Results and prospects from NA48 and NA62

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on behalf of the NA62 collaboration

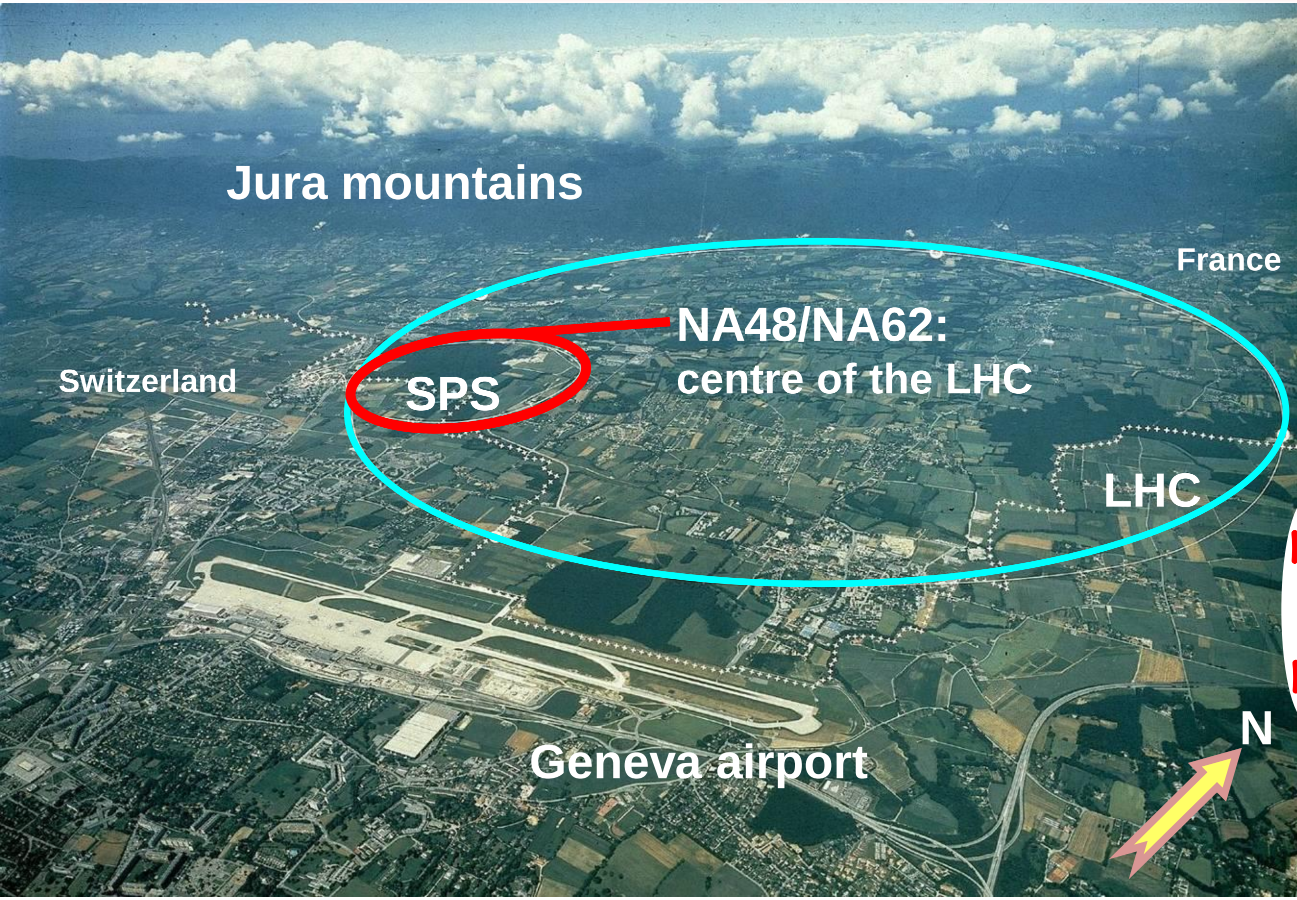
Outline:

1) $K^{\pm}$ decay experiments at CERN: NA48/2 and NA62
2) Neutrino portal: heavy neutral leptons
3) Vector portal: the dark photon
4) Summary

Exploration of the Hidden Sector workshop

CERN • 8 October 2015

Kaon experiments at CERN



Earlier: NA31

NA48 discovery of direct CPV	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 R_K phase	2007: $K^\pm_{e2}/K^\pm_{\mu 2}$	tests
	2008: $K^\pm_{e2}/K^\pm_{\mu 2}$	tests
NA62	2014: pilot run	
	2015–: data taking	

Kaon decay in flight experiments.
NA62: currently ~200 participants, ~30 institutions

Recent $K^{\pm}$ experiments

Experiment	NA48/2 ($K^{\pm}$)	NA62 (R_K phase) ($K^{\pm}$)	NA62 (K^{+})
Data taking period	2003–2004	2007–2008	2015–
Beam momentum, GeV/c	60	74	75
RMS momentum bite, GeV/c	2.2	1.4	0.8
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV/c	120	265	270
$M(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})$ resolution, MeV/c^2	1.7	1.2	0.8
K decays in fiducial volume	2×10^{11}	2×10^{10}	1.2×10^{13}
Main trigger	multi-track; $K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$	Min.bias + $e^{\pm}$	$K_{\pi\nu\nu}$ + ...

The NA48 detector (NA48/2, NA62 R_K phase) — New detector (NA62)

