EPOS and others

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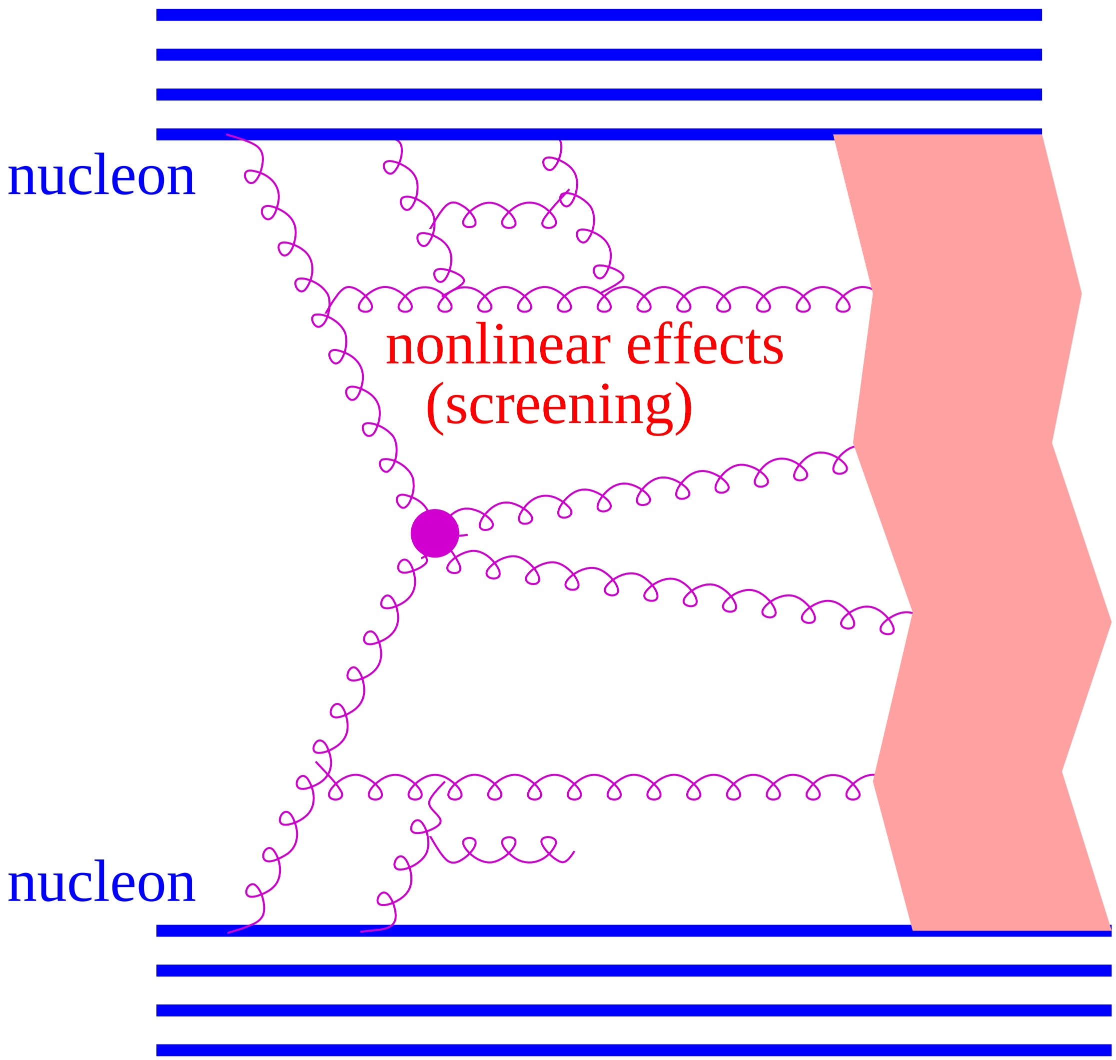
Outline

- □ Basic EPOS (Gribov-Regge type approch)
- □ Hydrodynamic expansion in AA
- □ Geometrical considerations in AA
- □ Consequences for pp (with particular emphasis on multiple scattering)

1 Basic EPOS

Gribov-Regge multiple scattering common to several models used for cosmic ray simulations, like QGSJET, SIBYLL, and EPOS



quasi longitudinal
color electric field

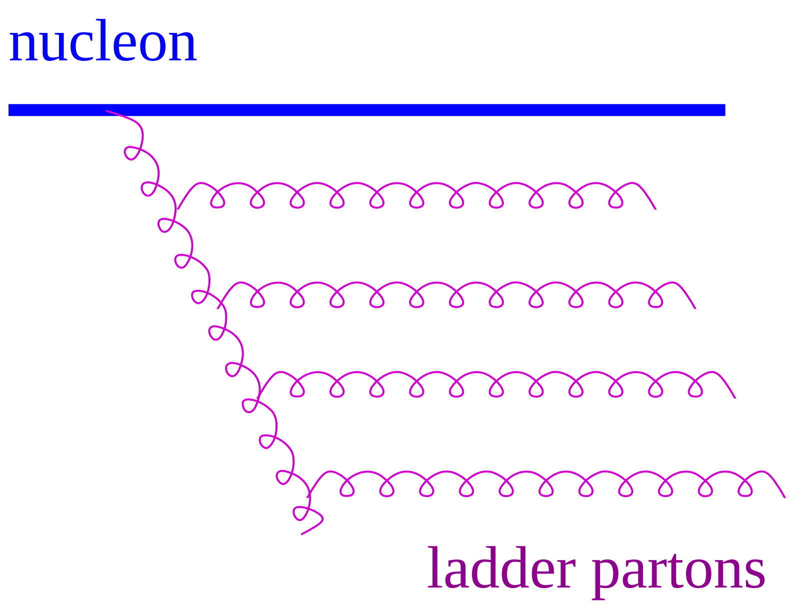
"flux tube"

gluons =
transverse
kinks

decay
via pair
production

Parton evolution

from projectile (target)
towards the center (small x)



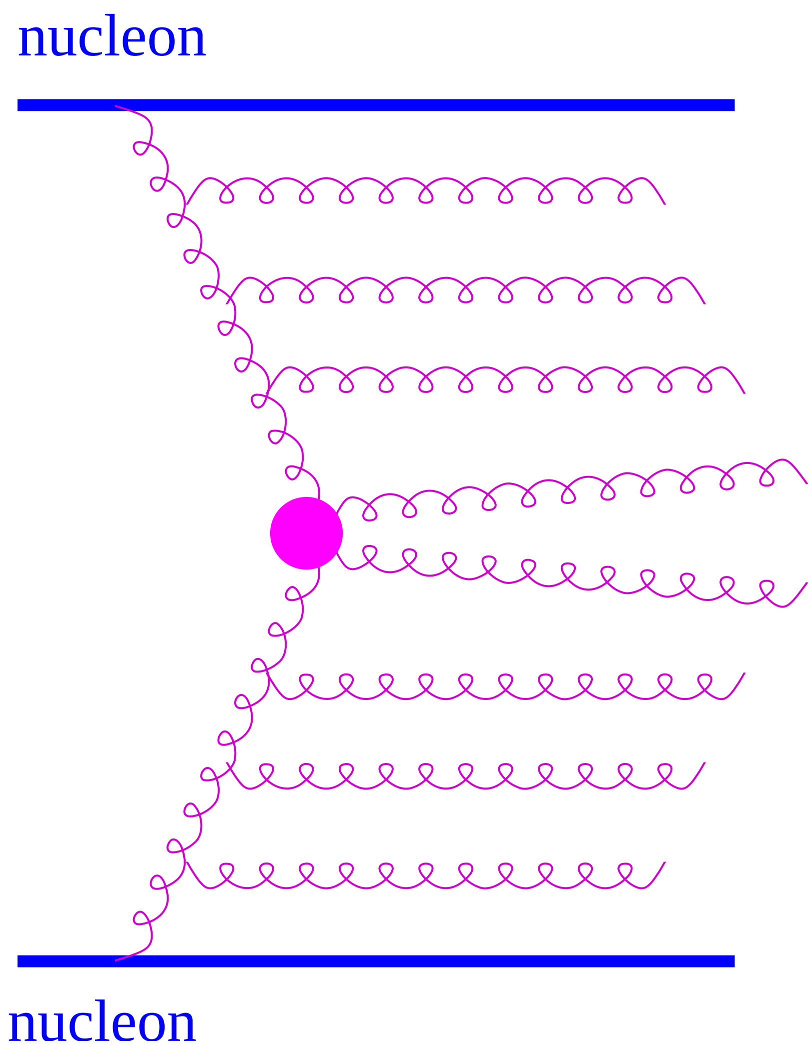
In the simplest case:

linear evolution equation (DGLAP)

Tested in DIS ($\gamma^* p$ scattering)

Elementary interaction: parton ladder

= parton evolution from both sides
towards the center (small x)



Important in particular at moderate energies (SPS, RHIC):

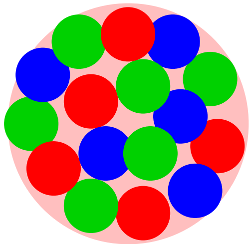
“parton ladder” is meant to contain two parts:

- the hard one (parton evolution following an evolution equation),
- a soft one -> purely phenomenological object, parametrized in Regge pole fashion.

The soft part essentially compensates for the infrared cutoffs, which have to be employed in the perturbative calculations.

High energy and/or nuclear collisions: **non-linear effects**

due to the fact that at small x the gluon densities get so high that gluon fusion becomes important (eventually: saturation)



$$\frac{\alpha_s N_c}{Q^2} \times \frac{1}{N_c^2-1} \frac{xG}{\pi R^2} \approx 1 \rightarrow \text{saturation scale}$$

Nonlinear effects could be taken into account by

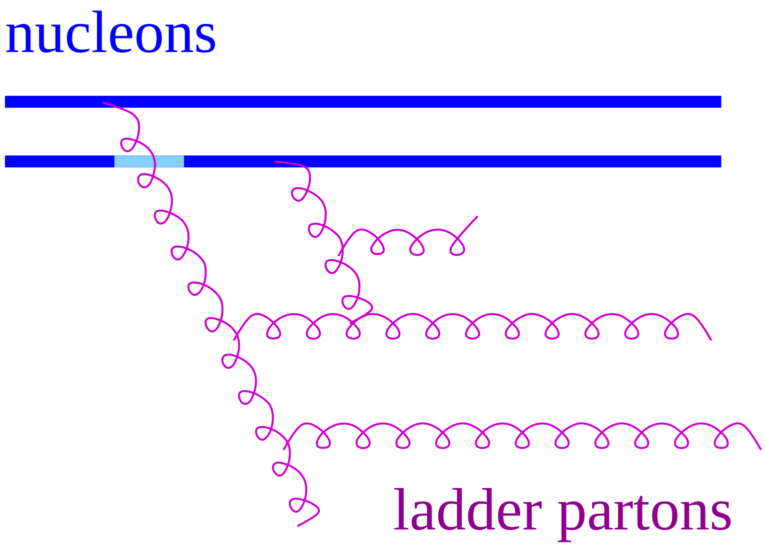
- using BK instead of DGLAP evolution or phenomenological approach (like simple parameterization of gluon distributions)

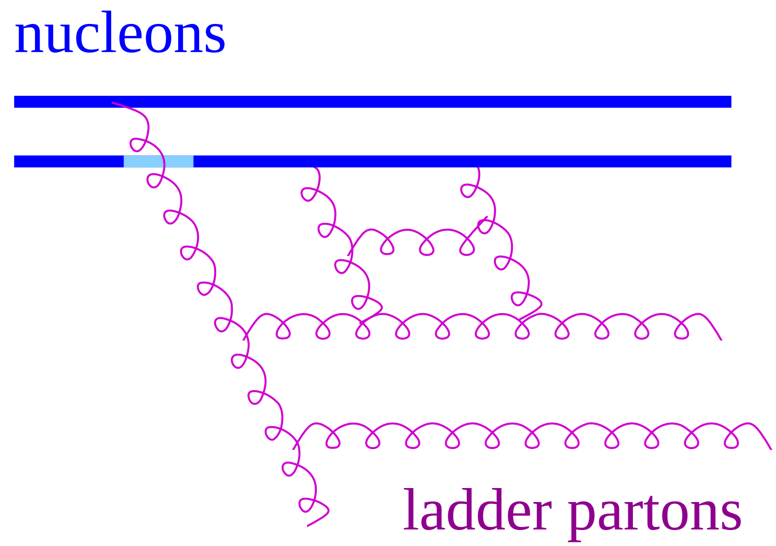
Here: phenomenological approach, which grasps the main features of these non-linear phenomena, and still remains technically doable

Two types of non-linear effects:

inelastic rescattering
(inelastic ladder splitting)

elastic rescattering of a ladder parton on a projectile or target nucleon
(elastic ladder splitting)





Affect total cross section and particle production

Elastic splitting
=> screening => saturation

(negative contribution to the cross section).

