Status and perspectives on feebly-interacting particles and other analyses from NA62

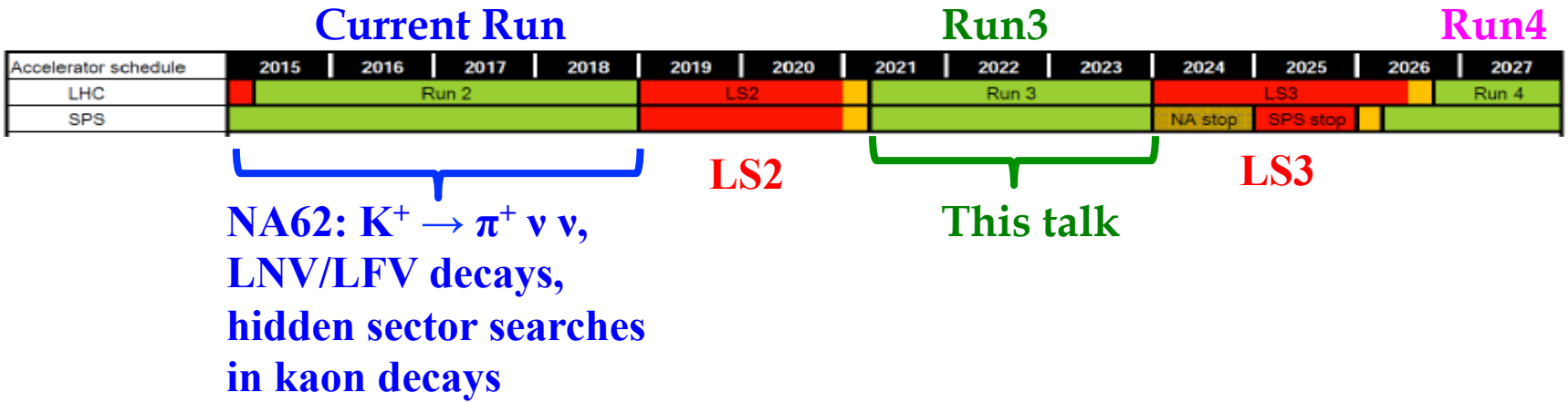
A cura di T. Spadaro e M. Piccini

Introduction

NA62 experiment approved to run until LS3

- **main goal**: measuring the BR($K^+ \rightarrow \pi^+ \nu$ anti-ν) with 10% accuracy;
- a broad physics program: searches for LFV/LNV modes, hidden sector particles

Present talk covers status + possible plans for dedicated searches in **Run3**



Physics at NA62 in Run 2 and Run 3

A rich field to be explored with minimal/no upgrades to the present setup

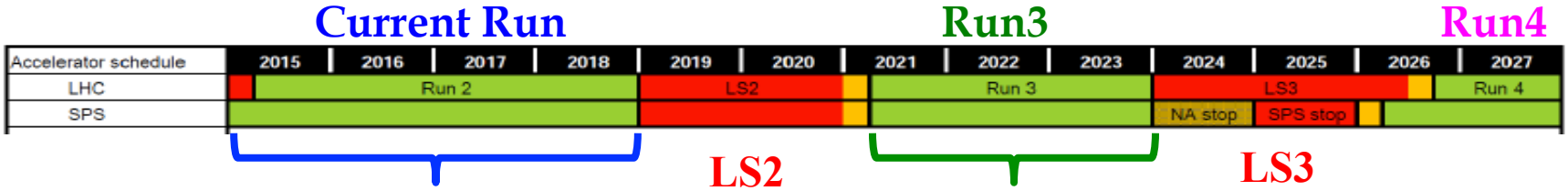
1. Present setup for K^+ beam + dedicated triggers: complete LFV/LNV high-sensitivity studies based on K^+/π^0, e.g. see recent talks at the Phenomenology 2021 symposium:

LFV/LNV, J. Swallaw https://indico.cern.ch/event/982783/contributions/4364566/

$K^+ \rightarrow \pi^+X$, $\pi^0 \rightarrow$ inv., $K^+ \rightarrow \mu\nu X$, R. Volpe https://indico.cern.ch/event/982783/contributions/4362249/

$K^+ \rightarrow e^+X$, $K^+ \rightarrow \mu^+X$, M. Mirra https://indico.cern.ch/event/982783/contributions/4362325/

2. In Run3, year-long run in "beam-dump" mode, new program of NP searches for MeV-GeV mass hidden-sector candidates: Dark photons, Heavy neutral leptons, Axions/ALP's, etc.



NA62: $K^+ \rightarrow \pi^+ \nu\nu$, LNV/LFV decays, hidden sector searches in K decays

LFV/LNV @ ultimate sensitivity, hidden sector searches (beam dump)

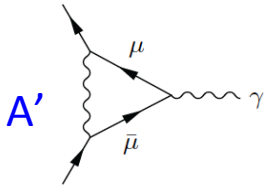
Hidden sector at NA62: motivations

If DM is a thermal relic from hot early universe, can hunt for it in particle-physics:
search for non-gravitational interactions DM-SM

A mediator of a hidden sector might exist, inducing DM-SM field **(feeble)** interactions
many possible dynamics: vector (A', aka dark photon), neutrino (HNL), axial (ALP a), scalar..

