Flow in proton-nucleus collisions at 5 TeV
Manifestation of flow:

Particle spectra affected by radial flow

\[ \frac{d\text{n}}{d\text{pt} d\text{y}} \]

\( \pi^{-}, K^{-}, \bar{p}, \Lambda \)

hydrodynamics (solid)
string decay (dotted)

\[ \langle p_{t} \rangle, \quad \text{lambda/K increase} \]
Ridges & flow harmonics

Ridges appear in

\[ R = \frac{1}{N_{\text{trigg}}} \frac{d\eta}{d\Delta\phi d\Delta\eta} \]

due to initial azimuthal anisotropies

(longitudinally invariant)
pPb data, interpreted in terms of hydrodynamic flow

Models:

analysis of pPb@5TeV

- Glauber model (wounded nucleon model) initial conditions
- Viscous hydrodynamic expansion, $\eta/s = 0.08$ or $0.16$
- Statistical hadronization using “Terminator”
A. Bzdak, B. Schenke, P. Tribedy, R. Venugopalan, arXiv:1304.3403

- Theoretical study of flow in pp, pA, dA
- Glauber model or Color Glass Condensate initial conditions
- Viscous hydrodynamic expansion, $\eta/s = 0.08$
EPOS3, B. Guiot, Y. Karpenko, T. Pierog, K. Werner

- Initial conditions:
  Gribov-Regge multiple scattering approach, elementary object = Pomeron = parton ladder, using saturation scale $Q_s \propto N_{part} \hat{s}^\lambda$

- Core-corona approach
  to separate fluid and jet hadrons

- Viscous hydrodynamic expansion, $\eta/s = 0.08$

- Statistical hadronization, final state hadronic cascade

**EPOS3 will be used in the following**
EPOS IC: Marriage pQCD+GRT+energy sharing
(Drescher, Hladik, Ostapchenko, Pierog, and Werner, Phys. Rept. 350, 2001)

\[ \sigma^{\text{tot}} = \sum_{\text{cut}} \int \sum_{\text{uncut}} \int \]

\[ \text{cut Pom : } G = \frac{1}{2\hat{s}} 2\text{Im} \{ \mathcal{F} \mathcal{T} \{ T \} \}(\hat{s}, b), \quad T = i\hat{s} \sigma_{\text{hard}}(\hat{s}) \exp(R_{\text{hard}}^2 t) \]

Nonlinear effects considered via saturation scale \( Q_s \propto N_{\text{part}} \hat{s}^\lambda \)
\[ \sigma^\text{tot} = \int d^2 b \int \prod_{i=1}^{A} d^2 b_i^A \ d z_i^A \ \rho_A(\sqrt{(b_i^A)^2 + (z_i^A)^2}) \]

\[ \prod_{j=1}^{B} d^2 b_j^B \ d z_j^B \ \rho_B(\sqrt{(b_j^B)^2 + (z_j^B)^2}) \]

\[ \sum_{m_1 l_1} \ldots \sum_{m_{AB} l_{AB}} \ (1 - \delta_0 \Sigma m_k) \ \int \prod_{k=1}^{A B} \left( \prod_{\mu = 1}^{m_k} d x_{k,\mu}^+ d x_{k,\mu}^- \prod_{\lambda = 1}^{l_k} d \tilde{x}_{k,\lambda}^+ d \tilde{x}_{k,\lambda}^- \right) \left\{ \right. \]

\[ \left. \prod_{k=1}^{A B} \left( \frac{1}{m_k!} \frac{1}{l_k!} \sum_{\mu = 1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, |\vec{b} + \vec{b}_A^{\pi(k)} - \vec{b}_B^{\tau(k)}|) \right) \right. \]

\[ \left. \prod_{\lambda = 1}^{l_k} -G(\tilde{x}_{k,\lambda}^+, \tilde{x}_{k,\lambda}^-, s, |\vec{b} + \vec{b}_A^{\pi(k)} - \vec{b}_B^{\tau(k)}|) \right) \]

\[ \prod_{i=1}^{A} \left( 1 - \sum_{\pi(k)=i} x_{k,\mu}^+ - \sum_{\pi(k)=i} \tilde{x}_{k,\lambda}^+ \right) \alpha \prod_{j=1}^{B} \left( 1 - \sum_{\tau(k)=j} x_{k,\mu}^- - \sum_{\tau(k)=j} \tilde{x}_{k,\lambda}^- \right) \]
The hydrodynamic equations (Israel-Stewart formulation) in arbitrary coordinate system (implemented/solved by Yuri Karpenko), always $\eta/S = 0.08$, $\zeta/S = 0$

\[
\begin{align*}
\partial_{;\nu} T^{\mu\nu} &= \partial_\nu T^{\mu\nu} + \Gamma^\mu_{\nu\lambda} T^{\nu\lambda} + \Gamma^\nu_{\nu\lambda} T^{\mu\lambda} = 0 \\
\gamma (\partial_t + v_i \partial_i) \pi^{\mu\nu} &= -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{NS}}{\pi} + I^{\mu\nu} \\
\gamma (\partial_t + v_i \partial_i) \Pi &= -\frac{\Pi - \Pi_{NS}}{\Pi} + I_{\Pi}
\end{align*}
\]

- $T^{\mu\nu} = \epsilon u^{\mu} u^{\nu} - (p + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu}$.
- $\partial_{;\nu}$ denotes a covariant derivative,
- $\Delta^{\mu\nu} = g^{\mu\nu} - u^{\mu} u^{\nu}$ is the projector orthogonal to $u^\mu$,
- $\pi^{\mu\nu}$ and $\Pi$ are the shear stress tensor and bulk pressure, respectively.