Realization:

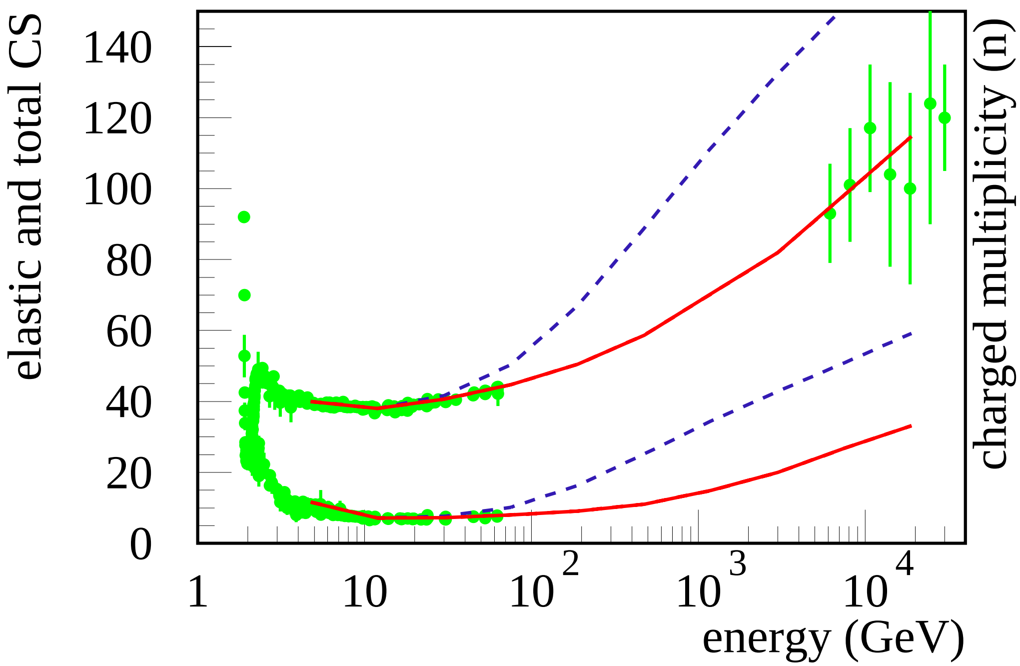
- ☐ fit parton-parton interaction [1] as $\alpha\,(x^{+})^{\beta}(x^{-})^{\beta}$ [2]
- ☐ modify as $\alpha\,(x^{+})^{\beta}(x^{-})^{\beta+\varepsilon}$,

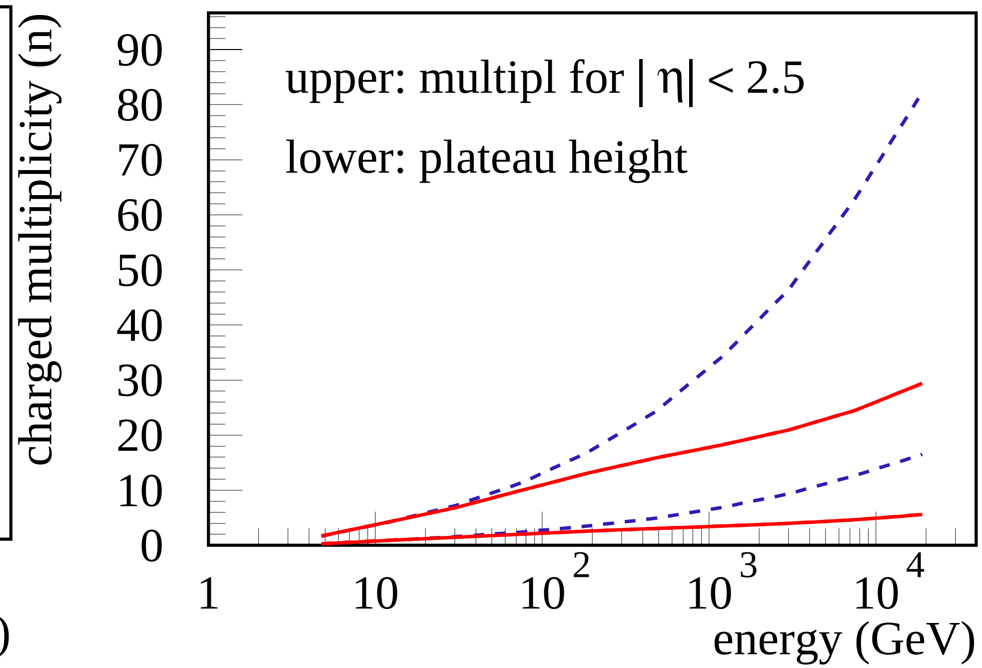
Effect can be summarized by a simple positive exponent ε (depending on $\log s$ and N_{particip})

[1] imaginary part of the corresponding amplitude in $b-$space
[2] x^{+}, x^{-}: light cone momentum fractions of the first ladder partons

Cross sections in pp

Multiplicities in pp

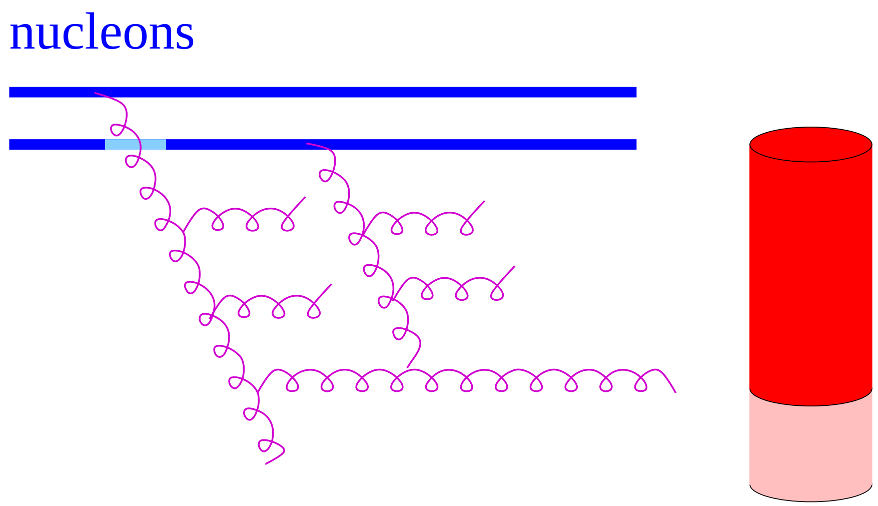




grow much too fast without ladder splitting

Inelastic splitting:

The parallel ladder pieces are close to each other in space => common color field



String language: “string fusion”
=> increased string tension κ.
Affects hadronization:
$q - \bar{q}$ break prob:
$\exp(-\pi m_q^2/\kappa)$

or treated as “droplet” which decays statistically

Hadronization

Parton ladder represents a (mainly) **longitudinal color field**, with transverse kinks (ladder rungs = gluons) [3].

- □ The fields decay via **pair production** (Schwinger mechanism).

- □ Tool to treat evolution and decay:

  classical string theory (use general symmetries).

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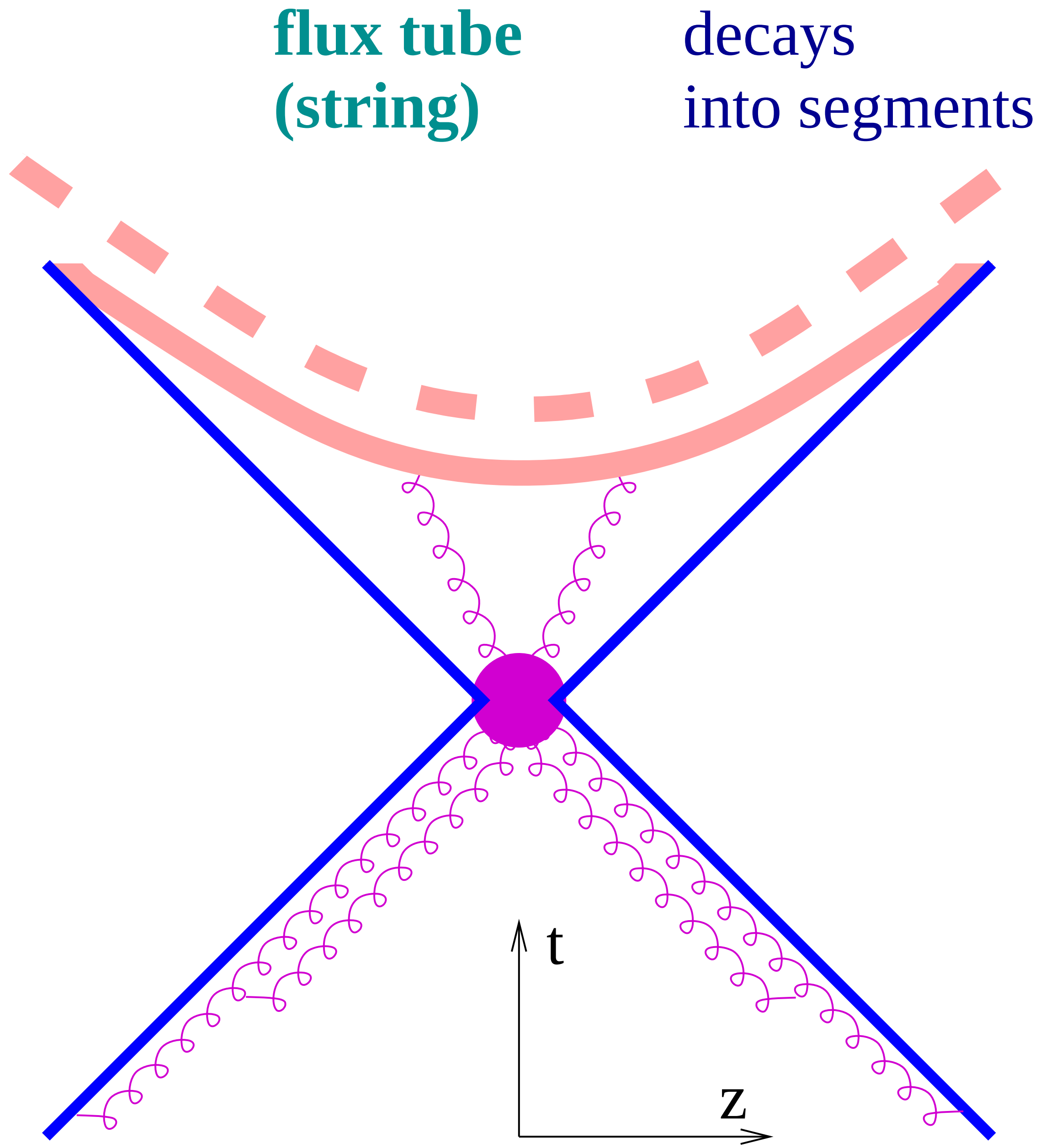
[3] Lund model idea, first e+e-, then generalized to pp, see also CGC

Flux tube stretches over wide range in rapdity

decay via pair production

Hadrons are NOT associated to individual partons!

unless one considers hard processes



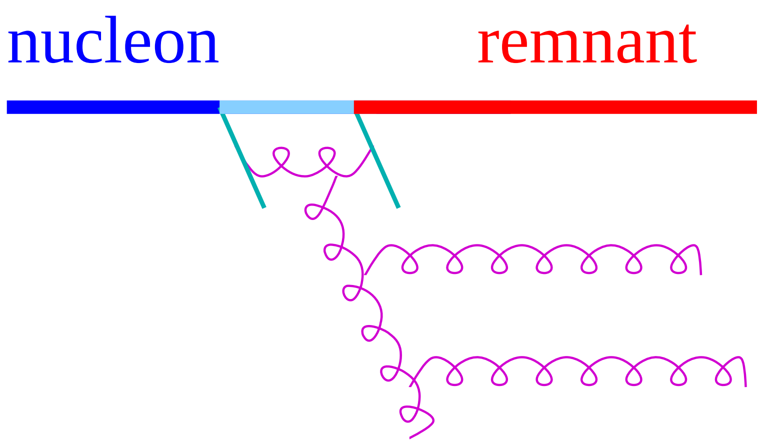
Remnants

Picture is not complete:

Interacting partons leave behind projectile/target remnants

Possible solution: color exchange.

Disfavored by strange antibaryon data at the SPS
M. Bleicher et al, Phys.Rev.Lett.88, 202501, 2002.



Better:

quark-antiquark pair takes part in interaction,

leaving behind a colorless (excited) remnant

Important in the fragmentation region
(data: low energy pp, pA; Hera)

Multiple Scattering

At high energies one has certainly multiple scattering even in pp.

Inclusive cross sections:

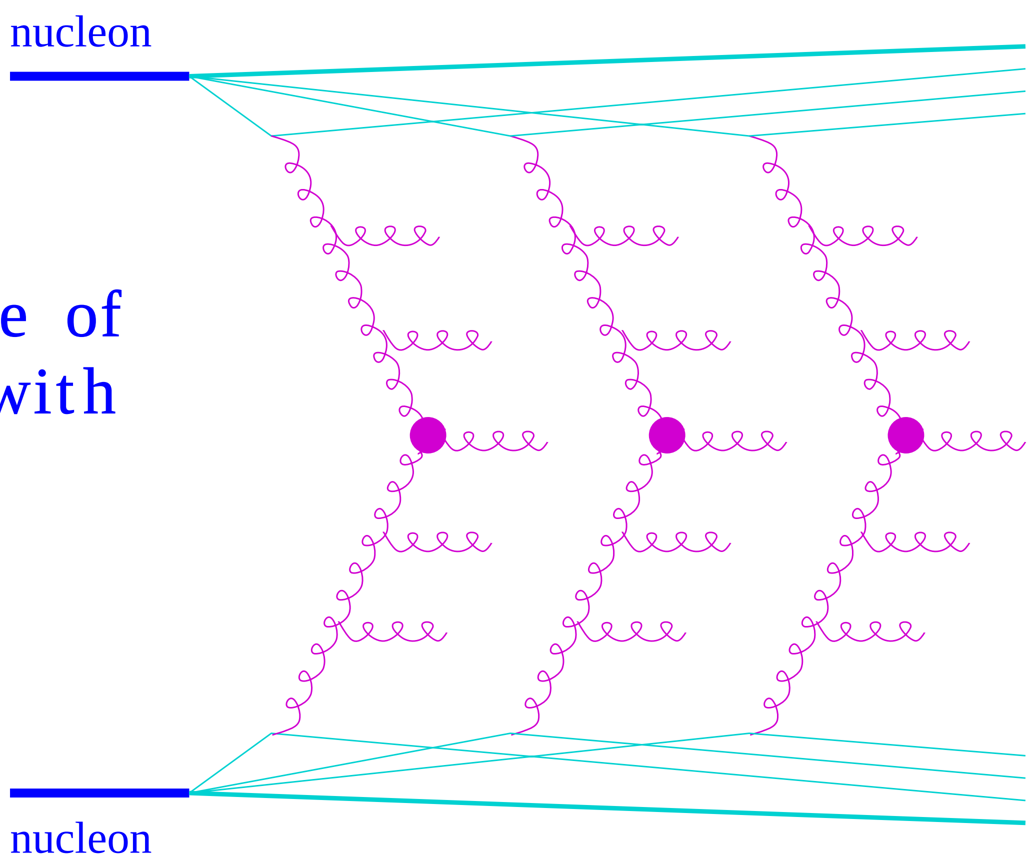
- quantum interference (“AGK cancellations”) may help to provide simple formulas referred to a “factorization” [4] (multiple scattering is “hidden”)

For exclusive quantities
and anyway for MC applications:

- one has to go beyond factorization and formulate a consistent multiple scattering theory

[4] not necessarily true, see recent papers by Collins

Possible solution: Gribov's Pomeron calculus, several Pomerons are exchanged in parallel (here: Pomeron = parton ladder)

