EPOS

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in collaboration with
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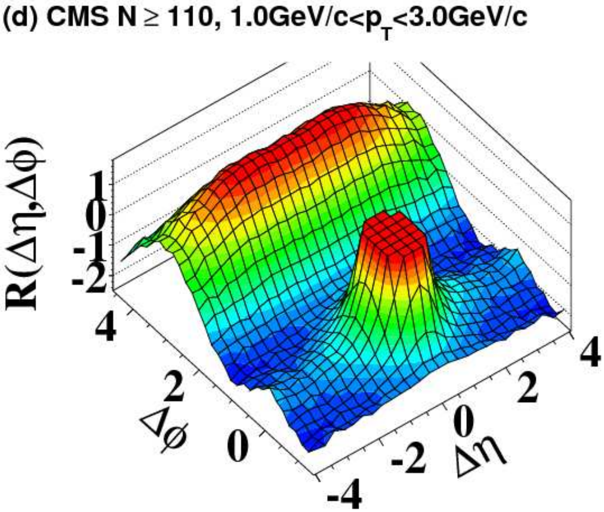
Dramatic change in understanding pp scattering:

☐ **2010: First discovery of**
“heavy ion like behavior” : the “CMS ridge”

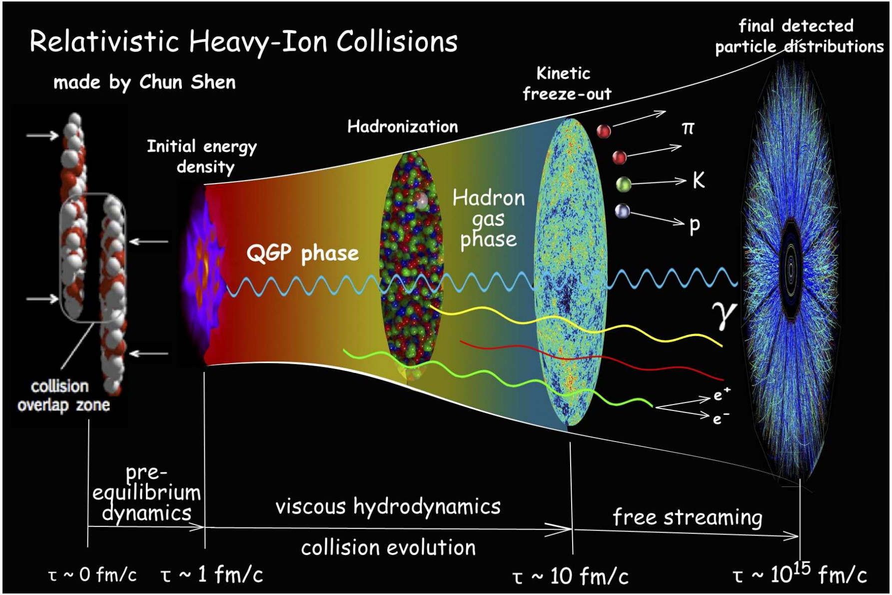
☐ **Many more such “signals” observed since**
(observables showing flow-like behavior, statistical particle production)

The “CMS Ridge” in dihadron correlations



JHEP 09 (2010) 091, arXiv:1009.4122

EPOS: Same scenario in pp, pA, and AA



Try to understand both

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

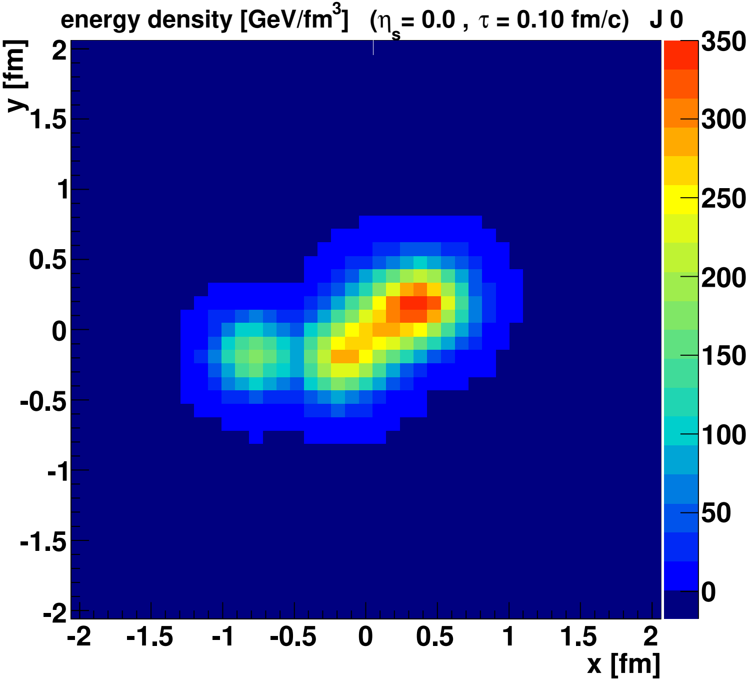
- ☐ **and HI like phenomena in pp, pA**
  collective effects, statistical hadronization

HI like effects:

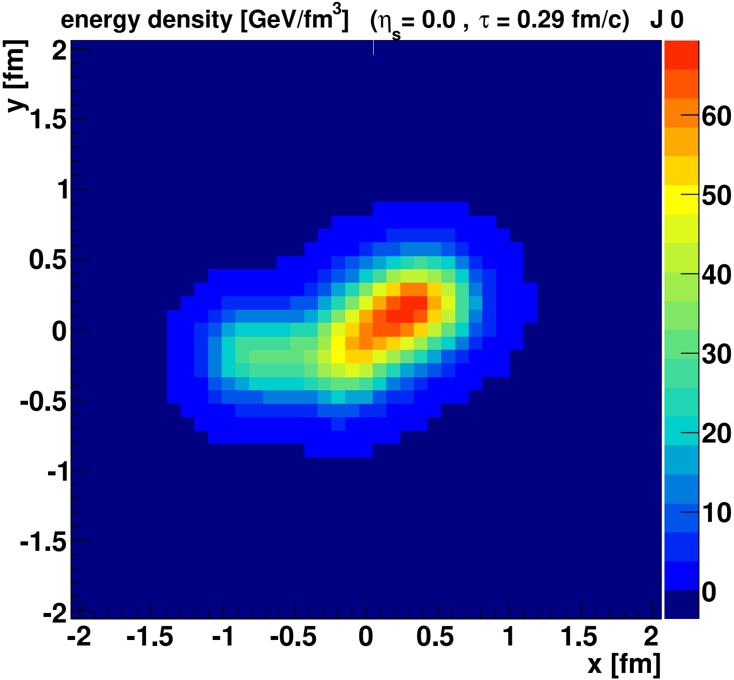
- ☐ **Primary interactions at t = 0**
- ☐ **Secondary interactions**
  formation of "matter" expanding collectively, like a fluid, which then decays statistically

