Resonance production

(from small to big systems)

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in collaboration with
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Resonance production: more than hadronic stage effects!

(to be discussed in this talk)

Aim:

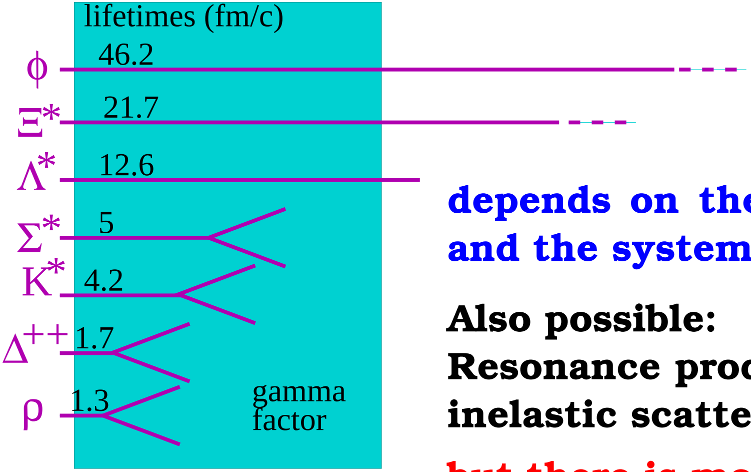
☐ **understand resonance (hadron) production from pp to pA to AA**

☐ **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**

Resonance suppression

in the hadronic stage (in-medium decay)



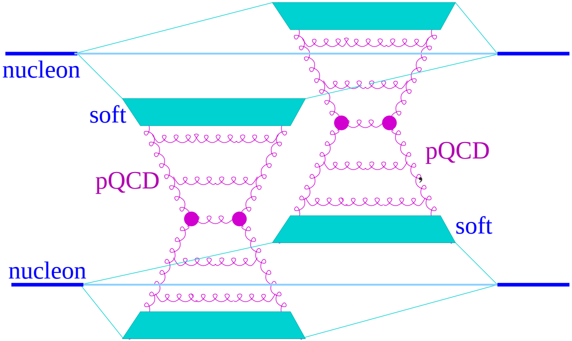
depends on the lifetime and the system size

Also possible:
Resonance production, inelastic scattering

but there is more

Using EPOS3.2 as analysis tool

EPOS: Gribov-Regge approach



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

Elastic scattering S-Matrix based on Pomerons

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

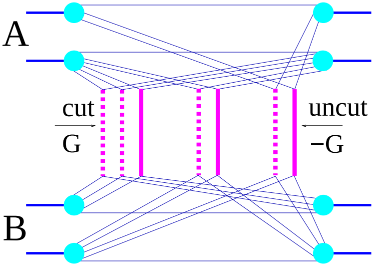
Cutting rules to get inelastic cross sections

Same principle for pp, pA, AA

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

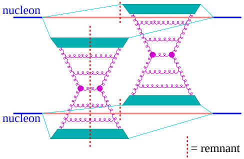
(even partial cross sections)

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

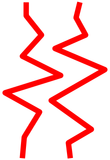


$$d\sigma_{\text{exclusive}}$$

=



=> kinky strings

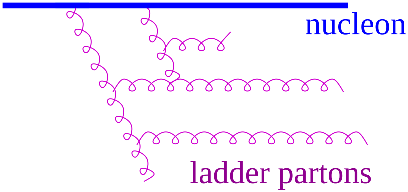


Non-linear effects

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



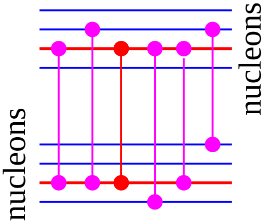
Solution: Instead of a constant Q_0, use a dynamical saturation scale for each Pomeron:

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

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**



We get $Q_s(N_{\mathbb{P}}, s_{\mathbb{P}})$ from fitting

- □ the energy dependence of elementary quantities (σ_{tot}, σ_{el}, σ_{SD}, $dn^{\mathrm{ch}}/d\eta(0)$) for pp
- □ the multiplicity dependence of dn^{π}/dp_t at large p_t for pp at 7 TeV

