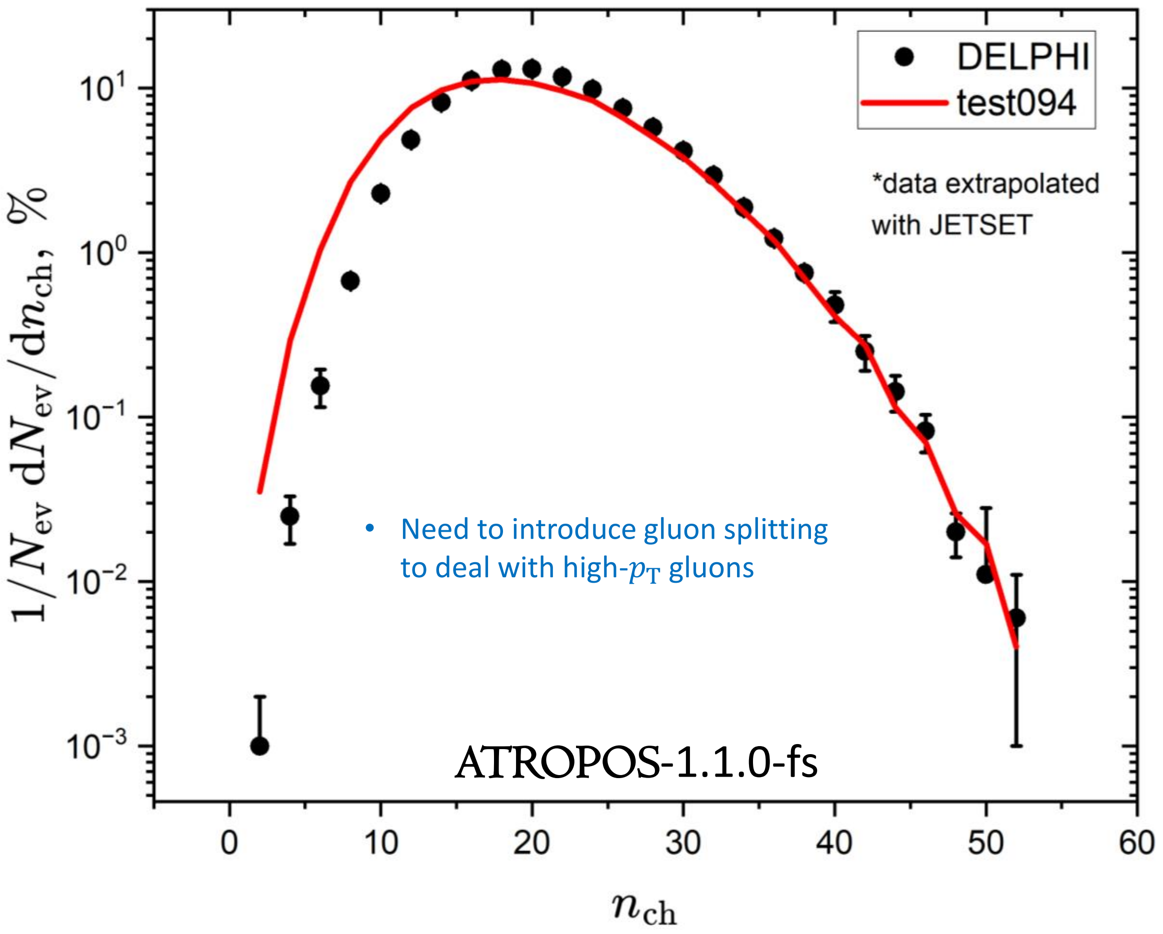
+ additional criteria?



