Search for the dark photon in π^0 decays

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on behalf of the NA48/2 Collaboration

The NA48/2 Collaboration
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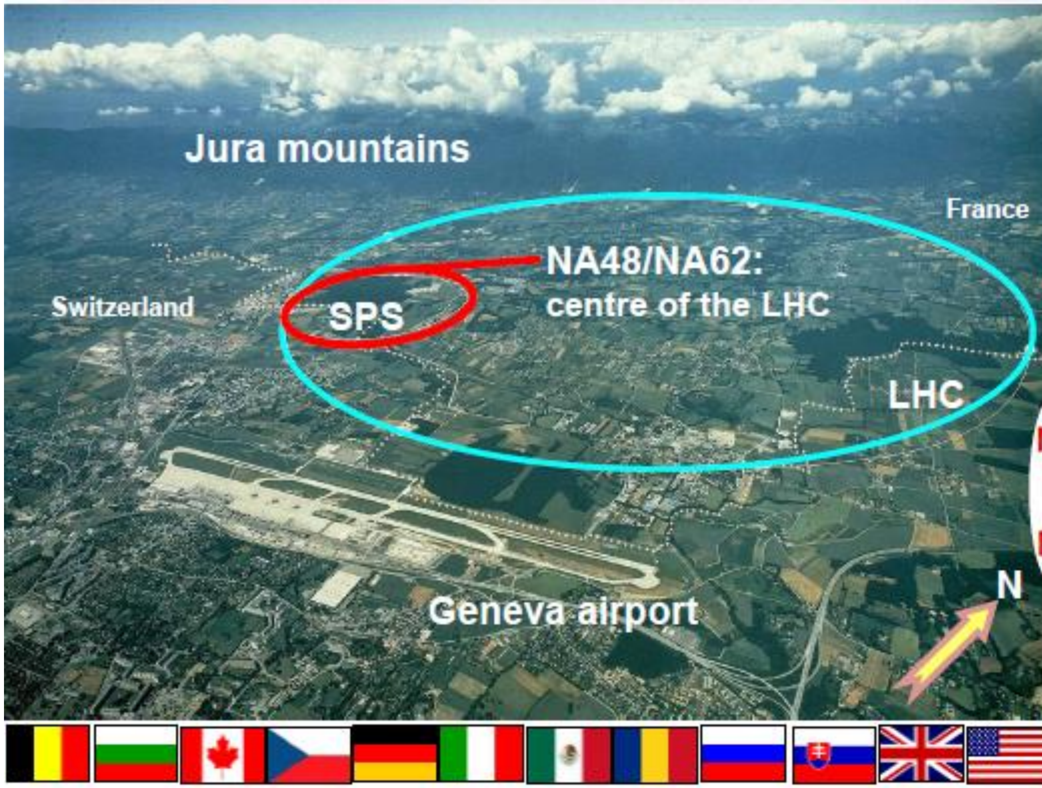
Outline

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

NA48: site and history



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	1st $K^+\rightarrow\pi^+\nu\bar{\nu}$ run	

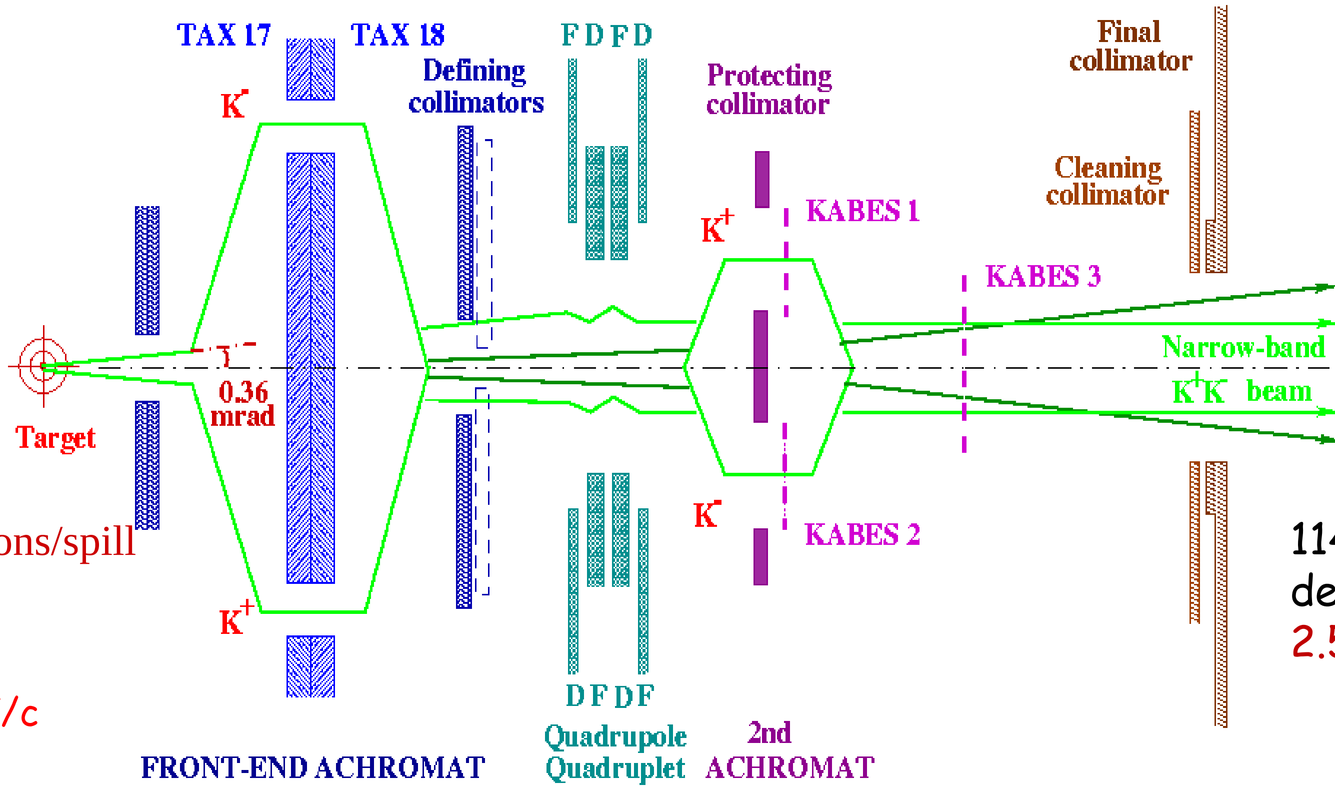
Kaon decay in flight experiments.

