Results on heavy ion collisions at LHCb

Yanxi ZHANG on behalf of the LHCb Collaboration
Laboratoire de l’Accélérateur Linéaire, Orsay
Outline

• The LHCb experiment
• Measurements with $p$Pb collisions
• First look at PbPb data
• Fixed target program
• Summary
LHCb experiment
Aiming for precision measurements in $b$, $c$ sectors

Vertex Locator (vertex reconstruction)
• IP resolution: 20µm
• Decay time resolution: 45 fs ($\tau_B \sim 1.5$ ps)

RICH detectors ($K/\pi/p$ separation)
• $\epsilon(K \rightarrow K) \sim 95$
• Mis-ID $\epsilon(\pi \rightarrow K) \sim 5$

Calorimeters (ECAL, HCAL) ($e/\gamma$ identification)
• $\delta E/E \sim 1\% \oplus 10\% \sqrt{E}$ (GeV)

Tracking system, TT T1-T3 (particle reconstruction)
• $\epsilon(\text{Tracking}) \sim 96$
• $\delta p/p \sim 0.5\%-1\%$ (5-200 GeV)
• $\sigma(m_{B \rightarrow hh}) \approx 22$ MeV

Muon system ($\mu$ identification)
• $\epsilon(\mu \rightarrow \mu) \sim 97$
• Mis-ID $\epsilon(\mu \rightarrow \mu) \sim 1 - 3$

Bending magnet
bending power: 4 Tm

Herschel
-7.5m, -20m, -114m

250 mrad
LHCb fully instrumented in the forward region ($2 < \eta < 5$)

- Heavy ion studies in a unique kinematic area: low $p_T$, large $y$, very small or large $x$
- Complementary to other LHC experiments
LHCb heavy ion data taking

- LHCb able to collect $pp$, $pPb$, $PbPb$, and $p$- or $Pb$- gas collisions
  - At different center-of-mass energy ($\sqrt{s_{NN}}$) and rapidity coverage

**Collider mode:** forward/backward rapidity

\[ \sqrt{s_{NN}} = 5, \ 8 \text{ TeV} \]

**Fixed target mode:** mid or backward rapidity, energies between SPS and RHIC

\[ \sqrt{s_{NN}} = 110 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 69 \text{ GeV} \]

GAS targets: He, Ne, Ar, Kr, Xe

Different sizes of colliding system

Data already available
LHCb heavy ion data taking

• 2013 $p$Pb runs: collected about 2 nb$^{-1}$
data at $\sqrt{s_{NN}} = 5$ TeV

• 2015
  ➢ Several fixed target data taking periods
    (p-He, p-Ne, p-Ar, Pb-Ar with $E_p = 6.5$ TeV)
  ➢ First participation in PbPb data taking
     successfully at $\sqrt{s_{NN}} = 5$ TeV, $\sim$150 h
Measurements with pPb collisions

- Study Cold Nuclear Matter effects (especially heavy flavor production)
  - Gluon shadowing
  - Parton saturation
  - Parton energy loss
  - Cronin effects
  - Nuclear absorption
  - Comovers
  - Radiative energy loss

- Provide important inputs to understand nucleus-nucleus collisions
**$pPb$ data taking (2013)**

- $pPb$ data collected at nucleon-nucleon (NN) center-of-mass energy $\sqrt{s_{NN}} = 5$ TeV
- NN center-of-mass system shifted by $\Delta y = 0.47$ in proton beam direction

**Two beam configurations:**

**$p$+Pb collisions (forward)**
- Rapidity coverage: $(1.5 < y^* < 4)$
- Data analyzed: $L_{\text{int}} \sim 1.1 \text{ nb}^{-1}$

**Pb+\(p\) collisions (backward)**
- Rapidity coverage: $(-5 < y^* < -2.5)$
- Data analyzed: $L_{\text{int}} \sim 0.5 \text{ nb}^{-1}$

On average, multiplicity higher for Pb+\(p\) collisions in LHCb

$y^*$: rapidity defined in NN center-of-mass frame

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Hard Probes 2016 (Yanxi ZHANG)
Heavy quarkonia production

- Candidates fully reconstructed from well identified muons
- Prompt $J/\psi$, $\psi(2S)$ and those from $b$ decay separated using pseudo-decay time ($t_z$)
  - LHCb is unique to separate the two components in the forward acceptance

$$t_z = \frac{(Z_{J/\psi} - Z_{PV}) \times M_{J/\psi}}{p_z}$$
Heavy quarkonia production

