

# Search for the dark photon in $\pi^0$ decay

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on behalf of the NA48/2 collaboration

# 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  $\Rightarrow$  efficiency

$$\sigma(p)/p = 1.0\% + 0.044\% p \text{ [GeV}/c]$$

**Charged hodoscope (scintillators):**

Fast trigger and precise time measurement ( $\sim 200$  ps on single track)

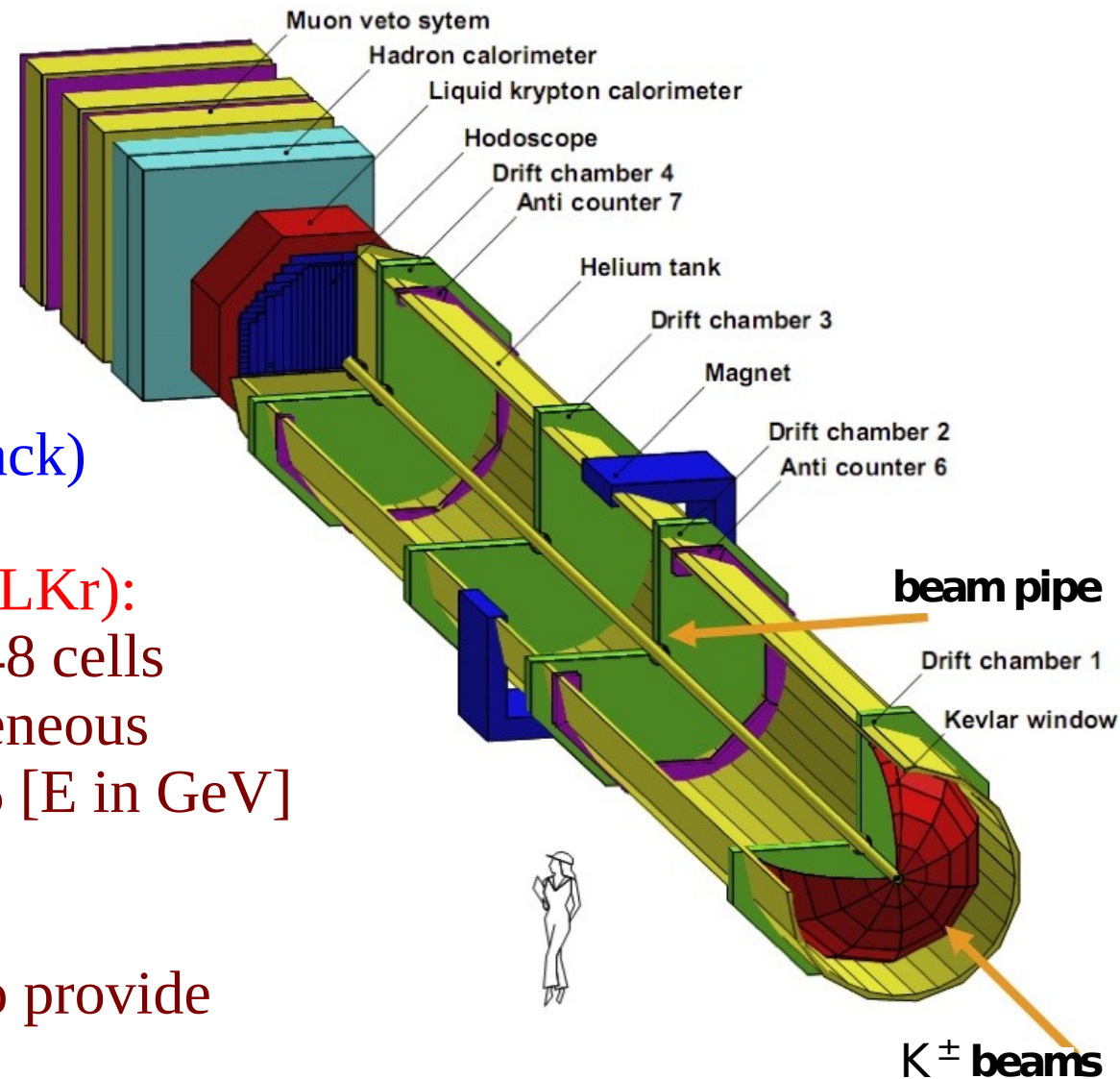
**Liquid Krypton E.M. Calorimeter (LKr):**

10 m<sup>3</sup> ( $\sim 22$  t), 1.25 m (27 X<sub>0</sub>), 13248 cells  
granularity: 2x2 cm<sup>2</sup>, quasi-homogeneous

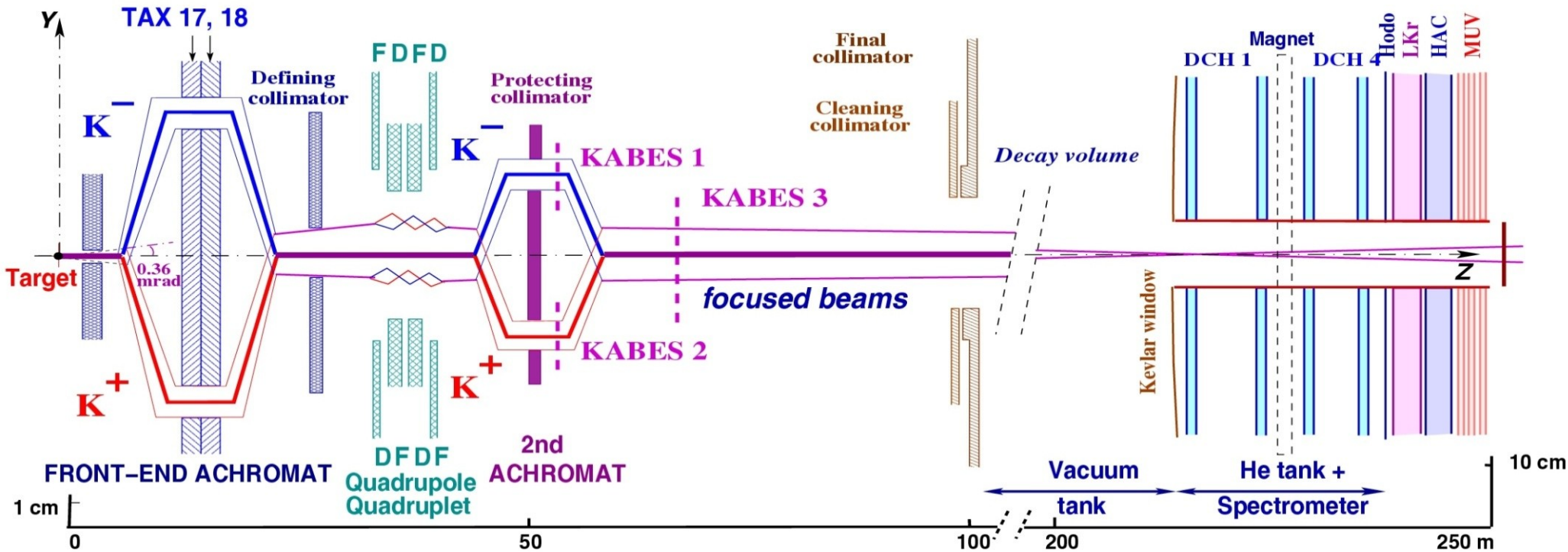
$$\sigma(E)/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\% \text{ [E in GeV]}$$

