EPOS perspective

(flow, non-flow, from small to big systems)

Klaus Werner

in collaboration with
T. Pierog, Y. Karpenko, B. Guiot, G. Sophys

To understand collectivity in small systems

- **we should understand the evolution of collective phenomena from pp to pA to AA**
- **even better its evolution as a function of multiplicity**
  (the generalization of the concept of centrality in AA)
- **from low multiplicity pp to central AA**

EPOS status and perspective:

Status 2015: 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

2015/2016/2017: "Fusion", to accommodate basic pp and HI features, public version;
Currently: EPOS3.2xx (beta version)

EPOS LHC publication, 2015

EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider T. Pierog, Iu. Karpenko, J.M. Katzy, E. Yatsenko , K. Werner, Phys.Rev. C92 (2015) no.3, 034906

First detailed publication on EPOS 3, 2014

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, Phys.Rev. C89 (2014) 6, 064903.

First detailed publication on EPOS + hydro, 2010

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

Theoretical basis of EPOS, 2001

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

ALICE data references (partly 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+-, 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 pp data points from Rafael Derradi de Souza, SQM2016

Aim: Get a global view, to see where EPOS works and where not, in pp, pA, AA, same version

Many aspects of collectivity ...

First step (discussed here) :

- **Radial flow, mean pt**
- **Hadron chemistry**

  (statistical production or string decay)

Not in this talk: Asymmetries

To get a global overview:

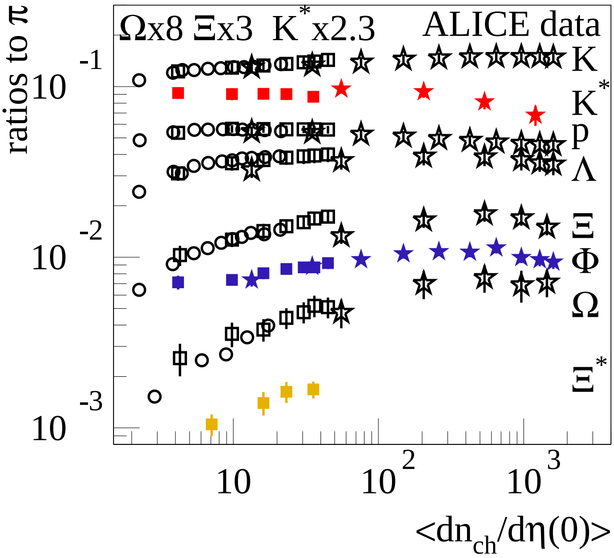
- **Chemistry: Particle ratios vs** $\left\langle \frac{dn_{\mathrm{ch}}}{d\eta}(0) \right\rangle$ **for pp, pPb, PbPb**

- **Flow: Average transverse momenta vs** $\left\langle \frac{dn_{\mathrm{ch}}}{d\eta}(0) \right\rangle$ **for pp, pPb, PbPb**

- **MS scheme: Charmed meson production vs** $\frac{dn_{\mathrm{ch}}}{d\eta}(0)$ **for pp, (pA)**

$\left\langle \frac{dn_{\mathrm{ch}}}{d\eta}(0) \right\rangle$ for multiplicity classes defined via forw multiplicities

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



circles = pp (7TeV)

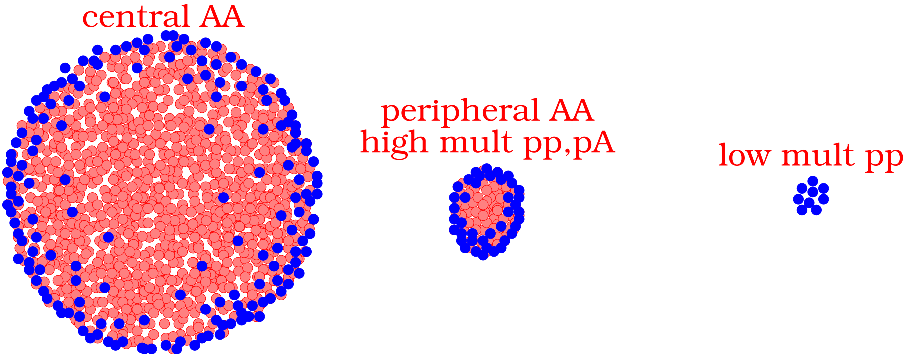
squares = pPb (5TeV)

stars = PbPb (2.76TeV)

