The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

SMR/1842-12

International Workshop on QCD at Cosmic Energies III

28 May - 1 June, 2007

Lecture Notes

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28 May 2007

EPOS at Cosmic Energies

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EPOS Basics

EPOS Overview

Energy conserving quantum mechanical multiple scattering approach

based on

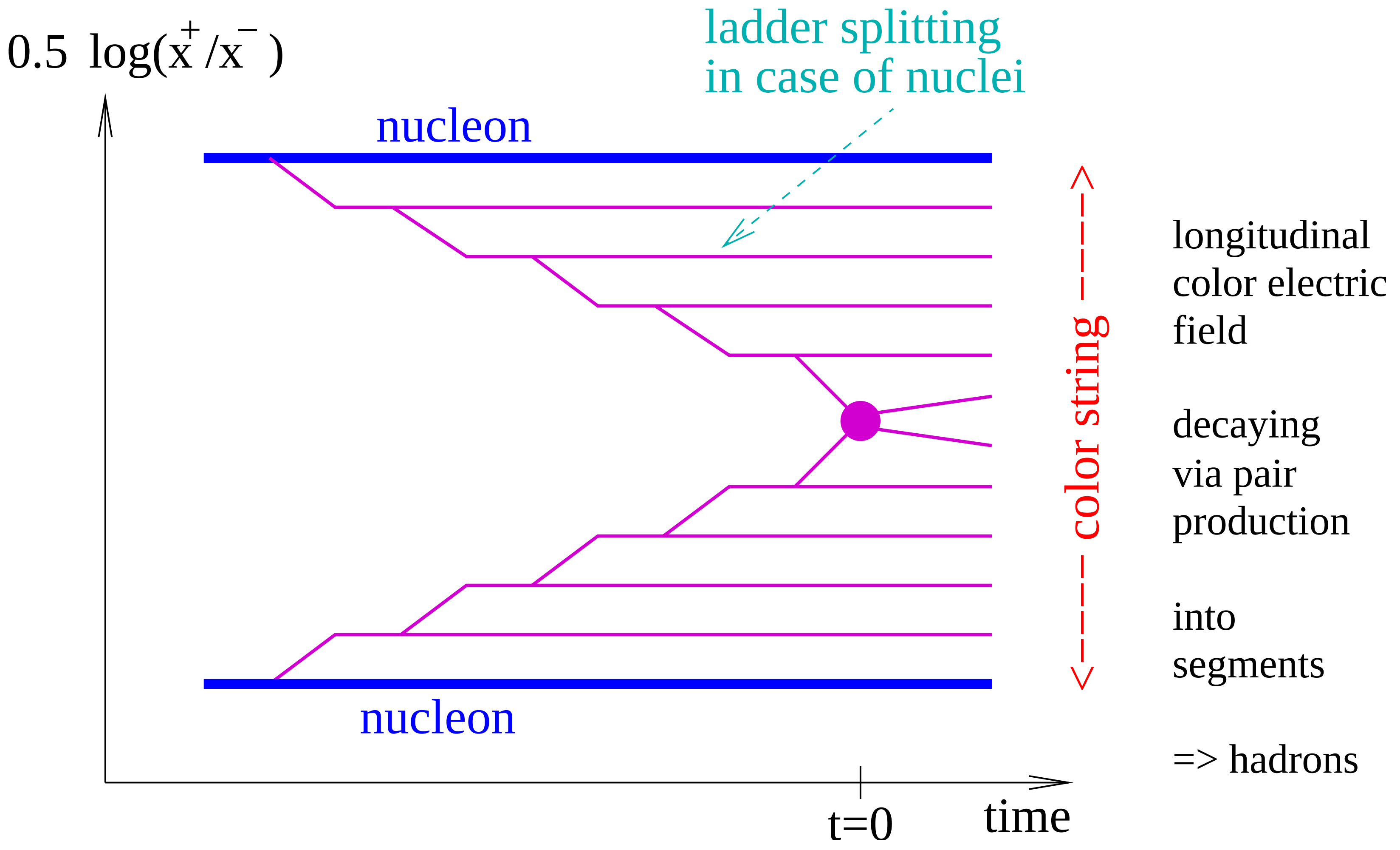
Partons, parton ladders, and strings

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:

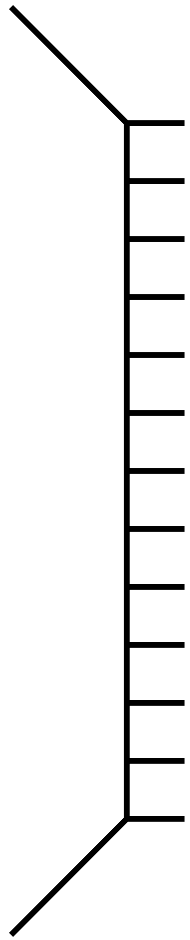
- ☐ One may easily **exrapolate from real hard processes[1] to purely soft ones**.

- ☐ **Soft processes** represent simply the limit of zero hard gluons; there is only a purely longitudinal color field.

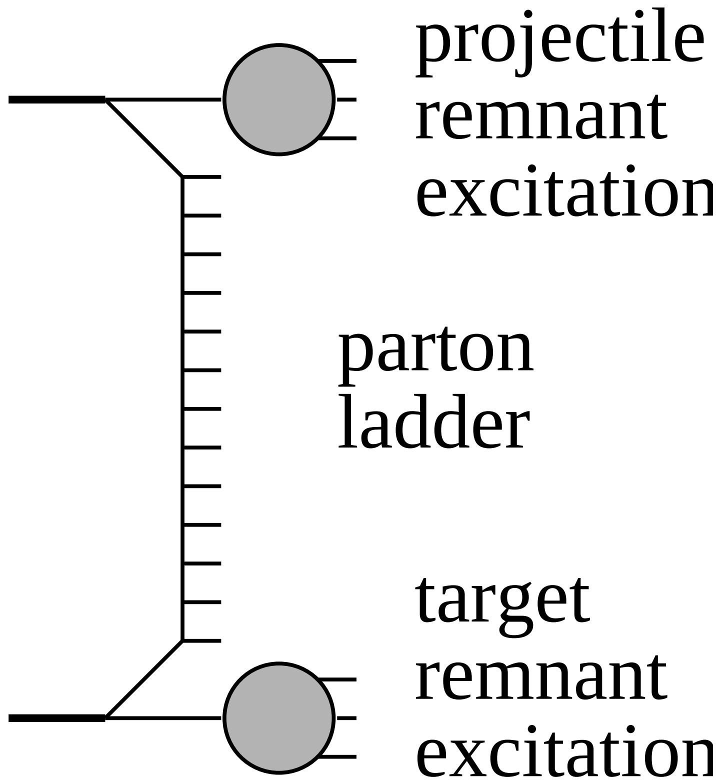
[1] with many perturbative gluons

Symbol representing
a parton ladder

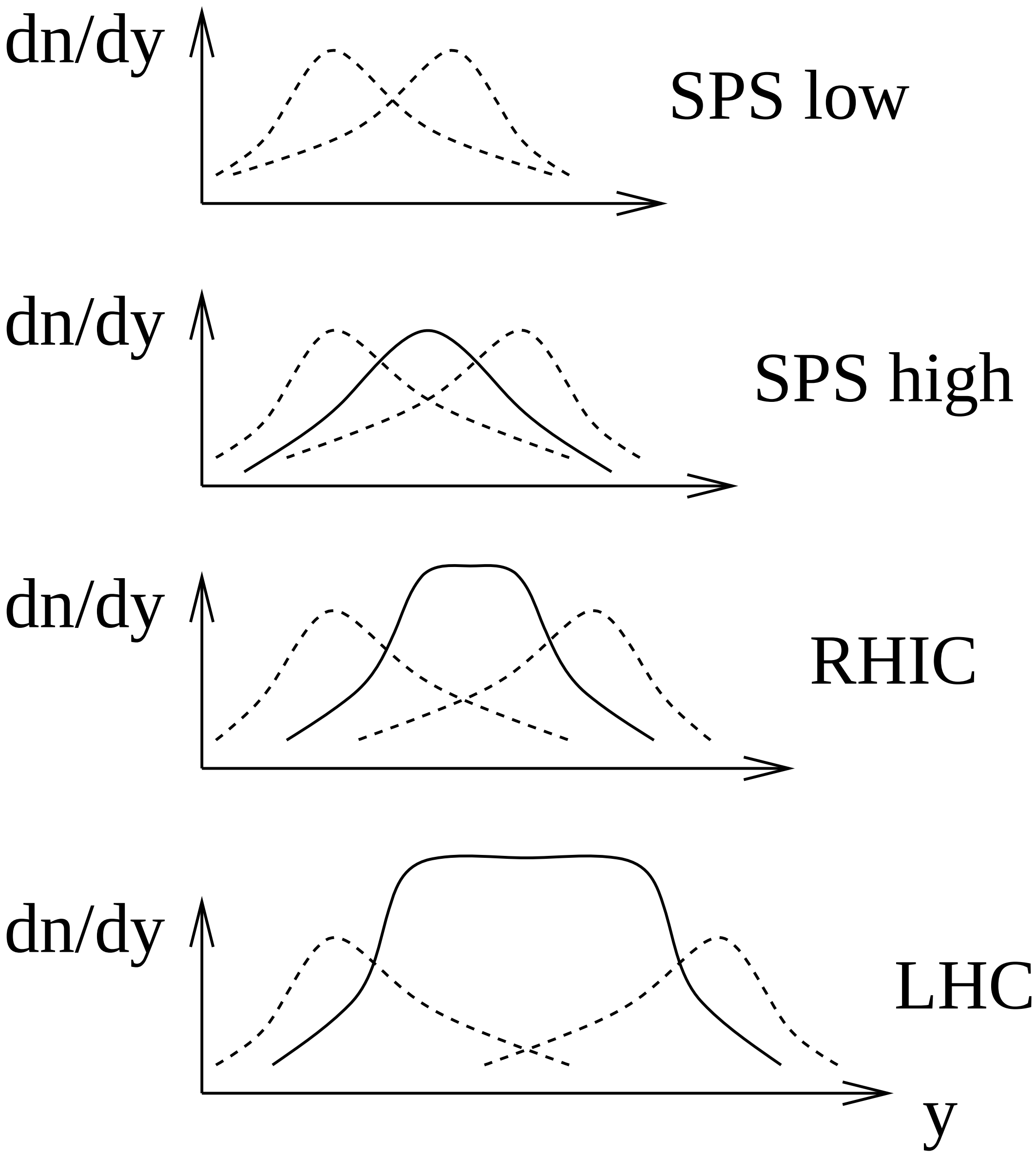
including soft part !



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



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



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

and “outer” contributions, from the remnants (dashed lines),

to the rapidity distribution of hadrons.

(Artists view)

Multiple scattering

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

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

=> **multiple scattering !!**

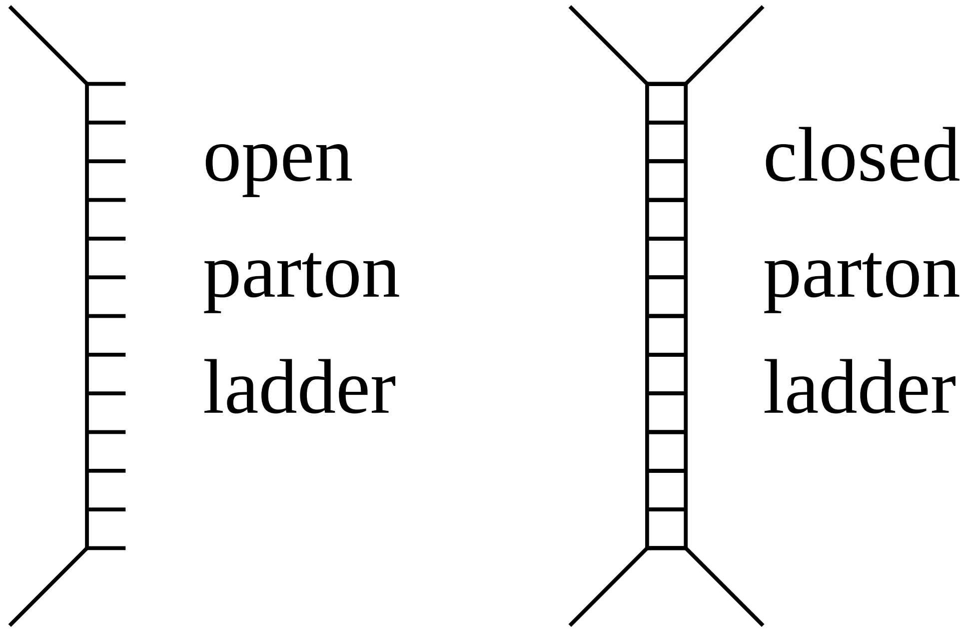
(several elementary parton-parton scatterings happening in parallel)[2]

---

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

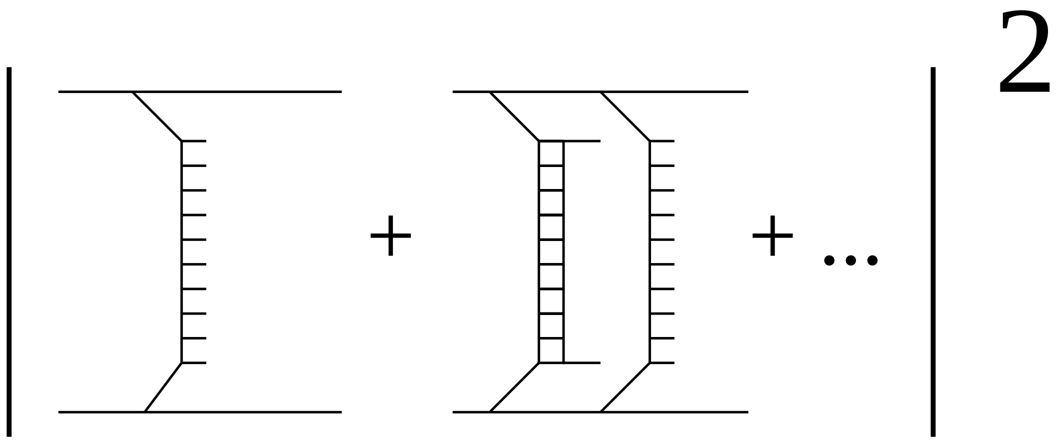
Consistent quantum mechanical formulation of multiple scattering:

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



Example

$\sigma^{pp}_{inel} \sim$



- 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 secton), 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 <-> kink)

- Particle production via quark **pair production**

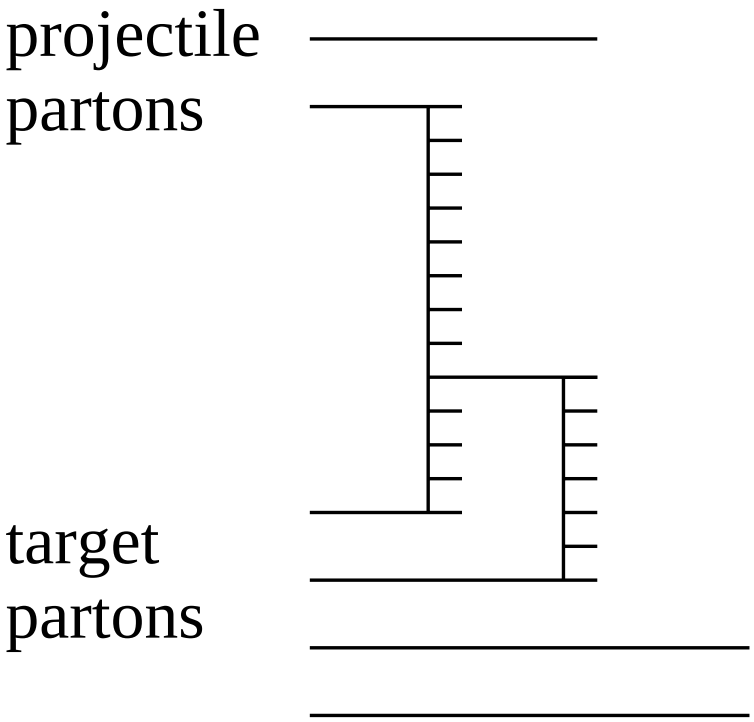
Splitting of parton ladders

When big nuclei are involved:

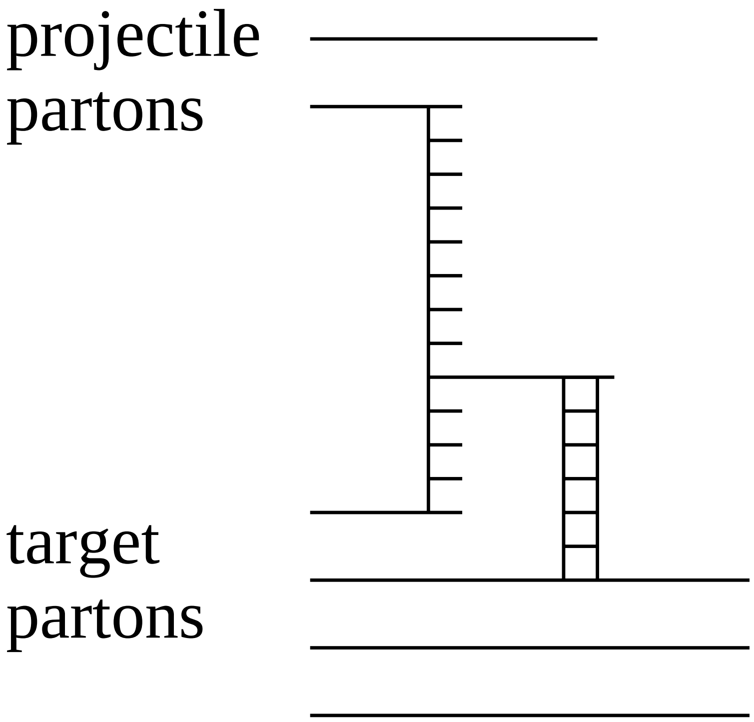
- □ Large parton densities

- □ "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)

