System size dependence of particle production in EPOS

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in collaboration with
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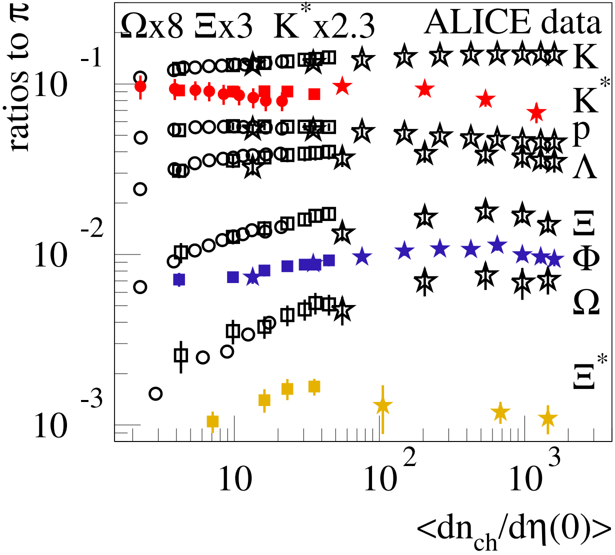
Last WW :

- ☐ **Multiplicity dependence of yields based on core-corona**
- ☐ **Core = Particle production via Cooper-Frye**

Question: Does canonical suppression play a role?

This talk :
First attemps (very preliminary) to answer...

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



circles = pp (7TeV)

squares = pPb (5TeV)

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

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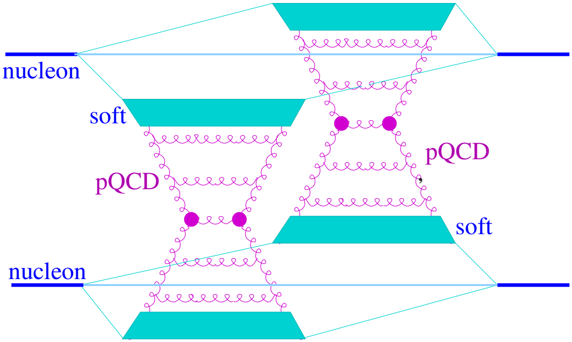
EPOS: Gribov-Regge approach



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

Elastic scattering S-Matrix based on Pomerons

Pomerons : Parton ladders (DGLAP), soft pre-evolution

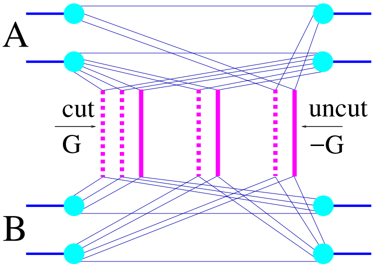
Cutting rules to get inelastic cross sections

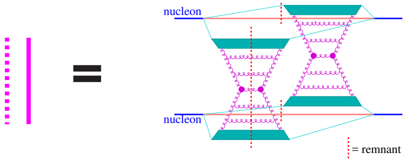
Same principle for pp, pA, AA

Explicite formulas for cross sections (Phys.Rept. 350 (2001) 93-289)

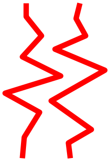
(even partial cross sections)

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





=> kinky strings

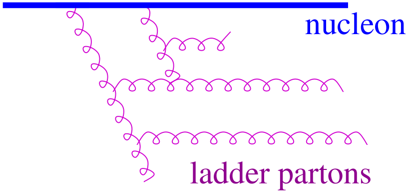


Non-linear effects (Major improvements the past few years)

Computing the expressions G for single Pomerons:
A cutoff Q_0 is needed (for the DGLAP integrals).

Taking Q_0 constant leads to a power law increase of cross sections vs energy (=> wrong)

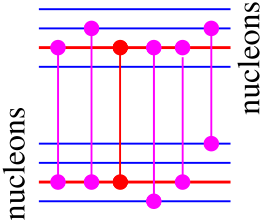
because non-linear effects like gluon fusion are not taken into account



Solution: Instead of a constant Q_0, use a dynamical saturation scale for each Pomeron:

$$Q_s = Q_s(N_{\mathbb{P}}, s_{\mathbb{P}})$$

with



$N_{\mathbb{P}}$ **= number of Pomerons connected to a given Pomeron (whose probability distribution depends on Q_s)**

