LHCb results relevant for dark matter searches

Murilo Rangel
on behalf of the LHCb Collaboration

02/09/2019
LHCb is a single arm spectrometer fully instrumented in the forward region (2.0<\eta<5.0). Designed for heavy flavour physics and also exploited for general purpose physics.

[Int. J. Mod. Phys. A 30, 1530022 (2015)]

**VELO**

~20μm IP resolution

**Muon**

ε~97% for misID~2%

**Tracking (magnet)**

0.4%-0.6% momentum resolution (0.2-100 GeV)

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[Int. J. Mod. Phys. A 30, 1530022 (2015)]
LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018

- 2018 (6.5 TeV): 2.19 /fb
- 2017 (6.5+2.5 TeV): 1.71 /fb + 0.10 /fb
- 2016 (6.5 TeV): 1.67 /fb
- 2015 (6.5 TeV): 0.33 /fb
- 2012 (4.0 TeV): 2.08 /fb
- 2011 (3.5 TeV): 1.11 /fb
- 2010 (3.5 TeV): 0.04 /fb

- **Pb-Pb 2018**
- **Pb-Pb 2015**
- **p-Pb 2013**
Motivation

**Dark Matter and LHCb**

→ Unification of Dark Matter and SM phenomenology predicts signatures at LHC.
→ Many signatures can be searched at LHCb
  + Dark bosons
  + Long lived particle (LLP)
  + Rare decays

**LHCb**

→ Unique coverage complementary to ATLAS/CMS
→ Soft trigger and forward acceptance → lower masses reach
→ Excellent secondary/tertiary vertex reconstruction → lower lifetimes (~ 1 ps).
Hidden Sector Bosons in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Different models hypothesize a field that could explain inflation, baryon asymmetry and/or dark matter.

Multivariate selection is applied to reduce the background further using uBoost algorithm.

Different models hypothesize a field that could explain inflation, baryon asymmetry and/or dark matter.

Search for a narrow dimuon peak is performed.

Limits for the axion model below are calculated.

M. Freytsis, Z. Ligeti, and J. Thaler, Constraining the axion portal with $B \to K \ell^+ \ell^-$. Phys. Rev. D 81, 034001 (2010).
→ Sensitive to DM sector with portals to SM
→ Three regions of dimuon decay time are selected to optimize limits using Run I data

Hidden Sector Bosons in $B^+ \rightarrow K^+ \mu^+ \mu^-$

PRD 95, 071101 (2017)
Hidden Sector Bosons in $B^+ \rightarrow K^+\mu^+\mu^-$

→ Model-independent limit with branching fraction normalised to $B^+ \rightarrow K^+\psi(\mu^+\mu^-)$
→ Lifetimes constrained relate to decay lengths $\sim 30$ mm to 30 cm

→ Interpretation for the inflaton model described in the references below is given for square of the mixing angle, $\theta^2$.

Hints from HyperCP experiment could indicate the existence of dark boson.

H. Park et al. (HyperCP Collaboration), Evidence for the Decay $\Sigma^+ \rightarrow p\mu^+\mu^-$, Phys. Rev. Lett. 94, 021801 (2005).
Using Run I data, LHCb found evidence for SM decay

\[ \mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8} \]

No significant peak in the dimuon mass.
Spin-0 particles can be copiously produced at LHC via gluon fusion

In the dimuon final state, searches at LHC usually exclude the Y region.
Due to the excellent mass resolution, search for a narrow dimuon resonance in the mass region between 5.5 and 15 GeV at LHCb is performed.
Mass independent multivariate selection is used to maximise the analysis sensitivity.
Due to the precise model of tails, LHCb sets first limits for spin-0 hypothetical light dimuon resonance in the mass range between 8.7 and 11.5 GeV.
→ Coupling may arise via kinetic mixing between the SM hypercharge and $A'$ field strength tensors
→ $A'$ can decay to pair of muons and search can be normalise to prompt production
→ Search is fully data-driven if very short lifetimes are considered

**Run II data:** $L=1.6/fb$ at 13 TeV

**Trigger:** Soft $p_T$ muons with no prescale
→ Di-muon masses down to $2m(\mu)$ up to 70 GeV
Dark Photons

$m(A') = 0.5$ GeV
$m(A') = 5$ GeV
$m(A') = 50$ GeV

$\rightarrow$ derived using J/$\psi$ and Z
$\rightarrow$ simulation corrected by data
$\rightarrow$ derived using same-sign muons

