Search for the dark photon in π^0 decay

Roberto Piandani
INFN Pisa
on behalf of the NA48/2 collaboration

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Outline

- ✔ The NA48/2 beam and detector
- ✔ The search for the dark photon
- ✔ Prospects and conclusions

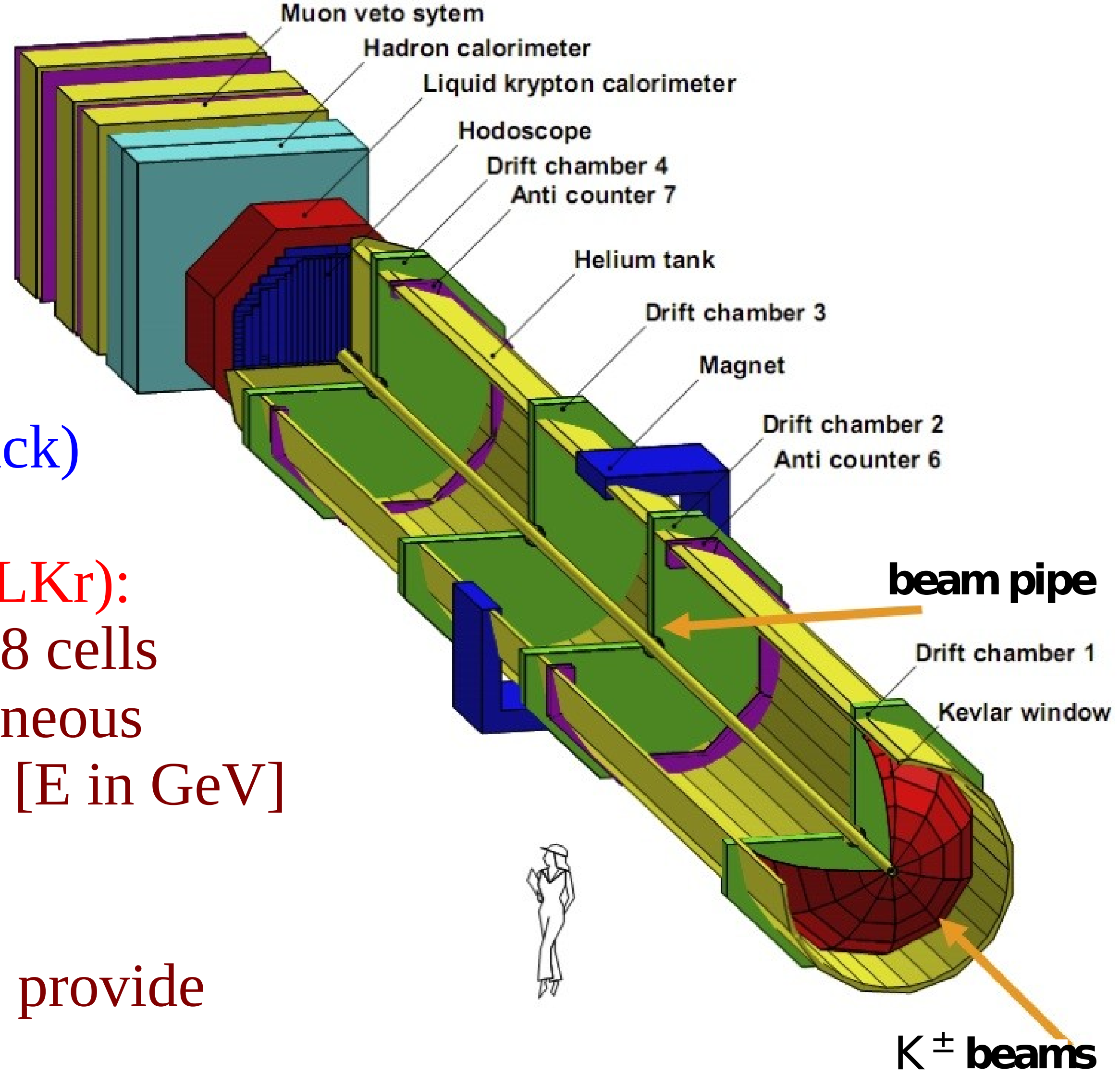
The NA48/2 Detector

Magnetic spectrometer (4 DCHs):
4 views: redundancy ⇒ efficiency
$\sigma(p)/p = 1.0\% + 0.044\%\ p$ [GeV/c]

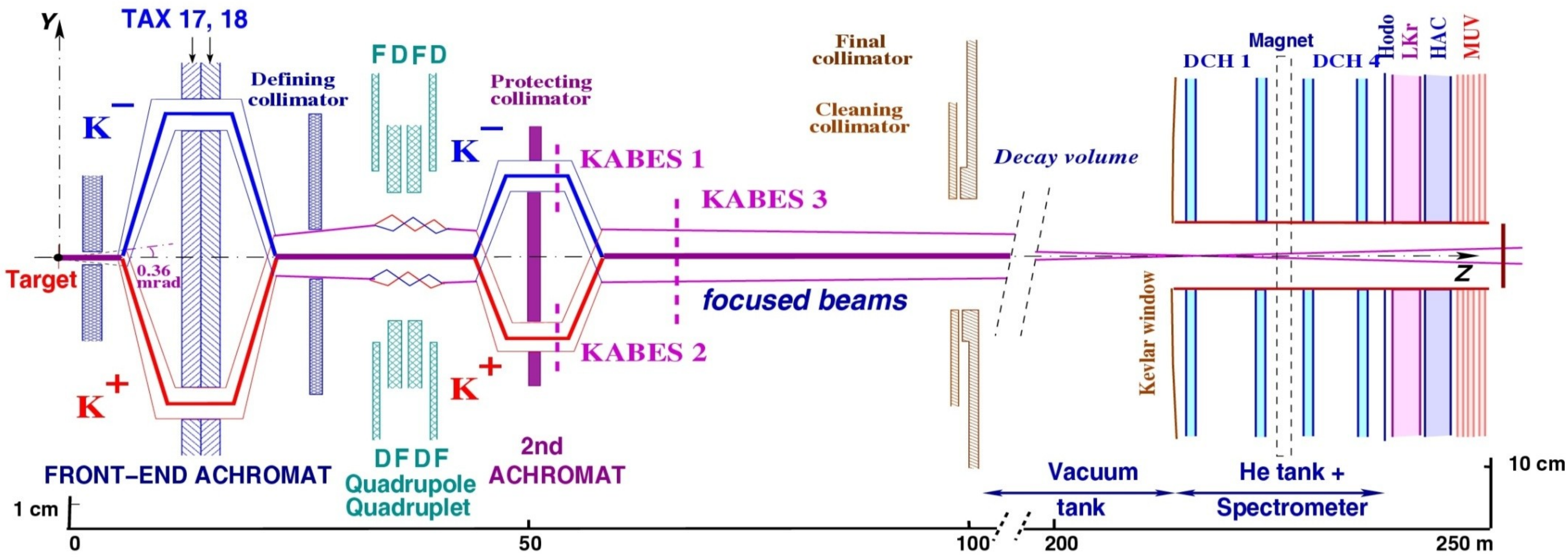
Charged hodoscope (scintillators):
Fast trigger and precise time measurement (~200 ps on single track)

