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Hydrodynamic Evolution in EPOS

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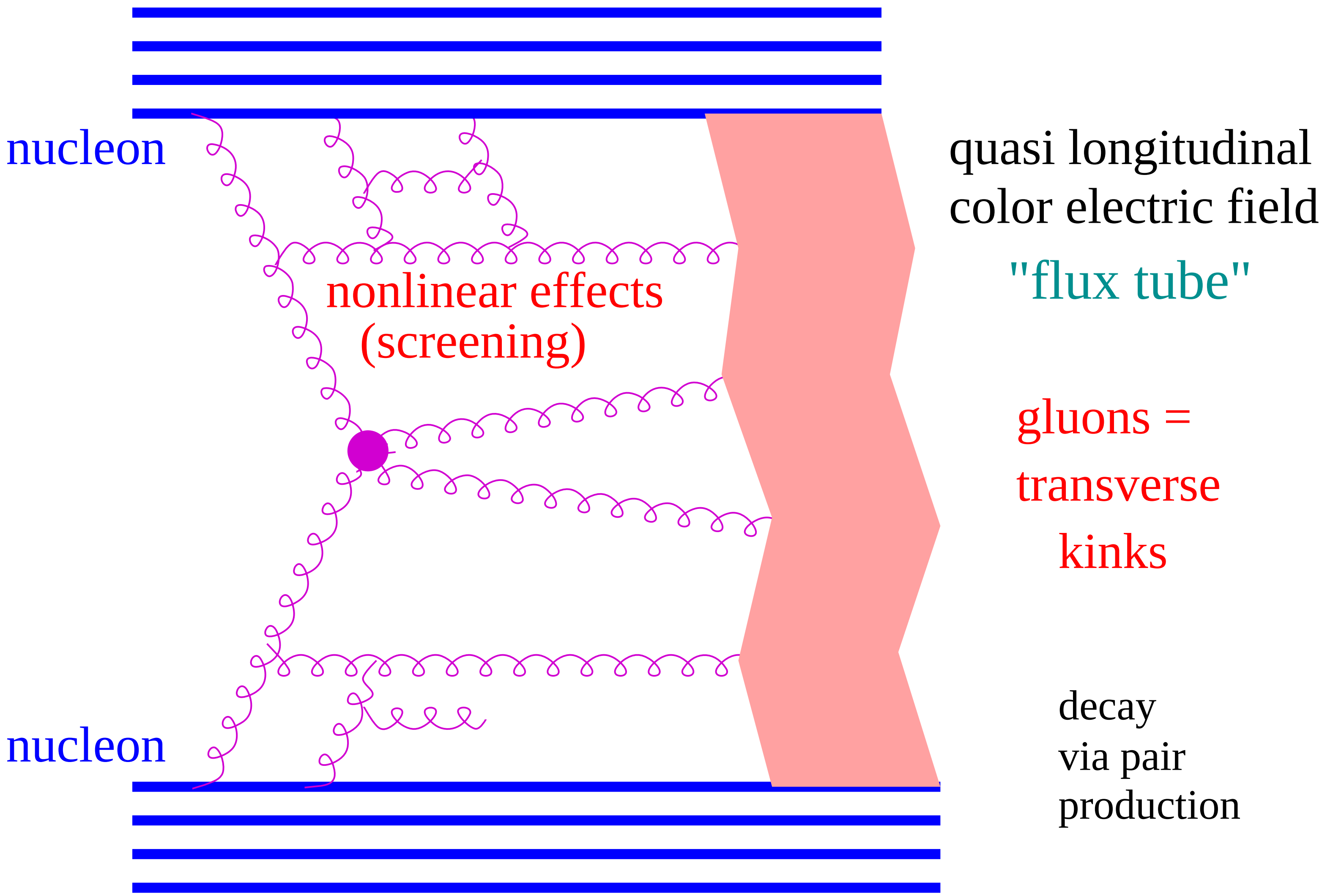
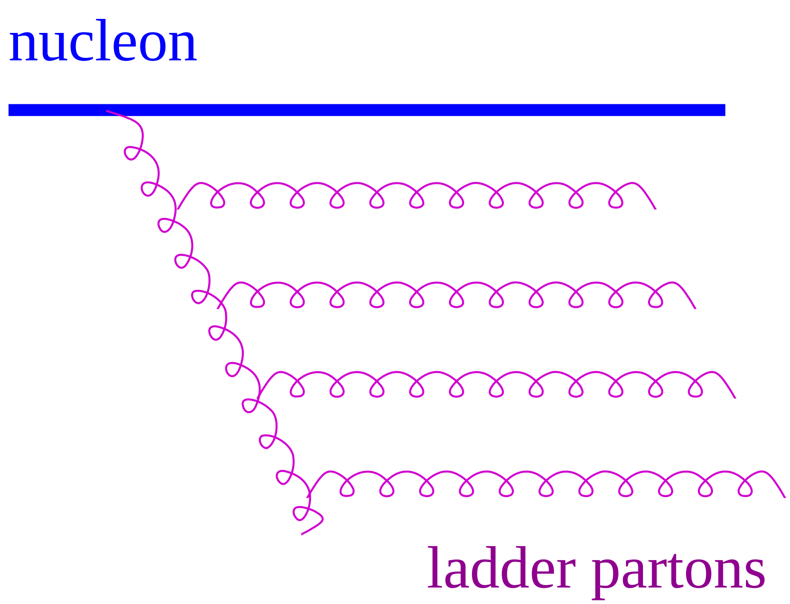
EPOS: in collaboration with T. Pierog
Hydro: in collaboration with T. Hirano and Y. Karpenko

