EPOS

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with

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Contents

Todays lecture:
short version of a detailed lecture (266 pages)

at the Joliot-Curie International School 2018

https://ejc2018.sciencesconf.org/data/pages/joliot.20.pdf

Today only some selected (important) topics ...

1 Introduction

EPOS is an event generator to treat consistently

- □ **e+e- annihilation** (test string fragmentation)
- □ **ep scattering** (test parton evolution)
- □ **pp, pA, AA collisions**

at high energies
(collision finished before particle production starts)

Basic structure of EPOS (for modelling pp, pA, AA)

- **Primary interactions**

  Multiple scattering, instantaneously, in parallel
  (Parton Based Gribov-Regge Theory)

  - **in pA and AA: multiple NN scattering**
  - **but also in pp : Multiple parton scattering**
    (or for each NN scattering in pA, AA)

- **Secondary interactions**

  formation of "matter" which expands collectively, like a fluid, decays statistically

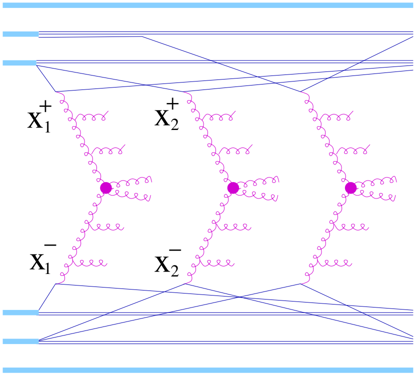
Some history of Gribov-Regge Theory (the heart of EPOS)

- ☐ 1960-1970: Gribov-Regge Theory of multiple scattering.
  pp = multiple exchange of "Pomerons"
  (with amplitudes based on Regge poles)

- ☐ 1980-1990: pQCD processes
  added into GRT scheme (Capella)

- ☐ 1990: M.Braun, V.A.Abramovskii, G.G.Leptoukh:
  problem with energy conservation
  (not done consistently)

- 2001: H.J.Drescher, M.Hladik, S.Ostapchenko, T. Pierog, and K. Werner, Phys. Rept. 350, p93:
  Marriage pQCD + GRT, with energy sharing (NEXUS)



Multiple scatterings
(in parallel !!)
in pp, pA, or AA

Single scattering

= hard elementary scattering including IS + FS radiation

$$\boxed{\sum x_i^{\pm} + x_{\mathrm{remn}}^{\pm} = 1}$$

□ ~ 2003 NEXUS split into

□ QGSJET (S. Ostapchenko)

– Triple Pomeron contributions and more, to all orders

□ EPOS (T. Pierog, KW)

– Saturation scale, secondary interactions

– two versions, EPOSLHC and EPOS3, going to be “fused”, with a rigorous (selfconsistent) treatment of new key features
(HF, saturation & factorization)
=> new public version (β version exists since few days ...)

Two of the key models used for airshower simulations

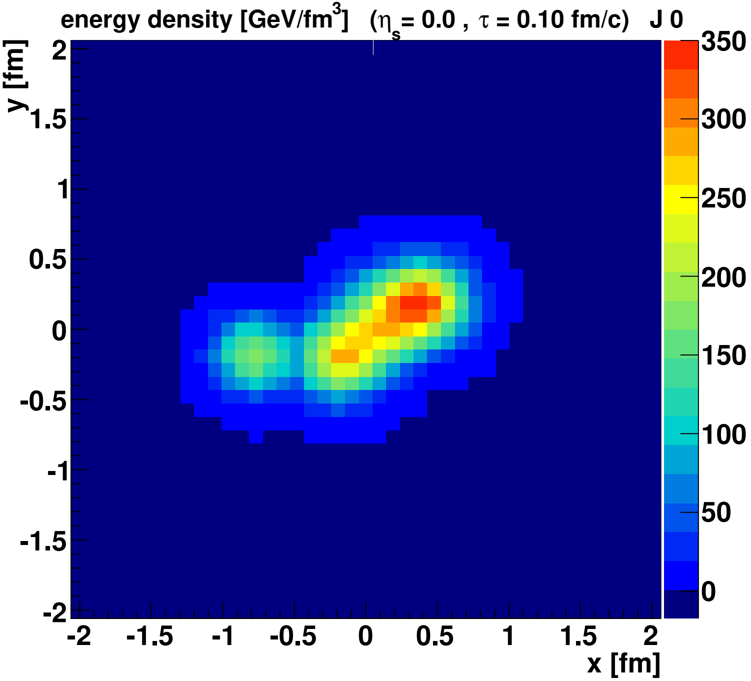
Secondary interactions:

Example:

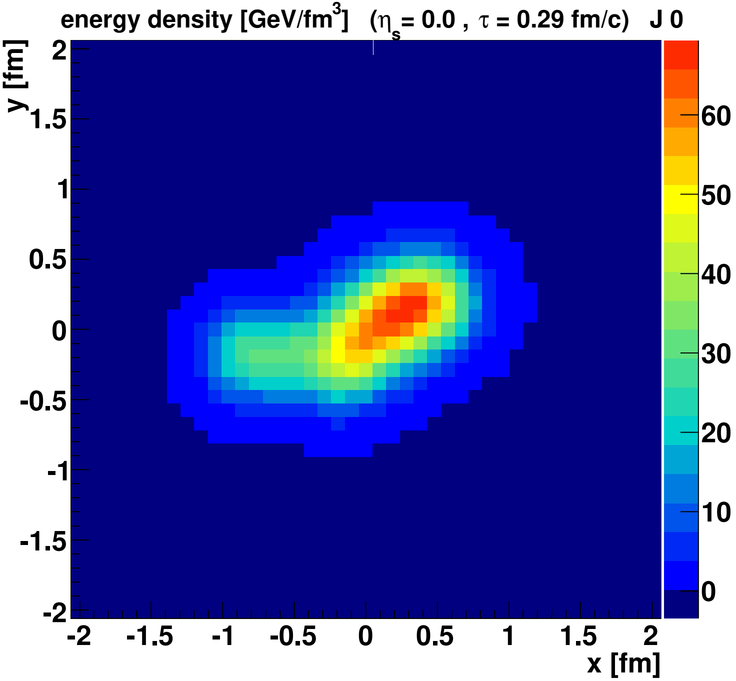
space-time evolution in pp

leading to collective flow

pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119



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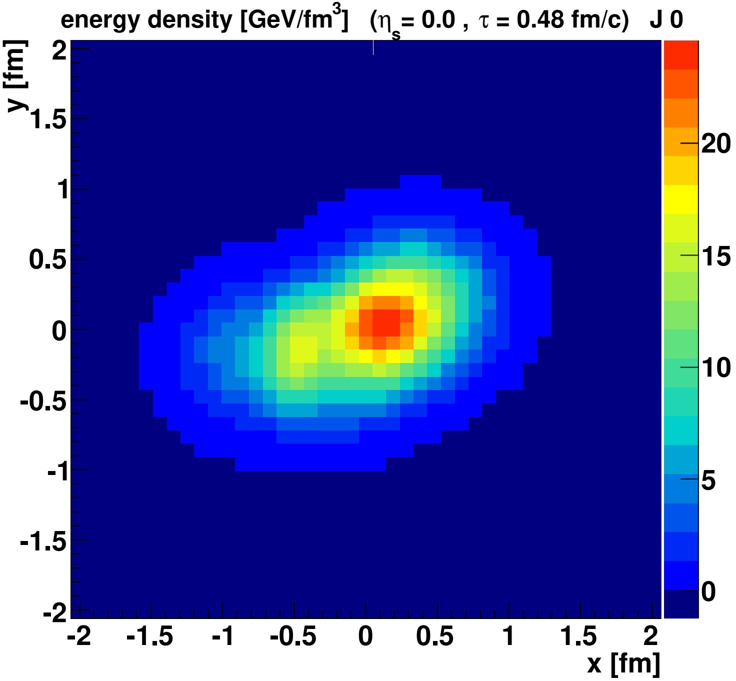