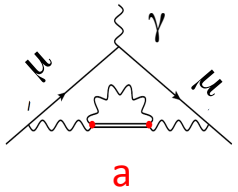
Various experimental hints for hidden sector at MeV-GeV, e.g., a_μ 3.5-σ discrepancy**:**

Might be due to a dark photon A' ...



[Okun, Holdom]

...or to an ALP a enhancing light-by-light?



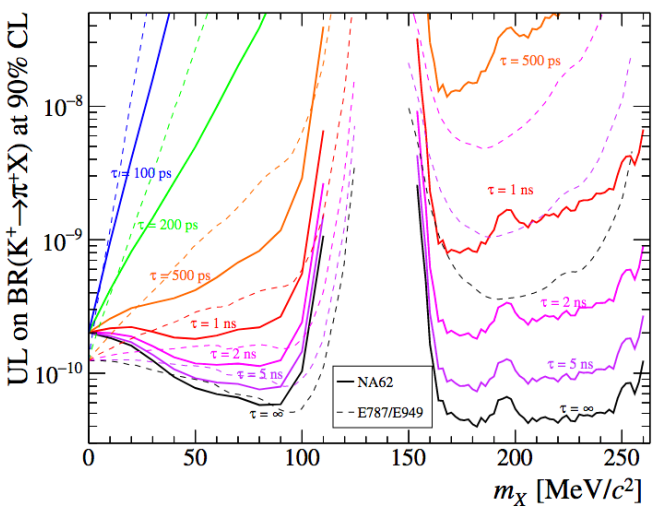
[Marciano, et al. arXiv:1607.01022]

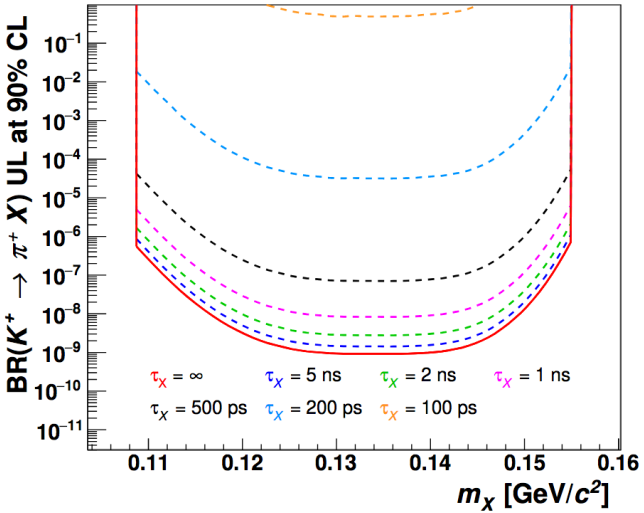
Model dependence: experimentally driven approach

Feeble interaction: ultra-suppressed production rate, **very** long-lived states
E.g.: 1-GeV mass HNL, $\tau \sim 10^{-5}$--10^{-2} s, decay length ~ 10--10000 Km at SPS energies, suppression at production 10^{-7}--10^{-10}

$K^+ \to \pi^+\nu\nu$ as a search for $K^+ \to \pi^+X$

Can re-interpret the search: assume a SM background for $\pi\nu\nu$ and assume X to be either long-lived/dominantly invisible [JHEP03 (2021) 058, **JHEP02 (2021) 201**]





"$\pi^0 \to$ **inv.**": improves on previous results (BNL) by x60

1/2 corresponding authors from INFN (TS)

Related on-going analyses with INFN contribution:

Improve search for BR($\pi^0 \to A' \gamma$) @ 10^{-8} using Run 2 data

Search for a massless A' from $K^+ \to \pi^+\pi^0$ A' @ 10^{-7} -- 10^{-8}

Interpretations as ALP and dark scalar possible, too

NA62 & hidden sector searches

1/2 WG coordinators from INFN

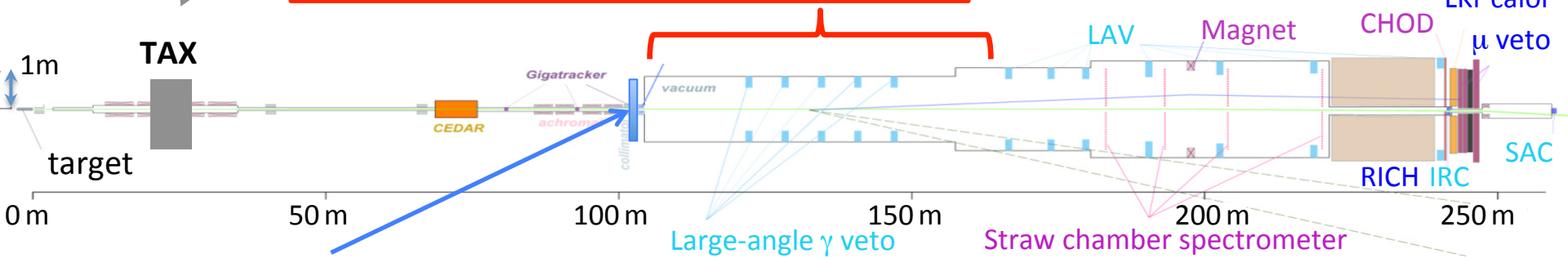
High-intensity 400-GeV proton beam → boost charm/beauty, other meson production

