Collectivity in EPOS

(flow, non-flow, and parton saturation)

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in collaboration with
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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**

Many aspects of collectivity ...

Here :

- □ **Radial flow, mean pt**

- □ **Hadron chemistry**

  (statistical production or string decay)

Not in this talk: Asymmetries

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

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

□ **Charmed meson production vs $\frac{dn_{\mathrm{ch}}}{d\eta}(0)$ for pp**

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

First step to get a global view, to see where EPOS works and where not, in pp, pA, AA, same version

Status 2015: Two parallel developments

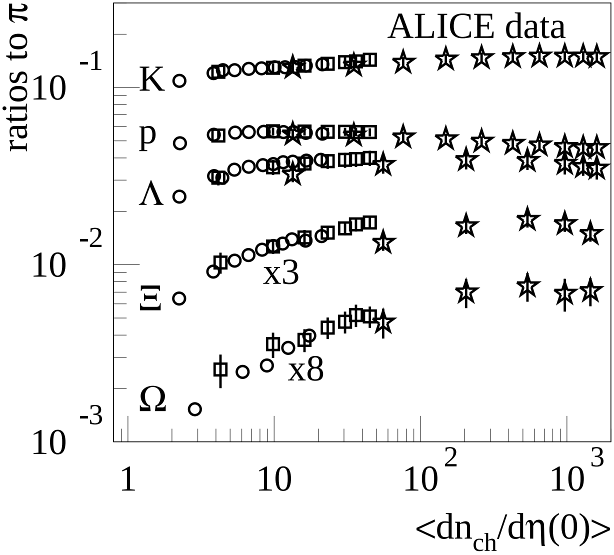
EPOS LHC: **Gribov Regge approach, parameterized flow as in EPOS1.99, tuned to LHC data (2012), very much used (and tested) by LHC pp groups, UE, forward physics etc, and used for air shower simulations**

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

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



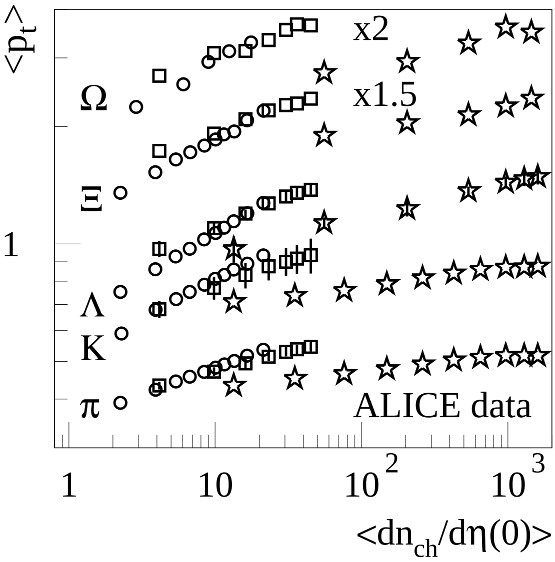
circles = pp (7TeV)

squares = pPb (5TeV)

stars = PbPb (2.76TeV)

Refs: next slide

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



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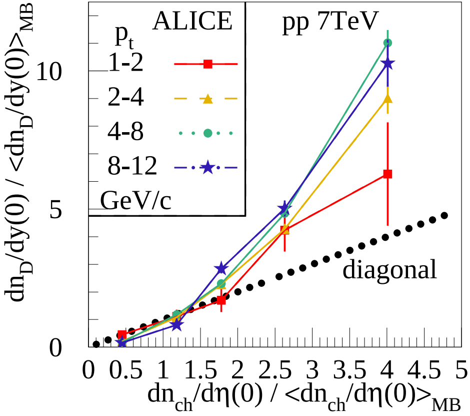
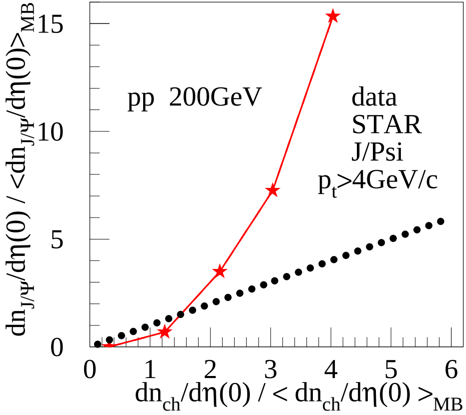
Data partly collected by A. G. Knospe
Refs:
<dNch/deta> in Pb+Pb: Phys. Rev. Lett. 106 032301 (2011)
pi+-, K+-, and (anti)protons in Pb+Pb: Phys. Rev. C 88 044910 (2013)
Lambda in Pb+Pb: Phys. Rev. Lett. 111 222301 (2013)
Xi- and Omega in p+Pb: Phys. Lett. B 758 389-401 (2016)
pi+-, K+-, (anti)protons, and 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 data points from Rafael Derradi de Souza, SQM2016