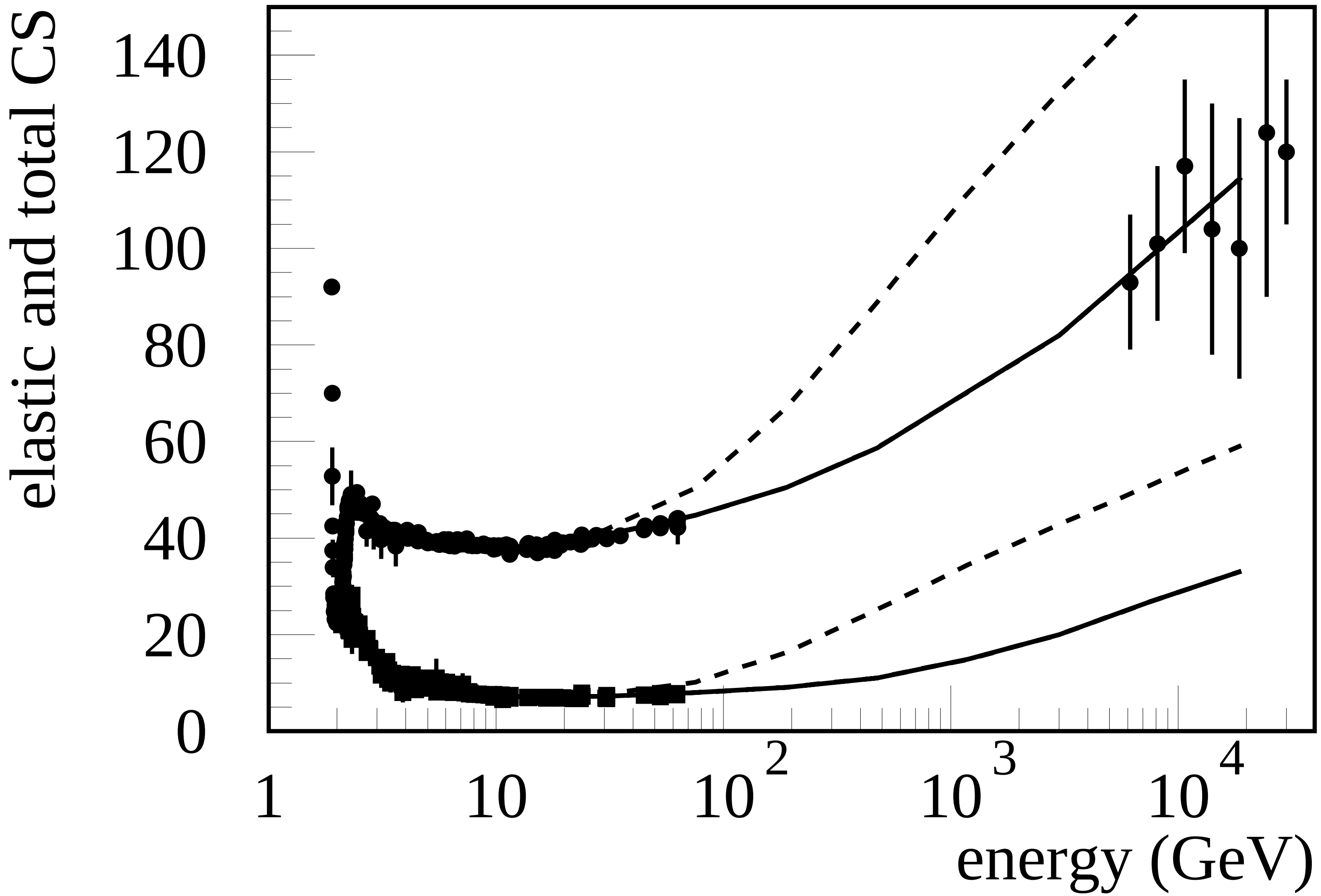
Realization of ladder splitting effects

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

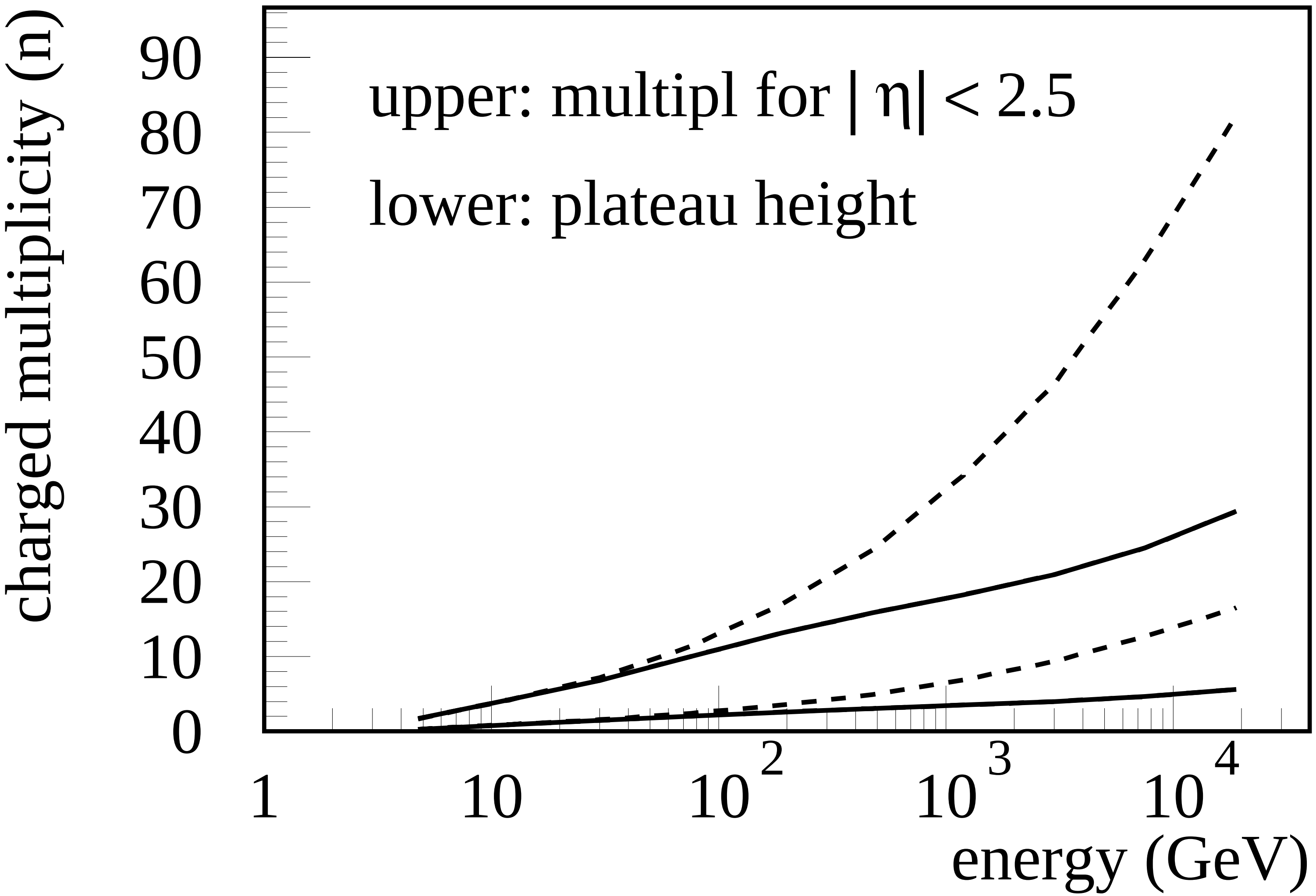
grow much too fast without ladder splitting



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

Multiplicities in pp

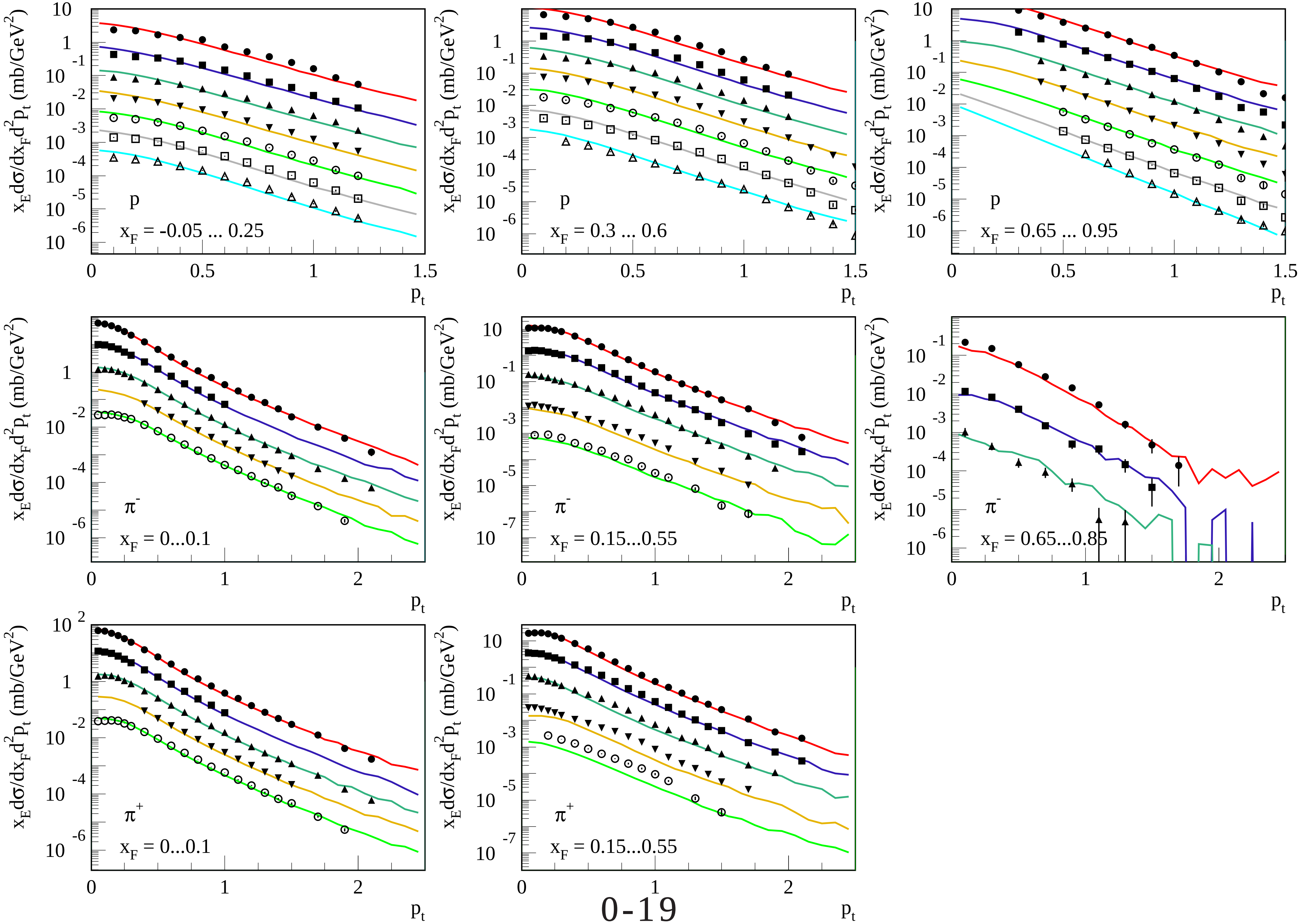
grow much too fast without ladder splitting



Tests:

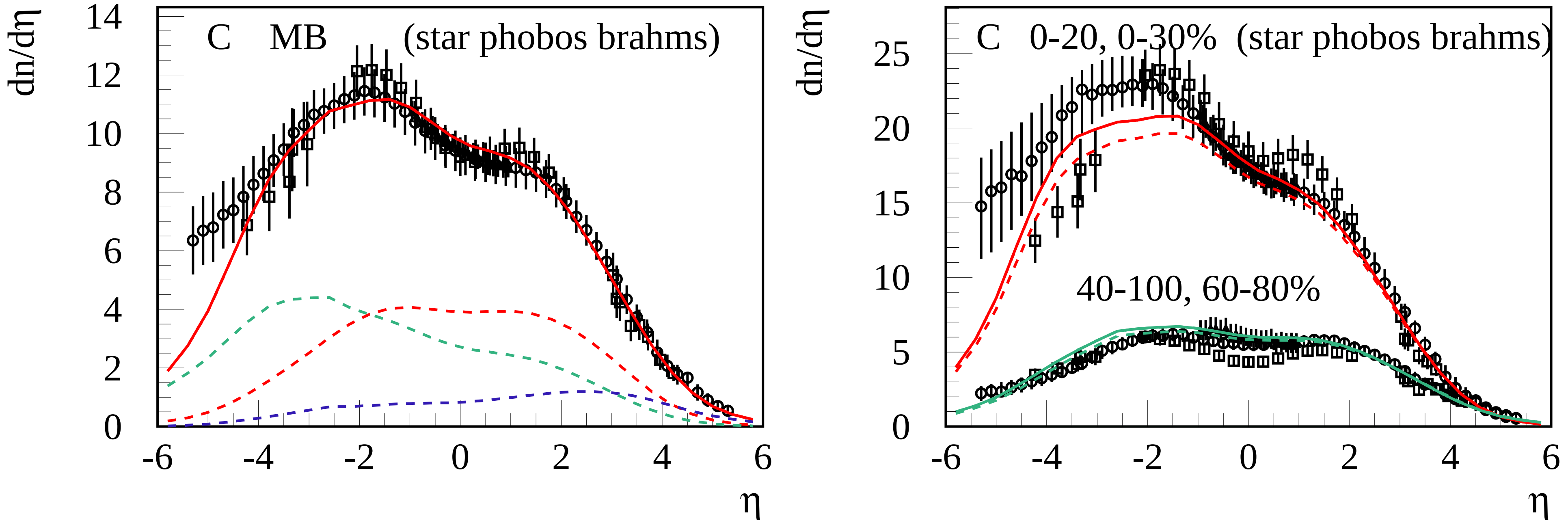
comparing hundreds of spectra at SPS and RHIC energies

pT spectra at given xF in pp@SPS



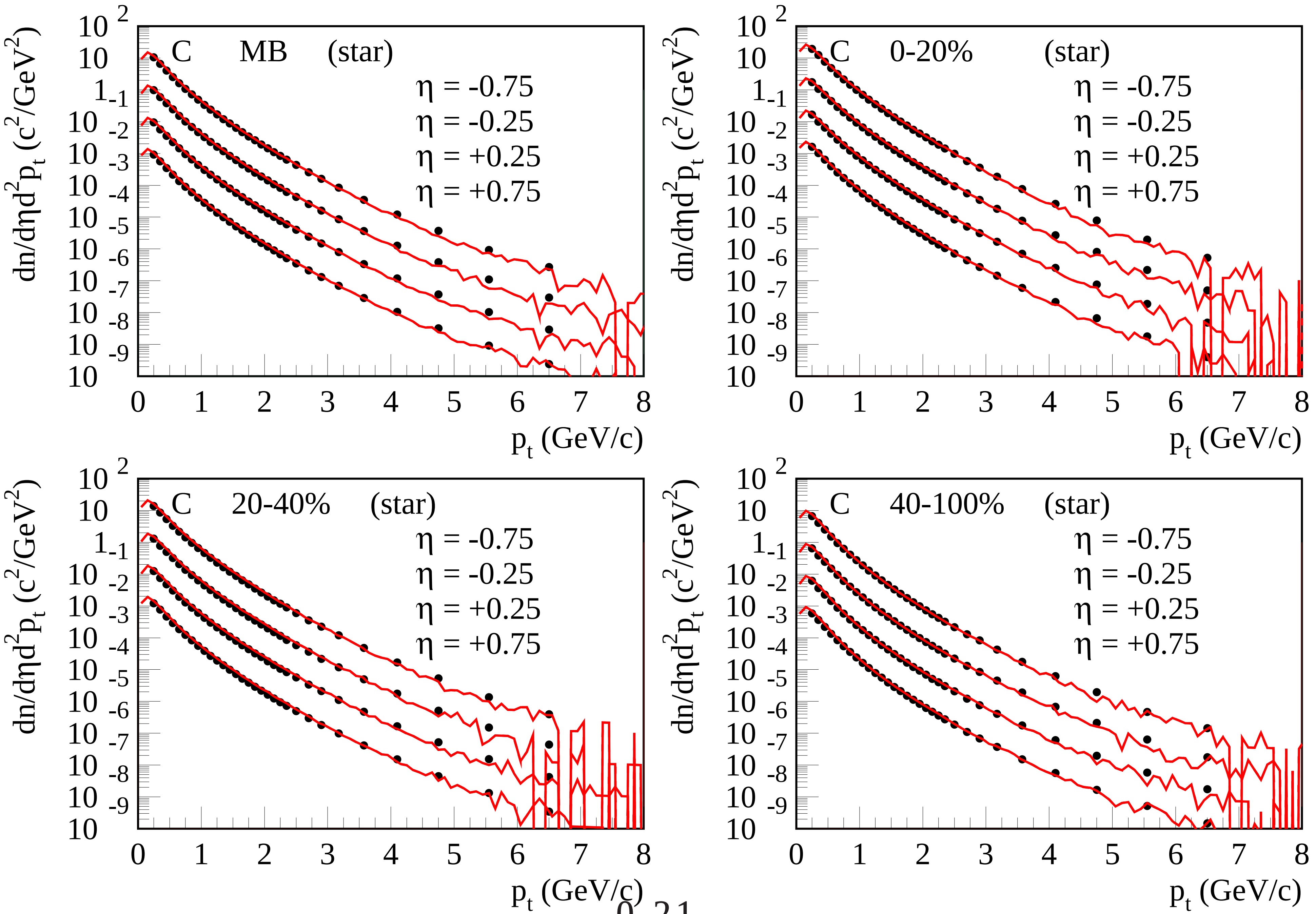
dAu@RHIC: Rapidity distributions of charged particles in

minimum bias different centralities



Very broad remnant distributions!