10^{18} POT / nominal year: 10^{12} POT/sec on spill, 3.5-s/16.8 s, 100 days/year, 60% run efficiency

10^{15} $D_{(S)}$, 10^{14} K, 10^{18} $\pi^0/\eta/\eta'/\Phi/\rho/\omega$ with ratios 6.4/0.68/0.07/0.03/0.94/0.95 (& B mesons, too)

Compact beam dump: ~20 λ_I Cu/Fe-based beam-defining collimator (TAX)
radioprotection-compliant even if target removed

Decay volume ~ 60 m long (in vacuum):
acceptance to long-lived states



New anti-halo in Run 3

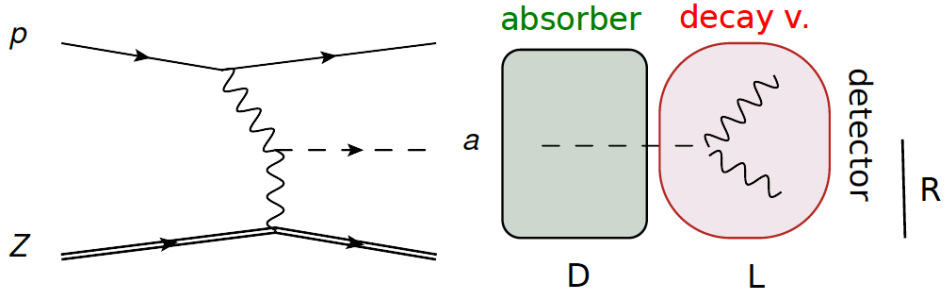
High-resolution tracking, PID, vetoing: high sensitivity to closed signatures

On the phenomenological effort for FIPs

While the searches should be kept mainly model-independent, a large effort still going on by the community devoted to evaluate production/decay of feebly interacting particles (FIP)

An example, photon-coupled ALP:

"Dominant" Primakoff production, proposed and computed in JHEP 1602 (2016) 018



Later, JHEP 05 (2019) 213: production from real photons from π^0 decay usually dominates

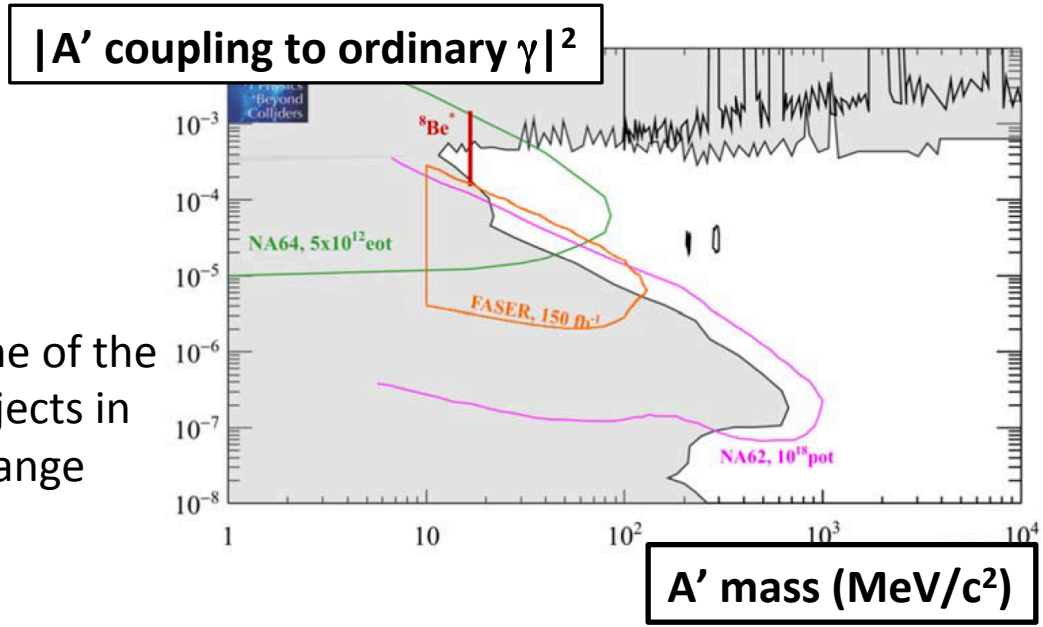
Systematic efforts thanks to 1st mandate of PBC WG at CERN, with relevant INFN presence

Search for visible decays of FIPs: A' search in Run3

Assume 10^{18} 400-GeV POT (Run 3 statistics, several months at full nominal intensity)