LHCb
$\sqrt{s} = 13$ TeV

prompt-like sample
$p_T(\mu) > 1$ GeV, $p(\mu) > 20$ GeV

Candidates / $\sigma(m(\mu^+ \mu^-)) / 2$
No significant excess found in the prompt-like search. First search for dark photon masses of 10 GeV.
Dark Photons

Long-lived search covers lower masses \([214-350]\) MeV

→ Excluded material map using beam-gas collisions (photon conversion background)
   based on material interactions from hadrons produced in beam-gas collisions
Long-lived search covers lower masses [214-350] MeV
→ Excluded material map using beam-gas collisions (photon conversion background)

90% CL upper limit on $n_{ob}^{A'}[m(A'), \varepsilon^2] / n_{ex}^{A'}[m(A'), \varepsilon^2]$

No significant excess found

First displaced search not from beam-dump experiments
Search for SM Higgs decaying to hidden valley particles → Single displaced vertex with two jets

The trigger explores displaced vertex topology and the limits use:
- Background model empirically modeled as HF decays material interaction
- Signal model obtained in simulation

Signal model (35 GeV/c², 10 ps) for $\mathcal{B}(H^0 \rightarrow \pi_V \pi_V) = 1$.
Best-fit signal model (35 GeV/c², 10 ps).
No significant excess found in the long-lived
Example: for $m_\pi = 50$ GeV and $\tau = [5-50]$ ps, BR $>$ 30% is excluded
Testing models:
- mSUGRA with R-parity violation
- Four simplified MSSM models
  - Possible decay of Higgs-like particle with mass between 50 and 130 GeV

Trigger on displaced vertex containing a muon and tracks

Selection based on MLP using 7 variables – $R_{xy}$ is the most discriminant

Limit setting from fits to LLP mass
  - Background model empirically modeled as two exponentials
  - Signal model obtained in simulation

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5 models tested and no significant excess found in the long-lived
Example above: $m(H)=125$ GeV, $\tau(\text{LLP})=5$ ps and $\text{BR}=10\%$, 
LLP mass < 30 GeV is excluded
Lepton-flavour-violating decay of Higgs-like particle will indicate the presence of unknown physics. Four decay channels are analysed and the search is performed for masses between 45 and 195 GeV.
Astroparticle experiments probe dark matter in the universe, but large uncertainties due to the antiproton production cross-section limit their sensitivity.

→LHCb is able to inject gas in the interaction region and become a fixed target experiment using SMOG device.
→6.5 TeV protons collide with He at $\sqrt{s} = 110.5$ GeV
→0.4/nb acquired in 2016

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Antiproton production in pHe collisions

33.7 million reconstructed pHe collisions for about 1.4 million antiprotons

First measurement of antiproton production in p-He collisions

Significant excess of anti-proton production over the EPOS

Measured range of the antiproton kinematic spectrum are crucial for interpreting the precise anti-proton cosmic ray measurements from the PAMELA and AMS-02 experiments by improving the precision of the secondary anti-proton cosmic ray flux prediction.
LHCb Upgrade

Run 1: 9.1/fb
Run 2: 25/fb
Run 3: 25/fb
Run 4: 50/fb
LHCb Upgrade
CERN-LHCC-2012-007

New VELO (Pixel Detector)

SciFi (new scintillating fibre tracker)

UT (new silicon tracker)

New mirrors and photon detectors

New readout electronics for the entire detector
Increase instantaneous luminosity:
\[ 4 \times 10^{32} \rightarrow 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \]

Replacement of tracking detectors
- finer granularity to cope with higher particle density
- new front-end electronics compatible with 30 MHz readout

Remove hardware trigger stage and operate software trigger at 30 MHz input rate with 5 x more pileup than Run 2.

HLT1 output: from 100 kHz to 1 MHz
Disk buffer contingency: from weeks to days
HLT2 output: from 0.6 GB/s to 10 GB/s
Extrapolations show good perspective to reach lower masses and lower lifetimes.


