# System size dependence of particle production in EPOS and some remarks about low energies

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in collaboration with
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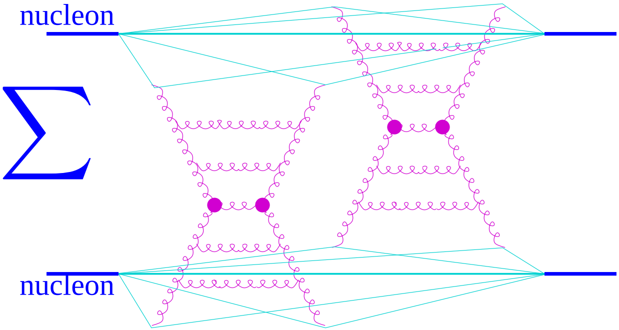
# EPOS = Gribov-Regge approach




**S-Matrix based on Pomerons**

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

Cutting rules to get inelastic cross sections.

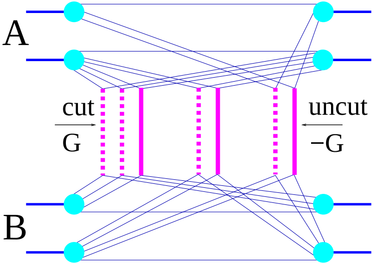
Same principle for pp, pA, AA

# Explicite formulas for cross sections

(even partial cross sections)

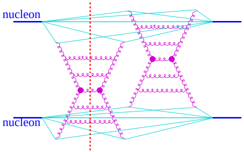
$$\sigma^{\rm tot} = \sum_{\rm cut\,P} \int \sum_{\rm uncut\,P} \int$$

(squared amplitude)

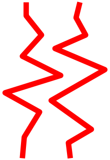



$d\sigma_{\rm exclusive}$

=




**=> kinky strings**

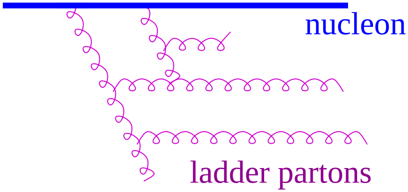


# Non-linear effects

**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 distr. 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 ($\sigma_{\rm tot}$, $\sigma_{\rm el}$, $\sigma_{\rm SD}$, $dn^{\rm ch}/d\eta(0)$) for pp
- □ the multiplicity dependence of $dn^{\pi}/dp_t$ at large $p_t$ for pp at 7 TeV

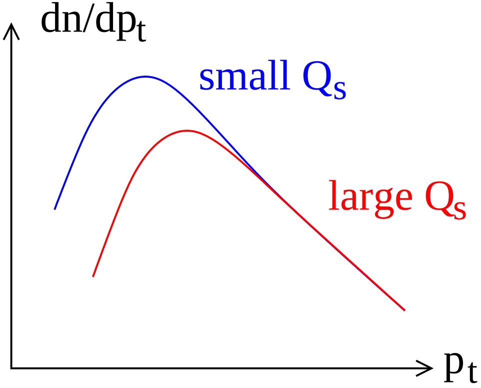
We find

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

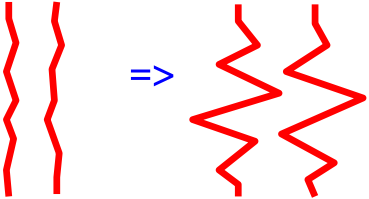
CGC for AA:

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

Parton distributions




Increasing multiplicity
=> increasing $N_{\mathrm{Pom}}$
=> Increasing $Q_s$
=> harder Pomerons
=> harder strings