search for displaced decays to two charged particles

assume zero-background, evaluate expected 90%-CL exclusion plot



Physics Beyond Colliders BSM report: J. Phys. G 47 (2020) 1, 010501

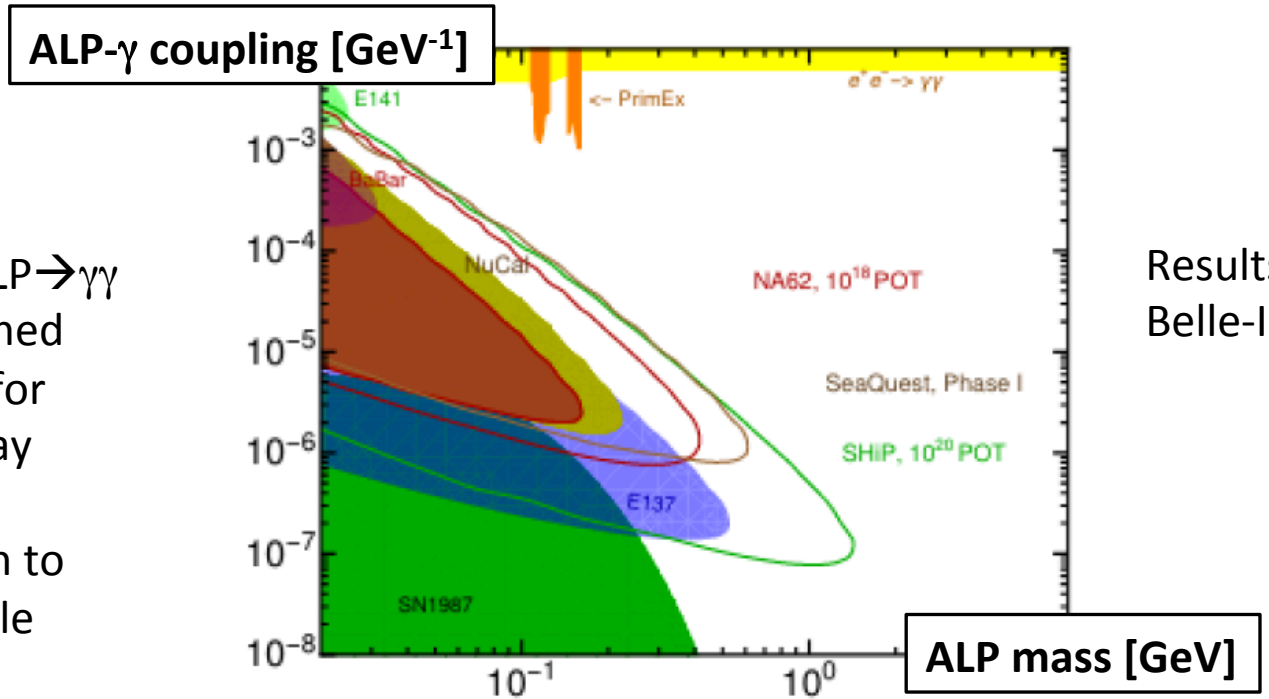
Compare to some of the competitive projects in the same time range

Similar scenarios for dark scalar, HNL shown in the PBS BSM report

Search for visible decays of ALP's in Run 3

Production: ALP Primakoff [JHEP 1602 (2016) 018] + real-γ induced [JHEP 05 (2019) 013]
Decay: ALP → γγ, account for geometrical acceptance, assume zero-background

Search for ALP→γγ less constrained than search for charged decay modes: no extrapolation to dump possible



Results from NA64, Belle-II missing

On the zero-background assumption

Ongoing background studies using Run 2 data:

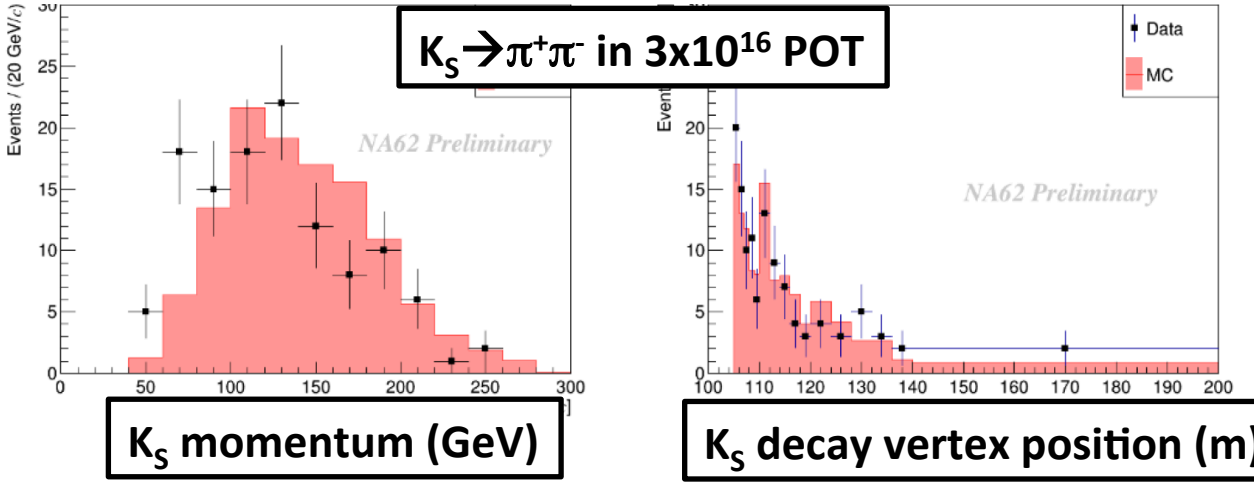
3×10^{16} POT taken in "beam dump" mode (no beam tuning, just TAX collimator closed)

2×10^{17} POT taken in "parasitic" mode during standard data taking with di-muon trigger

Ongoing effort using data and MC:

simulation of muons from the beam "halo" (π, K decays in dump, etc.)

background from K_S/Λ as tertiaries of survived K^+ mesons



NA62 SPSC report https://cds.cern.ch/record/2759557/files/SPSC-SR-286.pdf

Can use MC for background estimates @ 10^{18} POT?