We find

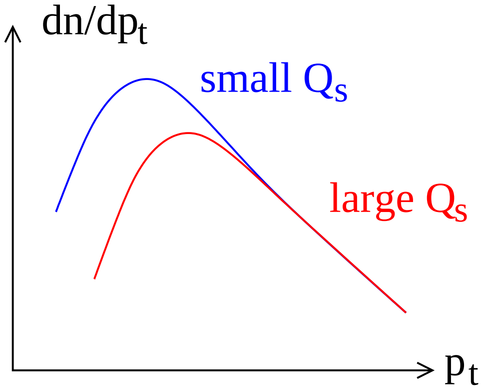
$$\boldsymbol{Q_s \propto \sqrt{N_{\mathbb{P}}} \times (s_{\mathbb{P}})^{0.30}}$$

CGC for AA:

$$Q_s \propto N_{\mathrm{part}} \times (1/x)^{0.30}$$

McLerran, Venugopalan, Phys. Rev. D 49, 2233 (1994)

Parton distributions



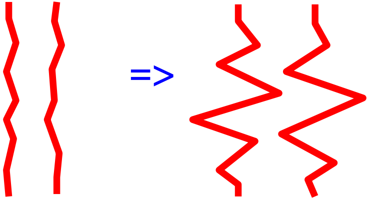
Increasing multiplicity

=> increasing N_{Pom}

=> Increasing Q_s

=> harder Pomerons

=> harder strings



=> more high pt particles

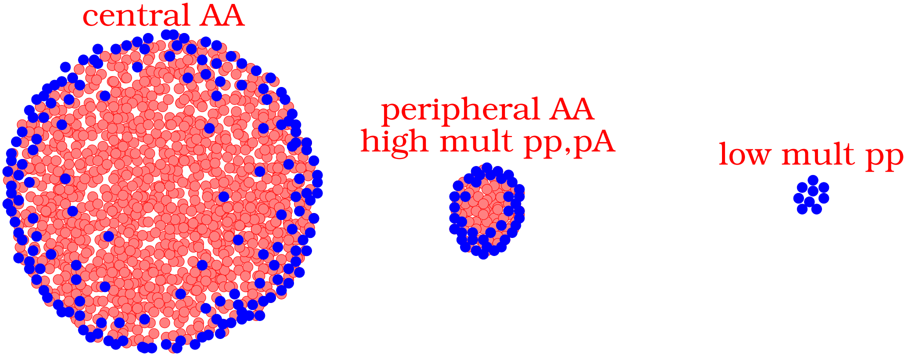
=> Strong increase of $\langle p_t \rangle$ with multiplicity

and gives a strong nonlinear increase of D or J/Psi multiplicity vs charged multiplicity in pp and pPb ...

Core-corona picture in EPOS

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

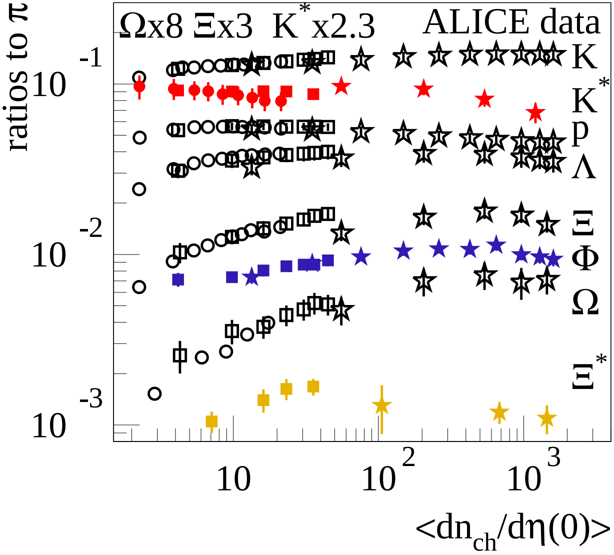
Gribov-Regge approach => (Many) kinky strings
=> core/corona separation (based on string segments)