pt spectra of charged particles in dAu@RHIC



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

AA over pp:

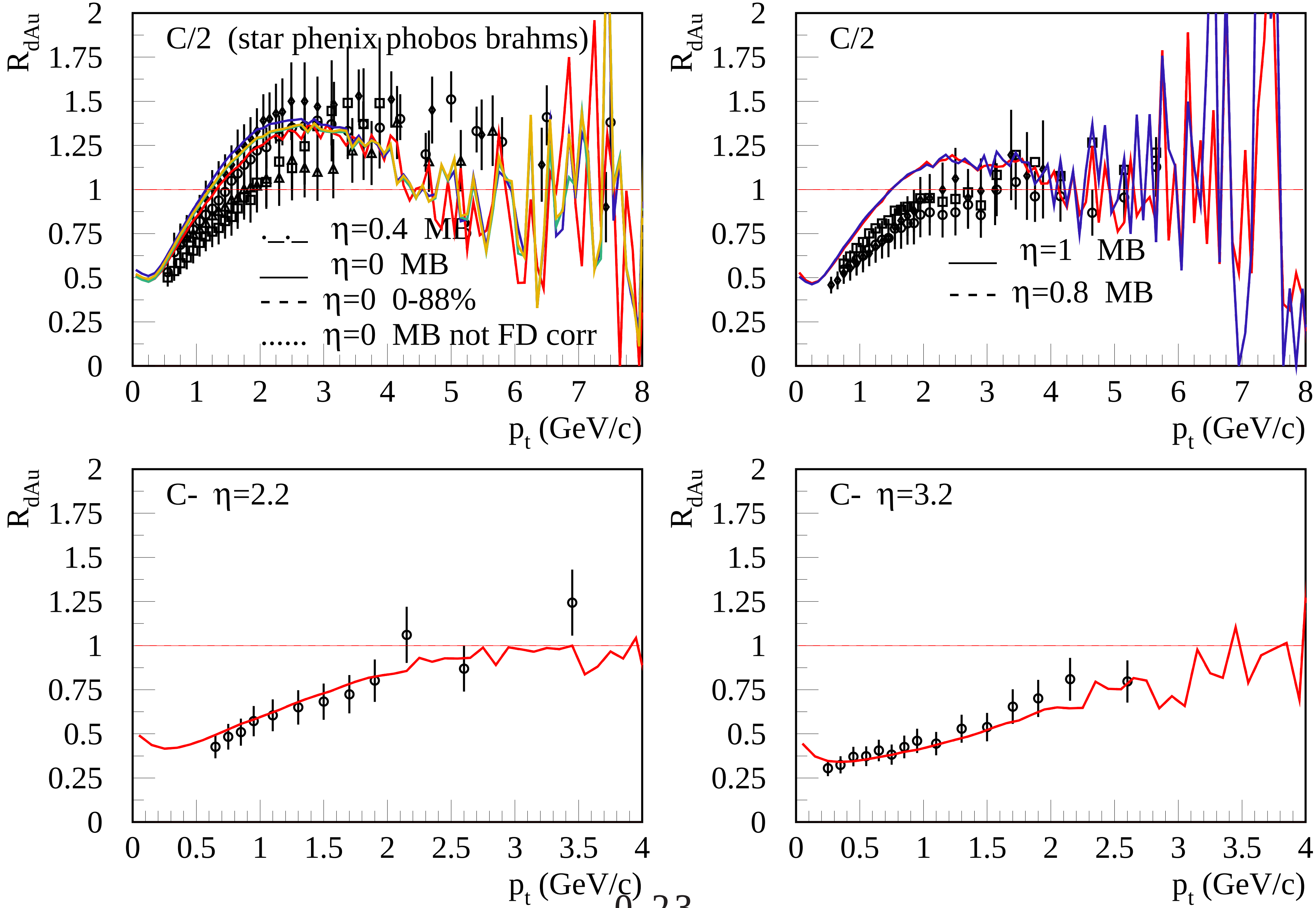
$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \frac{dn^{AA}}{d^2p_t\,dy} \Big/ \frac{dn^{pp}}{d^2p_t\,dy}\,. \qquad (1)$$

or central over peripheral:

$$R_{cp} = \frac{1}{N_{\mathrm{coll}}^{\mathrm{central}}} \frac{dn^{\mathrm{central}}}{d^2p_t\,dy} \Big/ \frac{1}{N_{\mathrm{coll}}^{\mathrm{peripheral}}} \frac{dn^{\mathrm{peripheral}}}{d^2p_t\,dy}\,. \qquad (2)$$

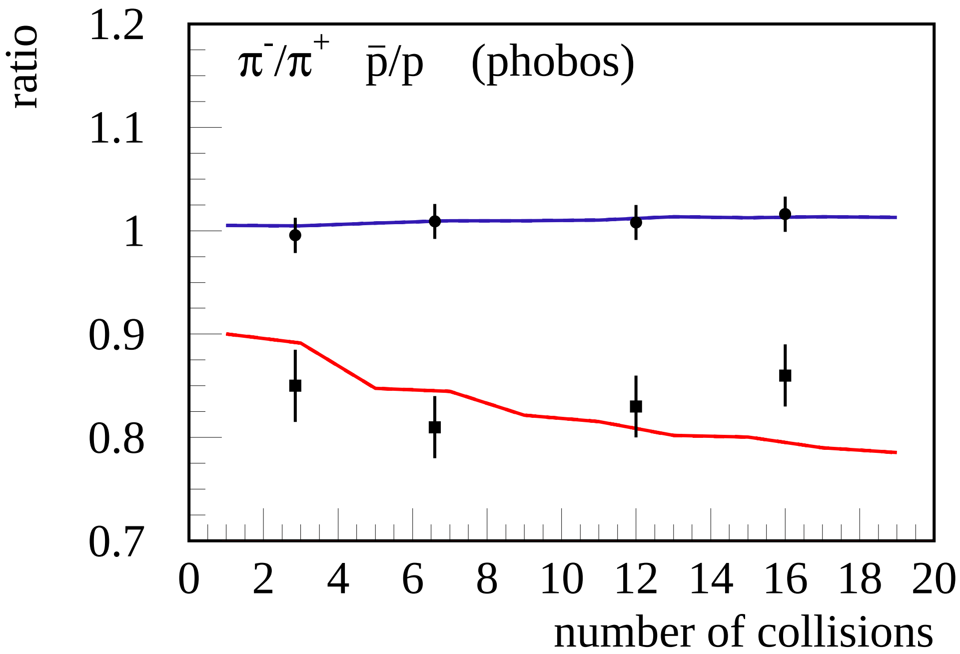
One naively expects $R = 1$ for large pt.

R_AA of charged particles in dAu@RHIC



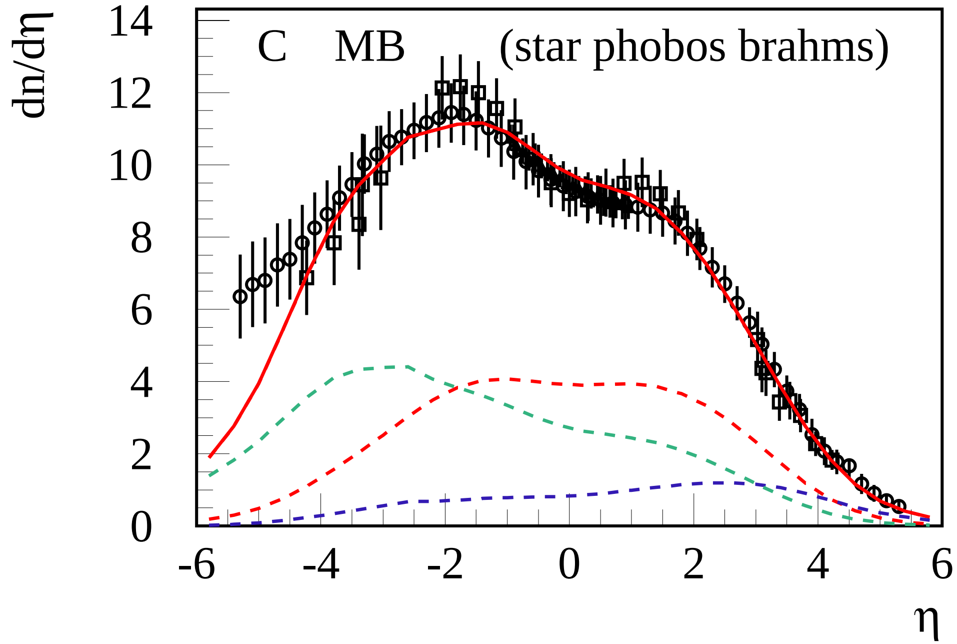
Ratios at $y = 0$ in dAu@RHIC

(related to stopping)



Little centrality dependence of $\bar{p}/p$

Rapidity distribution of charged ptls in dAu (already seen)

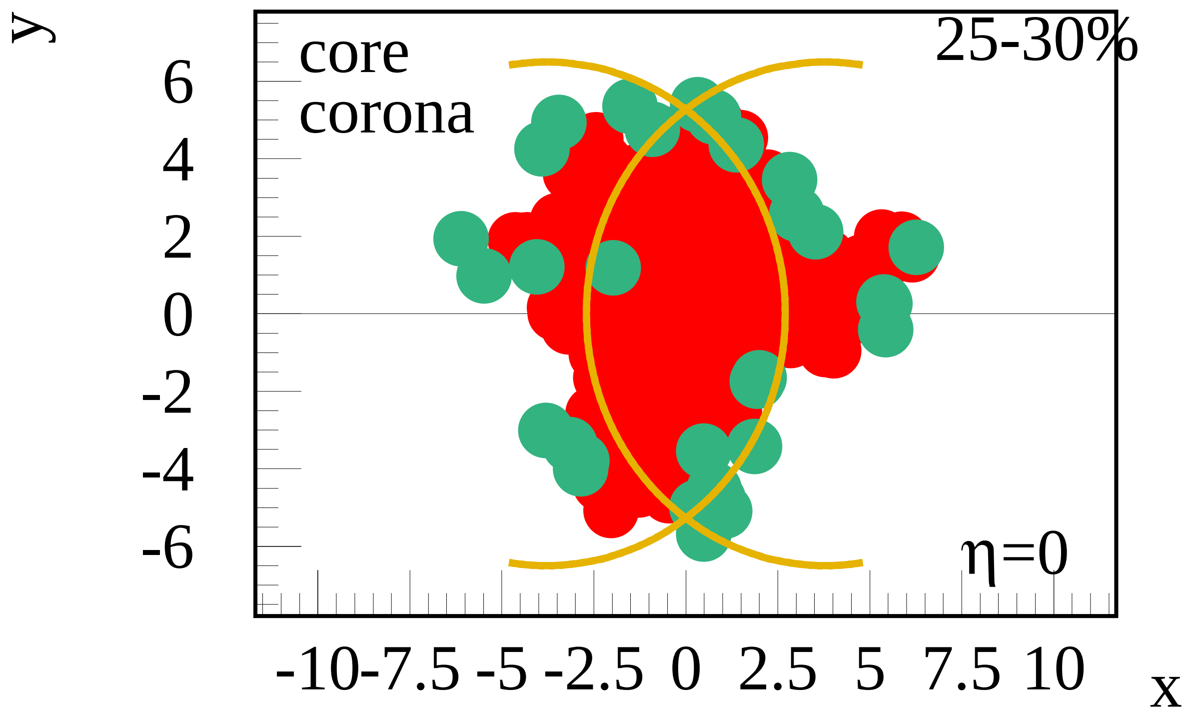


EPOS and Hydro for AA

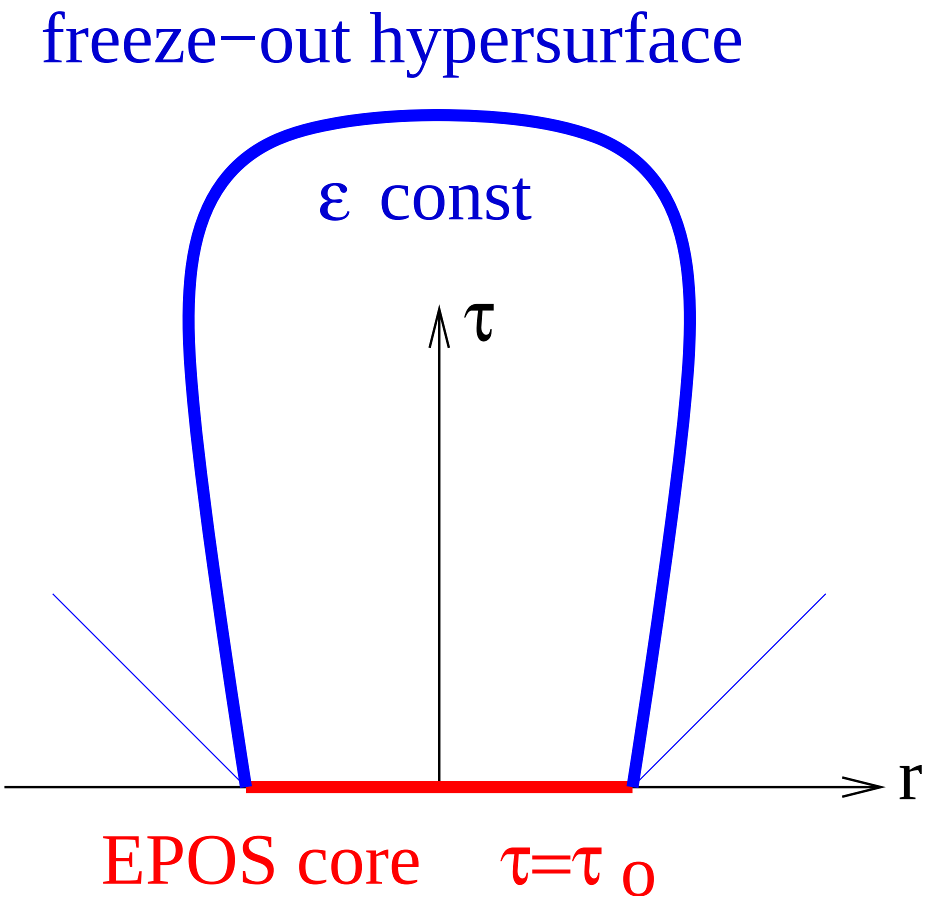
=> collective behavior, flow

Core-corona separation

EPOS as usual
$\rightarrow$
parton ladders
$\rightarrow$
string segments
$\rightarrow$
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**

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

on the **FO hypersurface** given as

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

What we need is the **FO rate**

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

All quantities depend on η.

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

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

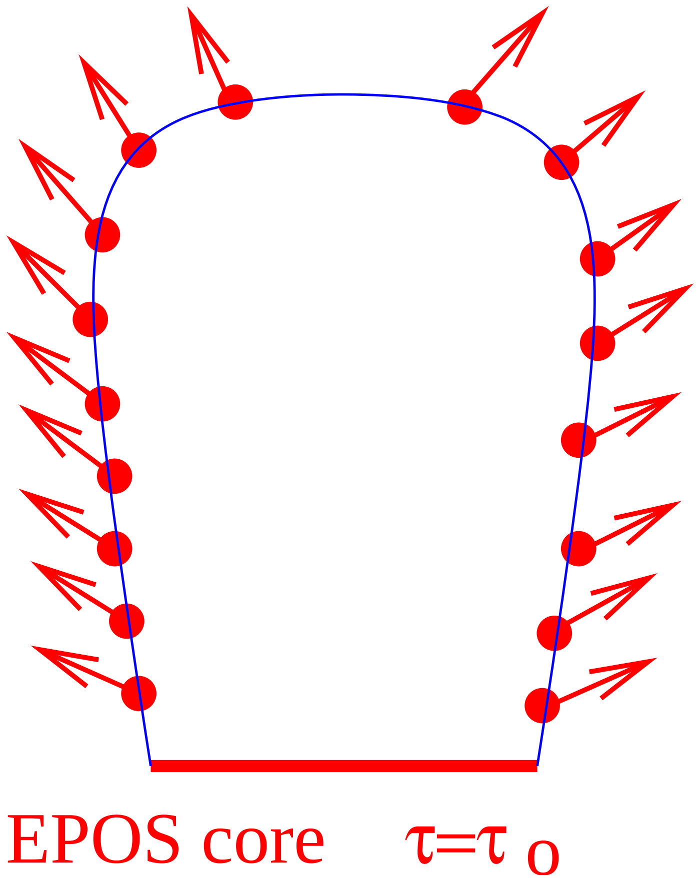
the energy is

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

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!

