

7 June 2007

EPOS: Physics and Predictions

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EPOS Basics

EPOS Overview

Energy conserving quantum mechanical multiple scattering approach

based on

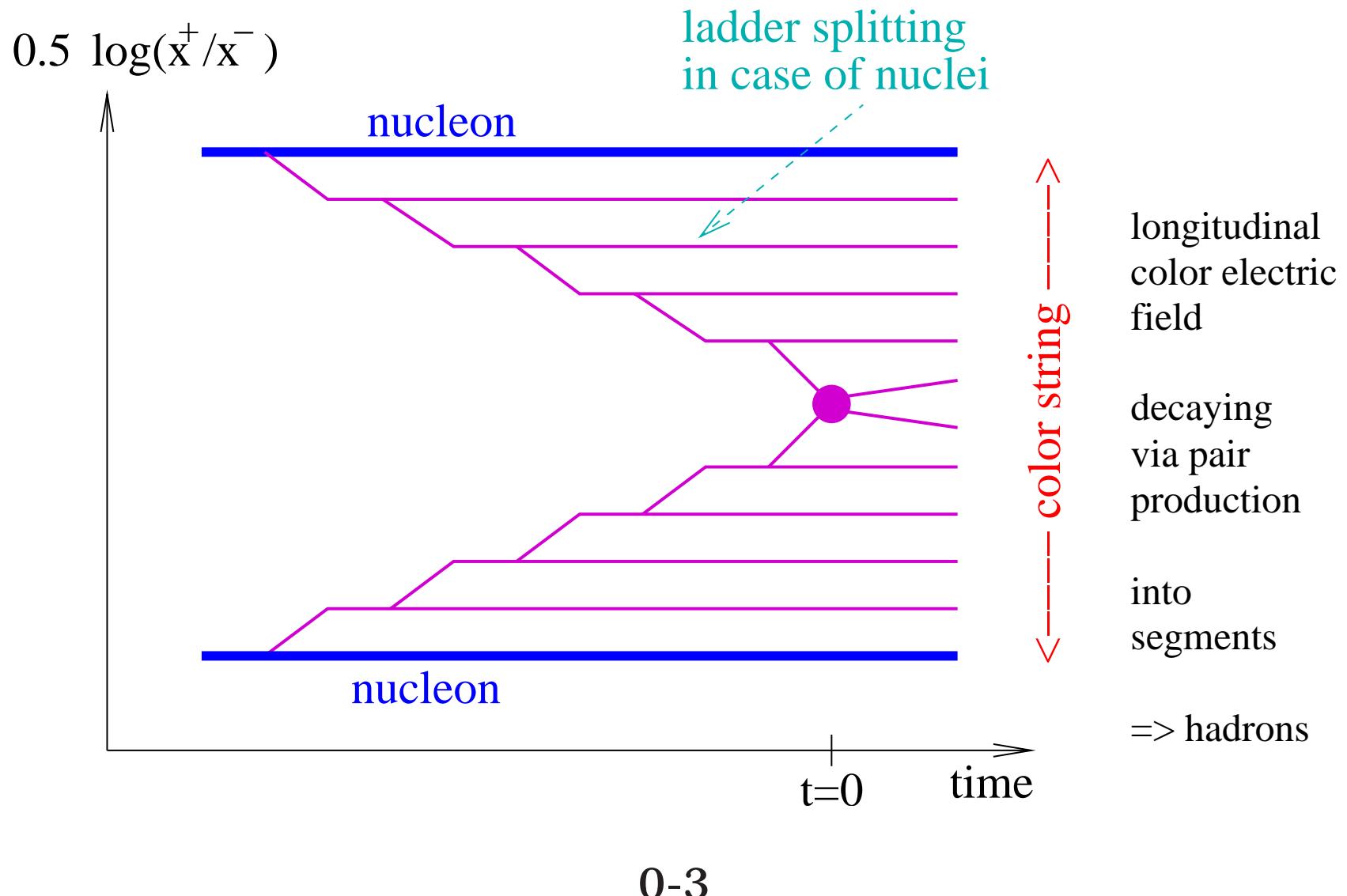
Partons, parton ladders, and strings

Off-shell remnants

Splitting of parton ladders

relevant for high parton densities

EPOS is a parton model, with many binary parton-parton interactions, each one creating a parton ladder.



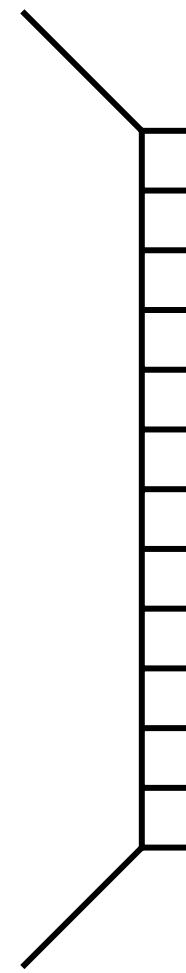
Nice feature about this
“parton ladder = field = string” interpretation:

- One may easily **extrapolate from real hard processes¹ to purely soft ones.**
- **Soft processes** represent simply the limit of zero hard gluons; there is only a purely longitudinal color field.

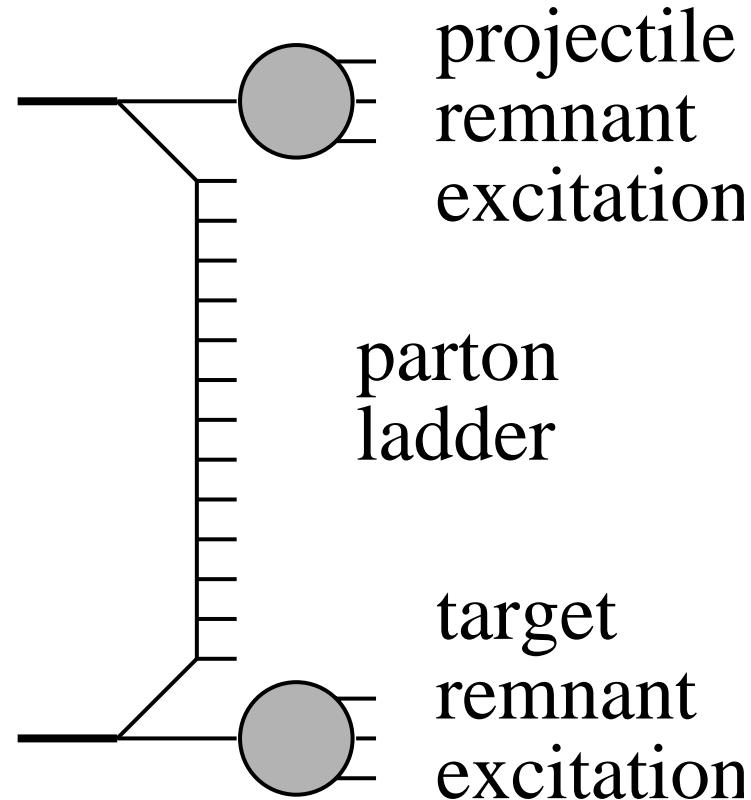
¹with many perturbative gluons

Symbol representing
a parton ladder

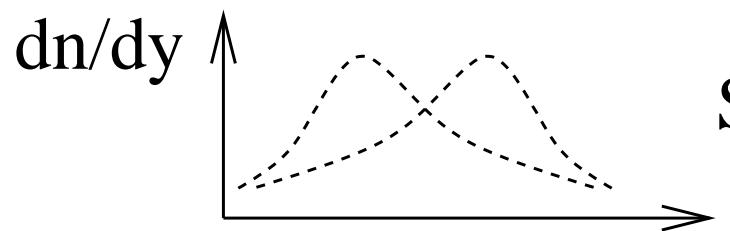
including soft part !



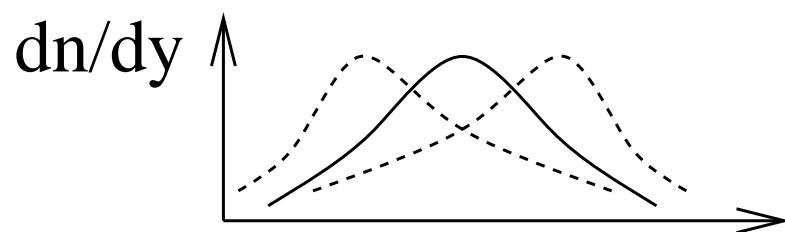
The **complete picture**, including **remnants**.



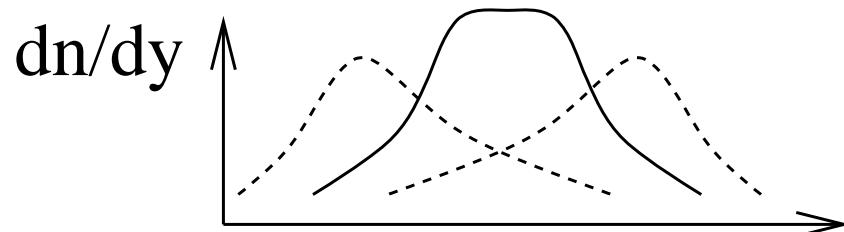
The remnants are an important source of particle production at RHIC energies



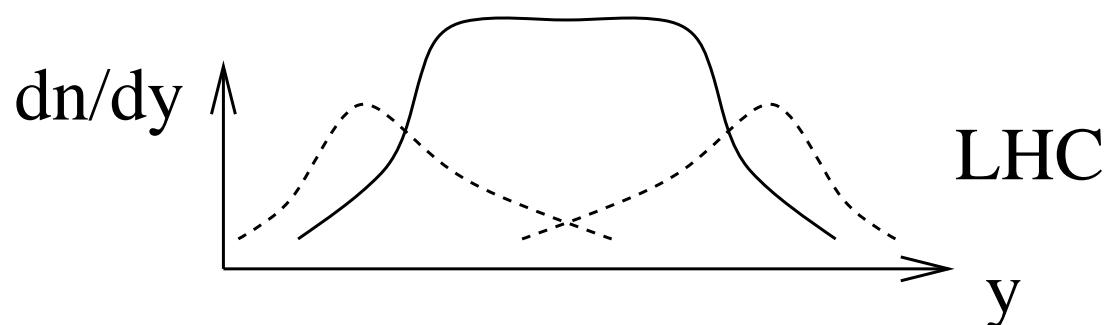
SPS low



SPS high



RHIC



LHC

Inner contributions,
from the parton ladder
(full lines),

and “outer” contribu-
tions, from the rem-
nants (dashed lines),

to the rapidity distri-
bution of hadrons.

(Artists view)

Multiple scattering

Above $\sqrt{s} = 50$ GeV:

Jet cross section $\sigma_{\text{jet}} = \int dt d\sigma_{\text{jet}}/dt > \sigma_{\text{tot}}$

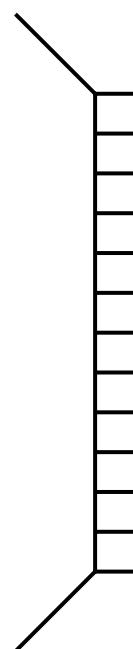
=> **multiple scattering !!**

(several elementary parton-parton scatterings
happening in parallel)²

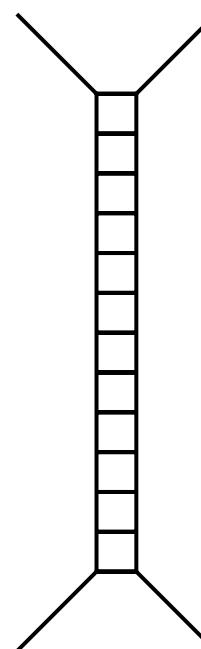
²Event generators like PYTHIA are interested in inclusive cross section =>
don't care much about MS

Consistent quantum mechanical formulation of multiple scattering:

In addition to **open** parton ladders, also **closed** ones are needed, representing elastic scattering (\Rightarrow optical theorem).



open
parton
ladder



closed
parton
ladder

Example

$$\sigma_{\text{inel}}^{\text{pp}} \sim \left| \begin{array}{c} \text{Diagram 1} \\ + \\ \text{Diagram 2} \\ + \dots \end{array} \right|^2$$

The equation shows the cross-section for proton-proton inelastic scattering. It is represented as a sum of diagrams enclosed in vertical brackets, followed by a square symbol indicating the magnitude squared.

Diagram 1: A single vertical line with a diagonal cut through it, representing a single interaction vertex.

Diagram 2: A more complex diagram showing multiple vertices connected by horizontal and vertical lines, representing a more complex interaction process.

- many interference terms
- complicated when you care about energy sharing
- really complicated for AA (Markov chain techniques)

Our consistent **multiple scattering approach** allows

- to compute **partial cross sections** (for example the one for double scattering = two ladders in pp scattering, with some momentum sharing $x_1^+, x_1^-, \vec{p}_{t1}, x_2^+, x_2^-, \vec{p}_{t2}$)
- and to generate the corresponding configurations

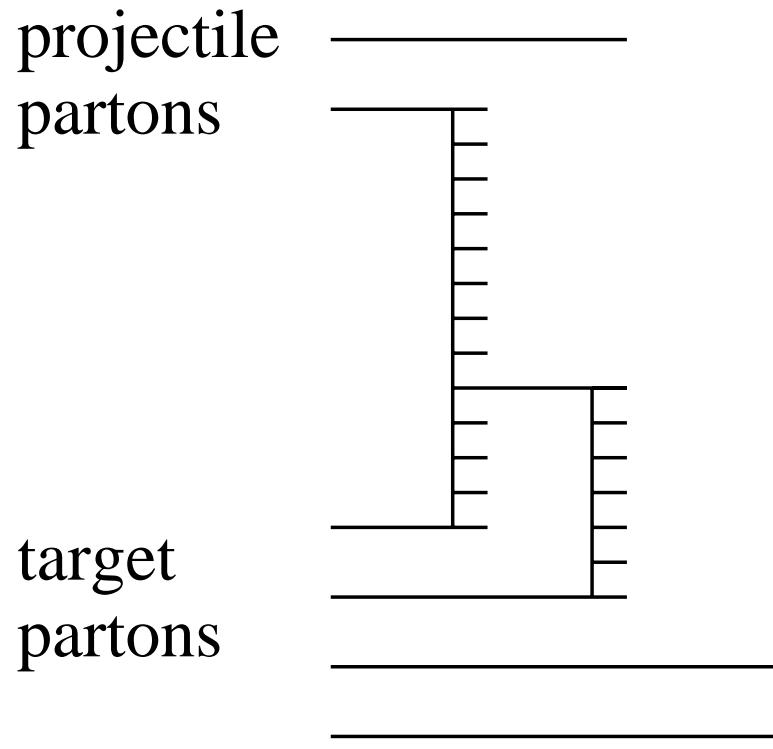
- For a given configuration (corresponding to a partial cross section), we **generate the partons** based on the same formulas as the cross sections themselves.
- Chaines of partons (from a ladder) are mapped to **kinky strings** (parton \leftrightarrow kink)
- Particle production via quark **pair production**

Splitting of parton ladders

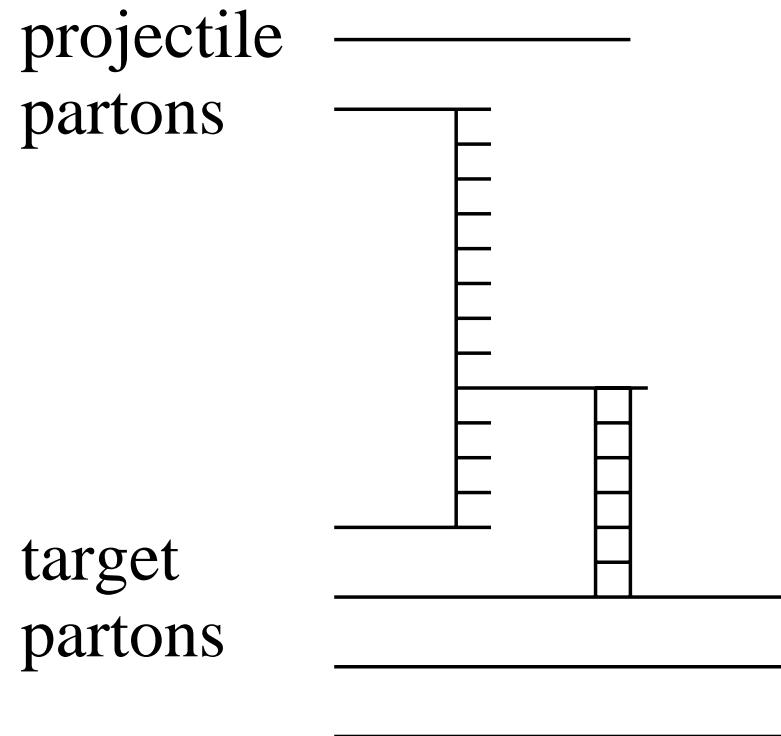
When big nuclei are involved:

- Large parton densities
- “Non-linear effects” => complications ...

A ladder parton may interact with a second target parton (splitting)



collective hadronization
(like string fusion)



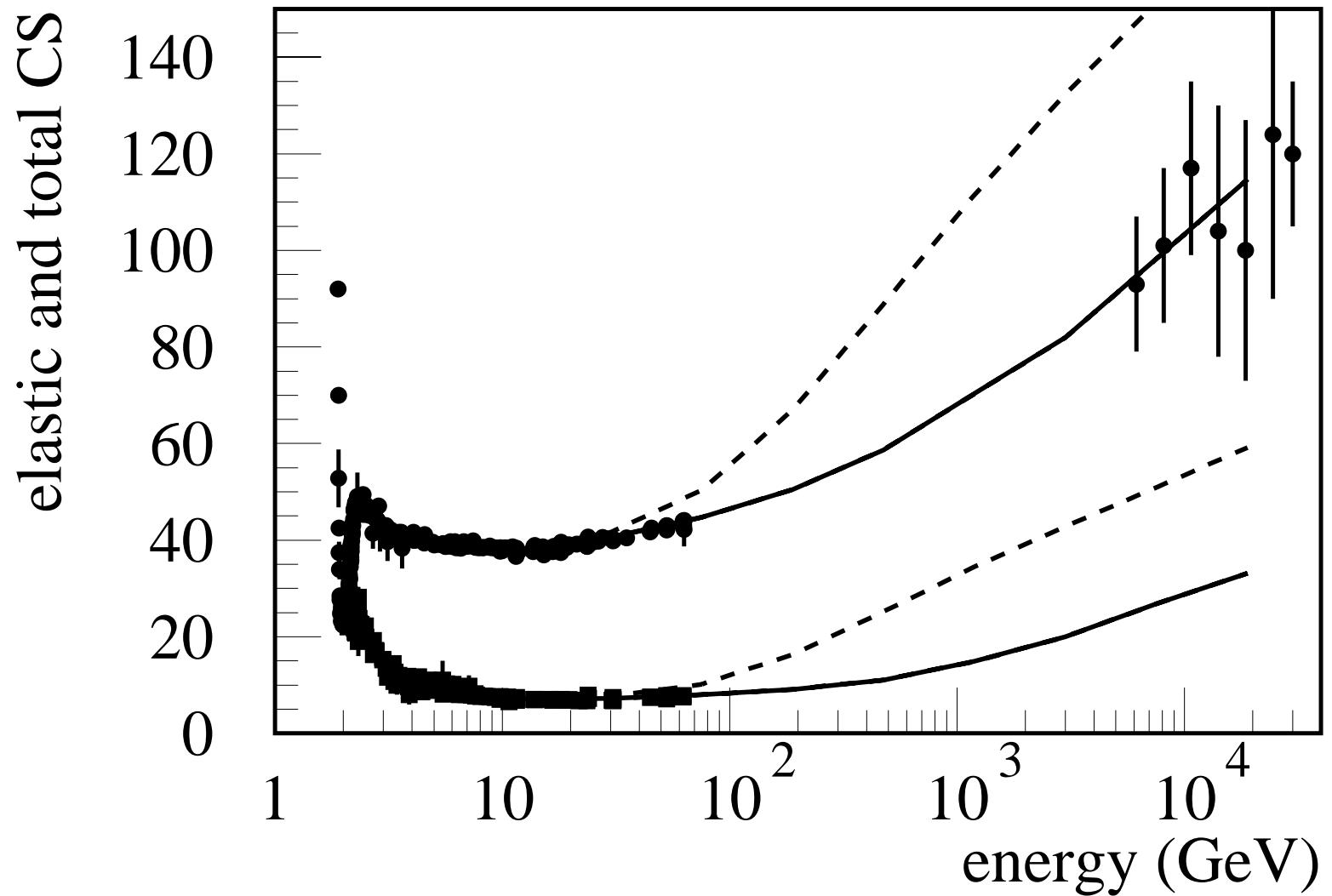
Screening (reduces
small x partons)

Realization of ladder splitting effects

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 the number of partons available for making additional legs.

