MPI in EPOS

(From small to big systems)

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in collaboration with
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Multiple Scattering in EPOS
= multiple Pomeron exchange

Crucial variable :

- **Number of Pomerons N_{Pom}**
- **closely related to multiplicity**

This talk : Discuss the production of stable and unstable hadrons vs multiplicity in pp, pA, AA

Status 2015: Two parallel developments

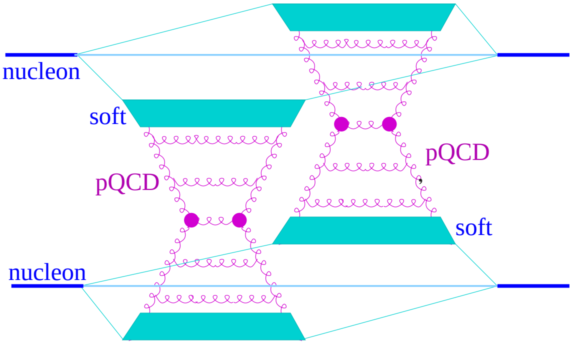
EPOS LHC: Gribov Regge approach, parameterized flow as in EPOS1.99, tuned to LHC data (2012), very much used (and tested) by LHC pp groups, UE, forward physics etc, and used for air shower simulations

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

EPOS: Gribov-Regge approach



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

Elastic scattering S-Matrix based on Pomerons

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

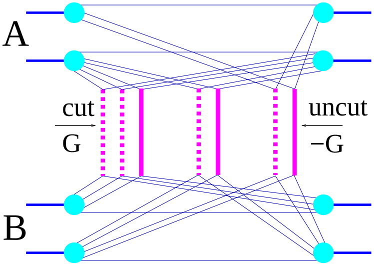
Cutting rules to get inelastic cross sections

Same principle for pp, pA, AA

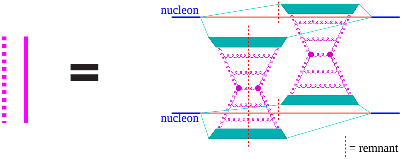
Explicite formulas for cross sections (Phys.Rept. 350 (2001) 93-289)

(even partial cross sections)

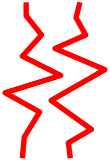
$$\sigma^{\mathrm{tot}} = \sum_{\mathrm{cut\,P}} \int \sum_{\mathrm{uncut\,P}} \int \underbrace{\qquad}_{d\sigma_{\mathrm{exclusive}}}$$



$d\sigma_{\mathrm{exclusive}}$



=> kinky strings

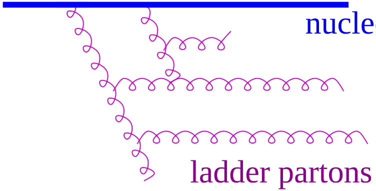


Non-linear effects (Major improvements the past few years)

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



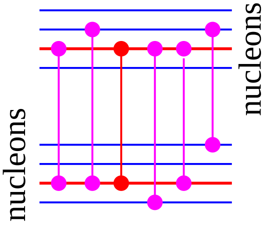
Solution: Instead of a constant Q_0, use a dynamical saturation scale for each Pomeron:

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

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**



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

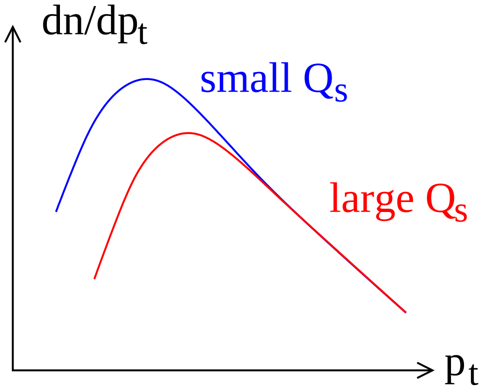
$$\boldsymbol{Q_s \propto \sqrt{N_{\mathbb{P}}} \times (s_{\mathbb{P}})^{0.30}}$$

CGC for AA:

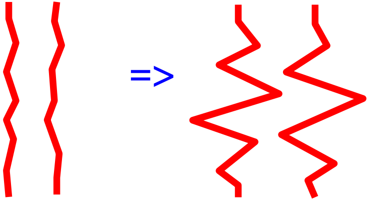
$$Q_s \propto N_{\mathrm{part}} \times (1/x)^{0.30}$$