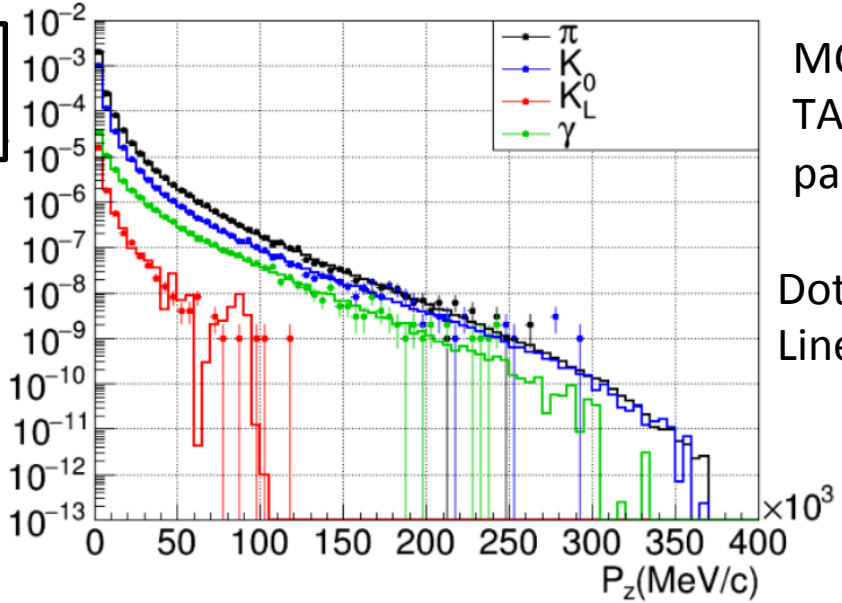
CPU power: low efficiency of simulation for muons from hadronic showers, ~10^{-4} μ/proton

NA62 work within the PBC: score + parameterize [https://doi.org/10.18429/JACoW-ICAP2018-SUPAG05]

SHiP coll.: MC gun using generative adversarial networks [JINST 14 (2019) P11028]

Biasing MC technique to boost by 2x10^3 with ~no information loss [2106.01932 [hep-ex]]

2106.01932 [hep-ex]
1 / 4 authors from INFN



MC: Muon yield from NA62 TAX mock-up by mother particle

Dots: brute-force MC (10^9 POT)
Lines: biased MC (10^8 POT)

Can use MC for background estimates @ 10^{18} POT?

Reliability of hadronic interaction simulation:

The SHiP collaboration gathered data for muon flux validation [2001.04784 [physics.ins-det]]
Data/MC agreement of ~20% for μ below 200 GeV (a factor x3 above), still remarkable

From the GEANT4 manual:

For the evaluation of systematic errors due to uncertainties in the Geant4 hadronic cross sections we recommend the following approach. Scaling up (e.g. **by 10%**, by using a scaling factor of 1.10) or down (e.g. using a scaling factor of 0.90) the cross sections, independently for elastic and inelastic interactions, and independently for different types of hadrons.

Even a relative uncertainty on interaction cross sections within FTFP-based models of ~10% can lead to ~x10 in flux of punch-through secondaries, e.g. K+

Known limitations from the treatment of multiple Coulomb scattering in Geant4 [Longhin, Paoloni *IEEE Trans.Nucl.Sci.* 62 (2015) 5]

Work ongoing within NA62 to track down various background sources

Conclusions: FIP searches at NA62

Run 2 data FIP-search analyses on-going with INFN contributions:

- **With standard setup: K $\rightarrow \pi^+\pi^0$ X, K $\rightarrow \pi^+$X, π^0 -> γX, X $\rightarrow \mu\mu$**
- **With few 10^{16} POT in "beam dump": ALP $\rightarrow \gamma\gamma$**

Imminent one year long data taking (10^{18} POT) in "beam dump mode" in Run 3:

- **Sensitivity to Dark photons, Heavy Neutral Leptons, Axion-like particles, etc.**
- **Rejection of upstream background improved with a new hodoscope (Anti-halo)**
- **Beam-line magnet tuning allows reduction of muon flux by x5**

Expected sensitivity competitive to that from other initiatives in the same time range

Data demonstrate background rejection power for the searches proposed, up to 10^{17} POT's

- **background to charged decay modes negligible at 10^{17} POT [tested for di-muon]**
- **background to $\gamma\gamma$ mode under control at 3×10^{16} POT**

Particularly appealing: searches for long-lived A', photon-coupled ALP visible decays

Other analyses

27/07/2021

On-going analyses

- BR measurement of the decay $K^+ \rightarrow e^+\nu\mu^+\mu^-$
- BR and FF measurement in $K^+ \rightarrow e^+\nu e^+e^-$
- BR and T violation parameter measurement in $K^+ \rightarrow \pi^0 e^+\nu\gamma$ (Ke3γ)
- Search for a dark scalar in the decay $K^+ \rightarrow \pi^+ S$ with $S \rightarrow \mu^+\mu^-$
- FF measurement of $\pi^0 \rightarrow \gamma e^+e^-$, with π^0 tagged from $K^+ \rightarrow \pi^+\pi^0$
- Search for $K^+ \rightarrow \mu^+\nu X$, $X \rightarrow \gamma\gamma$ (I. Panichi, A Bizzeti, F. Bucci, M. Lenti)
- Search for $K^+ \rightarrow \pi^+\pi^0 X$, X to invisible (P. Lo Chiatto, F. Bucci, A Bizzeti)