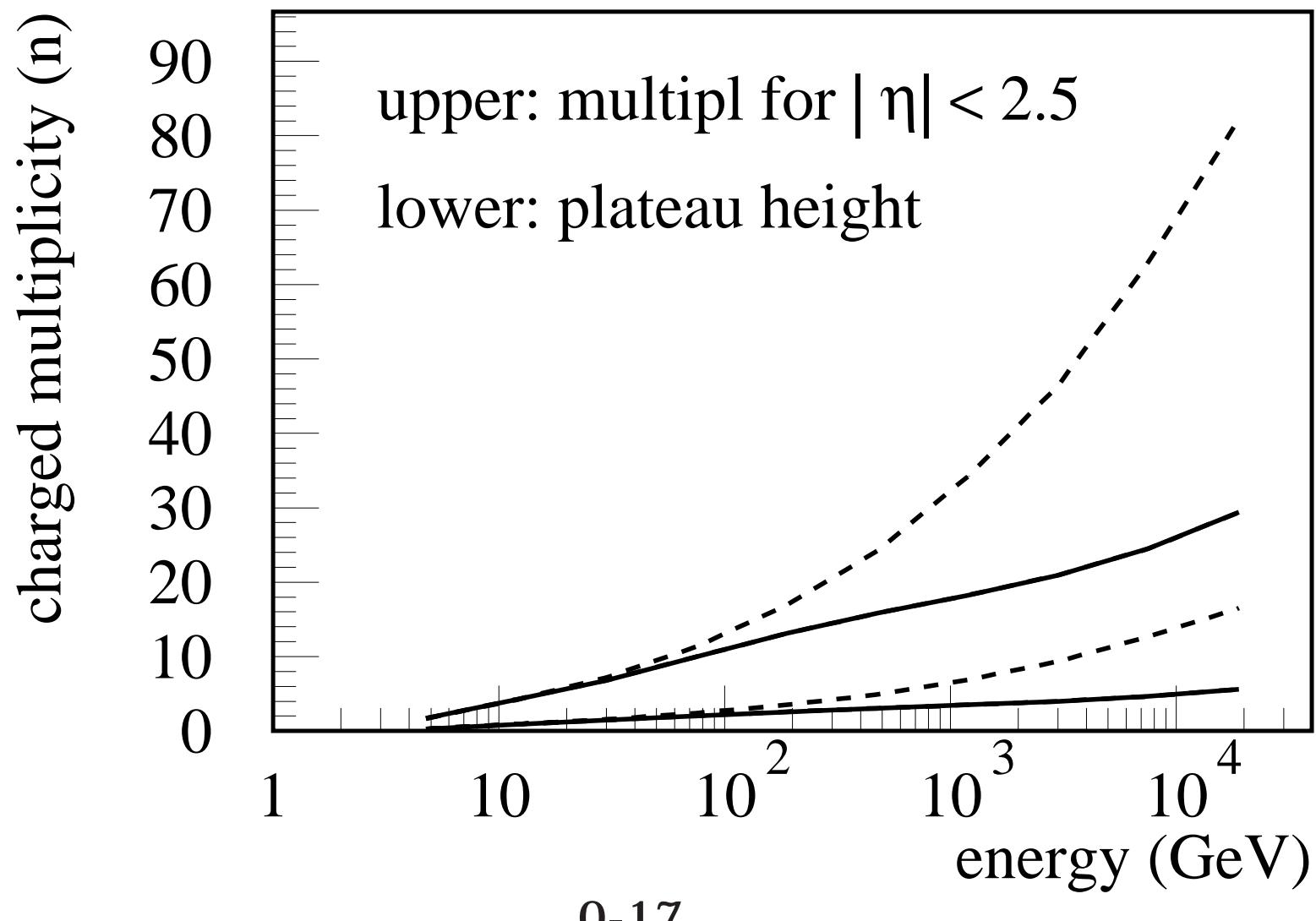
Cross sections in pp grow much too fast without ladder splitting



$$\tilde{\sigma}_{\text{cut}} = 1 - \Phi_2(s, b, 1, 1), \quad \tilde{\sigma}_0 = \Phi_2(s, b, 1, 1) - 2\Phi_1(s, b, 1, 1) + 1$$

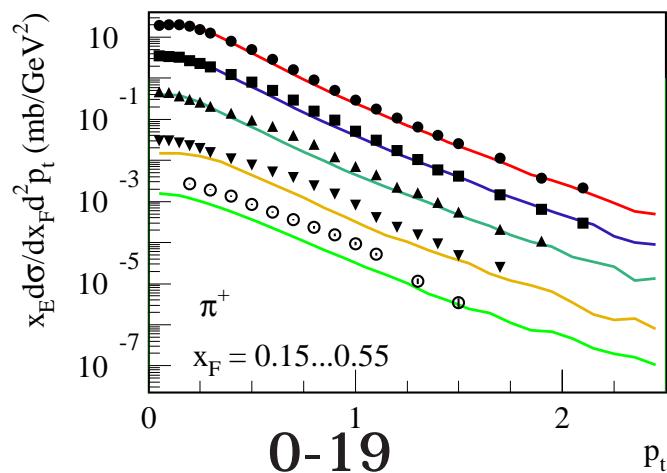
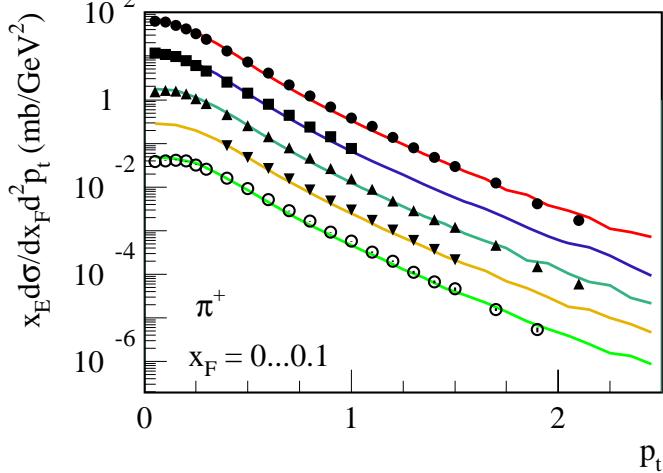
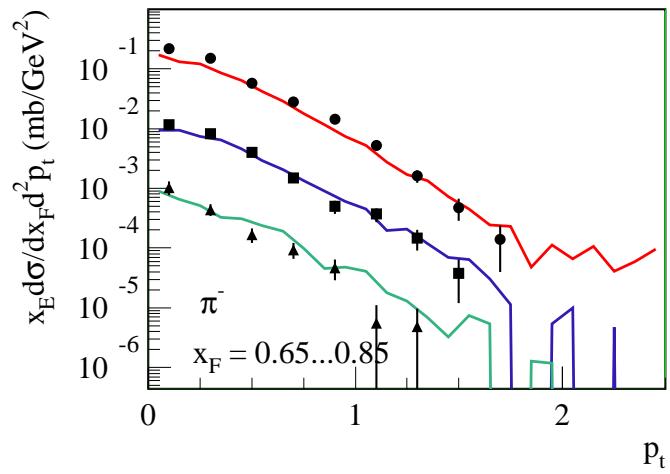
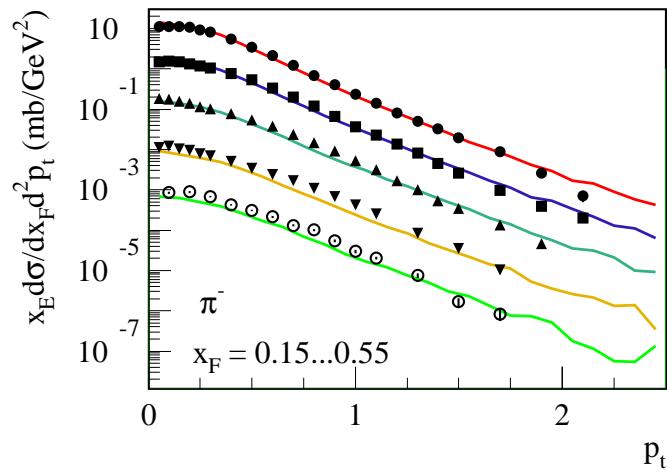
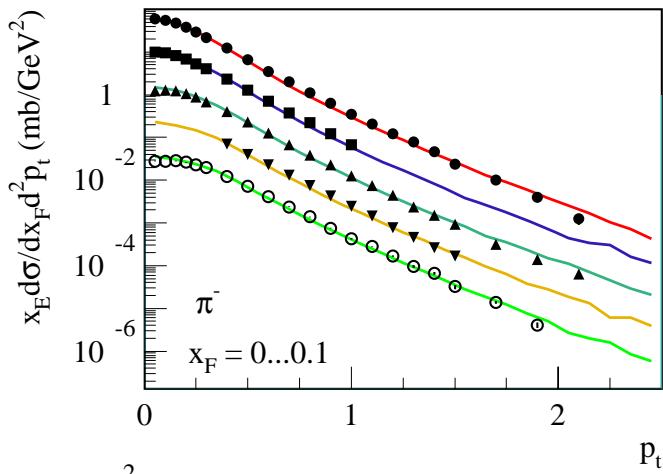
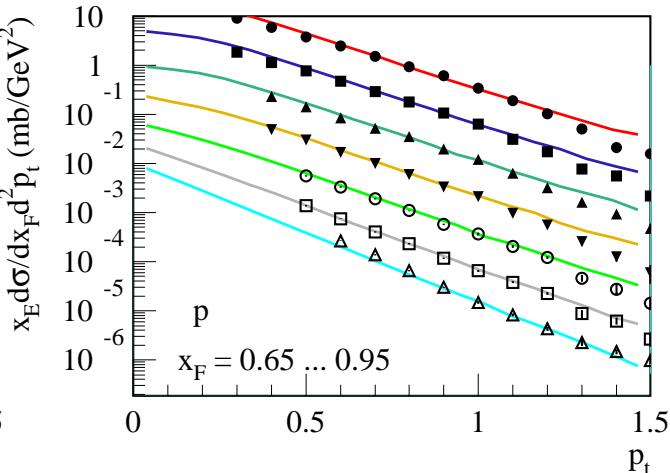
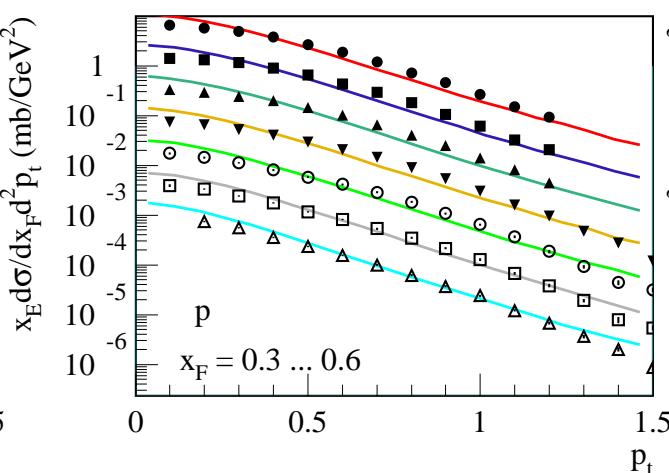
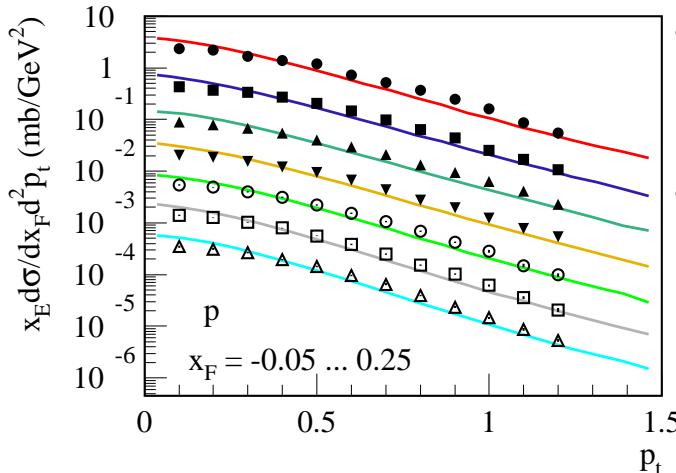
Multiplicities in pp

grow much too fast without ladder splitting



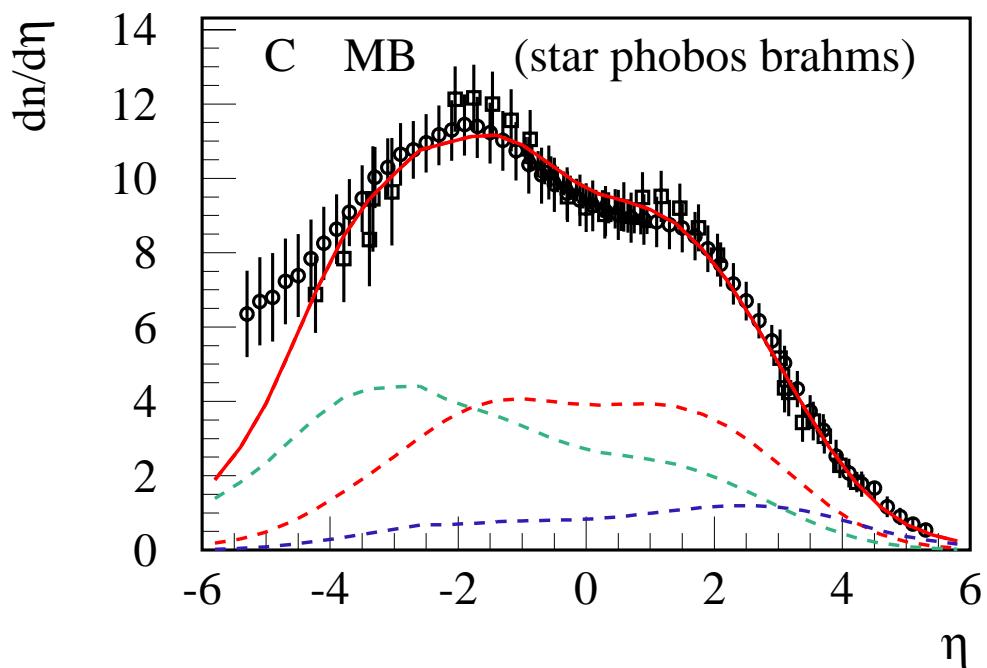
**Tests:
comparing hundreds of
spectra at SPS and RHIC
energies**

pT spectra at given xF in pp@SPS

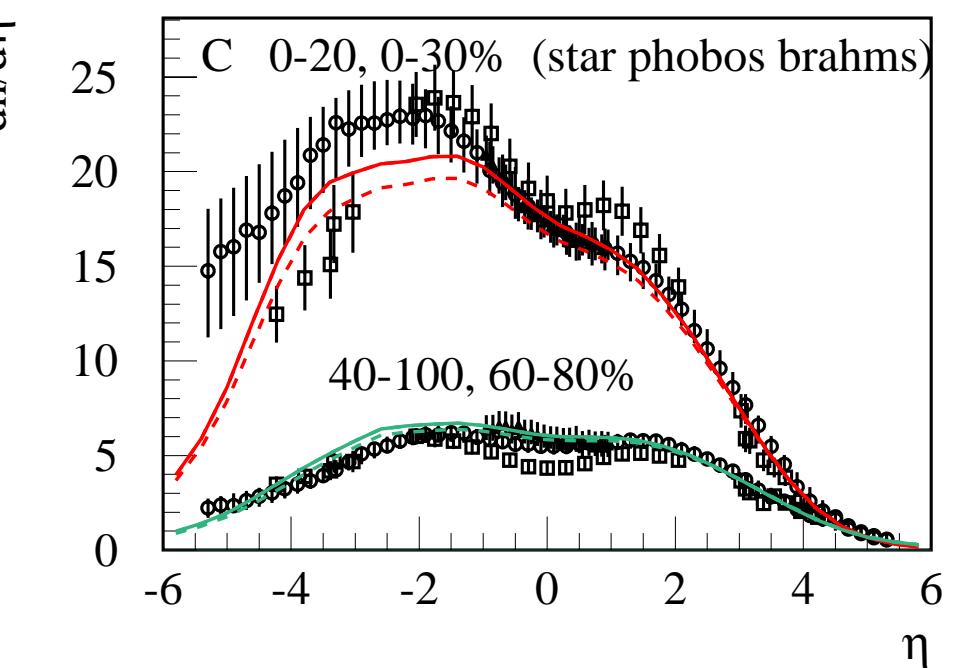


dAu@RHIC: Rapidity distributions of charged particles in minimum bias

different centralities

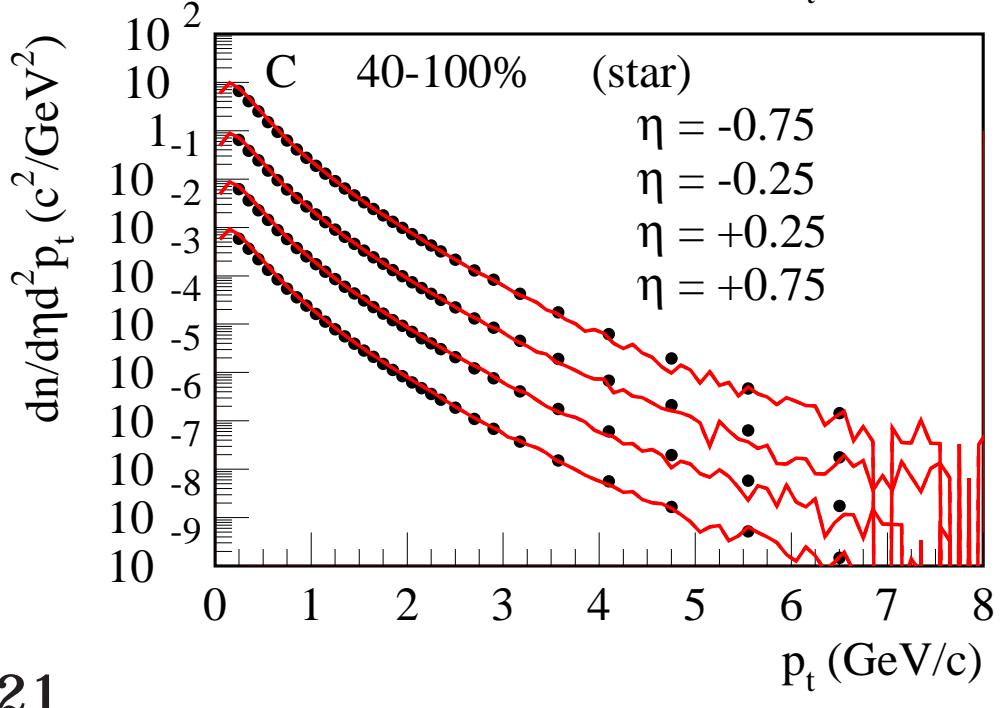
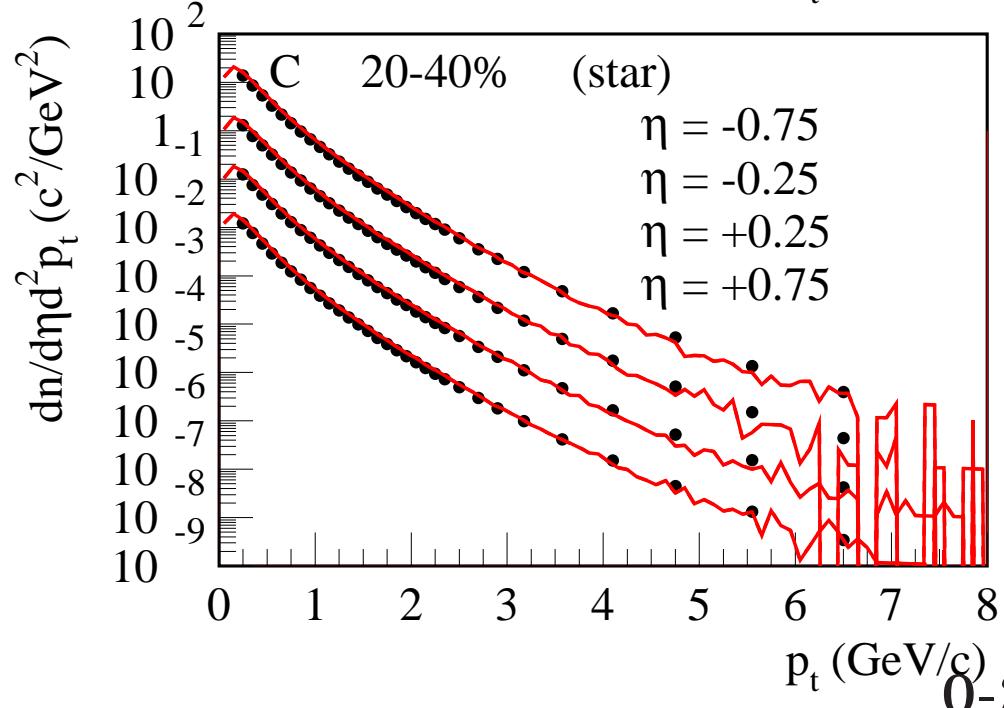
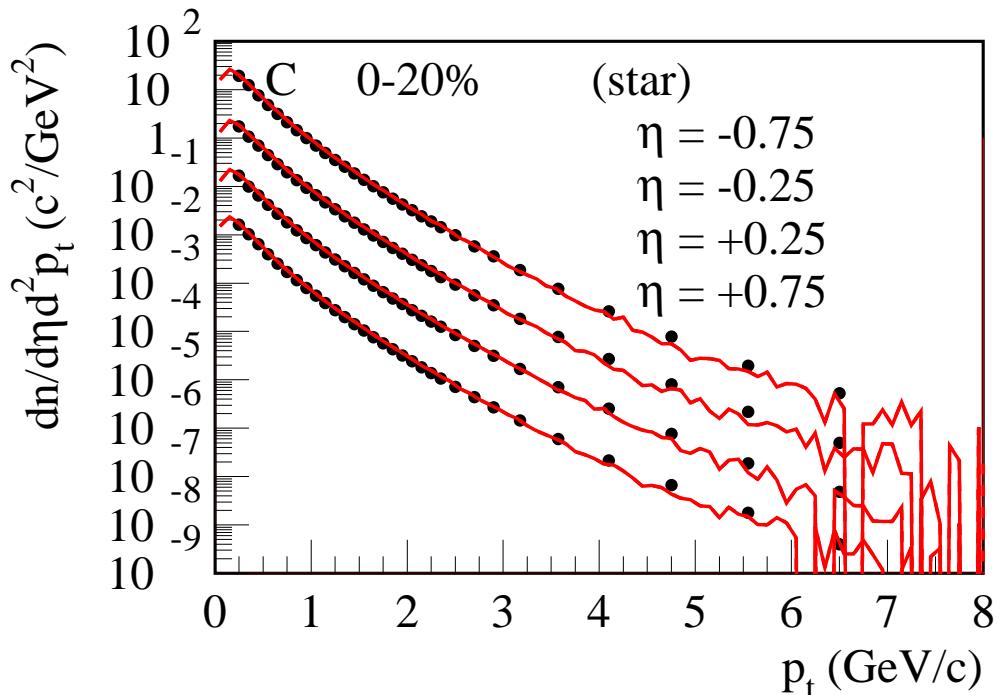
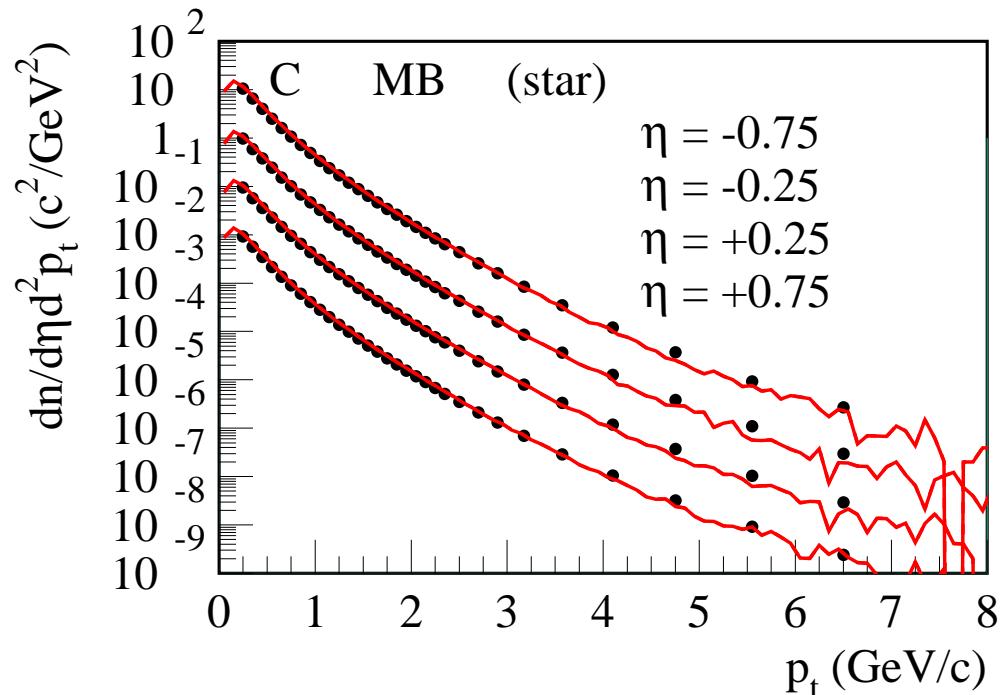


Very broad remnant distributions!



