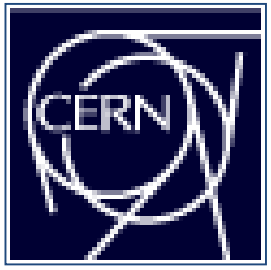


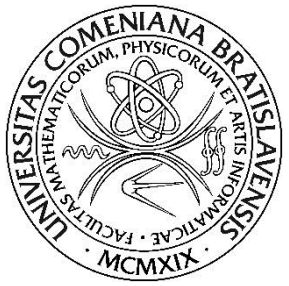


# Search for the Dark Photon in $\pi^0$ Decays by NA48/2 at CERN

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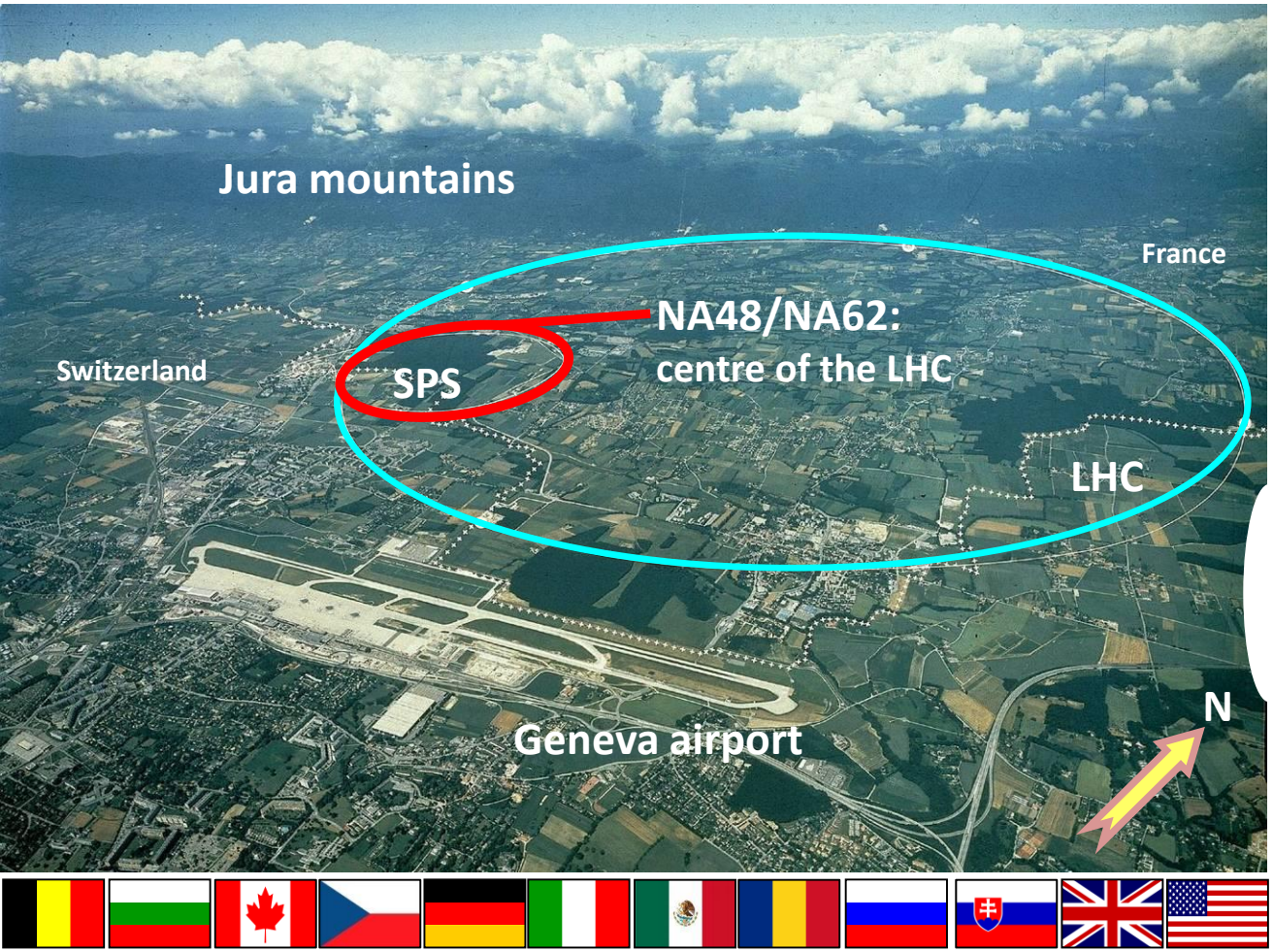
**on behalf of the NA48/2 collaboration**

**Invisibles15 Workshop**

***Madrid, Spain, 23 June 2015***

# CERN NA48/NA62 Experiments




Earlier: NA31

**NA48** discovery of direct CPV
- 1997: $\varepsilon'/\varepsilon$: $K_L+K_S$
- 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 $K^+ \to \pi^+ \nu\nu$ run

Kaon decay in flight experiments.

NA48/2: **~120** participants, **15** institutions

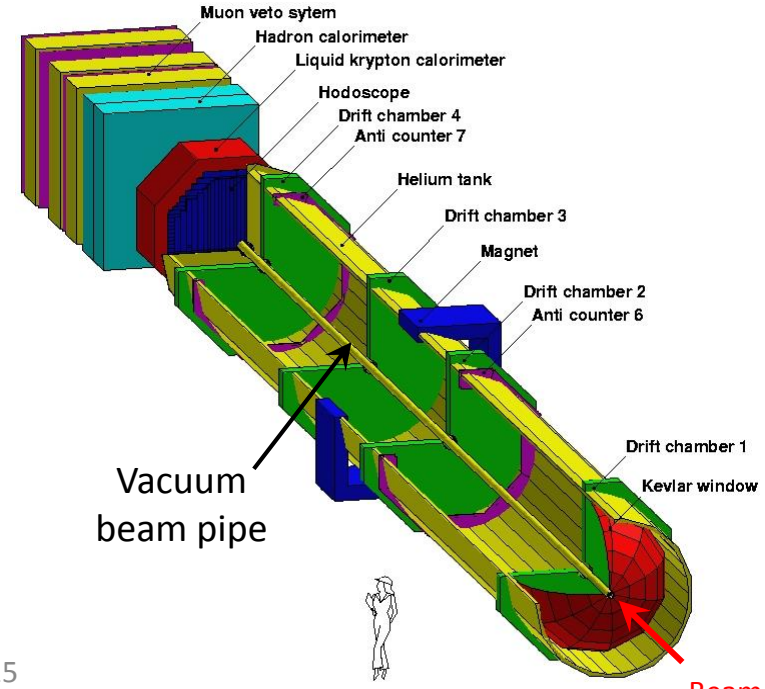
NA62: **~200** participants, **30** institutions

# 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 (4 DCHs)
  4 views/DCH: redundancy. High-level trigger.
  $\delta p/p = (1.02 \oplus 0.044p)\%$ [p in GeV/c]
- Scintillator hodoscope (HOD)
  Low-level trigger, time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = (3.2/E^{1/2} \oplus 9/E \oplus 0.42)\%$ [E in GeV];
  $\sigma_x = \sigma_y = (4.2/E^{1/2} \oplus 0.6)$mm (1.5mm@10GeV).