- Parton evolution in EPOS
- Hadronization
- Remnants
- Factorization and Multiple Scattering
- Initial Conditions for Hydro
- Hydrodynamic evolution


nucleon
quasi longitudinal
color electric field
"flux tube"
nonlinear effects
(screening)
gluons =
transverse
kinks
decay
via pair
production
nucleon

Parton evolution

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



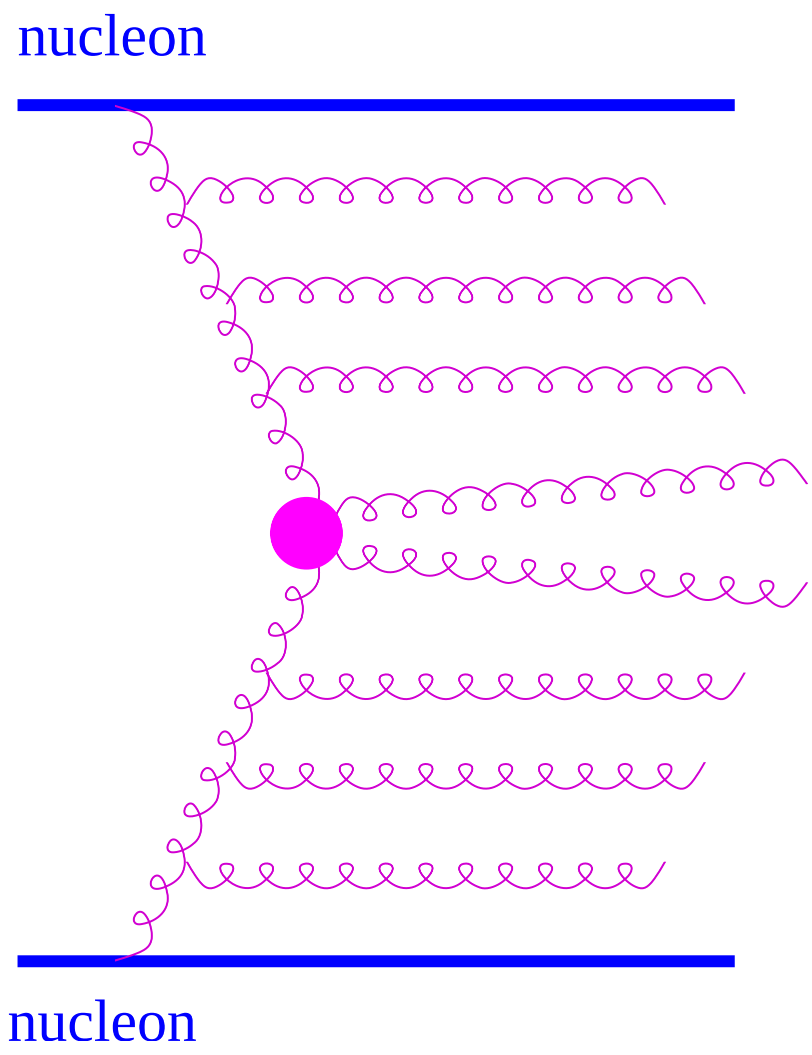
In the simplest case:

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 (RHIC):

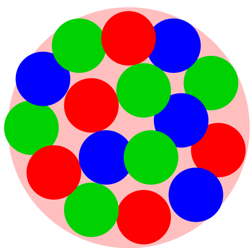
“parton ladder” is meant to contain two parts:

- □ 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

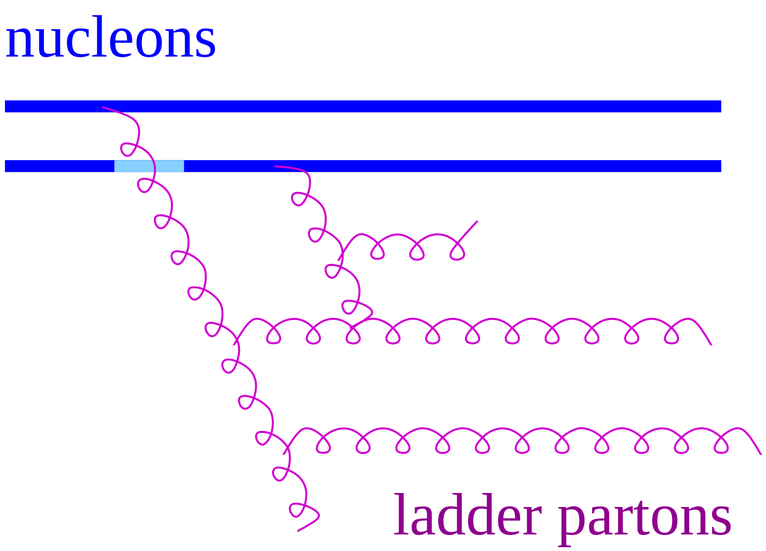
- □ using BK instead of DGLAP evolution or phenomenological approach (like simple parameterization of gluon distributions)

