NA48/2 studies of rare decays

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On behalf of the NA48/2 collaboration

Les Rencontres de Physique de la Vallée d'Aoste
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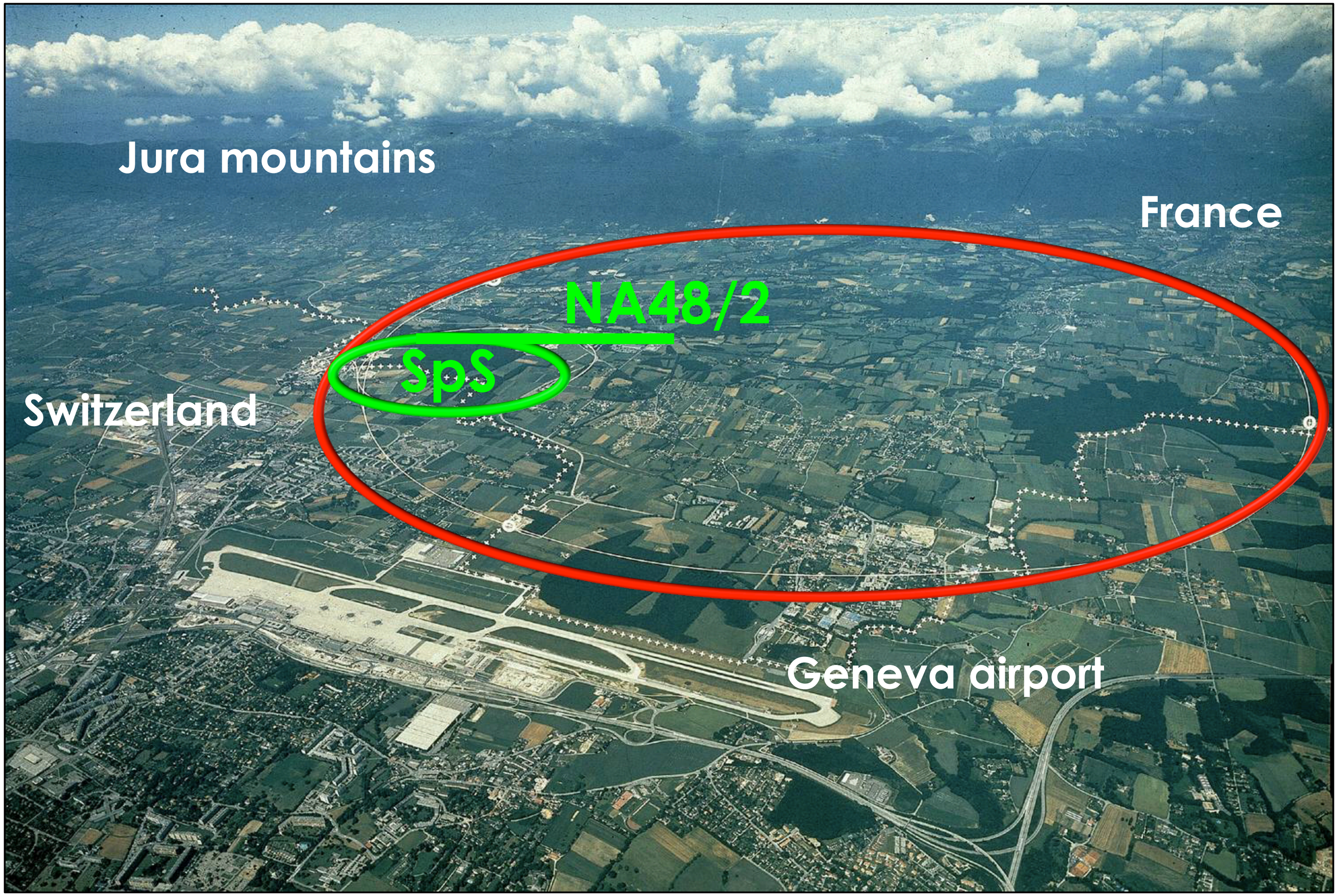
Outline

- NA48/2 experiments at CERN SPS
- $K^{\pm}$ ChPT studies history in NA48/2
- New measurement of $K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ (new)
- Search for the dark photon in π^{0} decays (preliminary)
- Conclusion

The NA48/2 experiment @ SPS north area



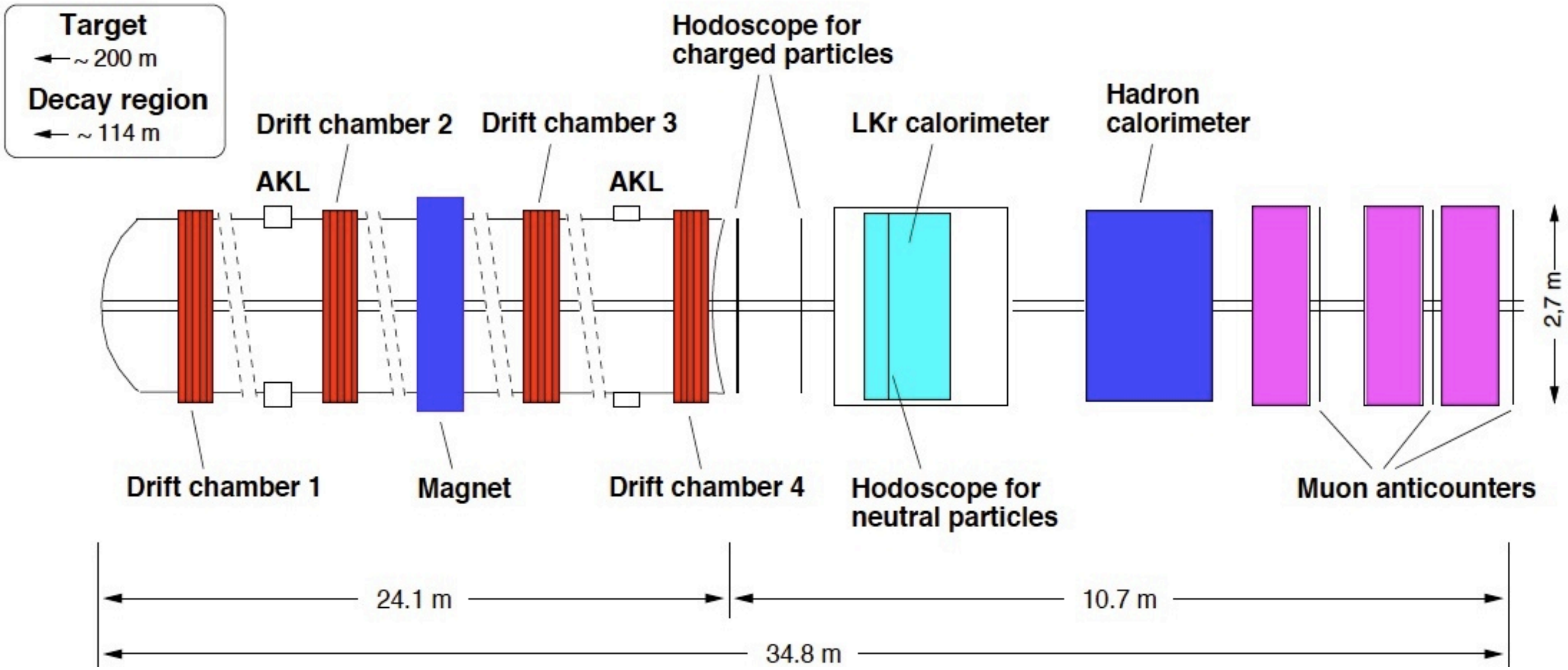
NA48/2 collaboration 15 institutes from:
Austria, France, Germany, Italy, Russia, CERN, UK, USA

