EPOS Overview

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in collaboration
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I Introduction : EPOS - A unified approach to simulate pp, pA, AA

II EPOS: General features

III Flow in small systemes

IV Recent developments
(Strangeness and charm enhancement with multiplicity in pp, pA, AA)

I

Introduction:
EPOS - A unified approach to simulate pp, pA, AA

Before 2010 (generally accepted prejudices) :

- ☐ **pp is elementary, conventional physics**
  (but not understood, complicated, not interesting)
- ☐ **pA still "baseline", but with "nuclear effects"**
- ☐ **in AA we see NEW PHYSICS**
  (QGP, eqilibration, flow, ...)

since 2010 interesting and unexpected pp and pPb results at the LHC (confirmed by RHIC).

Collective phenomena in pp, pPb ?

EPOS :

☐ **Unique approach, for pp, pA, AA**

(same formalism, same procedures)

☐ **Collective effects** (more or less) **important in all systems**

☐ **Collective effects: Creating a “medium” => flow, statistical hadron production,...**

How to detect flow, equilibration?

One may detect

- ☐ **Particular properties of particle production from the flowing medium (mass dependence)**
- ☐ **Particle ratios (string decay or statistical production)**
- ☐ Modification of the properties of initially produced particles in the flowing medium

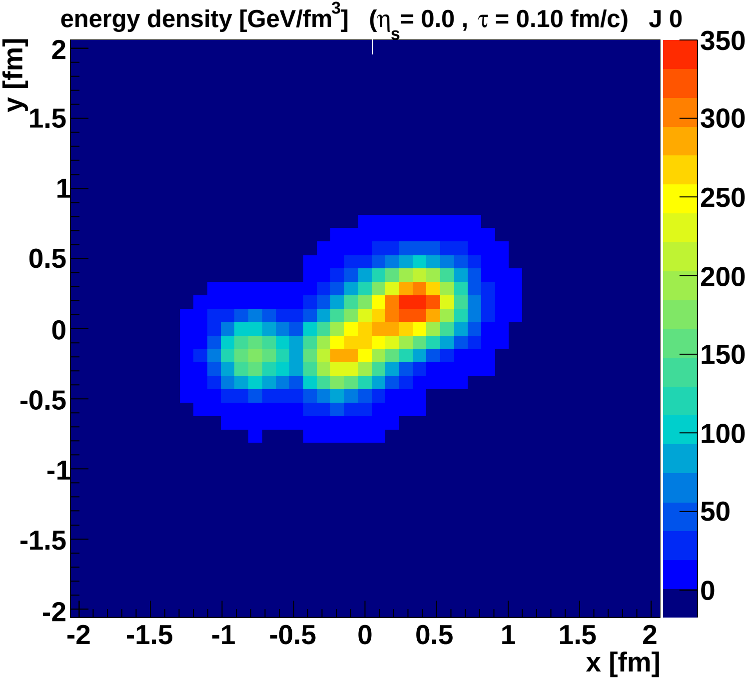
In the following:

- ☐ **"Flowing medium" as produced in EPOS with hydro evolution**

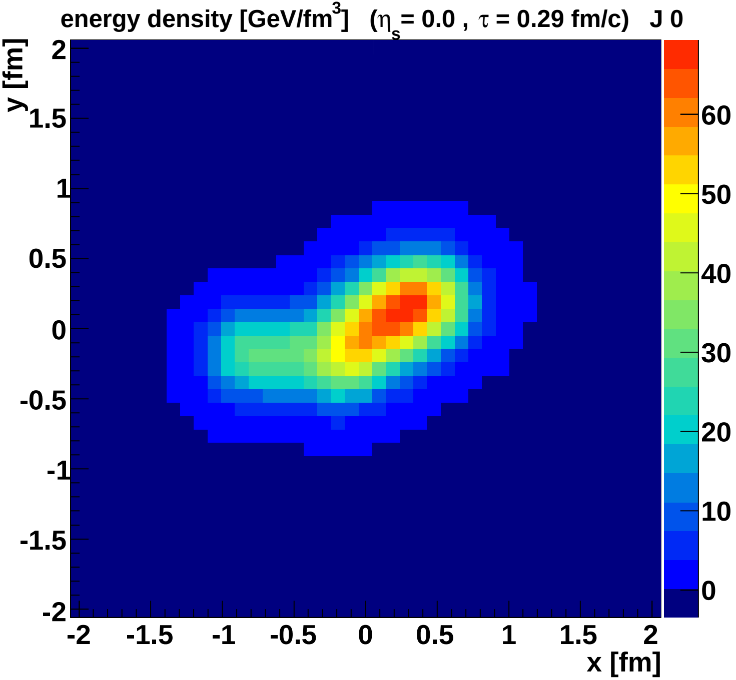
shown is the time evolution of the energy density

in the transverse plane, for $z = 0$, for pp at 7 TeV

pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119



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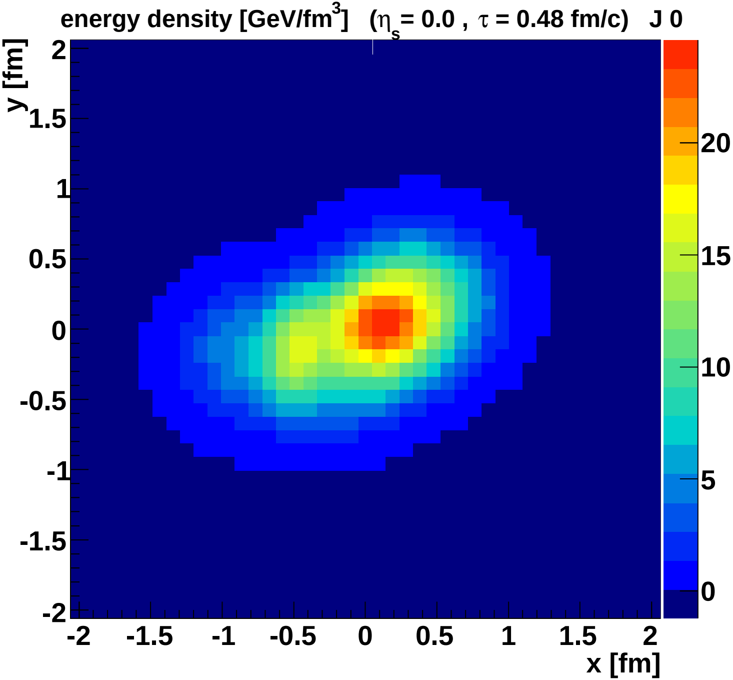
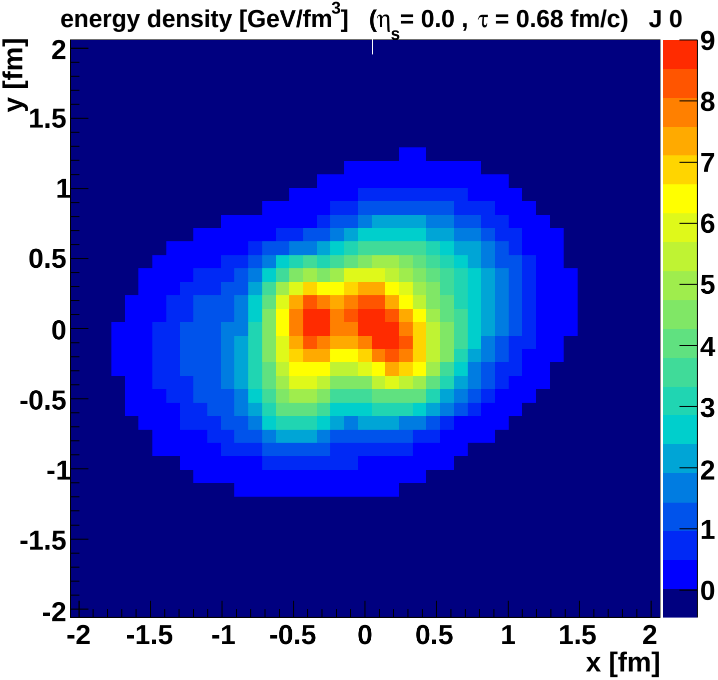
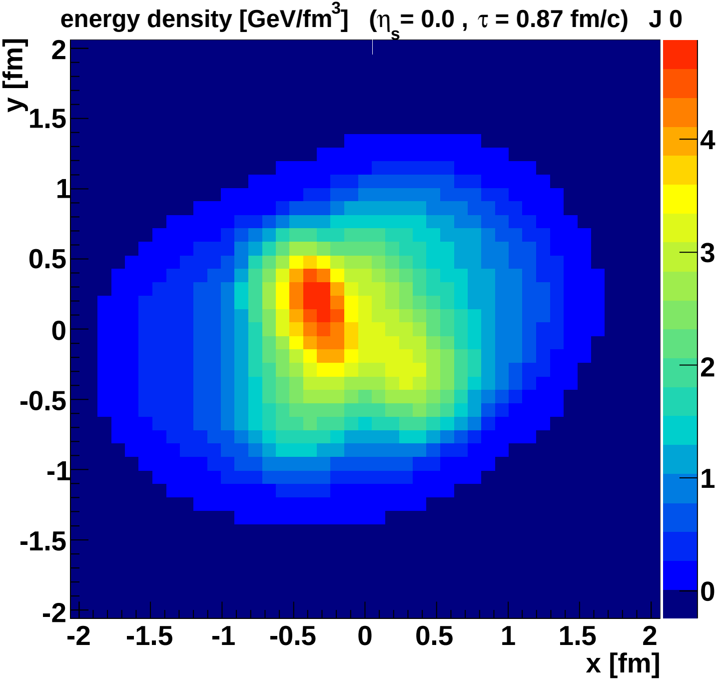