- Candidates fully reconstructed from well identified muons
- Prompt $J/\psi$, $\psi(2S)$ and those from $b$ decay separated using decay time

More data needed to study $\Upsilon(2S)$ and $\Upsilon(3S)$ productions
Nuclear modification factor ($J/\psi$)

\[
R_{pPb} = \frac{1}{A} \times \frac{d\sigma_{pPb}/dy}{d\sigma_{pp}/dy}
\]

- **Prompt $J/\psi$**: strongly suppressed in forward region, significant signs of CNM effects
  → Data well described by energy loss models w/ and w/o shadowing
- **$J/\psi$ from $b$**: modest suppression in forward region
  → Suggests suppression of $b$-hadron production
- **Backward rapidity**: compatible with no suppression

Models:
- EPS09LNO (shadowing + CEM): IJMP E 22 (2013) 1330007
- nDSg LO: PRC88 (2013) 047901
Nuclear modification factor ($\psi(2S)$)

$$R_{pPb} = \frac{1}{A} \times \frac{d\sigma_{pPb}/dy}{d\sigma_{pp}/dy}$$

- **Prompt $\psi(2S)$**: more suppressed than $J/\psi$, intriguing suppression in backward rapidity
  - Energy loss+shadowing don’t explain $\psi(2S)$ suppression in backward rapidity, requiring other mechanism (Comovers?)
- **$\psi(2S)$ from $b$**: suppression consistent with that of $J/\psi$ from $b$, as expected
Nuclear modification factor ($\Upsilon(1S)$)

$$R_{pPb} = \frac{1}{A} \times \frac{d\sigma_{pPb}/dy}{d\sigma_{pp}/dy}$$

- Suppression in forward region is smaller than for $J/\psi$, but close to that of $J/\psi$ from $b \to C$NM effects on open $b$ hadrons and bottomonia are not very different
- Hint of enhancement in the backward region → could be effect of anti-shadowing
- Data agree with prediction of energy loss + shadowing
Prompt $D^0$ production

- $D^0$ fully reconstructed through $D^0 \rightarrow K^-\pi^+$ decays
- Reconstruction and particle ID efficiency calibrated using data
- **Prompt $D^0$ yields** obtained from 2D fit to $D^0$ mass and impact parameter (IP) w.r.t. the primary vertex
  - LHCb unique to remove $D^0$-from-$b$ component down to zero-$p_T$

![Graph 1](image1)

![Graph 2](image2)
Prompt $D^0$ nuclear modification factor

$$R_{pPb} = \frac{1}{A} \times \frac{d\sigma_{pPb}/dy(dp_T)}{d\sigma_{pp}/dy(dp_T)}$$

$D^0$ cross-section in $pp$ collision at $\sqrt{s} = 5$ TeV extrapolated using LHCb measurements at 7 and 13 TeV

- Results will be updated with direct measurement of $D^0$ cross-section in $pp$ data at $\sqrt{s} = 5$ TeV

$R_{pPb}$ for $D^0$ meson has no strong dependence on $p_T$

Prompt $D^0$ nuclear modification factor

LHCb preliminary
pPb $s_{NN}=5$ TeV

$R_{pPb}$ for $D^0$ meson is smaller in forward rapidity

Data consistent with NLO MNR prediction using CTEQ6M+NLO EPS09 nPDF


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Prompt $D^0$ forward-backward ratio

- Calculated as $R_{FB}(|y^*|, p_T) = \frac{\sigma_{ppb}(+|y^*|, p_T, \sqrt{s_{NN}})}{\sigma_{pbp}(-|y^*|, p_T, \sqrt{s_{NN}})}$, systematic uncertainty largely cancels

- $R_{FB}$ for $D^0$ meson indicates significant production asymmetry in forward-backward rapidities (more important at large rapidity)
- Data consistent with NLO MNR prediction using CTEQ6M+NLO EPS09 nPDF

Two particle angular correlations

- Measurement of angular ($\Delta \eta, \Delta \phi$)-correlations of prompt charged particles, as a function of event activity (estimated as number of hits in VELO detector)

$p+Pb$: forward

- Away-side ridge (momentum conservation)
- Jet peak (particles from same hard process)

$p-Pb$: backward

- Near-side ridge elongated over large $\Delta \eta$

\[
\frac{1}{N_{\text{orig}}} \frac{d^2N_{\text{pair}}}{d\Delta \eta d\Delta \varphi} = \frac{S(\Delta \eta, \Delta \varphi)}{B(\Delta \eta, \Delta \varphi)} \times B(0,0)
\]