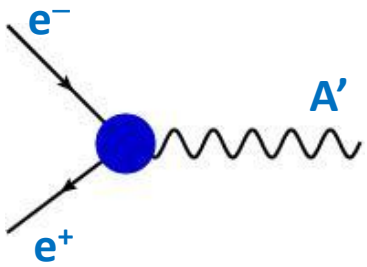
# The Dark Photon

*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 (**A'**).

QED-like interaction with SM fermions:

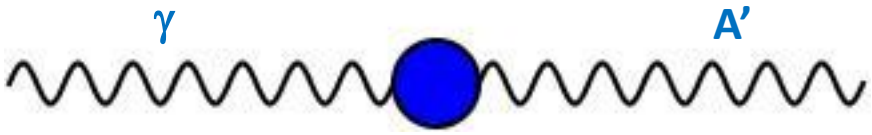
$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$




(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 **U(1)** gauge bosons

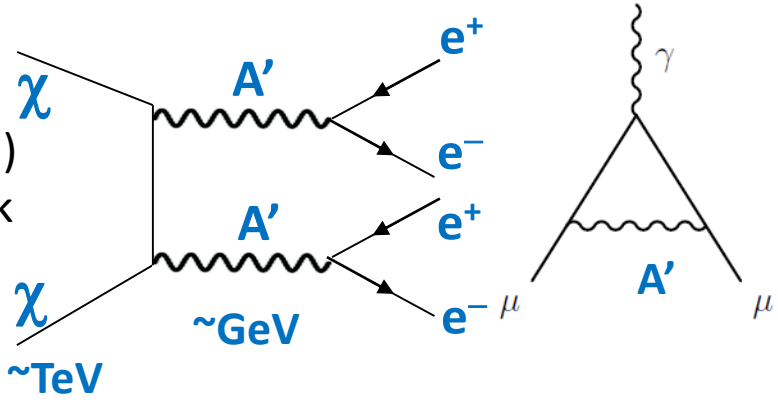
$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$




## Motivations:

1) Possible explanation for positron (but not antiproton) excess in cosmic rays (PAMELA, FERMI, AMS-02) by dark matter annihilation.

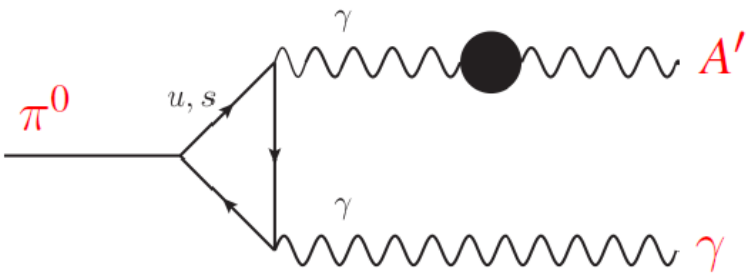
2) Possible solution for the muon **g-2** anomaly.



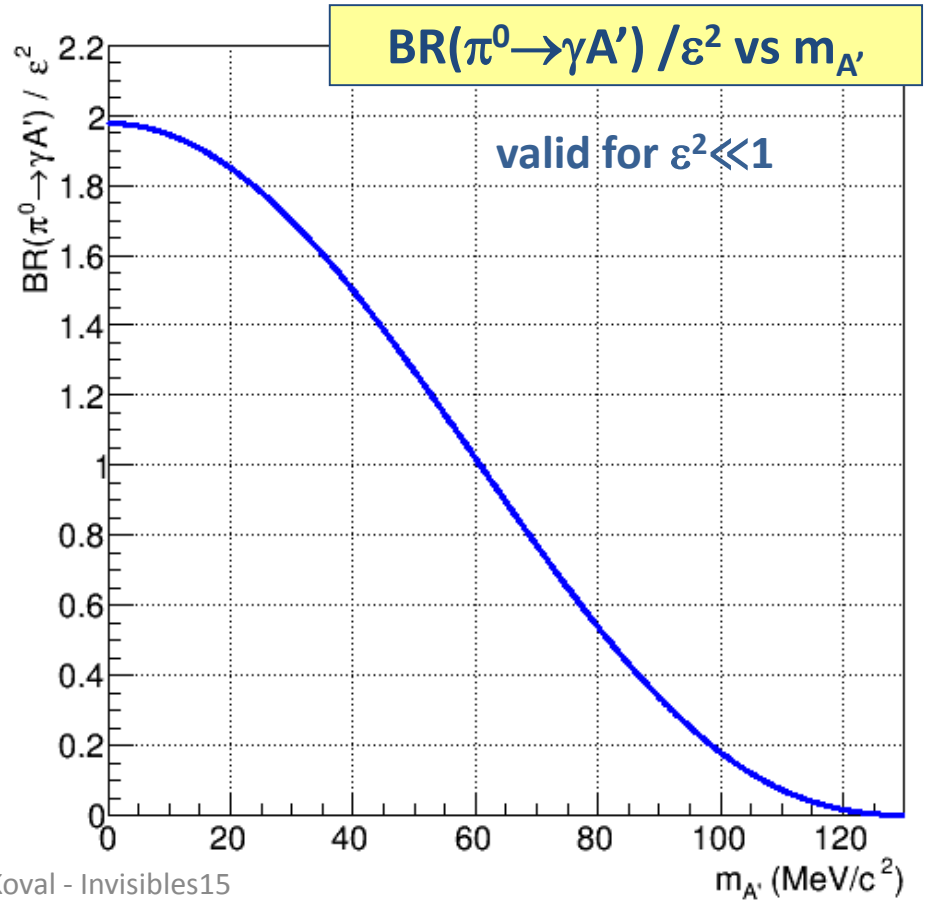
# DP Production in $\pi^0 \to \gamma A'$ Decay