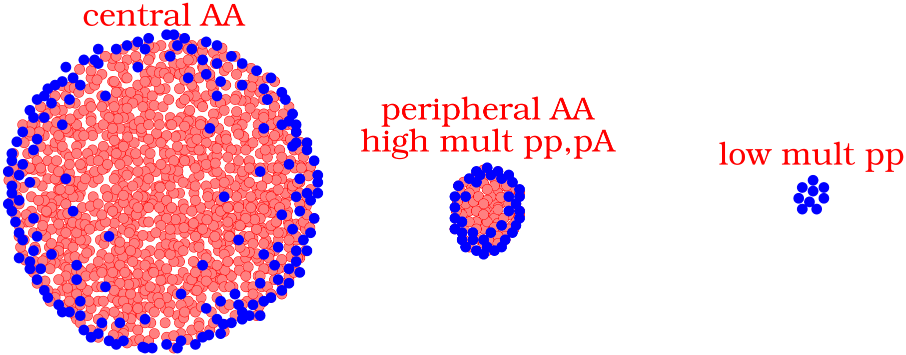
$s_{\mathbb{P}}$ **= energy of considered Pomeron**

$Q_s(N_{\mathbb{P}}, s_{\mathbb{P}})$ **from fitting elementary quantities**

Core-corona picture in EPOS

Phys.Rev.Lett. 98 (2007) 152301, Phys.Rev. C89 (2014) 6, 064903

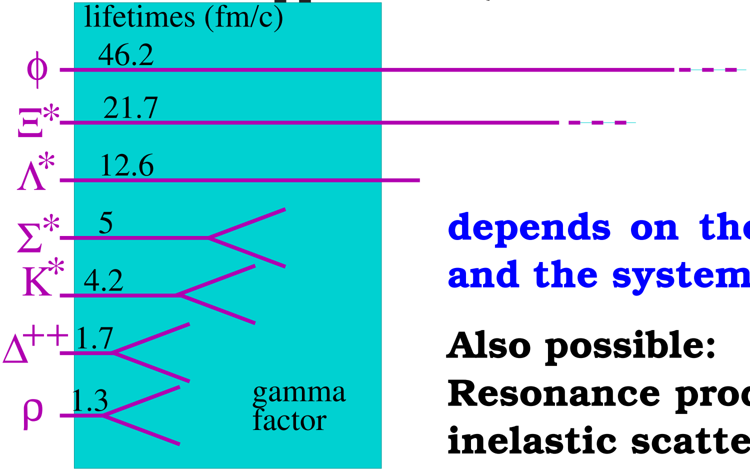
Gribov-Regge approach => (Many) kinky strings
=> core/corona separation (based on string segments)



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

Final state hadronic cascade:

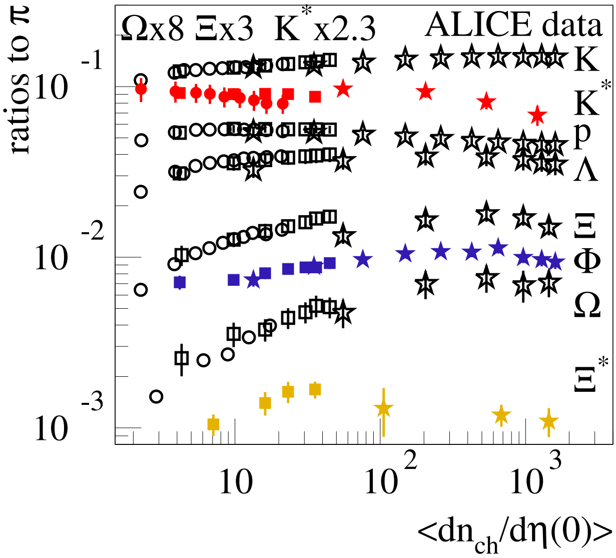
Resonance suppression (in-medium decay)



depends on the lifetime and the system size

**Also possible:
Resonance production, inelastic scattering**

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



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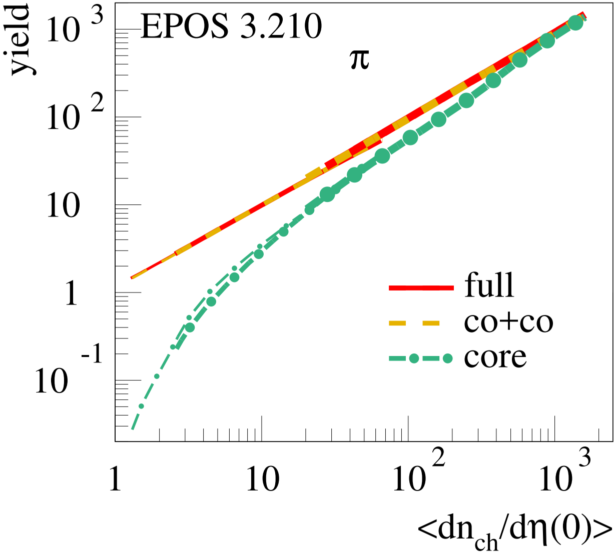
Pion yields: core & corona contribution