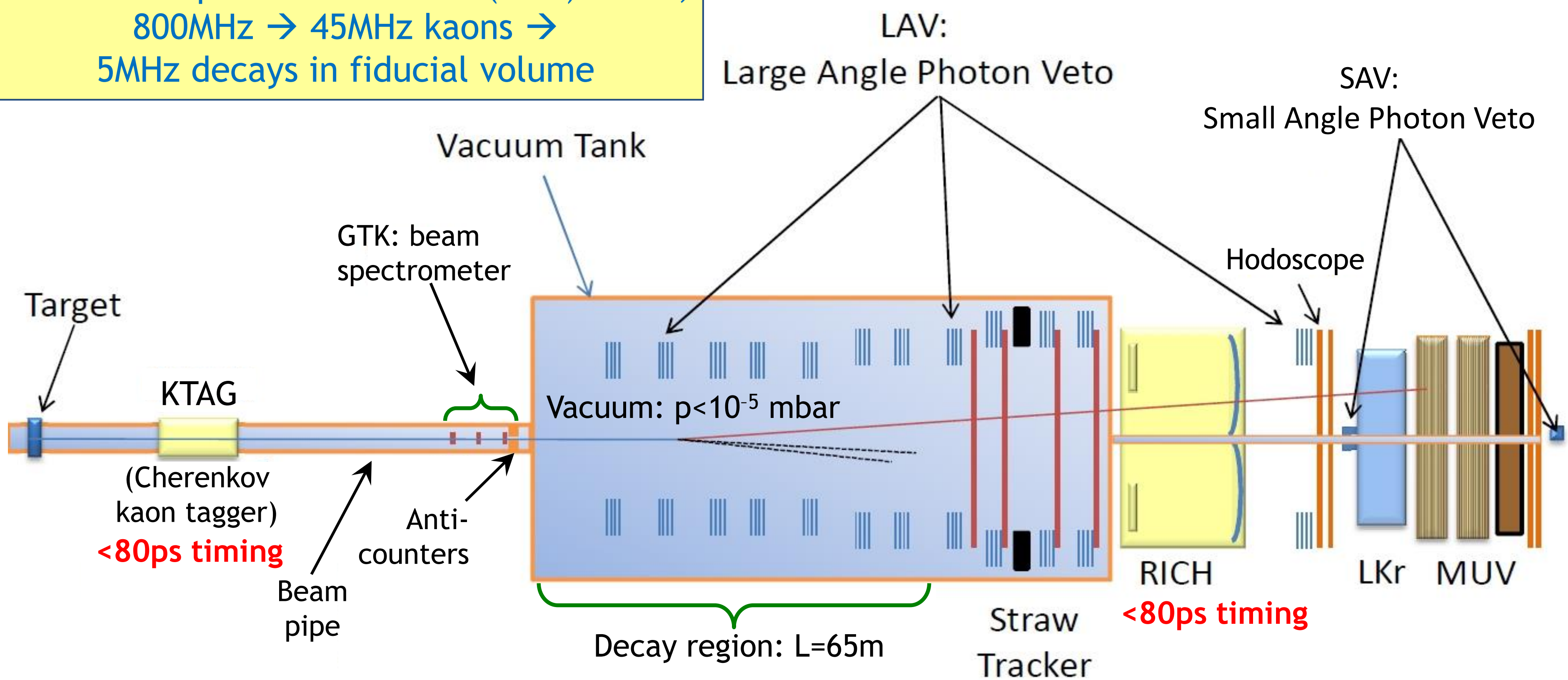
The NA62 experiment

- Main goal: collection of 100 SM $K^{+}\to\pi^{+}\nu\nu$ decays, $BR_{SM}=(9.1\pm0.7)\times10^{-11}$.
  Buras et al., arXiv:1503.02693
- Current $K^{+}\to\pi^{+}\nu\nu$ experimental status: $BR = (1.73^{+1.15}_{-1.05})\times10^{-10}$ from 7 candidates with expected background of 2.6 observed by BNL-E949.
  PRL101 (2008) 191802

The NA62 detector

Un-separated hadron ($p/\pi^+/K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons;
800MHz → 45MHz kaons →
5MHz decays in fiducial volume

Total length: ~270m



- Kinematic rejection factors (limited by beam pileup and tails of MCS): 5×10^3 for $K^+\to\pi^+\pi^0$, 1.5×10^4 for $K\to\mu^+\nu$.
- Hermetic photon veto: ~10^8 suppression of $\pi^0\to\gamma\gamma$.
- Particle ID (RICH+LKr+MUV): ~10^7 muon suppression.

The NA62 detector

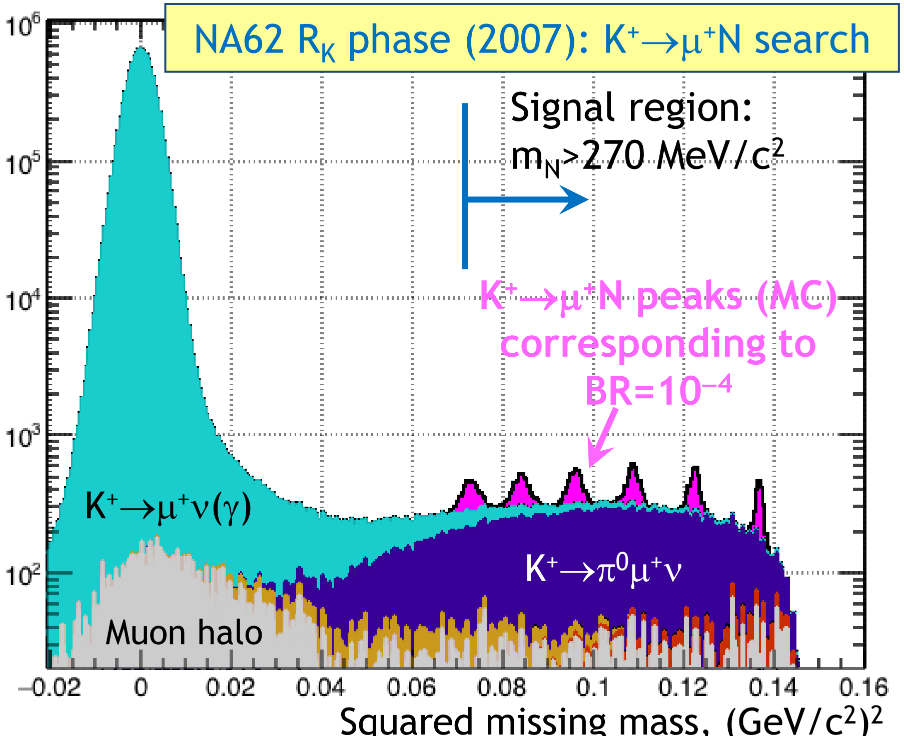
Physics data taking started in June 2015

Neutrino Portal: heavy neutral leptons

HNL: production searches

Neutrino minimal SM (νMSM): three heavy sterile RH Majorana νs ($N_{1,2,3}$).
DM candidate: m_1~10 keV/c^2.
HNLs (m_2~m_3~1 GeV/c^2) observable
(1) via peak search: production in meson decays; or
(2) decay search: e.g. $N \to \pi^{\pm}\ell^{\mp}$
Asaka et al., PLB 631 (2005) 151

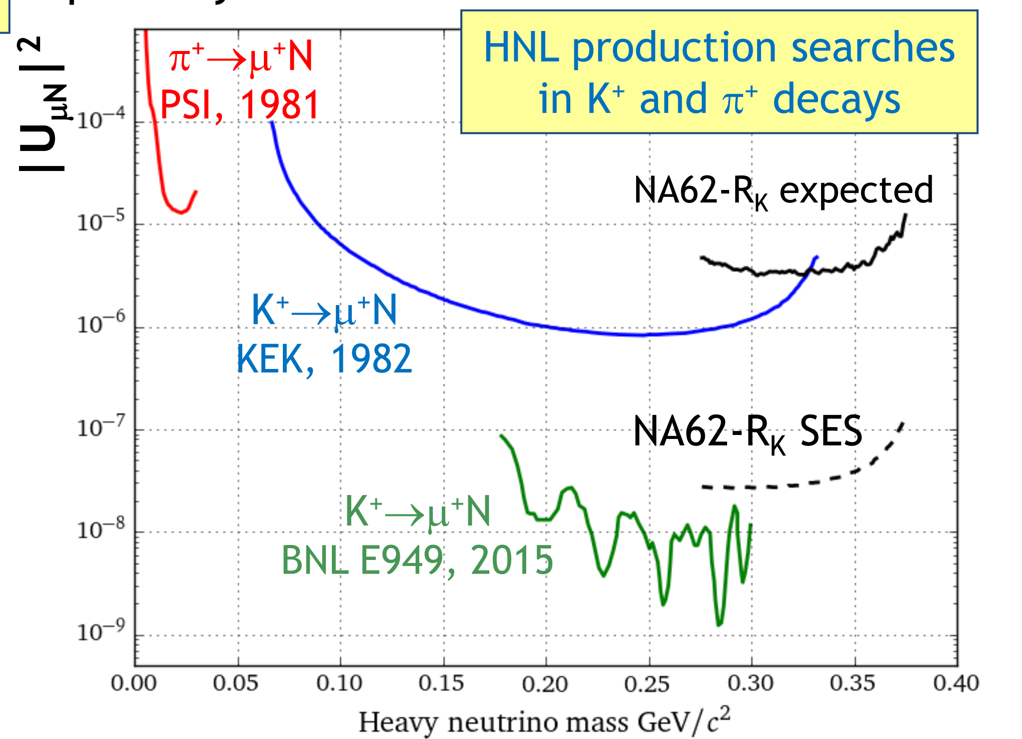
NA62 R_K phase (2007): $K^+\to\mu^+N$ search