**Neutral hodoscope**

Inside the calorimeter at  $\sim 9.5$  X<sub>0</sub> 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 ( $K^\pm$ )

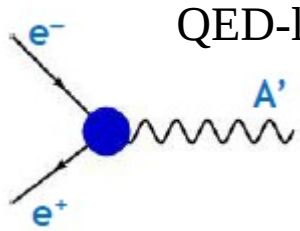
## Kaon beam momentum

- ✓ NA48/2 (2003 -2004)  $(60.0 \pm 2.2)\text{GeV}/c$

# 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

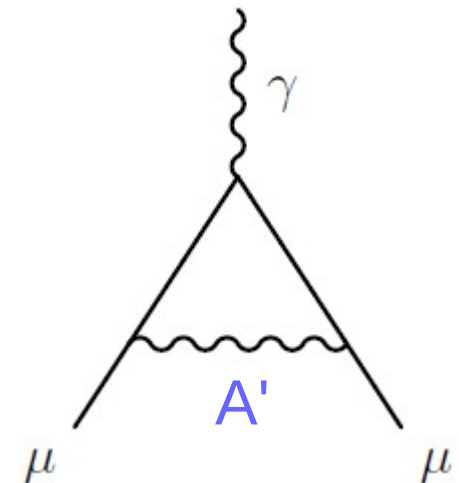
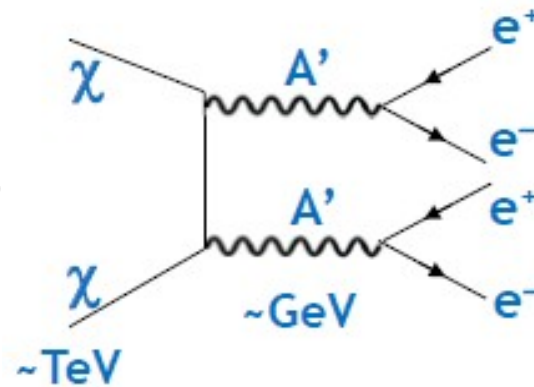
Coupling constant and charges can be generated through kinetic mixing between the QED and the new  $A'$  gauge boson



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

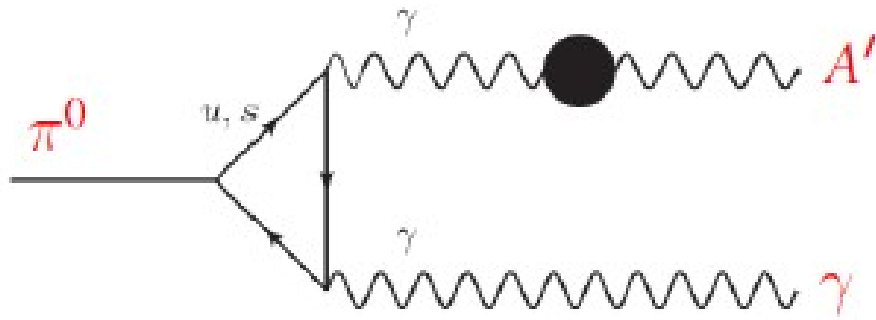
- ✓ Muon  $g-2$  anomaly



# The DP production in $\pi^0$ decay

Batell, Pospelov and Ritz,  
PRD80 (2009)095024

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



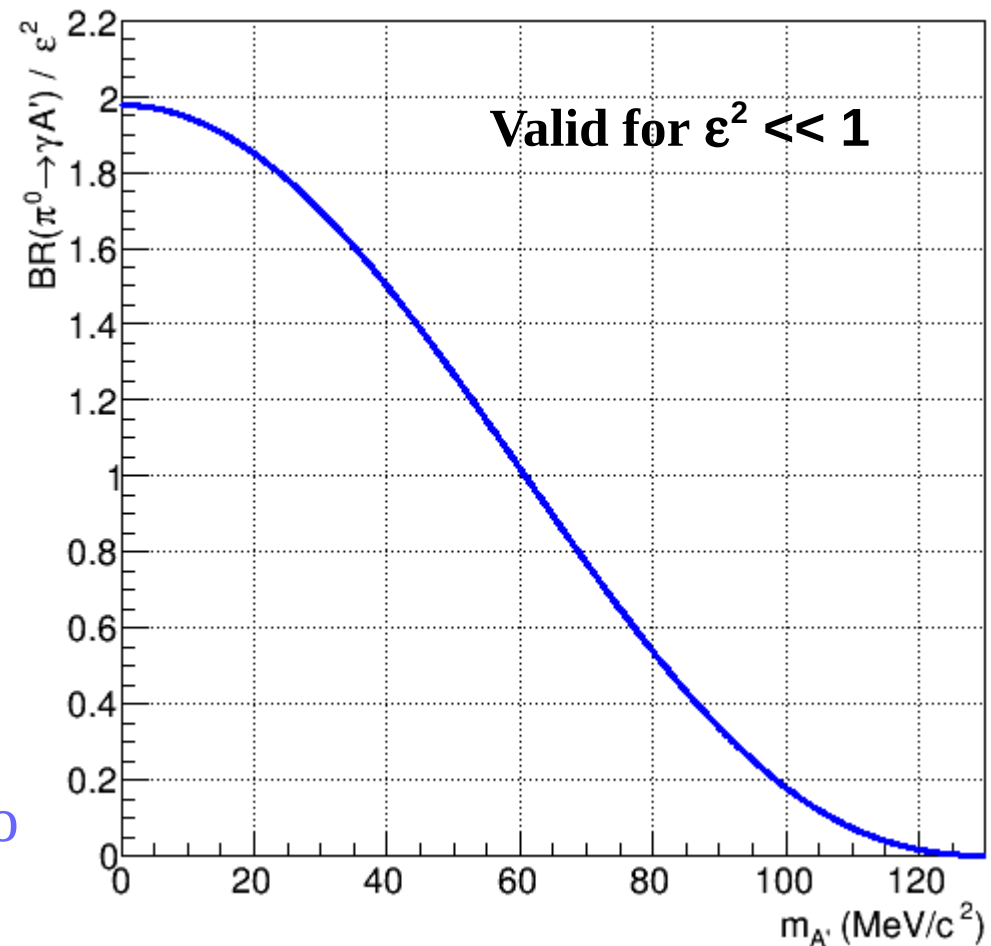
Two unknown parameters:

