Limits of fluid dynamics in small systems

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High multiplicity events in pp
Ridge in pp

(a) CMS MinBias, $p_T > 0.1\text{GeV/c}$

(b) CMS MinBias, $1.0\text{GeV/c} < p_T < 2.0\text{GeV/c}$

(c) CMS $N \geq 110$, $p_T > 0.1\text{GeV/c}$

(d) CMS $N \geq 110$, $1.0\text{GeV/c} < p_T < 3.0\text{GeV/c}$

(can we measure (calculate) $v_2$)

PB arXiv:1010.0405
Fireball shape in pp

E. Asar et al., 1009.5643
Casalderrey-Solana, Wiedemann, 0911.4400

Bozek, 0911.2397
Proton-Nucleus Collisions at the LHC: Scientific Opportunities and Requirements

Abstract
Proton-nucleus (p+A) collisions have long been recognized as a crucial component of the physics programme with nuclear beams at high energies, in particular for their role in the HEP reference system to test QCD and understand nucleus-nucleus data as well as for their potential to elucidate the partonic structure at low mass. Here, we summarize the main motivations that make a proton-nucleus run a decisive ingredient for a successful heavy-ion programme at the Large Hadron Collider (LHC) and we present unique scientific opportunities arising from these collisions. We also review the status of ongoing Physics discussions about operation plans for the p+A mode at the LHC.

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1. EXECUTIVE SUMMARY

No FSI expected

2. INTRODUCTION

LHC-Project-Report-1181
Fireball in p-Pb

\[ N_{\text{part}} \]

\[ b \text{ [fm]} \]

\( \text{p-Pb Glauber Monte-Carlo} \)

\( \text{P}(N_{\text{part}}) \)

\( 8 \leq N_{\text{Part}} \leq 10 \) (32-49%)

\( 11 \leq N_{\text{Part}} \leq 17 \) (4-32%)

\( 18 \leq N_{\text{Part}} \) (0-4%)

PB, arXiv:1112.0912
Collective elliptic flow in p-Pb? in p-p?

- Large enough density? yes
- Large enough eccentricity yes?
- Large enough size? (?) but should and can be tested
- Small enough gradients? no - beyond viscous hydro
- Yes (high mult.)
- (?)
- (???)
- no!

Piotr Bożek
Mini-Flow
elliptic flow in p-Pb

PB, arXiv:1112.0912

triangular flow
large elliptic flow

PB, arXiv:1112.0912

... it seems very interesting to look for collective effects in d-Au collisions at $\sqrt{s_N} = 200$GeV in RHIC experiments ...
collective flow effects \(\simeq\) peripheral Pb-Pb

- can be observed
- p-Pb (d-Pb) is not p-p superposition
- only p-p as baseline

PB, arXiv:1112.0912
$v_2$ in pPb and PbPb

Dash-dot line: peripheral subtracted

$v_2$ shows similar shape in pPb and PbPb, but is smaller in pPb

$v_2\{4\}$ is only 20% smaller than $v_2\{2\}$ below 2 GeV/c

“Peripheral subtraction” has small effect at high multiplicity
$v_3$ in pPb and PbPb

Dash-dot line: peripheral subtracted

$v_3$ has similar shape in pPb and PbPb; magnitude comparable

"Peripheral subtraction" makes essentially no difference

Hydro prediction: Bozek, $v_3$[PP], not including fluctuations
Ridge in p-Pb

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 110$

$1 < p_T < 3$ GeV/c

symmetric ridge also from CGC, K. Dusling, R. Venugopalan, arXiv:1210.3890, 1211.3701, 1302.7018

PB, W. Broniowski, arXiv:1211.0845
Elliptic and triangular flow

\[ \sum E \downarrow \text{GeV} \]

\[ p \rightarrow \text{CMS Data 0-2\%} \]

\[ p \rightarrow \text{ALICE Data 0-20\%} \]

PB, W.Broniowski, G. Torrieri arXiv:1306.5442

Piotr Bożek: Mini-Flow
Higher cumulants

\[ v_2 \{2\}^2 \simeq v_2^2 + \delta^2 \]

\[ v_2 \{4\} = v_2 \{6\} = v_2 \{8\} \simeq v_2 \]

Bzdak, PB, McLerran

\[ v_2 \{4\} \simeq v_2 \{6\} \simeq v_2 \{8\} < v_2 \{2\} \]
$v_2$ from late stage

$T_f = 150\text{MeV}$
- pions : 0.75 collisions after emission

$T_f = 140\text{MeV}$
- pions : 0.65 collisions after emission
$v_3$ - small mass splitting

limited mass splitting

resonance decays spoil mass ordering
d-Au at 200GeV

![Graph showing $V_2$ vs. $p_T^{h_2}$ for d-Au at 200GeV.]

