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Parton Ladder Splitting and Fusion: how to Understand Particle Production at RHIC and LHC

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Claim: All pp, dAu, AuAu data at RHIC, pp, CC, SiSi, PbPb data at SPS can be understood within a single picture!!

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1 Basic ideas

- ☐ Take a sophisticated parton model (EPOS), which works at pp, and which is formulated such that it can be generalized towards AA (unlike Pythia).
- ☐ Add an effective treatment of parton ladder splitting to account for nuclear effects in pA or dA (EPOS+).
- ☐ Add another feature, important for AA (EPOS++): consider the possibility that pieces of parton ladders (mainly in the middle) interact –> fuse to form clusters, when corresponding densities are high.

  Let the clusters decay according to phase space (covariant microcanonical procedure), allowing for radial flow (two parameters), at some given energy density (parameter). Very few parameters !!

- ☐ Works excellently for small pt's! Enormous predictive power! There are essentially three parameters, very little freedom, centrality dependence, system size dependence, is really predicted, nothing to tune.

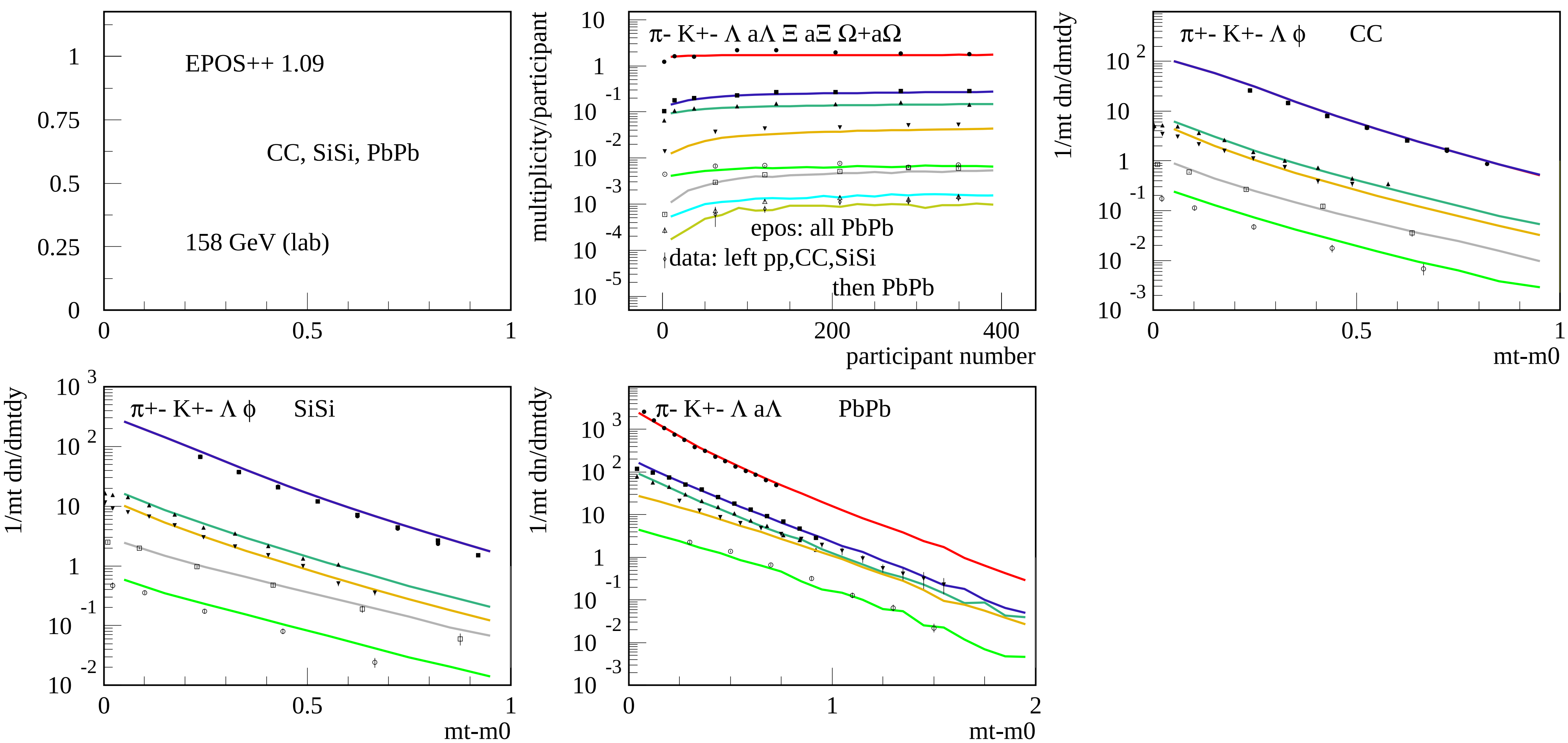
- ☐ Works even for intermediate pt's, with the exception of pions in central AuAu collisions...

  but this should be so
  (see discussion at the end)