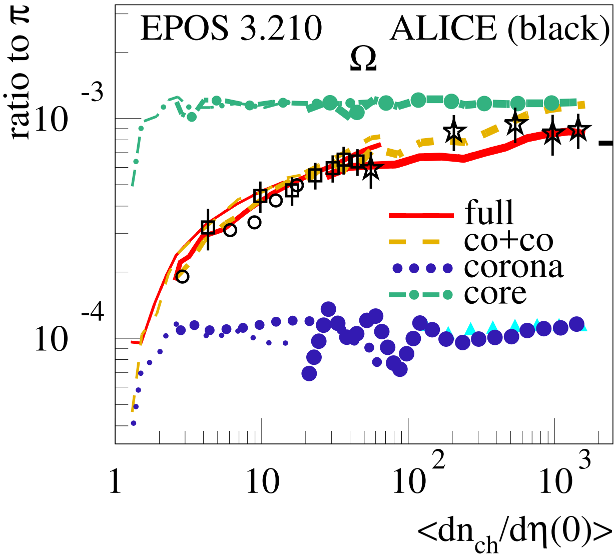
thin lines
= pp (7TeV)

intermediate lines
= pPb (5TeV)

thick lines
= PbPb (2.76TeV)

full = with hadronic cascade (UrQMD)

Omega to pion ratio



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What about canonical suppression?

… and energy conservation ?

in pp, up to 50% violated
(using CF)

Microcanonical hadronization in EPOS

(very preliminary)

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

$$x^0 = \tau \cosh \eta, \;\; x^1 = r \cos \varphi,$$
$$x^2 = r \sin \varphi, \;\; x^3 = \tau \sinh \eta,$$

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

Hypersurface element:

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

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

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

(with $A \in \{C, B, S\}$, corresponding electric charge, baryon number and strangeness)

Momentum and charges are conserved :

$$\begin{aligned} \int_{\Sigma_{\mathrm{FO}}} dP^{\mu} &= P^{\mu}_{\mathrm{ini}}, \\ \int_{\Sigma_{\mathrm{FO}}} dQ_A &= Q_{A\,\mathrm{ini}}. \end{aligned}$$

Invariant mass

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

four-velocity

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

volume element

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

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

Sub-hyper-surfaces: $\Sigma_{\mathbf{FO}} = \cup\Sigma^{n}_{\mathbf{FO}}$,

$$\begin{aligned} \boldsymbol{M_n} &= \int_{\Sigma^{n}_{\mathbf{FO}}} \boldsymbol{dM}, \\ \boldsymbol{V_n} &= \int_{\Sigma^{n}_{\mathbf{FO}}} \boldsymbol{dV}, \\ \boldsymbol{Q_{A\,n}} &= \int_{\Sigma^{n}_{\mathbf{FO}}} \boldsymbol{dQ_{A}}. \end{aligned}$$

defines “effective objects” O_n with masses M_n and charges $Q_{A\,n}$ ...

…which we **decay microcanonically**:

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

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

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

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

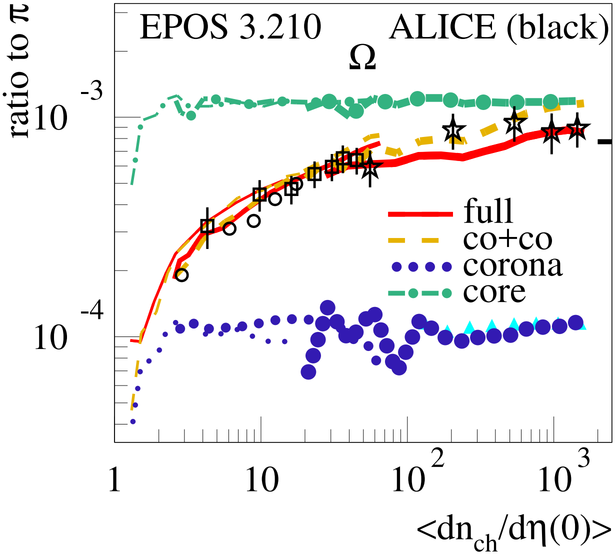
Work in progress (will come soon)