Other analyses with strong INFN contribution:

- First observation of the decay $K^+ \rightarrow \mu^+\nu\mu^+\mu^-$
- Search for the decay $K^+ \rightarrow \pi^+\mu^\pm e^\mp$ (E. Minucci) e-Print: 2105.06759
- New Ke2/Km2 = R_K measurement (M. Corvino)
- Search for the decay $K^+ \rightarrow \pi^+ X$ (R. Volpe) JHEP03 (2021) 058)

BR measurement of the decay $K^+ \to e^+\nu\mu^+\mu^-$

Motivations:

- Within the framework of Chiral Perturbation Theory (χPT) radiative kaon decays can serve both as an important test and as source of input parameters
- IB helicity-suppressed for Ke2γ, FF measurement more interesting

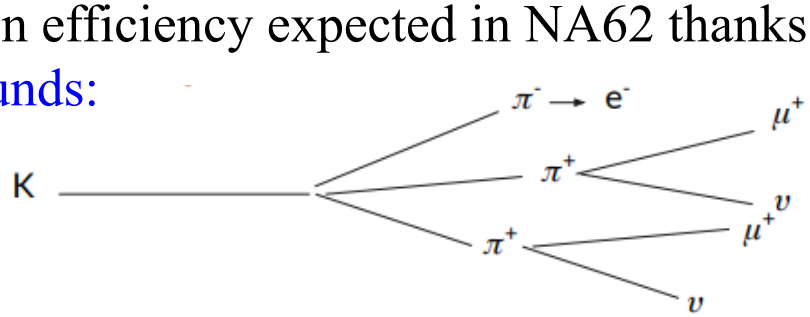
Status of the art:

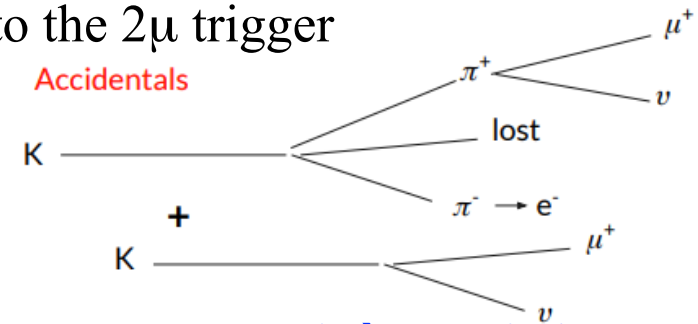
- evidence from E865 (2006): $BR(K^+ \to e^+\nu\mu^+\mu^-) = (1.72 \pm 0.45)\times10^{-8}$
- their selection is background limited, worse π/μ misID wrt NA62

Good collection efficiency expected in NA62 thanks to the 2μ trigger

Main backgrounds:

D. Soldi (50%)



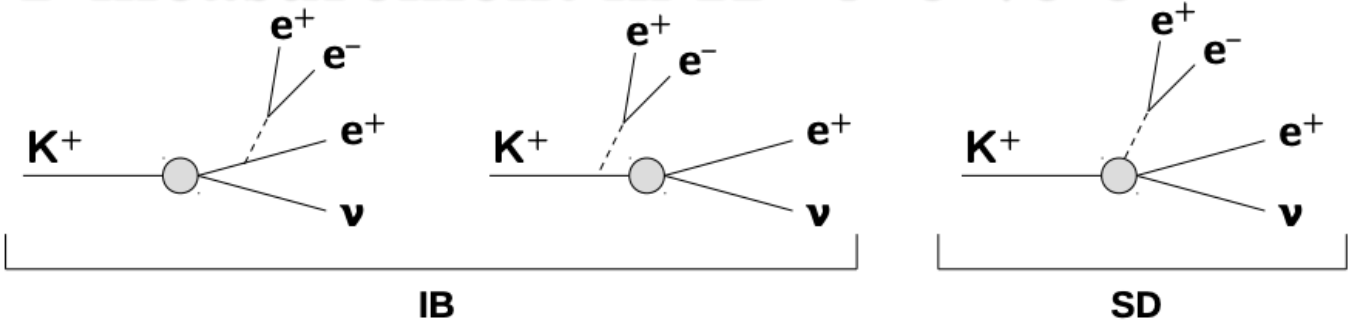


Internal note in preparation, also with search for the LNV channel $K^+ \to e^-\nu\mu^+\mu^+$

BR and FF measurement in $K^+ \rightarrow e^+\nu e^+e^-$

Motivations:

- See previous slide



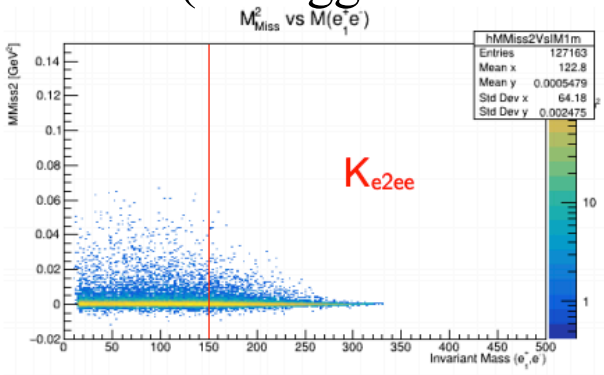
State of the art:

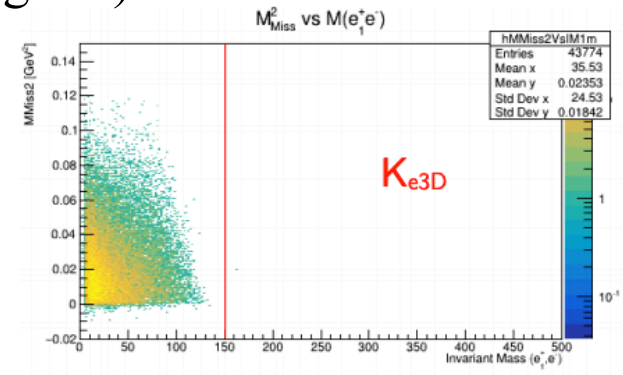
- K_{e2ee} already measured at Brookhaven (2002): Poblaguev et al., BNL E865 (PRL 89 061803)
- $BR = (2.48 \pm 0.14 \pm 0.14) \times 10^{-8}$ ($m_{ee} > 150$ MeV)

R. Lollini (50%)

Expected higher statistics in NA62 (2e trigger Downscaling = 8) from Run2

Strong cut against Ke3D (used as normalization channel) must be applied





BR and T parameter measurement in $K^+ \to \pi^0 e^+ \nu\gamma$

DE + IB (+INT)

T-odd observable ξ (in the kaon rest frame):

$$\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{m_K^3} \; ; \; A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

F. Brizioli (50%)

R_1 ($\times 10^2$)	$E_\gamma > 10$ MeV	$\theta_{e,\gamma} > 10^\circ$
R_2 ($\times 10^2$)	$E_\gamma > 30$ MeV	$\theta_{e,\gamma} > 20^\circ$
R_3 ($\times 10^2$)	$E_\gamma > 10$ MeV	$0.6 < \cos\theta_{e,\gamma} < 0.9$

State of the art for ξ:

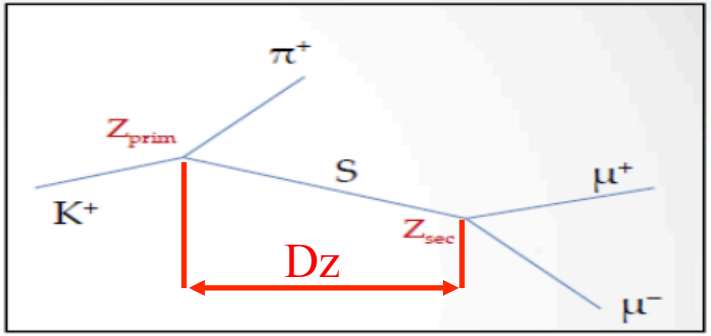
- $|A_\xi^{theory}| < 10^{-4}$
- $A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$
- No measurements provided for R_1 and R_2

Internal NA62 note in preparation (proto-paper), the preliminary result will be presented Thursday at EPS by Francesco, BR and ξ measurements in all the 3 regions: https://indico.desy.de/event/28202/contributions/107307/

Search for a DS in the decay $K^+ \rightarrow \pi^+ S$ with $S \rightarrow \mu^+\mu^-$

New approach to obtain competitive results wrt LHCb ($B \rightarrow K\ S$):
a search involving both prompt and displaced vertexes

V. Duk (100%)



Analysis principles:

- Prompt + displaced vertex approach **(cover all lifetimes)**
- (almost) background free in the displaced region
- Main variables: **M(πμμ) ; M(μμ) ; Dz**

Performing a blind analysis

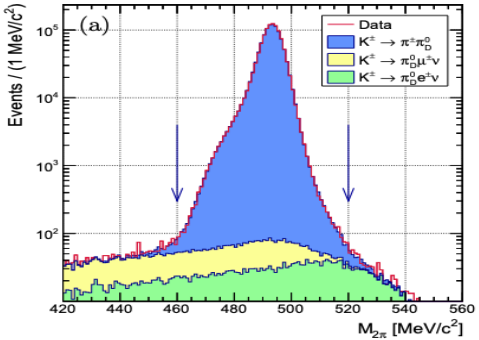
FF measurement of $\pi^0 \to \gamma e^+ e^-$ (from $K^+ \to \pi^+ \pi^0$)

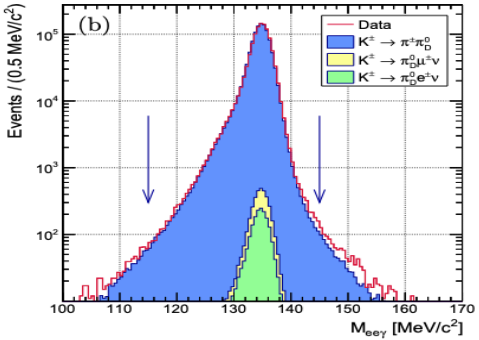
$$\frac{d^2\Gamma(\pi^0_D)}{dxdy} = \frac{\alpha}{4\pi}\Gamma(\pi^0_{2\gamma})\frac{(1-x)^3}{x}\left(1+y^2+\frac{r^2}{x}\right)(1+\delta(x,y))\,|\mathcal{F}(x)|^2 \longrightarrow \mathcal{F}(x) = 1+ax$$