0-20

pt spectra of charged particles in dAu@RHIC



To see details, better plot ratios, so-called **nuclear modification factors**:

AA over pp:

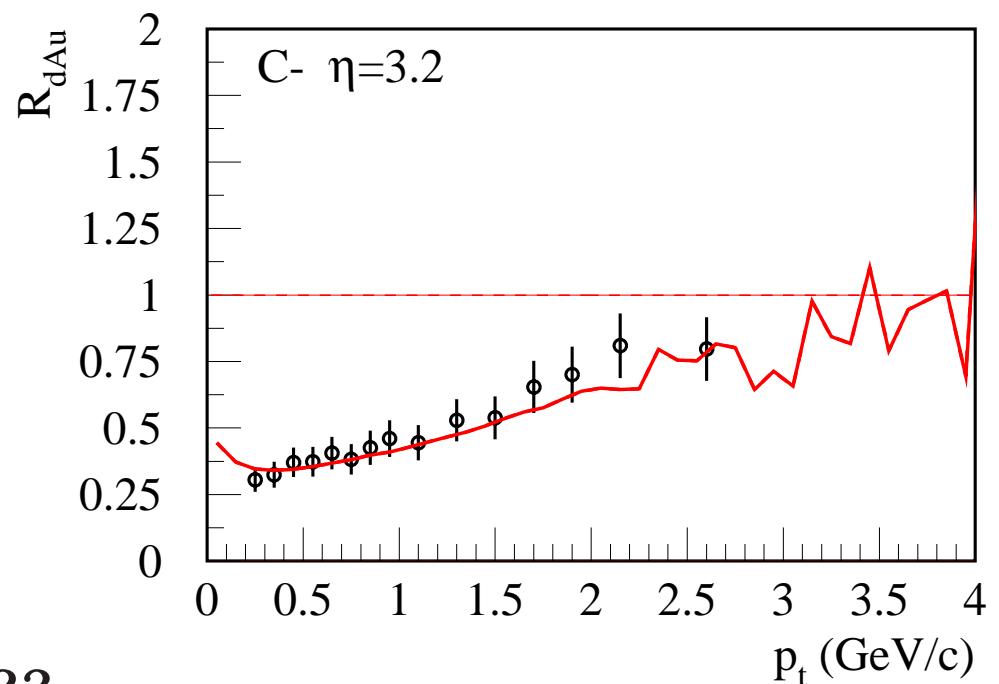
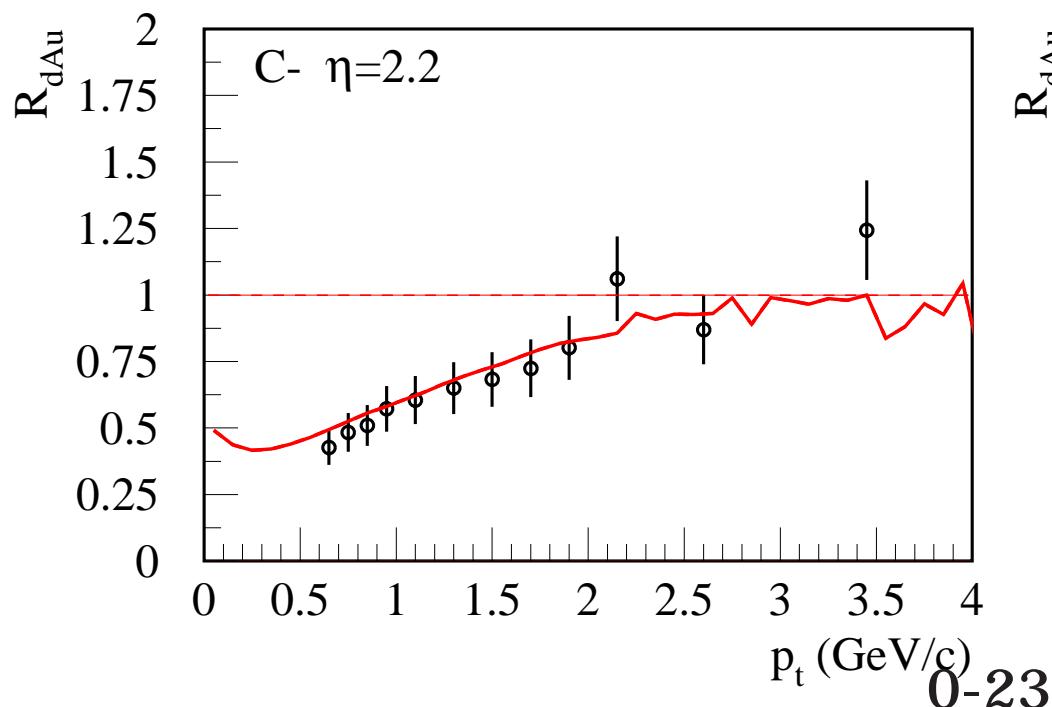
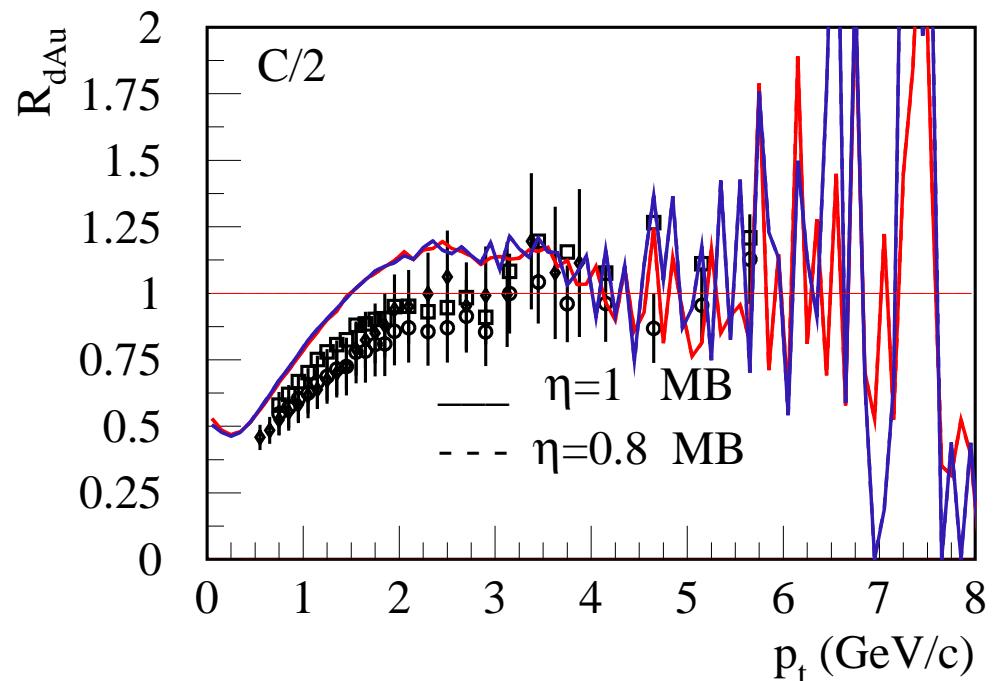
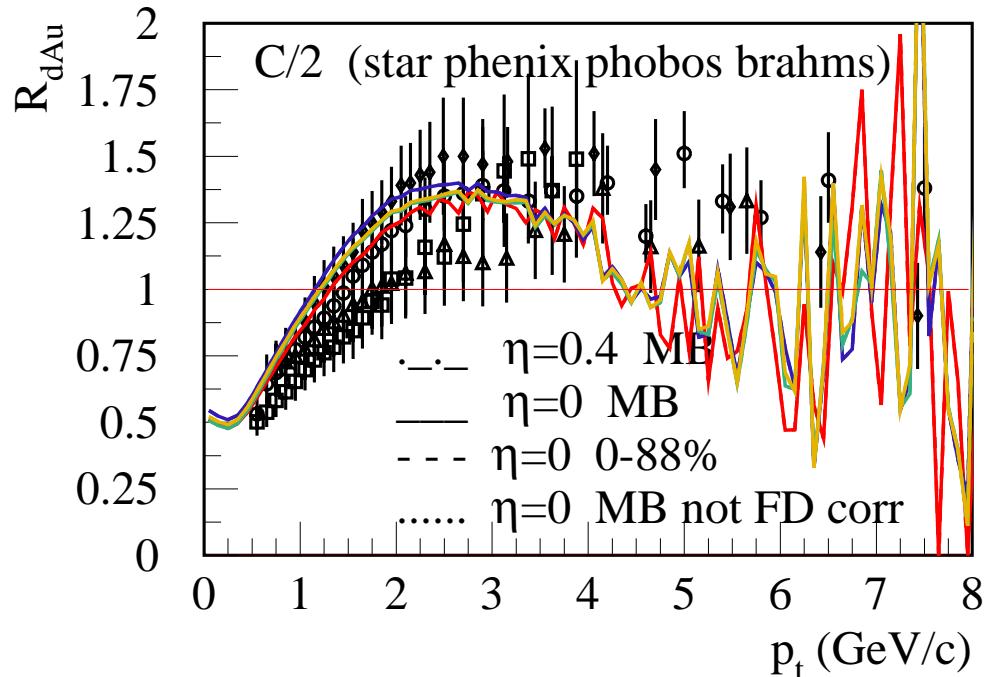
$$R_{AA} = \frac{1}{N_{\text{coll}}} \frac{dn^{AA}}{d^2 p_t dy} / \frac{dn^{pp}}{d^2 p_t dy}. \quad (1)$$

or central over peripheral:

$$R_{cp} = \frac{1}{N_{\text{coll}}^{\text{central}}} \frac{dn^{\text{central}}}{d^2 p_t dy} / \frac{1}{N_{\text{coll}}^{\text{peripheral}}} \frac{dn^{\text{peripheral}}}{d^2 p_t dy}. \quad (2)$$

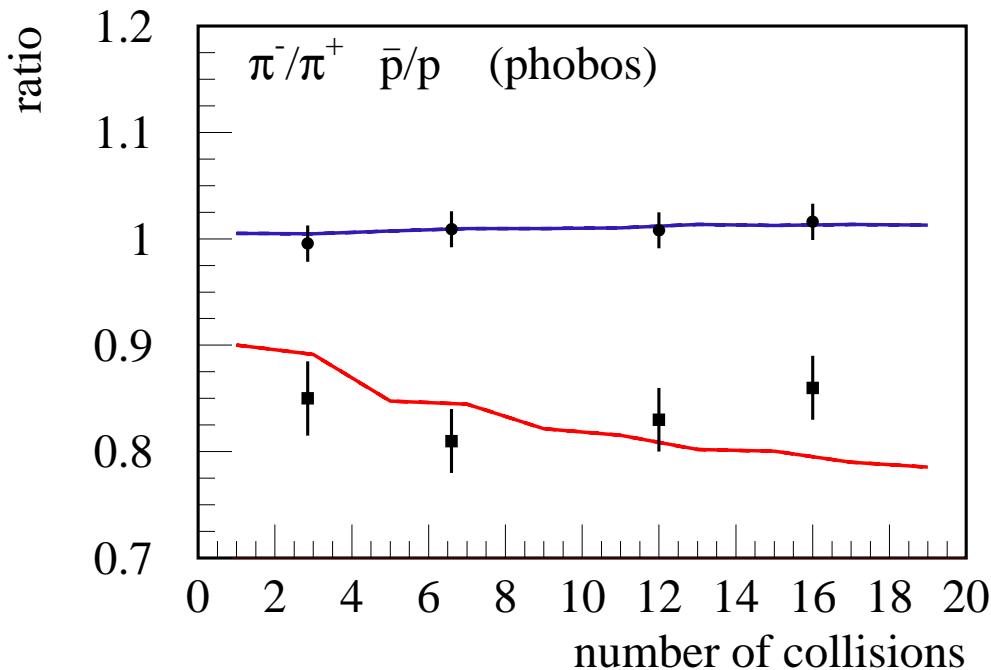
One naively expects $R = 1$ for large pt.

R_AA of charged particles in dAu@RHIC



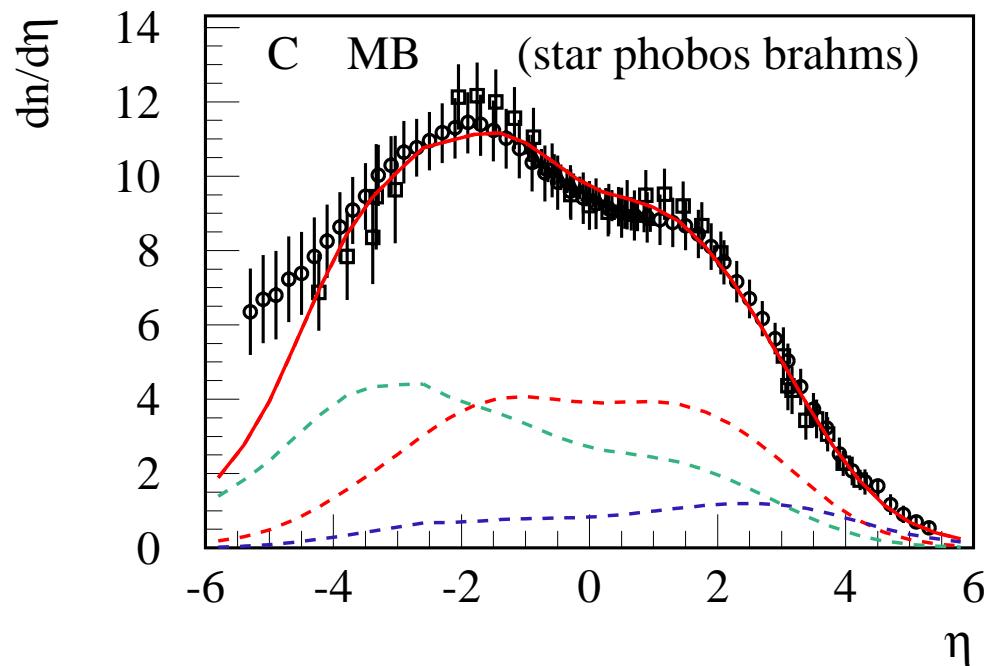
Ratios at $y = 0$ in dAu@RHIC

(related to stopping)



Little centrality dependence of \bar{p}/p

Rapidity distribution of charged ptls in dAu (already seen)



EPOS and Hydro for AA

=> collective behavior, flow

Core-corona separation

EPOS as usual



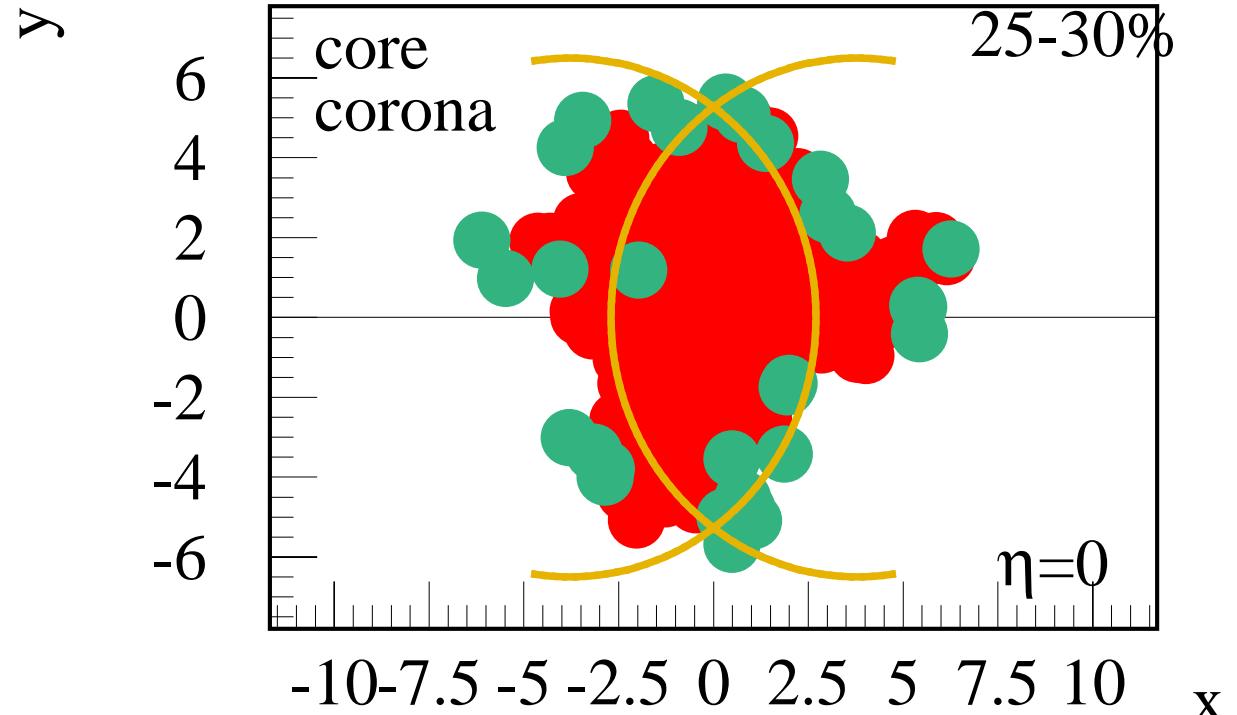
parton ladders



string segments

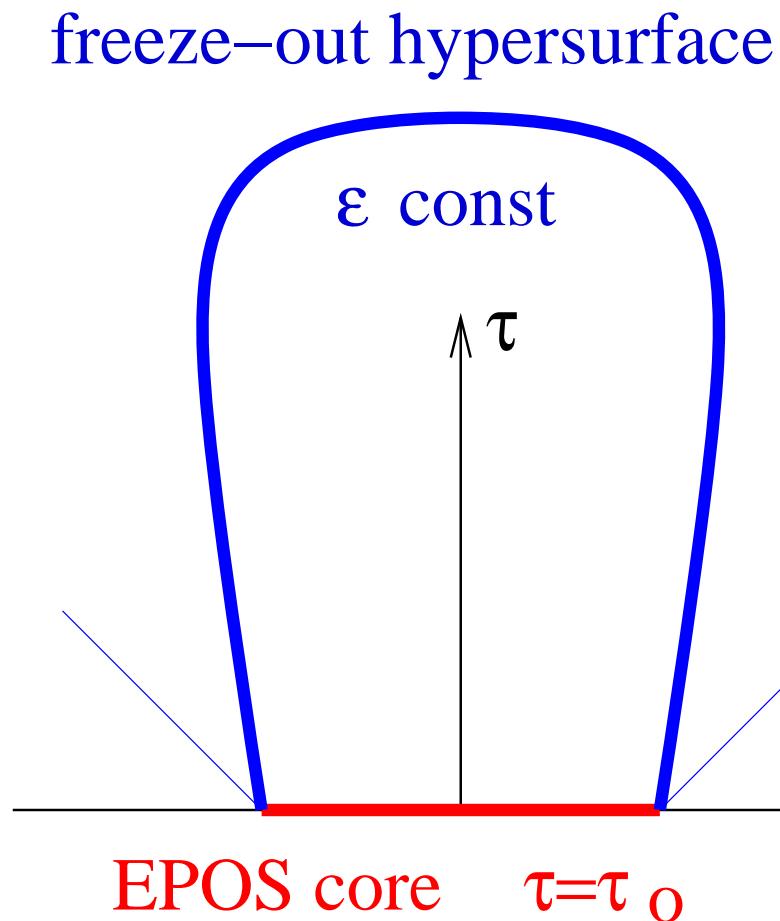


at $\tau = \tau_0$:
**core-corona
separation**



core: high density of string segments;
we include inwards moving corona segments

Concerning the
high-density core:



We need to link the
EPOS core at $\tau = \tau_0$
to the freeze-out
hypersurface

(having in mind a collective hydro-like expansion)

First option:

- Parameterization of the freeze-out properties**

Second option:

- Run hydro based on average EPOS initial conditions**
- Tabulate results** such that they can be used to treat the core evolution and hadronization (event by event).
- Compare the two procedures

In any case, the initial mass will be partly transformed into flow, characterized (at given η) by the **transverse rapidity**

$$y_{\text{FO}} = y_0(\tau) + y_2(\tau) \cos(2\varphi)$$

on the **FO hypersurface** given as

$$r_{\text{FO}} = r_0(\tau) + r_2(\tau) \cos(2\varphi).$$

What we need is the **FO rate**

$$\frac{dM}{d\eta d\varphi d\tau} = w_{\text{FO}} = w_0(\tau) + w_2 \cos(2\varphi)$$

All quantities depend on η .

