







Heavy Ion and Fixed Target Results of the LHCb Experiment

V. Pugatch ^{1,2} (on behalf of the LHCb Collaboration)

¹ Institute for Nuclear Research NASU, (KINR) ² EMMI (GSI)

Workshop "Heavy Ions and Hidden Sectors"

Centre for Cosmology, Particle Physics and Phenomenology (CP3) Université catholique de Louvain. Louvain-la-Neuve Belgium (04 - 05) -Dec.-2018

Outline

- Introduction
- HI studies at LHCb experiment:
 - >Physics goals
 - ➤Technical capabilities
 - Detector to search for the QGP signals
 - Fixed target regime at the LHCb
 - Proposals for Upgrade
 - Selected results
- Summary and Outlook



Heavy ions collisions:. Physics tasks and LHCb achievements

LHCb in heavy ion program

LHCb physics covers

pp, pA, AA interactions (heavy flavour, electroweak, soft QCD, ...

- proton-lead: p-Pb, Pb-p data at 5 and 8 TeV: D_0 , J/ Ψ , ψ (2S), Λ_c , Z, ...

- lead-lead: 5 TeV

- fixed target physics: unique opportunity with SMOG system (Ar, He, Ne) at various energies

 $> J/\Psi$ and D₀ in pAr @ Vs_{NN} = 110 GeV,

 \succ anti-proton production in p-He @ Vs_{NN} = 110 GeV

synergy - from SPS to LHC physics within a single experiment

The LHCb detector – forward spectrometer with excellent characterisitics

- Acceptance 2 < η < 5 & HERSHEL 8 < η < 10
- Momentum resolution about 0.5 %
- Track reconstruction efficiency > 96 % (pp-collisions)
- Impact parameter resolution: ~ 20 μm
- Decay time resolution: ~45 fs
- Invariant mass resolution: ~(10-20) MeV/c²
- Ring-Imaging Cherenkov Detectors and Muon system particle identification

(Perfect ID efficiency)



The LHCb experiment

LHCb: The Large Hadron Collider Beauty Experiment for Precise Measurements of CP-Violation and Rare Decays



The only LHC experiment fully instrumented at large η (2< η <5)

Techniques

>Detector for physics events reconstruction in search for the QGP

Fixed target regime at the LHCb

SMOG

V. Pugatch.Heavy Ions and Fixed Target Results of LHCb. "HI Hidden Sectors" Workshop. Louvain-la-Neuve. 05-Dec-2018 Noble gas only (very low chemical reactivity) He Ne Ar A = 4 20 40

Techniques

Detector for physics events reconstruction

in search for the QGP

Fixed target regime at the LHCb

The phase space compared to other experiments has the unique advantage:

- precise tracking /vertexing, calorimetry and powerful particle identification in the full acceptance.

for fixed target mode:

- the acceptance is central to backward.
- AA collisions generate energy densities between those achieved at the SPS and those probed at RHIC
- p-A collisions at the proton energy T = 7 TeV:

> $√s_{NN}$ = 114.6 GeV.

- measurements in fixed target and in colliding beam mode will bridge the gap between the SPS and the LHC in a single experiment.



THE LHCB ACCEPTANCE

High Rapidity Shower Counters at LHCb (HeRSCheL) JINST 13 (2018) P04017



Veto region (Run 2): -10<η<-5, 5<η<10

HeRSCheL -For separating background from the candidates to physics signals

Heavy ions collisions:. Selected LHCb results Collider mode. p-A.

Prompt J/ψ production in *p*Pb collisions at 8.16 TeV LHCb-PAPER-2017-014,PLB 774 (2017) 159.



$R_{pPb} = 1/A * \sigma_{pPb}/\sigma_{pp}$

Middle figure illustrates Principle of separation Prompt and delayed events (from b-decays)

strong suppression in p_{τ} distribution (right figure) at forward rapidity

Theoretical description:

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 (see next slide)

V. Pugatch. Heavy Ions and Fixed Target Results of LHCb. "HI Hidden Sectors" Workshop. Louvain-la-Neuve. 05-Dec-2018

Conclusion:

Results constrain nPDFs in unexplored area at low-x,

See PRL 121,052004(2018)

Adapted from: CERN LHC seminar 2018 Michael Winn,

LHCb Collaboration

Heavy ions collisions:. Selected LHCb results Collider mode. p-A.

