Modelling ultrarelativistic pp, pA, and AA collisions using EPOS

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in collaboration with
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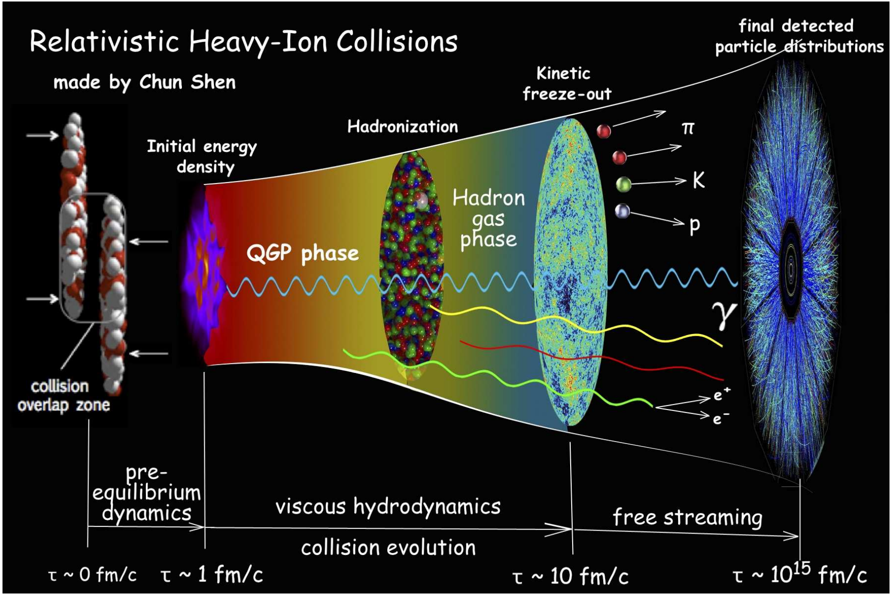
Time evolution pp, pA, AA collisions



Try to understand both

- **basic features in pp, pA**
  like cross sections, jet pt spectra ...
  (from primary scatterings)

- **and flow phenomena in pp, pA, AA**
  or collective effects
  (also for small systems)

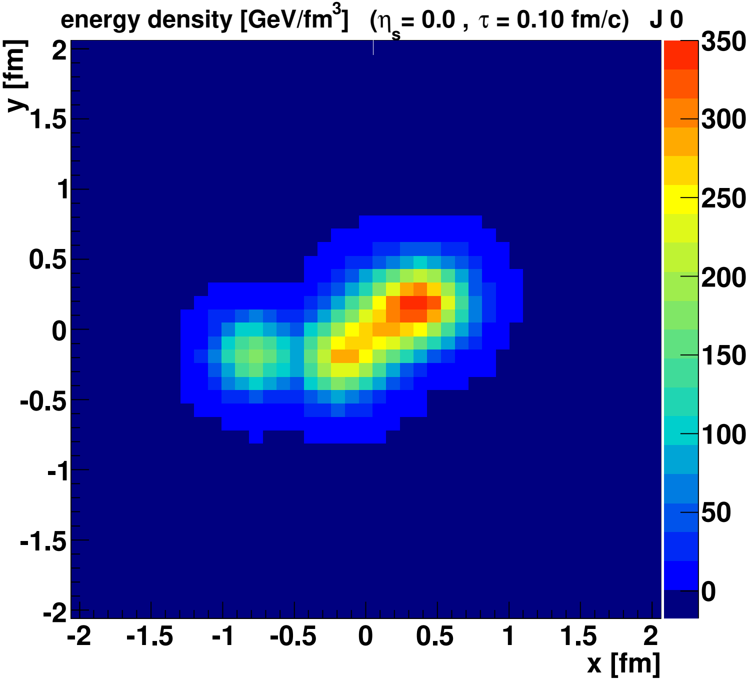
Collective effects means

- **Primary interactions at t = 0**
  (the same ones which determine basic features)

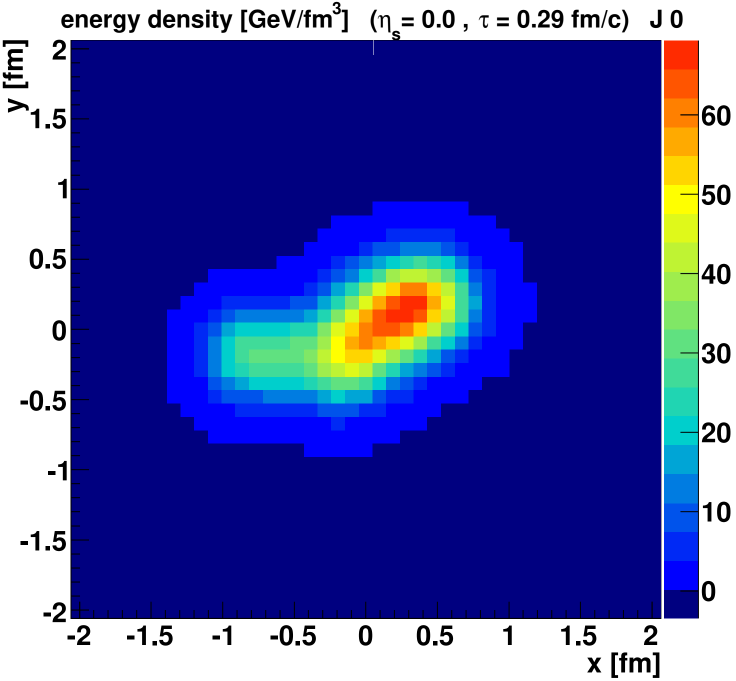
- **Secondary interactions**
  formation of "matter" which expands collectively, like a fluid

In the following:
An example of a EPOS simulation of expanding matter in pp scattering

pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119



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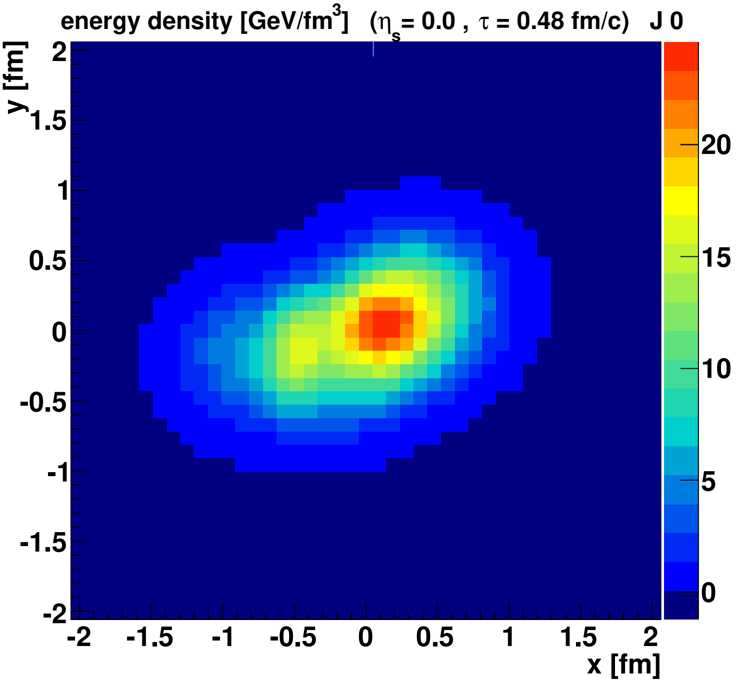
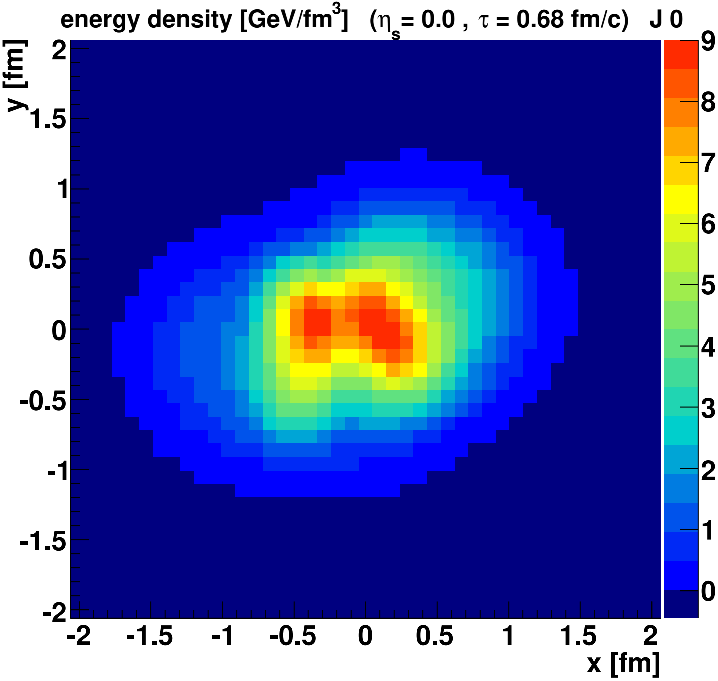
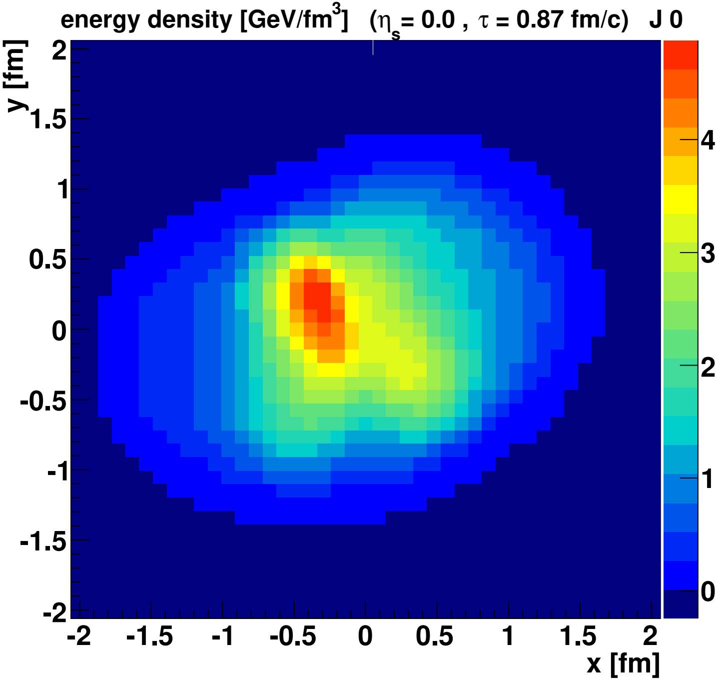