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

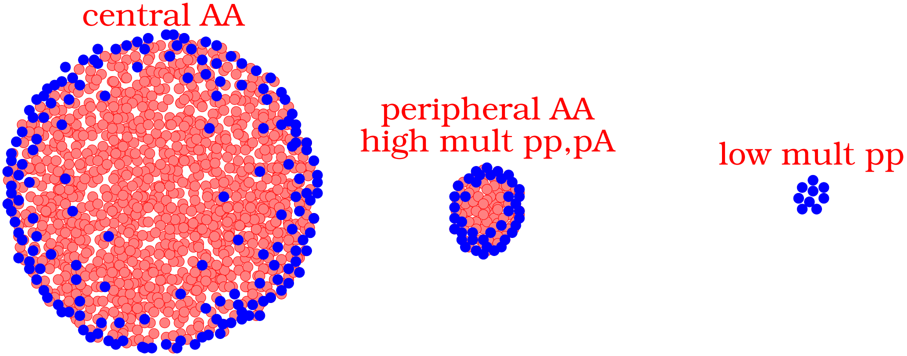
=> Strong increase of $\langle p_t \rangle$ with multiplicity
(checked for hadrons and resonances, not shown here)

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

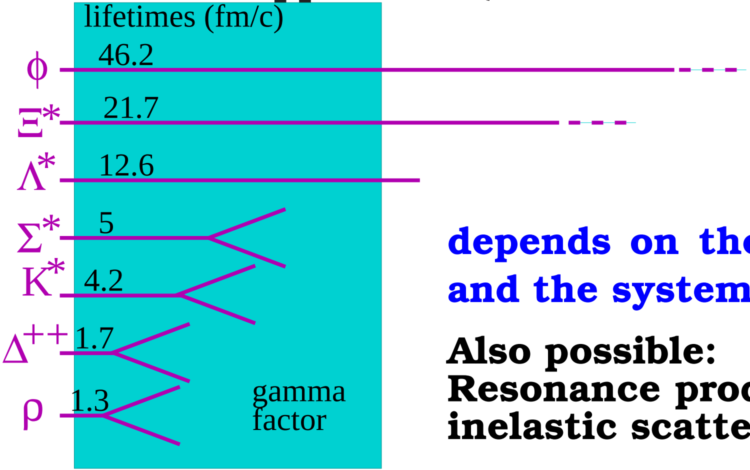
Gribov-Regge approach => (Many) kinky strings
=> core/corona separation (based on string segments)



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

Final state hadronic cascade:

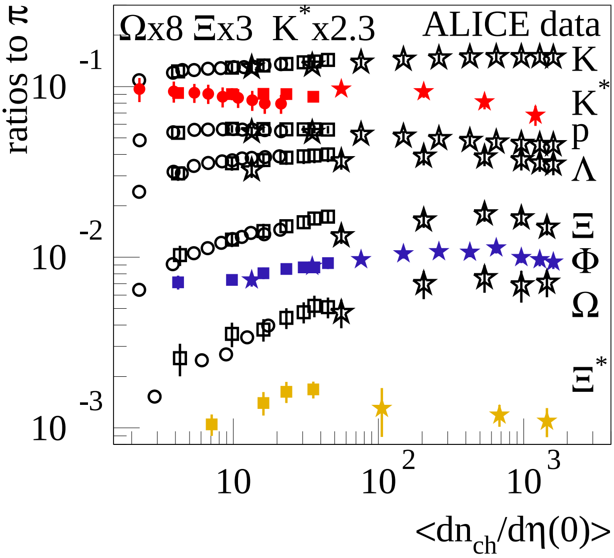
Resonance suppression (in-medium decay)



depends on the lifetime and the system size

Also possible:
Resonance production, inelastic scattering

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



circles = pp (7TeV)

squares = pPb (5TeV)