- $\pi^{\mu\nu}_{NS} = \eta(\Delta^{\mu\lambda} \partial_{;\lambda} u^{\nu} + \Delta^{\nu\lambda} \partial_{;\lambda} u^{\mu}) - \frac{2}{3} \eta \Delta^{\mu\nu} \partial_{;\lambda} u^{\lambda}$
- $\Pi_{NS} = -\zeta \partial_{;\lambda} u^{\lambda}$
- $I^{\mu\nu} = -\frac{4}{3} \pi^{\mu\nu} \partial_{;\gamma} u^{\gamma} - [u^{\nu} \pi^{\mu\beta} + u^{\mu} \pi^{\nu\beta}] u^{\lambda} \partial_{;\lambda} u_{\beta}$
- $I_{\Pi} = -\frac{4}{3} \Pi \partial_{;\gamma} u^{\gamma}$
EPOS3:

Pomeron $\rightarrow$ parton ladder $\rightarrow$ flux tube (kinky string)

String segments with high pt escape $\Rightarrow$ corona, the others form the core = initial condition for hydro depending on the local string density
CMS: Multiplicity dependence of pion, kaon, proton pt spectra
CMS, arXiv:1307.3442

We plot 4 “centrality” classes:

\[<N_{\text{tracks}}>=8, 84, 160, 235\text{ (in }|\eta|<2.4)\]

Multiplicity = centrality measure
in EPOS: high multiplicity = many Pomerons

Data compared to

- EPOS3 (hydrodynamic expansion, flow)
- QGSJETII (no flow effects, only string decay)
Pions

\(<\text{N\_tracks}> = 8, 84, 160, 235, \text{ from bottom to top, curves shifted by 0.9 spectra normalized to unity, lines = theory}\)

**Little change with <N_tracks> for pions**
**Kaons**

\[ <N_{\text{tracks}} > = 8, 84, 160, 235, \text{ from bottom to top, curves shifted by 0.9} \]

spectra normalized to unity, lines = theory

---

Kaons spectra change significantly with \( <N_{\text{tracks}} > \) in EPOS3: more and more flow contribution
Protons

\(<N_{\text{tracks}}> = 8, 84, 160, 235, \text{ from bottom to top}, \text{ curves shifted by 0.9}
spectra normalized to unity, lines } = \text{ theory}

Strong variation of proton spectra

=> flow helps
**ALICE: compare pt spectra for identified particles in different multiplicity classes: 0-5%, ..., 60-80%**

(in $2.8 < \eta_{\text{lab}} < 5.1$)

R. Preghenella, ALICE, talk Trento workshop 2013

Useful: ratios ($K/\pi$, $p/\pi$...)

**Significant variation of lambda/K – like in PbPb**
$K/\pi$

High multiplicity (0-5%, red), low multiplicity (60-80%, green)

lines = theory, points = data

No multiplicity dependence

not trivial to get the peripheral right!!
Significant multiplicity dependence

in EPOS, flow already affects the low multiplicity case

"flow peak" around 2-3 GeV/c, beyond 5 GeV/c corona (minjets) dominate
High multiplicity (0-5%, red), low multiplicity (60-80%, green)

Significant multiplicity dependence

again, flow already needed for low multiplicity (even in pp!)

flow dominates 2-5 GeV/c
“Ridges” in pA


\[ 2 < p_{T,\text{trigg}} < 4 \text{ GeV/c} \]
\[ p_{T,\text{assoc}} < 2 \text{ GeV/c} \]

p-Pb | \( s_{NN} = 5.02 \text{ TeV} \)

0-20%
Central - peripheral (to get rid of jets)

Double Ridge

ALICE

EPO3S3.074
Projection

\[ \sum 2a_n \cos(n\Delta \phi); \]

\[ \Rightarrow v_n = \sqrt{\frac{a_n}{b}} \]
Identified particle $v_2$

mass splitting, as in PbPb !!!
pPb in EPOS3

Pomerons (number and positions) characterize geometry (P. number $\propto$ multiplicity)

random azimuthal asymmetry

$\Rightarrow$

asymmetric flow seen at higher pt for heavier ptls

Robust results
$v_2$ for $\pi$, $K$, $p$ clearly differ

mass splitting, due to flow
different binning:

EPOS3.074

\[ v_2(\text{protons}) > v_2(\text{pions}) \text{ beyond } 2\text{GeV} \]
Summary

Analyzing pt-spectra, ratios, and dihadrons correlations for identified hadrons:

- **pPb looks very much like a hydrodynamically expanding system**
  (more clean than PbPb, where hydro and minijets heavily interact, as well as the final hadrons among themselves)
ALICE arXiv:1303.0737