Searching for X17 in π^0 decays by NA48/2 at CERN

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Outline:
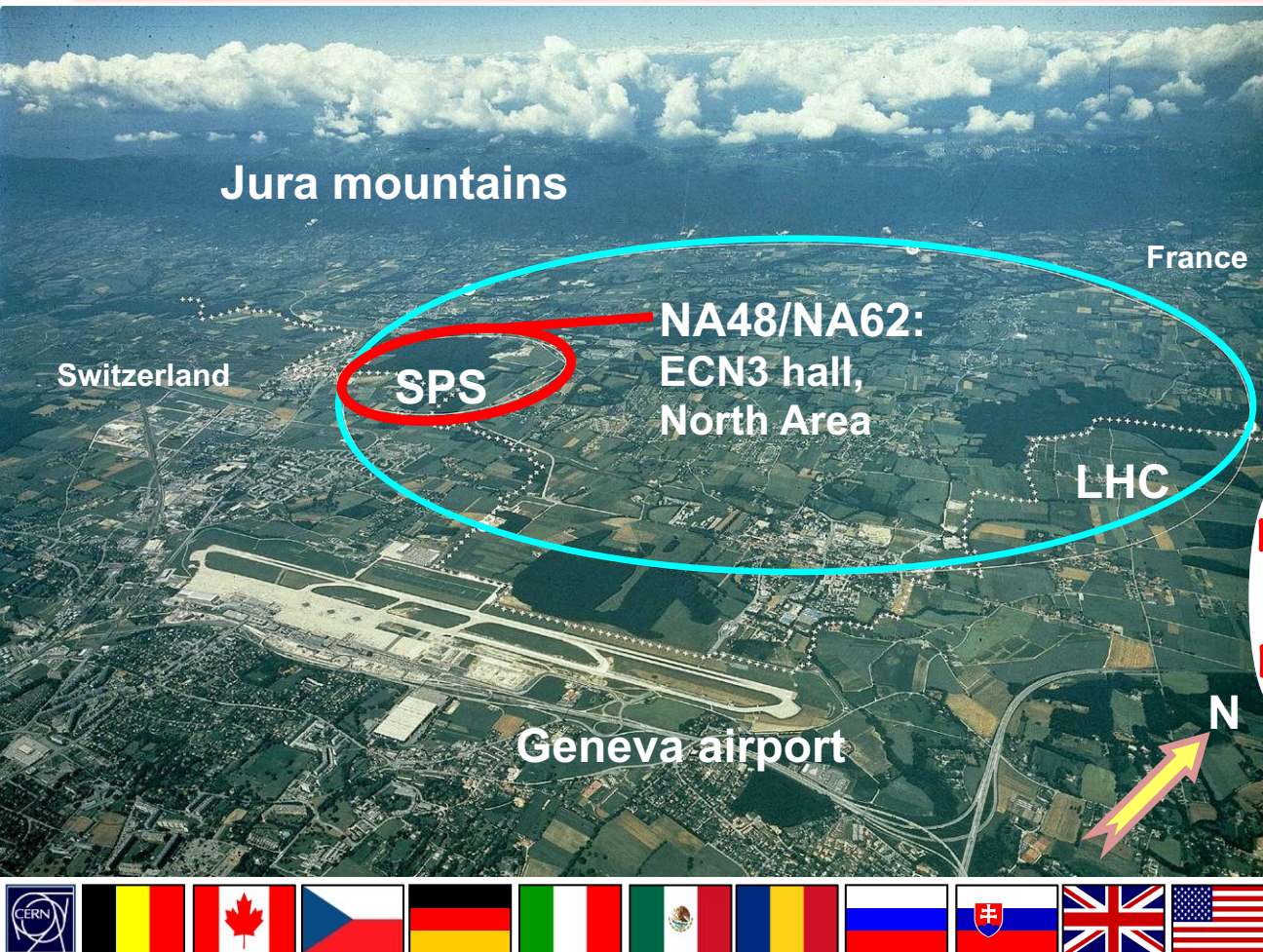
1) CERN kaon programme and the NA48/2 experiment
2) Dark photon production in π^0 decays
3) NA48/2 search for dark photon production and decay
4) Summary and outlook

Shedding light on X17
Rome • 6–8 September 2021

Kaon experiments at CERN

Jura mountains

France

Switzerland

NA48/NA62:
ECN3 hall,
North Area

SPS

LHC

N

Geneva airport

Main **NA62** goal: $K^+ \rightarrow \pi^+ \nu \nu$ measurement to **10%** precision with a novel decay-in-flight technique.

Currently **~300** participants from **31** institutions.

Earlier: NA31

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 discovery of direct CPV

NA48/1
2002: K_S/hyperons

NA48/2
2003: K^+/K^-
2004: K^+/K^-

NA62 R_K run
2007: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$	tests
2008: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$	tests

NA62
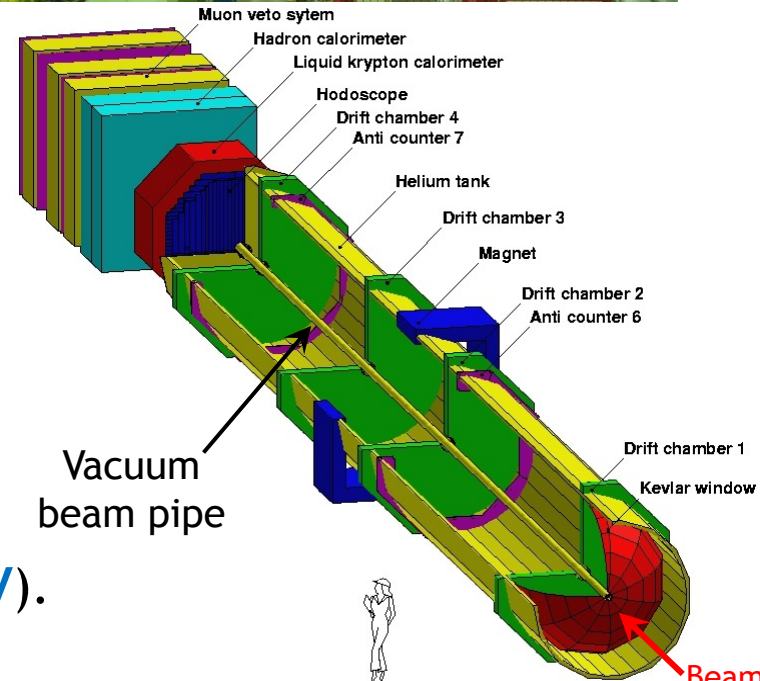| 2015: commissioning |
|---|
| 2016-18: physics run 1 |
| 2021-: physics run 2 |

NA48/2 experiment & detector

❖ Simultaneous coaxial narrow
  momentum band **K$^\pm$** beams:
  P_K = 60 GeV/c, $\delta P_K/P_K \approx 3\%$ (rms).

❖ Rate of **K$^\pm$** decays: **~100 kHz**.

❖ Data taking: six months in **2003–04**.