NA62: currently ~200 participants, 30 institutions

The NA48/2 Beam

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

$N(K^+)/N(K^-) = 1.8$



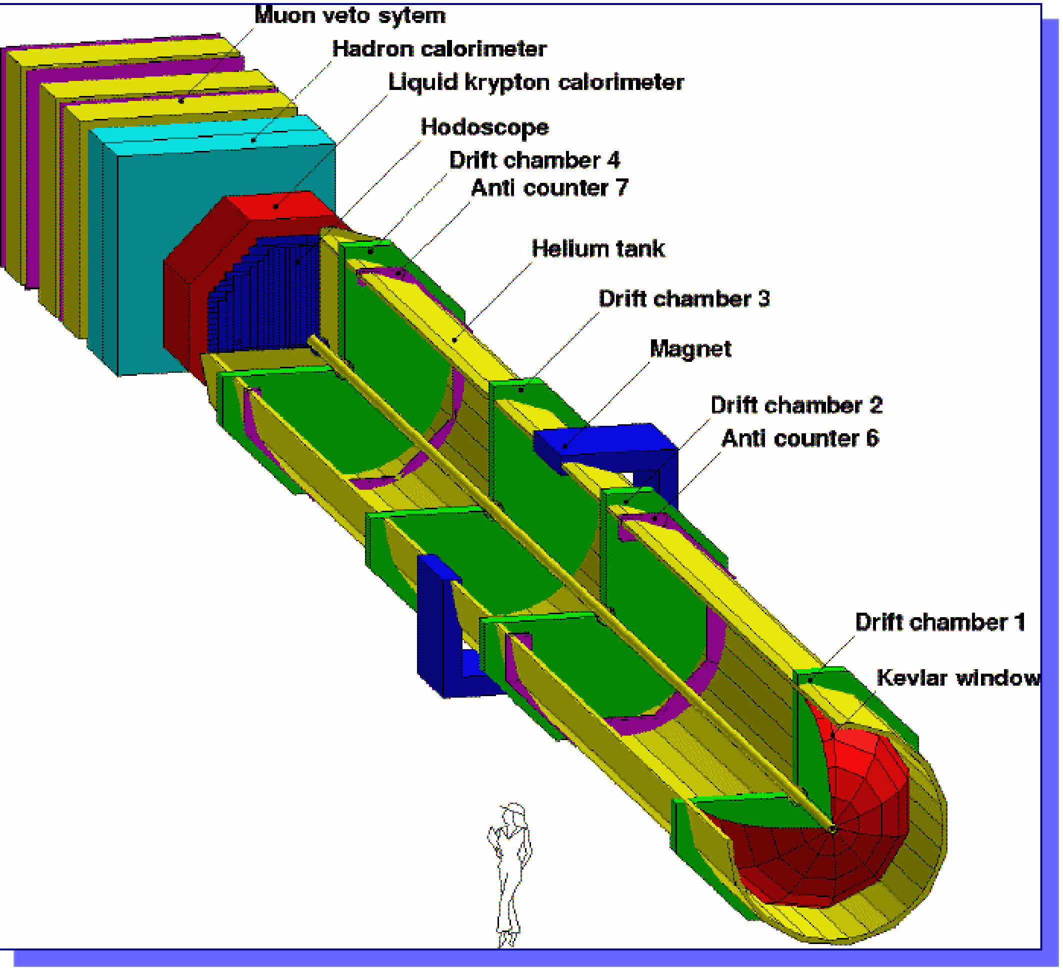
1.8x10^{12} protons/spill
400 GeV/c

$P_K = (60 \pm 3)$ GeV/c

114 m long
decay volume
2.5x10^7 K/spill

K decays in the vacuum tank: 22%
Beam size: 4x4 mm^2, 10x10 μr

The NA48/2 Detector



LKr Calorimeter:

$\sigma(E)/E \cong 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$

$\sigma(x) = \sigma(y) \cong (4.2/\sqrt{E} \oplus 0.6)$mm $\cong$ 1.5mm@ 10 GeV

Spectrometer:

$\sigma(P)/P \cong 1.02\% \oplus 0.044\, P[GeV/c]\%$

Scintillator hodoscope: fast trigger and good time resolution (150 ps)

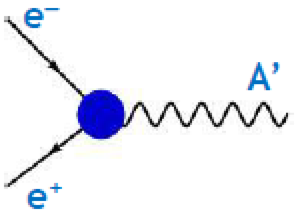
Efficient trigger chain for 3-track vertices using the hodoscope multiplicity at L1 and drift chamber track reconstruction at L2

The dark photon

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

The simplest hidden sector model introduces an extra U(1) gauge symmetry with its gauge boson: the dark photon

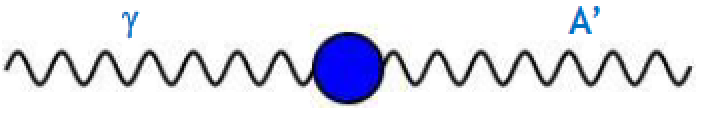
$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$



Not all fermions need to be charged under this new symmetry

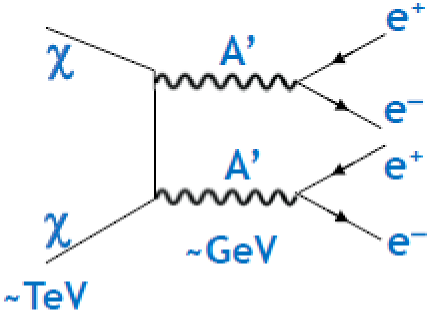
Coupling constant and charges can be generated through kinetic mixing between the QED and the new U(1) gauge boson

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

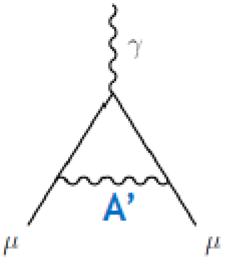


Possible explanations for:

Positron excess in cosmic rays (PAMELA, FERMI, AMS-02) by dark matter annihilation



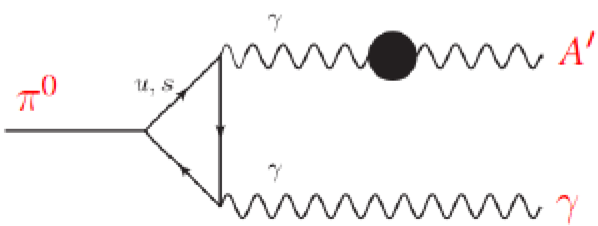
Muon g-2 anomaly



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

Batell, Pospelov and Ritz, PRD80 (2009) 095024

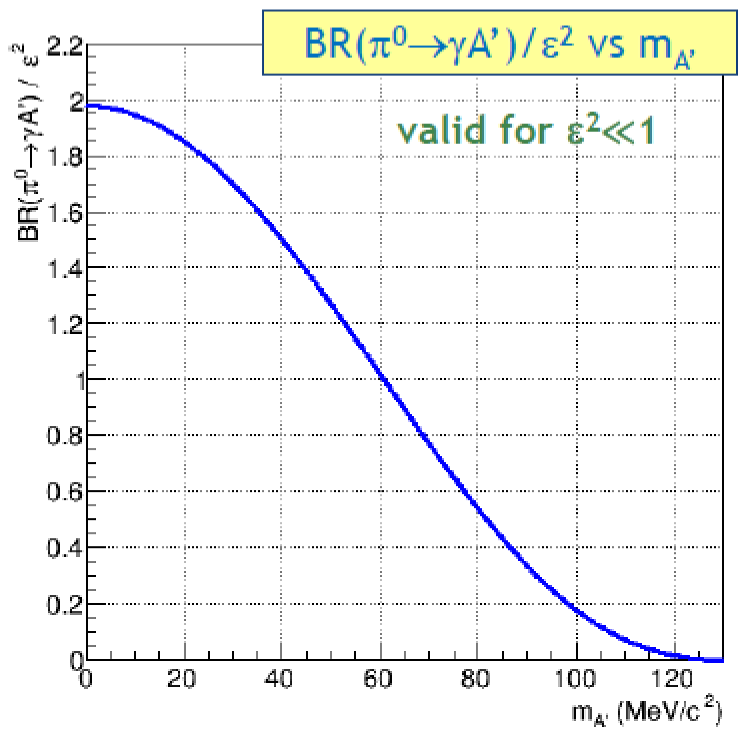
$$B(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$



Two unknown parameters: mass ($m_{A'}$) and mixing (ε^2)