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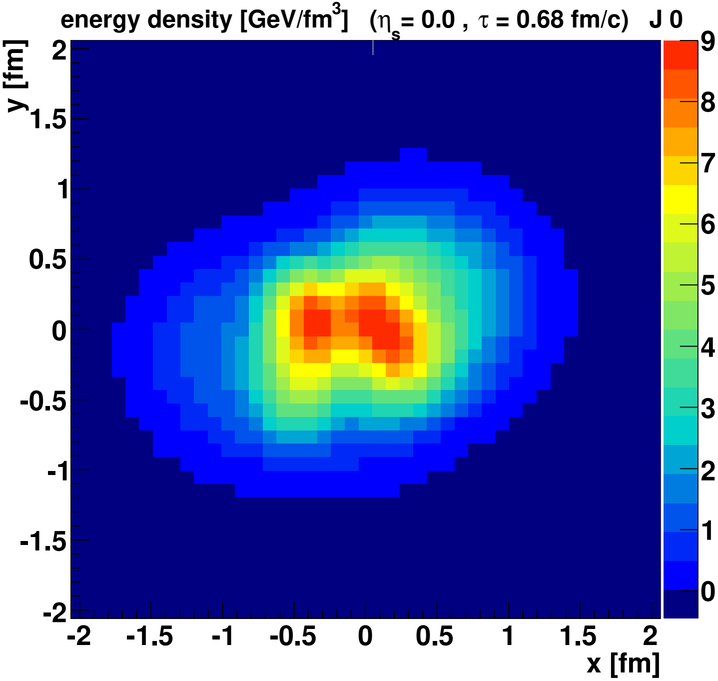
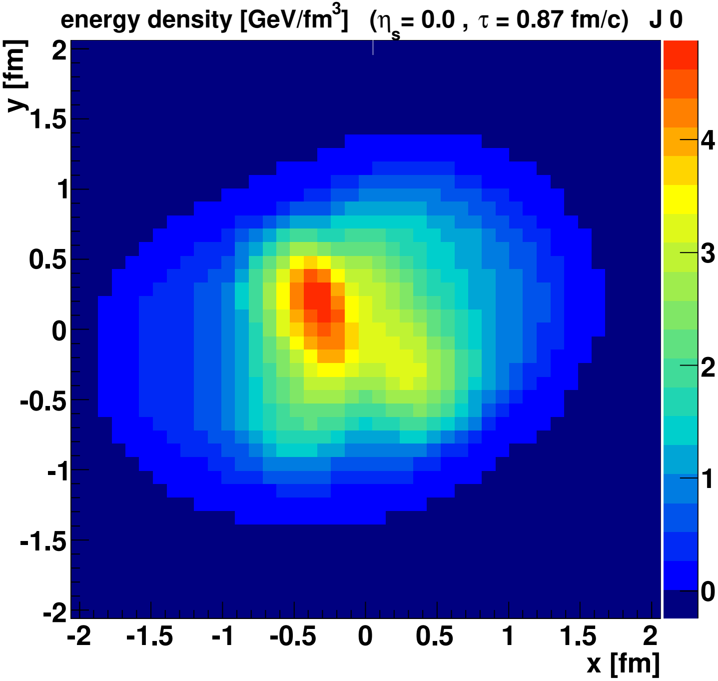
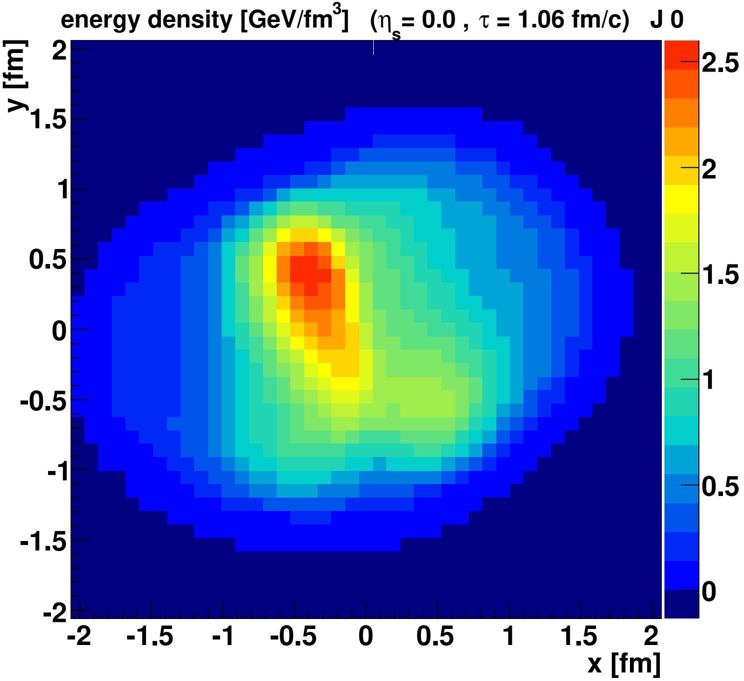


pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119



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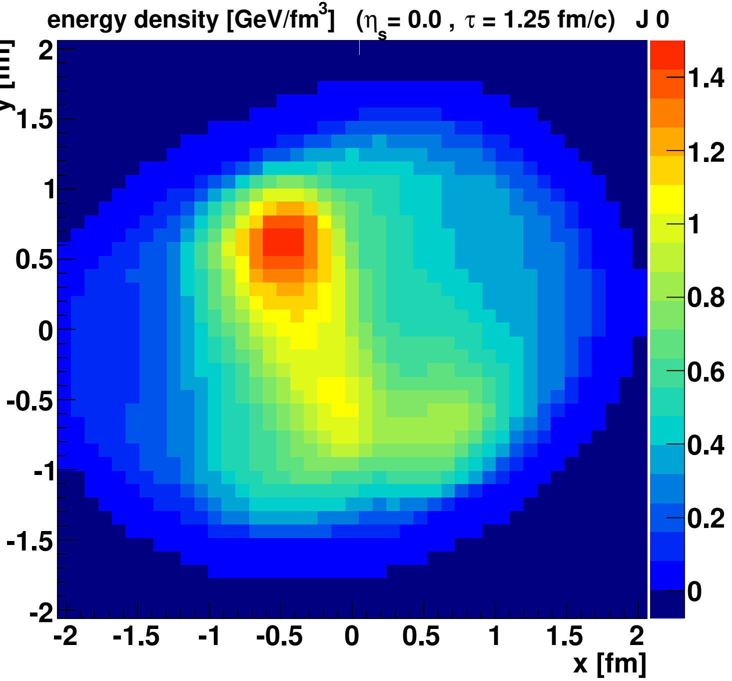

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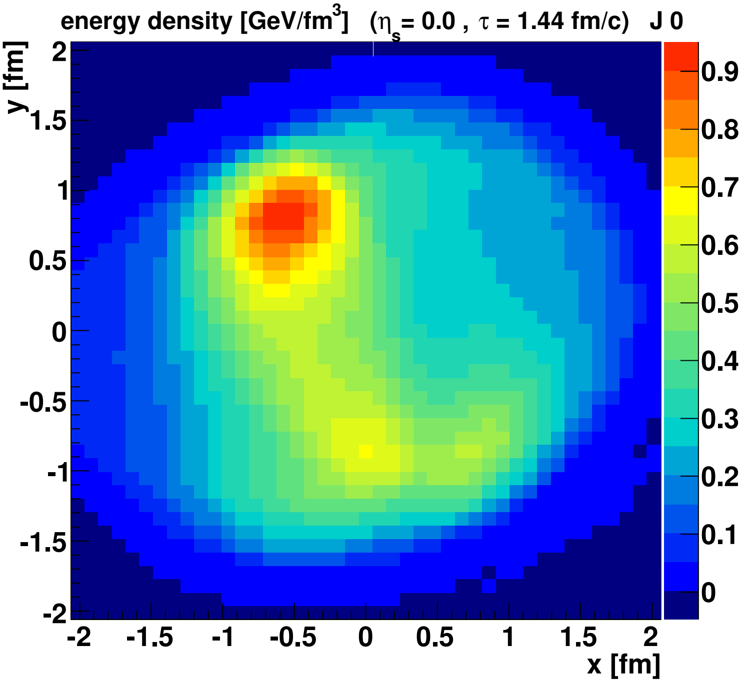

