“Recent results and prospects on Dark Interactions from NA48/2 & NA62”

Dark Interaction Workshop
October 4-7 2016
BNL

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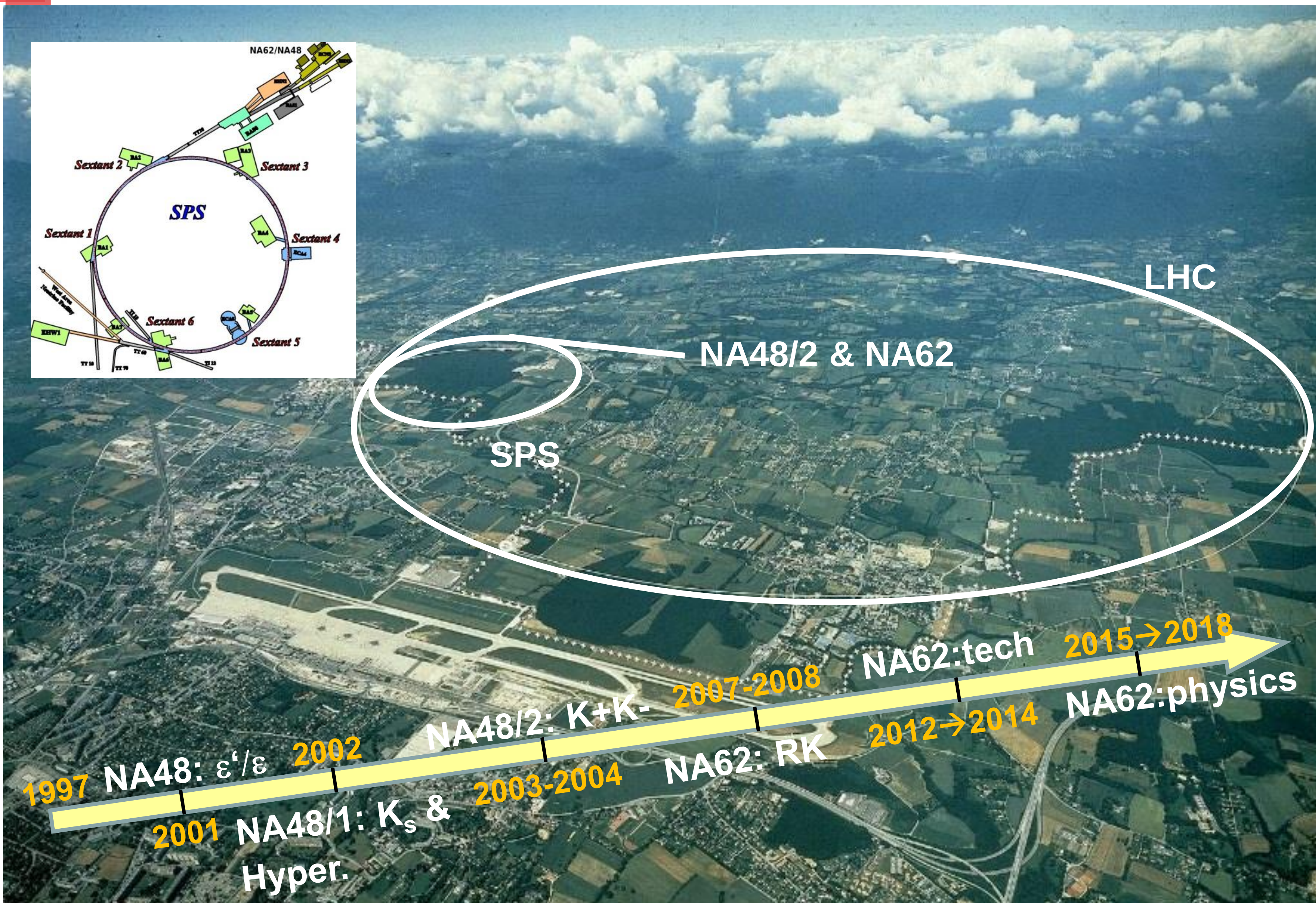
Kaon physics @ CERN



Why Kaons?

Non-MFV: FCNC decays with high suppression in the standard model and clean theoretical prediction.

The $K\to\pi\nu\bar{\nu}$ has a very clean SM prediction (λ^5 suppression).

New Physics effects in flavour physics and search for exotics in mesons decays

Clean environment in K: few decay channels, low background. Direct and indirect search for new states and DM portals.

Kaon Factory: NA62 & NA48/2

MFV: helicity suppressed observables are sensitive to SUSY ($B\to ll$, $B\to l\nu$, $K\to l\nu$). LFV decays forbidden in SM.

Easier in K: the B decays are suppressed (Vub<<Vus) while R_K is 10^{-5}. Cleaner environment to search for forbidden decays.

NA48/2: charged K CP violation

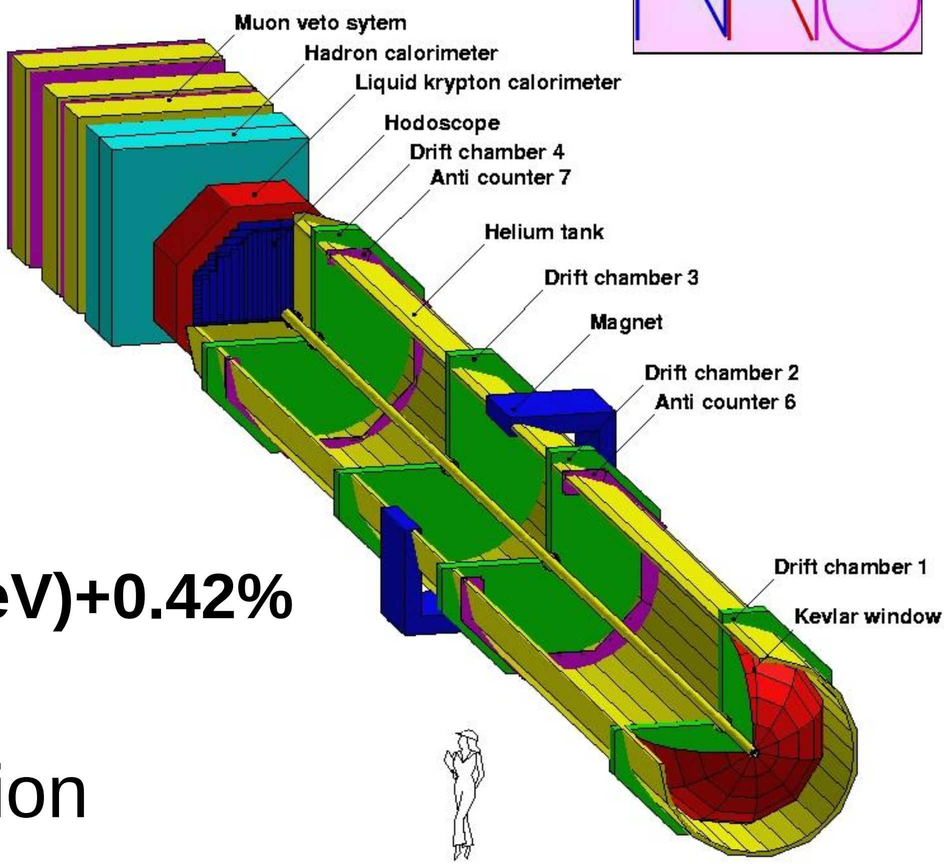
- K+/K- beams (60 GeV/c)
  - Produced in Be target from 400 GeV/c protons from SPS
- Main goal: study CP violation in **3π decays**
- Spectrometer: 4 DCH

$\sigma_P/p=1.02\%+ 0.044\%\ p(\text{GeV})$

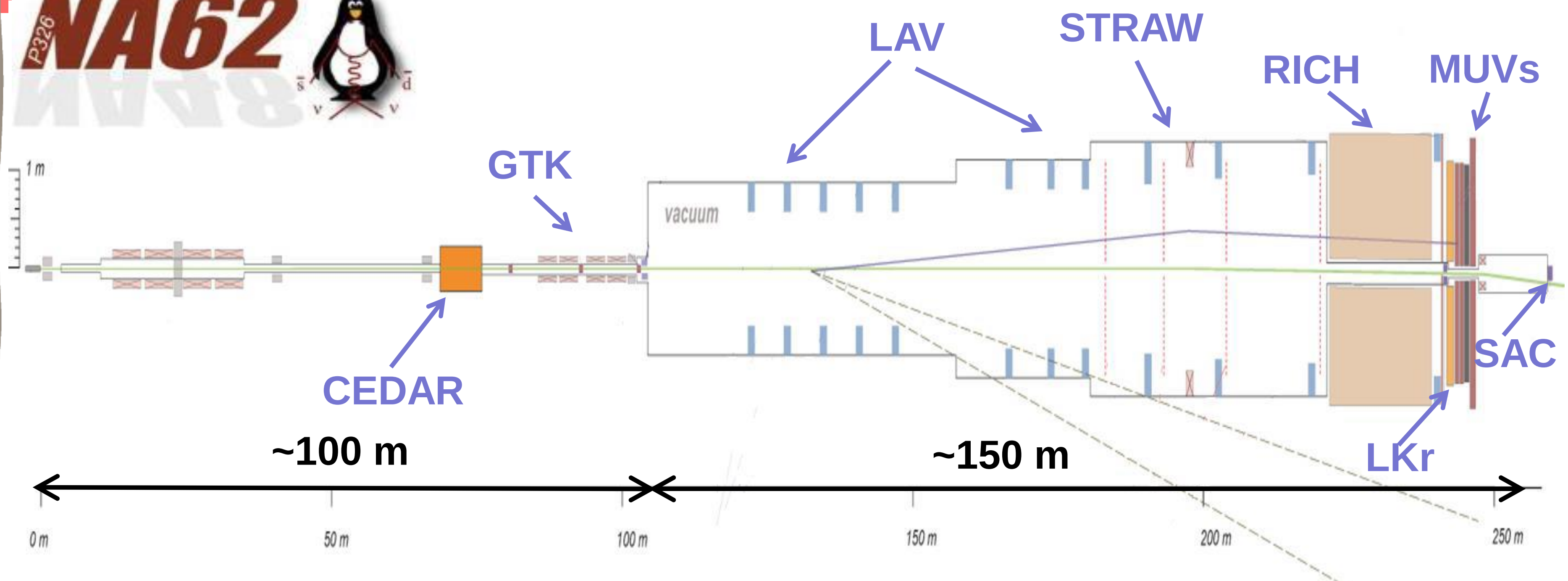
- LKr Calorimeter

$\sigma_E/E=3.2\%/\sqrt{E(\text{GeV})}+9\%/E(\text{GeV})+0.42\%$

- Veto system, fast timing, flexible trigger configuration
- Data collected in 2003+2004