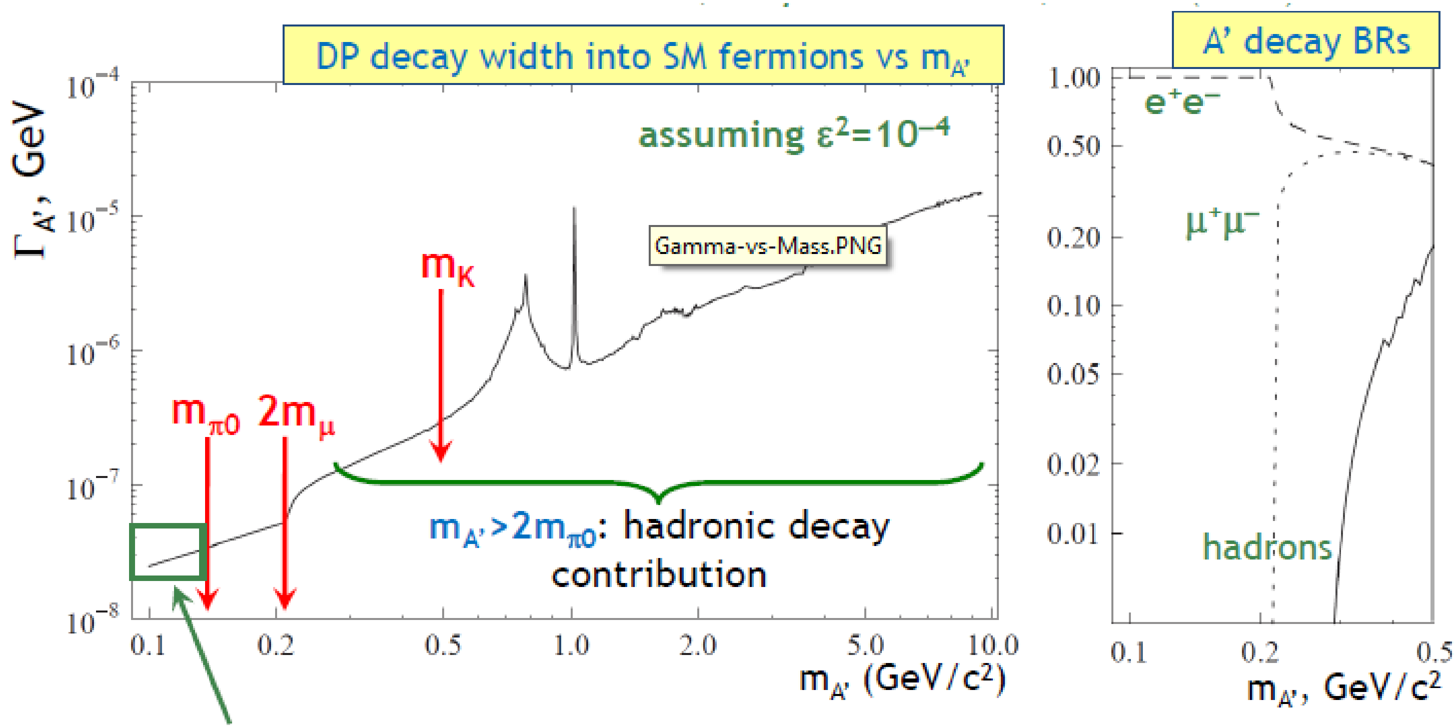
Sensitivity for $m_{A'} < m_{\pi 0}$

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



DP decays into SM fermions

Batell, Pospelov and Ritz, PRD79 (2009) 115008



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

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

DP lifetime and mean path

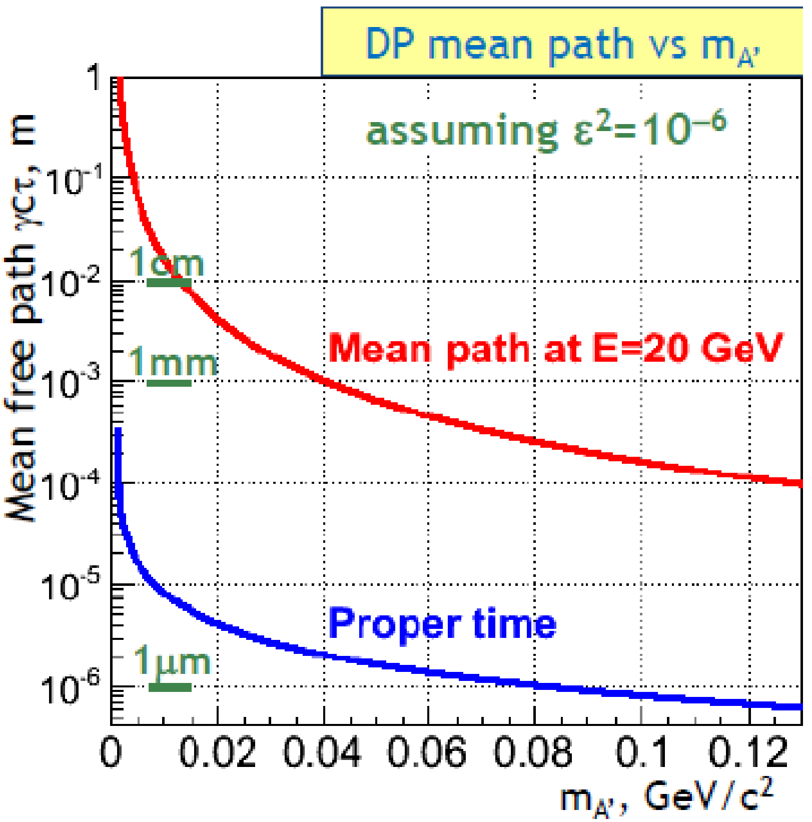
DP proper lifetime below the di-muon threshold