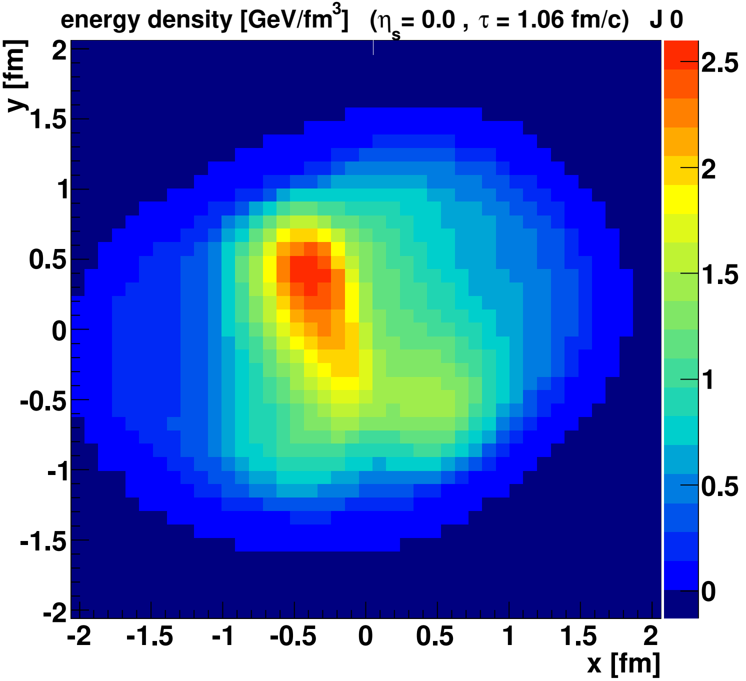
pp @ 7TeV EPOS 3.119



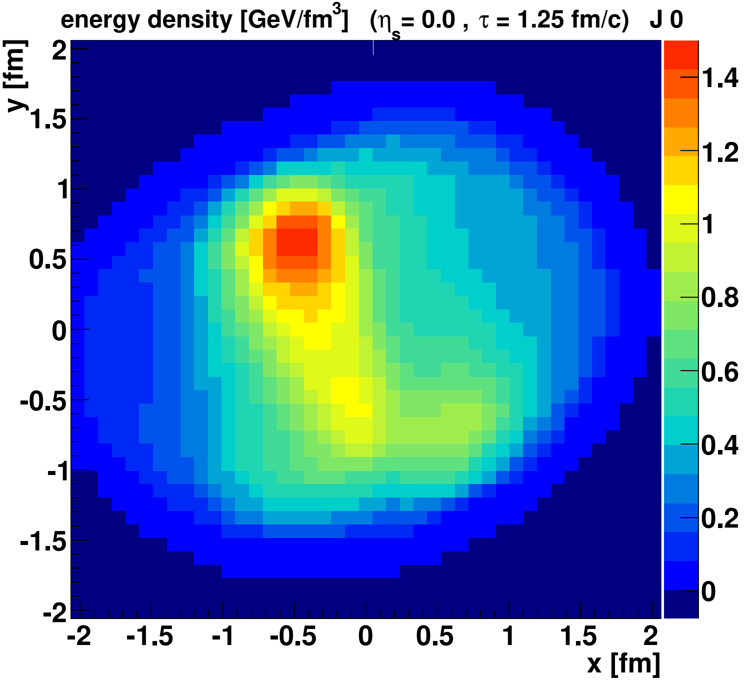
pp @ 7TeV EPOS 3.119



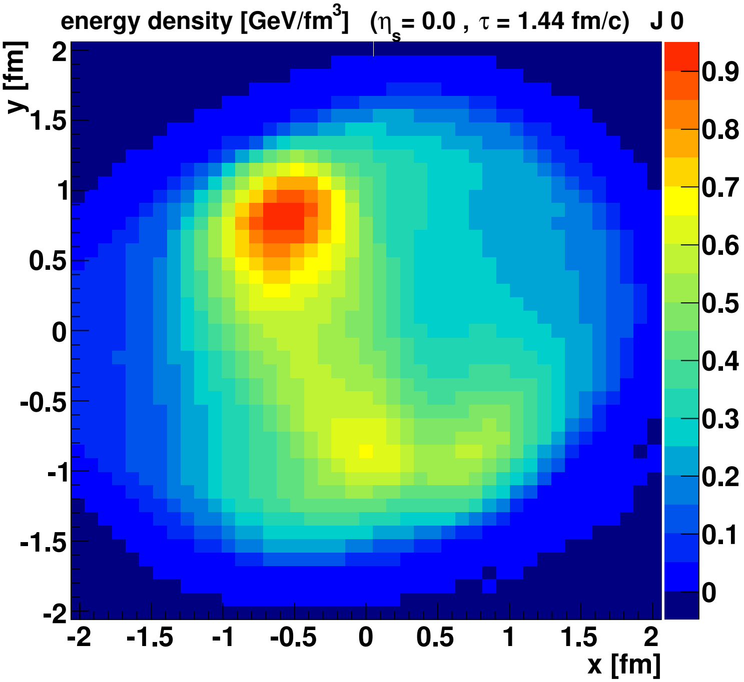
pp @ 7TeV EPOS 3.119



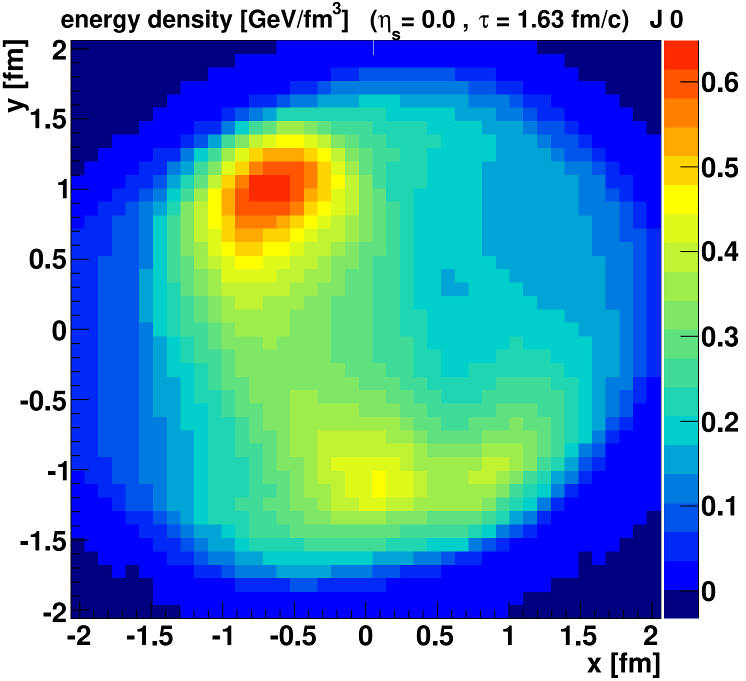
pp @ 7TeV EPOS 3.119



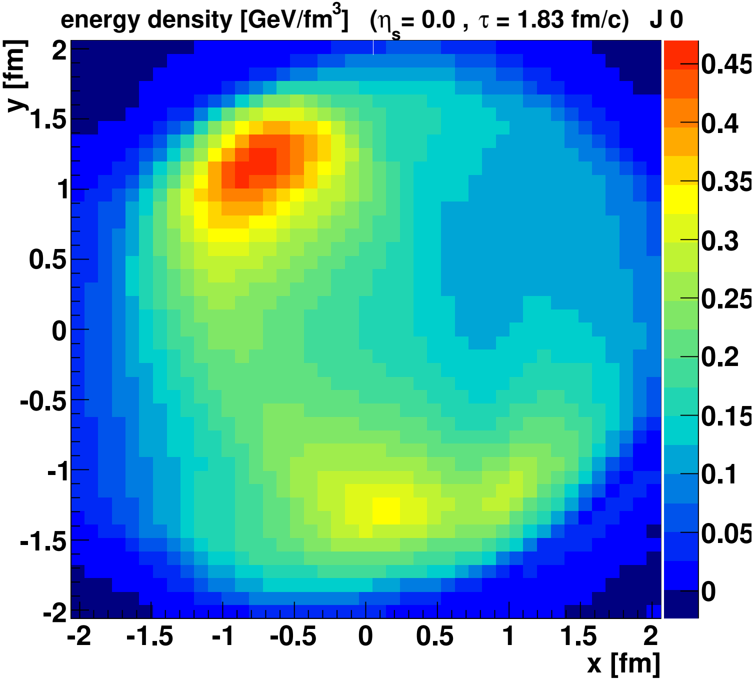
pp @ 7TeV EPOS 3.119



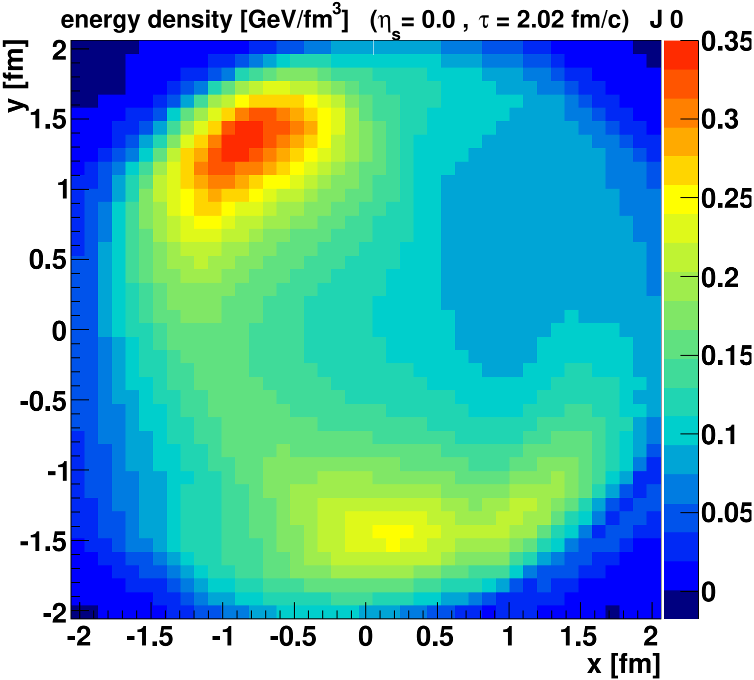
pp @ 7TeV EPOS 3.119



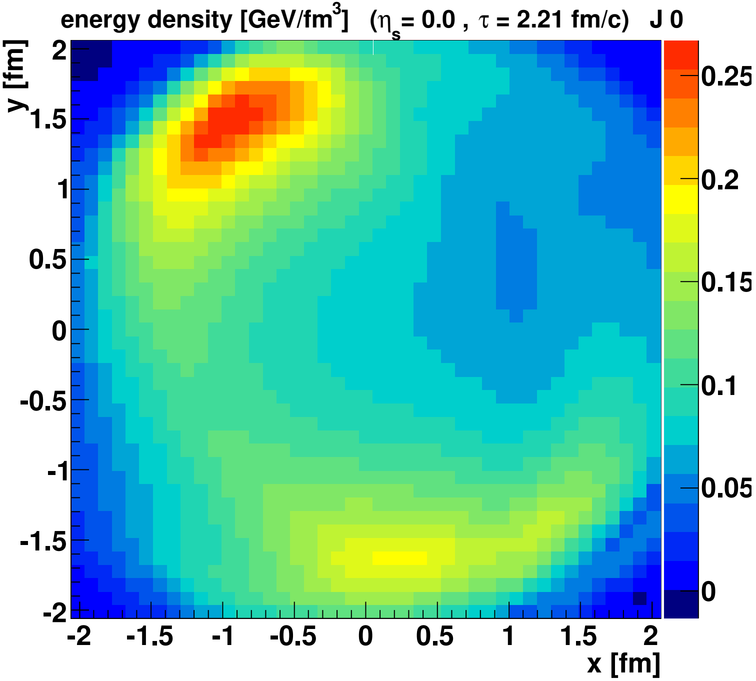
pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119



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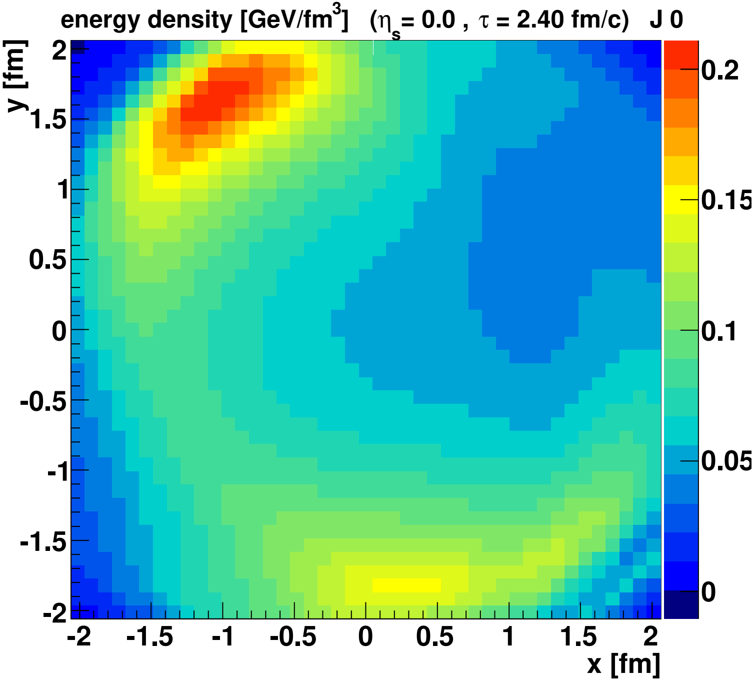
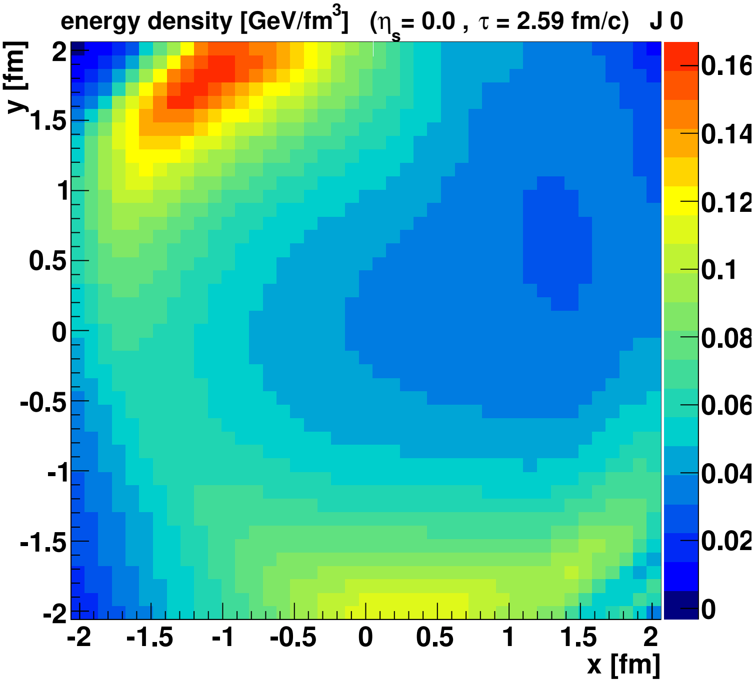
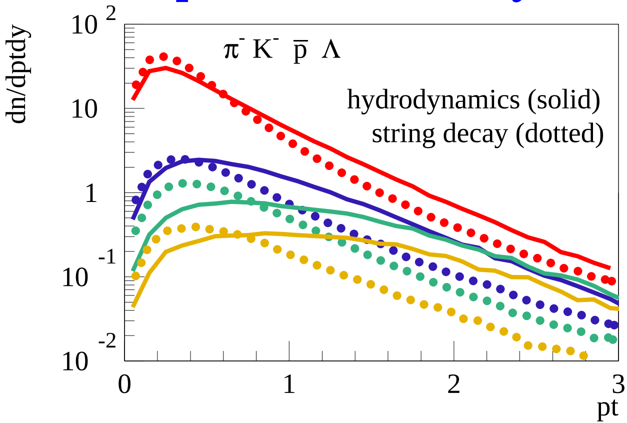


pp @ 7TeV EPOS 3.119



Radial flow visible in particle distributions

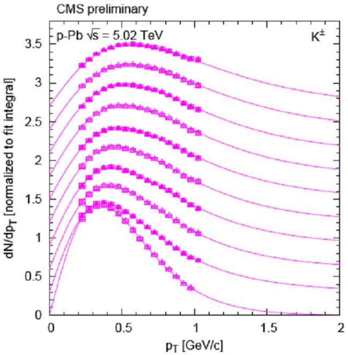
Particle spectra affected by radial flow