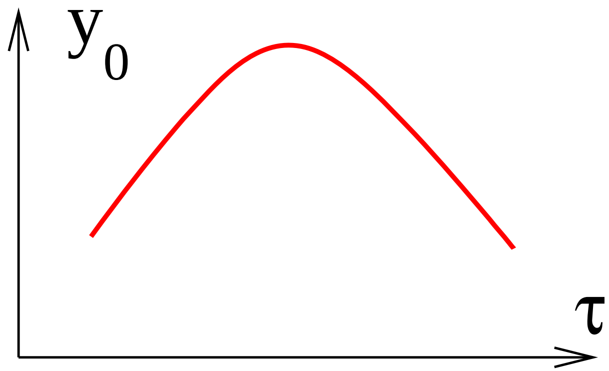
We suppose that the effective invariant mass



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 fuctions 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

$$f = \int w_{\mathrm{FO}} d\tau d\varphi / \int \cosh(y_{\mathrm{FO}}) w_{\mathrm{FO}} d\tau d\varphi.$$

- □ Decay the mass M according to microcanonical phase space (conserving energy, momentum, flavor)

- For each particle, generate randomly a transverse rapidity y_0 according to $w_0(y_0)$

- Generate randomly an angle φ according to

$$w_0(y_0) + w_2(y_0)\cos(2\varphi)$$

- Assign y, r, and τ to each particle as

$$y_{\rm FO} = y_0 + y_2(y_0)\ \cos(2\varphi),$$

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

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

First option: simply parameterize FO

We use [3]

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

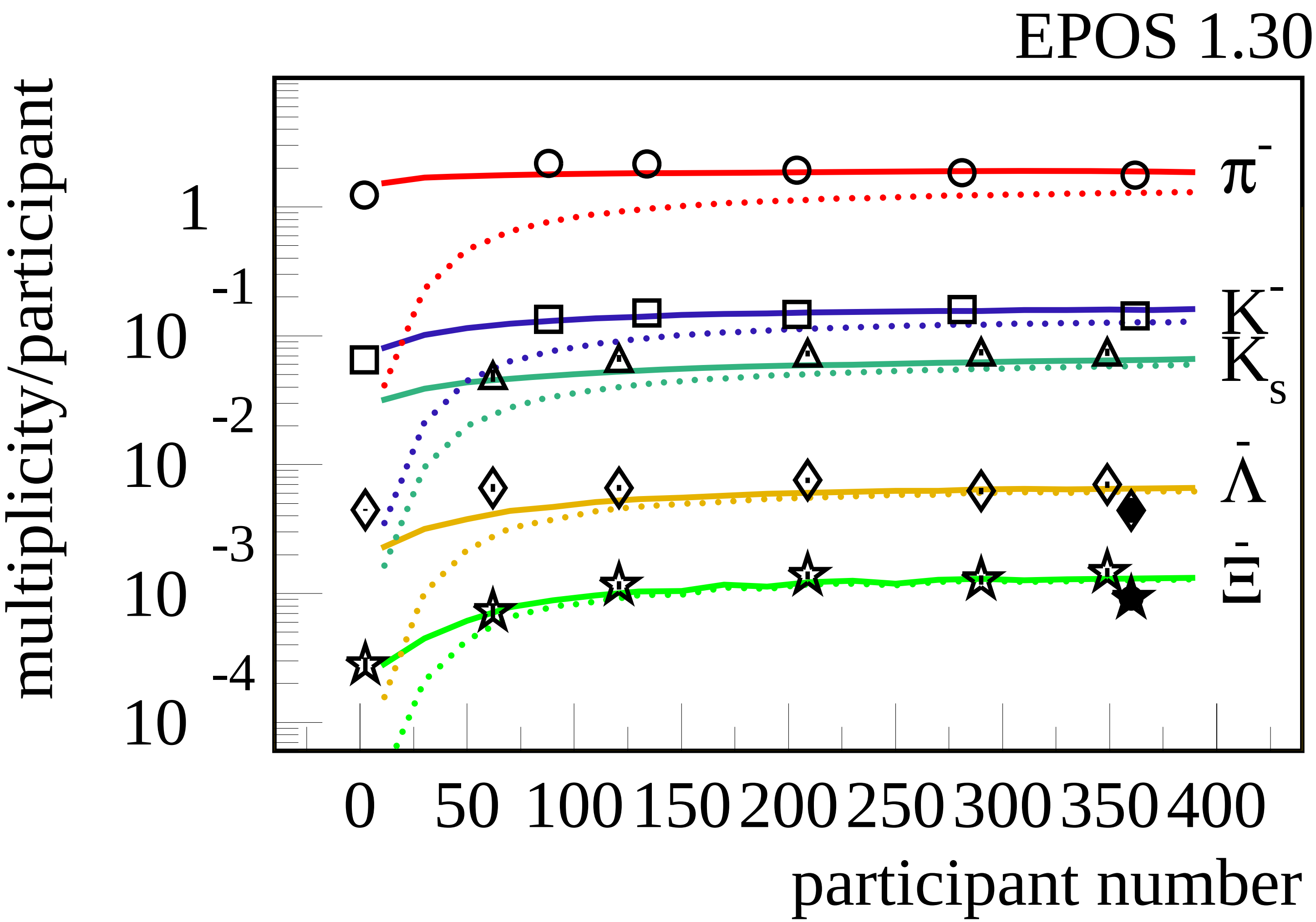
with $y_{\max}$ equal to 0.75 for RHIC and 0.55 for SPS.

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

[3] compare blast wave fit

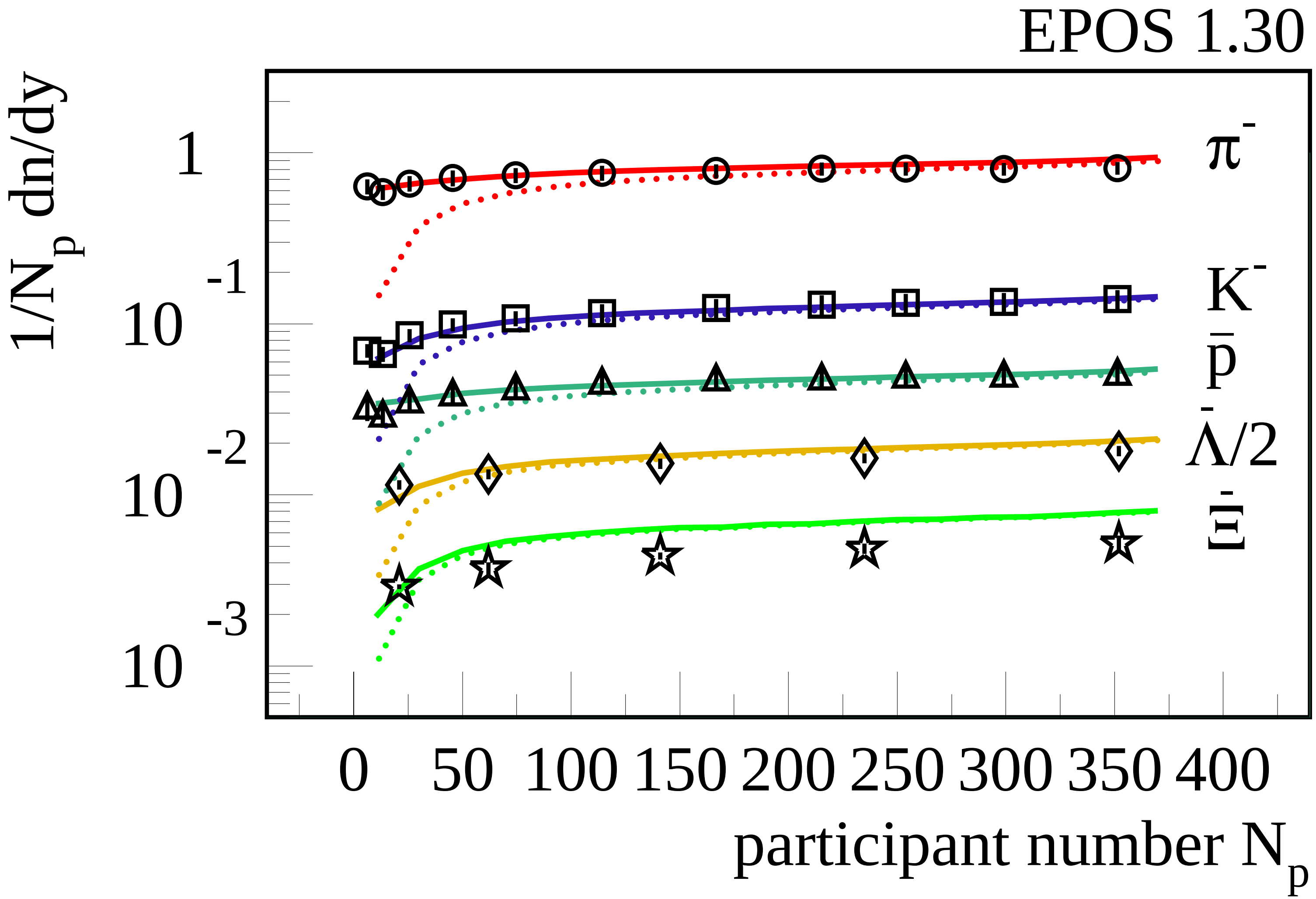
PbPb@SPS: Multipl/Npart vs Npart

grows faster for “rare” particles



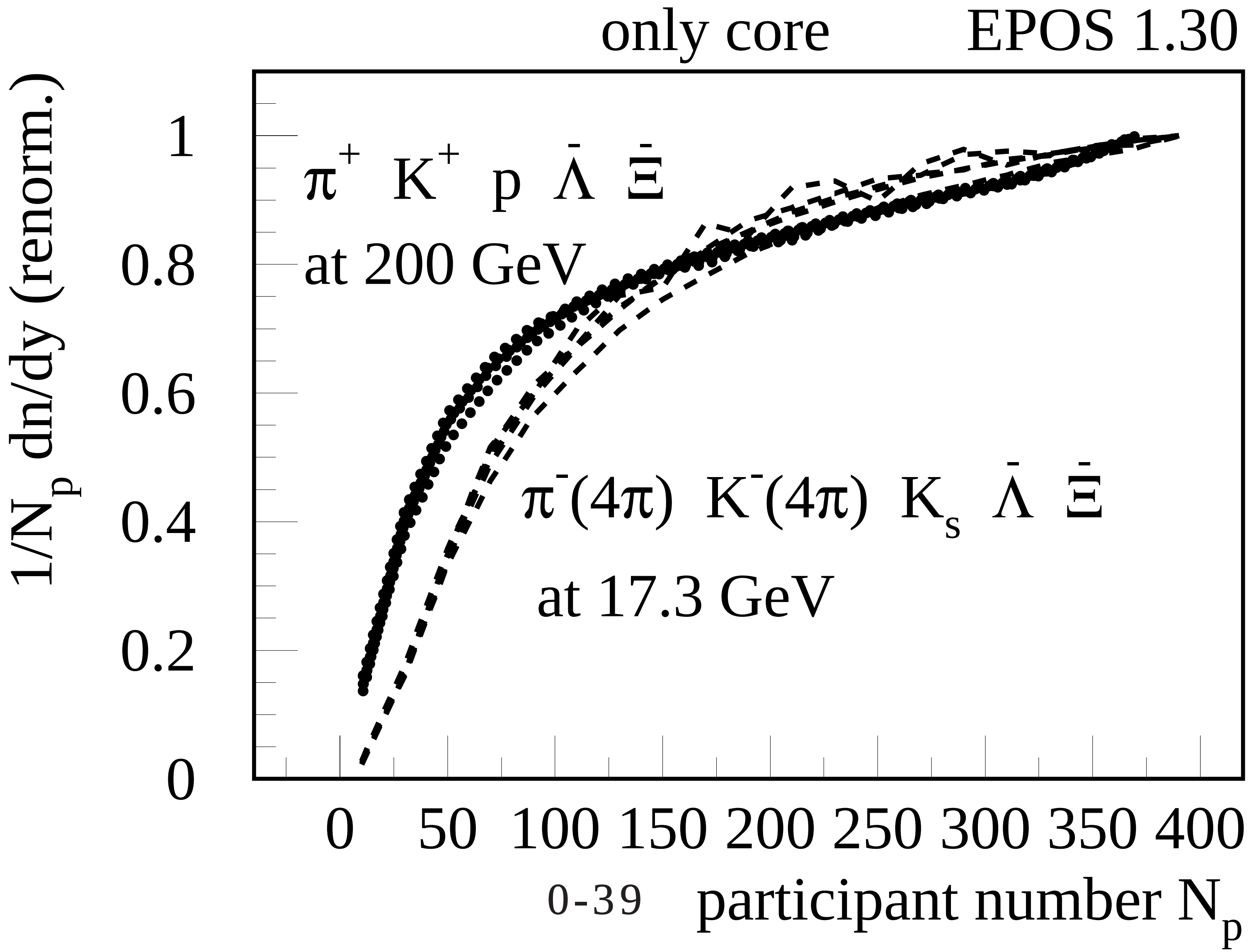
AuAu@RHIC: Multipl/Npart vs Npart

grows faster for “rare” particles



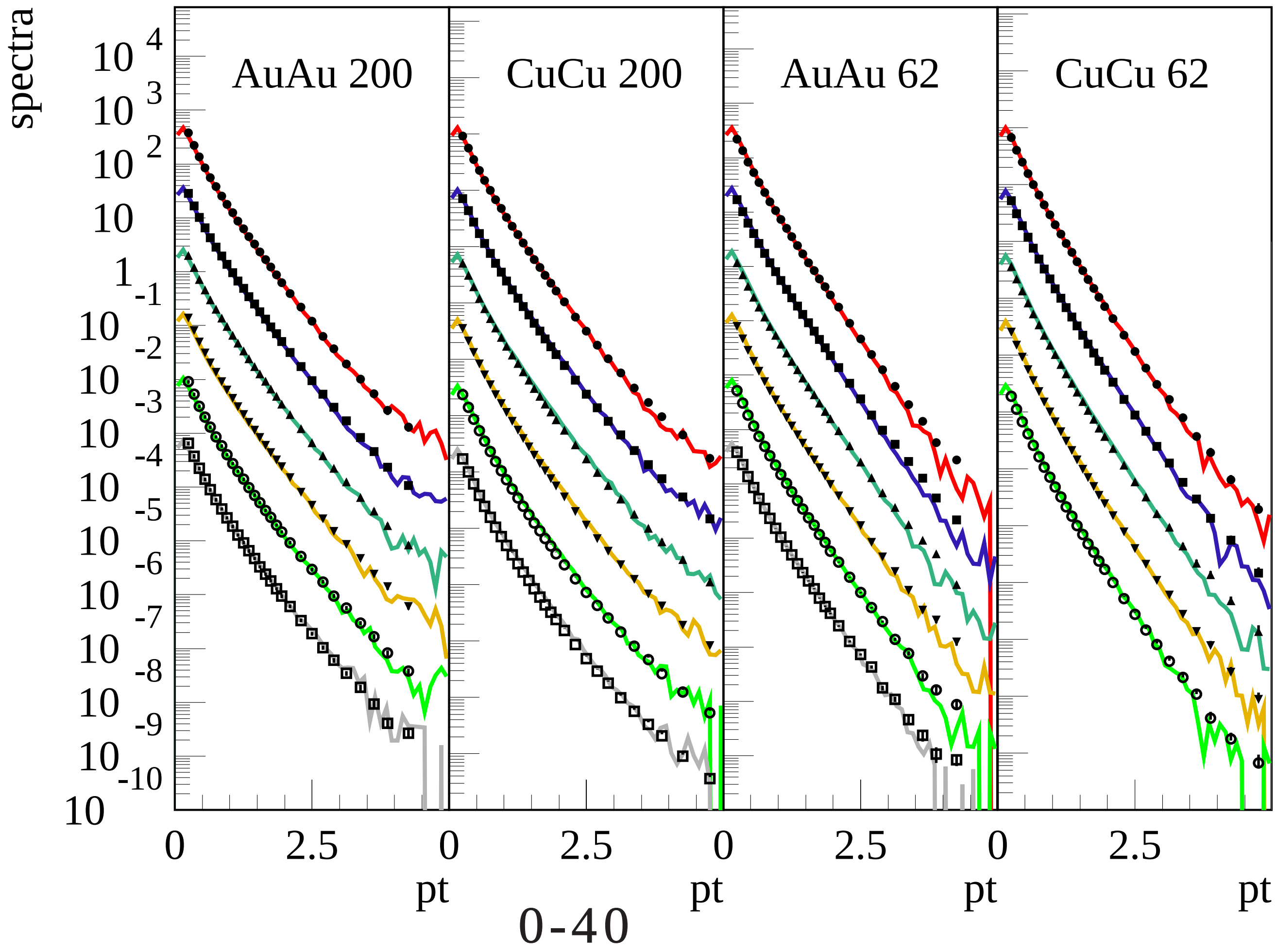
Multipl/Npart vs Npart

universal curves



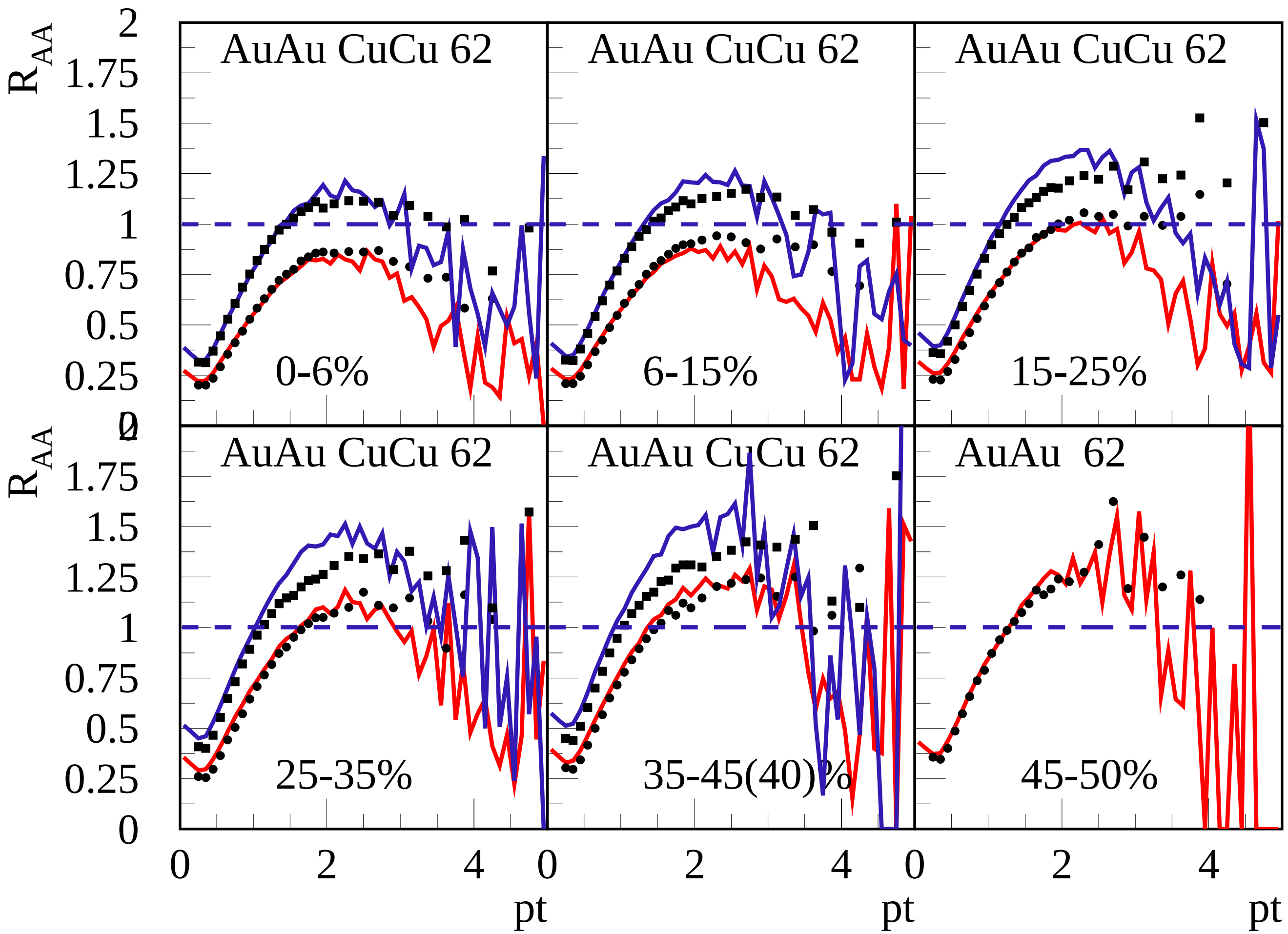
AA@RHIC: pt spectra

different energies, different nuclei (data=Phobos)