✗ mass ( $m_{A'}$ )

✗ mixing ( $\epsilon^2$ )

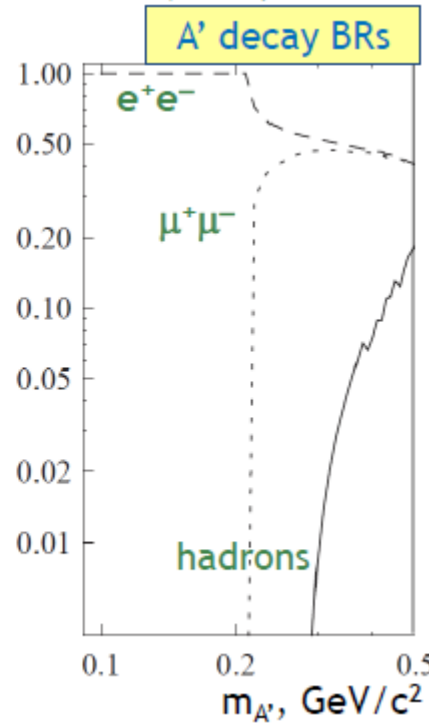
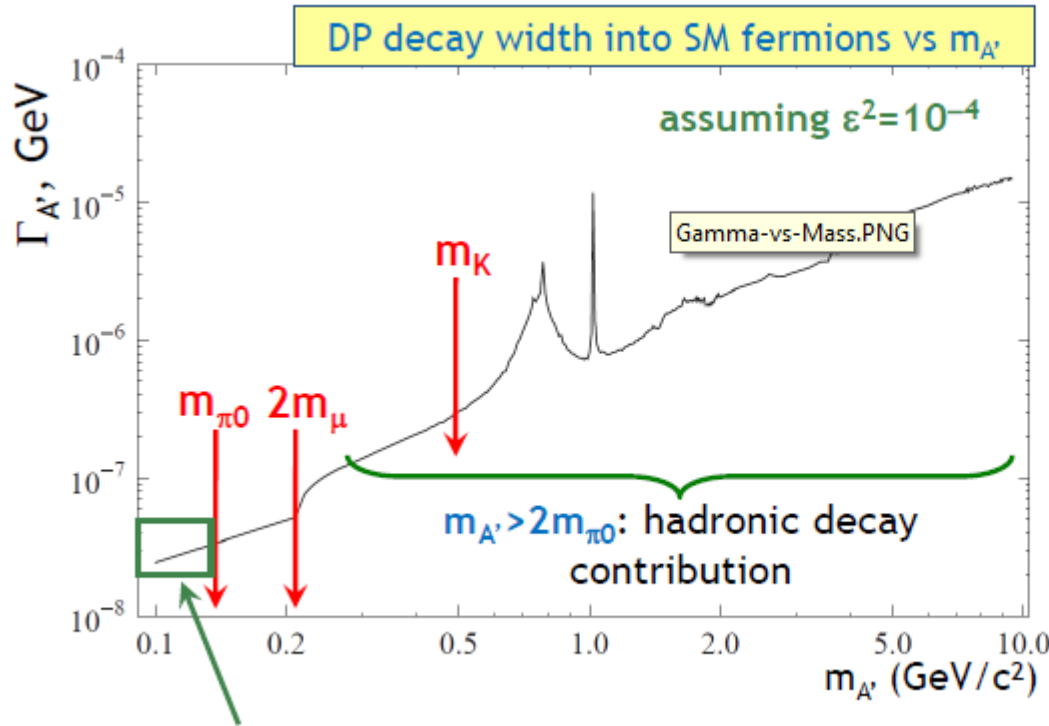
Sensitivity for  $m_{A'} < m_{\pi^0}$

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



# The DP decay

Batell, Pospelov and Ritz, PRD79 (2009)115008



Accessible in  $\pi^0$  decay (only in fermions)

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

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

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

**Assumptions:**

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

# NA48/2 Data Sample

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

- ✓ Production and decay in vacuum of  $\sim 5 \times 10^{10}$  tagged boosted  $\pi^0$  mesons (few  $\mu\text{m}$  of mean free path)..
- ✓ Sources of  $\pi^0$  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 $\pi^0$ Dalitz Sample