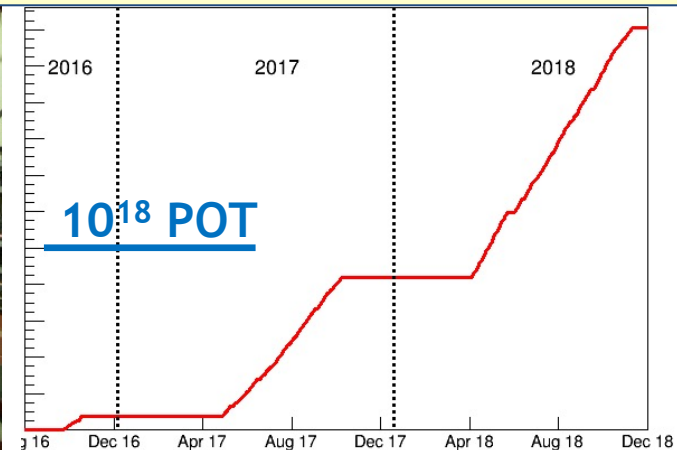❖ Main trigger: 3-track vertex.

Principal subdetectors:

❖ Magnetic spectrometer (four drift chambers)
  Four views/chamber. High-level trigger.
  $\delta p/p$ = (1.02 $\oplus$ 0.044p)% [**p** in GeV/c]

❖ Scintillator hodoscope (HOD)
  Low-level trigger, time measurement (**150 ps**).

❖ Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  σ_E/E = (3.2/E$^{1/2}$ $\oplus$ 9/E $\oplus$ 0.42)% [E in GeV];
  $\sigma_x = \sigma_y$ = (4.2/E$^{1/2}$ $\oplus$ 0.6) mm (**1.5mm@10GeV**).

Muon veto sytem
Hadron calorimeter
Liquid krypton calorimeter
Hodoscope
Drift chamber 4
Anti counter 7
Helium tank
Drift chamber 3
Magnet
Drift chamber 2
Anti counter 6
Vacuum beam pipe
Drift chamber 1
Kevlar window
Beam

NA62 Run 1 (2016–18) dataset

Run 1 integrated luminosity

10^{18} POT

**2.2×10^{18} POT collected**
(3×10^{16} from 50h in dump mode)
**Di-lepton triggers
are downscaled**

❖ NA48/2 (6 months, **2003–04**): **~2×10^{11}** useful **K⁺** decays.

❖ NA62 run **2016** (30 days, **~1.3×10^{12} ppp**): **2×10^{11}** useful **K⁺** decays.

❖ NA62 run **2017** (160 days, **~1.9×10^{12} ppp**): **2×10^{12}** useful **K⁺** decays.

❖ NA62 run **2018** (217 days, **~2.3×10^{12} ppp**): **4×10^{12}** useful **K⁺** decays.

❖ **NA62 Run 2**: started in **July 2021** (**~3×10^{12} ppp**).
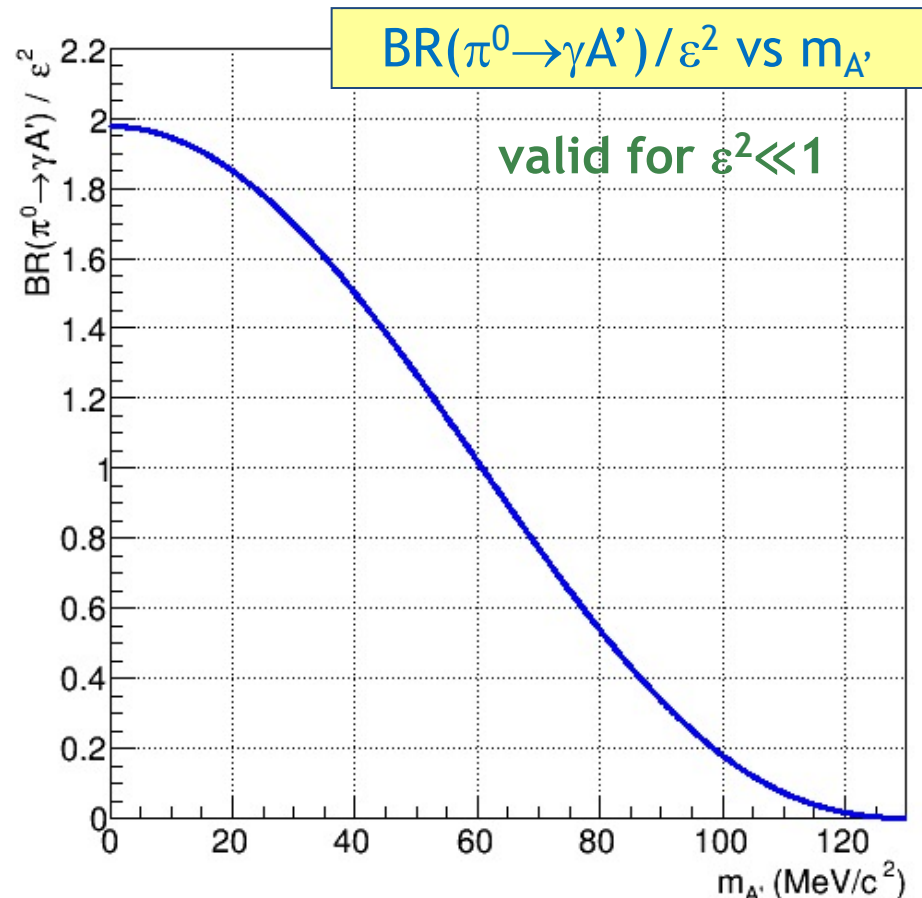
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Dark photon production: $\pi^0 \rightarrow \gamma A'$