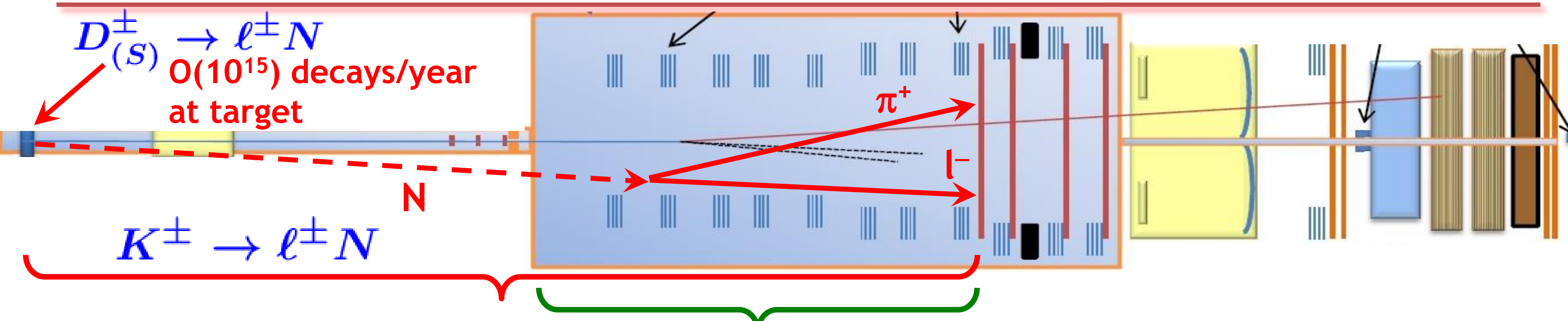
Peak search for $K^+\to\mu^+N$ at NA62 R_K phase:

- Downscaled trigger: small data sample, ~10^8 K^+ decays in fiducial volume.
- Sensitivity is limited by backgrounds.
- However sensitive above m_N=330 MeV/c^2.
- NA62: improved SES by factor ~500; low background (hermetic veto, K^+ tagger); signal region extended into lower m_N; possibly a search for $K^+\to e^+N$.

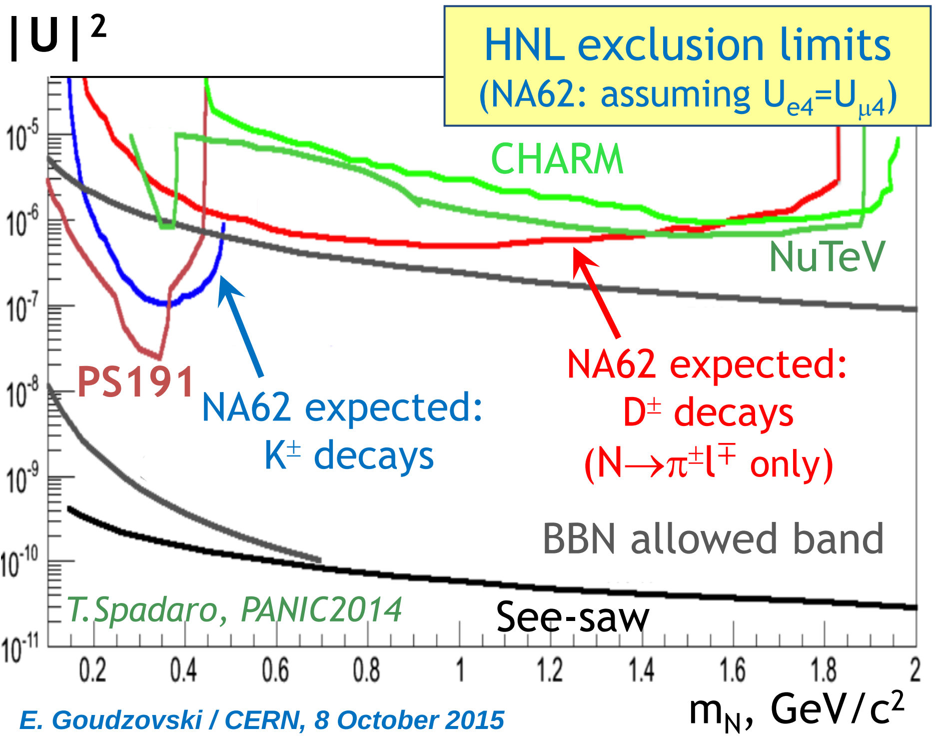
HNL production searches in K^+ and π^+ decays



HNL: decay searches



Search for decays: $N \to \pi^{\pm}\ell^{\mp}$ ($0.14\ GeV/c^2 < m_N < 1.9\ GeV/c^2$)
$N \to \rho^{\pm}\ell^{\mp}$ ($0.8\ GeV/c^2 < m_N < 1.9\ GeV/c^2$)



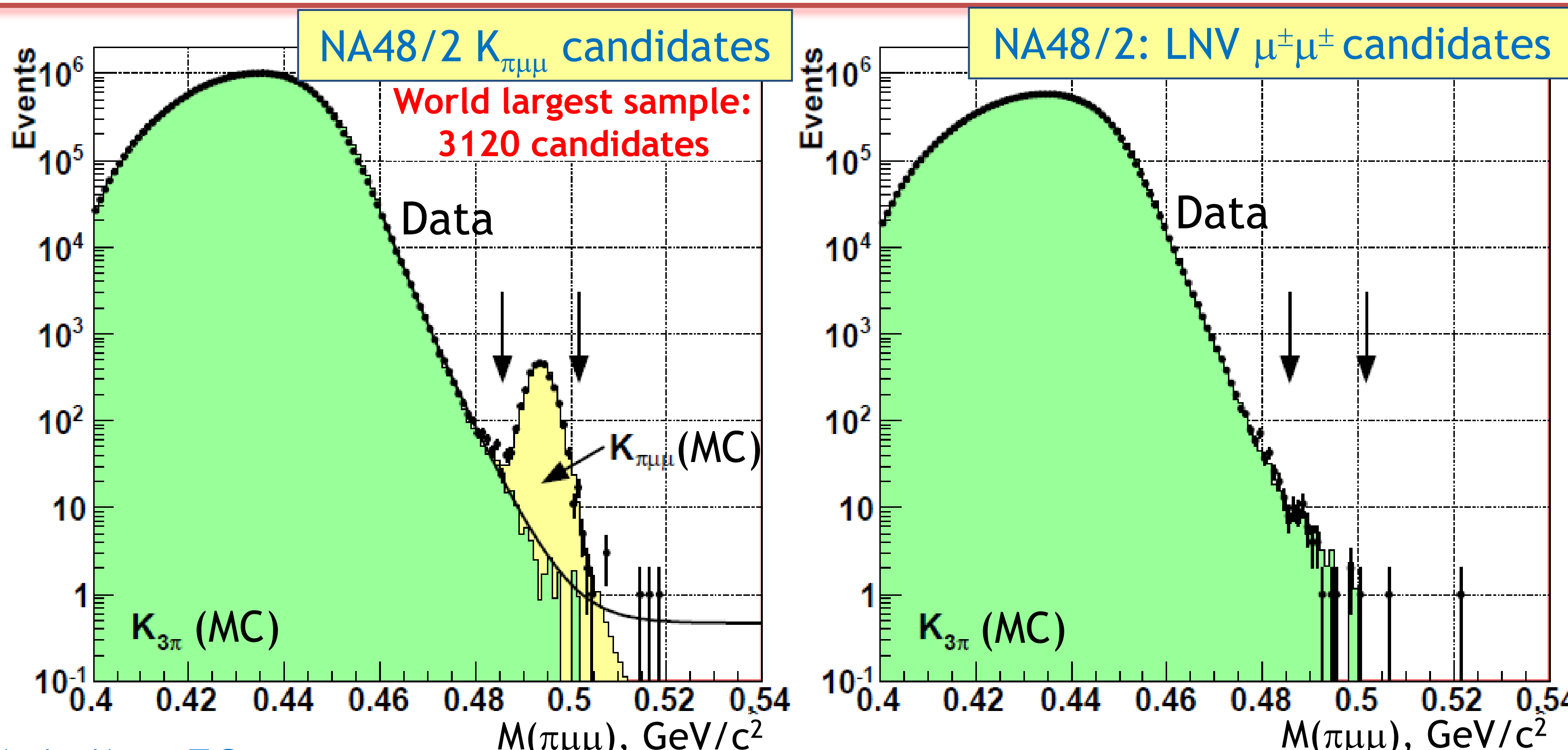
Compatible with the $K_{\pi\nu\nu}$ programme, subject to minor trigger development.