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

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

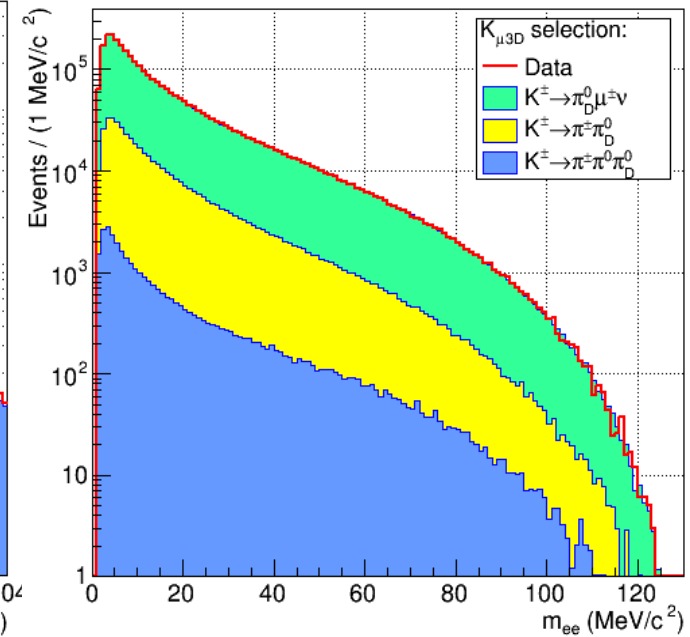
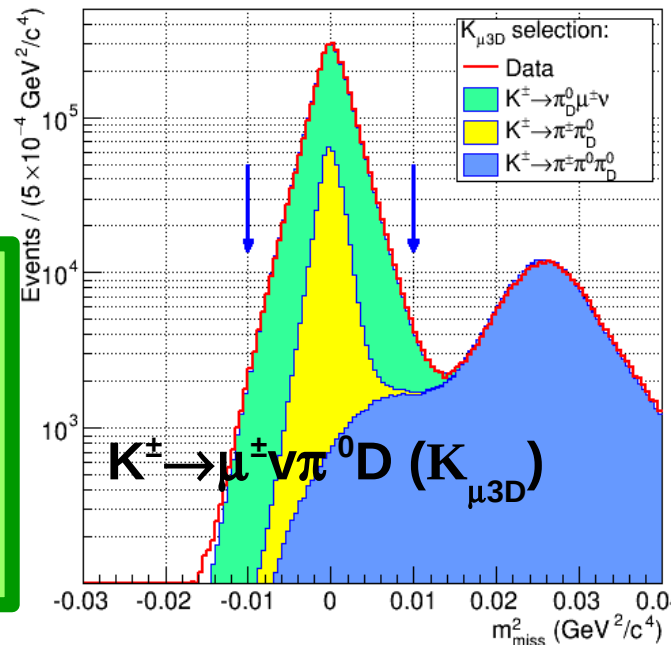
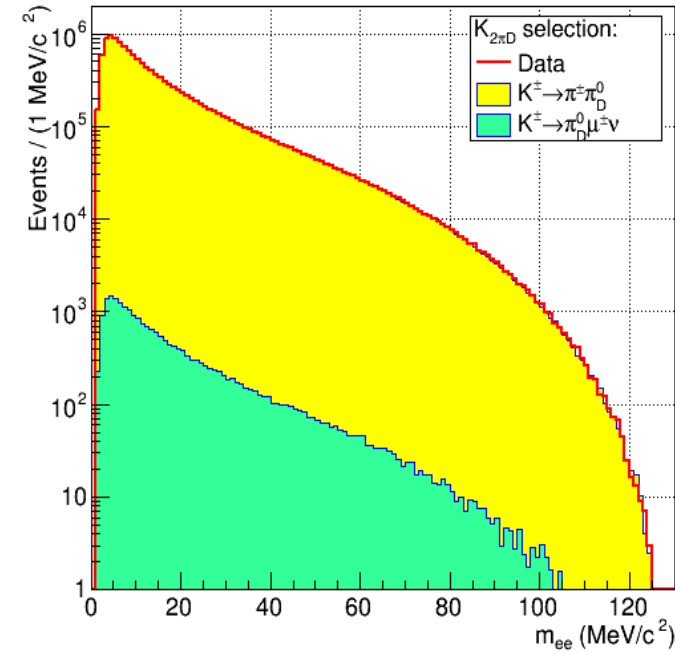
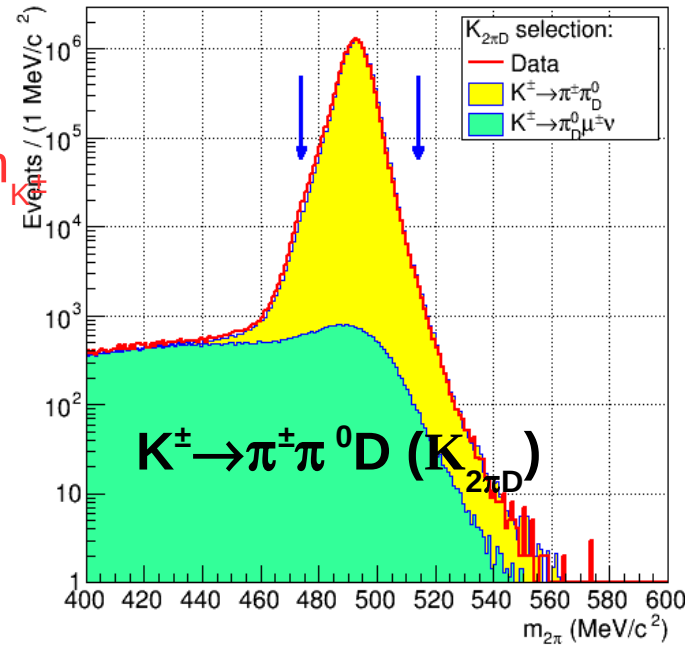
$K_{\mu 3D}$ :  $m_{2\text{miss}} = (P_K - P_\mu - P_{\pi^0})^2$   
compatible with  $m_{K^\pm}$   
missing total e transverse  
momentum  
 $m_{\gamma e^+e^-}$  compatible with  $\pi^0$

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

$\pi^0 D$  decay candidates:

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

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



# $\pi^0$ Dalitz simulation

## Kinematic variables:

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

## Lowest order differential decay rate:

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

## Radiative corrections:

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

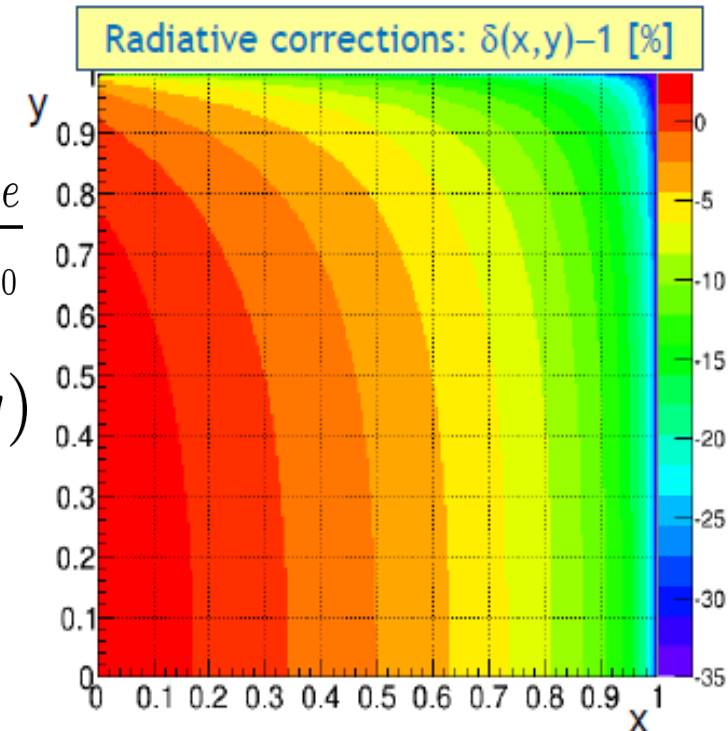
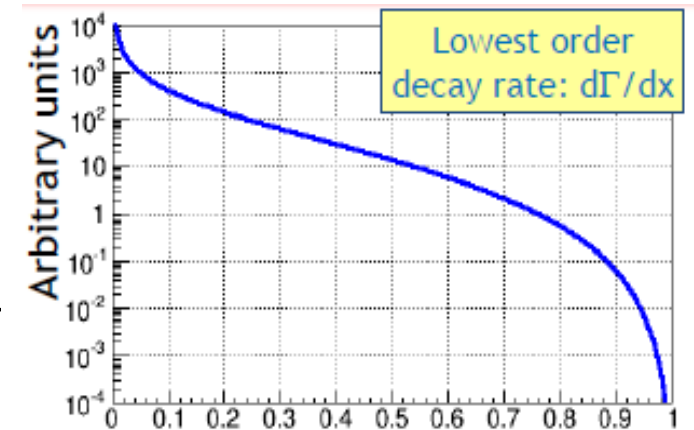
Limited by no emission of real photons

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

$\pi^0$  transition form factor:  $F(x)=1+ax$

Theory expectation for the slope ( $a=0.0307 \pm 0.0006$ ) or the PDG average cannot be used due to limited precision on the radiative corrections to p0D

Instead use a value obtained by the data itself, fitting the  $m_{ee}$  spectrum. Satisfactory for  $m_{ee} > 8 \text{ MeV}/c^2$



# Search for the DP signal (1)

## DP mass scan performed

- ✓ Between 9 and 120 MeV/c<sup>2</sup>
- ✓ At low  $m_{A'}$ , bckg acceptance has limited precision
- ✓ Variable DP mass step:  $\sim 0.5 \sigma_m$
- ✓ Optimize window to maximize sensitivity:  $\pm 1.5 \sigma_m$
- ✓ 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**

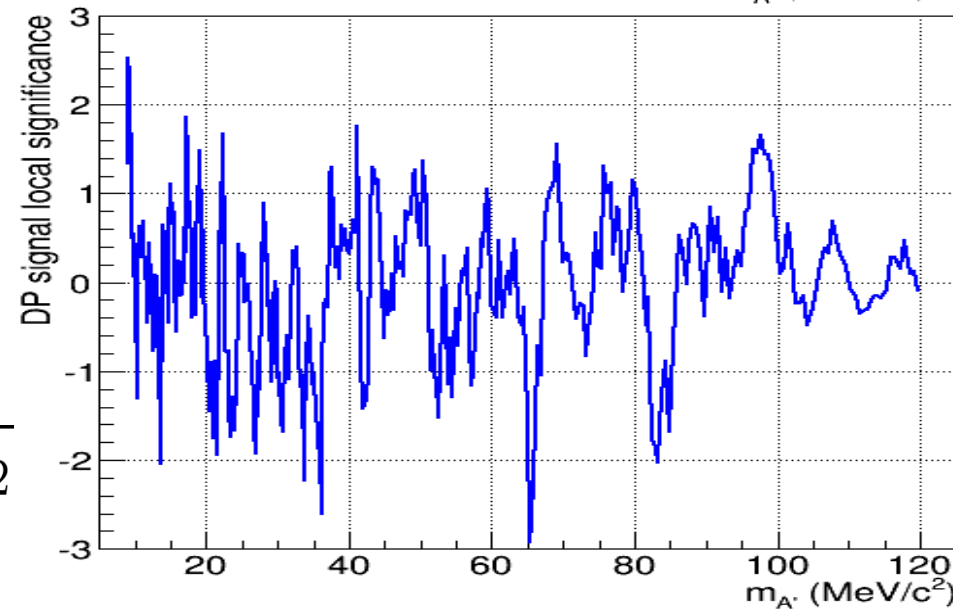
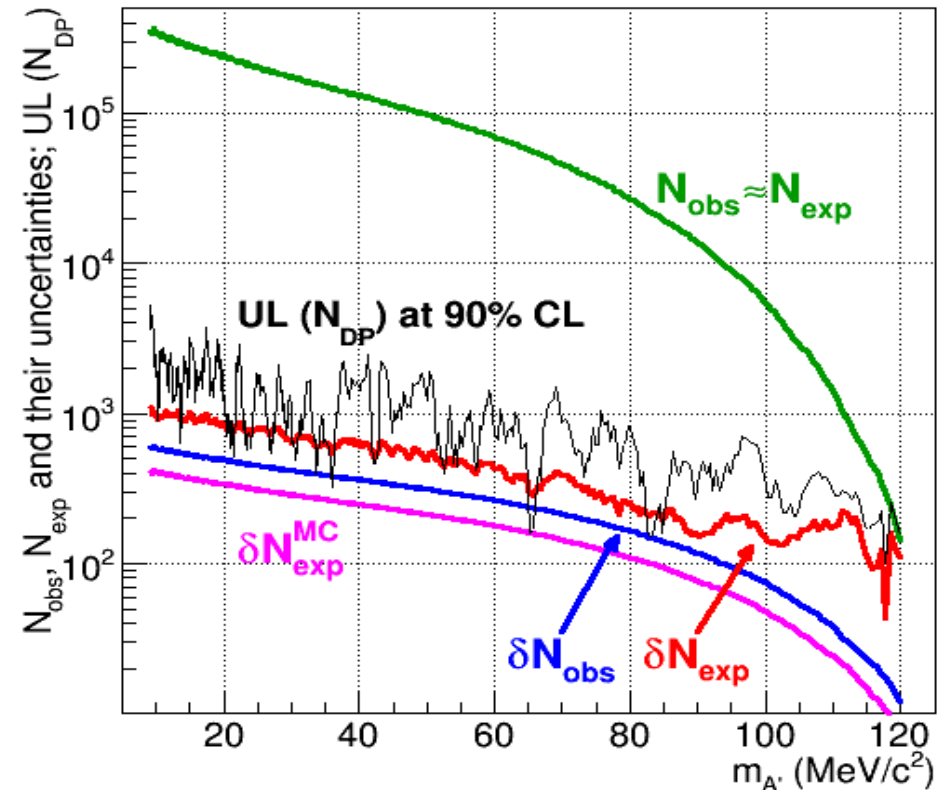
- ✓ Use Rolke-Lopez method

