Search for the dark photon in π^0 decays by NA48/2 at CERN

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Outline:

1) CERN kaon programme and the NA48/2 experiment
2) π^0_D decay study and dark photon search via $\pi^0 \to \gamma A'$ decay
3) Preliminary NA48/2 results on the dark photon

European Research Council
Established by the European Commission

MesonNet workshop

LNF, Frascati • 29 September 2014

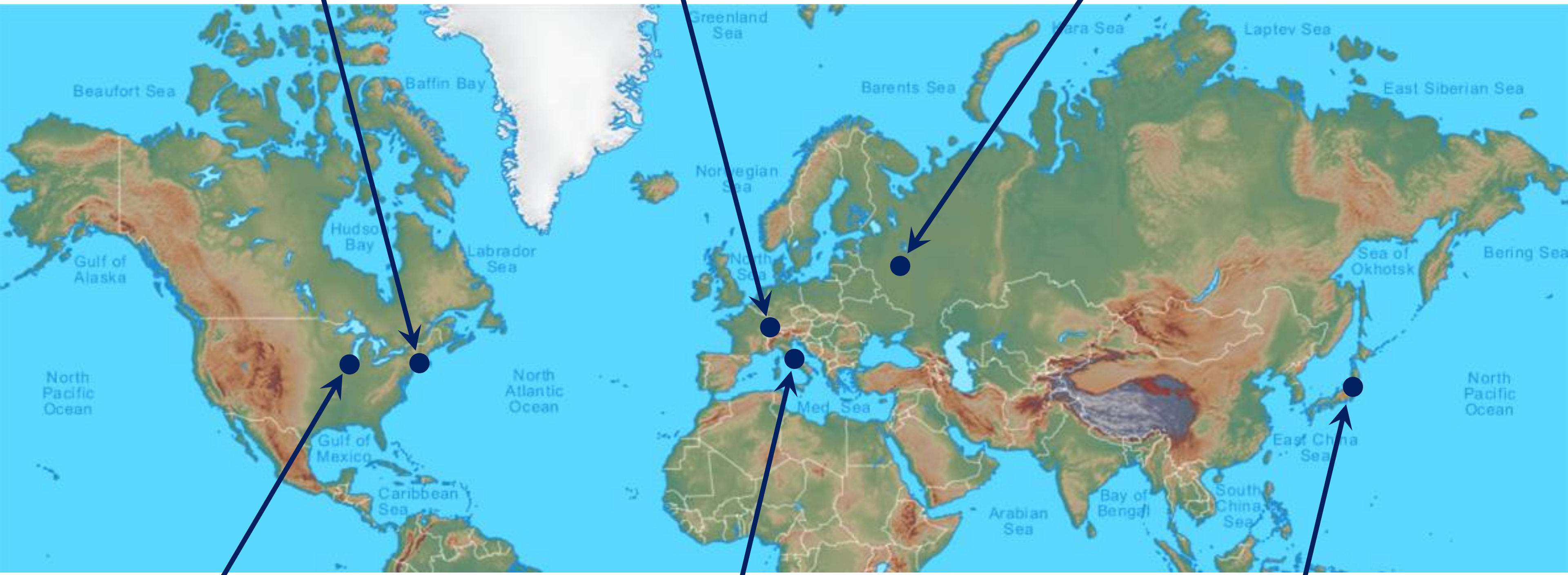
EXCELLENCE IN SCIENCE

Kaon physics facilities

BNL
E865, E777, E787, E949

CERN
NA48, **NA62**, **LHCb**

IHEP Protvino
ISTRA+, OKA, KLOD



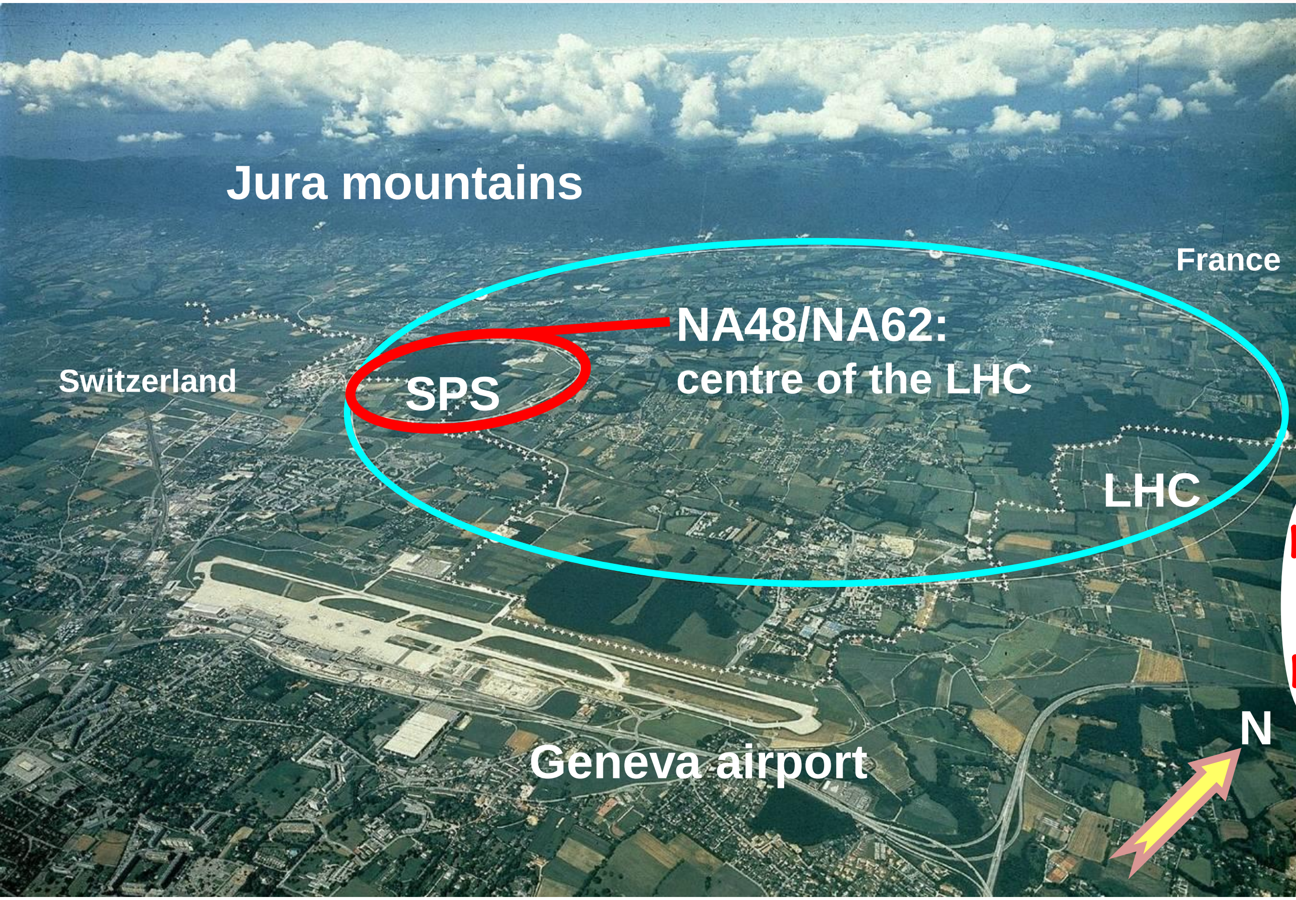
FNAL
KTeV

LNF
KLOE, KLOE-2

KEK/J-PARC
E391a, **KOTO**, TREK

A variety of experimental techniques:
K decay-in-flight (e.g. CERN), stopped **K⁺**, ϕ factory