pp @ 7TeV EPOS 3.119

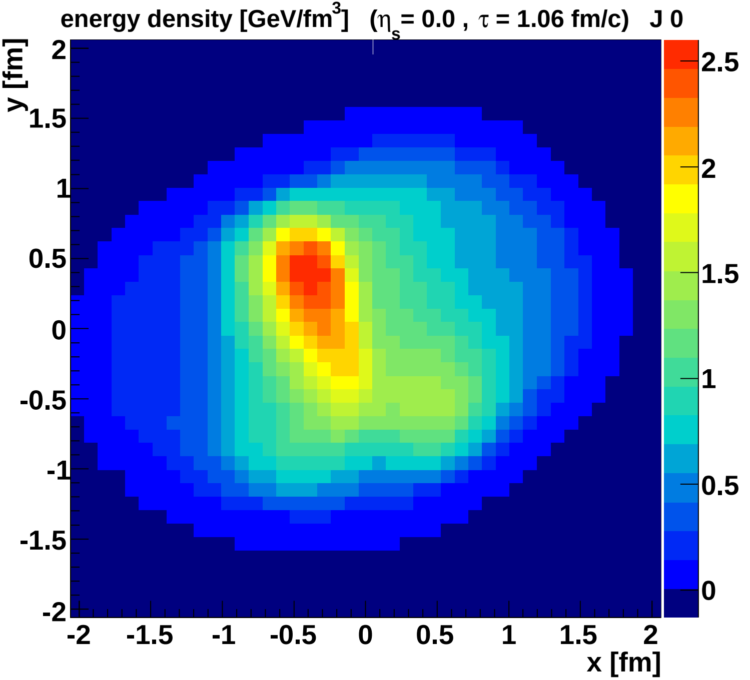


pp @ 7TeV EPOS 3.119

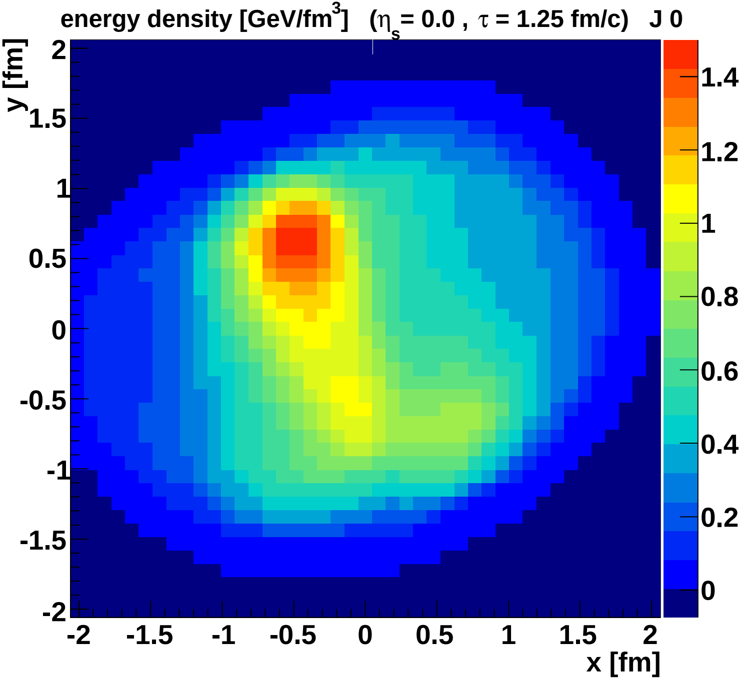


energy density [GeV/fm^3] (η_s = 0.0 , τ = 0.87 fm/c) J 0

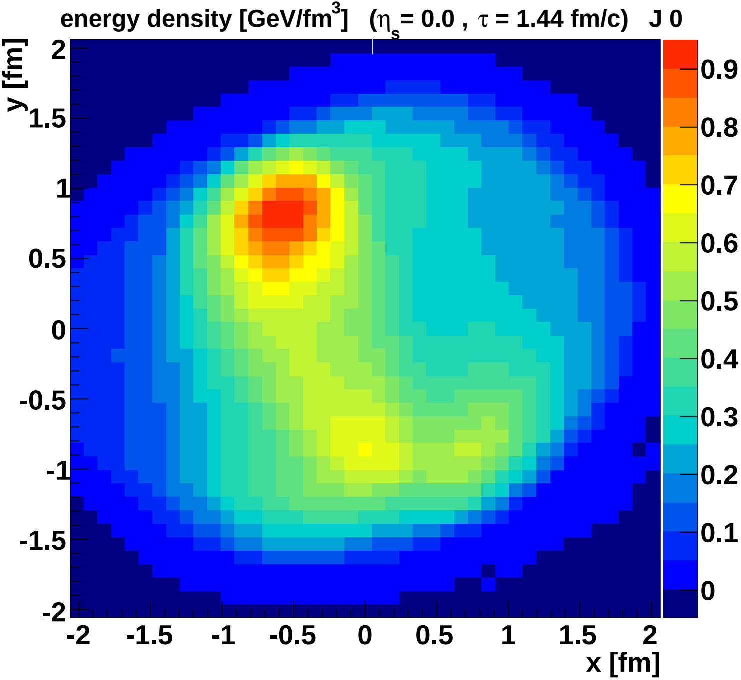
pp @ 7TeV EPOS 3.119



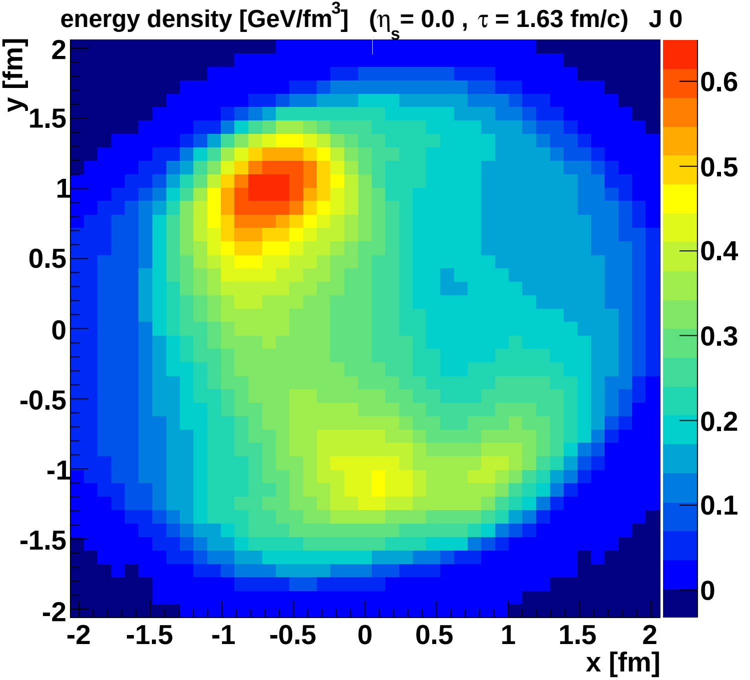
pp @ 7TeV EPOS 3.119



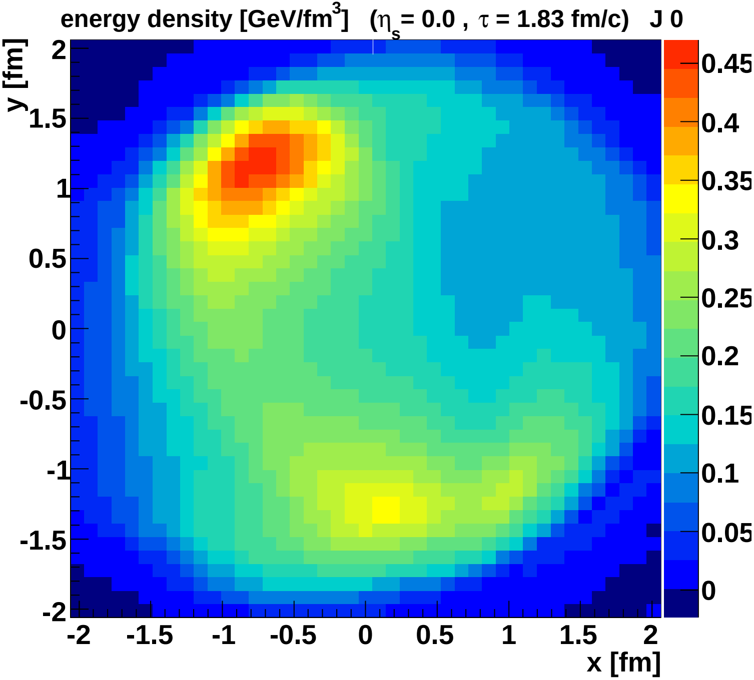
pp @ 7TeV EPOS 3.119


energy density [GeV/fm^3] (η_s = 0.0 , τ = 1.44 fm/c) J 0

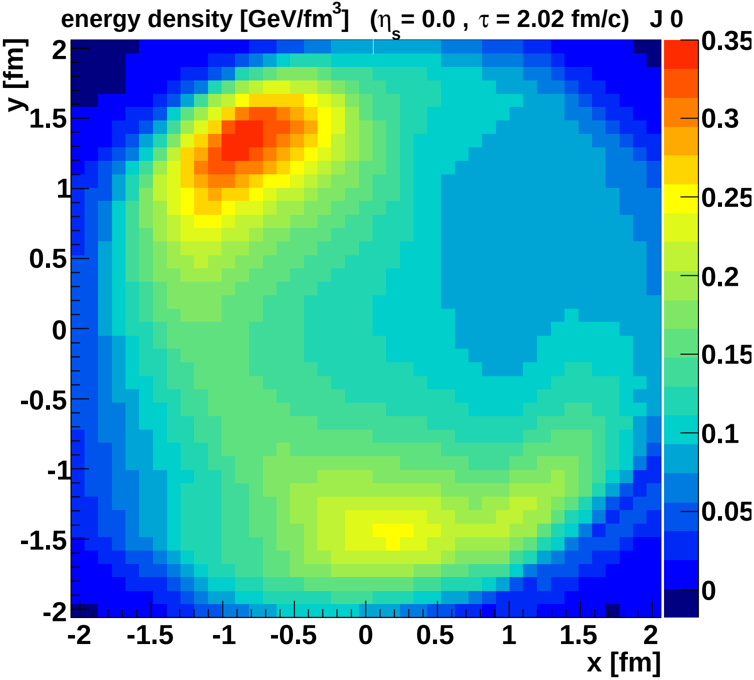
pp @ 7TeV EPOS 3.119



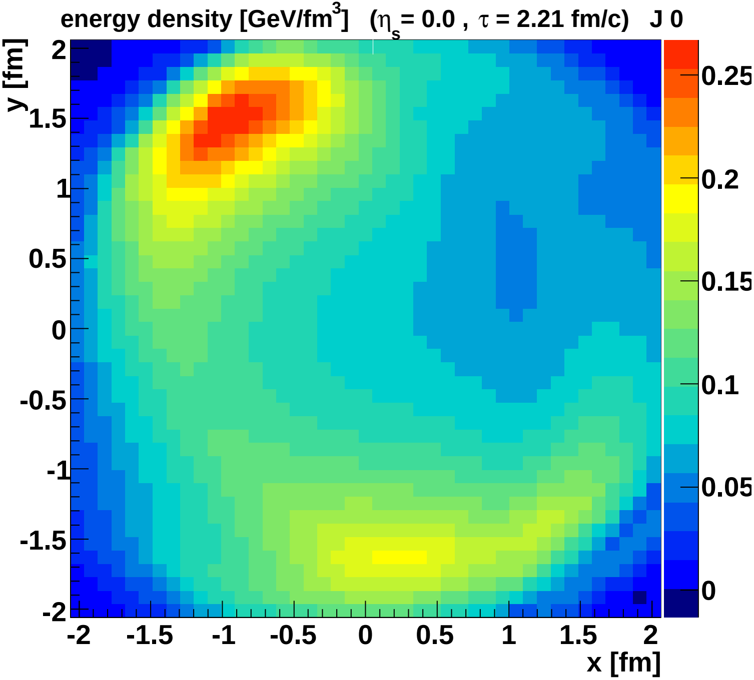
pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119

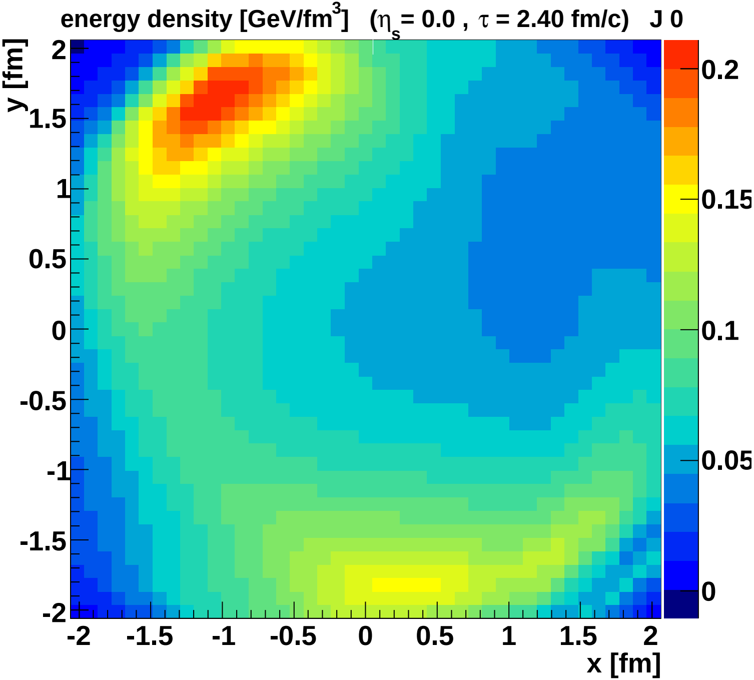


pp @ 7TeV EPOS 3.119

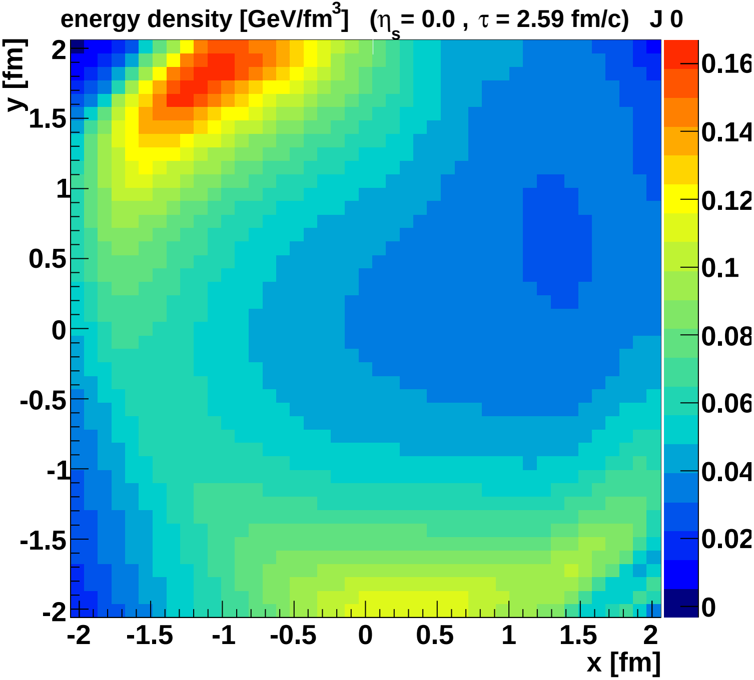