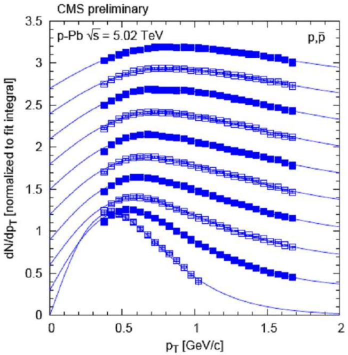


=> mass ordering of $\langle p_t \rangle$, lambda/K increase

pPb at 5TeV

CMS, arXiv:1307.3442



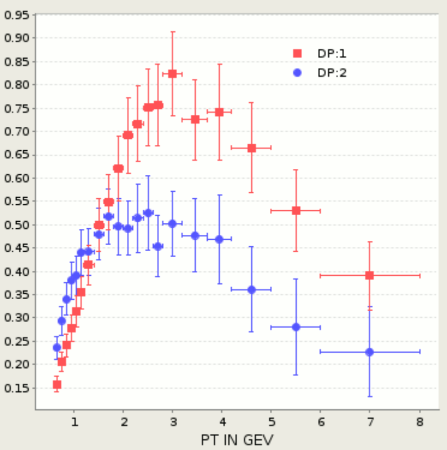


Strong variation of shape with multiplicity

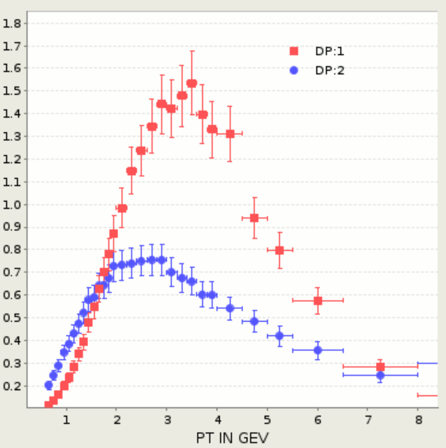
for kaon and even more for proton pt spectra

(flow like)

Λ/K_s **versus pT** (**high compared to low multiplicity**) **in pPb** (left) **similar to PbPb** (right)



ALICE (**2013**) arXiv:1307.6796



ALICE (**2013**) arXiv:1307.5530
Phys. Rev. Lett. 111, 222301 (2013)

In AA: partially due to flow

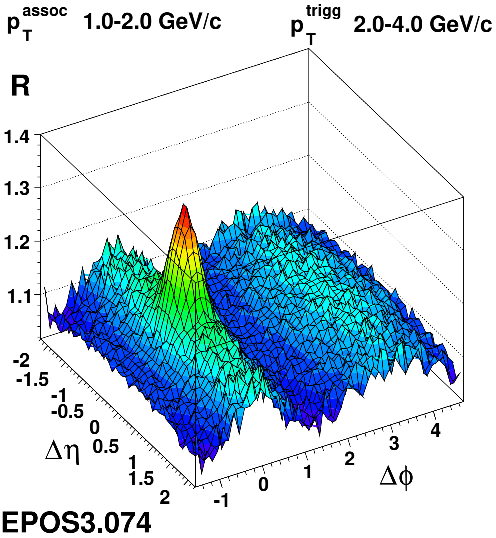
Ridges & flow harmonics

Ridges appear in

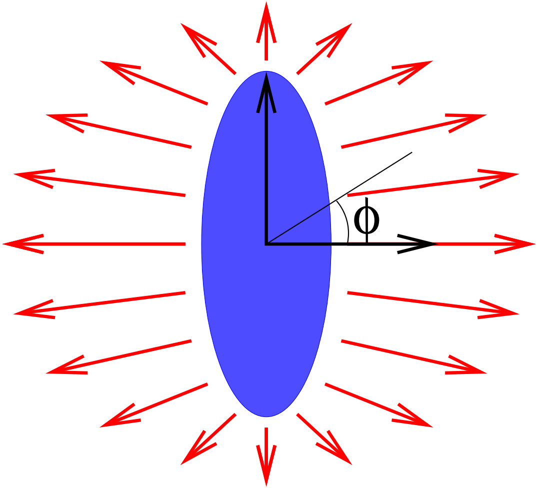
$$R = \frac{1}{N_{\text{trigg}}} \frac{dn}{d\Delta\phi\Delta\eta}$$

due to initial azimuthal anisotropies

(longitudinally invariant)



Initial "elliptical" matter distribution:



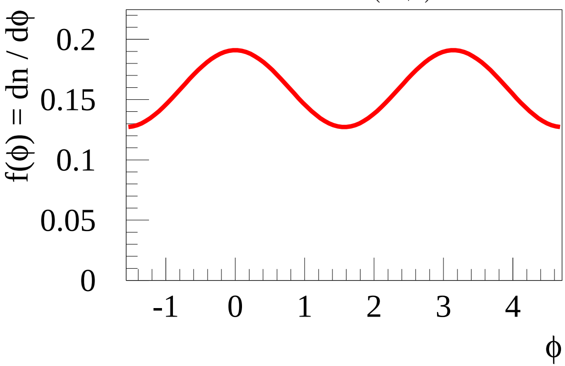
Preferred expansion along $\phi = 0$ and $\phi = \pi$

η_s-invariance
same form at any η_s

$\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$

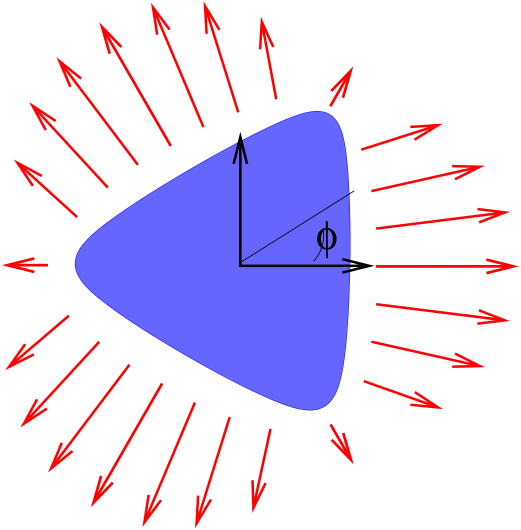
Particle distribution: Preferred directions $\phi = 0$ and $\phi = \pi$

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



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

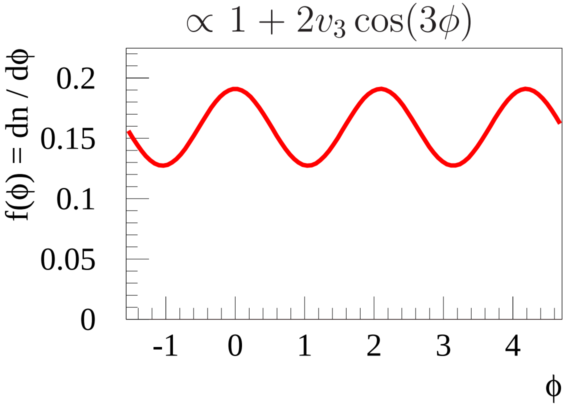
Initial "triangular" matter distribution:



Preferred expansion along $\phi = 0$, $\phi = \frac{2}{3}\pi$, and $\phi = \frac{4}{3}\pi$

η_s-invariance

Particle distribution: Preferred directions $\phi = 0$, $\phi = \frac{2}{3}\pi$, and $\phi = \frac{4}{3}\pi$



Dihadrons:
preferred $\Delta\phi = 0$, and $\Delta\phi = \frac{2}{3}\pi$, and $\Delta\phi = \frac{4}{3}\pi$
(even for large $\Delta\eta$)

In general, superposition of several eccentricities ε_n,

$$\varepsilon_n e^{in\psi_n^{PP}} = -\frac{\int dxdy\, r^2 e^{in\phi} e(x,y)}{\int dxdy\, r^2 e(x,y)}$$

Particle distribution characterized by harmonic flow coefficients

$$v_n e^{in\psi_n^{EP}} = \int d\phi\, e^{in\phi} f(\phi)$$

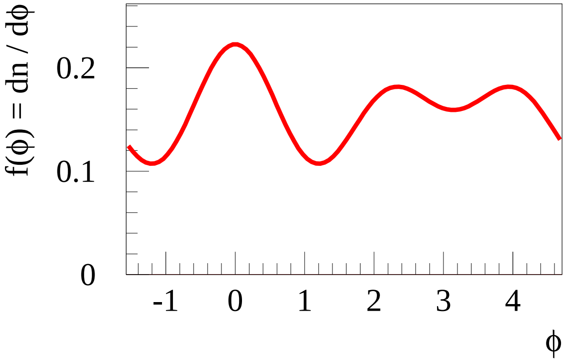
At $\phi = 0$:
The **ridge**

(extended in η)

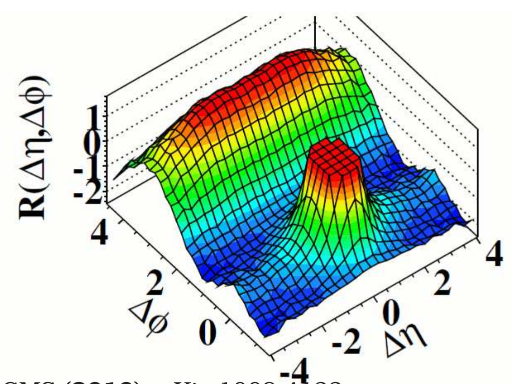
Awayside peak may originate from jets, not the ridge (for large $\Delta\eta$)

Here, v_2 and v_3 non-zero

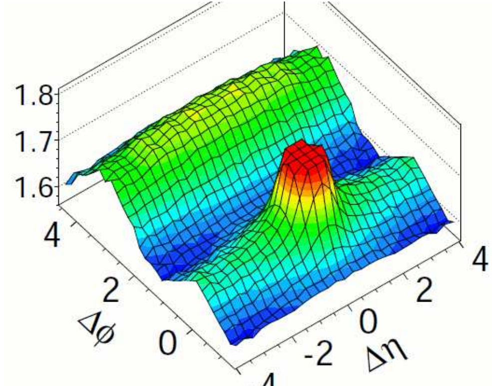
$$\propto 1 + 2v_2 \cos(2\phi) + 2v_3 \cos(3\phi)$$



CMS: Ridges (in dihadron correlation functions) also seen in pp (left) and pPb (right)



CMS (**2010**) arXiv:1009.4122
JHEP 1009:091,2010



CMS (**2012**) arXiv:1210.5482
Phys. Lett. B 718 (2013) 795

Looks like flow !