D or J/Ψ multiplicity vs $\frac{dn_{ch}}{d\eta}(0)$ in pp





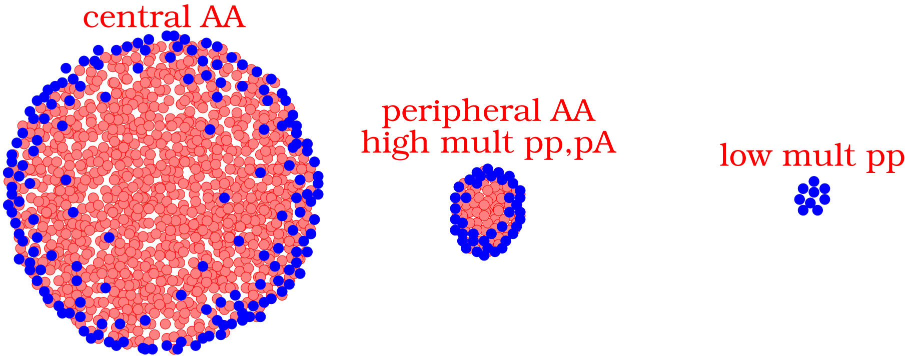
ALICE JHEP 09 (2015) 148, arXiv:1505.00664v1

STAR, shown at MPI2016

strongly nonlinear increase

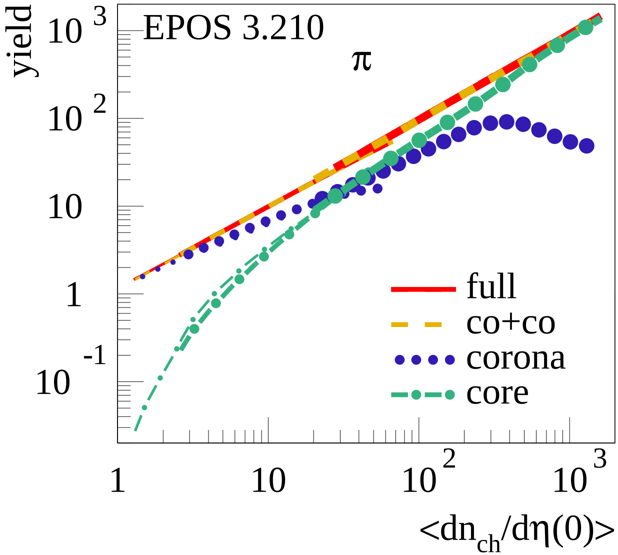
Core-corona picture in EPOS (details later)

