Recent results in small systems from CMS

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Large vs. small at the LHC

Pb-Pb
$\sqrt{s_{NN}} = 2.76$ TeV
$\sqrt{s_{NN}} = 5.02$ TeV

Xe-Xe
$\sqrt{s_{NN}} = 5.44$ TeV

p-Pb
$\sqrt{s_{NN}} = 5.02$ TeV
$\sqrt{s_{NN}} = 8$ TeV

pp
$\sqrt{s} = 2.76$ TeV
$\sqrt{s} = 5.02$ TeV
$\sqrt{s} = 7$ TeV
$\sqrt{s} = 8$ TeV
$\sqrt{s} = 13$ TeV

Strangeness in pp, pPb and PbPb collisions

CMS = 7 TeV)
$(-1)$ $6.2$ pb $= 5.02$ TeV)$NN$
$s$($(-1)$ $35$ nb $= 2.76$ TeV)$NN$
$s$($(-1)$ $b\mu^{2.3}$ trk offline $N_{10^2}$

Higher transverse kinematic energy
$\mathcal{h}_{KE}$ at higher multiplicities
for all systems

Faster increase
for heavier particles and smaller systems

Mass ordering also seen in $v_2$ in pp

E. Chapon (CERN)

Recent results from CMS

PLB 768, 103

PLB 765, 193

Parallel: Hong Ni, Thu 12:10

SQM 2017 17 / 19
What are ‘small’ systems?

‘Small’ qualifies the size of the colliding systems and/or the created medium

- **Traditional POV:** a priori too small to show characteristics of QGP physics
- **Alternative POV:** individual events show high particle multiplicity, energy density, etc
Main topics discussed in this talk:

**Looking at the observables** (there might be a personal bias!):

- Collective phenomena:
  - $p_T$ spectra, Fourier harmonics, event by event fluctuations,…

- Quarkonia and more hints for final state effects

- Cross section & Nuclear modification factors

**Flavours in CMS:-**

- **Light flavours**, strange and multi-strange hadrons
- **Heavy flavours**, charm and beauty: quarkonia, open HF
Strangeness in hadronic collisions

Probing collectivity with multiplicity

Hydrodynamic Blast-Wave model:

- Characterize spectral shapes and test collective radial flow
- Spectra from thermal sources $T_{\text{kin}}$ expanding with common velocity $<\beta_T>$

- Higher $<K_{E_T}>$ at higher multiplicities for all systems
- Faster increase for heavier particles and smaller systems
- Particle species dependence of $<K_{E_T}>$ is larger in small systems compared to Pb-Pb

Puzzle:
Onset of collectivity!
Blast-Wave fit parameters:

- Model dependent meaning of $T_{\text{kin}}$ and $\langle \beta_T \rangle$
- $p$-$p$ and $p$-$Pb$ show similar features as of $Pb$-$Pb$
- Large radial flow velocity in small systems:

$$\langle \beta_T \rangle_{pp} \ > \ \langle \beta_T \rangle_{pPb} \ > \ \langle \beta_T \rangle_{PbPb}$$
Strangness in hadronic collisions

Blast-Wave fit parameters:

- Model dependent meaning of $T_{\text{kin}}$ and $\langle \beta_T \rangle$
- p-p and p-Pb show similar features as of Pb-Pb
- Large radial flow velocity in small systems:
  
  $$\langle \beta_T \rangle_{pp} > \langle \beta_T \rangle_{pPb} > \langle \beta_T \rangle_{PbPb}$$

Several hints for collectivity from single particle spectra

Complementary information from two-particle correlations

PLB 768 (2017) 103
‘Ridge’: the small system puzzle

**Long-range** \((2 < |\Delta \eta| < 4)\), **near-side** \((\Delta \phi \approx 0)\) angular correlations in high multiplicity p-p and p-Pb collisions

Is this a sign of hydro in small systems?
Is it collective in small systems?
**Nature of the Ridge**

**PLB 765 (2017) 193**

Collectivity from large to small systems

\[ v_2 \{4, 6, 8\}: \]
- Similar for p-p and p-Pb: fluctuation-driven geometry
- Pb-Pb larger: accounted by average elliptic geometry

\[ \text{Basar, Teeny, arXiv:1408.3411} \]

- Multi-particle correlation
- Similar patterns for all systems
- Evidence of collectivity in p-Pb system!
Further proof of collectivity: geometry driven phenomena

First measurement of $v_3\{4\}$ in p-Pb collisions

More sensitive to initial state fluctuations

• Data & hydrodynamics-motivated fluctuation-driven IS calculations are in agreement

Prediction: \[
\frac{v_2\{4\}}{v_2\{2\}} = \frac{v_3\{4\}}{v_3\{2\}}
\]
Evidence for geometry driven

Prediction confirmed in p-Pb!

\[ \frac{v_2\{4\}}{v_2\{2\}} = \frac{v_3\{4\}}{v_3\{2\}} \]

Similar in p-Pb and PbPb

Small systems: evidence for fluctuation-driven initial state geometry
Correlation between harmonics

Study correlation between harmonics \((n, m)\):

- Via Symmetric Cumulant:
  \[ SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle \]
- Based on 4-particle cumulant calculations

Sensitive to:

- Initial State fluctuations \((v_2 \text{ vs. } v_3)\)
- Medium transport coefficient \((v_2 \text{ vs. } v_4)\)

Results from Pb-Pb:

- \(v_2, v_4\) correlated
- \(v_2, v_3\) anti-correlated

PRL 117 (2016) 182301
PRL 120 (2018) 092301

Figure: Graph showing the correlation between \(v_2\) and \(v_4\) versus \(v_2\) and \(v_3\) for Pb-Pb collisions.
Correlation between harmonics: the small system case