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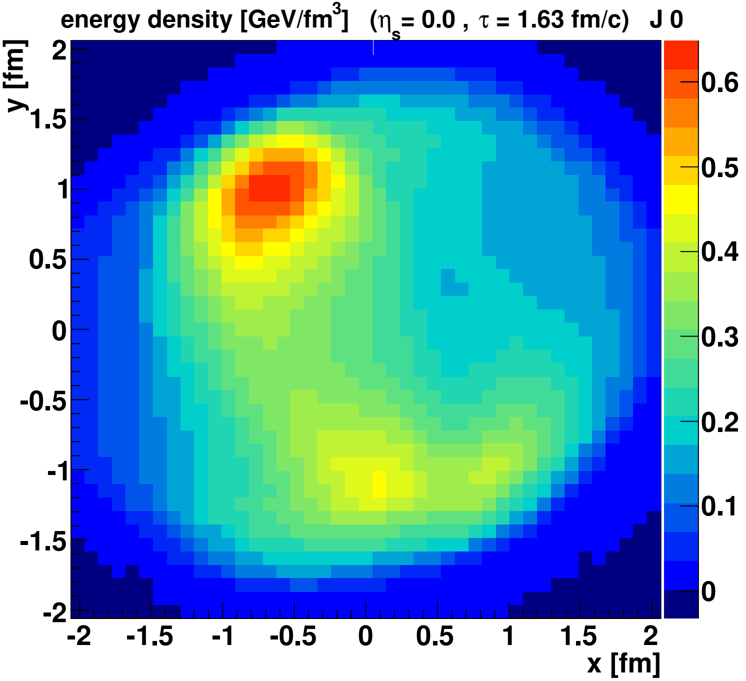

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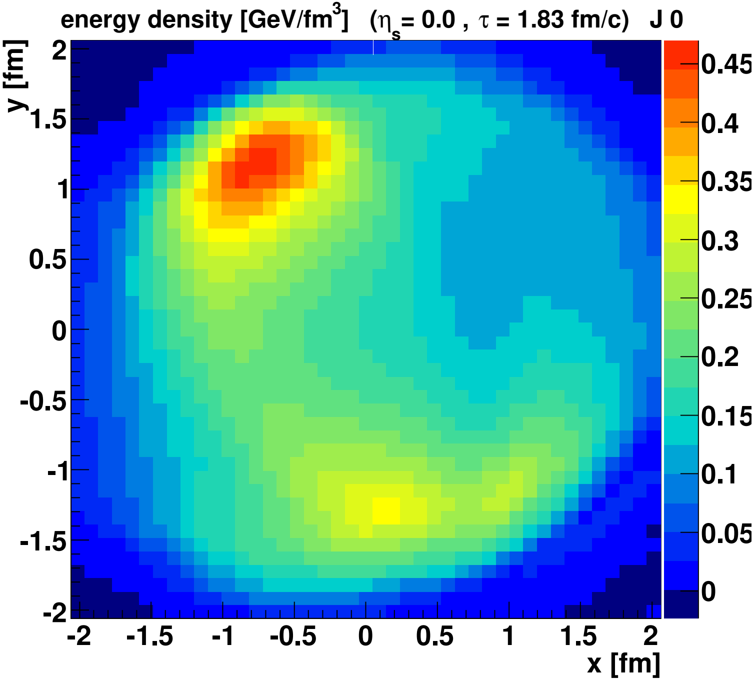

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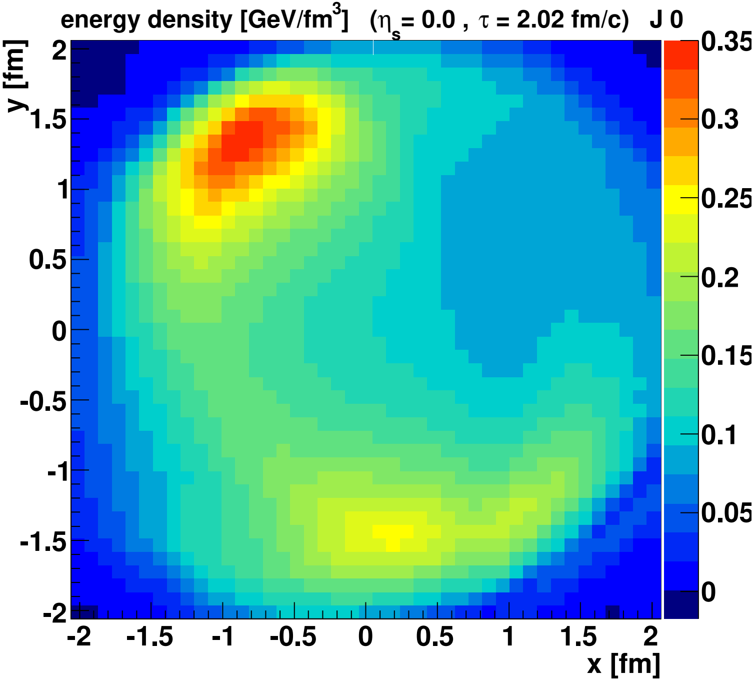

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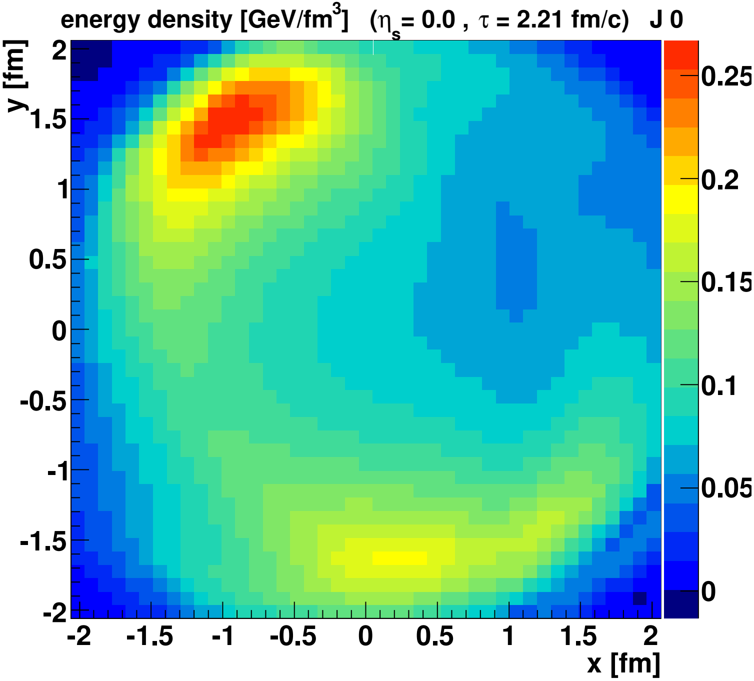

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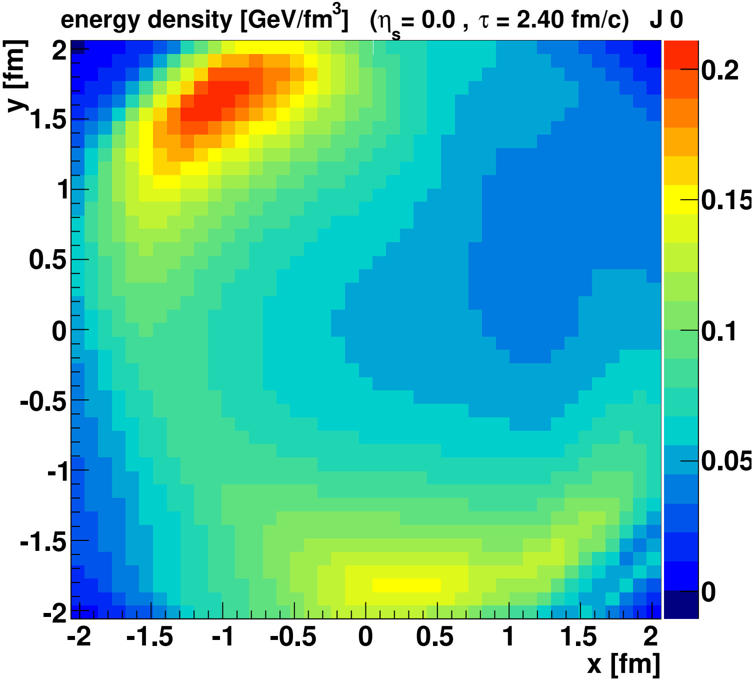