Liquid Krypton E.M. Calorimeter (LKr):
10 m^3 (~22 t), 1.25 m (27 X_0), 13248 cells
granularity: 2x2 cm^2, quasi-homogeneous
$\sigma(E)/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [E in GeV]

Neutral hodoscope
Inside the calorimeter at ~ 9.5 X_0 to provide neutral trigger



The beamline



NA48/2 beam (2003-2004): simultaneous and coaxial K^+/K^-

NA48/2 data taking

- ✔ 4 months in 2003 ($K^{\pm}$)
- ✔ 4 months in 2004 ($K^{\pm}$)

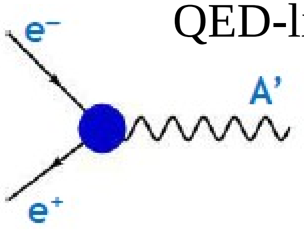
Kaon beam momentum

- ✔ NA48/2 (2003 -2004) (60.0 ± 2.2)GeV/c

The dark photon

B. Holdom, Phys. Lett. B166 (1986) 196

The simplest hidden sector model introduces a new gauge boson A' (the dark photon) associated to an extra U(1) gauge symmetry



QED-like interaction with the SM fermions

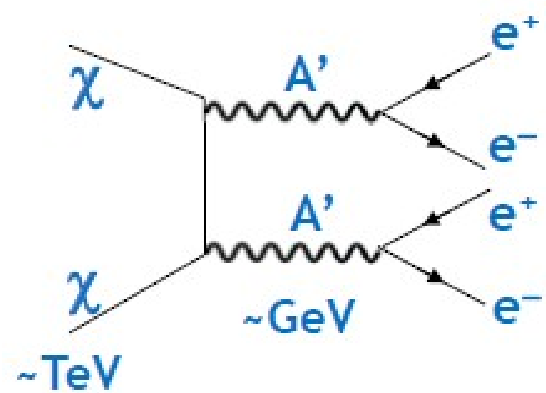
$$L \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

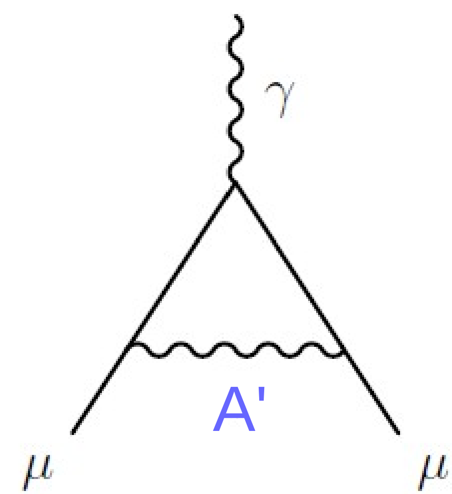
Not all SM fermions need to be charged under this new symmetry

Coupling constant and charges can be generated through kinetic mixing between the QED and the new A' gauge boson

The introduction of this new U(1) gauge boson can explain:

- ✔ Positron (but not antiproton) excess in cosmic rays (PAMELA, FERMI, AMS-02) by dark matter annihilation
- ✔ Muon g-2 anomaly

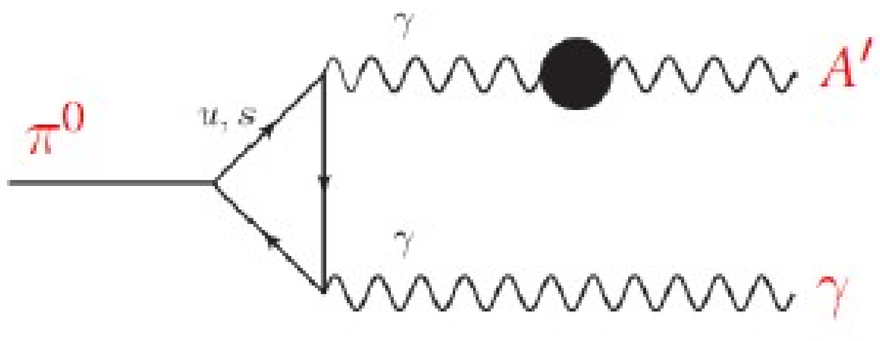




The DP production in π^0 decay

Batell,Pospelov and Ritz, PRD80 (2009)095024

$$Br(\pi^0 \to \gamma A') = 2\epsilon^2 (1 - \frac{m_{A'}^2}{m_{\pi^0}^2})^3 \times Br(\pi^0 \to \gamma\gamma)$$



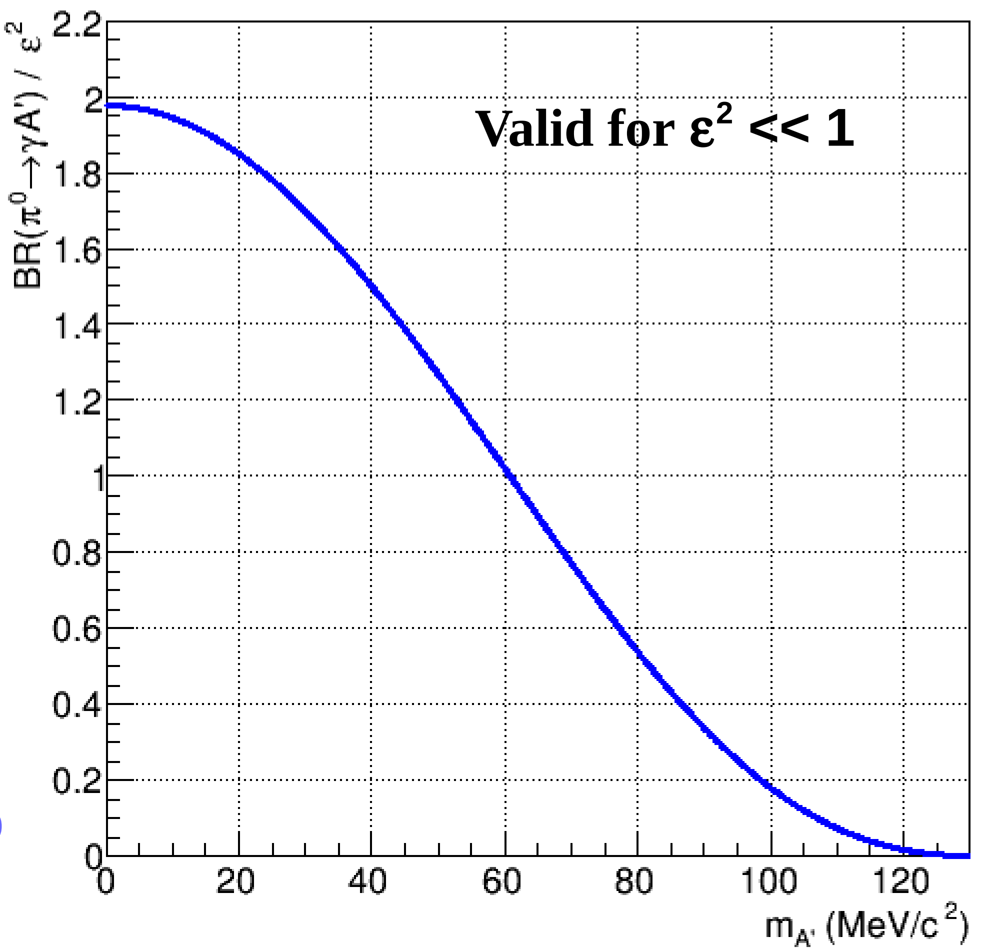
Two unknown parameters:

✗ mass ($m_{A'}$)

✗ mixing (ε^2)

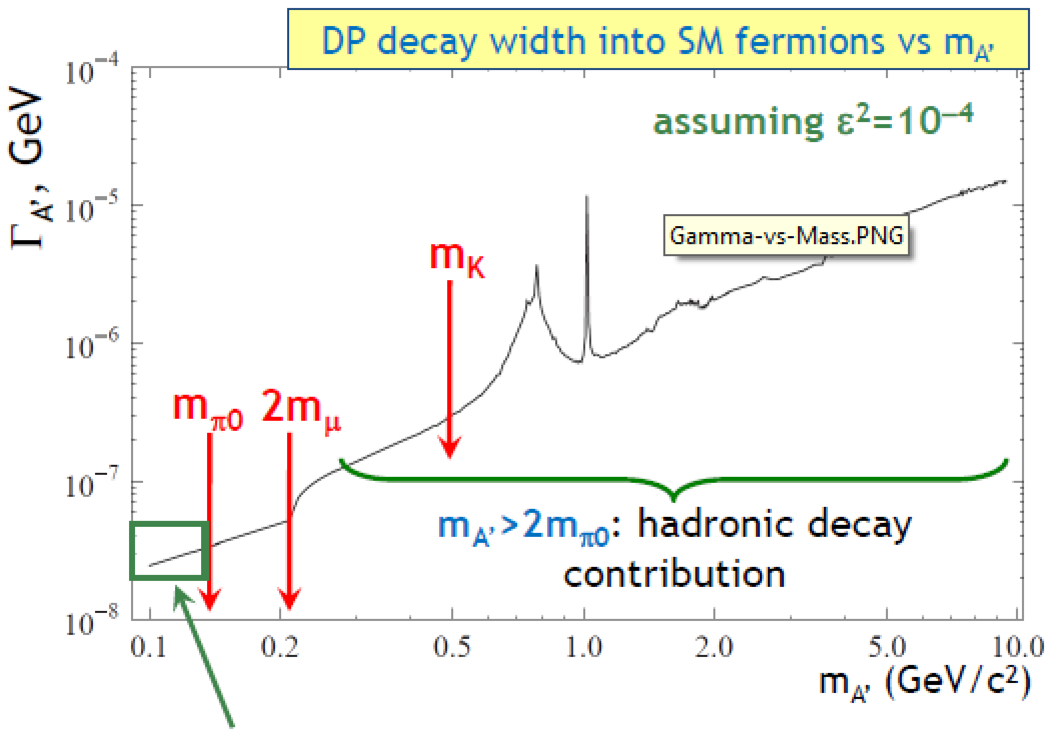
Sensitivity for $m_{A'} < m_{\pi 0}$

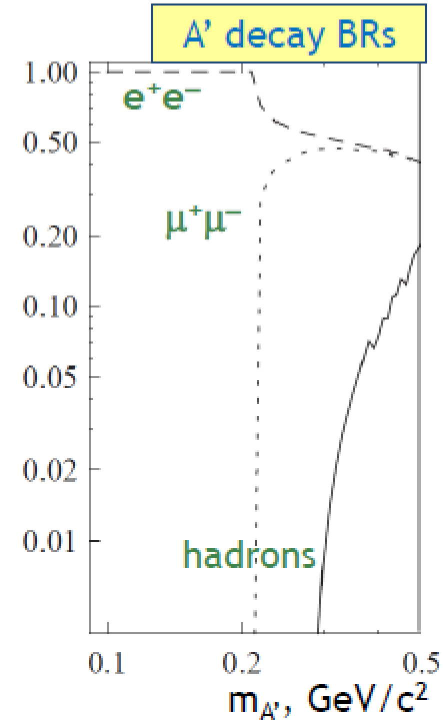
Low sensitivity to ε^2 near π^0 mass, due to kinematical suppression of the $\pi^0 \to \gamma A'$ decay



The DP decay

Batell,Pospelov and Ritz, PRD79 (2009)115008





Accessible in π^0 decay (only in fermions)

$$\Gamma_{A'} \approx \Gamma(A' \rightarrow e^+e^-) \approx \frac{\alpha\epsilon^2 m_{A'}}{3}$$

Assumptions:

1) No particles lighter the A' exist in the dark sector
2) A' decay only in fermisons ($m_{A'} < m_{\pi 0}$)

$$c\tau_{A'} = \frac{h}{2\pi\Gamma_{A'}} \approx 0.8\mu m(\frac{10^{-6}}{\epsilon^2})(\frac{100MeV/c^2}{m_{A'}})$$

→ negligible path length: prompt decay of DP at the production point ($\varepsilon^2 > 10^{-7}$)

NA48/2 Data Sample

NA48/2 data: ~2×10^{11} $K^{\pm}$ decays in the fiducial decay region (2003-2004).

- ✔ Production and decay in vacuum of ~5×10^{10} tagged boosted π^0 mesons (few μm of mean free path)..
- ✔ Sources of π^0 mesons considered:
  $K^{\pm}\rightarrow \pi^{\pm}\pi^0$decay (BR=20.7%) and $K^{\pm}\rightarrow\pi^0\mu^{\pm}\nu$ decay (BR=3.4%).

Search for the prompt $\pi^0\rightarrow\gamma A'$, $A'\rightarrow e^+e^-$ decay chain.