The expected sensitivity is evaluated assuming **zero background**.

Backgrounds to be considered: scattering of halo muons ($\mu^{\pm}N\to K^0X$), charge exchange in KTAG/GTK ($K^+n\to K^0p$), accidentals (K^+ decays, halo muons).

Background reduction: e.g. adding a halo detector in front of decay tank.

HNL production & decay: $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$



$N(\mu^{\pm}\mu^{\pm}) = 52$

$N_{bkg} = 52.6 \pm 19.8_{syst.}$ ⟹ $\mathcal{B}(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1 \times 10^{-9}$ @90% CL

NA48/2 collaboration, PLB 697 (2011) 107

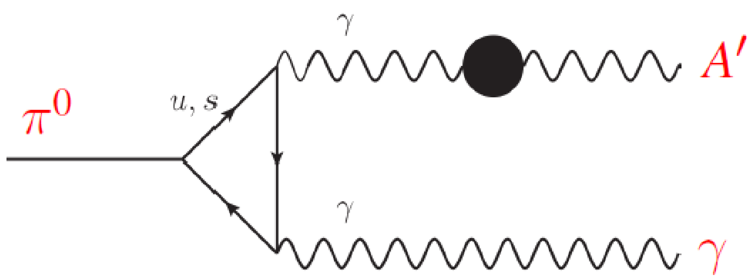
- ❖ Precision limited by background from $\pi^{\pm} \to \mu^{\pm}\nu$, despite SES ≈ 3×10^{-11}.
- ❖ Re-analysis (3-track vertex) in progress: reduced background, a scan in m_N and τ_N. Expected sensitivity to $BR(K^+ \to \mu^+ N) \times BR(N \to \mu^+\pi^-)$: ~$10^{-10}$ for $\tau_N < 10^{-9}$s. Searches for $K^+ \to \pi^+ X$, $X \to \mu^+\mu^-$ and $K^+ \to \mu^+ X$, $X \to \pi^+\mu^-$ can also be performed.
- ❖ NA62: a dedicated μμ trigger; displaced vertex analysis possible (τ_N up to 10^{-7}s).

Vector Portal:
the dark photon

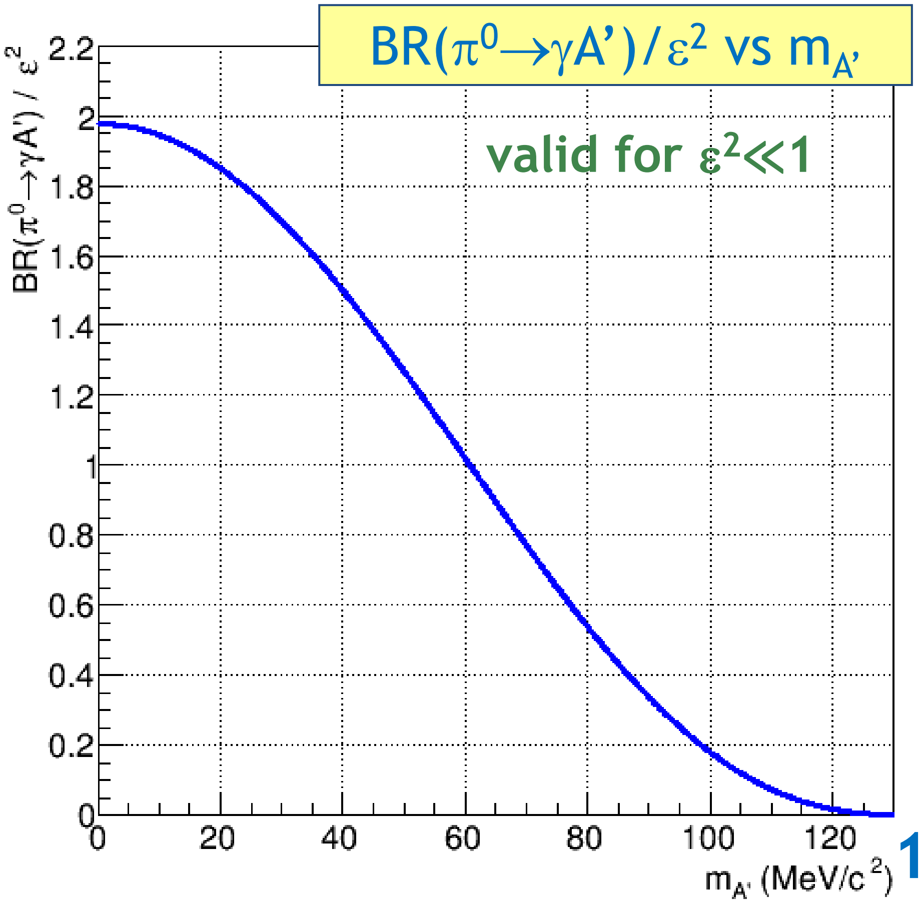
DP production in $\pi^0 \to \gamma A'$ decay