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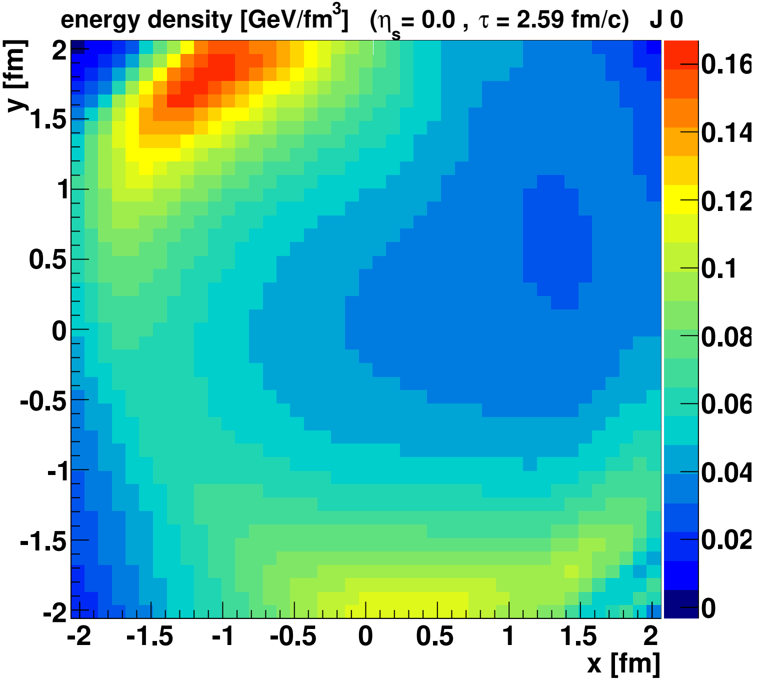
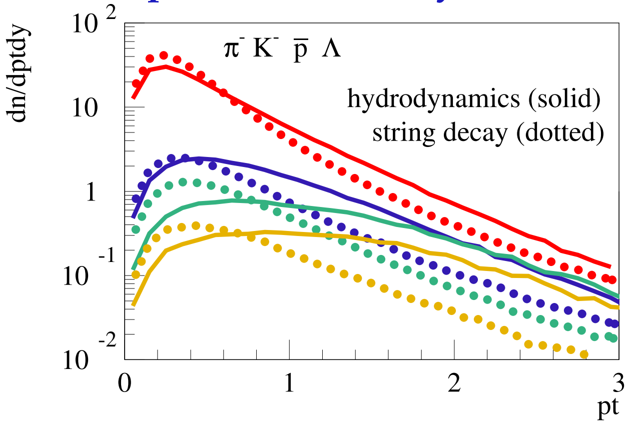


Radial flow visible in particle distributions

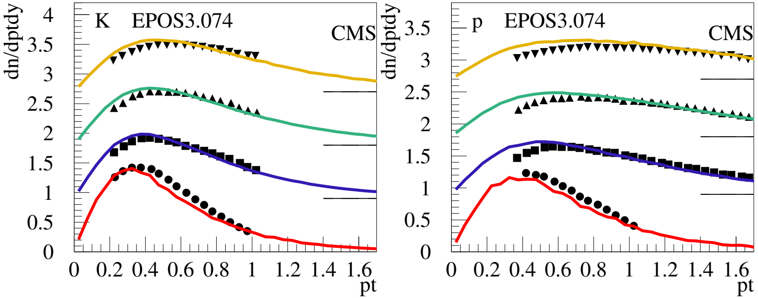
Particle spectra affected by radial flow



=> mass ordering of $\langle p_t \rangle$, lambda/K increase

pPb at 5TeV

CMS,EPJC 74 (2014) 2847, arXiv:1307.3442



Strong variation of shape with multiplicity

for kaon and even more for proton pt spectra

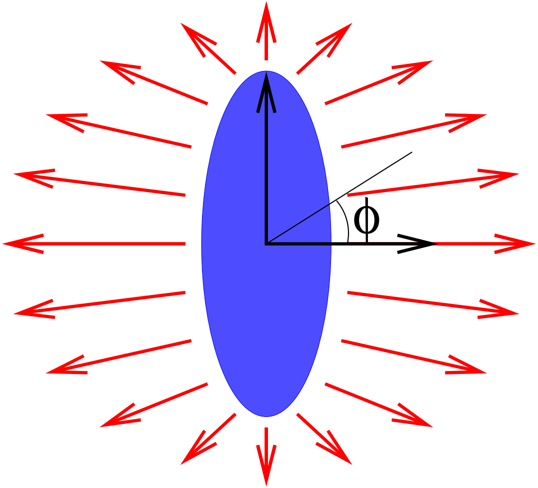
(EPOS curves: flow changes shapes)

Anisotropic radial flow
visible in dihadron-correlations

$$R = \frac{1}{N_{\mathrm{trigg}}} \frac{dn}{d\Delta\phi\Delta\eta}$$

Anisotropic flow due to initial
azimuthal anisotropies

Initial “elliptical” matter distribution:

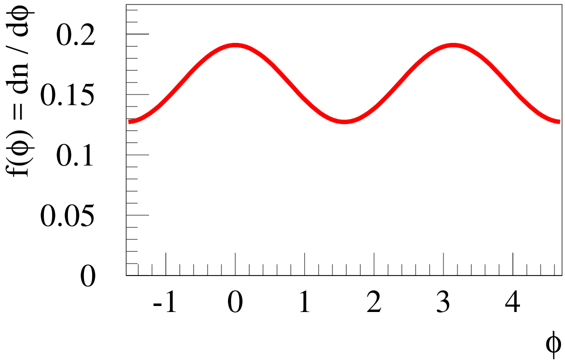


Preferred expansion along $\phi = 0$ and $\phi = \pi$

η_s-invariance
same form at any η_s
$\eta_s = \frac{1}{2} \ln \frac{t+z}{t-z}$

Particle distribution: Preferred directions $\phi = 0$ and $\phi = \pi$

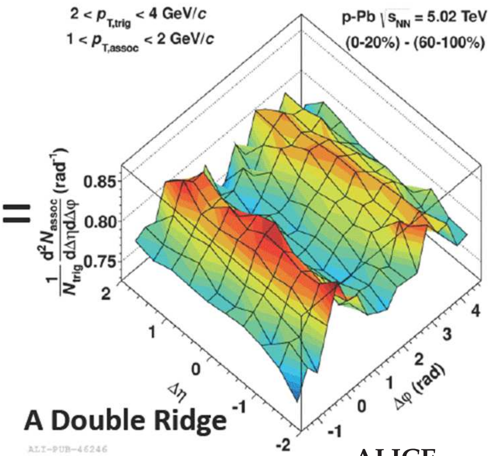
$\propto 1 + 2v_2 \cos(2\phi)$



Dihadrons:
preferred $\Delta\phi = 0$ and $\Delta\phi = \pi$ (even for big $\Delta\eta$)

Ridges (in dihadron correlation functions) seen in pPb (and even pp)

Central - peripheral (to remove jets) Phys. Lett. B 726 (2013) 164-177



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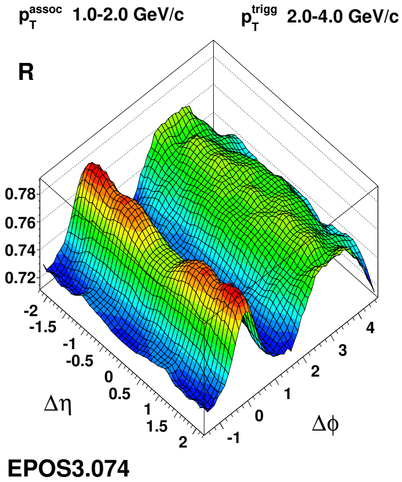


Heavy ion approach

= primary (multiple) scattering
+ subsequent fluid evolution

becomes interesting for pp and pA

2 Glauber and Gribov-Regge approach

concerning primary interactions

providing initial conditions
for secondary interactions

Glauber approach

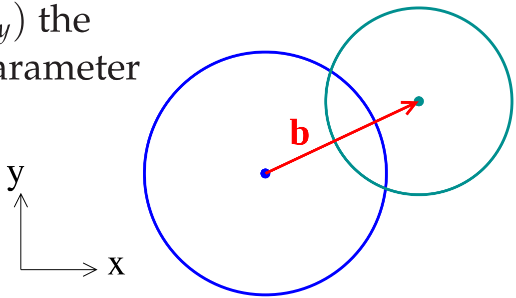
Nucleus-nucleus collision A + B :

- ☐ Sequence of independent binary nucleon-nucleon collisions
- ☐ Nucleons travel on straight-line trajectories
- ☐ The inelastic nucleon-nucleon cross-section σ_{NN} is independent of the number od NN collisions

Monte Carlo version: Two nucleons collide if their transverse distance is less than $\sqrt{\sigma_{NN}/\pi}$.

