Results and plans with heavy ion collisions at the LHCb experiment

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38th International Conference on High Energy Physics
Chicago, 3-10 August 2016
Outline

1 Introduction

2 p-Pb results

3 First look at PbPb collisions

4 Fixed-target physics

5 Summary
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LHCb detector

- Single arm spectrometer, fully instrumented in $2 < y < 5$
- Designed for heavy flavor physics, it is becoming a general purpose detector

Excellent vertex, IP and decay time resolution
- $\sigma(IP) \approx 20\mu m$ for high-$p_T$ tracks
- $\sigma(\tau) \approx 45fs$ for $B_s^0 \to J/\psi\phi$ decays

Very good momentum resolution
- $\delta p/p \approx 0.5 - 1\%$ for $0 < p < 200 \text{ GeV}/c$

Particle identification
- $\epsilon_{K \to K} \approx 95\%$ for $\epsilon_{\pi \to K} \approx 5\%$ up to 100 GeV/c
- $\epsilon_{\mu \to \mu} \approx 97\%$ for $\epsilon_{\pi \to \mu} \approx 1 - 3\%$
LHCb fully instrumented in $2 < y < 5$

Collider mode: Complementary to other LHC experiments

Data taking in fixed target mode: unique feature!

- SMOG: System for Measuring Overlap with Gas
- Noble gases injected in the interaction region
- Designed and used for luminosity measurements
- Allows measurement of p- or Pb-Gas collisions
LHCb running modes

**Collider mode**
- $\sqrt{s_{NN}} = 8.2$ TeV
- $\sqrt{s_{NN}} = 110$ GeV

**Fixed target mode**
- $\sqrt{s_{NN}} = 5.0$ TeV
- $\sqrt{s_{NN}} = 69$ GeV
- Collider: forward/backward rapidities
- Fixed target: mid and backward rapidities, energies between SPS and RHIC

LHCb bridges the gap from SPS to LHC in a single experiment

Kinematic coverage in rest frame
- Collider: forward/backward rapidities
- Fixed target: mid and backward rapidities, energies between SPS and RHIC

$y^*$: rapidty in the centre of mass frame
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**Goal:** study nuclear matter effects

- Two-particle angular correlations
  - Long range correlation measurements in Pb-Pb collisions interpreted as hydrodynamical flow of deconfined medium
  - Mid-rapidity measurements showed “the ridge” in p-Pb collisions. LHCb forward rapidity coverage is unique.

- Open and hidden heavy-flavours:
  - Produced in initial hard scatterings
  - Essential tools to study cold nuclear matter effects (CNM)
  - p-Pb measurements essential to disentangle QGP from CNM effects in AA collisions

- 1.6 nb$^{-1}$ collected in 2013.

- p and Pb beams reversal allows to study backward and forward rapidity regions

- Asymmetry in beam energies: rapidity coverage shifted by $\Delta y \sim 0.47$

\[ 1.5 < y^* < 4.5 \]

\[ -5.5 < y^* < -2.5 \]
p-Pb - Two particle angular correlations

Measurement of angular ($\Delta \phi, \Delta \eta$)-correlations of prompt charged particles

Low activity (50-100%)

High activity (0-3%)

In high activity events, near side ridge ($\Delta \phi = 0$) visible

arXiv:1512.00439
- $\Delta \phi$ projections away from the jet peak 
  $(2 < |\Delta \eta| < 2.9)$
- Subtraction of the Zero Yield At Minimum (ZYAM)

- Near side correlation increases with the event activity
- More evident in Pb-p collisions (backward)

- Absolute event activity classes
- Backward and forward near-side correlations of compatible strength

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**arXiv:1512.00439**
p-Pb - Prompt $D^0$ nuclear modification factor

- $D^0$ fully reconstructed in the decay $D^0 \rightarrow K^-\pi^+$, **down to** $p_T = 0$
- Minimum bias selections, particle identification and vertex displacement
- Prompt yields: 2D fit to $D^0$ mass and impact parameter

$$R_{pPb}(p_T, y^*) = \frac{1}{A} \cdot \frac{\sigma_{pPb}(p_T, y^*)}{\sigma_{pp}(p_T, y^*)}$$