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

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

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

Assumption of prompt decay, as for $\varepsilon^2 > 10^{-7}$ and $m_{A'} > 10 MeV/c^2$, the DP path length is smaller than the resolution on the vertex longitudinal coordinate (~1m)



Production and decay signature is identical to that of $\pi^0_D \longrightarrow \gamma e^+ e^-$

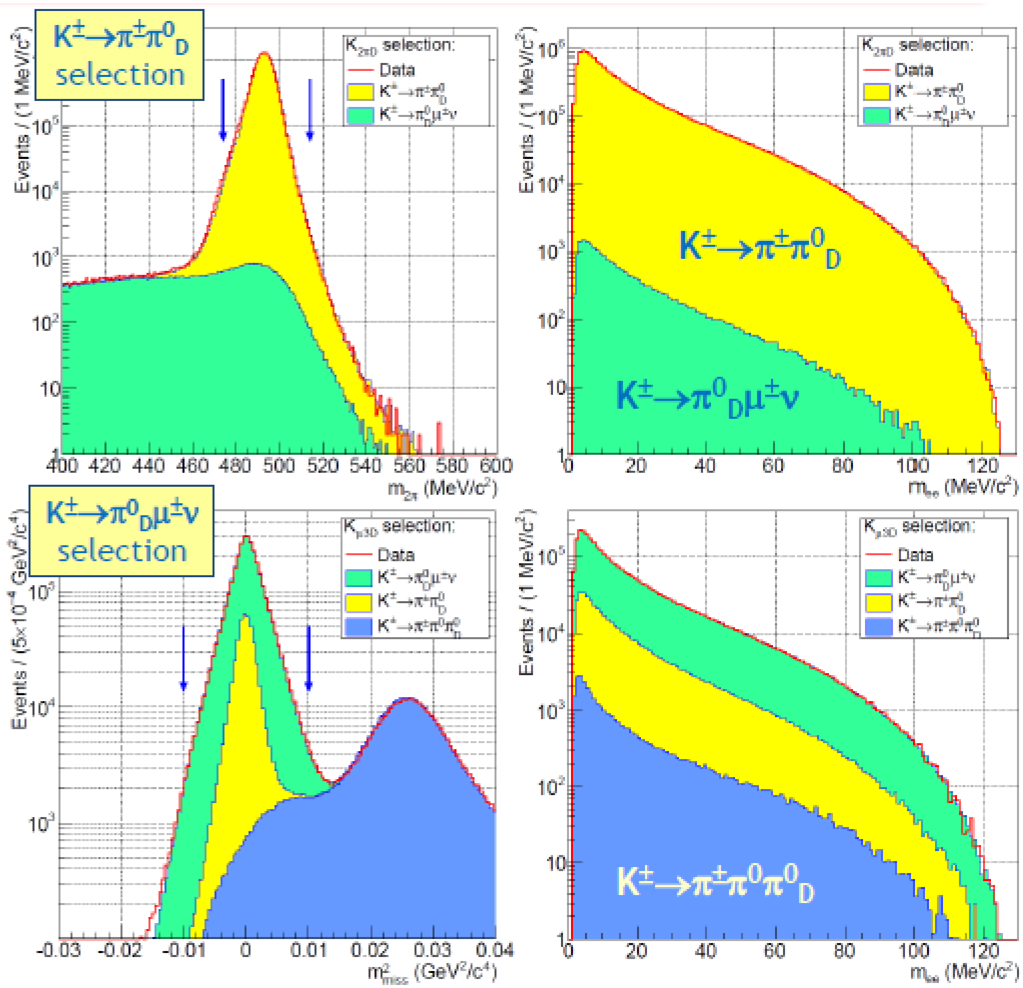
NA48/2 data sample

- Data collected in 2003 and 2004
  - $2 \cdot 10^{11}$ $K^\pm$ decays in the fiducial region
  - Production and decay of ~ $5 \cdot 10^{10}$ tagged and boosted π^0 mesons, with a negligible mean free path (~ few μm)
  - Select π^0 sources from $K^\pm \to \pi^\pm \pi^0$ (BR=20.7%) and $K^\pm \to \mu^\pm \pi^0 \nu$ (BR=3.4%)

- Search for prompt decay chain $\pi^0 \to \gamma A'$, $A' \to e^+e^-$
  - Same signature as $K^\pm \to \pi^\pm \pi^0_D$ and $K^\pm \to \mu^\pm \pi^0_D \nu$
  - Sensitivity determined by the irreducible $\pi^0 \to \gamma e^+e^-$ background (BR= 1.2%)
  - Search for a narrow peak in the e^+e^- invariant mass spectrum
  - Excellent e+e- mass resolution: $\sigma_m \sim 0.011 \cdot m_{ee}$
  - Acceptance for both signal chains, depending on $m_{A'}$, up to 4.5%