Analytical formulas for A + B scattering:

- □ Be ρ_A and ρ_B the (normalized nuclear densities), and
- □ $b = (b_x, b_y)$ the impact parameter

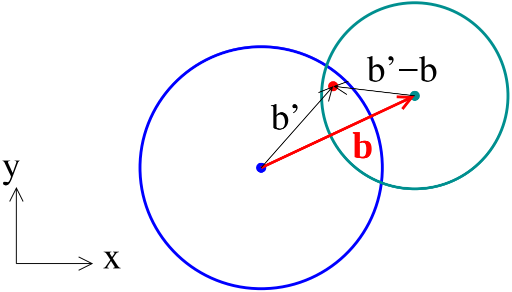


Define integral over nuclear density for each nucleus:

$$T_{A/B}(b') = \int \rho_{A/B}(b', z)dz,$$

and the “thickness function”

$$T_{AB}(b) = \int T_A(b')T_B(b'-b)d^2b'$$



Probability of interaction (for ρ_A and ρ_B normalized to 1)

$$P = T_{AB}(b)\,\sigma_{NN}$$

Having AB possible pairs: probability of n interactions :

$$P_n = \binom{AB}{n} P^n (1-P)^{AB-n}$$

Probability of at least one interaction (given b):

$$\sum_{n=1}^{AB} P_n = 1 - P_0 = 1 - (1-P)^{AB}$$

And finally the AB cross section (called optical limit):

$$\sigma^{AB} = \int \left\{1 - (1-P)^{AB}\right\} d^2b,$$

so the **probability of an interaction** is

$$\frac{d\sigma^{AB}}{d^2b} = 1 - \{(1 - T_{AB}(b)\,\sigma_{NN})^{AB}\}.$$

Glauber MC formula (with $\sigma_{NN} = \int f(b) d^2b$):

$$\frac{d\sigma^{AB}}{d^2b} = 1 - \left\{ \int \prod_{i=1}^{A} d^2b_i^A\, T_A(b_i^A) \prod_{j=1}^{B} d^2b_j^B\, T_B(b_j^B) \prod_{k=1}^{AB} (1 - f) \right\}.$$

In the MC version, one extracts N_{coll}, N_{particip}, and one usually employs a "wounded nucleon approach"

Does this make sense?

Theoretical justification?

... based on relativistic quantum mechanical scattering theory, compatible with QCD

=> Gribov-Regge approach

Gribov-Regge approach and cut diagrams

details see https://ejc2018.sciencesconf.org/data/pages/joliot.20.pdf
(266 page lecture for diploma and PhD students)

The scattering operator $\hat{S}$ is defined via

$$|\psi(t=+\infty)\rangle = \hat{S}\,|\psi(t=-\infty)\rangle$$

Unitarity relation $\hat{S}^\dagger\hat{S} = 1$ gives (considering a discrete Hilbert space)

$$\begin{aligned} 1 &= \langle i|\,\hat{S}^\dagger\hat{S}\,|i\rangle \\ &= \sum_f \langle i|\,\hat{S}^\dagger\,|f\rangle\,\langle f|\,\hat{S}\,|i\rangle \\ &= \sum_f \langle f|\,\hat{S}\,|i\rangle^*\,\langle f|\,\hat{S}\,|i\rangle \\ &= \sum_f S^*_{fi}S_{fi} \end{aligned}$$

Using $S_{fi} = \delta_{fi} + i(2\pi)^4\delta(p_f - p_i)T_{fi}$ and the Schwarz reflection principle ($T_{ii}(s^*, t) = T_{ii}(s, t)^*$) and

$$\mathrm{disc}\, T = T_{ii}(s + i\epsilon, t) - T_{ii}(s - i\epsilon, t)$$

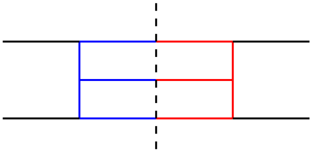
one gets

$$\frac{1}{\mathrm{i}}\mathrm{disc}\, T = (2\pi)^4\delta(p_f - p_i)\sum_f \left|T_{fi}\right|^2 = 2s\,\sigma_{\mathrm{tot}}$$

Interpretation: $\frac{1}{\mathrm{i}}\mathrm{disc}\, T$ can be seen as a so-called “cut diagram”, with modified Feynman rules, the “intermediate particles” are on mass shell.

Modified Feynman rules :

□ Draw a dashed line from top to bottom

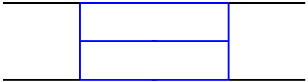


□ Use "normal" Feynman rules to the left

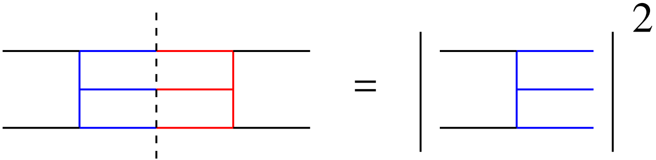
□ Use the complex conjugate expressions to the right

□ For lines crossing the cut: Replace propagators by mass shell conditions $2\pi\theta(p^0)\delta(p^2 - m^2)$

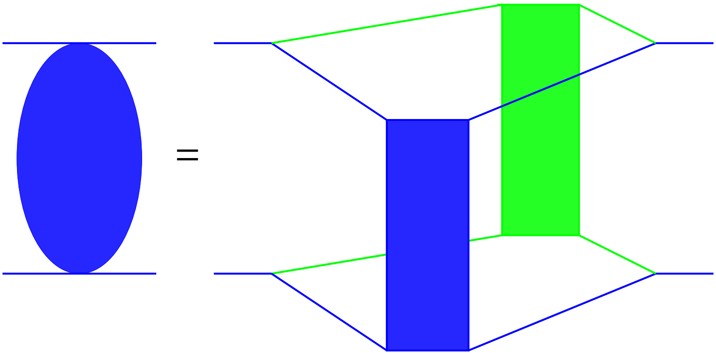
Cutting a diagram representing **elastic** scattering



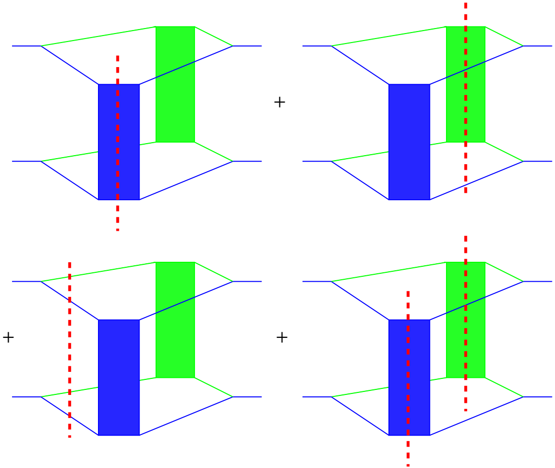
corresponds to **inelastic** scattering



Cutting diagrams is useful in case of substructures:

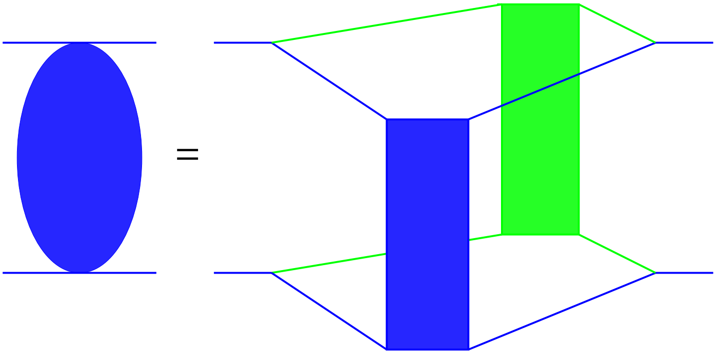


Precisely the multiple scattering structure in EPOS (QCD is hidden in the colored squares)



Cut diagram
= sum of products of cut/uncut subdiagrams
=> Gribov-Regge approach of multiple scattering

What are the blocks, called Pomerons?