Batell, Pospelov and Ritz, PRD80 (2009) 095024

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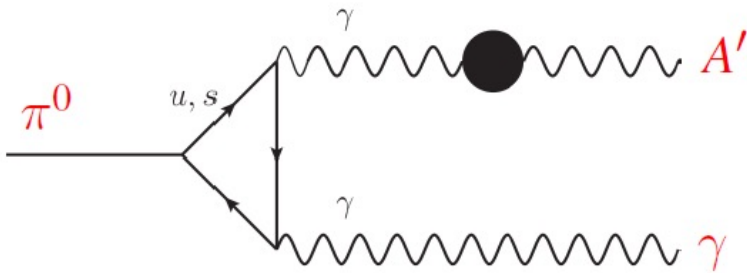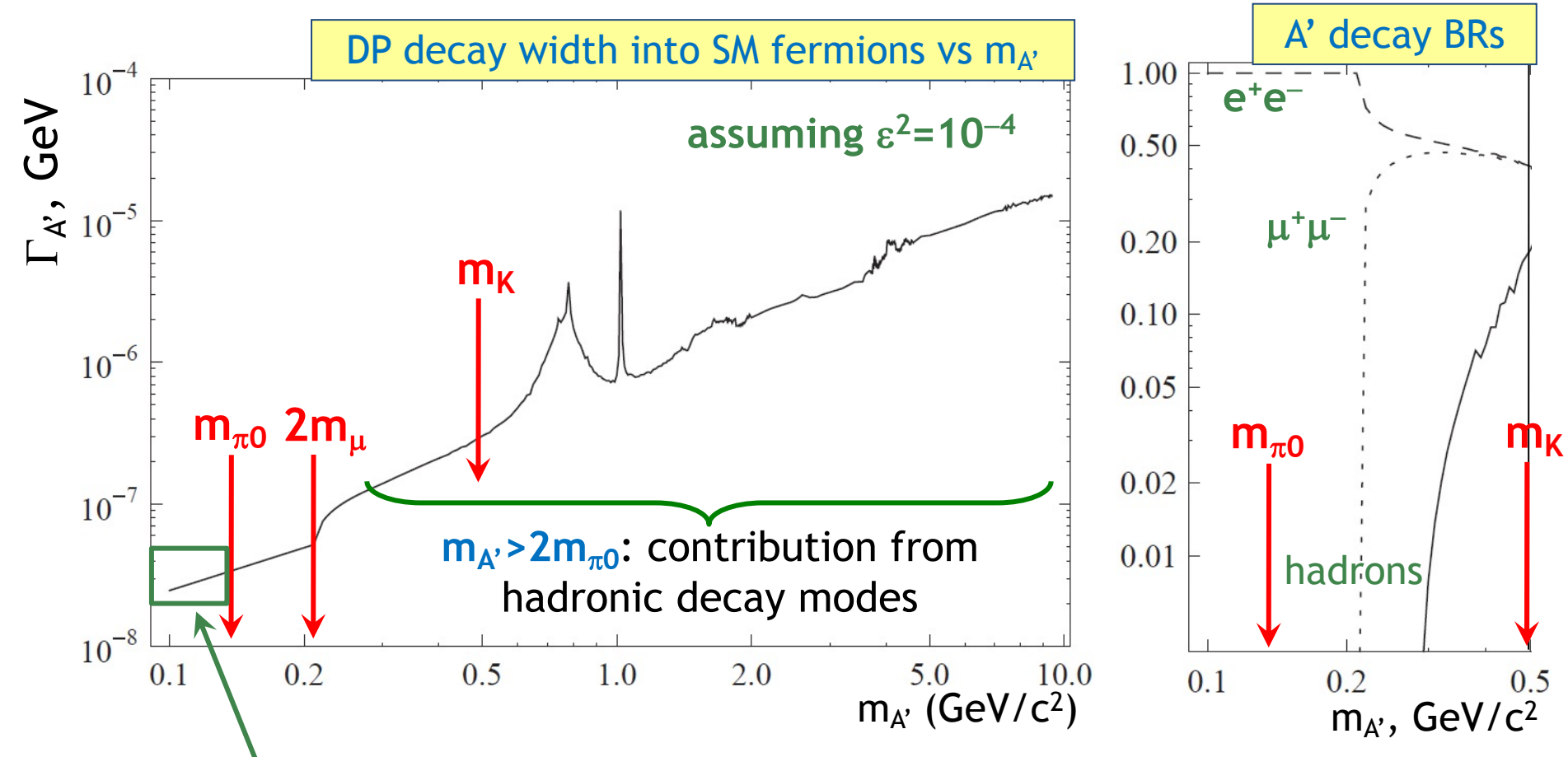

- ❖ Two free parameters:
  mass ($m_{A'}$) and mixing (ε^2).

- ❖ Sensitivity to DP for $m_{A'} < m_{\pi 0}$.

- ❖ Loss of sensitivity to ε^2
  at higher $m_{A'}$ values, due to
  kinematic suppression
  of the $\pi^0 \rightarrow \gamma A'$ decay.

BR($\pi^0 \rightarrow \gamma A'$)/$\varepsilon^2$ vs $m_{A'}$

valid for $\varepsilon^2 \ll 1$

DP decays into SM fermions

Batell, Pospelov and Ritz, PRD79 (2009) 115008

DP decay width into SM fermions vs $m_{A'}$

A' decay BRs

assuming $\varepsilon^2 = 10^{-4}$

m_K

$m_{\pi 0}$ $2m_\mu$

$m_{A'} > 2m_{\pi 0}$: contribution from hadronic decay modes

e^+e^-

$\mu^+\mu^-$

$m_{\pi 0}$

m_K

hadrons

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

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

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DP lifetime and mean path

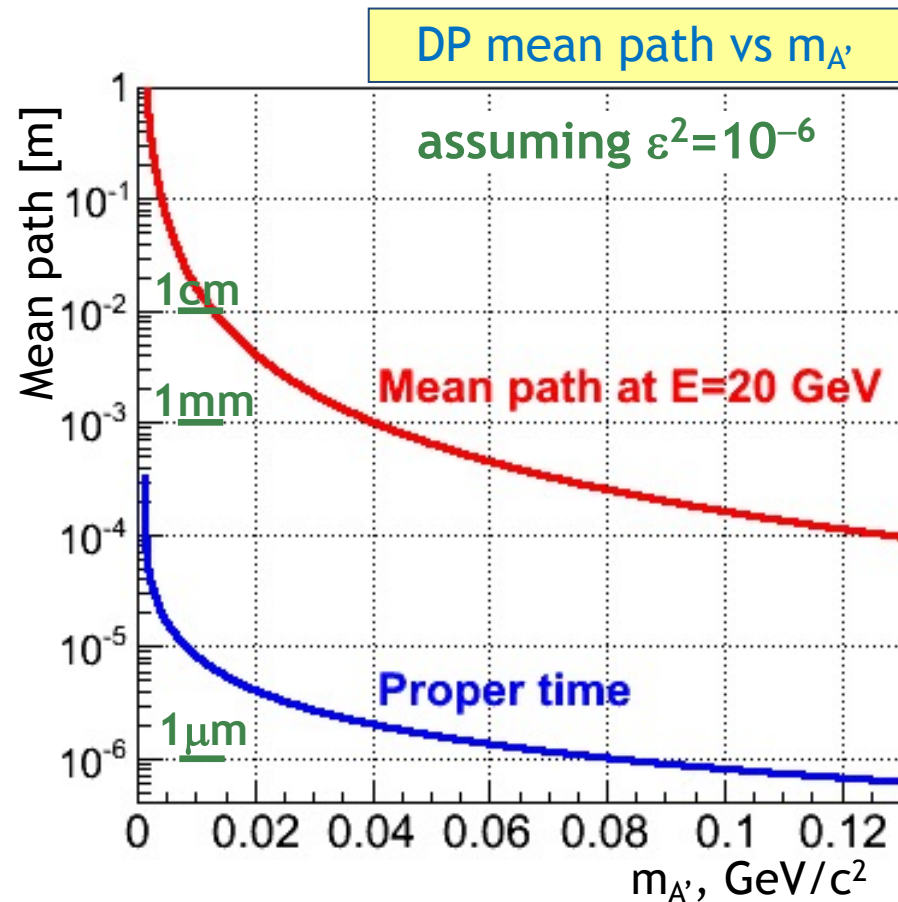Dark photon proper lifetime below the di-muon threshold:

$$c\tau_{A'} \approx 0.8\ \mu\text{m} \times \left(\frac{10^{-6}}{\varepsilon^2}\right) \times \left(\frac{100\ \text{MeV}}{m_{A'}}\right)$$

Mean path at $E_{A'}$=50 GeV
(maximum possible energy at NA48/2):

$$L_{\max} \approx 0.4\ \text{mm} \times \left(\frac{10^{-6}}{\varepsilon^2}\right) \times \left(\frac{100\ \text{MeV}}{m_{A'}}\right)^2$$

❖ For $\varepsilon^2 > 10^{-7}$ and $m_{A'} > 10$ MeV/c², DP path length is negligible with respect to the resolution on the vertex longitudinal coordinate (~1 m).

❖ DP decay can be considered prompt.

❖ DP production and decay signature ($\pi^0 \to \gamma A'$, $A' \to e^+ e^-$) is identical to that of the Dalitz decay, $\pi^0_D \to \gamma e^+ e^-$.