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

Resonance and stable hadron production

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



circles = pp (7TeV)

squares = pPb (5TeV)

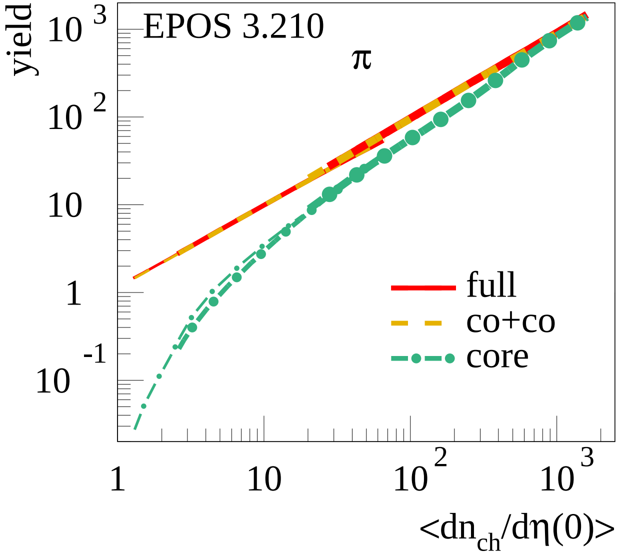
stars = PbPb (2.76TeV)

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

Pion yields: core & corona contribution



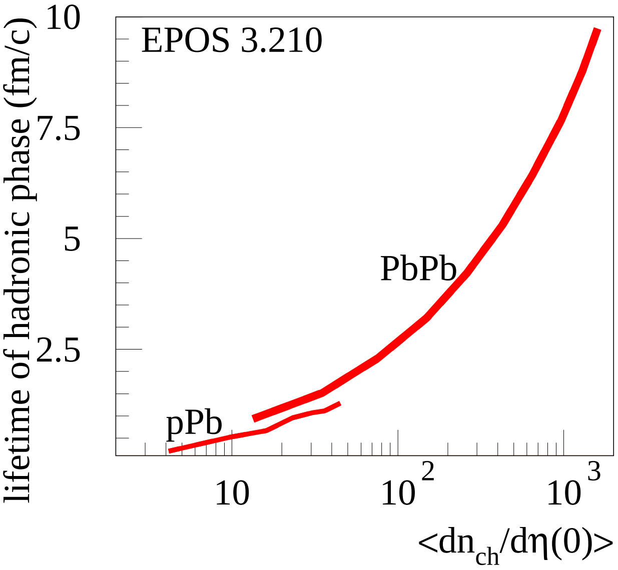
thin lines
= pp (7TeV)

intermediate lines
= pPb (5TeV)

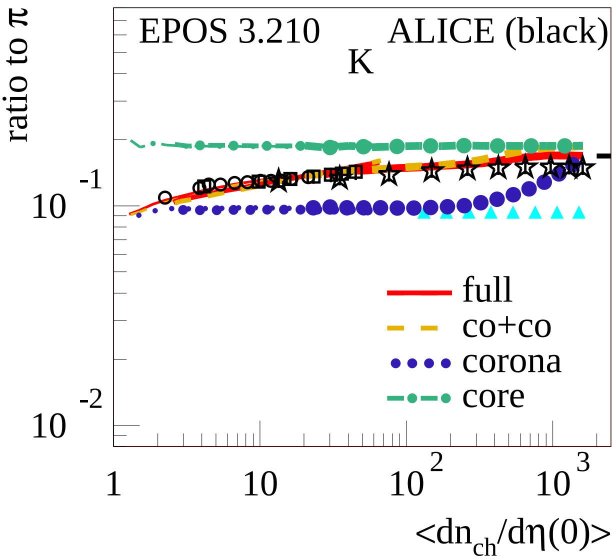
thick lines
= PbPb (2.76TeV)

full = with hadronic cascade (UrQMD)

Lifetime of hadronic phase



Kaon to pion ratio



core hadronization:

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

statistical model fit

(horizontal black line)

A. Andronic et al.,

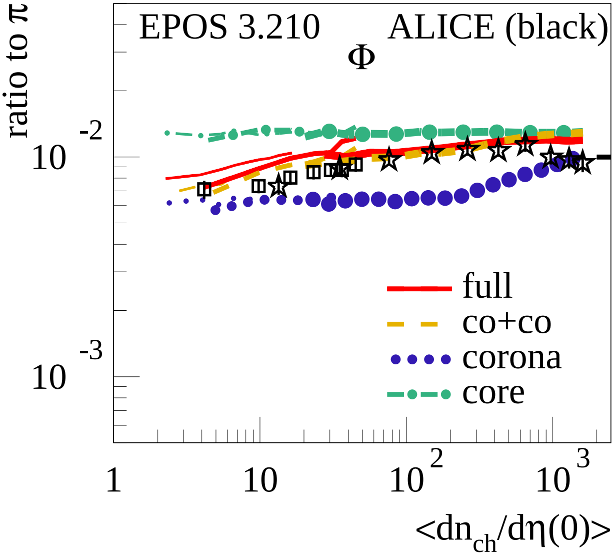
arXiv:1611.01347

$T = 156.5\,\mathrm{MeV}, \mu_B = 0.7\,\mathrm{MeV}$

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

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

Phi to pion ratio



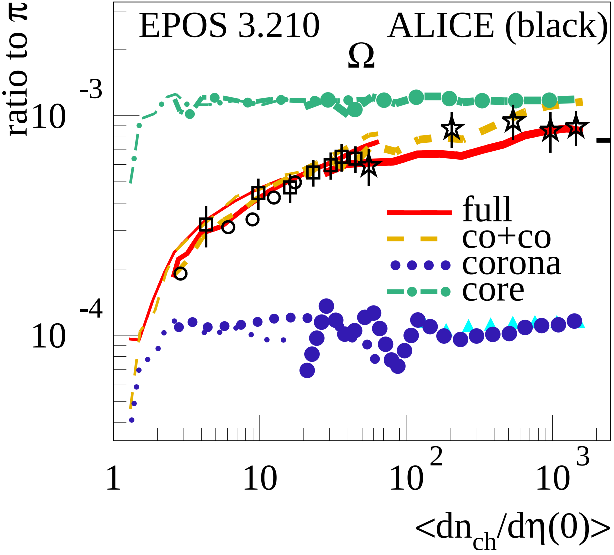
long-lived

$\tau \approx 46.2\,\mathrm{fm/c}$

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

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

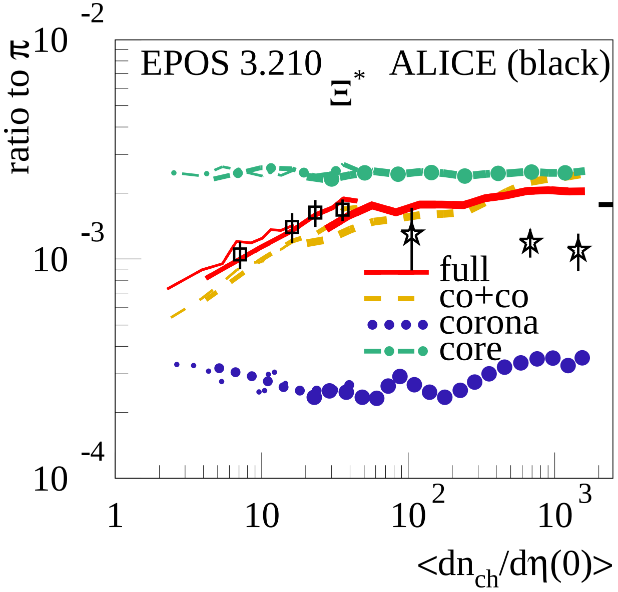
Omega to pion ratio



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