- Pomeron = parton ladders
- cut Pomerons => open ladder => kinky string

Gribov Regge for A+B scattering

In the GR framework, defining

$$\int dT_{AB} := \int \prod_{i=1}^{A} d^2b_i^A \, T_A(b_i^A) \prod_{j=1}^{B} d^2b_j^B \, T_B(b_j^B),$$

we obtain (neglecting energy sharing):

$$\frac{d\sigma^{AB}}{d^2b} = \int dT_{AB} \underbrace{\sum_{m_1} \ldots \sum_{m_{AB}}}_{\sum m_i \neq 0} \prod_{k=1}^{AB} \frac{W(b_k)^{m_k}}{m_k!} e^{-W(b_k)})$$

Relaxing the condition $\sum m_i \neq 0$ gives unity.

So

$$\frac{\sigma^{AB}}{d^2b} = 1 - \int dT_{AB} \left\{ \prod_{k=1}^{AB} e^{-W(b_k)} \right\}$$

Defining $f = 1 - e^{-W(b_k)}$, i.e. the probability of an interaction in pp, with $\sigma_{NN} = \int f(b) d^2b$,

we get the Gribov-Regge result

$$\boldsymbol{\frac{\sigma^{AB}}{d^2b} = 1 - \left\{ \int dT_{AB} \prod_{k=1}^{AB} (1 - f) \right\}}$$

which corresponds to "Glauber Monte Carlo".

So everything OK?

Even if the cross section formulas in GR and GMC are the same, particle production is done in a fundamentally different fashion

- **In Glauber**
  - **one has (usually) a hard component ($\sim N_{\mathrm{coll}}$)**
  - **and a soft one ($\sim N_{\mathrm{part}}$, wounded nucleons)**
- **In GR** (EPOS)
  - **remnants contribute only at large rapidities,**
  - **otherwise everything is coming from "cut Pomerons" associated to NN scatterings.**

Factorization

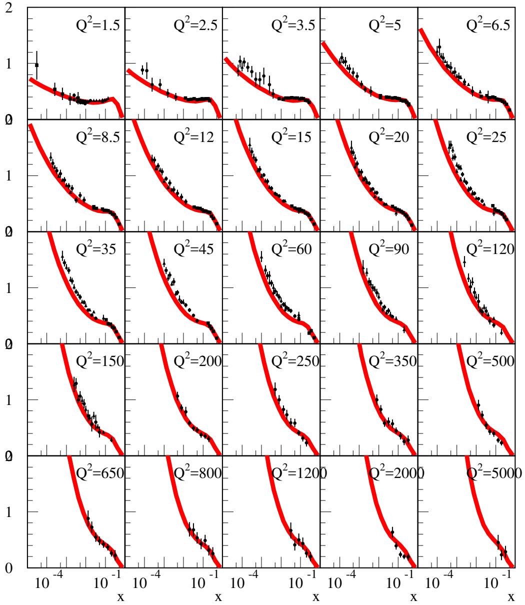
Factoriztion says that the pp inclusive cross section can be written as

$$\sum_{kl}\int dx dx' dp_\perp^2\, f_k(x, M_\mathrm{F}^2)\, f_l(x', M_\mathrm{F}^2) \frac{d\sigma_\mathrm{Born}^{kl}}{dp_\perp^2}(xx's, p_\perp^2),$$

with “parton distribution functions” obtained from DIS (*ep* scattering).

Not obvious in the EPOS GR framework, but one can prove that in the basic approach **factorization holds** (Phys. Rept. 350 (2001) p93)

Electron-proton scattering F_2 vs x



We can compute

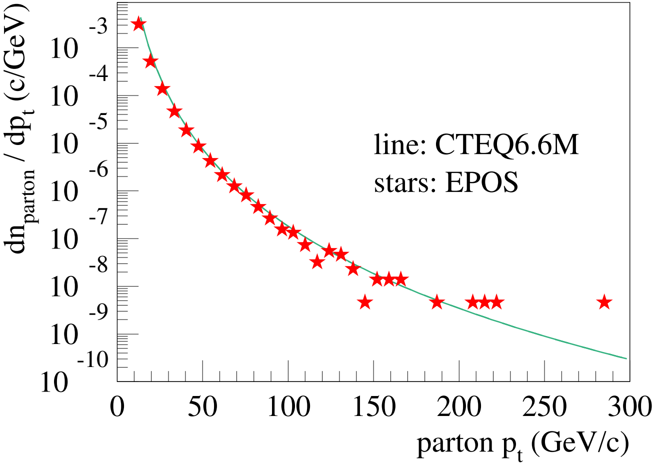
$$F_2 = \sum_k e_k^2 \, x \, f_k(x, Q^2)$$

with

$$x = x_B = \frac{Q^2}{2pq}$$

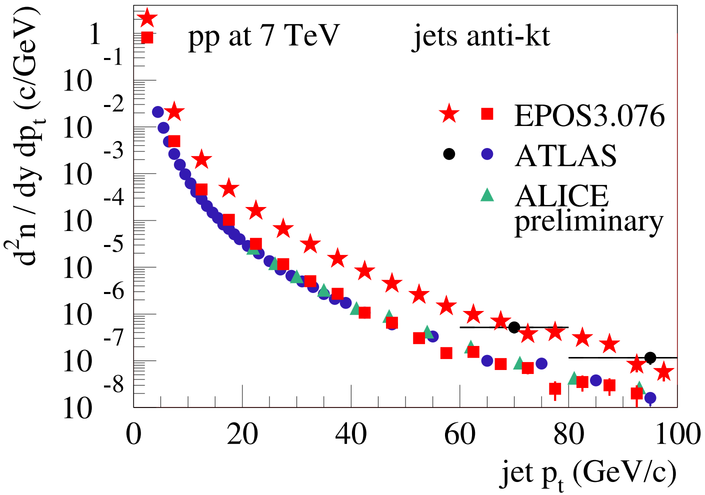
in the EPOS framework

Compare with parton model calculation using CTEQ PDFs for pp at 7 TeV



In EPOS we do not employ explicitely factorization!

Compare with data: jet production in pp at 7 TeV



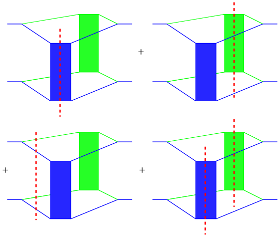
Why does factorization work ?

Easy to see in the GR picture without energy conservation, using simple assumptions.

Consider multiple scattering amplitude

$$iT = \prod iT_{\mathrm{P}}$$

cross section: sum over all cuts.

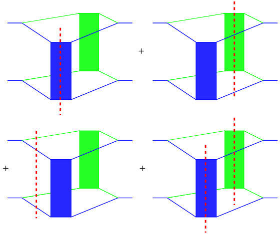


For each cut Pom:

$$\frac{1}{i}\mathrm{disc}T_{\mathrm{P}} = 2\mathrm{Im}T_{\mathrm{P}} \equiv G$$

For each uncut one:

$$iT_{\mathrm{P}} + \{iT_{\mathrm{P}}\}^{*}$$
$$= i\,(i\,\mathrm{Im}T_{\mathrm{P}}) + \{i\,(i\,\mathrm{Im}T_{\mathrm{P}})\}^{*}$$
$$= -2\mathrm{Im}T_{\mathrm{P}} \equiv -G$$



Inclusive particle production cross section σ_{incl}: Assume that each cut Pomerons produces N particles, an uncut one nothing.

Contribution to the inclusive cross section for n Pomerons (k refers to the cut Pomerons):

$$\sigma_{\mathrm{incl}}^{(n)} \propto \sum_{k=0}^{n} kN\, G^{k}\, (-G)^{n-k} \left(\begin{array}{c} n \\ k \end{array} \right)$$

$$\propto \sum_{k=0}^{n} (-1)^{n-k}\; k \times \left(\begin{array}{c} n \\ k \end{array} \right)$$

$\sum_{k=0}^{n} (-1)^{n-k}\; k \times \begin{pmatrix} n \\ k \end{pmatrix}$:

For $n = 2$:

$$+0 \times 1 - 1 \times 2 + 2 \times 1 = 0$$

No contribution !