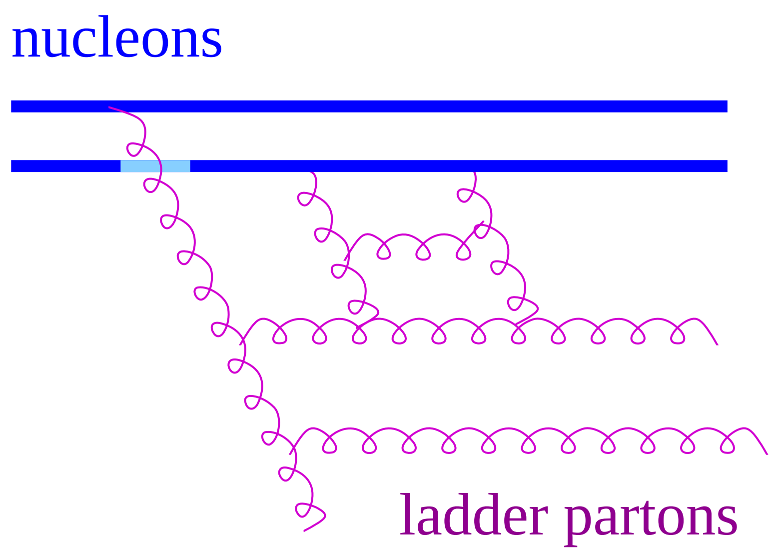
Here: phenomenological approach, which grasps the main features of these non-linear phenomena, and still remains technically doable

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})

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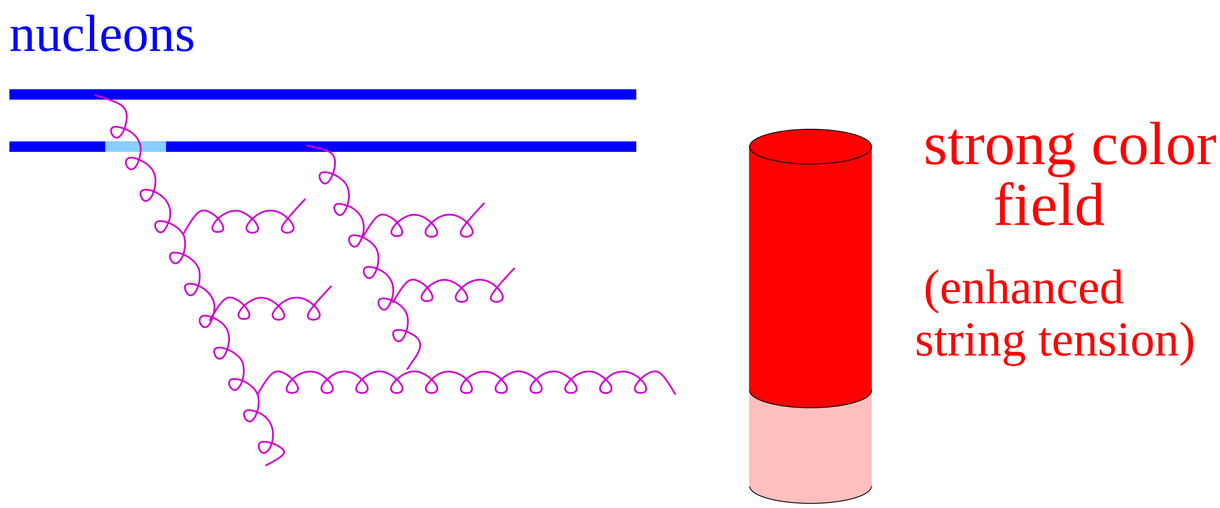
[1] imaginary part of the corresponding amplitude in $b-$space
[2] x^{+}, x^{-}: light cone momentum fractions of the first ladder partons

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 probability: $\exp(-\pi m_q^2/\kappa)$