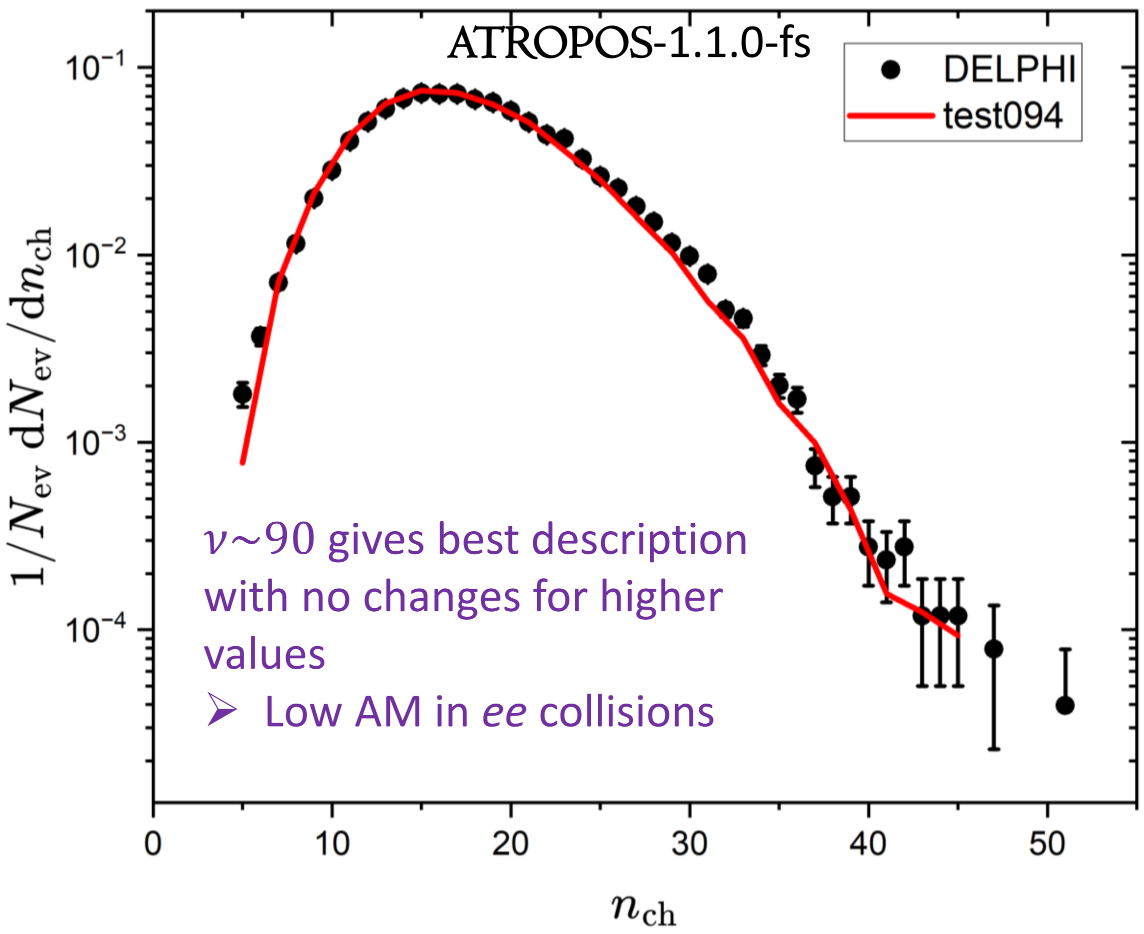
First results: e^+e^- collisions

$e^+e^- \to \gamma^*, Z \to \text{hadronic}, \sqrt{s} = 91.2$ GeV

Pythia 8.315 Parton Level



- Need to introduce gluon splitting to deal with high-p_T gluons

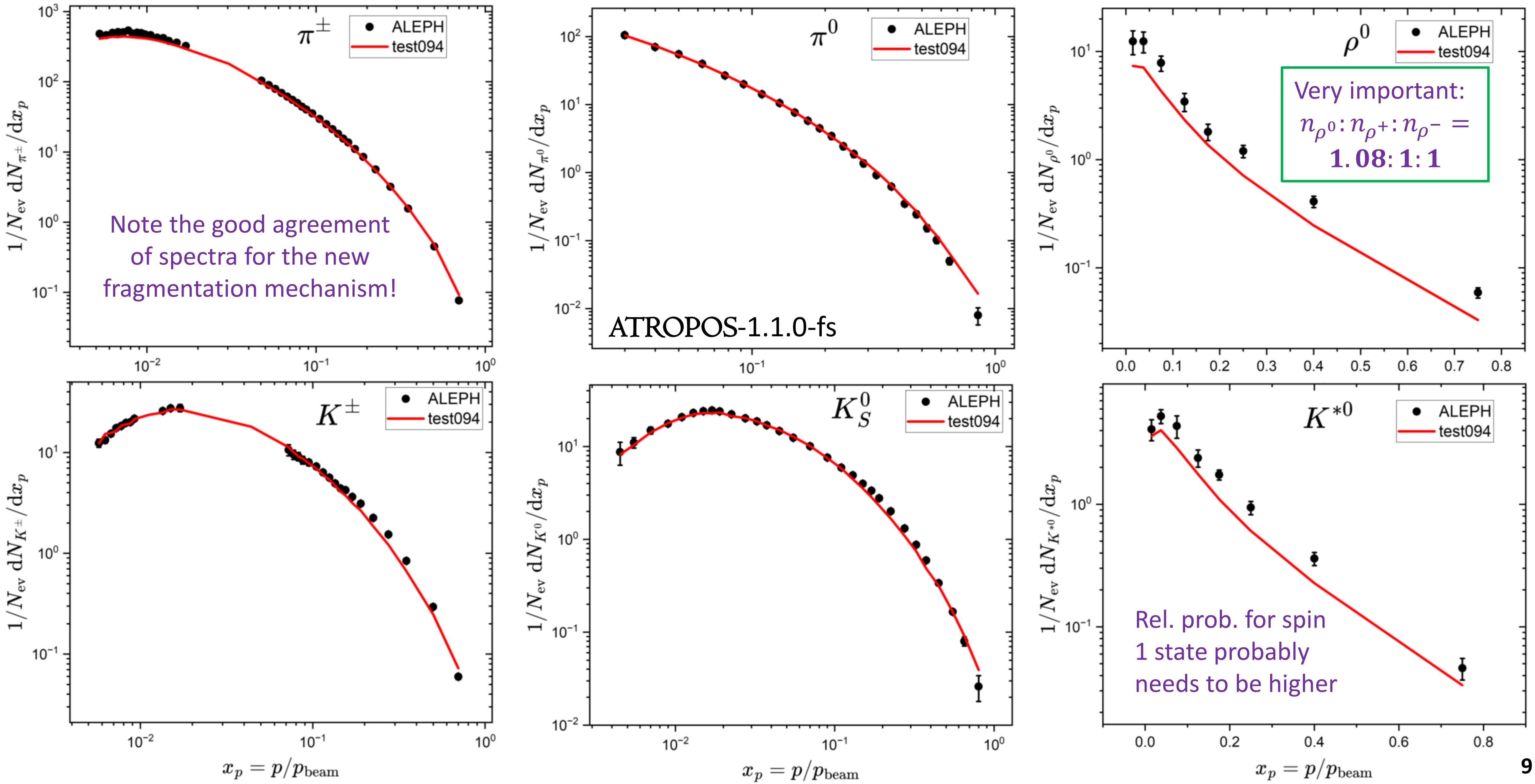


$\nu \sim 90$ gives best description with no changes for higher values

- ➢ Low AM in *ee* collisions

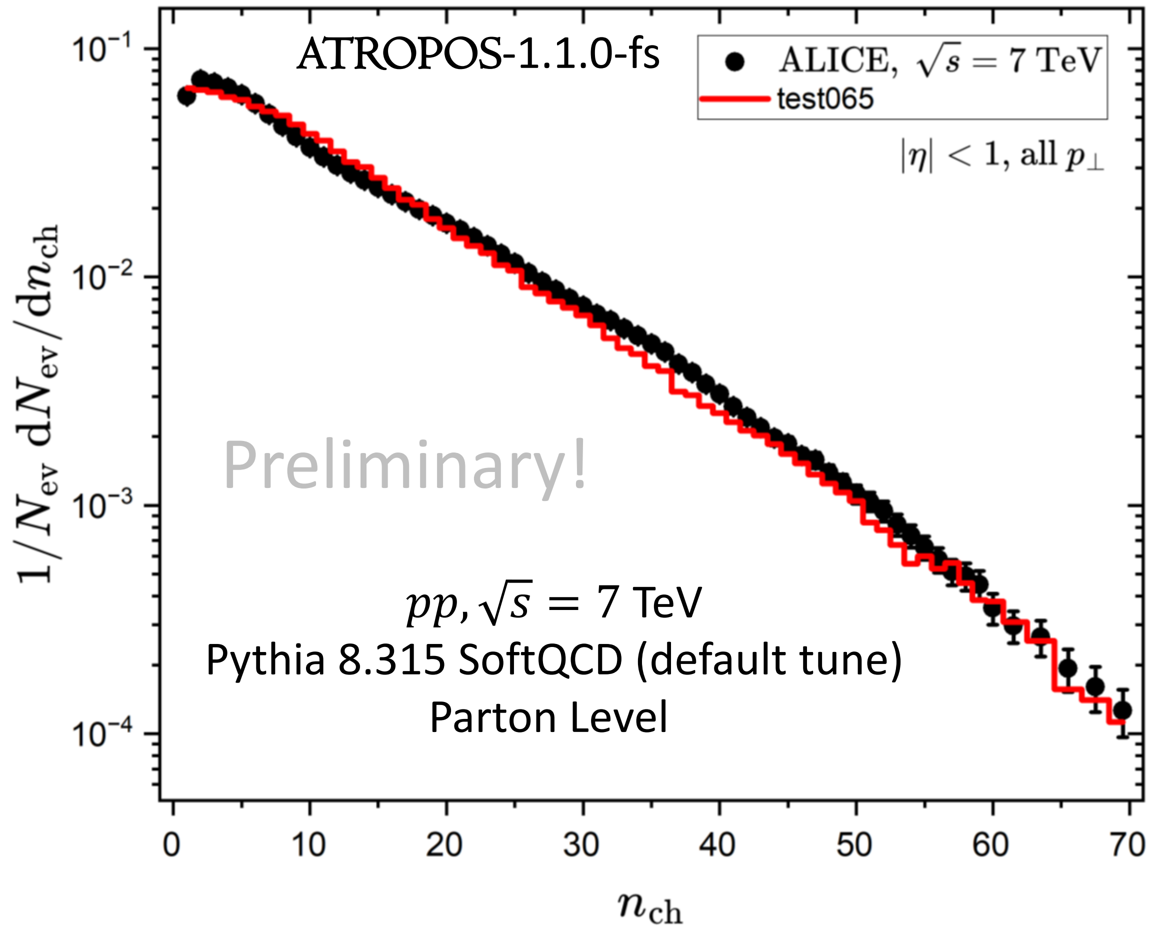
- More low-multiplicity events than in data, but note that data is extrapolated with JETSET (Pythia)
- Raw data is in much better agreement with the model

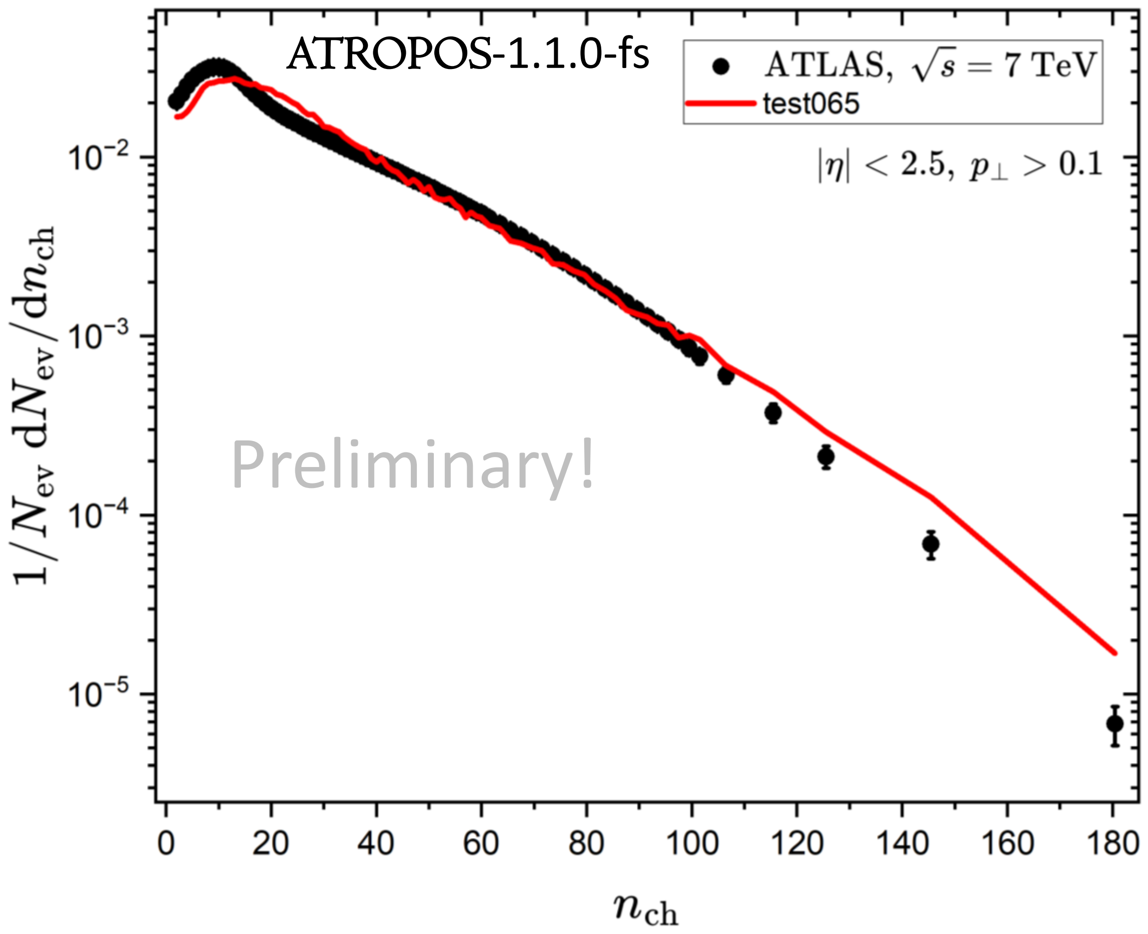
First results: e^+e^- collisions, tuning the particles yield (preliminary!)