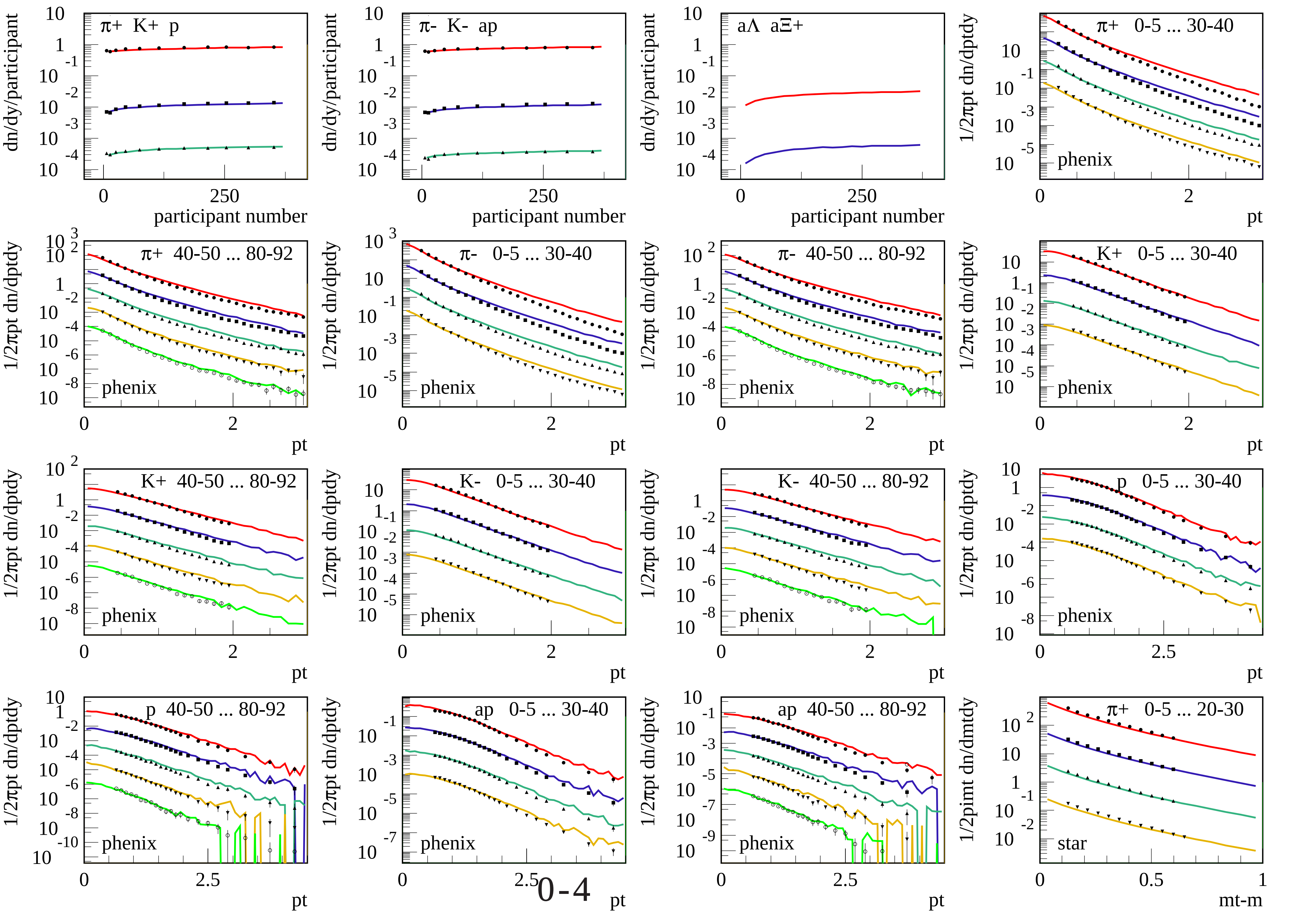
- ☐ There are some small deviations, but the RHIC simulation curves are usually between the PHENIX and STAR data points[3].

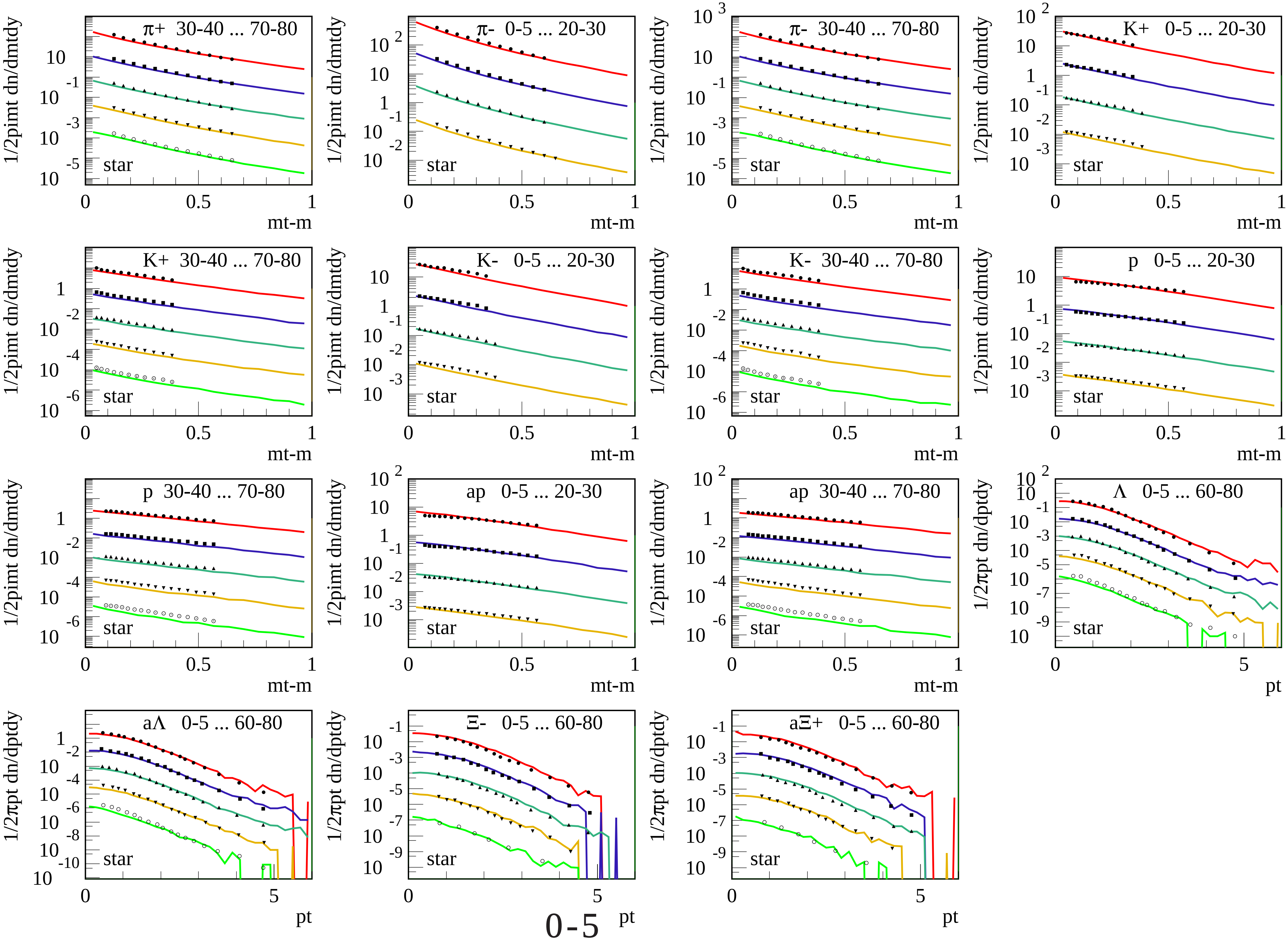
[3] presented differently, so I cannot plot them together (made on purpose???)