energy density [GeV/fm^3] (η_s = 0.0 , τ = 2.21 fm/c) J 0

pp @ 7TeV EPOS 3.119

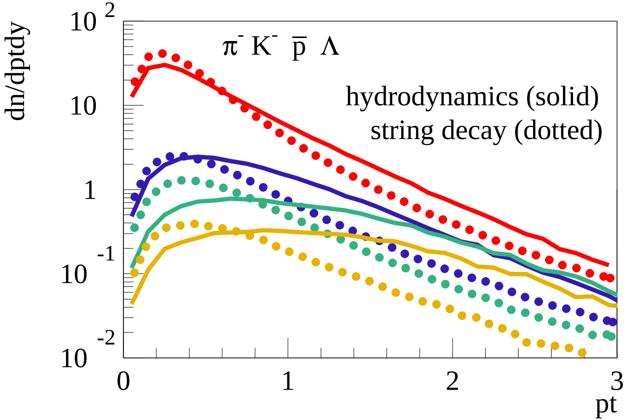


pp @ 7TeV EPOS 3.119



Radial flow

affects particle spectra



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

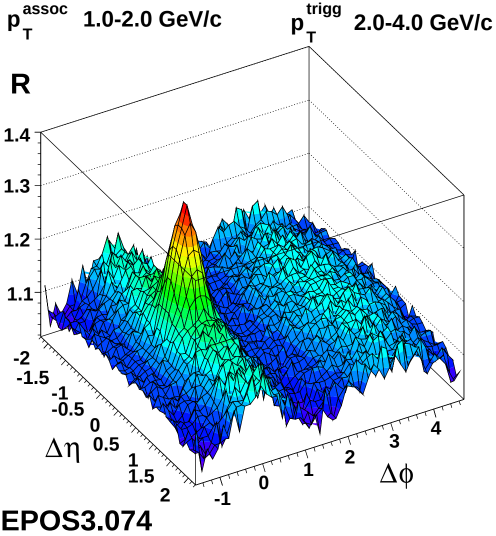
Flow asymmetries: Ridges & flow harmonics

Ridges appear in

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

due to initial azimuthal anisotropies

(longitudinally invariant)



II

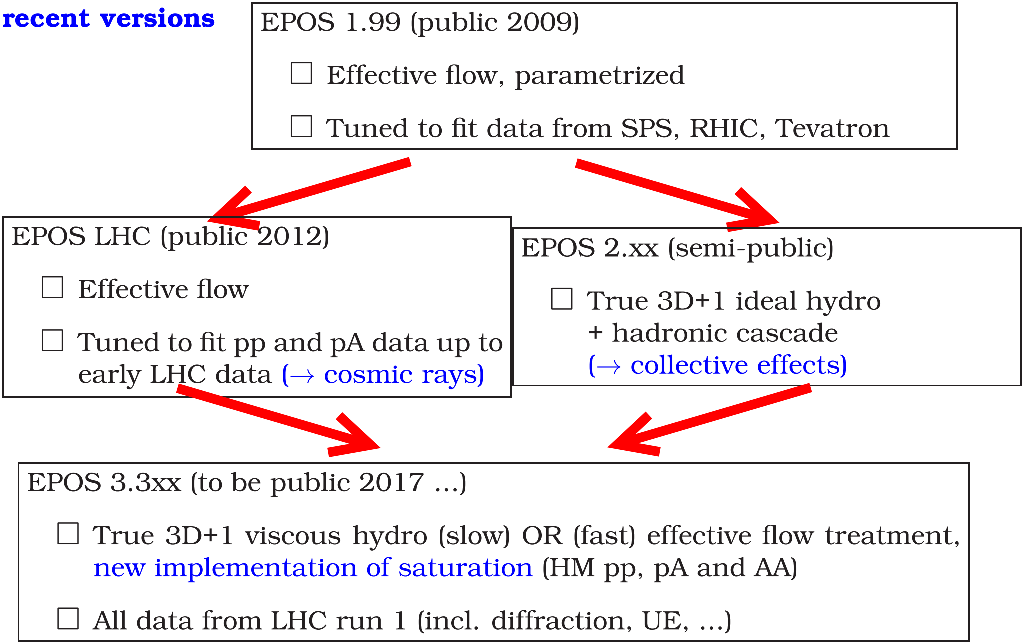
EPOS: General features

Parton based Gribov-Regge theory. By H.J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, K. Werner. hep-ph/0007198. Published in Phys.Rept. 350 (**2001**) 93-289.

