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Recent results from NA62 experiment at CERN

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The NA62 experiment at the CERN SPS, designed to measure the branching ratio of the $K^+ \to \pi^+\nu\nu$ with a decay in-flight technique, collected data in 2016-2018. New results on rare kaon decays from the analysis of 2018 data, the largest data set so far collected, will be presented. The result represents the most accurate measurement so far achieved of this ultra-rare decay. Thanks to the huge sample of kaon decays NA62 can also put stringent limits on lepton number and lepton flavour violating decays and on the heavy neutral lepton production.

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1. Introduction

Among the many flavour-changing neutral current rare K and B decays, the decays $K^+ \to \pi^+\nu\nu$ play a key role in the search for new physics [1,2]. The SM prediction using the CKM matrix elements is very precise BR($K^+ \to \pi^+\nu\bar{\nu}$) = $(8.4 \pm 1.0)\mathrm{x}10^{-11}$ [3].Previous experimental results for $K \to \pi\nu\nu$ were based on seven signal events collected by BNL- AGS-E787(E949) using stopped kaon, that yielded a branching ratio of $(1.73^{+1.15}_{-1.05}) \cdot 10^{-10}$ [4,5] . The branching ratio is 1 σ away from the SM prediction, but the measurement was based on only few events and the experimental uncertainties are large.

2. The NA62 experiment

The NA62 beam line and detector are described in detail in [6] and shown in Figure 1. The NA62 beam is produced by the interaction of a 400 GeV/c proton beam, from the CERN super proton syncroton (SPS), with a beryllium target. It is composed of positively charged particles of which 6% are kaons and it has a central momentum of 75 GeV/c with a momentum bite of 1%. The kaons in the beam are identified by a Cherenkov counter detector, KTAG, filled with N_2, with a time resolution of 70 ps. The kaon momentum, direction and the event time are measured by three silicon pixel stations of 6x3 cm^2 surface area exposed to the full 750 MHz beam rate. Then the kaons decay in vacuum in a 75 m long fiducial volume. Downstream a spectrometer, composed of 4 STRAW tube chambers and a dipole magnet, placed between the second and third STRAW chambers, measures the momentum and direction of charged particles coming from the kaon decay. A ring imaging Cherenkov detector (RICH) is located downstream of the vacuum tank. It consists of a 17.5 m long vessel filled with neon at atmospheric pressure, it is used to separate π, μ and e and provides a trigger reference time with 70 ps precision. The timing of charged particles is measured both with the RICH and with an array of scintillators (CHOD) located downstream of the RICH. Two hadronic calorimeters (MUV1 and MUV2) and a fast scintillator array (MUV3) provide further separation between π and μ. Photons are detected by an hermetic photon veto system covering angles up to 50 mrad from the beam axis. The photon veto system is composed of twelve annular lead glass detectors (LAV1–12), two lead/scintillator sampling calorimeters (IRC, SAC) close to the beam axis and a $27X_0$ thick quasi-homogeneous liquid krypton (LKr) electromagnetic calorimeter which provides measurements of energy, transverse coordinates, and time with an energy resolution of $\sigma_E/E = (4.8\sqrt{E} \oplus 11/E \oplus 0.9)\%$, where E is expressed in GeV. Particle identification is performed using the RICH, the LKr calorimeter and the muon detector. Two level triggers are built up : information from CHOD, RICH, MUV3 and LKr are used online to issue level zero trigger conditions and information from KTAG, CHOD, STRAW and LAV are used for a software second level trigger [11] .

