Flow of strange and charm particles in Pb-Pb at ALICE

Characterising the QCD matter

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Collective phenomena and flow

Hot QCD matter is created in HIC: strongly interacting phase

No direct experimental access to it

One of the main probes to this phase is anisotropic flow

Anisotropic flow:

Initial space asymmetry is converted into momentum anisotropy of the produced particles

This anisotropy is quantified by Fourier decomposition of azimuthal distribution

\[ v_n = \langle \cos [ n (\phi - \psi_n) ] \rangle \]
What does $v_2$ tell us?

- Very low viscous fluid
- At LHC integrated $v_2$ increases by 30%
- Constrains $\eta/s$

![Graph showing the relationship between $v_2$ and $\sqrt{s_{NN}}$ (GeV)](image)

PRL 105.252302 (2010)
What does $v_2$ tell us?

- Very low viscous fluid
- At LHC integrated $v_2$ increases by 30%
  - Constrains $\eta/s$
- Differential $v_2$ similar to RHIC
- $<pt>$ increased compared to RHIC
- Sensitivity to $<\beta>$

$$\langle v_2 \rangle = \frac{\int v_2 \ (p_T) \ \frac{d}{dp_T} N \ \frac{d}{dp_T}}{\int \frac{d}{dp_T} N \ \frac{d}{dp_T}}$$

More on particle production: F. Bellini
Elliptic flow at LHC

Alice Pb – Pb at $\sqrt{s_{NN}} = 2.76$ TeV

Adapted from ArXiv 1205.5761
Three distinct regions for analysis

INTERMEDIATE REGION
Quark coalescence?

MORE SENSITIVE TO THE BULK
η/s and <β>

ENERGY LOSS

Adapted from ArXiv 1205.5761

Alice Pb – Pb at $\sqrt{s_{NN}} = 2.76$ TeV
Three distinct regions for analysis

- [low pt] measure the intensive properties of the medium (\(\eta/s\) and \(\beta\))
- [intermediate pt] give handle on the hadronization mechanism
- [high pt] measure the path length dependence in medium

Adapted from ArXiv 1205.5761
→ Mass dependence of $v_2$ observed at LHC energies

→ Viscous-hydrodynamical calculations reproduce $v_2$ mass splitting
 Probe for properties of the bulk

Mass dependence of elliptic flow observed at LHC energies

Viscous-hydrodynamical calculations reproduce $v_2$ mass splitting for pions, kaons

Hydro alone does not reproduce protons for most central collisions

Additional collectivity might develop during hadronic phase
(e.g. two-phased models: hydro+UrQMD)
Probe for properties of the bulk

- Mass dependence of elliptic flow observed at LHC energies
- Viscous-hydrodynamical calculations describe $v_2$ for pions, kaons and hyperons rather well
- Baryons develop higher elliptic flow than mesons
  → coalescence?
Three distinct regions for analysis

- [low pt] measure the intensive properties of the medium (η/s and β)
- [intermediate pt] give handle on the hadronization mechanism
- [high pt] measure the path length dependence in medium

Adapted from ArXiv 1205.5761
Quark coalescence?

- Deviation from quark scaling observed
- Original coalescence picture broken
Quark coalescence?

- Deviation from quark scaling observed
- Original coalescence picture broken
- Scaled by \((m_T - m_0)/n_q\) baryons (and mesons separately) cluster together
- Results with higher statistics may clarify the picture
Three distinct regions for analysis

- **[low pt]** measure the intensive properties of the medium (\(\eta/s\) and \(<\beta>\))

- **[intermediate pt]** give handle on the hadronization mechanism

- **[high pt]** measure the path length dependence in medium

> Adapted from ArXiv 1205.5761
Path dependence in medium

More on high-pt $v_2$: A. Nyatha

$\pi^0$ $v_2$ WHDG LHC
Extrapolation

$\nu_2 \{EP, |\Delta \eta| > 2.0\}$
$\nu_2 \{4\}$
$\nu_2 \{EP, |\Delta \eta| > 2.0\}$
$\nu_{4/3} \{EP, |\Delta \eta| > 2.0\}$
$\nu_{4/3} \nu_2 \{EP, |\Delta \eta| > 2.0\}$

$P_t$ (GeV/c)

$V_2$

$\nu_2$ is sizeable, positive and weakly pt dependent from 10 GeV/c for all centralities

WHGD (coll & rad energy loss of partons) explains fairly well the data

Proton and pion $v_2$ are different up to 8 GeV/c

Measurements of other identified particles with strange quark content are coming

ALICE Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

ALICE

$\pi^+ + \pi^-$ (10-50%)
$p + \bar{p}$ (10-50%)
$\pi^0$ PHENIX (10-50%)
$\pi^0$ WHDG LHC Extrapolation (20-50%)
Charm: an insightful probe

- Charm is produced in the initial collision, not in medium
- High sensitivity to the early state of system

- Less radiative effect than lighter quarks while going through the medium?
- Path attenuation in medium might depend on azimuthal direction wrt symmetry plane
- Where (and how) does charm hadronize?
How was the D0 $v_2$ measured?