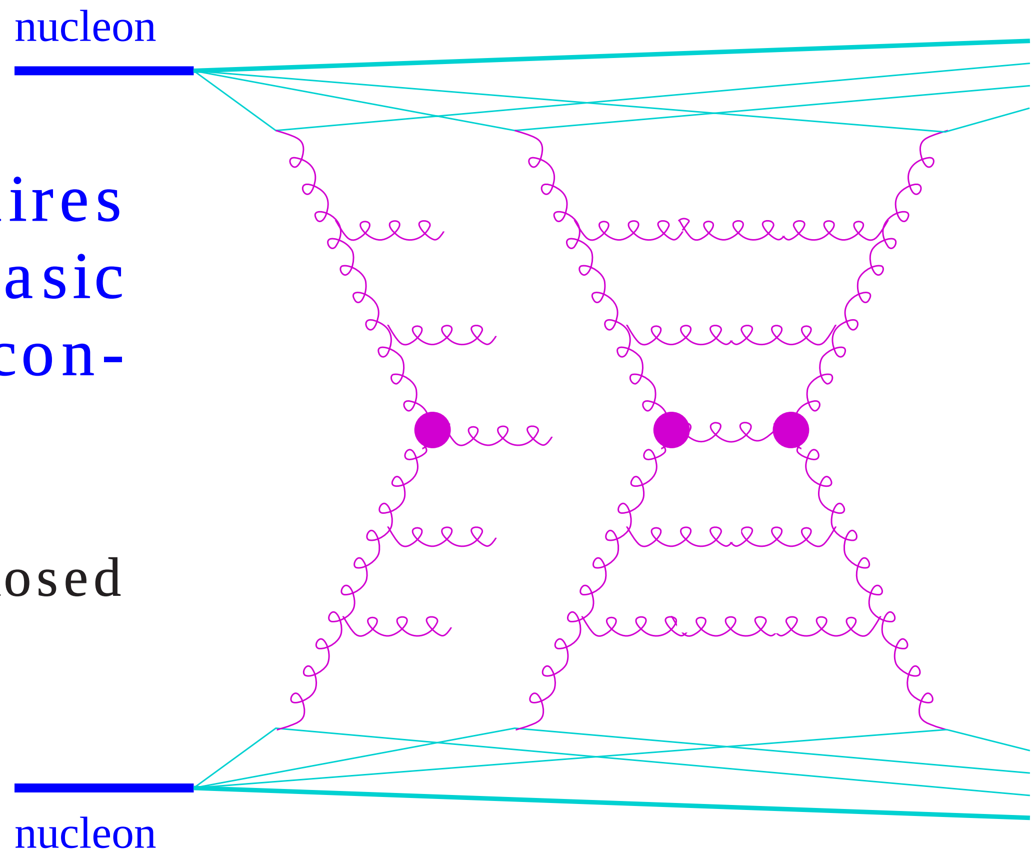


Better:
multiple exchange of parton ladders, with energy sharing

(our solution)

Consistency requires inelastic and elasic processes to be considered

(here: open and closed ladders)



Squaring such graphs leads to “cut diagrams”
→ handled by employing “cutting rule techniques”

Energy sharing requires Markov chain techniques

2 Hydrodynamic evolution: on the role of initial conditions and freeze-out

Hydrodynamic calculations

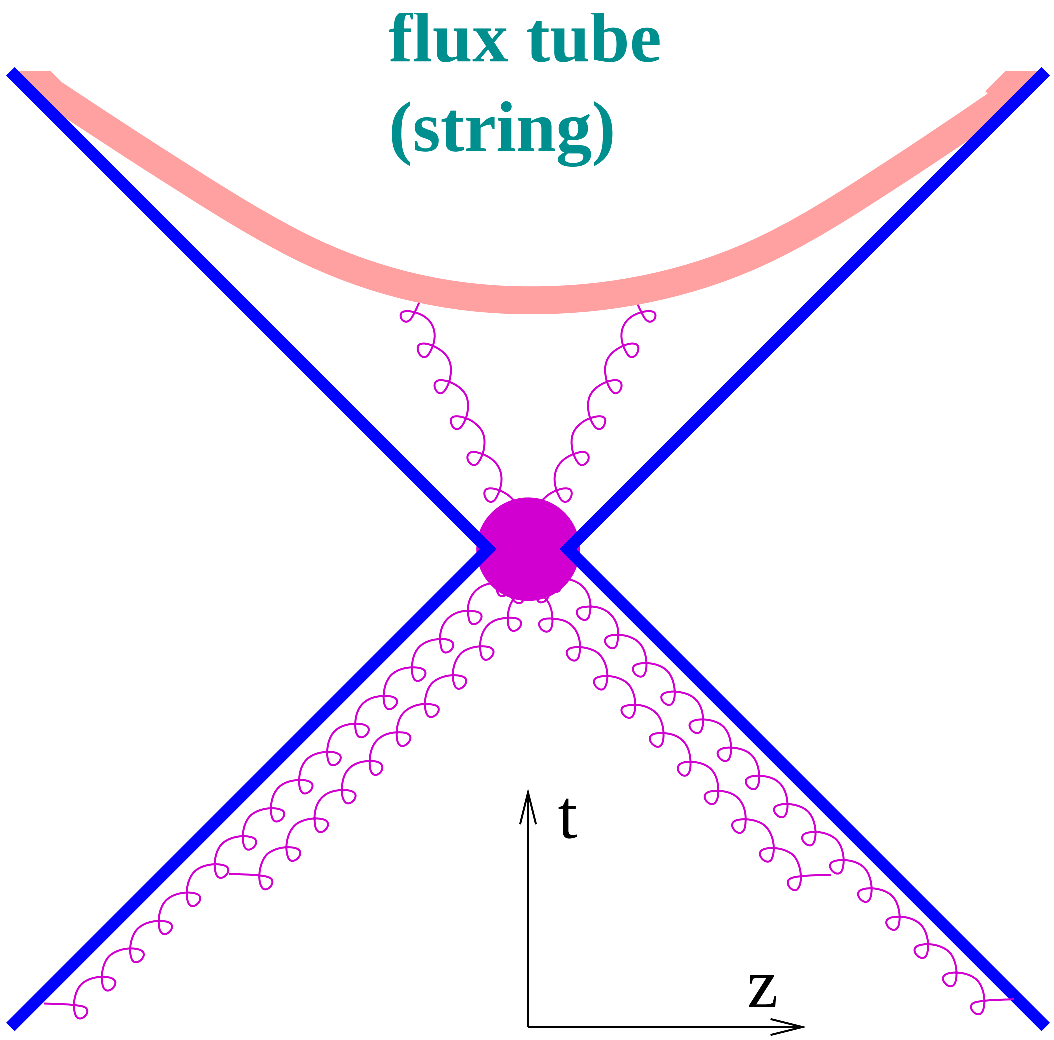
- □ Initial condition
- □ Hydrodynamic evolution (EoS)
- □ Freeze out (hadronic cascade)

We compare two options for initial conditions :

- □ parameterized, to optimize final results
  (Hirano, Heinz, Kharzeev, Lacey, Nara, Phys.Rev.C77: 044909,2008)
- □ or obtained from microscopic approach
  (EPOS, in collaboration with T. Pierog, S. Porteboeuf),
  based on the hypothesis that thermalization happens very quickly and is achieved at some τ_0

different FO scenarios (with, w/o hadronic cascade)

EPOS initial condition



in AA: many overlapping flux tubes

We consider color fields / flux tubes[a] as initial condition

not partons!

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[a] more precise: string segments

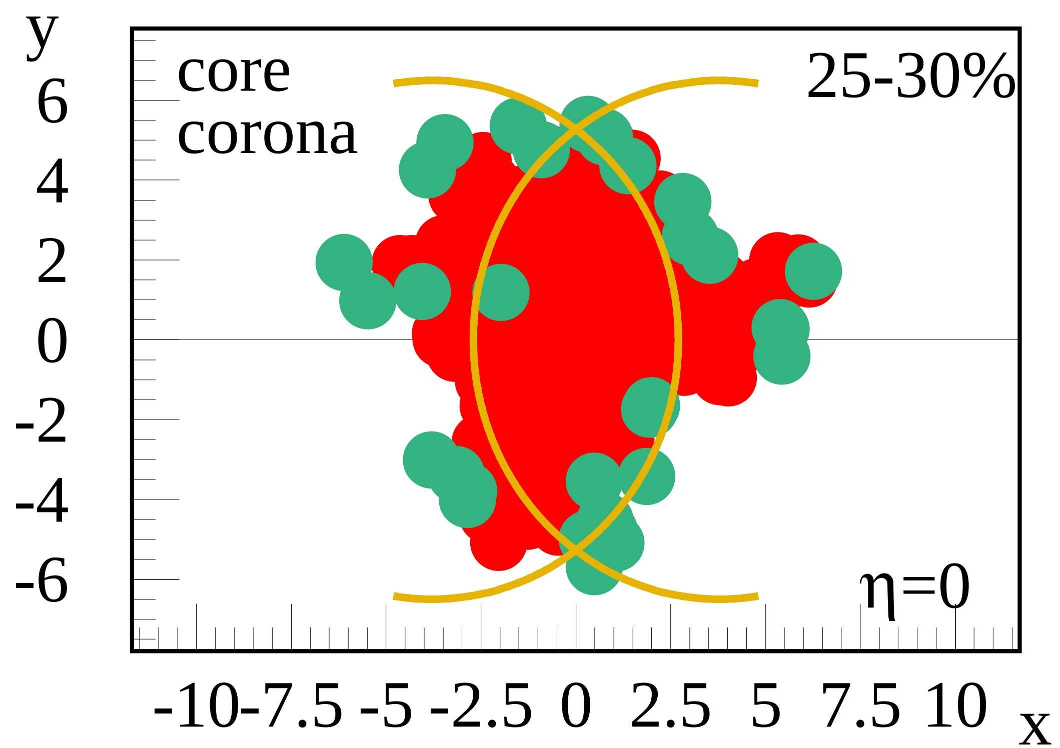
3D-Core-corona separation

Consider string segments at some $\tau = \tau_0$

number of segments per unit volume larger than ρ_0 : **core**

otherwise: **corona**

high pt segments count as corona



core: we include inwards moving corona segments

Only core used to compute initial conditions for hydrodynamical evolution

at τ_0 : from space and momentum four-vectors of the segments (which constitute the core) get[5]

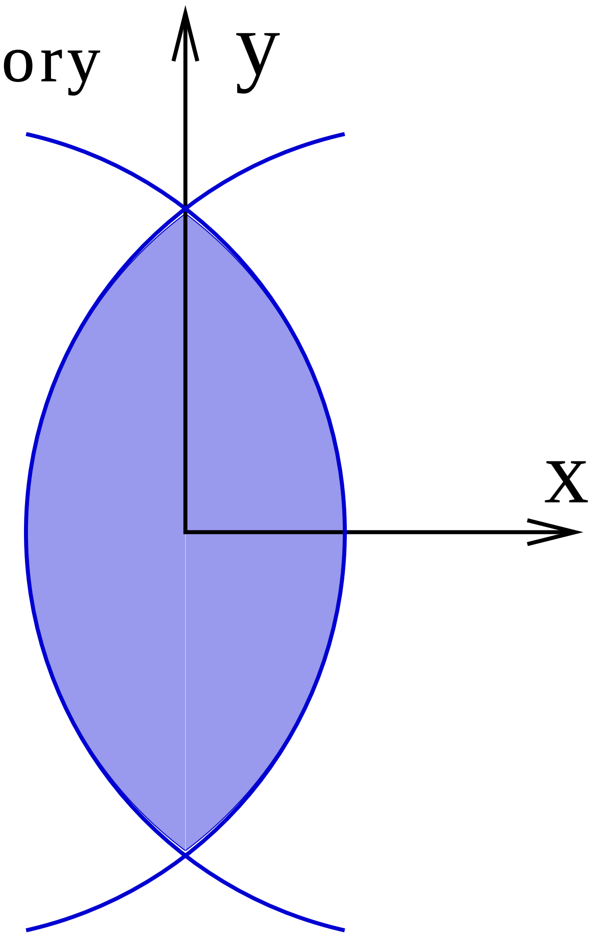
- energy density $\varepsilon(\vec{x})$,
- flow velocity $\vec{v}(\vec{x})$
- net flavor densities $f(\vec{x})$

[5] via $T^{\mu\nu} = \frac{1}{\Delta V} \sum_{i \in \Delta V} \frac{p_i^\mu p_i^\nu}{p_i^0}$, $N_q^\mu = \frac{1}{\Delta V} \sum_{i \in \Delta V} \frac{p_i^\mu}{p_i^0} q_i$,
based on "Kodama's T diagonalization"

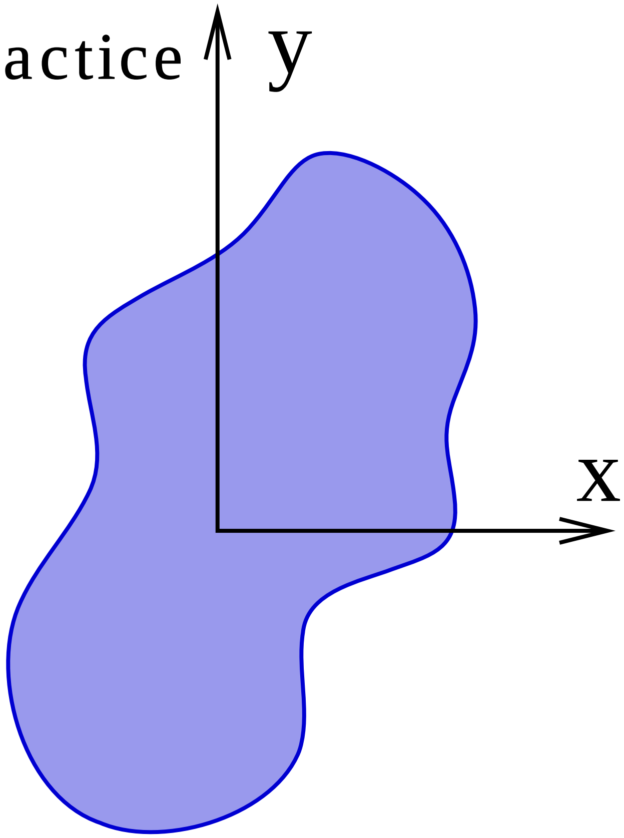
Random orientations

Transverse distribution of matter at τ_0

in theory

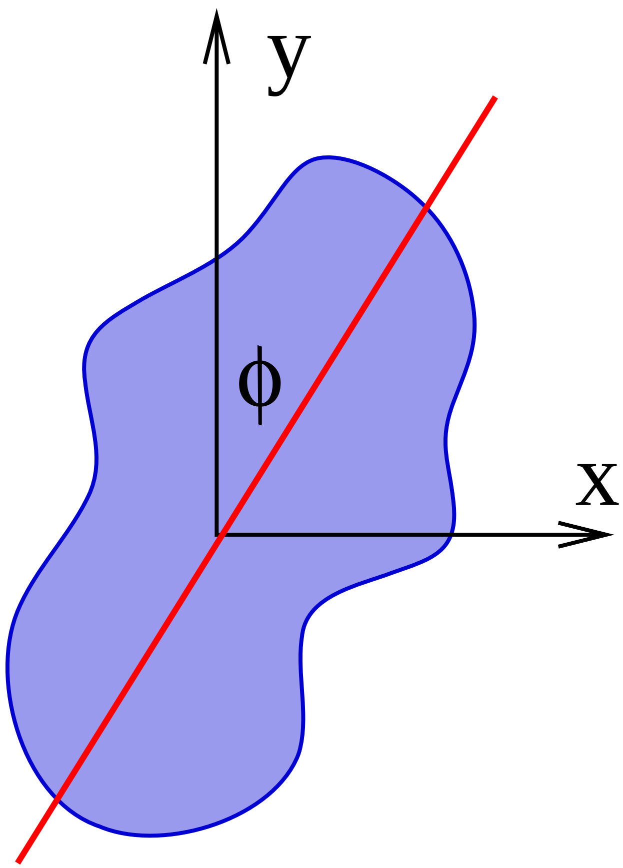


in practice



for a given event

For a given MC event, compute "inertial tensor" (based on transverse segment positions)