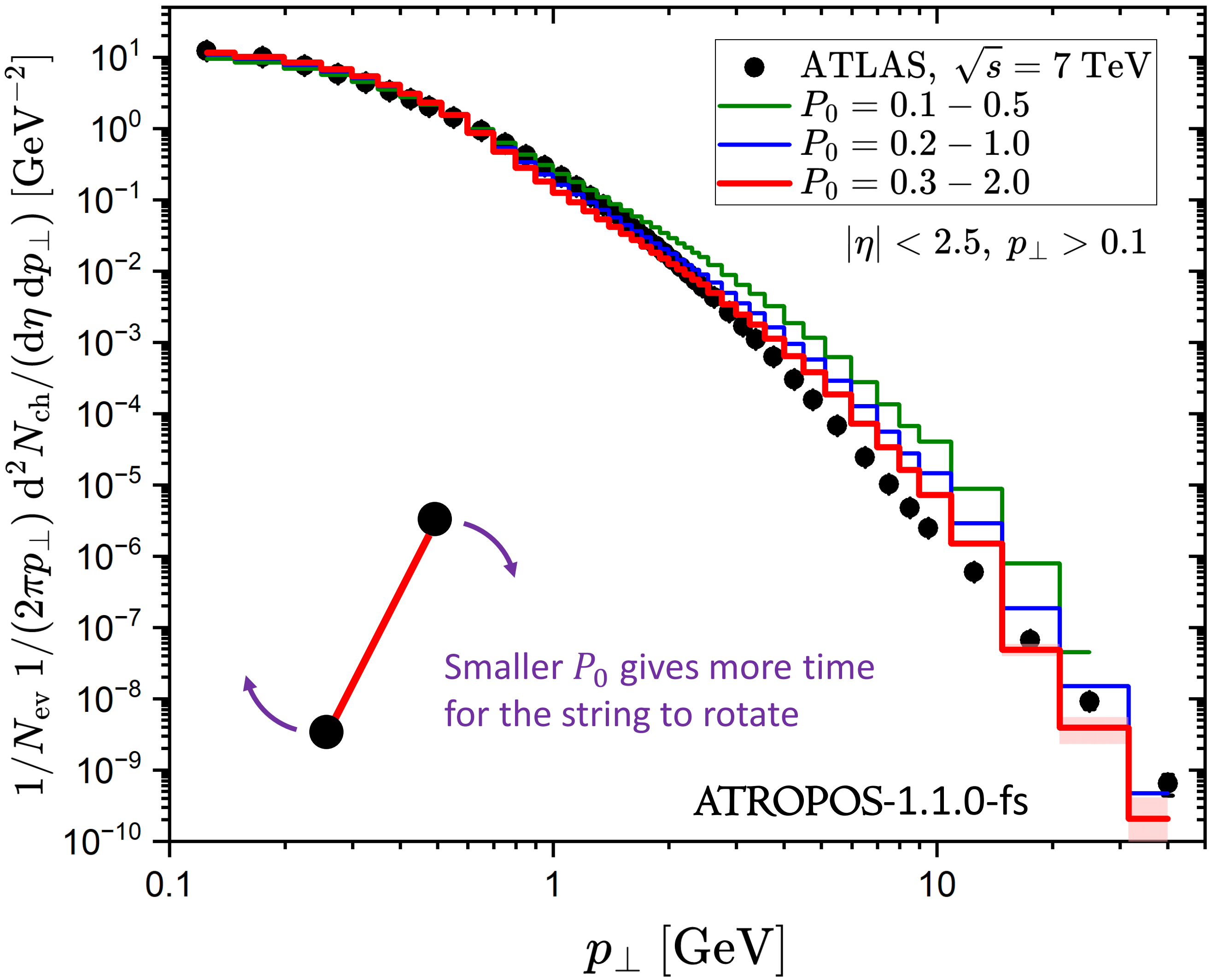
First results: pp collisions at LHC energies

- Multiplicities are sensitive to the low-limit mass of the string and to the eigenharmonic value $\boldsymbol{\nu}$:
  - Best agreement for $M_{\text{low}} \sim 7$ GeV (but may change with proper hard gluons treatment)
  - Eigenvalue $\boldsymbol{\nu} \approx 80 - 90$, but not higher (or too hard multiplicity spectra)!
  - Rotation for *pp* is sensible at this energies