NA48/2 experiment (2003-2004)

NA48/2 Data taking: 4 months in 2003 ($K^{\pm}$) + 4 months in 2004 ($K^{\pm}$)

Simultaneous K^{+} and K^{-} beam with N_{K+}/N_{K-} ~1.8

Total of ~$2 \cdot 10^{11}$ charged Kaon decays in the fiducial decay region



Magnetic Spectrometer

- 4 drift chambers and a dipole magnet

$$\frac{\sigma(p)}{p} = (1.02 \oplus 0.044\,p)\% \quad \text{p in GeV/c}$$

Liquid Krypton EM calorimeter (LKr)

- High granularity (13248 cells of 2x2 cm^2)
- Quasi-homogeneous, $7m^3$ liquid Kr ($27X_0$)

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.4\% \quad \text{E in GeV}$$

The ChPT weak chiral lagrangian

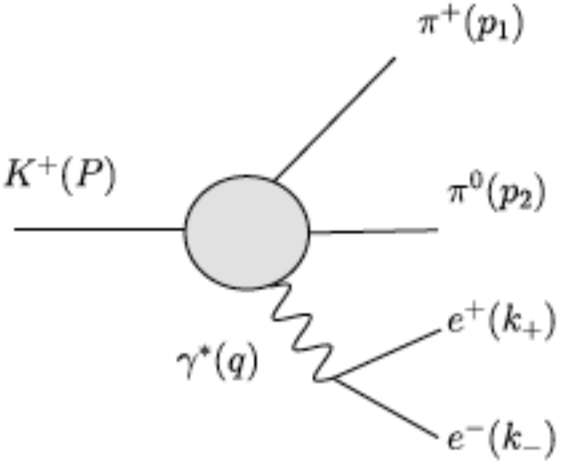
- The basic ΔS=1 O(p^4) chiral lagrangian can be written as:

$$L_{\Delta S=1} = L^2_{\Delta S=1} + L^4_{\Delta S=1} = \underbrace{G_8 F^4 \langle \lambda_6 D_\mu U^+ D^\mu U \rangle}_{K\to 2\pi/3\pi,\ \gamma\gamma} + \underbrace{G_8 F^2 \sum N_i W_i}_{K^+\to\pi^+\gamma\gamma,\ K\to\pi\gamma\gamma}$$

- 37 poorly known N_i coefficients and W_i operators
- Combinations of such couplings are accessible by measuring Kaon decays branching fractions and form factors D'Ambrosio PoS(EFT09)061
- NA48/2 can access all the charged decay with very high precision

Decay	$\mathscr{L}^4_{\Delta S=1}$ counterterms	
$K^+ \to \pi^+ l^+ l^-$	$N^r_{14} - N^r_{15}$	NA48/2 ee PLB 677 (2009) 246-254 μμ PLB 697 (2011) 107-115
$K_S \to \pi^0 l^+ l^-$	$2N^r_{14} + N^r_{15}$	NA48/1 ee Phys.Lett. B576 (2003) 43-54 μμ PLB 599 (2004) 197-211
$K^\pm \to \pi^\pm \gamma\gamma$	$N_{14} - N_{15} - 2N_{18}$	NA48/2 Phys.Lett. B730 (2014) 141-148
$K_S \to \pi^+\pi^-\gamma$	$N_{14} - N_{15} - N_{16} - N_{17}$	
$K^\pm \to \pi^\pm\pi^0\gamma$	$N_{14} - N_{15} - N_{16} - N_{17}$	NA48/2 EPJC 68 (2010) 75-87
$K_L \to \pi^+\pi^- e^+e^-$	$N^r_{14} + 2N^r_{15} - 3(N^r_{16} - N_{17})$	NA48 Eur.Phys.J. C30 (2003) 33-49
$K^+ \to \pi^+\pi^0 e^+e^-$	$N^r_{14} + 2N^r_{15} - 3(N^r_{16} - N_{17})$	**Still missing!**
$K_S \to \pi^+\pi^- e^+e^-$	$N^r_{14} - N^r_{15} - 3(N^r_{16} + N_{17})$	NA48 Eur.Phys.J. C30 (2003) 33-49

$K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}\gamma^{*} \longrightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$



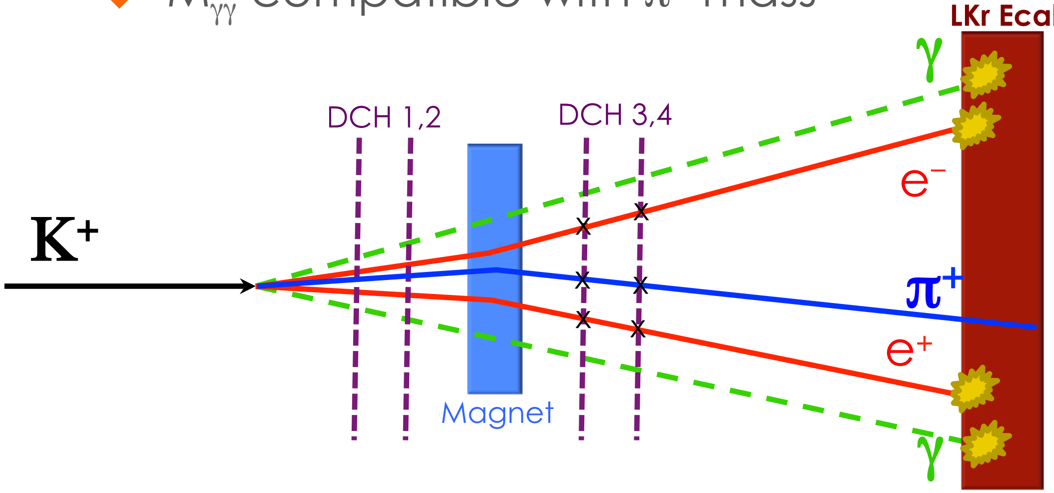
$$\frac{d^3\Gamma}{dE_\gamma^* \, dT_c^* \, dq^2} = \frac{d^3\Gamma_B}{dE_\gamma^* \, dT_c^* \, dq^2} + \frac{d^3\Gamma_E}{dE_\gamma^* \, dT_c^* \, dq^2} + \frac{d^3\Gamma_M}{dE_\gamma^* \, dT_c^* \, dq^2} + \frac{d^3\Gamma_{\mathrm{int}}}{dE_\gamma^* \, dT_c^* \, dq^2},$$