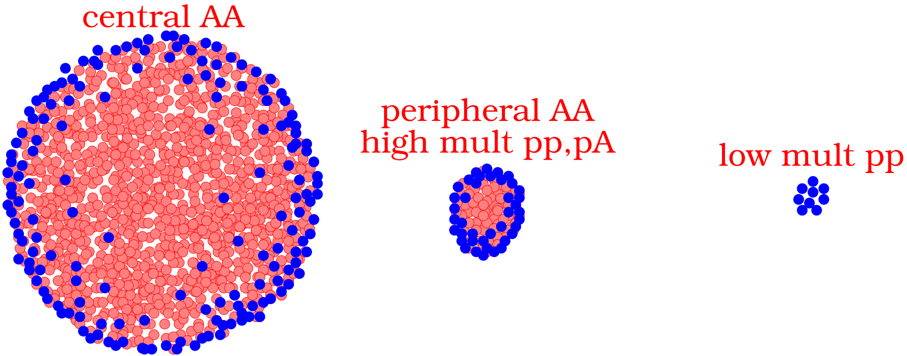

=> more high pt particles

**=> 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

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




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

# EPOS status and perspective:

## Status 2015: Two parallel developments

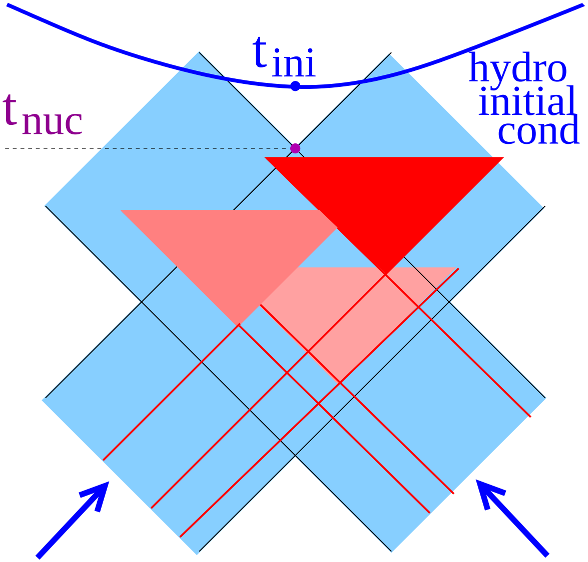
**EPOS LHC:** Gribov Regge approach, parameterized flow as in EPOS1.99, tuned to LHC data (2012), very much used (and tested) by LHC pp groups, UE, forward physics etc, and used for air shower simulations

**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)**

## What about EPOS at low energies?

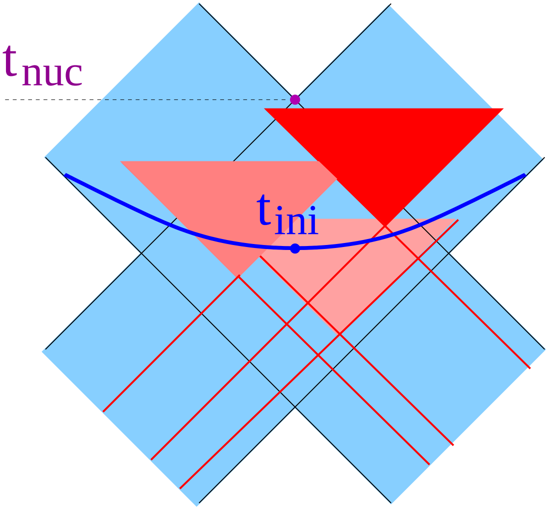
# Space time picture of a HI collision




**longitudinal dimension of each nucleus: $2R/\gamma$**

$t_{nuc} = R/\gamma v$
**big at low E**

**too little core, too little flow for $t_{ini} > t_{nuc}$**




**Solution:**

**take**

$t_{ini} < t_{nuc}$

# Back to LHC:

## Testing EPOS 3.210

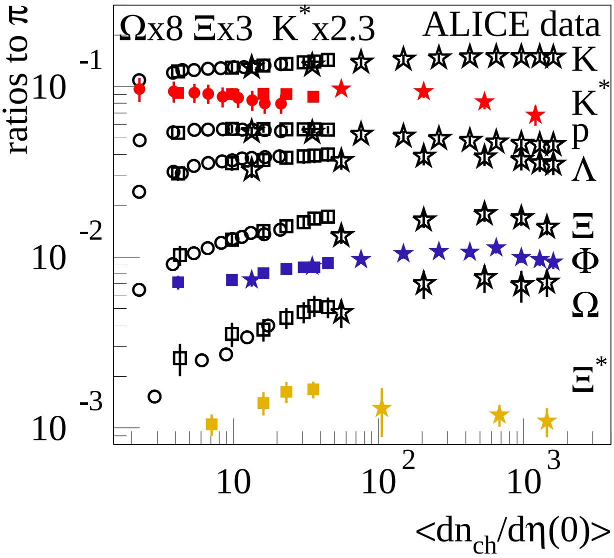
# To get a global overview:

