Fixed-target & heavy-ion collision results from LHCb

Michael Winn on behalf of the LHCb collaboration

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LHC seminar, CERN, 21.08.2018
The LHCb detector

- precise tests of the Standard Model in the flavour sector
- spectacular QCD spectroscopy and precision EW measurements
- flexible trigger down to low-$p_T$ with high rates in fixed-target geometry
- High-Energy Physics eagerly waiting for news from lepton universality

... LHCb is even more than this!

Unique forward kinematics in heavy-ion collider mode

- 2016 pPb run at $\sqrt{s_{NN}} = 8.16$ TeV:
  - $10^9$ minimum bias collisions in pPb and PbPb mode
  - 34 nb$^{-1}$ in pPb+PbPb for heavy-flavour/other probes processed in HLT:
    $\approx 0.5$ million J/$\psi$ in pPb, PbPb each

- Ion-ion: $10 \mu$b$^{-1}$ PbPb and $0.4 \mu$b$^{-1}$ XeXe
  $\rightarrow$ 2018 PbPb aiming for a factor 10 more

- heavy-ion and low-$x$ with inclusive and exclusive production channels
Unique fixed target mode at the LHC

System for measuring Overlap with Gas: most precise LHC luminosity


- used as internal gas target for physics parasitic to collider data taking
- cosmic ray and heavy-ion related physics with He, Ne and Ar targets
Today’s selection

▶ $\bar{p}$-production in $p$He fixed-target collisions: reference for direct cosmic rays
Final results at $\sqrt{s_{NN}} = 110$ GeV LHCb-PAPER-2018-031, arXiv:1808.06127

▶ charm production in fixed-target collisions in $p^4\text{He}/^{40}\text{Ar}$: intermediate/large-$x$ & reference for ion-ion collisions
$D^0$ and $J/\psi$ production LHCb-PAPER-2018-023, in preparation

▶ heavy-flavour and quarkonium production in $pPb$: low-$x$, energy loss tests & reference for ion-ion collisions
New $\Lambda_c^+$ at $\sqrt{s_{NN}} = 5$ TeV & $\Upsilon(nS)$ at $\sqrt{s_{NN}} = 8.16$ TeV
$J/\psi$ at $\sqrt{s_{NN}} = 8.16$ TeV LHCb-PAPER-2017-014, PLB 774 (2017) 159
$D^0$ at $\sqrt{s_{NN}} = 5$ TeV LHCb-PAPER-2017-015, JHEP 10 (2017) 090

▶ exclusive photonuclear $J/\psi$ production in ultra-peripheral PbPb collisions:
probe low-$x$ and nuclear shadowing
LHCb-CONF-2018-003
$\bar{p}$ from space: indirect search for the unknown

- **matter:**
  primary cosmic rays from Supernovae Remnants (SNR) and other sources

- **possible exotic antimatter sources in space:** dark matter annihilations

- **irreducible background:** primary cosmic rays hitting interstellar medium, Hydrogen and Helium, producing secondary cosmic rays containing $\bar{p}$

- **direct charged cosmic ray detection in space:** precision data with Pamela and AMS

Image: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker.
Production cross sections in $p$He: a crucial missing piece

comparsion with AMS data JCAP 1509 (2015) no.09, 023

$\bar{p}$-measurement kinematics, $z$-axis $\epsilon_{\text{rec}}$.

- flux prediction uncertainties in 10-100 GeV kinetic energy range: dominated by production cross sections uncertainties
- $\bar{p}$-production in $p$He collisions never directly measured
- LHCb in fixed-target mode: pioneer with well suited kinematics
Prompt $\bar{p}$-production in $p$He collisions at $\sqrt{s_{NN}} = 110$ GeV

- proton beam 1 hits He-gas pressure $O(10^{-7})$ mbar
- $\bar{p}$ momentum: 12-110 GeV/c $\bar{p}$ transverse momentum: 0.4-4 GeV/c
  lower bound: RICH $K^-$-threshold
- prompt: excluding weak hyperon decays
- trigger: activity in scintillator $\geq 1$ track at software stage
- event vertex: $-700 < z < 100$ mm
- simulation: minimum bias EPOS LHC PRC 92, 034906 (2015)
$ar{p}$-production in $p$He collisions: luminosity determination