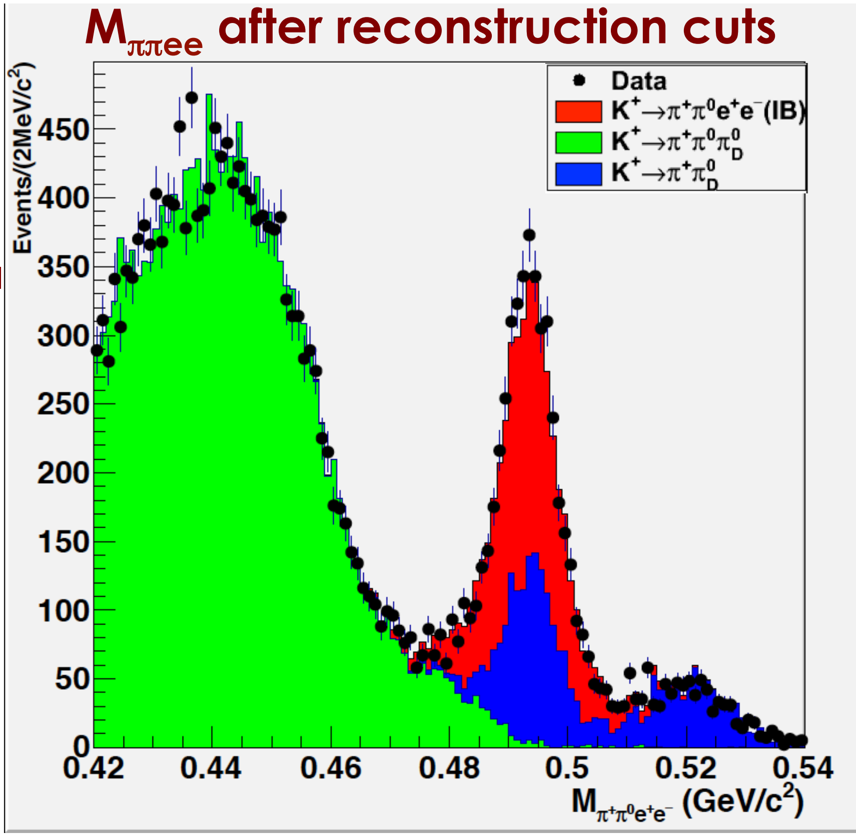
L. Cappiello,O. Catà, G. D'Ambrosio ,D.Gao
EPJC (2012) 72:1872

- $K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ offers various opportunity of chiral tests:
  - Interference Γ_B Γ_E can confirm the discrepancy in sign with the theoretical prediction observed by NA48/2 in $K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}\gamma$ EPJC 68 (2010) 75-87
  - Magnetic interference is genuine $\pi\pi$ee and can be used to extract the sign of the magnetic term Γ_M (impossible to extract in $\pi^{\pm}\pi^{0}\gamma$).
  - P violating observables in the dilepton pair coupling can be used to access short distance physics using K^+ only (NA62)
  - Charge asymmetry not contaminated by indirect CP violation (as in K^0)
- Never observed so far!

Reconstruction and background

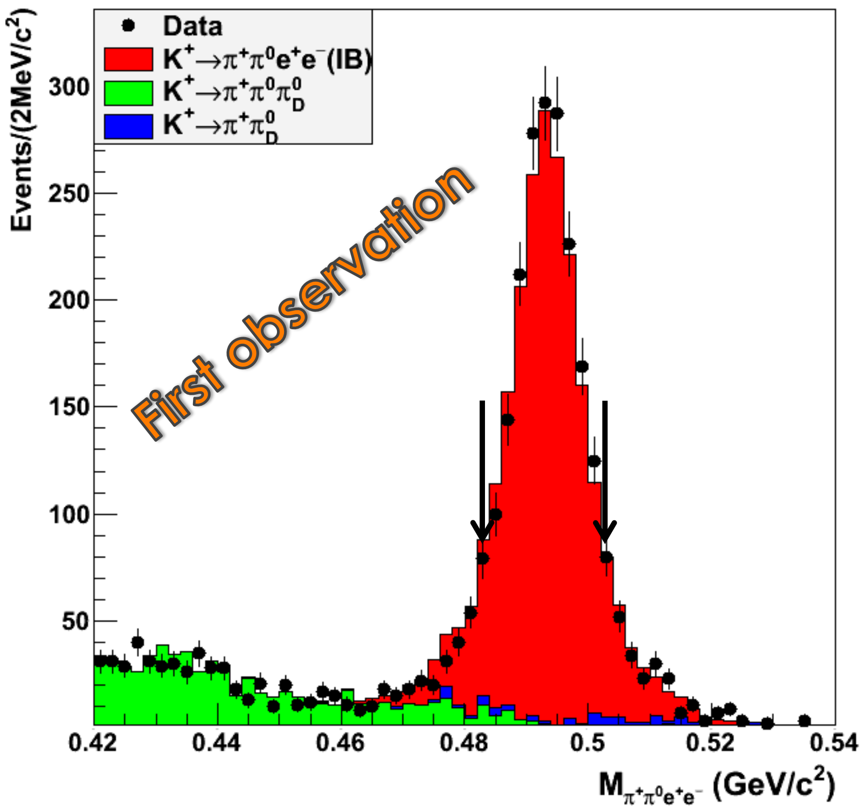
- Reconstruction strategy:
  - 3 good tracks, and 2 photon clusters
  - Identify 2 electron and a pion by E/p
  - $M_{\gamma\gamma}$ compatible with π^0 mass