Event-by-Event Simulation of the Three-Dimensional **Hydrodynamic Evolution** from Flux Tube Initial Conditions in Ultrarelativistic Heavy Ion Collisions. By K. Werner, Iu. Karpenko, T. Pierog, M. Bleicher, K. Mikhailov. arXiv:1004.0805 [nucl-th]. Published in Phys.Rev. C82 (**2010**) 044904.

Analysing radial **flow features in p-Pb** and p-p collisions at several TeV by studying identified particle production in EPOS3. K. Werner, B. Guiot, Iu. Karpenko, T. Pierog. arXiv:1312.1233 [nucl-th]. Published in Phys.Rev. C89 (2014) 6, 064903.

recent versions



EPOS 1.99 (public 2009)

- ☐ Effective flow, parametrized
- ☐ Tuned to fit data from SPS, RHIC, Tevatron

EPOS LHC (public 2012)

- ☐ Effective flow
- ☐ Tuned to fit pp and pA data up to early LHC data (→ cosmic rays)

EPOS 2.xx (semi-public)

- ☐ True 3D+1 ideal hydro + hadronic cascade (→ collective effects)

EPOS 3.3xx (to be public 2017 ...)

- ☐ True 3D+1 viscous hydro (slow) OR (fast) effective flow treatment, new implementation of saturation (HM pp, pA and AA)
- ☐ All data from LHC run 1 (incl. diffraction, UE, ...)

EPOS3: For ALL reactions (pp,pA,AA) same procedure

☐ **Primary interactions**

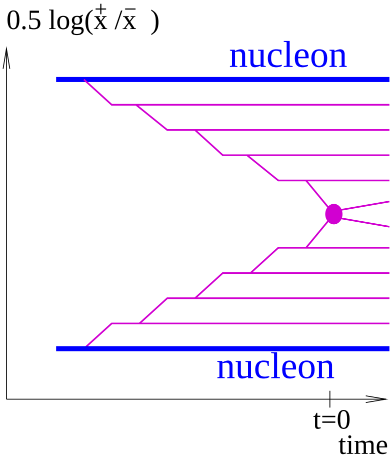
- Gribov-Regge multiple scattering approach
- Elementary object = Pomeron = parton ladder
- Implementing parton saturation

☐ **Secondary interactions**

- Core-corona approach (to separate fluid and jet hadrons)
- Viscous hydrodynamic expansion ($\eta/s = 0.08$)
- Statistical hadronization,
  final state hadronic cascade

Primary interactions

Single scattering
(single Pomeron)

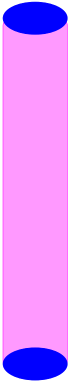


Parton ladder

- ☐ **Parton emission starts long before the actual interaction** (partons are very long-lived due to a large γ).
- ☐ Subsequent parton emissions towards smaller x-values and larger virtualities (from both sides).
- ☐ The final partons from either nucleon interact (“hard” collision).

For $t > 0$, such a parton ladder represents actually a (mainly) **longitudinal color field**,

where the ladder rungs (gluons) represent small transverse momentum components$^{(1)}$.



longi
tudinal
electric
field

= color string

$^{(1)}$ Lund model idea, first e+e-,
then generalized to pp, see also CGC

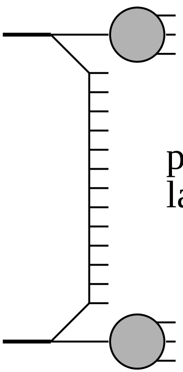
☐ The fields decay via **pair production** (Schwinger mechanism).

Realization: The one-dimensional character of the fields allow to treat their evolution and decay via the **classical string theory** (which does not use much more than some general symmetries):

☐ **Mapping: parton ladders -> kinky strings**

☐ **Classical string evolution + decay via area law**

Complete picture includes **remnants**.

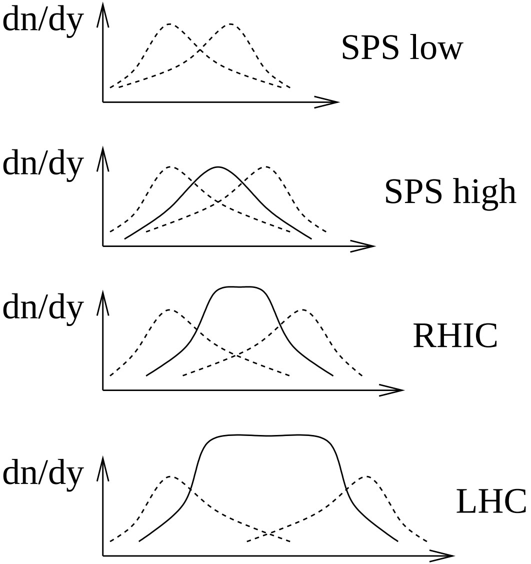


projectile
remnant
excitation

parton
ladder

target
remnant
excitation

The remnants are an important source of particle production.



Inner contributions, from the parton ladder (full lines),

and "outer" contributions, from the remnants (dashed lines),

to the rapidity distribution of hadrons.

(Artists view)

LHC: single scattering not enough

Multiple scattering

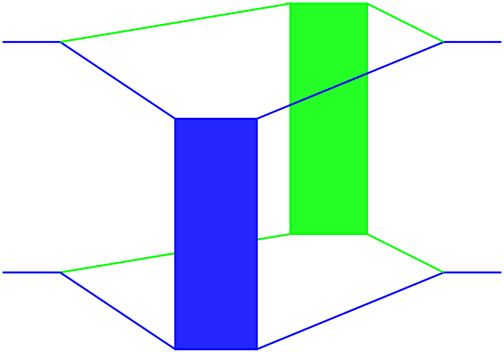
Be T the elastic (pp,pA,AA) scattering T-matrix =>

$$2s\,\sigma_{\mathrm{tot}} = \frac{1}{\mathrm{i}}\mathrm{disc}\,T$$

Basic assumption : Multiple "Pomerons"

$$T = \sum_k \frac{1}{k!}\{T_{\mathrm{Pom}} \times \ldots \times T_{\mathrm{Pom}}\}$$

Example: 2 “Pomerons”



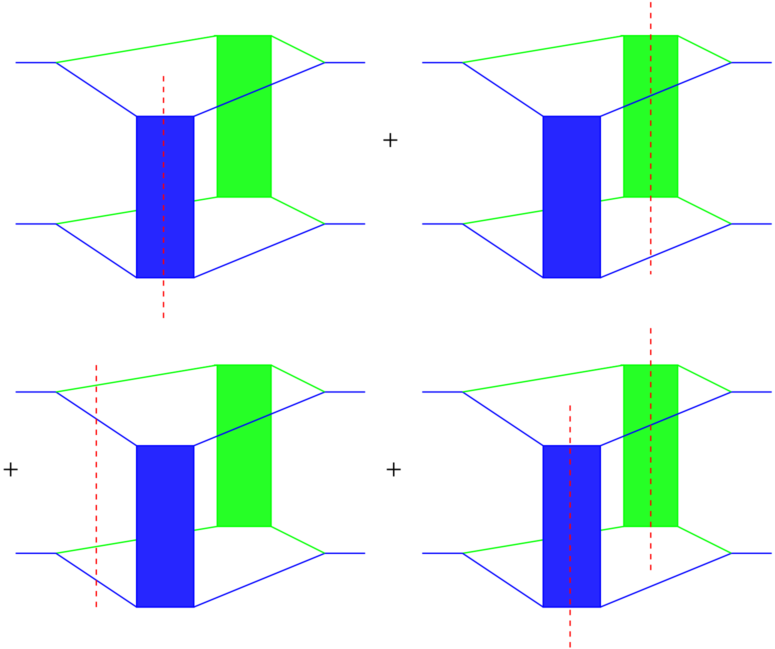
Evaluate

$$\frac{1}{\mathrm{i}}\mathrm{disc}\left\{T_{\mathrm{Pom}} \times \ldots \times T_{\mathrm{Pom}}\right\}$$