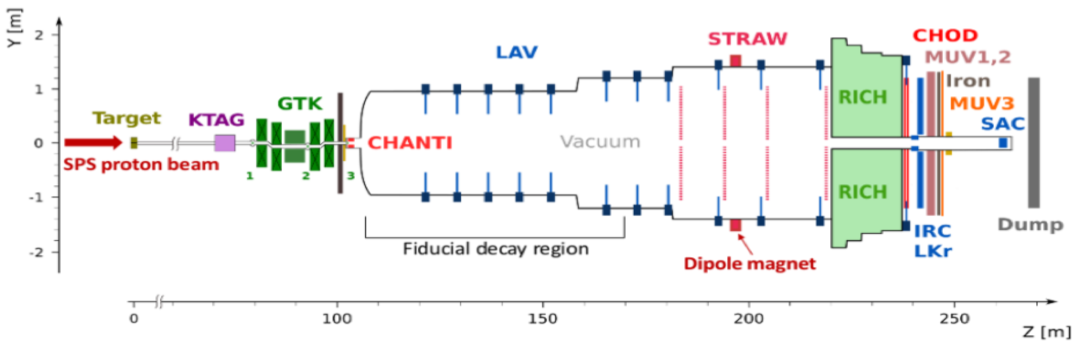


Fig.1 NA62 detector, top view

3. $K^+ \to \pi^+\nu\bar{\nu}$ analysis

The analysis of the complete 2018 data set is presented here, corresponding to a total of about $2.62x10^{12}$ kaon decays, the largest data set so far collected. Results from the combination with the

2016-2017 data set are also reported [7,8]. The experimental signature of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ is the presence of an incoming kaon track an outgoing pion track plus missing energy. The most discriminating kinematic variable is $M^2{}_{\text{miss}} = (P_{K^+} - P_{\pi^+})^2$, where P_{K^+} and P_{π^+} are the 4-momenta of theK^+ and π^+ respectively. Events with a single-track decay topology are selected using the downstream detectors STRAW, CHOD and RICH and the reconstructed track is associated to an in-time kaon in the KTAG detector. A cut on the reconstructed vertex is then applied requiring that it is inside the fiducial volume. The selected single-track events are shown in Figure 2. The downstream track is identified as a π using two complementary methods: multivariate analysis with Boosted Decision Trees (BDTs) using energy deposition, energy sharing and shower shape profiles in the electromagnetic (LKr) and hadronic calorimeters (MUV1/2), as well as signals from the muon veto(MUV3); a cut- based approach using the particle mass reconstructed by the RICH detector and a track-driven likelihood discriminant for π, μ, e separation.

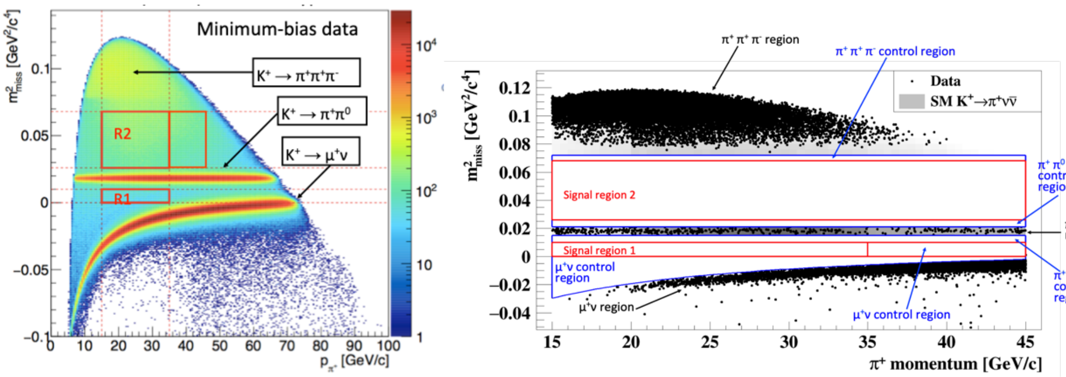


Figure 2,3: m^2 versus π momentum: the signal region (1,2) the background region and the back-ground control region are also indicated: (left) before selection, (right) after selection.

The algorithm for particle identification has an efficiency for identifying π of 64% and a muon mis-identification probability of 10^{-8}. A photon and multi-track rejection is applied based on information from all electromagnetic calorimeters (LKr, LAV, SAC and IRC) and the charged ho-doscope (CHOD) providing π^0 suppression $\varepsilon = (1.4 \pm 0.1)x10^{-8}$. The $m^2{}_{\text{miss}}$ distribution after selection is shown in Figure 3. The number of expected SM signal event is derived from:

$$N_{expected} = N_{\pi\pi}\varepsilon_{trig}\varepsilon_{RV}\frac{A_{\pi\nu\nu}BR(\pi\nu\nu)}{A_{\pi\pi}BR(\pi\pi)}$$