- $\sigma_{pp}(\sqrt{s} = 5\,\text{TeV})$: extrapolation using LHCb measurements at 7 and 13 TeV
- Analysis of the pp@5TeV reference run ongoing
- $R_{pPb}$ less than unity at forward rapidities
- pQCD calculations that uses EPS09 nuclear PDF parametrization reproduce the data
p-Pb - Prompt $D^0$ forward-backward ratio

$$R_{FB}(p_T, |y^*|) = \frac{\sigma_{pPb}(p_T, y^*)}{\sigma_{Pbp}(p_T, y^*)}$$

- Systematics uncertainties largely cancel
- Common rapidity range $2.5 < |y^*| < 4$

* Clear asymmetry forward/backward
* No $p_T$ dependence
* Asymmetry more important at larger $y^*$
* Within uncertainties, data are reproduced by pQCD calculations with EPS09 nPDF
p-Pb - $J/\psi$, $\psi(2S)$ and $\Upsilon(1S)$

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

Forward rapidity
- Significant suppression for $J/\psi$, even larger for $\psi(2S)$
- Modest suppression for non-prompt $J/\psi$, similar to $\Upsilon(1S)$

Backward rapidity
- No suppression for $J/\psi$ and $\Upsilon(1S)$
- Unexpected large suppression for $\psi(2S)$, not described by E.loss and shadowing

$J/\psi$ and $\Upsilon(1S)$ results reproduced by models
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First glimpse at PbPb data

- December 2015. First time of LHCb participation in Pb-Pb data taking
- Only 24 colliding bunches. Luminosity \( \approx 3-5 \, \mu b^{-1} \)
- Minimum bias trigger configuration: all inelastic interactions recorded on tape

Example of one PbPb event with more than 1000 charged tracks and a \( J/\psi \) candidate
PbPb - Centrality determination - ongoing

- Experimental observables: total energy in the calorimeters, EM (Ecal) or hadronic (Hcal)
- No saturation of calorimeter signals even for most central collisions

Event classification in terms of Ecal activity
- Saturation in Vertex Locator (VELO) clearly visible. Track reconstruction was performed up to \(~15k\) clusters
- Corresponding range: 50-100% event activity
PbPb - Looking for “heavy” signals...

\[ J/\psi \rightarrow \mu^+ \mu^- \]

Clear signals also in 50-70% event activity bin
PbPb - Looking for “strange” signals...

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

$\Lambda \rightarrow p\pi^+$

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Candidates of coherent photo-produced $J/\psi$ in PbPb ultra peripheral collisions

- These studies will benefit of the new Herschel detector
  - Possibility to define large rapidity gaps: $5 < |y| < 9$
  - Herschel was taking data in 2015
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• Data collected with different beams/targets and at different energies
• Example of an ongoing analysis: 
  $J/\psi$ and open charm production in $p$-Ne at $\sqrt{s_{NN}} = 110$ GeV

\[
J/\psi \rightarrow \mu^+ \mu^- \quad D^0 \rightarrow K^- \pi^+
\]

• Clear signals
• Luminosity determination is challenging: based on $pe^-$ elastic scattering
• Analysis ongoing on pHe, pNe, pAr and PbAr data sets
Fixed-target - Link with cosmic ray physics

- AMS-02 results show a possible excess of antiprotons with respect to secondary production in the interstellar medium ($pp \rightarrow \bar{p}X$ and $pHe \rightarrow \bar{p}X$)
- Possible evidence for Dark Matter contribution

![Graph showing antiproton data and error bars]

- Largest uncertainty: $\sigma(pHe \rightarrow \bar{p}X)$
- LHC proton beam on He at rest, good energy range for cross section measurements

- High energy neutrino physics: backgrounds from charm production.
- Possibility to study with LHCb intrinsic charm at large $x$
Summary