Emerging Jets

![Diagram of Emerging Jets](image)

LHCb dataset
- Published Run 1 at 2 fb⁻¹
- 23 fb⁻¹
- 50 fb⁻¹
- 300 fb⁻¹

LHCb-CONF-2018-006
Summary

★ LHCb has an extensive program of searches sensitive to Dark Matter

★ Analyses explore the unique LHCb capabilities for
  * separating primary, secondary and tertiary vertices with excellent resolution
  * triggering on soft particles

⇒ Future and other related results can be found here
THANK YOU!
Run 2 trigger

Trigger structure:

‡ **Hardware**: energies deposited in calorimeters and muon stations hits are used to bring 40 MHz to 1 MHz

‡ **Software**: events built at 1 MHz (~27000 physical cores)
  HLT1: fast tracking and inclusive selections
  1 MHz to 100 kHz
  HLT2: complete event reconstruction and selections

LHCb Run II Trigger Diagram (2015 - 2019)
Run 2 trigger

LHCb Trigger Run 2

- **Bunch crossing rate**
  - 40 MHz
- **L0 Hardware trigger**
  - high $p_T/E_T$ signatures
  - 1 MHz

High Level Trigger 1
- partial event reconstruction
  - 110 kHz
  - 12.5 kHz

Software trigger
- **10 PB buffer**
  - Alignment & Calibration
  - 110 kHz

High Level Trigger 2
- full event reconstruction
  - 110 kHz

Storage

- HLT Farm with 10 PB disk space
- At an average event size of 55 kB with 100 kHz: up to 2 weeks before HLT2 has to be executed
- 2x trigger CPU capacity since Farm is used twice for HLT (excess used for simulation)
Run 2 trigger

LHCb Trigger Run 2

- Bunch crossing rate: 40 MHz
- L0 Hardware trigger: 1 MHz
  - High $p_T/E_T$ signatures

High Level Trigger 1
- Partial event reconstruction: 110 kHz
- 10 PB buffer: 110 kHz
- Alignment & Calibration

High Level Trigger 2
- Full event reconstruction: 12.5 kHz
- Storage

JINST 14 (2019) no.04, P04013

~50% improvement in mass resolution

# Real-time alignment and calibration
# Dedicated HLT1 trigger lines supply samples for the alignment
# Alignment & calibration tasks run in parallel while events are being processed by HLT1
Run 2 trigger: Turbo

Bandwidth \([\text{GB s}^{-1}]\) $\propto$ Trigger output rate \([\text{kHz}]\) $\times$ Average event size \([\text{kB}]\)

Turbo data processing model

- Analyses that can be done using trigger objects can profit of reduced event size and higher trigger rate.
- Event size can be reduced from 70 kB to 7 kB depending on the persistence level.
- Calibration samples increased, reducing systematic uncertainties on efficiency measurements.
- 50% of HLT2 trigger lines are Turbo counting 10% of the bandwidth.
Run 2 Trigger: Turbo Analyses

**Study of $J/\psi$ Production in Jets**

R. Aaij *et al.* (LHCb Collaboration)  
Phys. Rev. Lett. **118**, 192001 – Published 8 May 2017

**Observation of the Doubly Charmed Baryon $\Xi_{cc}^{++}$**

R. Aaij *et al.* (LHCb Collaboration)  

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**Probing Quarkonium Production in Jets**

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**A Doubly Charming Particle**

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**LHCb 8 TeV**

- Data
- Total
- Signal
- Background

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**$z(J/\psi)$**

- Data (syst)
- DPS
- LO NRQCD
- SPS

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**$m_{\text{cand}}(\Xi_{cc}^{++})$**

- Candidates per 5 MeV/c^2

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Run 2 trigger: Plots

LHCb-CONF-2016-005

1.17 billion dimuons

Rare events: high efficiency
Copious production: high purity

630 million candidates
LHCb Run II trigger

Beam-beam crossing
30 MHz
L0
Hardware trigger
1 MHz
HLT1
Partial reconstruction
110 kHz
Buffer
10 PB
Alignment & calibration
TurCal
1 kHz
50 MB/s
HLT2
Full reconstruction
3 kHz
100 MB/s
Turbo
Full
8 kHz
420 MB/s
Figure 1: Dedicated SMOG runs collected since 2015. Beam-gas collisions have been recorded using different gas types (He, Ar, Ne) and beam energies.