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

Ξ^* to pion ratio



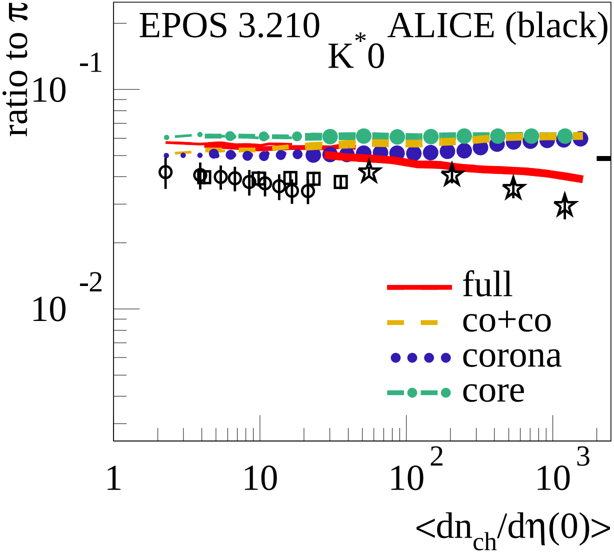
long-lived

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

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

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

K^* to pion ratio



core ≈ corona

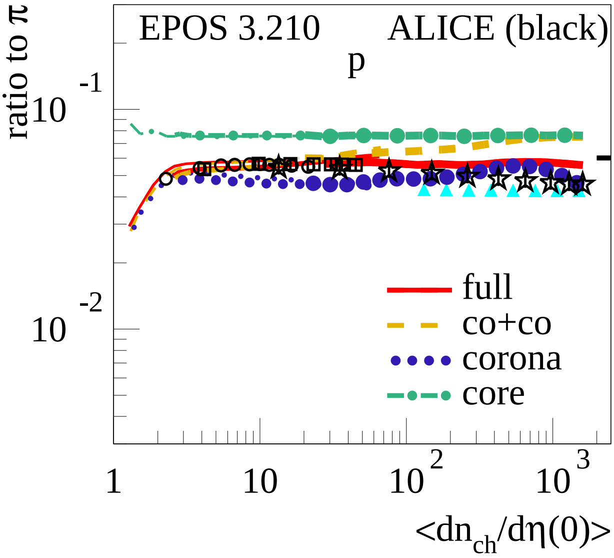
in-medium decay

$\tau \approx 4.2\,\mathrm{fm}/c$

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

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

Proton to pion ratio

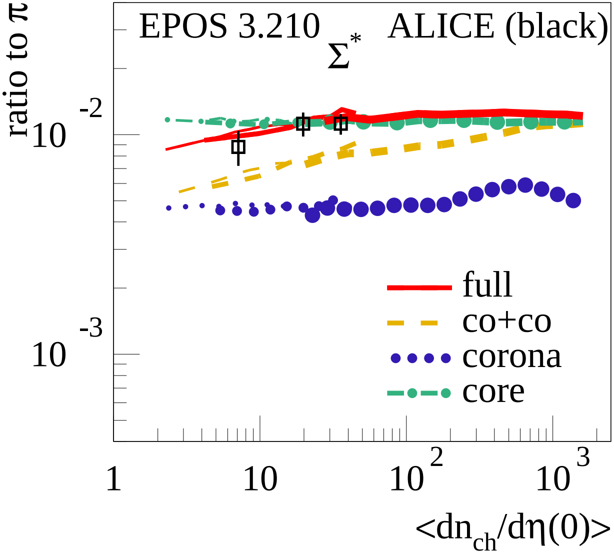


inelastic interactions (annihilation)