π^0_D sample

- $K^\pm \to \pi^\pm \pi^0_D$ selection
  - $|m_{\pi\gamma ee} - m_K| < 20$ MeV/c^2
  - $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/c^2
  - No missing momentum
- $K^\pm \to \mu^\pm \pi^0_D \nu$ 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
- π^0_D candidates
  - $N(K_{2\pi D}) = 1.38 \cdot 10^7$
  - $N(K_{\mu 3D}) = 0.31 \cdot 10^7$
  - Total $= 1.69 \cdot 10^7$
- Kaon decays in the fiducial region: $(1.57 \pm 0.05) \cdot 10^{11}$



Simulation of π^0_D background

Kinematic variables:

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

Differential decay rate (lowest order):

$$\frac{d^2\Gamma}{dxdy} = \Gamma_0 \frac{\alpha}{\pi} |F(x)|^2 \frac{(1-x)^3}{4x}\left(1+y^2+\frac{r^2}{x}\right), \quad r = \frac{2m_e}{m_{\pi^0}}$$

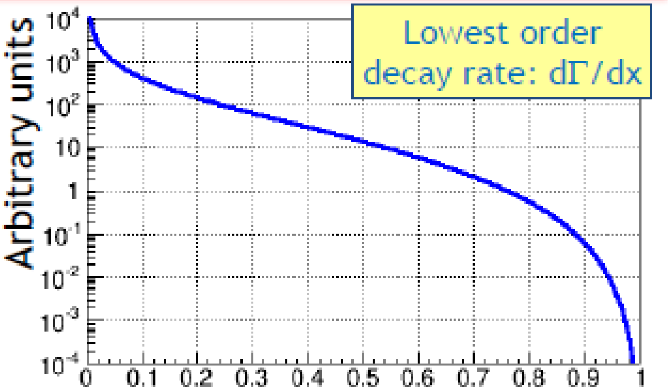
Radiative corrections: $\frac{d^2\Gamma}{dxdy} = \delta(x,y)\frac{d\Gamma^0}{dxdy}$

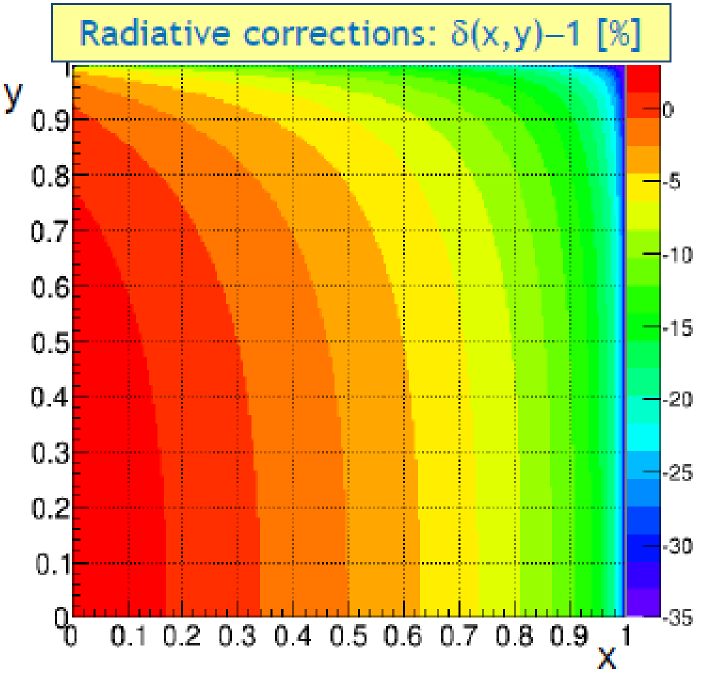
Limited by no emission of real photons

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 ($a=0.0307 \pm 0.0006$) or the PDG average cannot be used due to limited precision on the radiative corrections to π^0_D
Instead use a value obtained by the data itself, fitting the m_{ee} spectrum
Satisfactory for m_{ee}>8MeV/c