Refs: next slide

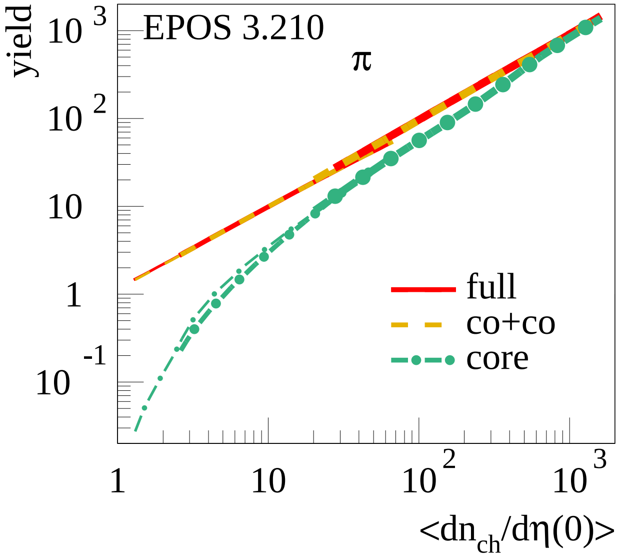
Core-corona picture in EPOS (details later)

Gribov-Regge approach => (Many) kinky strings
=> core/corona separation (based on string segments)



core => hydro => flow + statistical decay
corona => string decay

Pion yields: core / corona contribution



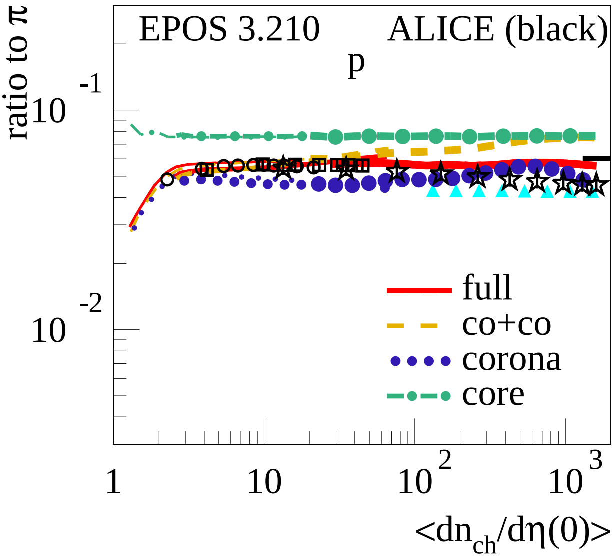
thin lines
= pp (7TeV)

intermediate lines
= pPb (5TeV)

thick lines
= PbPb (2.76TeV)

full = with hadronic cascade (UrQMD)

Proton to pion ratio



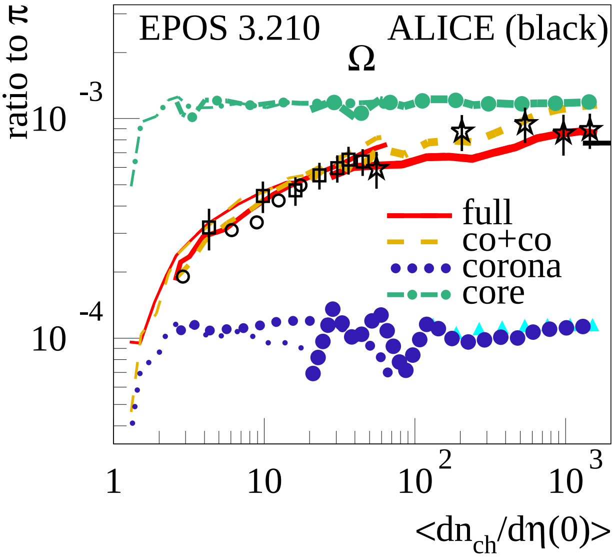
core hadronization:
$T = 164\,\mathrm{MeV},\ \mu_B = 0$

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)