CERN NA48/NA62 experiments



Kaon decay in flight experiments.
NA62: currently ~200 participants, 29 institutions

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	2012	technical run	
	2014	1st $K^+\to\pi^+\nu\bar{\nu}$ run	

Recent $K^{\pm}$ experiments at CERN

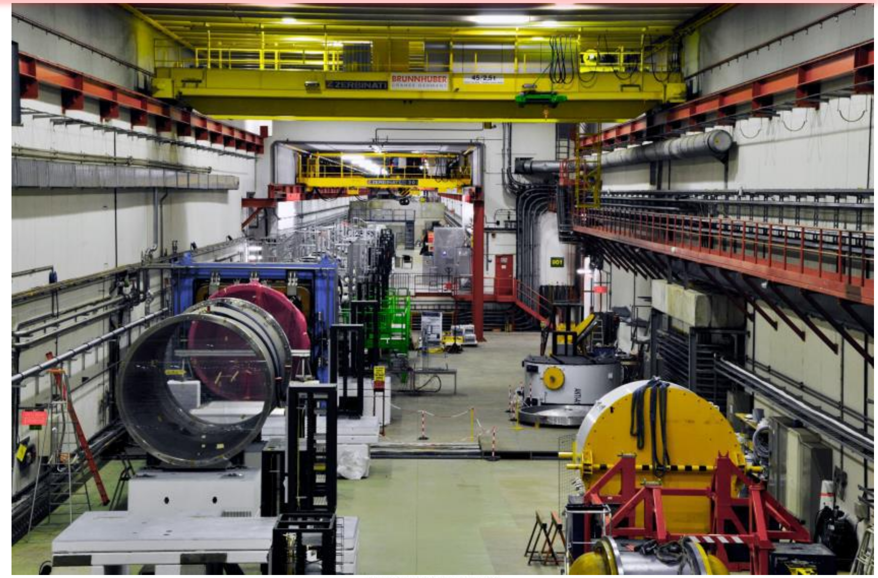
Experiment	NA48/2 ($K^{\pm}$)	NA62-R_K ($K^{\pm}$)	*NA62* (K^{+}; starting)
Data taking period	2003–2004	2007–2008	*2014–2017*
Beam momentum, GeV/c	60	74	75
RMS momentum bite, GeV/c	2.2	1.4	0.8
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV/c	120	265	270
$M(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})$ resolution, MeV/c^2	1.7	1.2	0.8
$K^{\pm}$ decays in fiducial volume	2×10^{11}	2×10^{10}	1.2×10^{13}
Main trigger	multi-track; $K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$	$e^{\pm}$	$K_{\pi\nu\nu}$ + …

Kaon beams: sources of large clean tagged π^0 samples.

- In a $K^{\pm}$ beam, ratio of number of decays $\pi^0/K^{\pm} \approx 1/3$.
- Principal π^0 source: $K^{\pm}\to\pi^{\pm}\pi^{0}$ (known as $K_{2\pi}$).
- Best data on many rare/forbidden π^0 decays come from K experiments.

The NA48/2 detector

2003–2008: charged kaon beams, the NA48 detector

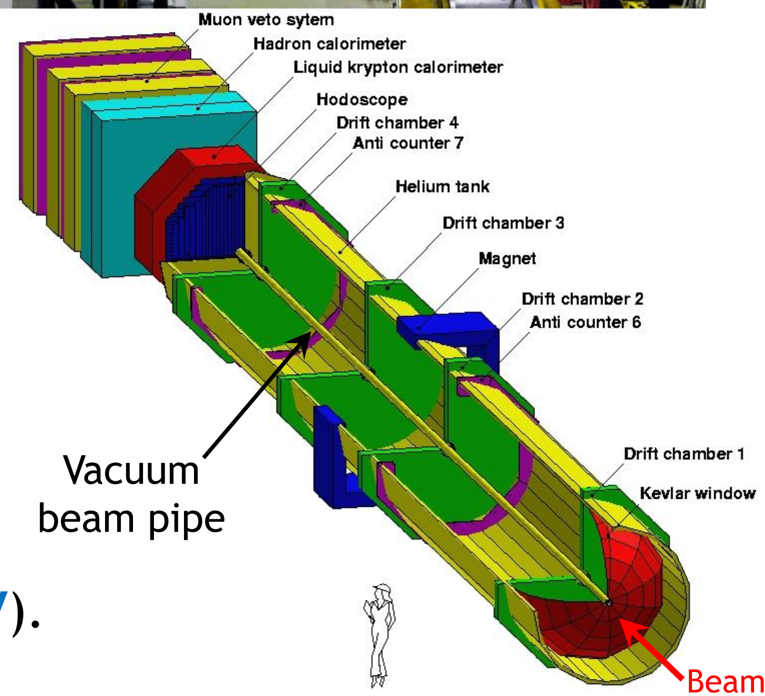


Narrow momentum band $K^{\pm}$ beams:
P_K= 60 (74) GeV/c, $\delta P_K/P_K$ ~ 1% (rms).

- Maximum $K^{\pm}$ decay rate ~100 kHz;
- **NA48/2:** six months in 2003–04;
- **NA62-R_K:** four months in 2007.

Principal subdetectors:

- Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy $\Rightarrow$ efficiency;
  $\delta p/p = 0.48\% \oplus 0.009\% p$ [GeV/c] (in 2007)
- Scintillator hodoscope (HOD)
  Fast trigger, time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$ [GeV];
  $\sigma_x=\sigma_y=4.2\text{mm}/E^{1/2} \oplus 0.6\text{mm}$ (1.5mm@10GeV).

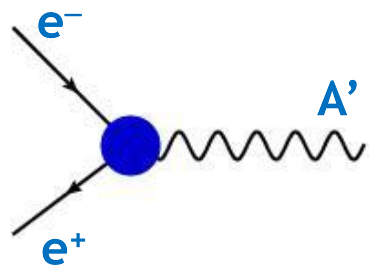


The dark photon

The simplest hidden sector model introduces one extra **U(1)** gauge symmetry and a corresponding gauge boson: the dark photon (**A'**).