- ✔ Identical signature to $K^{\pm}\rightarrow\pi^{\pm}\pi^0_D$ and $K^{\pm}\rightarrow\mu^{\pm}\pi^0_D\nu$ decays, three-track vertex topology.
- ✔ Sensitivity determined by irreducible $\pi^0\rightarrow e^+e^-\gamma$ background (BR=1.2%).
- ✔ Efficient trigger chain for 3-track vertices throughout the data taking based on CHOD multiplicity (L1) and DCH track reconstruction (L2).
- ✔ Search for a narrow peak in e^+e^- invariant mass spectrum.
- ✔ Excellent e^+e^- mass resolution: $\sigma_m \sim 0.011\times m_{ee}$.
- ✔ Acceptance for both signal chains: depending on $m_{A'}$, up to 4.5%.

The π^0 Dalitz Sample

Data selection optimized for $K_{2\pi D}$ and $K_{\mu 3D}$:

$K_{2\pi D}$: $m_{\pi^\pm \gamma e^+ e^-}$ compatible with $m_{K^\pm}$
no missing momentum
$m_{\gamma e^+ e^-}$ compatible with π^0

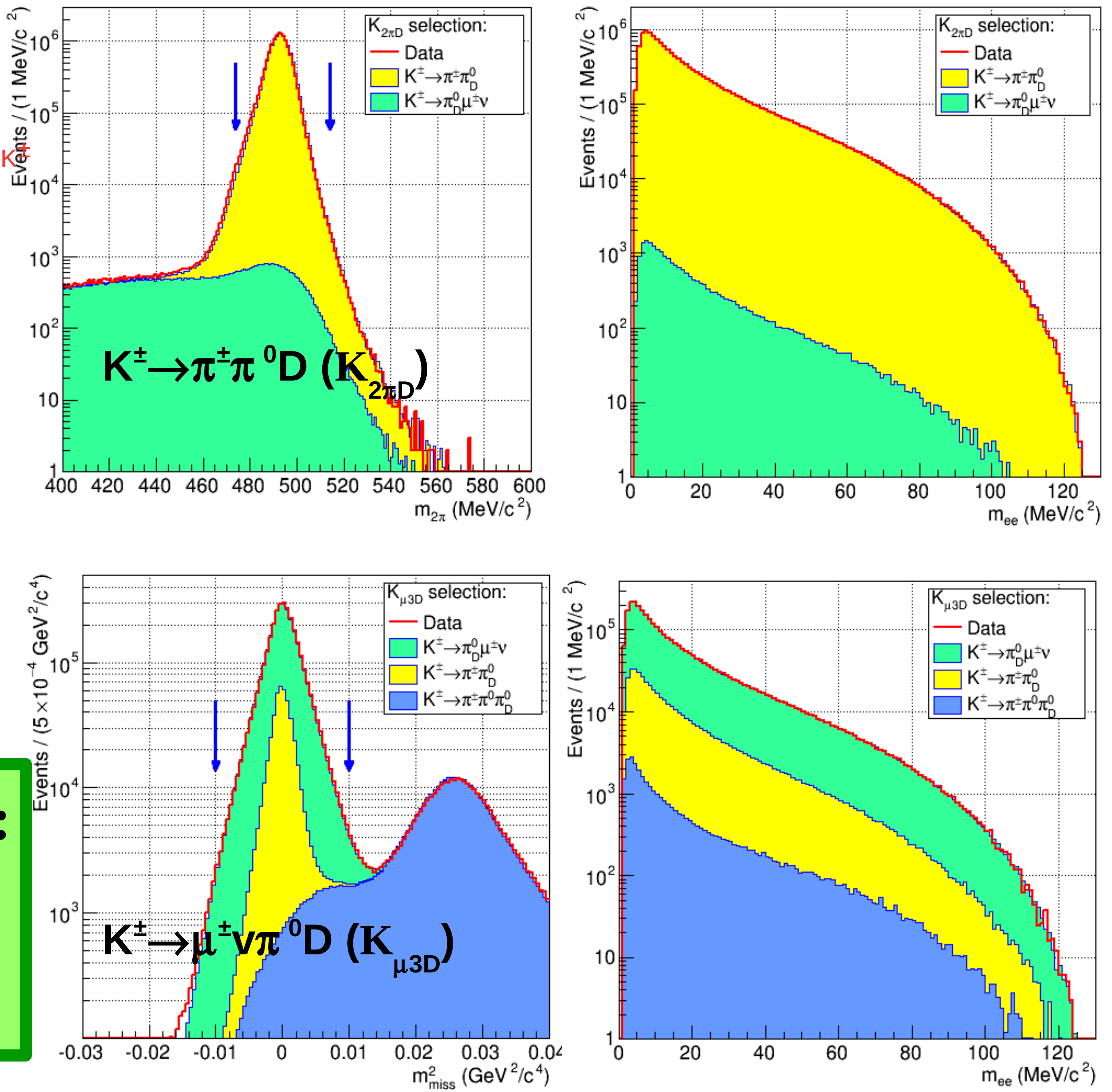
$K_{\mu 3D}$: $m_{2miss} = (P_K - P_\mu - P_{\pi^0})2$ compatible with $m_{K^\pm}$
missing total e transverse momentum
$m_{\gamma e^+ e^-}$ compatible with π^0

$(1.57 \pm 0.05) \cdot 10^{11}$ kaons in the decay fiducial volume

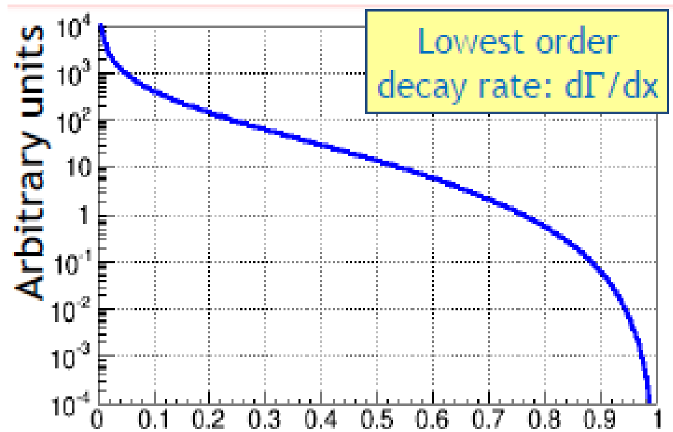
$\pi^0 D$ decay candidates:

$N(K_{2\pi D}) = 1.38 \cdot 10^7$

$N(K_{\mu 3D}) = 0.31 \cdot 10^7$



π^0 Dalitz simulation

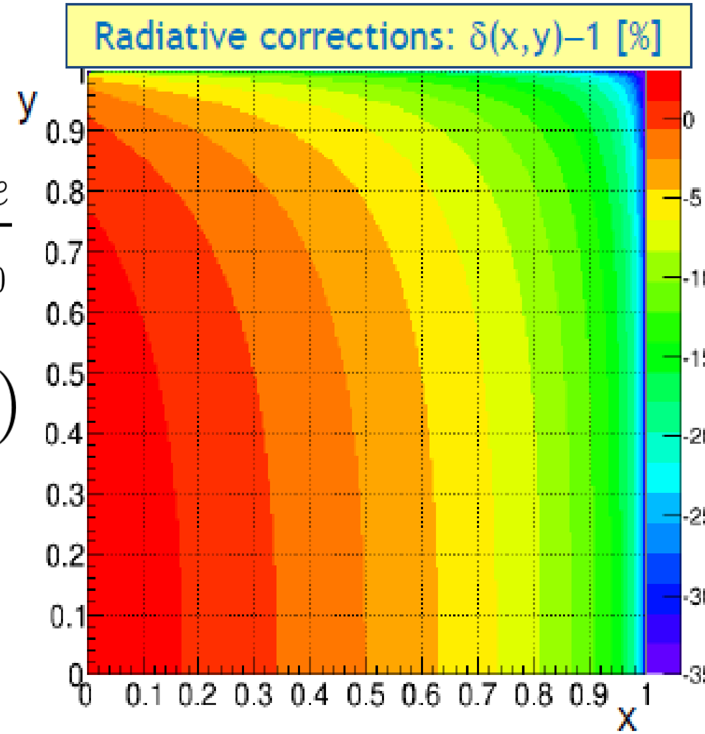


Kinematic variables:

$$x = \frac{(Q1+Q2)^2}{m_{\pi^0}^2} = \frac{m_{ee}^2}{m_{\pi^0}^2}, y = \frac{2P(Q1-Q2)}{m_{\pi^0}^2 \times (1-x)}$$

Lowest order differential decay rate:

$$\frac{\delta^2\Gamma(\pi_D^0)}{\delta x \delta y} = \Gamma(\pi^0 \to \gamma\gamma)\frac{\alpha}{\pi}|F(x)^2|\frac{(1-x)^3}{4x}(1+y^2\frac{r_e^2}{x}), r_e = \frac{2m_e}{m_{\pi^0}}$$



Radiative corrections: $$\frac{\delta^2\Gamma(\pi_D^0)}{\delta x \delta y} = \Gamma^0\delta(x,y)$$

Limited by no emission of real photons

Mikaelian and Smith, PRD5 (1972) 1763 Husek, Kampf and Novotný, arXiv:1504.06178

π^0 transition form factor: F(x)=1+ax

Theory expectation for the slope (a=0.0307 ±0.0006) or the PDG average cannot be used due to limited precision on the radiative corrections to π^0D

Instead use a value obtained by the data itself, fitting the m_{ee} spectrum. Satisfactory for m_{ee}>8MeV/c

Search for the DP signal (1)

DP mass scan performed

- ✔ Between 9 and 120 MeV/c2
- ✔ At low $m_{A'}$, bckg acceptance has limited precision
- ✔ Variable DP mass step: ~0.5 σ_m
- ✔ Optimize window to maximize sensitivity: ± 1.5 σ_m
- ✔ 404 mass hypotheses tested

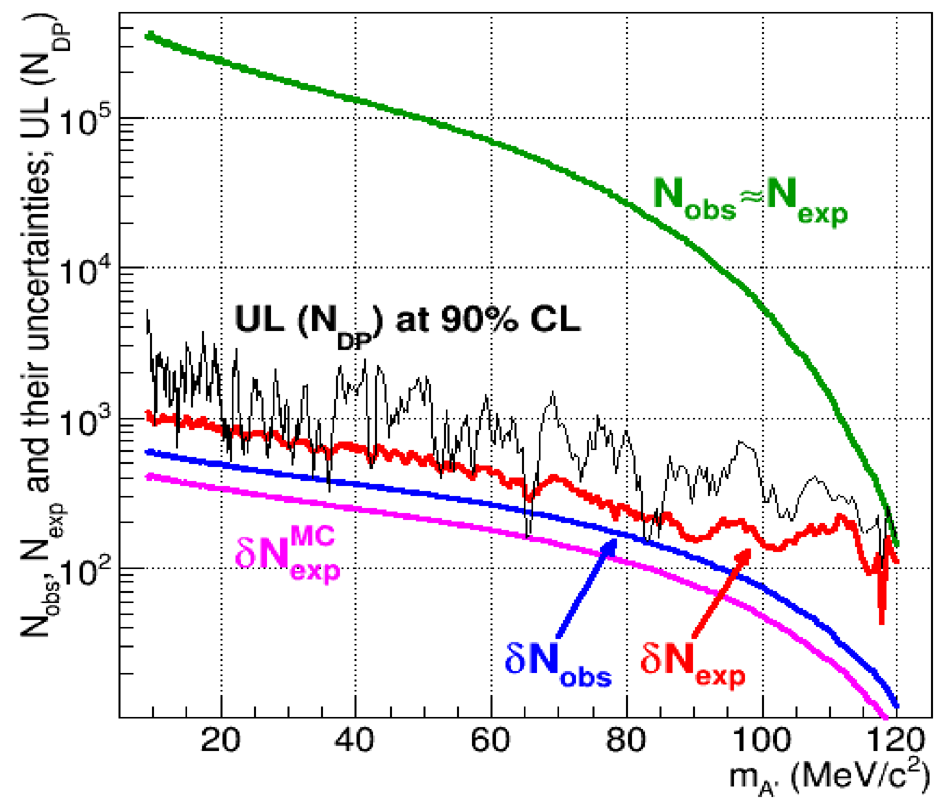
For each $m_{A'}$, frequentist confidence intervals for NDP obtained from the numbers of observed and expected events and their uncertainties

