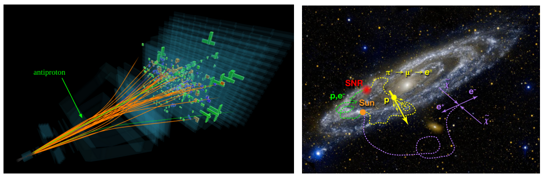
Exploring cosmic ray physics at LHCb

Advisor: Giacomo Graziani < giacomo.graziani@fi.infn.it >
Co-Advisors: Saverio Mariani < saverio.mariani@cern.ch >
Chiara Lucarelli < chiara.lucarelli@fi.infn.it >

LHCb is special in many respects among the LHC experiments, but its most surprising feature is the possibility to be operated simultaneously as a collider and as a fixed target experiment. Indeed, LHCb has the unique possibility to inject small quantities of noble gases, like helium or neon, into its vertex detector that is placed directly inside the LHC beam pipe vacuum. In this way, LHCb is able to record the collisions of protons or lead ions on the gas nuclei with the possibility to explore a wide physics programme ranging from heavy ion to cosmic ray physics.

In particular, the antimatter production such as anti-protons or positrons in collisions of LHC protons with helium (p-He) reproduces the primary cosmic ray protons colliding interstellar helium. This is the main background in searches for exotic antimatter sources performed by space-borne experiments such as AMS or PAMELA and the LHCb measurements are improving the accuracy of its modelling. The system used by LHCb to inject gas is named SMOG and was originally designed to measure the LHC luminosity at the LHCb interaction point.



Left: A p-He collision with a produced anti-proton recorded by LHCb; right: sketch of cosmic ray paths across the Milky Way

Our group pioneered the use of SMOG to perform precision measurements in the domain of cosmic ray physics, thus initiating a new way to exploit the LHC beams. In 2018 the production of anti-protons directly from p-He collisions was measured for the first time ever in this collision system. The result, published on PRL, was the first physics result obtained from fixed target collisions at the LHC. In 2022, the contribution from $p + He \to \bar{H}X \to \bar{p} + X$ was also investigated, where $\bar{H}$ is a baryon containing an $\bar{s}$ quark ($\bar{\Lambda}$, $\bar{\Sigma}^-$, $\bar{\Xi}^-$, $\bar{\Xi}^0$ or $\bar{\Omega}^-$) and X is any other particle. These measurements turned LHCb into a relevant contributor to cosmic ray physics.

Building on these successful measurements, LHCb decided to upgrade the SMOG system in the SMOG2 project, mainly consisting of the confinement of the injected gas in a cell upstream of the LHCb beam-beam interaction region. The injected pressure will be increased by up to two orders of magnitude with the same gas flow used in the previous LHC runs and a new gas feed system will offer a more precise control of the gas target density. Other gas species, such as hydrogen, nitrogen or oxygen, are expected to be injected in the coming years. All of this will result into a wide fixed target physics program, the only one exploiting the LHC complex.

The Ph.D. candidate will take part in this pioneering program, involving data analysis and simulation for understanding the detector in the new SMOG2 setup, development of high-level analysis tools aiming at the production of groundbreaking physics results. Among the possible topics are:

- measurement of inclusive anti-proton production in p-He, p-H, p-D collisions with SMOG and SMOG2; these measurements are expected to dramaticaly reduce the current uncertainties on the cosmic secondary antiproton production;
- measurement of inclusive pion and kaon production in p-He collisions; this would allow to estimate the rate of production of cosmic secondary positrons;
- production of anti-nuclei in p-He collisions; this topic is particularly challenging and will require development of innovative particle identification techniques;
- production of photons in p-He collisions; this topic is also extremely interesting for understanding the diffuse cosmic γ-ray background;
- development of a technique to precisely measure the luminosity of proton-gas collisions in SMOG/SMOG2;
- tracking and particle identification for SMOG2; tracking for SMOG2 will be performed in real time in the novel full-software trigger of LHCb and will require programming on GPUs and applications of modern machine learning techniques.

Further reading

- A. Reinert and M. W. Winkler, *A precision search for WIMPs with charged cosmic*, JCAP **01** (2018) 055
- F. Donato *et al*, *Production cross sections of cosmic antiprotons in the light of new data from the NA61 and LHCb experiments*, PoS ICRC2019 (2019)
- LHCb Collaboration, *Measurement of Antiproton Production in p-He Collisions at* $\sqrt{s_{NN}} = 110$ *GeV*, Phys. Rev. Lett. 121, 222001
- LHCb Collaboration, *Measurement of antiproton production from antihyperon decays in pHe collisions at* $\sqrt{s_{NN}} = 110$ *GeV*, arXiv:2205.09009
- G. Graziani, *et al.*, *Physics opportunities with the fixed-target program of the LHCb experiment using an unpolarized gas target*, CERN-LHCb-PUB-2018-015
- S. Mariani, *et al.*, *A Neural-Network-defined Gaussian Mixture Model for particle identification applied to the LHCb fixed-target programme*, JINST **17** (2022) P02018
- S. Mariani, *Fixed-target physics with the LHCb experiment at CERN*, CERN-THESIS-2021-313

About the group

Giacomo Graziani is Senior Researcher at INFN-Firenze and an early member of the LHCb Florence group. He pioneered the use of LHCb fixed-target capabilities for cosmic ray physics measurements and was the first convener of the related LHCb Physics Working Group. Dr. Graziani is currently coordinating the group of experimental physics with particle accelerators of INFN-Firenze.
Saverio Mariani is Post-Doc at INFN-Firenze. He is involved since his PhD in LHCb fixed target physics with focus on cosmic ray measurements. He is the main author of the measurement of antiprotons in p-He collisions through anti-hyperon decays for which he developed a novel machine-learning technique for particle identification. He is now in charge for the commissioning of the new SMOG2 apparatus at CERN. He has recently been awarded the "LHCb Early Career Researcher Award" for his work on fixed-target physics.
Chiara Lucarelli is PhD student at University of Florence. She is the reference person in LHCb for the simulation of the molecular flow inside of the SMOG2 device, crucial to fully exploit the possibility of injecting gases other than noble ones in the coming years, and to allow a precise measurement of the luminosity. Her PhD thesis work will be focused on the pioneering measurement of the production of anti-deuterons in p-He collisions.