IL NUOVO CIMENTO **45 C** (2022) 111
DOI 10.1393/ncc/i2022-22111-y

COMMUNICATIONS: SIF Congress 2021

Z' and dark Higgsstrahlung searches in events with muon pairs at Belle II

M. LAURENZA(1)(2)

(1) *INFN, Sezione di Roma Tre - Roma, Italy*
(2) *Dipartimento di Fisica, Università di Roma Tre - Roma, Italy*

received 31 January 2022

Summary. — The Belle II experiment at the SuperKEKB e^+e^- collider is a major upgrade of the Belle experiment. The main operations started in March 2019: an integrated luminosity of 267.9 fb^{-1} has been collected so far. This early dataset, with specifically designed low multiplicity triggers, already offers the possibility of searching for a large variety of dark sector particles in the GeV mass range. This paper reports on the first searches for a Z' light gauge boson and dark Higgsstrahlung process $A'h'$, A' and h' being the dark photon and the dark Higgsstrahlung, with muon pair final states. The existence of a Z' or a A' could explain the observed dark matter relic density. In addition, the Z' could concur to the understanding of the long-standing $(g-2)_\mu$ anomaly.

1. – Introduction

A variety of astrophysical observations suggest the existence of the Dark Matter (DM), consisting of particles that do not interact through strong or electromagnetic forces. The lack of evidence for non-standard model physics at the electroweak scale drives us to the possibility that DM and particles mediating its interaction with the Standard Model (SM) particles may have a mass at or below the GeV scale. This is called "light dark matter" scenario (LDM) where particles feebly interact with ordinary matter through a limited number of possible "portals", depending on the mediator (vector portal, pseudo-scalar portal, scalar portal, neutrino portal) [1]. In this report, I describe published and ongoing analyses for light dark matter searches at Belle II, focusing in particular on Z' and dark Higgsstrahlung in events with muon pairs.

2. – SuperKEKB and Belle II experiment

Belle II [2] is a full upgrade of the Belle experiment located at the KEK laboratory (Tsukuba, Japan). It is built around the interaction region of SuperKEKB, an asymmetric e^+e^- collider that operates mainly at a center-of-mass energy of 10.58 GeV, which corresponds to the $\Upsilon(4S)$ resonance mass. The higher beam currents and the smaller interaction region with respect to KEKB along with the usage of the large crossing-angle nano-beam scheme, allow SuperKEKB unprecedented instantaneous luminosities. Belle II is an excellent environment where searching for dark matter particles and mediators, thanks to its charged and neutral particles reconstruction performances and dedicated triggers [3]. We are carrying on a large number of analyses in the dark sector field.

3. – Z' and dark Higgsstrahlung searches in events with muon pairs

3˙1. *Z' searches.* – The Z' is a light gauge boson predicted by the $L_\mu - L_\tau$ SM extension [4], a scenario in which the Z' interacts only with the second and third generation of leptons with coupling constant g'. The $L_\mu - L_\tau$ model would explain some long-standing experimental anomalies [5]. Two different decay topologies are currently analyzed at Belle II, namely the visible and invisible ones.

The search for an invisibly decaying Z' radiated off a muon was performed with a data set of $276\,\text{pb}^{-1}$. The signature is a peak in the distribution of the invariant mass of the system recoiling against two tracks identified as muons (fig. 1(a)) and nothing else in the event. No excess over background expectations was found and an upper limit on the coupling constant g' was set (fig. 1(b)). The result has been published by Belle II as its first physics paper [6] and an updated measurement with about 300 times the luminosity is in preparation.

We also search for two visible Z' decays, $e^+e^- \to \mu^+\mu^- Z'(Z' \to \mu^+\mu^-)$ and $e^+e^- \to \mu^+\mu^- Z'(Z' \to \tau^+\tau^-)$.

The search for a Z' decaying into a muon pair has already been performed by BaBar with $514\,\text{fb}^{-1}$, providing an upper limit for g' [7]. Belle II plans to apply an aggressive background suppression, to be competitive with the existing results with less integrated luminosity. The main background is the SM $\mu^+\mu^-\mu^+\mu^-$ production: this is reduced by exploiting the differences of kinematic distributions in events with a $Z' \to \mu\mu$ resonance. The actual implementation is achieved through a multi-layer perceptron (MLP) based algorithm. The expected sensitivity from a preliminary study is shown in fig. 2(a).