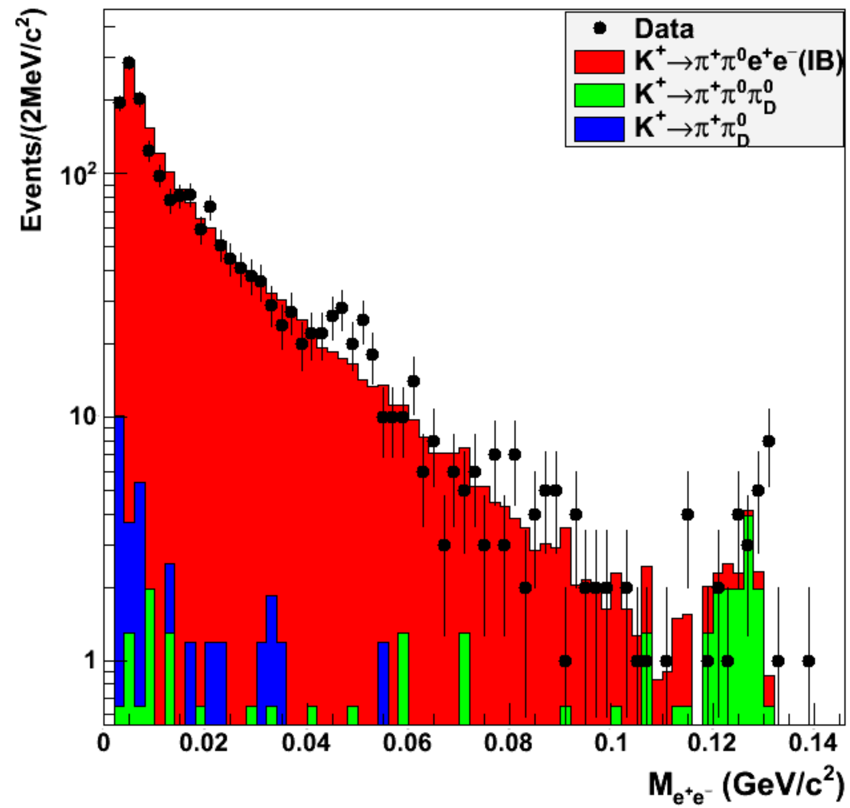




- The main background sources are:
  - $K^\pm \to \pi^\pm\pi^0_D(\gamma)\to\pi^\pm e^+e^-\gamma$ + extra or radiated γ
    - At least 1 $M_{ee\gamma}$ compatible with $M_{\pi 0}$
  - $K^\pm \to \pi^\pm\pi^0\pi^0_D(\gamma)\to\pi^\pm\pi^0 e^+e^-\gamma$ with a lost or merged γ
    - $M_{\pi+\pi 0}$ much smaller than in the signal due to original 3π final state

First observation of $K\rightarrow\pi^{\pm}\pi^{0}e+e-$



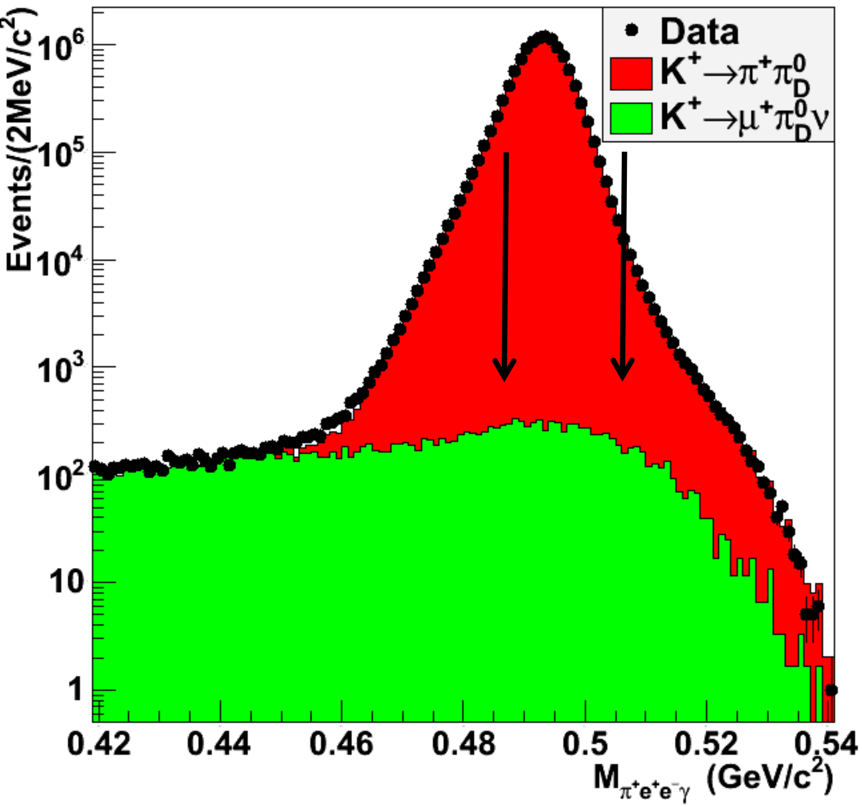


- After suppressing backgrounds:
  - K_{2pD} cutting on $|m_{ee\gamma} - m_{\pi 0}|>7$ MeV
  - K_{3pD} cutting on $m^2_{\pi\pi}>120$ MeV
- We select the mass region:
  - 483.677 MeV $<M_{\pi\pi ee}<$503.677 MeV

- Total number of $\pi^{\pm}\pi^{0}e^{+}e^{-}$ candidates 1916
  - BG candidates from K_{2pD} = 26±5.1
  - BG candidates from K_{3pD} = 30±5.5
- Number of pure $\pi^{\pm}\pi^{0}e^{+}e^{-}$ events **1860**

Normalization channel 2003 data only

Number of kaon decays measured by normalizing to $K^{\pm}\to\pi^{\pm}\pi^{0}_{D}(\gamma)$ decay



Quantity	Value	Value %
# of events	6714917±2591	0.04%
Statistical error		**0.04%**
Acceptance	(3.555±0.002)%	0.002%
Trigger efficiency	(97.64± 0.04)%	0.04%
BG in 2pD sample	3365±58	$8\cdot10^{-4}$ %
Radiative corrections	0.78%	0.78%
Systematic error		**0.78%**
$BR(\pi^{+}\pi^{0}_{D}(\gamma))$	$(2.425\pm0.073)\times10^{-3}$	3.01%
External error		**3.01%**

$$N_{Kdecays}=(7.97\pm0.03_{Stat}\pm0.06_{Sys}\pm0.24_{Ext})\cdot10^{10}=(7.97\pm0.25)\cdot10^{10}$$

Error dominated by external error $\delta BR(\pi^{0}\to\gamma e^{+}e^{-}) = 3.01\%$

$\pi^{\pm}\pi^{0}e+e-$ BR errors summary table

Error type	Value	Value in %
# signal candidates (1916)	0.095	2.35%
Statistical origin	**0.095**	**2.35%**
Radiative correction on IB	0.020	0.50%
Signal total acceptance	0.014	0.34% (statistical error)
	0.041	1.00% (fraction mixture)
Back ground subtraction	0.016	0.40% (statistical)
	0.002	0.05% (systematic Rad. Corr. 2pD)
Trigger efficiency	0.026	0.65% (statistical error)
Total systematics	**0.056**	**1.40%**
Normalization measurement		3.10% (from $\pi^{+}\pi^{0}_{D}$ decay BR)
Total external	**0.126**	**3.10%**