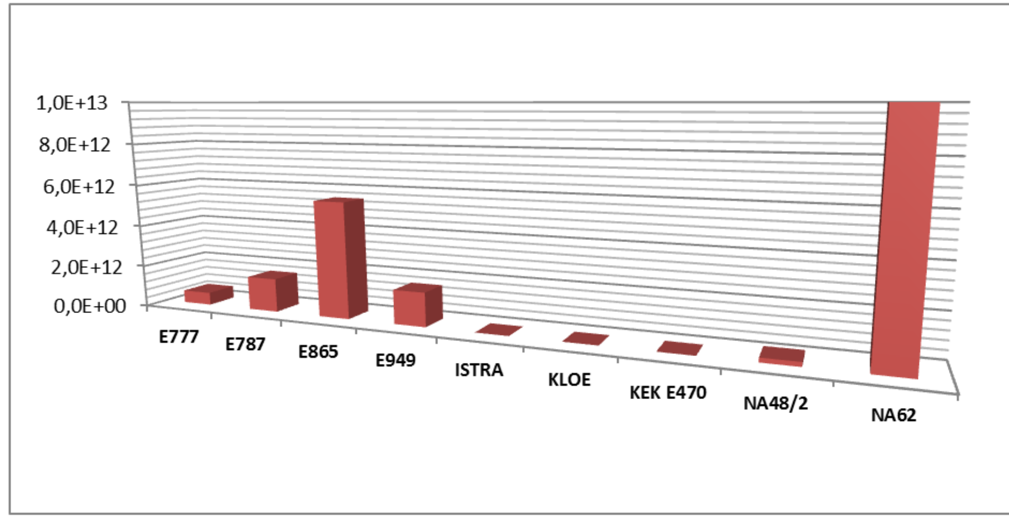
NA62: ultra-rare decays



- 75 GeV/c hadron beam (~8% K) from 400 GeV/c p from SPS
  - Total rate ~800 MHz, 10^{12} pot, 3.5 s spill
- Complete kinematics, quasi-hermetic veto system, PID system, calorimeters
- Main goal: **$K^+\rightarrow\pi\nu\bar{\nu}$ O(100) events with decay in flight**
  - 10^{13} K+ decays, 10% acceptance, bkg rejection >10^{12}

NA62: Broad K decays program

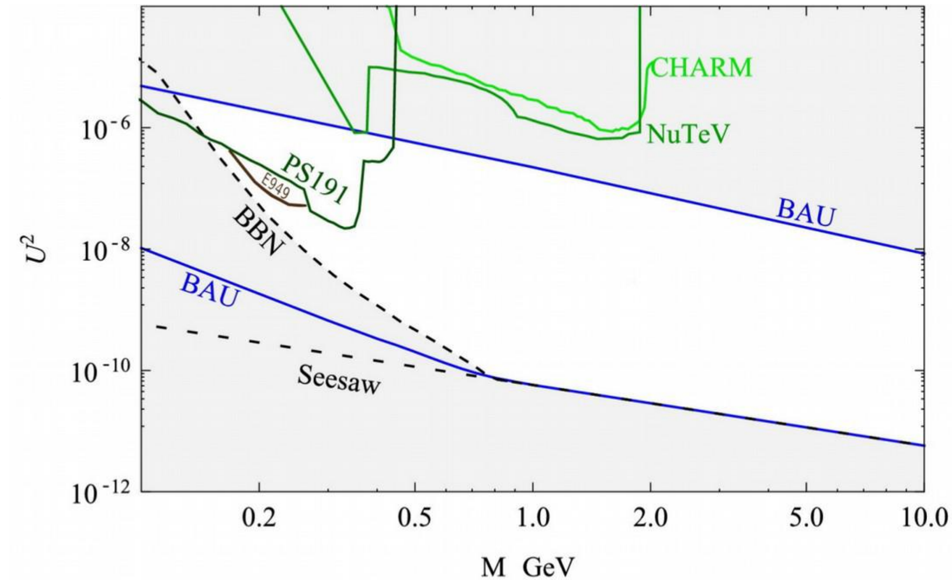
- Unprecedented statistics for many K+ decay modes
- Key point: **digital trigger**
  - Very flexible
  - Trigger path in common with readout electronics (FPGA based)
  - GPU trigger

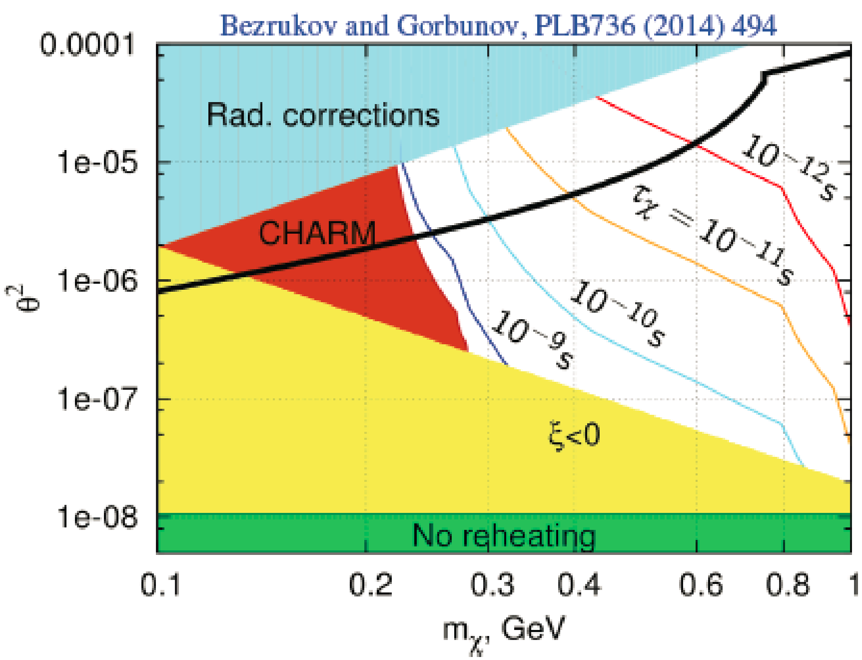


Process	Violates	90% C.L. limit	NA62 Acceptance
$K^+ \to \pi^+ \mu^+ e^-$	LF	$< 1.3 \times 10^{-11}$	~10%
$K^+ \to \pi^+ \mu^- e^+$	LF	$< 5.2 \times 10^{-10}$	~10%
$K^+ \to \pi^- \mu^+ e^+$	LF , LN	$< 5.0 \times 10^{-10}$	~10%
$K^+ \to \pi^- e^+ e^+$	LN	$< 6.4 \times 10^{-10}$	~5%
$K^+ \to \pi^- \mu^+ \mu^+$	LN	$< 1.1 \times 10^{-9}$	~20%
$K^+ \to \mu^- \nu e^+ e^+$	LN	$< 2.0 \times 10^{-8}$	~2%
$\pi^0 \to \mu^- e^+$	LF	$< 3.4 \times 10^{-9}$	~2%
$\pi^0 \to \mu^+ e^-$	LF	$< 3.8 \times 10^{-10}$	~2%
$\pi^+ \to \mu^- e^+ e^+ \nu$	LF	$<1.6\times10^{-6}$	~2%

NA48/2: the μμ sample

- Majorana/Sterile neutrinos (HNL): Asaka-Shaposhnikov *[PLB 620 (2005) 17]* model (νMSM)
  - Three sterile (Majorana) neutrinos N1 is the lightest (dark matter) N2, N3 produce ν masses and solve SM neutrinos problems and Baryon asymmetry
  - $K^+ \to \mu^+ N_{2,3}$ with $N_{2,3} \to \pi^{\pm}\mu^{\mp}$
  - BR $\sim |U_{\mu 4}|^4$



