Prompt $D^0 v_n$ harmonics in PbPb at 5.02 TeV with CMS

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Motivation

- Heavy quarks are primarily produced at the early stages of the collisions
  - Experience the full evolution of the medium
  - Good probes of the medium

- At low $p_T$, to what extent heavy quarks flow with the medium is a good measure of the interaction strength.
  - Information on the degree of medium thermalization

- At high $p_T$, $v_n$ harmonics are sensitive to the path length dependence of the heavy quark energy loss
  - Complementary to $R_{AA}$
Dataset and trigger

- 2015 PbPb run at 5.02 TeV
- Large minbias and centrality triggered PbPb sample
  - 0-100%: 170M events
  - 30-100%: 270M events

→ Measurement of $D^0 v_2$ and $v_3$ in PbPb at 5.02 TeV
  - Centrality classes 0-10%, 10-30% and 30-50%
  - Wide $p_T$ range (1-40 GeV)
  - CMS PAS HIN-16-007
Analysis workflow

- $D^0$ reconstruction
  - Candidates with two tracks
  - Topological selections

- Extract $D^0 \, \nu_n$ in data
  - Scalar product method
  - Fit on mass spectra and $\nu_n$ vs mass

- Evaluate the effect from non-prompt $D^0$
  - Prompt $D^0$ fraction from impact parameter fit
D^0 Reconstruction

- D^0 → K\pi, BR = 3.88\pm0.05\%, c\tau(D^0) = 122.9 \ \mu m

- D^0 candidates
  - Pairing oppositely charged tracks
  - Secondary vertex reconstruction

- Topological selections:
  - 3D decay length significance (d_0/\sigma(d_0))
  - Pointing angle \alpha
  - Secondary vertex probability
  - Impact parameter of D^0 candidates (b_0)
    - b_0 < 80 \ \mu m (0.008 cm)
Invariant mass spectra fit

**Invariant mass fitted with:**
- 3rd order polynomial for combinatorial background
- Double gaussian for signal
- Single gaussian for $k-\pi$ swapped candidates
  - No PID. Candidates with wrong mass assignment on tracks
Scalar Product Method

\[ Q_n = \sum_j w_j e^{in\phi_j} \]

Sum over tracks (tracker), or towers (HF)

\( w_j \): tower \( E_T \) for HF, track \( p_T \) for tracker

\[ v_n \{ \text{SP} \} = \sqrt{\frac{\langle Q_n \cdot Q_{nA}^* \rangle}{\langle Q_{nA} \cdot Q_{nB}^* \rangle}} \frac{\langle Q_{nA} \cdot Q_{nC}^* \rangle}{\langle Q_{nB} \cdot Q_{nC}^* \rangle} \]

Large \( \eta \) gap applied (\(|\Delta \eta|>3.0\))

\( v_n \{ \text{SP} \} \), non-ambiguous measure of \( \sqrt{\langle v_n^2 \rangle} \)

Luzum, Ollitrault PRC87 (2013), 044907
Extract $v_n$ of $D^0$

$$
\nu_n^{ Sig+Bkg}(m_{inv}) = \alpha(m_{inv})\nu_n^{ sig} + (1 - \alpha(m_{inv}))\nu_n^{ Bkg}(m_{inv})
$$

$$
\alpha(m_{inv}) = (Signal(m_{inv}) + Swapped(m_{inv}))/ (Signal(m_{inv}) + Swapped(m_{inv}) + Bkg(m_{inv}))
$$

- $\alpha(m_{inv})$ is the signal fraction from mass spectrum fit
- $\nu_n^{ S+B}$ is $v_n$ of $D^0$ candidates in each mass bin.
- $\nu_n^{ Sig}$ is the $v_n$ of $D^0$, a fit parameter
- $\nu_n^{ Bkg}$ is $v_n$ of combinatorial background candidates and modeled by a linear function of mass
Extract $v_n$ of $D^0$

- Simultaneous fit on invariant mass distribution and $v_n$ vs mass is performed
Systematic uncertainty from non-prompt $D^0$

- $D^0$ in data is a mixture of prompt and non-prompt $D^0$
  \[ v_n^{\text{sig}} = f_{\text{prompt}} v_n^{\text{prompt}} + (1-f_{\text{prompt}}) v_n^{\text{non-prompt}} \]

- To evaluate the effect from non-prompt $D^0$, prompt $D^0$ fraction is needed

- Different $b_0$ distributions of prompt $D^0$ and non-prompt $D^0$
- Template fit on $b_0$ distributions to evaluate prompt $D^0$ fraction
  - Fit in whole $b_0$ region
The prompt $D^0$ fraction is around 75-95% after all analysis cuts.

The impact parameter cut suppress the non-prompt $D^0$ by around 50%.
Systematic uncertainties from non-prompt $D^0$ are evaluated in a data driven method based on:

- $v_n$ of $D^0$ with all analysis cut and w/o $b_0$ cut
- Fractions of prompt $D^0$ with all analysis cut and w/o $b_0$ cut

**All analysis cut:**

$$v_{n,1}^{\text{sig}} = f_{p,1} v_{n}^{p} + (1-f_{p,1}) v_{n}^{np}$$

**Without $b_0$ cut:**

$$v_{n,2}^{\text{sig}} = f_{p,2} v_{n}^{p} + (1-f_{p,2}) v_{n}^{np}$$

$$v_{n}^{p} = v_{n,1}^{\text{sig}} + \frac{1-f_{p,1}}{f_{p,1}-f_{p,2}} (v_{n,1}^{\text{sig}} - v_{n,2}^{\text{sig}})$$