**Local signal significance never exceeds**

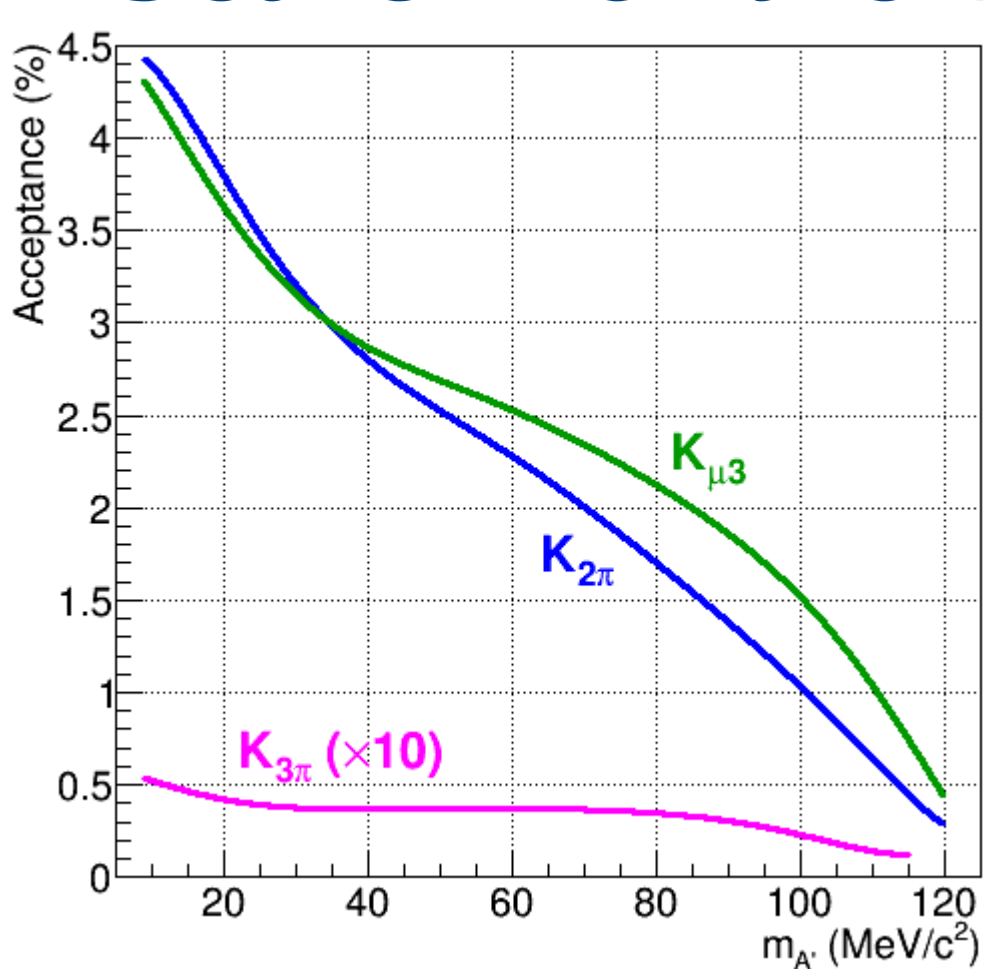
**$3\sigma$ : no DP signal observed**

- ✓ Local significance estimated as

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



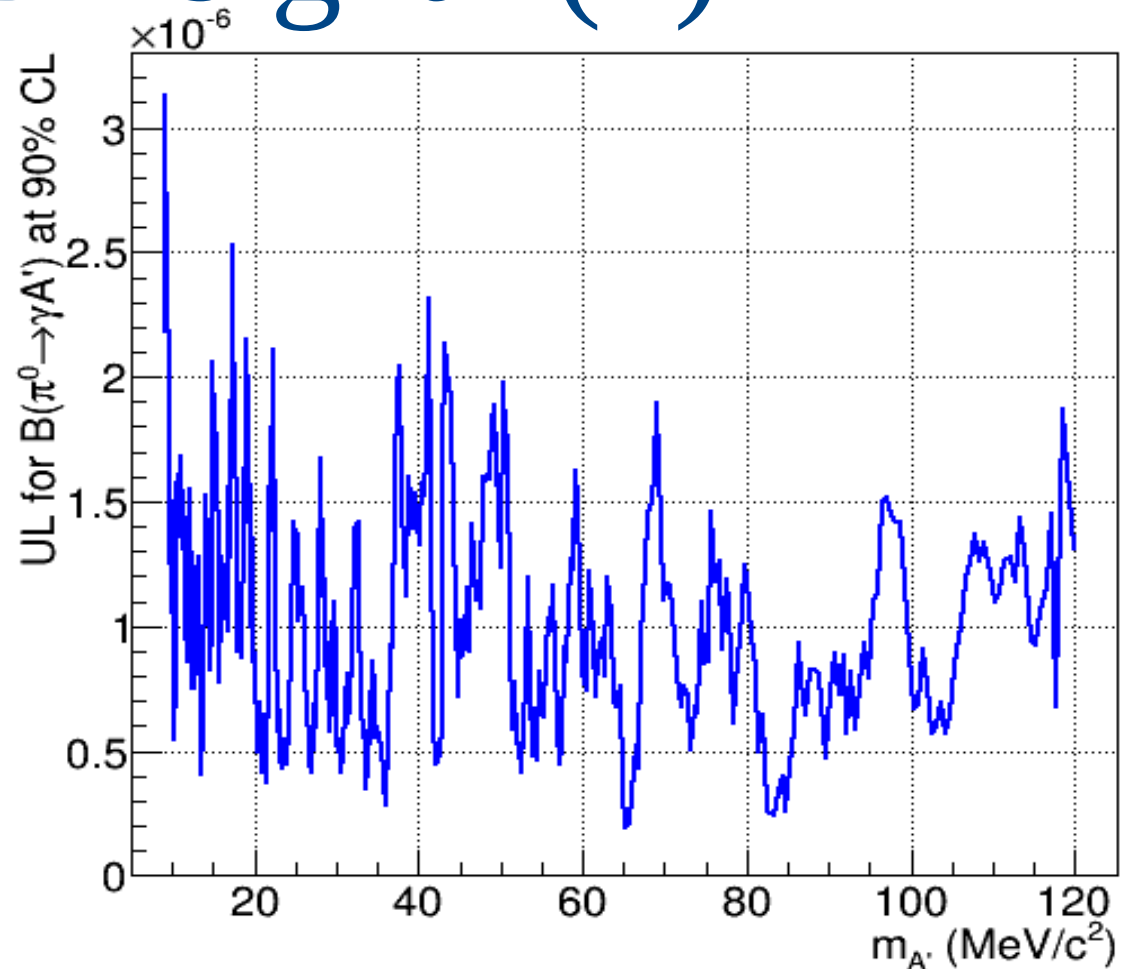
# Search for the DP signal (2)