- Systematic error dominated by model dependent acceptance
- External error from BR($\pi^{0}_{D}\rightarrow e^{+}e^{-}\gamma$) dominates the total error

Total ππee BR measurement

- With the present data sample NA48/2 is not sensitive to DE and INT
  - Model dependent BR computed using total acceptance in which the relative weight of the 3 components are obtained from (Eur. Phys. J. C (2012) 72:1872)

$$Acc_{ppee}^{Tot} = \frac{Acc(IB) + Frac(DE)_{Th} \cdot Acc(DE) + Frac(INT)_{Th} \cdot Acc(INT)}{1 + Frac(DE)_{Th} + Frac(INT)_{Th}}$$

  - Using values from table below

Quantity	Value
N_{ppee}	1916 (1860 ± 51 after BG sub)
N_{BG}	55.8±7.4
K_{flux}	$(7.97\pm0.24_{tot})\times10^{10}$
Acceptance (Acc^{TOT}_{ppee})	(0.583±0.0019)%
Trigger efficiency (ε_{ppee})	(98.7±0.65)%

  - We obtain a preliminary total branching ratio measurement

$$BR(ppee) = \frac{N_{ppee} - N_{BG}}{K_{Flux} \cdot Acc_{ppee}^{TOT} \cdot \varepsilon_{ppee}} = (4.06 \pm 0.10_{stat} \pm 0.06_{sys} \pm 0.13_{ext}) \cdot 10^{-6}$$

PRELIMINARY

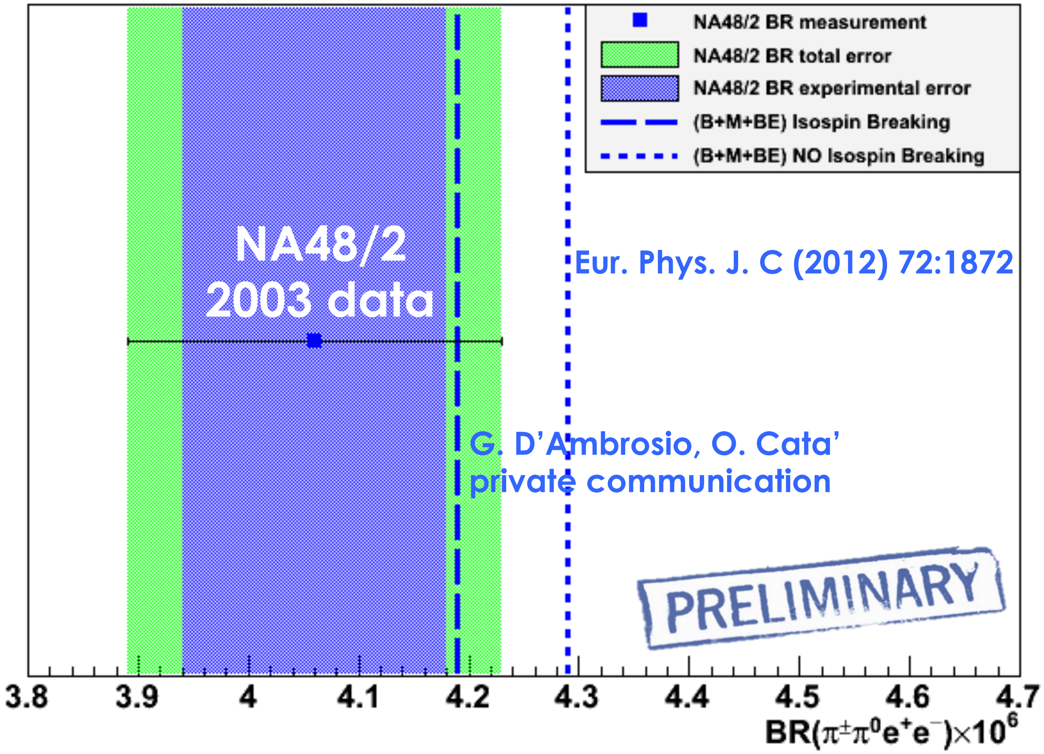
Comparison with theory

Total BR prediction from D'Ambrosio et al (private communication isospin breaking):

$BR_{TOT}^{Theory} = 4.0995 \cdot 10^{-6}(1+1/71+1/128) = 4.19 \cdot 10^{-6}$

Results are in good agreement within $<1\sigma$ even with missing radiative corrections

$$BR(ppee)^{Theory}_{Total} = 4.19 \cdot 10^{-6} \qquad BR(ppee)^{NA48/2}_{Total} = (4.06 \pm 0.17_{Tot}) \cdot 10^{-6}$$



Radiative correction included in the NA48/2 montecarlo by using photos

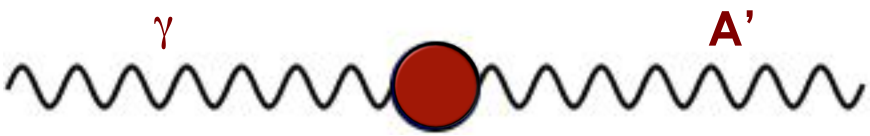
No radiative correction included in **Eur. Phys. J. C (2012) 72:1872**

Simplest dark photon model

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

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

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

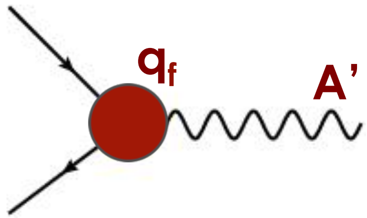


B. Holdom Phys.Lett. B166 (1986) 196

  - In this **case the new coupling constant = eε** is just proportional to electric charge and it is equal for both quarks and leptons.