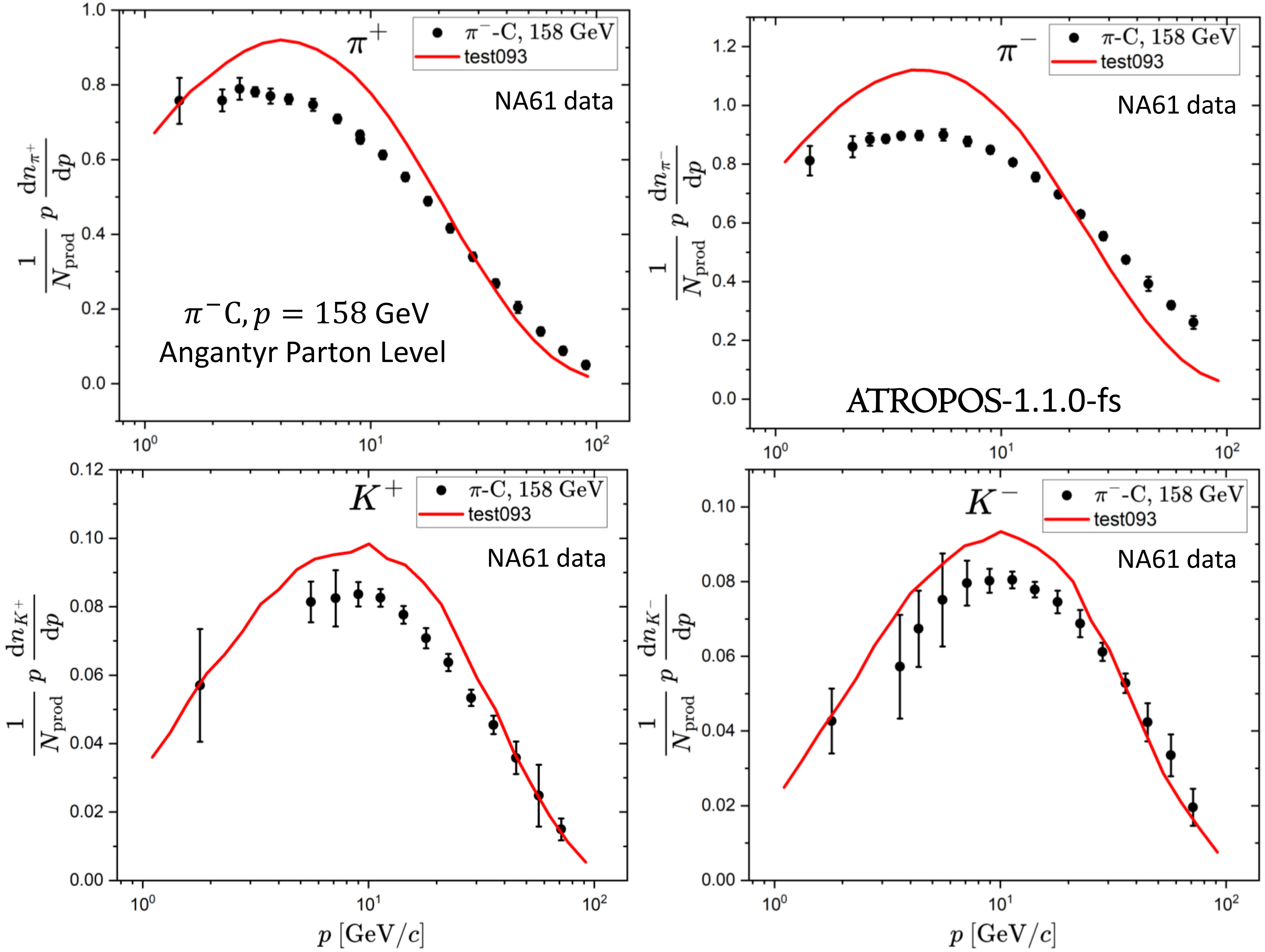


First results: pp collisions at LHC energies



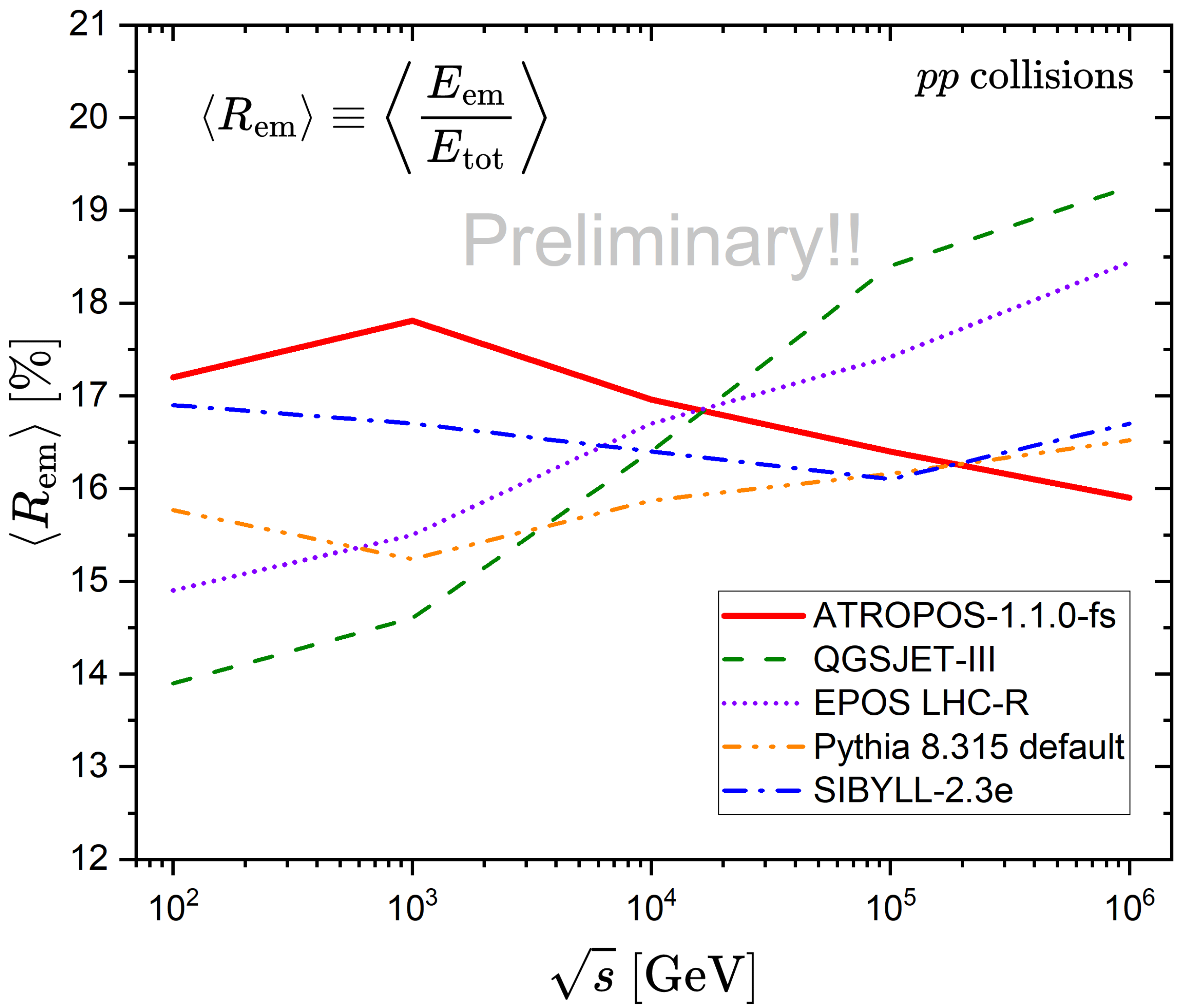
- String decay is governed by the Area Decay Law (Artru and Mennesieur):
$$\frac{dP}{\kappa dA} = \text{const} \equiv P_0,$$
where A is an invariant area of the world sheet of the string.
- In ATROPOS:
$$P(\tau) \propto \exp\left(-\frac{P_0 M^2 \tau}{2\kappa(\sigma_2 - \sigma_1)}\right)$$
- It seems that the best fit is obtained when P_0 is taken to be slowly increasing with string mass
- Small values of P_0 lead to too high transverse momentum of final hadrons
  - ➢ **A reliable way to tune P_0!**
- **Increases forward particle production for heavier strings**!

First results: π^-C collisions



- Qualitatively good agreement, but not ideal
  - Low-energy physics needs improvement
- Best fit for eigenvalue $\boldsymbol{\nu} \approx 20$!
  - Already noticeable AM
  - But also driven by need to keep low-mass limit
- Light-string behavior is important (mini-string in Pythia)

Impact on the EAS physics



- Electromagnetic energy ratio is an essential parameter for muon production in EAS (H. Dembinski, T. Pierog)
- Affected by leading π^0 fraction and neutral-to-charged pions ratio
- ATROPOS shows **decreasing** $\langle R_{\rm em}\rangle$ at $\sqrt{s} > 1$ TeV
  - That is due to the hadron production mechanism: hadron selection is based on mass and spin sampling, so at higher energies more heavy resonances are produced
  - Suppressed direct production of light mesons
- But more tests and tuning are required

Summary

- ATROPOS is the first string hadronization model to implement **angular momentum conservation** to the fragmentation process.

- A string in ATROPOS is seen as a rigidly rotating "folded" rod with "joints" being the only permitted points for string breaking
  - ➢ Forward particle production is enhanced for large-mass strings

- **The fragmentation in ATROPOS is non-universal for different collision systems: different AM values favor *ee*, *pp* and *hA* collisions.**

Plans for future:

- Integrate ATROPOS in **CRMC** package (R. Ulrich, T. Pierog and C. Baus) to allow interface with CR models

- Integration into **EPOS.LHC-R** (with Tanguy Pierog): **work in progress**
  - ➢ First test runs in coming weeks…

- Optimize computation time: use pre-generated tables of string fragmentation modes

Thank you for your attention!

BACK UP SLIDES

Orthonormal gauge in the Nambu-Goto theory

Nambu-Goto string action:

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

$x_\mu(\tau,\sigma)$ is a 2-parameter definition of the string world sheet, where σ numerates the points of the string, and τ defines the evolution in time.

$$\dot{x}_\mu \equiv \frac{\partial x_\mu(\tau,\sigma)}{\partial \tau}$$
$$x'_\mu \equiv \frac{\partial x_\mu(\tau,\sigma)}{\partial \sigma}$$

It produces the following equations of motion (EM):

$$\frac{\partial}{\partial \tau}\left(\frac{(\dot{x}x')x'_\mu - {x'}^2\dot{x}_\mu}{\sqrt{(\dot{x}x')^2 - \dot{x}^2{x'}^2}}\right) + \frac{\partial}{\partial \sigma}\left(\frac{(\dot{x}x')\dot{x}_\mu - \dot{x}^2 x'_\mu}{\sqrt{(\dot{x}x')^2 - \dot{x}^2{x'}^2}}\right) = 0.$$

To simplify the EM, a special gauge is selected to define two relations between τ and σ:

$$\boldsymbol{\dot{x}^2 + {x'}^2 = 0,\ \ \dot{x}x' = 0.}$$

It is called an orthonormal gauge and allows to simplify the EM:

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

How Virasoro conditions restrict the string motion

Substitute the solution to the EM into the orthonormal gauge expressions:

$$x_\mu(\tau,\sigma) = Q_\mu + P_\mu \frac{\tau}{\pi\kappa} + \frac{i}{\sqrt{\pi\kappa}} \sum_{\substack{n=-\infty \\ n\neq 0}}^{+\infty} e^{-in\tau} \frac{\alpha_{n\mu}}{n} \cos(n\sigma) \qquad \begin{cases} \dot{x}^2 + x'^2 = 0 \\ \dot{x}x' = 0. \end{cases}$$

The resulting set of equalities is called the **Virasoro conditions**:

$$\Rightarrow \sum_{m=-\infty}^{+\infty} \boldsymbol{\alpha_{n-m}\,\alpha_m = 0}, \qquad \boldsymbol{n = 0, \pm 1, \pm 2, \ldots}$$

Here $\alpha_{n\mu}$ are Fourier amplitudes defined as

$$\alpha_{n\mu} = \sqrt{\frac{\kappa}{\pi}} \int_0^\pi d\sigma \cos(n\sigma) \left(v_\mu(\sigma) - in\rho_\mu(\sigma) \right), \qquad n \neq 0, \qquad \alpha_{0\mu} = \frac{P_\mu}{\sqrt{\kappa\pi}}.$$

The functions $\boldsymbol{v_\mu(\sigma)}$ and $\boldsymbol{\rho_\mu(\sigma)}$ define velocity and coordinates of the string at the initial moment in time.