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

✗ MC simulation

✗  $K_{\mu 3}$  acceptance scaled x10 for visibility



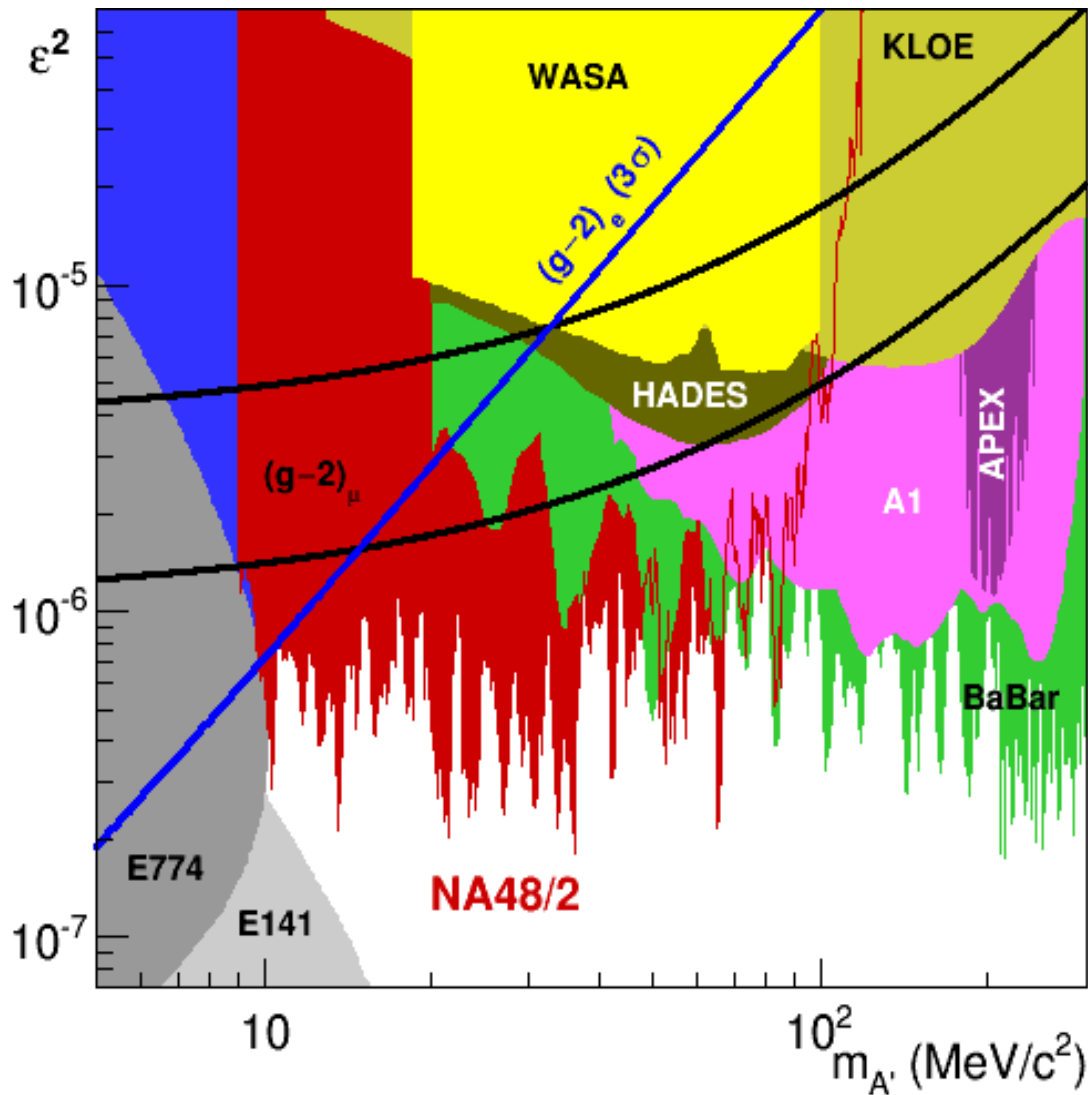
Upper limits at 90% C.L. on  $BR(\pi^0 \rightarrow \gamma A')$  for each DP mass value:  $O(10^{-6})$

✗ assume  $BR(A' \rightarrow e+e^-) \approx 1$  and  $A'$  decays into fermions only ( $m_{A'} < 2m_\mu$ )