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



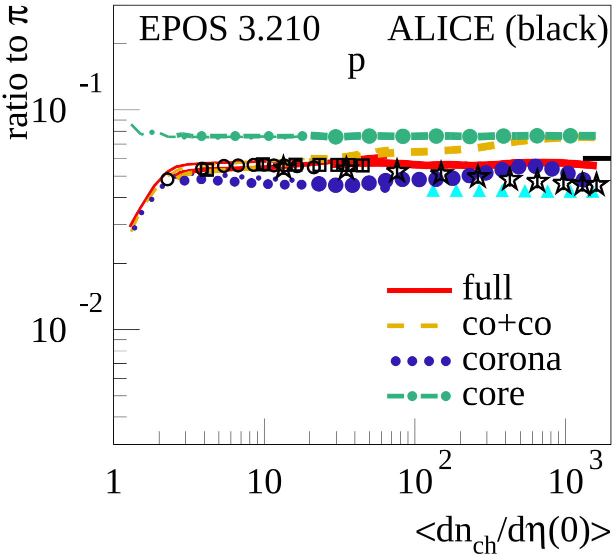
thin lines
= pp (7TeV)

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)
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thick lines = PbPb (2.76TeVVV)

circles = pp (7TeV)
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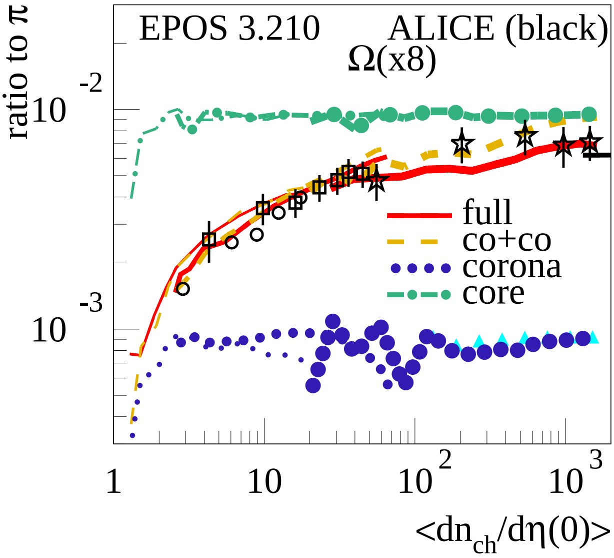
Omega to pion ratio



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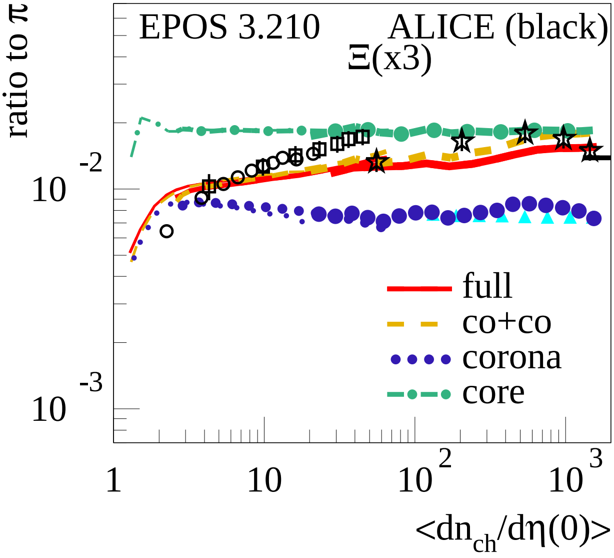
Xi to pion ratio



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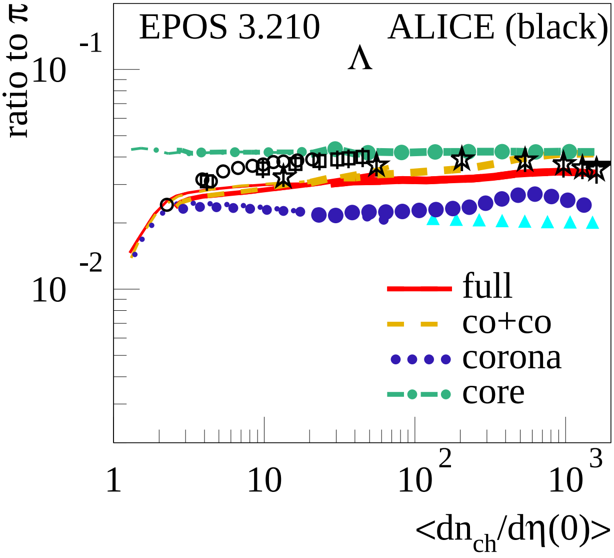
stars = PbPb (2.76TeV)

