Measurement of $D^0$ Meson Production and Azimuthal Anisotropy in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

Guannan Xie

University of Science and Technology of China
Lawrence Berkeley National Laboratory
(for the STAR Collaboration)
Motivation

Charm quarks: $m_c >> T_C$, $\Lambda_{QCD}$, $m_{u,d,s}$ $T_{QGP}(RHIC/LHC)$
- Produced early in collision at RHIC through hard scattering
- Experience the whole evolution of the system -> good probe for medium properties

Perturbative QCD calculations (FONLL) are consistent with experimental data.

Charm cross section follows number of binary collisions scaling at RHIC.

STAR Preliminary

\[ d\sigma/dp_T|_{y=0} \]

Transverse Momentum $p_T$ (GeV/c)

<table>
<thead>
<tr>
<th>$p + p(\bar{p}) \rightarrow D^0/D^+ + X$</th>
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<tr>
<td>$D^0$ (CDF)</td>
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<td>$D^+D^-$ (STAR)</td>
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| $pp$ 7 TeV [x10^3] |
| $pp$ 1.96 TeV [x10^3] |
| $pp$ 500 GeV [x10] |
| $pp$ 200 GeV |

FONLL

\[ \sqrt{S_{NN}} = 200 \text{ GeV} \]

Sys. error

NLO err.

$pp$ in $p+p$

$Au+Au (D^0)$

$D^0(D^0+D^+)$

$dd+Au (D^0+e)$

$FONLL$ in $p+p$

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Hard Probes 2016, Wuhan, China
**STAR Detector**

- **Time Projection Chamber:** Tracking, PID ($dE/dx$)
- **Time Of Flight detector:** PID ($1/\beta$)
- **Heavy Flavor Tracker**

**HFT:**
- **Silicon Strip Detector:** $r \sim 22$ cm
- **Intermediate Silicon Tracker:** $r \sim 14$ cm
- **PIXEL detector:** $r \sim 2.8 & 8$ cm, MAPS, $20 \times 20 \, \mu m^2$, $0.4%X_0$ per layer, air-cooled

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HFT Performance

Au+Au @ 200GeV Run 2014, with Heavy Flavor Tracker
~780M minimum bias events analyzed (out of 1.2B events recorded in 2014)

PIXEL detector

DCA (Distance of Closest Approach) resolution
• DCA resolution < 50 µm for Kaons at p = 750 MeV/c, and ~ 30 µm for p > 1.2 GeV/c, achieved from Run 2014 using Al-cables.
• With Al-cables for entire PXL in Run 2016, the overall pointing resolution will be better.
Direct topological reconstruction through hadronic channel:

\[ D^0(D^0) \rightarrow K^\pm \pi^\pm \text{(BR 3.89\%)} \]

\[ c\tau \approx 120 \mu m \]

With HFT:
Greatly reduced combinatorial background

Topological cuts optimized by TMVA (Toolkit for Multi-Variate Analysis)
Clean $D^0$ signals reconstructed with significantly enhanced signal-to-background ratios with the HFT in a broad range of transverse momentum.
D\(^0\) Nuclear Modification Factors (R\(_{AA}\))

- High \(p_T\): significant suppression in central Au+Au collisions. New results have improved precision.

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v$_2$: Event Plane Method

- Event plane reconstructed using charged hadrons within STAR TPC acceptance (|η|<1)
  - Hadrons within |Δη| < 0.15 around D$^0$ candidates removed from event plane reconstruction
- Corrected for detector acceptance and non-uniform efficiency
- Yields in φ-Ψ bins corrected for event plane resolution
- \( v_2 = v_2^{\text{obs}} \times \left\langle \frac{1}{\text{E.P. Resolution}} \right\rangle \)
- Non-flow contribution estimated from D-h correlations in p+p collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \)
  \[ v_2^{\text{nonFlow}} = \frac{\langle \sum_h \cos(2(\phi_{D^0} - \phi_h)) \rangle}{Mv_2^h} \]

Event plane resolution:
D^0 Meson v_2

- D^0 v_2 significantly above zero for p_T > 2 GeV/c
- B->D feed down is negligible at RHIC energies (<5% relative contribution)
D⁰ v₂ vs. Light Hadrons

- D⁰ v₂ is below light hadrons for 0.5 < (mₜ-m₀)/nₗ < 1.5 GeV/c² in 0-80% centrality bin

- D⁰ production is biased towards central collisions. Comparison in finer centrality bins is needed
Model Comparison: TAMU