PLB 774 (2017) 159-178

J/Ψ production in proton-lead @ 8.16TeV

(Exploring powerful LHCb vertexing tool (few tens fs in time) for separation prompt and delayed events)

Nuclear modification factor – prompt J/Ψ

Nuclear modification factor - J/Ψ from b



Heavy ions collisions:. Selected LHCb results Collider mode. p – A.

Non-prompt J/ψ production in *p*Pb collisions at 8.16 TeV



Suppression at forward rapidity first precise *b*-production measurement in *p*Pb at low pT input for PbPb phenomenology

Constraining nPDFs at low-x, see PRL 121, 052004 (2018)

$$x \simeq \frac{m_{J/\psi} e^{-y}}{\sqrt{s}}$$

With LHCb acceptance at 13 TeV pp collision, x down to 10⁻⁶

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PbPb collision at 5 TeV, x > 5 \cdot 10^{-6}
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Heavy ions collisions:. Selected LHCb results Collider mode. p-A.

D^{θ} production in *p*Pb collisions at 5 TeV



The (left) $M(K \neq \pi \pm)$ and (right) log10($\chi 2$ IP(D0)) distributions and the fit result for the inclusive D0 mesons in the forward data sample in the kinematic range of 2 < pT < 3 GeV/c and 2.5 < y * < 3.0.



Nuclear modification factor $R_{pPb} = 1/A * \sigma_{pPb}/\sigma_{pp}$ $R_{pPb}(p_{T}, y^{*}) \equiv \frac{1}{A} \frac{d^{2}\sigma_{pPb}(p_{T}, y^{*})/dp_{T}dy^{*}}{d^{2}\sigma_{pp}(p_{T}, y^{*})/dp_{T}dy^{*}},$

Observations:

s of LHCb. "HI

Strong suppression in the forward Rapidity(right bottom figure). (Similar to J/Psi results see slides 7,8)

Theoretical description:

Nuclear PDFs & Color Glass Condensate calculations agree with observations

-> Contribution to constraining nPDFs at low-Bjorken x (PRL 121, 052004 (2018)) JHEP 10 (2017) 090

Heavy ions collisions:. Selected LHCb results Collider mode. A-A.

J/ψ production at ultra-peripheral collisions. Pb - Pb at 5TeV



- Gluon saturation at low *x*, nPDFs, CGC
- Transverse momentum fit allows to separate coherent and incoherent events
- σ (γA) -> nuclear PDFs (or shadowing)

 $\begin{array}{c} & & & \\ & & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & &$

pA collisions

Ph

- $\sigma_{P\gamma}$ enhanced by Z^2 in UPC
- σ PP enhanced by $A^{1/3}$

AA collisions $\sigma_{\gamma\gamma}$ enhanced by Z⁴ in UPC

2018: expected 10x luminosity Also other J/Psi states may become reachable

Techniques

> Detector for physics events reconstruction

in search for the QGP

Fixed target regime at the LHCb

Fixed target regime at the LHCb

Fixed Target regime extends the LHCb physics programme.

QCD phase diagram may have interesting features observable at scattering TeV beams on fixed target.

For instance: J/ψ , and $\psi(2S)$ modification of cross-sections due to hard production and suppression by hadronic dissociation in QGP.

- Collect data in p-p (for reference), p-A and A-A heavy-nuclei collisions:
- \succ Measure: production cross-sections and the nuclear modification factors ratios, $R_{pA,AA}$

$$R_{\rm AA} \equiv dN_{\rm AA}/dy / (dN_{\rm pp}/dy \cdot \langle N_{\rm coll} \rangle)$$

 $\ \ \, \square \quad R_{pA,AA} \text{ different from the unity}$

> Possible indication that the QGP has modified the production ratios

Data taking time (example)

The p-Ne data: dedicated run of one week per year (corresponding to 1.5 pb^{-1})

the Pb–Ne in parallel with the PbPb collisions (24 days or 0.7 nb⁻¹ per year).



Internal Gas-Target SMOG.