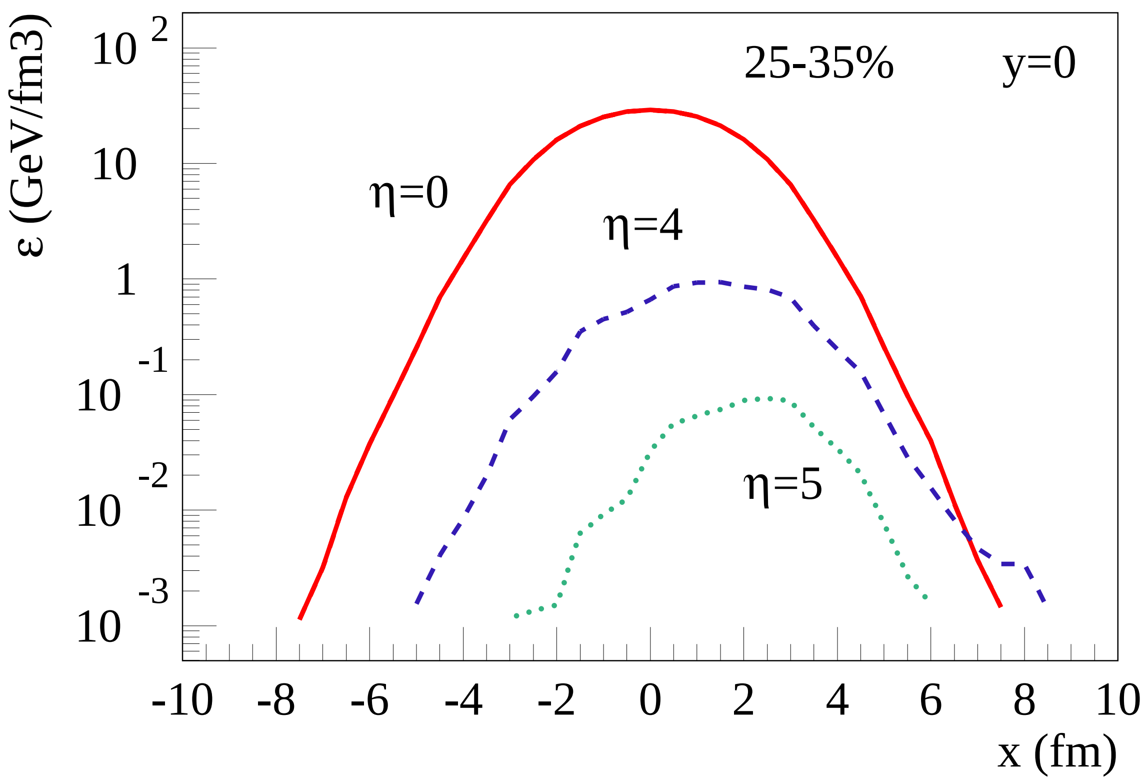


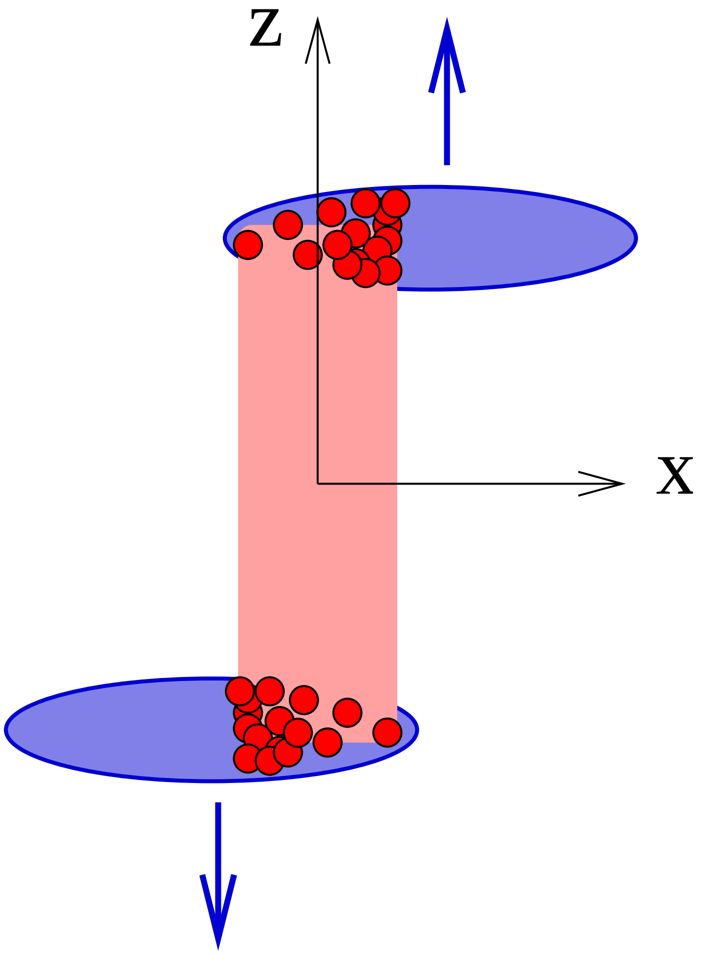
- □ determine pricipal axis (red)
- □ rotate object by ϕ
- □ use the coordinates after rotation to compute contribution to $T^{\mu\nu}$.

non-zero eccentricity even for $b = 0$

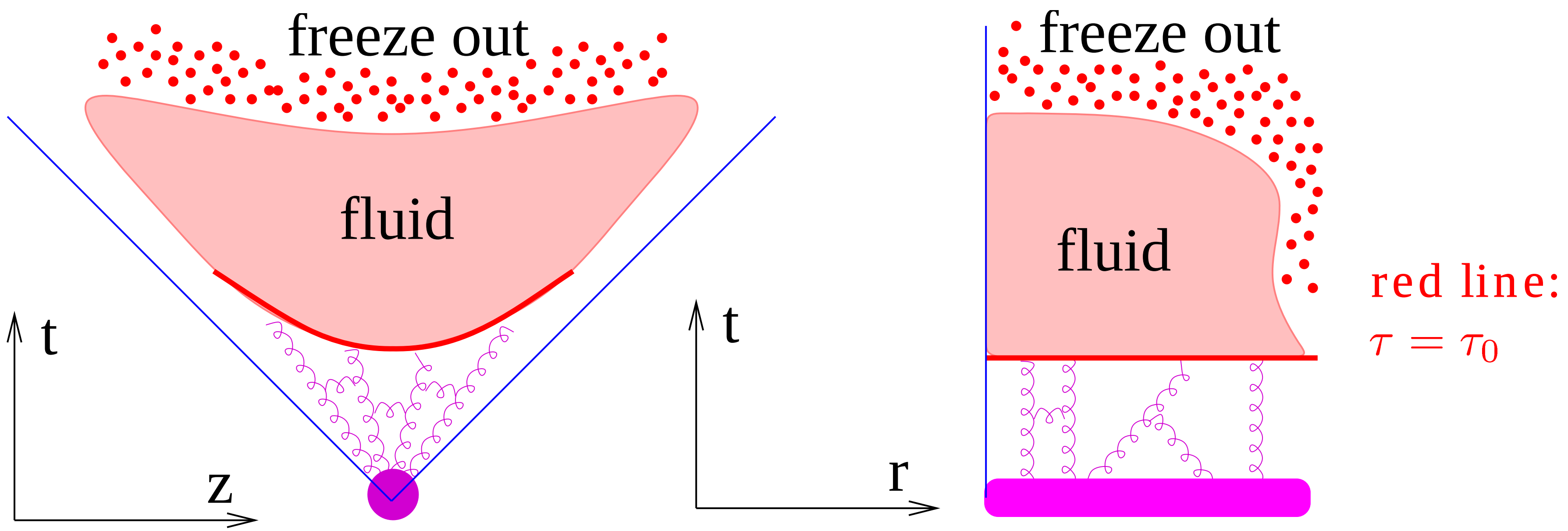
Asymmetry

$\varepsilon(\tau_0, x, y, \eta) \neq \varepsilon(\tau_0, -x, y, \eta)$ for large η (remnant effect)





Hydro evolution / freeze out



For $\tau > \tau_0$: 3D hydrodynamic evolution
(with T.Hirano and Y.Karpenko)

determine freeze out hypersurface and collective velocities

particle production via Cooper-Frye formula

... more precisely

- Make first FO tables (storing FO surface and flows) based on hydro calculations with EPOS initial conditions (for given T_{FO})
  (in collaboration with T. Hirano, Y. Karpenko)

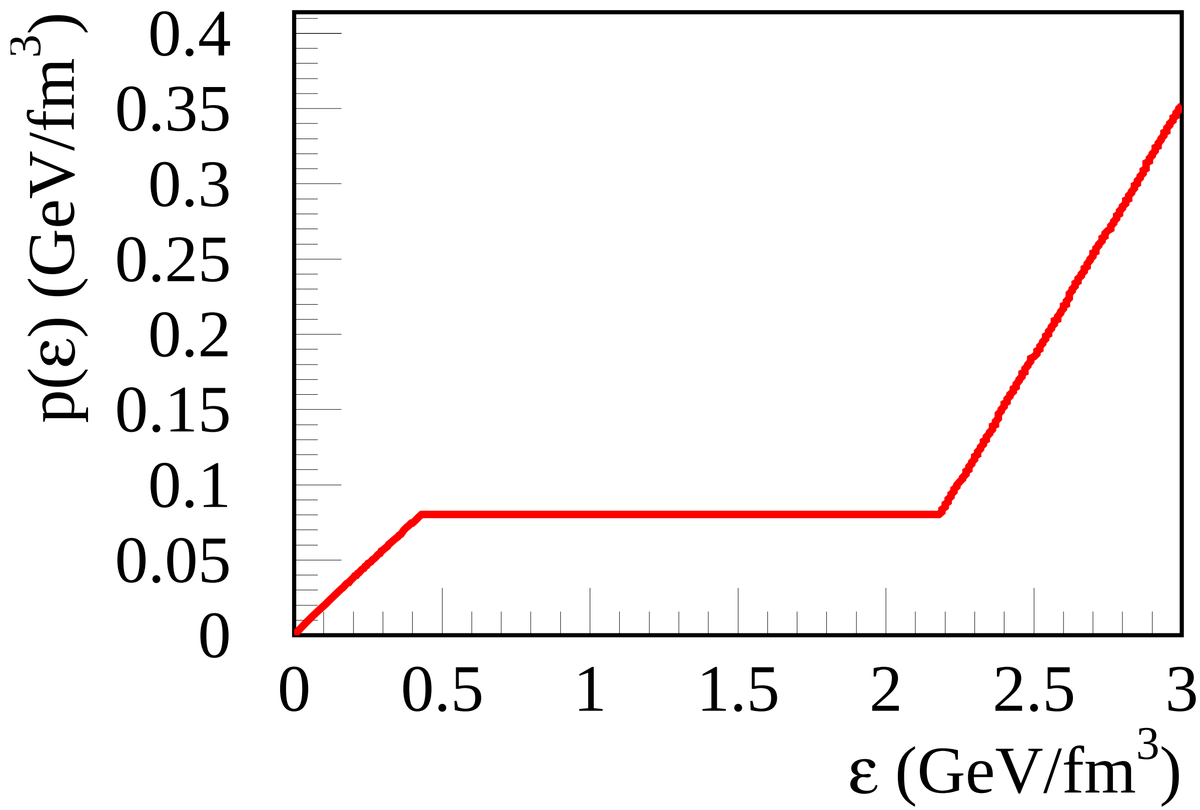
- Generate particles EbE from the core using FO tables; completely equivalent to Cooper-Frye

- Possibility to use (or not) final state hadronic cascade for final state hadronic rescatterings
  (UrQMD in collaboration with S.Haussler, M.Bleicher, S. Porteboeuf)

useful: modular structure

Hydro evolution

EoS: Massless quarks and gluons, $p = \frac{1}{3}(\varepsilon - 4B)$, with $B^{1/4} = 247.19$MeV; hadron resonance gas, PCE, implementing chemical FO at $T = T_c = 170$ MeV (from Hirano)



EbE particle generation

- **Monte Carlo procedure, using an acceptance-rejection method, completely equivalent to Cooper-Frye.**

Cooper-Frye

$$dn_i = \frac{d^3p}{E}\, d\Sigma_\mu\, p^\mu\, f_i(pu).$$

Define volume element

$$dV^* = d\Sigma_\mu\, u^\mu,$$

Proposal: Monte Carlo generation in LRF according to

$$dn_i = \alpha\, d^3p^*\, dV^*\, f_i(E^*),$$

accepted with probability

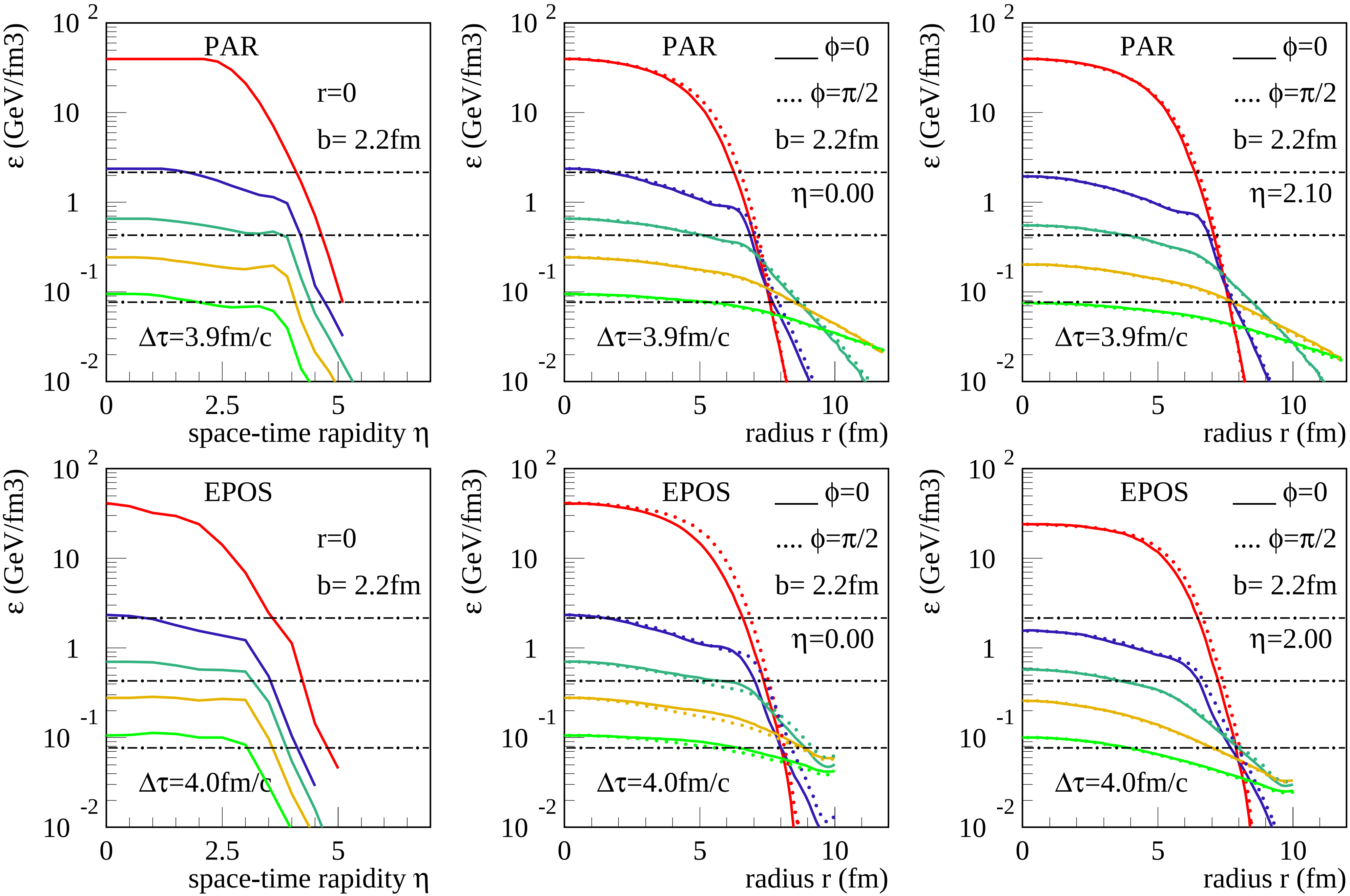
$$\kappa = \frac{d\Sigma_\mu\, p^\mu}{\alpha\, dV^*\, E^*}$$