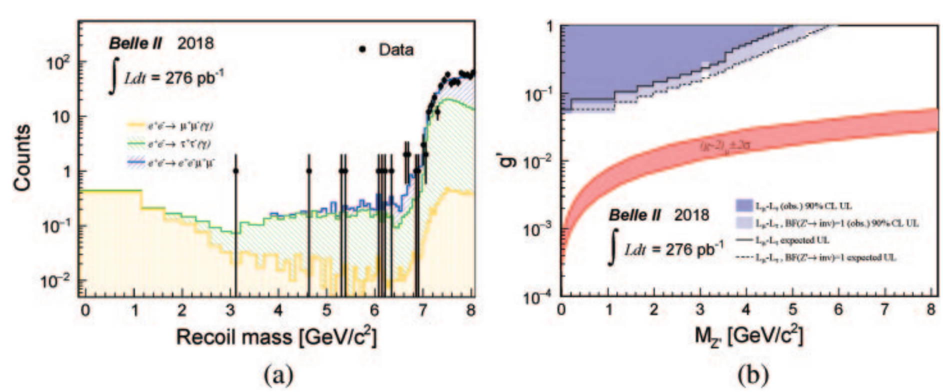

Fig. 1. – (a) Recoil mass distribution for signal candidates reconstructed in $276\,\text{pb}^{-1}$ of early Belle II data, with simulation expectations overlaid. (b) Upper limit on the coupling constant g' as a function of Z' mass resulting from the analysis of $276\,\text{pb}^{-1}$ of early Belle II data.

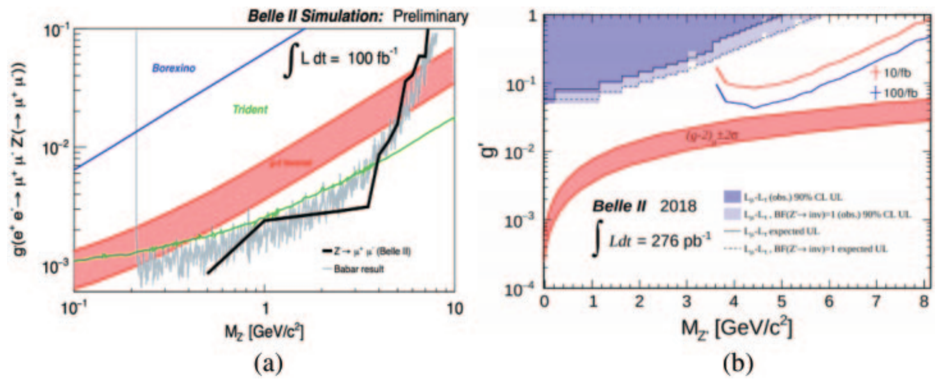

Fig. 2. – (a) Expected upper limit on the coupling constant g' as a function of Z' mass assuming a data set of $100\,\mathrm{fb}^{-1}$ for the $Z' \to \mu\mu$ analysis. (b) Expected upper limit on the coupling constant g' as a function of Z' mass assuming a data set of $10\,\mathrm{fb}^{-1}$ (in red) and $100\,\mathrm{fb}^{-1}$ (in blue) for the $Z' \to \tau\tau$ analysis.

The $Z' \to \tau\tau$ analysis is optimized to search for a Z' radiated off a muon and producing a τ pair followed by a one prong decays ($\tau \to e, \mu, \pi$). No previous searches for a $\tau\tau$ resonance in a $\mu\mu\tau\tau$ final state exist. The challenge is the presence of neutrinos, which does not allow the full Z' mass reconstruction. An MLP classifier exploits kinematic properties to distinguish between signal and background events, whose main contributions come from $ee \to \tau\tau$, $q\bar{q}$, $ee\mu\mu$ and $\mu\mu$ events. A preliminary 90% confidence level upper limit on the coupling constant g' is shown in fig. 2(b).