- **Thus, the Virasoro conditions restrict the initial data of the boundary-value problem for the string motion**.

FOEE method to define the initial conditions of the string

The problem:

Most of the functions do not satisfy the Virasoro conditions if the string is massive ($M \neq 0$)

A new method:

- Let us express the initial data functions as a finite series over the Sturm-Liouville boundary problem eigenfunctions (**F**inal-**O**rder **E**igenfunction **E**xpansion, **FOEE**):

$$v_\mu(\sigma) = a_{0\mu} u_0(\sigma) + \sum_{k=1}^{N} a_{k\mu} u_k(\sigma)\,, \qquad \rho_\mu(\sigma) = b_{0\mu} u_0(\sigma) + \sum_{k=1}^{N} b_{k\mu} u_k(\sigma)\,.$$

- For a free string:

$$v_\mu(\sigma) = a_{0\mu} + \sum_{k=1}^{N} a_{k\mu} \cos(k\sigma)\,, \qquad \rho_\mu(\sigma) = b_{0\mu} + \sum_{k=1}^{N} b_{k\mu} \cos(k\sigma)\,.$$

Constructing the FOEE system

- The eigenfunctions of the S.-L. problem are orthogonal, so the system is finite**:**

$$\begin{cases} \sum_{\substack{m=\max(n-N,-N) \\ m\neq 0, m\neq n}}^{\min(n+N,N)} (a_{n-m}a_m - m(n-m)b_{n-m}b_m) + \frac{4}{\kappa\pi}Pa_n = 0 \\ \sum_{\substack{m=\max(n-N,-N) \\ m\neq 0, m\neq n}}^{\min(n+N,N)} (ma_{n-m}b_m + (n-m)a_m b_{n-m}) - \frac{4n}{\kappa\pi}Pb_n = 0, \end{cases} \quad n \neq 0, \quad \begin{cases} \sum_{\substack{m=-N \\ m\neq 0}}^{N} (a_{-m}a_m + m^2 b_{-m}b_m) = -\frac{2P^2}{(\kappa\pi)^2} \\ \sum_{\substack{m=-N \\ m\neq 0}}^{N} m(a_{-m}b_m - a_m b_{-m}) = 0. \end{cases}$$

- Add conservation laws:

$$\kappa\int_0^\pi d\sigma\, v_\mu(\sigma) = \kappa\int_0^\pi d\sigma\, \dot{x}_\mu(0,\sigma) = P_\mu,$$

$$\kappa\int_0^\pi d\sigma\left[\rho_\mu(\sigma)v_\nu(\sigma) - \rho_\nu(\sigma)v_\mu(\sigma)\right] = \kappa\int_0^\pi d\sigma\left[x_\mu(0,\sigma)\dot{x}_\nu(0,\sigma) - x_\nu(0,\sigma)\dot{x}_\mu(0,\sigma)\right] = M_{\mu\nu}.$$

The FOEE system: 1^{st} order

The initial data functions:

$$v_\mu(\sigma) = a_\mu + b_\mu \cos(\sigma)$$
$$\rho_\mu(\sigma) = c_\mu + d_\mu \cos(\sigma)$$

$$\begin{cases} \alpha_{0\mu} = \dfrac{P_\mu}{\sqrt{\kappa\pi}} \\ \alpha_{1\mu} = \dfrac{\sqrt{\kappa\pi}}{2}\left(b_\mu - i d_\mu\right) \\ \alpha_{-1\mu} = \dfrac{\sqrt{\kappa\pi}}{2}\left(b_\mu + i d_\mu\right) \end{cases}$$

Fourier amplitudes

System of the Virasoro conditions:

$$\begin{cases} b^2 - d^2 = 0 \\ bd = bP = dP = 0 \\ b^2 + \dfrac{2P^2}{(\kappa\pi)^2} = 0 \end{cases}$$

4-momenta conservation gives: $a_\mu = \dfrac{P_\mu}{\kappa\pi}$

AM tensor conservation: $c_\mu P_\nu - c_\nu P_\mu + \dfrac{\kappa\pi}{2}\left(d_\mu b_\nu - d_\nu b_\mu\right) = M_{\mu\nu}.$

15 equations, 16 variables

- **Very difficult to solve the system due to its non-linearity.**

FOEE(1)-string in the center-of-mass

- Define the string with:

$P_0 \equiv M, P_i = 0, i = 1, 2, 3.$

- Rotate the coordinate system so that string rotation occurred in a XZ-plane:

$$\mathcal{M}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathcal{M}_{13} \\ 0 & 0 & 0 & 0 \\ 0 & -\mathcal{M}_{13} & 0 & 0 \end{pmatrix}.$$

Get the following initial data functions:

$$\boldsymbol{v}^*_\mu(\boldsymbol{\sigma}) = (\boldsymbol{\kappa\pi})^{-1}\boldsymbol{M}\left[\boldsymbol{\delta}_{0\mu} + \boldsymbol{\delta}_{1\mu}\cos(\boldsymbol{\sigma})\right], \qquad \boldsymbol{\rho}^*_\mu(\boldsymbol{\sigma}) = -(\boldsymbol{\kappa\pi})^{-1}\boldsymbol{\xi}\boldsymbol{M}\boldsymbol{\delta}_{3\mu}\cos(\boldsymbol{\sigma}),$$

wher $\delta_{\mu\nu}$ is the Kronecker delta, ξ is a string rotation signature:

$$\boldsymbol{\xi} = \mathbf{sign}\mathcal{M}_{13}.$$

FOEE(1)-string in the center-of-mass

- Obtain the following formula for string coordinates:

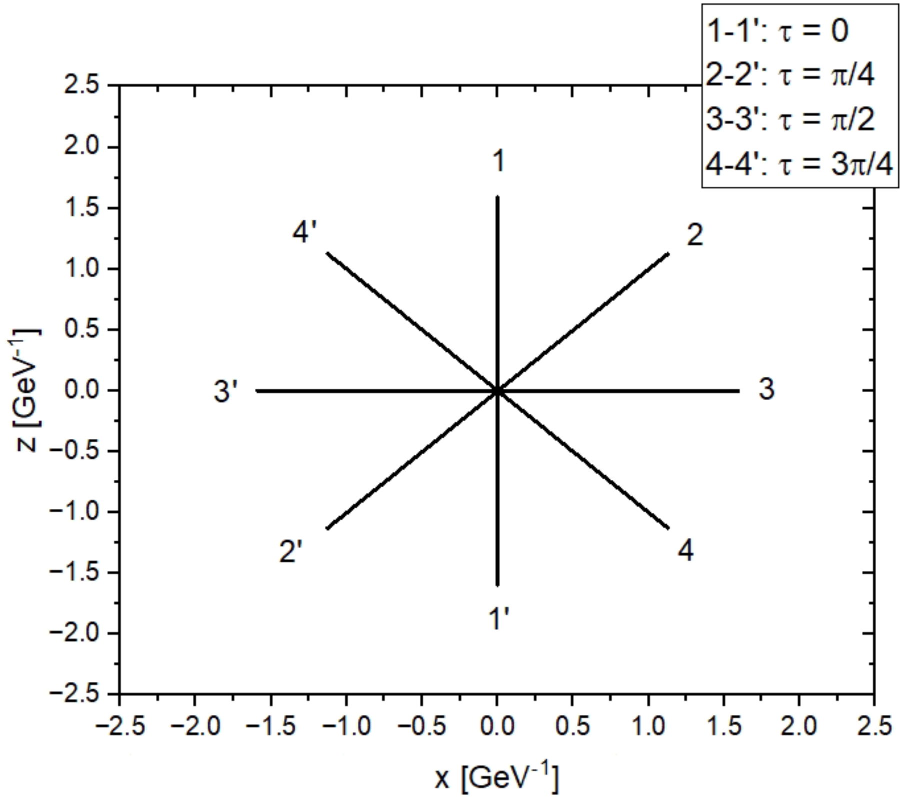
$$x_\mu(\tau,\sigma) = (\kappa\pi)^{-1} M\big(\delta_{0\mu}\tau + [\delta_{1\mu}\sin(\tau) - \xi\delta_{3\mu}\cos(\tau)]\cos(\sigma)\big).$$

- An important relation:

$$2\kappa\pi|\mathcal{M}_{13}| = M^2.$$

  - ➢ String must rotate (have spin) to be massive!

- important: FOEE(1)-string satisfies the conditions for the tangent vectors to the string world sheet.