*Batell, Pospelov and Ritz, PRD80 (2009) 095024*

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

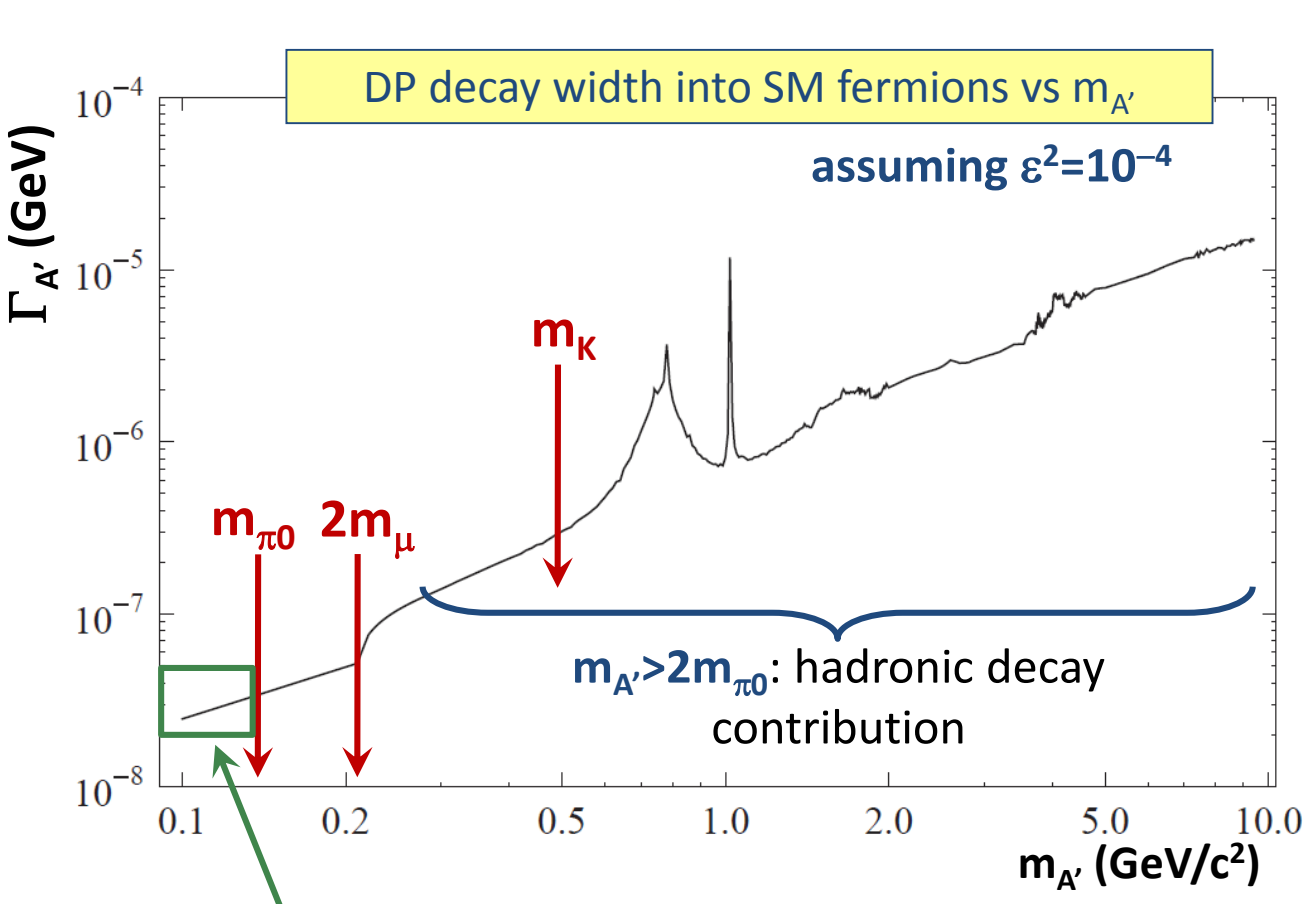


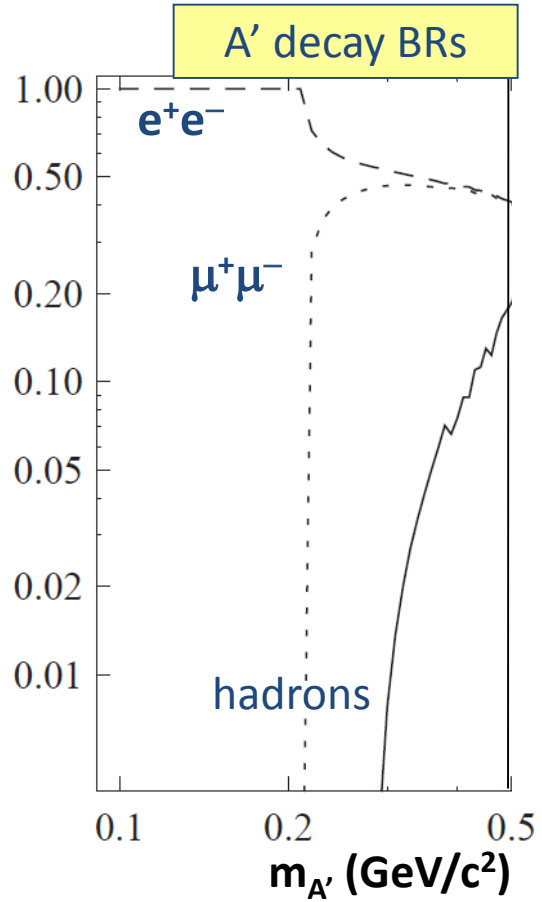

- Two unknown parameters: mass ($m_{A'}$) and mixing ($\varepsilon^2$).
- Sensitivity to DP for $m_{A'} < m_{\pi 0}$.
- Loss of sensitivity to $\varepsilon^2$ as $m_{A'}$ approaches $m_{\pi 0}$, due to kinematical suppression of the $\pi^0 \to \gamma A'$ decay.