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

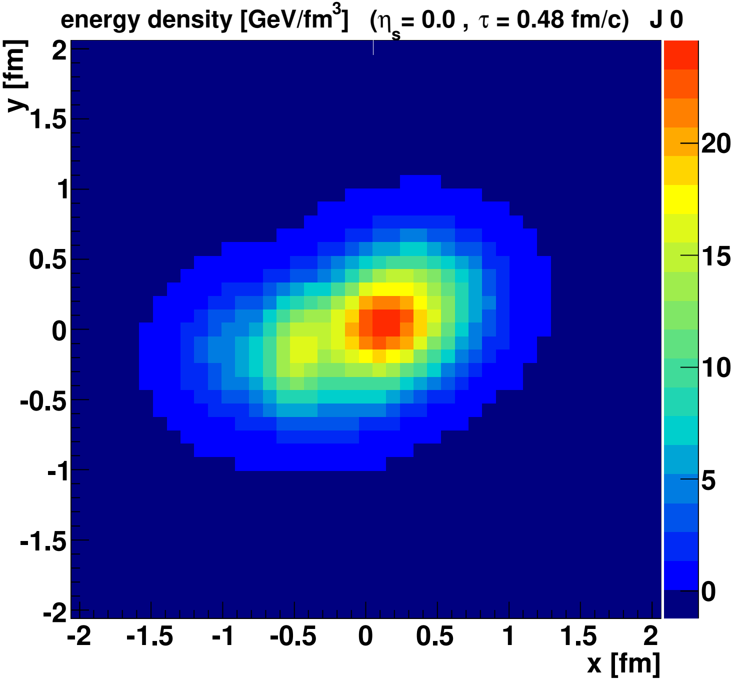
pp @ 7TeV EPOS 3.119



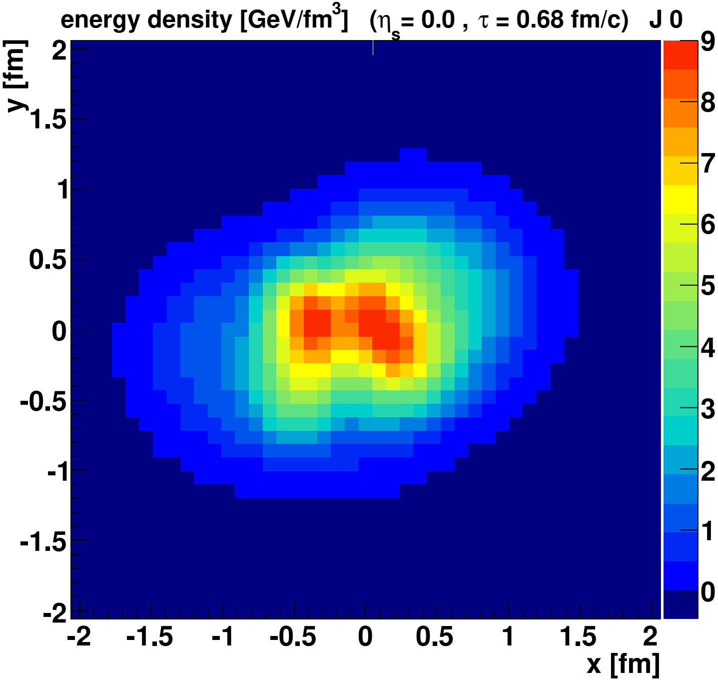
pp @ 7TeV EPOS 3.119


energy density [GeV/fm^3] (η_s = 0.0 , τ = 0.29 fm/c) J 0

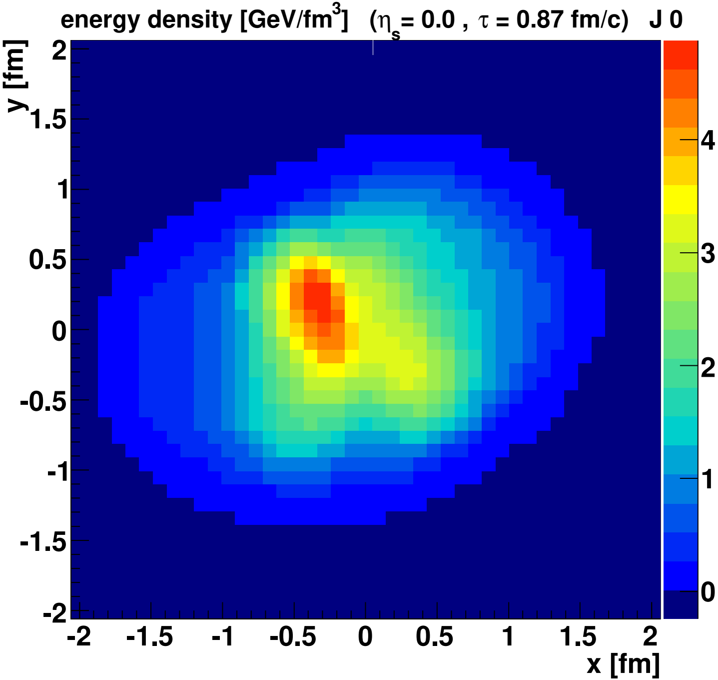
pp @ 7TeV EPOS 3.119



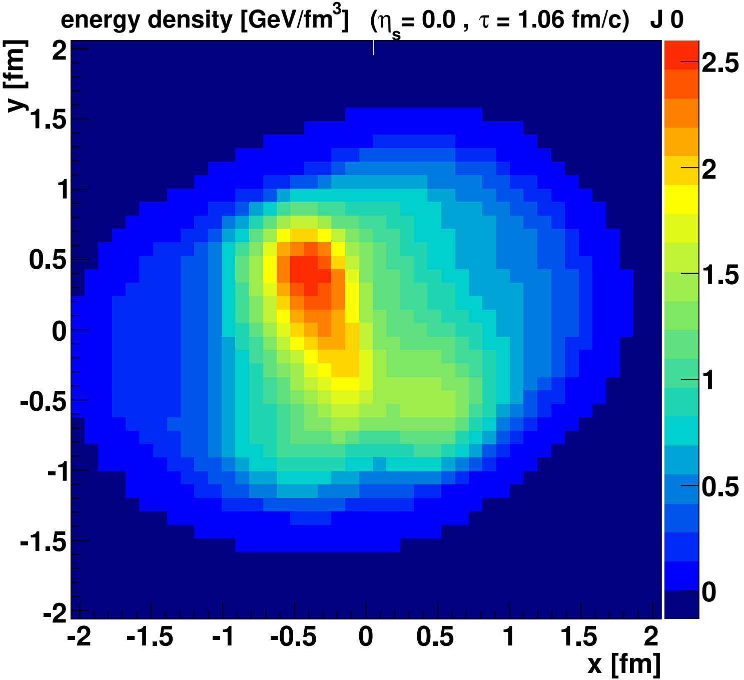
pp @ 7TeV EPOS 3.119