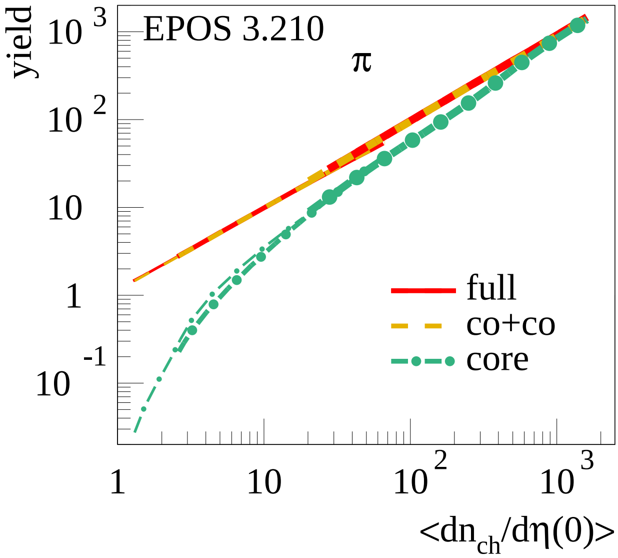
stars = PbPb (2.76TeV)

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



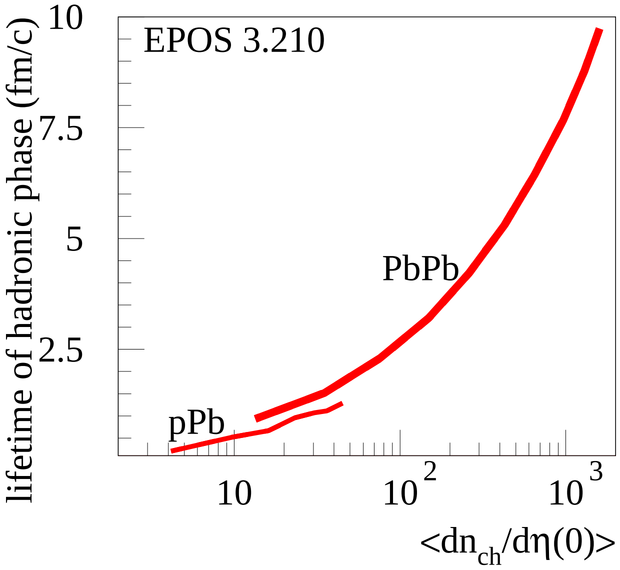
thin lines
= pp (7TeV)

intermediate lines
= pPb (5TeV)

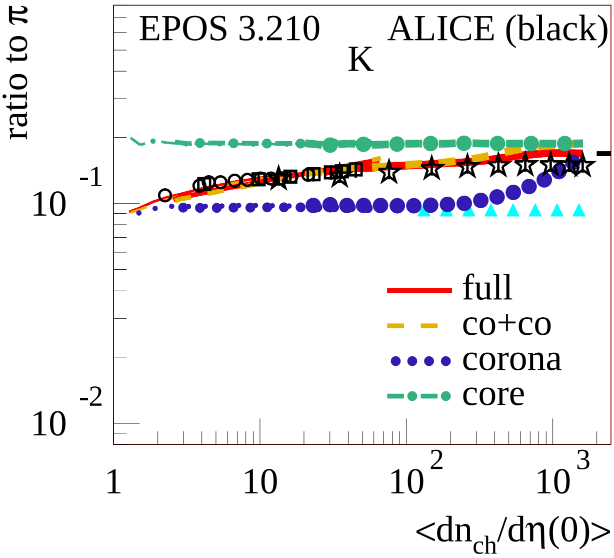
thick lines
= PbPb (2.76TeV)

full = with hadronic cascade (UrQMD)

Lifetime of hadronic phase



Kaon to pion ratio



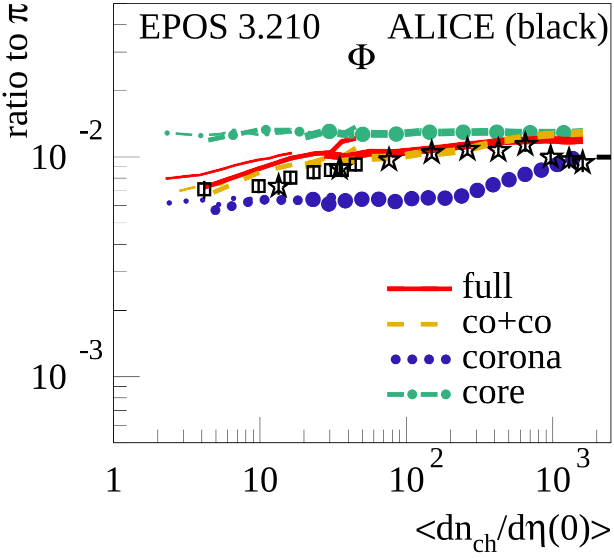
core hadronization:
$T = 164\,\mathrm{MeV},\ \mu_B = 0$