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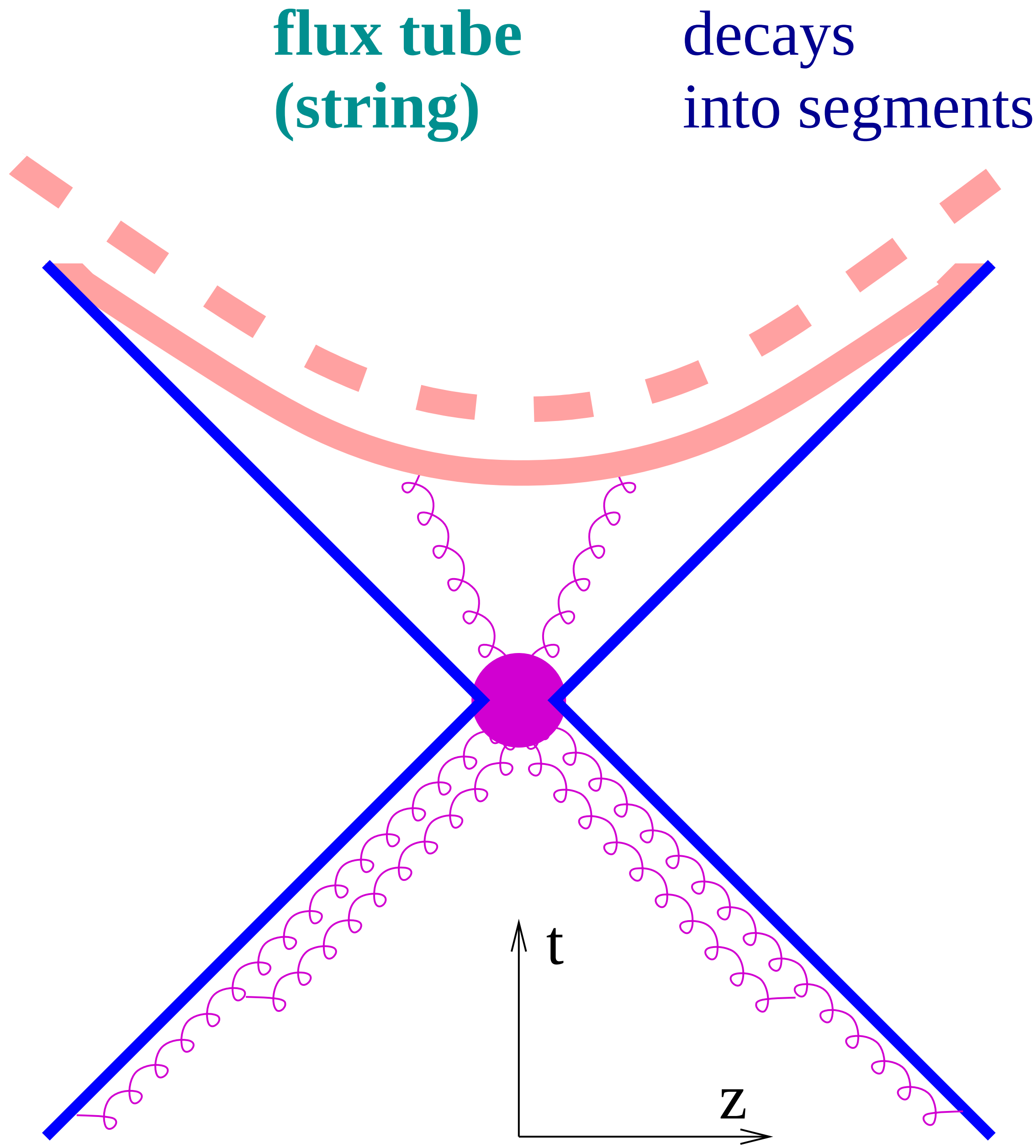
[3] Lund model idea, first e+e-, then generalized to pp, see also CGC

Flux tube stretches over wide range in rapdity

decay via pair production

Hadrons are NOT associated to individual partons!

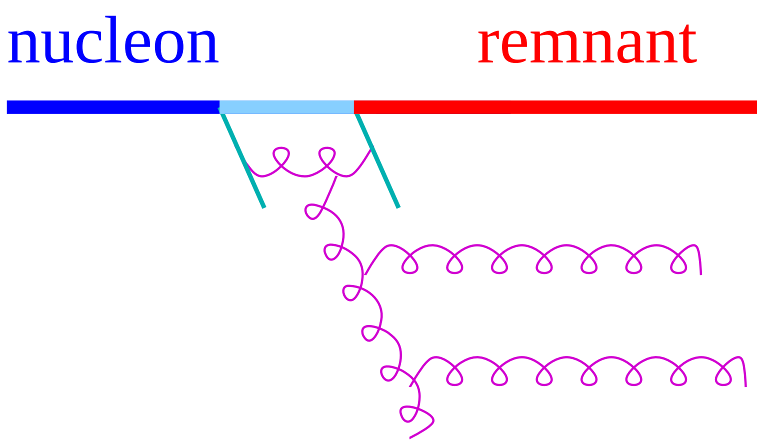
unless one considers hard processes



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 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

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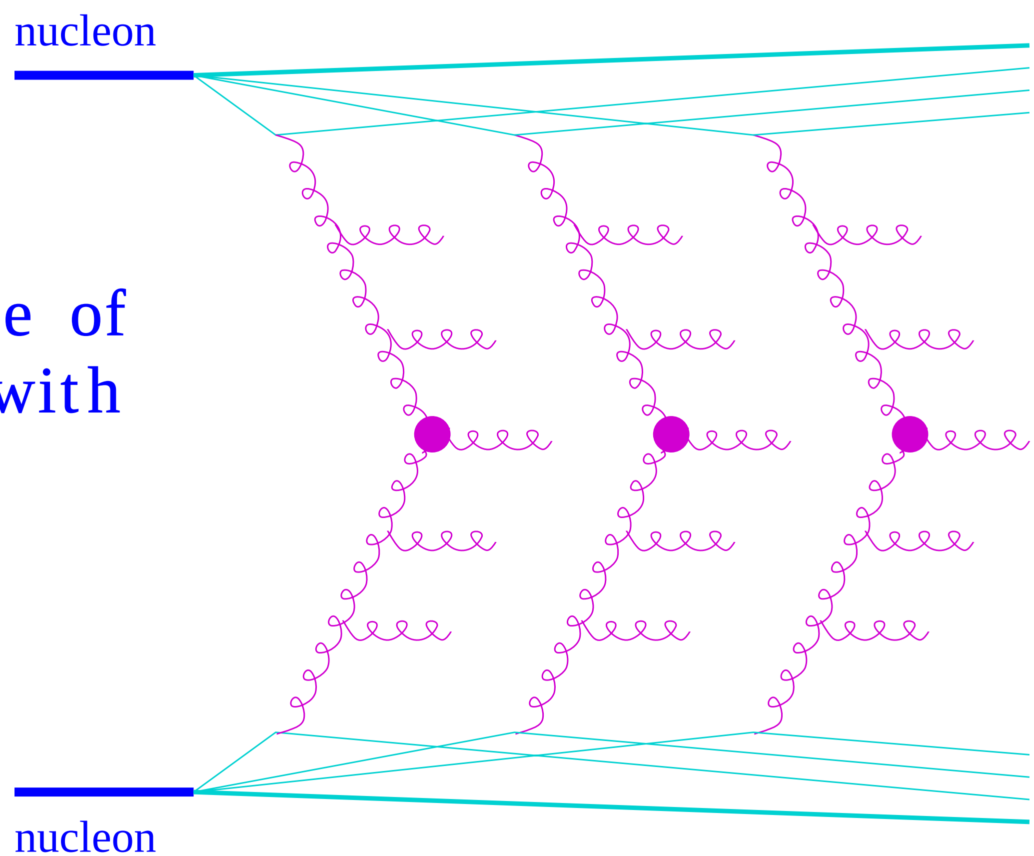
[4] not necessarily true, see recent papers by Collins