# DP Decays into SM Fermions

*Batell, Pospelov and Ritz, PRD80 (2009) 095024*




Accessible in $\pi^0$ decays: assuming decays only into SM fermions,

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

# DP Lifetime and Mean Path

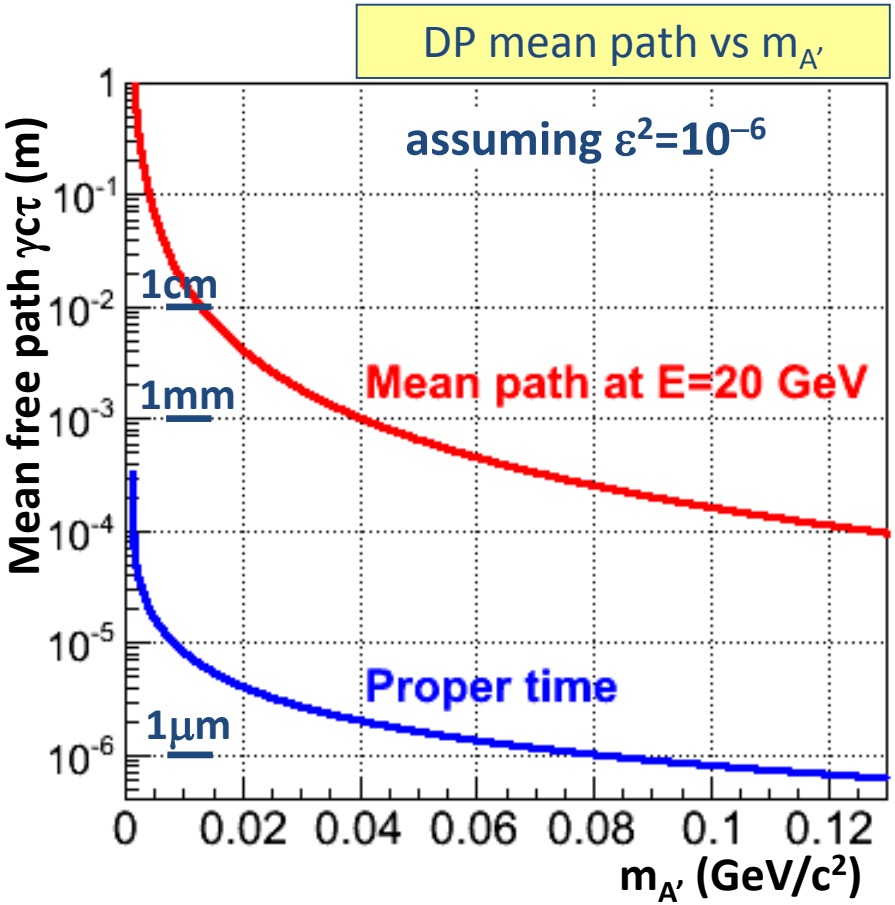
DP proper lifetime below the di-muon threshold:

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

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

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

- For $\varepsilon^2 > 10^{-7}$ and $m_{A'} > 10\ \mathrm{MeV}/c^2$, DP path length is negligible with respect to the resolution on the vertex longitudinal coordinate (~1 m).
- Therefore prompt DP decay is assumed.
- DP production and decay signature ($\pi^0 \to \gamma A'$, $A' \to e^+e^-$) is identical to that of $\pi^0_D \to \gamma e^+e^-$ decay.



# NA48/2 Data Sample

- NA48/2 data: **~$2\times10^{11}$ $K^{\pm}$** decays in the fiducial decay region.
  - Production and decay in vacuum of **~$5\times10^{10}$** tagged boosted $\pi^0$ mesons.
  - Mean free path of the $\pi^0$ is negligible (few $\mu$m).
  - Sources of $\pi^0$ mesons considered:
    $K^{\pm}\to\pi^{\pm}\pi^0$ decay (**BR=20.7%**) and $K^{\pm}\to\pi^0\mu^{\pm}\nu$ decay (**BR=3.4%**).

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

- Acceptance for both $K^{\pm}\to\pi^{\pm}\pi^0$ and $K^{\pm}\to\pi^0\mu^{\pm}\nu$ signal chains: depending on $m_{A'}$, up to **4.5%**.

# The $\pi^0_D$ 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:

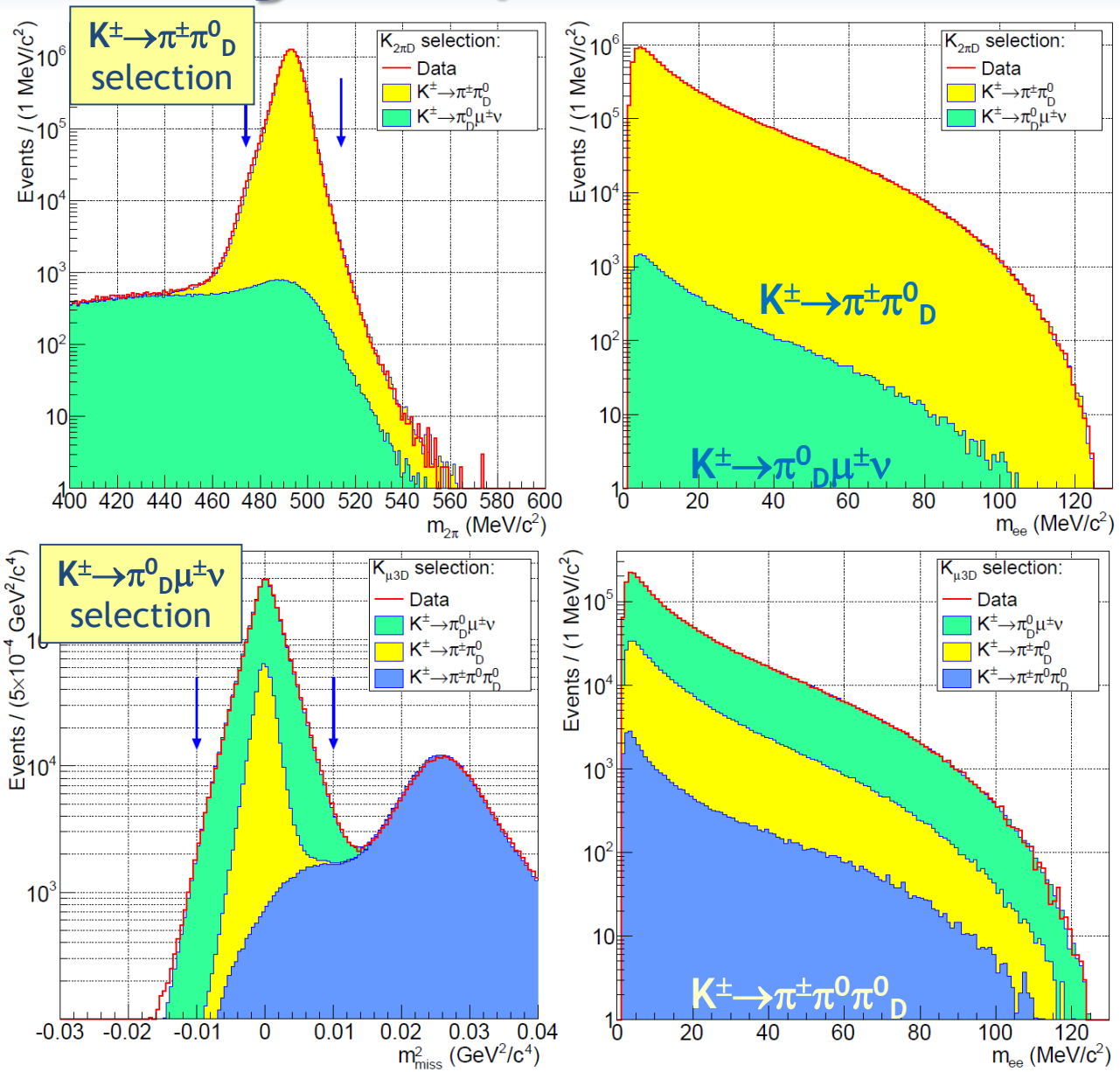
- $m_{miss}^2 = (P_K - P_\mu - P_{\pi 0})^2$ compatible with zero;
- $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/$c^2$;
- missing total and transverse momentum.