- gas pressure not precisely known
  $\rightarrow$ indirect luminosity measurement

- elastic scattering of proton beam with atomic $e^-$ of He-gas:
  $\rightarrow$ QED and proton form factors

- simulation: ESEPP for $e^-$ scattering
  \cite{J. Phys. G41 (2014) 115001}
$ar{p}$-production in pHe collisions: luminosity determination

- single soft $e^-$ in $11 < \Theta < 21$ mrad: $\langle \epsilon_{\text{rec}} \rangle = 16.3\%$
- loose $e^-/e^+$-ID via energy in ECal
- background charge symmetric: $e^+$ as background proxy from data
- BDT-based selection on geometry, kinematics + exclusivity: $\epsilon = 96\%$
- main uncertainty low $\langle \epsilon_{\text{rec}} \rangle$: 5 % relative uncertainty
\( \bar{p} \)-production in \( p\text{He} \) collisions: particle identification

- negatively charged tracks: \( \pi^- \), \( K^- \) and \( \bar{p} \); 1.7 % fakes (simulation)
- PID with 2 RICH detectors
- 3 set of templates:
  - \( p\text{He} \) simulation (default)
  - \( p\text{He} \) data: tracks from weakly decaying light-flavour and \( \phi \to KK \)
  - \( pp \) data: as in \( p\text{He} \) and \( D \)-meson decays
- 2 methods:
  - 2-dimensional binned extended-max. likelihood fit
  - cut & count
Prompt $\bar{p}$-production in $p$He collisions: uncertainties

- luminosity and PID dominating uncertainties
- uncertainties below 10% for most kinematic bins

CERN LHC seminar 2018   Michael Winn, LHCb Collaboration
Prompt $\bar{p}$-production cross section results in $p$He collisions

- uncertainties smaller than model spread
differ by hadronisation & parton model+dynamics

- EPOS LHC tuned on LHC collider data underestimates $\bar{p}$-production

\[ \frac{\sigma_{\text{vis}}^{\text{LHCb}}}{\sigma_{\text{vis}}^{\text{EPOS-LHC}}} = 1.08 \pm 0.07 (\text{lumi}) \pm 0.03 (\text{primary vertex}) \]
\[ \rightarrow \text{discrepancy: } \bar{p} \text{ yield/event} \]

- unique and precise:
decisive contribution to shrink background uncertainties in dark matter searches in space

- natural $p$He extensions:
  - inclusive $\bar{p}$ with hyperon decays
  - charged $\pi, K, p$ spectra
  - $\sqrt{s_{NN}} = 87 \text{ GeV data}$


EPOS LHC, EPOS 1.99, QGSJET-II, QGSJETII-04m, Hijing, PYTHIA 6.4, ICRC ’17: difference summary by T. Pierog

CERN LHC seminar 2018  Michael Winn, LHCb Collaboration
Charm production in fixed-target $p$He and $p$Ar

- nuclear modification of parton distribution function
- 'valence-like' intrinsic charm via backward rapidity coverage
- reference for future Pb–A fixed target studies for Quark-Gluon Plasma: quarkonium suppression patterns and open charm: intermediate $\sqrt{s}$ between SPS & top RHIC energy

PRD 75 (2007) 054029
EPJC 77 (2017), 163.
Charm production in fixed-target configuration: data sets

- Tevatron/HERA fixed-target up to $\sqrt{s_{NN}} = 42$ GeV
- RHIC at $\sqrt{s_{NN}} = 200$ GeV

- $p\text{He}$ at 87 GeV: luminosity as for 110 GeV $\bar{p}$-analysis
- Indirect luminosity not available for 2015 $p\text{Ar}$