DP mean path vs $m_{A'}$

assuming $\varepsilon^2 = 10^{-6}$

1cm

1mm

Mean path at E=20 GeV

Proper time

1μm

Mean path [m] vs $m_{A'}$, GeV/c²

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NA48/2 data sample

❖ NA48/2 data: **~2×10¹¹ K±** decays in the fiducial decay region.

- ✓ Production and decay in vacuum of **~5×10¹⁰** tagged, boosted π^0 mesons.
- ✓ Mean path of the π^0 is negligible (**few µm**).
- ✓ Sources of π^0 mesons considered:
  K±→π±π⁰ decay (**BR=20.7%**) and **K±→π⁰µ±ν** decay (**BR=3.4%**).

❖ Search for the prompt **π⁰→γA'**, **A'→e⁺e⁻** decay chain.

- ✓ Identical signature to the **K±→π±π⁰_D** and **K±→π⁰_Dµ±ν** decays,
  three-track vertex topology.
- ✓ Sensitivity is limited by irreducible **π⁰_D→γe⁺e⁻** background (**BR=1.2%**).
- ✓ Efficient trigger chain for 3-track vertices based on
  HOD multiplicity (**L1**) and **spectrometer** track reconstruction (**L2**).
- ✓ Search for a narrow peak in **e⁺e⁻** invariant mass spectrum.
- ✓ Good **e⁺e⁻** mass resolution: $\sigma_m \approx 0.011 \times m_{ee}$.

❖ Acceptances for both **K±→π±π⁰** and **K±→π⁰µ±ν** signal chains:
depending on $m_{A'}$, up to **4.5%**.

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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/c²;
- $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/c²;
- 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/c²;
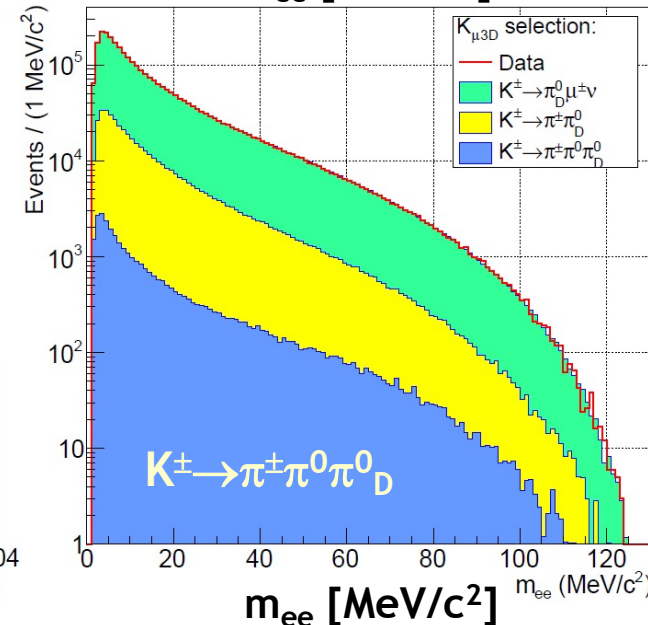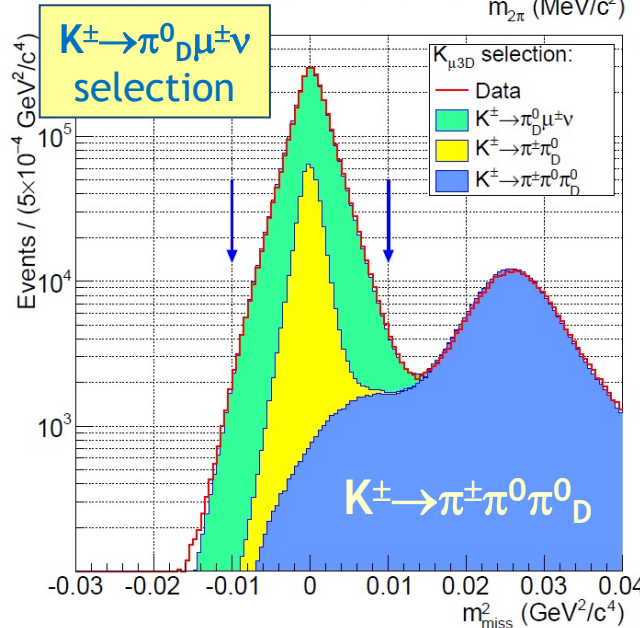- non-zero missing total & transverse momentum.
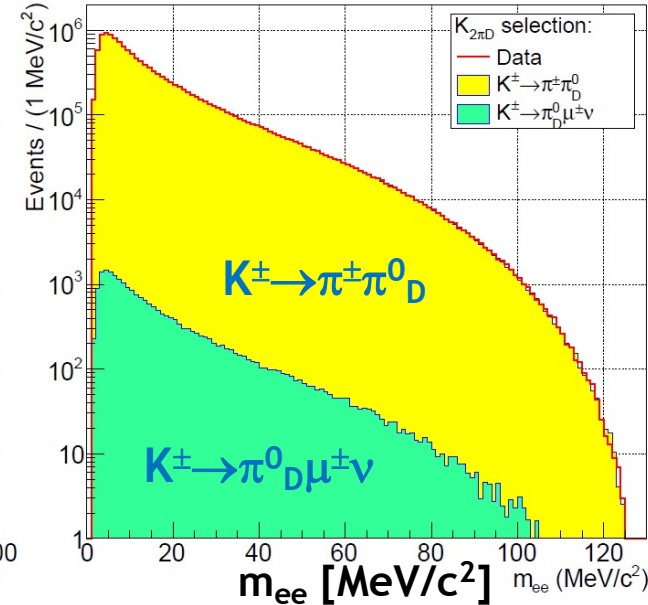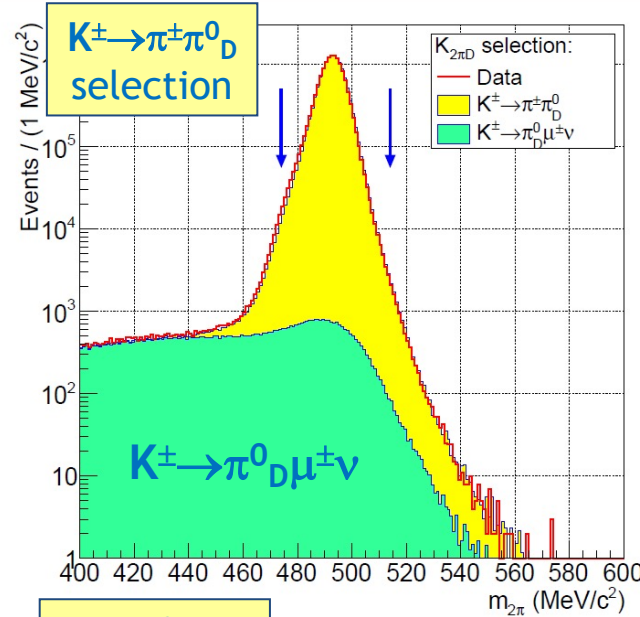
Reconstructed π^0_D decay candidates:

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

$K^\pm$ decays in fiducial region:
$N_K = (1.57 \pm 0.05) \times 10^{11}$.