Lambda to pion ratio



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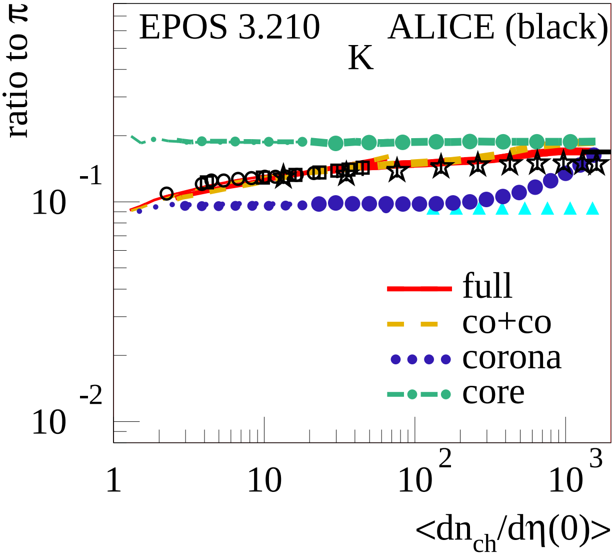
Kaon to pion ratio



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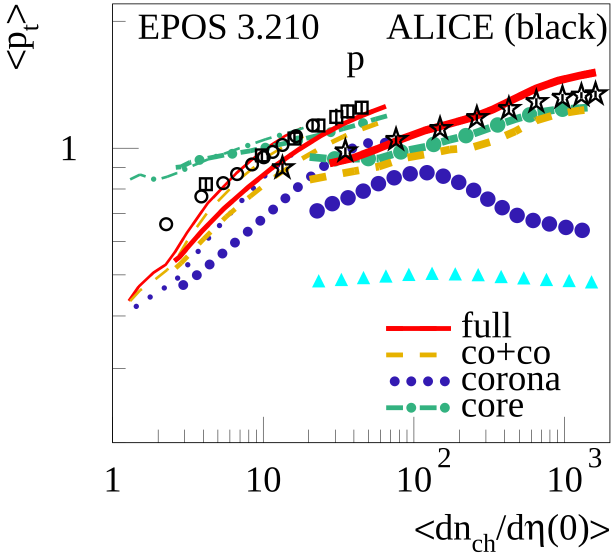
Ratios h/π **for** $h = p, K, \Lambda, \Xi, \Omega$ **vs** $\left\langle \frac{dn}{d\eta}(0) \right\rangle$**:**

Core and corona contributions separately roughly constant

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

=> inceasing slope

Average p_t of protons



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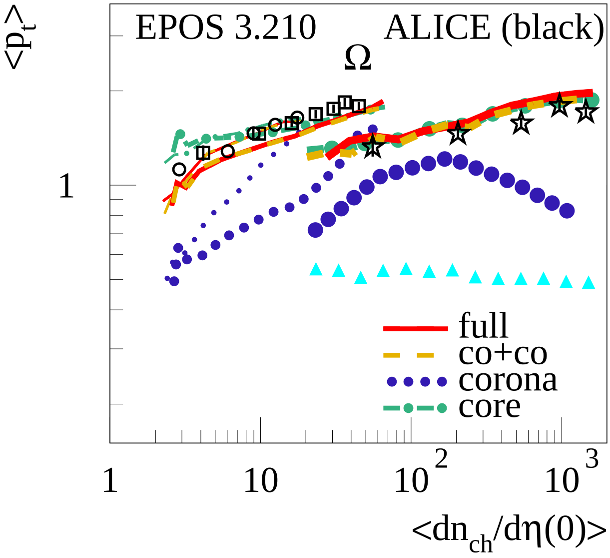
Average p_t of Omegas