QED-like interaction:

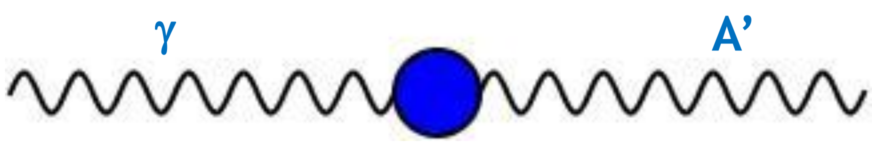
$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$



(not all SM fermions need to be charged under this new symmetry)

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

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

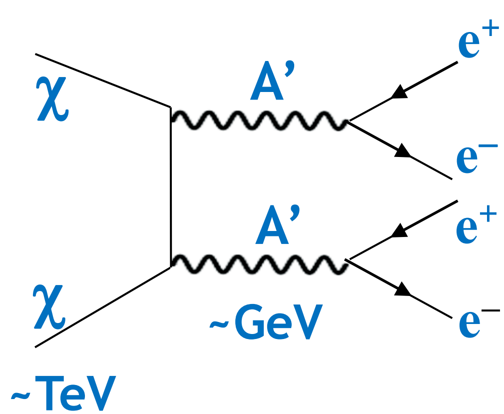


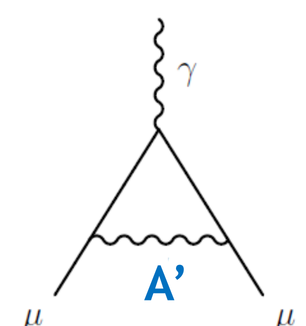
Motivations:

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:

$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi} \varepsilon^2 F(m_V/m_\mu)$$



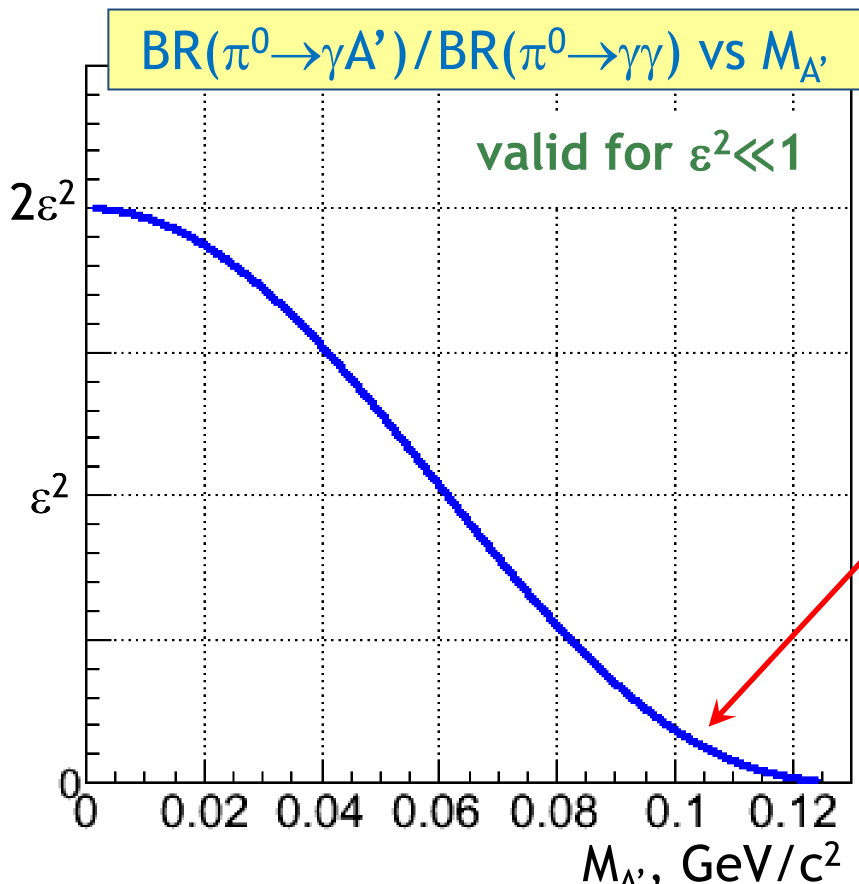


DP production in $\pi^0 \to \gamma A'$ decay

Batell, Pospelov and Ritz, PRD80 (2009) 095024

$$\frac{\mathcal{B}(\pi^0 \to \gamma U)}{\mathcal{B}(\pi^0 \to \gamma\gamma)} \approx 2\epsilon^2 |F(M_U^2)|^2 \left(1 - \frac{M_U^2}{M_\pi^2}\right)^3$$

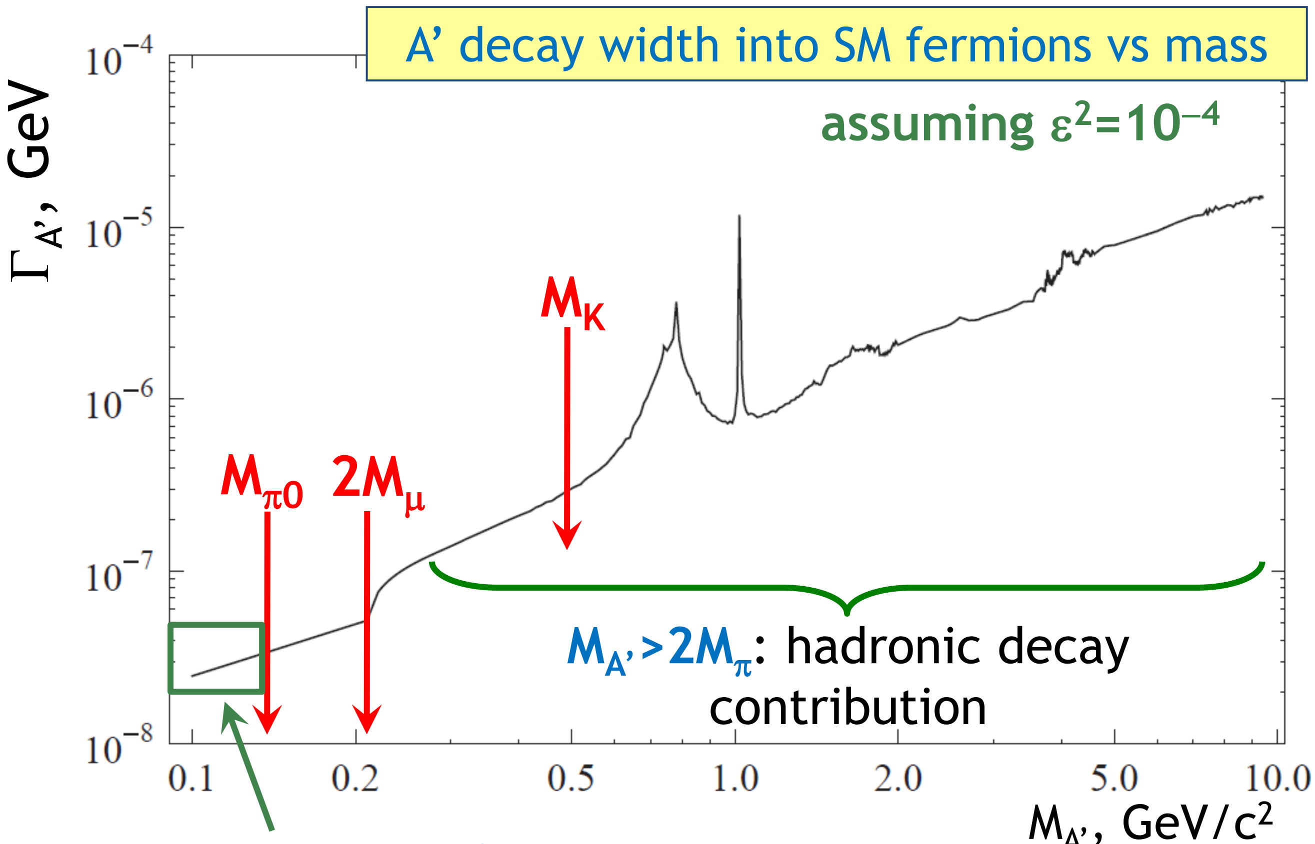
π^0 transition form factor: a small correction