$D^0$ $v_n$ with all analysis cuts as central value

As systematics from non-prompt $D^0$
Prompt $D^0 v_2$ results

- Positive prompt $D^0 v_2$ observed in studied $p_T$ range
  - Low $p_T$: charm quarks take part in the collective motion of the system
  - High $p_T$: indicates path length dependence of energy loss

- Peaks around 3 GeV, then decrease vs $p_T$

- Low $p_T$: $v_2$ (0-10%) $< v_2$ (10-30%) $\approx v_2$ (30-50%)
Prompt $D^0$ $v_2$ compared with $v_2$ of charged particle

- In 0-10%, consistent with $v_2$ of charged particles
- In 10-30% and 30-50%
  - Low $p_T$: $v_2$ (prompt $D^0$) < $v_2$ (charged particle)
  - High $p_T$: $v_2$ (prompt $D^0$) ≈ $v_2$ (charged particle)
- Similar shape
- At low $p_T$, smaller centrality dependence in 10-50% than charged particle $v_2$
Prompt $D^0 v_2$ compared with model calculations

- **LBT**: linearized Boltzmann transport model for jet propagation in QGP
- **TAMU**: non-perturbative transport model with thermodynamic T-matrix approach
- **CUJET3**: jet quenching model based on DGLV
- **L. Pang**: second order viscosity hydrodynamic model

**Theory prediction for prompt $D^0$**

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

- **Cent. 0-10%**
  - |y| < 1.0
  - Charged particle
  - CMS-PAS-HIN-15-014

- **Filled box**: syst. from non-prompt $D^0$
- **Open box**: other syst.

- **Theory prediction for prompt $D^0$**
  - LBT
  - TAMU
  - CUJET3

- **LBT**: Cao, Luo, Qin, Wang PRC 94 014909 (2016)
- **TAMU**: He, Fries, Rapp PLB 735 (2014) 445
- **CUJET3**: Xu, Liao, Gyulassy JHEP 1602 (2016) 169
Prompt $D^0 v_3$ results

- First measurement of $D^0 v_3$
- $p_T$ dependence
  - Low $p_T$: $v_3$ (prompt $D^0$) $> 0$;
  - High $p_T$: $v_3$ (prompt $D^0$) $\approx 0$
  - Peaks around 3 GeV, then decrease vs $p_T$
- Little centrality dependence
Prompt $D^0$ $v_3$ compared with $v_3$ of charged particle

- In 0-10%, consistent with $v_3$ of charged particles
- In 10-30% and 30-50%
  - Low $p_T$: $v_3$ (prompt $D^0$) $<$ $v_3$ (charged particle)
  - High $p_T$: $v_3$ (prompt $D^0$) $\approx$ $v_3$ (charged particle)
- Similar shape
- Both have little centrality dependence
Prompt D⁰ v₃ compared with model calculations

LBT: linearized Boltzmann transport model for jet propagation in QGP

LBT: Cao, Luo, Qin, Wang PRC 94 014909 (2016)
Summary

- Prompt $D^0$ $v_2$ and $v_3$ is measured for centrality 0-10%, 10-30% and 30-50%
  - First measurement of $D^0$ $v_3$
  - Positive $v_2$ in both low and high $p_T$ ranges
  - Positive $v_3$ in low $p_T$ range

- The prompt $D^0$ $v_2$ and $v_3$ is compared with those of charged particle
  - Low $p_T$: $v_n$ (prompt $D^0$) < $v_n$ (charged particle)
  - High $p_T$: $v_n$ (prompt $D^0$) ≈ $v_n$ (charged particle)

- The results provide important input for theoretical studies
CMS has measured $R_{AA}$ of prompt $D^0$ in PbPb both at 2.76 TeV and 5.02 TeV.

$D^0$ flow and $R_{AA}$ can be used simultaneously to constrain models.

See J. Wang’s talk on $D^0$ $R_{AA}$, 24 Sep. 14:40
More mass spectra fit

Top: \( p_T \) 1-2 GeV for centrality 10-30% and 30-50%

Bottom: \( p_T \) 2-3 GeV for centrality 0-10%, 10-30% and 30-50%
D^0 v_2 compared with ALICE and STAR results

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

CMS preliminary results are consistent with ALICE results within uncertainties

M. Lomnitz, QM 2015 talk
**Δφ Bins Method**

- D⁰ v<sub>n</sub> can also be measured by fitting d⁰N/(dp<sub>T</sub>dΔφ) with:
  \[ N_0(1+2v_n^{obs}\cos(n\Delta\phi)) \]
  - Δφ between D⁰ candidates and event planes
  - Large η gap applied (|Δη|>3.0)

- v<sub>n</sub><sup>obs</sup> corrected by event plane resolution: v<sub>n</sub><sup>sig</sup> = v<sub>n</sub><sup>obs</sup>/R<sub>n</sub>

- Measuring ambiguous value between average v<sub>n</sub> and RMS of V<sub>n</sub>

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Luzum, Ollitrault PRC87 (2013), 044907
D⁰ v₂ from SP and Δφ bins method

Results from SP method and Δφ bins method are consistent within uncertainties
❖ Small differences are expected
Results from SP method and $\Delta \phi$ bins method are consistent within uncertainties

- Small differences are expected
Prompt $D^0 R_{AA}$ compared with LBT model

S. Cao SQM 2016 talk
G. Qin SQM 2016 talk

CMS PAS HIN-16-001
CMS PAS HIN-15-015

LBT: Cao, Luo, Qin, Wang PRC 94 014909 (2016)