here $N_{\pi\pi}$ is the number of $K^+ \rightarrow \pi^+\pi^0$ decays selected from minimum bias sample, A is the acceptance for the signal and ππ decay derived from Monte Carlo, ε_{trig} and ε_{RV} are the signal trigger efficiency and the random veto efficiency measured in data using controlsamples. In particular ε_{RV} is defined as one minus the probability for a signal event to be randomly rejected by the photon veto conditions. Finally the branching ratios are the SM expectation for the two decay channels. The Single Event Sensitivity defined as $S.E.S. = \frac{BR(\pi\nu\nu)}{N_{expected}}$, is measured to be $1.11 \pm 0.07\ x10^{-11}$, which corresponds to a number of expected SM signal events $N_{expected} = (7.58 \pm 0.40_{sys} \pm 0.75_{ext})$. The background from the more abundant kaon decays in the signal regions is estimated using a data control sample. The agreement between expected and observed background events in suitable control regions of $m^2{}_{\text{miss}}$ validates this estimation, see fig.4. An additional background source is upstream background originated from decays or interactions of K^+ occurring upstream of the final collimator. These daughter pions mimic a signal event if accidentally matched to random beam particles, geometrical distribution of upstream events is used to define analysis cuts and background estimation in the selected signal sample. The background expected in the signal region in the 2018 data sample is $N_{bck} = 5.28^{+0.99}_{-0.74}$ of which $3.30^{+0.98}_{-0.73}$ is from the upstream background.

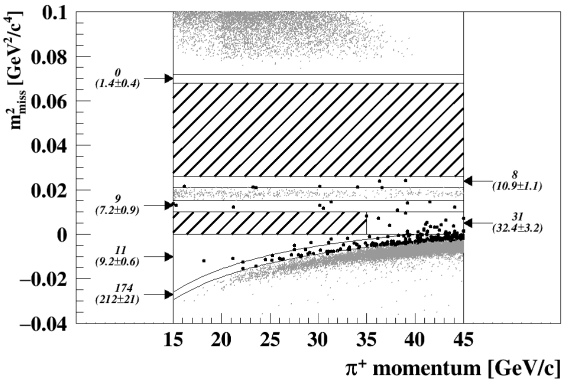


Fig. 4: m^2_{miss} versus π momentum after all the cuts, background control regions are unblinded to compare with the expectation

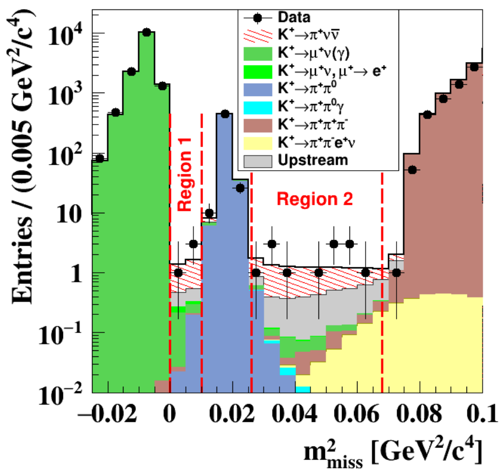
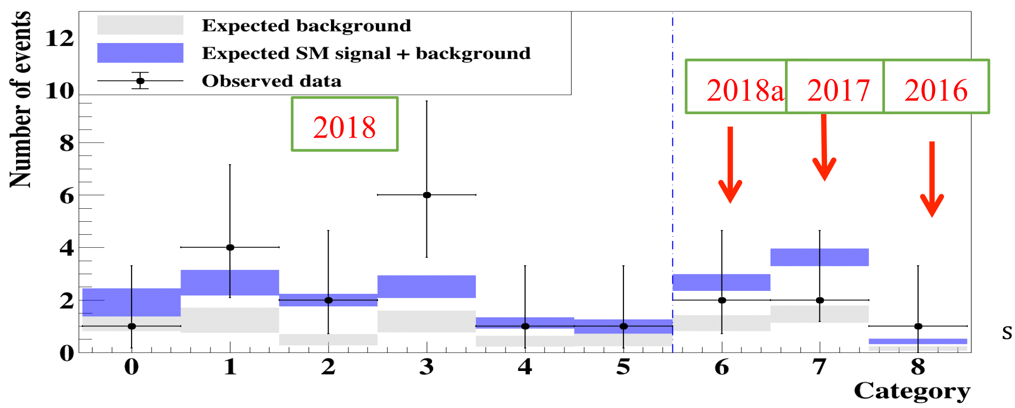


Fig. 5: m^2_{miss} distribution of the selected events, data are compared with montecarlo.