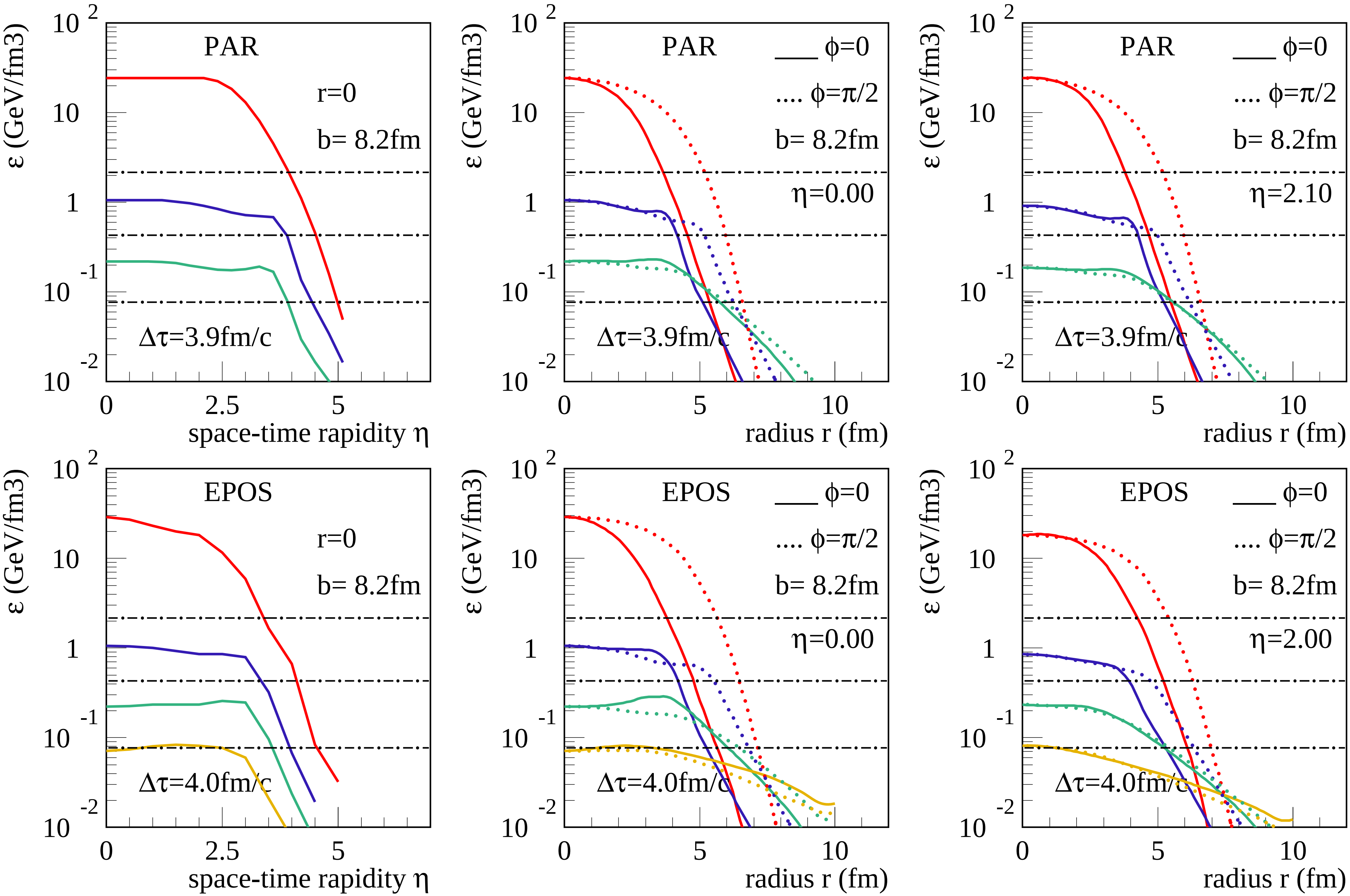
In the following

EPOS refers to hydro evolution based on EPOS initial conditions

PAR refers to hydro evolution based on the parameterized initial conditions of Hirano et al, Phys.Rev.C77: 044909,2008.

both calculation use $\tau_0 = 0.6$fm/c, and the same EoS


PAR
r=0
b= 2.2fm
Δτ=3.9fm/c
ε (GeV/fm3)
space-time rapidity η
PAR
___ φ=0
.... φ=π/2
b= 2.2fm
η=0.00
Δτ=3.9fm/c
radius r (fm)
PAR
___ φ=0
.... φ=π/2
b= 2.2fm
η=2.10
Δτ=3.9fm/c
radius r (fm)
EPOS
r=0
b= 2.2fm
Δτ=4.0fm/c
space-time rapidity η
EPOS
___ φ=0
.... φ=π/2
b= 2.2fm
η=0.00
Δτ=4.0fm/c
radius r (fm)
EPOS
___ φ=0
.... φ=π/2
b= 2.2fm
η=2.00
Δτ=4.0fm/c
radius r (fm)



PAR
r=0
b= 8.2fm
Δτ=3.9fm/c
ε (GeV/fm3)
space-time rapidity η
PAR
___ ϕ=0
.... ϕ=π/2
b= 8.2fm
η=0.00
Δτ=3.9fm/c
radius r (fm)
PAR
___ ϕ=0
.... ϕ=π/2
b= 8.2fm
η=2.10
Δτ=3.9fm/c
radius r (fm)
EPOS
r=0
b= 8.2fm
Δτ=4.0fm/c
space-time rapidity η
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b= 8.2fm
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Δτ=4.0fm/c
radius r (fm)
EPOS
___ ϕ=0
.... ϕ=π/2
b= 8.2fm
η=2.00
Δτ=4.0fm/c
radius r (fm)

In the following, for both PAR and EPOS, always three curves:

dashed refers to pure hydro, with FO at 100 MeV

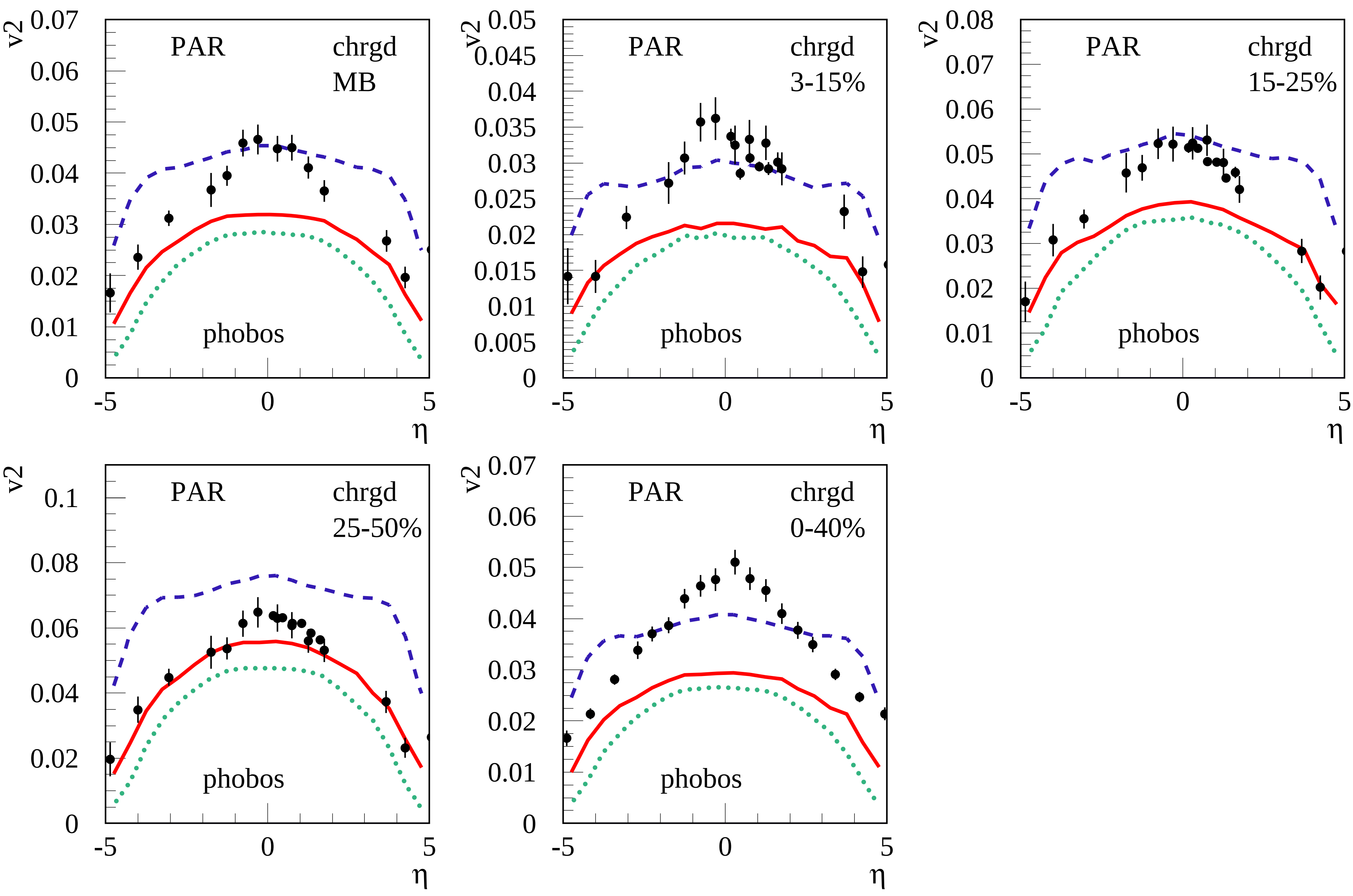
dotted refers to pure hydro, with FO at 169 MeV.

full refers to hydro with FO at 169 MeV, and subsequent hadronic cascade (UrQMD)

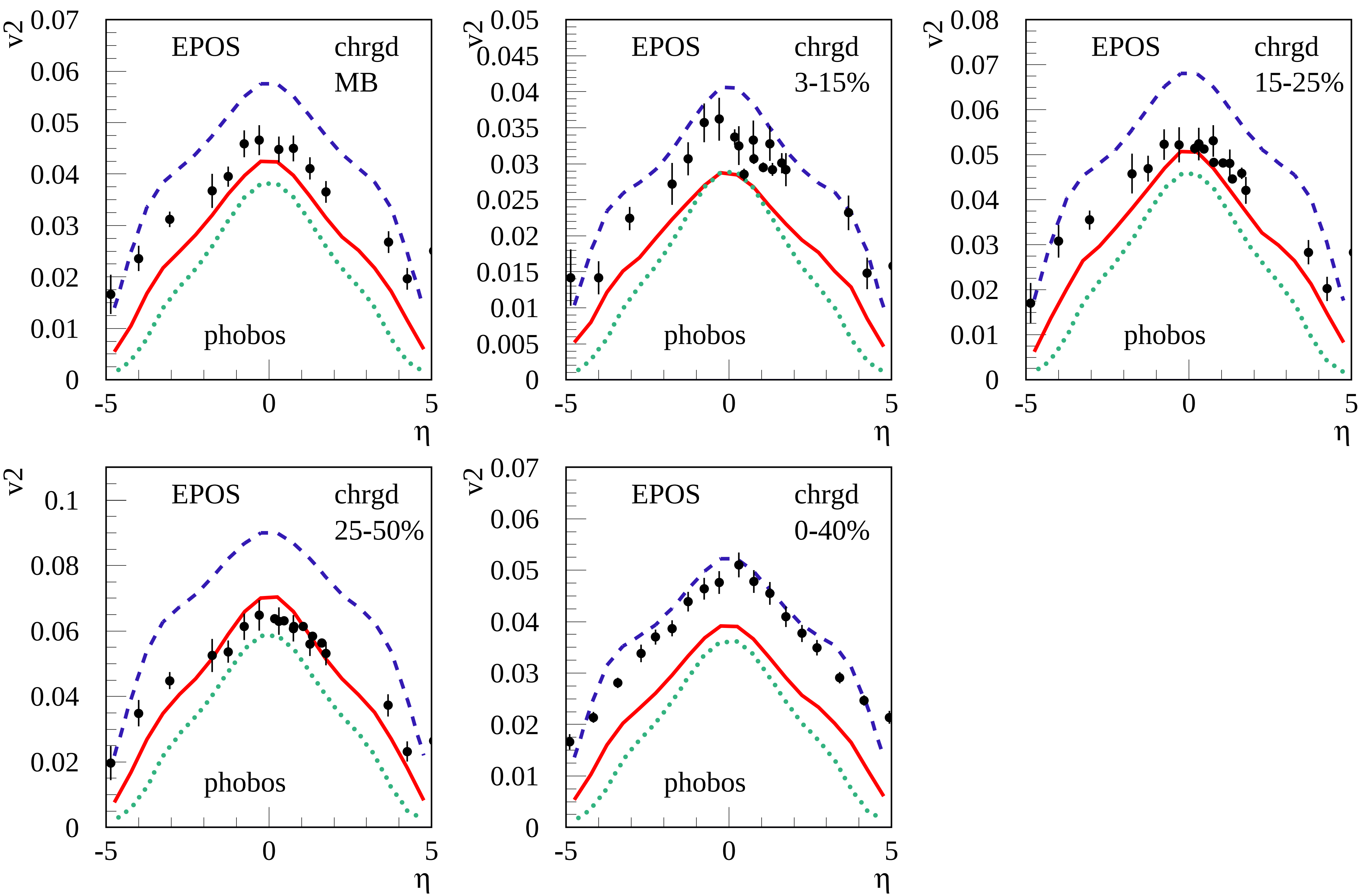
reminder: $T_c = 170\mathrm{MeV}$;