$p-Pb$ (forward): $\Delta \varphi = 0$ near side ridge visible in high event activity class (however not very pronounced)

$Pb+p$ (backward): $\Delta \varphi = 0$ near side ridge very pronounced in high event activity class

LHCb $p+Pb$ ($\sqrt{s_{NN}} = 5$ TeV)

1.0 $< p_t < 2.0$ GeV/c

Event class 50-100%

LHCb $Pb+p$ ($\sqrt{s_{NN}} = 5$ TeV)

1.0 $< p_t < 2.0$ GeV/c

Event class 50-100%

LHCb $Pbp$ ($\sqrt{s_{NN}} = 5$ TeV)

1.0 $< p_t < 2.0$ GeV/c

Event class 0-3%

LHCb $p+Pb$ ($\sqrt{s_{NN}} = 5$ TeV)

1.0 $< p_t < 2.0$ GeV/c

Event class 0-3%

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Two particle angular correlations

- Projected on $\Delta \phi$ for $\Delta \eta$ in range $2 < |\Delta \eta| < 2.9$ (excluding jet peak)
- Subtraction of the Zero Yield At Minimum (ZYAM)

- Near-side correlation yield increases with event activity
- More pronounced in backward configuration, due to larger event activity in backward configuration

For same absolute event activity, near-side correlation yield compatible in the forward and backward samples
PbPb collisions at LHCb

Display of one reconstructed PbPb event
Centrality reach at LHCb

- LHCb is designed for low multiplicity events, need to know up to which centrality class events can still be reconstructed
- Event activity measurements: counting energy deposited in calorimeters, which are not saturated even at large multiplicities

- VELO detector (tracking) saturates at ~15K hits → 50% event activity class
$J/\psi$ and $D^0$ signals in PbPb collisions

$J/\psi \rightarrow \mu^+ \mu^-$

$D^0 \rightarrow K^- \pi^+$

Full statistics

LHCb preliminary $\sqrt{s_{NN}} = 5$ TeV

Candidates per 8.0 MeV/c$^2$

50%<Event Activity<70%

Candidates per 8.0 MeV/c$^2$

50%<Event Activity<70%

Candidates per 8.0 MeV/c$^2$

50%<Event Activity<70%

Candidates per 8.0 MeV/c$^2$

50%<Event Activity<70%
$K_S^0$ and $\Lambda^0$ signals in PbPb collisions

$K_S^0 \rightarrow \pi^+\pi^-$

$\Lambda^0 \rightarrow p\pi^-$

One run
Ultra-peripheral PbPb collisions: $J/\psi$

- Low multiplicity events: only two muons in the detector

- Further information about event activity can be obtained from new Herschel detectors, active during PbPb data:
  - Installed in both backward and forward directions
  - Extending rapidity gap coverage of $5 < |\eta| < 9$
Fixed target programs
Fixed targets setup

• Fixed target beam configuration implements the SMOG System for Measuring the Overlap with Gas
  ➢ Primarily for high precision luminosity measurements
  ➢ Injection of noble gas into interaction region
  ➢ Allows to study p or Pb-Gas collisions at different $\sqrt{s_{NN}}$

Distribution of primary vertex positon
Fixed targets data

• SMOG data collected
  - pHe at $\sqrt{s_{NN}} = 110$ GeV
  - pNe at $\sqrt{s_{NN}} = 87$ GeV, 110 GeV
  - pAr at $\sqrt{s_{NN}} = 69$ GeV, 110 GeV
  - PbNe at $\sqrt{s_{NN}} = 54$ GeV
  - PbAr at $\sqrt{s_{NN}} = 69$ GeV

pNe collisions at $\sqrt{s_{NN}} = 110$ GeV, ~12 h (2015)
Summary

• LHCb can contribute to heavy ion studies, in a unique kinematic range
• LHCb successfully participated in p-Pb data taking in 2013
  ➢ Measurements of quarkonia and open charm production
    ✓ Cold nuclear matter effects studied in $J/\psi, \psi(2S), \Upsilon(1S)$ and $D^0$ production
  ➢ Studied charged particle correlations, indicating near side ridge effects in high event activity collisions
  ➢ More data ($\times 10$) will be collected this year
    ➢ Drell-Yan and associated production ($J/\psi-D^0$), improvements for $\psi(2S), \Upsilon(nS)$
• LHCb detector also collected PbPb collisions, first results will come soon
• LHCb is unique to do fixed target physics
  ➢ Will provide measurements in many different environments