Batell, Pospelov and Ritz, PRD80 (2009) 095024

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

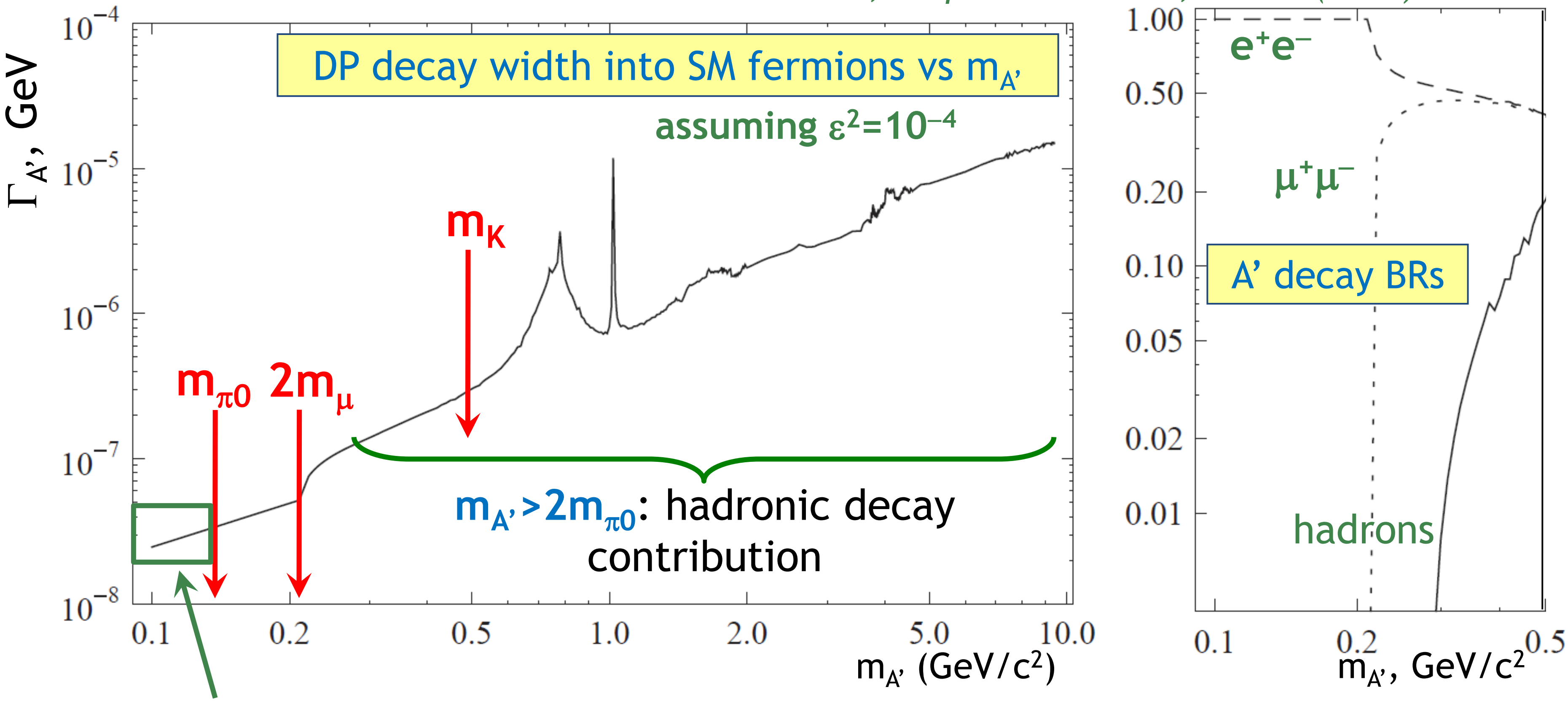


- Two unknown parameters: mass ($m_{A'}$) and mixing (ε^2).
- Sensitivity to DP for $m_{A'} < m_{\pi 0}$.
- Loss of sensitivity to ε^2 as $m_{A'}$ approaches $m_{\pi 0}$, due to kinematical suppression of the $\pi^0 \to \gamma A'$ decay.



DP decays into SM fermions

Batell, Pospelov and Ritz, PRD79 (2009) 115008



Accessible in π^0 decays: assuming decays only into SM fermions,

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

⇨ For $\varepsilon^2>10^{-7}$ and $m_{A'}>10$ MeV/c^2, **prompt A' decay** (z vertex resolution ~1 m).
Therefore $\pi^0_D \to e^+e^-\gamma$ is an irreducible background.

NA48/2: the π^0_D sample

Two exclusive selections

$K^\pm \to \pi^\pm \pi^0_D$ selection:

- $|m_{\pi\gamma ee} - m_K| < 20$ MeV/c^2;
- $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/c^2;
- no missing momentum.

$K^\pm \to \pi^0_D \mu^\pm \nu$ selection:

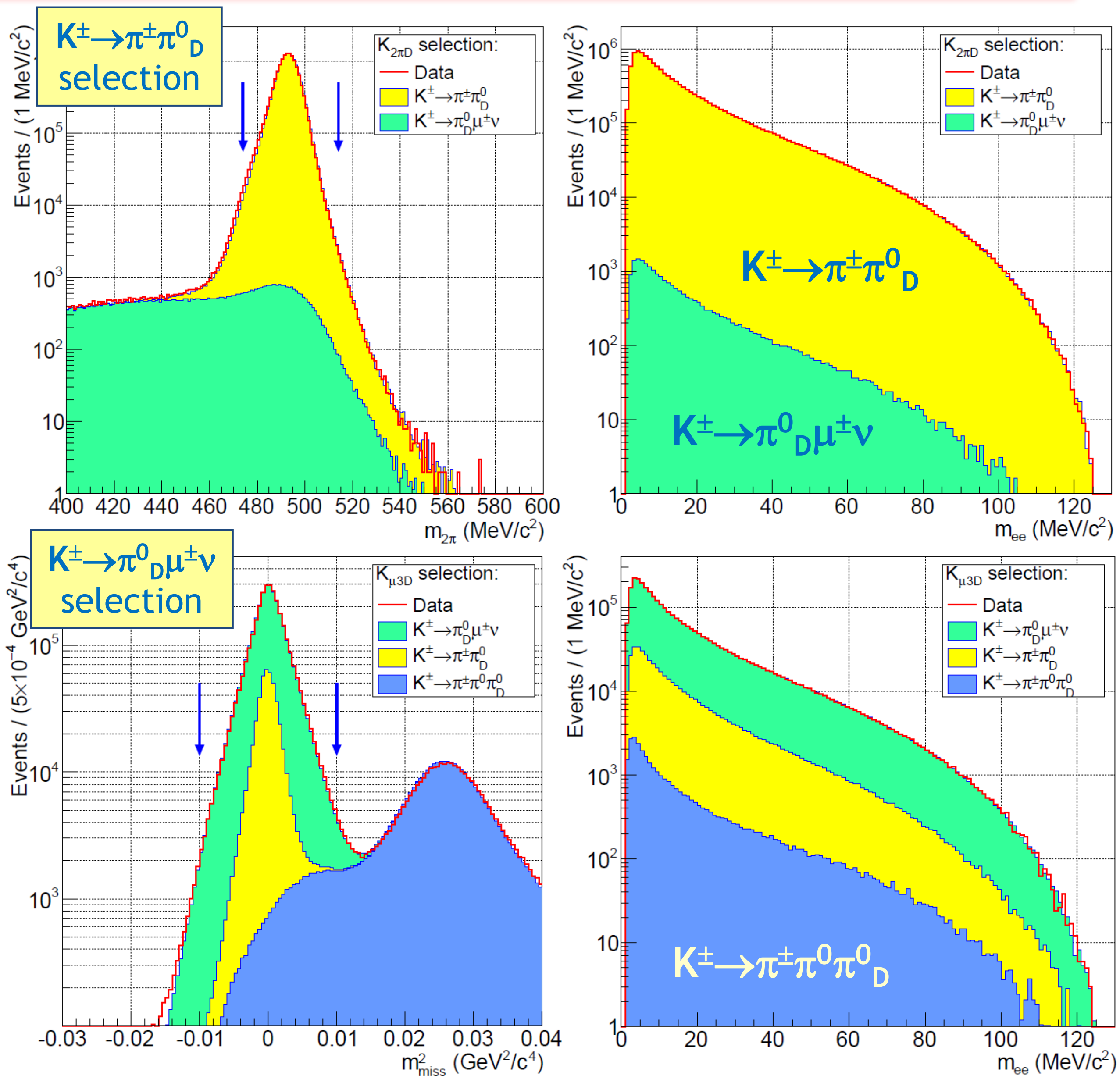
- $m_{miss}^2 = (P_K - P_\mu - P_{\pi 0})^2$ compatible with zero;
- $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/c^2;
- missing total and transverse momentum.

Reconstructed π^0_D decay candidates:

- $N(K_{2\pi D}) = 1.38 \times 10^7$,
- $N(K_{\mu 3D}) = 0.31 \times 10^7$,
- total $= 1.69 \times 10^7$.