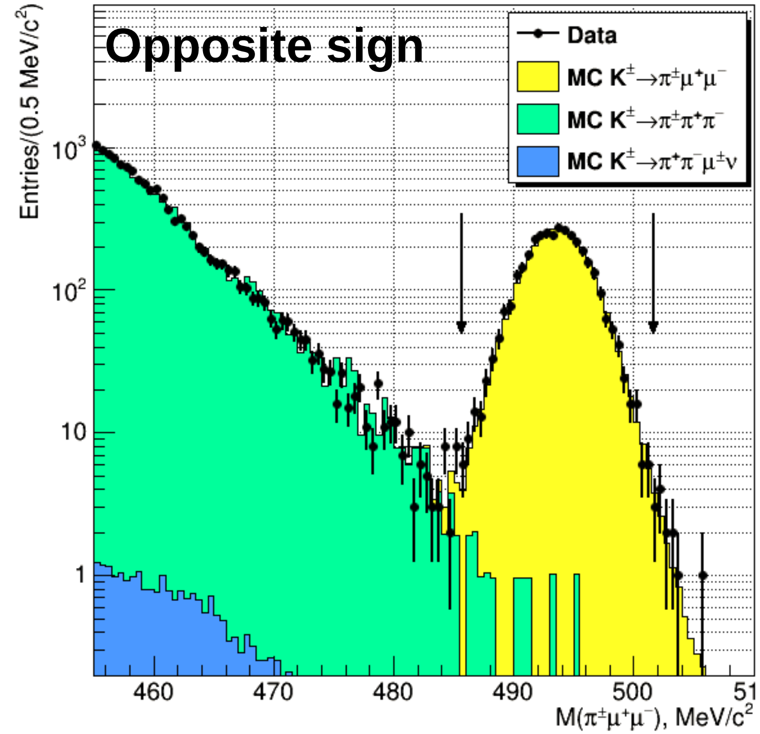


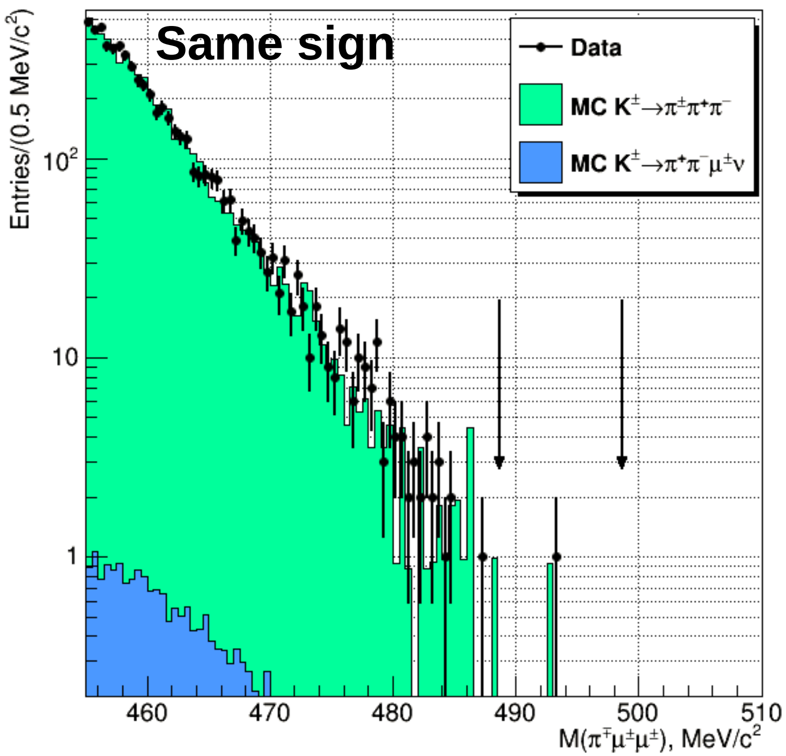
- Inflatons: Shaposhnikov-Tkachev *[PLB 639 (2008) 414]*
  - Add a real scalar field (**inflaton χ**) to νMSM to explain Universe homogeneity and isotropy
  - Mixing with Higgs boson: θ
  - m_χ < 354 MeV/c² with kaons (**$K^+ \to \pi^+\chi$**)
  - **$\chi \to \mu^+\mu^-$** considered in this analysis

$$BR(K^{\pm} \to \pi^{\pm}\chi) = 1.3 \times 10^{-3} \left(\frac{2|p_\chi|}{M_K}\right)\theta^2$$

LNV & LNC selection

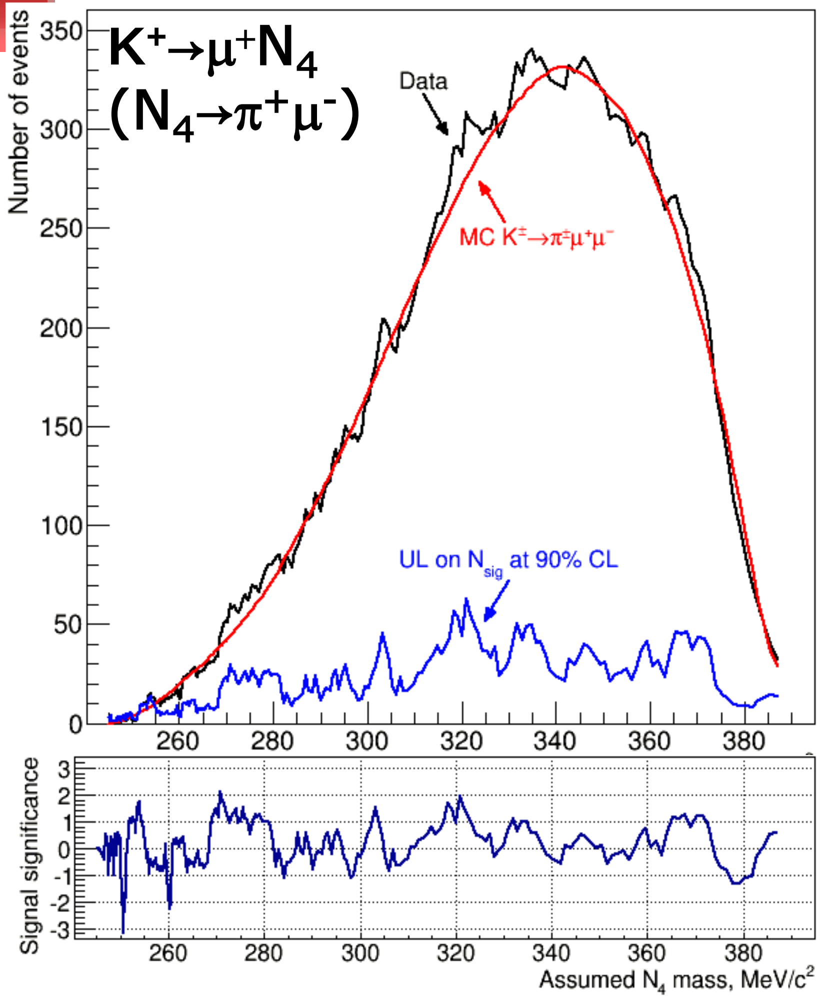
- 3 track topology
  - Opposite/same sign muons
  - No missing momentum
  - Total mass close to K mass (5 MeV/c^2)
- Background:
  - $K_{3\pi}$, $K_{\mu4}$

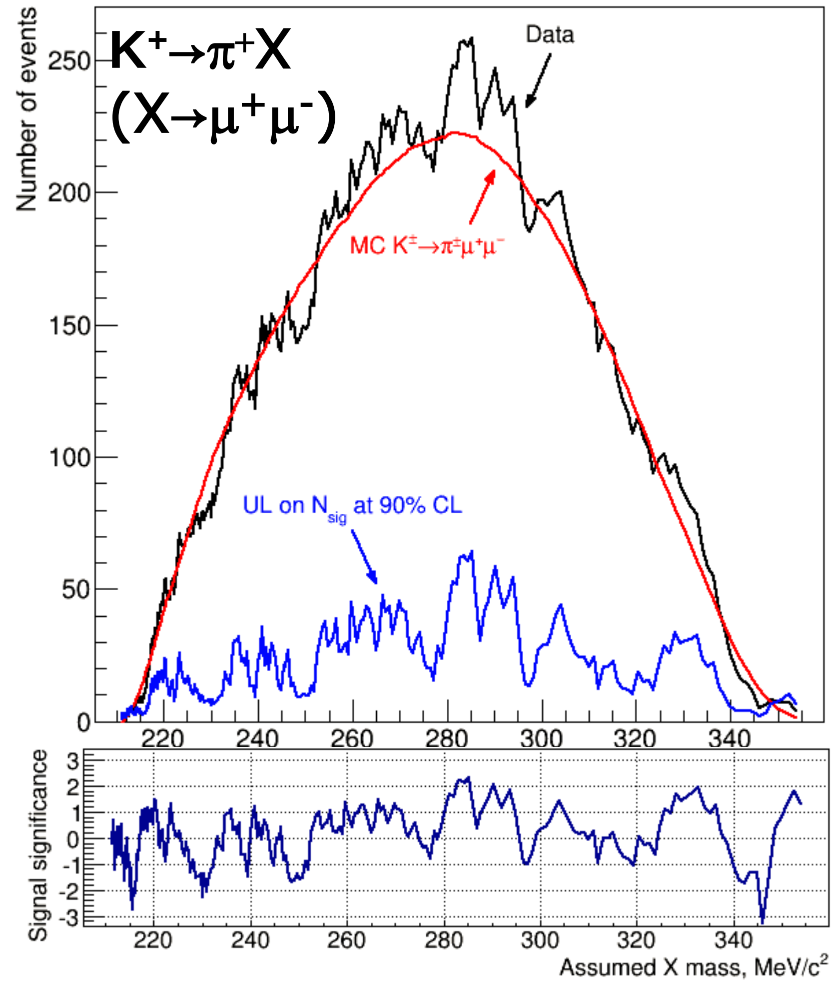




- 1.64×10^{11} K decays in fiducial region
  - Opposite sign: **3489** events ((0.36±0.10)% bkg)
  - Same sign: **1** events (1 bkg)

