New results on “soft" probes in PbPb collisions from Run 2

Zhoudunming Tu (Kong)
Rice University
On behalf of CMS collaboration
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Heavy ion collisions

Time

Initial state Energy Stopping Hard Collisions Hydrodynamic Evolution Hadron Freezeout
Heavy ion collisions

“Glauber-like” IS + (η/s ≈ 0.2)
Heavy ion collisions

"Glauber-like" IS + ($\eta/s \approx 0.2$)

CMS PbPb $\sqrt{s_{NN}}$ = 2.76 TeV

low shared viscosity $\rightarrow$ A “perfect” fluid
Previous measurement


- CMS from RUN 1 measured $v_2$ up to 60 GeV/c
- Can RUN 2 do better?
High-\( p_T \) trigger

- 2015 PbPb run at LHC
  - \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \), 404 \( \mu \text{b}^{-1} \)
  - MinimumBias \( (p_T < 14 \text{ GeV/c}) \)
- High \( p_T \) track trigger
  - \( |\eta| < 1.0 \), \( 14.0 < p_T < 100 \text{ GeV/c} \)

![Graph showing efficiency as a function of \( p_T \).]

![Graph showing efficiency as a function of Offline leading track \( p_T \).]
How to measure $v_n$

$\nu_2\{SP\}$

$Q_n = \sum_j w_j e^{i\phi_j}$

$\eta_{gap} > 3.0$

It’s measuring $v2$ RMS

$\eta_{gap} > 3.0$

$-0.75 < \eta(Q_{n_c}) < 0.75$

$Q_{n_A}$

$Q_{n_B}$

$Q_{n_c}$

$Q_n \{SP\} = \frac{\langle Q_n \cdot Q_{nA}^* \rangle}{\sqrt{\langle Q_{nA} \cdot Q_{nB}^* \rangle \langle Q_{nA} \cdot Q_{nC}^* \rangle}}$
How to measure $v_n$

Cumulant

$Q_n = \sum_j w_j e^{i\phi_j}$

HF

(-5 \leq \eta \leq -3.0)

-2.4

-1.0

1.0

2.4

HF

(3 \leq \eta \leq 5.0)
How to measure $v_n$

Cumulant

$Q_n = \sum_j w_j e^{in\phi_j}$

$\{4\}$

$\{6\}$

$\{8\}$

$\{4\}$

$\{6\}$

$\{8\}$

Reference flow

- $1.0 < p_T < 5.0$ GeV/c
- Full tracker region

$\nu_n \{4\} = \frac{4}{\sqrt{-c_n \{4\}}}$

$\nu_n \{6\} = \frac{6}{\sqrt{c_n \{6\}}} / 4$

$\nu_n \{8\} = \frac{8}{\sqrt{-c_n \{8\}}} / 33$
How to measure $v_n$

**Cumulant**

$Q_n = \sum_j w_j e^{i\phi_j}$

**Differential flow**
- 1 particle at a given $p_T$
- $(m-1)$ Ref particles

$v_n\{4\}(p_T) = \frac{-d_n\{4\}}{(-c_n\{4\})^{3/4}}$

$v_n\{6\}(p_T) = \frac{d_n\{6\}}{4} \left(\frac{c_n\{6\}}{4}\right)^{5/6}$

$v_n\{8\}(p_T) = \frac{-d_n\{8\}}{33} \left(\frac{-c_n\{8\}}{33}\right)^{7/8}$

**Reference flow**
- $1.0 < p_T < 5.0$ GeV/$c$
- Full tracker region

$v_n\{4\} = \frac{4}{3} \sqrt{-c_n\{4\}}$

$v_n\{6\} = \frac{6}{4} \sqrt{c_n\{6\}} / 4$

$v_n\{8\} = \frac{8}{33} \sqrt{-c_n\{8\}} / 33$
How to measure $v_n$:

Cumulant $\rightarrow v_2\{2\} \approx v_2\{SP\}$

**Differential flow**
- 1 particle at a given $p_T$
- $(m-1)$ Ref particles

$$v_n\{4\}(p_T) = \frac{-d_n\{4\}}{c_n\{4\}^{3/4}}$$

$$v_n\{6\}(p_T) = \frac{d_n\{6\}}{4 \left(\frac{c_n\{6\}}{4}\right)^{5/6}}$$

$$v_n\{8\}(p_T) = \frac{-d_n\{8\}}{33 \left(\frac{-c_n\{8\}}{33}\right)^{7/8}}$$

**Reference flow**
- $1.0 < p_T < 5.0$ GeV/c
- Full tracker region

$$v_n\{4\} = 4\sqrt{-c_n\{4\}}$$

$$v_n\{6\} = 6\sqrt{c_n\{6\}} / 4$$

$$v_n\{8\} = 8\sqrt{-c_n\{8\}} / 33$$
Soft probe, low $p_T \cdot v_2 @ 5\text{TeV}$