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



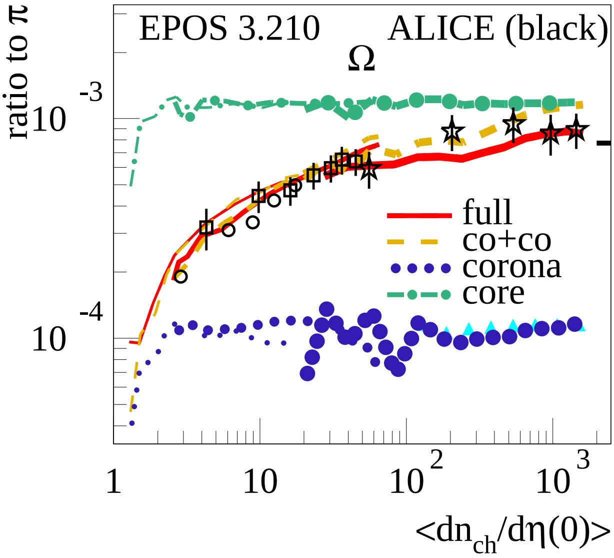
long-lived

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

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

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

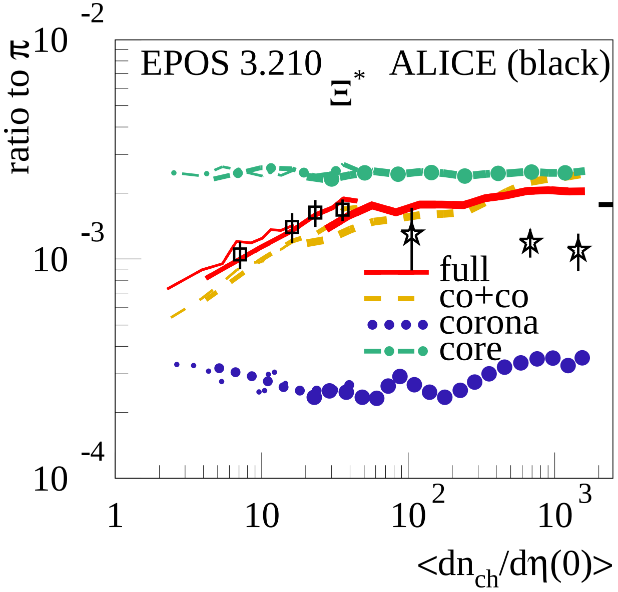
Omega to pion ratio



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



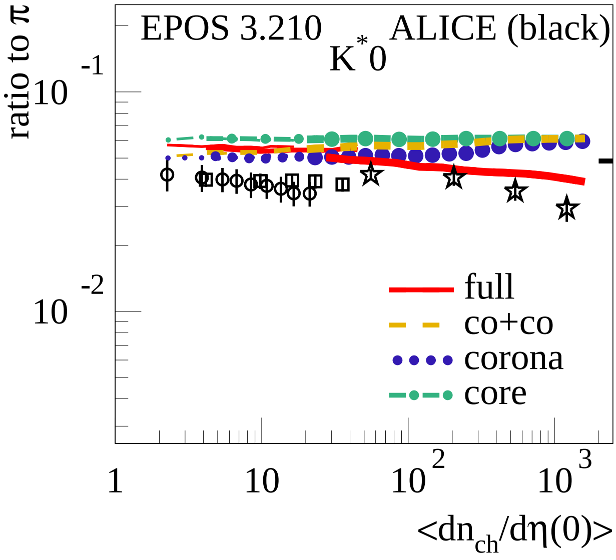
long-lived

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

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

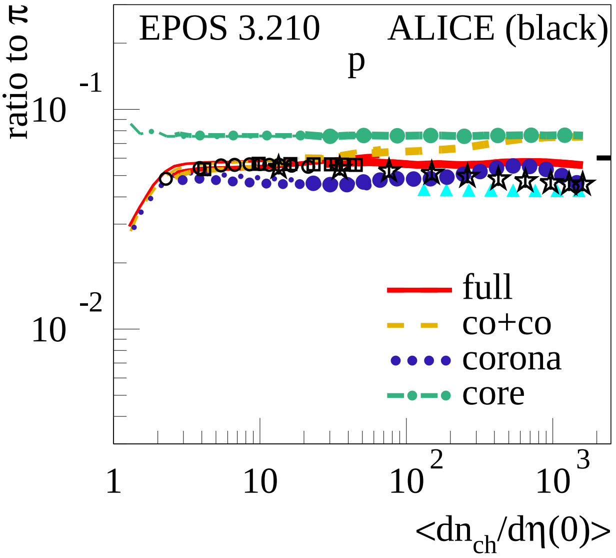