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

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

Σ^* to pion ratio



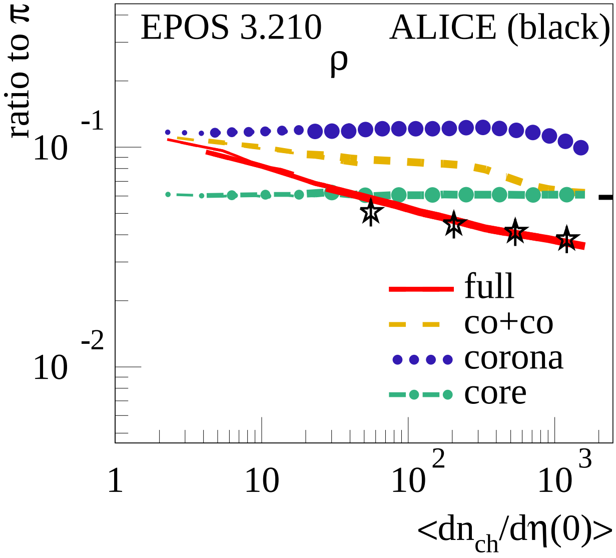
resonance production and in-medium decay

$\tau \approx 5\,\mathrm{fm/c}$

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

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

ρ to pion ratio



corona bigger !

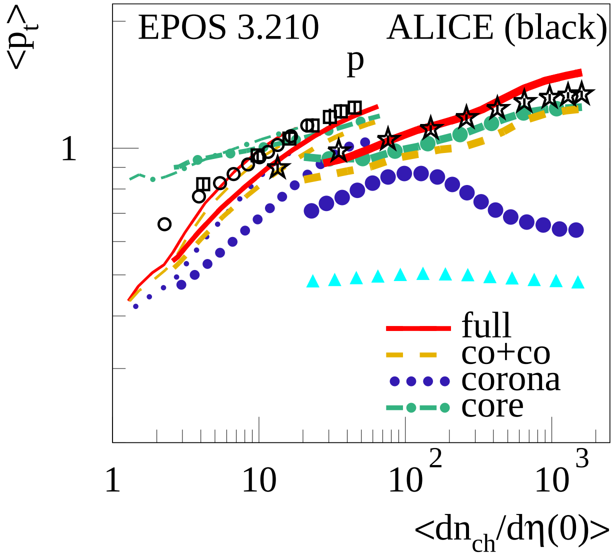
in-medium decay

$\tau \approx 1.3\,\mathrm{fm/c}$

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

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

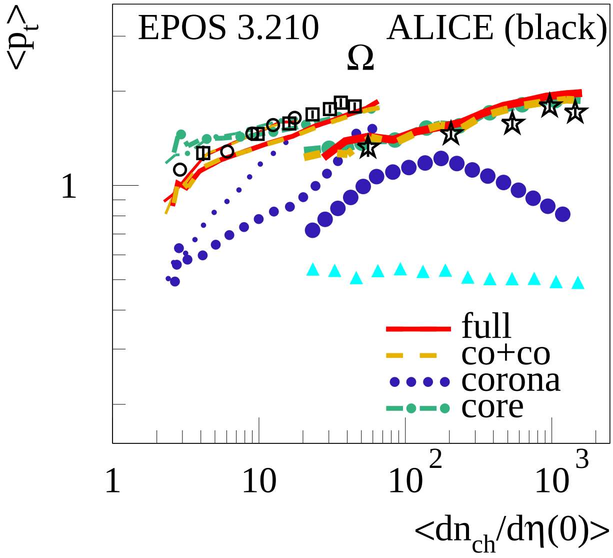
Consistency check: Average p_t of p



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 Ω



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

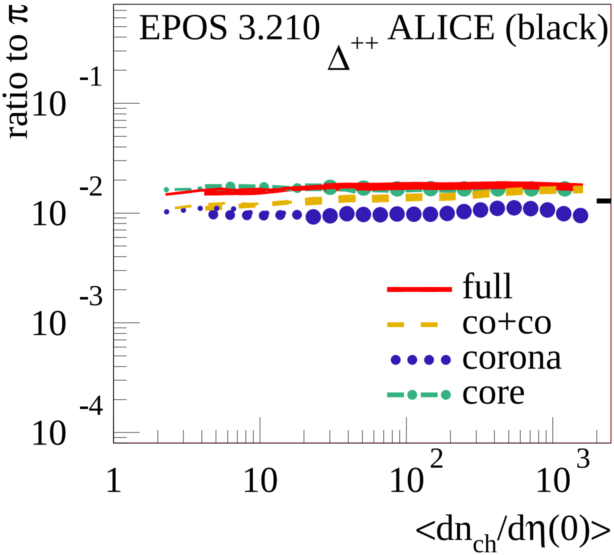
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