An effective invariant mass M (in a given η range) is given as

$$M = \int w_{\text{FO}} d\tau d\varphi,$$

the energy is

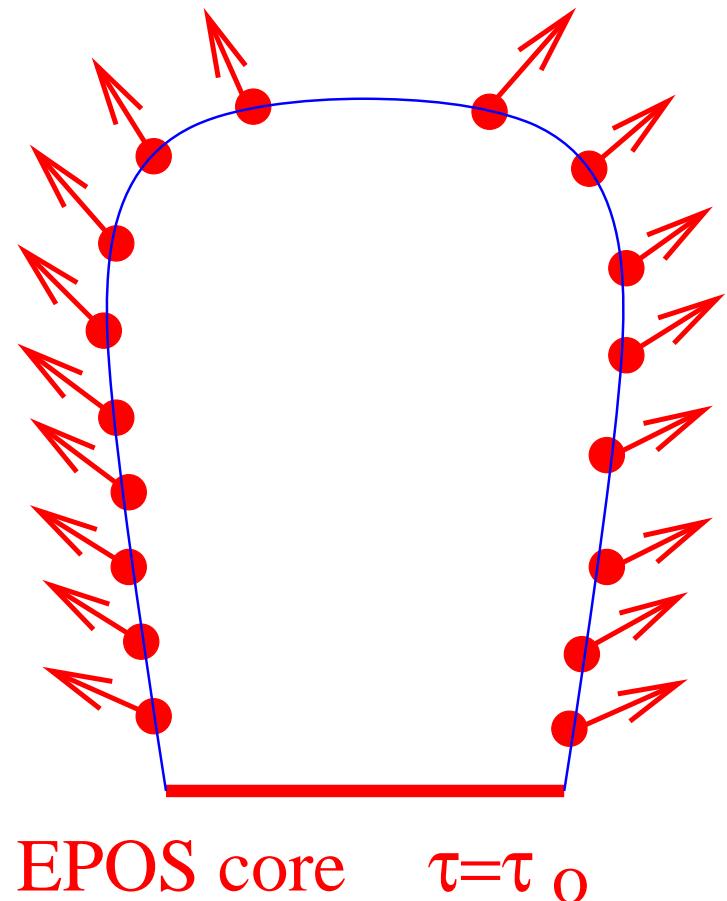
$$E = \int \cosh(y_{\text{FO}}) w_{\text{FO}} d\tau d\varphi,$$

which must be equal to the initial invariant mass M_0 at $\tau = \tau_0$.

Only M and not M_0 is available for particle production!

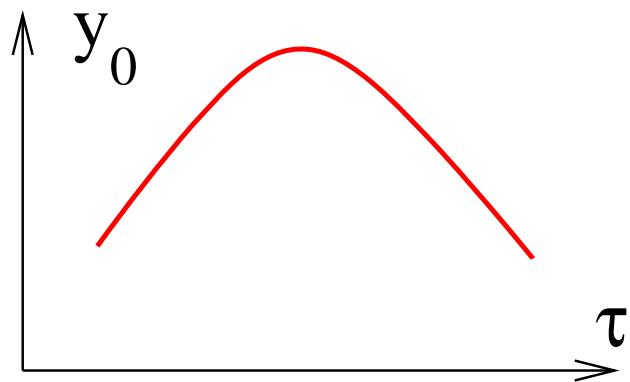
We suppose that the effective invariant mass

M decays according to covariant microcanonical phase space.



The particles adopt the flow according to the corresponding position on the FO hypersurface.

Changing FO hypersurface parameters



Useful to employ the **transverse rapidity** y_0 rather than τ to parameterize the FO hypersurface.

(two branches!)

We define

$$w_i(y_0) = \int w_i(\tau) \delta(y_0(\tau) - y) d\tau.$$

And we consider y_2 as well as r_0 , r_2 as functions of y_0 (and also τ).

Advantage:

investigate the different FO characteristics one after the other, looking at different observables.

- Particle spectra → we just need $w_0(y_0)$.
- Looking a elliptic flow → consider $w_2(y_0)$ and $y_2(y_0)$
- HBT → consider $\tau(y_0)$ as well as $r_0(y_0)$ and $r_2(y_0)$

Procedure

- After core-corona separation, determine the core Mass M_0 at $\tau = \tau_0$, and its net flavor.
- Get FO properties r_{FO} , y_{FO} , w_{FO} .
- Compute effective mass $M = M_0 f$ with
$$f = \int w_{\text{FO}} d\tau d\varphi / \int \cosh(y_{\text{FO}}) w_{\text{FO}} d\tau d\varphi.$$
- Decay the mass M according to micro-canonical phase space (conserving energy, momentum, flavor)

- For each particle, generate randomly a transverse flow rapidity y_0 according to $w_0(y_0)$, and an angle φ according to

$$w_0(y_0) + w_2(y_0) \cos(2\varphi)$$
- Boost the particle with $y_{\text{FO}} = y_0 + w_2(y_0) \cos(2\varphi)$
- Assign r , and τ to each particle as

$$r_{\text{FO}} = r_0(y_0) + r_2(y_0) \cos(2\varphi),$$

$$\tau = \tau(y_0).$$

First option: simply parameterize FO

We use ³

$$w_0(y_0) \propto \begin{cases} y_0 & \text{if } y_0 \leq y_{\max} \\ 0 & \text{otherwise} \end{cases},$$

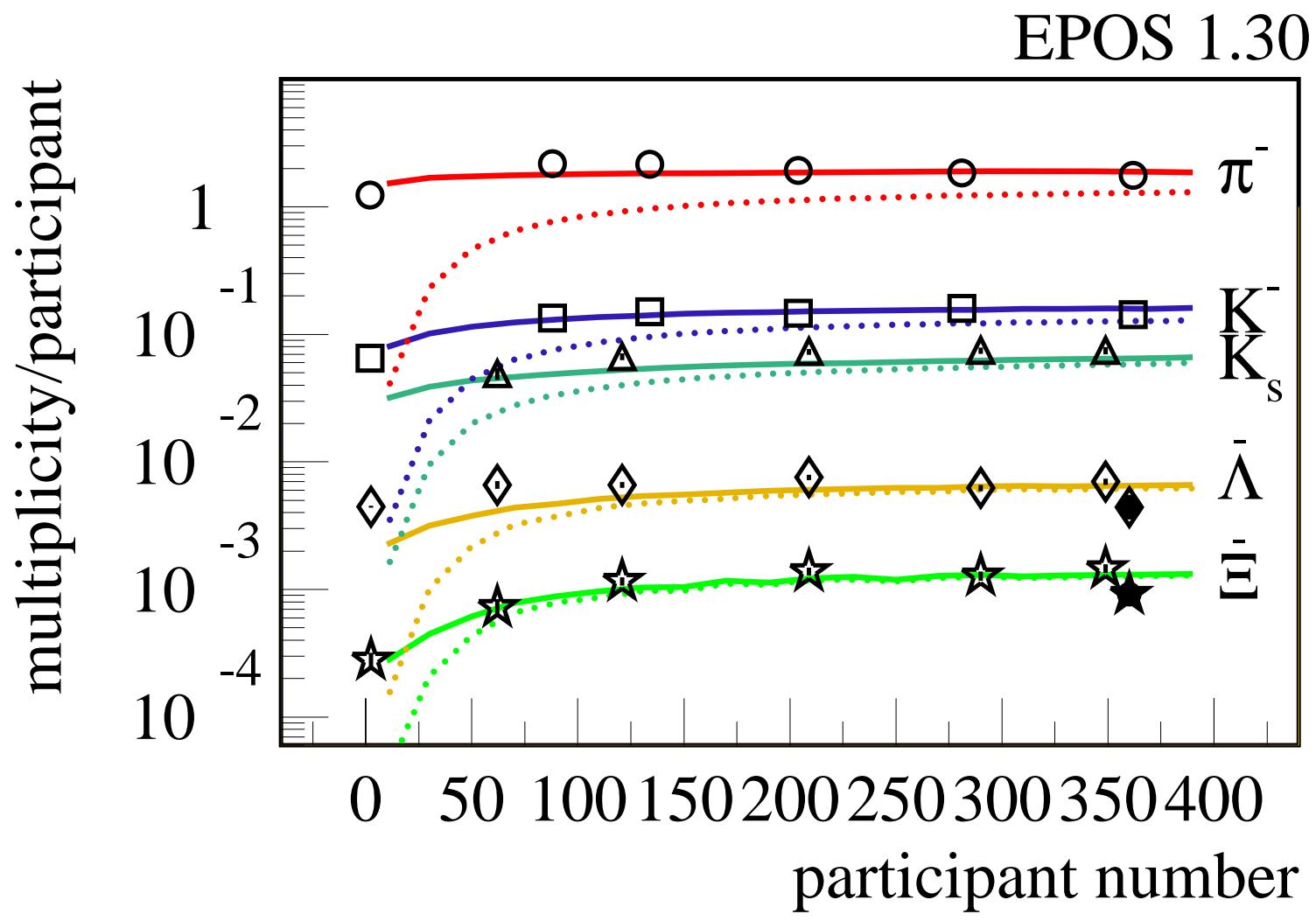
with y_{\max} equal to 0.75 for RHIC and 0.55 for SPS.

Works quite well for all RHIC and SPS pt spectra, all centralities, all particle species.

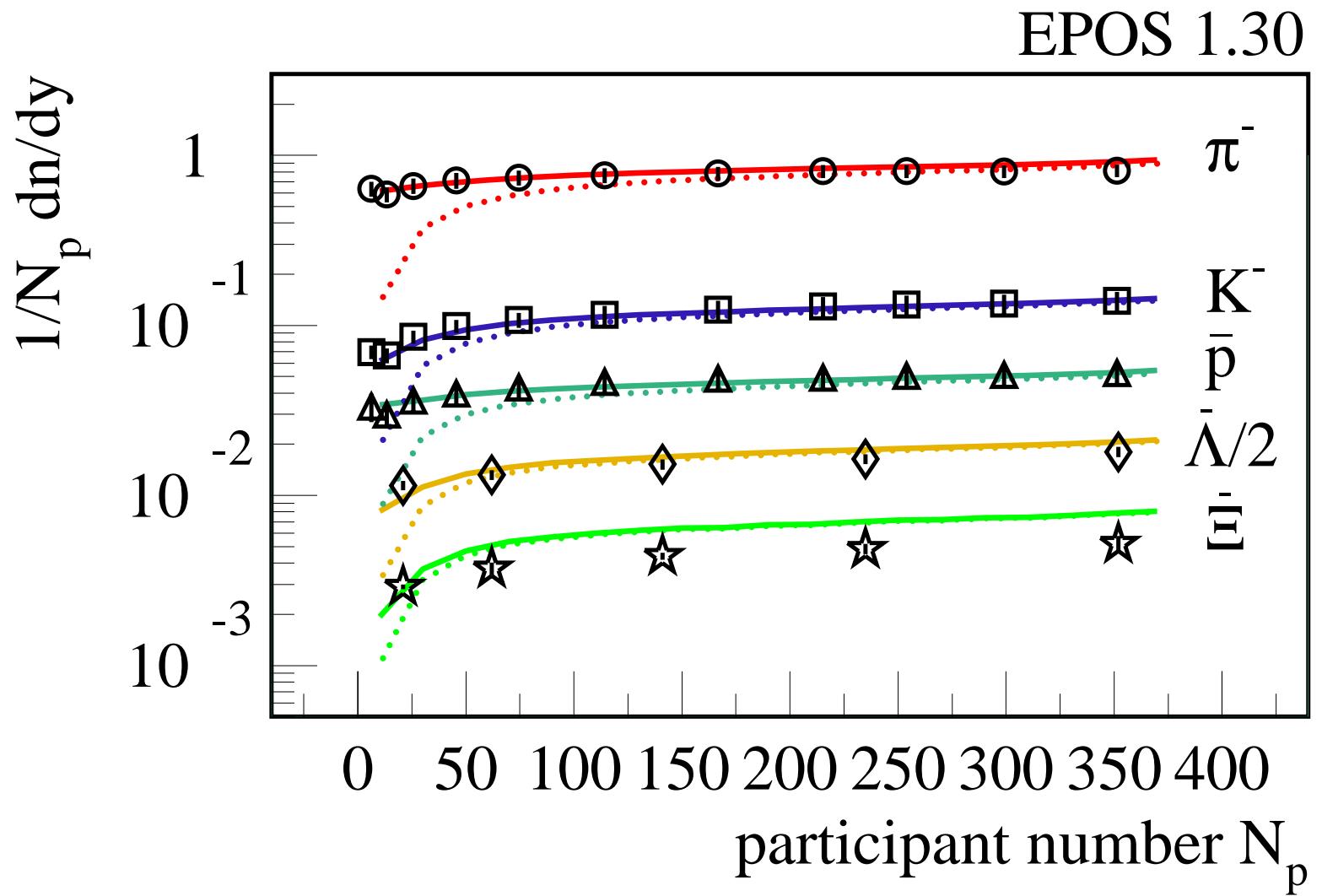
³compare blast wave fit

PbPb@SPS: Multipl/Npart vs Npart

grows faster for “rare” particles

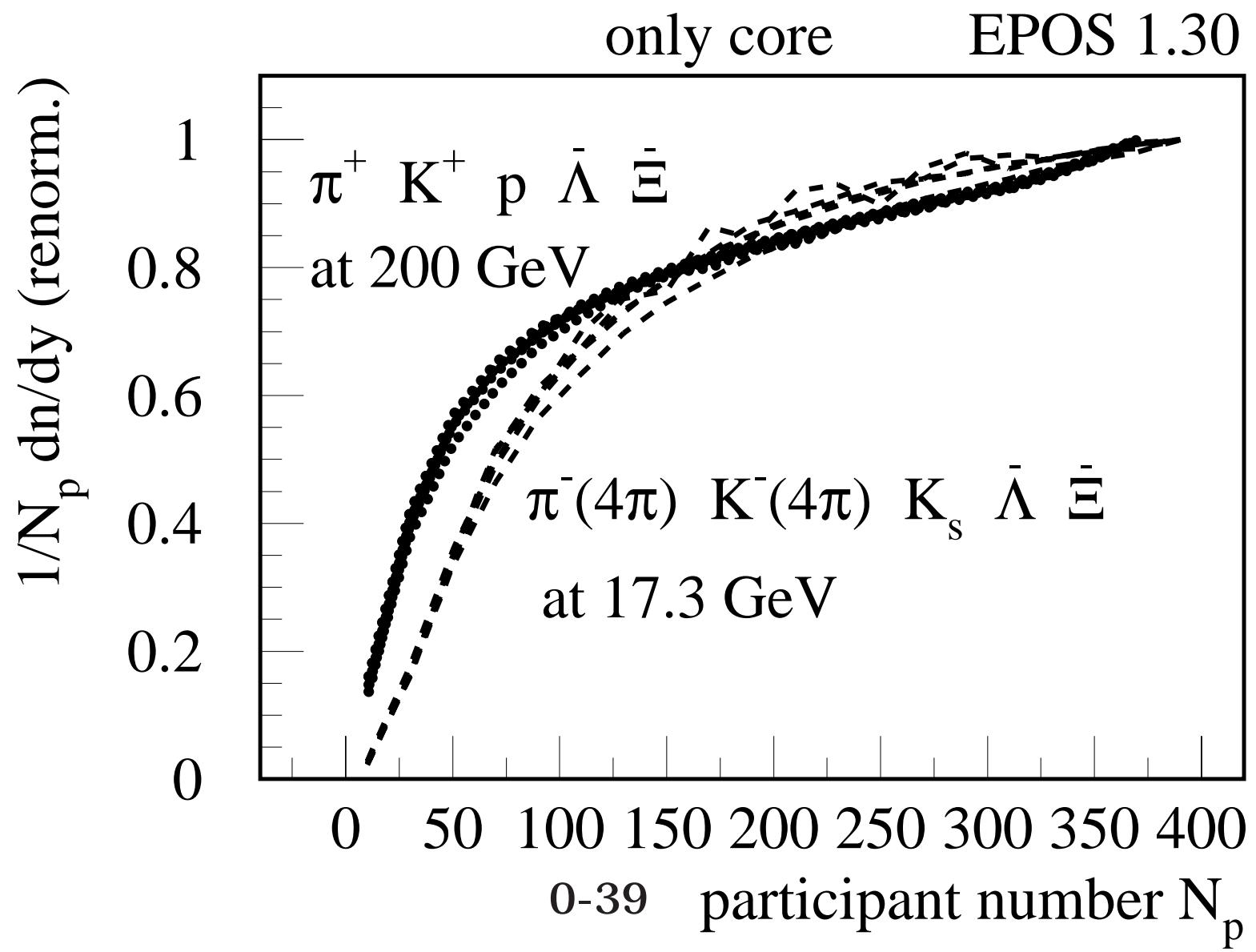


AuAu@RHIC: Multipl/Npart vs Npart grows faster for “rare” particles



Multipl/Npart vs Npart

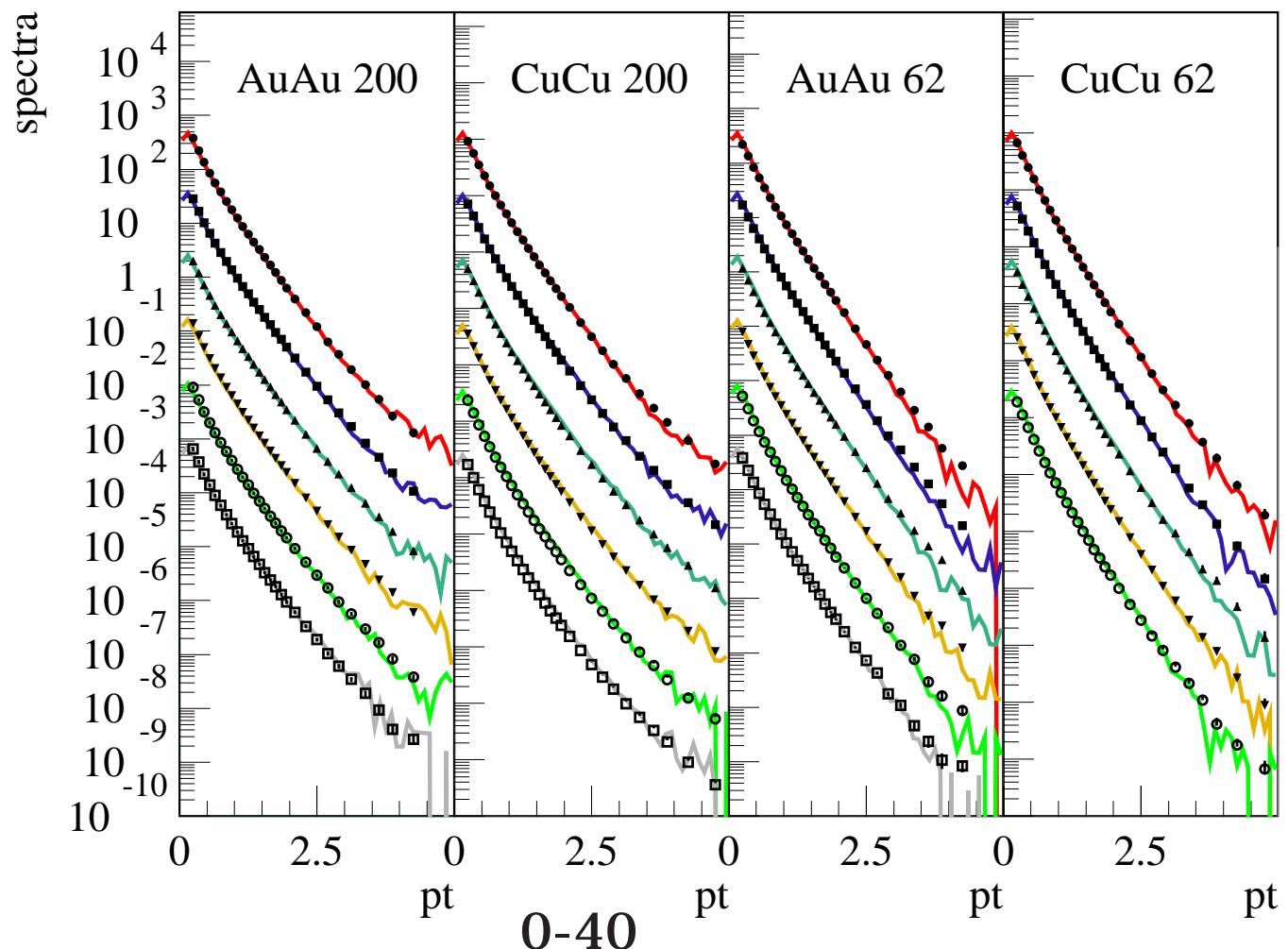
universal curves



AA@RHIC: pt spectra

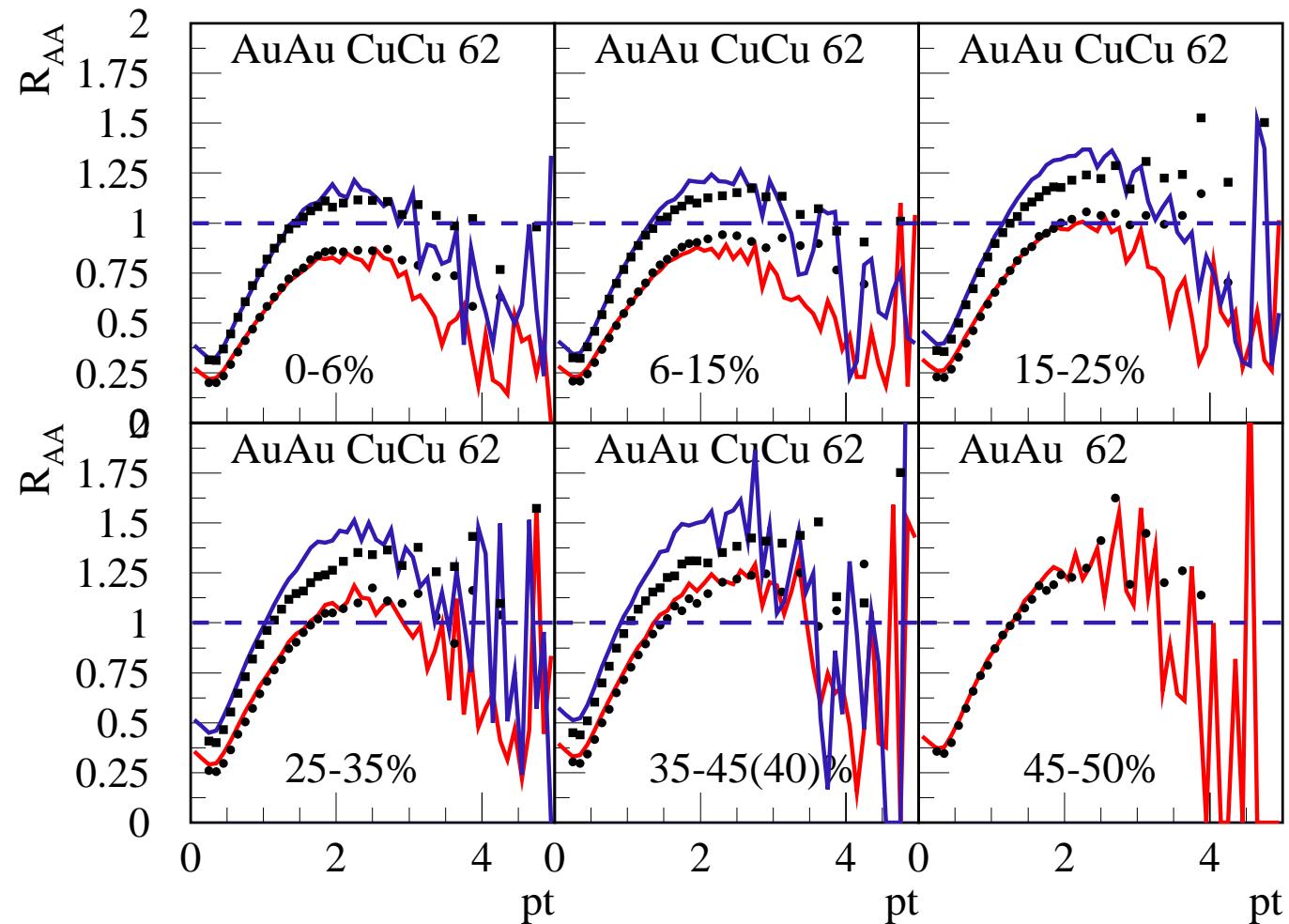
different energies,
(data=Phobos)