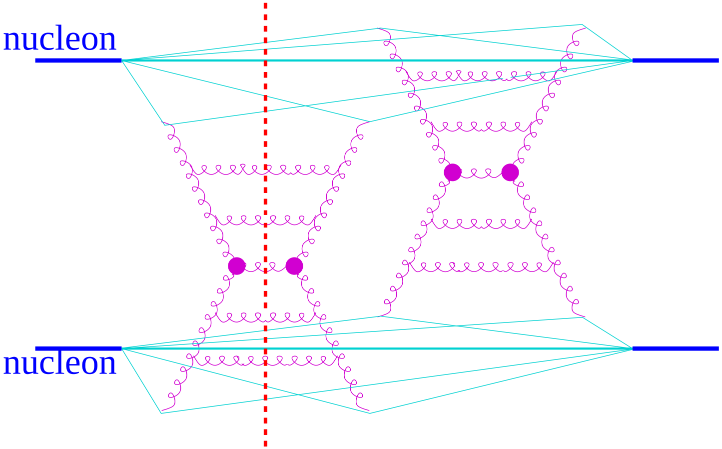
using “cutting rules” :

A “cut” multi-Pomeron diagram
amounts to the sum of all possible cuts

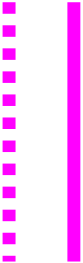
Example of two Pomerons



Using “Pomeron = parton ladder”, we have (first diagram)



Using a simplified notation for “cut” and “uncut” Pomeron



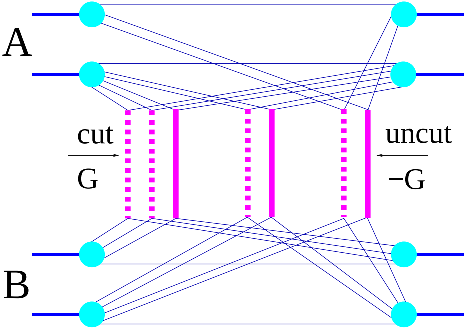
one gets ...

Complete result

(Drescher, Hladik, Ostapchenko, Pierog, and Werner, Phys. Rept. 350, 2001)

For pp, pA, AA:

$$\sigma^{\text{tot}} = \sum_{\text{cut P}} \int \sum_{\text{uncut P}} \int \underbrace{\qquad\qquad}_{d\sigma_{\text{exclusive}}}$$



Dotted lines : Cut Pomerons (parton ladders)

Nonlinear effects considered via saturation scale Q_s

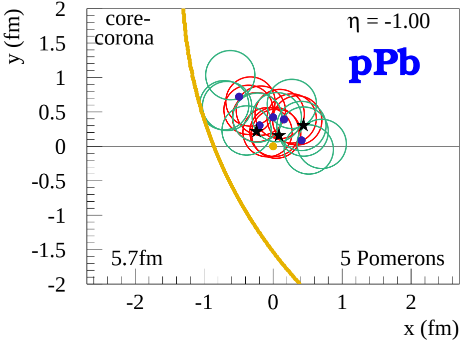
$$
\begin{aligned}
\sigma^{\mathrm{tot}} = \int d^2 b \int \prod_{i=1}^{A} d^2 b_i^A \, dz_i^A \, \rho_A\Big(\sqrt{(b_i^A)^2 + (z_i^A)^2}\Big) \\
\prod_{j=1}^{B} d^2 b_j^B \, dz_j^B \, \rho_B\Big(\sqrt{(b_j^B)^2 + (z_j^B)^2}\Big) \\
\sum_{m_1 l_1} \ldots \sum_{m_{AB} l_{AB}} (1 - \delta_{0 \Sigma m_k}) \int \prod_{k=1}^{AB} \left(\prod_{\mu=1}^{m_k} dx^+_{k,\mu} dx^-_{k,\mu} \prod_{\lambda=1}^{l_k} d\tilde{x}^+_{k,\lambda} d\tilde{x}^-_{k,\lambda} \right) \Bigg\{ \\
\prod_{k=1}^{AB} \left(\frac{1}{m_k!} \frac{1}{l_k!} \prod_{\mu=1}^{m_k} G(x^+_{k,\mu}, x^-_{k,\mu}, s, |\vec{b} + \vec{b}^A_{\pi(k)} - \vec{b}^B_{\tau(k)}|) \right. \\
\left. \prod_{\lambda=1}^{l_k} -G(\tilde{x}^+_{k,\lambda}, \tilde{x}^-_{k,\lambda}, s, |\vec{b} + \vec{b}^A_{\pi(k)} - \vec{b}^B_{\tau(k)}|) \right) \\
\prod_{i=1}^{A} \left(1 - \sum_{\pi(k)=i} x^+_{k,\mu,} - \sum_{\pi(k)=i} \tilde{x}^+_{k,\lambda} \right)^{\alpha} \prod_{j=1}^{B} \left(1 - \sum_{\tau(k)=j} x^-_{k,\mu} - \sum_{\tau(k)=j} \tilde{x}^-_{k,\lambda} \right)^{\alpha} \Bigg\}
\end{aligned}
$$

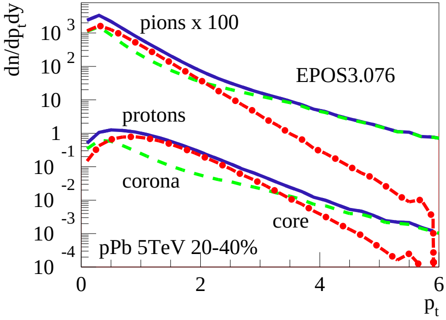
Secondary interactions

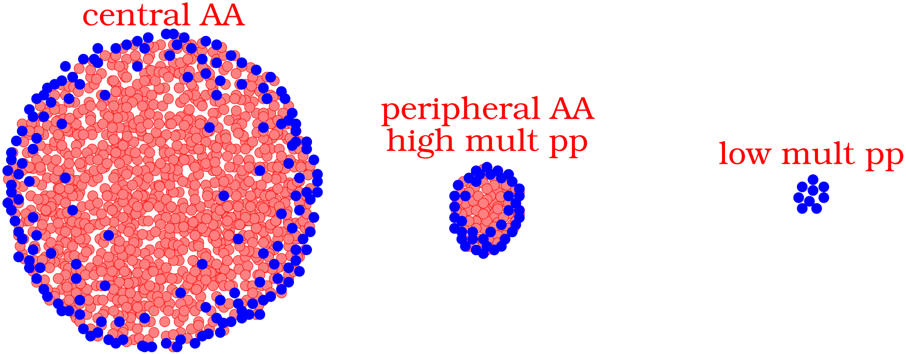
Core-corona procedure (for pp, pA, AA)

(Many) Pomerons => parton ladders => flux tubes (kinky strings)

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







core => hydro => statistical decay ($\mu = 0$)
corona => string decay

Hydro (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 168 MeV, Cooper-Frye $E\frac{dn}{d^3p} = \int d\Sigma_\mu p^\mu f(up)$, equilibrium distributions

Hadronic afterburner (UrQMD)

Marcus Bleicher
Jan Steinheimer

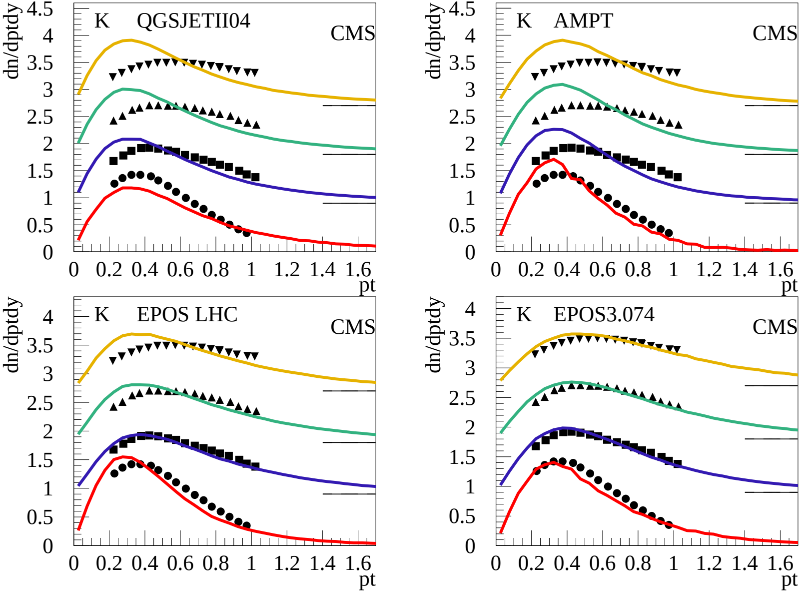
III

Flow in small systems (pPb)

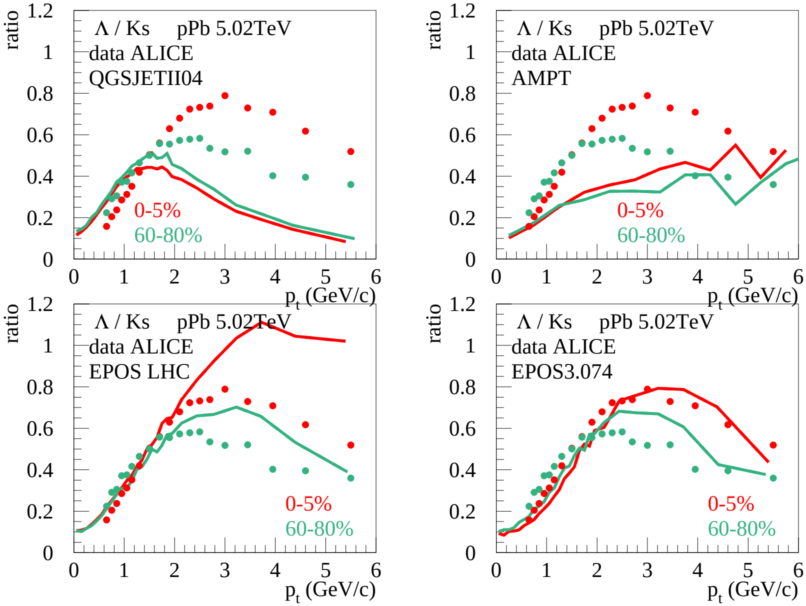
Few selected results : EPOS / other models / data

spectra or ratios, for different centralities, v2

Much more:
Analysing radial **flow features in p-Pb** and p-p collisions at several TeV by studying identified particle production in EPOS3. K. Werner, B. Guiot, Iu. Karpenko, T. Pierog. arXiv:1312.1233 [nucl-th]. Published in Phys.Rev. C89 (2014) 6, 064903.