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circles = pp (7TeV)
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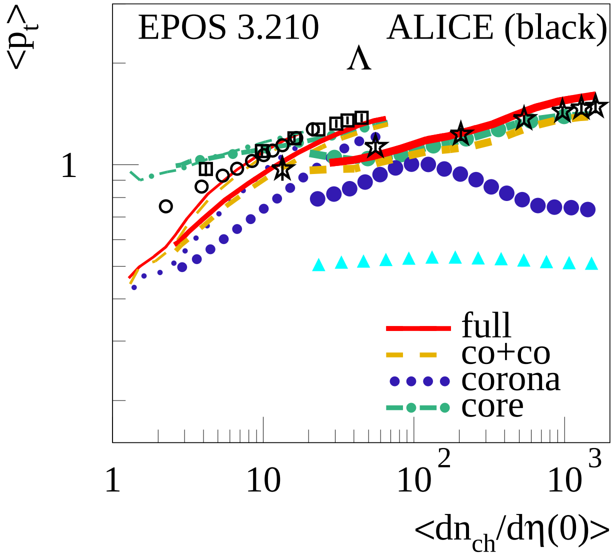
Average p_t of lambdas



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thick lines = PbPb (2.76TeVVV)

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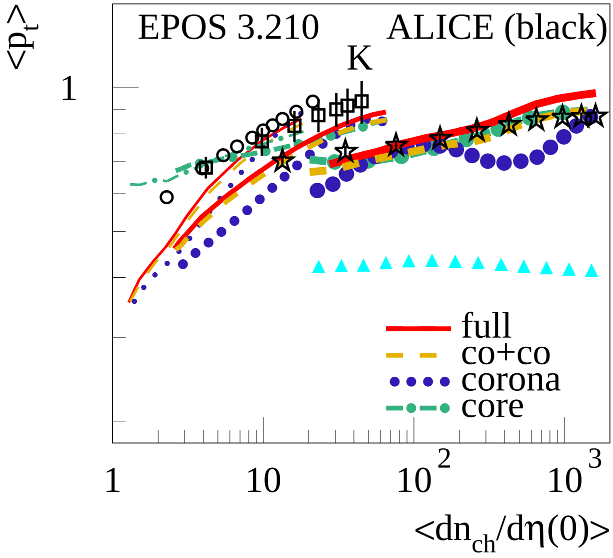
Average p_t of kaons



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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)

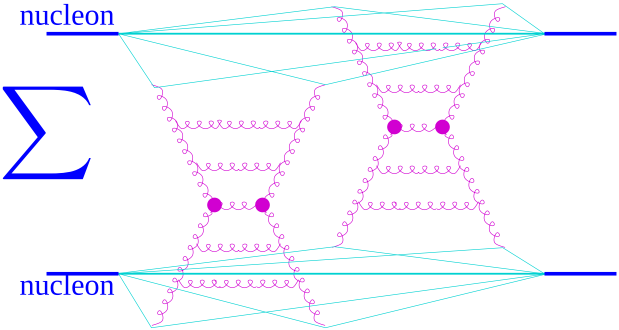
Slope(pp) > slope(pPb) >> slope(PbPb)

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)

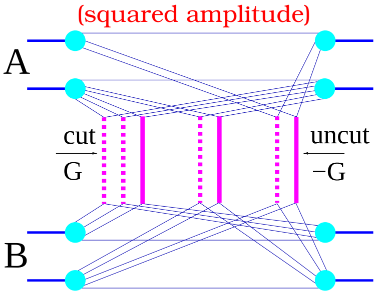
Cutting rules to get inelastic cross sections.

Same principle for AA

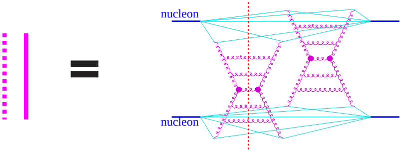
Explicite formulas for cross sections

(even partial cross sections)

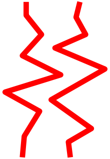
$$\sigma^{\text{tot}} = \sum_{\text{cut P}} \int \sum_{\text{uncut P}} \int$$