<table>
<thead>
<tr>
<th>System</th>
<th>$\sqrt{s_{NN}}$</th>
<th>Protons on target</th>
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<tr>
<td>$p\text{Ar}$</td>
<td>110 GeV</td>
<td>4 \cdot 10^{22}</td>
<td>40</td>
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<tr>
<td>$p\text{He}$</td>
<td>87 GeV</td>
<td>5 \cdot 10^{22}</td>
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<td>$7.58 \pm 0.47$ nb$^{-1}$</td>
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</table>
$J/\psi$ production in $pAr$ collisions at $\sqrt{s_{NN}} = 110$ GeV


- ▶ backward hemisphere in centre-of-mass probing Bjorken-$x$: 0.02-0.16
  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y^*}$

- ▶ shape in agreement for rapidity with phenomenological parametrisation
  JHEP 1303 (2013) 122

- ▶ HELAC-onia model EPJC 77 (2017) designed and tuned for collider data
  reasonable for rapidity, not working very well for $p_T$
$D^0$ production in $p\text{Ar}$ collisions at $\sqrt{s_{NN}} = 110$ GeV

![Graphs showing $dN_{D^0}/dy^*$ and $dN_{D^0}/dp_T$](image)


- **probing Bjorken-$x$:** 0.02-0.16
  
  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y^*}$

- **HELAC-onia model** [EPJC 77 (2017)] designed for collider data reasonable for rapidity, not working very well for $p_T$
J/ψ production in pHe collisions at $\sqrt{s_{NN}} = 87$ GeV

- probing Bjorken-$x$: 0.03-0.37
  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y^*}$
  - in agreement for rapidity, tension for $p_T$ with phenomenological parametrisation JHEP 1303 (2013) 122
  - HELAC-onia model designed for collider data reasonable for rapidity, not working well for $p_T$ and requiring scale factor of 1.78 EPJC 77 (2017)

$D^0$ production in $p\text{He}$ collisions at $\sqrt{s_{NN}} = 87$ GeV


▶ probing Bjorken-$x$: 0.03-0.37
estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y^*}$

▶ HELAC-onia model designed and tuned for collider reasonable for rapidity, not working well for $p_T$ and requiring a scale factor of 1.44 [EPJC 77 (2017)]

▶ no indication of visible valence-like intrinsic charm in rapidity distribution

▶ starting point for more detailed $p$-ion and future ion-ion collisions: open charm & charmonium down to 0 $p_T$ at $\sqrt{s_{NN}} = 69$ GeV on Neon targets
$p$–nucleus collider: control & limits of collinear factorisation

- no HERA equivalent for lepton-nuclei: partons largely 
  unconstrained for LHC heavy-ions

- saturation scale \( Q_s^2 \propto A_{\text{nucleus}}^{1/3} \) → linear parton evolution break-down?

- Other effects?
  as coherent energy loss by enhanced small-angle gluon radiation \( \text{JHEP 1303 (2013) 122} \)

- LHCb: forward acceptance + heavy-flavour → low, but perturbatively amenable \( Q^2 \) to reach low-\( x \)
$D^0$ production in $p$Pb collisions at 5.02 TeV: precision data

- strong suppression at forward rapidity, modification factor at backward rapidity close to 1, increasing in most backward bins
- nuclear PDFs EPJC 77 (2017) & color glass condensate calculation PRD91 (2015) no.11, 114005 accounting for observations
  - coherent energy-loss JHEP 1303 (2013) 122 qualitatively similar expectation
- assuming no other effect:
  - constraining nPDFs in unexplored area at low-$x$, see PRL 121, 052004 (2018)
$\Lambda_c$ production in $p\text{Pb}$ collisions at 5.02 TeV: test of charm fragmentation

▶ input for hadronisation phenomenology: crucial comparison with other collision systems

▶ hadronisation pattern of $c\bar{c}$ similar to model tuned to $pp$
Prompt $J/\psi$ production in $pPb$ collisions at 8.16 TeV:
precision nuclear modification

▶ strong suppression at forward rapidity: increasing from 0.5 at lowest $p_T$
reaching 1 at highest $p_T$

▶ nuclear PDFs EPJC77 (2017) 1 & Color Glass Condensate calculations PRD91
(2015) no.11, 114005 accounting for observations
coherent energy-loss JHEP 1303 (2013) 122 accounting for rapidity dependence