EPOS here means pure hydro, no corona

dashed=FO_100 dotted=FO_169 full=FO_169+cascade



dashed=FO_100 dotted=FO_169 full=FO_169+cascade



Triangular η dependence

EPOS initial conditions: $\varepsilon(\eta_s)$ already “triangular” !
η = pseudorapidity; η_s= space-time rapidity

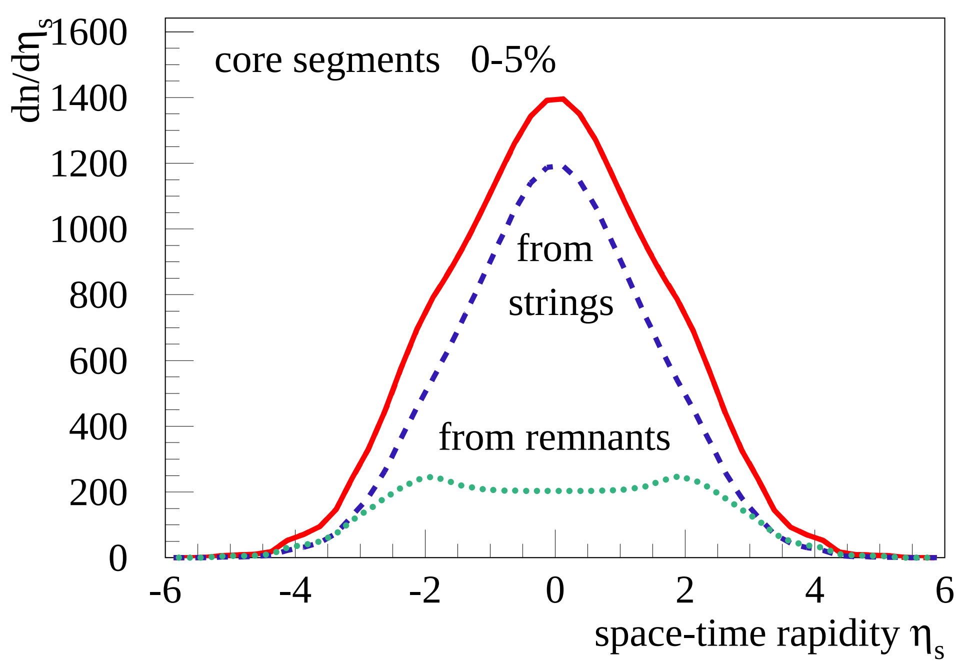
Large η_s : small initial ε, mixed phase is reached earlier, smaller flow (compared to flat $\varepsilon(\eta_s)$)

Why triangular shape in η_s ?

Because we use strings as basis, not partons !

String segments from one string cover some range $\Delta\eta_s$, with varying width and position,

but always covering $\eta_s = 0$
$\rightarrow$ triangular shape of $dn_{segm}/d\eta_s$



Summary (initial conditions)

- EPOS initial conditions: triangular $v_2(\eta)$
  - caused by triangular initial $\varepsilon(\eta_s)$
  - due to “string based ” initial conditions rather than “parton based” initial conditions
- Spectra similar to Hirano et al., $dn/d\eta$ much less affected by initial conditions than $v_2(\eta)$
- Cascade models JAM and UrQMD give similar results

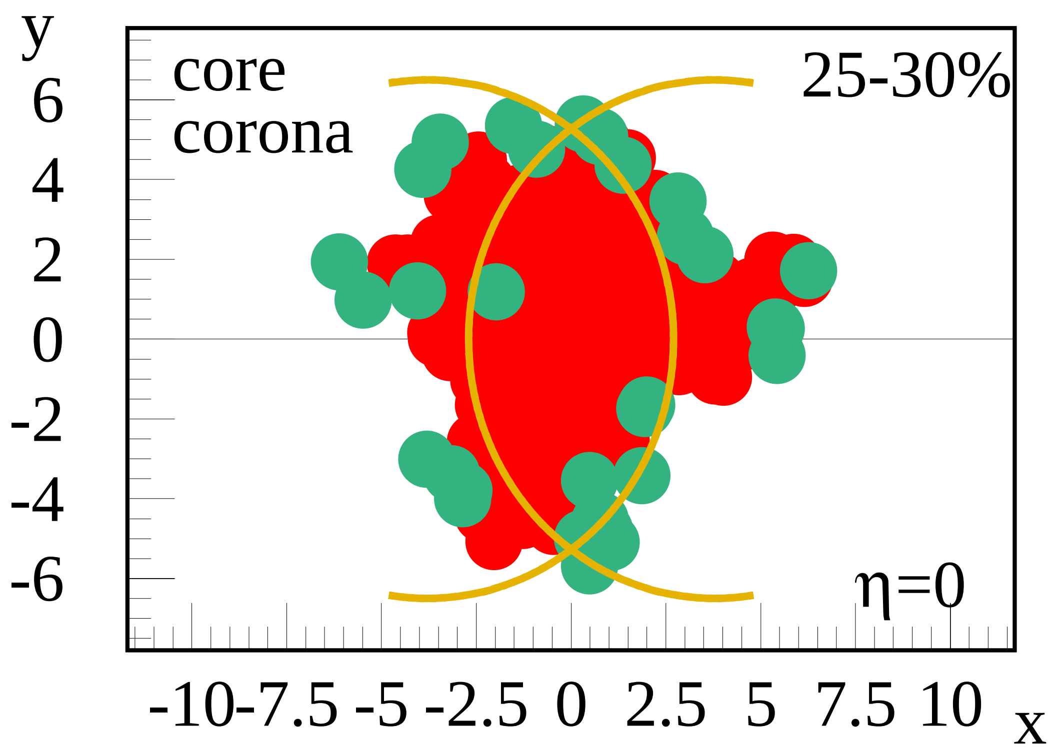
3 Core-corona: only geometry, but crucial to understand RHIC data

Core-corona means:

distinguishing high density **core** areas (collectively expanding)

from

peripheral low density **corona** areas (hadronizing pp-like)



core-corona explains centrality dependence at RHIC and SPS:

K.W., Phys. Rev. Lett. 98, 152301 (2007):

see also F. Becattini, J. Manninen, J. Phys. G 35, 104013 (2008)

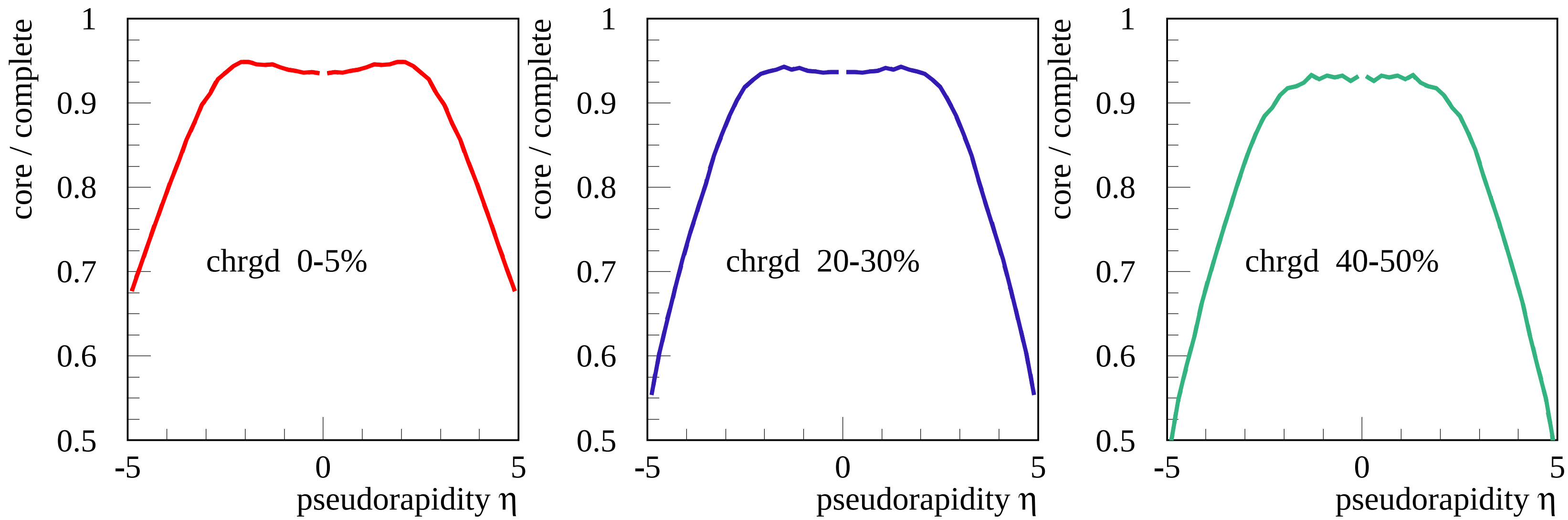
Estimate of corona importance

Consider hydrodynamical evolution, based on EPOS initial conditions, FO right after mixed phase, then hadronic cascade (as discussed earlier)

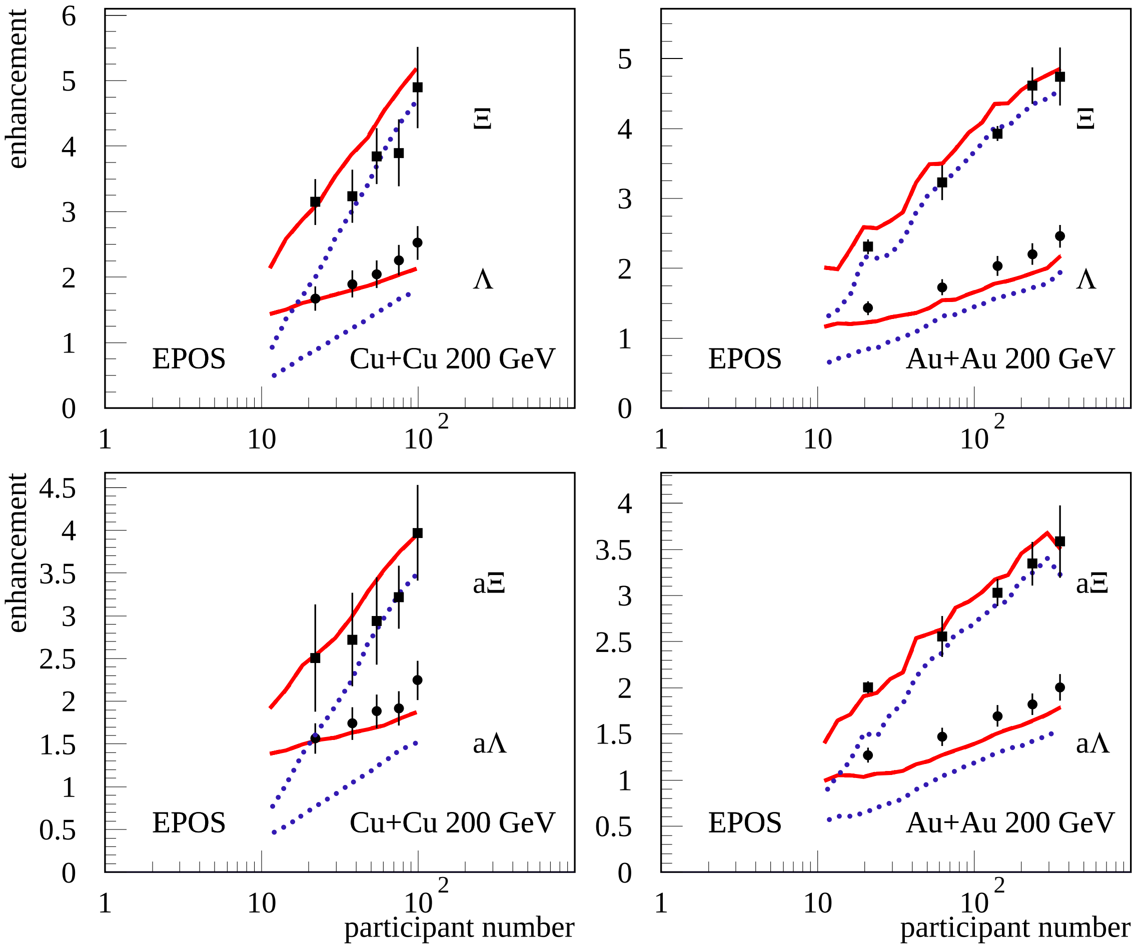
(A) ignoring completely the corona

(B) taking into account corona (corona particles may interact with cascade hadrons)

Following plot: ratio $\frac{dn}{d\eta}^{(A)} / \frac{dn}{d\eta}^{(B)}$



Centrality dependence: CuCu - AuAu



enhancement =

$$\frac{AA\,\text{multiplicity} \,/\, N_{part}}{pp\,\text{multiplicity} \,/ 2}$$

CuCu curves steeper

same maximum (but for different Npart)

EPOS shows similar trend

Core-corona important for Npart < 100

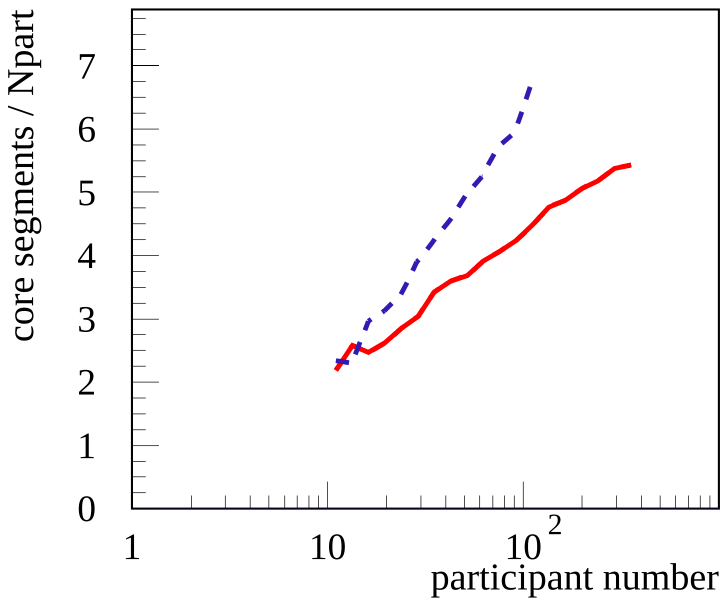
data: STAR

lines: EPOS; here older version, “hydro like” treatment; dotted: only core

For large Npart: corona contribution small, nevertheless enhancement increases with Npart

because core contribution per participant increases with Npart

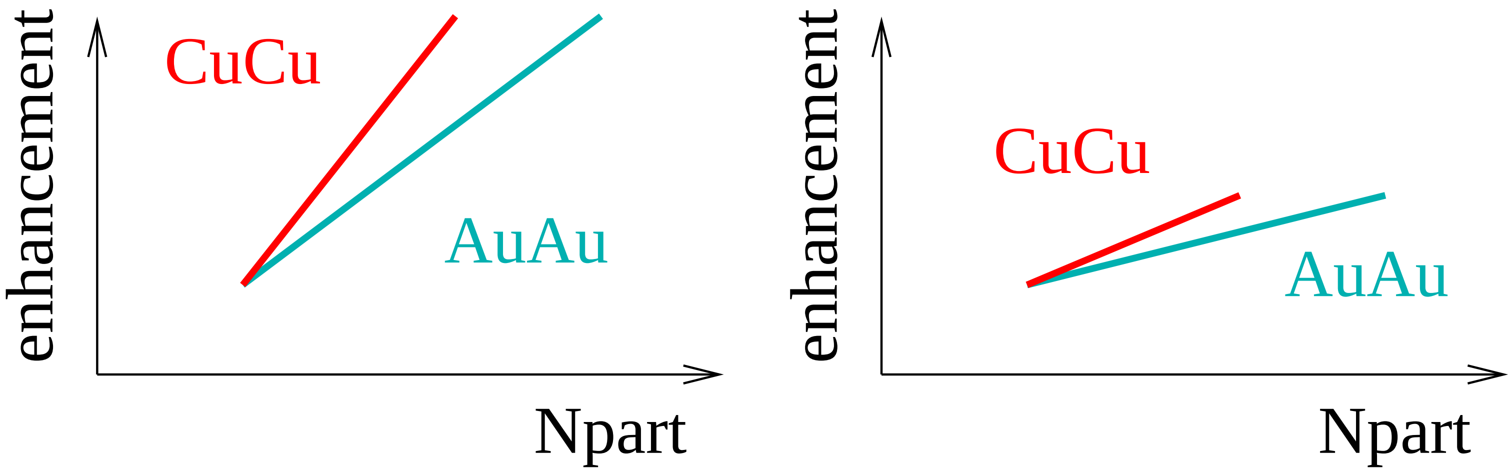
increase faster for CuCu compared to AuAu



Ladders in EPOS proportional to the number of collisions!