Consistent results observed with other experiment

Link
High-$p_T$ $v_n$ is NOT flow
High-\(p_T\) \(v_n\) is NOT flow
High-$p_T v_n$ is NOT flow

- A high energy jet interacts with the medium $\rightarrow$ “Jet quenching”

- High-$p_T v_2$ tells us the energy loss mechanism from:
  - Geometry, path length dependence
  - Initial state fluctuations
High-p$_T$ v$_2$

- Non-zero v$_2$ at very high p$_T$, indicating energy loss depends on "directions" and/or initial state fluctuations
High-\(p_T\) \(v_3\)

- **Non-zero** \(v_2\) at very high \(p_T\), indicating energy loss depends on “directions” and/or initial state fluctuations
- First time measurement of high \(p_T\) \(v_3\) up to 100 GeV!
High-$p_T v_2$ compare with theory

First time up to 100 GeV/c

- CUJET calculation can describe part of the data!
- Missing initial state fluctuations?
\( v_2 \text{ vs } R_{AA} \)

- \( v_2 \) and \( R_{AA} \) both describe the energy loss of the medium
- But it’s a puzzle to model them simultaneously

RUN1 DATA

- Models with initial state fluctuations. Puzzle solved?
- Looking forward to 5 TeV calculations!

arXiv:1602.03788
\( v_2 \) vs \( R_{AA} \)

- \( v_2 \) and \( R_{AA} \) both describe the energy loss of the medium
- But it’s a puzzle to model them simultaneously

CMS has measured both \( v_n \) and \( R_{AA} \) up to very high \( p_T \) @ 5 TeV!
Multi-particle $v_2$

$v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$

- Collectivity observed in soft region from Run 1
Multi-particle $v_2$

$v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 5.02$ TeV

- Multi-particle $v_2$ measured up to 100 GeV/c
- Collectivity holds up to high $p_T$
Soft correlates with Hard?
Soft correlates with Hard?

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 5.02$ TeV

$v_2$ is linear between soft and hard particles as in different centralities
Soft correlates with Hard?

- $v_2$ is linear between soft and hard particles as in different centralities

- Indicates similar origin of the correlation (Geometry + fluctuations)
What do we learn so far?

• $V_n$ has been measured at the highest nuclear-nuclear energy @ 5TeV
  
  • $V_2$ & $V_3$ measured up to 100 GeV/c $\Rightarrow$ constrain the energy loss models

• Multi-particle correlation $\Rightarrow$ collectivity from soft region to intermediate (hard) region

• Strong correlation between soft (low $p_T$) and hard (high $p_T$) particles $\Rightarrow$ same origin

[Link to Physics Analysis Summary (PAS)]

Stay tuned! pPb @ 8 TeV is coming later this year
Backups
Backups

\[ v_2^{\{m\}} / v_2^{\{SP\}} \]

CMS Preliminary

PbPb \( \sqrt{s_{NN}} = 5.02 \) TeV

5 - 10%  10 - 20%  20 - 30%
30 - 40%  40 - 50%  50 - 60%

\[ p_T \ (\text{GeV/c}) \]

\[ \begin{align*}
& v_2^{\{4\}} / v_2^{\{SP\}} \\
& v_2^{\{6\}} / v_2^{\{SP\}} \\
& v_2^{\{8\}} / v_2^{\{SP\}}
\end{align*} \]
Backups

CMS Preliminary
PbPb $\sqrt{s_{\text{NN}}} = 5.02$ TeV

ALICE, |$\eta$| < 0.8
- $v_2^2$, |$\Delta \eta$| > 1
- $v_3^2$, |$\Delta \eta$| > 1
- $v_4^2$

CMS, |$\eta$| < 1.0
- $v_2^2$, |$\Delta \eta$| > 3
- $v_3^2$, |$\Delta \eta$| > 3
- $v_4^2$

0-5%

10-20%

30-40%

20-30%

$V_n$

$p_T$ (GeV/c)

FIRST time measure of $v_3\{\text{SP}\}$ up to 100 GeV/c
Consistent with 0 for $p_T > 20$ GeV/c
Backups

$25.8 \text{ pb}^{-1} \text{(5.02 TeV pp)} + 404 \mu\text{b}^{-1} \text{(5.02 TeV PbPb)}$

**CMS**

*Preliminary*

$R_{AA}$ and lumi. uncertainty

$|\eta|<1$

$0-100\%$

$p_T (\text{GeV})$
25.8 pb⁻¹ (5.02 TeV pp) + 404 µb⁻¹ (5.02 TeV PbPb)

**CMS Preliminary**

- **SCETₐ 0-10%**
- **CUJET 3.0 0-10% (h²+π⁰)**

**Tₐₐ and lumi. uncertainty** $|η|<1$

- **0-10%**
- **30-50%**