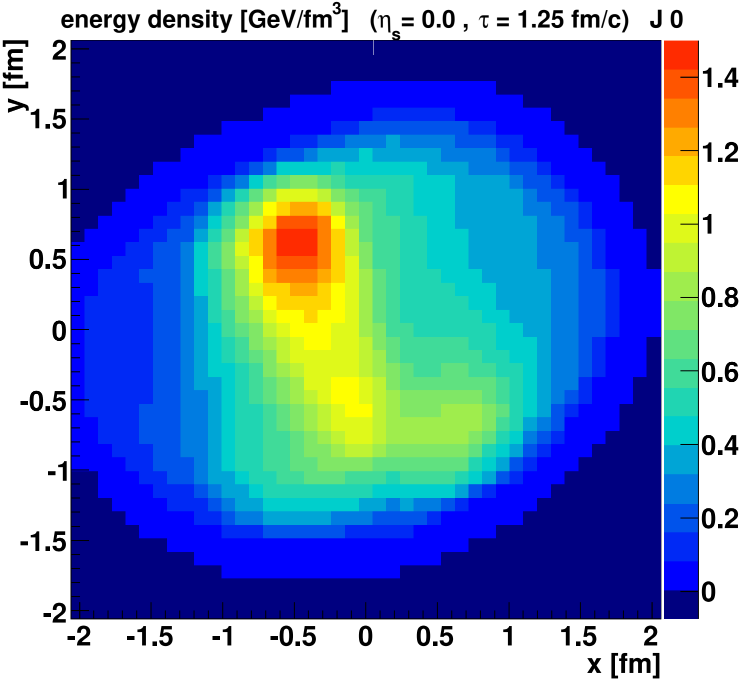
pp @ 7TeV EPOS 3.119



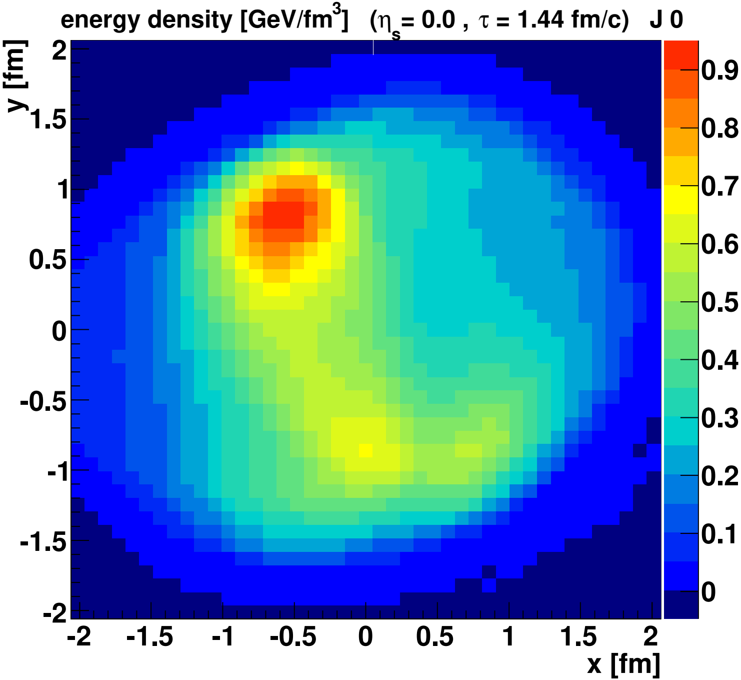
pp @ 7TeV EPOS 3.119



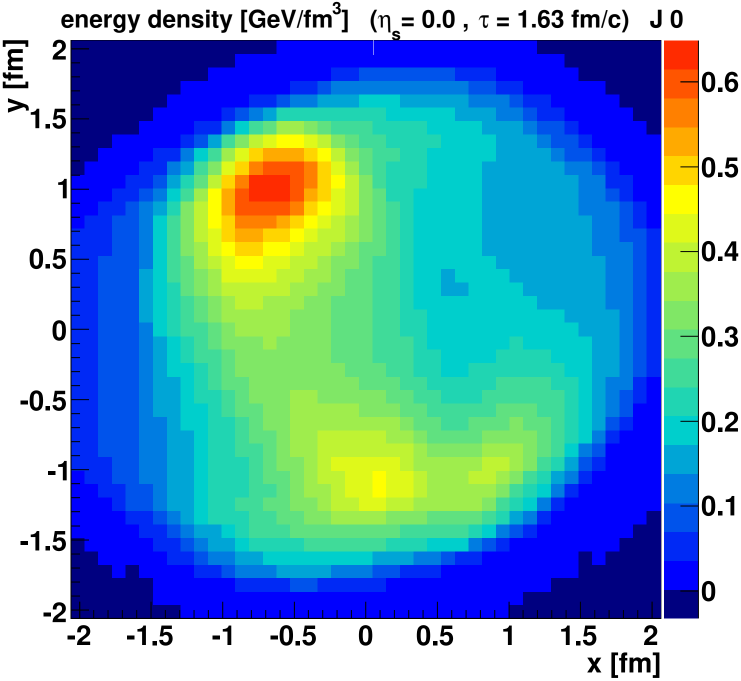
pp @ 7TeV EPOS 3.119



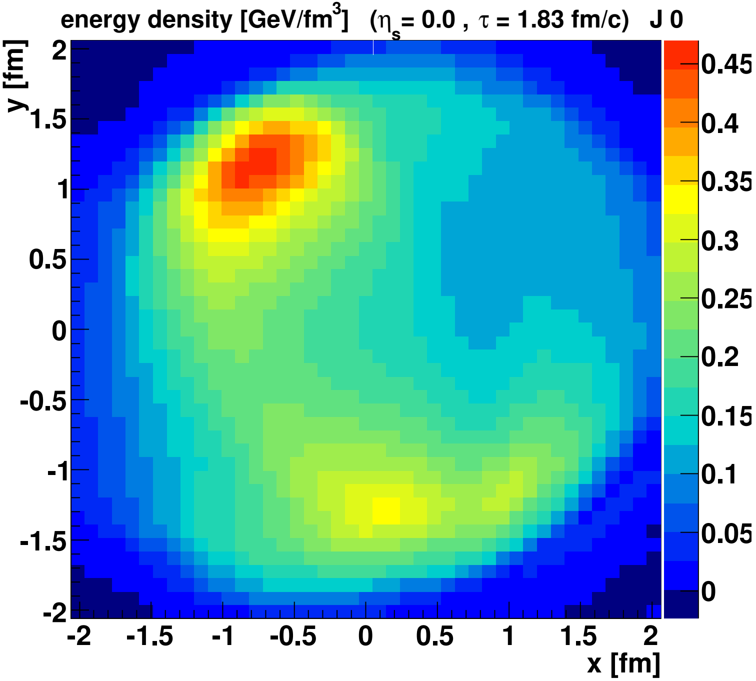
pp @ 7TeV EPOS 3.119



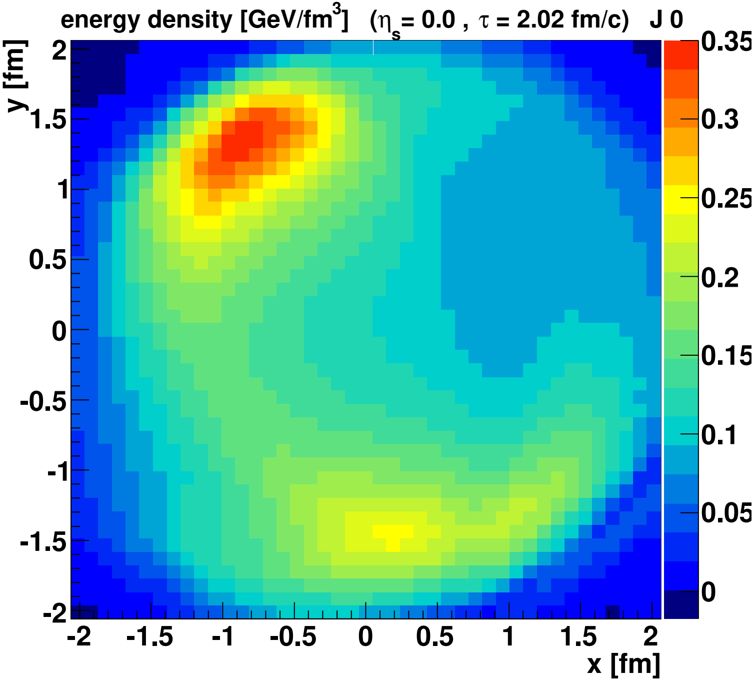
pp @ 7TeV EPOS 3.119



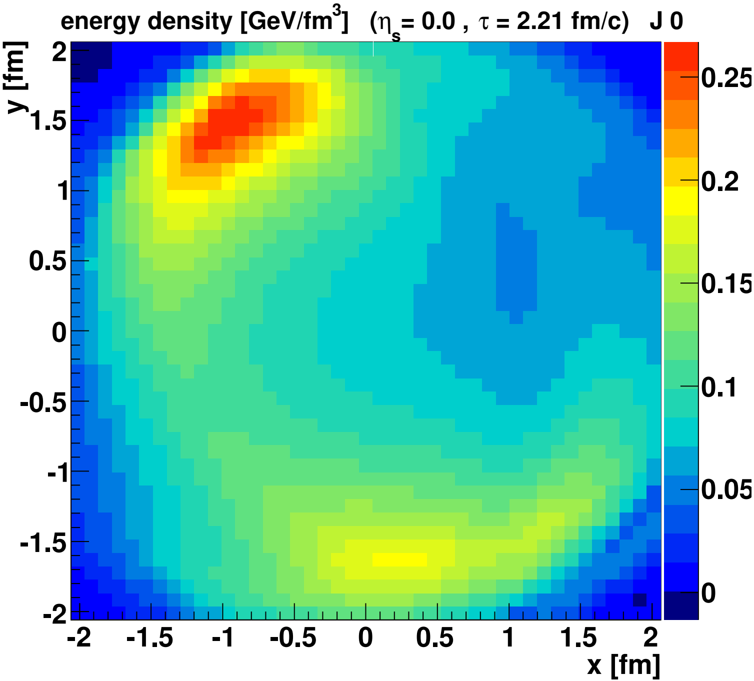