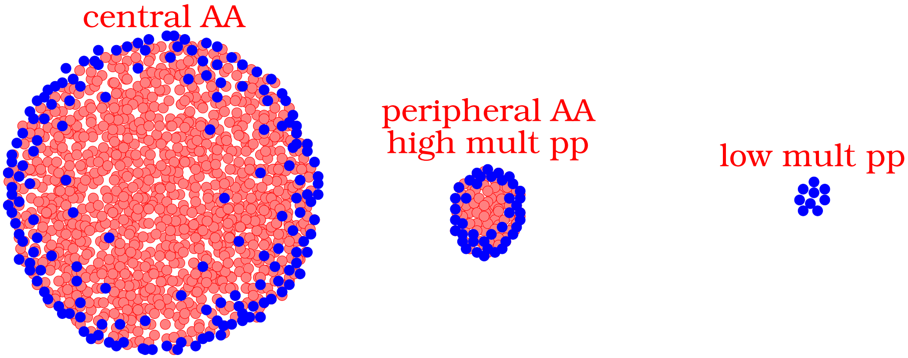
$$d\sigma_{\text{exclusive}}$$



=> kinky strings



Based on string segments: core-corona separation



core: string segments "melt" => fluid

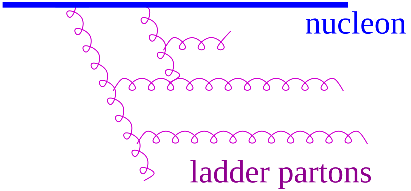
corona: strings survive (ordinary kinky strings from parton ladders)

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

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(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

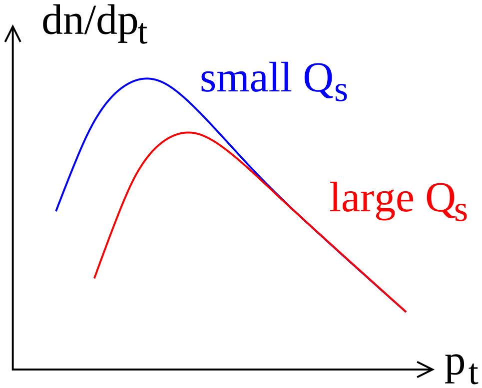
$$\boxed{G_{\mathrm{eff}} = A\ (N_{\mathrm{Pom}})^{B}\ G(Q_s)}$$

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

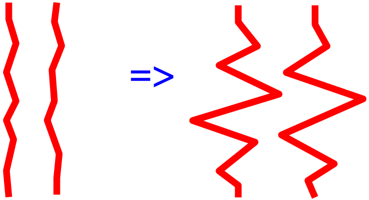
We find

$$Q_s = Q_s(x^+x^-) \propto (x^+x^-)^{0.30}$$

Parton distributions



Increasing $\langle dn/d\eta(0)\rangle$ corresponds to increasing N_{Pom}
=> Increasing Q_s
=> harder Pomerons
=> harder strings



=> more high pt particles

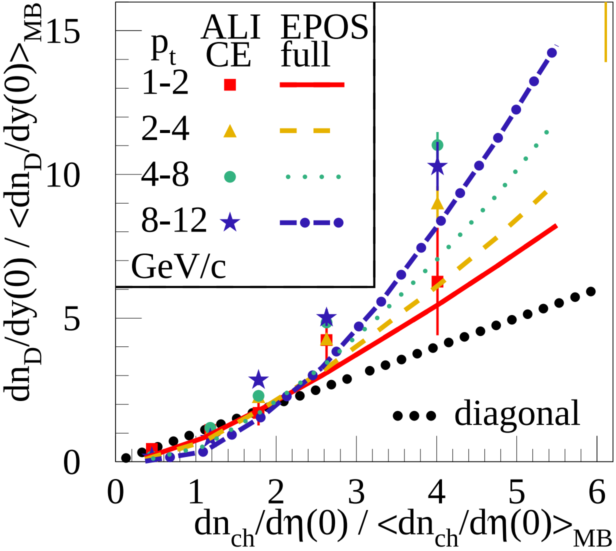
=> Strong increase of $\langle p_t\rangle$ with $\langle dn/d\eta(0)\rangle$