different nuclei



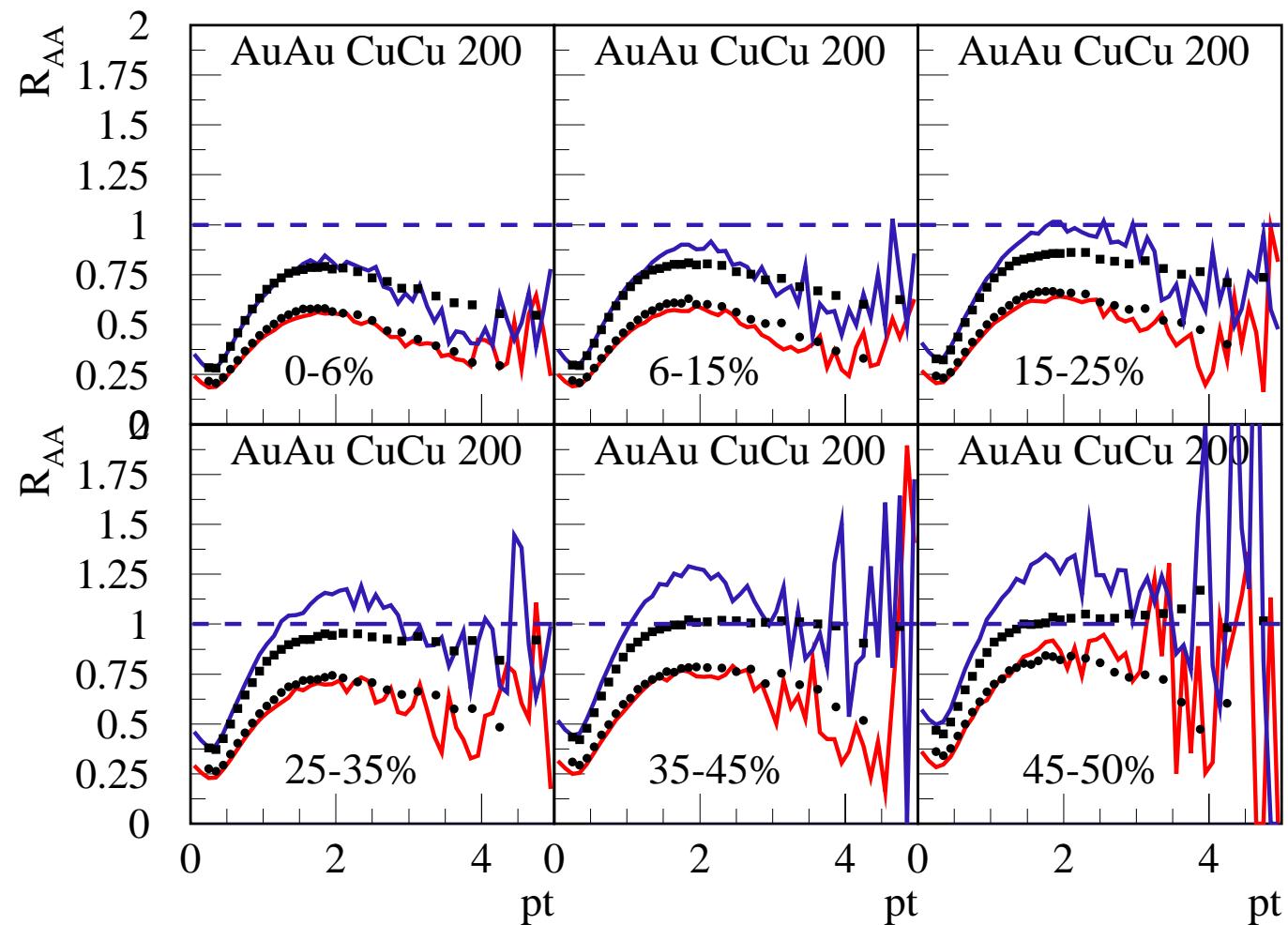
AA@RHIC: R_AA

62 GeV, different nuclei (data=Phobos)



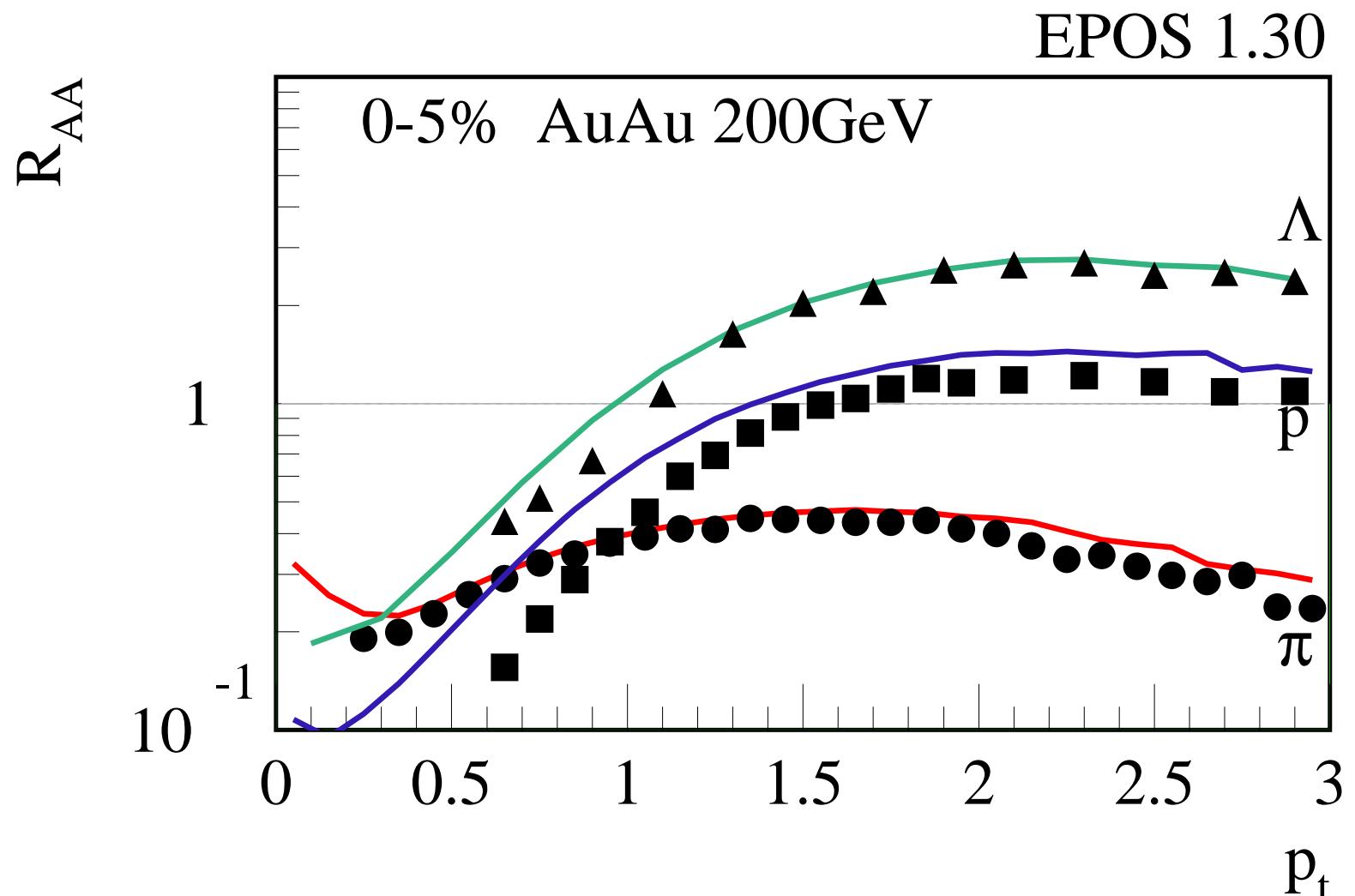
AA@RHIC: R_AA

200 GeV, different nuclei (data=Phobos)



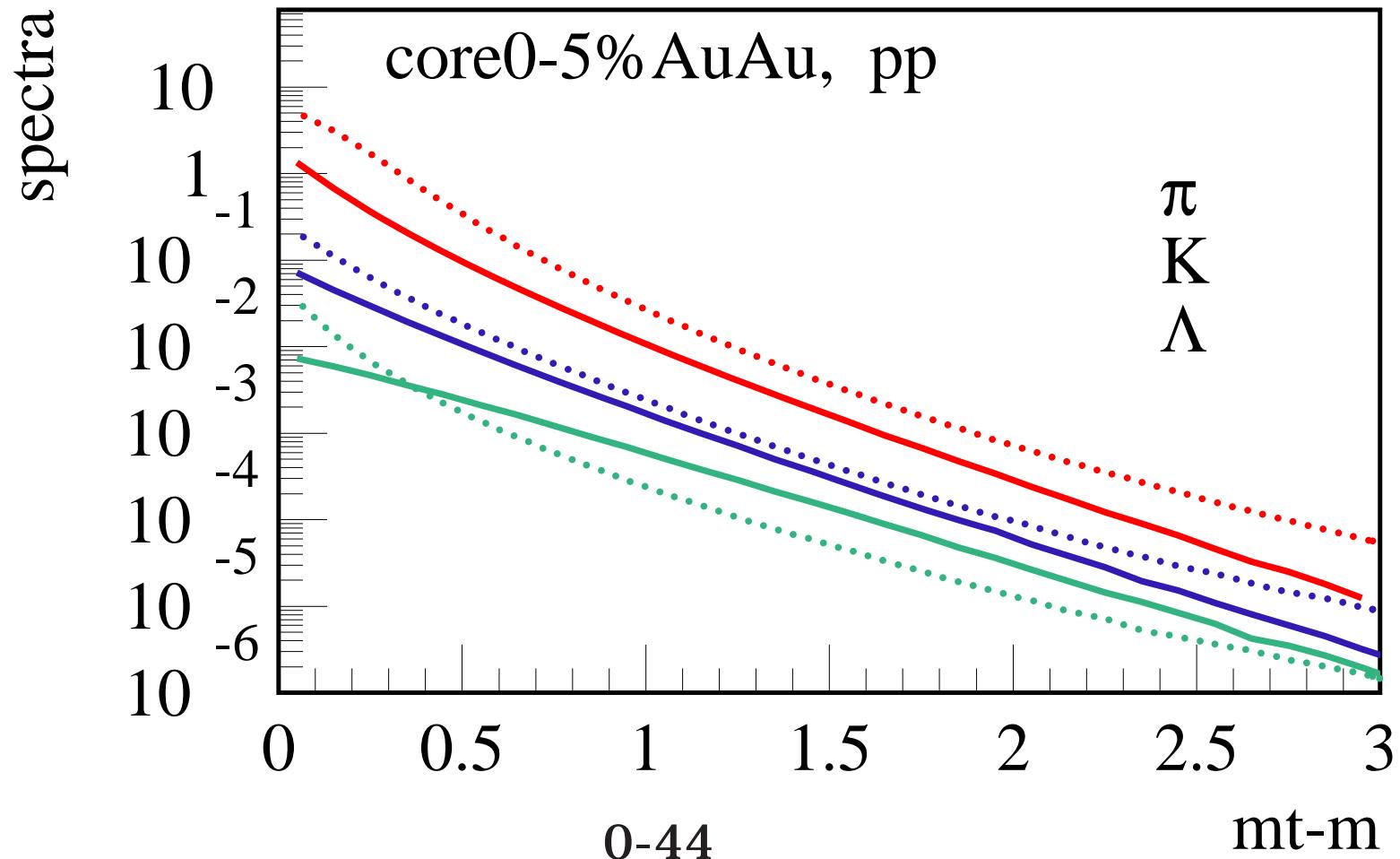
central AuAu@RHIC: R_AA

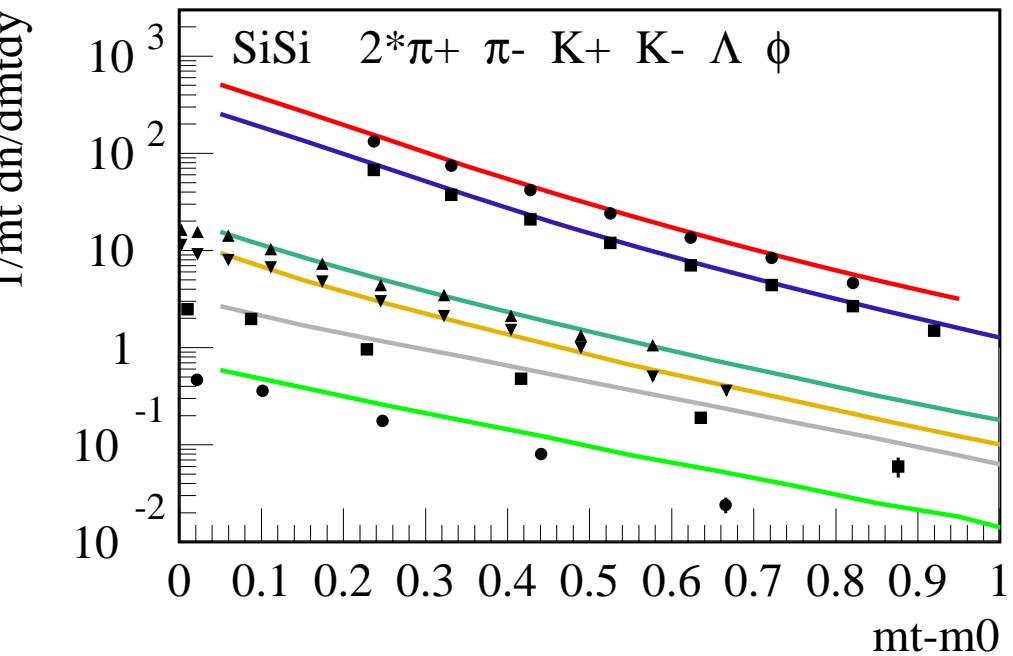
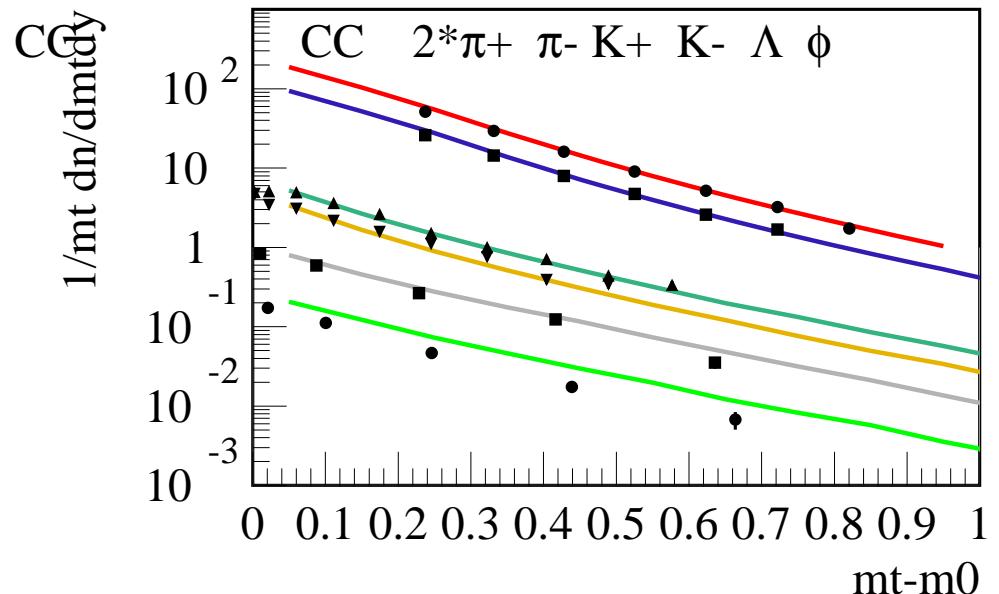
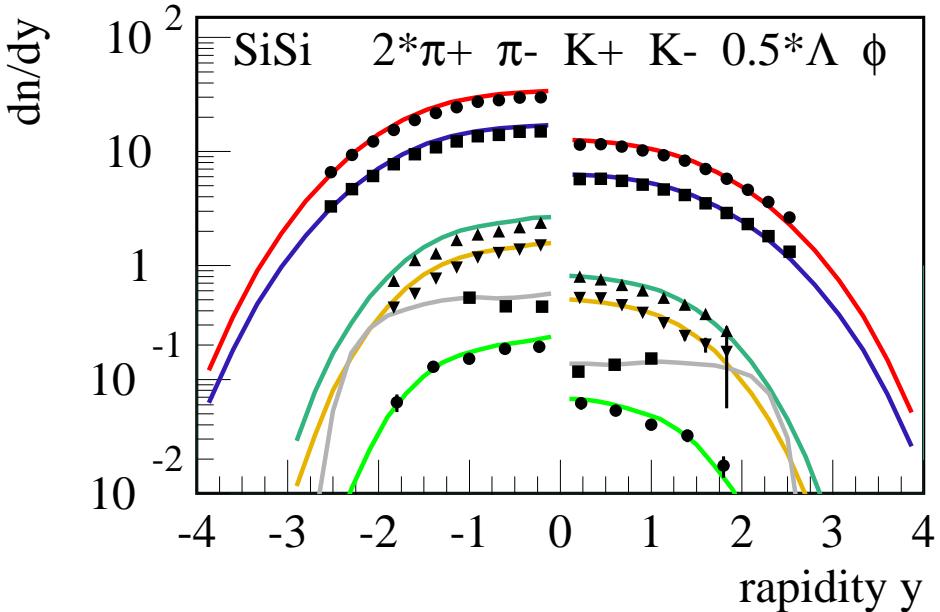
different particles