- ☐ **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**

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

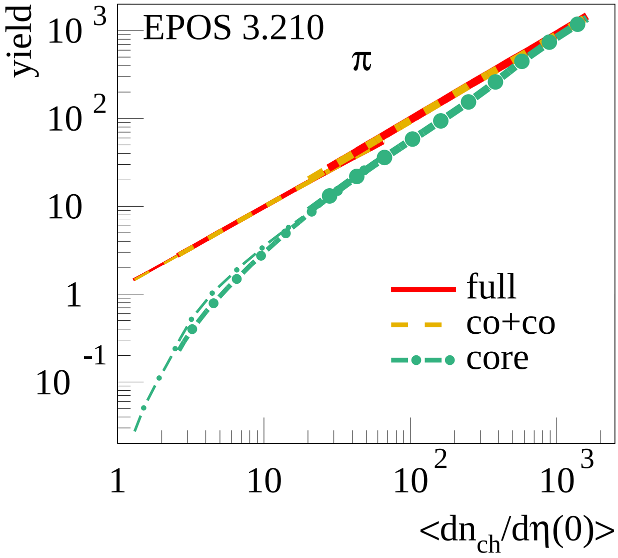
squares = pPb (5TeV)

stars = PbPb (2.76TeV)

**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



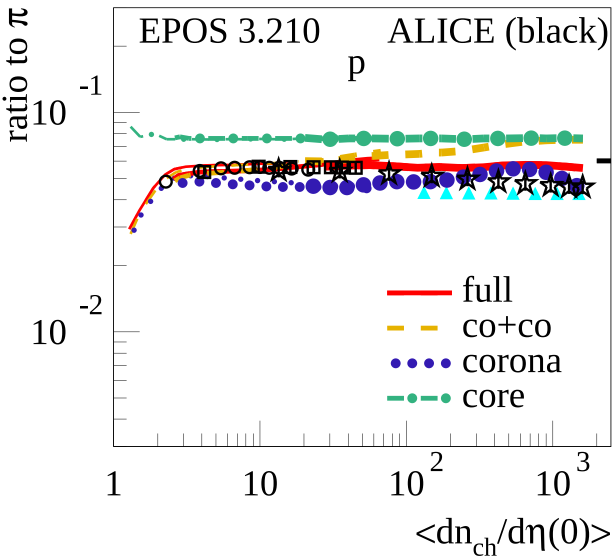

thin lines
= pp (7TeV)

intermediate lines
= pPb (5TeV)

thick lines
= PbPb (2.76TeV)

full = with hadronic cascade (UrQMD)

# 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
$T = 156.5\,\text{MeV}, \mu_B = 0.7\,\text{MeV}$

thin lines = pp (7TeV)
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circles = pp (7TeV)
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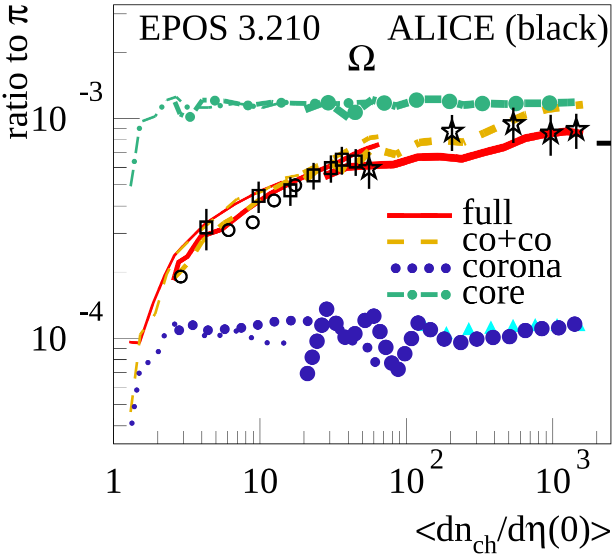
# Omega to pion ratio

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thick lines = PbPb (2.76TeVVV)

circles = pp (7TeV)
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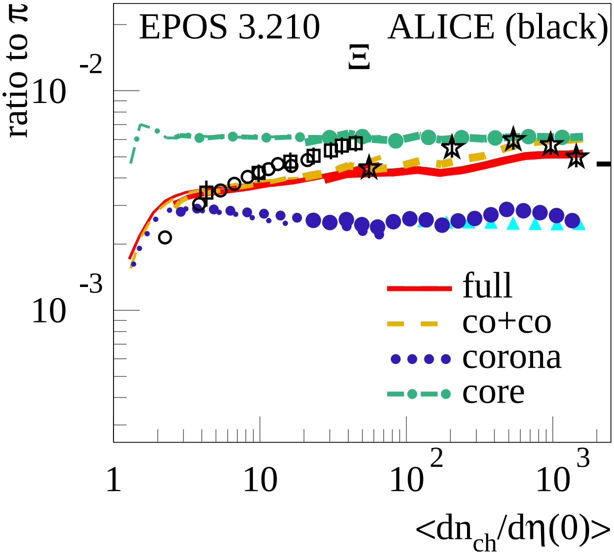
stars = PbPb (2.76TeV)