For $n = 3$:

$$-0 \times 1 + 1 \times 3 - 2 \times 3 + 3 \times 1 = 0$$

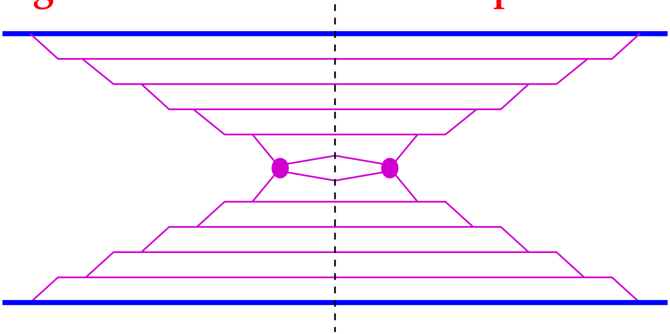
No contribution either !

Actually, for any $n > 1$:

$$\sum_{k=0}^{n} (-1)^{n-k} \, k \times \binom{n}{k} = 0$$

- □ **Almost all of the diagrams (i.e. n=2, n=3, ...) do not contribute at all to the inclusive cross section**
- □ **Enormous amount of cancellations (interference), only n=1 contributes**
- □ **AGK cancellations**
  (Abramovskii, Gribov and Kancheli cancellation (1973))

simple diagram even in case of multiple scattering



corresponds to factorization:

$$\sigma_{\mathrm{incl}} = f \otimes \sigma_{\mathrm{elem}} \otimes f$$

The F_2 discussed earlier: Half of this diagram

Since it is known that **factorization** works, the ansatz

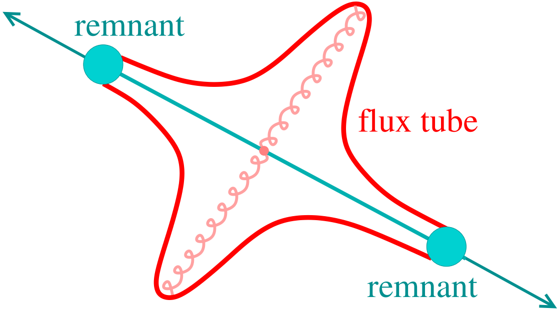
$$\boldsymbol{\sigma_{\mathrm{incl}} = f \otimes \sigma_{\mathrm{elem}} \otimes f}$$

may be used as starting point, with f taken from DIS (electron-proton).

3 Collectivity

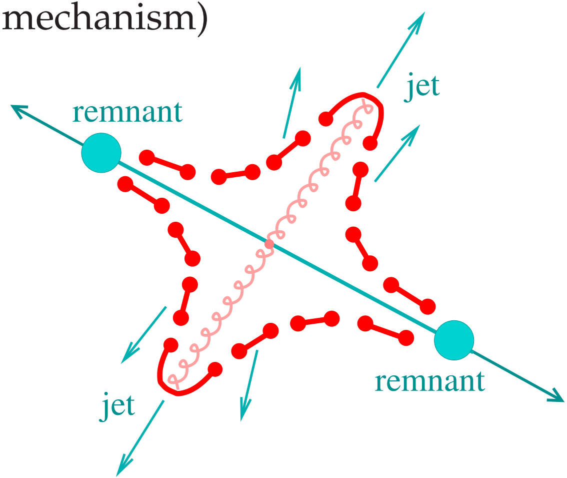
Pomerons =>

Parton ladders = color flux tubes = **kinky strings**



(here no IS radiation, only hard process producing two gluons)

which expand and break
via the production of quark-antiquark pairs
(Schwinger mechanism)

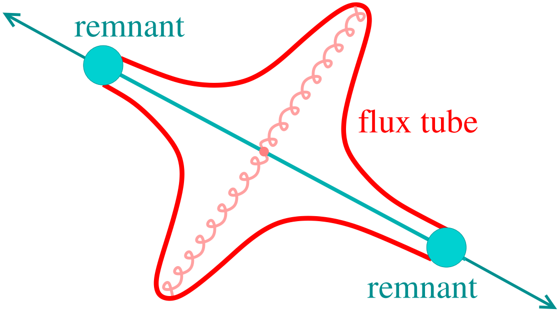


String segment = hadron. Close to “kink”: jets

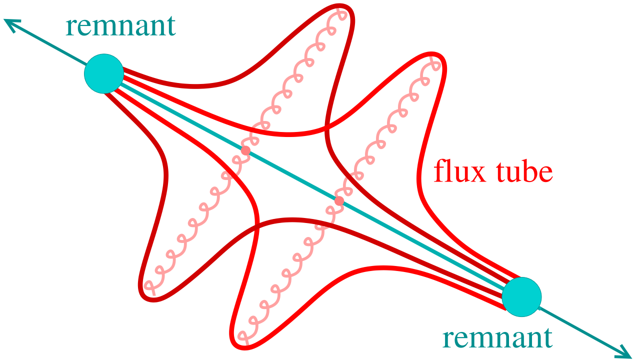
Consider heavy ion collisions

or high energy & high multiplicity pp events:

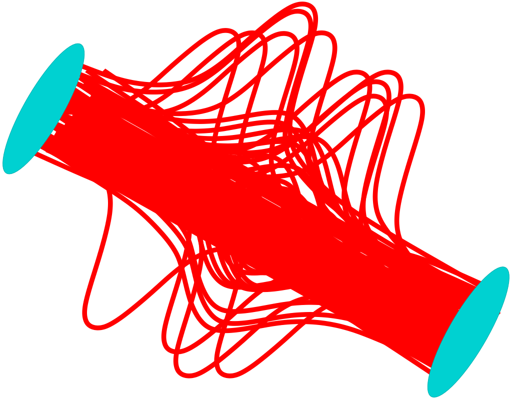
again: single scattering => 2 color flux tubes



... two scatterings => 4 color flux tubes



... many scatterings (AA) => many color flux tubes



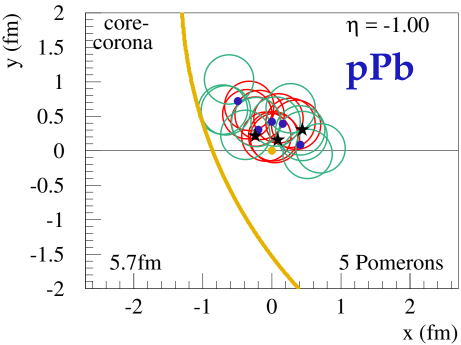
=> matter + escaping pieces (jets)

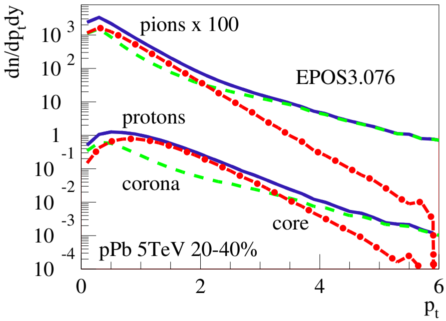
Core-corona procedure (for pp, pA, AA):

Pomeron => parton ladder => flux tube => string segments

High pt segments escape => corona
The others => core

(core = initial condition for hydro depending on the local string density)





Hydrodynamic evolution of the core

The evolution of the system for $\tau \geq \tau_0$ treated **macroscopicly**, solving the equations of **relativistic hydrodynamics**:

Three equations concerning conserved currents:

$$\partial_\nu N_q^\nu = 0$$

with

$$N_q^\nu = n_q\, u^\nu$$

and n_q ($q =u\,,d, s$) representing (net) quark densities, u^ν is the velocity four vector.

Four equations concerning energy-momentum conservation:

$$\partial_\nu T^{\mu\nu} = 0.$$

The energy-momentum tensor $T^{\mu\nu}$ is

- the flux of the μth component of the momentum vector
- across a surface with constant ν coordinate (using four-vectors)

$\boldsymbol{T^{00}}$: **Energy density** $dE/dx^1dx^2dx^3$ (x^0 const)

$\boldsymbol{T^{01}}$: **Energy flux** $dE/dx^0dx^2dx^3$ (x^1 const)

$\boldsymbol{T^{i0}}$: **Momentum density**

$\boldsymbol{T^{ij}}$: **Momentum flux**

The equation

$$\partial_\nu T^{\mu\nu} = 0$$

is very general, no need for thermal equilibrium, no need for particles.

The energy-momentum tensor is

the **conserved Noether current**

associated with **space-time translations**.