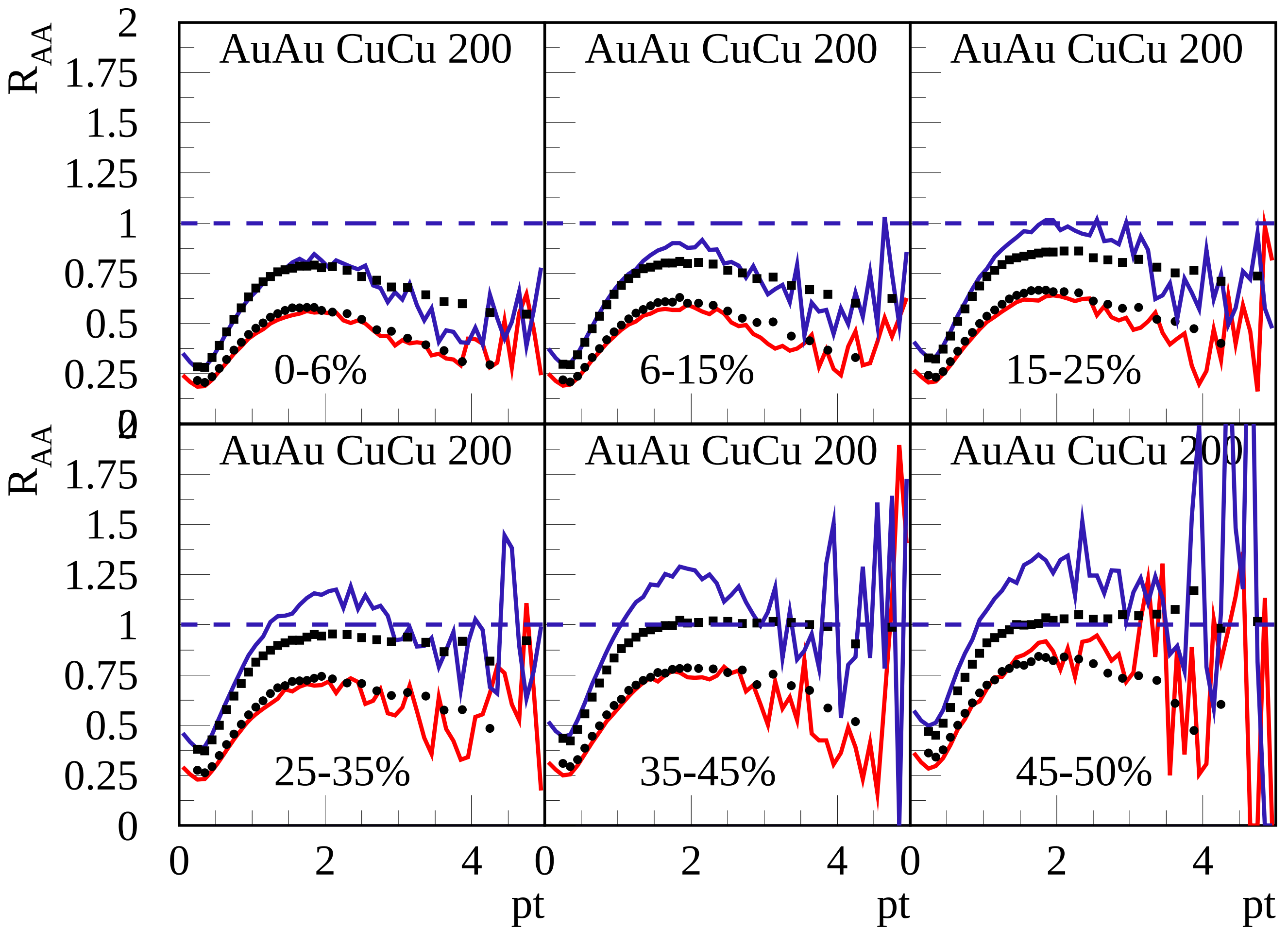
AA@RHIC: R_AA

62 GeV, different nuclei (data=Phobos)



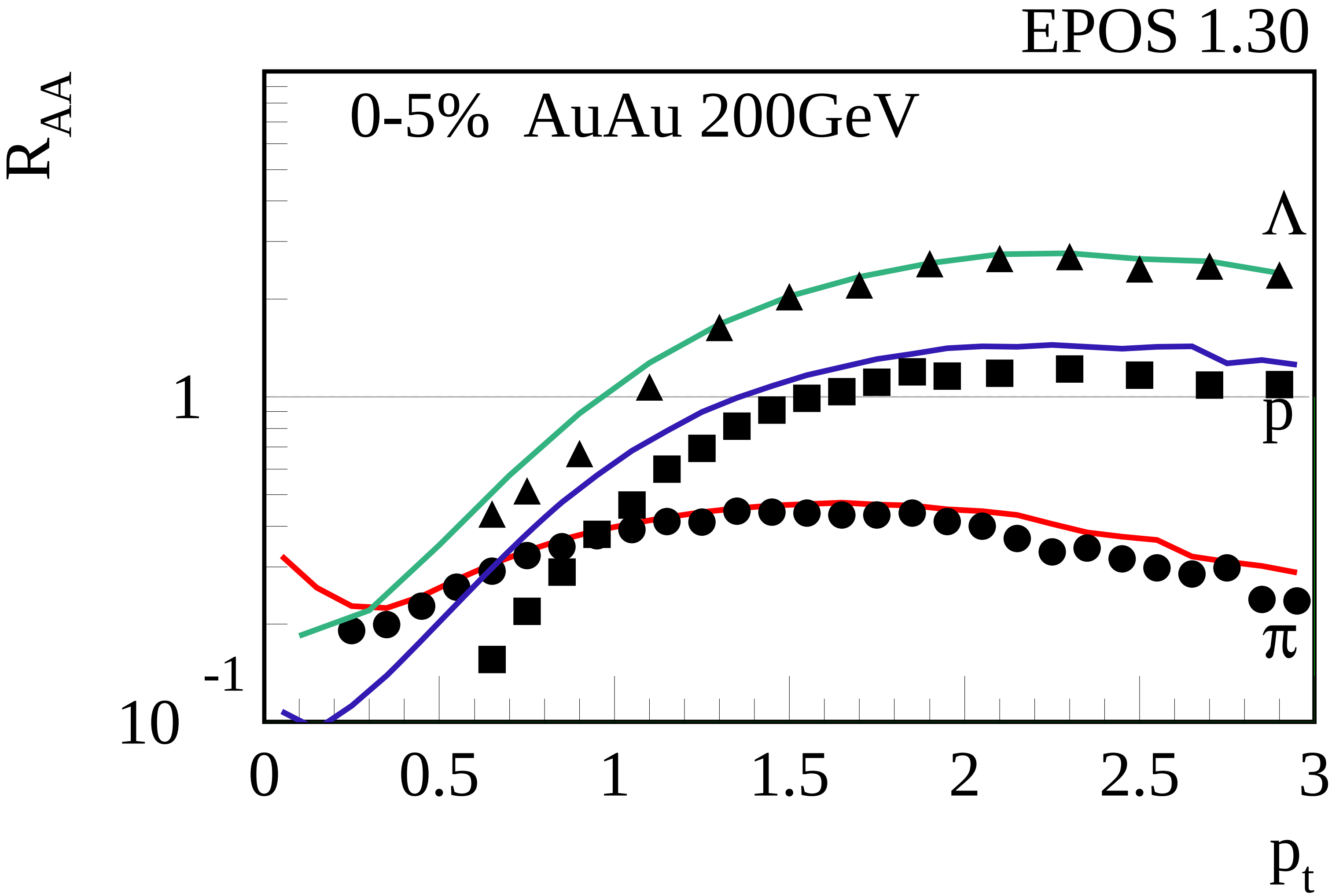
AA@RHIC: R_AA

200 GeV, different nuclei (data=Phobos)



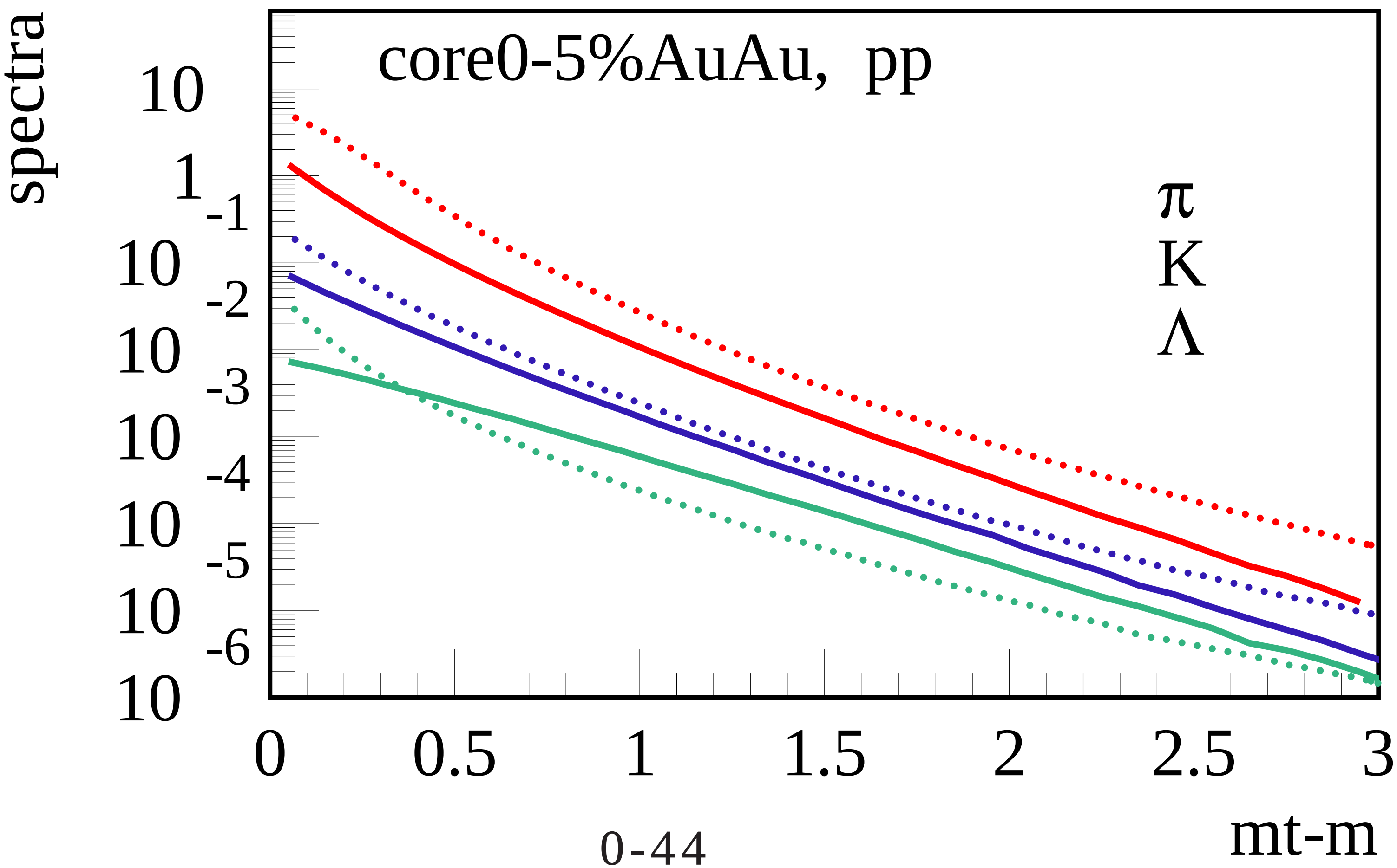
central AuAu@RHIC: R_AA

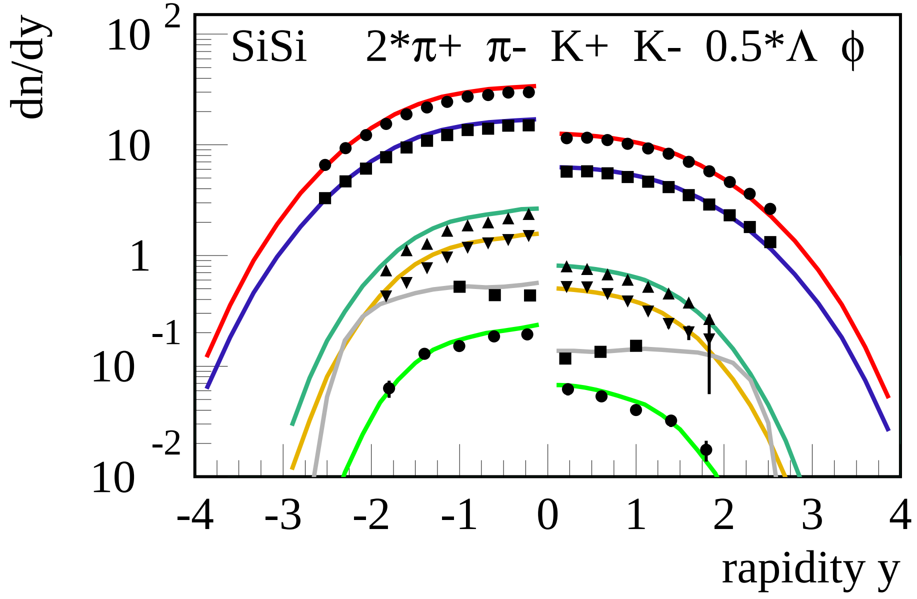
different particles

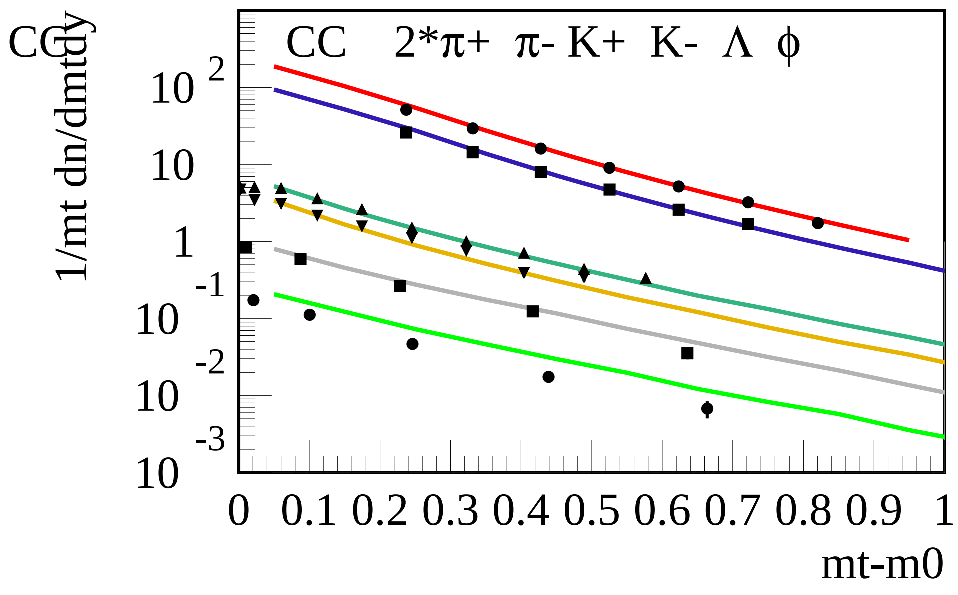


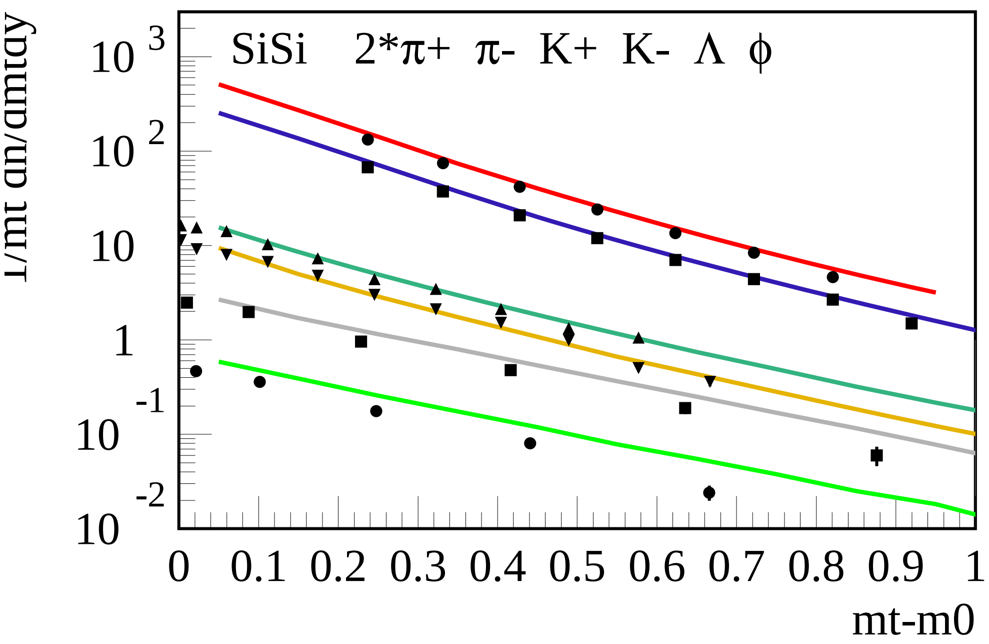
R_AA easy to understand: compare core and pp