2 Spectra


EPOS++ 1.09
CC, SiSi, PbPb
158 GeV (lab)
π- K+- Λ aΛ Ξ aΞ Ω+aΩ
epos: all PbPb
data: left pp,CC,SiSi
then PbPb
multiplicity/participant
participant number
π+- K+- Λ φ CC
1/mt dn/dmtdy
mt-m0
π+- K+- Λ φ SiSi
π- K+- Λ aΛ PbPb

EPOS++ 1.09 AuAu 200GeV





π+ 30-40 ... 70-80
π- 0-5 ... 20-30
π- 30-40 ... 70-80
K+ 0-5 ... 20-30
K+ 30-40 ... 70-80
K- 0-5 ... 20-30
K- 30-40 ... 70-80
p 0-5 ... 20-30
p 30-40 ... 70-80
ap 0-5 ... 20-30
ap 30-40 ... 70-80
Λ 0-5 ... 60-80
aΛ 0-5 ... 60-80
Ξ- 0-5 ... 60-80
aΞ+ 0-5 ... 60-80
star
1/2pimt dn/dmtdy
1/2πpt dn/dptdy
mt-m
pt
0-5

3 EPOS

Energy conserving quantum mechanical multiple scattering approach

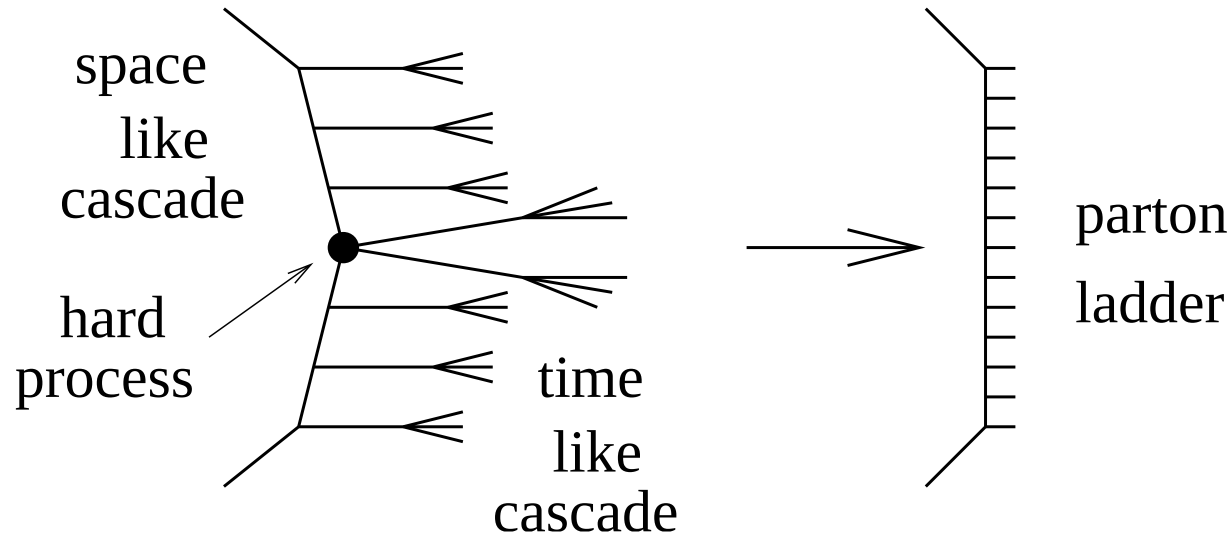
based on

Partons, Pomerons (parton ladders)

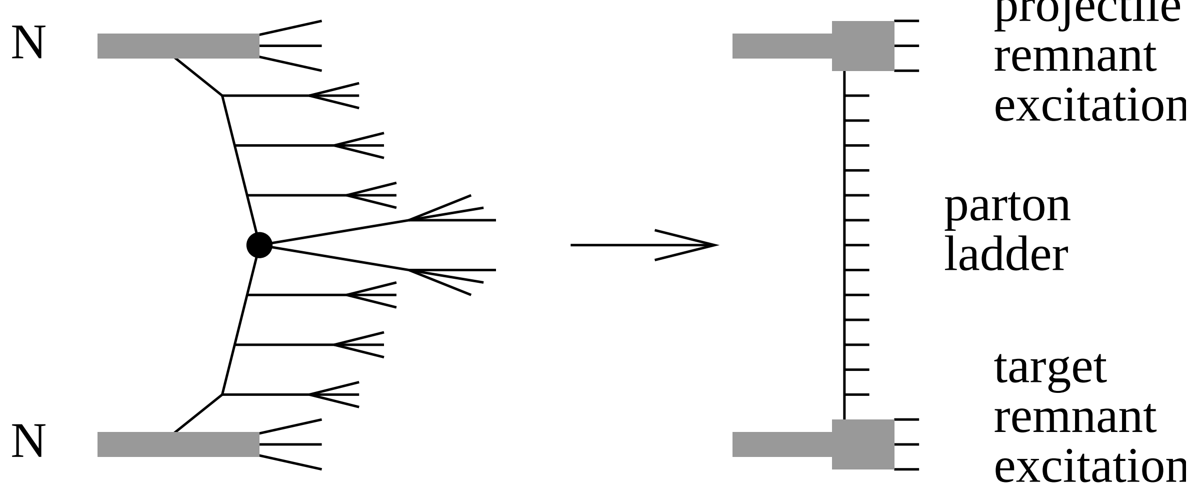
Off-shell remnants

Strings

Parton-parton scattering :



The complete picture, including remnants. The remnants are an important source of particle production at RHIC energies.