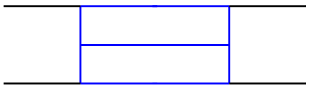
EPOS primary scatterings

- **Defined via elastic scattering S matrix**

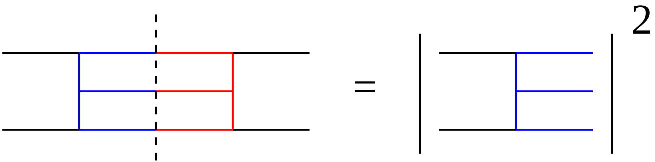
- **Cutting rules to get inelastic cross sections**

Phys.Rept. 350 (2001) 93-289.

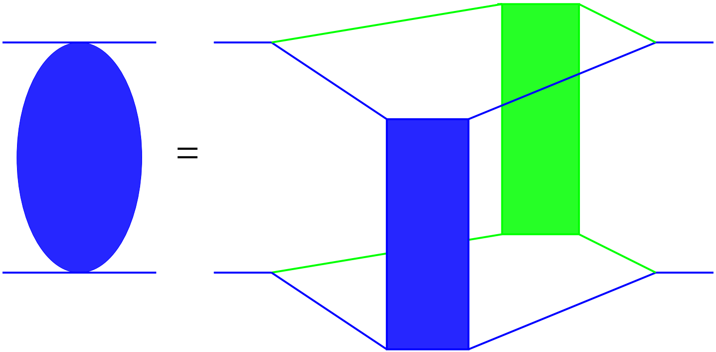
Cutting a diagram representing **elastic** scattering



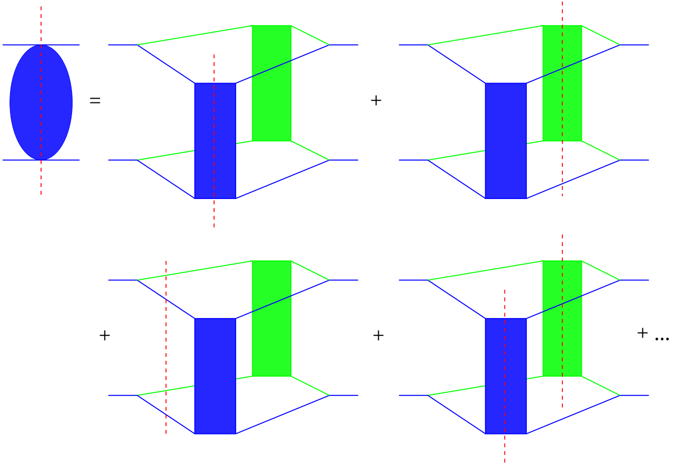
corresponds to **inelastic** scattering



Cutting diagrams is useful in case of substructures:



Precisely the multiple scattering structure in EPOS



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

Inclusive cross section: The multiplicity for k cut Pomerons is (roughly) kN, if N is the multiplicity per cut Pomeron.

- ☐ Contribution to the inclusive cross section for n Pomerons:

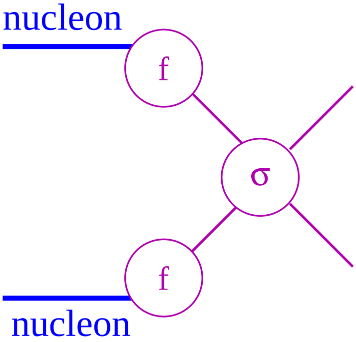
$$\sigma_{\mathrm{incl}}^{(n)} \propto \sum_{k=1}^{n} kN\, G^k \, (-G)^{n-k} \begin{pmatrix} n \\ k \end{pmatrix} = 0 \text{ for } n > 1$$

Only n=1 contributes (single Pomeron) !!

AGK cancellations for n>1

... which leads to simple formulas for inclusive cross sections:

$$\sigma_{\mathrm{jet}} = \int dx_1 dx_2 \int dp_t^2 \sum f_i(x_1, p_t^2)\, f_j(x_2, p_t^2)\, \frac{d\sigma_{ij}}{dp_t^2}(\hat{s}, \hat{t})$$



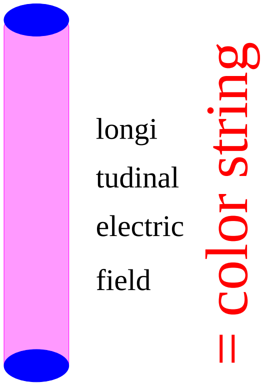
Multiple Pomeron cross sections => weights for configurations => Monte Carlo

Each Pomeron (= parton ladder): generate Partons

From partons to strings:

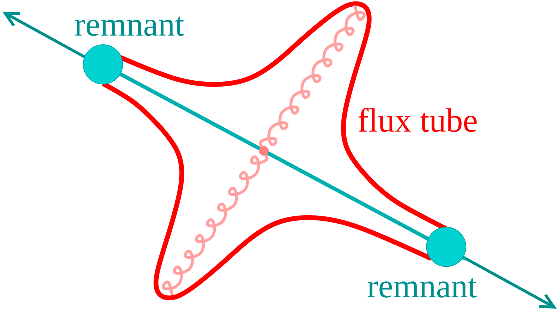
For $t > 0$, a (cut) Pomeron represents actually a (mainly) **longitudinal color field**,

where the ladder rungs (gluons) represent small transverse momentum components.



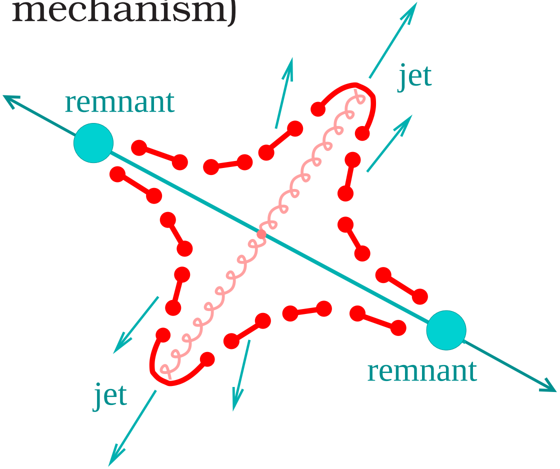
Jets:

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



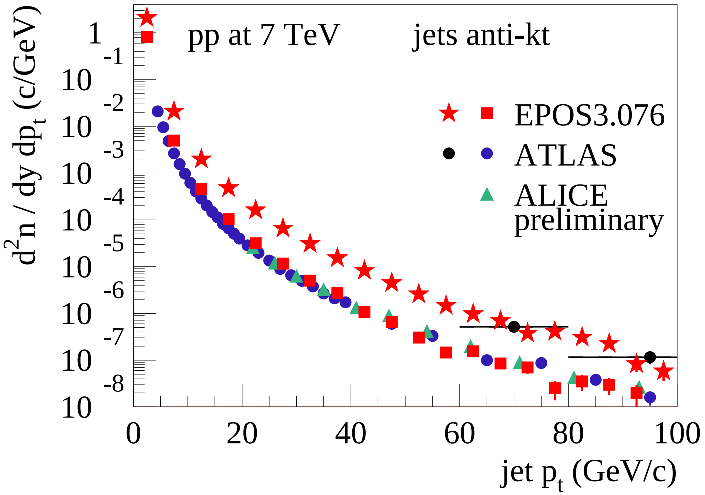
(here no IS radiation, only hard process producing two gluons)

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



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

Check: jet production in pp at 7 TeV



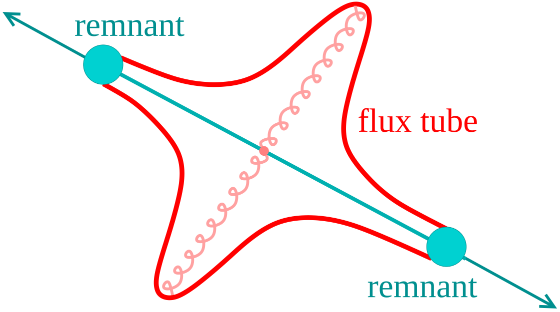
Heavy ion collisions
or high energy & high multiplicity pp events:

=> Secondary scattering !