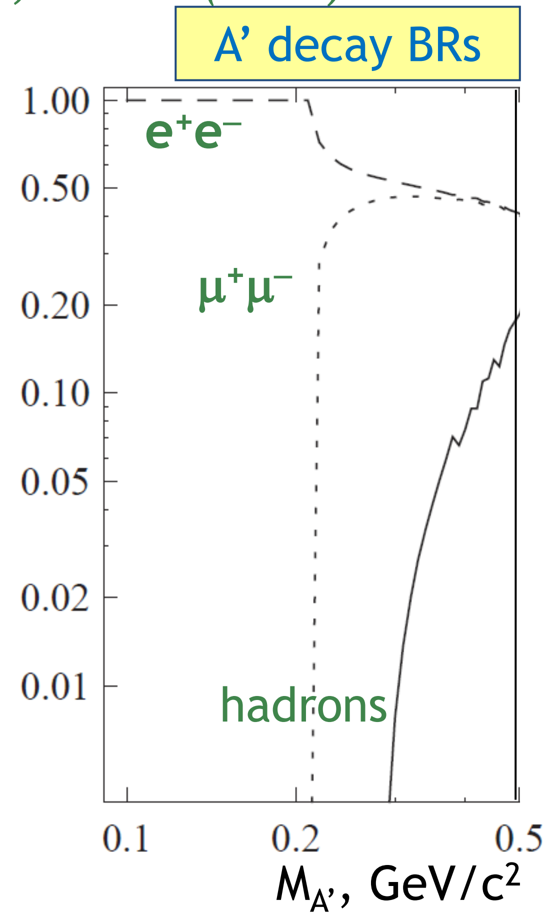


Kinematical suppression of $\pi^0 \to \gamma A'$ decay for large $M_{A'}$

DP decays into SM fermions

Batell, Pospelov and Ritz, PRD79 (2009) 115008





Accessible in π^0 decays:

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

Assuming decays only into SM fermions, $BR(A'\to e^+e^-)=1$ for $M_{A'}<2M_\mu$.

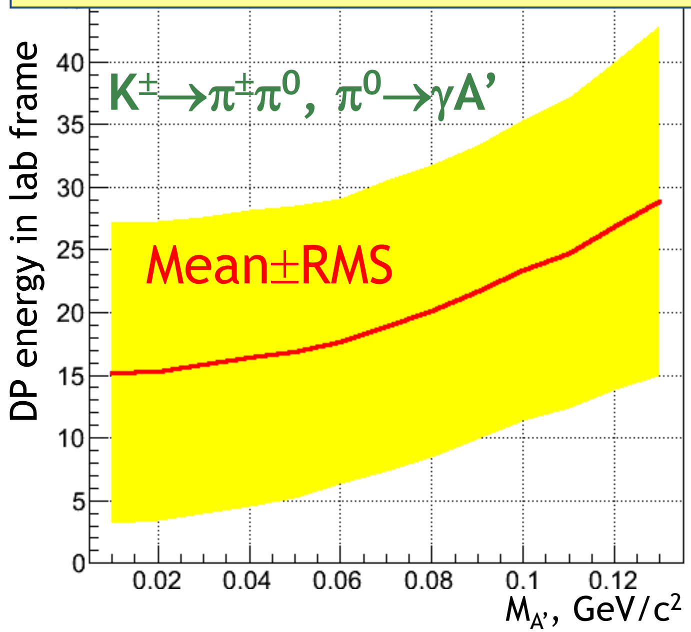
DP lifetime and mean path

Assuming decays to SM fermions only,
decay width for $M_e \ll M_{A'} < 2M_\mu$: $\Gamma_{A'} \approx \alpha\varepsilon^2 M_{A'}/3$, $BR(A' \to e^+e^-)=1$

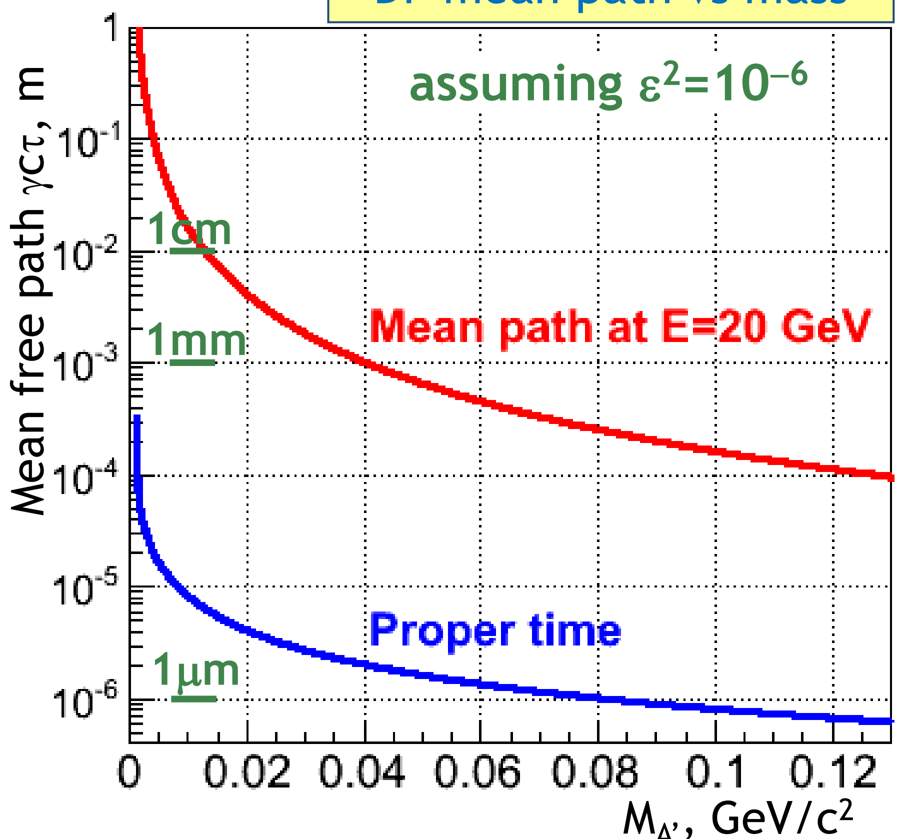
Proper lifetime:

$$c\tau = \frac{\hbar c}{\Gamma_U} \approx 80\ \mathrm{nm} \times \frac{10^{-6}}{\epsilon^2} \times \left(\frac{M_U}{\mathrm{GeV}}\right)^{-1}$$

DP energy in lab frame vs mass



DP mean path vs mass



Prompt production (negligible path length) for $\varepsilon^2 > 10^{-7}$:
standard "3-track vertex" analysis

NA48/2 data sample

- Method: exclusive search for the decay chain $K^{\pm}\to\pi^{\pm}\pi^0$, $\pi^0\to\gamma A'$, $A'\to e^+e^-$. Fully reconstructed final state, 3-track vertex topology.