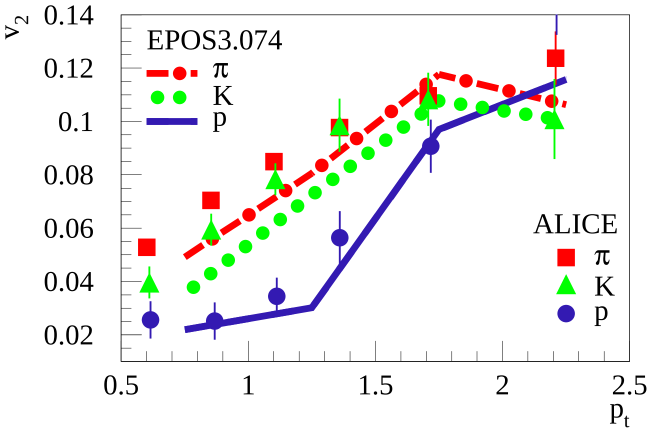


Kaon spectra change with multiplicity CMS, arXiv:1307.3442



Λ/K: Significant multiplicity dependence. Flow helps

v2 for π, K, p clearly differ



mass splitting, due to flow

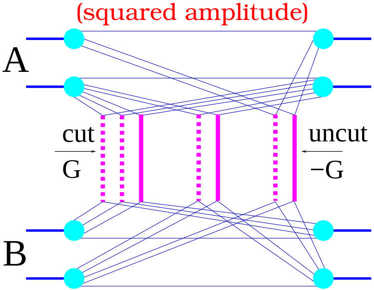
IV

Recent developments

Strangeness and charm enhancement with multiplicity and its relation with core-corona separation and saturation

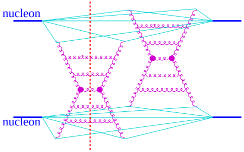
Reminder :

$$\sigma^{\rm tot} = \sum_{\text{cut P}} \int \; \sum_{\text{uncut P}} \int$$



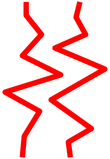
$$\underbrace{\qquad\qquad\qquad\qquad}_{d\sigma_{\rm exclusive}}$$

=



parton ladders

=> kinky strings

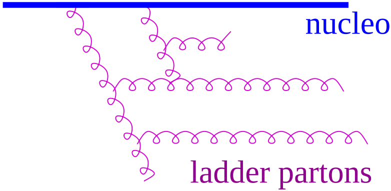


Parton-ladders$^{(1)}$ are perfectly fitted$^{(2)}$ as $\boxed{G = \alpha\,(x^+x^-)^\beta}$.

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

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(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**
(took 10 years to learn how)

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

$$\boxed{\boldsymbol{G_{\mathrm{eff}} = A\ (N_{\mathrm{Pom}})^{B}\ G(Q_s)}}$$

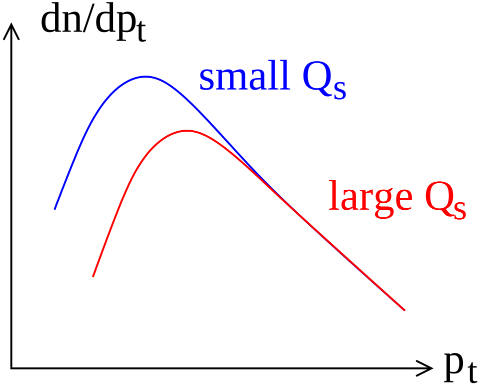
and then considering the parton ladder with the cutoff Q_s
(thus changing the internal structure! => consistent!)

We find

$$Q_s = Q_s(x^+x^-) \propto (x^+x^-)^{0.30}$$

Parton distributions

in pA but also in pp

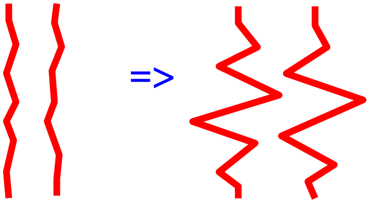


Increasing $\langle dn/d\eta(0)\rangle$ corresponds to increasing $N_{\rm Pom}$

=> Increasing Q_s

=> harder Pomerons

=> harder strings



=> more high pt particles

=> Strong increase of $\langle p_t\rangle$ with $\langle dn/d\eta(0)\rangle$

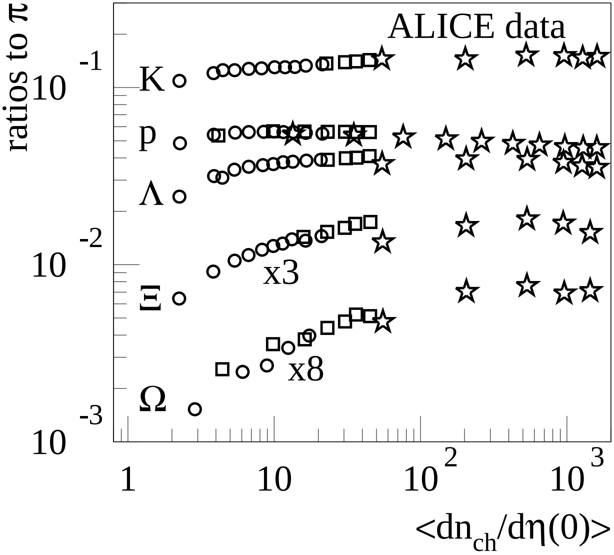
These saturation effects concern the corona !

What about multiplicity dependence of core-corona separation ?

- ☐ **First check particle ratios**
  (core-corona)
- ☐ **Then mean pt vs multiplicity**
  (core-corona+saturation)

We compare simulations (mainly) to ALICE data

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



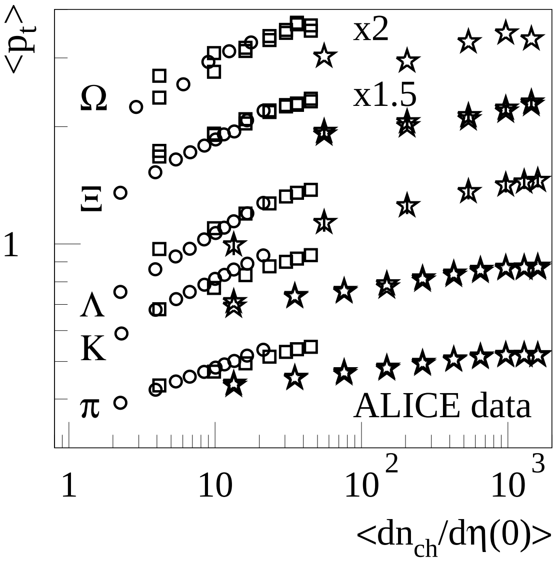
circles = pp (7TeV)

squares = pPb (5TeV)

stars = PbPb (2.76TeV)

Refs: next slide

Mean p_t vs $\left\langle \frac{dn_{\mathrm{ch}}}{d\eta}(0) \right\rangle$



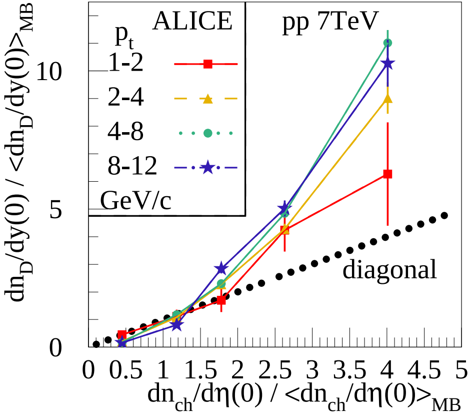
circles = pp (7TeV)

squares = pPb (5TeV)

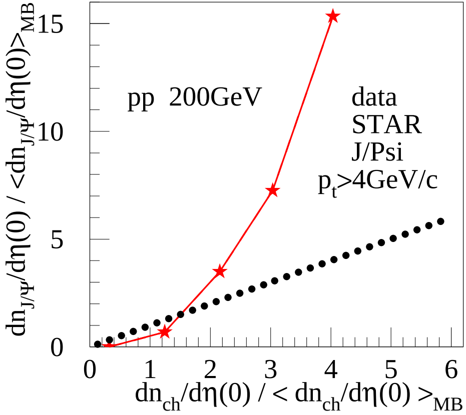
stars = PbPb (2.76TeV)