Reconstructed $\pi^0_D$ 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

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



# Simulation of $\pi^0_D$ Background

**Kinematic variables:**

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

**Differential decay rate** (lowest order):

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

(**$r=2m_e/m_\pi$**)

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

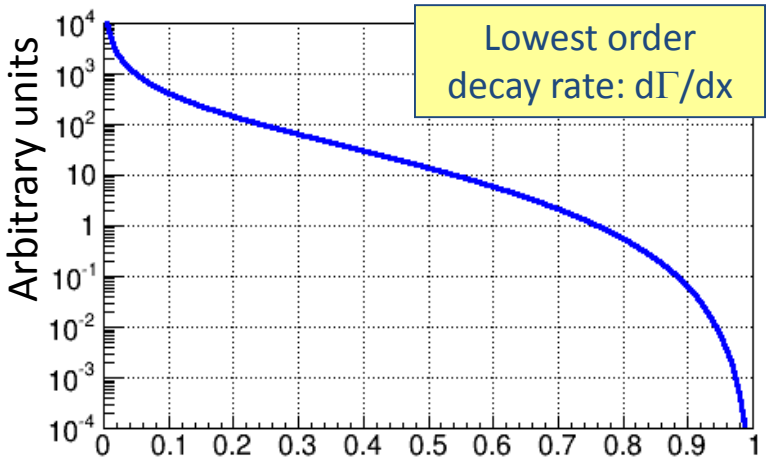
Limitation: no emission of real photons.

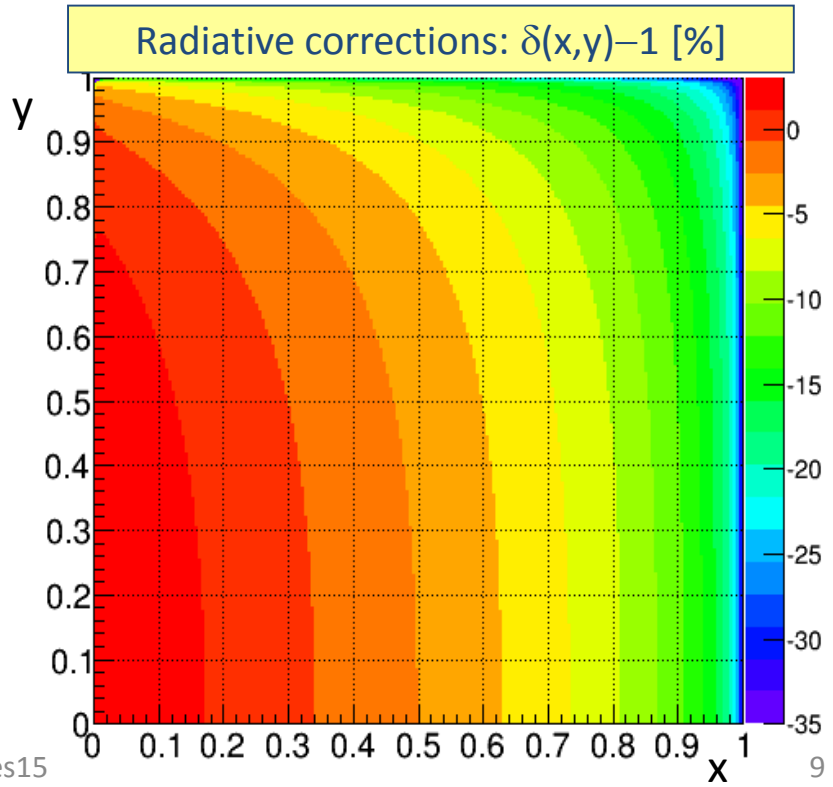
*Mikaelian and Smith, PRD5 (1972) 1763*

*Husek, Kampf and Novotný, arXiv:1504.06178*

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

- Theory expectation for the TFF slope: **a=0.0307±0.0006** *[Hoferichter et al., 2014]* or the PDG average **a=0.032±0.004** *[PDG 2014]* cannot be used due to limited precision on the radiative corrections to **$\pi^0_D$**.
- An effective TFF slope value is obtained from the **$\pi^0_D$** data sample itself.