LNC: mass scan



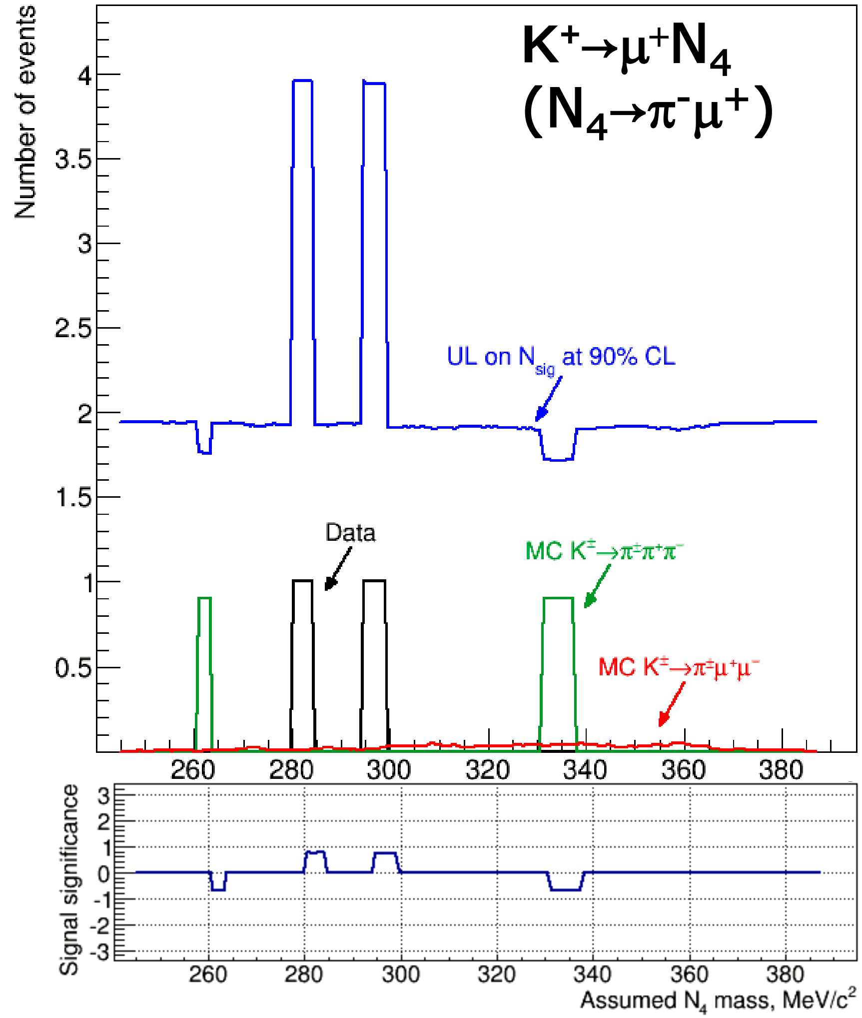


- Mass scan:
  - About **280** mass bins
  - The signal significance never exceed 3σ: **no signal observed**

$$z = \frac{n_{obs} - n_{exp}}{n_{obs} \oplus n_{exp}}$$

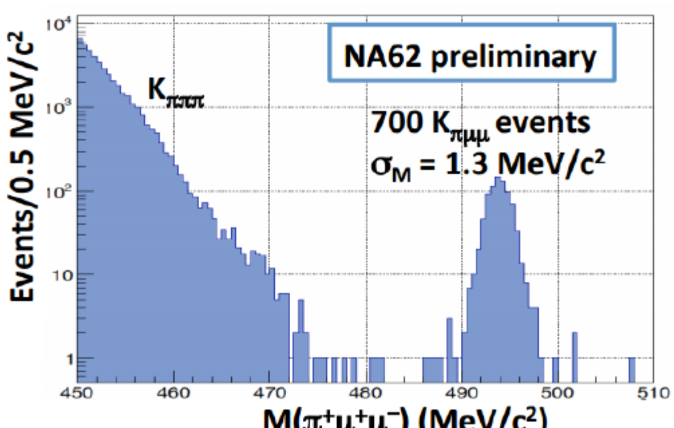
LNV: mass scan

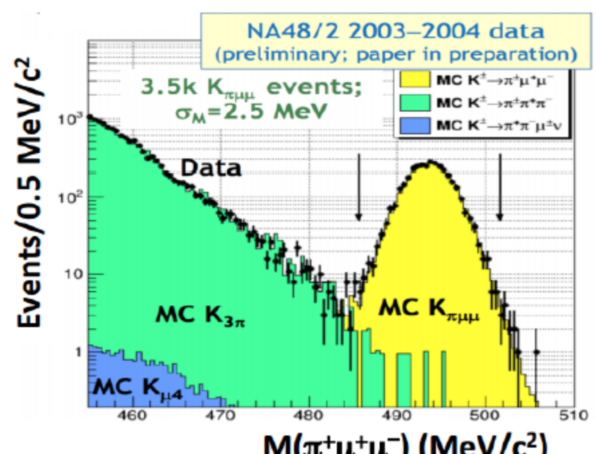
- **UL 8.6x10^{-11} @ 90% CL**
- Mass scan:
  - About **280** mass bins
  - The signal significance never exceed 3σ: **no signal observed**
- Both for opposite/same sign muons the acceptance is studied as a function of the heavy neutrinos/inflaton lifetime



NA48/2 μμ sample summary & NA62 prospects

- Sample of about **2×10^{11} K** decays, from 2003+2004 NA48/2 run
  - Search for LNV $K^+\to\pi^-\mu^+\mu^+$: UL 8.6×10^{-11} @ 90% CL
  - Search for Majorana sterile neutrinos $K^+\to\mu^+N_4$ ($N_4\to\pi^-\mu^+$): UL $\sim10^{-10}$ for $\tau<100$ ps
  - Search for heavy sterile neutrinos $K^+\to\mu^+N_4$ ($N_4\to\pi^+\mu^-$): UL $\sim10^{-9}$ for $\tau<100$ ps
  - Search for inflatons $K^+\to\pi^+X$ ($X\to\mu^+\mu^-$): UL $\sim10^{-9}$ for $\tau<100$ ps
- NA62 will improve both statistics and systematics: potentially two orders of magnitude





Dark Photon

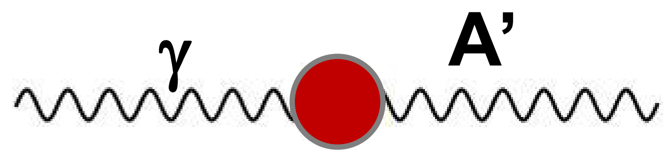
- The most economic SM extension in the dark sector is the introduction of a vector field through a new U(1) symmetry
  - The dark photon (A') is the boson associated to this symmetry

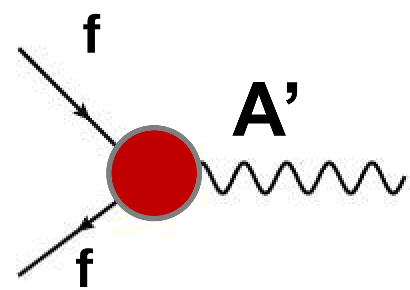
$$\mathcal{L}_{mix} = -\frac{\varepsilon}{2} F_{\mu\nu}{}^{QED} F^{\mu\nu}{}_{dark}$$

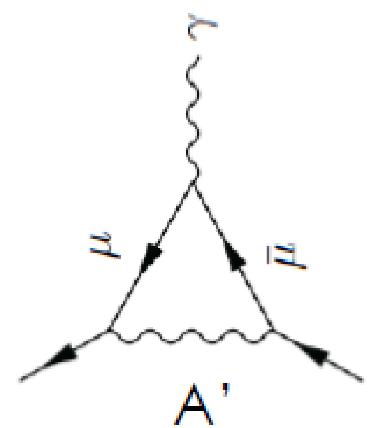
  - In the most generic case the mixing with quarks and leptons could be different (qf)

$$\mathcal{L} \sim g' q_f \overline{\psi_f} \gamma^{\mu} \psi_f U'$$

- The Dark Photon could be a good dark matter portal candidate and can explain positrons excess
- For free: the dark photon could explain the g-2 anomaly *[M. Pospelov Phys.Rev. D80 (2009) 095002]*



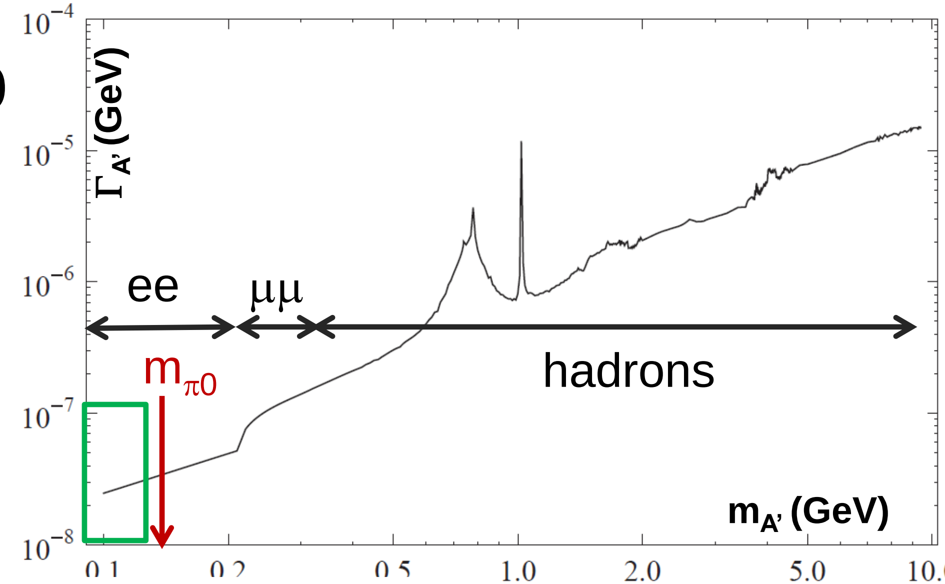




Dark Photon in π^0 decays

[Batell, Pospelov and Ritz, PRD79 (2009) 115008]

- Kaon factory is also a π^0 factory
- The A' in $\pi^0 \rightarrow \gamma A'$ is described by