Data partly collected by A. G. Knospe
Refs:
<dNch/deta> in Pb+Pb: Phys. Rev. Lett. 106 032301 (2011)
pi+-, K+-, and (anti)protons 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+-, (anti)protons, and Lambda 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> in p+p 7 TeV: Eur. Phys. J. C 68 345-354 (2010)
pi+-, K+-, and (anti)protons 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 data points from Rafael Derradi de Souza, SQM2016

D or J/Ψ multiplicity vs $\frac{dn_{\mathrm{ch}}}{d\eta}(0)$ in pp



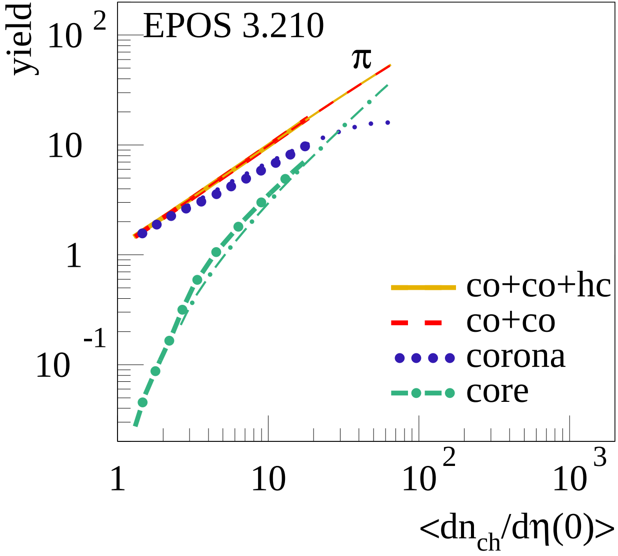
ALICE JHEP 09 (2015) 148,
arXiv:1505.00664v1



STAR, shown at MPI2016

strongly nonlinear increase

Pion yields: core & corona contribution



thick lines

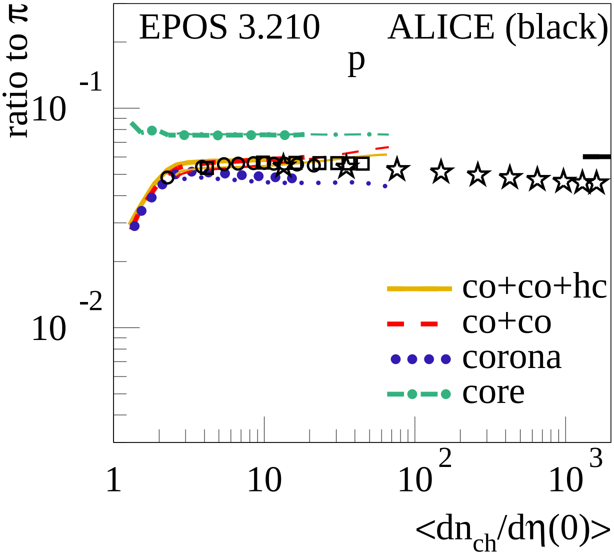
= pp (7TeV)

thin lines
= pPb (5TeV)

hc = hadronic cascade

(UrQMD)

Proton to pion ratio

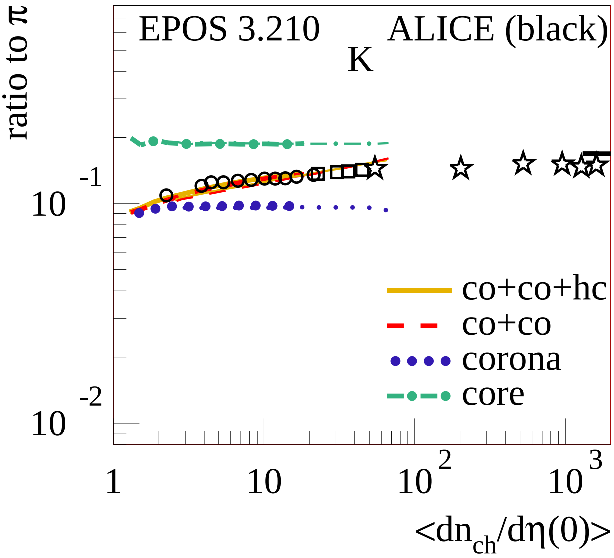


core hadronization:
$T = 164\,\text{MeV},\ \mu_B = 0$

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

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

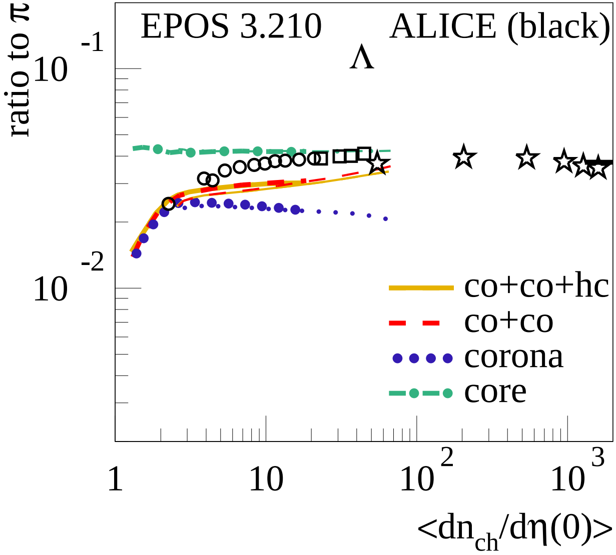
Kaon to pion ratio



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

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

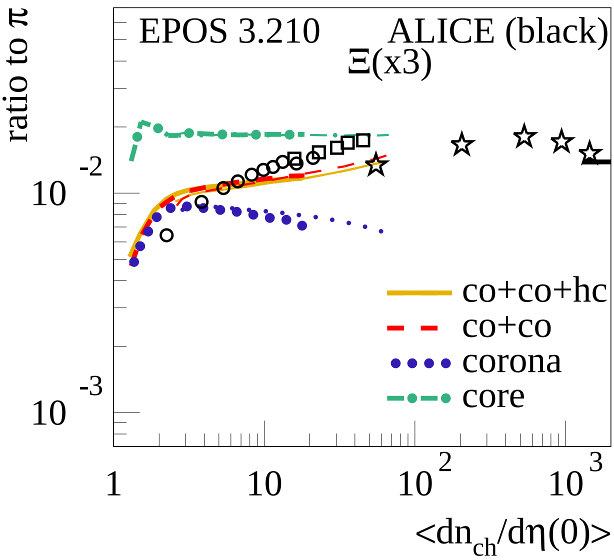
Lambda to pion ratio



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

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

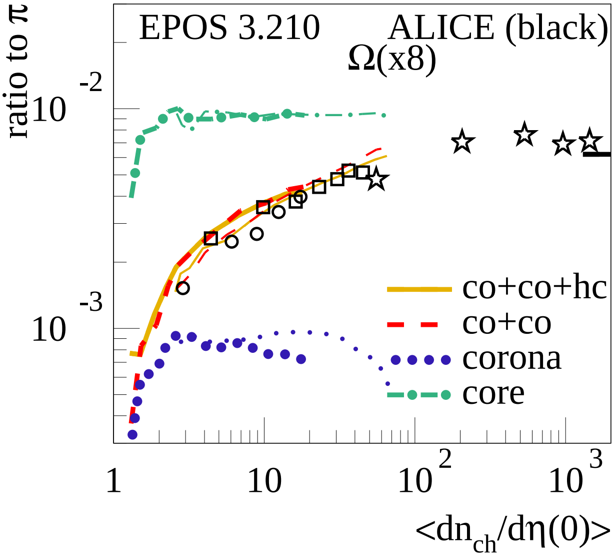
Xi to pion ratio



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

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

Omega to pion ratio



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

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

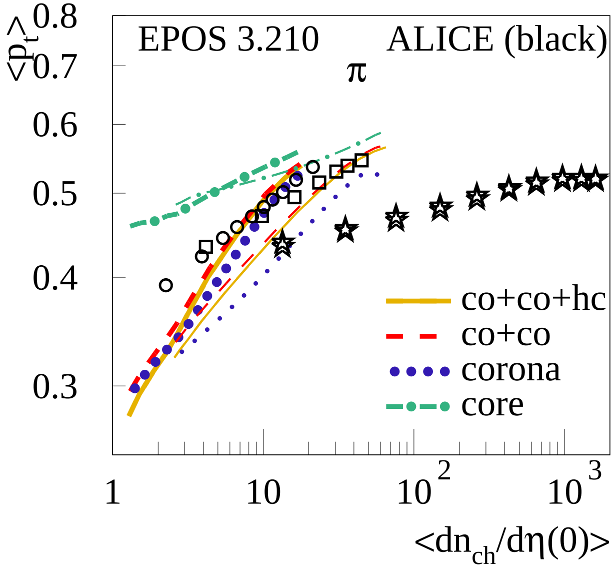
Ratios h/π for $h = p, K, \Lambda, \Xi, \Omega$ vs $\left\langle \frac{dn}{d\eta}(0) \right\rangle$:

Core and corona contributions separately roughly constant

Difference (core - corona) increasing for $p \to K \to \Lambda \to \Xi \to \Omega$

=> increasing slope o
(not enough for Λ, Ξ)