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)

Initial Condition for Hydro

There seems to be no doubt that RHI collisions (at least at RHIC) follow a hydrodynamic evolution

Initial conditions of hydro phase:

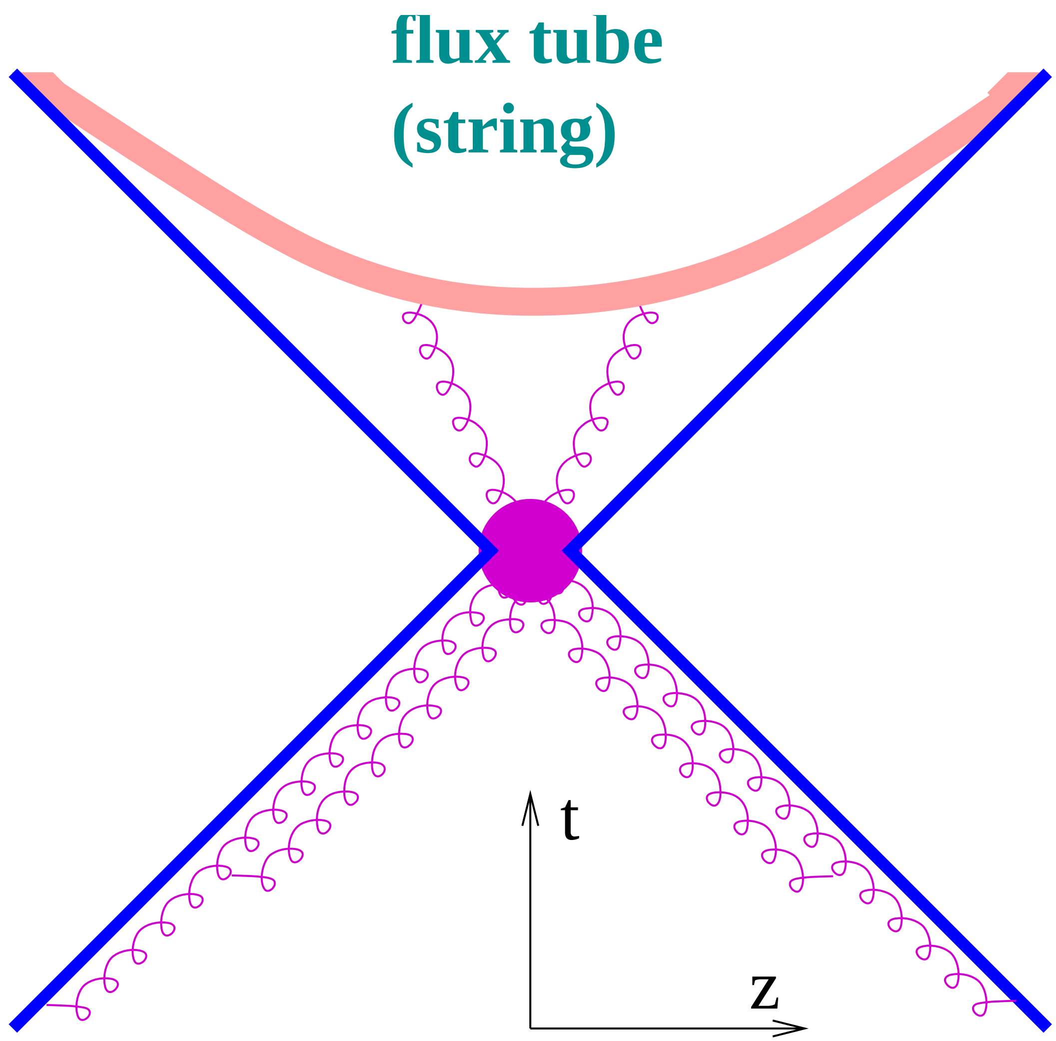
- □ parameterized, to optimize final results
- □ or obtained from microscopic approach, based on the hypothesis that thermalization happens very quickly and is achieved at some τ_0

Here: second option, using EPOS

We consider
color field / flux tube [a]
as pre-initial condition

actually many overlapping flux tubes

not partons!