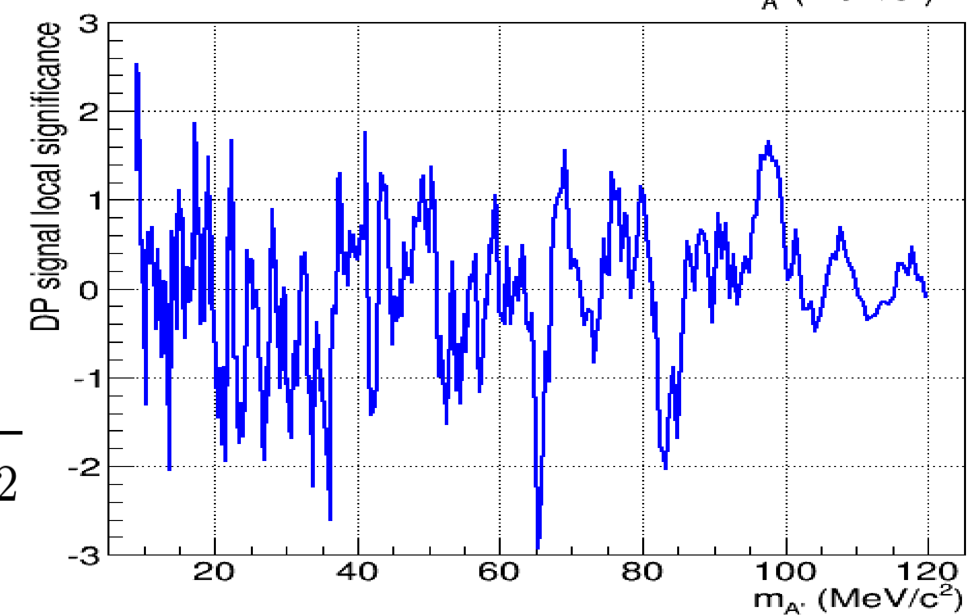
- ✔ Use Rolke-Lopez method

Local signal significance never exceeds 3σ: no DP signal observed

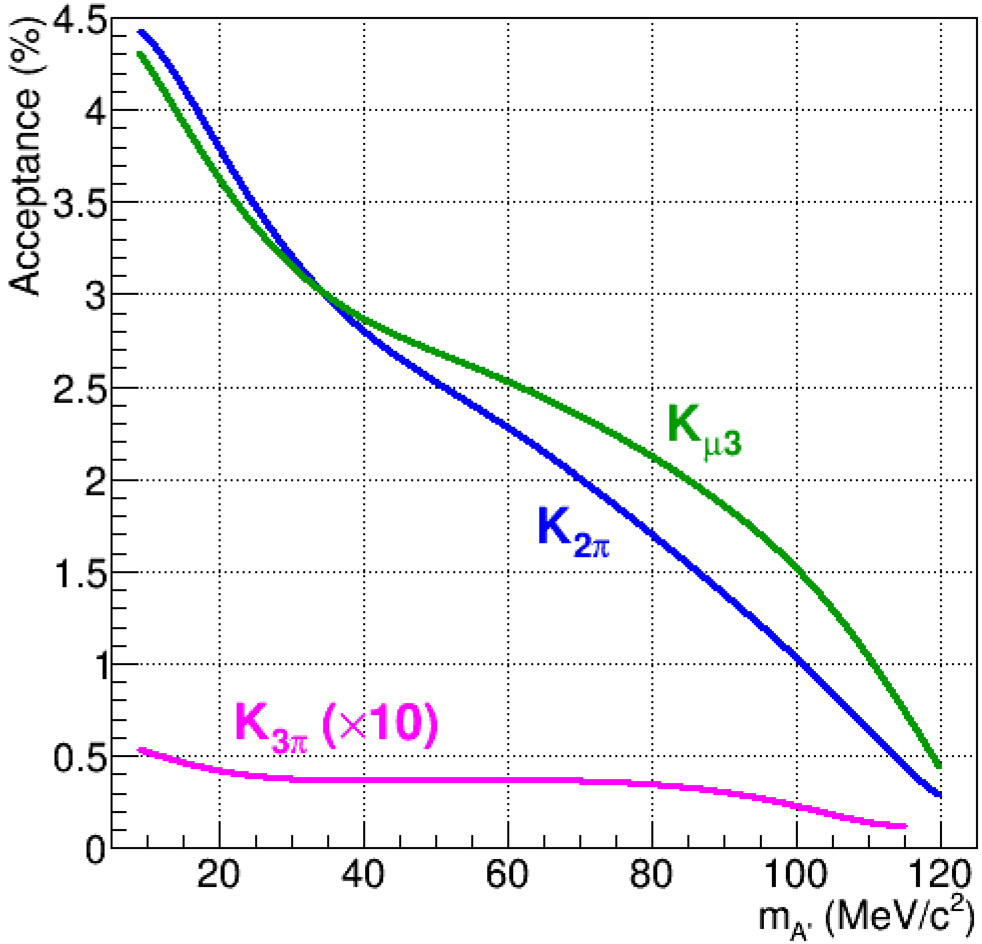
- ✔ Local significance estimated as

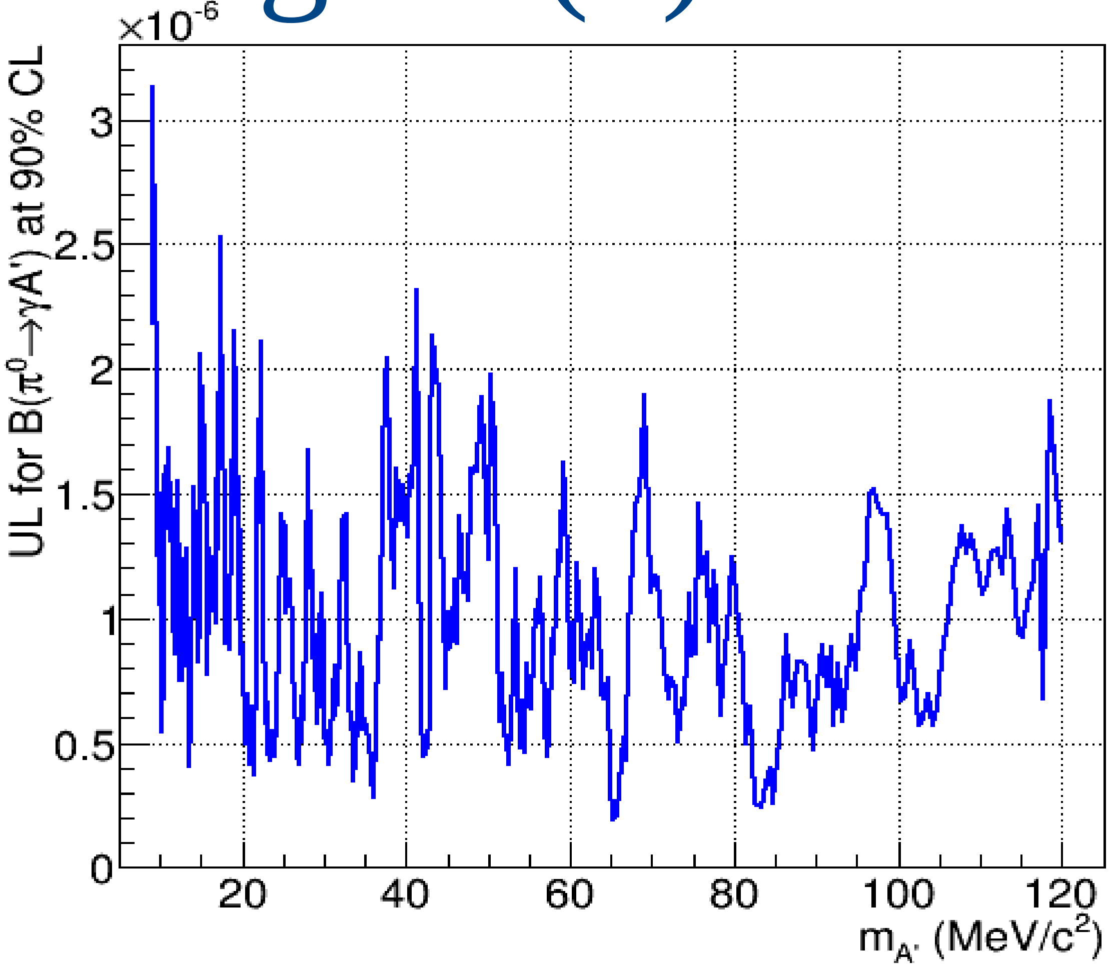
$$Z = (N_{obs} - N_{exp})/\sqrt{(\delta N_{obs})^2 + (\delta N_{exp})^2}$$