- Full T-matrix treatment, non-perturbative model with internal energy as heavy quark potential
- Diffusion coefficient extracted from calculation $2\pi T \times D = 3-11$
- Good agreement with $D^0$ meson $v_2$. Data favor model including charm-quark diffusion in the medium
• MC@sHQ calculation with latest EPOS3 initial conditions
• Diffusion coefficient extracted from calculations $2\pi T \times D \sim 2-4$
• Good agreement between model and experiment data for both $v_2$ and $R_{AA}$ in entire $p_T$ range
Model Comparison: DUKE

- Diffusion coefficient is a free parameter, and the input value here is fixed to be $2\pi T \times D = 7$ by fitting to LHC results
- Model underestimates $v_2$ in experimental data


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• $D^0 v_2$ and $R_{AA}$ can be described by models with values of $2\pi T x D$ between 2 and ~12
• Lattice calculations, although with large uncertainties, are consistent with values inferred from data
• Differences between models need to be resolved
• First measurement of $D^0 R_{AA}$ using STAR HFT.
• $D^0 v_2$ is finite and lower than that of light quarks for $1 < p_T < 4.0$ GeV/c in 0-80% centrality bin
• Data favor model where charm quarks flow
• $D^0 v_2$ and $R_{AA}$ can be simultaneously described by models with values of $2\pi T x D$ between 2 and ~12, and differences between models need to be resolved
• Run14: with improved HFT tracking efficiency after discovering and fixing a decoder issue in PXL offline reconstruction software, factor 2-4 improvement expected with reprocessed data, therefore measuring centrality dependence for $v_2$ is feasible

• Run16: with full Al-cables and 2B MB events, factor 2-3 further improvement, thus further improved precision for $v_2$ and first precise measurement for $v_3$ are expected.
Thank You
BackUp
Slide 2 LEFT Plots
CDF: PRL 91 (2003) 241804
ALICE: JHEP01 (2012) 128
FONLL: PRL 95 (2005) 122001

Slide 2, RIGHT Plots
FONLL: PRL 95 (2005) 122001

Slide 3, Plots
STAR D0: PRL 113 (2014) 142301
PHENIX π0: PRL 101 (2008) 232301
ALICE D: PRL 111 (2013) 102301
ALICE D: JHEP 03 (2016) 081

Slide 11 Plots
STAR:PRC 77 (2008) 54901
PRL 116 (2016) 62301

Slide 12,13,14, Plots
STAR: PRL 113 (2014) 142301
DUKE: PRC 92 (2015) 024907
Private comm
Recent Developments and Understanding

- RHIC and LHC: D-meson $R_{AA} \ll 1$ at high $p_T$ -> strong charm-medium interactions
- LHC: $D^0 v_2$ results are compatible with light flavor $v_2$. Charm thermalized?

- Comparable suppression at high $p_T$
  - collisional and radiative $\Delta E$
- Possibly different physics at low $p_T$
  - Initial parton distributions
    - $x_T$ at 2 GeV/c $\sim 10^{-2}$ (RHIC) $\sim 10^{-3}$ (LHC)
  - “Cronin” effect
  - Charm quark flow
- $R_{AA}$ can be understand as integral of $v_2$ for phi differencal
- Low $p_T$ $v_2$ is especially sensitive to the partonic medium: scattering strength, transport properties

References in backup
Data-Driven Fast Simulation Package

\[ D^0 \text{ efficiency} = \text{TPC tracking eff} \otimes \text{HFT tracking eff} \otimes \text{topological cuts} \]

Assumptions:
1) Factorization of tracking efficiency: \( \frac{HFT}{MC} = \frac{HFT}{TPC} \times \frac{TPC}{MC} \)
2) Spatial resolution of HFT is encoded in two variables: DCA_{XY} and DCA_{Z} (correlated)
3) Vertex resolution, which is possibly folded in the DCA resolution of single tracks and correlated, is a negligible, at least for semi-central to central events
4) The contribution of feed-down particles from secondary decays to DCA is negligible
5) D^0 with mis-matched daughter tracks are removed by topological cuts

Ingredients:
1) Extract Vz distributions from data (centrality dependent)
2) Extract ratio of HFT matched tracks to TPC tracks from data.
3) Extract DCAXY - DCAZ distributions from data.
4) Extract TPC efficiency and momentum resolution from embedding

Our fast-simulator was validated by full GEANT simulation
Our data-driven fast-simulation package can well describe our topology distribution.
Scan different values of the diffusion coefficient to find best agreement to data

Best agreement for diffusion coefficient $2\pi T \times D = \sim 1 - 3$

This model seems to underestimate the data for $p_T > 3$ GeV/c