in-medium decay

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

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

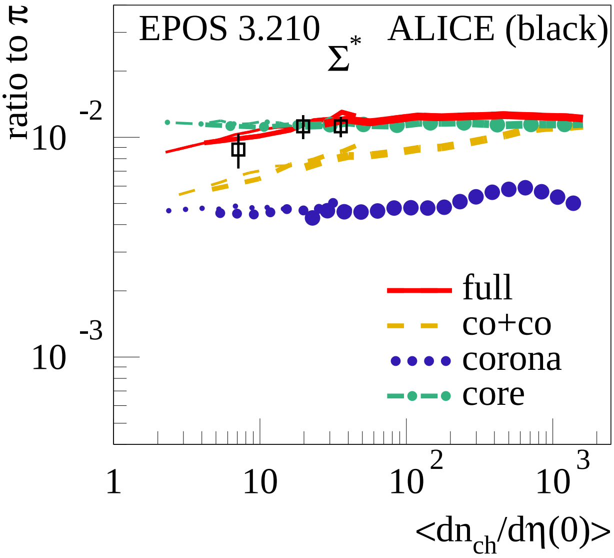


inelastic interactions (annihilation)

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



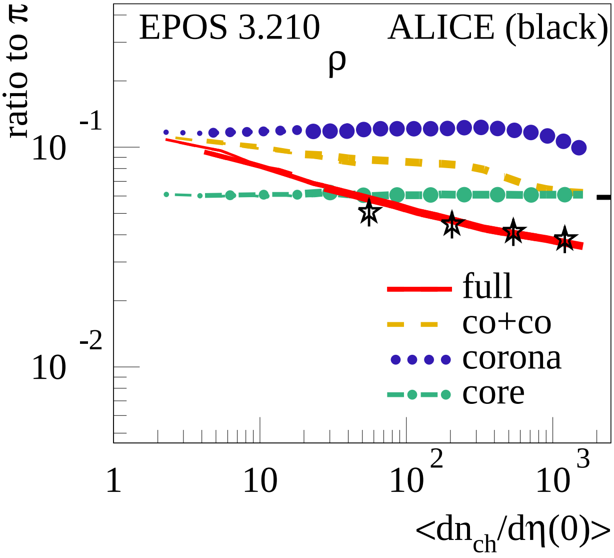
resonance production and in-medium decay

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

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)
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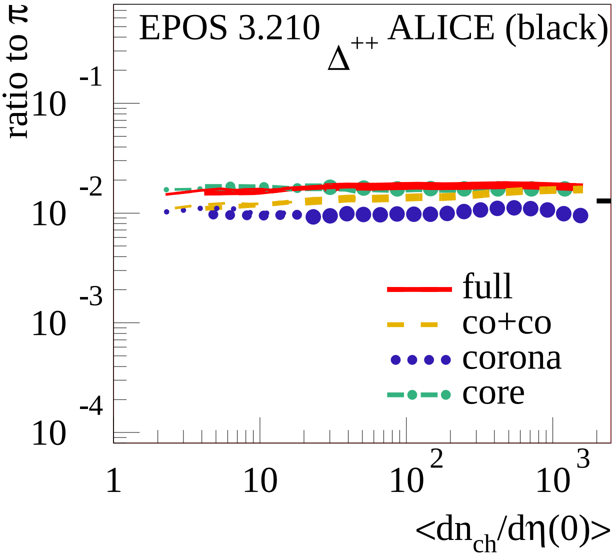
stars = PbPb (2.76TeV)