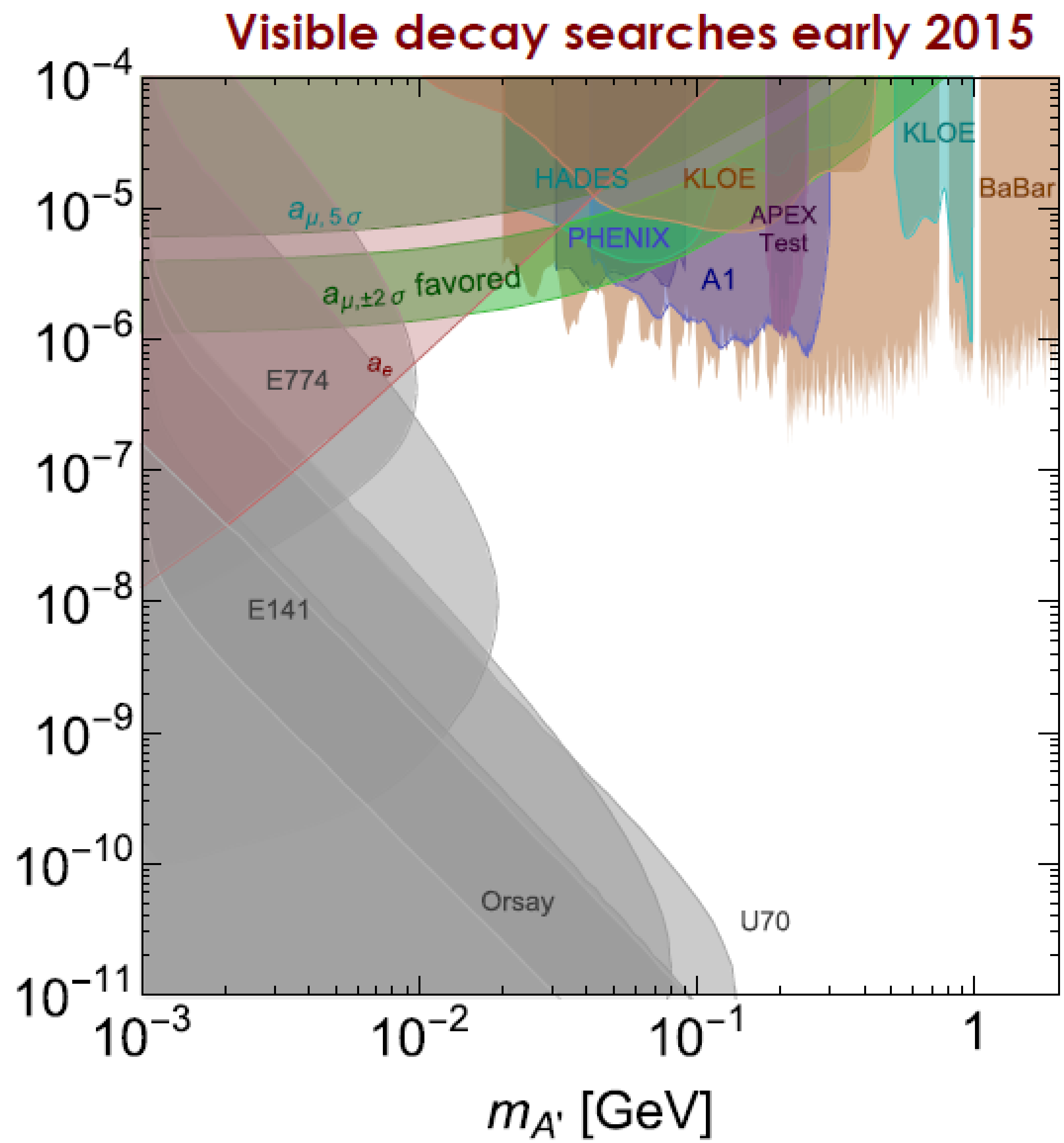
$$\mathcal{B}(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathcal{B}(\pi^0 \to \gamma\gamma)$$

- In the mass region allowed for the π^0, the A' width is

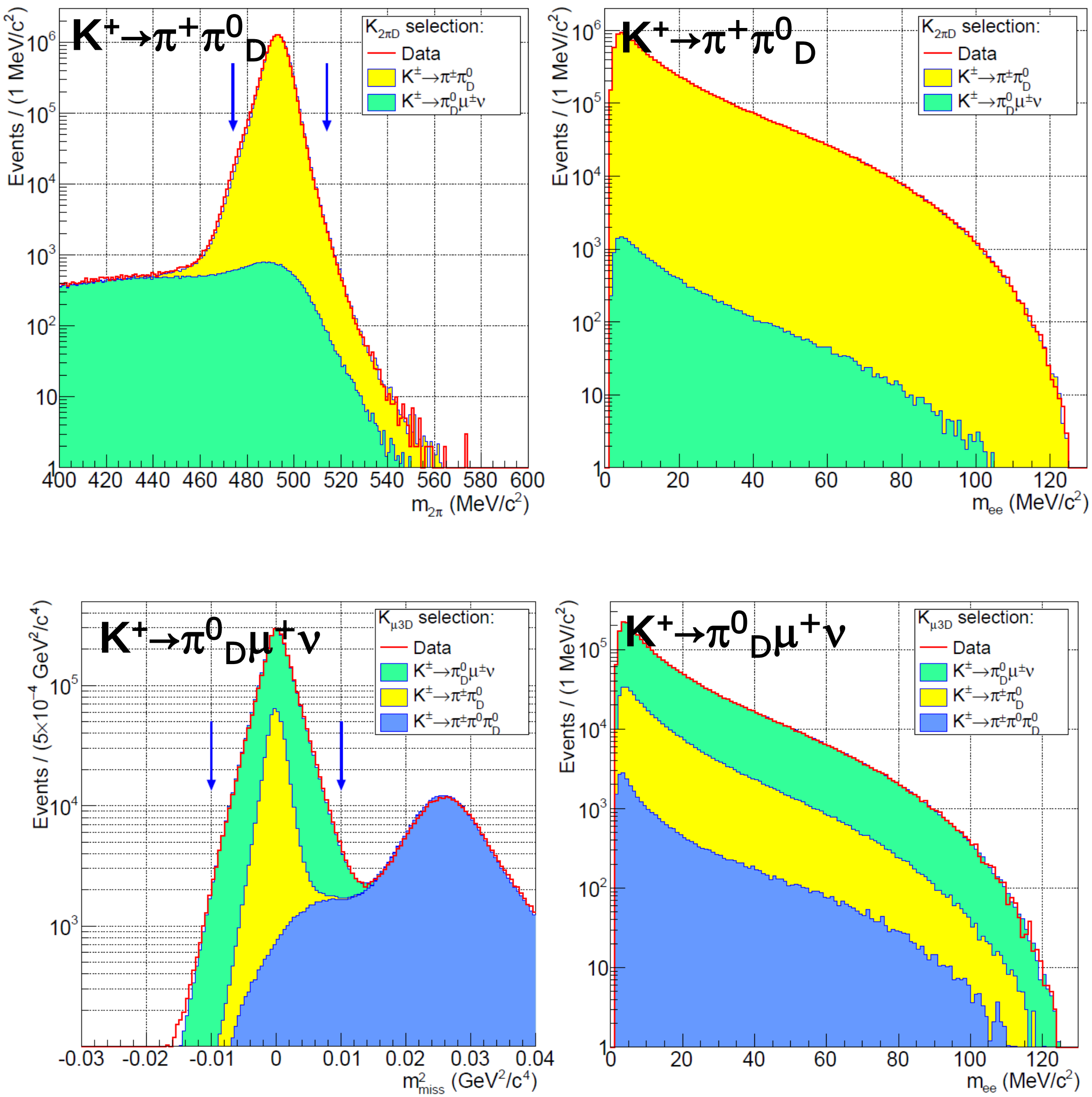
$$\Gamma_{A'} \approx \Gamma(A' \to e^+e^-) = \frac{1}{3}\alpha\varepsilon^2 m_{A'}\sqrt{1 - \frac{4m_e^2}{m_{A'}^2}}\left(1 + \frac{2m_e^2}{m_{A'}^2}\right) \approx \alpha\varepsilon^2 m_{A'}/3$$

Status of visible searches in early 2015

- The visible decay (in fermions) is constrained by various experiments:
  - Beam dump
  - Fix target
  - Meson decays
- Room for Dark Photon parameters to explain g-2
- The invisible decay has much less constraints