Therfore CuCu preferred compared to AuAu at same Npart!

Why is the difference between CuCu and AuAu more or less important (for different hadrons)?



because the enhancement vs Npart is proportional to the core/particip over pp/2 ratio – depends on the hadron species !

$\rightarrow$ big effect for Ξ, smaller effect for Λ

Summary (geometry, core-corona)

- Data on centrality dep. of strangeness enhancement:
  - CuCu much steeper than AuAu
  - same maximal enhancement, but at different Npart
- Partly core/corona, also important a binary collision component
- Species dependence: big effect for Ξ, smaller one for Λ meson
- Strong case in favor of Glauber geometry

4 QGP formation in pp?

Multiple Scattering

At high energies one has certainly multiple scattering even in pp.

Inclusive cross sections:

- quantum interference (“AGK cancellations”) may help to provide simple formulas referred to a “factorization” [6] (multiple scattering is “hidden”)

For exclusive quantities
and anyway for MC applications:

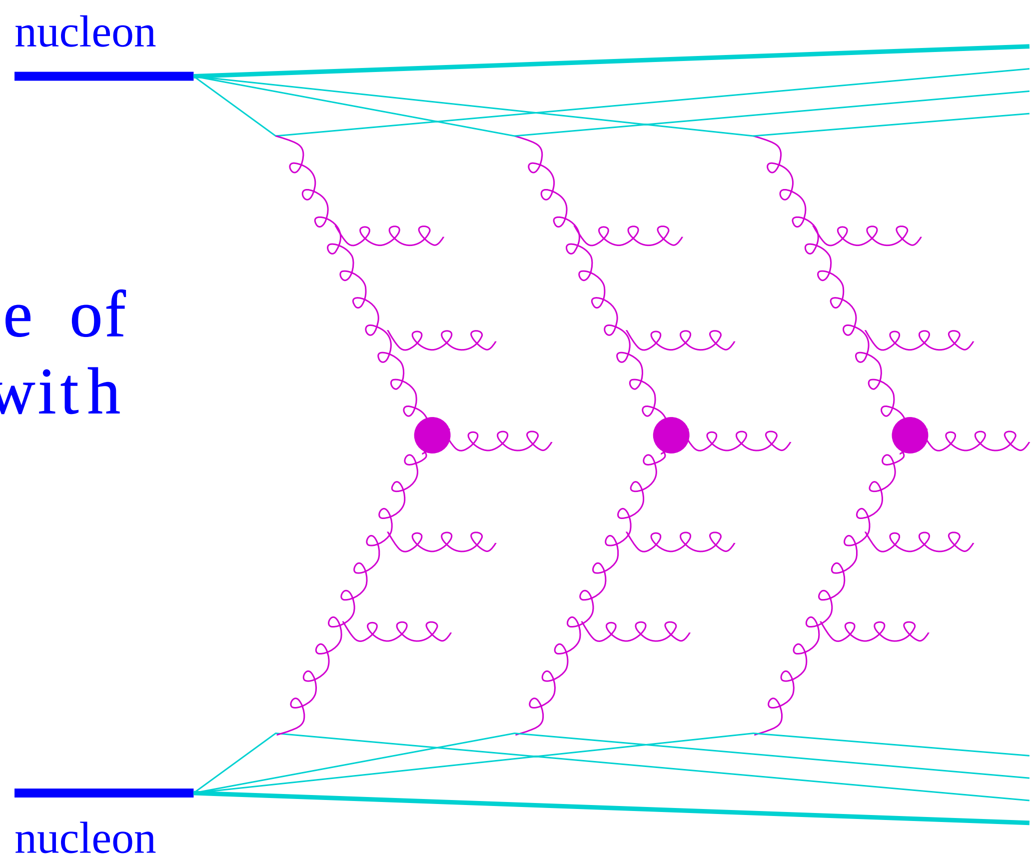
- one has to go beyond factorization and formulate a consistent multiple scattering theory

[6] not necessarily true, see recent papers by Collins

Possible solution: Gribov's Pomeron calculus, several Pomerons are exchanged in parallel (here: Pomeron = parton ladder)

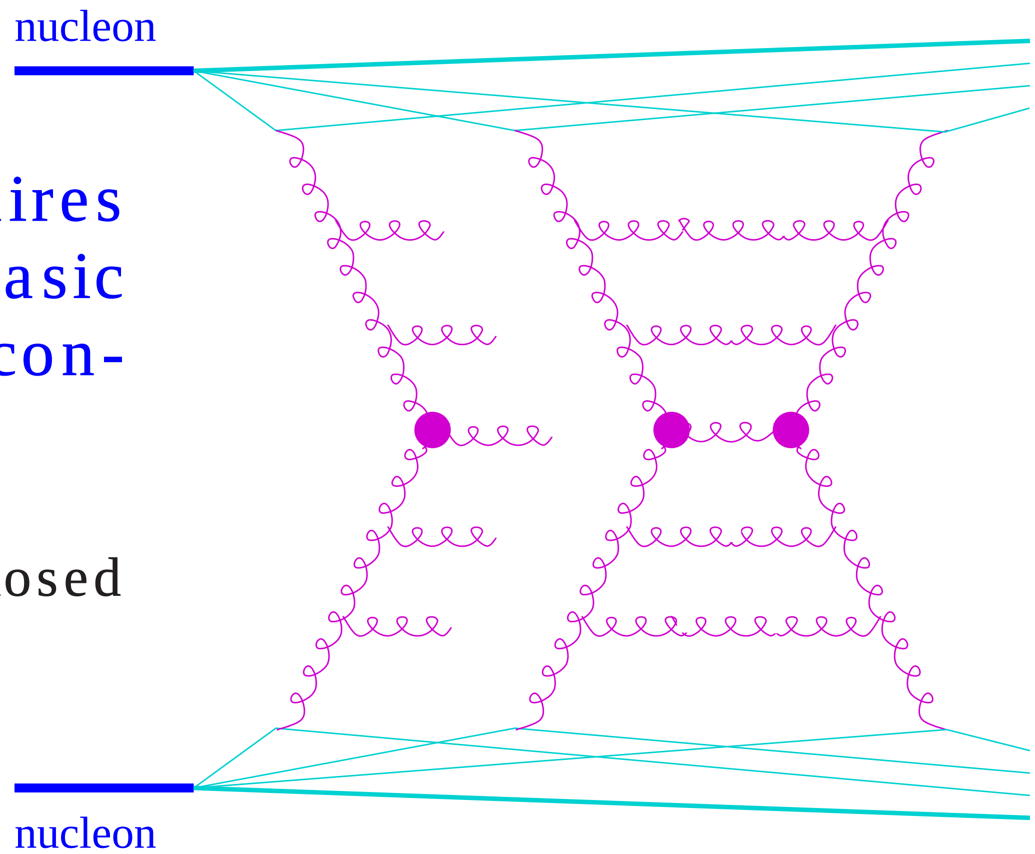
Better: multiple exchange of parton ladders, with energy sharing

(our solution)



Consistency requires inelastic and elasic processes to be considered

(here: open and closed ladders)



Squaring such graphs leads to “cut diagrams”
→ handled by employing “cutting rule techniques”

Energy sharing requires Markov chain techniques

More details:

Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289

Parton ladder splitting and the rapidity dependence of transverse momentum spectra in deuteron-gold collisions at RHIC, K. Werner, F.M. Liu, T. Pierog, hep-ph/0506232, Phys. Rev. C 74, 044902 (2006)

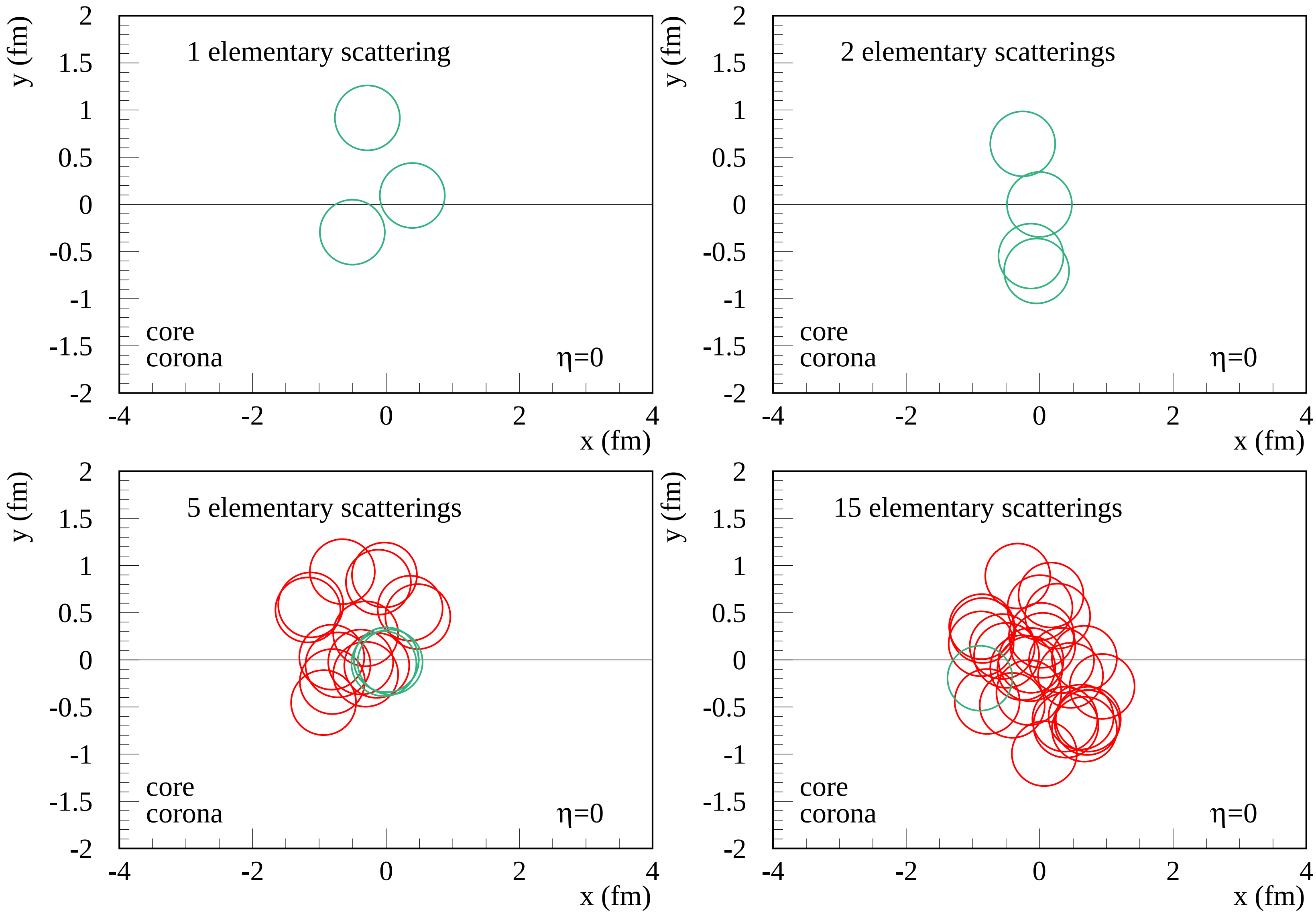
Be $\nu_{\rm inel}$ the number of inelastic elementary scatterings.

The total charged multiplicity $n_{\rm ch}$ is certainly a monotonic (linear?) function of $\nu_{\rm inel}$.

Instead of centrality dependence as in AA ,

here we study the $\nu_{\rm inel}$ or $n_{\rm ch}$ dependence of observables.