Don’t miss talks by Burkhard and Xianglei on Saturday for more details of LHCb heavy ion results

Thank you for your attention
Additional material
Separation from prompt and detached

Pseudo-decay time of $\psi$

$$t_\psi = \frac{(Z_{J/\psi} - Z_{PV}) \times M_{J/\psi}}{M_{J/\psi}}$$

IP of $D^0$

From $B$

Prompt
Backward distributions

• X

\[ \frac{J/\psi}{\Xi} \]

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Nuclear modification factor of $\psi(2S)$

$\psi(2S)$ suppression measured by LHCb consistent with ALICE in both forward and backward samples

ALICE: JHEP 12 (2014) 073
Forward backward production ratio

- Calculated as $R_{FB}(|y^*|) = \frac{d\sigma_{p\bar{p}}/d|y^*|}{d\sigma_{p\bar{p}}/d|y^*|}$

Large forward-backward asymmetry for $J/\psi$ and $\Upsilon(1S)$
Not conclusive for $\psi(2S)$

LHCb measurements consistent with theoretical predictions
$D^0$ invariant mass and IP

- Backward sample
$D^0$ cross section in pPb

- Forward and backward sample

\[ \sigma_{Fwd}(p_T < 8 \text{ GeV/c}, 1.5 < |y^*| < 4) = 237 \pm 1 \pm 15 \text{ mb} \]

\[ \sigma_{Fwd}(p_T < 8 \text{ GeV/c}, 2.5 < |y^*| < 4) = 124 \pm 1 \pm 8 \text{ mb} \]

\[ \sigma_{Bwd}(p_T < 8 \text{ GeV/c}, 2.5 < |y^*| < 5) = 259 \pm 3 \pm 19 \text{ mb} \]

\[ \sigma_{Bwd}(p_T < 8 \text{ GeV/c}, 2.5 < |y^*| < 4) = 174 \pm 2 \pm 13 \text{ mb} \]
Cross-section extrapolation

- Cross-section in pp at 5 TeV extrapolated using LHCb measurements at 7 and 13 TeV

\[
\sigma(\sqrt{s}) = \begin{cases} 
p_1(\sqrt{s})^{p_0} & \text{power law,} \\
p_1 + p_0\sqrt{s} & \text{linear,} \\
p_1(1 - \exp(-\sqrt{s}/p_0)) & \text{exponential.} 
\end{cases}
\]

\[
\sigma_{pp}(5 \text{ TeV}; p_T < 8 \text{ GeV/c}, 2.5 < |y^*| < 4) = 713 \pm 95(\text{LHCb}) \pm 47(\text{fit model}) \text{ \(\mu b\)}
\]
Z production

- At first order produced from collision of a sea and a valence quark
  - Probes quark nuclear PDF at large $x_A$ ($10^{-1}$) and low $x_A$ ($10^{-4}$)
- Muon selection: $p_T > 20$ GeV, $2.0 < \eta < 4.5$, $60 < M(\mu^+\mu^-) < 120$ GeV

**Clean signals:** 11 forward candidates ($1.6 \text{ nb}^{-1}$) and 4 backward candidates ($0.52 \text{ nb}^{-1}$)

$$\sigma_{Z \rightarrow \mu^+\mu^-} (\text{fwd}) = 13.5^{+5.4}_{-4.0} \text{ (stat.)} \pm 1.2 \text{ (syst.) nb} \quad (\text{Forward})$$

$$\sigma_{Z \rightarrow \mu^+\mu^-} (\text{bwd}) = 10.7^{+8.4}_{-5.1} \text{ (stat.)} \pm 1.0 \text{ (syst.) nb} \quad (\text{Backward})$$
Z production

\[ \sigma_{Z\rightarrow \mu^+\mu^-} \text{ [nb]} \]

- syst.
- syst. \(\oplus\) stat.

LHCb
\[ p\text{Pb }\sqrt{s_{NN}} = 5 \text{ TeV} \]

- FEWZ NNLO + MSTW08
- FEWZ NNLO + MSTW08 + EPS09 (NLO)

backward

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Event activity in $p$Pb

Forward

Backward

Activity class
- 50-100% (low)
- 30-50% (med/low)
- 10-30% (med/high)
- 0-10% (high)
- 0-3% (very high)

LHCb $p$+Pb
$\sqrt{s_{NN}} = 5$ TeV

LHCb Pb+p
$\sqrt{s_{NN}} = 5$ TeV
Gluon-Quark PDFs

→ ratios of nucleon PDFs: $F_N(\text{Pb}) / F_N(\text{free})$