Search for the DP signal (2)





Acceptances of DP selection for $K_{2\pi}$, $K_{\mu 3}$ and $K_{3\pi}$ events followed by $\pi^0 \to \gamma A'$, $A' \to e+e-$

- MC simulation
- $K_{3\pi}$ acceptance scaled x10 for visibility

Upper limits at 90% C.L. on BR($\pi^0 \to \gamma A'$) for each DP mass value: O(10^{-6})

- assume BR($A' \to e+e-$) ≈ 1 and A' decays into fermions only ($m_{A'} < 2m_\mu$)
- no strong dependence on DP mass

DP exclusion limits: final NA48/2

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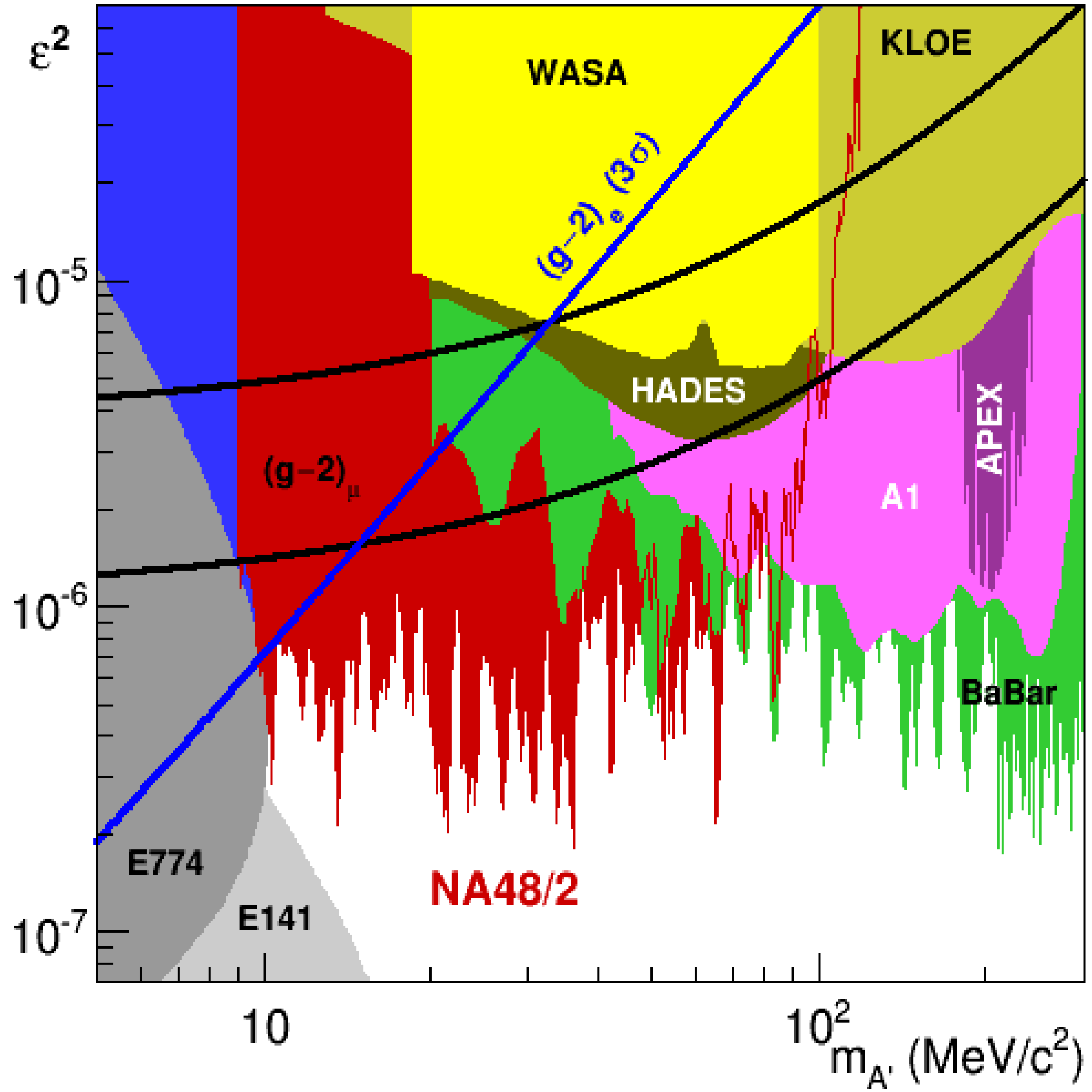
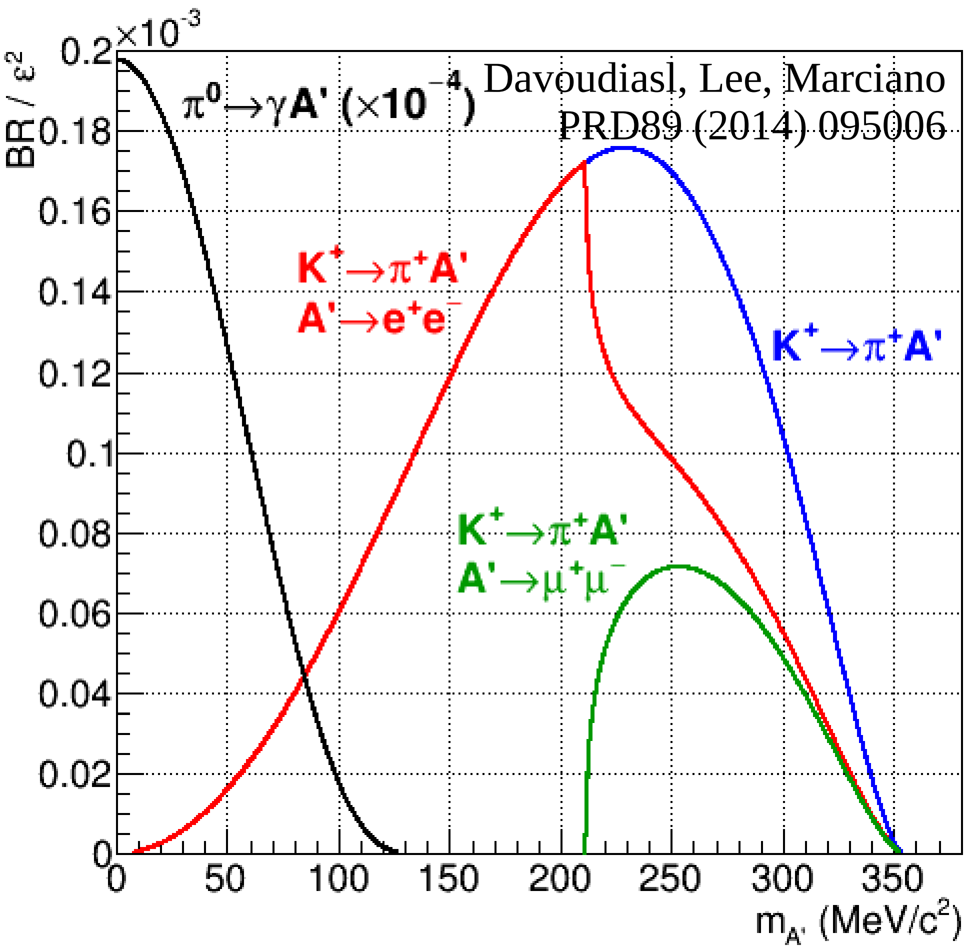
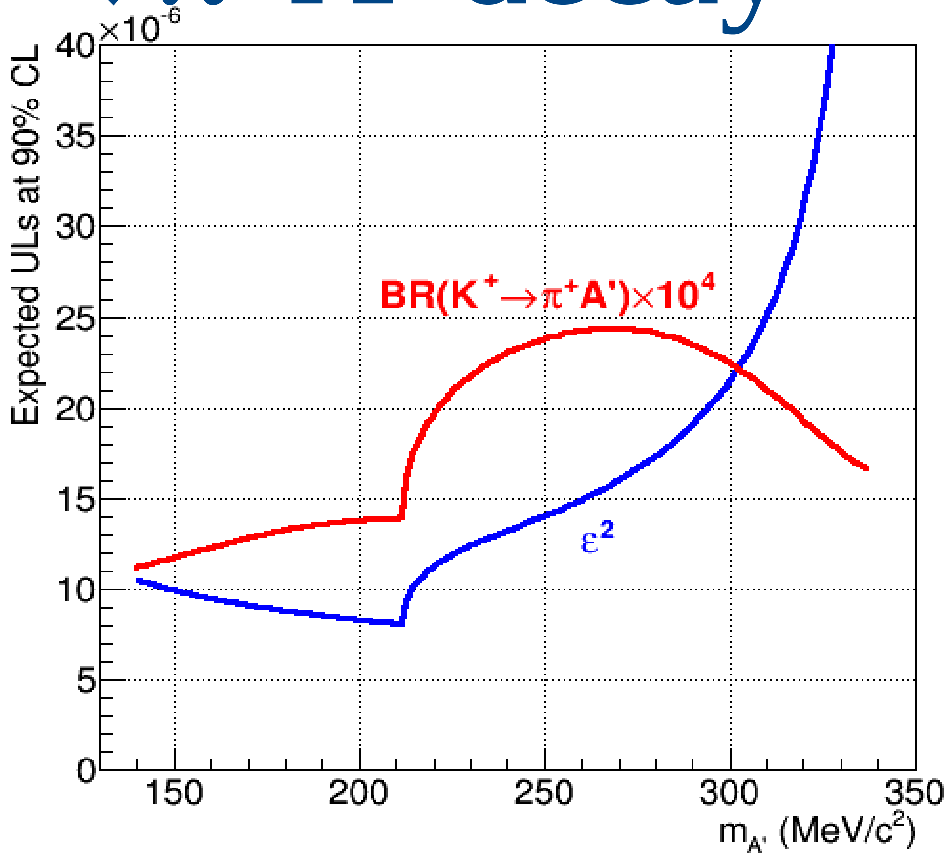


