CMS results on heavy ion collisions

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The Quark-Gluon Plasma (QGP):
- a state of matter where the quarks and gluons are the relevant degrees of freedom
- existed few micro-second (µs) after the Big-Bang (the Universe crossed this phase after expanding and cooling down)

Studying the strong phase transition → study the primordial matter (QGP) -> guidance from lattice QCD calculations

Phase transition beyond a critical temperature (~155 MeV) and energy density (0.5 GeV/fm³)

Accessible in the laboratory → heavy-ion collisions at relativistic speed
CMS detector at the LHC

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- Weight: 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm): ~16 m² ~66M channels
- Microstrips (80x180 μm): ~200 m² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips: ~16 m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
Large vs. small at the LHC

Pb-Pb
\( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)
\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

Xe-Xe
\( \sqrt{s_{NN}} = 5.44 \text{ TeV} \)

pp
\( \sqrt{s} = 2.76 \text{ TeV} \)
\( \sqrt{s} = 5.02 \text{ TeV} \)
\( \sqrt{s} = 7 \text{ TeV} \)
\( \sqrt{s} = 8 \text{ TeV} \)
\( \sqrt{s} = 13 \text{ TeV} \)

p-Pb
\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
\( \sqrt{s_{NN}} = 8 \text{ TeV} \)
What are ‘small’ systems?

Traditional POV: a priori too small to show characteristics of QGP physics

Alternative POV: individual events show high particle multiplicity, energy density, etc

‘Small’ qualifies the size of the colliding systems and/or the created medium
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
Collective phenomena in hadronic collisions

Hydrodynamical evolution:

- Initial hot and dense partonic matter rapidly expands
- Collective flow develops and the system cools down
- Phase transition to hadron gas when $T_c$ is reached

Consequence:

- Mass dependence of the $p_T$ spectra
- Azimuthal anisotropic flow patterns (initial spatial anisotropy)
- The longitudinal width of the correlation is related to the time the correlation was established

Can we understand better the underlying mechanism behind this collective effects?
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
- Particle species dependence of $<K E_T>$ is larger in small systems compared to Pb-Pb

Puzzle:
Onset of collectivity!
- 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:

$$\langle \beta_T \rangle_{pp} > \langle \beta_T \rangle_{pPb} > \langle \beta_T \rangle_{PbPb}$$
• 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
Two-particle correlation and “Ridge”

Collective (anisotropic) flow

Probing: correlation functions and flow harmonics (elliptic, triangular, quantrangular, …)

Long-range ($2 < |\Delta \eta| < 4$), near-side ($\Delta \phi \approx 0$) angular correlations

Physics origin

(a) CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 \leq N_{\text{off}} < 260$

$1 < p_{T}^{\text{assoc}} < 3$ GeV/c

$1 < p_{T}^{\text{trig}} < 3$ GeV/c

Collective effect

PLB (2013) 06, 028
Flow paradigm in A-A collisions

Fourier bases: \( f(p_T, \eta, \phi) = N(p_T, \eta) \sum_{n=-\infty}^{+\infty} \vec{V}_n(p_T, \eta) e^{-in\phi} \)

Vn depends on:
- Initial state geometry
- Initial state fluctuations
- Medium transport coefficients

Well understood in A-A collisions with hydro.
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

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

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

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: $\frac{v_2\{4\}}{v_2\{2\}} = \frac{v_3\{4\}}{v_3\{2\}}$

arXiv:1904.11519
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 (\(v_2\) vs. \(v_3\))
- Medium transport coefficient (\(v_2\) 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

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Correlation between harmonics: the small system case

Similarities observed for SCs in all systems

.kafka· (v², v³) anti-correlated
.kafka· (v², v⁴) correlated
.kafka· Small energy dependence (see p-Pb results)
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)

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

⇒ Normalization needed for comparison

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PRL 120 (2018) 092301
Normalized SCs (NSCs)

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!

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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!
Strong $D^0$ flow:
- $D^0 v_2$ is similar to $K_s^0$ at higher $p_T$
- May be some indication of $v_2(c) < v_2 (u,d,s)$?
What does NCQ scaling tell us?

Constituent quark number scaling:

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?
Heavy flavour $v_n$ — adding the $J/\psi$

- 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
J/ψ v₂ : the puzzle is coming!

OK… what’s the problem?
(Surprisingly!?) large (J/ψ) v₂ 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
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!
Prompt J/ψ vs. prompt ψ(2s)

- Higher suppression of the excited state (ψ(2s)) than the ground state (J/ψ) both in p-Pb and Pb-Pb collisions
- Points to different nuclear effects in the production of ψ(2s) compared to J/ψ
Topics I could’t cover in this talk

- Heavy flavour production
- Constraining nPDF
- Modification of jet shapes

... and many more!
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!