- Identical to $K^{\pm}\to\pi^{\pm}\pi^0_D$, $\pi^0_D\to\gamma e^+e^-$; $BR(K_{2\pi D})=0.24\%$: sensitivity is limited by the irreducible $K_{2\pi D}$ background.

- Sensitivity: $UL(\varepsilon^2) \sim (\text{Kaon Flux})^{-1/2} \times (\text{Acceptance})^{-1/2} \times (M_{ee}\ \text{resolution})^{+1/2}$.

- Number of **kaon decays**: $N_K \approx 2\times10^{11}$.
  - ✓ That is $\approx 4\times10^{10}$ π^0 decays in vacuum from $K^{\pm}\to\pi^{\pm}\pi^0$ decays, leading to $\sim10^{10}$ fully reconstructable tagged π^0 decays.
  - ✓ Efficient trigger chain for 3-track vertices throughout the data taking based on HOD multiplicity (L1) and DCH track reconstruction (L2).

- Signal **acceptance**: depending on $M_{A'}$, up to 2.5%.

- Spectrometer **mass resolution**: $\sigma_{Mee} \approx 0.012\times M_{ee}$.

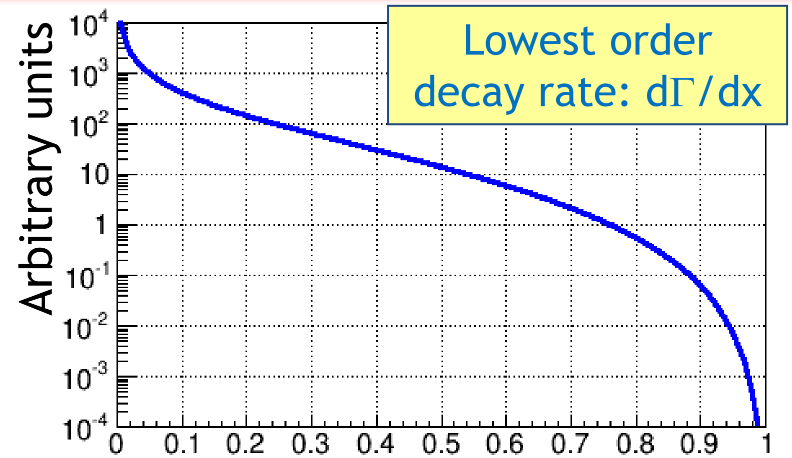
Kinematic variables:
$x = (q_1+q_2)^2/m_\pi^2 = (m_{ee}/m_\pi)^2$
$y = 2p(q_1-q_2)/[m_\pi^2(1-x)]$

π^0_D background study

(1) Differential decay rate (lowest order):

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

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

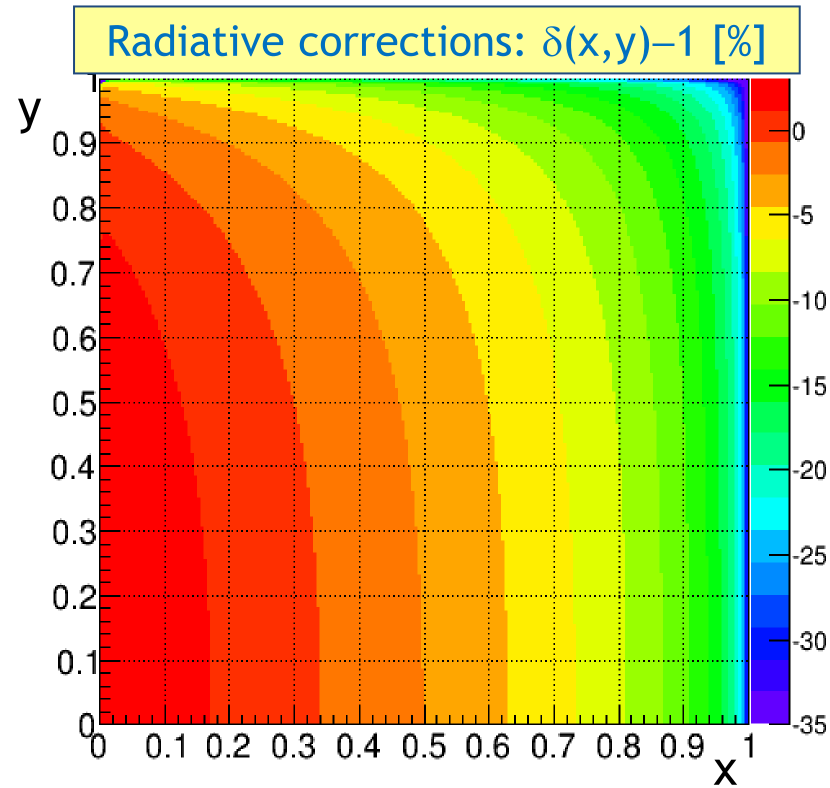


(2) Radiative corrections:

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

Mikaelian and Smith, PRD5 (1972) 1763
Improved numerical precision:
Husek, Kampf and Novotný, to be published

Limitation: no emission of real photons.
Is it possible to improve on that?