pp @ 7TeV EPOS 3.119



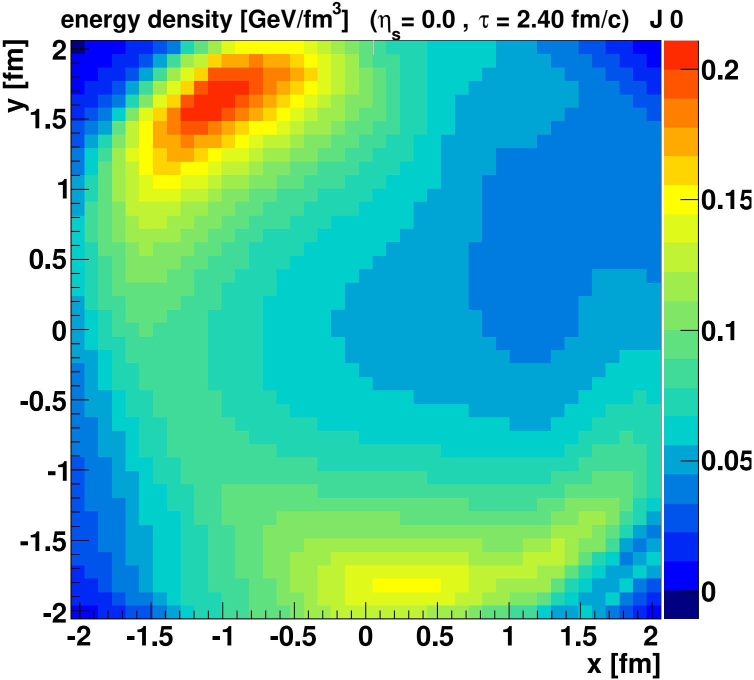
pp @ 7TeV EPOS 3.119



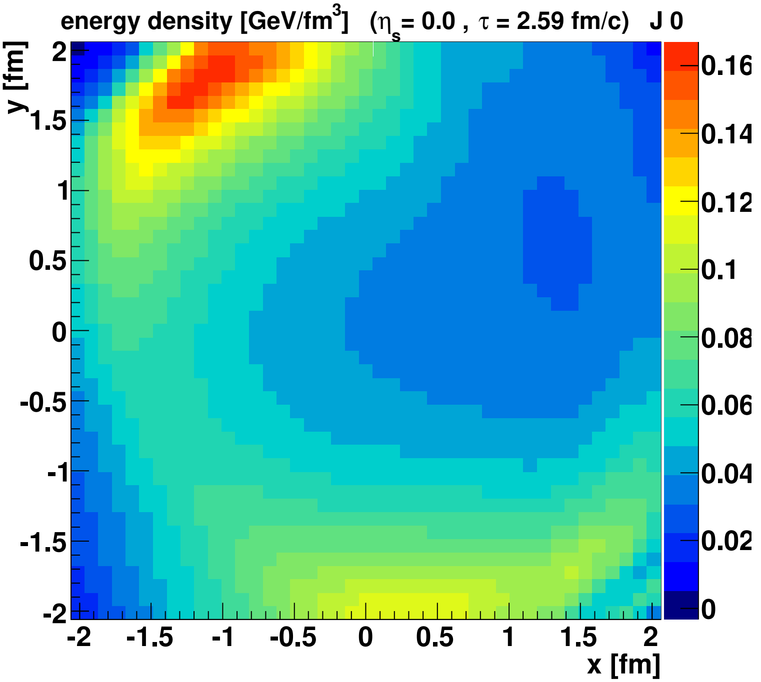
pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119

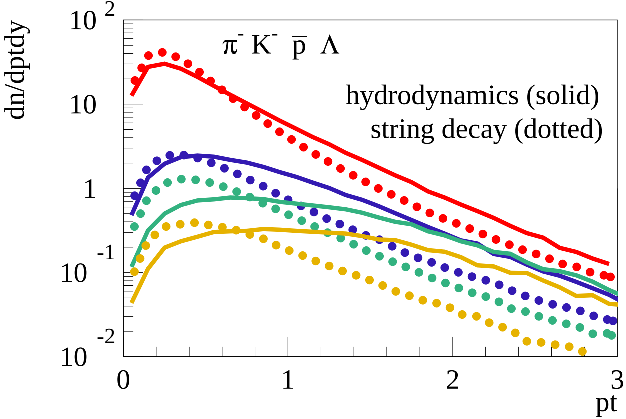


pp @ 7TeV EPOS 3.119



Radial flow visible in particle distributions

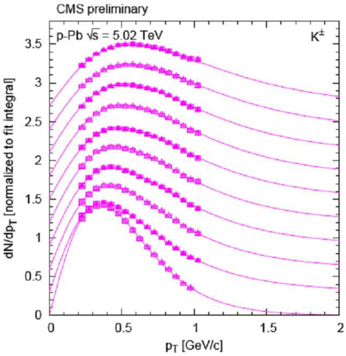
Particle spectra affected by radial flow

