Multiplicity-dependent production of heavy mesons with strangeness in small systems at LHCb

Chenxi Gu, Tsinghua University
on behalf of the LHCb collaboration
Motivation

• Strangeness enhancement was one of the first proposed signatures of quark-gluon plasma (QGP) formation in heavy ion collisions
  ➢ strangeness production proceeds mainly via gluons fusion in QGP.
  ➢ s quark mass lower than QGP temperature, $s\bar{s}$ quark pairs can be produced thermally.
• Recently, enhanced strangeness production is also observed in high multiplicity $pp$ and $pPb$ collisions.
• The QGP conditions could be approached in $pp$ collisions where a large number of particles are produced.

Hadronization Process

• Fragmentation mechanism
  - Lots of partons produced by outgoing quarks form into hadrons.

• Coalescence mechanism
  - Multiple quark wave functions overlap in position and velocity phase space.
  - Hadrons enhancement at low $p_T$.

• B mesons offer unique probes of the hadronization process
  - There is no b content in incoming beam particles.
  - Production well described by pQCD.
  - Fragmentation functions measured with B mesons.
  - Enhanced production of $B_s^0$ relative to $B^0$ as particle density increases could be caused by coalescence.
LHCb detector

- A single-arm spectrometer in the forward direction, charm & beauty factory
  - Vertex Locator (20 μm IP resolution)
  - Tracking system ($\Delta p/p = 0.5 – 1.0\%$)
  - RICH: $p/K/\pi$ separation
  - Flexible software trigger

- VELO tracks: have hits in the VELO
- Back tracks: subset of VELO tracks, point in the backward direction
Fragmentation functions ratios in $pp$ collisions

- Fragmentation functions measured with B mesons: \( \frac{f_s}{f_d} \propto \frac{N_{corr}(B_s^0)}{N_{corr}(B^0)} \)

- $\frac{f_s}{f_d}$ is observed to depend on the B meson transverse momentum.
- No dependence on the collision energy.

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Strangeness enhancement with B mesons in $pp$ collisions at 13TeV

• The $pp$ 13TeV data was taken in 2016+2017+2018 with 5.4 fb$^{-1}$.

• Ratio of $B_s^0/B^0$ cross sections versus multiplicity, in several $p_T$ bins
  ➢ Both states are simultaneously accessible in $J/\psi\pi^+\pi^-$, Relative corrections are generally close to 1.

\[
\frac{\sigma_{B_s^0}}{\sigma_{B^0}} = \frac{N_{B_s^0}}{N_{B^0}} \times \frac{B_{B_s^0}}{B_{B^0}} \times \frac{\varepsilon_{acc}^{B_s^0}}{\varepsilon_{acc}^{B^0}} \times \frac{\varepsilon_{trig}^{B_s^0}}{\varepsilon_{trig}^{B^0}} \times \frac{\varepsilon_{PID}^{B_s^0}}{\varepsilon_{PID}^{B^0}} \times \frac{\varepsilon_{reco}^{B_s^0}}{\varepsilon_{reco}^{B^0}},
\]

• Event characterization:
  ➢ Multiplicity represented by VELO tracks or back tracks
  ➢ Restrict to events a single reconstructed primary vertex
  ➢ Require $z$ position of primary vertex to fall in the central area for stable VELO acceptance
Event characterization

- NoBias events are selected based on the LHC beam clock, which indicates that a bunch crossing has occurred, without any other trigger requirements.
- $B^0$ signal events are extracted from the data, and background is removed using the sPlot method.
- Events with B mesons have significantly different charged particle densities than nobias events.

$< N_{tracks}^{VELO} >_{\text{NoBias}} = 37.7$
$< N_{back}^{tracks} >_{\text{NoBias}} = 11.1$
$< N_{tracks}^{VELO} >_{B^0} = 71.1$
$< N_{back}^{tracks} >_{B^0} = 17.4$
Yield

- Fit model: Crystal Ball functions + exponential function

\[
\frac{\sigma_{B_s^0}}{\sigma_{B^0}} = \frac{N_{B_s^0}}{N_{B^0}} \times \frac{\mathcal{B}_{B_s^0}}{\mathcal{B}_{B^0}} \times \frac{\varepsilon_{acc}^{B_s^0}}{\varepsilon_{acc}^{B^0}} \times \frac{\varepsilon_{trig}^{B_s^0}}{\varepsilon_{trig}^{B^0}} \times \frac{\varepsilon_{PID}^{B_s^0}}{\varepsilon_{PID}^{B^0}} \times \frac{\varepsilon_{reco}^{B_s^0}}{\varepsilon_{reco}^{B^0}},
\]