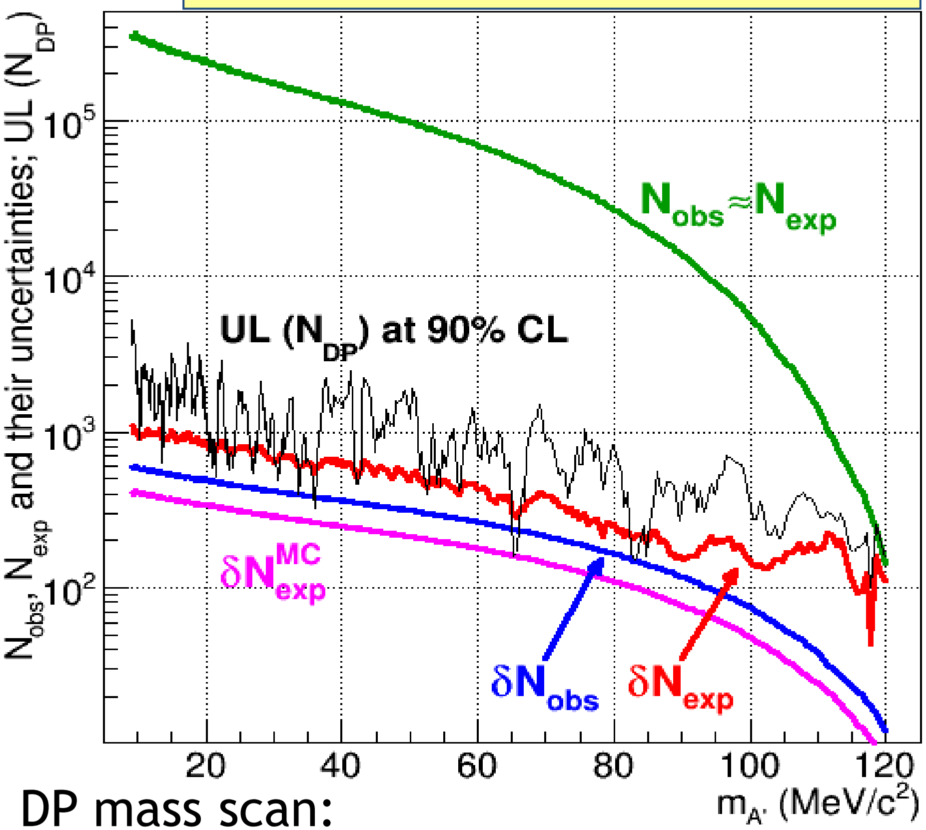
$K^\pm$ decays in fiducial region:

$N_K = (1.57 \pm 0.05) \times 10^{11}$.

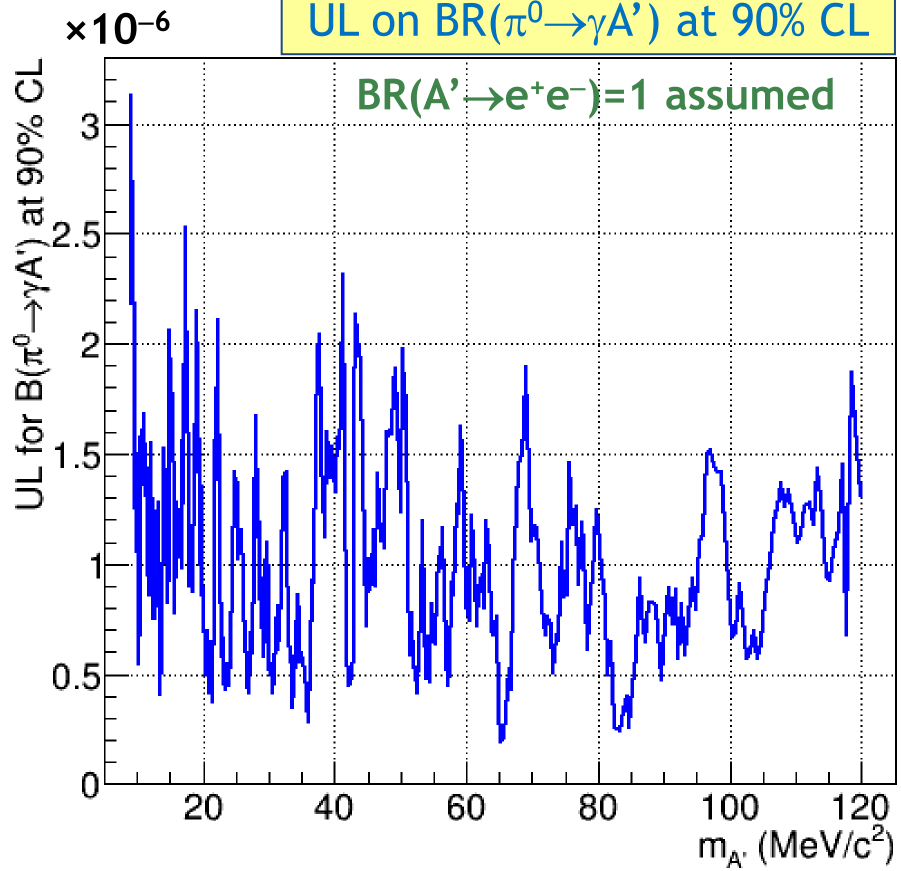


NA48/2: search for DP signal

UL on the number of DP candidates



UL on BR($\pi^0 \to \gamma A'$) at 90% CL



DP mass scan:

- range: **9 MeV/$c^2 \le m_{A'} <$ 120 MeV/c^2**;
- mass step **$0.5\sigma_m$**, signal window **$\pm 1.5\sigma_m$**;
- DP mass hypotheses tested: **404**.

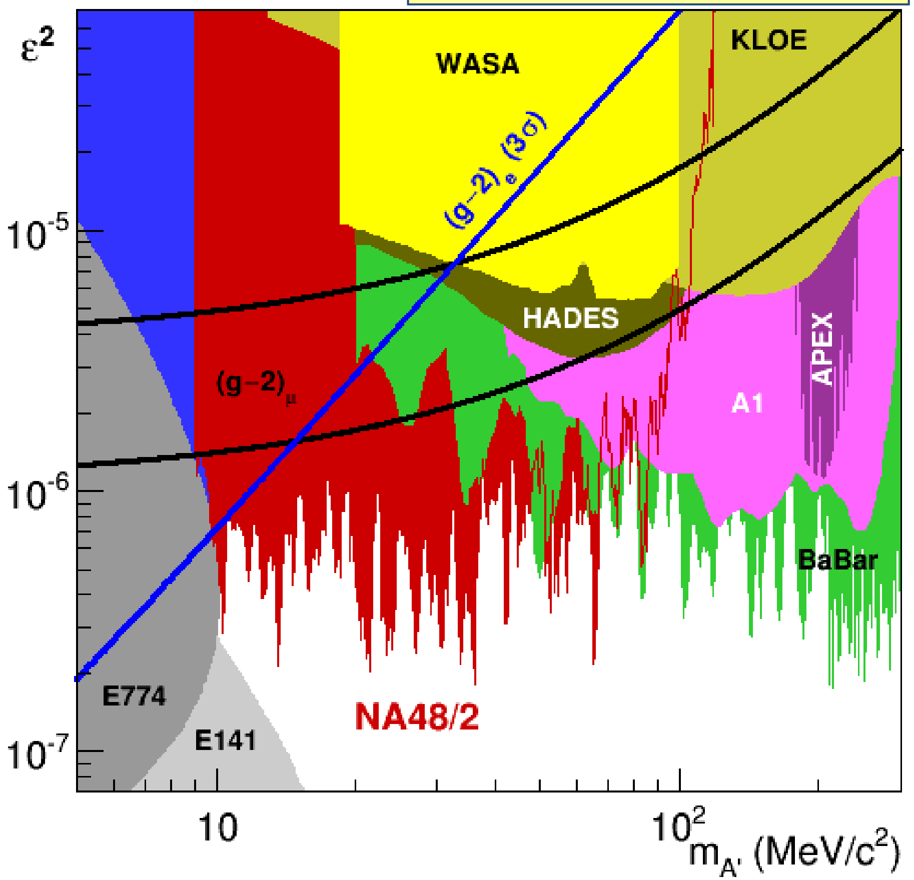
Local signal significance never exceeds **3σ**:
no DP signal is observed.