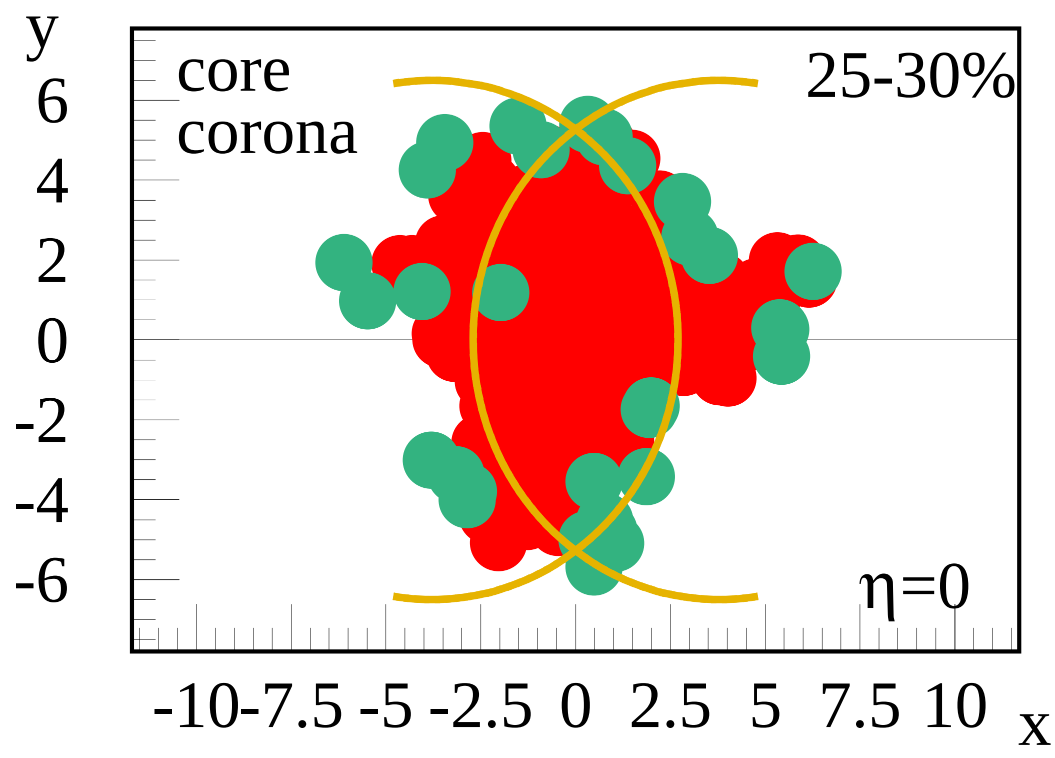
[a] more precise: string segments

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

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

otherwise:
corona (green)

high pt segments count as corona



core: we include inwards moving corona segments

Hydro evolution: three modes:

- Usual case:
  - Average initial condition (many simul.), then 3D hydro calculation (T.Hirano and Y.Karpenko)
- Ideal, but very slow:
  - IC for single event, then 3D hydro
- Compromise:
  - Average initial condition (many simul.)
  - then 3D hydro calculation & tabulation of FO surface and FO properties
  - Run EPOS EbyE, determine energy density at τ_0, hadronize acc to FO tables (shortcut IC→FO)

In addition:

possibility to use (or not) UrQMD afterburner
for final state hadronic rescatterings

(in collaboration with S.Haussler, M.Bleicher)

FO surface and properties

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

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

The invariant volume element moving through the FO surface 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

$$dV^* = w\, d\tau d\varphi d\eta,$$

with

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

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.

Storing the FO surface and properties means actually tabulating

- the FO radius $r = r(\tau, \varphi, \eta)$,
- the flow components $v^r(\tau, \varphi, \eta)$, $v^t(\tau, \varphi, \eta)$, $v^3(\tau, \varphi, \eta)$,
- the FO weight $w(\tau, \varphi, \eta)$.