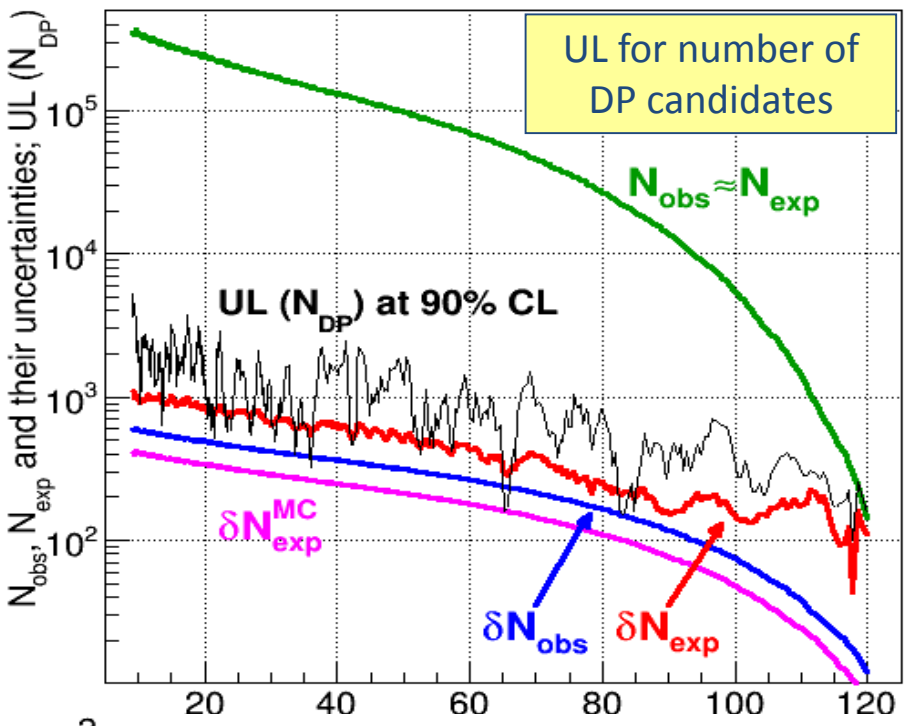


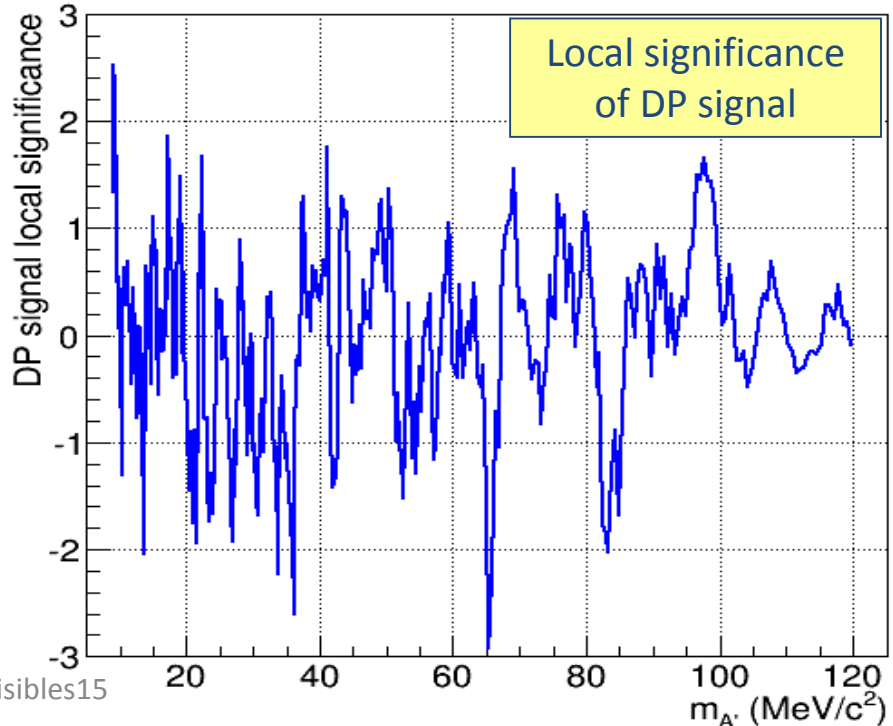



# Search for DP Signal

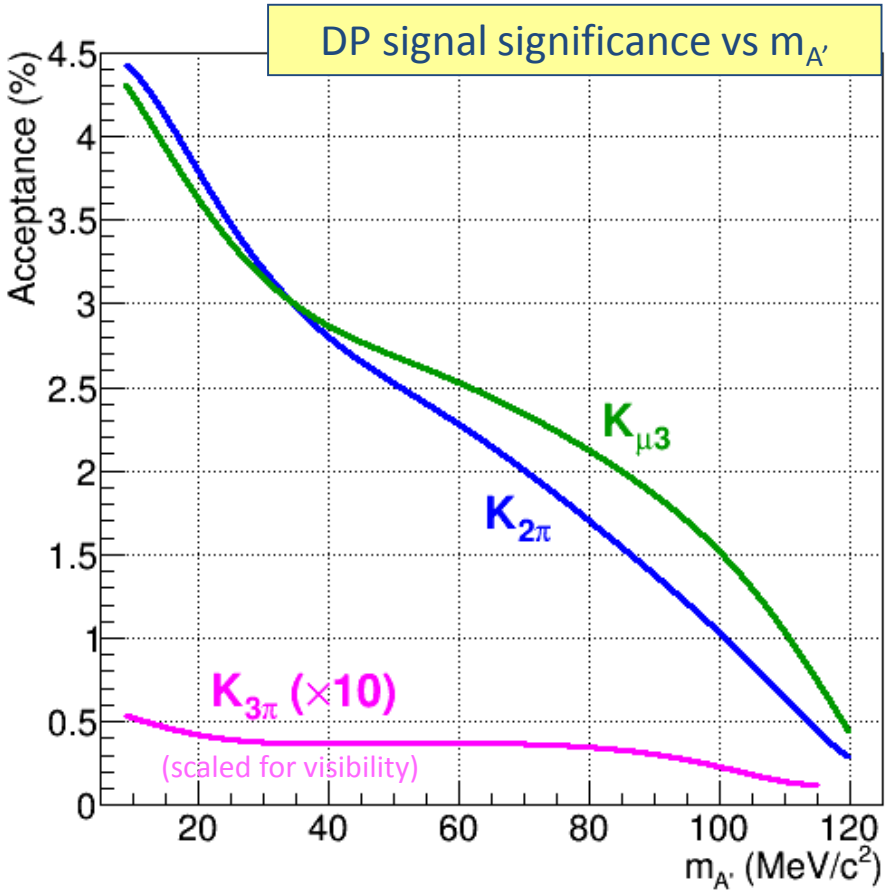
DP signal: a narrow peak in the $m_{ee}$ spectrum of $\pi^0_D$ candidates