✗ no strong dependence on DP mass

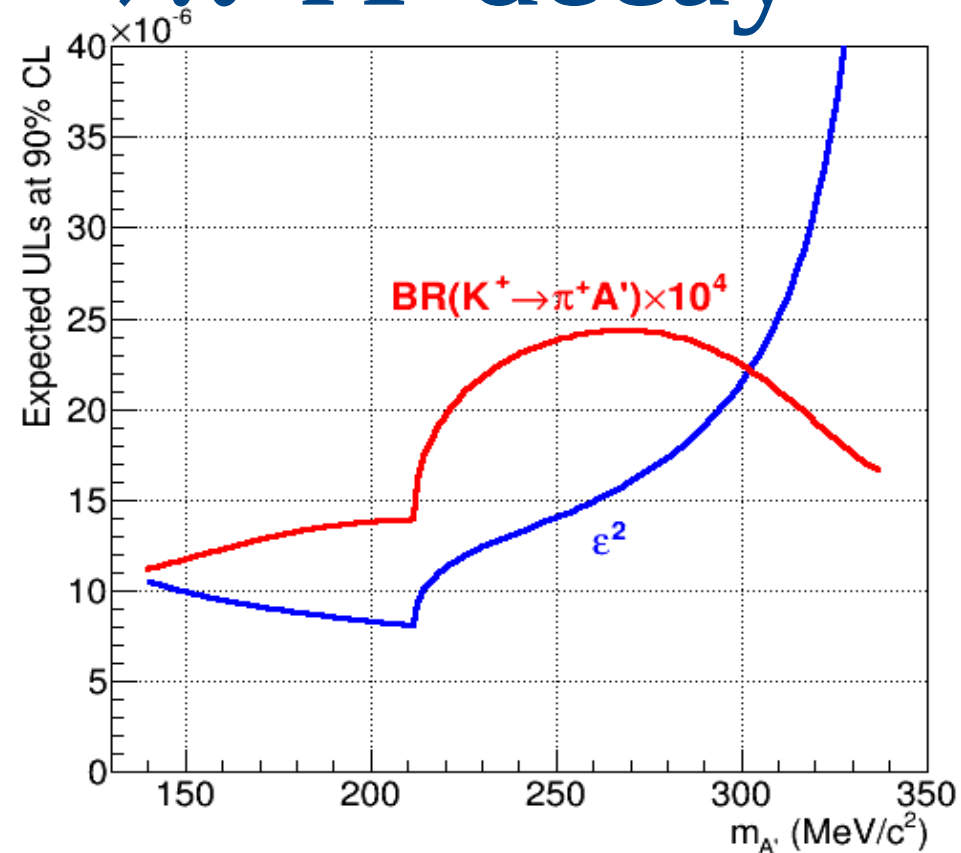
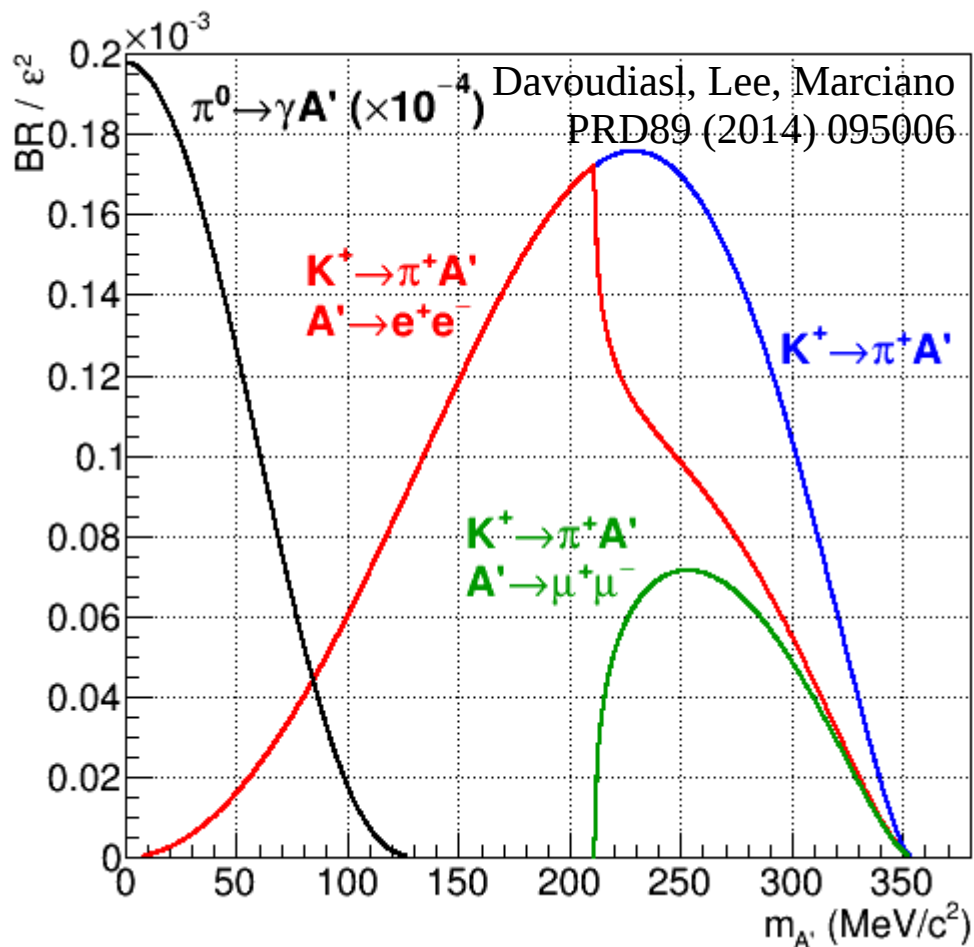
# DP exclusion limits: final NA48/2

Published in Phys. Lett. B746 (2015) 178



- ✓ Improvements on the existing limits for  $9 < m_{A'} < 70 \text{ MeV}/c^2$
- ✓ Most stringent limits at low  $m_{A'}$ 
  - Weak kinematic suppression
- ✓ Sensitivity limited by the irreducible  $\pi^0 D$  background. Uls are 2-3 order of magnitude above SES
- ✓ Upper limit on  $\epsilon^2$  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 $K^\pm \rightarrow \pi^\pm A'$ decay



**Complementary  $m_{A'}$  interval to  $\pi^0$  decay...  
but not competitive to existing limits**

**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 ( $\times 4$ ), favourable  $K/\pi^0$  flux ratio ( $\times 4$ ).
- 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  $BR(K^\pm \rightarrow \pi^\pm A')/BR(\pi^0 \rightarrow \gamma A') \sim 10^{-4}$  giving expected  $\epsilon^2$  limits  $\sim 10^{-5}$ .

# Conclusions

A new result on dark photon search in  $\pi^0$  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  $\epsilon^2$  in the 9-70 MeV/c<sup>2</sup> mass range.
- The strongest limits has been found at  $\sim 10$  MeV/c<sup>2</sup> mass ( $\epsilon^2 \sim 2 \cdot 10^{-7}$ ).
- The whole region favoured by  $(g-2)_\mu$  is excluded.
- Background-limited measurement: hard to improve below  $\epsilon^2 = 2 \cdot 10^{-7}$ .
- Search via  $K^\pm \rightarrow \pi^\pm A'$  ( $m_{\pi^0} < m_{A'} < m_K - m_\pi$ ) is not competitive.

## Possible future directions:

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