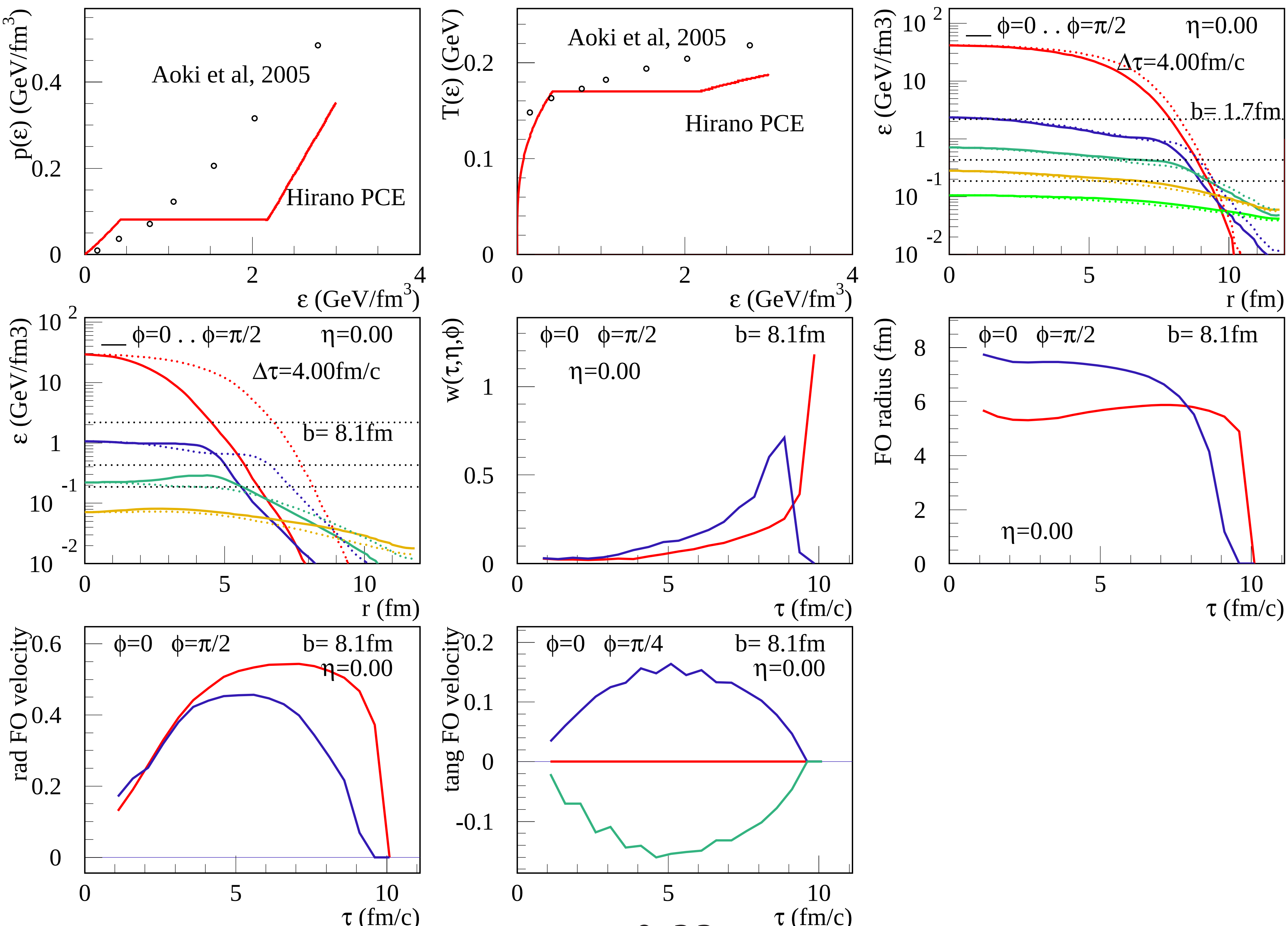
FO is the done as follows (equivalent to Cooper-Frye):

- one generates hadrons h in a proper volume element $dV^* = w\, d\tau d\varphi d\eta$ isotropically as

  $$dn_h = f_E \frac{dV^*}{(2\pi\hbar)^3} \exp\left(-\frac{\sqrt{p^2 + m_h^2} - \mu_h}{T}\right) d^3p$$

  with f_E to assure energy conservation despite EbE fluctuations of core energy
- and then boost the momenta to the global frame