- **As in QED**, this will generate new interactions with SM fermions of type:

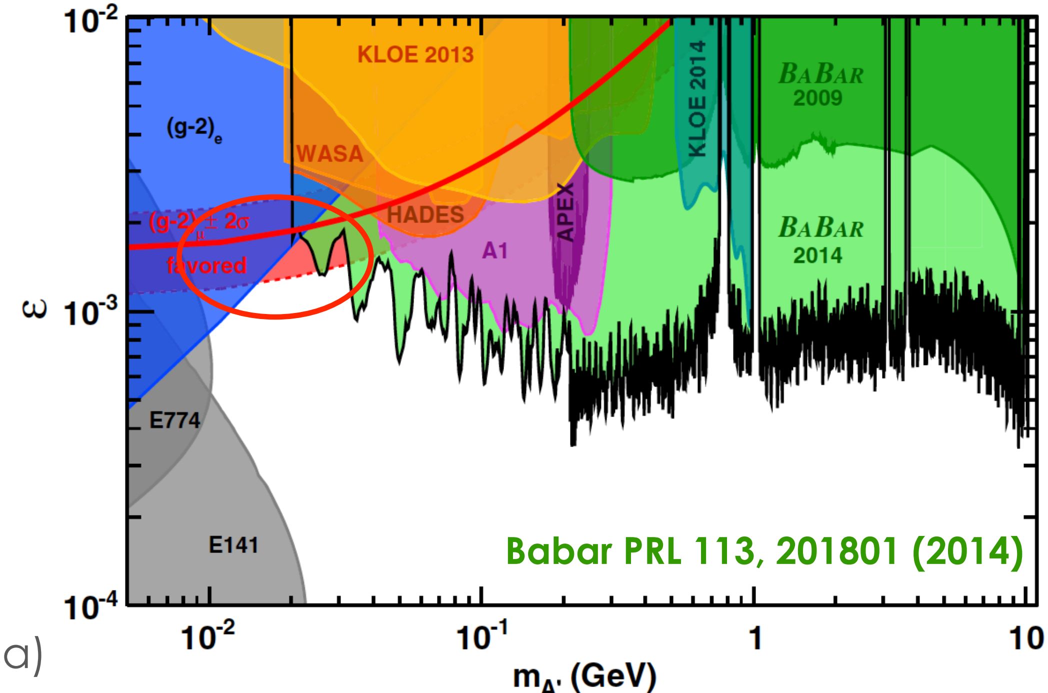
$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$



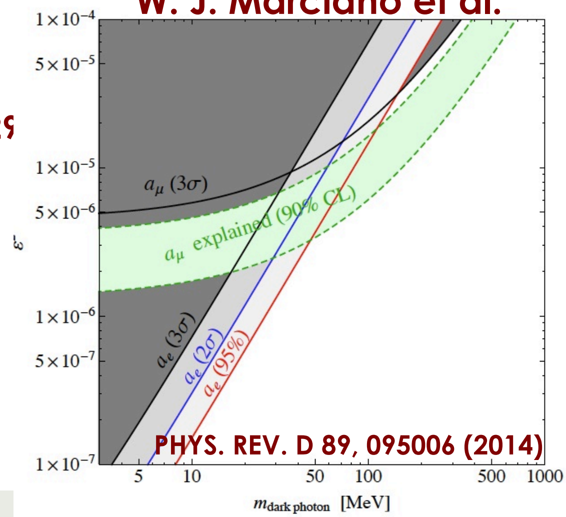
  - Not all the SM particles need to be charged under this new symmetry
  - In the **most general case q_f is different in between leptons and quarks** and can even be 0 for quarks. **P. Fayet, Phys. Lett. B 675, 267 (2009)**)

Dark photon searches status

- Visible decays: A'→ ee, μμ, ππ,
  - Kinetic mixed dark photons
- Favored parameters values explaining muon g-2 (**red** band)
  - A'-boson light 10-100 MeV
- Status of dark photon searches
  - Beam dump experiments (grey)
  - Fixed target (Apex, A1)
  - Mesons decays (**Babar**, KLOE, Wasa)
- Theoretical exclusion from g_e-2 g_μ-2
  - Recent tight limit form α_{EM} (**blue** filled area) **PhysRevD.86.095029**
- Much less constraints on "Invisible" decay mode
  - A'→χχ,
  - No assumption on α_D and no kinetic mixing

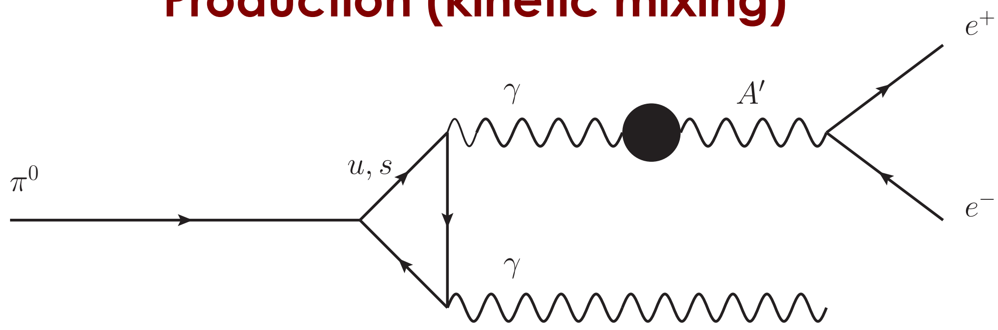


W. J. Marciano et al.

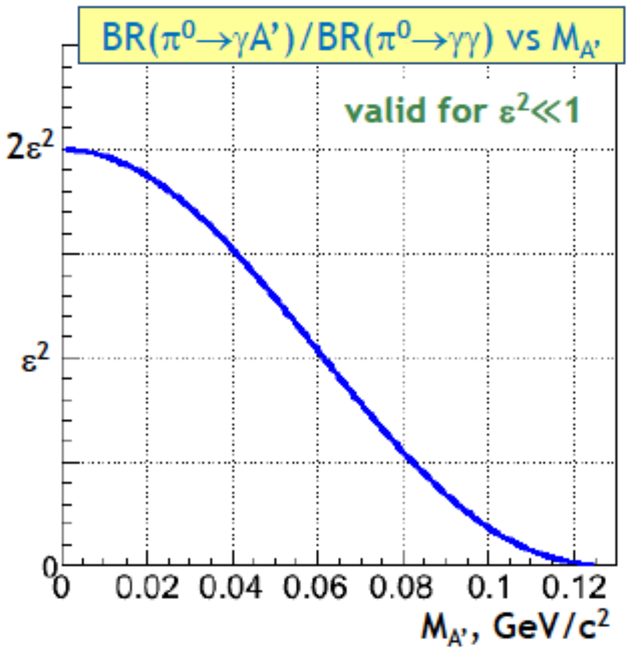


Dark photon in π^0 decays

Production (kinetic mixing)