Although here projections at $100\,\mathrm{fb}^{-1}$ for $Z' \to \mu\mu$ and $Z' \to \tau\tau$ analyses are shown, we plan to use a larger data set, of about $200\,\mathrm{fb}^{-1}$ for both these searches.

3˙2. *Dark Higgsstrahlung search.* – The dark photon A' is the simplest and most studied case of vector portal. Since it needs to be massive, one can implement, in

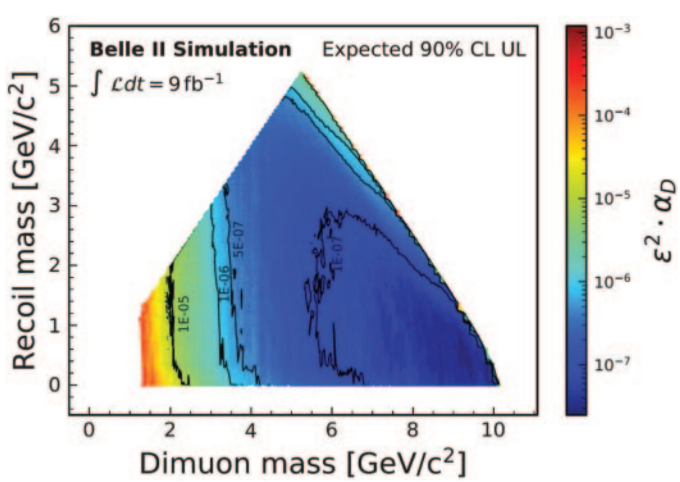

Fig. 3. – Sensitivity in the coupling $\varepsilon^2 \cdot \alpha_D$ as a function of recoil *vs.* dimuon masses.

close analogy with the SM, a spontaneous symmetry breaking mechanism, introducing a Higgs-like particle h', called dark Higgs. The h' can be produced in the Higgsstrahlung process $e^+e^- \to A'^* \to h'A'(A' \to \mu^+\mu^-)$, which is also sensitive to the dark coupling constant α_D. At Belle II we are investigating the case when $m_{h'} < m_{A'}$, with an invisible (long-lived) h'. The only available result in this mass region comes from KLOE [8]. The signature for these events consist of two oppositely charged muons and missing energy with a peak in the distributions of both dimuon and recoil masses. In fig. 3, the expected sensitivity for the effective coupling of the process, $\varepsilon^2 \cdot \alpha_D$, being ε the kinetic mixing parameter and α_D the dark coupling constant, is shown in the recoil *vs.* dimuon mass plane. Belle II has access to unconstrained regions, which are well beyond the KLOE coverage, providing encouraging results, even with $9\,\mathrm{fb}^{-1}$ only.

4. – Conclusion

Belle II at SuperKEKB has an unprecedented reach for light dark matter and mediator searches. It has already reported world leading results with luminosity collected during the 2018 pilot run ($500\,\mathrm{pb}^{-1}$). The total dataset collected to date amounts to $267.9\,\mathrm{fb}^{-1}$, using which we are currently searching a light Z' and dark Higgsstrahlung processes with muon pair final states that could potentially solve the dark matter puzzle and also the long-standing anomaly of the muon $(g-2)_\mu$. A lot of other dark sector searches are in progress, with world-leading results expected.

REFERENCES

[1] Batell B., Pospelov M. and Ritz A., *Phys. Rev. D*, **80** (2009) 1.
[2] Kou E., Urquijo P. *et al.*, *Prog. Theor. Exp. Phys.*, **2019** (2018) 12.
[3] Abe T. *et al.*, *Belle II technical design report*, arXiv:1011.0352 (2010).
[4] Shuve B. and Yavin I., *Phys. Rev. D*, **89** (2014) 1.
[5] Altmannshofer W. *et al.*, *JHEP*, **12** (2016) 6.
[6] Adachi I. *et al.*, *Phys. Rev. Lett.*, **124** (2020) 141801.
[7] Lees J. P. *et al.*, *Phys. Rev. D*, **94** (2016) 011102.
[8] Anastasi A. *et al.*, *Phys. Lett. B*, **747** (2015) 365.