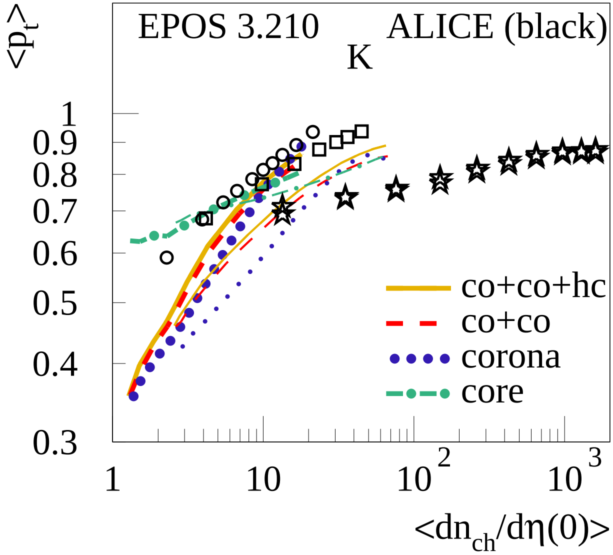
Average p_t of pions



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

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

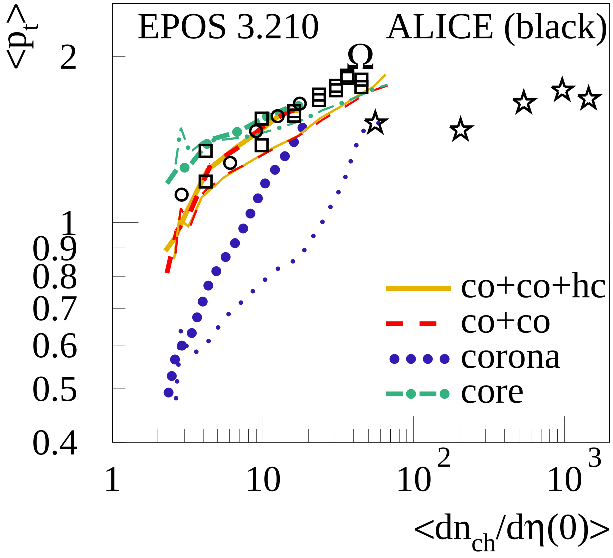
Average p_t of kaons



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

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

Average p_t of Omegas



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

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

Average p_t of $\pi, K, (p, \Lambda, \Xi), \Omega$ vs $\left\langle \frac{dn}{d\eta}(0) \right\rangle$:

Moderate increase of core contribution

(same for pp and pPb, similar to PbPb)

Strong increase of corona contribution

(stronger for pp compared to pPb)

Slope(pp) > slope(pPb) >> slope(PbPb)

The multiplicity dependence of the corona contribution is crucial (=> saturation scale)

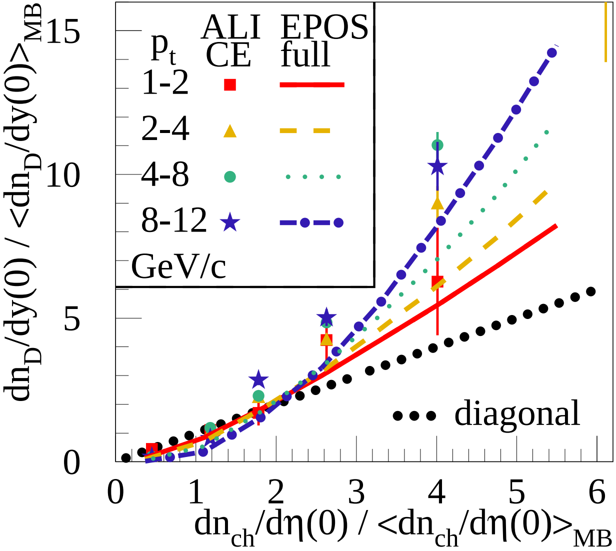
Presently: Corona mean pt too small at small multiplicity

Very closely related to this discussion:

The multiplicity dependence of charm production (D, J/Ψ,...)

The "ultimate tool" to test multiple scattering (and the implementation of parton saturation)

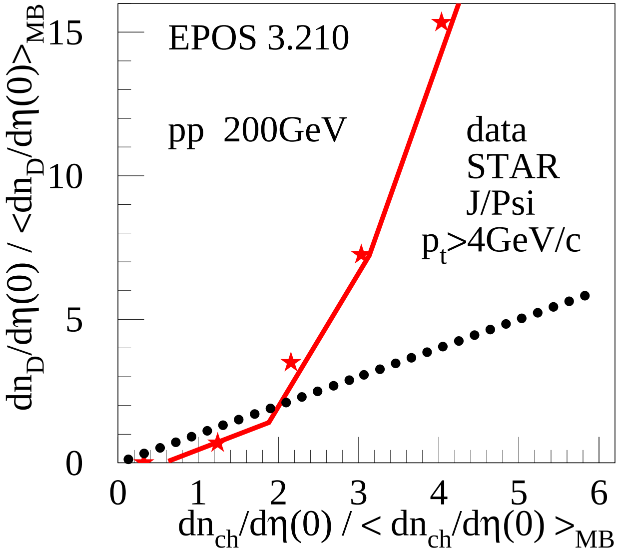
EPOS 3 compared to ALICE data



hadronic cascade
on/off
has no effect

hydro on/off
has small effect

EPOS 3 compared to RHIC data

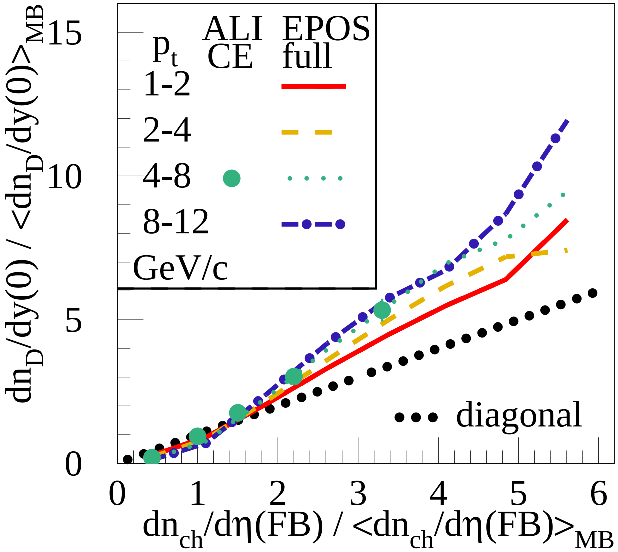


Calculations:
D mesons

Data: J/Ψ

Increase stronger than at LHC

Multiplicity at FB rapidity (LHC)



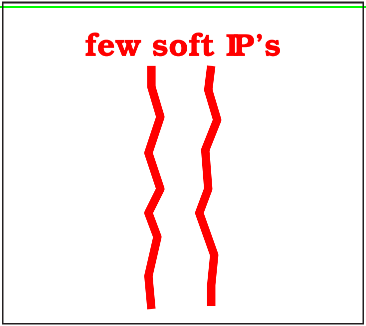
FB = forward/backward rapidity range:

$$2.8 < \eta < 5.1$$
and
$$-3.7 < \eta < -1.7$$

Smaller increase

Low multiplicity (LM)

Small N_{Pom}



few soft $\mathbb{P}$'s

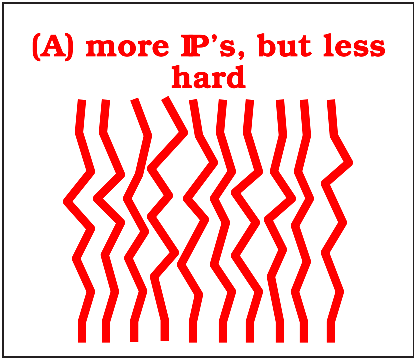
$\mathbb{P}$ = Pomeron

"Hardness" increases with N_{Pom}

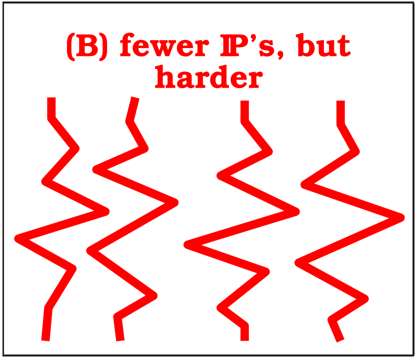
(larger Q_s)

High multiplicity (HM)

many hard $\mathbb{P}$'s on avg



(A) more $\mathbb{P}$'s, but less hard



(B) fewer $\mathbb{P}$'s, but harder

LM → HM:

Pomerons get harder (larger Q_s)

→ favors high pt or large masse production

in particular due to case B (fewer $\mathbb{P}$'s, but harder)
for highest pt bins !

Bigger effect at RHIC due to much narrower N_{Pom} distribution (harder $\mathbb{P}$'s are needed)

Smaller effect for $\frac{dn}{d\eta}(FB)$ as multipl. variable

(case B is replaced by case C: fewer $\mathbb{P}$'s, but more covering the FB rapidity range)

Summary

- ☐ **EPOS: ALL reactions (pp,pA,AA) same procedure**
  - **Primary interactions**
    - Gribov-Regge multiple scattering approach
    - Elementary object = Pomeron = parton ladder
    - Implementing parton saturation
  - **Secondary interactions**
    - Core-corona approach to separate fluid and jet hadrons
    - Viscous hydrodynamic expansion, $\eta/s = 0.08$
    - Statistical hadronization, hadronic cascade
- ☐ **Reproduces many flow-like features in pp, pA**
- ☐ **Recent develpoments: More sophisticated treatment of parton saturation**
  - **Helps understanding strangeness and charm enhancement with multiplicity**