Summary

- ☐ **Resonance production contains a wealth of information, allowing to disentangle and better understand the different ingredients:**
  - **Core (Flow) => mini plasma in pp!!**
  - **Corona (Non-flow)**
  - **Hadronic cascade**
- ☐ **Consistency checks: mean pt vs multiplicity**
  (additional uncertainties ... but enormous amount of data)

Thank you!

Δ^{++} to pion ratio



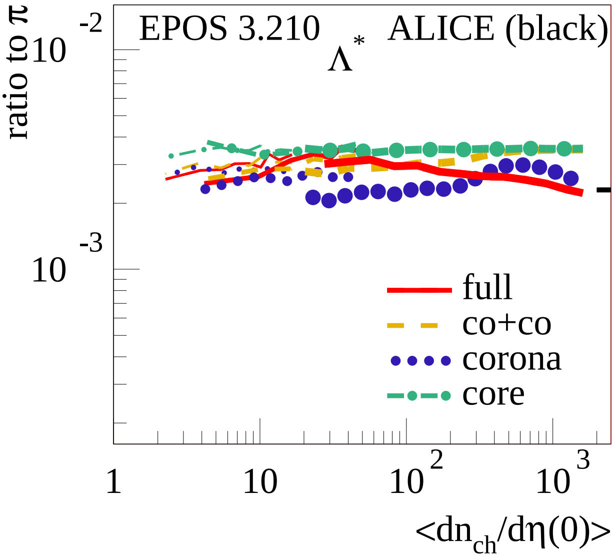
resonance production and in-medium decay

$\tau \approx 1.7\,\mathrm{fm/c}$

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

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

Λ^* to pion ratio



inelastic interactions ?

little in-medium decay

$\tau \approx 12.6\,\mathrm{fm/c}$

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

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

Hydro evolution (Yuri Karpenko)

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

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

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

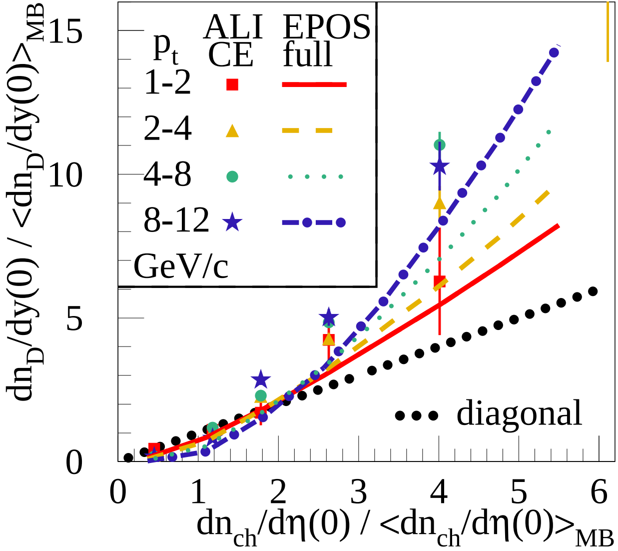
- ☐ $T^{\mu\nu} = \epsilon u^\mu u^\nu - (p+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$,
- ☐ $\partial_{;\nu}$ denotes a covariant derivative,
- ☐ $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$ is the projector orthogonal to u^μ,
- ☐ $\pi^{\mu\nu}$, Π shear stress tensor, bulk pressure
- ☐ $\pi^{\mu\nu}_{\text{NS}}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