flow affects shape of heavy particles









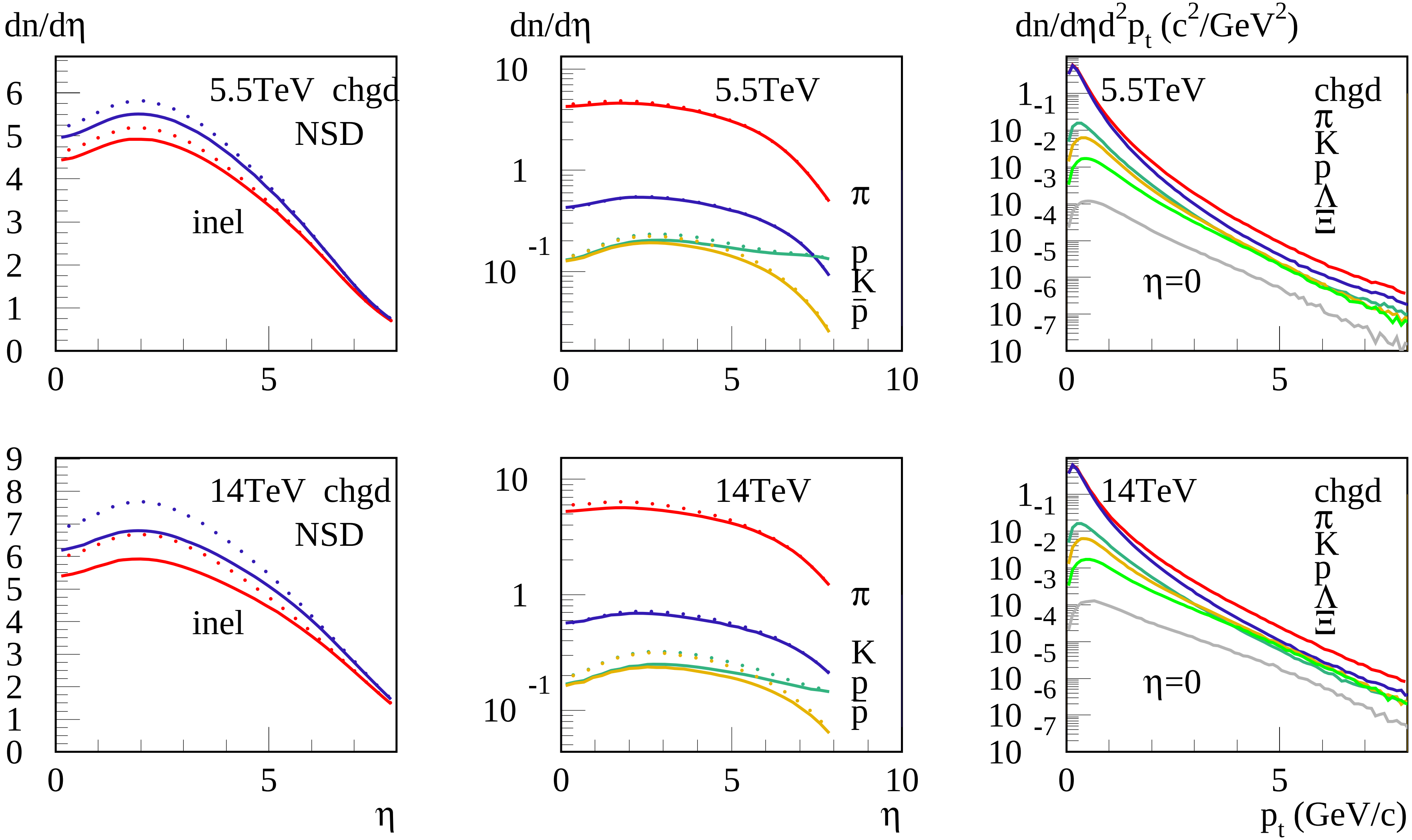
CC, SiSi at SPS

rapidity distr,
pt spectra

EPOS Predictions for LHC

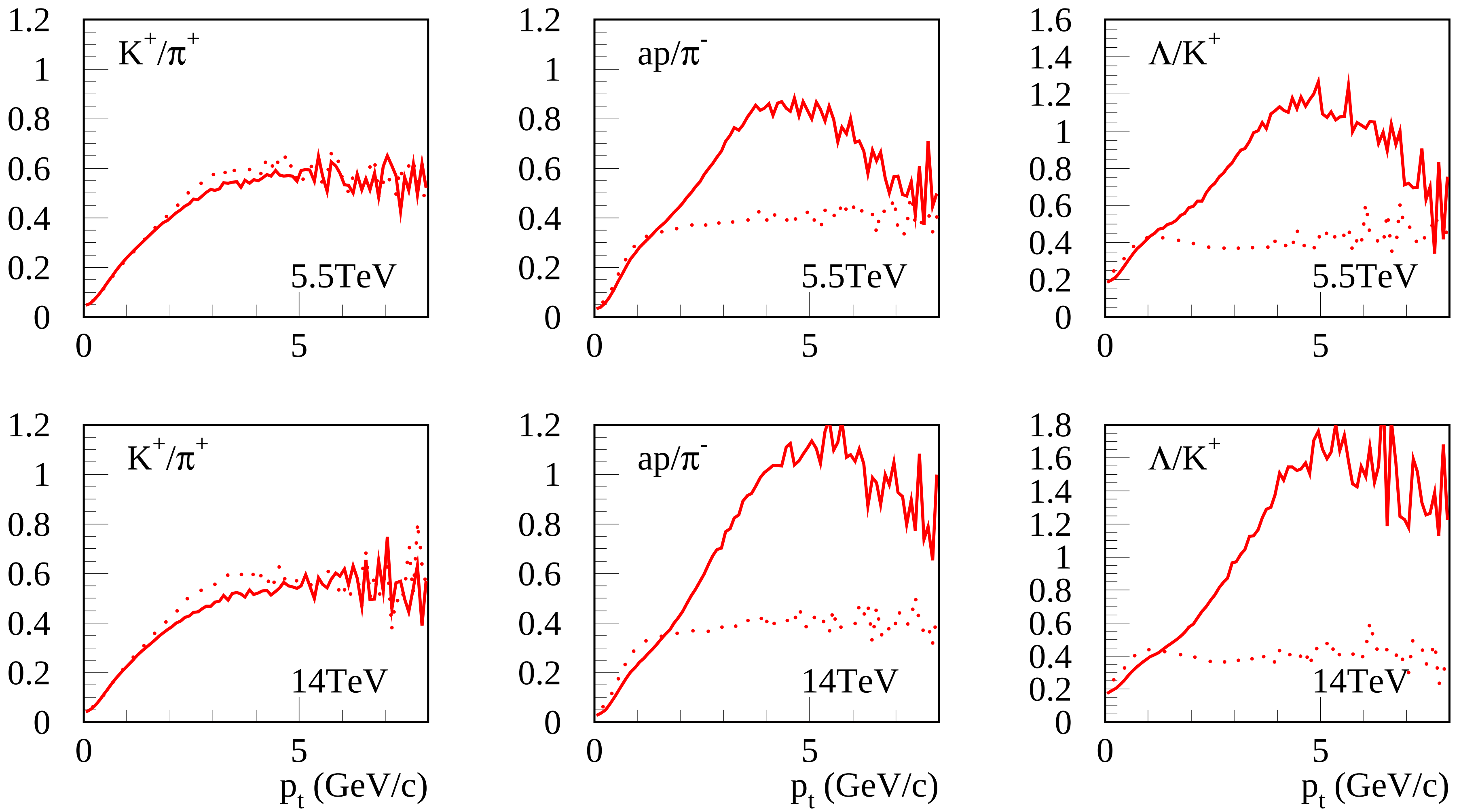
pp at LHC: particle spectra

with and without "mini-plasma"



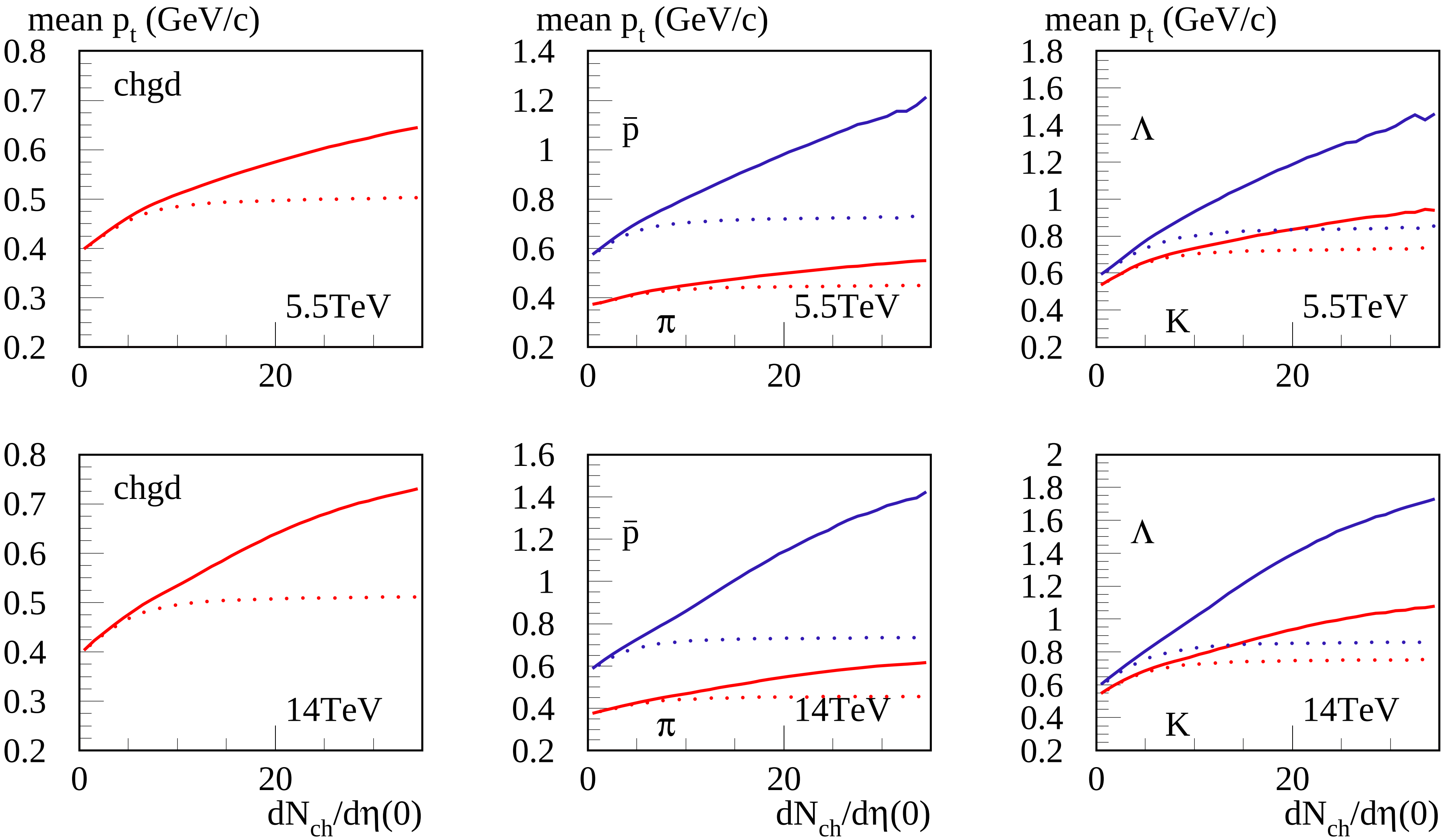
pp at LHC: particle ratios

with and without "mini-plasma"

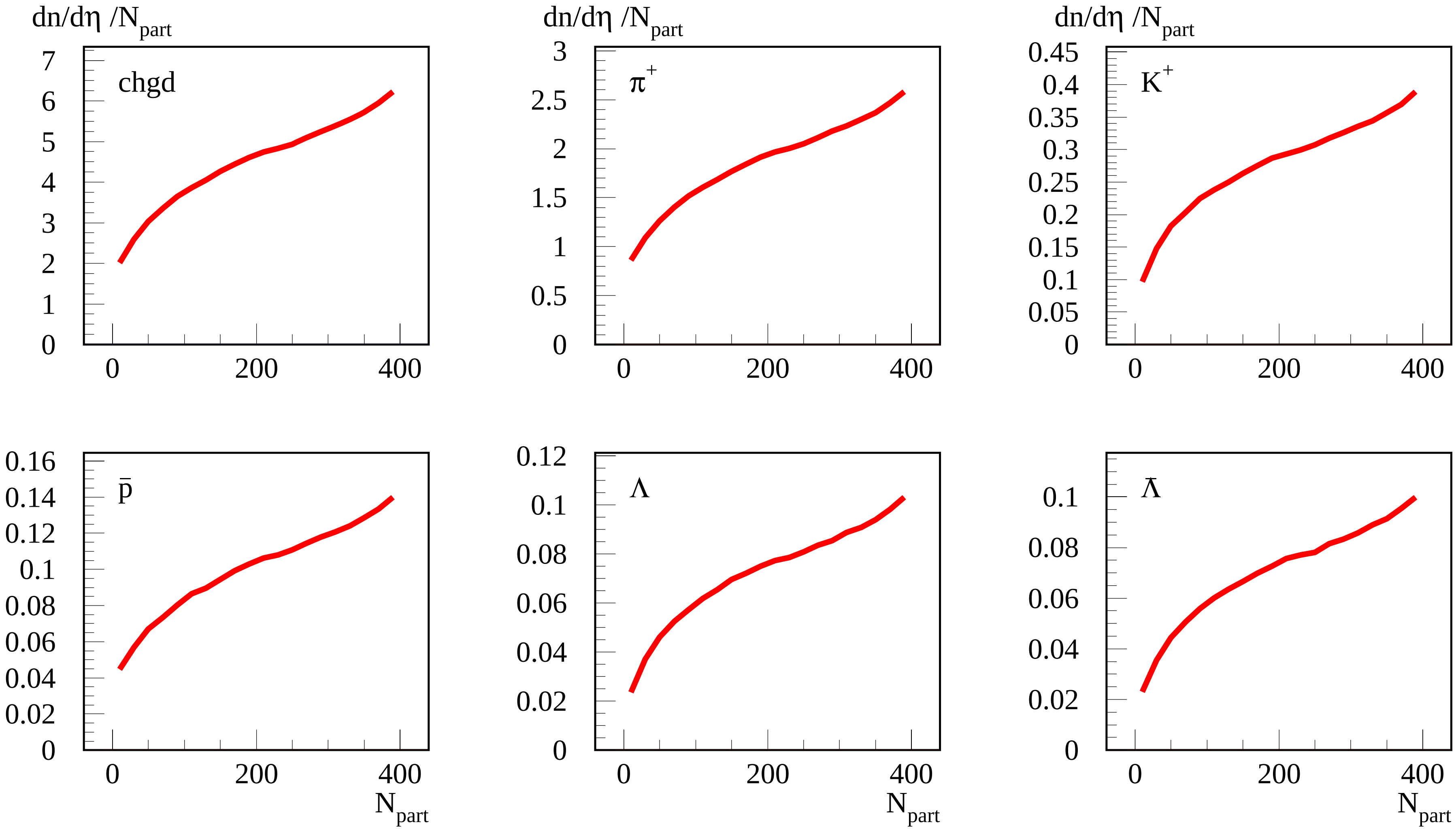


pp at LHC: mean pt vs multiplicity

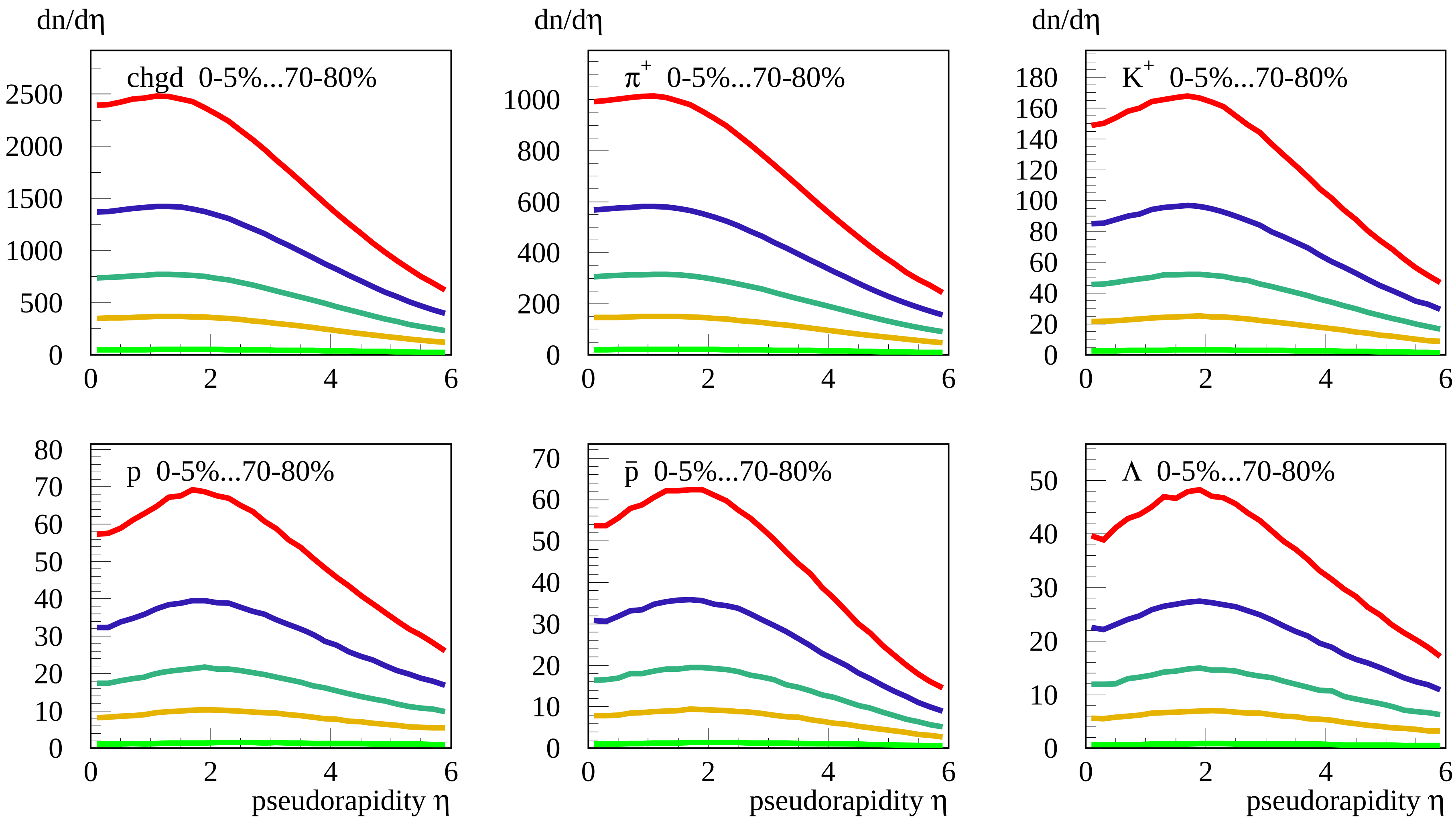
with and without "mini-plasma"