**Similarities observed for SCs in all systems**

- $(v_2, v_3)$ anti-correlated
- $(v_2, v_4)$ correlated
- Small energy dependence (see p-Pb results)

![Graph showing correlation between harmonics](image)

PRL 120 (2018) 092301
Correlation between harmonics: the small system case

Similarities observed for SCs in all systems

专业知识点1: \( (v_2, v_3) \) anti-correlated

专业知识点2: \( (v_2, v_4) \) correlated

专业知识点3: Small energy dependence (see p-Pb results)

In general: \( v_n(p-p) \neq v_n(p-Pb) \neq v_n(Pb-Pb) \)

⇒ Normalization needed for comparison

PRL 120 (2018) 092301
Normalized SCs (NSCs)

arXiv: 1905.09935
PRL 120 (2018) 092301

- Similar behaviour in p-Pb and Pb-Pb
- Points to similar IS fluctuations

**Common paradigm?**

- Ordering observed:
  - p-p > p-Pb > Pb-Pb
  - What is the origin?

Need of further non-flow suppression!
SCs with sub-events

- Non-flow suppressed at low multiplicities
- Similar results at high multiplicities for SC(2,3)
- Different results between *no-* and *n-subevents* for SC(2,4) at high multiplicities
  - SC(2,4) has a greater sensitivity to non-flow
Strange hadrons flow in small systems

- Significant $v_2$ signal. Follow mass ordering at low $p_T$ (radial flow)
- Similar pattern for all systems? Similar origin?

**Reminiscent of A-A observation!**
Heavy quark collectivity in small systems

PRL 121 (2018) 082301

PbPb 8.16TeV

CMS

\[ v_2^{D^0} \text{ is similar to } v_2^{K_S^0} \text{ at higher } p_T \]

\[ \text{May be some indication of } v_2(c) < v_2(u,d,s) \]?
What does NCQ scaling tell us?

Constituent quark number scaling: PRL 121 (2018) 082301

**Small system:**
- Shrink system size: $N_{\text{trk}} \sim 900 \rightarrow N_{\text{trk}} \sim 200$
- $D^0$ $v_2$ consistently lower: $v_2(c) < v_2(u,d,s)$
  - **Hydro like**: less flow/thermalization for charm quarks in p-Pb due to a much reduced small system size?
Charmonia can be sensitive to additional effects:
- Recombination of cc pairs
- Initial correlation from Plasma

Small systems:
$v_2 (c) < v_2 (u,d,s) \Rightarrow v_2 (J/\psi) < v_2(D^0)$ ?

- Large $v_2$ observed for charm quark
- Similar magnitude for $(J/\psi)$ and $D^0$
- Smaller than light flavour hadrons at low $p_T$
- The observed pattern is similar to A-A
- Uncertainties are still large
OK… what’s the problem?

(Surprisingly!?) large \( J/\psi \) \( v_2 \) signal

Final state interaction alone cannot explain this

LHC data. We are therefore forced to conclude that this signal must be in large part due to initial-state (or pre-equilibrium) effects not included in our approach. This situation
Heavy flavour: nuclear modification factors

Prompt J/\(\psi\) in pp and pPb:

- Small modification in p-Pb collisions
- \(R_{FB}\) shows a significant decrease for increasing \(y_{CM}\)

Role of Cold Nuclear Matter (CNM) effects!
• Higher suppression of the excited state ($\psi(2s)$) than the ground state ($J/\psi$) both in p-Pb and Pb-Pb collisions
• Points to different nuclear effects in the production of $\psi(2s)$ compared to $J/\psi$
The excited \( \Upsilon \) states are suppressed but any bias? — normalise to \( Z^0 \)

\( J/\psi \) to \( \Upsilon(1S) \) ratio vs. \( N_{\text{trk}} \) — suppress or enhance?
Summary

**Collectivity in small systems**

- Particle mass dependence of $p_T$ spectra
- Non-zero collective flow from multi-particle correlations
- Strong evidence for initial-geometry driven flow harmonics in HM ($N_{\text{trk}} > 100$) via high precision measurements

**Heavy flavour**

- Significant $D^0$ and $J/\psi$ elliptic flow measured in small system
- **QGP hypothesis:** $D^0$ results indicates less thermalized charm
- Intriguing results for $J/\psi$

**New opportunity ahead from higher statistics, more ion species and better instrumentations**

— *Stay tuned!*
Topics I couldn’t cover in this talk

•Jets and their modifications
•Open heavy flavour observables
•Vector bosons and constraints on nPDF
•Exclusive vector-meson photo production
•… and many more
• ‘Recent results on heavy flavour from CMS’
  — Russian Chistov

• ‘Recent results in small systems from CMS’
  — Prabhat Pujahari

• ‘CMS upgrade plan for high-luminosity era and outlook on heavy-quark production in nuclear collisions’
  — Byungsik Hong

• ‘Λc production in pp and PbPb collisions with the CMS detector’
  — Rui Xiao

• ‘Strange and non-strange charm production in pp and PbPb collisions’
  — Cheng-Chieh Peng

• ‘Measurement of strange and non-strange beauty production in PbPb collisions’
  — Fuqiang Wang

• ‘Bottomonium production in pp, pPb and PbPb collisions’
  — Daniele Fasanella

• ‘Study of jet fragmentation in J/ψ and D mesons with CMS’
  — Xiao Wang

Don’t miss all the fun & excitement! 😊