Probe initial stages and final state interactions with heavy flavor spectra and D\bar{D} correlations in PbPb

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for the CMS Collaboration

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The MIT HIG’s work is supported by US DOE-NP
- **Slow but hard:**
  produced in early hard process even at low $p_T$
  $(Q \sim m_c, m_b, \tau \sim 1/Q)$
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- **“Simple”**: Brownian motion diffusion, diffusion coefficient $D_s$ ($m_c, m_b \gg T_{QGP}$)

\[
\frac{\partial}{\partial t} \langle \vec{p}, t \rangle = \frac{2}{\Delta p} \left( M \cdot \vec{f}(\vec{p}, t) + \frac{2}{\Delta p} \cdot (D_s \cdot \vec{f}(\vec{p}, t)) \right)
\]
- **Slow but hard**: produced in early hard process even at low $p_T$ ($Q \sim m_c, m_b$, $\tau \sim 1/Q$)

- **“Simple”**: Brownian motion diffusion, diffusion coefficient $D_s$ ($m_c, m_b \gg \Lambda_{QCD}$)

- **“Feasible”**: production calculable with pQCD at low $p_T$ ($m_c, m_b \gg T_{QGP}$)
- Slow but hard: produced in early hard process even at low $p_T$ ($Q \sim m_c, m_b, \tau \sim 1/Q$)

- “Feasible”: production calculable with pQCD at low $p_T$ ($m_c, m_b \gg \Lambda_{QCD}$)

- “Simple”: Brownian motion diffusion, diffusion coefficient $D_s$ ($m_c, m_b \gg T_{QGP}$)

- Clean: hardly produced in medium ($m_c, m_b \gg T_{QGP}$)

Probe IS + FS interactions: why HF? (4/4)
Probe Initial Stage: Prompt $D^0 v_3$

- Prompt $D^0 + \bar{D}^0$, $2.0 < p_T < 8.0$ GeV/c
- $v_2$, $|y| < 1$
- $v_3$, $|y| < 1$
- $v_2$, $1 < |y| < 2$
- $v_3$, $1 < |y| < 2$

- Non-zero $v_3$
- Heavy quarks can also probe initial geometry
- No obvious centrality dependence as expected
- Opposite to $v_2$
- No rapidity dependence

Prompt $D^0 v_3$ coefficients:

- No obvious centrality dependence as expected

Submitted to PLB

Probe Initial Stage: Prompt $D^0$ $v_2\{4\}$

- Prompt $D^0$ $v_2\{4\}$ compared to $v_2\{2\}$
  - Probe event-by-event fluctuations

\[ v_n(2)^2 \approx \langle v^2 \rangle + \bar{\delta} + \sigma^2, \quad v_n(4)^2 \approx \langle v^2 \rangle - \sigma^2 \]

- Fluctuations include initial geometry (low-$p_T$) and energy loss (high-$p_T$) fluctuation
- $D^0$ $v_2\{4\} < v_2\{2\}$: charm quark can probe the E-by-E fluctuation by multi-particle correlation

More details see Liuyao’s talk

CMS-PAS-HIN-20-001
PRC 102 (2020) 024906
• Classic observables: $R_{AA}$ and $v_2$ have been measured widely in heavy flavor regime

CMS

$R_{AA}$

27.4 pb\(^{-1}\) (5.02 TeV pp) + 530 \(\mu\)b\(^{-1}\) (5.02 TeV PbPb)

CMS | PbPb 0.58 nb\(^{-1}\) (5.02 TeV)

$R_{AA}$ and lumi. uncertainty

$\frac{p_T}{(\text{GeV/c})}$

$|y| < 2.4$ and lumi.

$\frac{p_T}{(\text{GeV/c})}$

Prompt $D^0 + \overline{D}^0$

| $|y| < 1$ | $1 < |y| < 2$ |

$|y| < 2.4$

CMS

Submitted to PLB

**Extract Diffusion coefficient $D_s$**

- $D_s$ can be extracted by combining $R_{AA}$ and $v_2$ measurements.

*Figure:*

- **$D_s$ extracted (Catania)**
  - $D_s$ can be extracted by combining $R_{AA}$ and $v_2$ measurements.