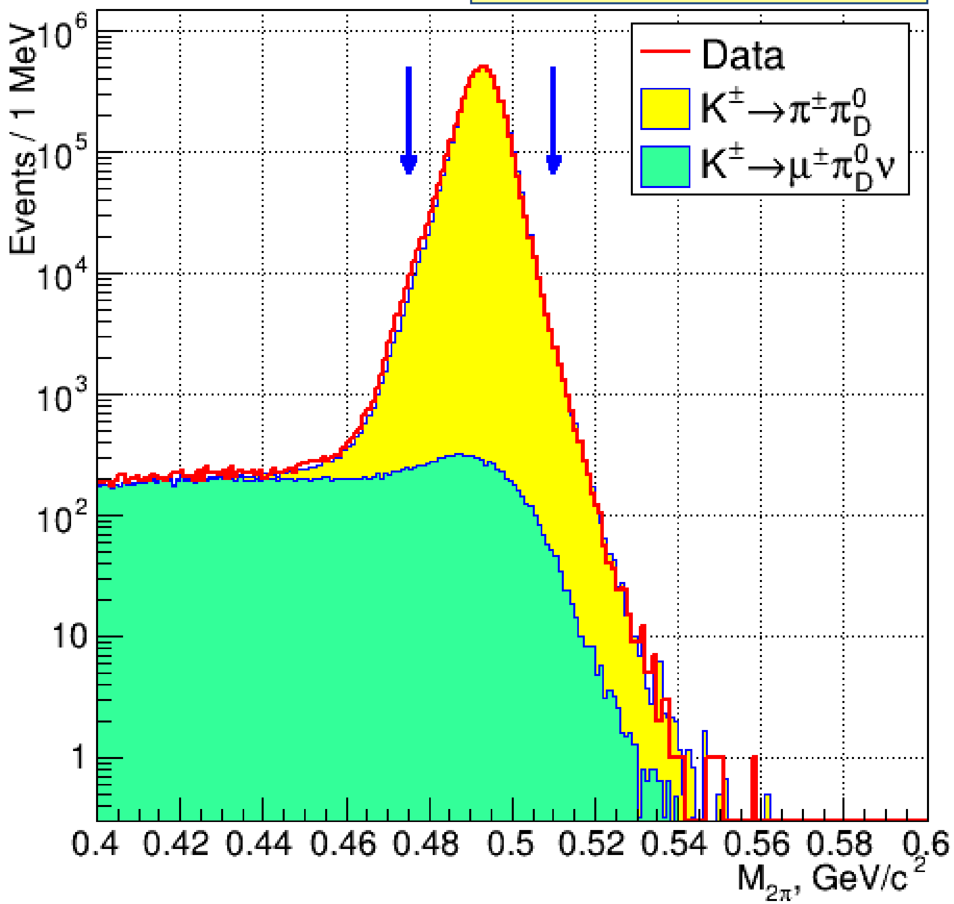


(3) π^0 transition form-factor: $F(x)=1+ax$.

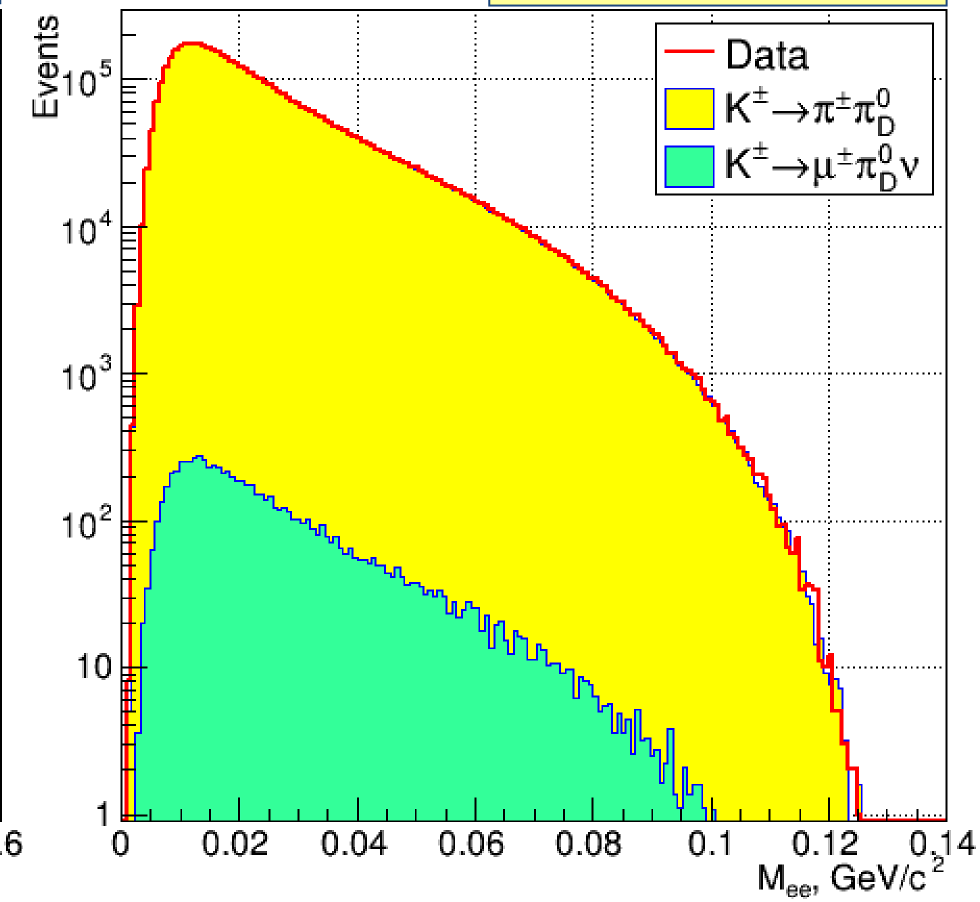
- ✓ TFF slope (PDG, dominated by $e^+e^-\to e^+e^-\pi^0$ measurement): $a=0.032\pm0.004$.
- ✓ Modified TFF slope value is used for an adequate data description.
- ✓ TFF slope measurement in progress.
- ✓ Limited sensitivity to TFF in π^0_D decays: will not improve on the PDG precision.