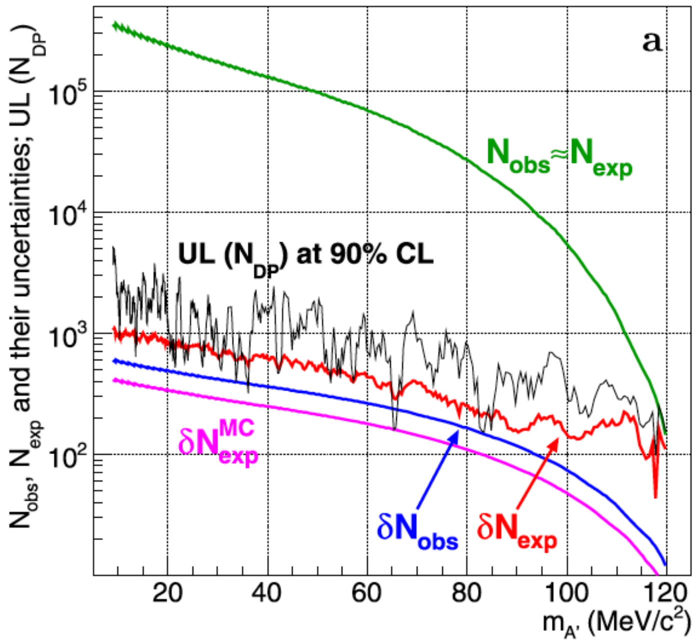


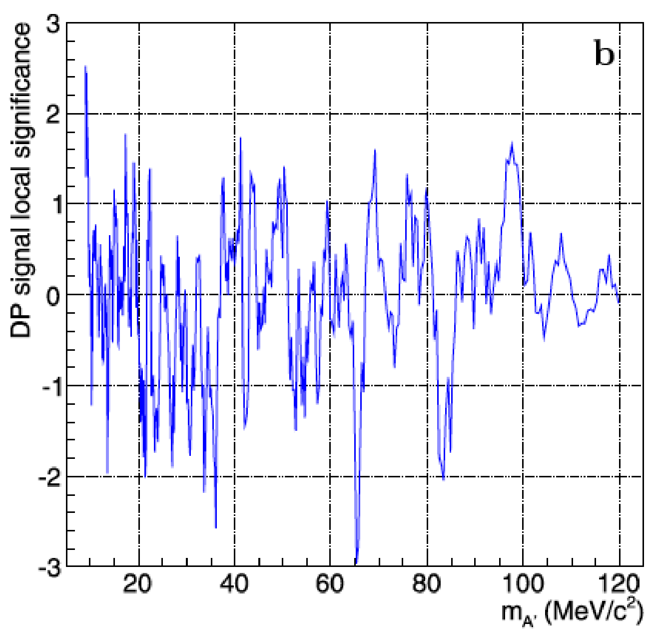
π^0_D Data selection



- **(1.57±0.05)x10^{11}** kaon decays
- $K^+\to\pi^+\pi^0_D$ selection
  - m_K in 20 MeV, $m_{\pi 0}$ in 8 Mev, no missing momentum
  - **1.38x10^7 events** selected
- $K^+\to\pi^0_D\mu^+\nu$ selection
  - Neutrino mass compatible with zero, $m_{\pi 0}$ in 8 MeV, missing total and transverse momentum
  - **0.31x10^7 events** selected
- **Total: 1.69x10^7**

UL from Dalitz decays

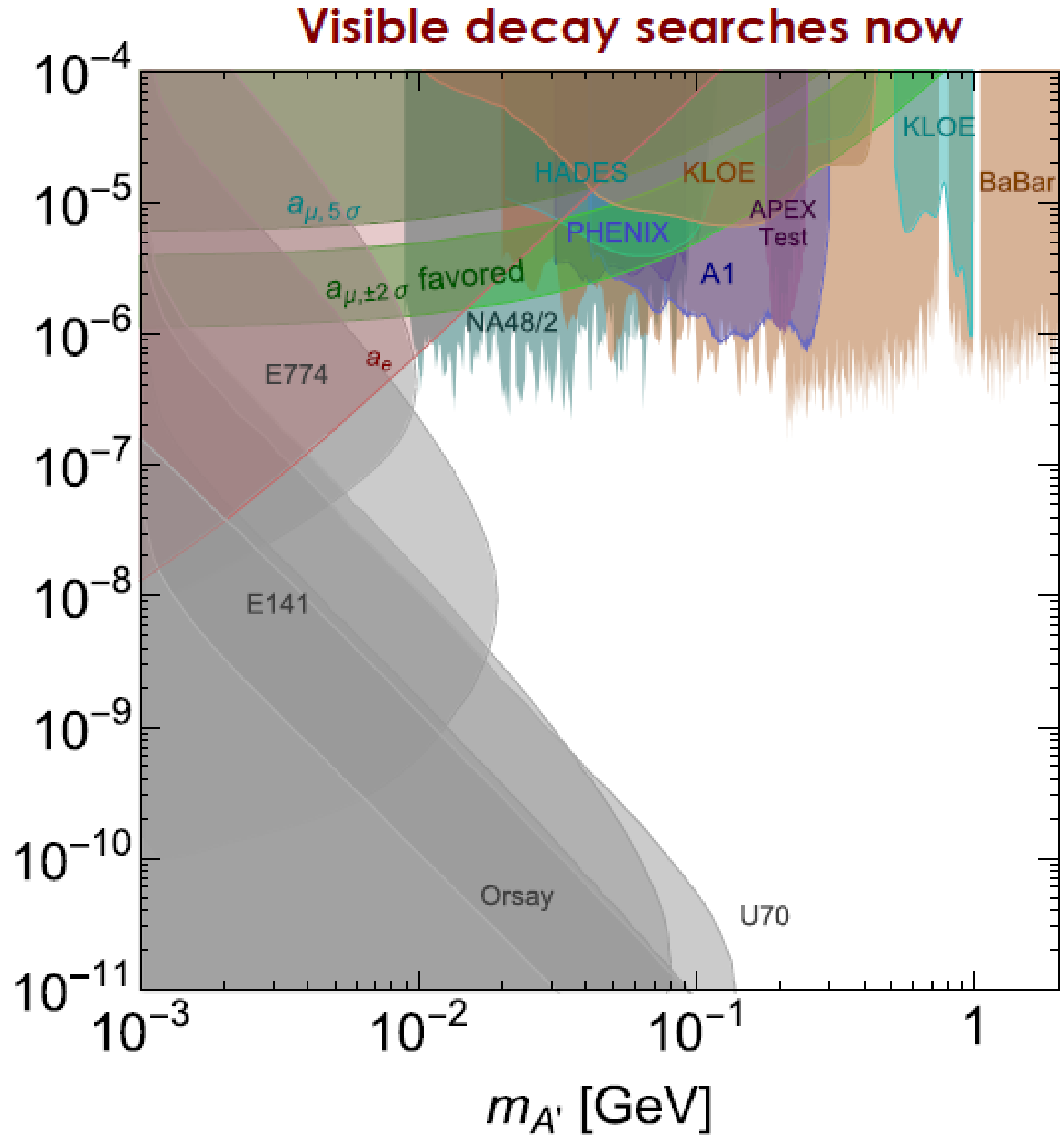




- The dark photon should appear as a **narrow peak** in the π^0_D spectrum
- Mass scan:
  - 404 bins in 9 MeV/c^2<$m_{A'}$<120 MeV/c^2
- For each beam the confidence interval is obtained comparing observed and expected events.
- Local significance never exceed 3σ: **no dark photon signal**

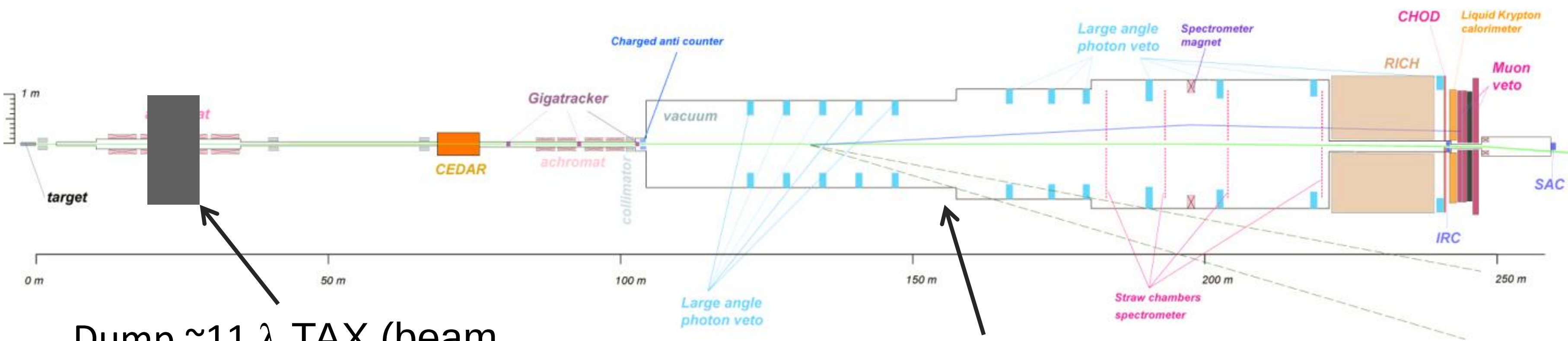
NA48/2 results on Dark Photon

- The limit obtained is background limited
- Modest improvement with larger statistics **$\sim(1/N_K)^{1/2}$**
- If A' couples with quarks and decays in leptons then the g-2 explanation is almost ruled out.
  (see also KLOE results Y.Kolomensky)



[Phys.Lett. B746 (2015) 178]