- ✔ Improvements on the existing limits for $9 < m_{A'} < 70$ MeV/c^2
- ✔ Most stringent limits at low $m_{A'}$
  - Weak kinematic suppression
- ✔ Sensitivity limited by the irreducible π^0D background.
- ✔ Upper limit on ε^2 scales as $\sim(1/N_K)^{1/2}$
  - Modest improvements with larger samples
- ✔ If DP couples to quarks and decays mainly to SM fermions, it is ruled out as the explanation for the anomalous $(g-2)_\mu$

Prospect for the $K^{\pm} \to \pi^{\pm} A'$ decay





Complementary $m_{A'}$ interval to π^0 decay....
but not competitve to exiting limits

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: $BR(K^{\pm} \to \pi^{\pm} e+e-) \sim 10^{-7}$ vs $BR(\pi^0 D) \sim 10^{-2}$.
- Higher acceptance (×4), favourable K/π^0 flux ratio (×4).
- Therefore the expected BR limits: $BR(K^{\pm} \to \pi^{\pm} A') \sim 10^{-9}$ vs $BR(\pi^0 \to \gamma A') \sim 10^{-6}$.
- However $BR(K^{\pm} \to \pi^{\pm} A')/BR(\pi^0 \to \gamma A') \sim 10^{-4}$ giving expected ε^2 limits $\sim 10^{-5}$.

Conclusions

A new result on dark photon search in π^0 decays has been published by the NA48/2 collaboration Phys.Lett. B746 (2015) 178:

- $1.57 \cdot 10^{11}$ kaon decays in flight analyzed
- Assumption: DP decays into SM fermions only.
- Improved limits on DP mixing e^2 in the 9-70 MeV/c^2 mass range.
- The strongest limits has been found at ~10 MeV/c^2 mass ($\varepsilon^2 \sim 2 \cdot 10^{-7}$).
- The whole region favoured by $(g-2)_\mu$ is excluded.
- Background-limited measurement: hard to improve below $\varepsilon^2 = 2 \cdot 10^{-7}$.
- Search via $K^\pm \to \pi^\pm A'$ ($m_{\pi^0} < m_{A'} < m_K - m_\pi$) is not competitive.

Possible future directions:

- Larger π^0 samples giving a better resolution at NA62
- Study of invisible A' decays at NA62 ($K^+ \to \pi^+$ + nothing)
- Probing lower ε^2: sensitivity studies for $\pi^0 \to \gamma A'$ with a displaced $A' \to e^+e^-$ vertex