$K_{2\pi D}$ data sample

$M_{2\pi}$: data and MC



M_{ee}: data and MC



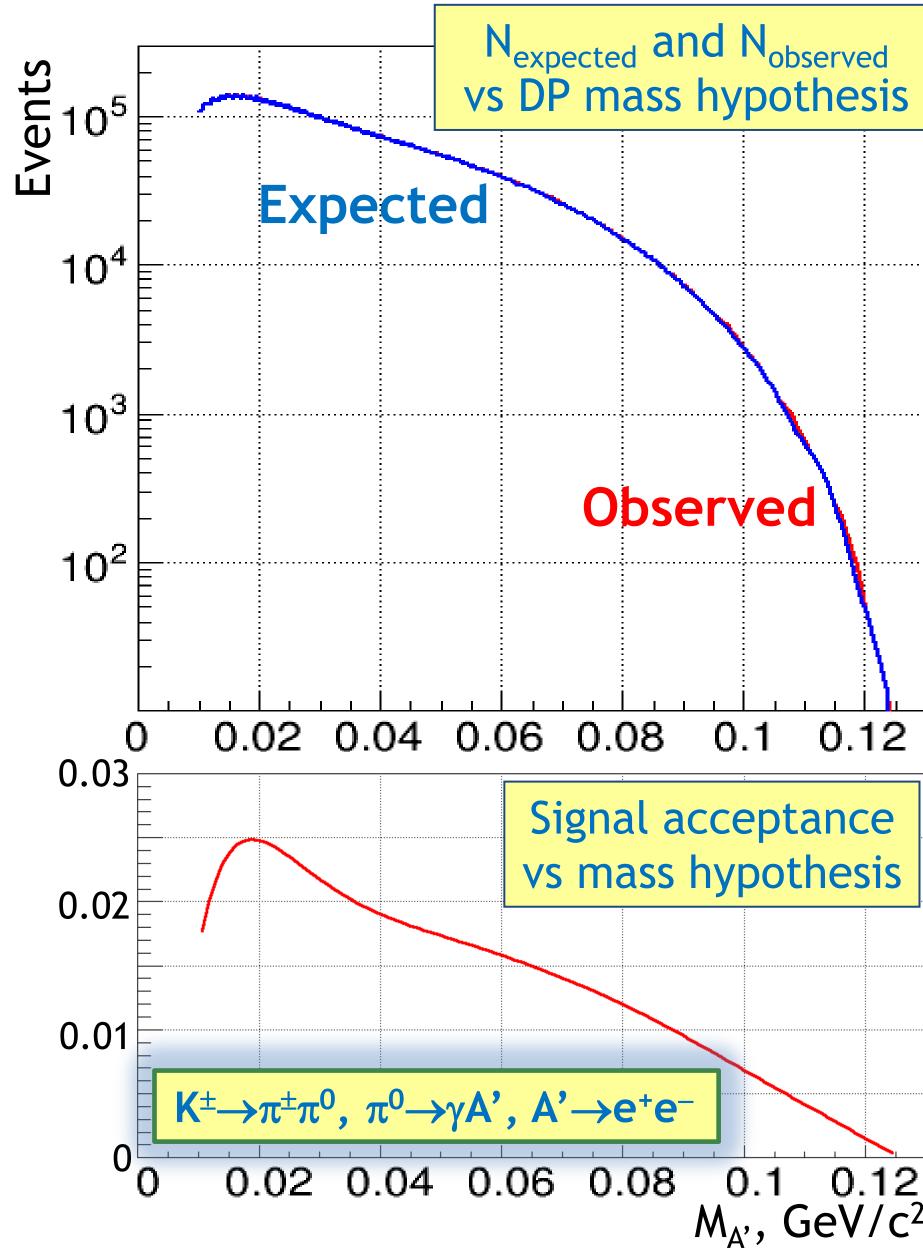
Selection optimized for $K_{2\pi D}$ (total P_T consistent with zero).

Candidates: $N(K_{2\pi D}, M_{ee}>10\text{MeV}/c^2)=4.687\times10^6$, $K_{\mu 3D}$ contribution: **0.15%**.

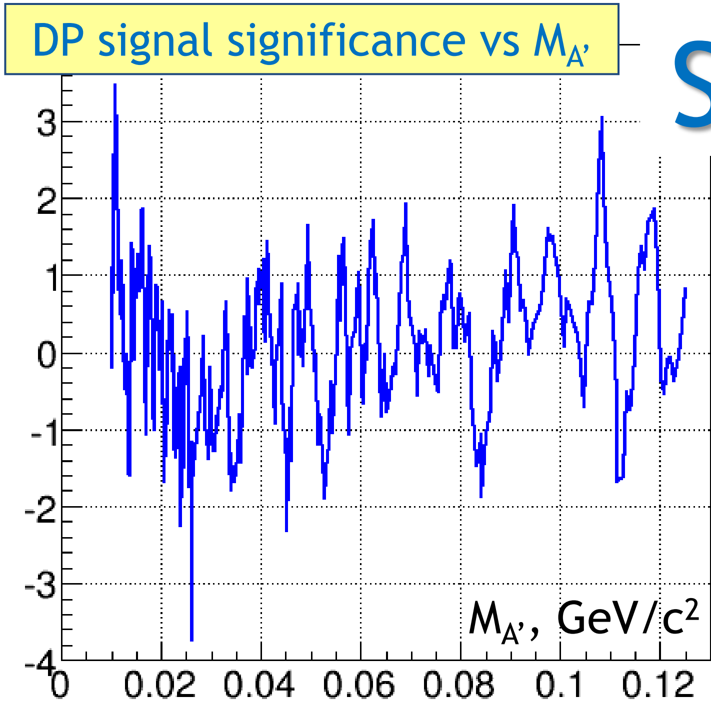
Semileptonic $K^\pm$ decays ($K^\pm\to\pi^0_D l^\pm\nu$, large P_T) can be included.