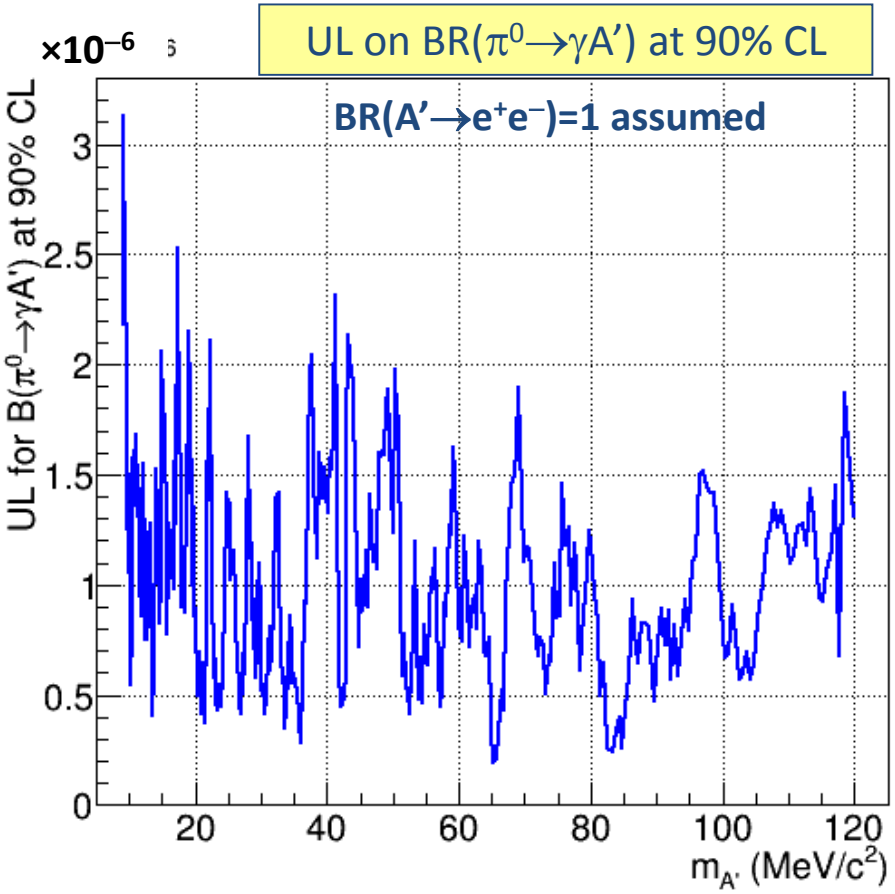
- DP mass scan performed:
  - range: $9\ MeV/c^2 \le m_{A'} < 120\ MeV/c^2$;
  - at lower $m_{A'}$, background acceptance simulation has limited precision;
  - variable DP mass step: $\approx 0.5\sigma_m$;
  - signal mass window optimized to maximize expected sensitivity: $\pm 1.5\sigma_m$;
  - DP mass hypotheses tested: **404**.
- For each $m_{A'}$, frequentist confidence intervals for $N_{DP}$ obtained from numbers of observed and expected events ($N_{obs}$, $N_{exp}$) and their uncertainties.
- Local signal significance never exceeds $3\sigma$: **no DP signal** is observed.



# Search for DP Signal (2)



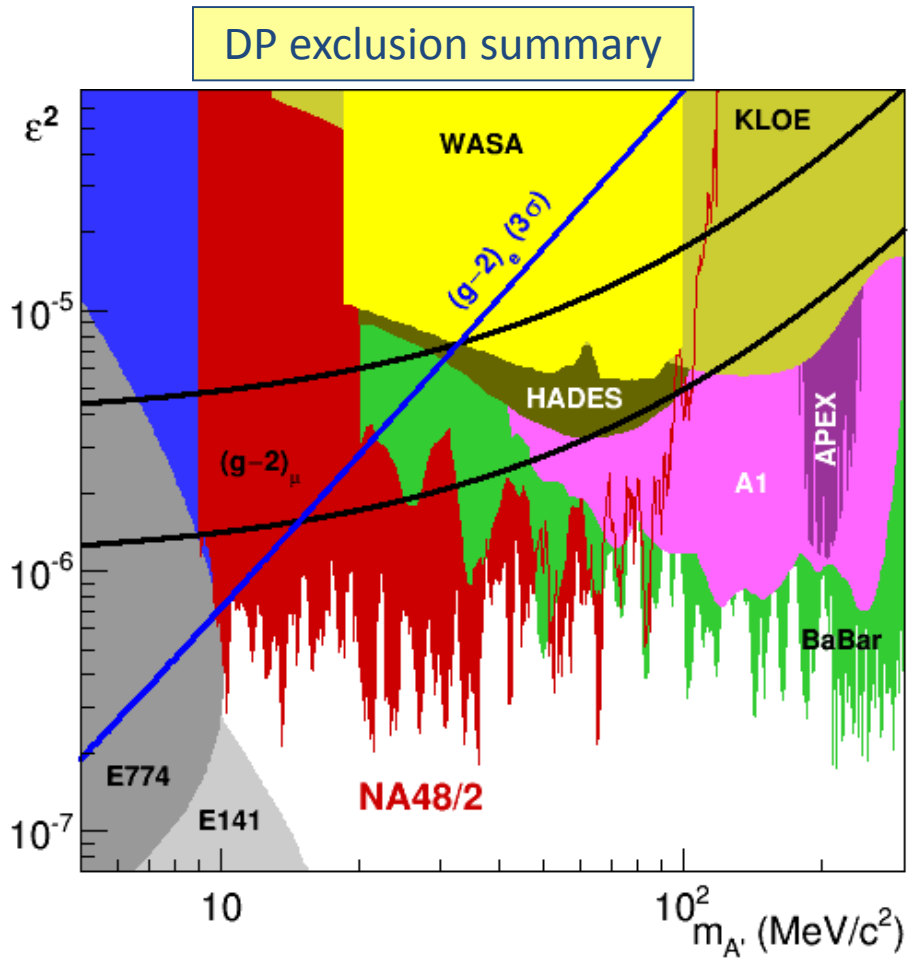




Acceptances of the DP selection for $K^{\pm} \to \pi^{\pm}\pi^0$, $K^{\pm} \to \pi^0\mu^{\pm}\nu$ and $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ decays followed by the prompt $\pi^0 \to \gamma A'$, $A' \to e^+e^-$ decay chain.

- Weak $m_{A'}$ dependence: cancellation of $m_{A'}$ dependencies of background fluctuation and acceptance.
- The obtained limits are background-limited (2–3 orders of magnitude above single event sensitivity).