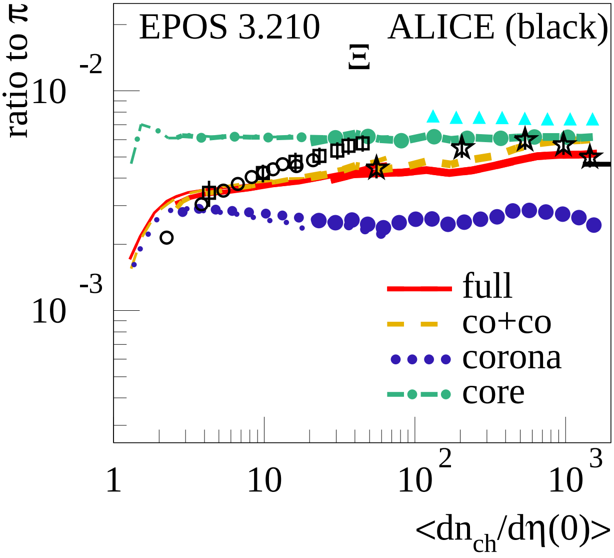
Omega to pion ratio



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

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

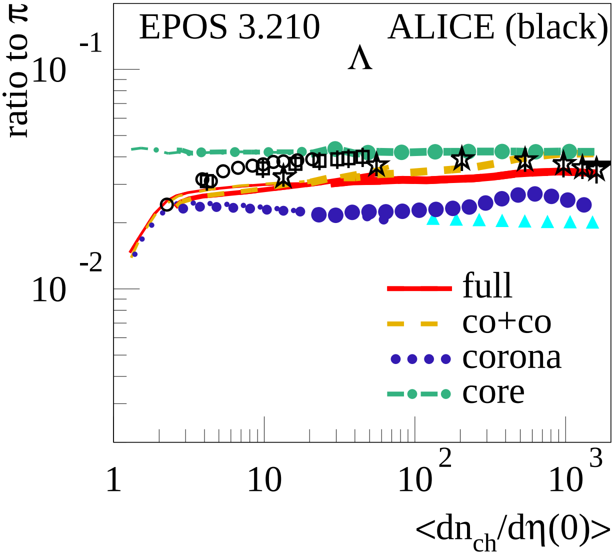
Xi to pion ratio



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

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

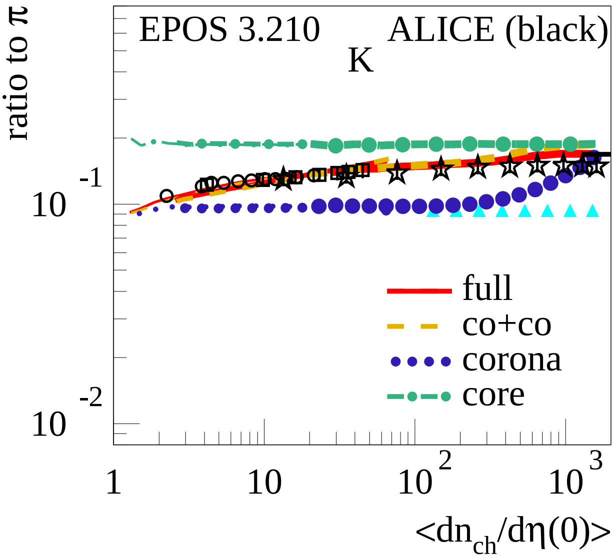
Lambda to pion ratio



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

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

Kaon 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)

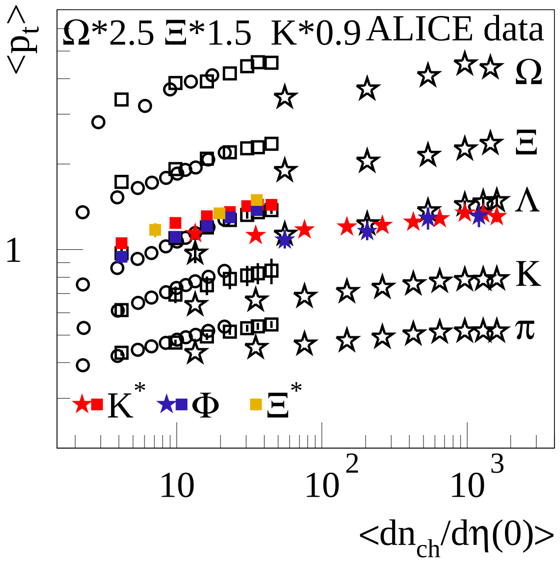
Ratios h/π for $h = p, K, \Lambda, \Xi, \Omega$ vs $\left\langle \frac{dn}{d\eta}(0) \right\rangle$:

Core and corona contributions separately roughly constant

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

=> inceasing slope

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

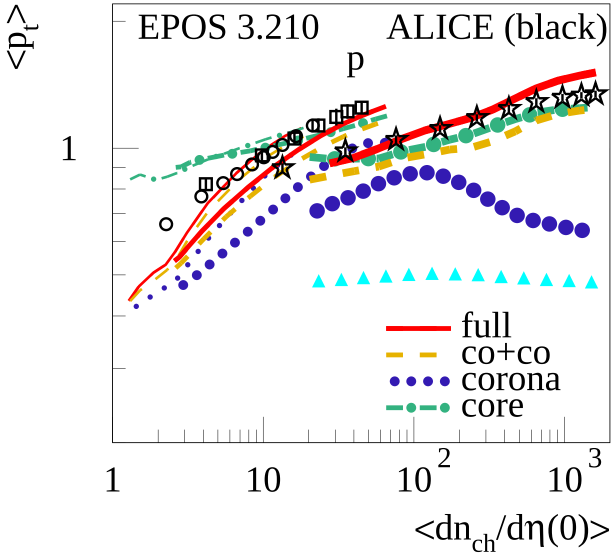


circles = pp (7TeV)

squares = pPb (5TeV)

stars = PbPb (2.76TeV)