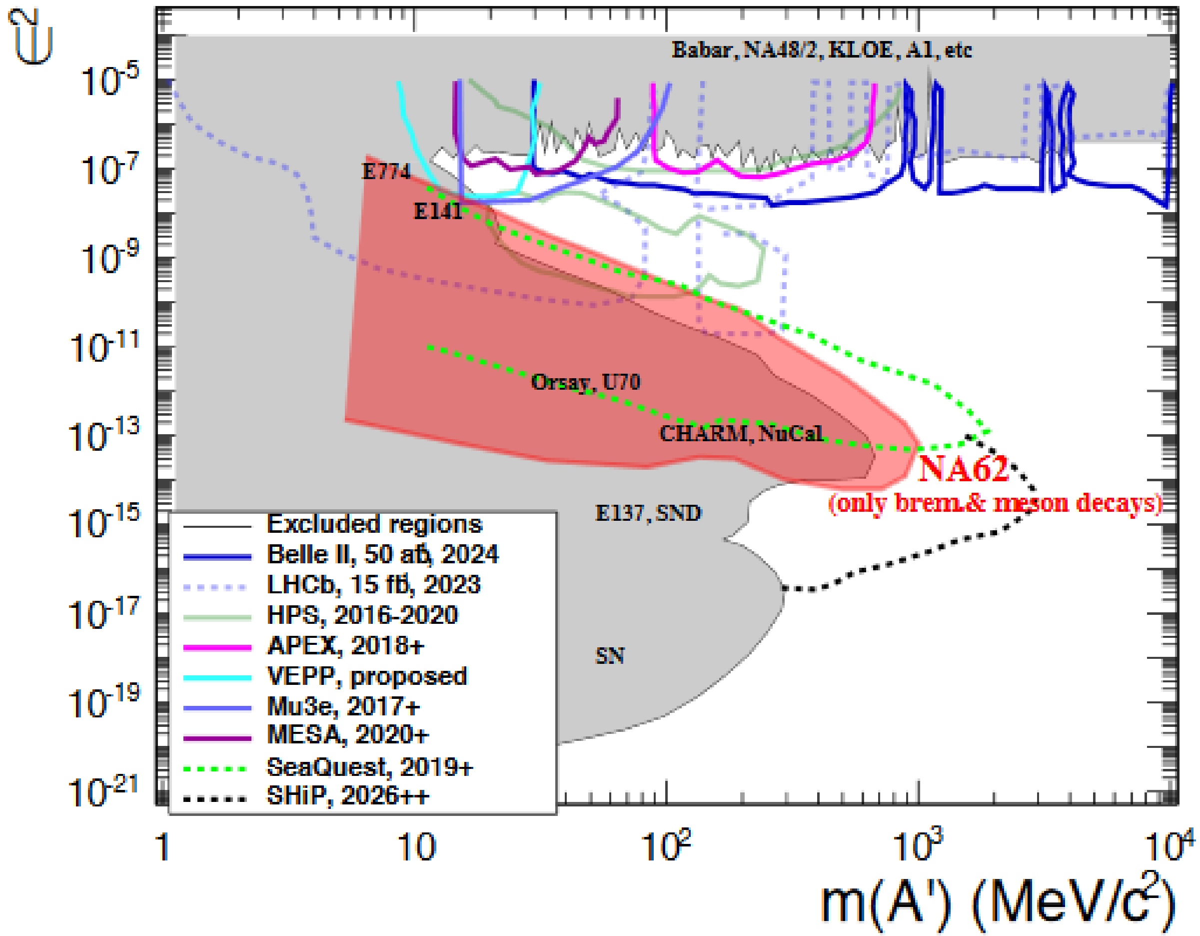
Hidden search in NA62 (>2018)



Dump ~11 λ TAX (beam defining collimator)

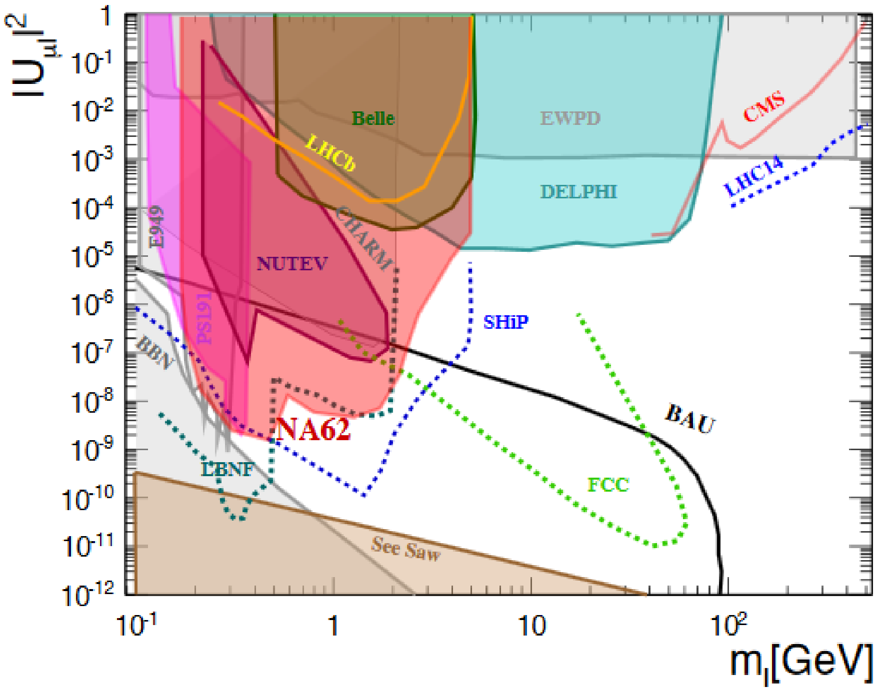
Decay region

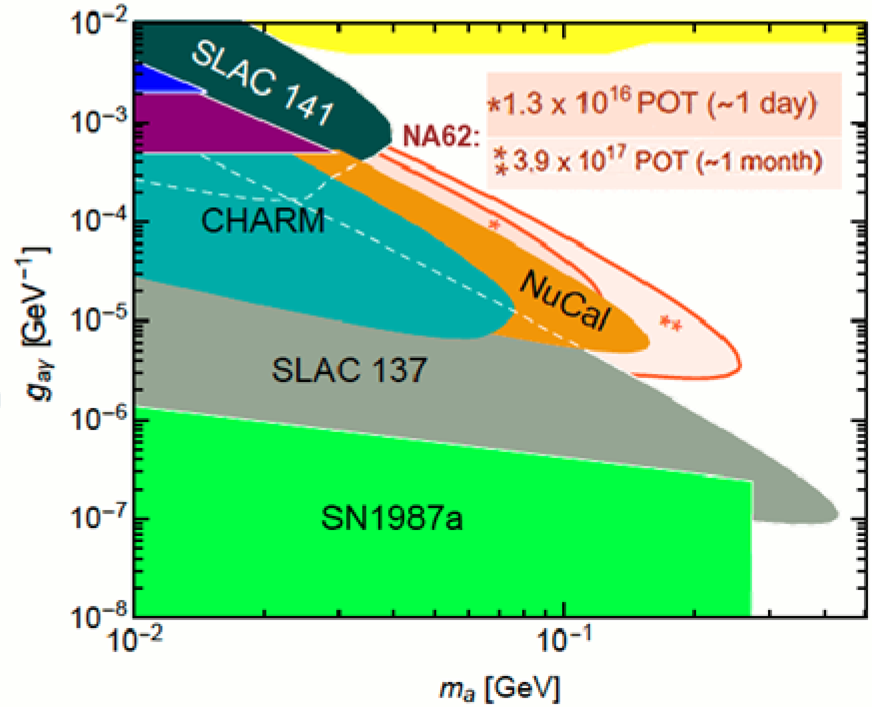
- A' are produced either in the target or in the TAX
  - Hadrons are stopped in the TAX
  - NA62 decay region and detectors essentially untouched
- 10^{18} POT per year



- A’ decays in ee or μμ
- 90% C.L. assuming 2x10^{18} POT and 0 background
- Only A’ produced in the target (not in the dump) are considered

HNL & ALPs





- Heavy Neutral Leptons: assuming 2×10^{18} POT, NA62 could cover a broad region in MeV-GeV
  - HNL→πe, πμ
  - Sensitivity will increase including semileptonic and hadronics decay modes
- ALPs: are produced by Primakoff effect *[JHEP 1602 (2016) 018]*, and decay in γγ
  - Significant contribution below 200 MeV (assuming 0 bkg and 4×10^7)
  - Preliminary test in 2015 (10^{14} POT) demonstrates that 0 bkg is achievable

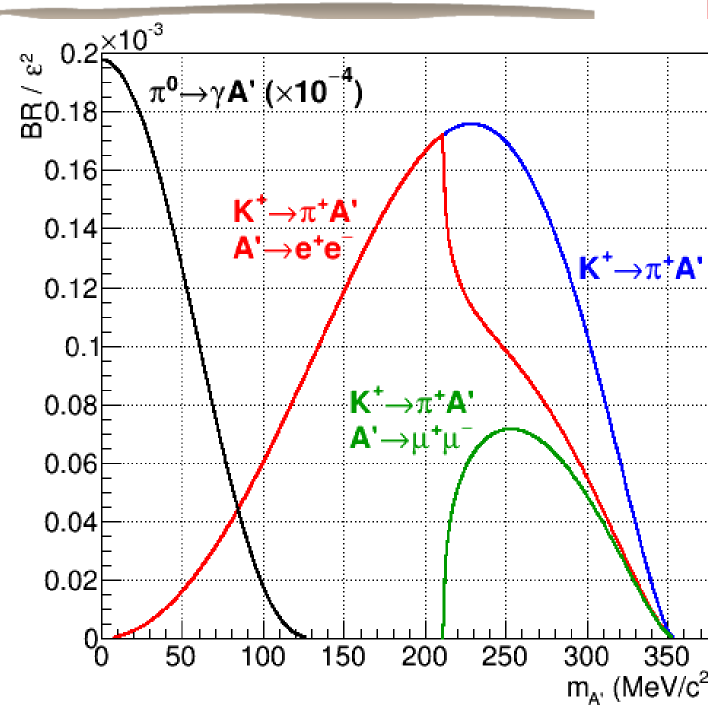
Conclusions

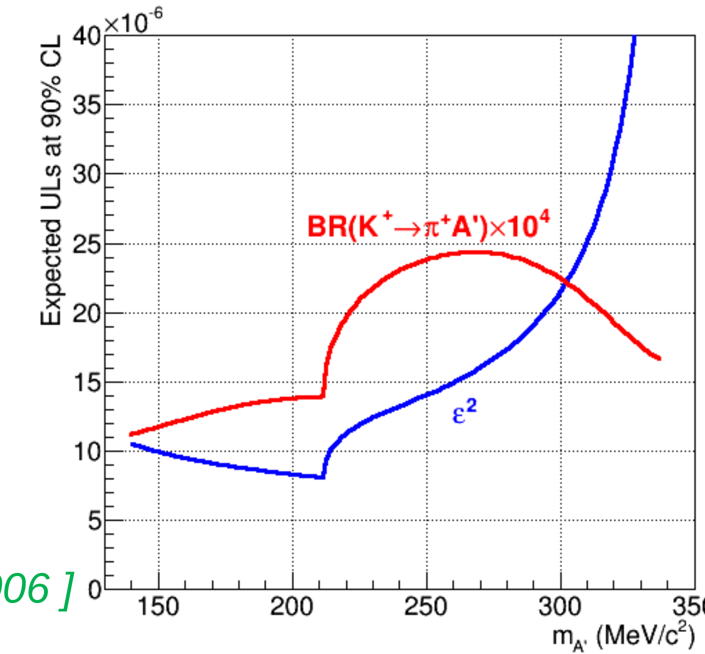
- **NA48/2** has improved limits on the search for dark matter portals and exotics
  - **HNL, Majorana, Inflatons, Dark Photons**
- **NA62** is taking data to search for ultra-rare $\pi\nu\nu$ decay.
- Thanks to a very flexible trigger system, along with the main goal, other searches will be carried out with huge statistics and better resolution.
- The possibility to run in **“dump” mode** to improve searches of DP (vector portal), HNL (neutrino portal), ALPs (axial portal) in higher masses regions will be also considered.