The obtained limits are background limited: 2–3 orders of magnitude above single event sensitivity

NA48/2: dark photon in π^0 decays

PLB746 (2015) 178

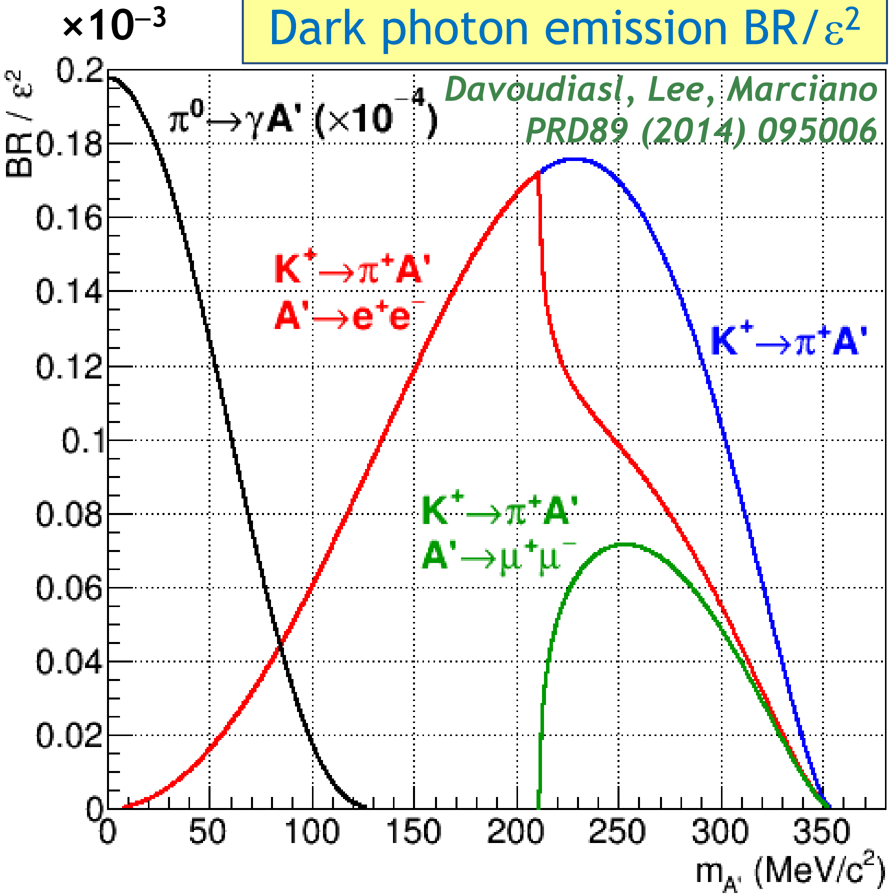
DP exclusion summary



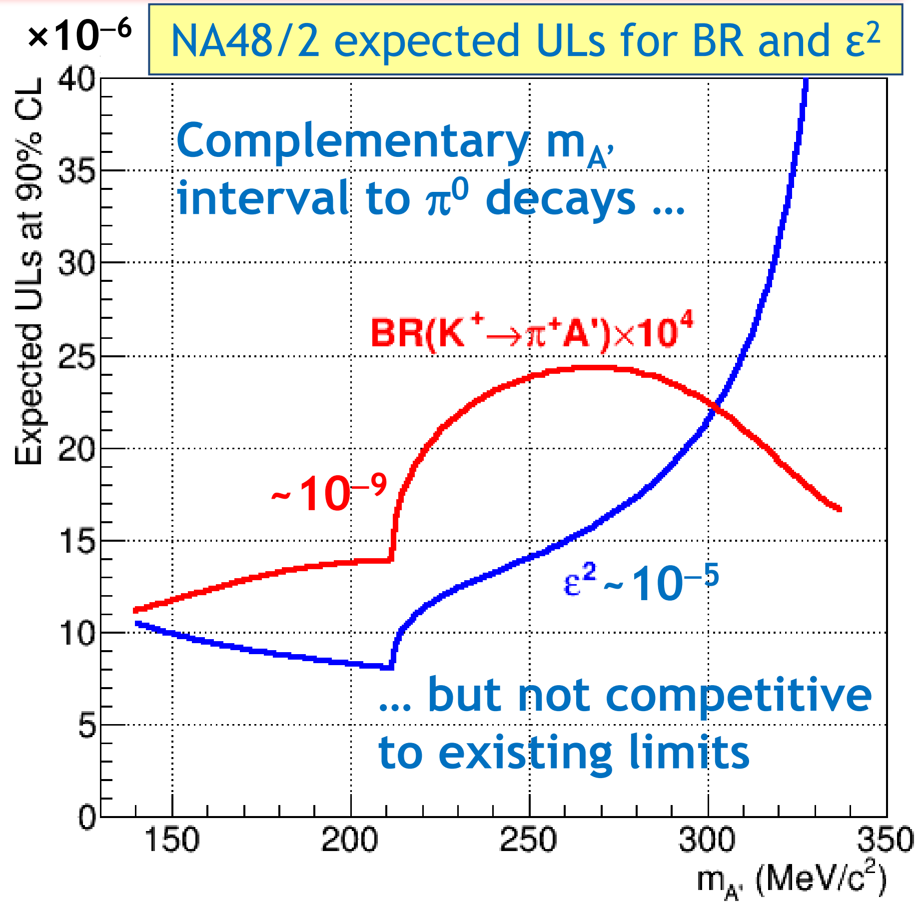
- Improvement on the existing limits in the $m_{A'}$ range **9–70 MeV/c²**.
- Most stringent limits are at low $m_{A'}$ (kinematic suppression is weak).
- Sensitivity limited by irreducible π^0_D background: upper limit on ε^2 scales as **$\sim(1/N_K)^{1/2}$**, modest improvement with larger samples (e.g. at NA62).
- If DP couples to quarks and decays **mainly to SM fermions**, it is ruled out as the explanation for the anomalous **$(g-2)_\mu$**.
- Sensitivity to smaller ε^2 with displaced vertex analysis is under investigation.

Prospects for $K^{\pm}\to\pi^{\pm}A'$, $A'\to l^+l^-$

Dark photon emission BR/ε^2



NA48/2 expected ULs for BR and ε^2

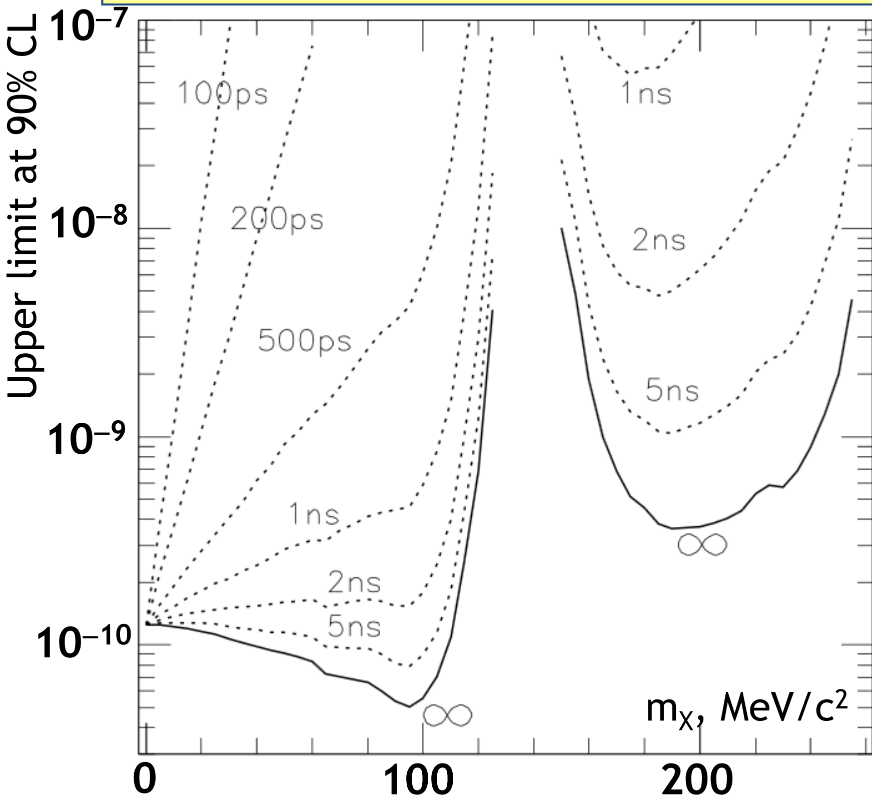


Comparison of ($K^{\pm}\to\pi^{\pm}A'$, $A'\to e^+e^-$, $m_{A'}>m_{\pi 0}$) vs ($\pi^0\to\gamma A'$, $A'\to e^+e^-$, $m_{A'}<m_{\pi 0}$):