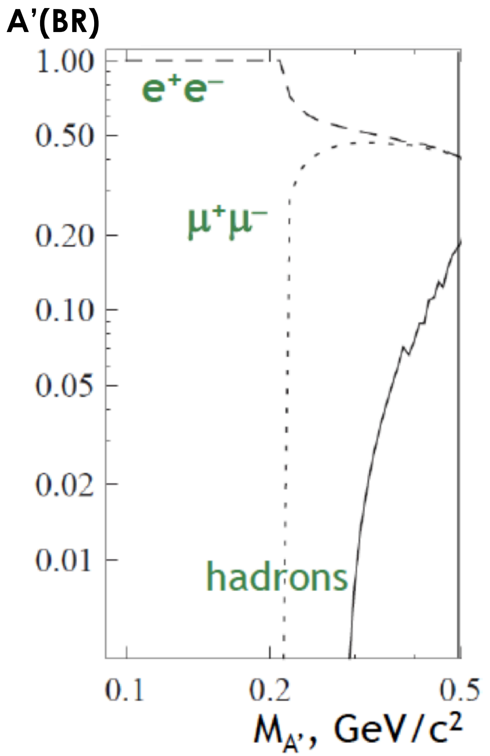
$$\frac{BR(\pi^0 \to \gamma A')}{BR(\pi^0 \to \gamma\gamma)} \approx 2\varepsilon^2 |F(M_{A'}^2)|^2 \left(1 - \frac{M_{A'}^2}{M_\pi^2}\right)^3$$



Batell, Pospelov and Ritz
PHYS. REV. D 80, 095024 (2009)

Decay (No light dark sector)

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



$M_{A'} < M_{\pi 0}$ and no lighter wrt A' dark sector particles exist $BR(A' \to e^+e^-) = 1$

NA48/2 data sample

- Number of kaon decays in NA48/2 ('03/'04): $N_K \approx 2 \cdot 10^{11}$
  - $4 \cdot 10^{10}$ π^0 tagged decays from $K^\pm \to \pi^\pm \pi^0$ decays
  - High efficiency trigger chain for 3-track vertices throughout the data taking
- 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 $K^\pm \to \pi^\pm \pi^0_D$ (K_{2pD}), $\pi^0_D \to \gamma e^+e^-$;
  - $BR(K_{2pD}) = 2.4 \cdot 10^{-3}$
  - Sensitivity is limited by the irreducible K_{2pD} background.
- Very good spectrometer mass resolution: $\sigma_{Mee} \approx 0.012 \times M_{ee}$
- Signal acceptance: depending on $M_{A'}$, up to 2.5%.

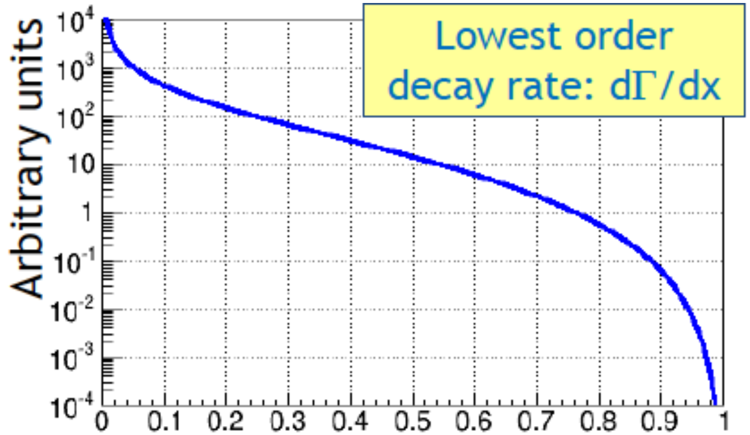
Modeling the background

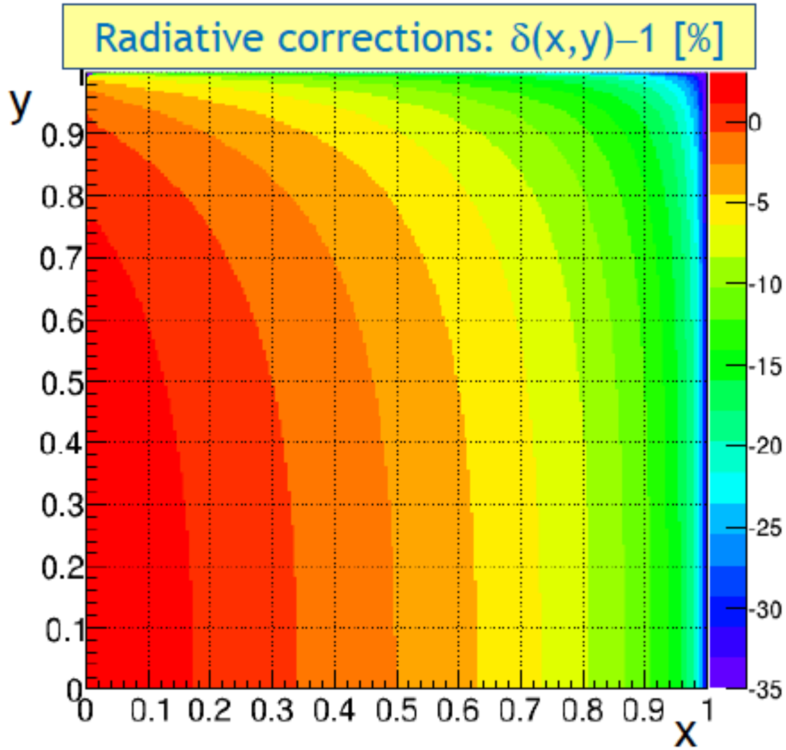
Differential decay rate (lowest order):