# Xi to pion ratio




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

circles = pp (7TeV)
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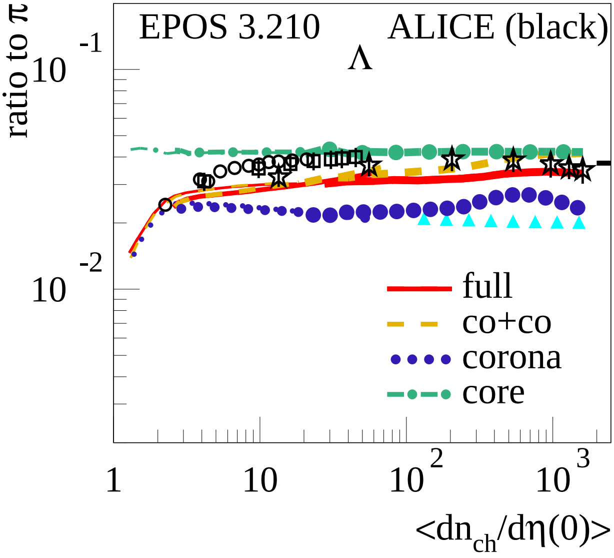
stars = PbPb (2.76TeV)

# Lambda to pion ratio

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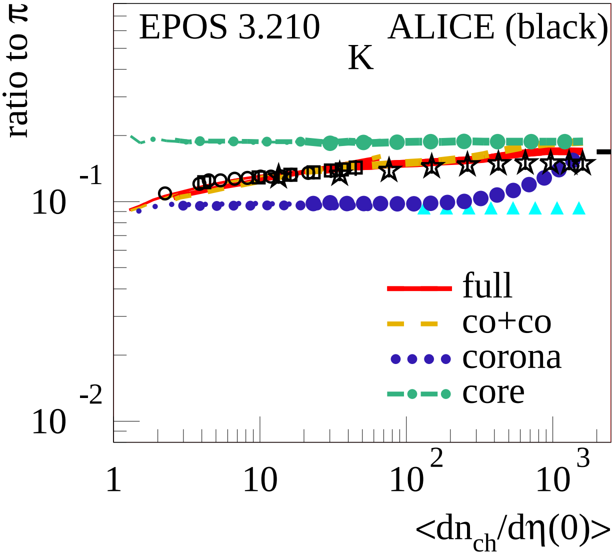
# Kaon to pion ratio

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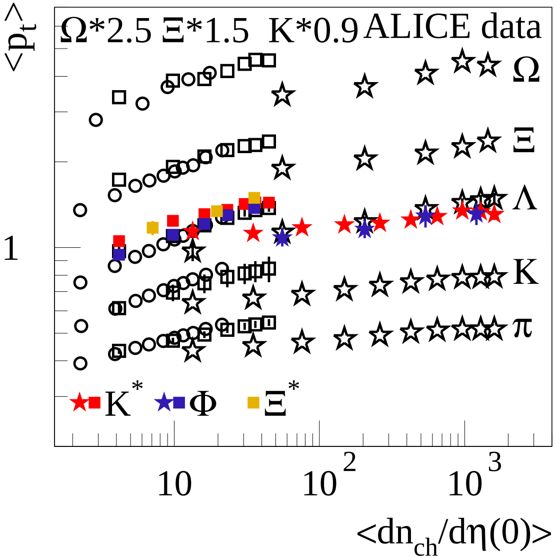
**Ratios $h/\pi$ for $h = p, K, \Lambda, \Xi, \Omega$ vs $\left\langle \frac{dn}{d\eta}(0) \right\rangle$:**

**Core and corona contributions separately roughly constant**

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

**=> inceasing slope**

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

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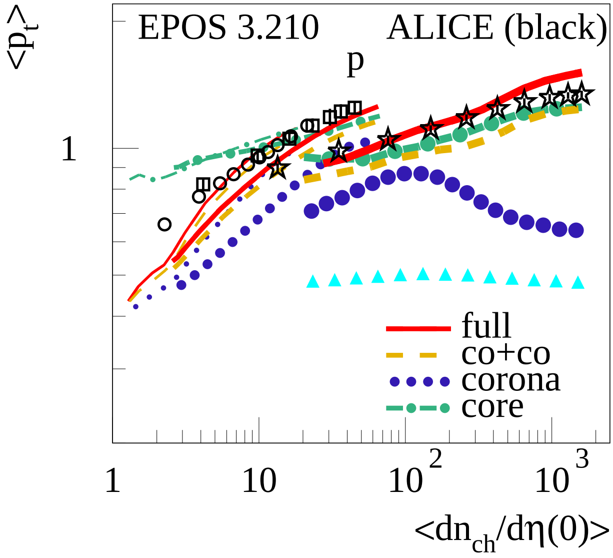
# Average $p_t$ of protons