- Lower irreducible background: $BR(K^{\pm}\to\pi^{\pm}e^+e^-)\sim10^{-7}$ vs $BR(\pi^0_D)\sim10^{-2}$.
- Higher acceptance (×4), favourable K/π^0 flux ratio (×4).
- Therefore the expected BR limits: $BR(K^{\pm}\to\pi^{\pm}A')\sim10^{-9}$ vs $BR(\pi^0\to\gamma A')\sim10^{-6}$.
- However $BR(K^{\pm}\to\pi^{\pm}A')/BR(\pi^0\to\gamma A')\sim10^{-4}$, expected ε^2 limits are $\varepsilon^2\sim10^{-5}$.

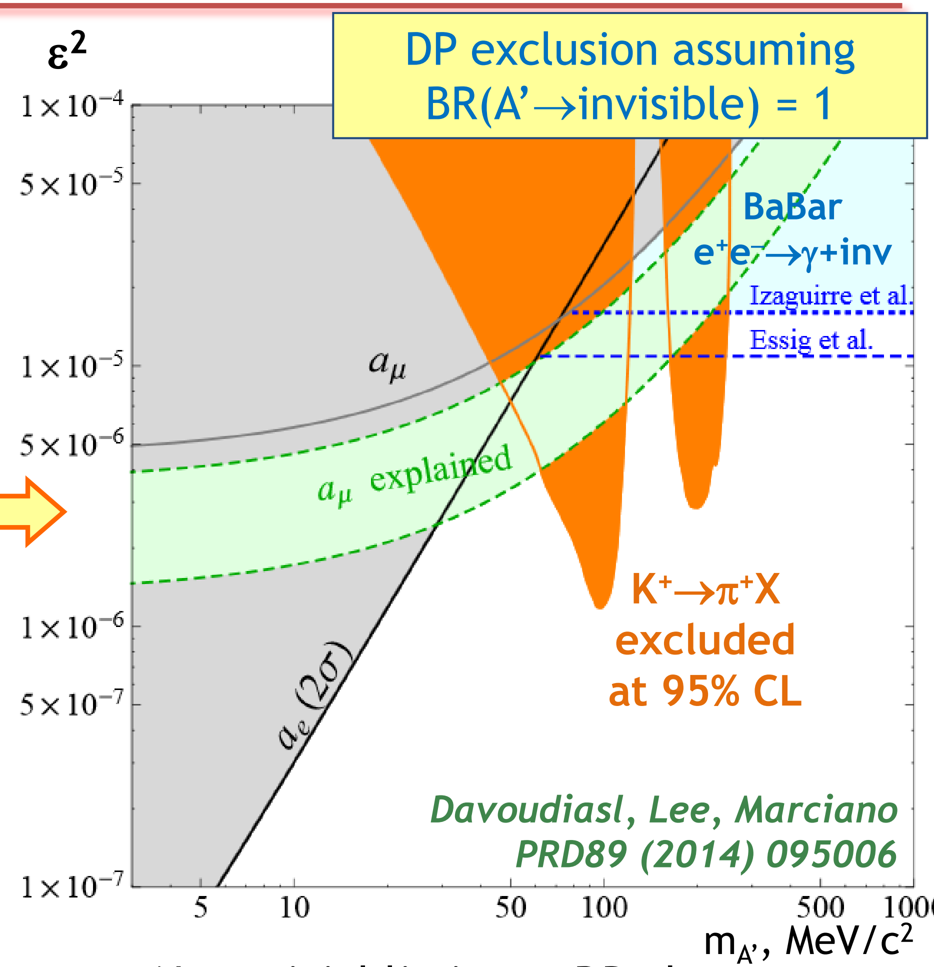
$K^\pm \to \pi^\pm A'$, $A' \to$ invisible

BNL-E949: limits on BR($K^+ \to \pi^+ X$) vs τ_X



The E949 $K^+ \to \pi^+ \nu\nu$ analysis:
$K^+ \to \pi^+ X$ search (where X is invisible)
PRD79 (2009) 092004

BR($\pi^0 \to$ invisible)<2.7×10^{-7} at 90% CL
PRD72 (2005) 091102



Non-trivial limits on DP phase space
Including the $(g-2)_\mu$ favoured band,
assuming invisible DP decays.

NA62: expect an order of magnitude improvement

Summary

- NA62 physics data taking started in 2015.
- NA62 is capable of improving the current limits on:
  - ✓ NHL production in K^+ decays, $0.1\ \mathrm{GeV} < m_N < 0.4\ \mathrm{GeV}$.
  - ✓ Possibly HNL decays, $0.4\ \mathrm{GeV} < m_N < 1.5\ \mathrm{GeV}$?
  - ✓ Neutral particles ($\chi \to l^+ l^-$) with $m_\chi < 0.35\ \mathrm{GeV}$ and $\tau_\chi < 10^{-7}$ s.
  - ✓ LFV and LNV in K^+ and π^0 decays.
  - ✓ DP production in K^+ and π^0 decays ($0.01\ \mathrm{GeV} < m_{A'} < 0.35\ \mathrm{GeV}$), assuming both visible ($A' \to l^+ l^-$) and invisible A' decays.
- Further sensitivity studies (axions, inflatons) are in progress.
- New ideas are very welcome!

Spares

NA62 & SHiP design parameters

Primary beam for both NA62 and SHiP: 400 GeV/c SPS protons

	NA62 (running experiment)	SHiP (proposal)
Years of operation	3	5
POT per SPS spill	3×10^{12}	4×10^{13}
POT total	5×10^{18}	2×10^{20}
Decay volume (m^3)	260 m^3	1780 m^3
Decay volume distance to target	104–183 m	64–124 m
Decay volume pressure (bar)	10^{-9} bar	10^{-6} bar
Halo muon rate in spectrometer	6 MHz	few kHz
Straw chamber area	0.06m<R<1.05m	R_1=5m, R_2=10m

LFV in $K^{\pm}$ and π^0 decays

Mode	UL at 90% CL	Experiment	Reference
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL E777/E865	PRD 72 (2005) 012005
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$	1.1×10^{-9}	CERN NA48/2	PLB 697 (2011) 107
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva-Saclay	PL 62B (1976) 485
$K^+ \to e^-\nu\mu^+\mu^+$	no data		
$\pi^0 \to \mu^+e^-$	3.6×10^{-10}	FNAL KTeV	PRL 100 (2008) 131803
$\pi^0 \to \mu^-e^+$	3.6×10^{-10}	FNAL KTeV	PRL 100 (2008) 131803

* CERN NA48/2 sensitivities for these three modes are similar to those of BNL E865

Expected NA62 single event sensitivities:
~10^{-12} for $K^{\pm}$ decays, ~10^{-11} for π^0 decays.

- ❖ NA62 is capable of improving on all these decay modes.
- ❖ Sensitivity will depend on the trigger selectivity.