![Graph showing $v_2/\varepsilon_2$ vs. $dN_{ch}/d\eta|_{\eta=0}$ for various experiments.]
$^3\text{He-Au}$  $^{12}\text{C-Pb}$

PHENIX proposal $\rightarrow v_3$

$\alpha$ clusters in $^{12}\text{C}$ Broniowski, Arriola 1312.0289
Glauber + NB
fluctuations from subnuclear dynamics

\[ P(n) = \sum_i P_{\text{part}}(i) N p \lambda_i, \kappa_i(n) \]

Additional fluctuations of density (compared to Glauber)
very different source sizes

\[ \langle r^2 \rangle^{1/2} \text{ [fm]} \]

large source (standard)

\[ \text{pPb 5020GeV } N_{\text{part}}=19 \]

compact source

\[ \text{pPb 5020GeV } N_{\text{part}}=19 \]
HBT systematics

PB, W. Broniowski, arXiv:1301.3314

small system corrections! - Sinyukov, Shapoval - arXiv:1209.1747
larger $<p_{\perp}>$ in smaller systems

Bzdak, Skokov, arXiv:1306.5442
Spectra - $< p_{\perp} >$

**a) 3+1D Hydro**

p-Pb 5.02 TeV  
ALICE Data (preliminary)

**b) HIJING**

CMS  
\( p_{\text{Pb}}, \sqrt{s_{NN}} = 5.02 \text{ TeV}, L = 1 \mu \text{b}^{-1} \)

PB, W.Broniowski, G. Torrieri arXiv:1306.5442
$\langle p_\perp \rangle$ rapidity dependence

different prediction of CGC and hydro

PB, Bzdak, Skokov, 1309.7358
Asymmetric emission


\[
\rho(\eta, x, y) \propto f_+(\eta)N_+(x, y) + f_-(\eta)N_-(x, y)
\]

bremsstrahlung (Adil Gyulassy, Phys. Rev. C72, 034907 (2005))
Directed flow - tilted source

![Graph showing directed flow and tilted source](image)


\[
\begin{align*}
\partial_\tau u_x &= -\frac{\partial_x p_\perp}{p + \epsilon} \\
\partial_\tau Y &= -\frac{\partial_\eta p_\parallel}{\tau(p + \epsilon)}
\end{align*}
\]

tilted source $\rightarrow$ transverse pressure + longitudinal pressure

Glauber model
Asymmetric distributions

**ATLAS Preliminary**

\( \text{p+Pb L_{int}} = 1 \, \mu\text{b}^{-1} \)

\( \sqrt{s_{NN}} = 5.02 \, \text{TeV} \)

\( y_{cm} = -0.465 \)

- 0-1%
- 1-5%
- 5-10%
- 10-20%
- 20-30%
- 30-40%
- 40-60%
- 60-90%

**p-Pb 5.02 TeV**

- 0-20%
- 40-50%
pressure anisotropy

 PB, I. Wyskiel - arXiv:1009.0701
- early pressure anisotropy irrelevant!
FSI scenarios

fields + thermalization
- color fields

hydrodynamics
- hydrodynamic expansion

local thermalization $\rightarrow$ hadronization

hadronization, statistical emission

Give similar flow
Flow without jet quenching?
Collectivity in pPb@LHC explains $v_2$, $v_3$, ridge, $<p_\perp>$.
Observations consistent with collective flow many exp. results; several calculations.
Limits of hydro!

**Final State Interactions in p-Pb!**
- Why hydrodynamics would work?
- Effective theory for transverse expansion
- We need observables for longitudinal pressure
energy-momentum tensor

\[ T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p + \Pi & 0 & 0 \\ 0 & 0 & p + \Pi & 0 \\ 0 & 0 & 0 & p + \Pi \end{pmatrix} + \pi^{\mu\nu} \]

- shear viscosity

\[ \Delta^{\mu\alpha} \Delta^{\nu\beta} u^{\gamma} \partial_\gamma \pi_{\alpha\beta} = \frac{2\eta \sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{1}{2} \pi^{\mu\nu} \frac{\eta T}{\tau_\pi} \partial_\alpha \left( \frac{\tau_\pi u^\alpha}{\eta T} \right) \]

- bulk viscosity

\[ u^{\gamma} \partial_\gamma \Pi = \frac{-\zeta \partial_\gamma u^\gamma - \Pi}{\tau_\Pi} - \frac{1}{2} \Pi \frac{\zeta T}{\tau_\Pi} \partial_\alpha \left( \frac{\tau_\Pi u^\alpha}{\zeta T} \right) \]

- viscosity corrections from velocity gradients

- initial stress tensor - pressure anisotropy

- equation of state
fireball asymmetry - flow asymmetry

- Ev-by-Ev hydro response to geometry valid
- response strength depends on details
Extracting the flow correlations

$v_3(\Delta \eta), v_2(\Delta \eta)$ [%]

$0.3 < p_T < 3 \text{GeV}$
Charge balancing

local charge conservation

charge balance function

STAR data

Unlike-sign

Like-sign

PB, W.Broniowski, arXiv: 1204.3580
dependence on model details

- response strength depends on details, initial eccentricity
No final-state effects

- Excellent situation to extract initial-state effects

also see H. Paukkunen's and J. Qiu's talks yesterday

K. Tywoniuk (UB)