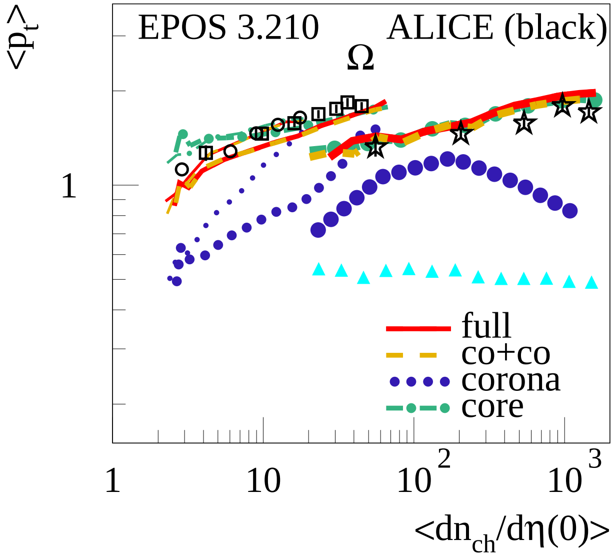
Average p_t of protons



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

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

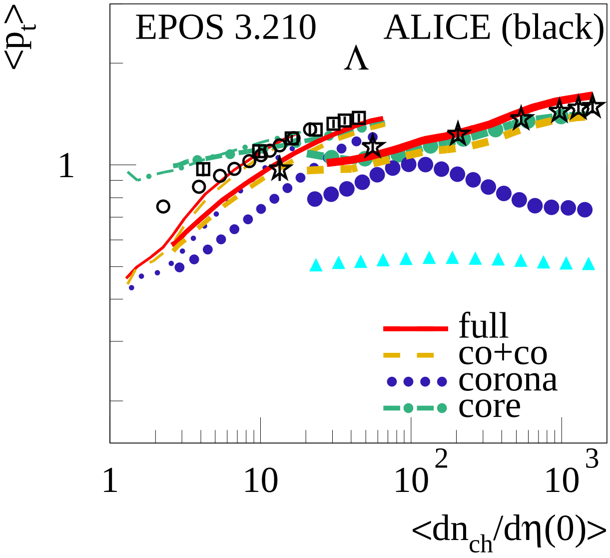
Average p_t of Omegas



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

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

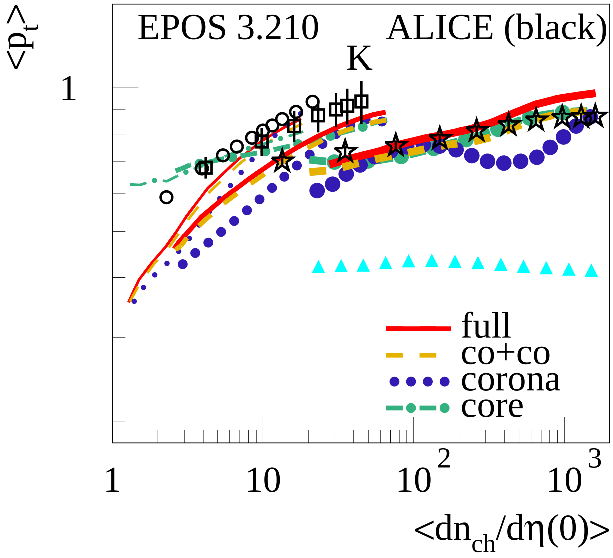
Average p_t of lambdas



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

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

Average p_t of kaons



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

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

Average p_t of $K, p, \Lambda, \Xi, \Omega$ 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 than for pPb, much stronger than for PbPb)

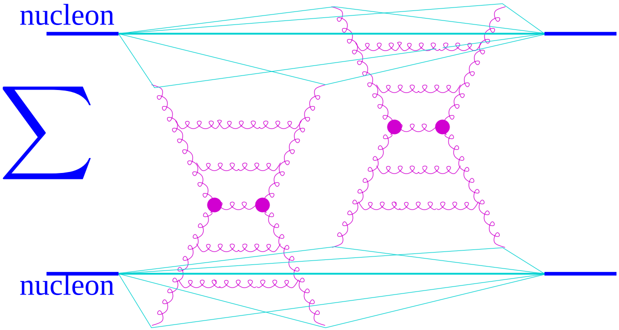
Slope(pp) > slope(pPb) >> slope(PbPb)

K, π : **pp-pPb splitting**

The multiplicity dependence of the corona contribution is crucial

Why such a strong mean pt increase with multiplicity for corona particles?

EPOS: Gribov-Regge approach



S-Matrix based on Pomerons

Pomerons :
Parton ladders (initial and final state radiation, DGLAP)

Cutting rules to get inelastic cross sections.

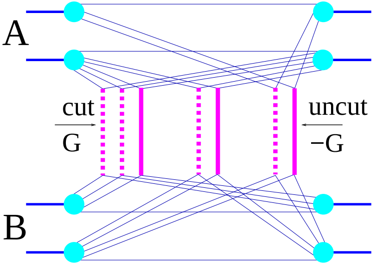
Same principle for AA

Explicite formulas for cross sections

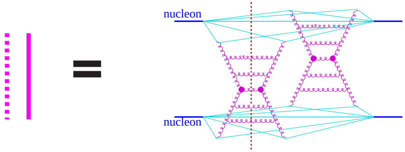
(even partial cross sections)

(squared amplitude)

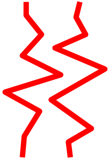
$$\sigma^{\text{tot}} = \sum_{\text{cut P}} \int \sum_{\text{uncut P}} \int$$



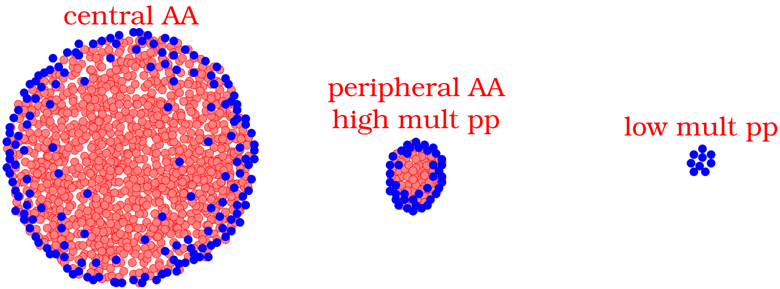
$d\sigma_{\text{exclusive}}$



=> kinky strings



Kinky strings: core-corona separation



core: string segments "melt" => fluid

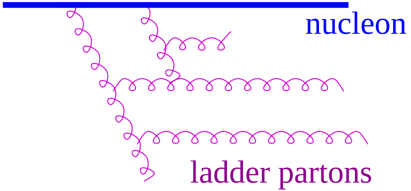
corona: strings segments survive
(from kinky strings associated to parton ladders)