3.1 $K^+ \to \pi^+\nu\bar{\nu}$ results

Unblinding the signal region we find 17 events. The $m^2{}_{miss}$ distribution for the 2018 data integrated over the full range of π momentum. is shown in figure 5 compared with the MC. The final Branching Ratio is then obtained by combining the 2018, 2017 and 2016 data sample [7,8,9]. The 2018 data is divided into six sample , 5 GeV/c wide momentum bins from 15 to 45 GeV/c, and according to data taking condition, 80% of 2018 data were collected after the installation of a new collimator to reduce upstream background, as shown in fig. 6



Using a maximum likelihood fit based on the signal and background expectation in each category with the branching ratio as free parameter we obtain:

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4} stat \pm 0.9 syst)$$

at 3.5σ significance. This is the most precise measurement of the branching ratio so far and it is compatible with the SM expectation within one standard deviation. The NA62 measurement together with the preliminary KOTO limit for the are shown in fig.7 (left), the Grossman-Nir limit: BR($K_L \to \pi^0\nu\bar{\nu}$) <4.3 BR($K^+ \to \pi^+\nu\bar{\nu}$) it is also reported [10] . In fig.7 (right) NA62 result is compared with different Beyond Stan- dard Model scenarios, although some models with large deviations from the SM expectation seem to be excluded, a more precise measurement is needed.

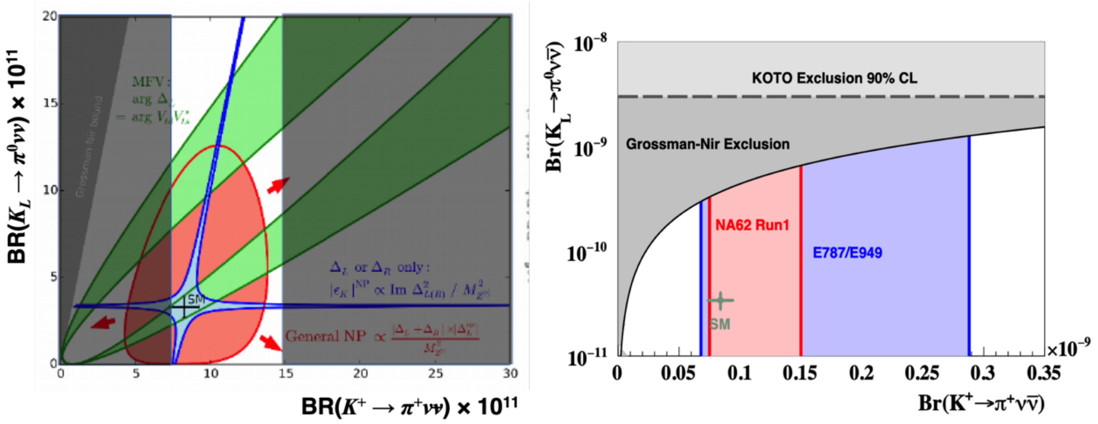
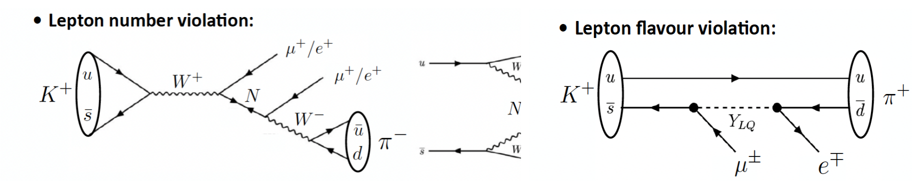


Figure 7: K_L vs K^+ branching ratio compared with models.

4. Lepton Flavour and Lepton Number violation decays

The observation of lepton number (LN) or lepton flavor number (LF) violation would be a clear indication of new physics; as they are conserved quantum numbers in the standard model (SM.Their conservation is not imposed by any local gauge symmetry. Observation of neutrino oscillations provided the first proof of the nonconservation of LF, however no evidence of LN violation has been observed so far. The seesaw mechanism provides a source of LN violation through the exchange of Majorana neutrinos, as in neutrinoless double beta decay. Searches for kaon decays violating LN and LF conservation are powerful probes of models beyond the SM at mass scales up to O(100) TeV.
LF violation decays can occur for example via the exchange of leptoquarks, a Z0 boson or light pseudoscalar bosons.