FOEE(1)-string rotates as a rigid rod in CM

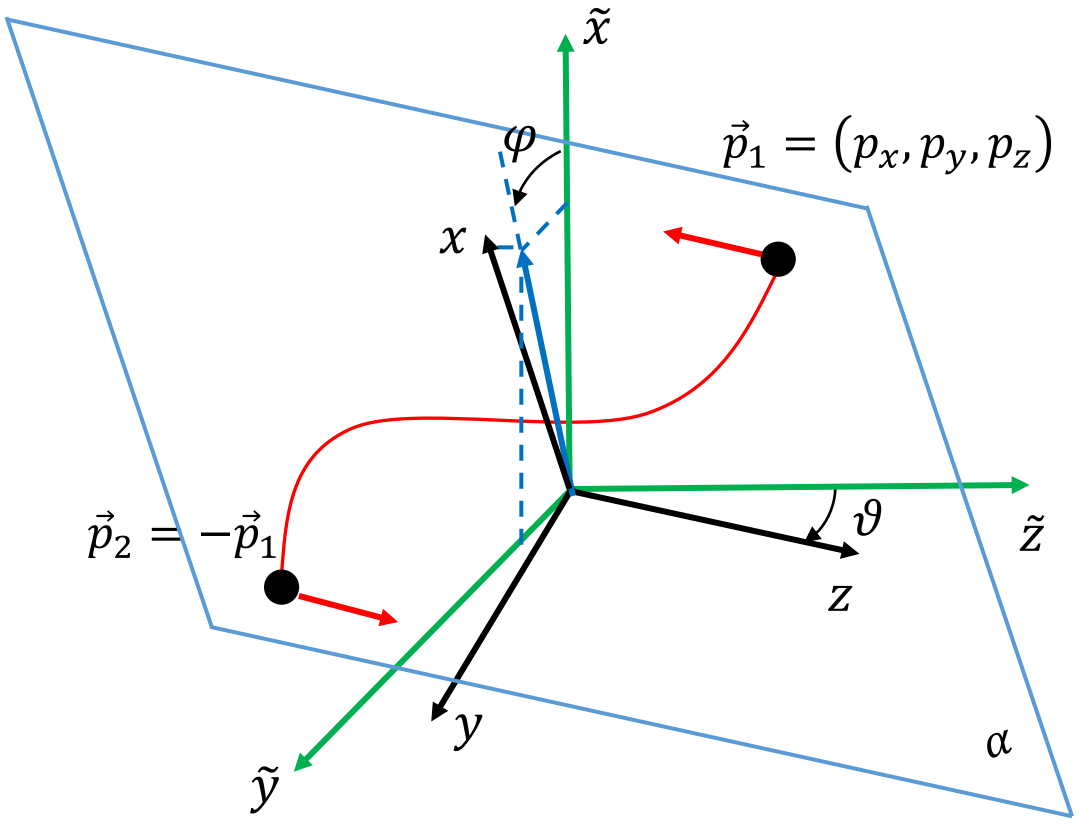
FOEE(1)-string in arbitrary system

Lorentz boost to the system where string has momentum $\vec{P}$:

$$v_0(\sigma) = \frac{P_0 v_0^*(\sigma) + \vec{P}\vec{v}^*(\sigma)}{M},$$
$$\vec{v}(\sigma) = \vec{v}^*(\sigma) + \vec{P}\frac{v_0(\sigma) + v_0^*(\sigma)}{P_0 + M}.$$

Rotate the coordinate axis:

$$R(\vartheta,\varphi) = \begin{pmatrix} \cos\varphi & -\sin\varphi\cos\vartheta & \sin\varphi\sin\vartheta \\ \sin\varphi & \cos\varphi\cos\vartheta & -\cos\varphi\sin\vartheta \\ 0 & \sin\vartheta & \cos\vartheta \end{pmatrix},$$
$$\cos\vartheta = \frac{p_z}{\sqrt{p_x^2 + p_y^2 + p_z^2}}, \qquad \cos\varphi = \frac{p_y}{\sqrt{p_x^2 + p_y^2}}.$$



The scheme of the coordinate axis rotation in the CM of the string

FOEE(1)-string in arbitrary system

Initial conditions:

$$\boldsymbol{v_\mu(\sigma) = (\kappa\pi)^{-1}\left[P_\mu + \xi\left(M\psi_\mu - (P\psi)\chi_\mu\right)\cos(\sigma)\right]}, \qquad \boldsymbol{\rho_\mu(\sigma) = (\kappa\pi)^{-1}\left(M\lambda_\mu - (P\lambda)\chi_\mu\right)\cos(\sigma)},$$

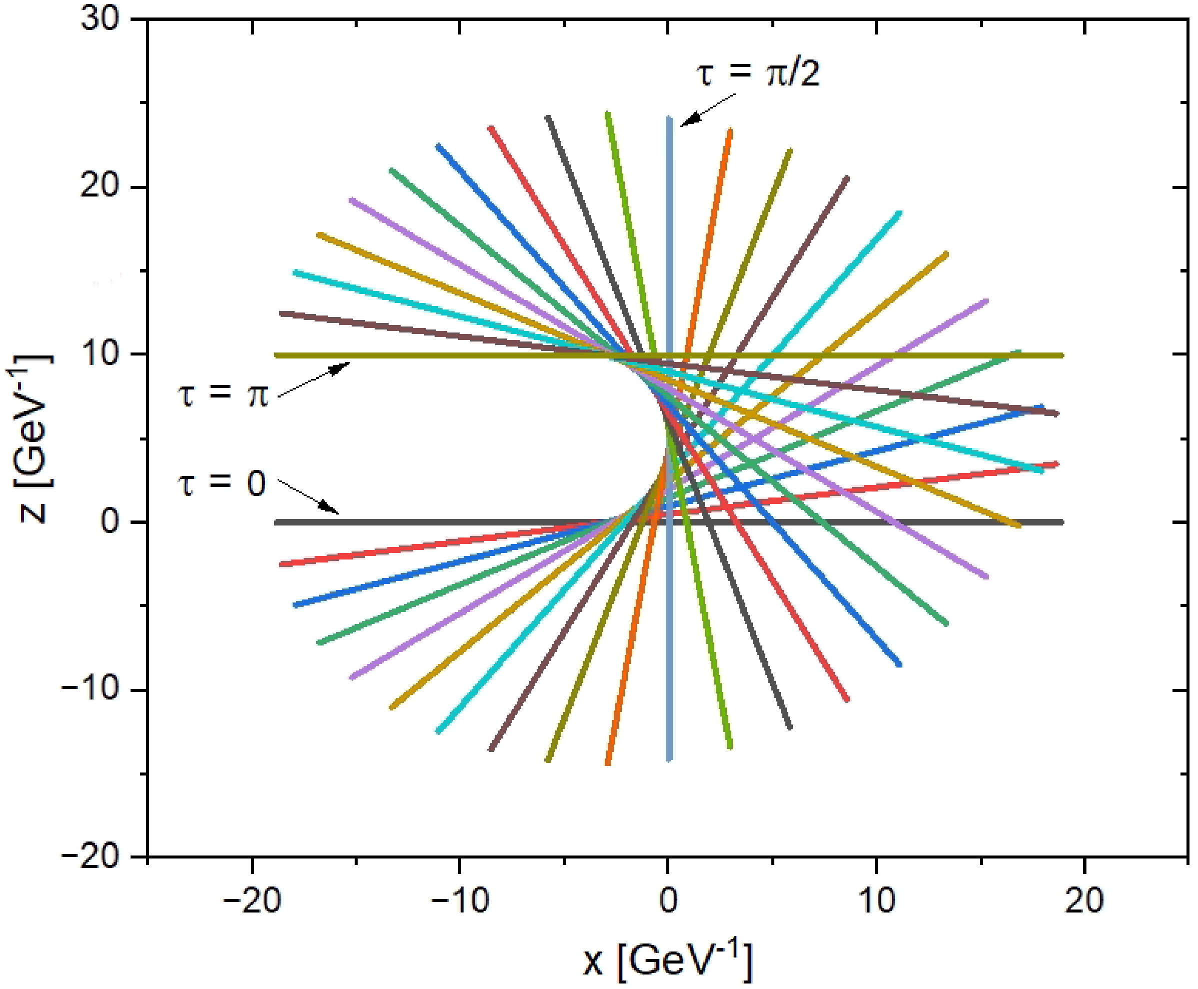
$$\psi_\mu = \begin{pmatrix} 0 \\ \sin\varphi\sin\vartheta \\ -\cos\varphi\sin\vartheta \\ \cos\vartheta \end{pmatrix}, \qquad \lambda_\mu = \begin{pmatrix} 0 \\ \cos\varphi \\ \sin\varphi \\ 0 \end{pmatrix}, \qquad \chi_0 \equiv 1, \qquad \vec{\chi} = \frac{\vec{P}}{P_0 + M}.$$

The formula for the coordinates of the string:

