PHENIX Measurements of Heavy Flavor & DY in p+p and p+Au at 200 GeV

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- Introduction
- Heavy flavor
  - Charm from p+p
  - Bottom from p+p and p+Au
- Drell Yan from p+p and p+Au
- Summary
Heavy Flavor Measurements in p+p and p+Au

- In p+p test pQCD calculations
  - Sensitive to relative importance of LO and NLO QCD processes

  (a) s-channel Flavor Creation
  (b) t-channel Flavor Creation
  (c) Flavor Excitation
  (d) Gluon Splitting

  Relative contributions dependent on $\sqrt{s}$
  Study through $q\bar{q}$ pair correlations

- In p+Au sensitive to modifications of the PDF and to initial/final state effects
Semi-leptonic Decays of Charm and Bottom

**Charm**
- Single leptons: $e^\pm, \mu^\pm$
- Lepton pairs: $e^+e^-, \mu^+\mu^-$
- Mixed lepton pairs: $e^\pm\mu^\mp$

**Bottom**
- Single leptons: $e^\pm, \mu^\pm$
- Lepton pairs: $e^+e^-, \mu^+\mu^-, e^{\pm}\mu^{\pm}$
- Mixed lepton pairs: $e^\pm\mu^\pm, e^{\pm}\mu^{\mp}$

- $c/b$ from single electrons in $p+p$ at 200 GeV:
- $c/b$ and DY from dimuons in $p+p$ at 200 GeV:
- $c/b$ correlations from $\mu^+\mu^-, \mu^+\mu^-, e^+e^-, e^\pm\mu^\mp$ in $p+p$ at 200 GeV:
- $b$ from $\mu^+\mu^-$ in $p+Au$ at 200 GeV:
- $DY$ from $\mu^+\mu^-$ in $p+Au$ at 200 GeV:

arXiv:1805.04075v1
The PHENIX Experiment

Central Arms
|\eta| < 0.35

Muon Arms
1.2 < |\eta| < 2.2

Vertex Tracker

\textit{VTX}: |\eta| < 0.35

\textit{FVTX}: 1.2 < |\eta| < 0.35
Single Lepton Measurement in p+p

- Charm and Bottom life time:
  - $B^\pm \rightarrow 491 \, \mu m$
  - $D^\pm \rightarrow 312 \, \mu m$

- VTX detector
  - 2 pixel layers
  - 2 strip-pixel layers
  - Measure DCA$_T$ with $\sigma_{DCAT} \sim 100 \, \mu m$

- Bayesian unfolding method to separate charm and bottom
  - **Input:**
    - differential cross section of HF electrons
    - $p_T$ dependent DCA$_T$ distributions incl. electrons
    - Fraction of photonic electrons
  - **Output:**
    - Charm and bottom hadron spectra
  - **Refolding:**
    - Single electrons from charm and bottom
Charm and Bottom from Single Leptons


- Refolded heavy flavor electrons
  - Results are self-consistent

- $D^0$ results compared to STAR
  - Good agreement
Charm and Bottom Electron Results

**Bottom fraction**
- Results consistent with previous publications
- FONLL predictions consistent with measurements

**Differential cross section vs FONLL**
- Data more accurate than FONLL
- Difference is shape and magnitude

*At low $p_T$ bottom (and charm) factor 2 above pQCD central value*
Muon Pair Measurements in p+p and p+Au

- Iterative simultaneous fit $\mu^+\mu^-$ and $\mu^+\mu^\pm$ in mass-$p_T$:
  - Combinatorial and correlated background mostly from $\mu$ from K, $\pi$
  - Decays from $\eta, \eta' \rightarrow \mu^+\mu^-\gamma$; $\rho$, $\omega$, $\phi$, $J/\psi$, $\psi'$, and $Y \rightarrow \mu^+\mu^-$
  - Charm, Bottom, Drell-Yan

Combinatorial and correlated background mostly from $\mu$ from K, $\pi$ Decays from $\eta, \eta'$ $\rightarrow \mu^+\mu^-\gamma$; $\rho$, $\omega$, $\phi$, $J/\psi$, $\psi'$, and $Y \rightarrow \mu^+\mu^-$

Good agreement of data and cocktail of sources

*Note: p+p only

Extrapolate to $4\pi$ phase space

$$\sigma_{bb} = 3.75 \pm 0.24\text{(stat)} \pm 0.45\text{ (global)} \pm 0.35\text{ (sys)} \mu b$$

Most precise measurement
Consistent with earlier publications using different methods

Compare to pQCD calculations
Different pQCD results very consistent
At RHIC data factor ~2 above pQCD
Better agreement at higher energy

Indication for missing ($\sqrt{s}$ dependent) effect?
Opening Angle of $c\bar{c}$ and $b\bar{b}$ Pairs in p+p