LHCb $pp \sqrt{s} = 13$ TeV
30 < $N_{\text{VELO tracks}}^{\text{VELO}}$ ≤ 40

- Total fit
- Background

$B^0 \rightarrow J/\psi \pi^+ \pi^-$
$B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

Counts/(5 MeV/c²)

Counts/(5 MeV/c²)

Strangeness enhancement

arXiv:2204.13042

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Efficiencies

- \( \frac{\varepsilon_{acc}^{B_0^0}}{\varepsilon_{acc}^{B_s^0}} = 1 \pm 0.01 \), \( \frac{\varepsilon_{trig}^{B_0^0}}{\varepsilon_{trig}^{B_s^0}} = 1 \pm 0.01 \), \( \frac{\varepsilon_{PID}^{B_0^0}}{\varepsilon_{PID}^{B_s^0}} = 1 \pm 0.01 \)

- \( \frac{\varepsilon_{reco}^{B_0^0}}{\varepsilon_{reco}^{B_s^0}} = 0.86 \pm 0.04 \): Due to the difference in the dipion mass distributions produced in the \( B_s^0 \) and \( B^0 \) decays.

- Due to the similarities of the \( B_s^0 \) and \( B^0 \) decays, many systematic uncertainties partially cancel in this ratio of cross sections.
Results: $B_s^0/B^0$ vs VELO tracks

- The vertical error bars represent uncorrelated uncertainties.
- The vertical error boxes represent fully correlated uncertainties.
- The horizontal bands show the values measured in $e^+e^-$ collisions.
- The ratio shows an increasing trend with the VELO tracks.
- At low multiplicity, consistent with fragmentation in vacuum.

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Results: $B_s^0 / B^0$ vs back tracks

- No significant dependence of forward $B_s^0 / B^0$ ratio on backward multiplicity.
- The results indicate that the mechanism responsible for the ratio increase is related to the local particle density.
Results: $B^0_s/B^0$ in low $p_T$ bins

- The $\sigma_{B^0_s}/\sigma_{B^0}$ ratio increases with multiplicity (slope significance = 3.4$\sigma$). Consistent with coalescence mechanism qualitatively.
- At low multiplicity the ratio is consistent with values measured in $e^+e^-$ collisions.
Results: $B_s^0/B^0$ in high $p_T$ bins

- No significant dependence on multiplicity and consistent with data from $e^+e^-$ collisions.
- High $p_T$ b quarks have less overlap with the low-$p_T$ bulk of the quarks, thereby dominantly hadronize via fragmentation.

arXiv:2204.13042
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Work in progress: $D_s^+/D^+$ ratio in $p$Pb collisions at 8.16TeV

- We are studying strangeness enhancement in $p$Pb collision by $D_s^+/D^+$ ratio.
  - We use the same strategy as B analysis, the statistics of D mesons are larger.
- ALICE has studied in 5.02 TeV $p$Pb collision.

\[
D^+ \rightarrow K^-\pi^+\pi^+
\]

\[
D_s^+ \rightarrow K^+K^-\pi^+
\]

\[
R_{D_s^+/D^+}(p_T, y^*, PV \text{ nTracks}) = \frac{N(D_s^+ \rightarrow K^+K^+\pi^\mp)}{N(D^+ \rightarrow K^+\pi^\mp\pi^\mp)} \times \frac{\mathcal{B}(D^+ \rightarrow K^+\pi^\mp\pi^\mp)}{\mathcal{B}(D_s^+ \rightarrow K^+K^+\pi^\mp)} \times \frac{\epsilon_D^+}{\epsilon_{D_s^+}}
\]

LHCb preliminary
$p$-Pb, $\sqrt{s_{NN}} = 8$ TeV
~13 nb$^{-1}$
Summary and outlook

• In $pp$ system, the $B_s^0/B^0$ enhancement is observed at low $p_T$ and consistent with coalescence mechanism qualitatively.

• No significant dependence on backwards multiplicity.

• In $p$Pb system, the $D_s^+/D^+$ vs multiplicity is in progress.

• In Run3, we have more small systems, such as OO, $p$O to study multiplicity dependency.