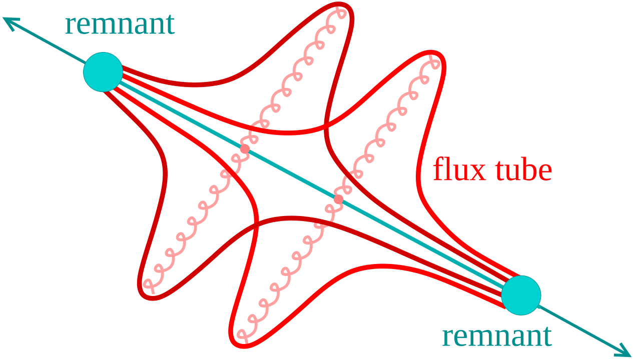
Some string pieces will constitute bulk matter evolving hydrodynamically, others show up as jets

These are the same strings (all originating from hard processes at LHC) which constitute BOTH jets and bulk !!

again: single scattering => 2 color flux tubes



... two scatterings => 4 color flux tubes



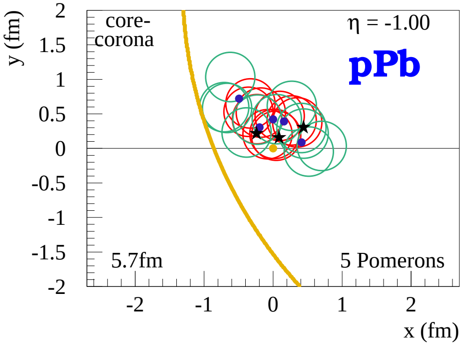
... many scatterings (AA) => many color flux tubes

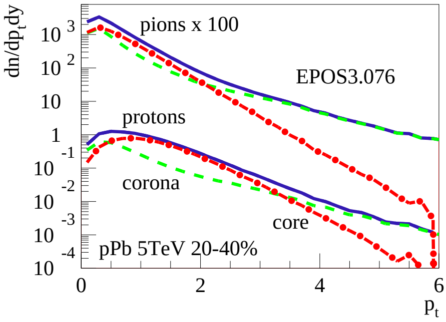
=> matter + escaping pieces (jets)

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

Pomeron => parton ladder => flux tube (kinky string)

String segments with high pt escape => **corona**,
the others form the **core** = initial condition for hydro
depending on the local string density





pPb results

We will compare EPOS3 with data

and also with

EPOS LHC

LHC tune of EPOS1.99, :
same GR, but uses **parameterized flow**
T. Pierog et al, arXiv:1306.5413

AMPT

Parton + hadron cascade **-> some collectivity**
Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang and S. Pal, Phys. Rev. C 72, 064901 (2005).

QGSJET

GR approach, **no flow**
S. Ostapchenko, Phys. Rev. D74 (2006) 014026

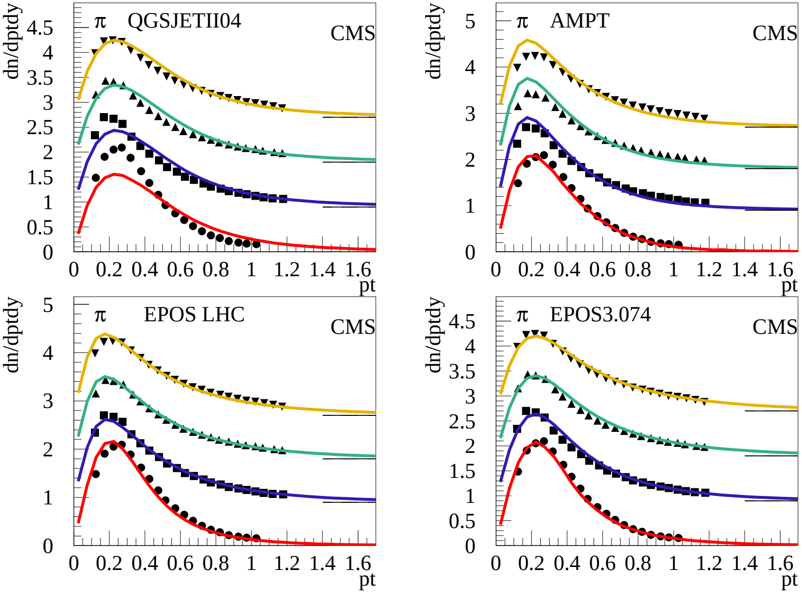
CMS: Multiplicity dependence of pion, kaon, proton pt spectra

CMS, EPJC 74 (2014) 2847

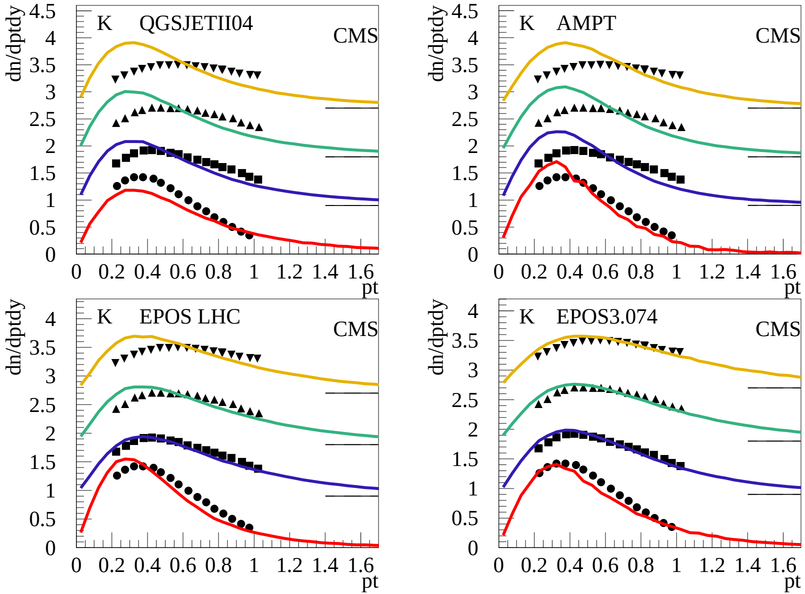
We plot 4 centrality classes:

$\langle N_{\mathbf{trk}}^{\mathrm{offline}} \rangle$ = 8, 84, 160, 235 (in $|\eta| < 2.4$)

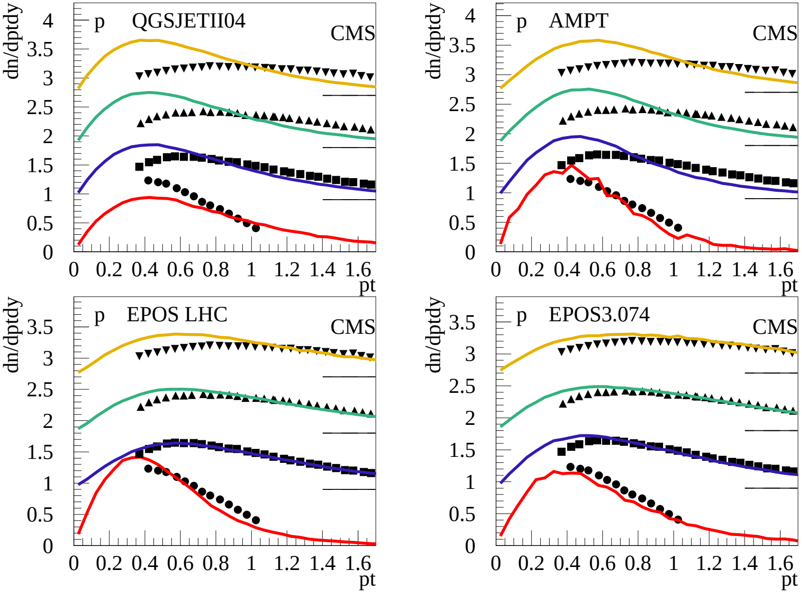
Multiplicity = centrality measure



Little change with multiplicity for pions



Kaon spectra change with multiplicity

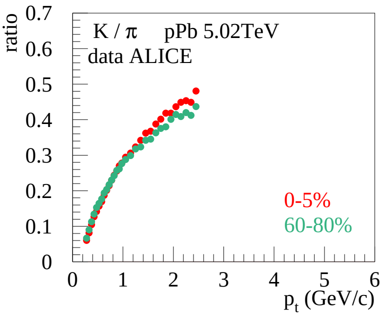


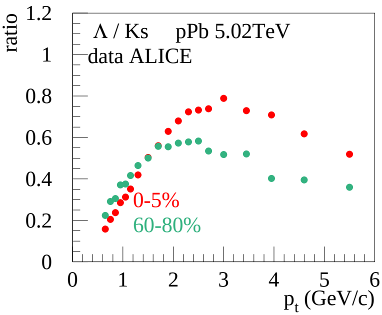
Strong variation of proton spectra => flow helps

ALICE: compare pt spectra for identified particles in different multiplicity classes: 0-5%,...,60-80%