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)

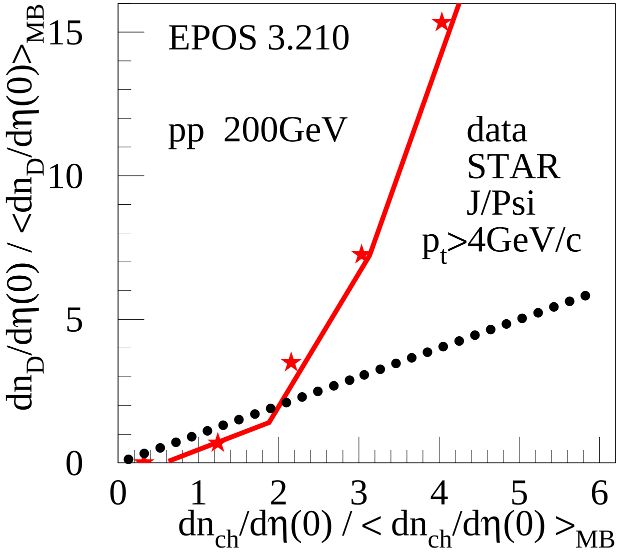
EPOS 3 compared to ALICE data



hadronic cascade on/off has no effect

hydro on/off has small effect

EPOS 3 compared to RHIC data

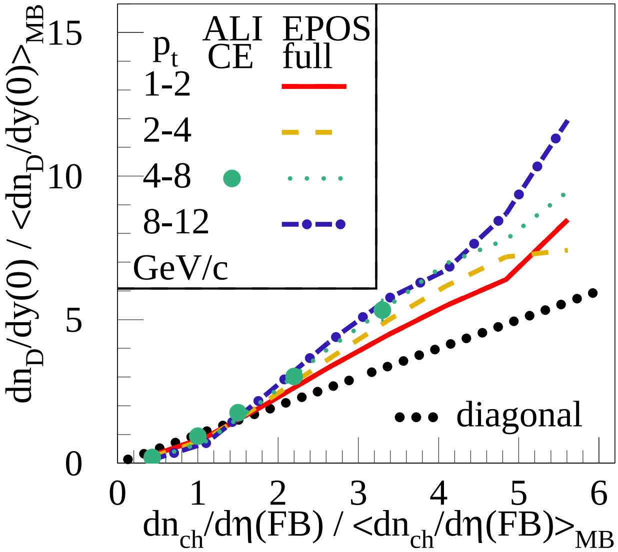


Calculations:
D mesons

Data: J/Ψ

Increase stronger than at LHC

Multiplicity at FB rapidity (LHC)



FB = forward/backward rapidity range:

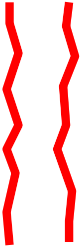
$$2.8 < \eta < 5.1$$
and
$$-3.7 < \eta < -1.7$$

Smaller increase

Low multi-plicity (LM)

Small N_{Pom}

few soft $\mathbb{P}$'s



$\mathbb{P}$ = Pomeron

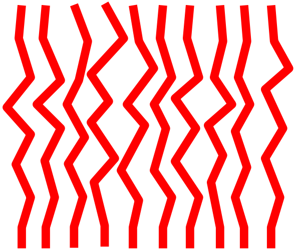
"Hardness" increases with N_{Pom}

(larger Q_s)

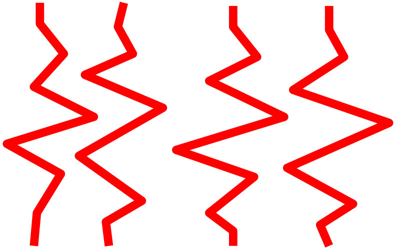
High multi-plicity (HM)

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:

<u>Pomerons</u> <u>get</u> <u>harder</u> (larger Q_s)

$\rightarrow$ 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)

Summary

- **To understand "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: 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**

Core => Hydro evolution (Yuri Karpenko)

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

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

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

- $T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$,
- $\partial_{;\nu}$ 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