R_AA easy to understand: compare core and pp

flow affects shape of heavy particles



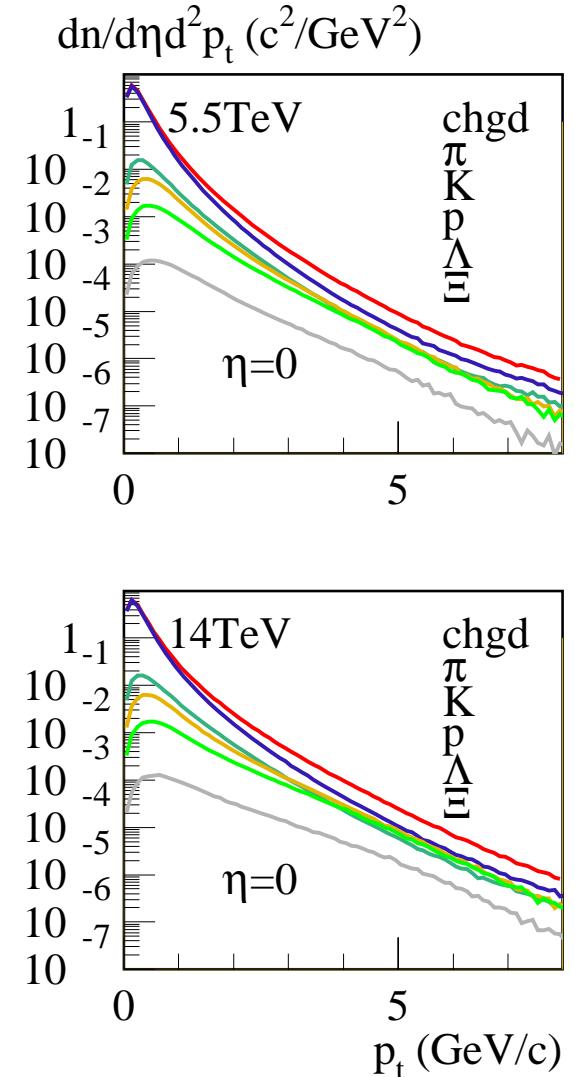
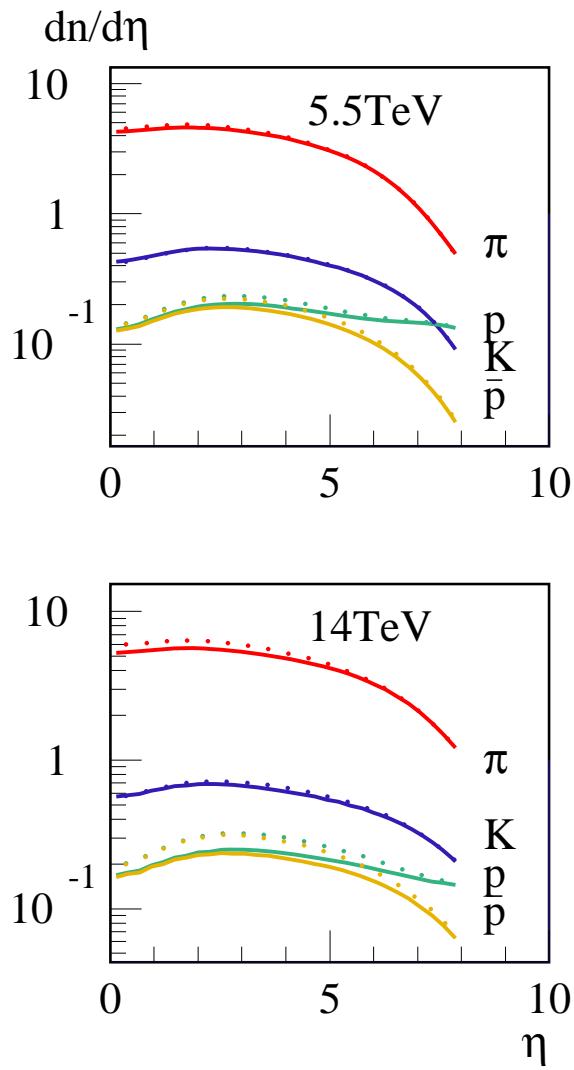
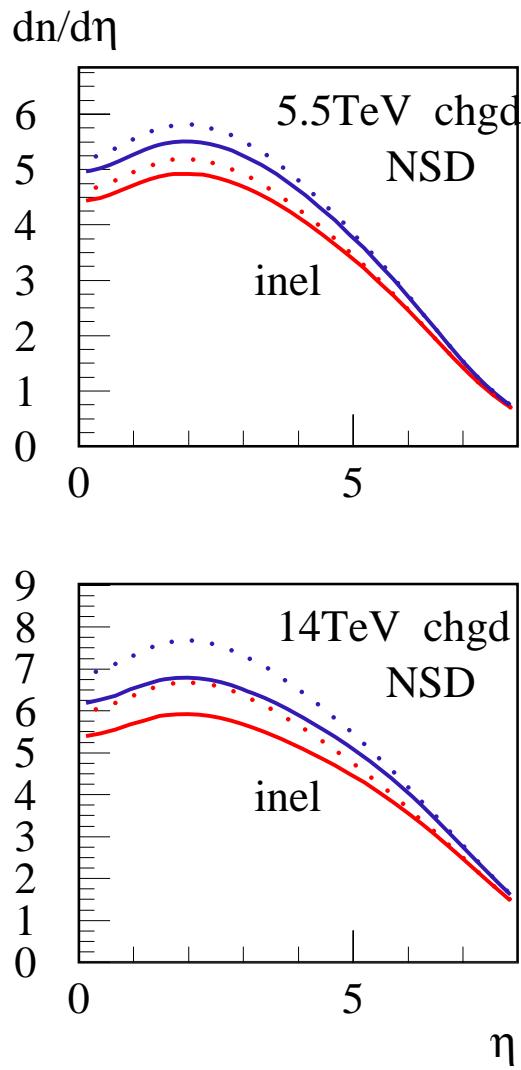


CC, SiSi at SPS

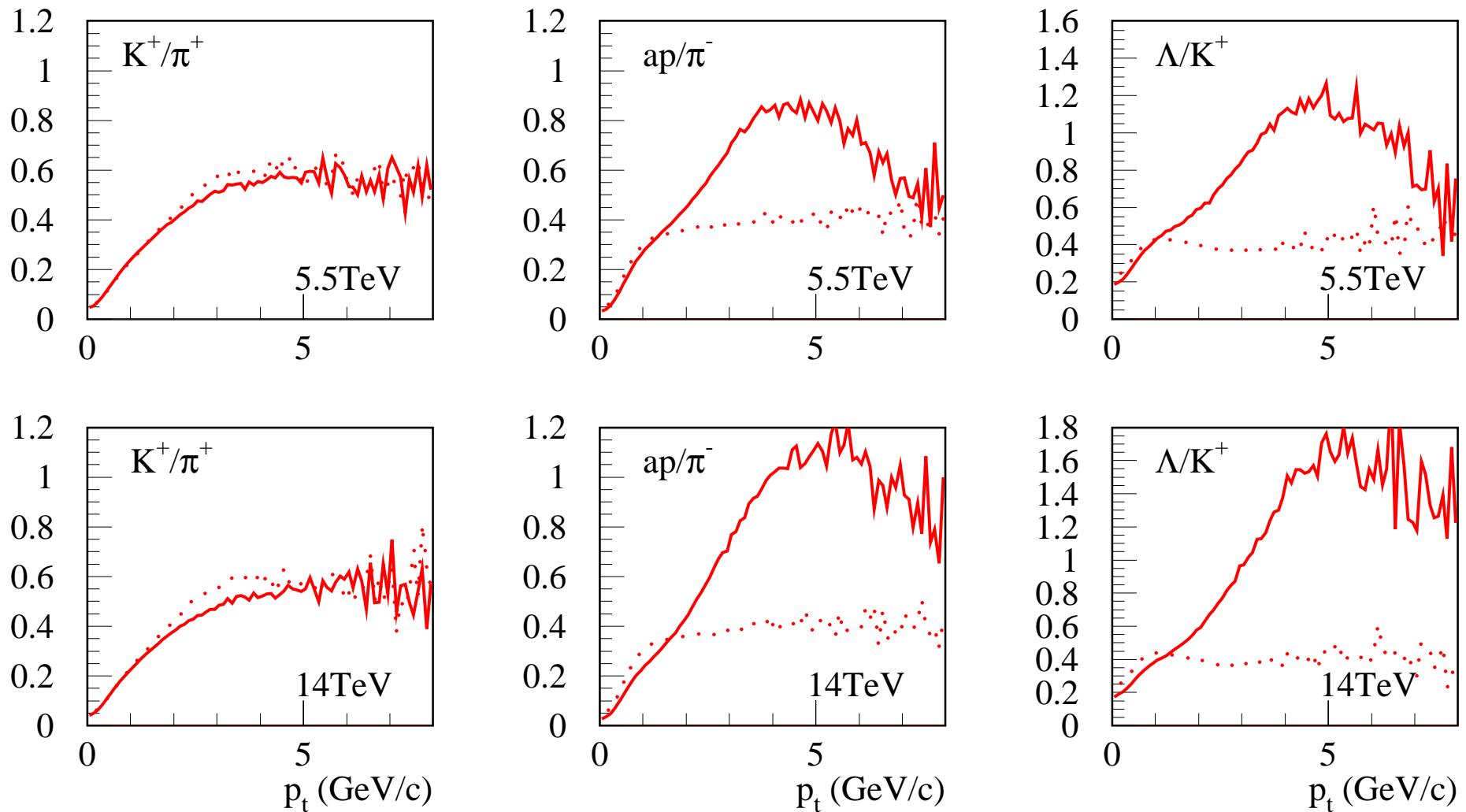
rapidity distr,
pt spectra

EPOS Predictions for LHC

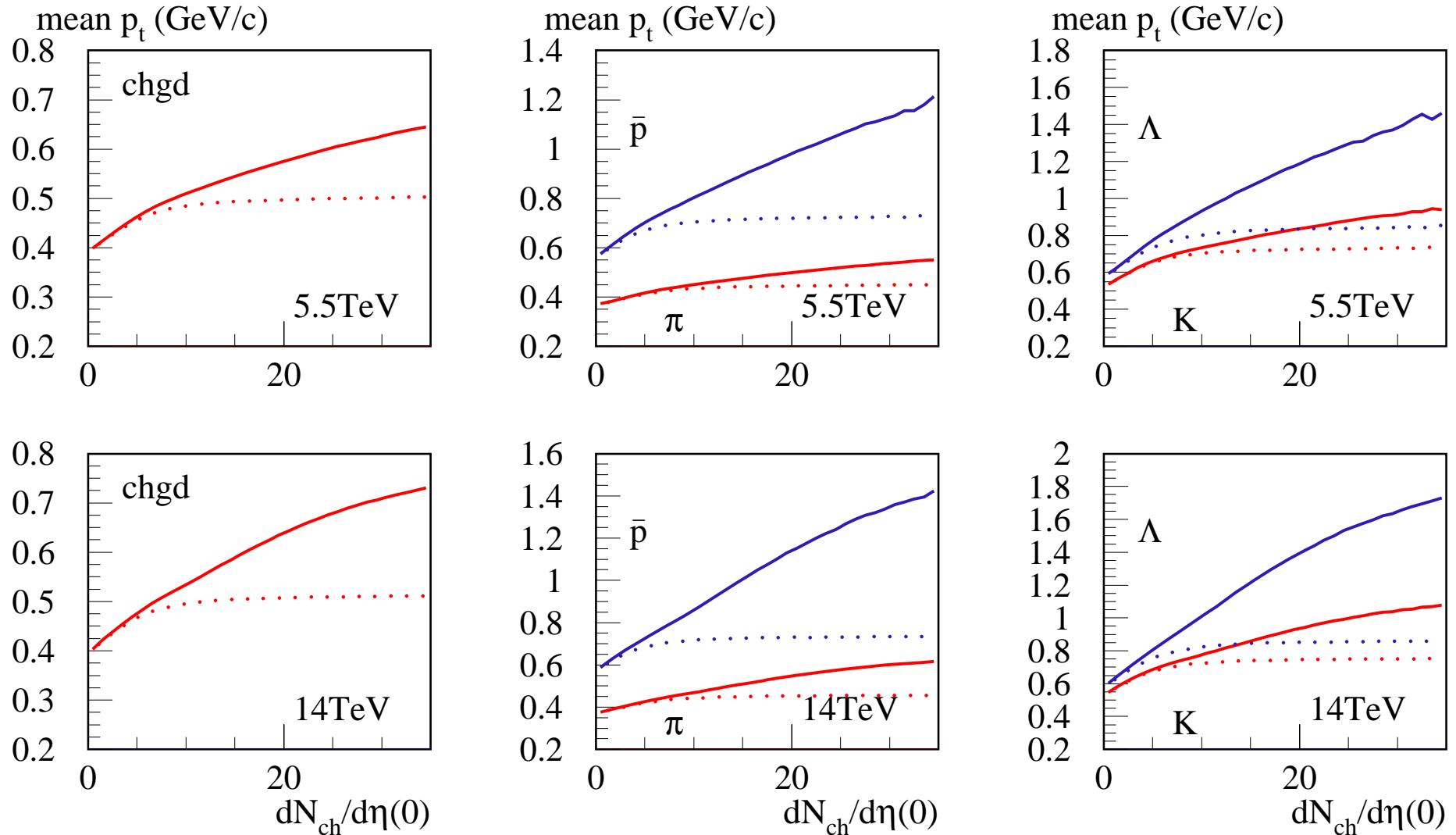
pp at LHC: particle spectra with and without “mini-plasma”



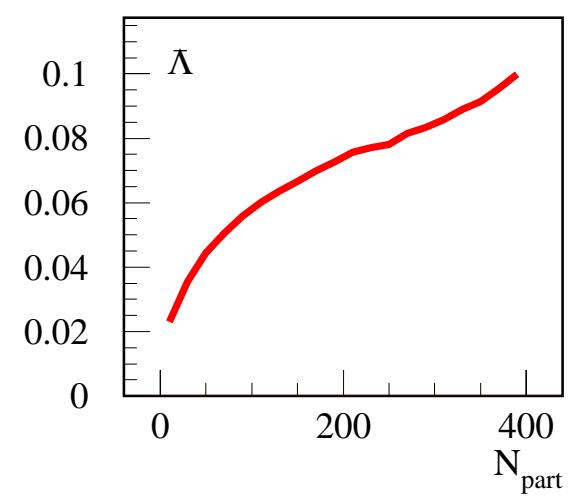
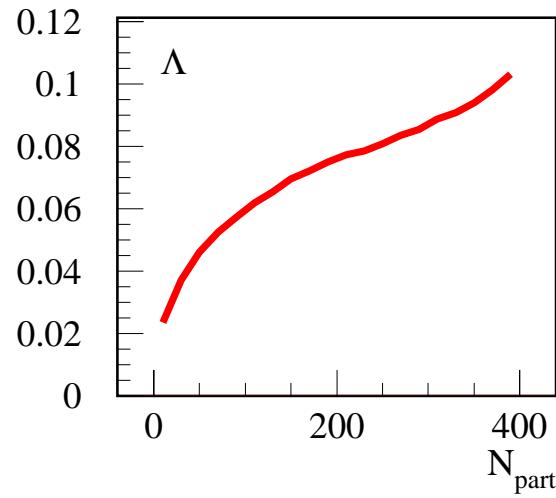
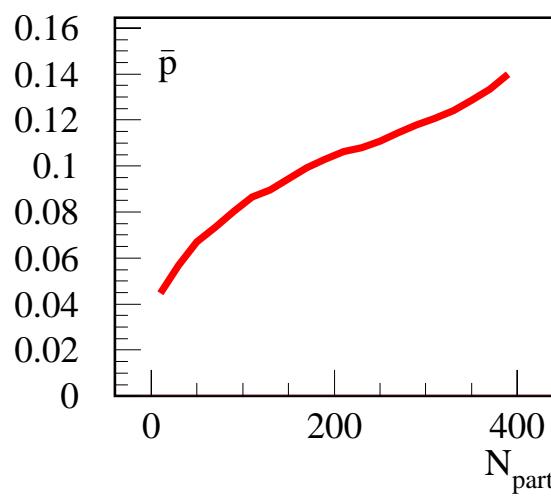
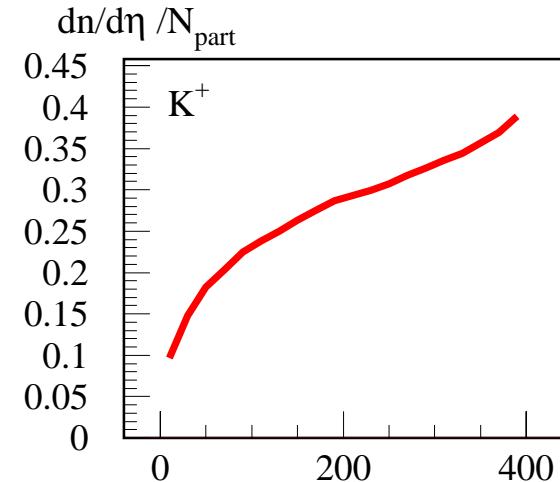
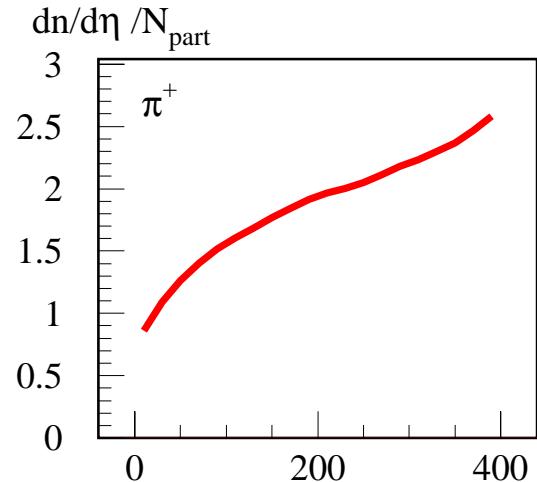
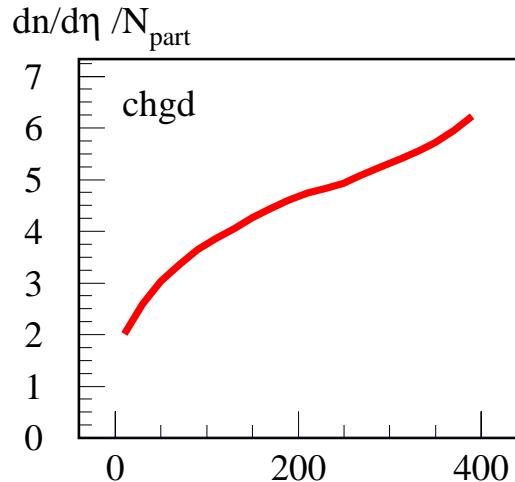
pp at LHC: particle ratios with and without “mini-plasma”



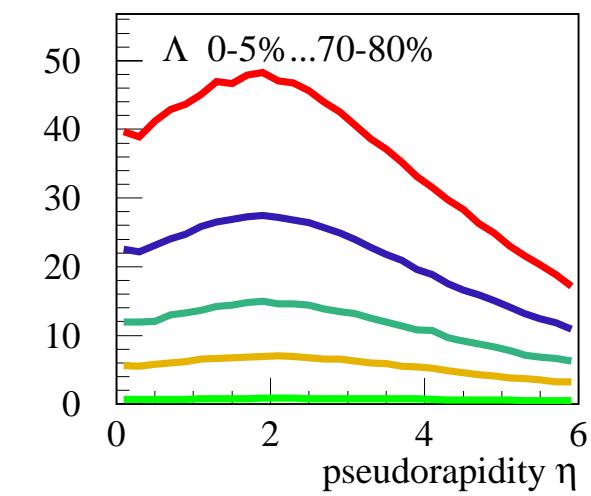
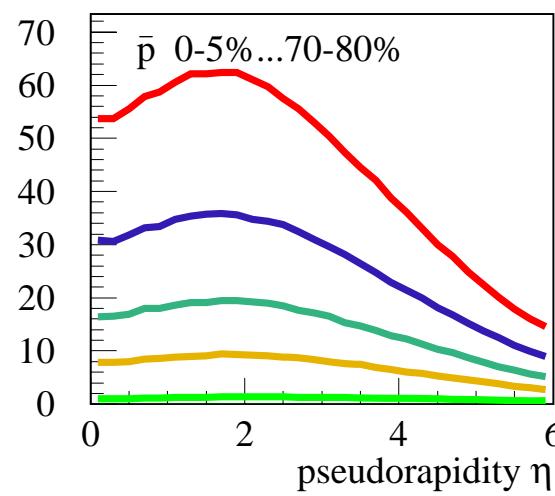
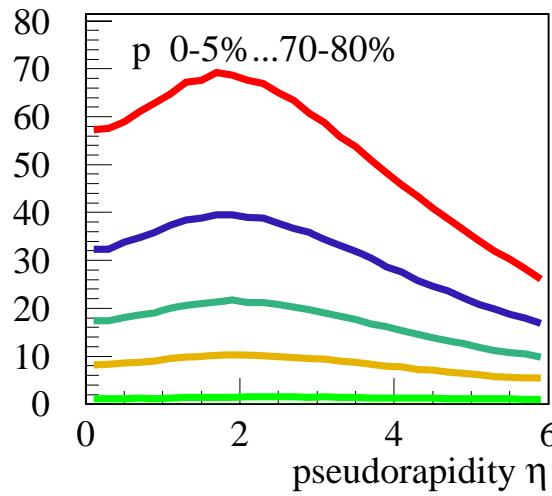
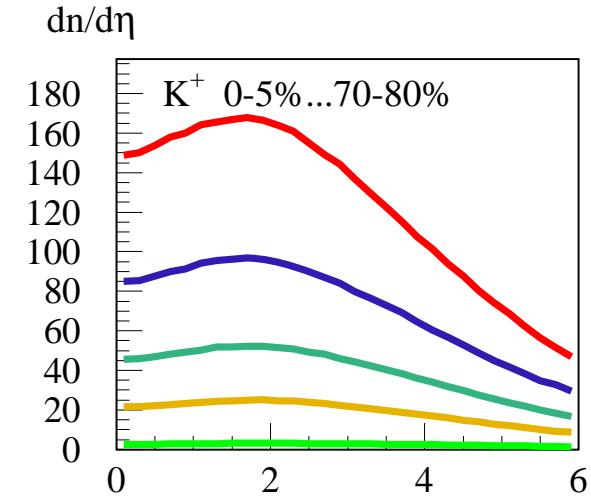
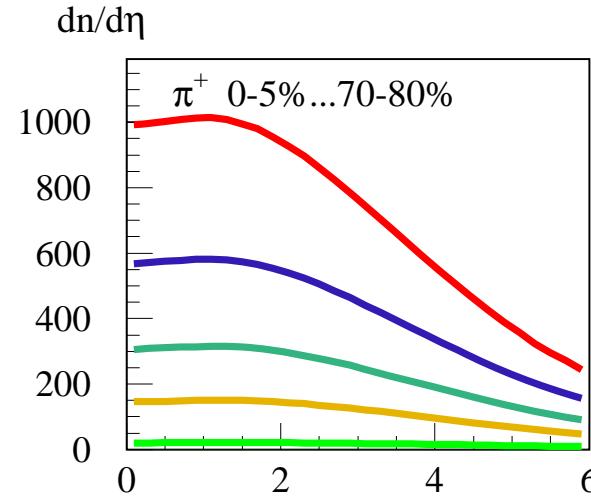
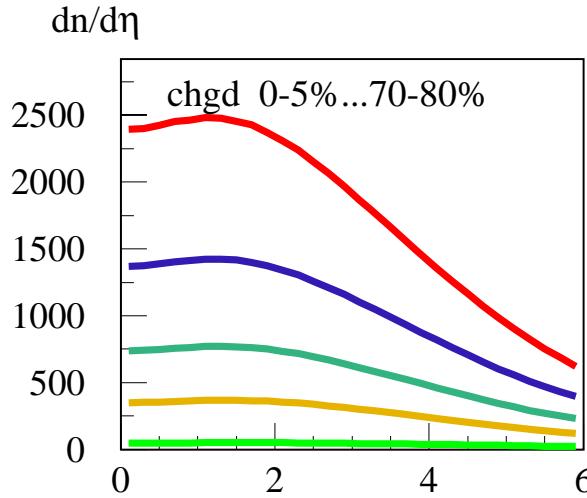
pp at LHC: mean p_t vs multiplicity with and without “mini-plasma”