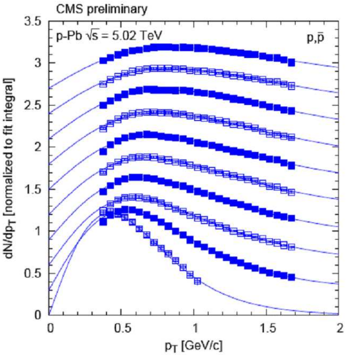


=> mass ordering of $\langle p_t \rangle$, lambda/K increase

pPb at 5TeV

CMS, arXiv:1307.3442



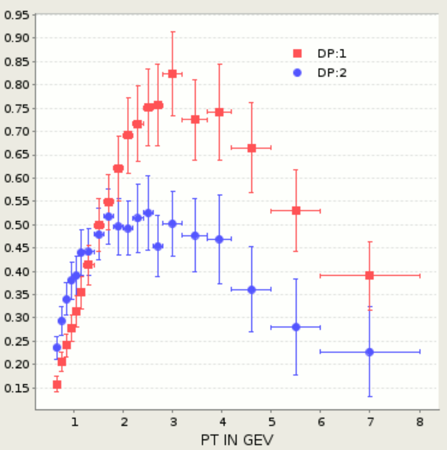


Strong variation of shape with multiplicity

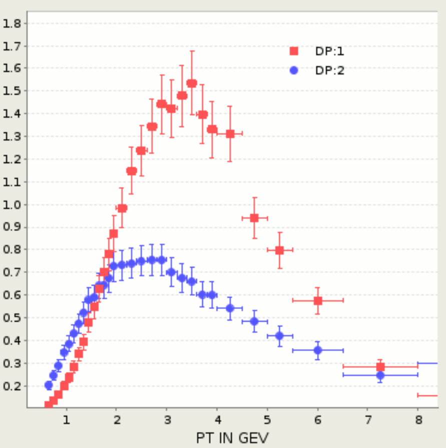
for kaon and even more for proton pt spectra

(flow like)

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



ALICE (**2013**) arXiv:1307.6796

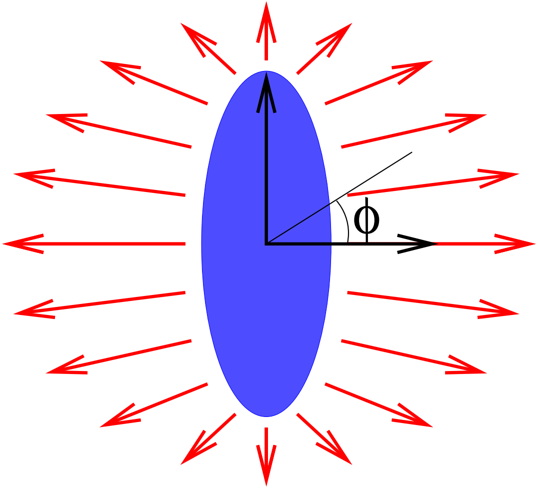


ALICE (**2013**) arXiv:1307.5530
Phys. Rev. Lett. 111, 222301 (2013)

In AA: partially due to flow

Ridges & flow harmonics

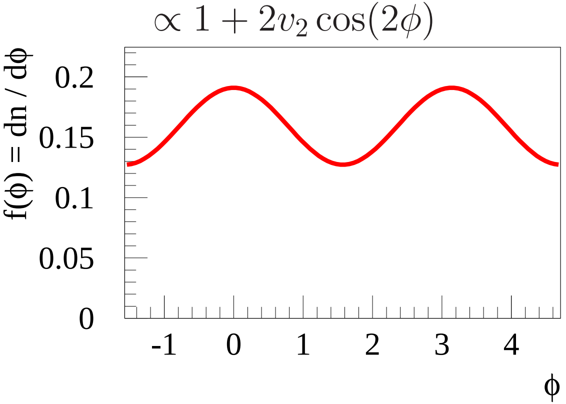
Initial "elliptical" matter distribution
(in transverse plane):



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

longitudinally invariant

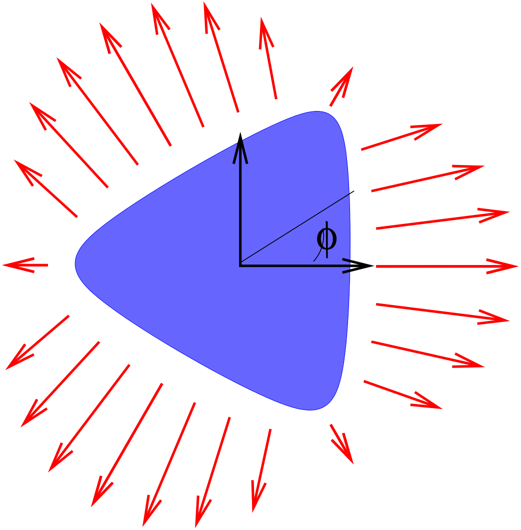
Particle distribution:
Preferred directions
$\phi = 0$ and $\phi = \pi$



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

Fourier coeff v_2 (flow harmonics)

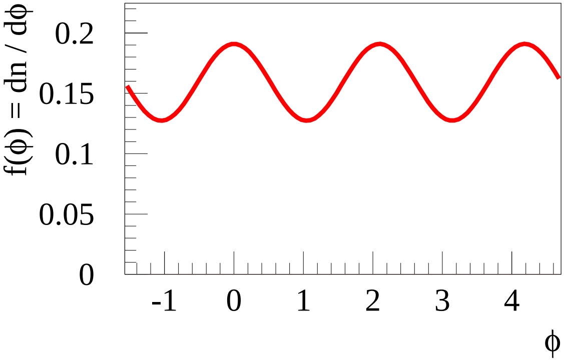
Initial “triangular” matter distribution:



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

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

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



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

“elliptical” + “triangular”

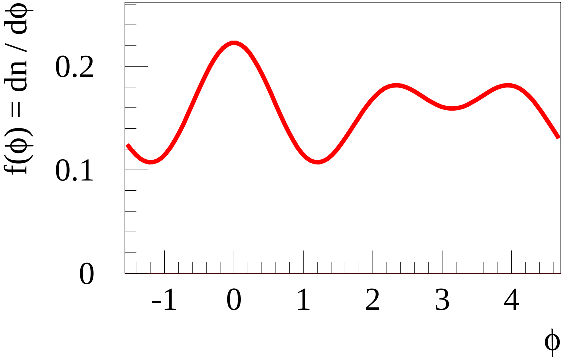
At $\phi = 0$:
The **ridge**

(extended in η)

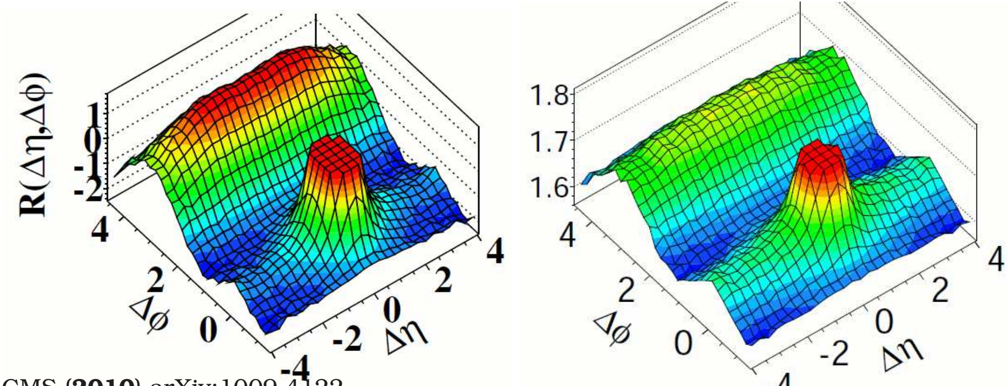
Awayside peak may originate from jets, not the ridge (for large $\Delta\eta$)

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 !