**Compare $\Delta\phi$ to POWHEG and PYTHIA tune A**
- Normalized to measured cross sections
- Bayesian analysis fit pair creation, flavor excitation, and gluon splitting to data (PYTHIA)

**Charm**
- POWHEG predicts broader distribution; Data favor PYTHIA
- Fit to data consistent with PYTHIA
  - $F_{FE} > F_{PC} > F_{GS}$
  - Flavor excitation dominate

**Bottom**
- POWHEG and PYTHIA describe data within uncertainties
- Fit to data consistent with PYTHIA
  - $F_{PC} > F_{FE} \gg F_{GS}$
  - Pair creation dominant
  - Gluon splitting small
Extending the $c\bar{c}$ Phase Space

- **Data**
  - Yields of $e^+e^-$ and $e^\pm\mu^\mp$ dominated by charm
  - Cover wide kinematic range

- **POWHEG and PYTHIA normalized to $\mu^+\mu^-$ analysis**
  - PYTHIA consistent with data over large kinematic range
  - Distributions from POWHEG broader for all datasets

*PHENIX: arXiv:1805.04075v1*
**$b\bar{b}$ Pairs in p+Au**


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![Graphs showing $b\bar{b}$ pair distributions and $R_{pA}$ values](image)

- **$p_T$ spectra**
  - p+Au in large-\(x\) (Au-going)
  - small-\(x\) (p-going) consistent!
  - Possible modification compared to p+p (see $R_{pA}$)

- **Opening angle distribution**
  - p+p and p+Au (forward/backward) no modification

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**Comparison to nuclear PDFs**

- EPPS16 predicts constant $R_{pA}$ as function of $p_T$
- Systematic deviation of data from prediction observed, though with limited significance
First Drell-Yan measurement at RHIC constrain:
- Unpolarized TMD PDFs
- Nuclear PDFs
- Nuclear initial state effects

Drell-Yan in p+p
- NLO calculations consistent with data

Drell-Yan in p+Au
- Backward $x \sim 0.1$ (Au-going)
  $R_{pA}$ consistent with EPPS16
- Forward $x \sim 0.005$ (p-going)
  $R_{pA}$ shows possible enhancement for $p_T > 2$ GeV/c

Summary

- Heavy flavor production in p+p at $\sqrt{s} = 200$ GeV
  - Separation of charm and bottom
  - Single electrons with vertex tracking
  - Muon pairs
  - Data more precise than pQCD calculations
  - Measured cross sections 2x larger than pQCD central values
  - Charm production dominated by NLO Flavor Excitation
  - Bottom production dominated by LO Pair Creation

- Bottom production from p+Au at $\sqrt{s} = 200$ GeV
  - Hint of possible $p_T$ dependent modification compared to p+p

- First Drell-Yan measurements at RHIC in p+p and p+Au
  - p+p cross section well described by pQCD
  - p+Au consistent with nPDF ESSP16, with possible deviation for $p_T > 2$ GeV/c at low x
Backup Slides
DY measurements from Fermilab

Solid: Fe/Be, W/Be from 800 GeV/c p-Be, Fe, W (E866)
Open: Fe/C, W/C from 800 GeV/c p-C, Fe, W (E772)
Line: Shadowing calculations (EKS98, MRST)

$m = 4.0-8.4$ GeV/$c^2$
$x_2 \sim 0.04$

“Characteristic of multiple scattering of incident partons traversing the nucleus” PhysRevLett.83.2304
**Charm**

**Bottom**

**PHENIX (a)** \( pp \rightarrow c\bar{c} X \rightarrow \mu^+\mu^- X \)

- \( p_{\mu} > 3 \text{ GeV}/c, 1.2 < |\eta| < 2.2 \)
- \( 1.5 < m_{\mu^+\mu^-} \text{ [GeV}/c^2] < 2.5 \)
- Global Uncertainty 12.0%

\[ \text{arXiv:1805.02448} \]

**PHENIX (b)** \( pp \rightarrow b\bar{b} X \rightarrow \mu^+\mu^- X \)

- \( p_{\mu} > 3 \text{ GeV}/c, 1.2 < |\eta| < 2.2 \)
- \( 3.5 < m_{\mu^+\mu^-} \text{ [GeV}/c^2] < 10.0 \)
- Global Uncertainty 12.0%

\[ \text{arXiv:1805.02448} \]
ALICE pp $\sqrt{s} = 13$ TeV

$p_{T,e} > 0.2$ GeV/c, $|\eta_e| < 0.8$

$1.03 < m_{ee} < 2.86$ GeV/c$^2$

±5% global unc. not shown

- Data
- Cocktail (PYTHIA)
- $cc \rightarrow e^+e^-$ (PYTHIA)
- $bb \rightarrow e^+e^-$ (PYTHIA)
- Cocktail (POWHEG)
- $cc \rightarrow e^+e^-$ (POWHEG)
- $bb \rightarrow e^+e^-$ (POWHEG)