▶ assuming no other effect:
constraining nPDFs in unexplored area at low-$x$, see PRL 121, 052004 (2018)
Non-prompt $J/\psi$ production in $p$Pb collisions at 8.16 TeV: precision data on beauty

- suppression at forward rapidity, modification factor at backward rapidity close to 1
- first precise $b$-production measurement in $p$Pb down to 0 $p_T$
- crucial input for PbPb phenomenology
- assuming no other effect: constraining nPDFs in unexplored area at low-$x$, see PRL 121, 052004 (2018)
\( \Upsilon(nS) \) in heavy-ions: probe of deconfinement

- quarkonium: QCD hydrogen atom → probe deconfinement in PbPb
- \( \Upsilon(nS) \) suppression patterns in PbPb by CMS and ALICE
- observed additional suppression of \( \psi(2S) \) and \( \Upsilon(2S,3S) \) at low-\( p_T \) also in \( pPb/Pbp \) by LHC collaborations in Run 1
- LHCb Run 1 \( \Upsilon(nS) \) in \( pPb/Pbp \) statistically limited
\(\Upsilon(nS)\) production in \(p\text{Pb}\) and \(\text{Pb}p\) collisions with LHCb


- LHCb: factor 20 more luminosity in 2016 than in Run 1 to scrutinize the situation
  - fully profiting thanks to resolution and excellent \(\mu\)-PID
$\Upsilon(1S)$ in $pPb$ and $Pbp$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV

$\Upsilon(1S)$: suppressed forward, compatible with unity backward $\rightarrow$ within nPDF uncertainties

$p_T$-integrated $\Upsilon(1S)/J/\psi$-from-$b$ similar in $pp$ & in $pPb/Pbp$:
$\rightarrow$ naive approximate expectation in pure nuclear PDF & coherent energy-loss
$\rightarrow$ 'additional' suppression limited for ground state
$\rightarrow$ new observable:
proxy for 'natural' normalisation by total $b\bar{b}$ with same final state
$\Upsilon(nS)$ suppression patterns in $pPb$ and $PbP$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV

\[
\begin{align*}
R(pPb/pp)[\Upsilon(2S)] &= 0.86 \pm 0.15 \\
R(pPb/pp)[\Upsilon(3S)] &= 0.81 \pm 0.15 \\
R(Pbp/pp)[\Upsilon(2S)] &= 0.90 \pm 0.21 \\
R(Pbp/pp)[\Upsilon(3S)] &= 0.44 \pm 0.15
\end{align*}
\]


- additional suppression of excited states observed in inclusive collisions:
  - significant for $\Upsilon(3S)$ in $Pbp$
  - \(\rightarrow\) factorisation with respect to final state broken

- in qualitative agreement with models invoking late time interactions in $pPb/Pbp$


- comprehensive understanding: ingredient for ion-ion collisions
  - \(\rightarrow\) upcoming prompt $\psi(2S)$ LHCb measurement at 8.16 TeV will contribute
Ultra-peripheral PbPb collisions: $\gamma$-probe of the nucleus

- exclusive vector meson production via $\gamma$-pomeron scattering
- sensitive to generalised gluon distributions for Bjorken-$x \in 10^{-2}-10^{-5}$
- for small $q\bar{q}$ at leading twist, leading $\ln(1/x)$, $t \to 0$: $\sigma \propto (\text{gluon PDF})^2$

PRD50 (1994) 3134-3144

- LHCb well suited for exclusive production studies with Pb-beams: resolution, PID & very forward detector HerSChel

- LHCb experience: unique $\gamma$-p production studies in $pp$ with quarkonium

Ultra-peripheral PbPb collisions at 5.02 TeV: first $J/\psi$ results

- coherent $J/\psi$ production can be well separated from incoherent part
- covered rapidity range and precision constraining model space:
- heavy-ions: Mäntysaari-Schenke requires fluctuations to describe data as for $\nu_n$ coefficients from particle correlations in $p$Pb collisions
- final publication: include HerSchel information
- 2018 data waiting with 10× larger luminosity and exploiting other final states in exclusive $\gamma$-induced reactions