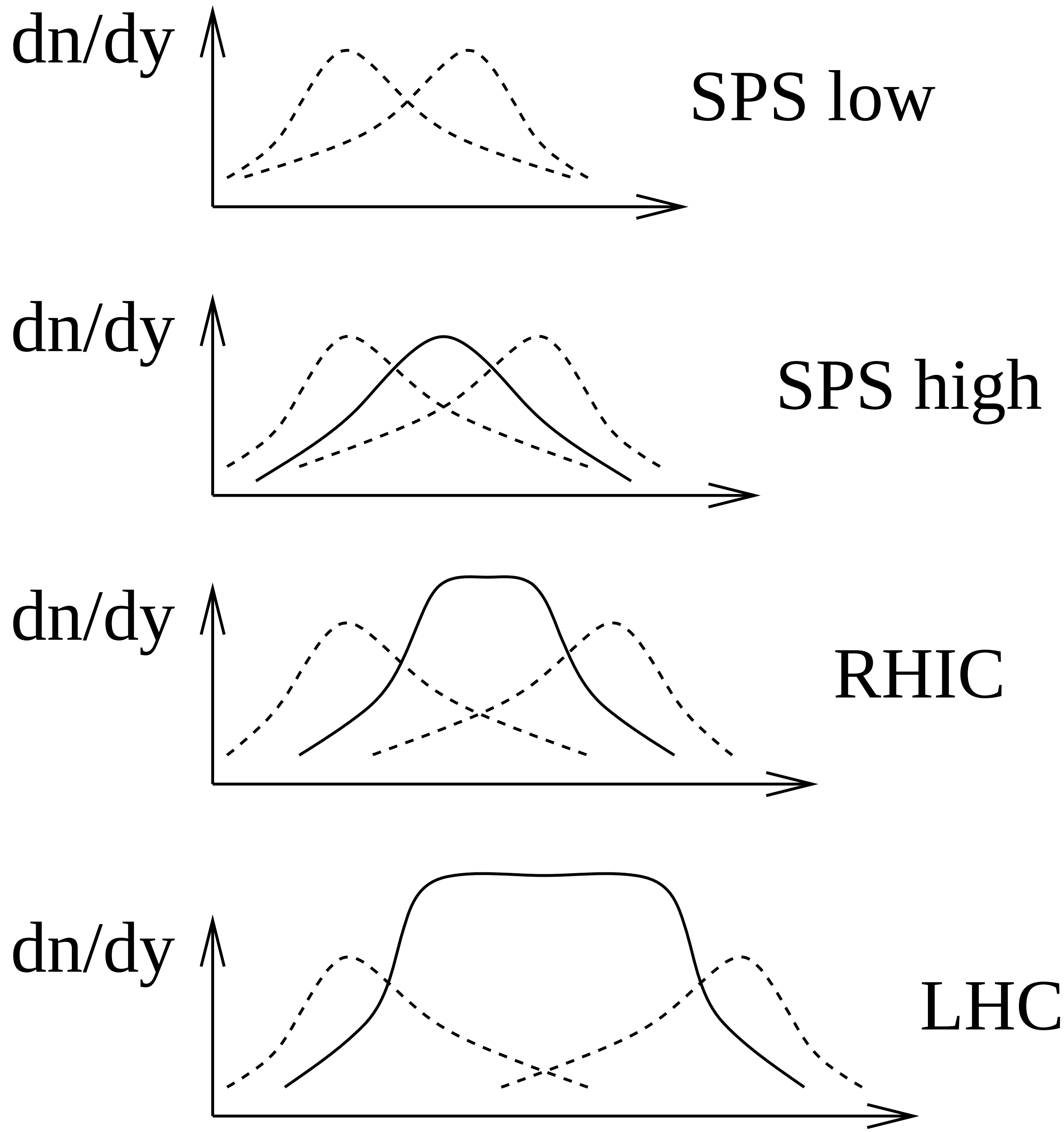


Contributions from remnants and inner partons

full = inner

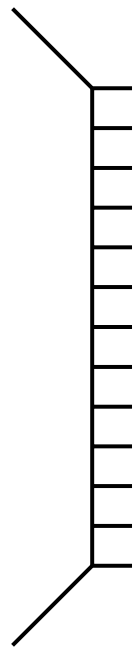
dashed = remnants

checking SPS is always important!

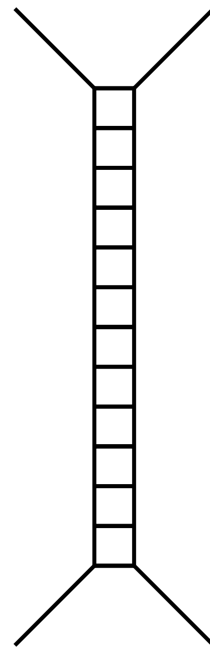


EPOS+

Basic elements for generalizations:



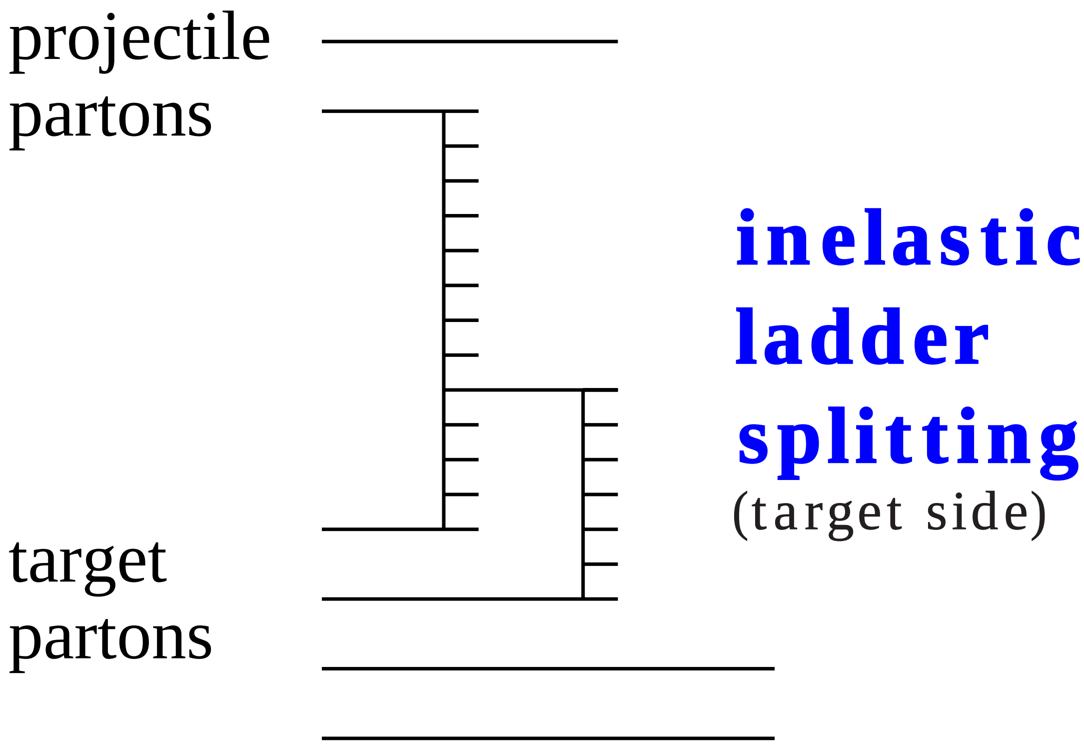
open
parton
ladder



closed
parton
ladder

Same symbol for soft and hard

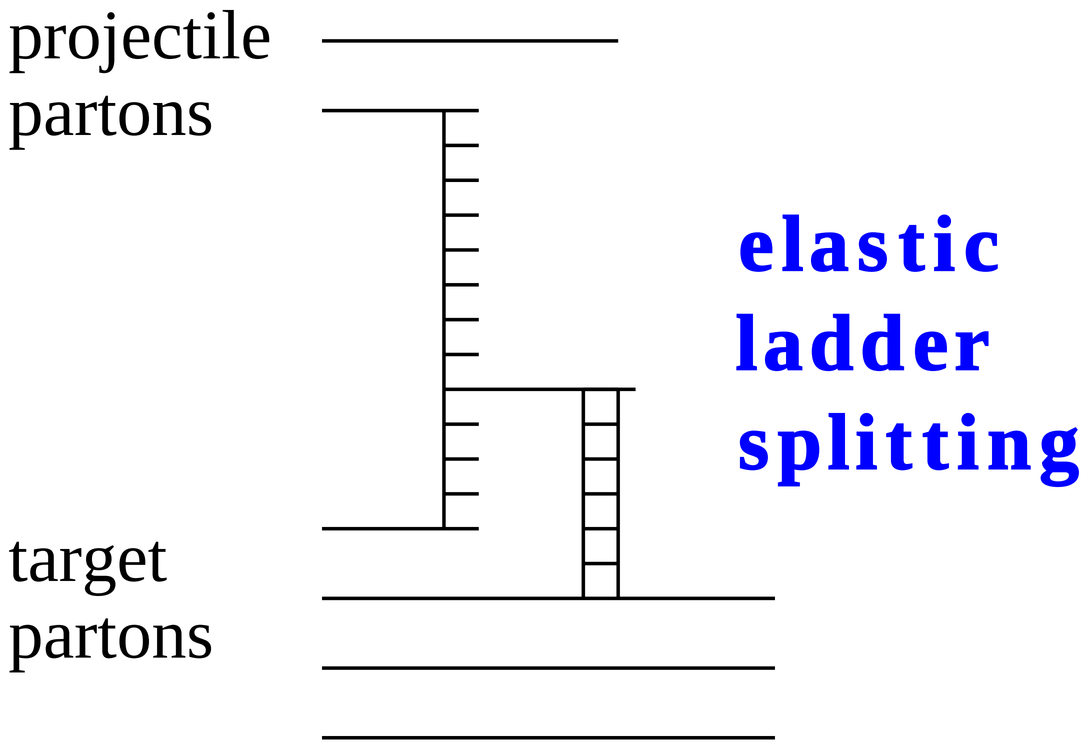
High parton densities (say on the target side):



Affects:

- ☐ multiplicities, hadronization properties

... another possibility:



- ☐ interference with simple contribution
- ☐ provides negative contribution to the cross section → **screening**

Effects of elastic splitting:

- The squared amplitude for an elementary inelastic interaction involving two partons with light cone momentum shares x^+ and x^- can be parametrized quite accurately as

$$\alpha\,(x^+)^\beta (x^-)^\beta, \tag{1}$$

with two parameters α and β (depending on the s and b). Elastic splitting modifies the corresponding squared amplitude as

$$\alpha\,(x^+)^\beta (x^-)^{\beta+\varepsilon}, \tag{2}$$

and therefore the whole effect can be summarized by a simple positive exponent ε.

- Another effect: Transfer of transverse momentum

Effects of inelastic splitting:

- ☐ two ladders in parallel, which are in addition close in space
- ☐ hadronization of the two ladders is certainly not independent
- ☐ we expect some kind of a “collective” hadronization of two interacting ladders (one may also imagine three or more close ladders, hadronizing collectively).

Realization:

Basic quantity : the number Z of partons available for additional legs, more precisely we have a Z_T for counting legs on the target side, and Z_P for counting legs on the projectile side.

Let us treat Z_T. Consider a parton in projectile nucleon i which interacts with a parton in target nucleon j. The number $Z_T(i,j)$ of addition legs has two contributions, one counting the legs attached to the same nucleon j, and one counting the legs attached to the other nucleons $j' \neq j$. We assume the following form:

$$Z_T(i,j) = z_0 \exp(-b_{ij}^2/2{b_0}^2) + \sum_{\text{target nucleons } j' \neq j} z_0' \exp(-b_{ij'}^2/2{b_0}^2), \qquad (3)$$

where b_{ij} is the distance in impact parameter between i and j. The coefficients z_0 and z_0' depend logarithmically on the energy, as

$$z_0 = w_Z \log s/s_M\,, \qquad (4)$$

$$z_0' = w_Z \sqrt{(\log s/s_M)^2 + {w_M}^2}\,, \qquad (5)$$

$(\log(x) := \max(0, \ln(x)))$, $b_0 = w_B \sqrt{\sigma_{\mathrm{inel}\,pp}/\pi}$.

We then define

$$Z_T(j) = \sum_i Z_T(i,j). \tag{6}$$

We suppose that all the effects of the parton ladder splitting can be treated effectively, meaning that the correct explicit treatment of splittings is equivalent to the simplified treatment without splittings, but with certain parameters modified, expressed in terms of Z.

So which quantities depend on Z, and how? In the following the symbols a_i are constants, used as fit parameters. The elastic splitting leads to screening, which is expressed by the screening exponents $\varepsilon = \varepsilon_S$ (for soft ladders) and $\varepsilon = \varepsilon_H$ (for hard ladders), and here we assume

$$\varepsilon_S = a_S\,\beta_S\,Z\,, \quad \varepsilon_H = a_H\,\beta_H\,Z\,, \tag{7}$$

where β_S and β_H are the usual exponents describing soft and hard amplitudes.

A second effect is transport of transverse momentum, here we suppose

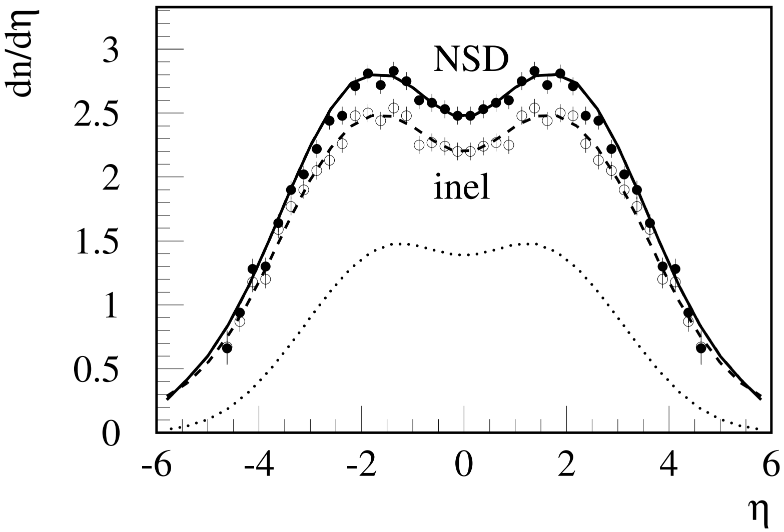
$$\Delta p_t = a_T\, p_0\, n_q\, Z, \tag{8}$$

where n_q is the number of quarks of the objects in the hadronization process (1 for quarks, 2 for diquarks), and $p_0 = 0.5$ GeV is just used to define a scale.