**Two DeltaPhi Bins**
1. Divide phase space into two phi regions
2. Compute the asymmetry in yield

**Multi-band particle correlations**
1. Correlate candidates per mass band with Q
2. Fit simultaneously the yield and $v_2$
How was the D0 $v_2$ measured?

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Multi-band particle correlations
1. Correlate candidates per mass band with Q
2. Fit simultaneously the yield and $v_2$

Three different estimators arise to the same $v_2$
Does charm flow?

- There may be room for sensitivity to the bulk
- $3\sigma$ effect for open charm in CC 30-50%
- Charm picking up light quarks from the bulk?
Conclusions

- Anisotropic flow measurements provide strong constrains on $\eta/s$, $\beta$ and $\rho$ of the hot QCD matter

- The main features of $v_2$ below 2 GeV/c are consistent with hydrodynamic model calculations
  - $v_2$ mass splitting at LHC is larger than at RHIC top energy
  - $v_2$ of pion and kaon are described well by hydrodynamic models
  - Significant part of proton $v_2$ might be developed during hadronic phase

- We have a hint of open charm flow

Thanks
Frequently asked questions
How is the centrality determined?

Centrality estimated by scaling multiplicity using Glauber model

More details in PhysRevLett.106.032301
How does ALICE identify particles?

**Time Projection Chamber (TPC)**

- ALICE Performance
- Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV min. bias
- 18/05/2011

**Time Of Flight (TOF)**

**Reconstruction through decay topology**

- $K^0 \xrightarrow{69.2\%} \pi + \pi$
- $\Lambda^0 \xrightarrow{63.9\%} p + \pi$
- $D^0 \xrightarrow{3.89\%} K + \pi$
How does ALICE identify particles?

- Single track PID: we can go down to 0.15 GeV/c
- n-prongs and cascades also down to very low pt
What about conversions?

Very light material budget allows for high precision low pt tracking and vertex determination.
vn of identified particles says more

**Level 1: Hadron analysis**

- **Radial** flow boosts **spectra** of species
- **Elliptic** flow constrains $\eta/s$
  - Higher harmonics even more sensitive to shear viscosity

**Level 2: Parton analysis**

- Collectivity of **deconfined partons**
  - Handle on particle production mechanism

**Level 3: Hot QCD system analysis**

- All different components give strong constrains to the thermodynamic properties of the rapidly expanding QCD matter

Complementary information for all-in-one characterization (together with spectra, abundances, HBT, particle correlations, quenching, ... )
Mass dependence of elliptic flow also observed at LHC energies

Viscous hydro describes $v_2$ for pions and kaons rather well
  - For protons, there is a clear discrepancy

Low viscosity of the system allow for sizeable higher harmonics
  - Mass ordering from Hydro also observed

Hydro: Shen, Heinz, Huovinen & Song
arXiv:1105.3226
v3 as a more sensitive $\eta/s$ probe

- Low viscosity of the system allow for sizeable higher harmonics
  - $v3$ expected to be even more sensitive to $\eta/s$

- $v3$ also present mass ordering as predicted by hydrodynamical models
Probe for hadronization mechanism

Deviation from quark scaling for heavy particles observed

Original coalescence picture broken

For \((m_t - m_0)/n_q\) scaling, \(\xi\) and omegas cluster together with protons.

Meson-baryon “mechanism”?
Punch-through of jet though medium?

- Protons v2 is significantly higher than pion v2 up to 8 GeV/c
- Qualitatively explained by models

ArXiv 1205.5761

Graph showing v2 and v3 versus p_t (GeV/c) for different particle types in Pb-Pb collisions at √s_{NN}=2.76 TeV. The graph illustrates the difference in v2 and v3 between protons and pions up to 8 GeV/c.
How is the event plane determined?

The Q vector

\[ Q_n = \sum_{i=1}^{M} \text{Exp} \left[ i n \phi_i \right] \]

The “Event Plane” angle

\[ \psi_2 = \text{Arg} \left[ Q_2 \right] \]

Event plane estimated by TPC tracks

Pb-Pb at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

05/05/11

Stat. errors only

\( \Delta \eta > 0.4 \) (\( \eta \) sub-events)

Full event (random sub-events)
→ Charm picking up quarks from the bulk?

→ At low pt (2-5 GeV/c) there may be room for sensitivity to the bulk

→ 3 sigma effect for open charm in CC 30-50%

→ 2.2 sigma effect for in-plane anisotropy in forward quarkonia in 2-4 GeV/c
Does charm flow?

- Charm picking up quarks from the bulk?
  - At low pt (2-5 GeV/c) there may be room for sensitivity to the bulk
    - 3 sigma effect for open charm in CC 30-50%

- Some of the available models for charm reproduce the effect
  - But failed to ensemble it together with the nuclear modification factor

Exciting times ahead!