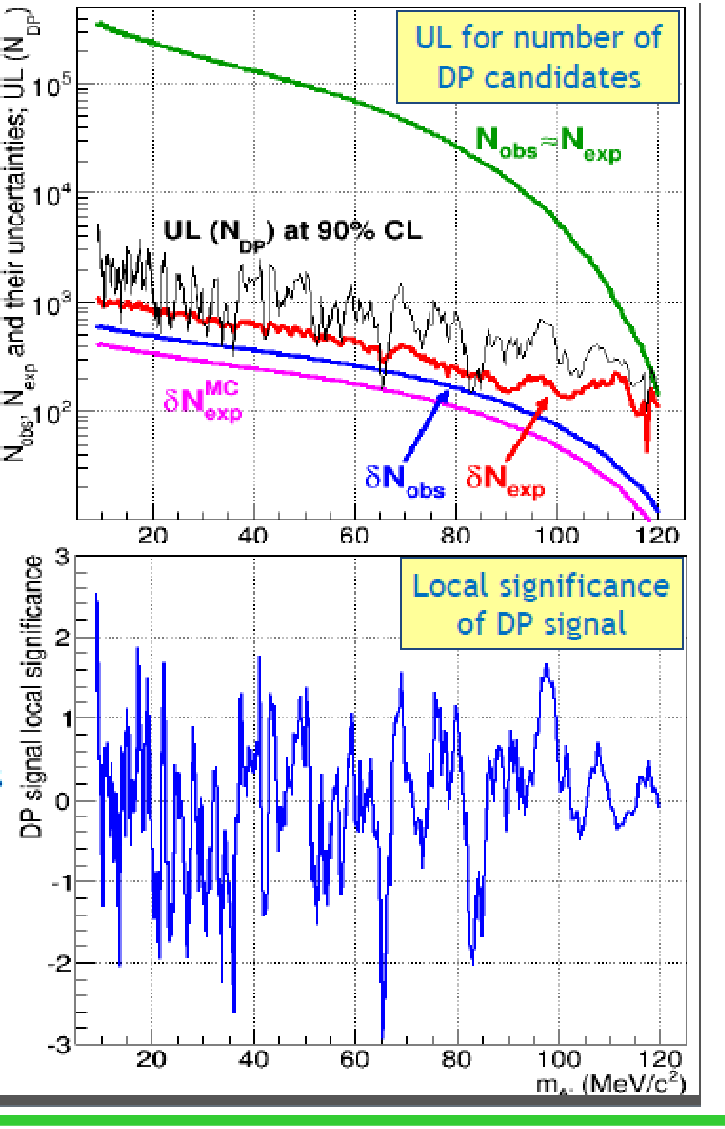
Search for DP signal (1)

- 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

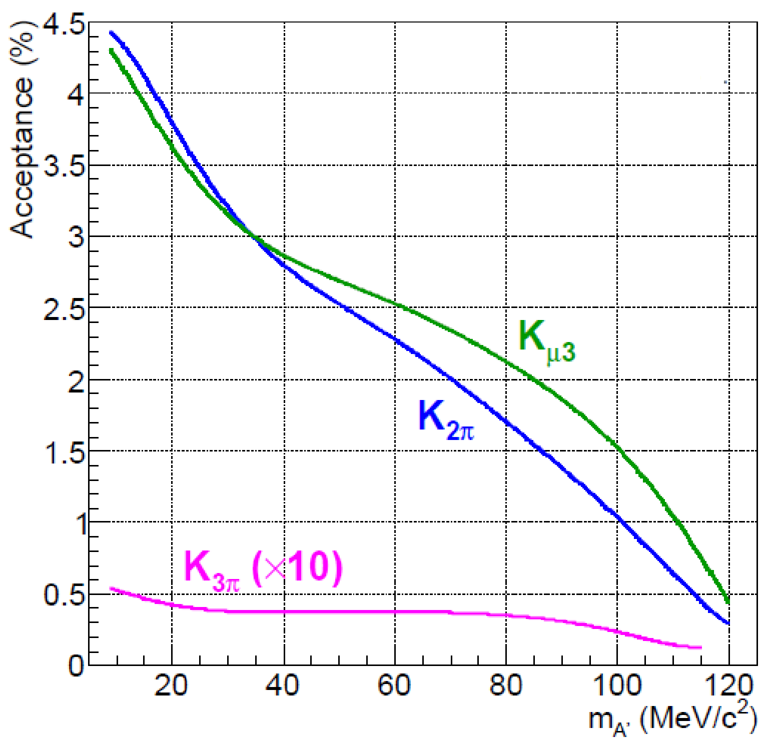
- For each $m_{A'}$, frequentist confidence intervals for N_{DP} obtained from the numbers of observed and expected events and their uncertainties
  - Use Rolke-Lopez method

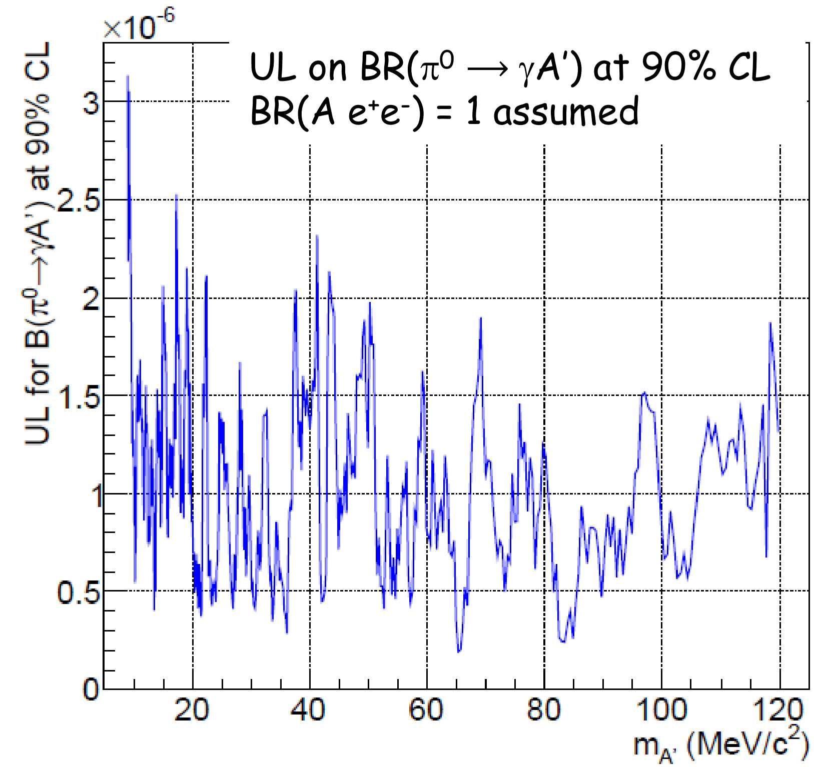
- Local signal significance never exceeds 3σ: no DP signal observed
  - Local significance estimated as