The π^0_D background

Kinematic variables:

$$x = \frac{(Q_1 + Q_2)^2}{m_{\pi^0}^2} = (m_{ee}/m_{\pi^0})^2, \qquad y = \frac{2P(Q_1 - Q_2)}{m_{\pi^0}^2(1-x)}$$

Differential decay rate (lowest order):

$$\frac{d^2\Gamma}{dxdy} = \Gamma_0 \frac{\alpha}{\pi} |F(x)|^2 \frac{(1-x)^3}{4x} \left(1 + y^2 + \frac{r^2}{x}\right)$$

(r=2m_e/m_π)

Radiative corrections: $\dfrac{d\Gamma}{dxdy} = \delta(x,y)\dfrac{d\Gamma^0}{dxdy}$

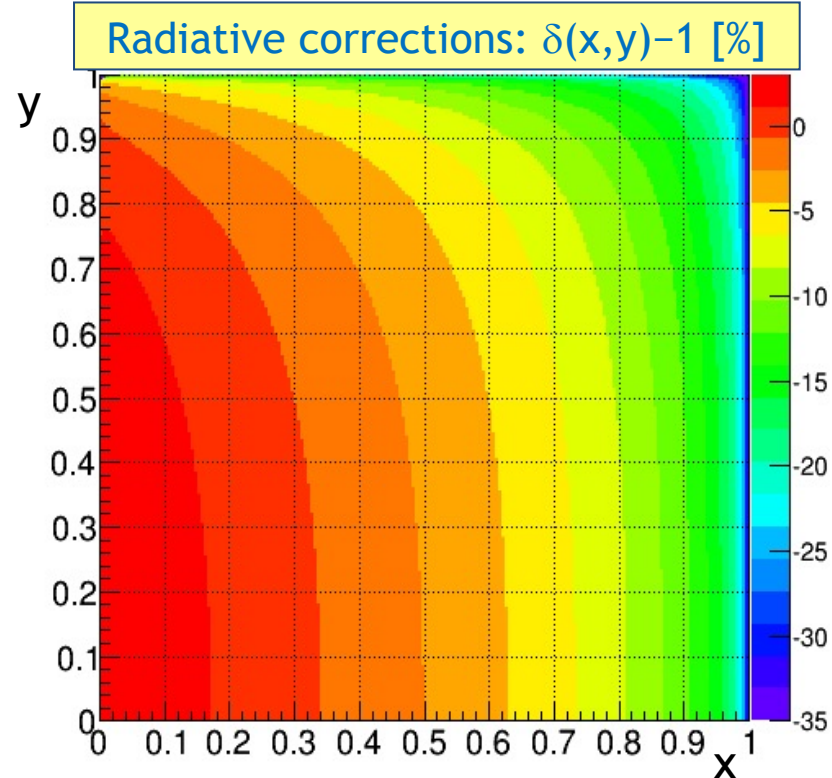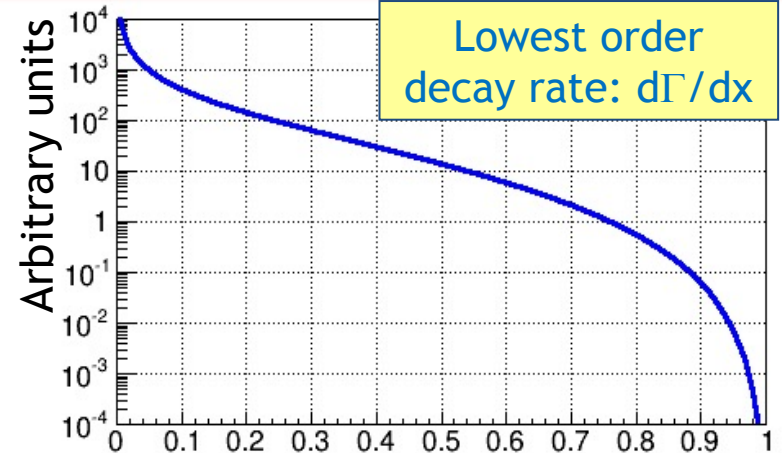❖ Real photon emission is included.
  [Husek et al., PRD 92 (2015) 054027]

❖ Electromagnetic π^0 form factor (FF):
  F(x) = 1+ax

❖ The most precise FF slope measurement in the time-like momentum transfer region:

  a = (3.68±0.57)×10^{-2}

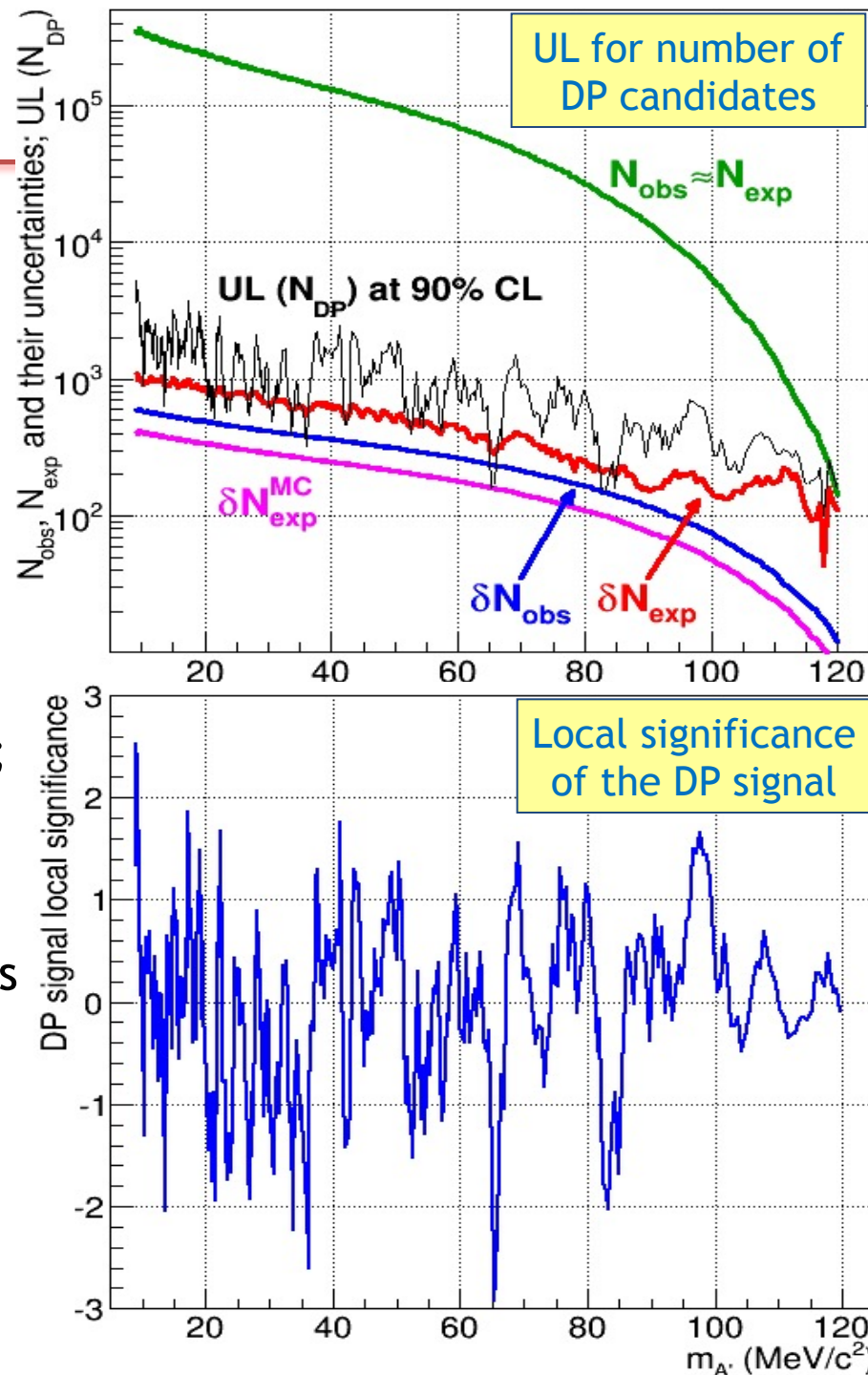*[NA62-RK collab., 2007 data, PLB768 (2017) 38]*