Acquired SMOG (see next slide) data sample sizes, given in terms of proton (or Pb) on target. The unit of 10²² corresponds to about 5/nb per 1 m of gas, at the nominal SMOG pressure.

LHCb Internal Gas Target (SMOG)

JINST 9 (2014) P12005

Initial purpose for injection of noble gas in the VELO tank:

luminosity measurement from reconstructed vertices originated by

proton beam-gas nuclei interactions (1.2% precision !)

Since Run 2- internal gas target (SMOG):

Targets: He, Ne or Ar), with unique coverage of the high-x regime in the target nucleon.

Collisions at an energy scale of $\sqrt{s_{NN}} \sim 100 \text{ GeV}$.

Run 2 data allow for:

- studies particle production in the soft QCD regime, of particular relevance to cosmic ray physics
- collection samples of charmed mesons
 - > to discriminate cold nuclear matter effects from the effect of deconfinment,
 - to study nuclear PDFs at large x.



 J/ψ and D⁰ production cross-sections in p He @ $yJs_{NN} = 86.6 \text{ GeV}$ and Ar @ 110 GeV Paper Submitted to PRL

 $p + He -> anti-p + X @ Vs_{NN} = 110$ GeV, an input for cosmic rays physics Phys. Rev. Lett. 121 (2018), 222001

Anti-proton production cross sections in *p*-He collisions @ $vs_{NN} = 110$ GeV





Reconstruction efficiency rec for antiprotons,
including acceptance and track
reconstruction in per cent.
Only the kinematic region considered
in this analysis is shown,
with the chosen bins represente
by the red rectangles

- flux prediction uncertainties in 10-100 GeV kinetic energy range: dominated by production cross sections uncertainties
- p-production in pHe collisions never directly measured
- LHCb in fixed-target mode: pioneer with well suited kinematics
- published PRL 121 (2018), 222001

CERN LHC seminar 2018 Michael Winn, LHCb Collaboration

Heavy ions collisions:.

Selected LHCb results Fixed Target mode. Prompt p-production cross section results in pHe collisions @ $vs_{NN} = 110$ GeV



Antiproton production cross-section as a function of momentum, integrated over various p_{τ} regions.

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

EPOS LHC tuned on
 LHC collider data underestimates
 anti-p production

LHCb EPOS /LHC

- $= 1.08 \pm 0.07$ (*lumi*) ± 0.03
- unique and precise

decisive contribution to shrink background uncertainties in dark matter searches in spac

Production cross-sections J/ψ , D^0 in pHe @ $\sqrt{s_{NN}} = 86.6$ GeV J/ψ , D^0 in pAr @ $\sqrt{s_{NN}} = 110$ GeV



LHCb-PAPER-2018-022

energy region between 20 GeV (SPS) and 200 GeV (RHIC)

Access nPDF anti-shadowing region and intrinsic charm content in the nucleon

Production Cross-sections J/ψ , D^0 in pHe @ $\sqrt{s_{NN}} = 86.6$ GeV J/ψ , D^0 in pAr @ $\sqrt{s_{NN}} = 110$ GeV



Reasonable agreement with nPDF predictions

• No strong intrinsic charm contribution observed

Production Cross-sections J/ψ , D^0 in pHe @ $\sqrt{s_{NN}} = 86.6$ GeV J/ψ , D^0 in pAr @ $\sqrt{s_{NN}} = 110$ GeV



V. Pugatch.Heavy Ions and Fixed Target Results of LHCb. "HI Hidden Sectors" Workshop. Louvain-la-Neuve. 05-Dec-2018 LHCb-PAPER-2018-022

Heavy ions collisions:.

DETECTOR

LHCb Upgrade

Fixed Target mode.

The LHCb collaboration is presently considering several proposals to extend Heavy Ion Fixed Target programme

Upgrades with crystal target for c-quark MDM, EDM, polarised target further upstream & wire targets are under discussion



HL-LHC ERA

Motivation for the Fixed Metal Targets in the LHCb Experiment

- LHCb success in the Ion Physics and Fixed (Gas) Target studies
- Fixed Metal Targets: New domains of colliding nuclei and energies at LHC (~ 80 - 110 GeV, nucleon/nucleon c.m.s.) <u>http://dx.doi.org/10.1155/2015/760840</u>
- Immense variety of colliding nuclei: enrichment of LHC physics tasks
 >QGP signatures (Nuclear Modification Factors)
 - possible dependence on ground state properties of colliding nuclei
 - > Nuclear (and possibly atomic) dependence of the quarkonia production
 - from N interaction points:
 - > N metal targets in LHC beam, simultaneously.