- ☐ 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 (CF)



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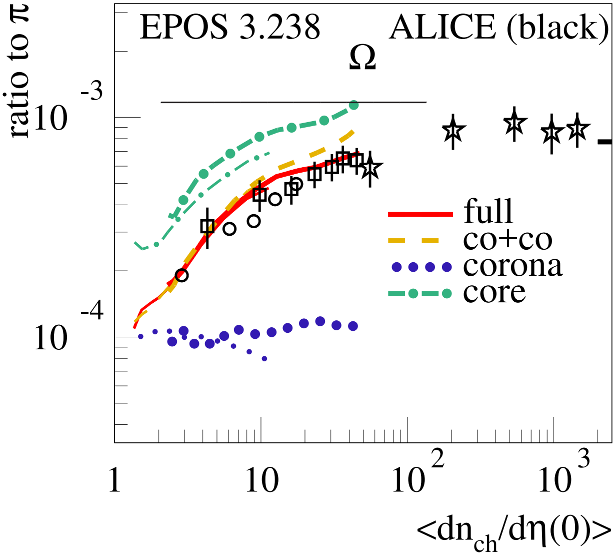
Omega to pion ratio (microcanonical)



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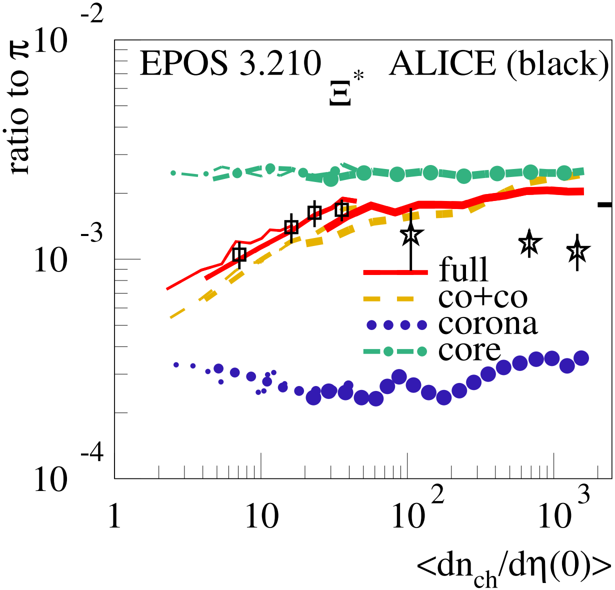
Ξ^* to pion ratio (CF)



long-lived

$\tau \approx 21.7\,\mathrm{fm/c}$

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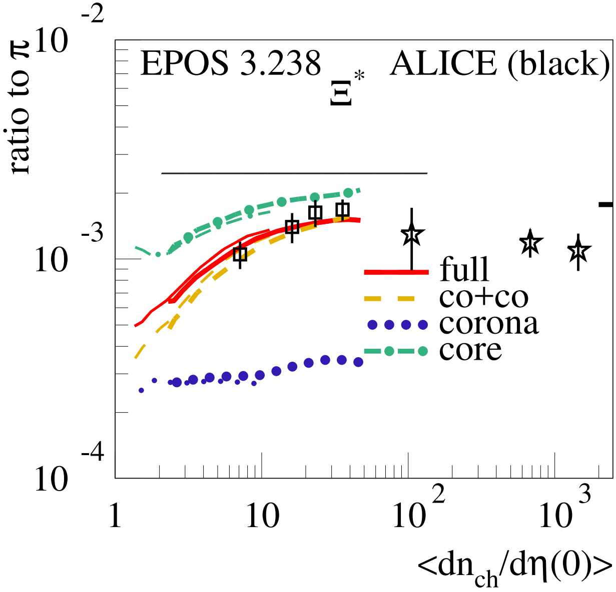
Ξ* to pion ratio (microcanonical)



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Summary

☐ **Very preliminary results concerning microcanonical particle production in EPOS show:**

- **Microcanonical suppression of Ω and (somewhat less) of Ξ^* in pp and pPb**
- **But core-corona still essential**

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