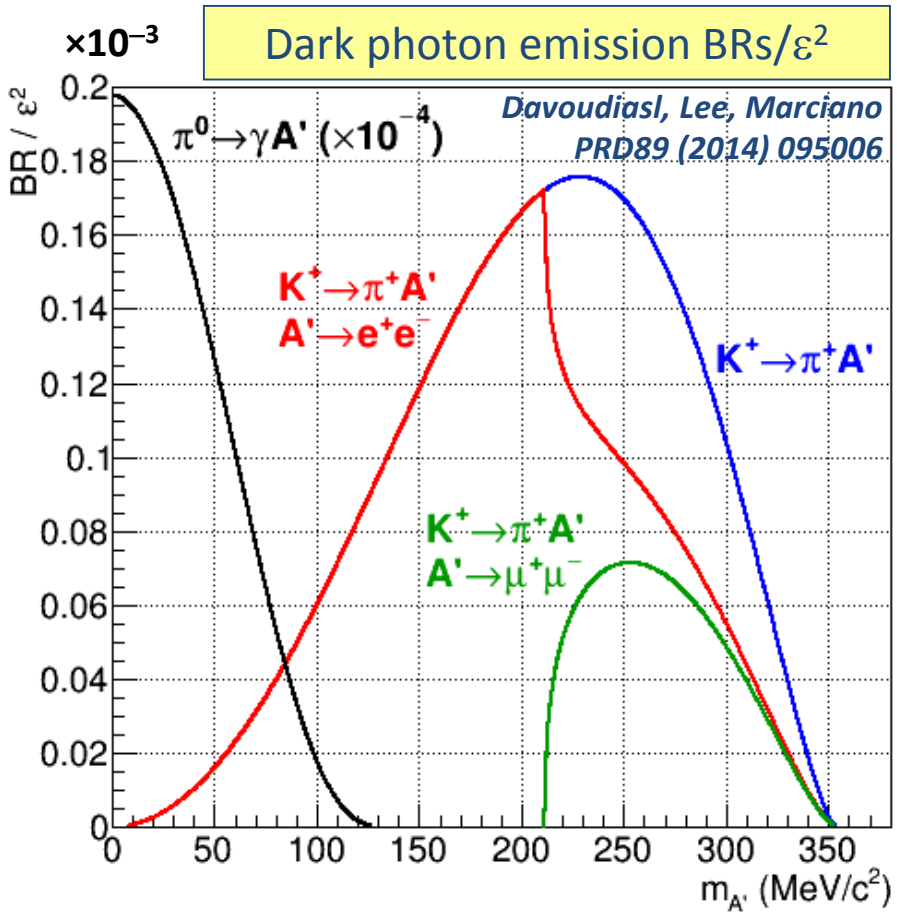
# DP Exclusion: Final NA48/2 Result

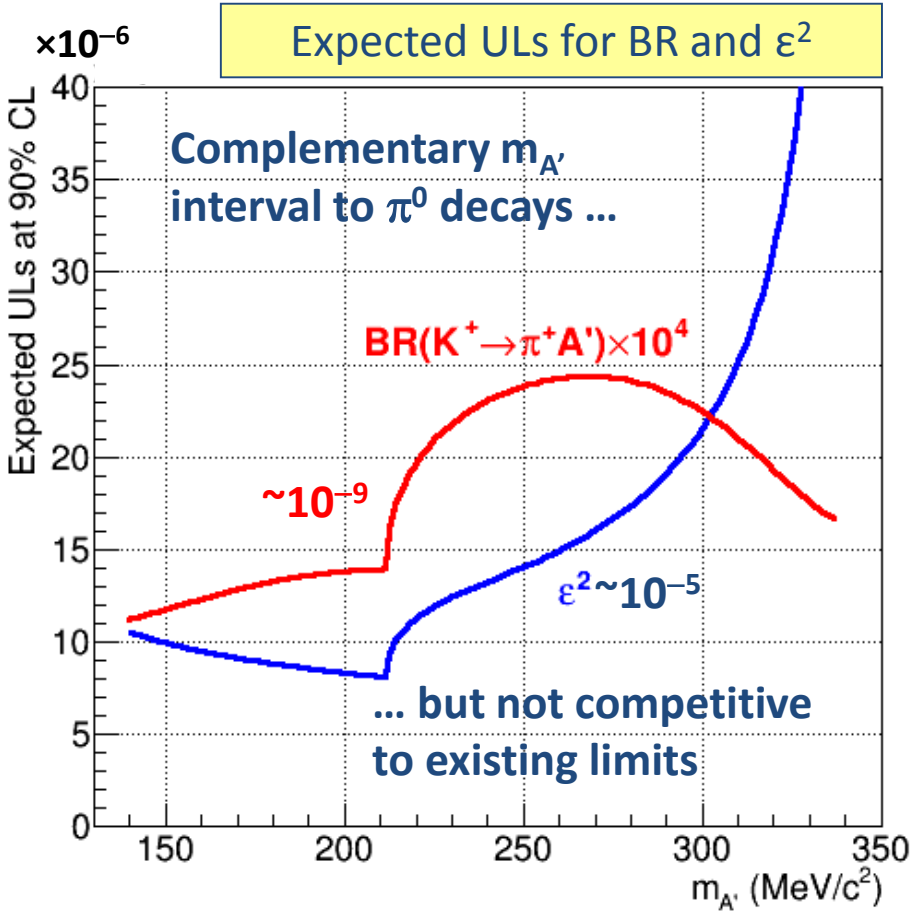
*Phys.Lett. B746 (2015) 178*




- Improvement on the existing limits in the $m_{A'}$ range **9–70 MeV/$c^2$**.
- Most stringent limits are at low $m_{A'}$ (kinematic suppression is weak).
- Sensitivity limited by the irreducible $\pi^0_D$ background, ULs are 2–3 orders of magnitude above SES.
- Upper limit on $\varepsilon^2$ scales as **$\sim(1/N_K)^{1/2}$**: modest improvement with larger samples.
- If DP couples to quarks and decays mainly to SM fermions, it is ruled out as the explanation for the anomalous **$(g-2)_\mu$**.

# Prospects for the $K^{\pm}\to\pi^{\pm}A'$ Decay




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 $K/\pi^0$ 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 $\varepsilon^2$ limits are $\varepsilon^2\sim10^{-5}$.

# Summary and Outlook

- New **NA48/2** result on dark photon search in $\pi^0$ decays:
  ***Phys.Lett. B746 (2015) 178***

  - Integrated kaon flux analysed: **$1.7\times10^{11}$** decays in flight.
  - Assumption: DP decays into SM fermions only.
  - Improved limits on DP mixing $\varepsilon^2$ in the **9–70 MeV/$c^2$** mass range.
  - The strongest limits ($\varepsilon^2\sim2\times10^{-7}$) are at **~10 MeV/$c^2$** mass.
  - The whole region favoured by **$(g-2)_\mu$** is excluded now.
  - Background-limited measurement: hard to improve below $\varepsilon^2=10^{-7}$.
  - Search via **$K^\pm\to\pi^\pm A'$** ($m_{\pi0}<m_{A'}<m_K-m_\pi$) is not competitive.

- Possible further directions:

  - Larger $\pi^0$ decay sample from **$K^+$** decays and improved resolution at **NA62**.
  - Studies of invisible **A'** decays at NA62 (**$K^+\to\pi^+$ + nothing**).
  - Probing lower $\varepsilon^2$: sensitivity studies for **$\pi^0\to\gamma A'$**
    with a displaced **$A'\to e^+e^-$** vertex.