Techniques:

Metal microstrip detector-target

Superthin Wire Target - HOW-and When TO-DO it at LHCb ? VELO – VErtex Locator construction after (LS3 ?) upgrade





Metal Microstrip Detector – MMD-1024.

Nano-technologies evolve fast – already nowadays- carbon nano-tubes, fullerene structures, graphenes, ... May become a nano-wire target components.

Techniques:

Metal microstrip detector-target Steering of the targets

Equalization of the luminosities Charge Integrated in Individual Targets data for the steering feedback system at HERA





Eight targets

Four targets

Proof of the principle – Vertices are equally distributed over inserted targets.

8 targets simultaneously could be handled providing 40 MHz interaction rate

http://dx.doi.org/10.1063/1.1291460

Some beneficial features of the LHCb Metal Microstrip Fixed Target setup

• Physics

- **Extension of the nuclei range for Nuclear Modification Factor studies**
 - (including isotopic enriched targets)
- Impact of the individual nuclear properties (nuclear shell effects, spin, parity, deformation) on quark-gluon plasma generation
- > Nuclear Modification Factor for neutron-rich nuclei
- Search for Neutron nuclei
- ≻ ...

• Technique:

- > Well localized interaction region (about 100 μ m)
- > Taking data for many targets in a single Run
 - relative comparison of physics data with minimized systematic errors
- > Perfect tuning/monitoring of the individual luminosity
- ➤ Safe and reliable operation

Summary and Outlook

- LHCb has successfully joined the Heavy Ion Sector (HIS) of research
- Superior technical features of the experimental setup allowed to obtain precise data on quarkonia production cross-sections in both subsectors of HIS: colliding and fixed target modes.
- Double differential cross-sections for production of charm, strange and bottom hadrons are measured at 5, 8 and ~0.1 TeV in various combinations of HI collisions. The striking feature was observed in the derived from these measurements Nuclear Modification Factors essential suppression at some kinematical/physical conditions.
- Interpretation of the obtained results has been performed in frames of existing theoretical approaches. Within the statistical/theoretical uncertainties no indication of signals from the Hidden Sector objects.
- Fixed Target mode is unique for the experiments at LHC. Four proposals to extend this area of studies in the RUN3, Run4. are under discussion. The most advanced one upgraded version of the current gas target (SMOG2).

Acknowledgements

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Thank you for your attention!



Welcome to Kyiv!

Backup slides

Q (MD) & A (GG)

 Q1. The focus of the workshop is the search for new physics, i.e., new elementary particles or new phenomena in heavy ion collisions. Do you think that fixed target experiments can do improvement there? They have lower collision energies than LHC collisions, but probably more protons on target, right? How do they e.g. compare to NA62 (10^18 POT) or SHiP (10^20POT)?

A1. So far we could use also He, Ne and Ar targets, i.e. smaller collisions systems wrt collisions with Pb beams. The POT are typically well above SPS experiments (we have plan to increase by 2-3 orders of magnitude in Run 3), but the density of the target is much lower. The maximum int. luminosity aquired so far is 0.1/pb, we could reach up to 100/pb in the future.

Note however that the detector was not conceived for hidden sector searches like NA62 and SHIP: we have limited sensitivity to long-lived particles (unless proposed extensions like CODEX-b are implemented) and also missing energy techniques are difficult due to the limited acceptance.

Q (MD) & A (GG) (continue-1)

• Q2. Are the thermodynamic properties of the hadronic matter in fixed target collisions different from the normal LHC?