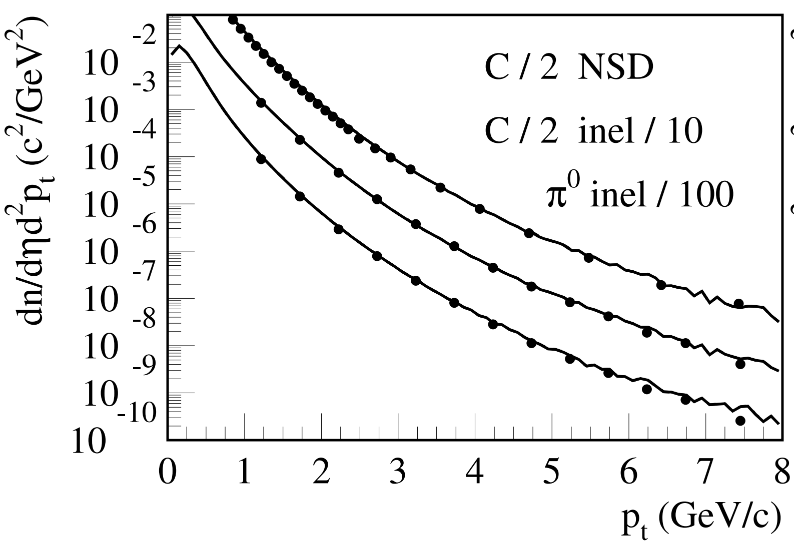
Collective hadronization. We will actually "absorb" the multiple ladders into the remnants, which are usually treated as strings. Now we treat them as strings with modified string break parameters, to account for the collective hadronization. We modify the break probability (per unit space-time area) p_B, which determines whether a string breaks earlier or later, the diquark break probability p_D, the strange break probability p_S, and the mean transverse momentum $\bar{p}_t$ of a break, as

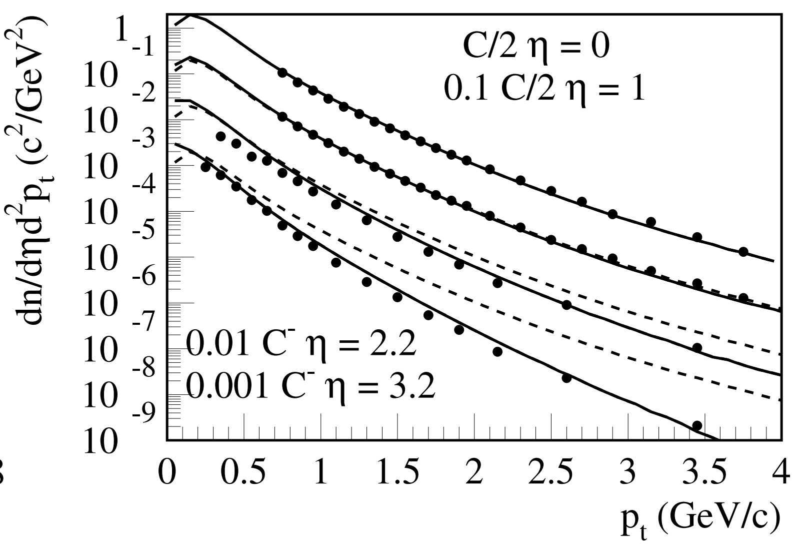
$$\begin{aligned} p_B &\rightarrow p_B - a_B\, Z\,, && (9)\\ p_D &\rightarrow p_D\, (1 + a_D\, Z)\,, && (10)\\ p_S &\rightarrow p_S\, (1 + a_S\, Z)\,, && (11)\\ \bar{p}_t &\rightarrow \bar{p}_t\, (1 + a_P\, Z)\,. && (12) \end{aligned}$$