NA62 has searched for LN violating K+ $\to \pi^-\mu^+e^+$ decay (π^- channel), and the LF violating decays $K^+ \to \pi^+\mu^-e^+$ (μ^- channel) and $\pi^0 \to \mu^-e^+$, using the data collected in 2017-2018.

4.1 Lepton Flavour and Lepton Number violation decays results

The event selection requires three in time tracks generated from a vertex in the fiducial volume and with a total momentum compatible with the kaon momentun. The LKr calorimeter, the muon veto system and the RICH detector are used to identify e, π, μ. The kinematic variable used to distinguish between signal and background is the invariant mass of the three charged tracks, $m_{\pi\mu e}$, in the π, μ, e mass hypotheses.. The $m_{\pi\mu e}$ region close to the charged kaon mass 478–510 MeV/c^2 is kept masked, this includes the signal region and the background control regions immediately below and above the signal region. The $m_{\pi\mu e}$ resolution is 1.4 MeV/c^2. For the $K^+ \to \pi^+\pi^0(\pi^0 \to \mu^-e^+)$ and additional constraint requires the mass of the two leptons to be compatible with π^0 mass. The main background comes from 3 pion decay where π are misidentified and decay in flight, the background is measured with data and the prediction is verified in the control region. We normalize to $K^+ \to \pi^+\pi^+\pi^-$ which has a similar topology to the signal decays and allows a first order cancellation of systematic effects related to trigger conditions and detector inefficiencies.
The background is estimated using simulation, the misidentification probability is measured by control data sample and is used to weight the events, the discrepancies between data and simulations in energy deposited by π in the LKr, as well as in the beam momentum spectrum is taken into account.

The invariant mass distribution for the μ^- channel is reported in fig.8 compared with the different backgrounds contribution, the signal (pink) and the control region (grey) are masked. The background estimation, reported in table 1 for the control region agrees with the observation. Unblinding the signal region we observe 2 events with a background of 0.92±0.34.

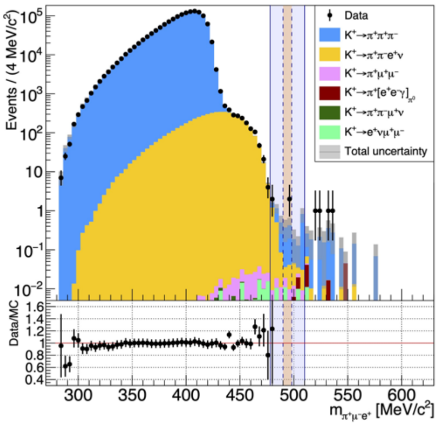


Fig.9 Invariant mass

	NCRB	NCRA
exp. bkg	3.41 ± 0.54	1.27 ± 0.40
Observed events	2	0

Tab.1 Expected and observed bkg event in control regions

A similar analysis has been done for the other decay mode.

The observations are consistent with the background predictions, and upper limits are set for the branching ratios using the C.L method with a likelihood ratio test statistic. The upper limits obtained at 90% C.L. are:

$B(K^+ \rightarrow \pi^-\mu^+e^+) < 4.2 \times 10^{-11}$

$B\ (K^+ \rightarrow \pi^+\mu^-e^+) < 6.6 \times 10^{-11}$

$B(\pi^0 \rightarrow \mu^-e^+) < 3.2 \times 10^{-10}$

These results improve on previous searches by an order of magnitude [12].

5. Search for Heavy Neutral Lepton (HNL) in kaon decays

Right handed neutrinos or Heavy Neutral Leptons (HNL) are included in several extensions of the Standard Model and can generate neutrino masses via the see-saw mechanism assuming O(100) MeV HNL masses [13].
HNL produced in decays have similar experimental signature of the SM decay $K^+ \rightarrow l^+\nu$ assuming that the HNL lifetimes are greater than 50 ns and the decay products escape detection.
The branching ratio for the electron and muon modes is related to the SM decay by:

$$B(K^+ \rightarrow l^+N) \sim B(K^+ \rightarrow l^+\nu) \cdot \rho_l(m_N) \cdot |U_{l4}|^2$$

Where $\rho(m_N)$ is a kinematic factor, O(1), and $|U_{l4}|^2$ is the squared neutrino mixing parameter.