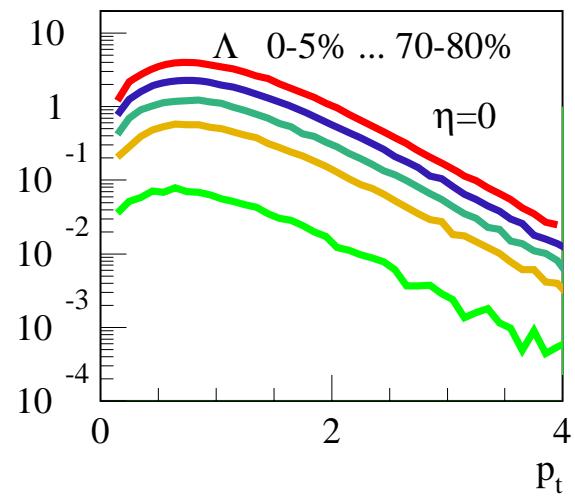
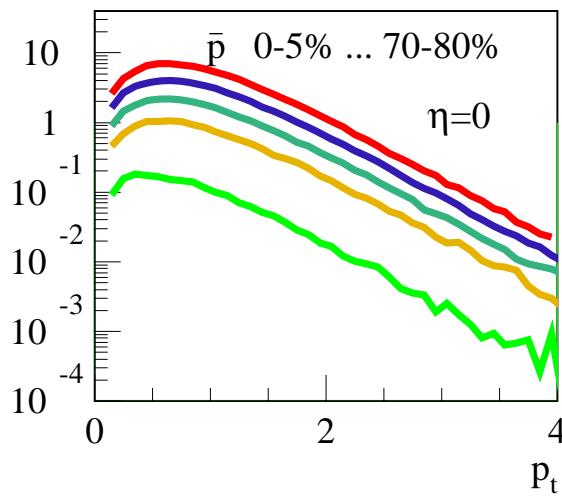
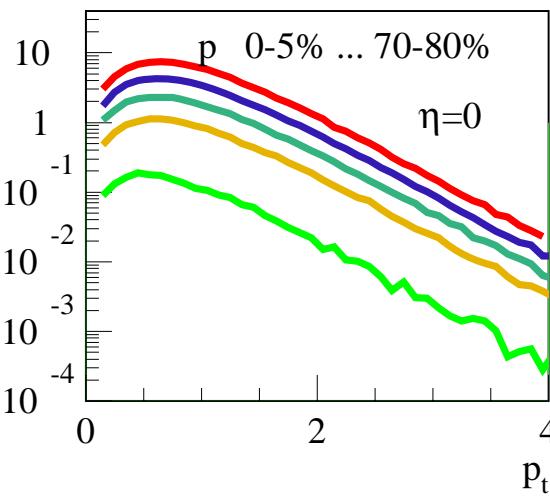
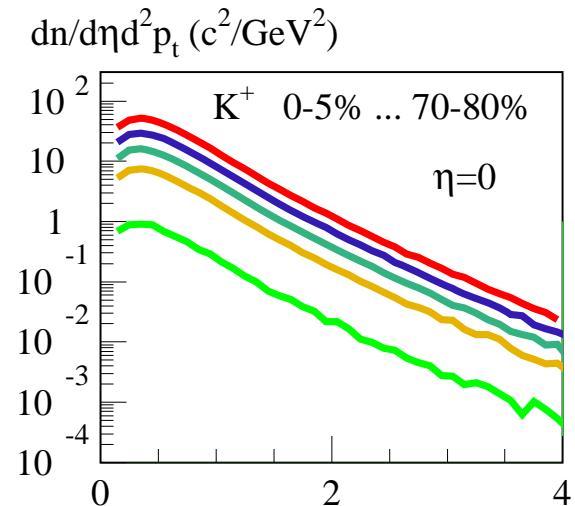
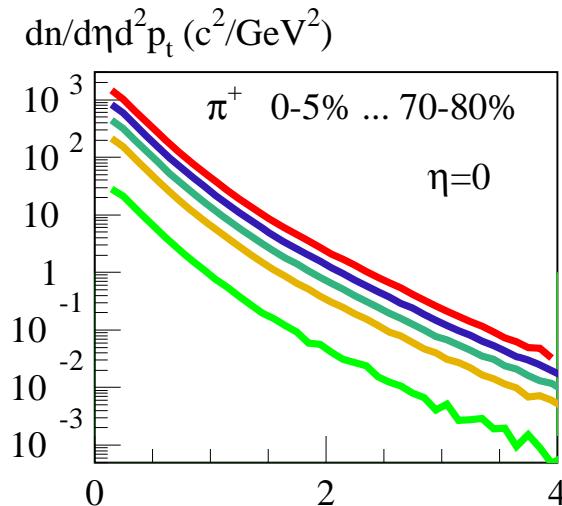
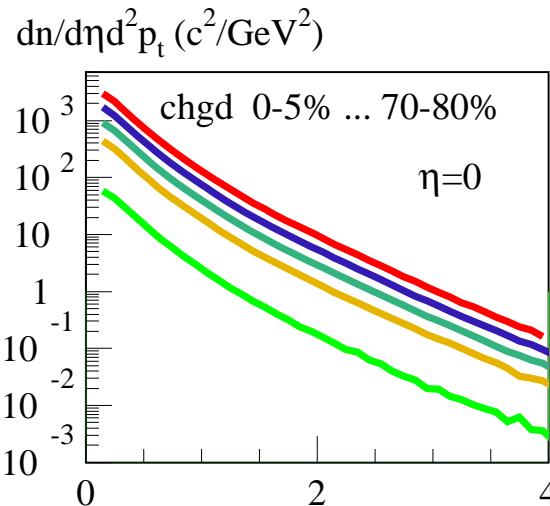
PbPb at LHC: Multipl/Npart vs Npart



PbPb at LHC: Pseudorapidity distributions

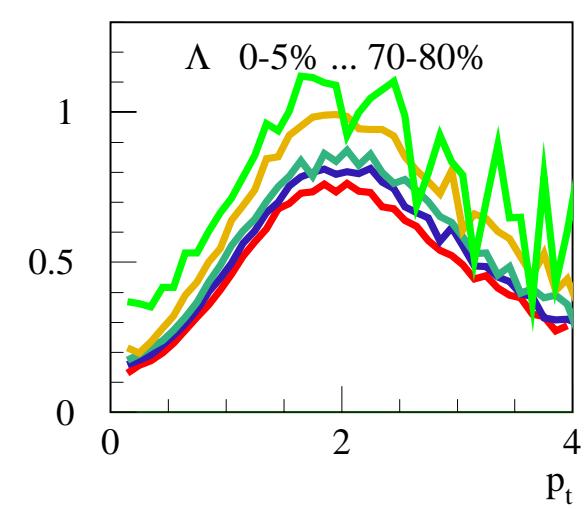
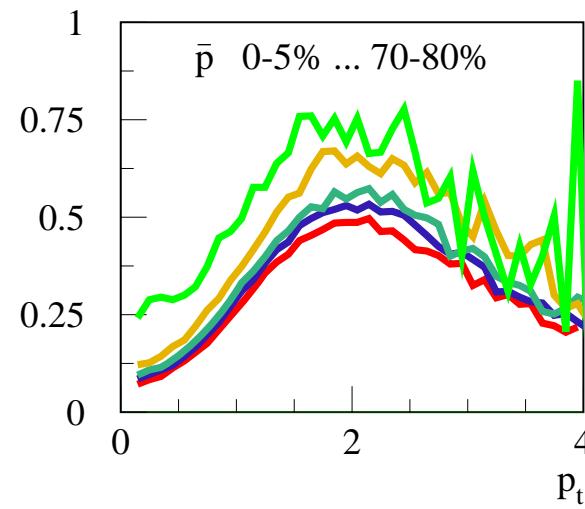
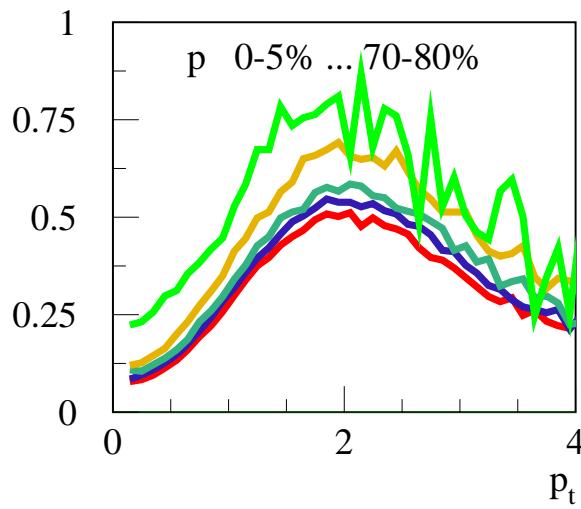
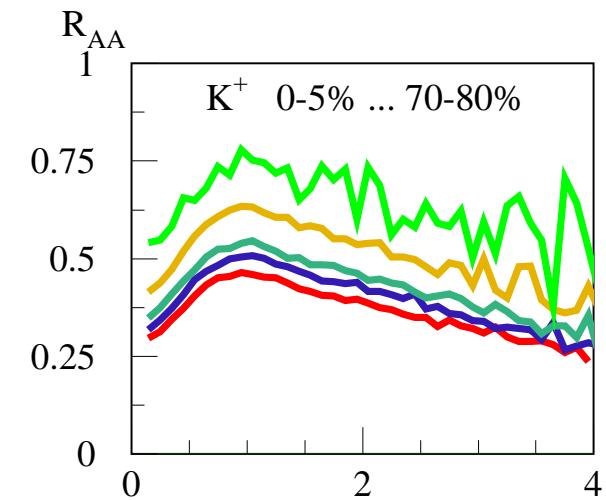
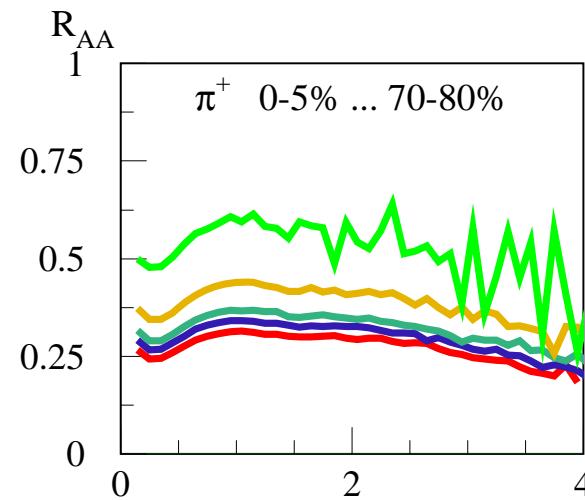
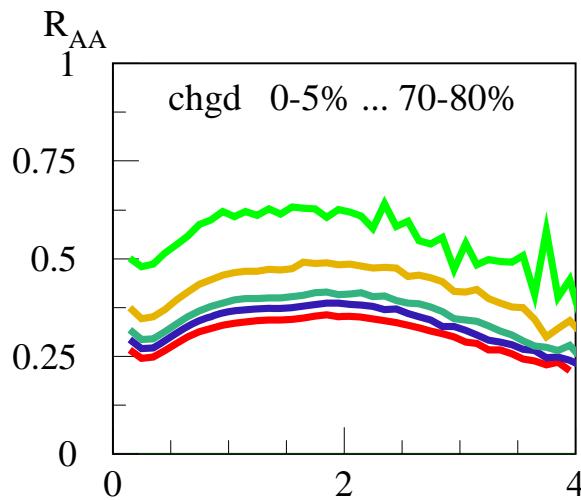


PbPb at LHC: pt spectra

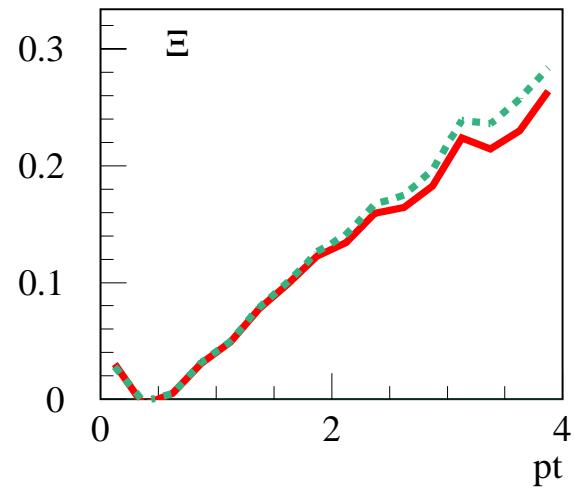
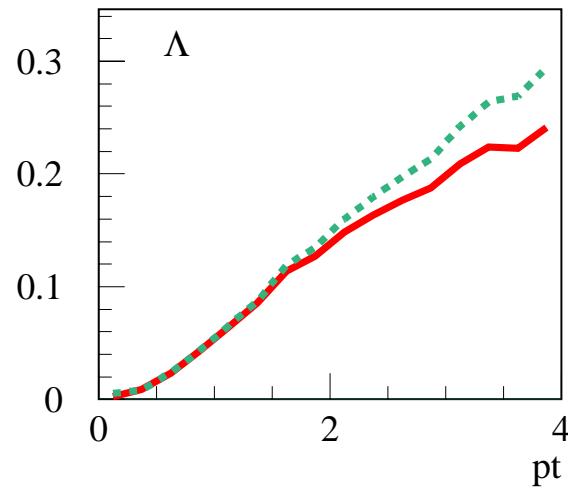
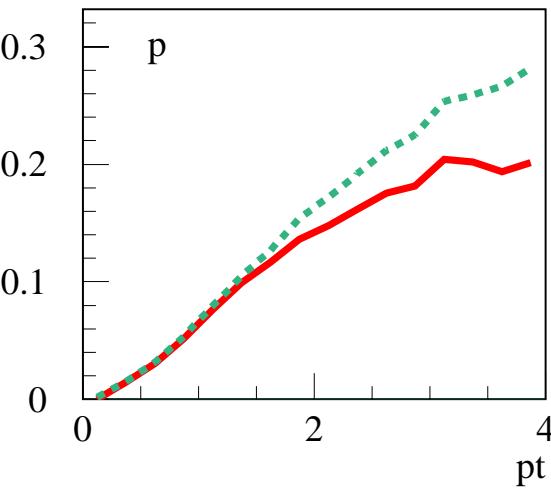
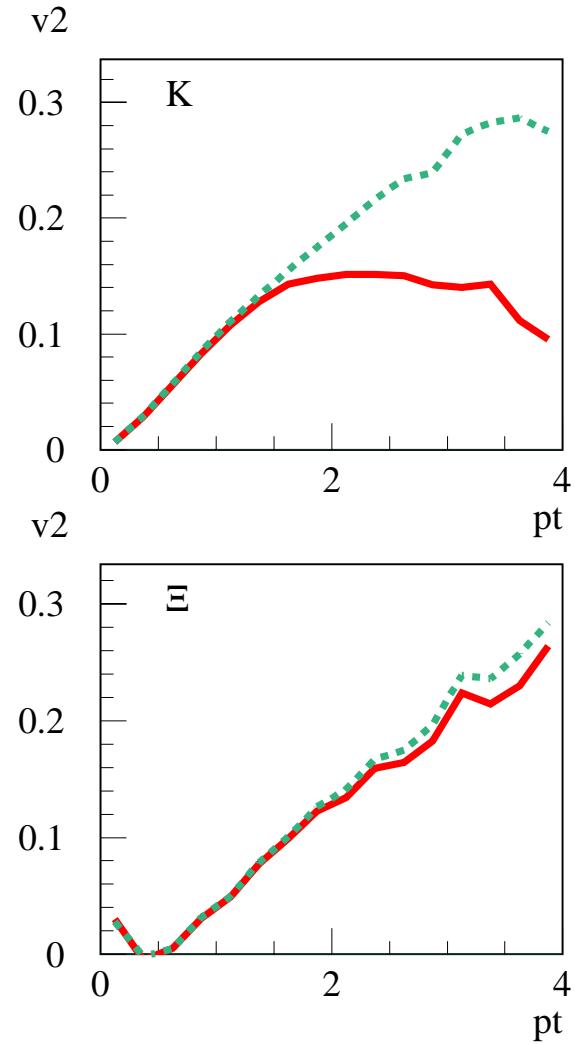
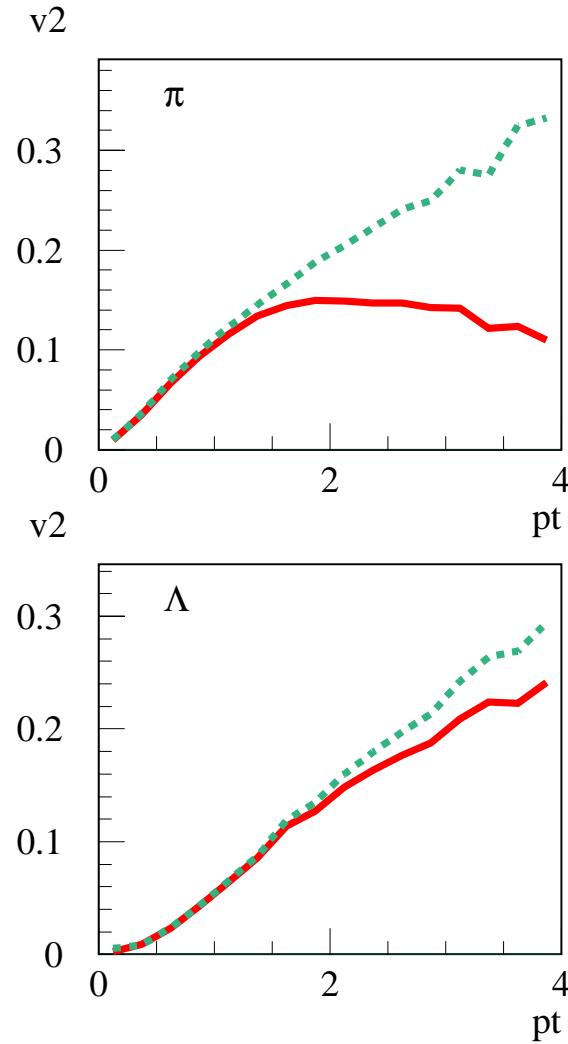
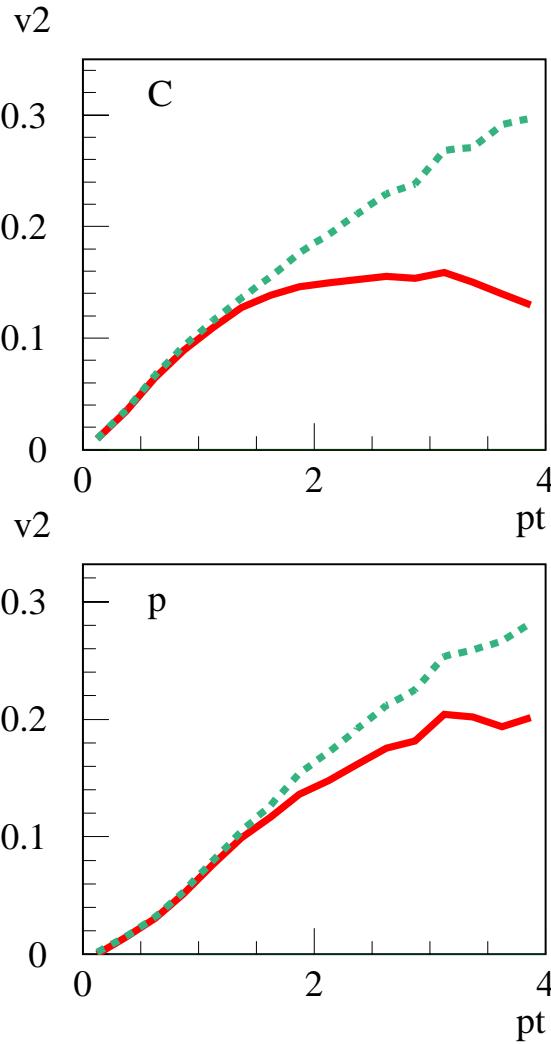


PbPb at LHC: R_AA

pp already flowing !