Lowest order decay rate: dΓ/dx

Radiative corrections: δ(x,y)−1 [%]

Search for DP signal
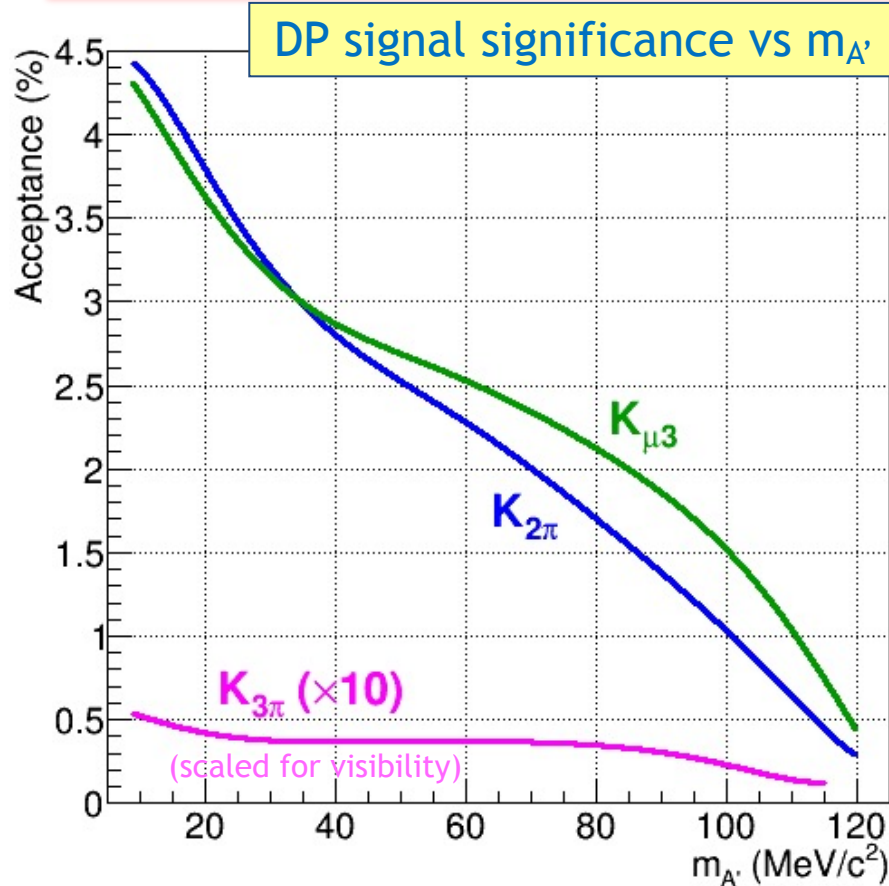
DP signal: a narrow peak in
the m_{ee} spectrum of π^0_D candidates

❖ Dark photon mass scan:

• range: **9 MeV/c² ≤ $m_{A'}$ < 120 MeV/c²**;
• at lower **$m_{A'}$**, background acceptance
simulation has limited precision;
• variable mass step of **0.5σ_m**;
• signal mass window optimised to
maximize expected sensitivity: **±1.5σ_m**;
• mass hypotheses tested: **404**.

❖ For each **$m_{A'}$**, frequentist confidence
intervals for **N_{DP}** obtained from numbers
of observed and expected events
(**N_{obs}**, **N_{exp}**, **dN_{exp}**).

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

UL for number of
DP candidates

Local significance
of the DP signal

Search for DP signal (2)

DP signal significance vs $m_{A'}$

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

BR($A' \to e^+ e^-$)=1 assumed

Acceptance (%)

$K_{\mu 3}$

$K_{2\pi}$

$K_{3\pi}$ (×10)

(scaled for visibility)

$m_{A'}$ (MeV/c^2)

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

×10^{-6}

$m_{A'}$ (MeV/c^2)

Acceptances of the DP selection for $K^\pm \to \pi^\pm \pi^0$, $K^\pm \to \pi^0 \mu^\pm \nu$ and $K^\pm \to \pi^\pm \pi^0 \pi^0$ decays followed by the prompt $\pi^0 \to \gamma A'$, $A' \to e^+ e^-$ decay chain.
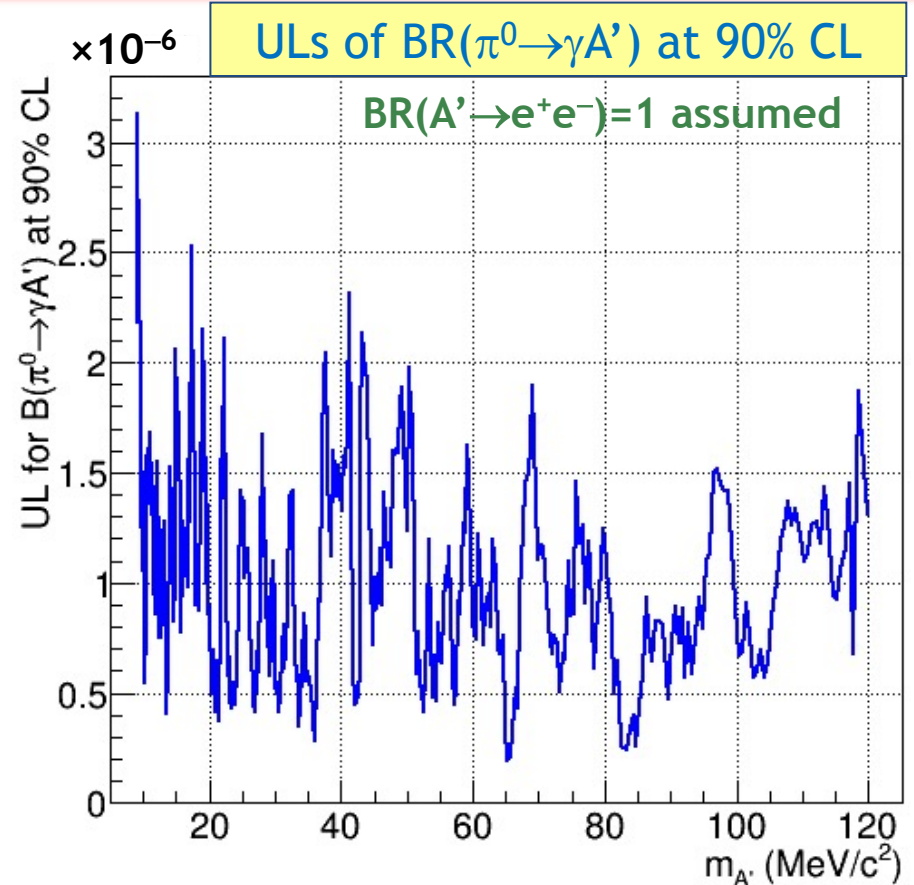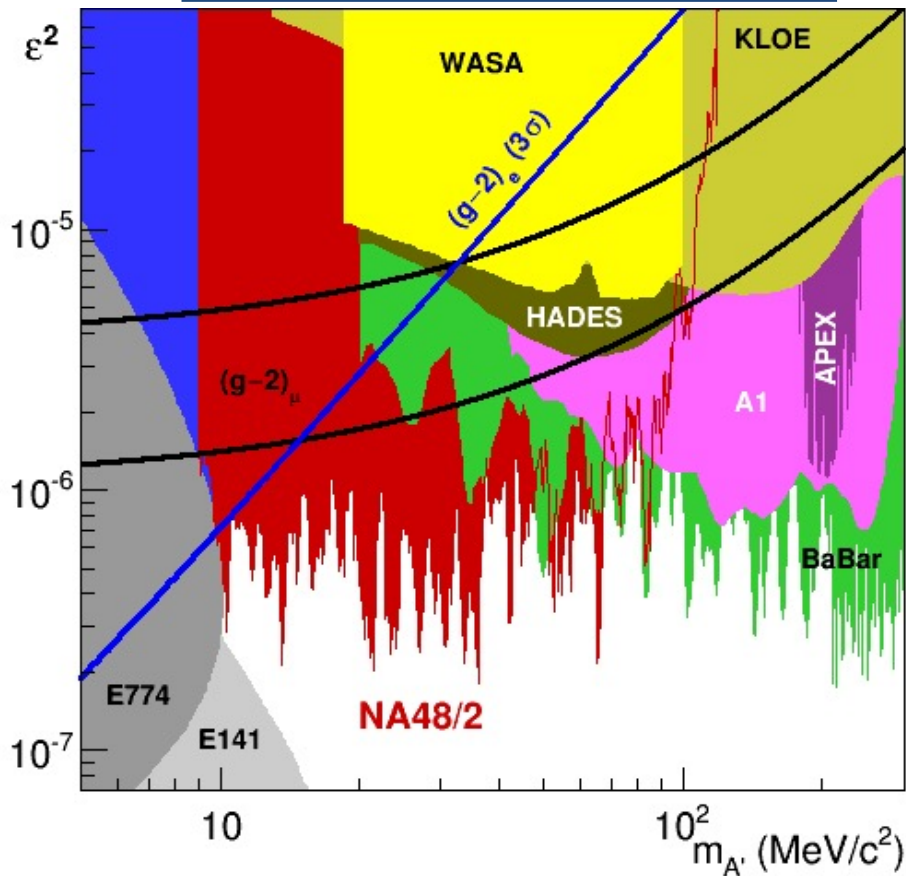
❖ Weak $m_{A'}$ dependence: cancellation of $m_{A'}$ dependences of background fluctuation and acceptance.