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

Multiplicity dep. of D production

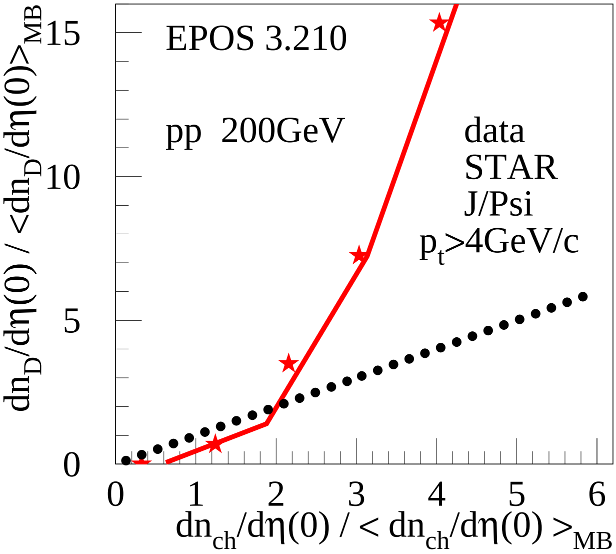


(no free params)

hadronic cascade
on/off
has no effect

hydro on/off
has small effect

J/Psi multiplicity vs Nch at RHIC

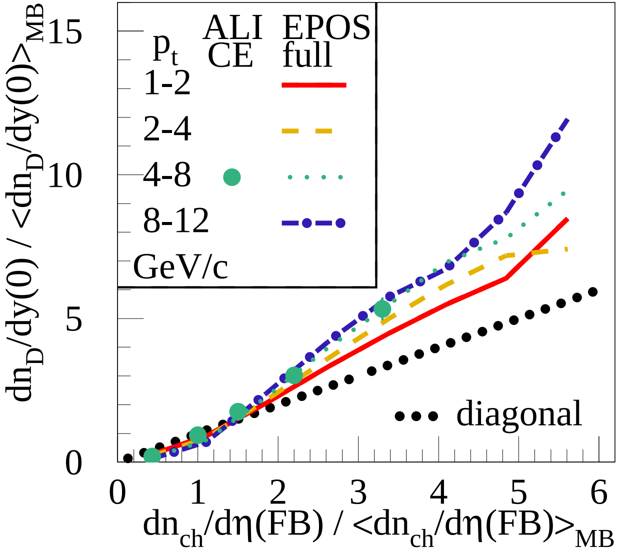


Calculations:
D mesons

Data: J/Ψ

Increase stronger than at LHC

D multiplicity vs N_FB at LHC



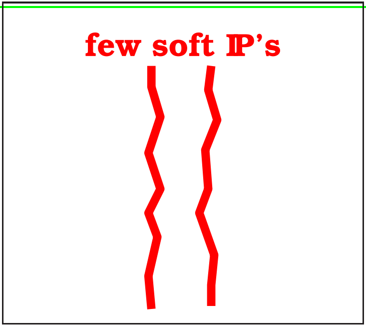
FB = forward/backward rapidity range:

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

Smaller increase

Low multiplicity (LM)

Small N_{Pom}



few soft $\mathbb{P}$'s

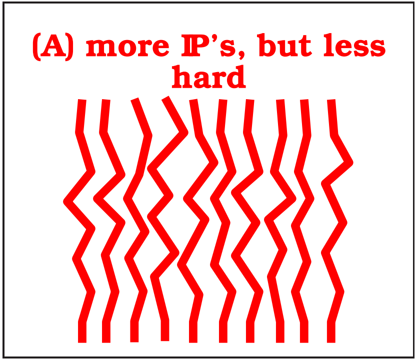
$\mathbb{P}$ = Pomeron

"Hardness" increases with N_{Pom}

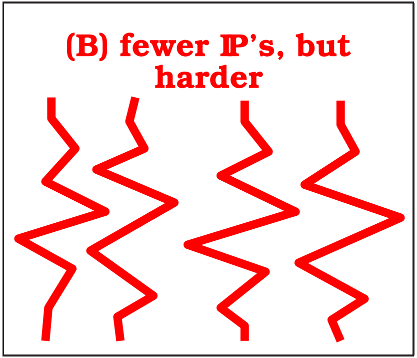
(larger Q_s)

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 mass 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)