- LHCb demonstrated that it can play an important role in heavy ion physics
- Successful data taking in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV in 2013
  - Two-particle angular correlations: similar behaviour backward-forward rapidities in absolute event activity classes
  - Cold nuclear matter effects visible in heavy quarkonia and open charm measurements
- PbPb collisions collected in 2015
  - For the moment, measurements will be carried out for peripheral and ultra-peripheral collisions
  - Clear physics signals, analysis ongoing
- Fixed-target physics
  - Unique feature!!
  - Exploiting colliding system of different sizes and energies

More to come:

- Looking forward to collecting pPb collisions at $\sqrt{s_{NN}} = 5$ and 8 TeV in 2016
- At 8 TeV, 10x more statistics with respect to previous pPb run
- Possibility to study more observables ($\Upsilon(3S)$, Drell-Yan, associated $J/\psi - D^0$, W boson ...)
- In the meanwhile, additional fixed target campaigns are foreseen.

Stay tuned!
• Clean signal: 11 forward candidates, 4 backward candidates
• Cross sections in agreement with predictions, although the production of Z in the backward region appears slightly higher than prediction
p-Pb - Prompt $D^0$

Events / (0.1)

$\sqrt{s_{_{\text{NN}}}} = 5 \text{ TeV}$

Forward

- Data
- Signal+Bkg
- Signal
- Bkg
- $D^0$-from-b

$M(K^+\pi^+) \text{ [MeV}/c^2]$}

Events/(4 MeV/c$^2$)

$\sqrt{s_{_{\text{NN}}}} = 5 \text{ TeV}$

Forward

- Data
- Signal+Bkg
- Signal
- Bkg
- $D^0$-from-b

Events / (0.1)

$\sqrt{s_{_{\text{NN}}}} = 5 \text{ TeV}$

Backward

- Data
- Signal+Bkg
- Signal
- Bkg
- $D^0$-from-b

$M(K^+\pi^+) \text{ [MeV}/c^2]$}

Events/(4 MeV/c$^2$)

$\sqrt{s_{_{\text{NN}}}} = 5 \text{ TeV}$

Backward

- Data
- Signal+Bkg
- Signal
- Bkg
- $D^0$-from-b
p-Pb - Prompt $J/\psi$

(a) LHCb pPb (Fwd) $|S_{NN}| = 5$ TeV

2.5 < $y$ < 3.0
$p_T < 14$ GeV/c

Candidates / (5 MeV/c$^2$) [MeV/c$^2$]

(b) LHCb pPb (Bwd) $|S_{NN}| = 5$ TeV

$-4.0 < y < -3.5$
$p_T < 14$ GeV/c

Candidates / (5 MeV/c$^2$) [MeV/c$^2$]

(c) LHCb pPb (Fwd) $|S_{NN}| = 5$ TeV

2.5 < $y$ < 3.0
$p_T < 14$ GeV/c

Candidates / (0.2 ps)

(d) LHCb pPb (Bwd) $|S_{NN}| = 5$ TeV

$-4.0 < y < -3.5$
$p_T < 14$ GeV/c

Candidates / (0.2 ps)
p-Pb - Prompt $\psi(2S)$

LHCb
$p\bar{p}(Fwd)$ $\sqrt{s_{NN}} = 5$ TeV

$1.5 < y < 4.0$
$p_T < 14$ GeV/$c$

Candidates / (10 MeV/$\mu\mu M^2$)

$M_{\mu\mu}$ [MeV/$c^2$]

Candidates / ps

$t_z$ [ps]

LHCb
$p\bar{p}(Bwd)$ $\sqrt{s_{NN}} = 5$ TeV

$-5.0 < y < -2.5$
$p_T < 14$ GeV/$c$

Candidates / (10 MeV/$\mu\mu M^2$)

$M_{\mu\mu}$ [MeV/$c^2$]

Candidates / ps

$t_z$ [ps]
p-Pb - $J/\psi$, $\psi(2S)$ and $\Upsilon(1S)$

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

Models
- EPS09LNO (shadowing + CEM): IJMP E22 (2013) 1330007
- nDSg LO: PRC88 (2013) 047901