A2. We are at much lower energy, so definetly yes. Indeed the scale of ~100 GeV in the c.m. system is relatively unexplored and very interesting to study the transition between cold and hot nuclear matter.

are two aspects that make LHCb • 03. there interesting. . . . verv - Q3-1: you can see (and record) final states with very low p_T. It would be interesting to see go in heavy ion and in low proton collisions. how can vou - A3-1. We could measure production of heavy flavours (D0, J/psi...) down to 0 p_T

Q3-2: the sensitivity to forward going particles - how many more hidden particles from B meson decays one can see because of that (compared to ATLAS and CMS).
A3-2. The response is very model-dependent. But certainly the capabilities for B decays are the best at the LHC, not only because of the acceptance: proper time and mass resolutions are much better, trigger with much lower p_T threshold

Q (MD) & A (GG) (continue-2)

• Q4. The big disadvantage of LHCb is of course the reduced instantaneous luminosity. There it would be interesting to see how much luminosity the detector could in principle take in heavy ion or proton runs.

A4. we are limited by the detector occupancy in pp collision (presently $4 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$, i.e. factor of 10 less than ATLAS/CMS, (n the upgrade we will increase by a factor 5). However, in heavy ion runs we could exploit the full luminosity provided by the machine, and in principle get the same as ATLAS and CMS. Practicaly, so far we had ~ an order of magnitude less integrated luminosities due to technical (machine optics) and other reasons.

The CODEX-b way to long-lived particle searches at LHCb

• Analogously to long-lived SM particles such as the K0 meson, BSM theories generically predict

the existence of metastable states, also known as long-lived particles (LLPs). LLPs with lifetimes up to the sub-second regime are broadly consistent with cosmological bounds, and havebeen studied in a wide variety of BSM theories.

- Because the range of possible LLP lifetimes and masses is very large, many different existing and future experiments have searched for or proposed to search for LLPs, including ATLAS and CMS, Belle II, SHiP [671], FASER [672], MATHUSLA [673], and DUNE [674].
- The CODEX-b detector, described more fully in Ref. [675], has been proposed to augment LHCb's ability to search for LLPs. This is an additional detector system which is not part of the baseline LHCb Upgrade II programme. Its key features are a relatively compact detector volume, simple shielding to ensure a zero-background environment, and the ability to integrate into LHCb's triggerless DAQ and potentially tag or characterize observed LLP candidates based on activity within LHCb.



Figure A.1: Dimuon mass distrib. In the dark photon search at LHCb [446]. Note that the heavy-flavour background has been greatly suppressed.

Motivation

Physics tasks requirements and ... dreams about 'NEW'

Impact of the ground state properties on Nuclear Modification Factor ?



- Nuclei in ground state have different shape, angular momentum, ...
- Nuclei with closed p-, n-shells (double-magic) are spherical
- Nuclear matter density distribution is not uniform
- Neutron-rich nuclei have large radius
- Neutron excess may create neutron nuclei in collisions ?

Different fixed targets behave differently in collisions ...

Bullet Time | City Gallery Wellington

Physics:

Three-nuclei interaction – two nuclei from LHC beams and one from the LHCb Microstrip Target

http://images.iop.org/objects/ccr/cern/53/4/18/CCfir5_04_13.jpg

Events with three nuclei interaction !

- Intriguing opportunity with metal microstrip target never explored in earlier experiments !
- Might be very interesting phenomenon what is the interaction energy of three nucleons (two from LHC beams and one from the fixed target) ?
- What will be the Equation of State ?
- Which temperatures and densities of the hot matter part might be ?

Outlook (as private communication)

- Theoretical prediction of the HS's objects has to reveal their specific properties.
- The method of proximity 'scattering' might be useful to discover very short-living objects in such scattering.
- Experimental search with current detection technique at colliders will profit from that making corresponding triggering/selection of events from HS.
- Efforts are needed to develop detection technique based on new principles. Integration of the detecting properties with readout (MAPS, ...) is on that way.
- It might be worthy to think about 'solid-photo-plates', which are irradiated first and analyzed later on aiming to find specific tracks of the HS's object. On that way it is also interesting to search for tracks left by the HSO in the 'samples' of the Earth exposed for hundreds or ... millions of years (anchient diamonds, extractions from the sea bottom, etc.)
- Natural way would be to explore electric fields inside the crystal. Comparison of traditional magnet and 'bending crystal' A step from atom's scale to nuclear one could significantly reduce the mass and volume of a detector.