Core-corona approach in pp



Core-corona in AA:

- separation of volume into (central) core and (peripheral) corona part

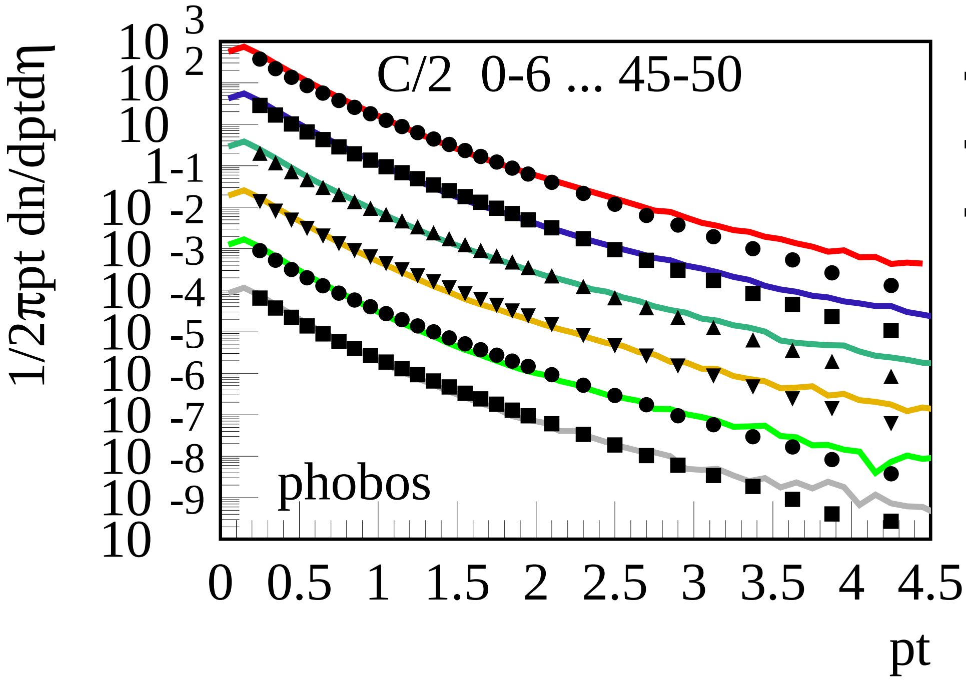
Completely different in pp:

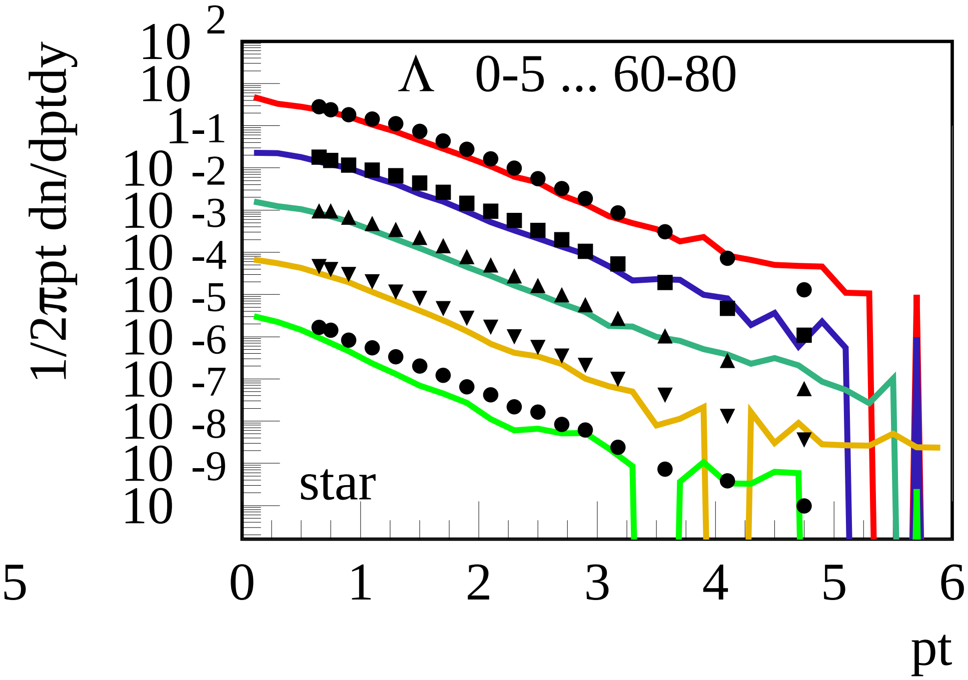
- separation of events into two classes:
  core and corona events

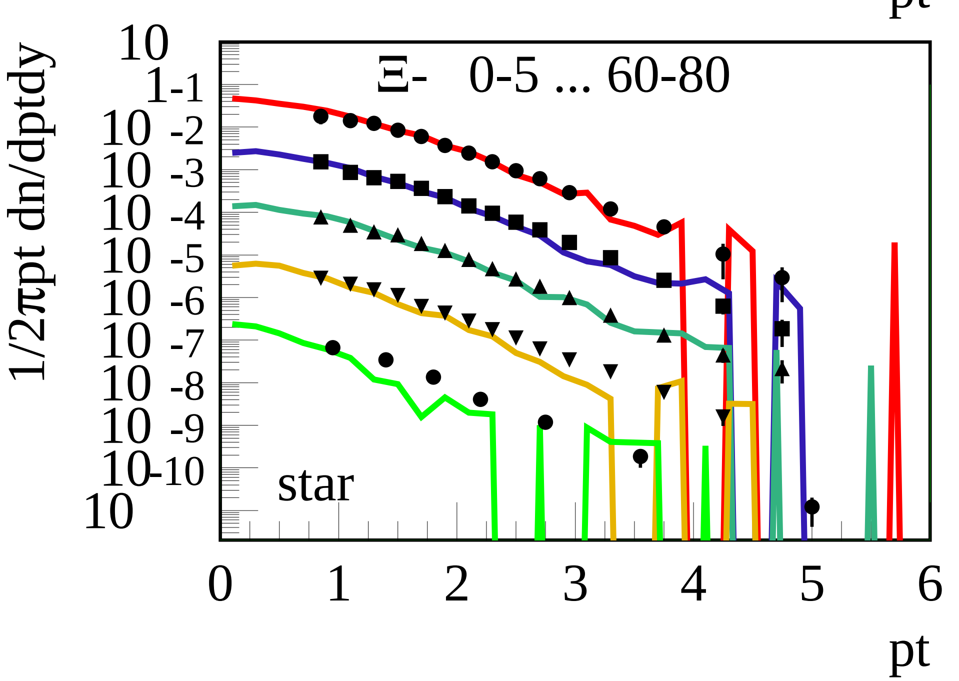
If employing same philosophy as in AA:

- core events expand collectively, decay statistically ("mini-plasma")
- corona events hadronize via string decay

Are there already “mini-plasma” signatures, at the Tevatron in particular?







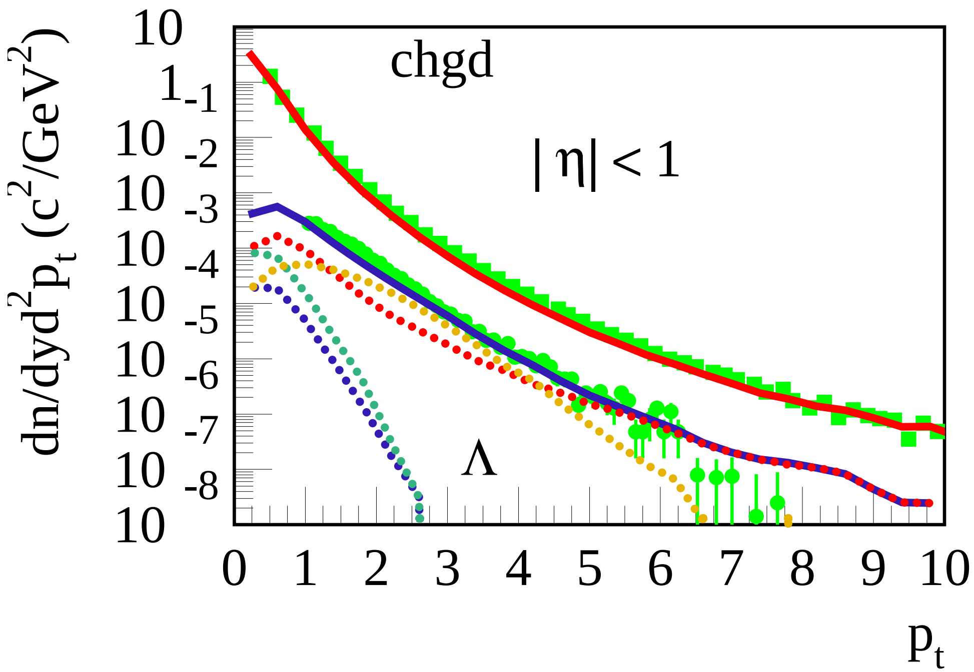
reminder:
in AuAu at 200 GeV:

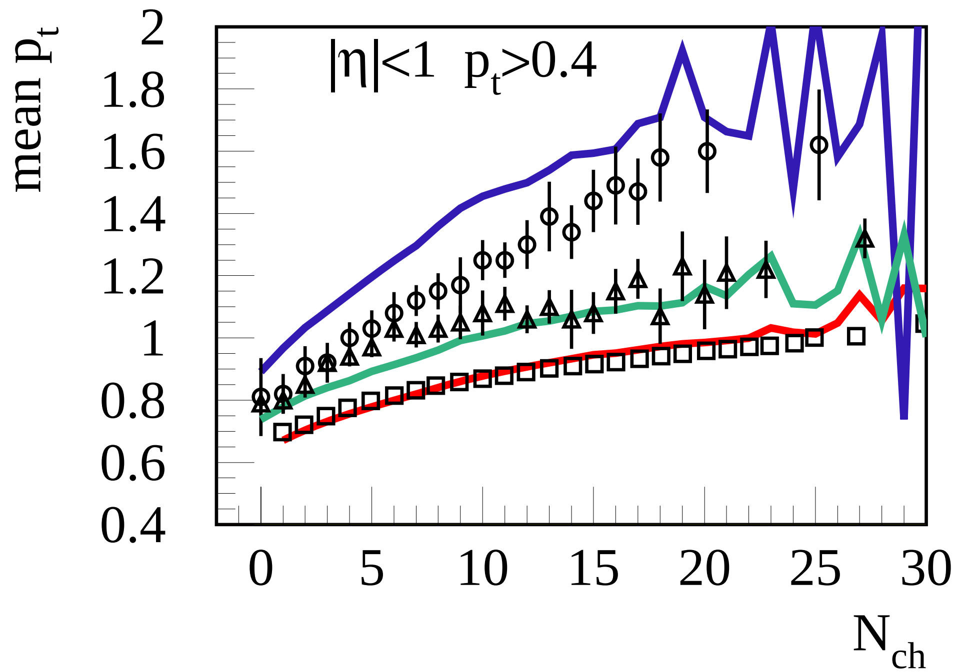
typical flow behavior:

light particles → concave
heavy particles → convexe

Collective effects in $p\bar{p}$?

Charged particle and lambda pt spectra: different shapes (as in AA)





Tevatron 1.8 TeV

EPOS w plasma

Increase of mean pt vs multiplicity of charged ptls, K_s, Λ (as in AA)

Summary (collective effects in pp)

- Core-corona procedure separates events into two classes: core and corona events
- employing same philsophy as in AA:
  - core events expand collectively, decay statistically ("mini-plasma")
  - corona events hadronize via string decay
- some "indications" at Tevatron
- LHC: study multiplicity dependence of observables (spectra, v2,...)

Some technical details ...

FO surface

We parameterize the hyper-surface $x^\mu = x^\mu(\tau,\varphi,\eta)$ as

$$x^0 = \tau\cosh\eta, \quad x^1 = r\cos\varphi, \quad x^2 = r\sin\varphi, \quad x^3 = \tau\sinh\eta,$$

with $r = r(\tau,\varphi,\eta)$ being some function of the three parameters τ, φ, η. The hypersurface element is

$$d\Sigma_\mu = \varepsilon_{\mu\nu\kappa\lambda}\frac{\partial x^\nu}{\partial\tau}\frac{\partial x^\kappa}{\partial\varphi}\frac{\partial x^\lambda}{\partial\eta}d\tau d\varphi d\eta,$$

with $\varepsilon^{\mu\nu\kappa\lambda} = -\varepsilon_{\mu\nu\kappa\lambda} = 1$. Computing the partial derivatives $\partial x^\mu/d\alpha$, with $\alpha = \tau$, φ, η, one gets

$$\begin{aligned}
d\Sigma_0 &= \left\{-r\frac{\partial r}{\partial\tau}\tau\cosh\eta + r\frac{\partial r}{\partial\eta}\sinh\eta\right\}d\tau d\varphi d\eta,\\
d\Sigma_1 &= \left\{\frac{\partial r}{\partial\varphi}\tau\sin\varphi + r\,\tau\cos\varphi\right\}d\tau d\varphi d\eta,\\
d\Sigma_2 &= \left\{-\frac{\partial r}{\partial\varphi}\tau\cos\varphi + r\,\tau\sin\varphi\right\}d\tau d\varphi d\eta,\\
d\Sigma_3 &= \left\{r\frac{\partial r}{\partial\tau}\tau\sinh\eta - r\frac{\partial r}{\partial\eta}\cosh\eta\right\}d\tau d\varphi d\eta.
\end{aligned}$$

Invariant expressions

The invariant volume element is

$$dV^* = d\Sigma_\mu u^\mu,$$

with u being the flow four-velocity in the global frame, which can be expressed in terms of the four-velocity $\tilde{u}$ in the "Bjorken frame" as

$$\begin{aligned} u^0 &= \tilde{u}^{\,0} \cosh\eta + \tilde{u}^{\,3} \sinh\eta \,, \\ u^1 &= \tilde{u}^{\,1} \,, \\ u^2 &= \tilde{u}^{\,2} \,, \\ u^3 &= \tilde{u}^{\,0} \sinh\eta + \tilde{u}^{\,3} \cosh\eta \,. \end{aligned}$$

Using $\gamma = \tilde{u}^{\,0}$ and the flow velocity $v^\mu = \tilde{u}^{\,\mu}/\gamma$, we get

$$dV^* = \gamma \left\{ -r\frac{\partial r}{\partial \tau}\tau + r\,\tau\,v^r + \frac{\partial r}{\partial \varphi}\tau v^t - r\frac{\partial r}{\partial \eta}v^3 \right\} d\tau d\varphi d\eta,$$

with $v^r = v^1\cos\varphi + v^2\sin\varphi$ and $v^t = v^1\sin\varphi - v^2\cos\varphi$ being the radial and the tangential transverse flow.

Similar treatment for the invariant expression

$$d\Sigma_\mu p^\mu .$$

The momentum four-vector p can be expressed in terms of the four-vector $\tilde{p}$ in the “Bjorken frame” as

$$\begin{aligned} p^0 &= \tilde{p}^{\,0} \cosh\eta + \tilde{p}^{\,3} \sinh\eta \,, \\ p^1 &= \tilde{p}^{\,1} \,, \\ p^2 &= \tilde{p}^{\,2} \,, \\ p^3 &= \tilde{p}^{\,0} \sinh\eta + \tilde{p}^{\,3} \cosh\eta \,, \end{aligned}$$

which leads to

$$d\Sigma_\mu p^\mu = \left\{ -r \frac{\partial r}{\partial \tau} \tau \, \tilde{p}^{\,0} + r\,\tau\,\tilde{p}^{\,r} + \frac{\partial r}{\partial \varphi} \tau \tilde{p}^{\,t} - r \frac{\partial r}{\partial \eta} \tilde{p}^{\,3} \right\} d\tau d\varphi d\eta,$$

where we use again radial and the tangential components. Furthermore one gets

$$up = u_\mu p^\mu = \gamma \left(\tilde{p}^{\,0} - v^r \tilde{p}^{\,r} - v^t \tilde{p}^{\,t} - v^3 \tilde{p}^{\,3} \right) .$$

Local rest frame particle generation

Particle multiplicity in volume dV^* according to

$$N_i = \int d^3p \, \frac{dV^*}{(2\pi\hbar)^3} \exp(-\frac{\sqrt{p^2+m_i^2}-\mu_i}{T})$$

particle momentum according to

$$\mathrm{prob}(p) = \frac{1}{N_i} 4\pi p^2 \, \frac{dV^*}{(2\pi\hbar)^3} \exp(-\frac{\sqrt{p^2+m_i^2}-\mu_i}{T})$$

making use of the fact that the sum of three exponential random numbers is distributed as $x^2 \exp(-x)$.