SPARE

Prospects from $K^+ \to \pi^+ A'$

- $K^+ \to \pi^+ A'$ is favorite wrt $\pi^0 \to \gamma A'$ from an experimental point of view:
  - Lower irreducible background (πee vs π^0_D)
  - Higher flux (x4)
  - Higher acceptance
- But the BR is ~10^{-4} wrt π^0. The expected limit (for $m_{A'} > m_{\pi 0}$) is $\varepsilon^2 \sim 10^{-5}$. Not competitive with existing limits

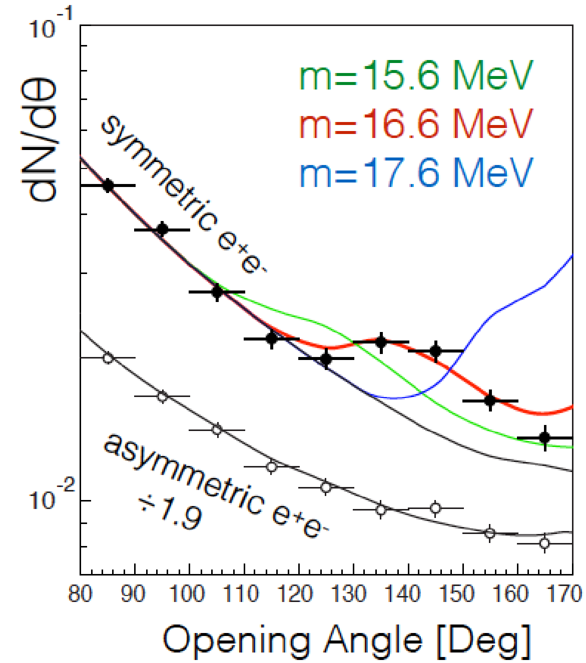


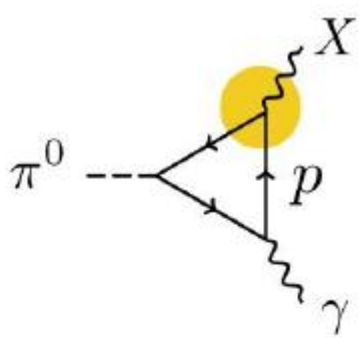


[Davoudiasl, Lee, Marciano PRD89 (2014) 095006]

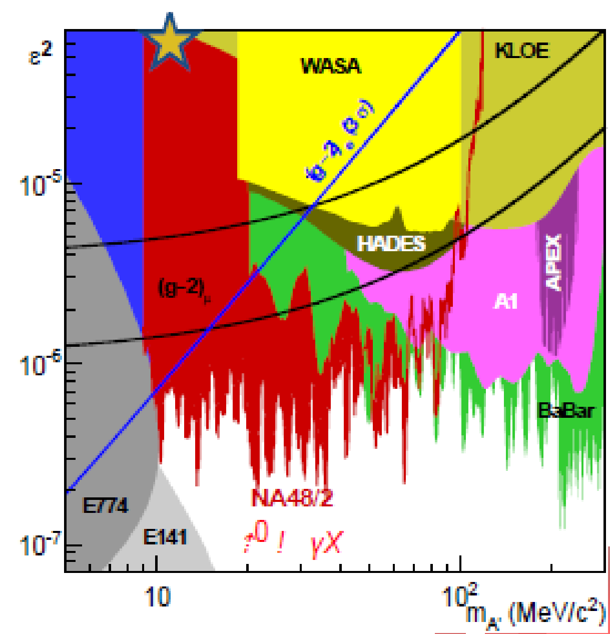
Protophobic DP interaction

- A recent results in Be8 [PRL 116, 042501 (2016)] indicates a possible DP in the region excluded by NA48/2
- This is possible if the DP is proto-phobic. In this case the production through the π^0 decay is prohibited

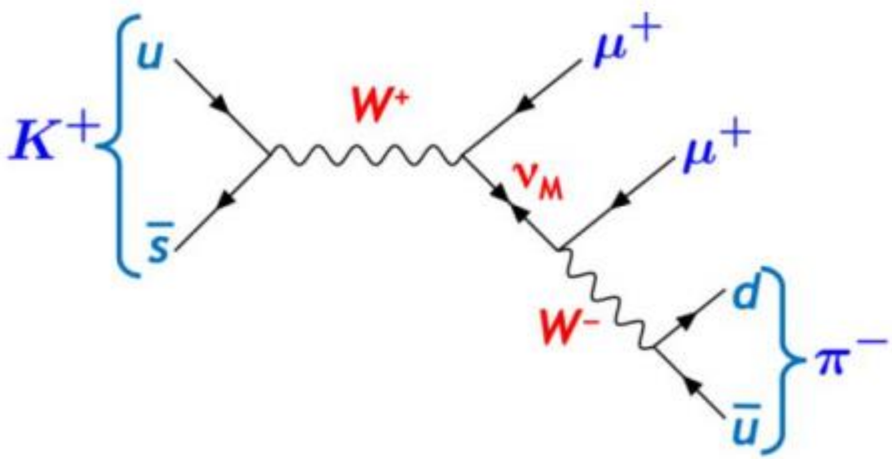


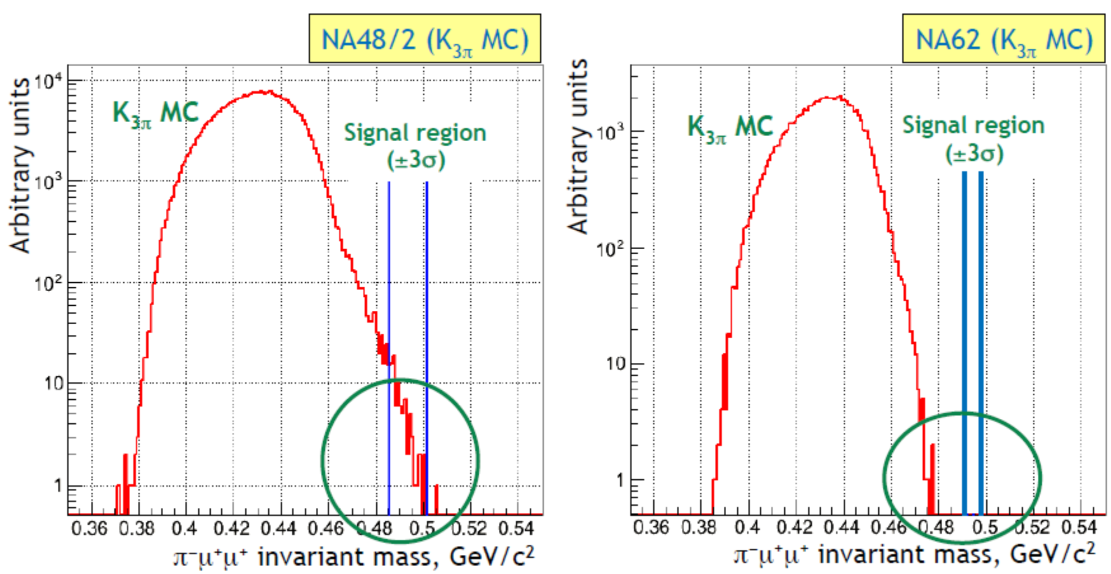


ProtoPhobic coupling

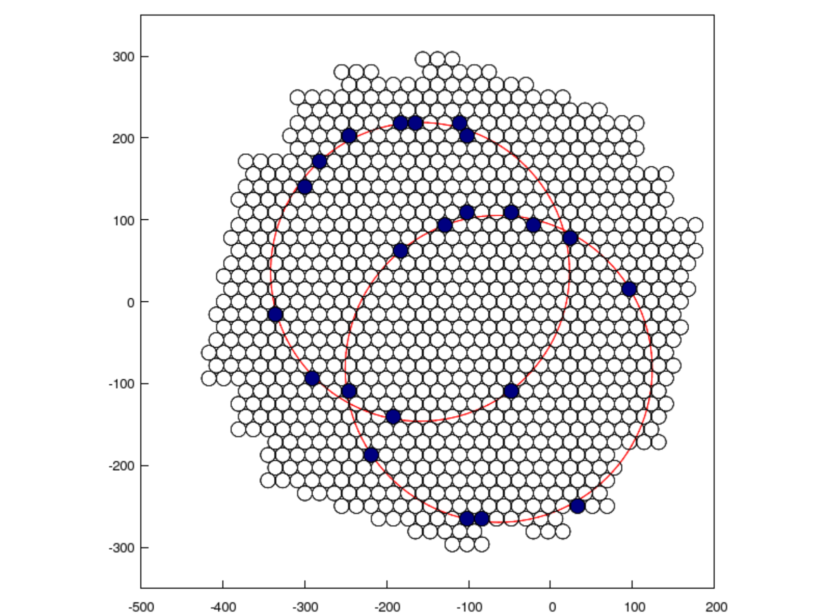


- Majorana neutrino in second family





GPU trigger: almagest algorithm



- Tesla K20
- Only computing time presented
- <0.5 us per event (multi-rings) for large buffers