Δ^{++} to pion ratio



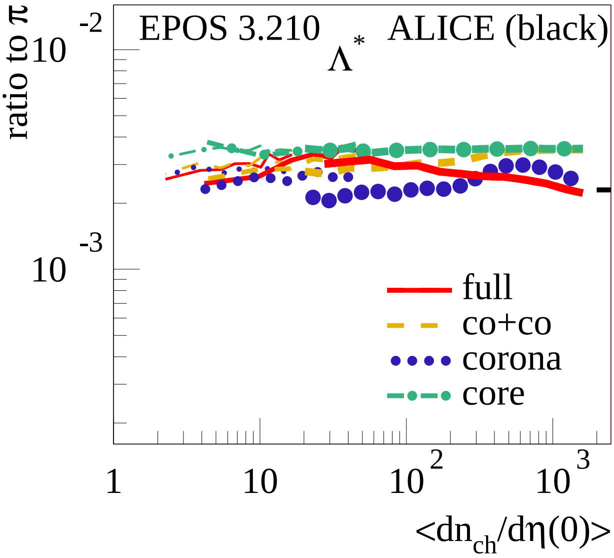
resonance production and in-medium decay

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

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)

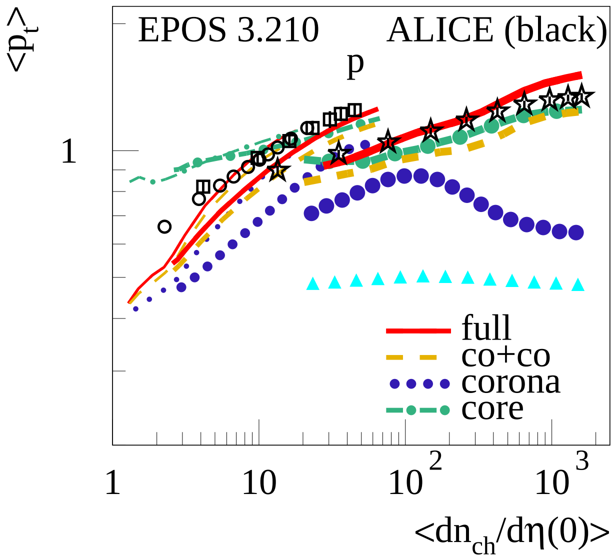
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

Summary

- **Hadron and 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**
  (see SQM talk)
- **To be checked: Microcanonical decay**

Thank you!

Consistency check: Average p_t of p



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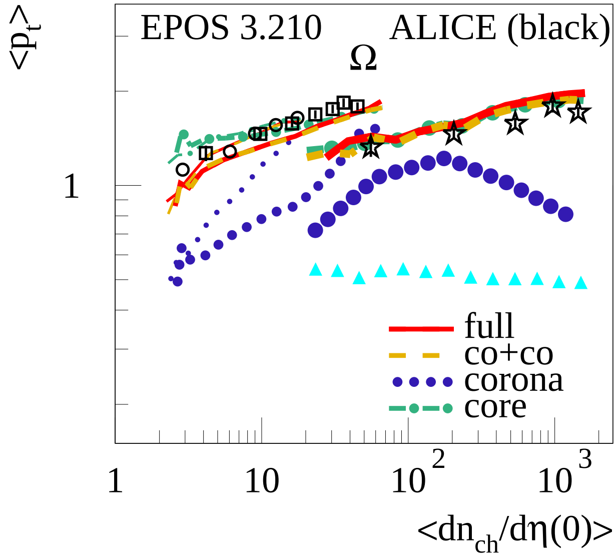
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

Average p_t of Ω



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circles = pp (7TeV)
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Hydro evolution (Yuri Karpenko)

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

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

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

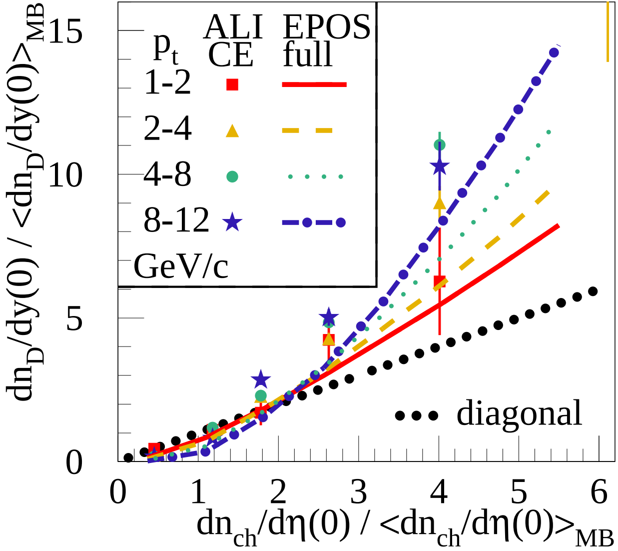
- $T^{\mu\nu}=\epsilon u^\mu u^\nu-(p+\Pi)\Delta^{\mu\nu}+\pi^{\mu\nu}$,
- $\partial_{;\nu}$ denotes a covariant derivative,
- $\Delta^{\mu\nu}=g^{\mu\nu}-u^\mu u^\nu$ is the projector orthogonal to u^μ,
- $\pi^{\mu\nu}$, Π shear stress tensor, bulk pressure
- $\pi^{\mu\nu}_{\mathrm{NS}}=\eta(\Delta^{\mu\lambda}\partial_{;\lambda}u^\nu+\Delta\nu\lambda\partial_{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