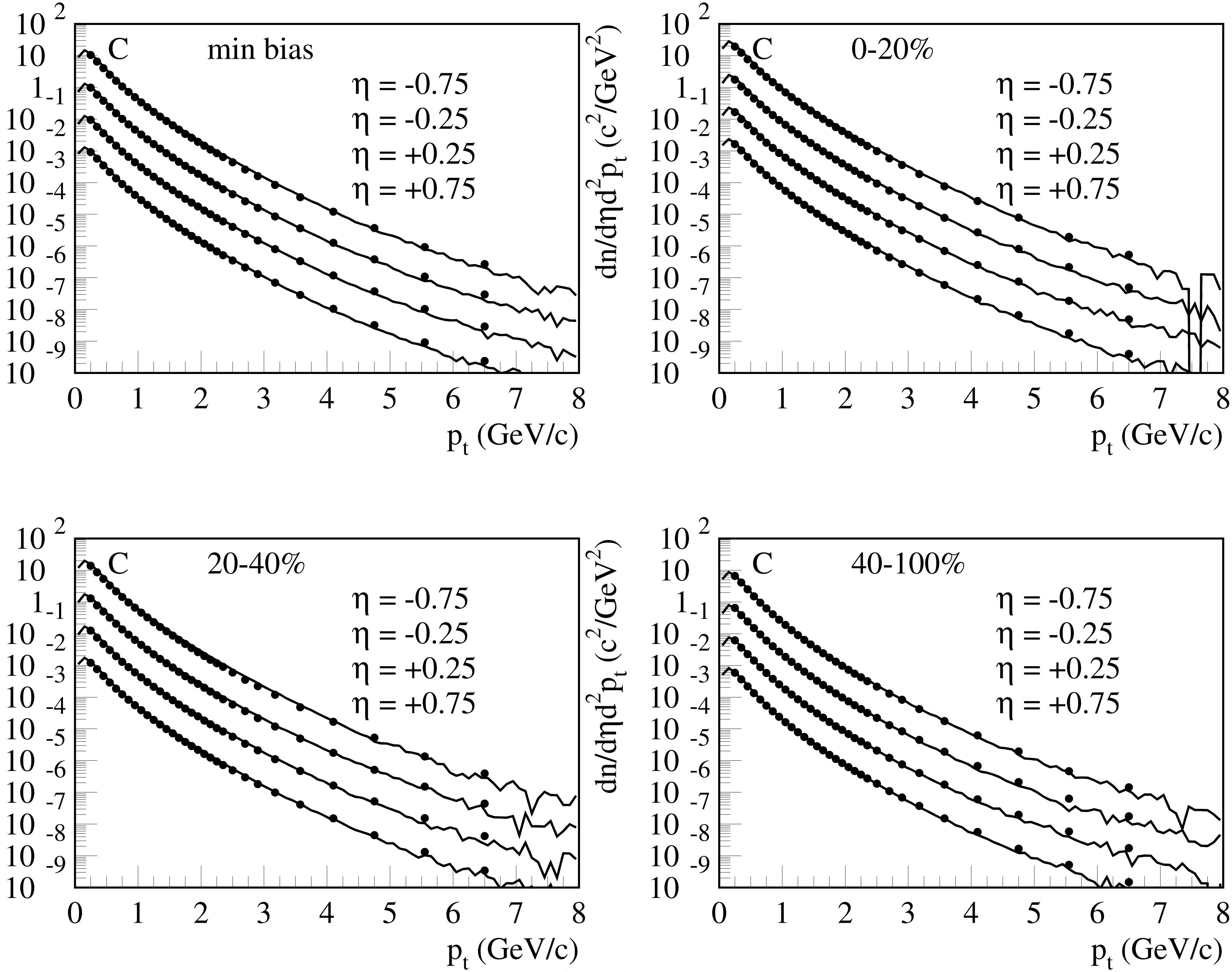
5 Results pp, dAu



pp ($p\bar{p}$) at 200 GeV





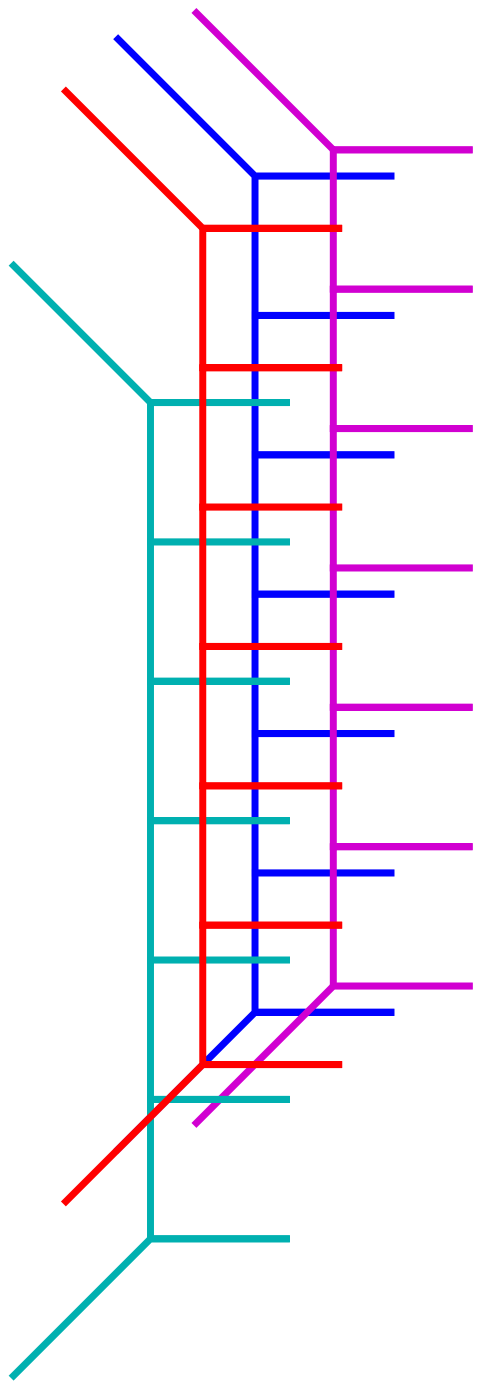

C
min bias
0-20%
20-40%
40-100%
η = -0.75
η = -0.25
η = +0.25
η = +0.75
dn/dηd²p_t (c²/GeV²)
p_t (GeV/c)

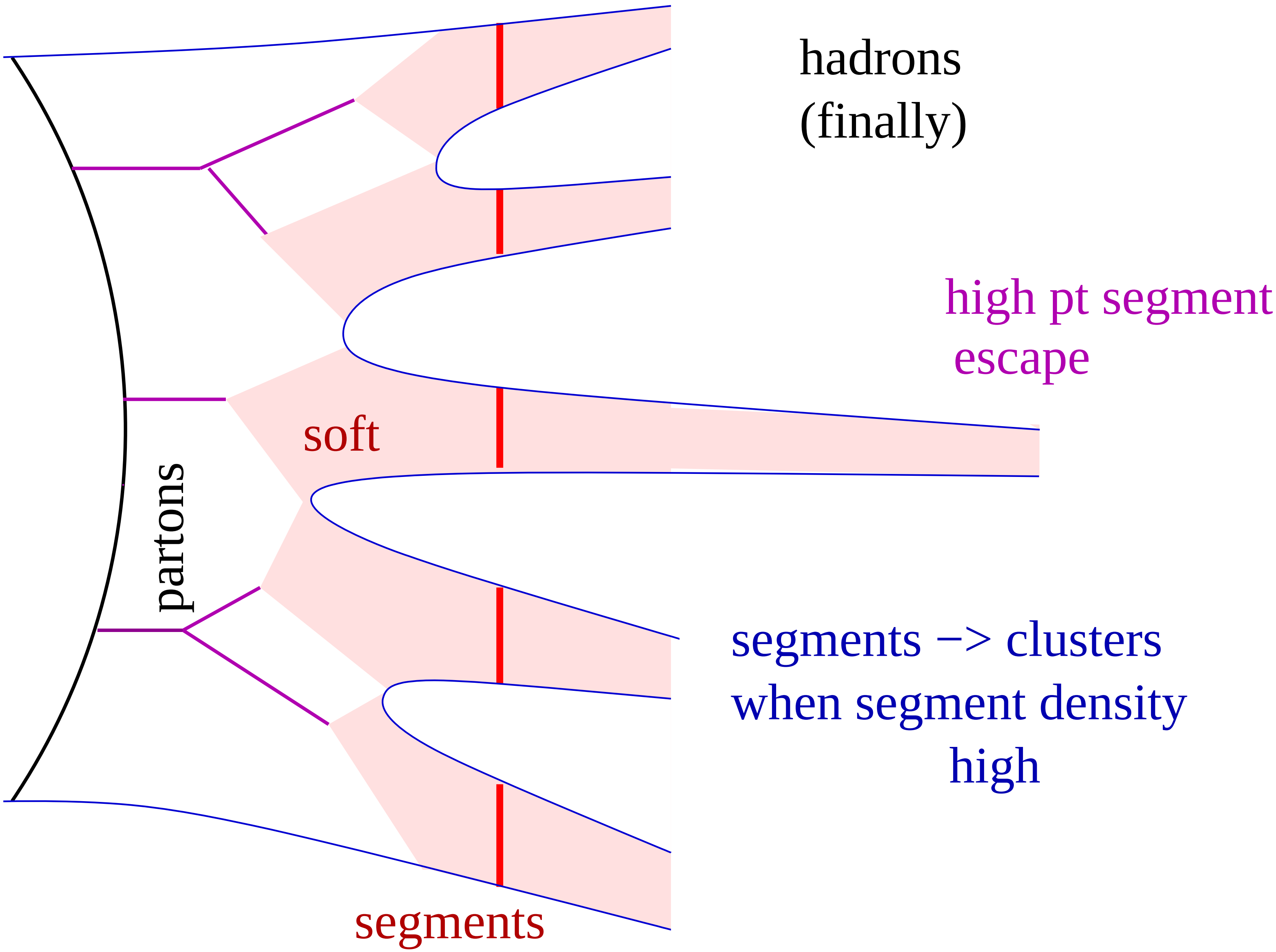
dAu

6 EPOS++

In (central) AA there are many parton ladders in parallel, impossible to hadronize independently

→collective hadronization




hadrons
(finally)
high pt segment
escape
soft
partons
segments -> clusters
when segment density
high
segments

In practice:

- □ We define a grid in $x - y - \eta - \tau$ coordinates. The corresponding volume element $\Delta\tilde{V}$ is considered to be the "proper volume" of the local matter.
- □ We consider the segments at some τ_0. If the density of segments per "proper volume" is bigger than some ρ_{clu}, the the corresponding segments are considered to be part of the cluster,
- □ unless a segment has a p_t bigger than some p_{clu}.