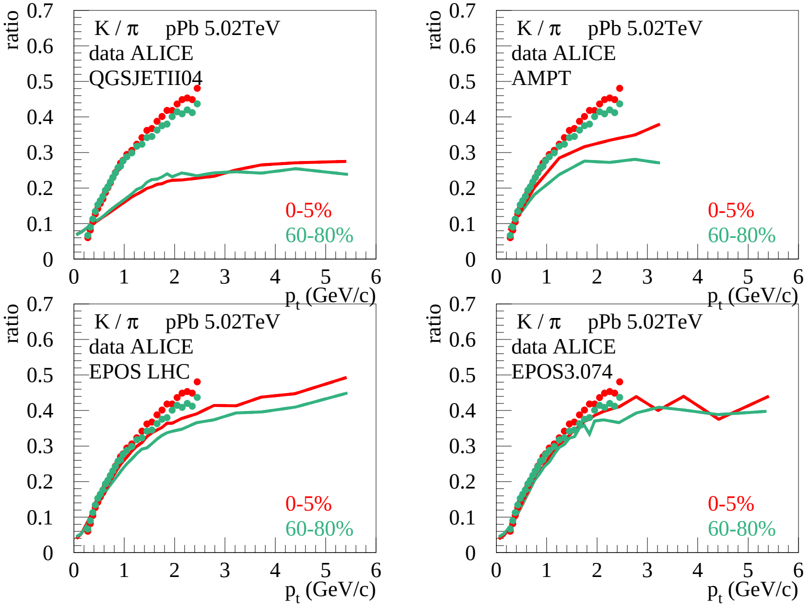
(in $2.8 < \eta_{\mathrm{lab}} < 5.1$) From R. Preghenella, ALICE, talk Trento workshop 2013

Useful : ratios (K/pi, p/pi...)

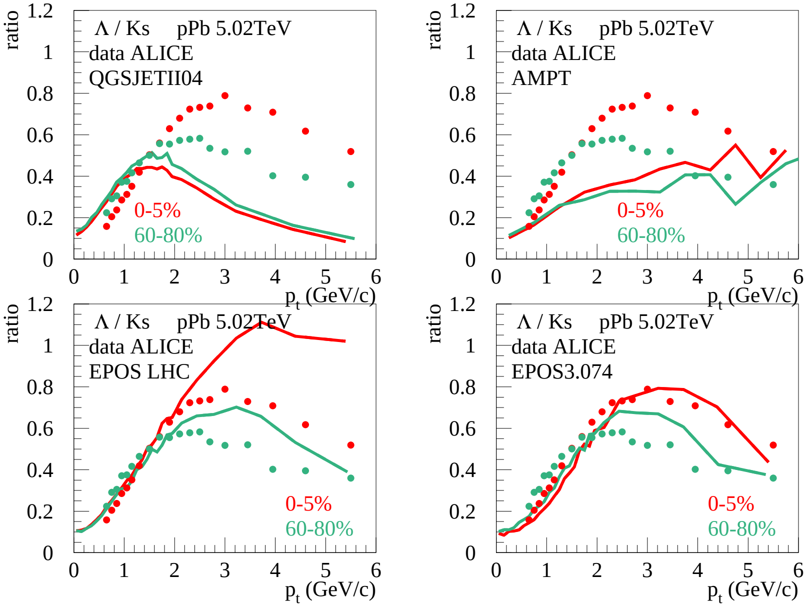




Significant variation of lambda/K – like in PbPb



No multiplicity dependence (not trivial to get the peripheral right)



Significant multiplicity dependence. Flow helps

EPOS: Two parallel developments

EPOS LHC: **Gribov Regge approach, parameterized flow as in EPOS1.99, tuned to LHC data (2012), very much used (and tested) by LHC pp groups, UE, forward physics etc, and used for air shower simulations**

EPOS 3.0xx: **Gribov Regge approach, viscous hydro, parton saturation, mainly used for HI and collectivity in pp**

Current project: "Fusion", to accommodate basic pp and HI features, public version;

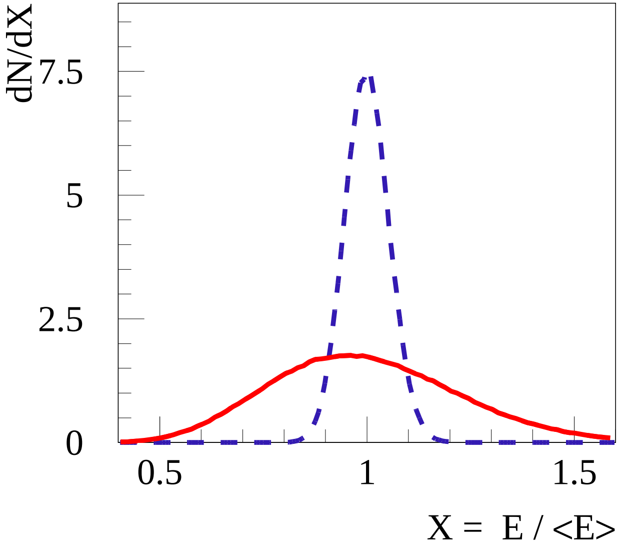
One problem: hadronization of fluid is done differently

- **EPOS LHC microcanonically**
- **EPOS3 Grand canonically (Cooper Frye)**

Quite different for small systems ...

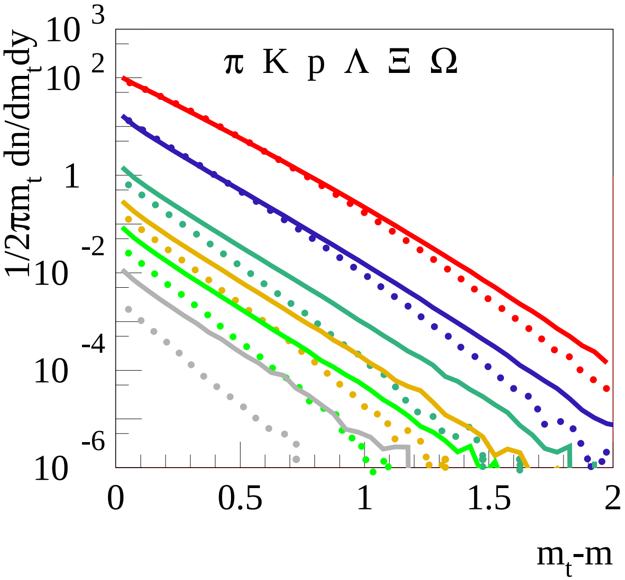
Grand canonical decay, T = 130 MeV

V=50 fm^3; V=1000 fm^3



Microcanonical decay, E/V= 0.050 GeV/fm^3

solid: E=160 GeV; dotted: E=10 GeV



Microcanonical hadronization in EPOS

(very preliminary)

Hadronization hyper-surface $x^\mu(\tau, \varphi, \eta)$:

$$\begin{aligned} x^0 &= \tau \cosh \eta, \\ x^1 &= r \cos \varphi, \\ x^2 &= r \sin \varphi, \\ x^3 &= \tau \sinh \eta \end{aligned}$$

with $r = r(\tau, \varphi, \eta)$, representing the **FO condition**.

Hypersurface element:

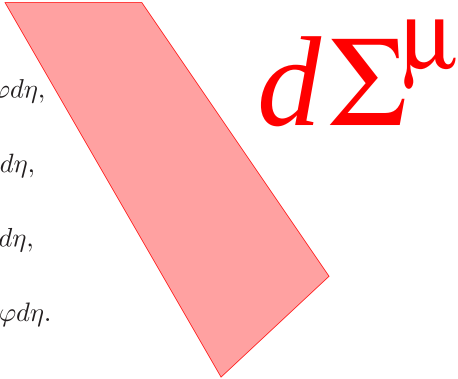
$$d\Sigma_\mu = \varepsilon_{\mu\nu\kappa\lambda} \frac{\partial x^\nu}{\partial \tau} \frac{\partial x^\kappa}{\partial \varphi} \frac{\partial x^\lambda}{\partial \eta} \, d\tau \, d\varphi \, d\eta.$$

$$d\Sigma_0 = \left\{ -r\frac{\partial r}{\partial \tau}\tau \cosh\eta + r\frac{\partial r}{\partial \eta} \sinh\eta \right\} d\tau d\varphi d\eta,$$

$$d\Sigma_1 = \left\{ \frac{\partial r}{\partial \varphi}\tau \sin\varphi + r\,\tau\cos\varphi \right\} d\tau d\varphi d\eta,$$

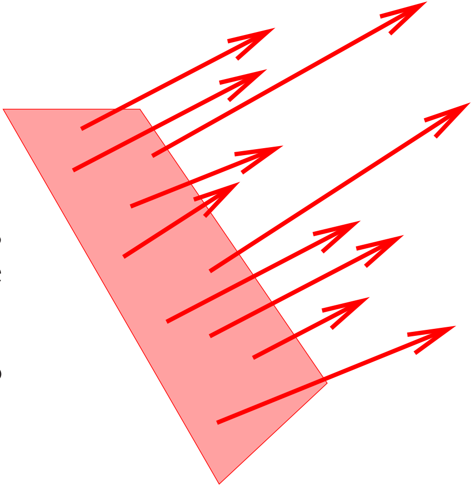
$$d\Sigma_2 = \left\{ -\frac{\partial r}{\partial \varphi}\tau \cos\varphi + r\,\tau\sin\varphi \right\} d\tau d\varphi d\eta,$$

$$d\Sigma_3 = \left\{ r\frac{\partial r}{\partial \tau}\tau \sinh\eta - r\frac{\partial r}{\partial \eta} \cosh\eta \right\} d\tau d\varphi d\eta.$$