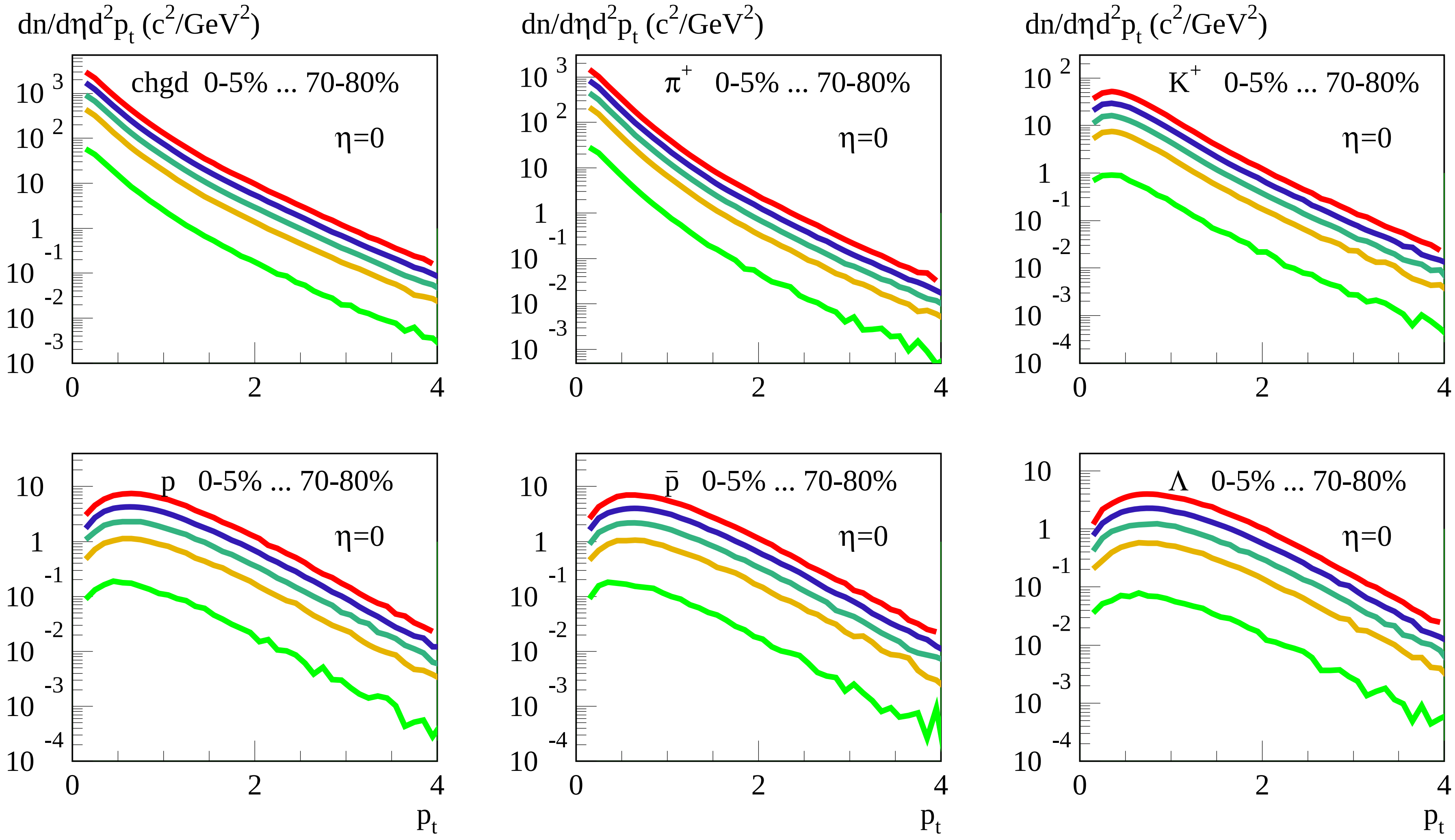
PbPb at LHC: Multipl/Npart vs Npart



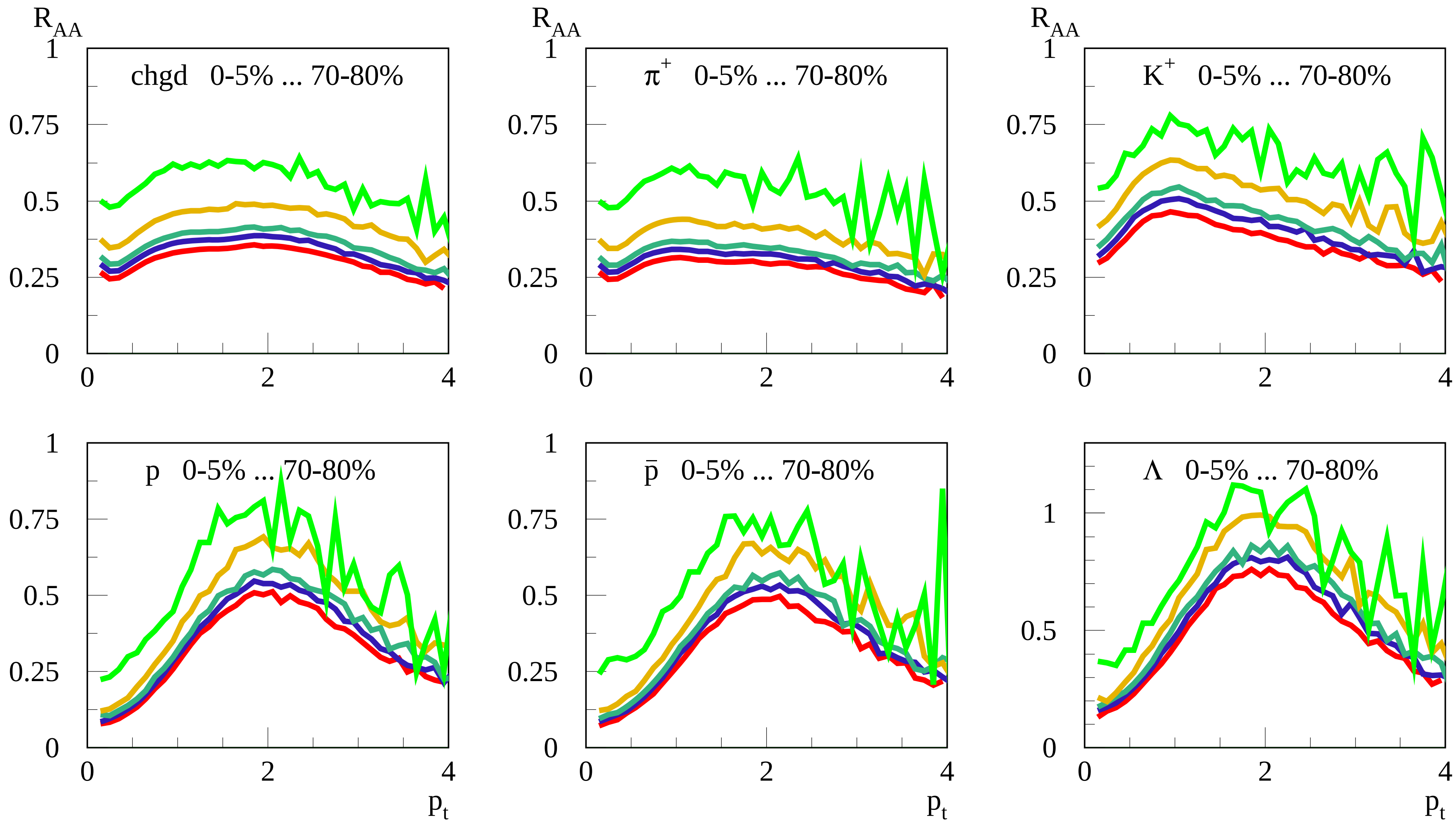
PbPb at LHC: Pseudorapidity distributions