LHCb-CONF-2018-003.
Outlook collider

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<tr>
<td>Run 5: LHCb upgrade Phase II</td>
<td>LS 5</td>
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- heavy-ion Run 2 data started to be exploited:
  → largest heavy-flavour statistics in \( pPb \), forward acceptance & PID
- Phase I: \( \approx 5 \times L_{\text{inst}}(\text{Run II}) \) in \( pp \) \[ \text{LHCBTDR-12 – 17} \]
  - extend ion-ion capabilities
  - increase \( pA \) luminosity for low-\( x \) sector
- Phase II in design phase: \( \approx 50 \times L_{\text{inst}}(\text{Run II}) \) in \( pp \)
  → dream detector for heavy-ion physics

Physics case for an LHCb Upgrade II; CERN-LHCC-2018-026; LHCBTDR-019
Outlook fixed target

- pNe data sample from 2017: $\approx 10 \times \text{pHe/pAr}$
- large PbNe sample in 2018
- Run 3: plan for storage cell upstream, allow for non-noble gas targets, in particular $H^2$ and $D^2$ as references
- 10-100 $\times$ larger instant. luminosity per unit length
- upgrades with crystal target for $c$-quark MDM, EDM polarised target further upstream & wire targets under discussion
Conclusions:
LHCb as versatile lab for heavy-ion & fixed-target collisions

- **fixed-target pHe:**
  - reference for direct cosmic ray $\bar{p}$ measurements
  - uncertainties mostly $<10\%$: improve baseline for darkmatter searches

- **fixed-target pA:**
  - high-$x$ tests: intrinsic charm & gluon pdfs at low scales
  - $y$ & $p_T$-distributions with $D^0$ & $J/\psi$ at backward $y$ with $A=4/40$:
    - $y$-dependence reproduced by models

- **pPb and PbPb collider:**
  - tests of low-$x$ with perturbative probes in gluon and $\gamma$-induced reactions
  - nuclear suppressions in $p$Pb: up to 50% at low-$p_T$ in $p$Pb forward with charm and 20-30% for beauty
  - $d\sigma/dy$ of coherent $J/\psi$-production in PbPb collision constraining models
  - test heavy-flavour bound state hadronisation & fragmentation down to low-$p_T$ with $\Lambda_C$ and $\Upsilon(nS)$
Conclusions:
LHCb as versatile lab for heavy-ion & fixed-target collisions

A precision experiment at low/moderate $Q^2$:

Unique acceptance at a hadron collider
- the world of colour charges & hadrons

A chance:
- to measure soft QCD
- to probe the partonic content of nucleons and nuclei
- to investigate QCD many body systems

*Thanks a lot for two exciting years!*
Back-up
Heavy-ion collisions at the LHC as a probe of QCD matter

The QCD many-body system in the lab: nucleus-nucleus collisions

- measure equilibrium properties:
  deconfinement, chiral restoration, thermodynamic&transport properties

- quantify QCD properties:
  QCD radiation, hadronisation, phase transition characteristics

- understand non-equilibrium dynamics and relation to equilibrium

p/T^4: pressure over temperature^4

HRG: Hadron Resonance Gas

HTL: Hard thermal loop

SB: Stefan-Boltzmann limit of non-interacting quarks and gluons

T-range probed at the LHC according to hydrodynamic models
PLB 370 (2014), T-range from PRC 89, 044910 (2014)
\( p\)-nucleus and \( pp \) as a test of the heavy-ion paradigm

Left: arXiv:1404.7327 \( Kn = L_{\text{micro}}/L_{\text{macro}} \). Right: arXiv:1611.00329

- correlations & bulk production@low-\( p_T \) & large multiplicity:
  'same' patterns as in PbPb where assumption of local thermalisation

- \textbf{hydro} in large multiplicity \( p\)Pb: set-up as in PbPb describing data
  despite \textbf{precondition doubts} PLB772 (2017) 681-686

- role of kinetic theory: to be quantified arXiv:1805.04081

- debate on saturation explanations of observed anisotropies arXiv:1808.01276
  arXiv:1805.09342


- LHCb: acceptance + heavy-flavour as hard scale: ideal testing ground