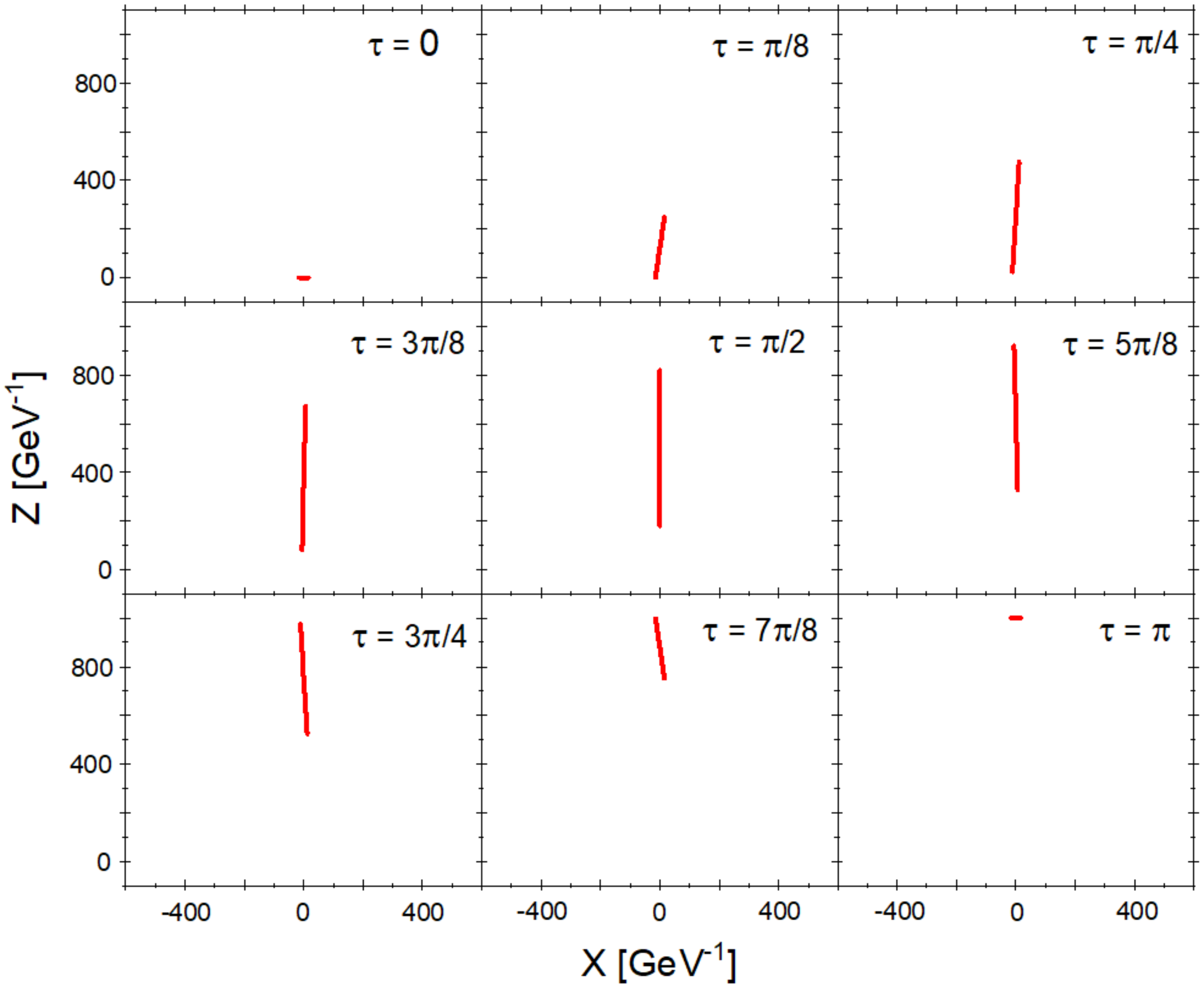
$$\boxed{\boldsymbol{x_\mu(\tau,\sigma) = (\kappa\pi)^{-1}\left(P_\mu\tau + \left[M\Omega_\mu(\tau) - \left(P\Omega(\tau)\right)\chi_\mu\right]\cos(\sigma)\right)},}$$

$$\Omega_\mu(\tau) = \lambda_\mu\cos(\tau) + \xi\psi_\mu\sin(\tau), \qquad \Lambda_\mu(\tau) = \psi_\mu\cos(\tau) - \xi\lambda_\mu\sin(\tau).$$

Examples of the FOEE(1)-string motion



Motion of FOEE(1)-string of mass 12 GeV and $P_z = 2$ GeV



Motion of FOEE(1)-string of mass 10 GeV and P_z =100 GeV

Generalization for the case of the higher order eigenharmonic

- FOEE(1)-string can have eigenharmonic with non-zero amplitude of arbitrary order:

$$\begin{cases} v_\mu(\sigma) = a_\mu + b_\mu \cos(\sigma) \\ \rho_\mu(\sigma) = c_\mu + d_\mu \cos(\sigma) \end{cases} \Rightarrow \begin{cases} v_\mu(\sigma) = a_\mu + b_\mu \cos(\boldsymbol{\nu}\sigma) \\ \rho_\mu(\sigma) = c_\mu + d_\mu \cos(\boldsymbol{\nu}\sigma) \end{cases}$$

$\boldsymbol{\nu}$ is natural number

- The resulting equation of motion is similar to the case $\boldsymbol{\nu = 1}$:

$$\boldsymbol{x_\mu(\tau,\sigma) = (\kappa\pi)^{-1}\left(P_\mu\tau + \nu^{-1}\left[M\Omega_\mu(\tau,\nu) - \left(P\Omega(\tau,\nu)\right)\chi_\mu\right]\cos(\sigma)\right),}$$

$$\Omega_\mu(\tau,\boldsymbol{\nu}) = \lambda_\mu \cos(\boldsymbol{\nu}\tau) + \xi\psi_\mu \sin(\boldsymbol{\nu}\tau)\,.$$

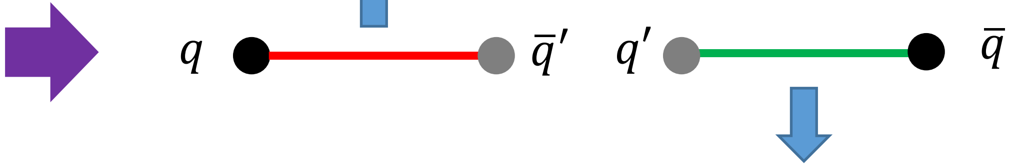
Some features of the model

1. The string fragmentation process is *naturally* limited: there is always a last “fragmentable” string composed of the 3 segments (2 in case the production at rest is permitted)

The “shortest” string that can fragment

(string is shown “unfolded”)

No more “joints” on the daughters -> fragmentation stops

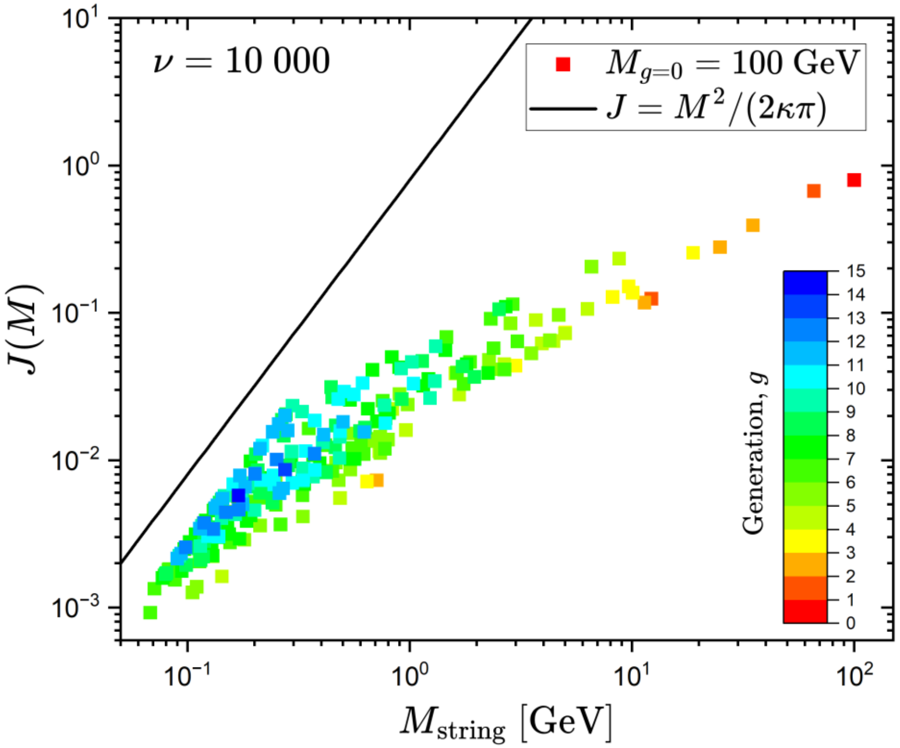


2. Close-to-Regge behavior of the spin-mass relation for light daughter strings

- The connection between the slope of the Regge trajectory α and the string tension κ is derived in the string theory based on $J(M)$ dependence:

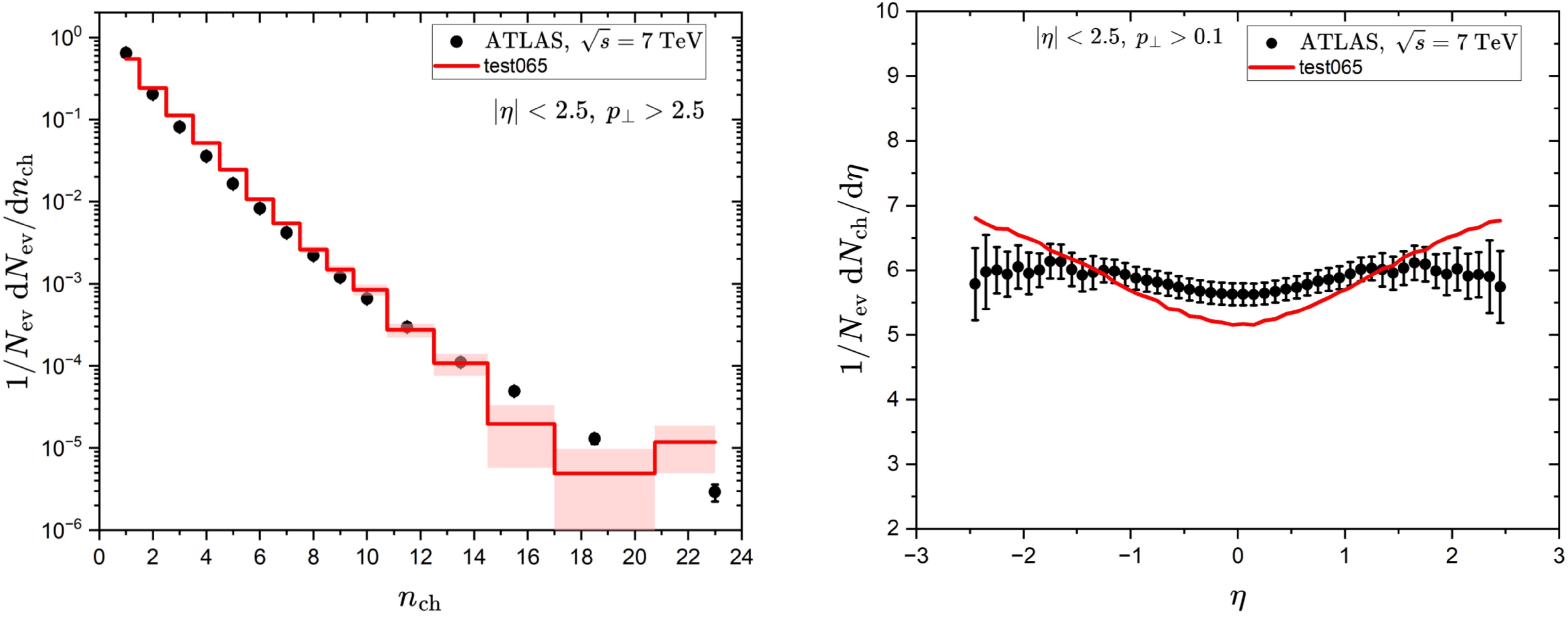
$$\alpha = (2\kappa\pi)^{-1}$$

- This would lead to huge AM for heavy strings, but in the ATROPOS model, the proportionality coefficient between J and M^2 decreases with the daughter string generation.

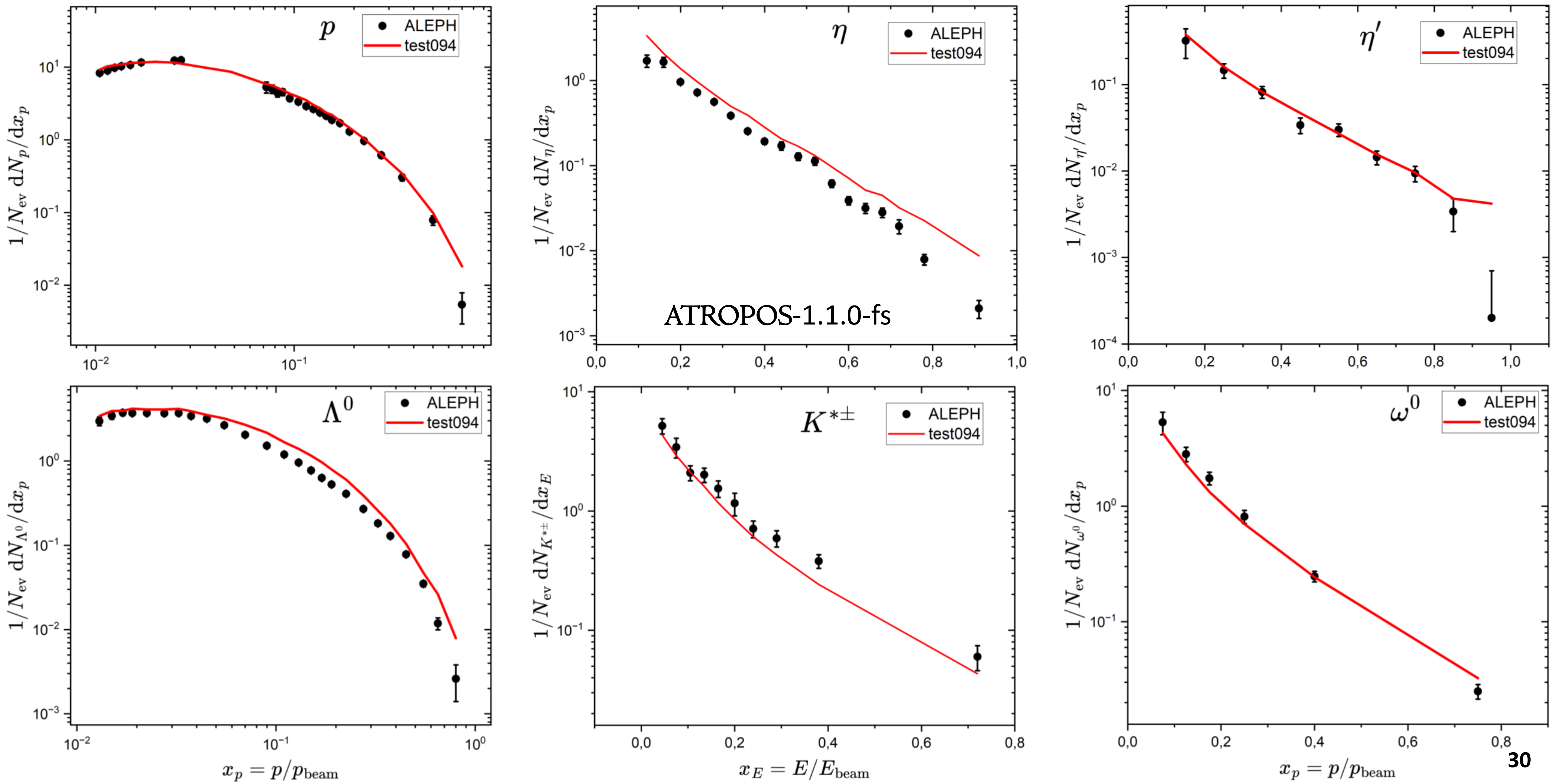


An example of sampled values of the daughter strings AM for a primary string of mass $M = 100$ GeV and with $\nu = 10^4$

First results: pp collisions at LHC energies



First results: e^+e^- collisions, additional



Free parameters tuning: set FPS-55

Parameter	Physical meaning	Value
κ	String tension	$0.2\ \mathrm{GeV}^2$
P_0	Area Decay constant	$P_0 = 0.3 + 1.7\, M_{\mathrm{string}}/(7\ \mathrm{TeV})$
$P_{u\bar{u}} = P_{d\bar{d}}$	Relative pair production probability	0.3645
$P_{s\bar{s}}$	Relative pair production probability	0.12
$P_{uu\overline{uu}} = P_{dd\overline{dd}} = P_{ud\overline{ud}}$	Relative pair production probability (diquark)	0.04
$P_{us\overline{us}} = P_{ds\overline{ds}}$	Relative pair production probability (diquark)	0.015
$P_{ss\overline{ss}}$	Relative pair production probability (diquark)	0.001
SHMT	String-to-hadron transition mass tolerance (relative to hadron mass)	0.1
DIQ01S	Suppression of spin 1 state to spin 0 for diquarks in pairs (if diff. flavor)	0.3
HFSS	Suppression of co-directional spin projections of string end-point partons	0.5 (probably too strong suppression)
M_{indiv}	Indivisible string mass (low-mass limit -> phase decay)	11 GeV for ee and πC, 7 GeV for pp (hard gluons are important)