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

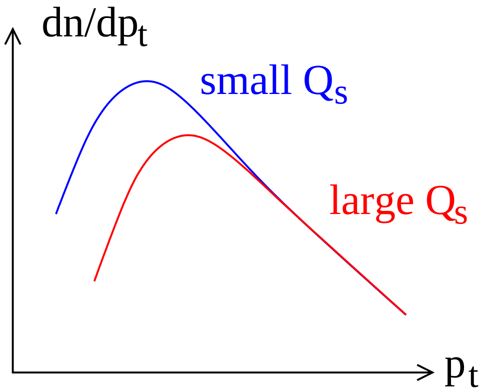
$$\boldsymbol{G_{\text{eff}} = A\ (N_{\text{Pom}})^{B}\ G(Q_s)}$$

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

We find

$$Q_s \propto \sqrt{N_{\text{Pom}}} \times (x^{+}x^{-})^{0.30}$$

Parton distributions

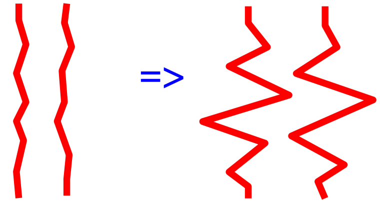


Increasing $\langle dn/d\eta(0)\rangle$ corresponds to increasing N_{Pom}. With $Q_s(N_{\mathrm{Pom}})$

=> Increasing Q_s

=> harder Pomerons

=> harder strings



=> more high pt particles

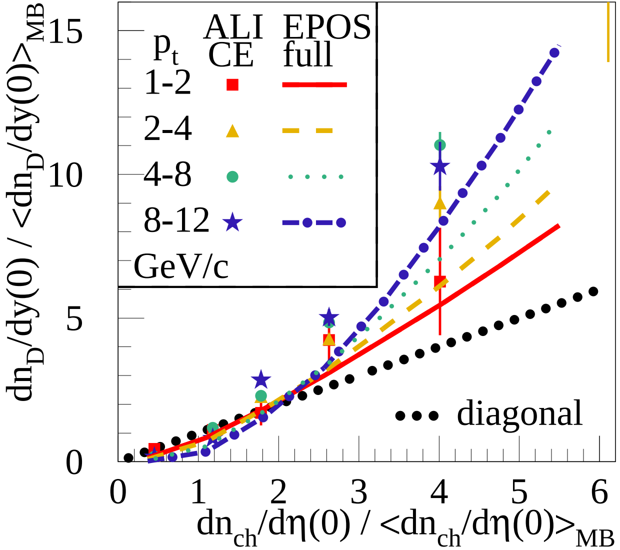
=> Strong increase of $\langle p_t\rangle$ with $\langle dn/d\eta(0)\rangle$

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 Q_S)

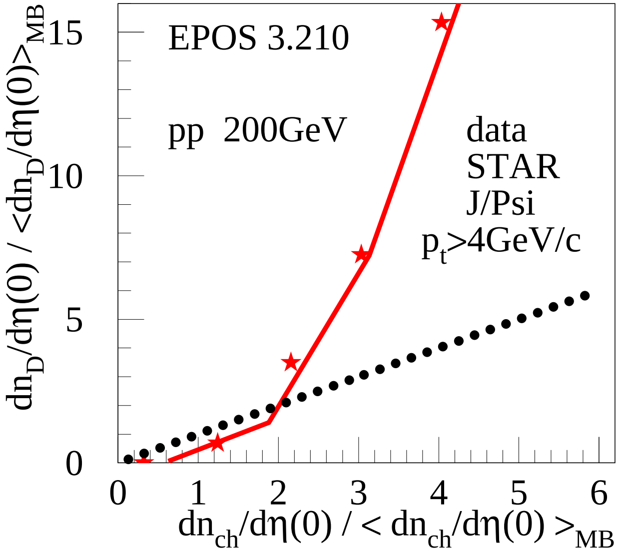
EPOS 3 compared to ALICE data (no free params)