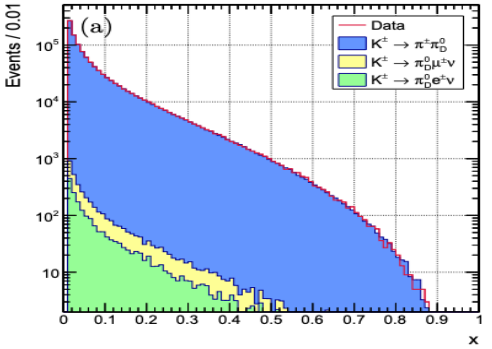
Measuring *a* fitting $x = \left(\frac{M_{ee}}{m_{\pi^0}}\right)^2$, status of the art: $a = (3.68 \pm 0.57) \times 10^{-2}$

NA62 [2017]
2007 data
[PLB 768 38]

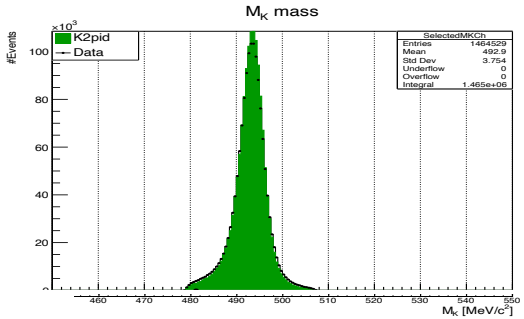
E. Lari (100%)

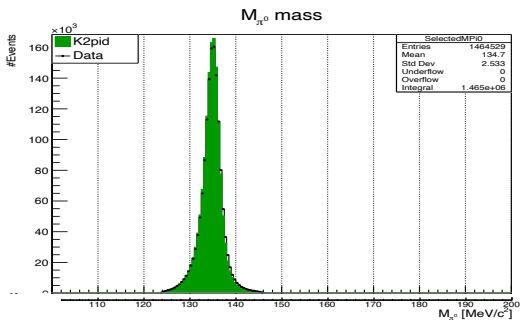






Analysis ongoing, data-MC comparison before BG subtraction (only 2018E)





First observation of the decay $K^+ \to \mu^+ \nu \mu^+ \mu^-$

Expected BR in the χPT framework $\sim 10^{-8}$, never observed before

M. Boretto (100%)

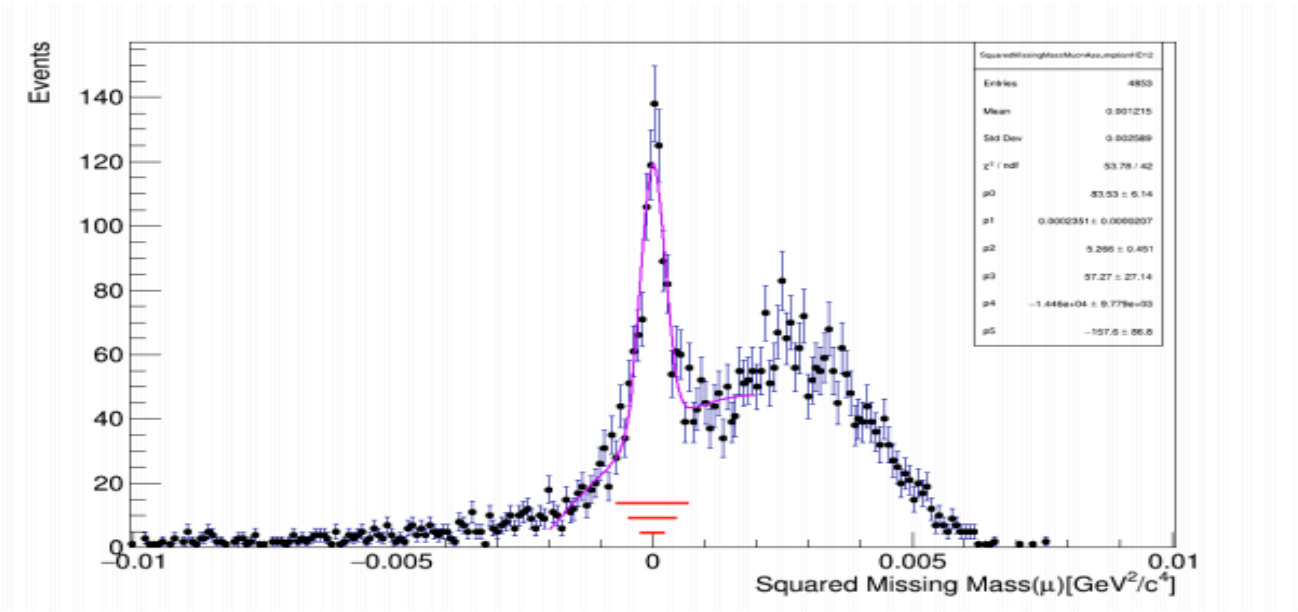


Figure 4.16: $K_{\mu\nu\mu\mu}$ squared missing mass spectrum for 2017 data. The horizontal bars in red below the peak represent the 1σ, 2σ and 3σ signal region according to the value obtained with the fit.