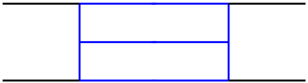
EPOS primary scatterings

☐ **Defined via elastic scattering S matrix**

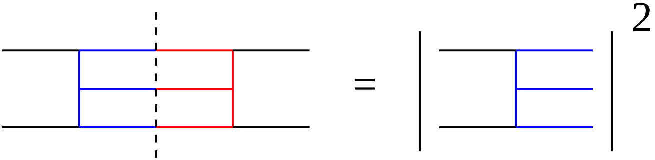
☐ **Cutting rules to get inelastic cross sections**

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

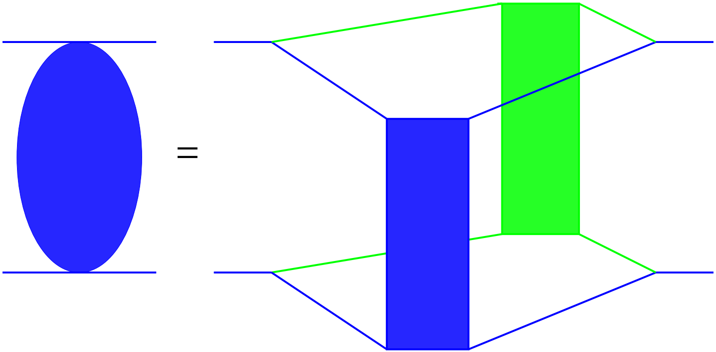
Cutting a diagram representing **elastic** scattering



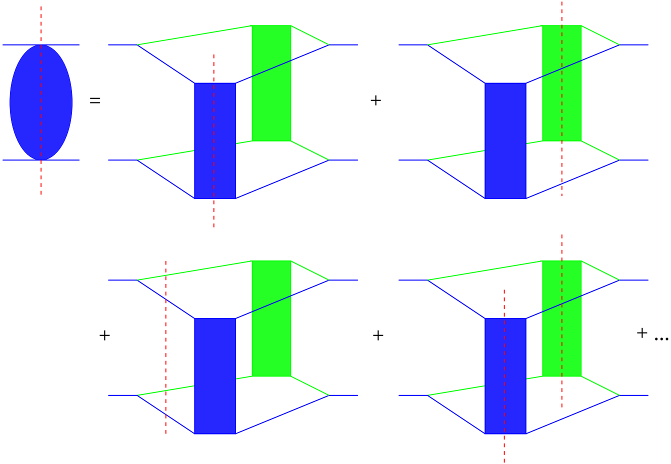
corresponds to **inelastic** scattering



Cutting diagrams is useful in case of substructures:



Precisely the multiple scattering structure in EPOS (multiple Pomeron exchange)

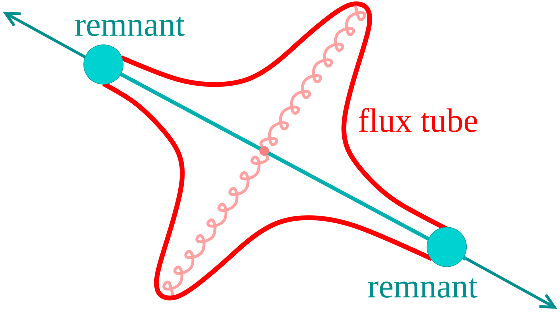


Cut diagram

= sum of products of cut/uncut subdiagrams

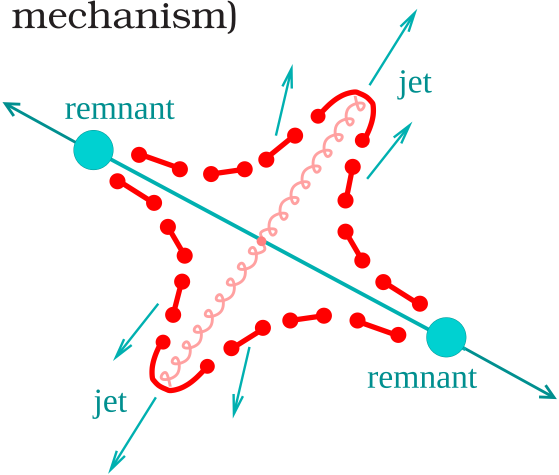
=> Gribov-Regge approach of multiple scattering

Link with QCD:
Pomeron = parton ladder => two kinky strings



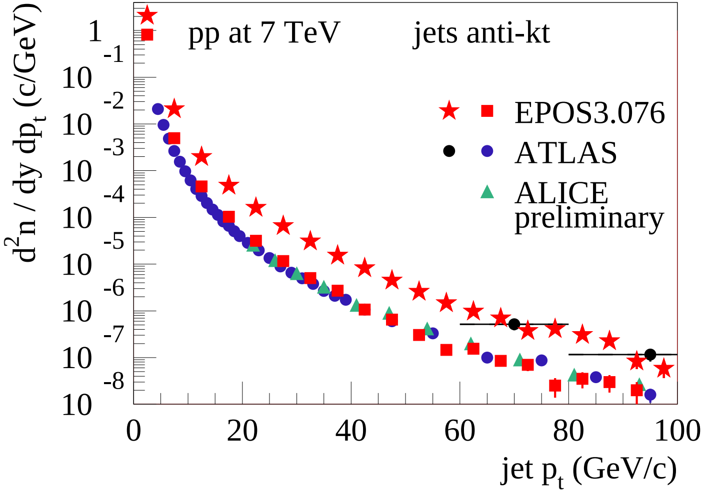
(here no IS radiation, only hard process producing two gluons)

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



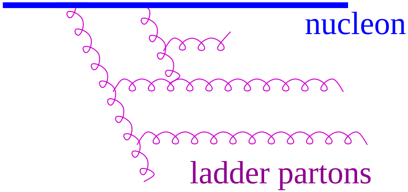
Saturation

Parton-ladders$^{(1)}$ are perfectly fitted$^{(2)}$ as $\boxed{G = \alpha\,(x^+x^-)^{\beta}}$.

G depends on the vituality cutoff: $G = G(Q_0)$.

To mimic the effects of gluon fusion, the fits are modified (for pp) as $\boxed{\alpha\,(x^+x^-)^{\beta+\varepsilon}}$**, referred to as** $\boxed{G_{\mathrm{eff}}}$**.**

The exponent $\varepsilon = \varepsilon(s)$ is chosen to reproduce the energy dependence of cross sections.