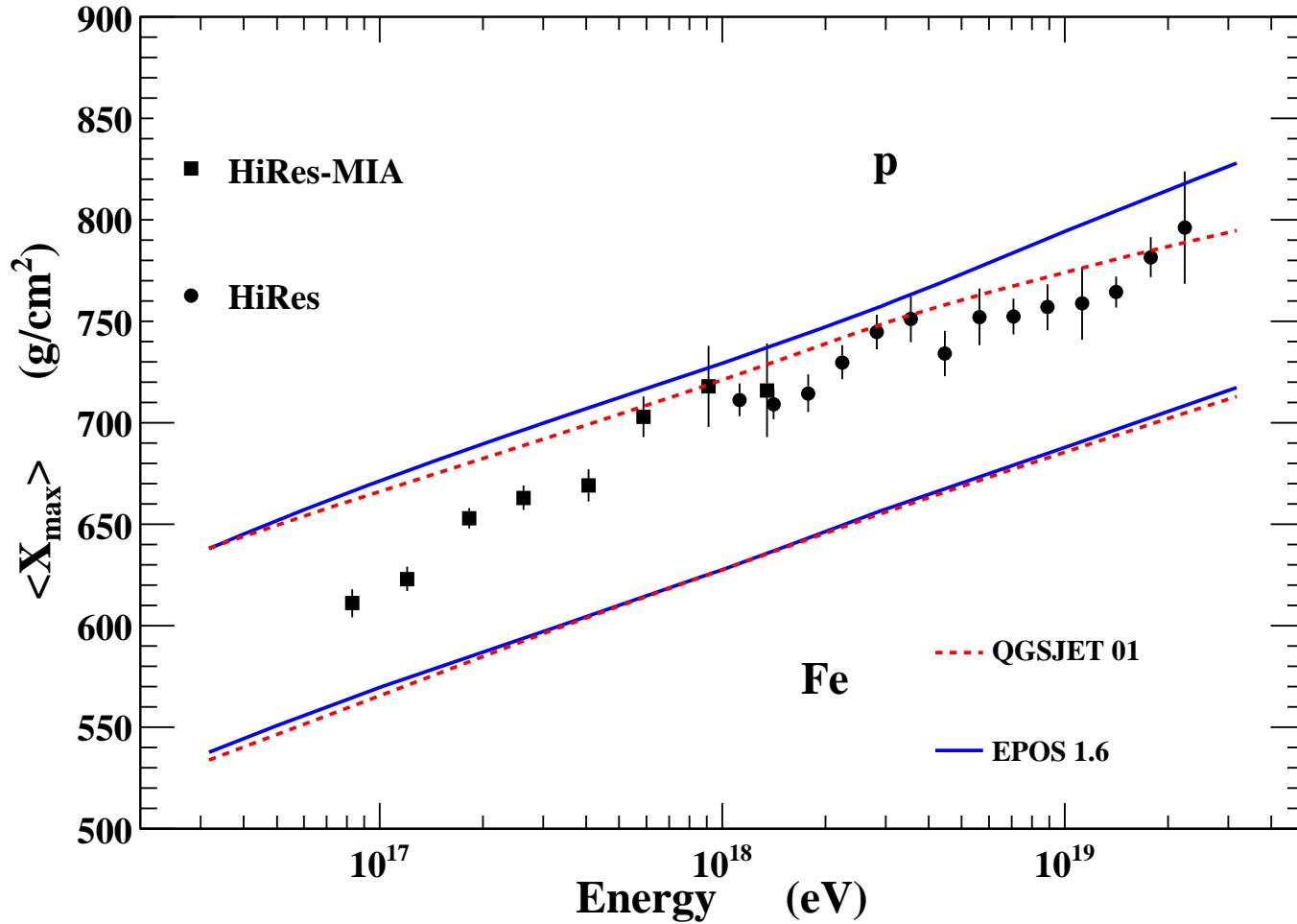


PbPb at LHC: elliptical flow



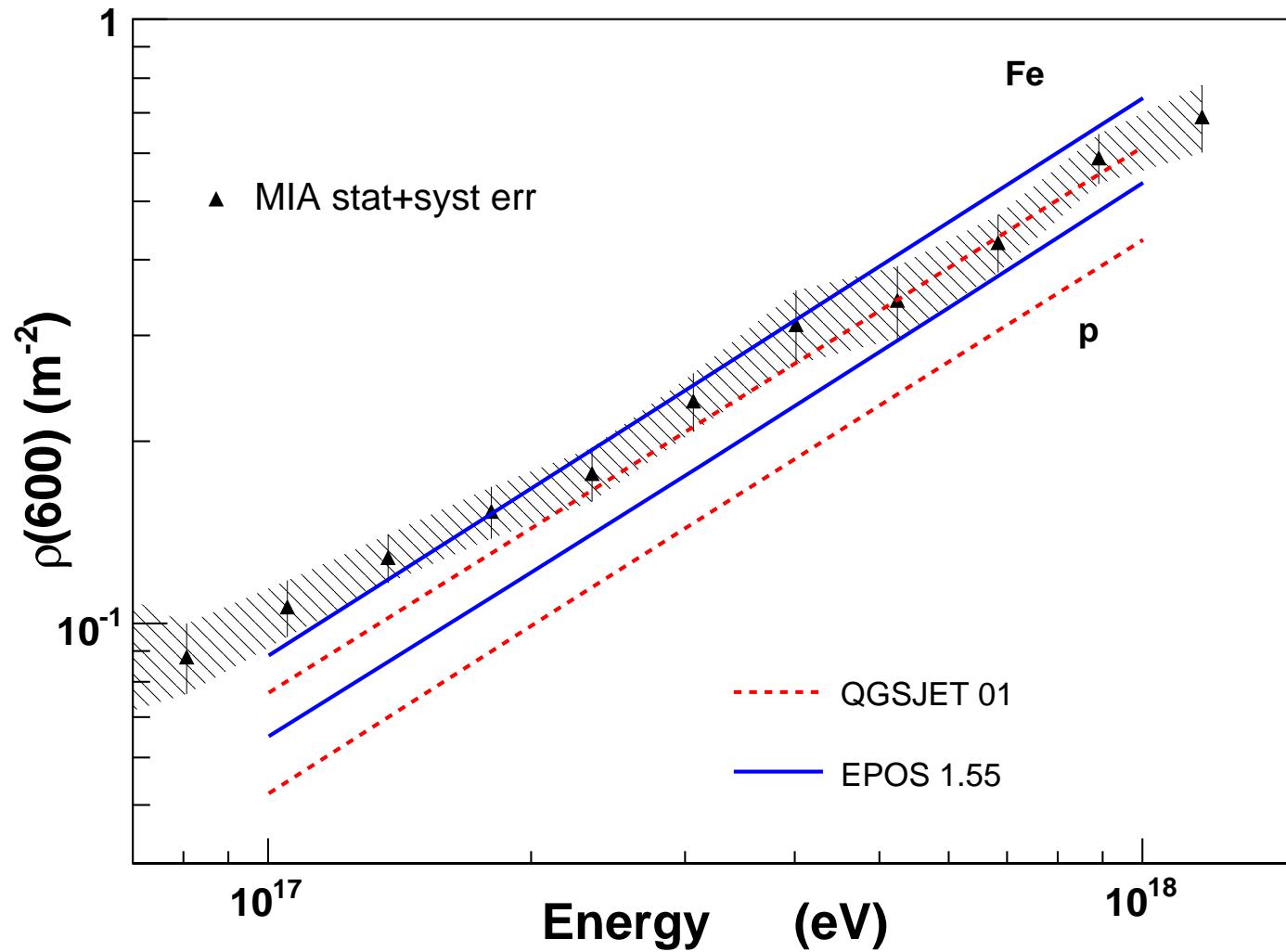
Simulating Cosmic Ray Air Showers Using EPOS

EAS using EPOS: Xmax



We employ CONEX or CORSIKA, and GHEISHA as low energy model

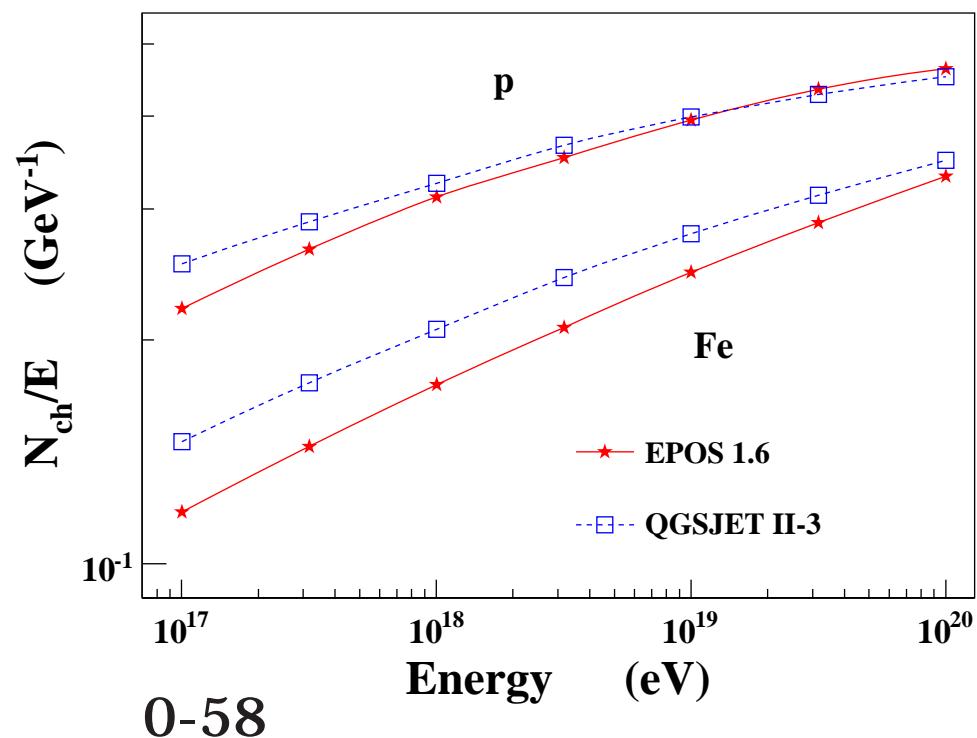
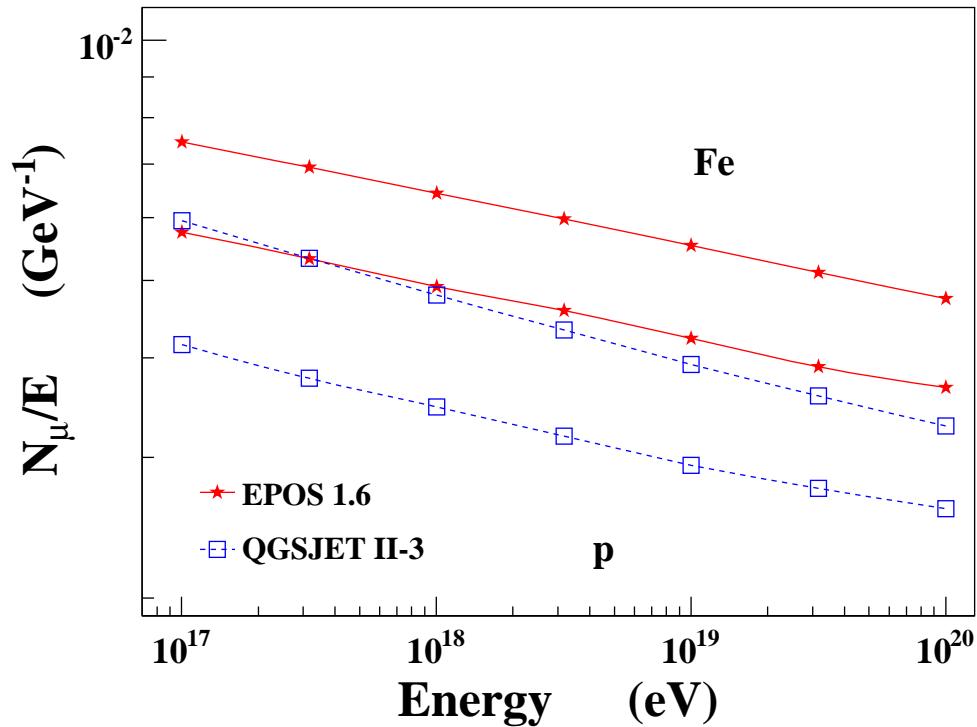
Muon density $\rho(600)$



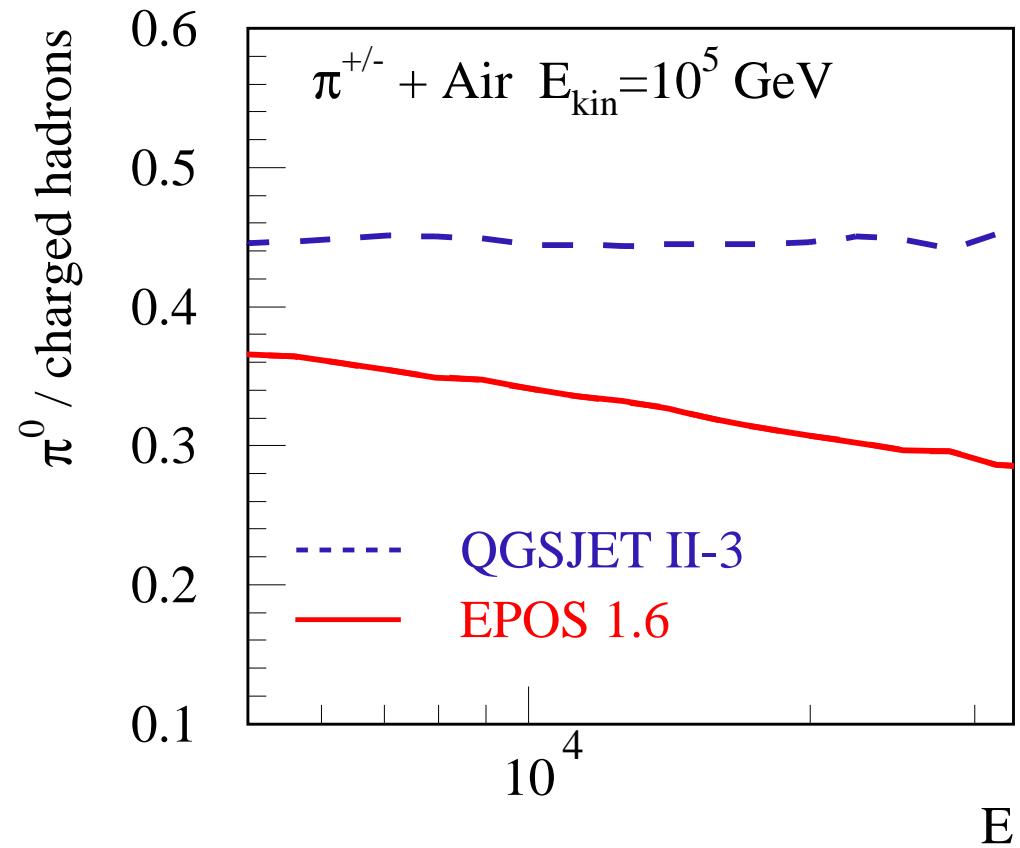
much more
muons in
EPOS

charged par-
ticles similar

compared to
other models



Why so many muons?



EPOS red, QGSJET II blue dashed,

Pion-Air
collisions:

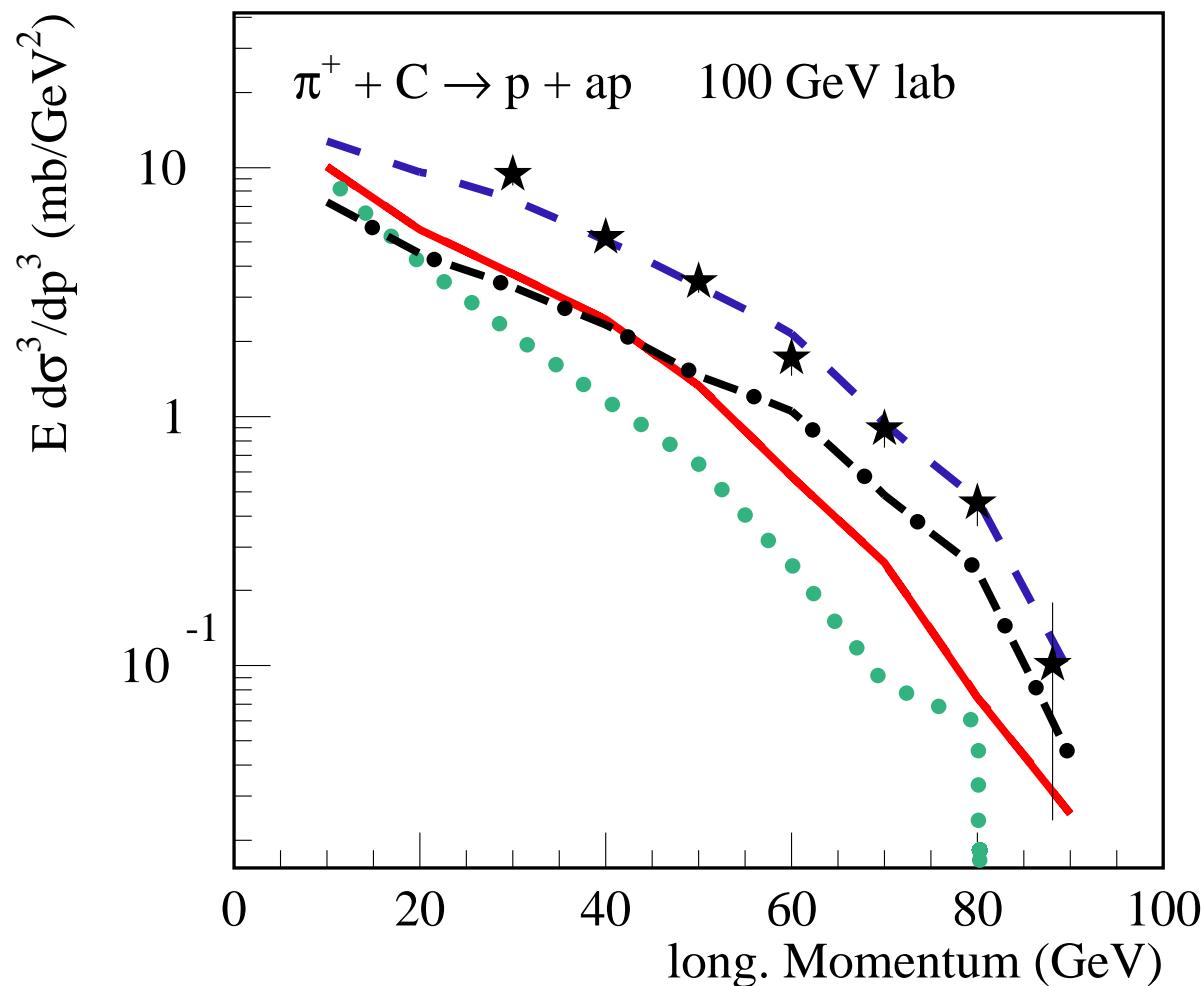
$$R = \frac{\pi^0}{\text{charged hadrons}}$$

R is smaller
in EPOS com-
pared to all
other models

→ more muons

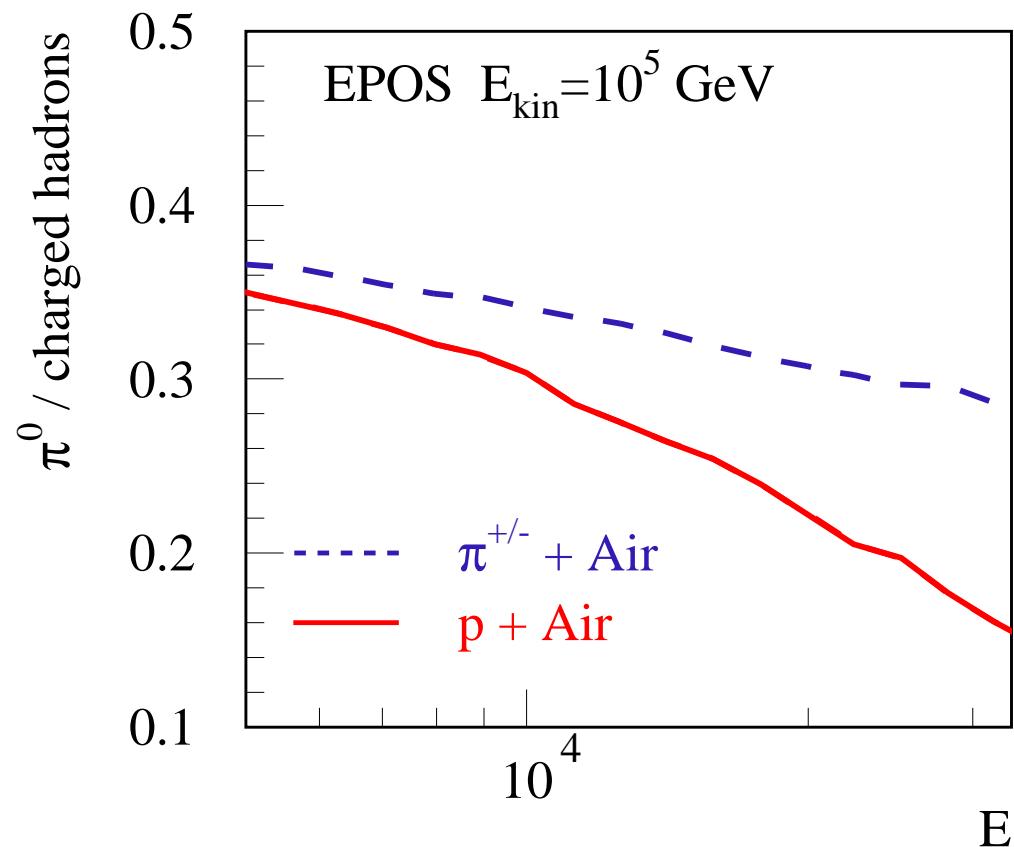
Smaller R in EPOS

one reason: more p, \bar{p} in pion-Air



additional protons increase muon number even more

since $p + \text{Air}$ gives softer π^0 spectrum than $\pi + \text{Air}$



remark:
more protons
due to ladder
splitting!

Summary

EPOS = hadronic interaction model constructed to understand accelerator data, used for CRs

- Multiple scattering done on a solid theoretical basis
- Treats nonlinear effects ($\Rightarrow dAu @ RHIC$)
- Collective effects
- Carefully tested (hh, hA, AA)
- “Mini-plasma” in pp at LHC
- CRs: more muons than other models