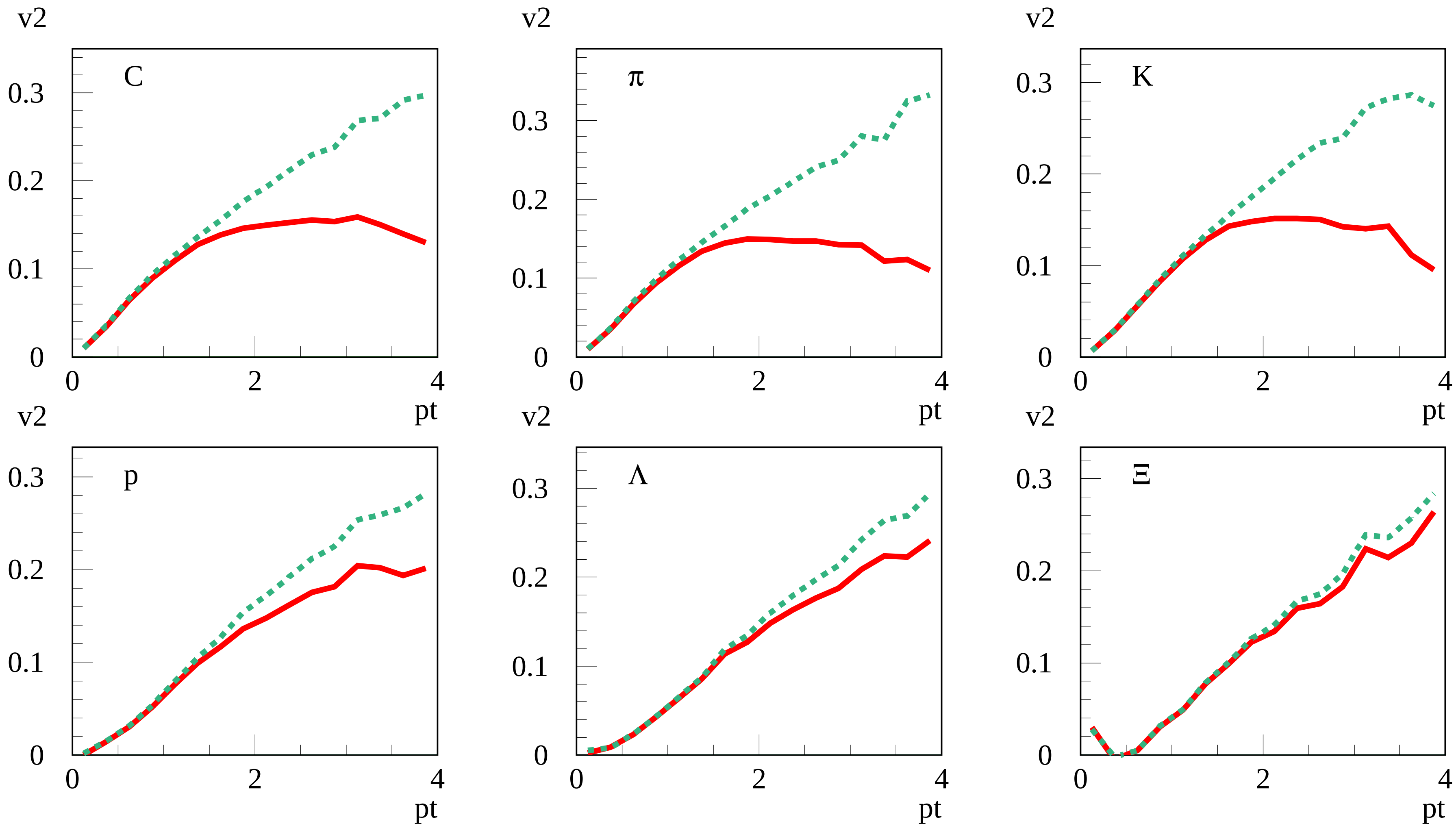
PbPb at LHC: pt spectra



PbPb at LHC: R_AA **pp already flowing !**



PbPb at LHC: elliptical flow

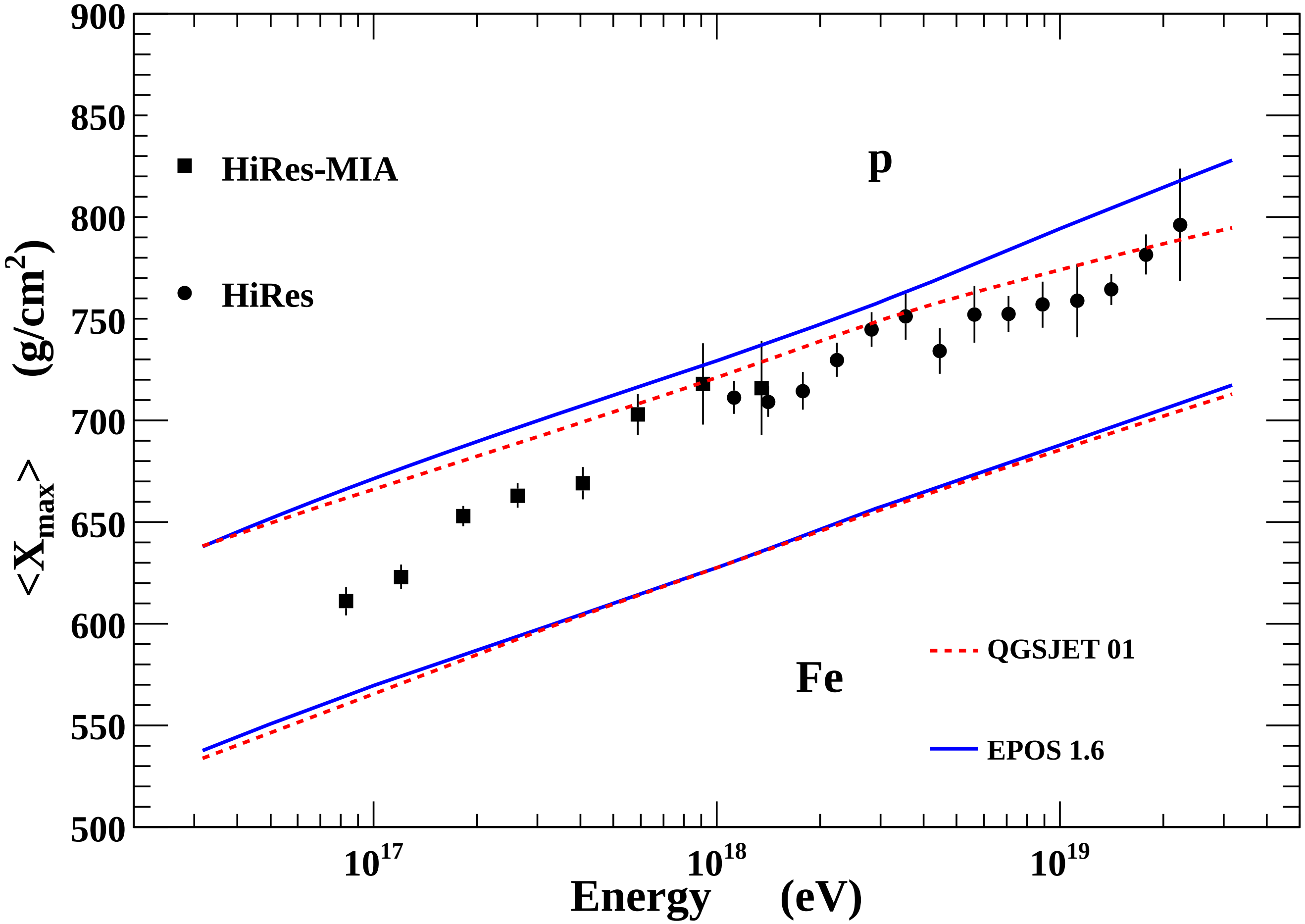


Simulating

Cosmic Ray Air Showers

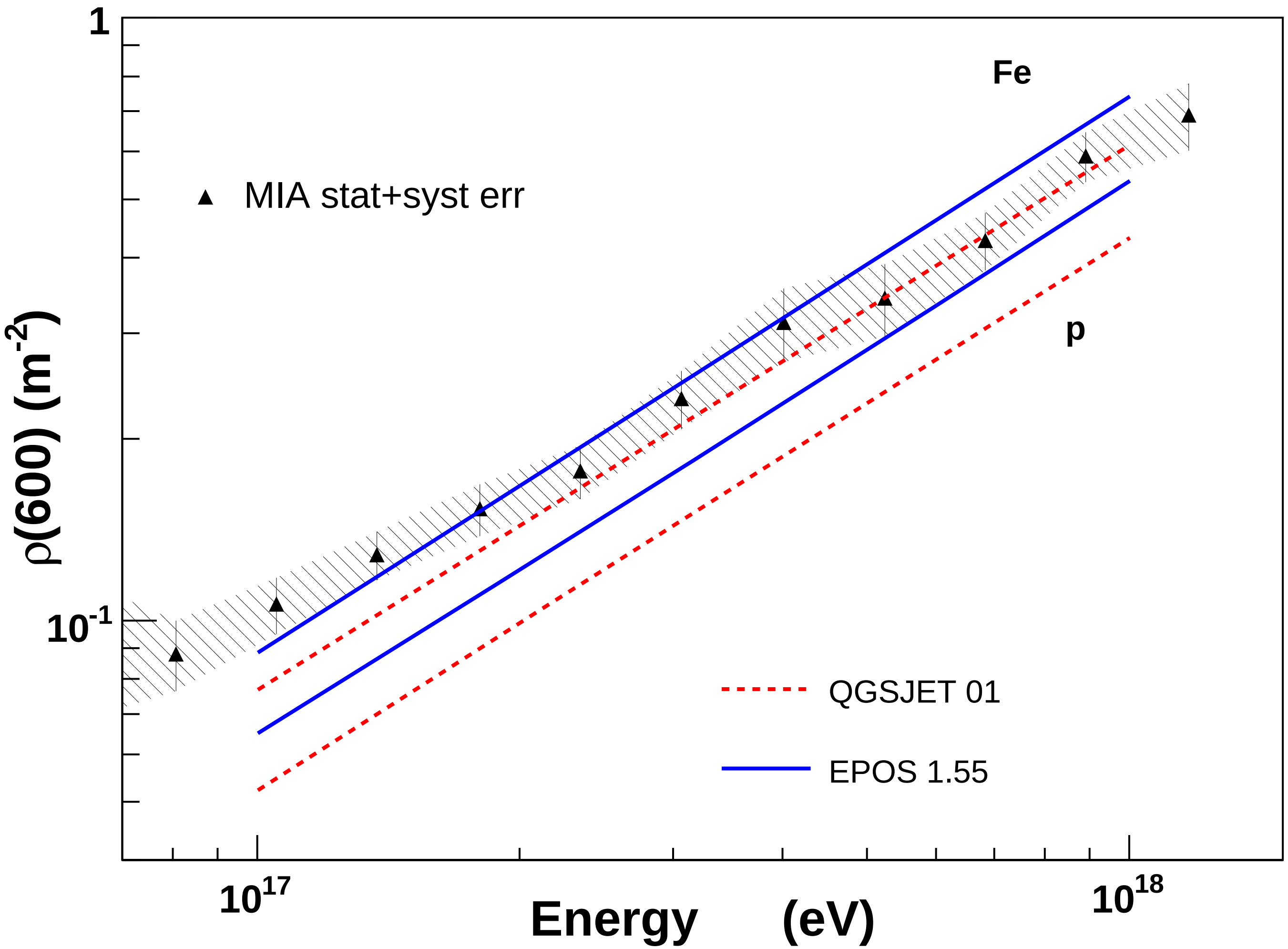
Using EPOS

EAS using EPOS: Xmax

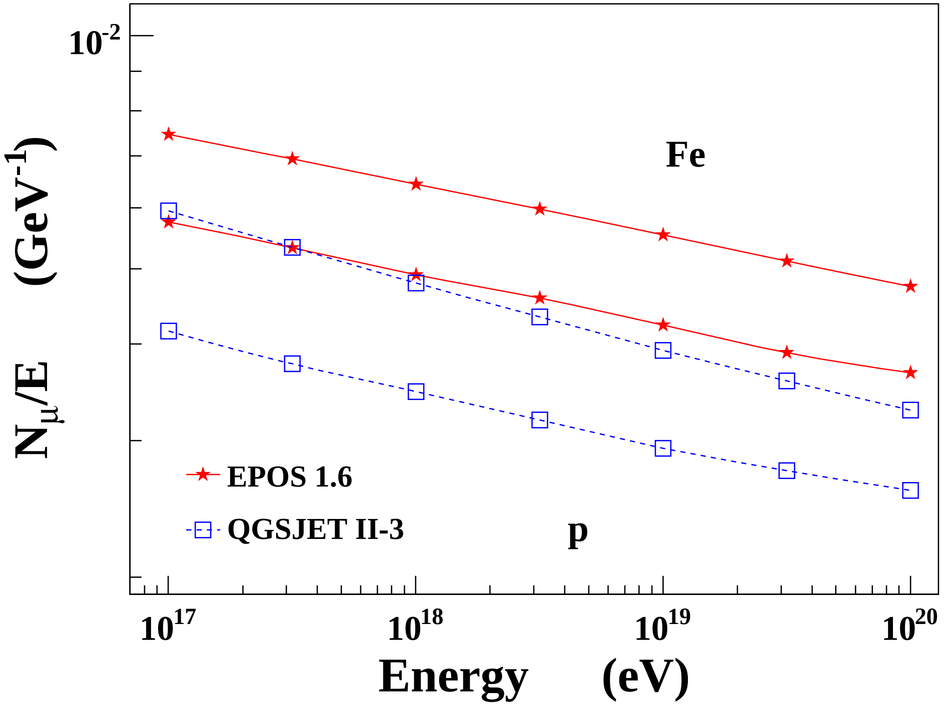


We employ CONEX or CORSIKA, and GHEISHA as low energy model

Muon density $\rho(600)$

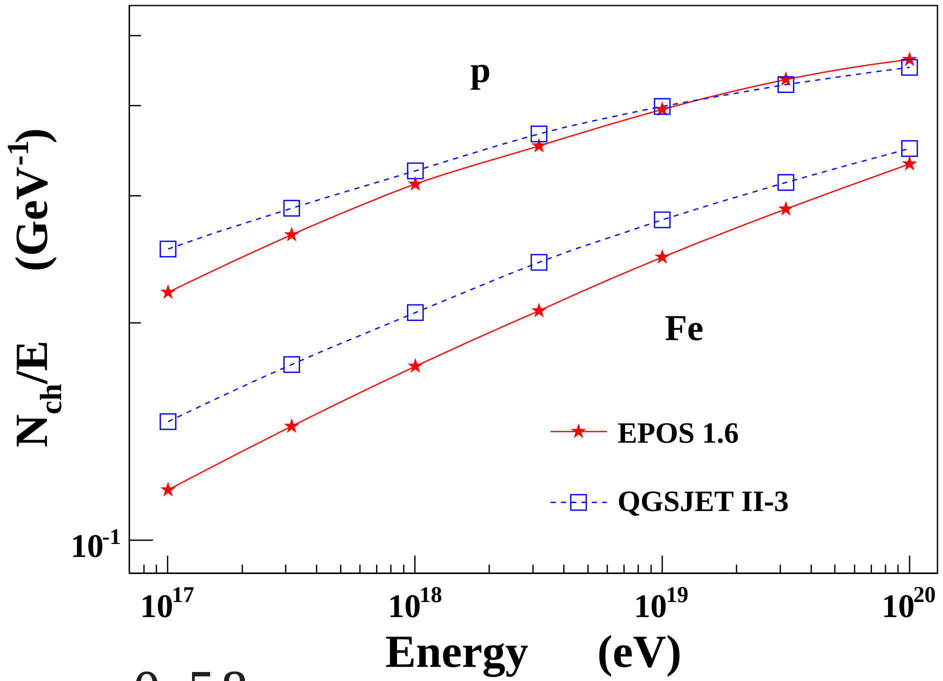


much more muons in EPOS

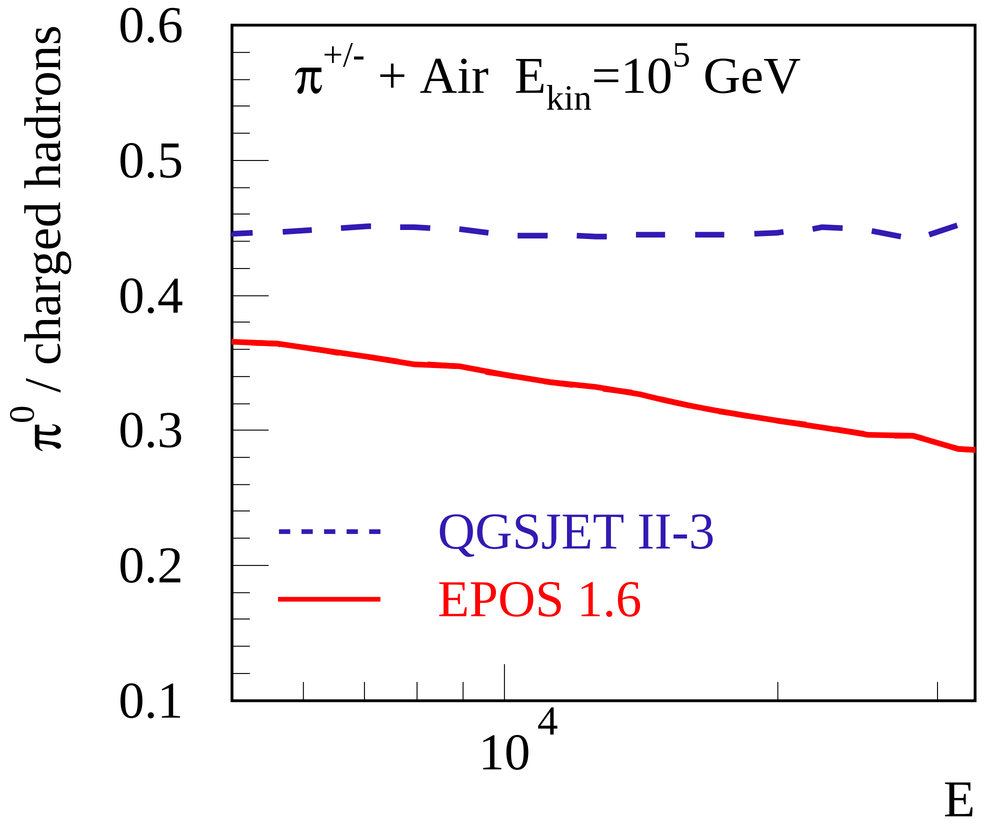


charged particles similar

compared to other models



Why so many muons?



EPOS red, QGSJET II blue dashed,

Pion-Air collisions:

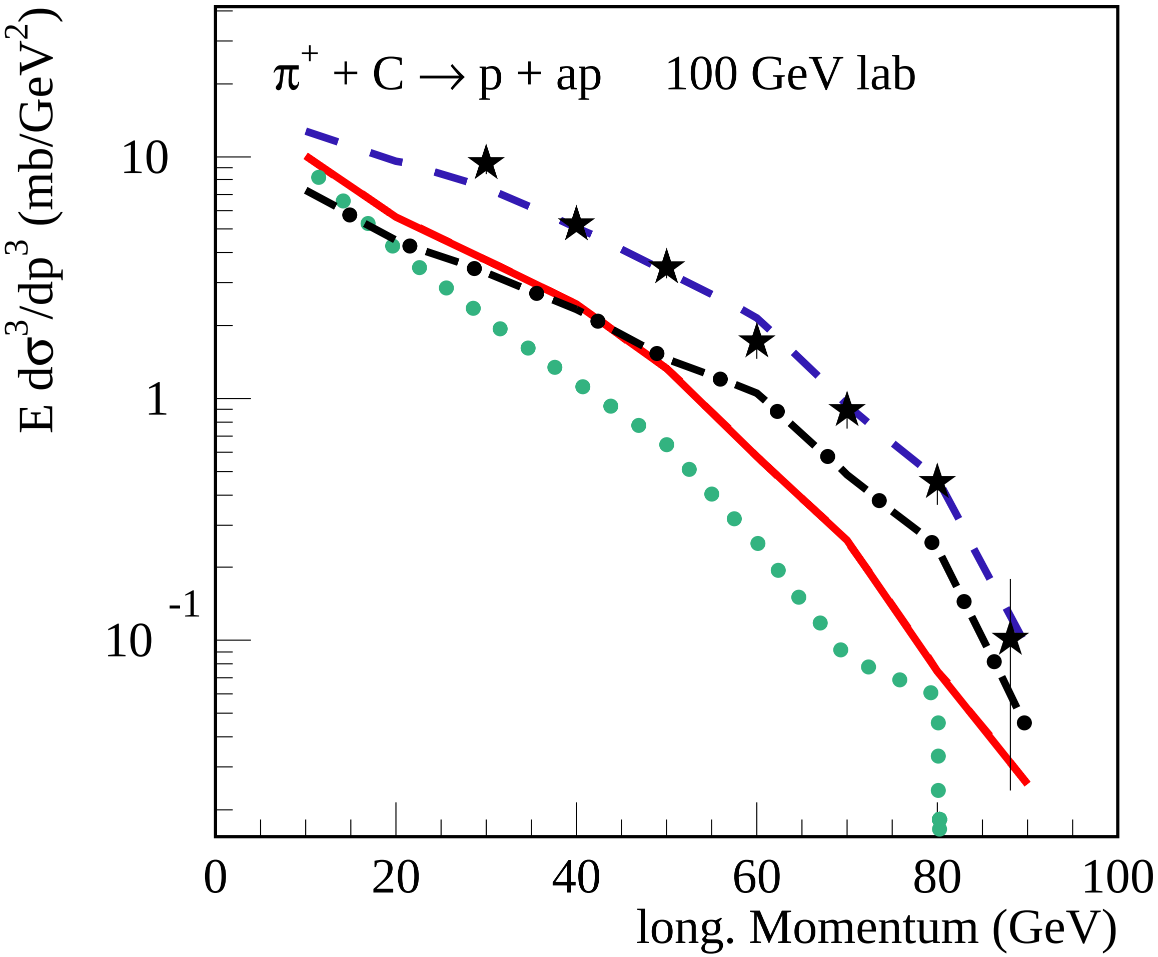
$$R = \frac{\pi^0}{\text{charged hadrons}}$$

R is smaller in EPOS compared to all other models

$\rightarrow$ more muons

Smaller R in EPOS

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



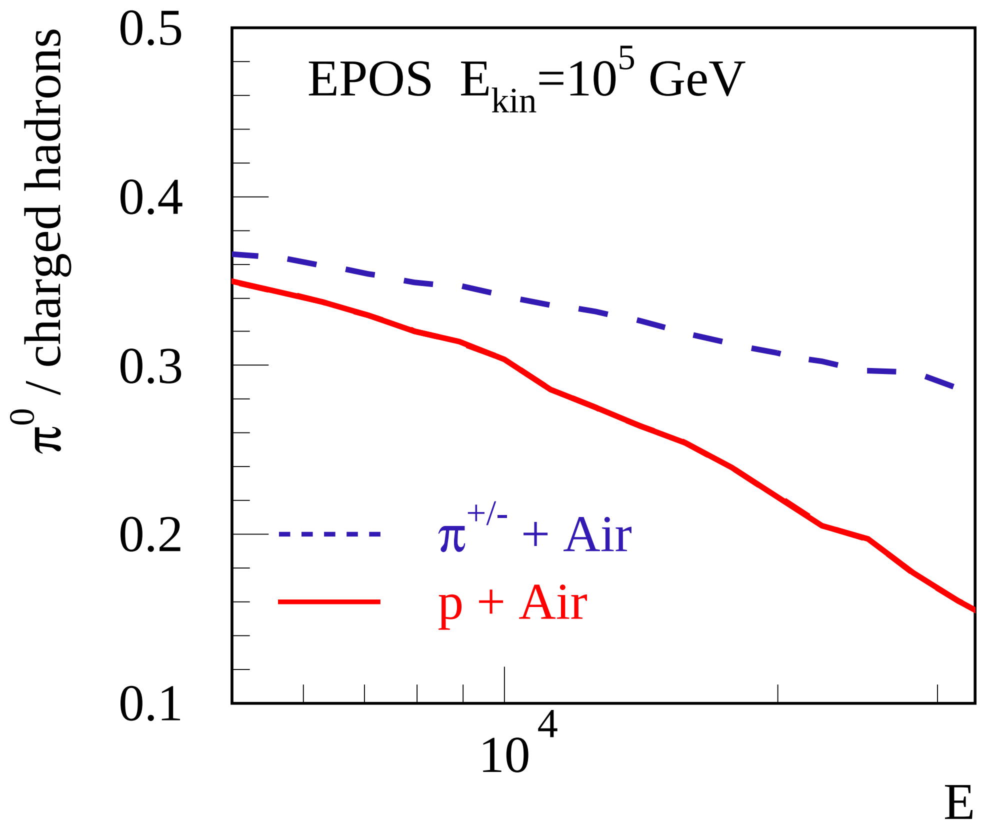
EPOS
blue dashed

QGSJET II
red full

SIBYLL
black dash-dot

QGSJET1
green dotted

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 (=>dAu@RHIC)
- ☐ Collective effects
- ☐ Carefully tested (hh, hA, AA)
- ☐ "Mini-plasma" in pp at LHC
- ☐ CRs: more muons than other models