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

Marcus Bleicher, Jan Steinheimer

Multiplicity dep. of D production

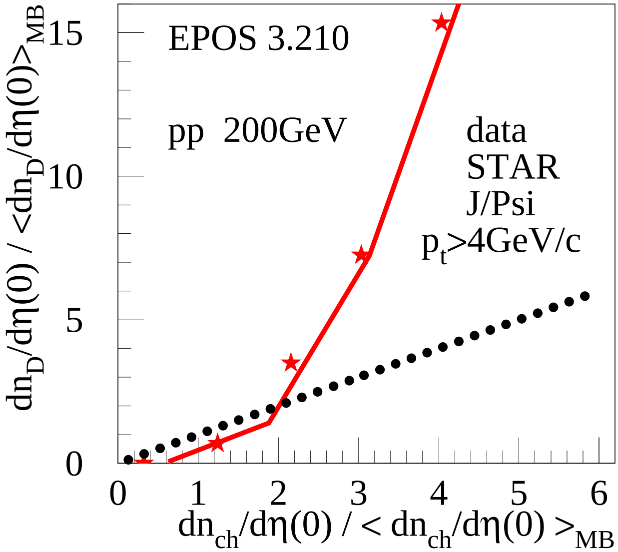


(no free params)

hadronic cascade on/off has no effect

hydro on/off has small effect

J/Psi multiplicity vs Nch at RHIC

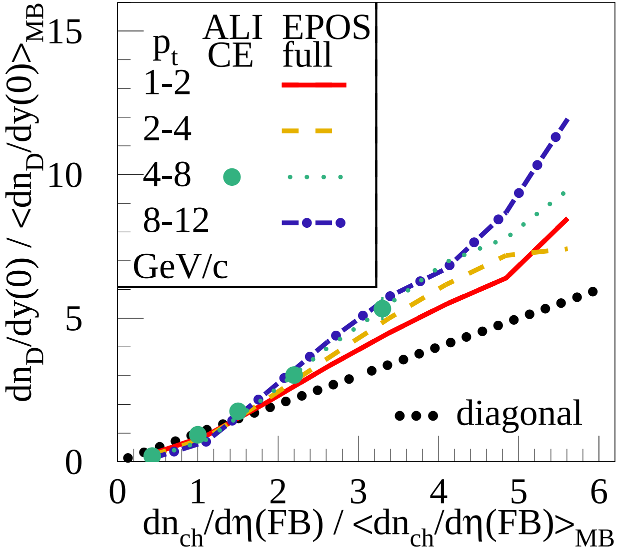


Calculations:
D mesons

Data: J/Ψ

Increase stronger than at LHC

D multiplicity vs N_FB at LHC



FB = forward/backward rapidity range:

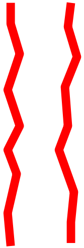
$$2.8 < \eta < 5.1$$
and
$$-3.7 < \eta < -1.7$$

Smaller increase

Low multi-plicity (LM)

Small $N_{\rm Pom}$

few soft $\mathbb{P}$'s



$\mathbb{P}$ = Pomeron

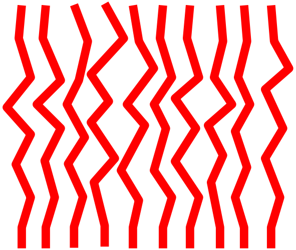
"Hardness" increases with $N_{\rm Pom}$

(larger Q_s)

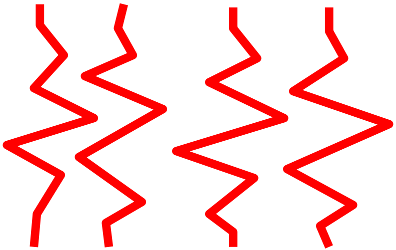
High multi-plicity (HM)

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

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



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



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)