Procedure employed in EPOS LHC

---

(1) Imaginary part G of the corresponding amplitude in $b-$space
(2) x^+, x^-: light cone momentum fractions of the Pomeron end

But adding an exponent ε

- ☐ **must be accompanied by a corresponding modification of the internal structure of the Pomeron**

This can be done by defining a **saturation scale** Q_s via

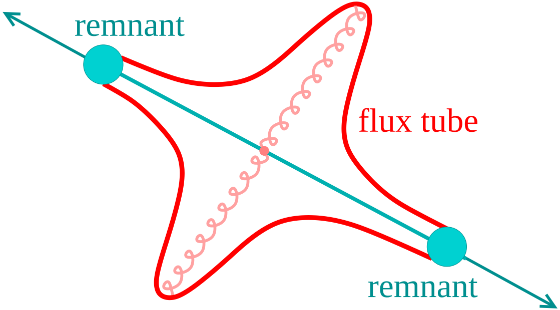
$$\boxed{G_{\mathrm{eff}} = f \times G(Q_s)}$$

and then considering the parton ladder with the cutoff Q_s

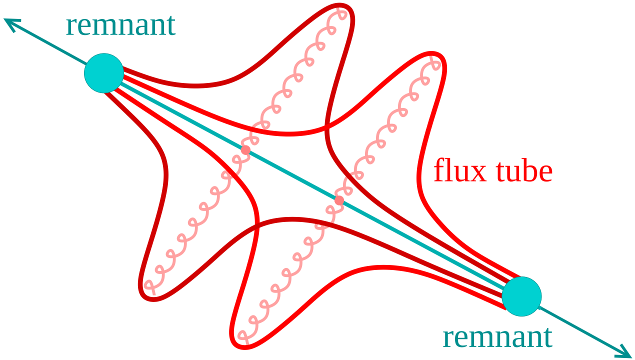
thus changing the internal structure! => consistent!

Secondary scattering

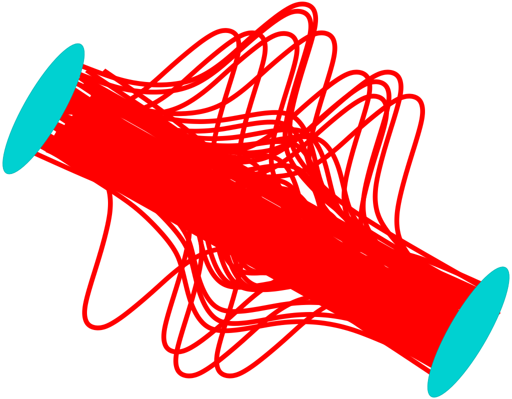
again: single scattering => 2 color flux tubes



… two scatterings => 4 color flux tubes



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

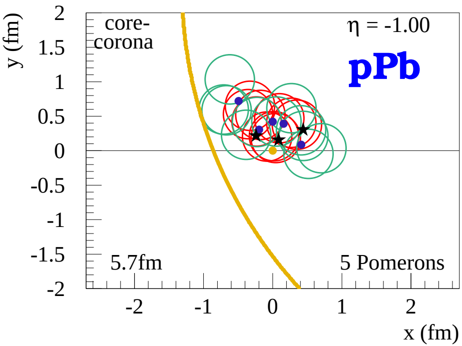


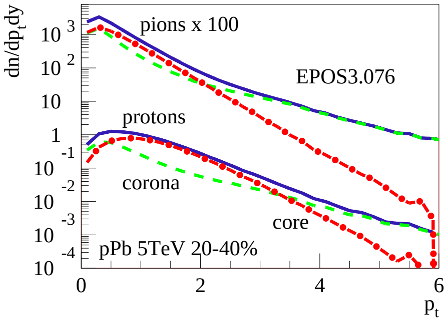
=> matter + escaping pieces (jets)

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





Important for particle production

- ☐ **Flow**
- ☐ **Statistical hadronization rather than string decay**

Two parallel developments

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

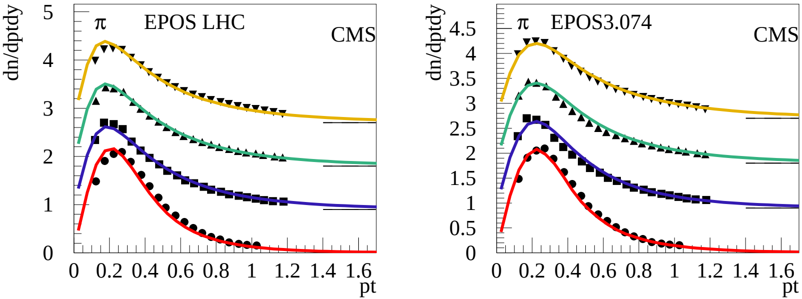
EPOS 3.0xx: **Gribov Regge approach, viscous hydro, parton saturation, statistical decay, mainly used for HI and collectivity in pp**

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

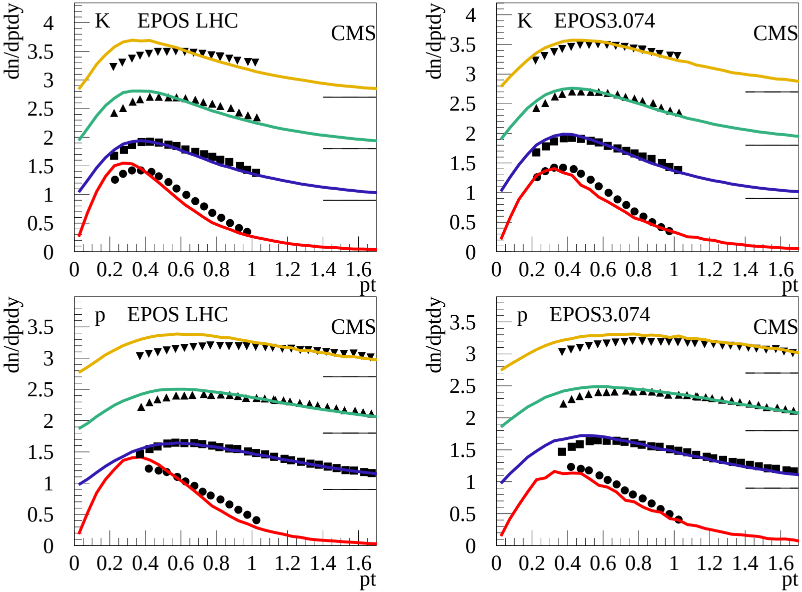
Results concerning flow (pPb)

Comparing EPOS3 and EPOS LHC with CMS multiplicity dependence of pion, kaon, proton pt spectra (CMS, EPJC 74 (2014) 2847)

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

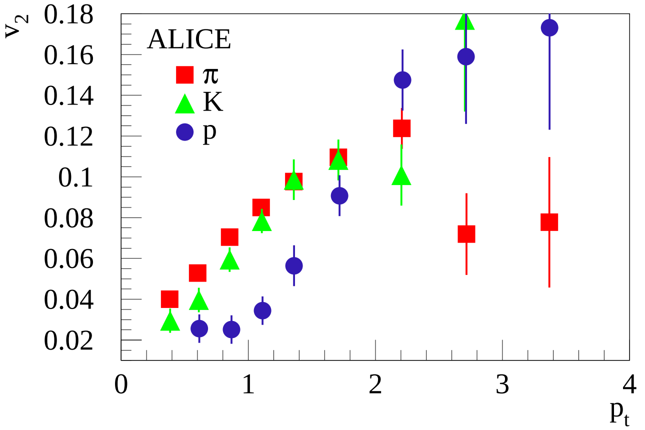


Little change with multiplicity for pions



Strong variation of K and p spectra => flow helps

Flow anisotropy in pPb: Fourier coefficients v2 of identified particles

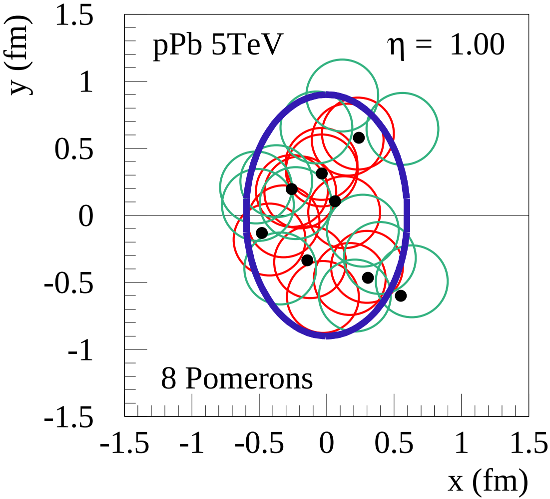


mass splitting, as in PbPb !!!