❖ The obtained limits are background-limited (2–3 orders of magnitude above single event sensitivity).
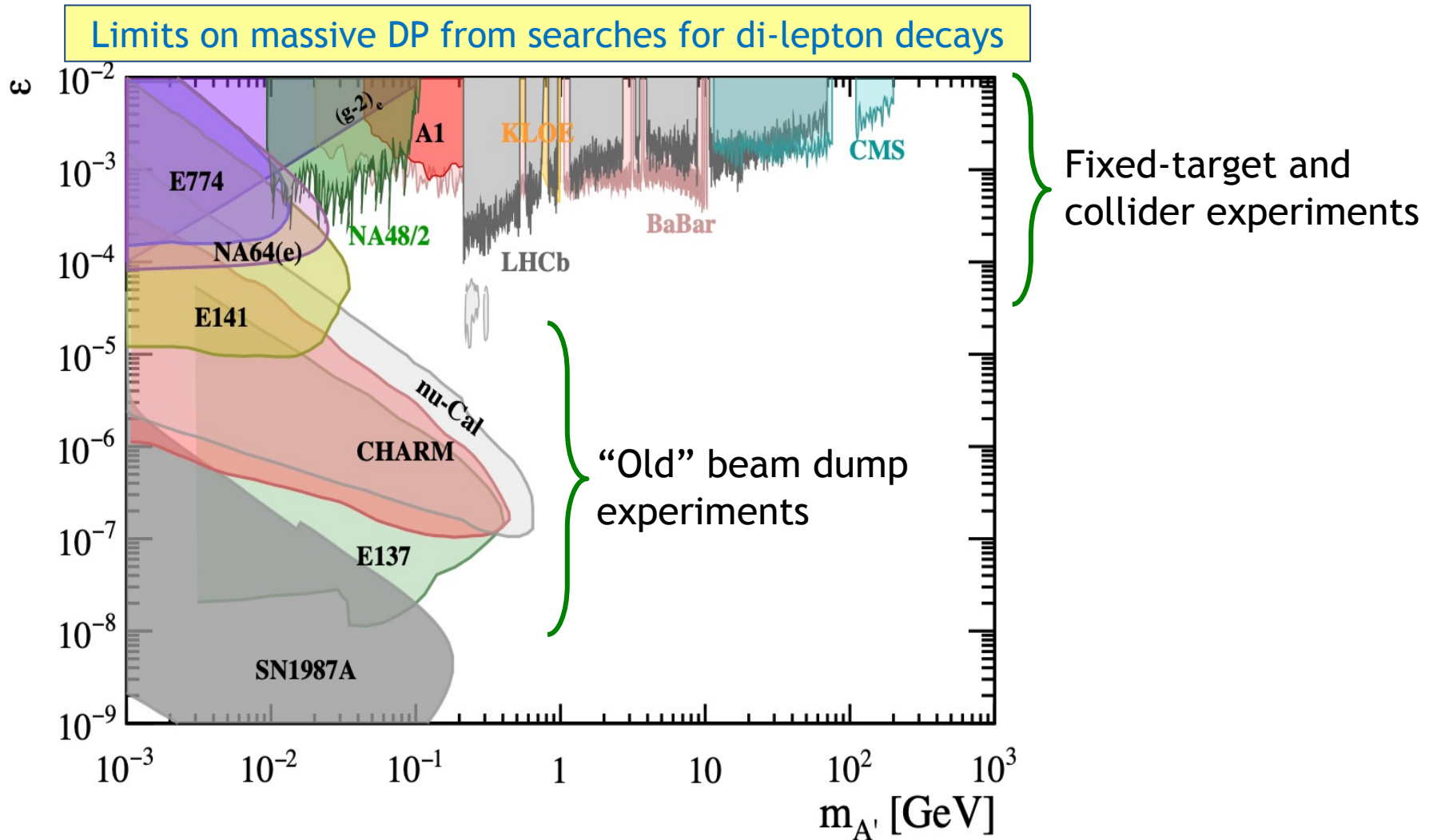
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DP exclusion: the results

DP exclusion summary (from the NA48/2 paper of 2015)

❖ Improvement on the earlier 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 the irreducible π^0_D background, ULs are 2–3 orders of magnitude above SES.

❖ Upper limit of ε^2 scales as $\sim(1/N_K)^{1/2}$: difficult to improveme with larger samples.