- Connected cluster cells build global clusters, which are expected to expand and acquire flow.

- The cluster decays at some energy density $\epsilon_{\rm clu}$, which is taken to be the same for all energies and centralities.

- We assume a linear transverse flow profile (in transverse rapidity), with some maximum transverse rapidity increasing logarithmically with energy: $y_{\rm rad}^{\rm max} = a_{\rm rad} + b_{\rm rad} \log \sqrt{s/s_{\rm SPS}}$.

- The cluster decays according to the covariant microcanonical phase space :

$$\prod_{\text{species}\,\alpha} \frac{1}{n_\alpha!} \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi\hbar)^3 2E} g_i |M|^2 \delta(E - \Sigma\varepsilon_i)\, \delta(\Sigma\vec{p}_i)\, \delta_{Q,\Sigma q_i},$$

  where we assume that $|M^2|$ is proportional to the total proper volume. In addition, there is a factor $1 \pm \epsilon$ for each strange particle (sign plus inside a baryon, sign minus inside a meson). (maybe not necessary?)

- In the whole procedure, we perfectly conserve energy, momentum, and flavor.

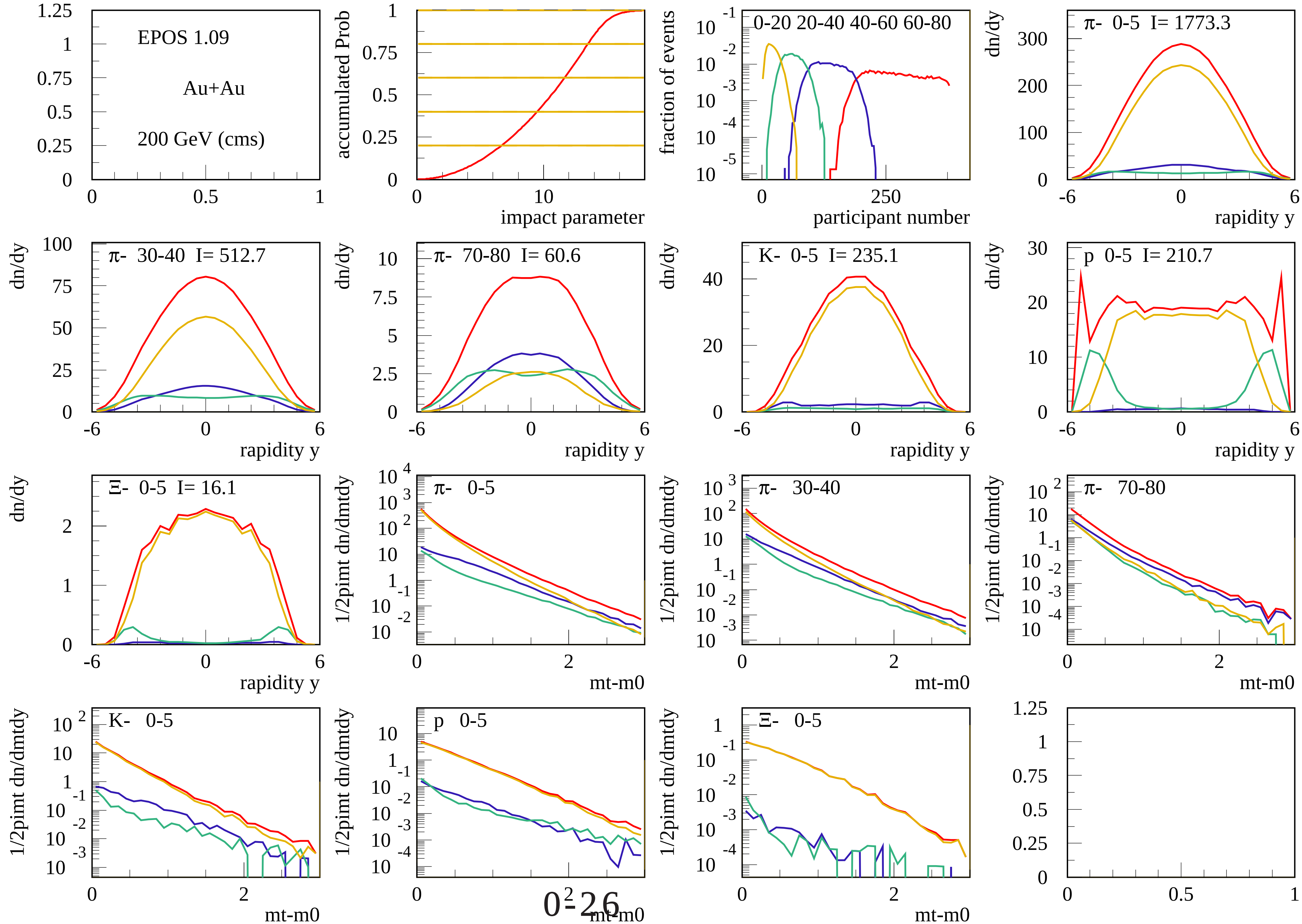
- The cluster formation parameters are not too much affecting the results,

- the "real" parameters are the decay density ϵ_{clu} and the flow parameters a_{rad},b_{rad}.

7 Can we understand the data?

- **The model works very well (considering the available parameters, the predictive power is enormous!)**
- **Why ?**
- **To understand the data , we first have to understand that we have always two contributions : cluster decay and "normal stuff" (as in pp). In central collisions this "normal" contribution is very small, but it grows with decreasing centrality**
- **...and it is exactly this interplay between these two contributions which explains everything !**

EPOS++ 1.09 AuAu 200GeV



- ☐ **How to understand the centrality dependence? Why does the Omega or Xi yield increase so much?**

- ☐ **This is because Ω's or Ξ's are much less suppressed in phase space decay compared to string decay, so the cluster makes relatively much more Ω's and Ξ's than we observe in the "normal" contribution.**

- ☐ **And the change of the relative weight of these two contributions with centrality explains this strong centrality dependence.**

- ☐ **Why do baryon nuclear modification functions behave so differently compared to mesons?**

- ☐ **Look at the pt spectra of of Ξ's. They are totally dominated by cluster contributions, well beyond 3 GeV (flow!!!).**

- ☐ **But concerning pions: even for central collisions, the normal contribution exceeds the cluster particles already at 1.5 GeV.**

- ☐ **So what we observe is flow!**