- **$D_s$ extracted (LBT)**
Diffusion coefficient $D_s$ at statistics limit

- $D_s$ can be extracted by combining $R_{AA}$ and $v_2$ measurements
- $D_s$ still not ideally determined at statistics limit

Jing Wang (MIT), 1.11.2021, Initial Stages 2021
Observables: $R_{AA}$ and $v_2$

- $R_{AA}$ and $v_2$ have weak discrimination power for energy loss mechanisms, diffusion coefficients and other model ingredients.
Observables: Correlation

- Correlation is a more sensitive observable than inclusive $R_{AA}$ and $v_2$
- D-jet correlation measured with 2015 data
  - first measurement of $D^0$ w.r.t. dominant energy flow axis
  - will update with 2018 data (higher statistics)
Observables: Correlation

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  ➔ first measurement of $D^0$ w.r.t. dominant energy flow axis
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- However
  ➔ Convoluted with complex jet shape modification and complication of jet calculation

D-jet correlation vs. models

PRL 125 (2020) 102001
Observables: D-\bar{D} Correlation

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- D-jet correlation measured with 2015 data
  ➔ first measurement of $D^0$ w.r.t. dominant energy flow axis
  ➔ will update with 2018 data (higher statistics)
- However
  ➔ Convoluted with complex jet shape modification and complication of jet calculation
- D-\bar{D} correlation
  ➔ Double the magnitude of diffusion effect
  ➔ Low $p_T$ accessible

PRL 125 (2020) 102001
D-\bar{D} Correlation Analysis

Analyzer

We are still working on it…
2018 data stats are feasible for this analysis

Analyzer

Looking forward to theoretical predictions!
D-\bar{D} Correlation in PYTHIA8

- Disclaimer: PYTHIA is LO generator
  - NLO processes not accurate

Simulation

CMS 5.02 TeV

PYTHIA8 5.02 TeV

- Total
- Pair creation
- Flavor excitation
- Gluon splitting
- Not pair
- Multi charm
- Other

$p_T^{trig} > 4$ GeV
$p_T^{asso} > 2$ GeV
$|\eta^D| < 5$

$\Delta \phi(D^0, \bar{D}^0) / \pi$

$|D^0's mothers have more than 1 charm |

$|\text{not pair}|

$|\text{two D}^0 \text{ from different } c\bar{c} \text{ pair}|$
D-$\bar{D}$ Correlation in pPb

- D-$\bar{D}$ Correlation has been explored in pPb
  - to study SPS and DPS processes
  - theoretically [0] and experimentally [1]

$\Delta\Phi(D\bar{D})$ in pPb

- $\sqrt{s} = 8.16$ TeV
- $2 < y < 4$
- $3 < p_T < 12$ GeV

Single parton scattering

Double parton scattering

More details see Hannu’s talk

[0] PLB 800 (2020) 135084

PRD 85 (2012) 094034
Summary

• Prompt $D^0 v_3$ and $v_2\{4\}$ have been measured to probe the initial stages of QGP

• Correlation between $D^0$ and jets have been measured ➞ more sensitive observable than $R_{AA}$ and $v_2$

• $D-\bar{D}$ correlation measurement is under analyzing ➞ avoid complication in jet calculation ➞ lower $p_T$ regime accessible

Thanks for your attention!
Back up

Thanks for your attention!
v_2\{4\}: D^0 vs. charged particles

Charged particles: initial geometry (soft) fluctuation dominates

D^0 vs. charged particles: energy loss (hard) fluctuation

Theory curves

- HQ interaction models (DAB-MOD)
  - Energy loss: parameterize dE/dx
  - Langevin: parameterize D_s

- Initial conditions
  - MCKLN: a CGC k_T-factorization model
  - Trento: tuned to IP-Glasma

CMS Preliminary PbPb 0.58 nb\(^{-1}\) (5.02 TeV)

Prompt D^0+\bar{D}^0, |y| < 1

2.0 < p_T < 8.0 GeV

Calculation for prompt D^0

v_2\{2\}, v_2\{4\}, Energy Loss

Calculation for prompt D^0

Energy loss, Langevin

CMS-PAS-HIN-20-001

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D-$\bar{D}$ Correlation in pPb

LHCb, pPb
\[ \sqrt{s_{NN}} = 8.16 \text{ TeV} \]

\[ p_T(D) > 2 \text{ GeV/c} \]

\[ \frac{1}{\sigma} \frac{d\sigma}{d(\Delta\phi/\pi)} \]

\[ \Delta\phi(DD)/\pi \]

[Graph showing correlation data]

\[ \sqrt{s} = 8.16 \text{ TeV} \]
\[ 2 < y < 4 \]
\[ 3 < p_T < 12 \text{ GeV} \]

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