- $\partial_\nu T^{\mu\nu}$ represents 4 equations, so we should express T in terms of 4 quantities (unknowns)

- and/or find additional equations

- which means additional assumptions

First approach: **Ideal Fluid**

In the local rest frame of a fluid cell:

- □ $T^{00} = \varepsilon$ (energy density in LRF)
- □ $T^{0i} = 0$ (no energy flow)
- □ $T^{0i} = 0$ (no momenum in LRF)
- □ $T^{ij} = \delta_{ij} p$ (p = isotropic pressure)

In arbitrary frame:

$$T^{\mu\nu} = (\varepsilon + p)u^{\mu}u^{\nu} - pg^{\mu\nu}$$

+ Equation of state $p = p(\varepsilon)$ of QGP from lQCD

=> 4 equations for 4 unknowns (ε, velocity)

Beyond ideal (viscous hydro):

The energy-momentum tensor may be expressed via a systematic expansion in terms of gradients (of $\ln \varepsilon$ and u):

$$T^{\mu\nu} = T^{\mu\nu}_{(0)} + T^{\mu\nu}_{(1)} + T^{\mu\nu}_{(2)} + ...,$$

with the "equilibrium term" $T^{\mu\nu}_{(0)}$

Mueller-Israel-Steward (MIS) approach
(second order + shear stress tensor and bulk pressure dynamical quantities, governed by relaxation equations)

Freeze out

happens at a hypersurface Σ (constant energy density).

Cooper-Frye hadronization amounts to calculating

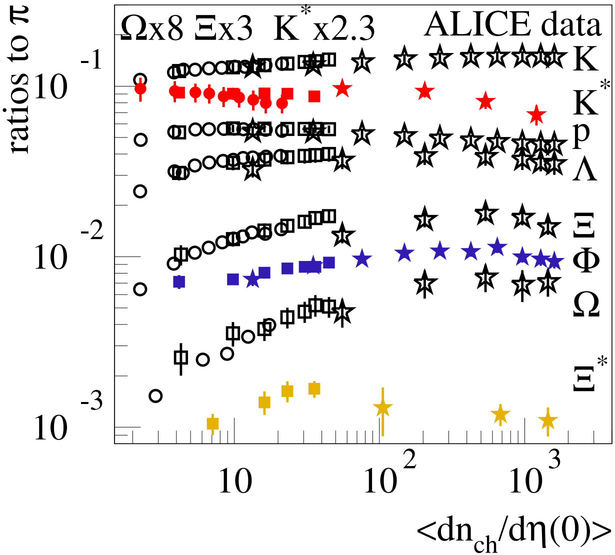
$$E\frac{dn}{d^3p} = \int d\Sigma_\mu p^\mu f(up),$$

f is the Bose-Einstein or Fermi-Dirac distribution
(in case of ideal hydro).

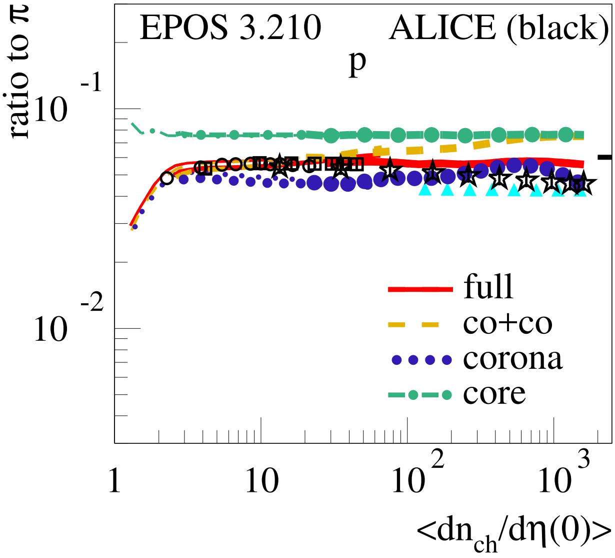
How does hydro evolution affect results?

- ☐ **Mass dependent broadening of pt spectra (flow)**
- ☐ **Particular dihadron correlations**
- ☐ **Statistical particle production (compared to string decay)**

Particle ratios to pions vs $\left\langle \frac{dn_{ch}}{d\eta}(0) \right\rangle$



Proton to pion ratio (sofar GC)



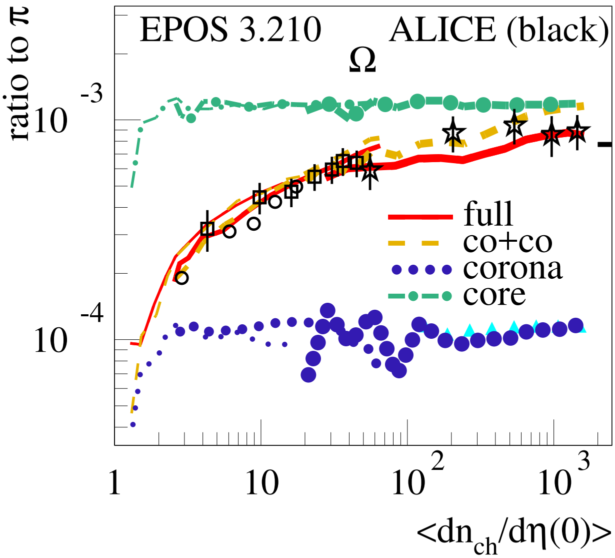
core hadronization:
$T = 164\,\mathrm{MeV},\ \mu_B = 0$

statistical model fit
(horizontal black line)
A. Andronic et al.,
arXiv:1611.01347
$T = 156.5\,\mathrm{MeV}, \mu_B = 0.7\,\mathrm{MeV}$

thick lines = pp (7TeV)
thin lines = pPb (5TeV)

circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

Omega to pion ratio (GC)



thick lines = pp (7TeV)
thin lines = pPb (5TeV)

circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

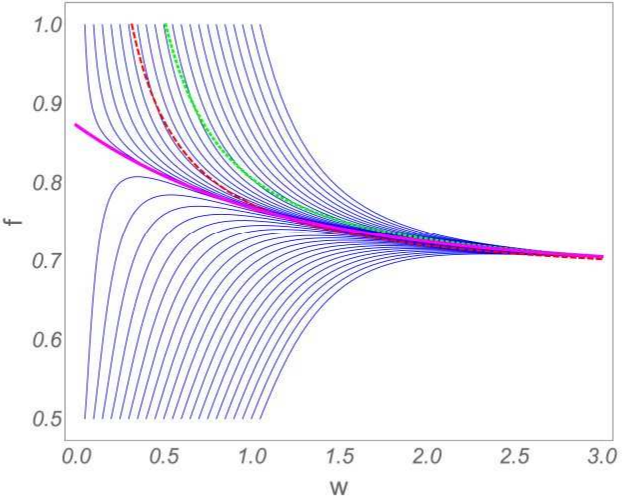
New trends on the foundations of hydrodynamics

- ☐ **A systematic way get the equations of relativistic hydrodynamics is via a formal gradient expansion of $T^{\mu\nu}$** (in terms of gradients (of $\ln\varepsilon$ and u)

- ☐ **The hydrodynamic gradient expansion has (maybe) a vanishing radius of convergence**

- ☐ **There are tools to deal with that. Need to go beyond perturbative expansions.**

In hydro toy models (Heller, Spalinski, PRL 115, 072501 (2015)) one can show that the **hydrodynamical expansion** (gradient expansion) **is divergent**, but numerically on gets an **attractor**



Picture from Heller, M. Spalinski.

well defined solutions even at small times,

contrary to the perturbative expansion.

=> well defined solutions "far off equilibrium"

Same results via "resummation"

What do these “resummation” results tell us?

- Hydro may be applicable even far off equilibrium (in particular relevant for small systems)

- => True solution : Hydrodynamic attractor
  Accessible (in principle) via resummation

- Frequently asked question:
  “Why do small systems thermalize so quickly?”
  Maybe they simply don´t ...

4 Summary

- **Multiple NN scattering in pA and AA: Essentially geometry => Glauber approach. Same cross section formula in Gribov-Regge, using Pomerons, but completely different particle production scheme**

- **In the EPOS GR approach, multiple scattering naturally extends to pp => multiple cut Pomerons => overlapping strings => matter formation**

- **Attractive option: Implementing hydrodynamic expansion (provides observed flow effects) + statistical hadronization**