hadronic cascade on/off has no effect

hydro on/off has small effect

EPOS 3 compared to RHIC data

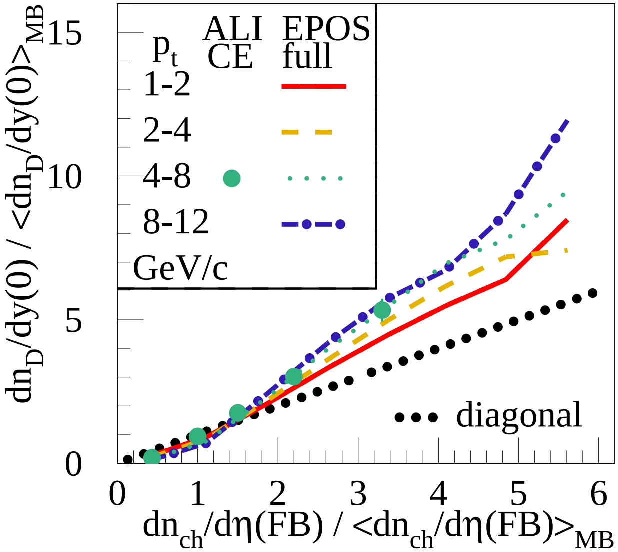


Calculations:
D mesons

Data: J/Ψ

Increase stronger than at LHC

Multiplicity at FB rapidity (LHC)



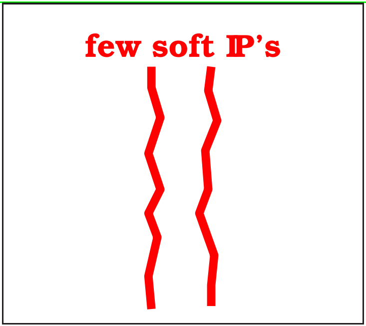
FB = forward/backward rapidity range:

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

Smaller increase

Low multi-plicity (LM)

Small N_{Pom}



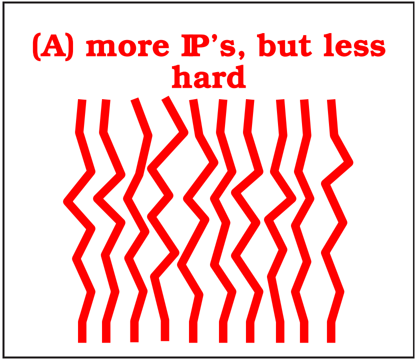
IP = Pomeron

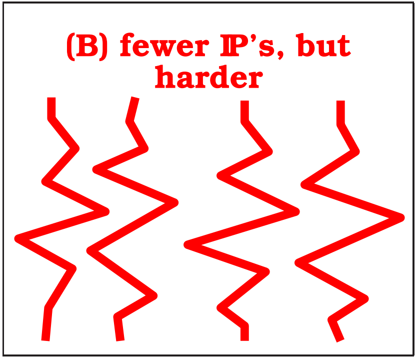
"Hardness" increases with N_{Pom}

(larger Q_s)

High multi-plicity (HM)

many hard IP's on avg





LM $\rightarrow$ HM:

Pomerons get harder (larger Q_s)

$\rightarrow$ favors high pt or large mass production

in particular due to case B (fewer IP's, but harder)
for highest pt bins !

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

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

(case B is replaced by case C: fewer IP's, but more covering the FB rapidity range)

Summary

- **To understand "thermalization and flow" in small systems, we have to understand the "non-flow" part ("corona")**
- **The latter one dominates low multiplicity pp, but its relative weight decreases continuously with multiplicity (but is never zero)**
- **Investigating the multiplicity dependence of particle ratios and mean pt in pp, pA, AA: EPOS's core-corona picture describes the trend**
- **Strong increase of corona pt due to the N_{Pom} dependence of the saturation scale ...**
- **which explains also the strong lonlinearity of the D (J\Psi) multiplicity vs charged one**
- **Crucial control parameter:**

  N_{Pom} **and not** N_{part} (always 2 in pp) **!!**

Core => 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