❖ If DP couples to quarks and decays mainly to SM fermions, it is ruled out as the explanation for the anomalous $(g{-}2)_\mu$.
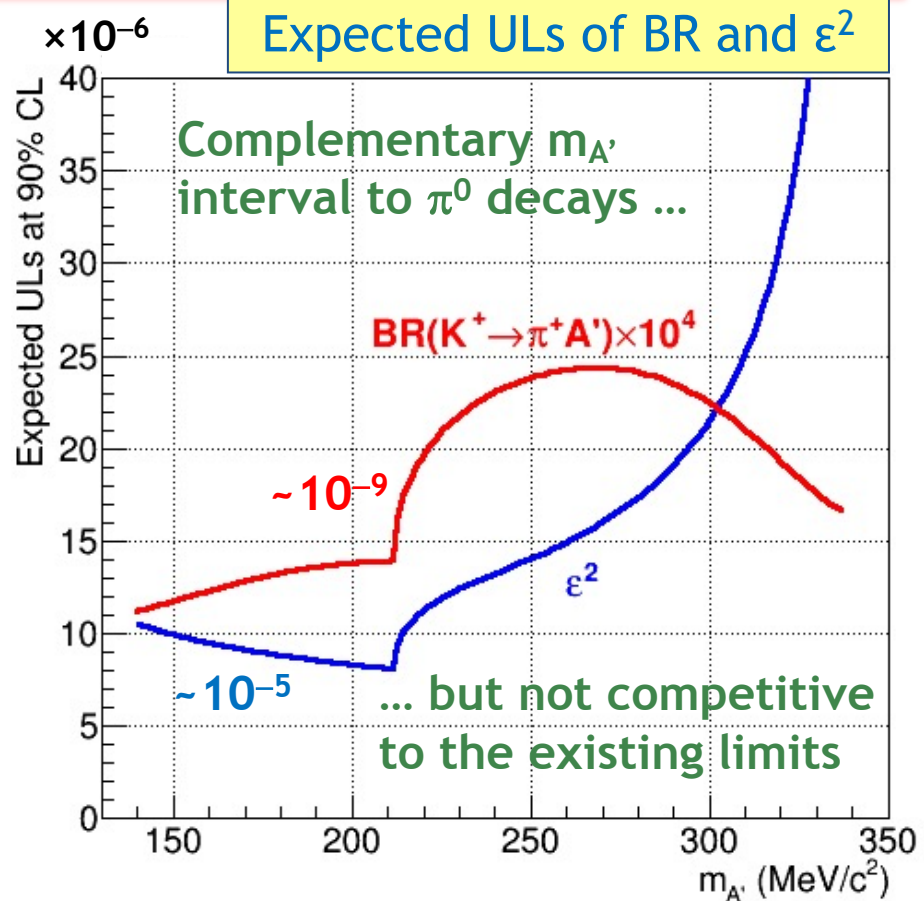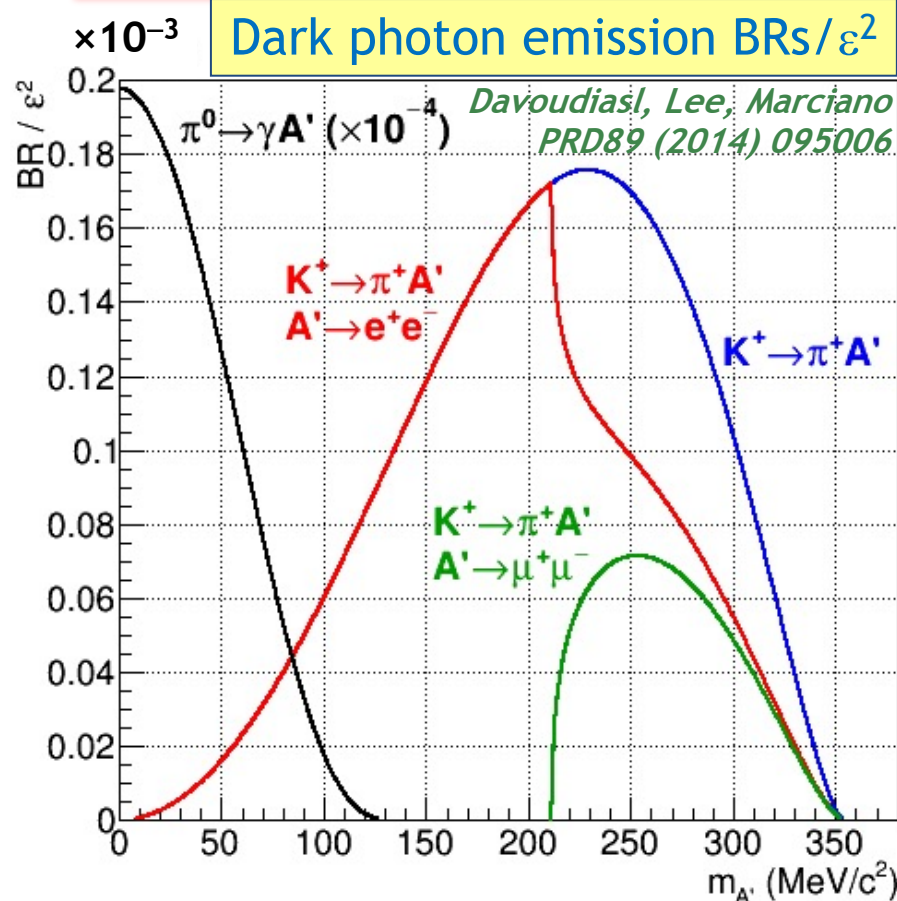
A more recent exclusion plot

Fabbrichesi, Gabriellli, Lanfranchi, arXiv:2005.01515

Limits on massive DP from searches for di-lepton decays

Fixed-target and collider experiments

"Old" beam dump experiments

Prospects for the $K^{\pm} \rightarrow \pi^{\pm} A'$ decay

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

❖ Lower irreducible background: $BR(K^{\pm} \rightarrow \pi^{\pm} e^+ e^-) \sim 10^{-7}$ vs $BR(\pi^0_D) \sim 10^{-2}$.

❖ Higher acceptance (×4), favourable K/π^0 flux ratio (×4).

❖ Therefore the expected BR limits: $BR(K^{\pm} \rightarrow \pi^{\pm} A') \sim 10^{-9}$ vs $BR(\pi^0 \rightarrow \gamma A') \sim 10^{-6}$.

❖ However $BR(K^{\pm} \rightarrow \pi^{\pm} A')/BR(\pi^0 \rightarrow \gamma A') \sim 10^{-4}$, expected ε^2 limits are $\varepsilon^2 \sim 10^{-5}$.

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Summary and outlook

❖ Dark photon search in π^0 decays: *[PLB746 (2015) 178]*

  ✓ Integrated $K^\pm$ flux analysed: 1.7×10^{11} decays in flight.
  ✓ Assumption: DP decays into SM fermions only.
  ✓ Limits obtained on DP mixing are still state-of-the-art.
  ✓ The strongest limits ($\varepsilon^2 \sim 2 \times 10^{-7}$) are at the ~10 MeV/c² mass.
  ✓ A background-limited measurement.
  ✓ Search via $K^\pm \to \pi^\pm A'$ ($m_{\pi 0} < m_{A'} < m_K - m_\pi$) is not competitive.

❖ Can we expect improvements at NA62?

  ✓ Downscaled e^+e^- trigger: Run 1 π^0_D sample is comparable to NA48/2.
  ✓ Improved e^+e^- mass resolution: factor ~2.5 lower background.
  ✓ More forward geometry: lower acceptance at low m_{ee}.
  ✓ Lower ε^2, $\pi^0 \to \gamma A'$ with a displaced $A' \to e^+e^-$ vertex?
    Sensitivity needs to be studied.
  ✓ See also: NA62 results on $K^+ \to \pi^+$ + invisible). *[JHEP 02 (2021) 201]*

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