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circles = pp (7TeV)
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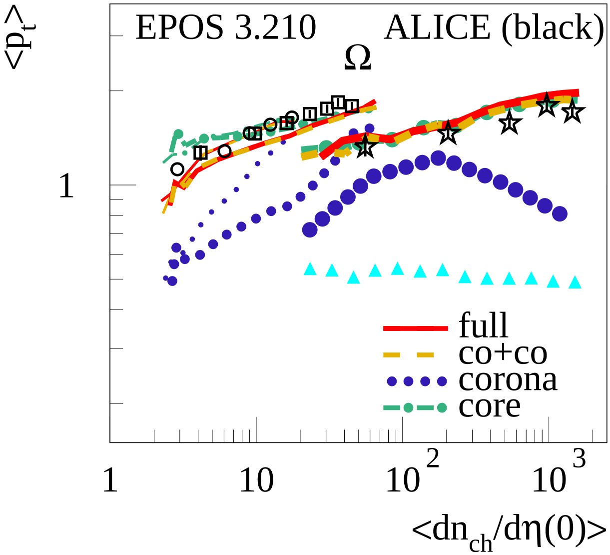
stars = PbPb (2.76TeV)

# Average $p_t$ of Omegas

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circles = pp (7TeV)
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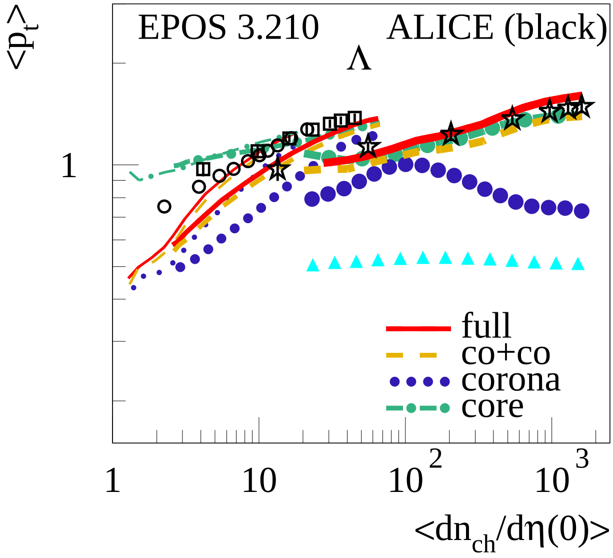
stars = PbPb (2.76TeV)

# Average $p_t$ of lambdas

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circles = pp (7TeV)
squares = pPb (5TeV)
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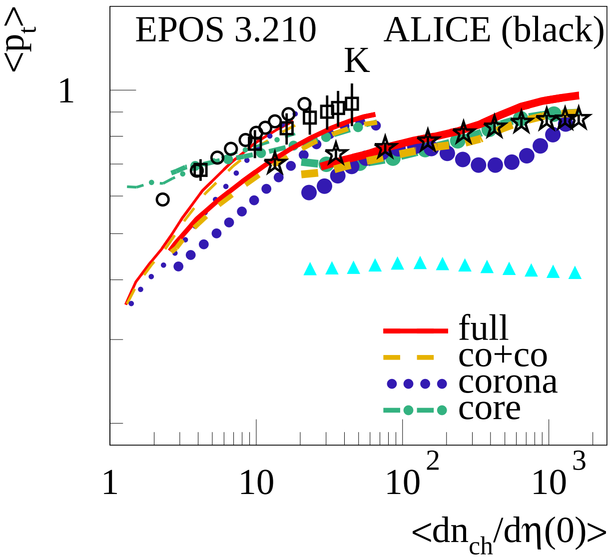
# Average $p_t$ of kaons

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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)**

$K$, $\pi$ : **pp-pPb splitting**

**The multiplicity dependence of the corona contribution is crucial**

# Summary

- ☐ **To understand multiplicity dependence of particle production we have to understand the corona contribution (= non-flow).**

- ☐ **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 $N_{\mathrm{Pom}}$ dependence of the saturation scale ...**

# **Core => Hydro evolution** (Yuri Karpenko)

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

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

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

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

**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