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



Search for DP signal (2)

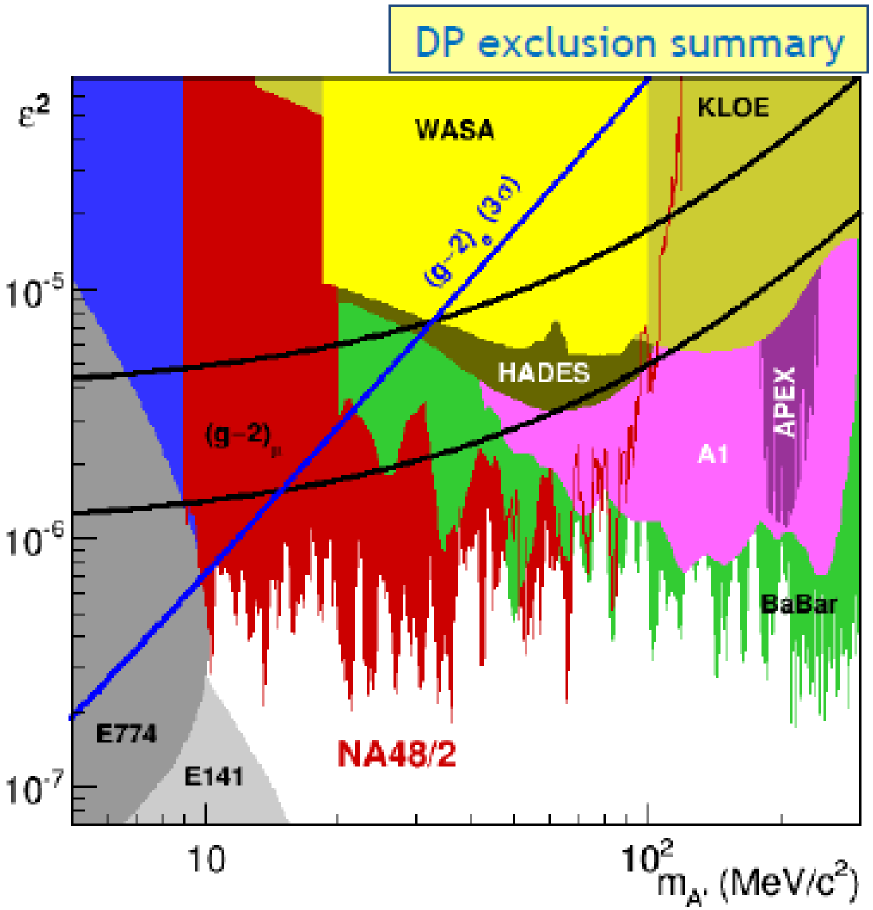




Acceptance of the DP selection for $K^\pm \to \pi^\pm \pi^0_D$, $K^\pm \to \mu^\pm \pi^0_D \nu$ and $K^\pm \to \pi^\pm \pi^0 \pi^0$ decays followed by the prompt decay chain $\pi^0 \to \gamma A'$, $A' \to e^+e^-$

Weak m_A' dependence
Obtained limits are background limited (2-3 order of magnitude above SES)

DP exclusion: final NA48/2 result



Published in Phys. Lett. B746 (2015) 178
Numerical UL data for each mass hypothesis available on HepData:
http://hepdata.cedar.ac.uk/view/ins1357601

- 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^0_D background. ULs are 2-3 order of magnitude above SES
- 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 $(g-2)_\mu$

Summary and outlook

- New NA48/2 result on dark photon search in π^0 decays
  - $1.57 \cdot 10^{11}$ kaon decays in flight analyzed
  - Assume DP decays in SM fermions only
  - Improved limits on DP mixing ε^2 in the mass range 9-70 MeV/c^2
  - The strongest limits are at ~10 MeV/c^2 mass
  - The region favored by $(g-2)_\mu$ is excluded
  - Limits from the background: hard to go below $\varepsilon^2 = 10^{-7}$
  - Published in Phys. Lett. B746 (2015) 178
- Possible future directions
  - Larger π^0 samples (but modest improvement) and 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