Results __ IC EPOS 1.87 __ Hydro Hirano PCE __ Tfo=130MeV



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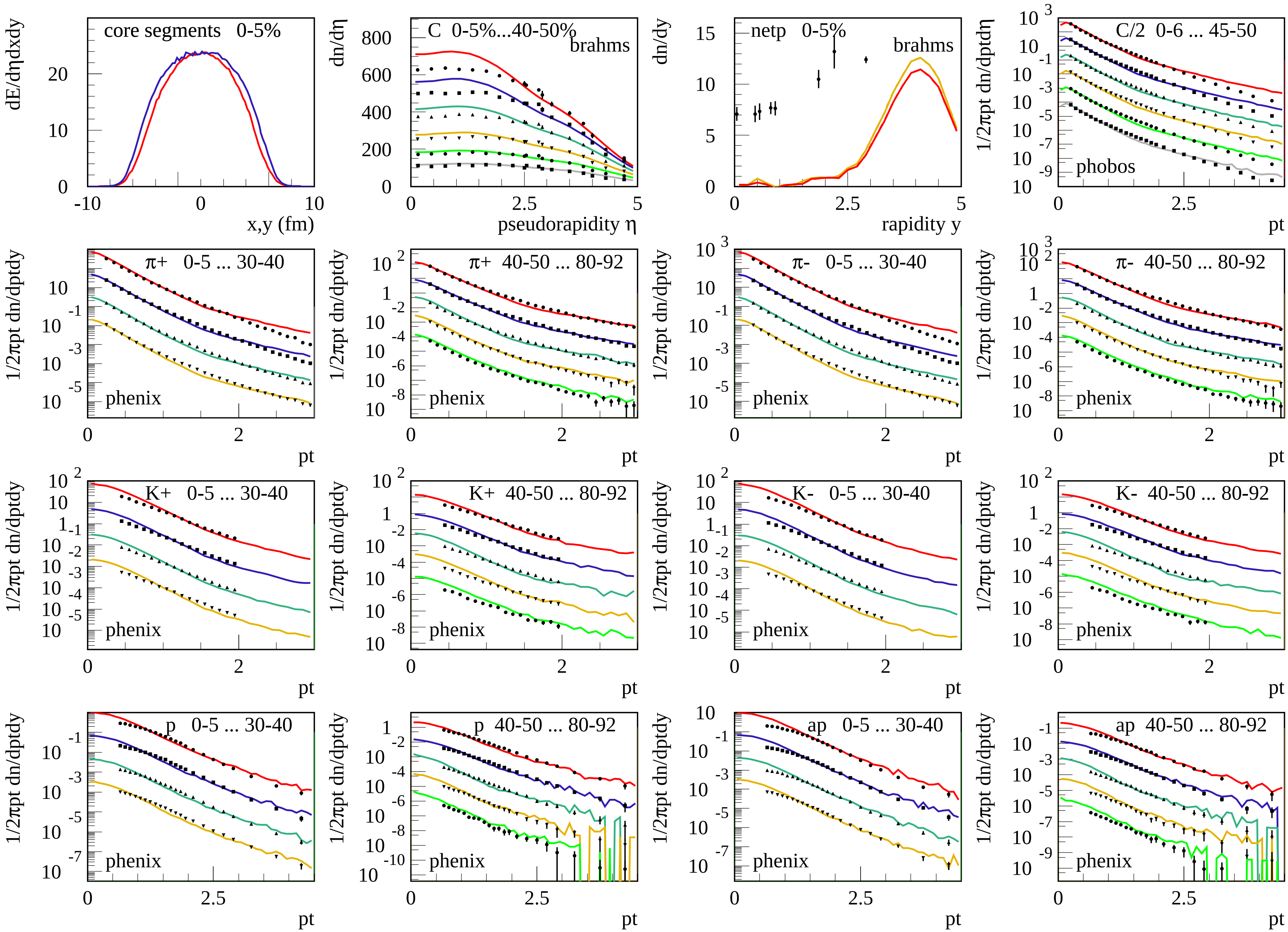
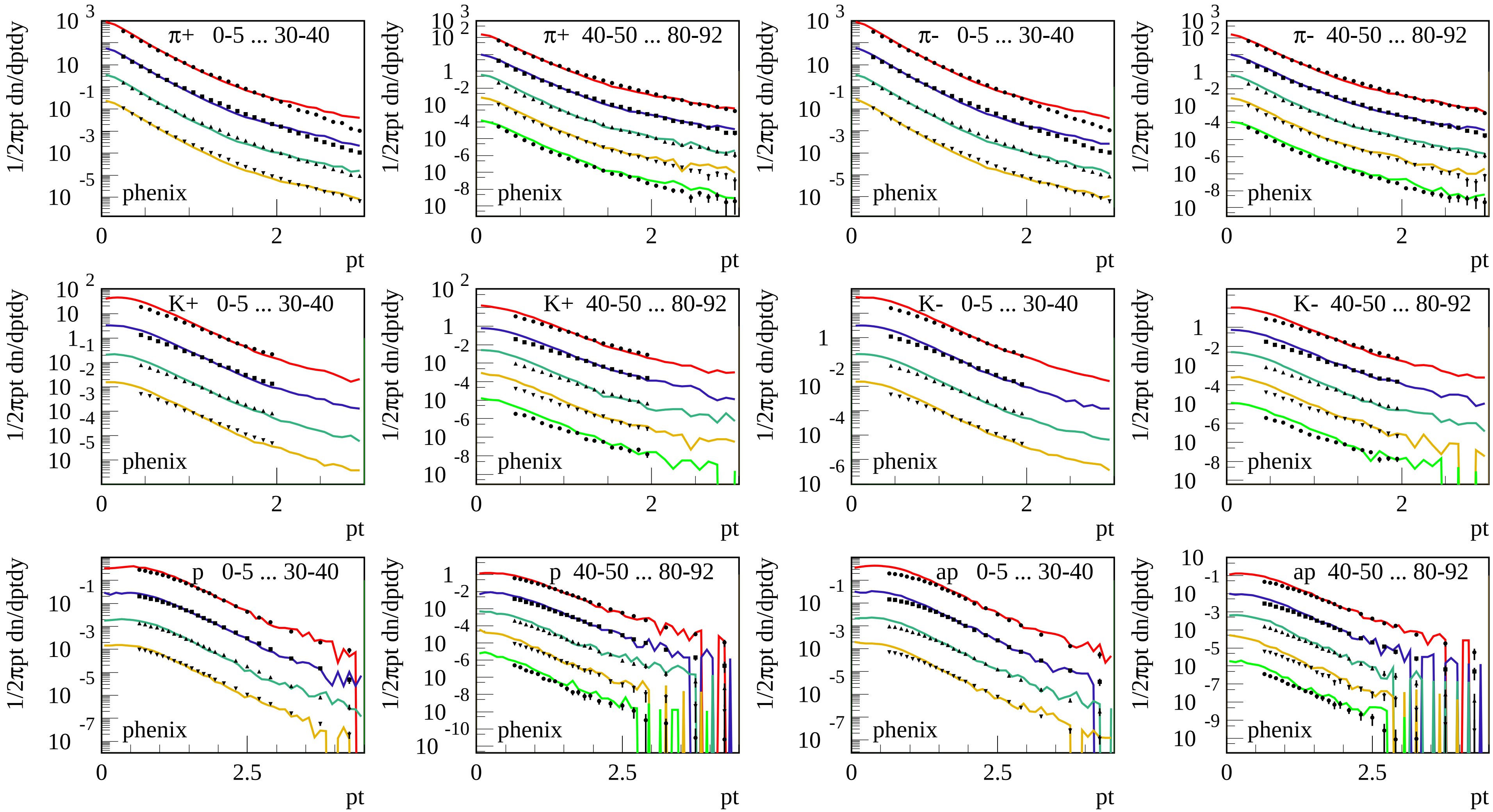


__ UrQMD final state IA__



Summary

- Latest EPOS takes into account
  - recent developments on nonlinear parton evolution
    (concerning cross sections and particle production)
  - remnants ; flux tube picture
- EPOS (carefully checked agains pp, pA) provides initial conditions for hydro
  - EbyE procedure based on tabulated FO properties
  - detailed comparisons with data possible (and under way)