The event selection is based on precise track reconstruction and vertex identification , $K^+/e^+/\mu^+$ identification, and O(100ps) detector time resolution to veto extra in-time activity .

The experimental signature of the $K^+ \rightarrow l^+N$ decay is a sharp bump in the positive m^2_{miss} side-band of the SM $K^+ \rightarrow l^+\nu$ decays. The m^2_{mis} distribution for $K^+ \rightarrow e^+\nu$ decays is reported in figure 10.

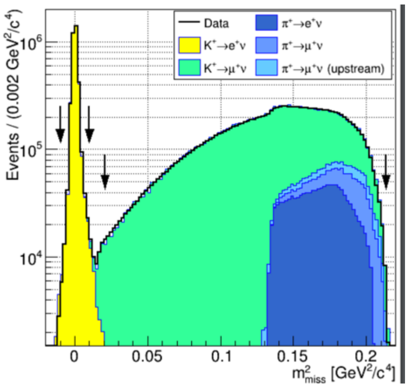


Fig.10 Missing mass

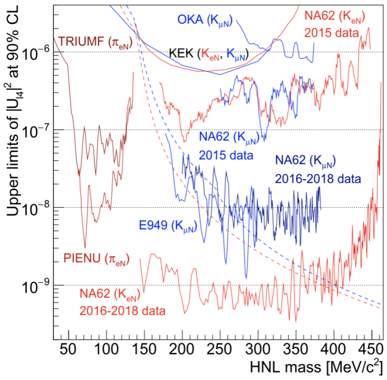


Fig.11 $|U_{l4}|^2$ for different HNL mass

The number of observed events, N_{obs}, within the signal window, the number of expected background events, N_{exp}, and its uncertainty, δNexp, are used to evaluate the upper limit at 90% CL of the number of $K^+ \rightarrow e^+N$ decays, NS, in each HNL mass hypothesis using the C.L.S method. The number of background events expected is evaluated from data and verified with simulation.

The limits on the squared neutrino mixing parameter, $|U_{l4}|^2$, are reported in figure 11 for the muon and electron channel, these limits improve significantly upon those of previous production and decay searches [13,14].

6. Conclusions

NA62 has succeeded in measuring BR($K^+ \rightarrow \pi^+\nu\nu$) with the decay-in-flight technique. The most precise measurement obtained so far has been achieved, the result is compatible with the SM prediction within one standard deviation. Limits on Lepton Flavour Violation and Lepton Number Violation in kaon decays have been improved by one order of magnitude compared to previous searches . World's best limits on the squared neutrino mixing parameter $|U_{e4}|^2$ and $|U_{\mu4}|^2$ have been reached.

NA62 is taking data for a Run2 with an upgraded experimental setup, this will allow substantial improvement to the precision of rare kaon decays branching ratio measurements and limits.

References

[1] BurasAJ,Buttazzo D and Knegjens R 2015 JHEP 1511 166
[2] Isidori et al.,Eur.Phys.J.C (2017)77 618
[3] Buras A J, Buttazzo D, Girrbach Noe J and Knegjens R 2015 JHEP 1511 033
[4] Artamonov A V et al 2008 Phys.Rev.Lett.101 191802
[5] Artamonov A V et al 2008 Phys. Rev. D 79 092004
[6] E. Cortina Gil et al., JINST 12 (2017) P05025.
[7] CortinaGil et al,Phys.Lett.B791(2019)156-166
[8] Cortina Gil et al, Journal of High Energy Physics, Volume 2020, Issue 11, page 42 arXiv:2007.08218, hep-ex
[9] Cortina Gil et al, Journal of High Energy Physics, Volume 2021, Issue 6, page 93
[10] GrossmanYandNirY,Phys.Lett.B398,163(1997)
[11] R. Ammendola et al., Nucl. Instr. Meth. A929 (2019) 1.
[12] R. Aliberti et al, PRL 127 131802 (2021)
[13] E.Cortina Gil et al, PLB 807 (2020) 135599
[14] E.Cortina Gil et al, PLB 816 (2021) 136259