GC particle production via Cooper-Frye

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



assuming that "matter" is a thermalized resonance gas

(adding δf for viscous hydro, close to equilibrium)

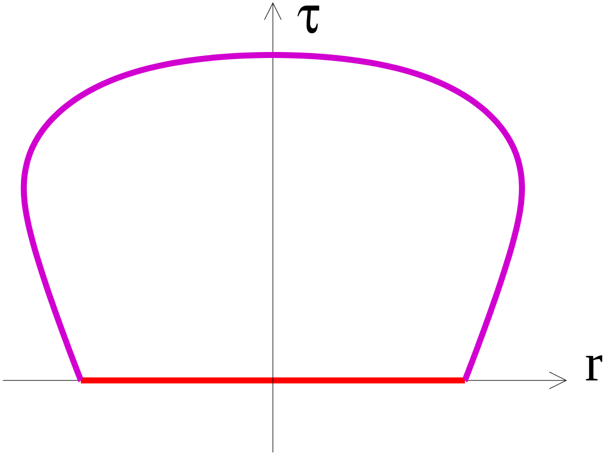
More general:

Flow of momentum vector dP^μ and conserved charges dQ_A through the surface element:

$$
\begin{aligned}
dP^\mu &= T^{\mu\nu} d\Sigma_\nu, \\
dQ_A &= J_A^\nu d\Sigma_\nu.
\end{aligned}
$$

Momentum and charges are conserved :

$$\int_{\Sigma_{FO}} dP^\mu = P^\mu_{\text{ini}},$$
$$\int_{\Sigma_{FO}} dC_A = C_{A\,\text{ini}}$$



Construct an **effective mass** by summing surface elements:

$$M = \int_{\text{surface area}} dM,$$

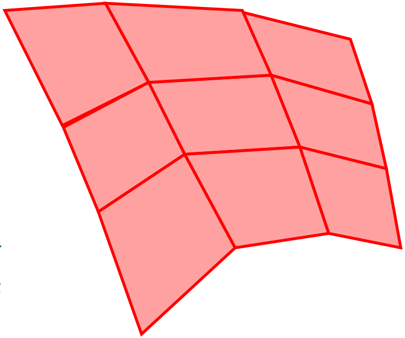
with

$$dM = \sqrt{dP^\mu dP_\mu},$$

knowing for each element four-velocity and volume element

$$U^\mu = dP^\mu / dM,$$

$$dV = u^\mu d\Sigma_\mu.$$



The four-velocity U^μ is NOT equal to the fluid velocity u^μ! (Only in case of zero pressure)

These effective masses we **decay microcanonically**:

$$dP = C_{\mathrm{vol}}\, C_{\mathrm{deg}}\, C_{\mathrm{ident}} \times \delta(E - \Sigma\varepsilon_i)\, \delta(\Sigma\vec{p}_i) \prod_A \delta_{Q_A,\Sigma q_{A\,i}} \prod_{i=1}^{n} d^3p_i,$$

$$C_{\mathrm{vol}} = \frac{V^n}{(2\pi\hbar)^{3n}}\,, \quad C_{\mathrm{deg}} = \prod_{i=1}^{n} g_i\,, \quad C_{\mathrm{ident}} = \prod_{\alpha\in\mathcal{S}} \frac{1}{n_\alpha!}\,,$$

(n_α is the number of particles of species α, $\mathcal{S}$ is the set of particle species)

then **boost the particles** according to velocities U^μ.

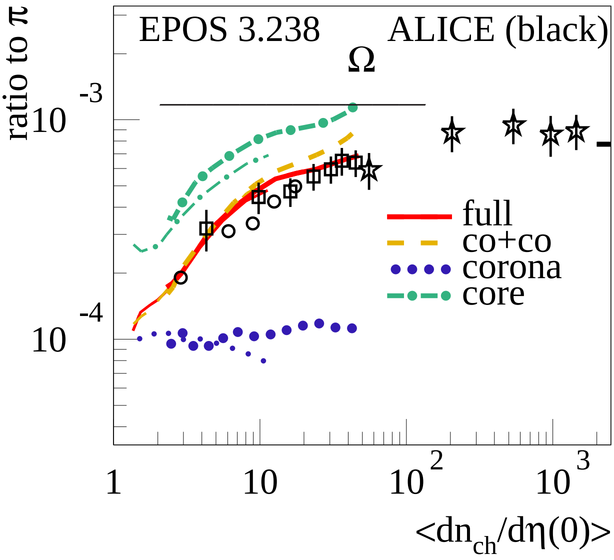
Work in progress (will come soon)

- □ This procedure based on FO surface & flow from viscous hydro as in EPOS3
- □ Large particle table (used presently in EPOS3)

Here (as first tests) for pp and pPb:

- □ FO surface & flow parametrized,
- □ limited particle table

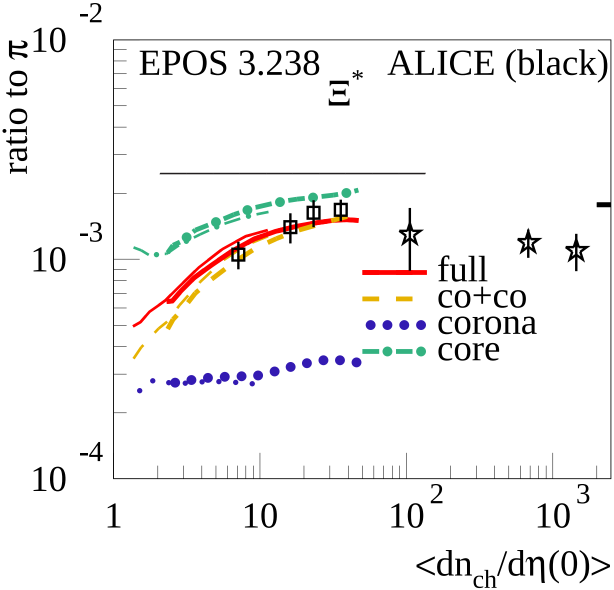
Omega to pion ratio (microcanonical)



thin lines = pp (7TeV)
intermediate lines = pPb (5TeV)
thick lines = PbPb (2.76TeV)

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

Ξ* to pion ratio (microcanonical)



thin lines = pp (7TeV)
intermediate lines = pPb (5TeV)
thick lines = PbPb (2.76TeV)

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

Summary

- **EPOS can explain many experimental curves, concerning basic quantities and flow observables**

- **BUT for the moment based on different approaches (EPOS LHC, EPOS 3)**

- **Progress concerning the “fusion” towards a unique approach, covering LHC but also RHIC physics (BES)**

Thank you!

Hydro evolution (Yuri Karpenko)

Israel-Stewart formulation, $\eta - \tau$ coordinates, $\eta/S = 0.08$, $\zeta/S = 0$

$$\partial_{;\nu} T^{\mu\nu} = \partial_\nu T^{\mu\nu} + \Gamma^\mu_{\nu\lambda} T^{\nu\lambda} + \Gamma^\nu_{\nu\lambda} T^{\mu\lambda} = 0$$

$$\gamma\left(\partial_t + v_i \partial_i\right)\pi^{\mu\nu} = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_\pi} + I^{\mu\nu}_\pi \qquad \gamma\left(\partial_t + v_i \partial_i\right)\Pi = -\frac{\Pi - \Pi_{\text{NS}}}{\tau_\Pi} + I_\Pi$$

- ☐ $T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$,
- ☐ $\partial_{;\nu}$ denotes a covariant derivative,
- ☐ $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$ is the projector orthogonal to u^μ,
- ☐ $\pi^{\mu\nu}$, Π shear stress tensor, bulk pressure
- ☐ $\pi^{\mu\nu}_{\text{NS}} = \eta(\Delta^{\mu\lambda}\partial_{;\lambda}u^\nu + \Delta\nu\lambda\partial_{;\lambda}u^\mu) - \frac{2}{3}\eta\Delta^{\mu\nu}\partial_{;\lambda}u^\lambda$
- ☐ $\Pi_{\text{NS}} = -\zeta\partial_{;\lambda}u^\lambda$
- ☐ $I^{\mu\nu}_\pi = -\frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma}u^\gamma - [u^\nu\pi^{\mu\beta} + u^\mu\pi^{\nu\beta}]u^\lambda\partial_{;\lambda}u_\beta$
- ☐ $I_\Pi = -\frac{4}{3}\Pi\partial_{;\gamma}u^\gamma$

Freeze out: at 164 MeV, Cooper-Frye $E\frac{dn}{d^3p} = \int d\Sigma_\mu p^\mu f(up)$, equilibrium distr

Hadronic afterburner: UrQMD

Marcus Bleicher, Jan Steinheimer