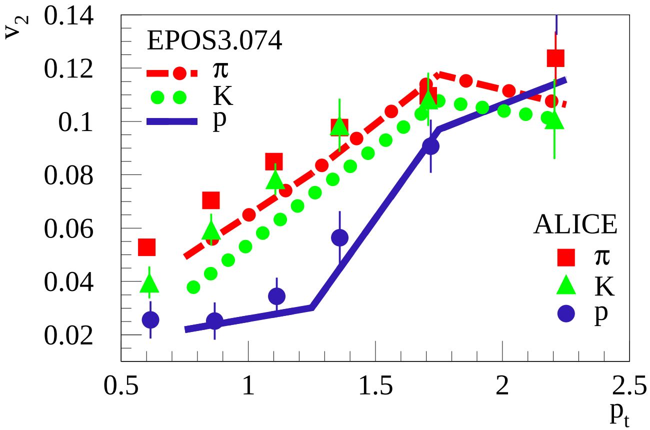
pPb in EPOS3:

Pomerons (number and positions) characterize geometry **(P. number ∝ multiplicity)**

random
azimuthal
asymmetry
=>
asymmetric flow
seen at higher pt
for heavier ptls

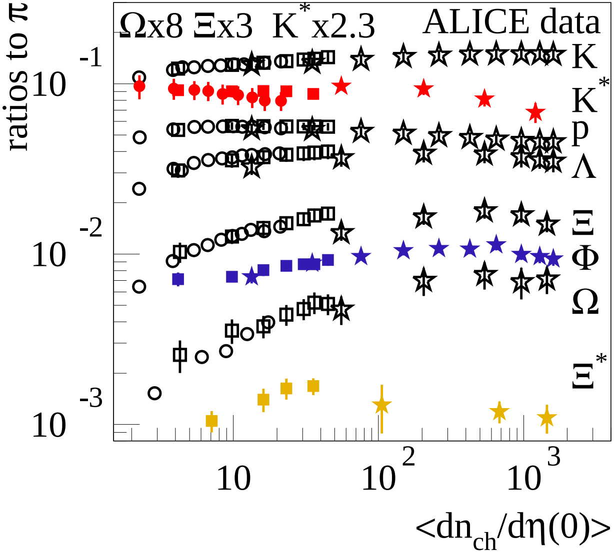


v2 for π, K, p clearly differ



mass splitting, due to flow

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



circles = pp (7TeV)

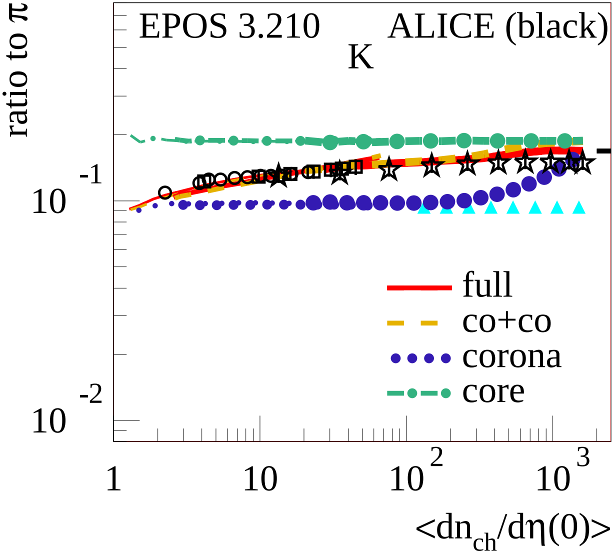
squares = pPb (5TeV)

stars = PbPb (2.76TeV)

ALICE data references (collected by A. G. Knospe)

<dNch/deta> in Pb+Pb: Phys. Rev. Lett. 106 032301 (2011)
pi+-, K+-, p+- in Pb+Pb: Phys. Rev. C 88 044910 (2013)
Lambda in Pb+Pb: Phys. Rev. Lett. 111 222301 (2013)
Xi- and Omega in p+Pb: Phys. Lett. B 758 389-401 (2016)
pi+-, K+-, p+-, Λ in p+Pb: Phys. Lett. B 728 25-38 (2014)
<dNch/deta> in p+Pb: Eur. Phys. J. C 76 245 (2016)
Xi- and Omega in p+Pb: Phys. Lett. B 758 389-401 (2016)
<dNch/deta> p+p 7 TeV: Eur. Phys. J. C 68 345-354 (2010)
pi+-, K+-, p+- in p+p 7 TeV: Eur. Phys. J. C 75 226 (2015)
Xi- and Omega in p+p 7 TeV: Phys. Lett. B 712 309 (2012)
and pp data points from Rafael Derradi de Souza, SQM2016

Kaon to pion ratio



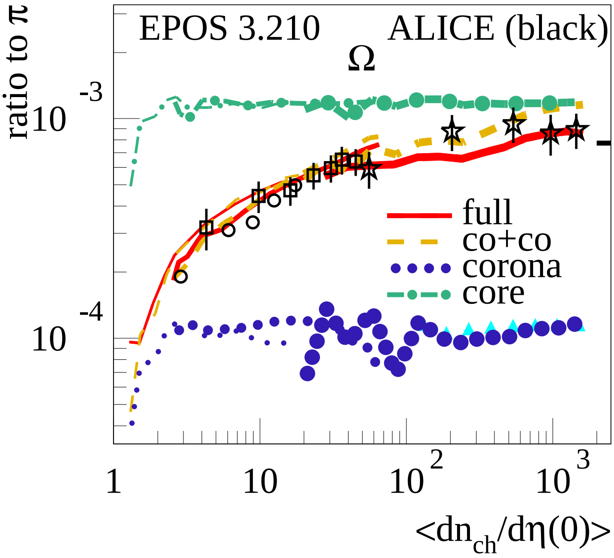
core hadronization:
$T = 164\,\mathrm{MeV},\ \mu_B = 0$

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

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

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

Omega to pion ratio



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

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

Summary

- ☐ **EPOS can explain many experimental curves, concerning basic quantities and HI like effects**
- ☐ **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, $\eta/S = 0.08$, $\zeta/S = 0$

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

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

☐ $T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$,

☐ $\partial_{;\nu}$ 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

☐ $\pi^{\mu\nu}_{\mathrm{NS}} = \eta(\Delta^{\mu\lambda}\partial_{;\lambda}u^\nu + \Delta\nu\lambda\partial_{;\lambda}u^\mu) - \frac{2}{3}\eta\Delta^{\mu\nu}\partial_{;\lambda}u^\lambda$

☐ $\Pi_{\mathrm{NS}} = -\zeta\partial_{;\lambda}u^\lambda$

☐ $I^{\mu\nu}_\pi = -\frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma}u^\gamma - [u^\nu\pi^{\mu\beta} + u^\mu\pi^{\nu\beta}]u^\lambda\partial_{;\lambda}u_\beta$

☐ $I_\Pi = -\frac{4}{3}\Pi\partial_{;\gamma}u^\gamma$

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

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