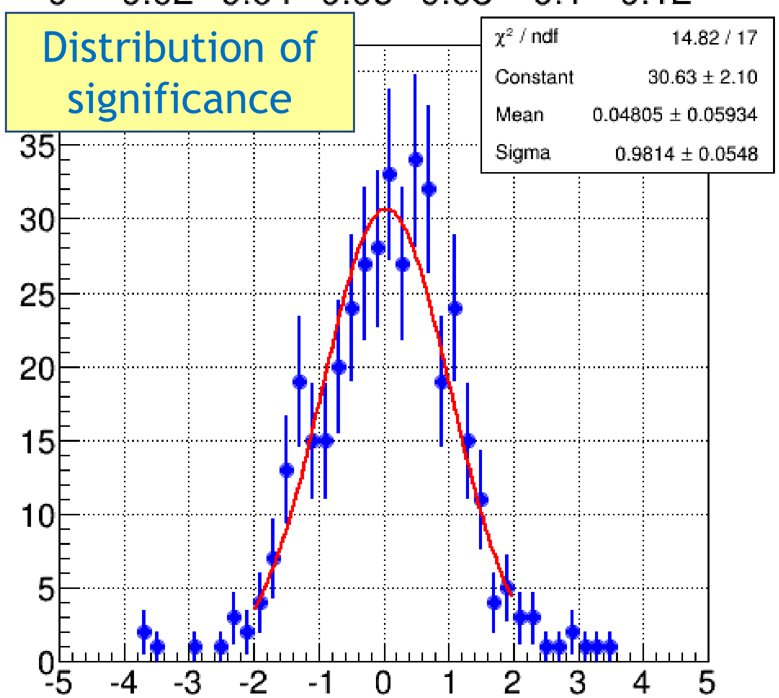
DP signal: peak in M_{ee} spectrum

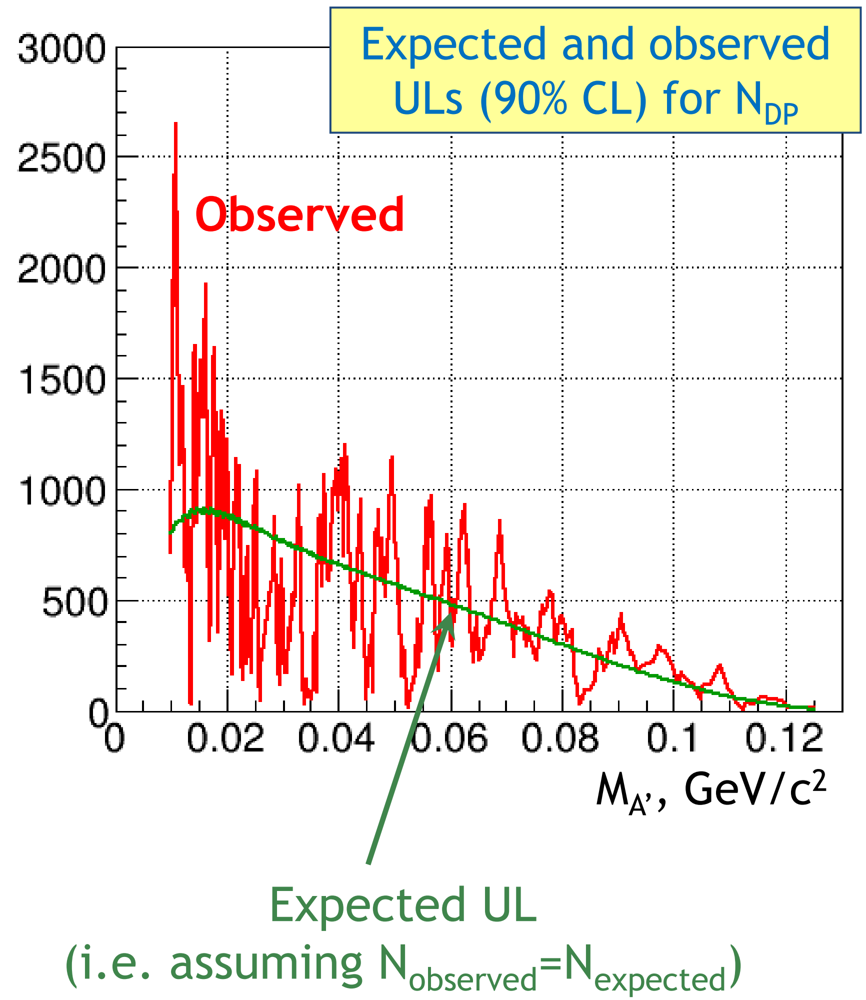
- Scanned DP mass range: **$10\ MeV/c^2 < M_{DP} < 125\ MeV/c^2$**.
- Below **$10\ MeV/c^2$**, acceptance is low and difficult to simulate.
- Variable DP mass step: **$\approx 0.5\sigma_{Mee}$**.
- DP mass hypotheses tested: **398**.
- Confidence intervals for $N_{A'}$ are computed from $N_{observed}$, $N_{expected}$ and $\delta N_{expected}$ in the signal mass window using the Rolke-Lopez method.
- Signal mass window optimized for maximum sensitivity: **$\pm 1.5\sigma_{Mee}$** (acceptance vs π^0_D background).
- $\delta N_{expected}$ is a statistical uncertainty: limited MC statistics and the limited control sample for trigger efficiency measurement.



Statistical significance



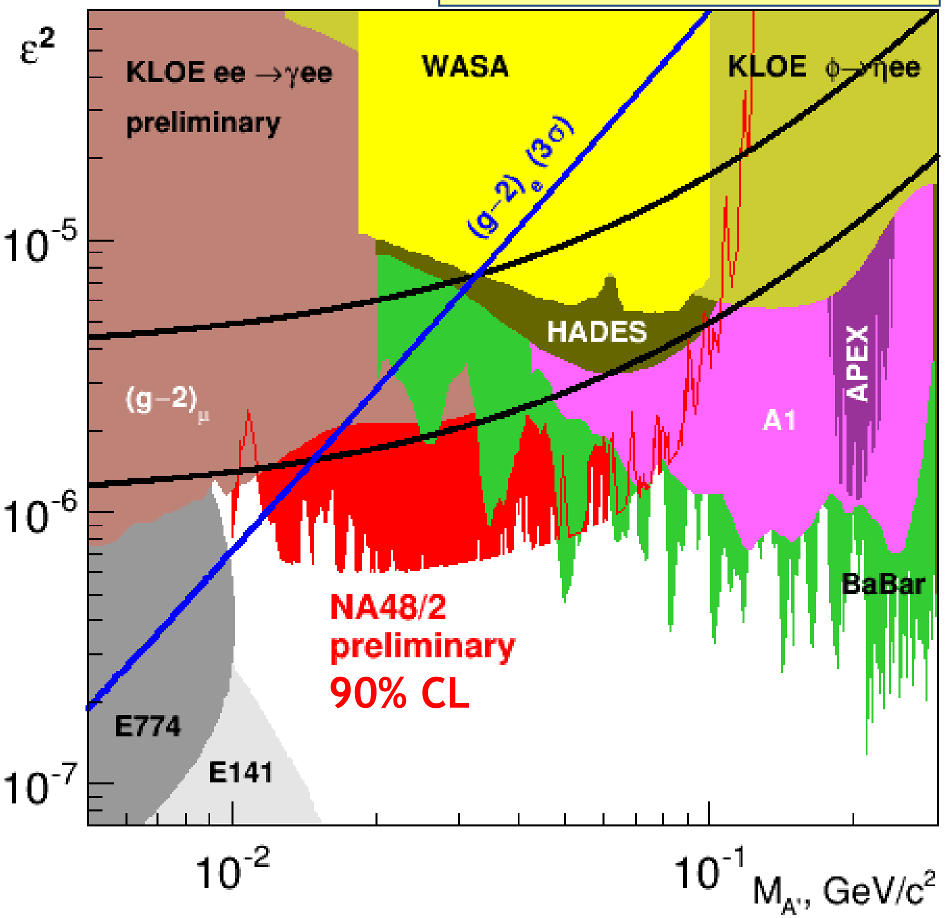




NA48/2 preliminary limit

[NEW: September 2014]

DP exclusion summary



- We conservatively assume $N_{observed}=N_{expected}$ in cases when $N_{observed}<N_{expected}$. Therefore there are no downward spikes.
- Improvement of the existing limits in the range **10–60 MeV/c²**.
- If DP couples to SM fermions and photons and decays only to electrons, it is ruled out as the explanation for anomalous **$(g–2)_{\mu}$**.

Summary

- The **NA48/2** experiment at CERN has been exposed to **$\sim 2\times 10^{11}$ $K^{\pm}$** decays in flight in 2003–2004: a precision multi-purpose $K^{\pm}$ experiment but also a π^0 facility.
  $\sim 10^{10}$ tagged π^0 decays in vacuum: $\pi^0 \to e^+e^-\gamma$, e^+e^-, $4e^{\pm}$ recorded.
- At **NA62**, **~50** times more π^0 decays expected (but downscaled).
- New preliminary **NA48/2** result presented: DP search in π^0 decay.
  - ✓ 90% CL limits are $\varepsilon^2 < 10^{-6}$ for $12\ \mathrm{MeV}/c^2 < M_{A'} < 55\mathrm{MeV}/c^2$;
  - ✓ the strongest limit ($\varepsilon^2 < 6\times 10^{-7}$) is for $M_{A'} \approx 20\mathrm{MeV}/c^2$;
  - ✓ existing limits improved in mass range 10–$60\ \mathrm{MeV}/c^2$.
- Background-limited measurement: will not improve with this technique beyond $\varepsilon^2 = 10^{-7}$ in near future.
- The π^0_D decay is irreducible background. π^0 TFF measurement is in progress. Open issue: radiative corrections.