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

With $x = (m_{ee}/m_\pi)^2$, $y = 2p(q_1-q_2)/[m^2_\pi-(1-x)]$
$r = 2m_e/m_\pi$

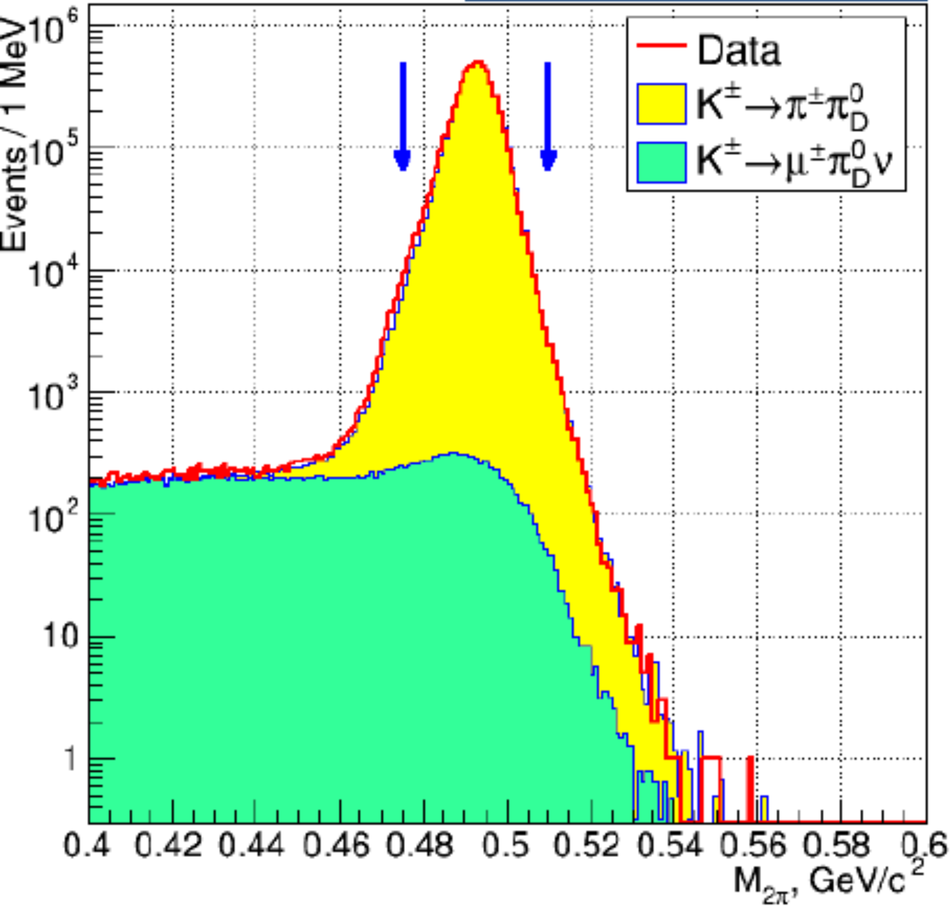
- Radiative corrections
  - Mikaelian and Smith, PRD5 (1972) 1763
  - Improved numerical precision by Husek, Kampf and Novotný (to be published)
- π^0 transition form factor F(X)=1+ax
  - PDG TFF slope found inadequate
  - Modified TFF slope used for better data description
  - TFF slope measurement in progress



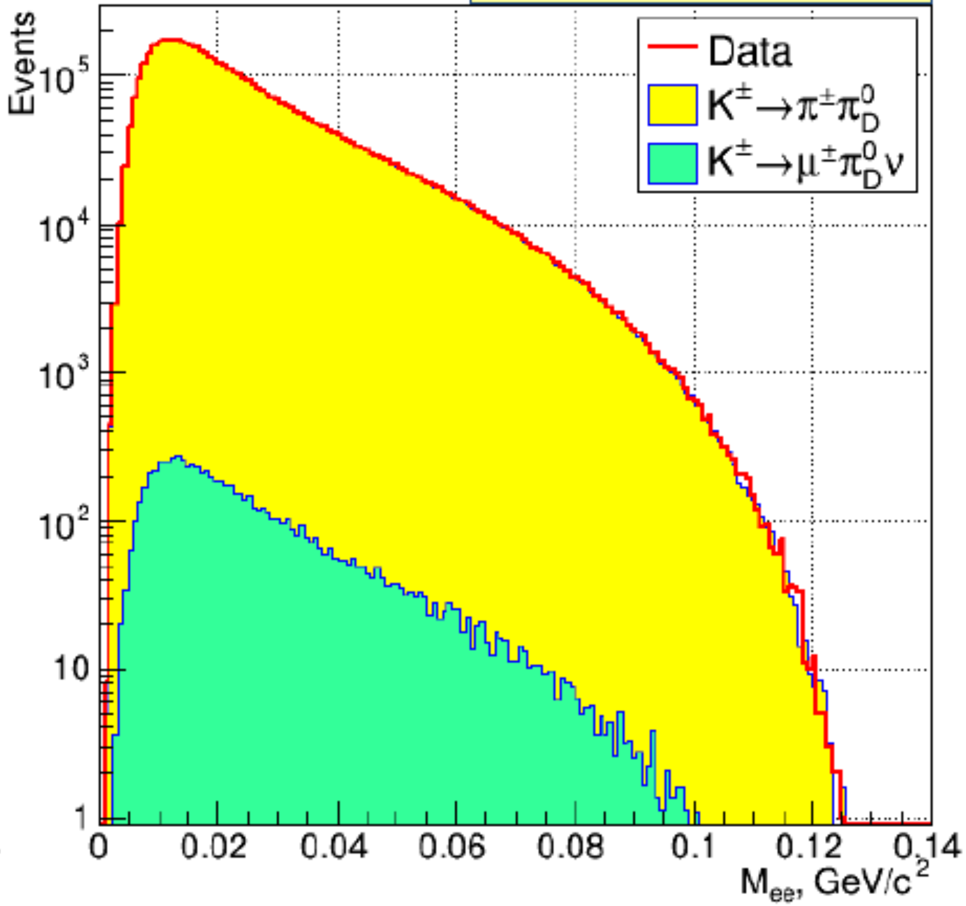


Data sample: $K_{2\pi D}$ analysis

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

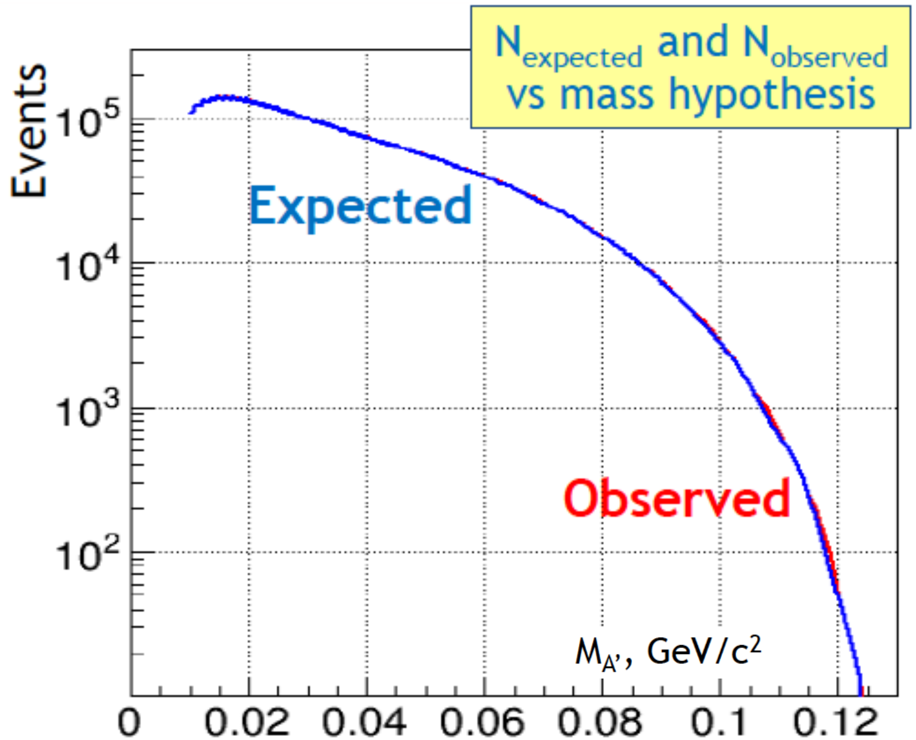


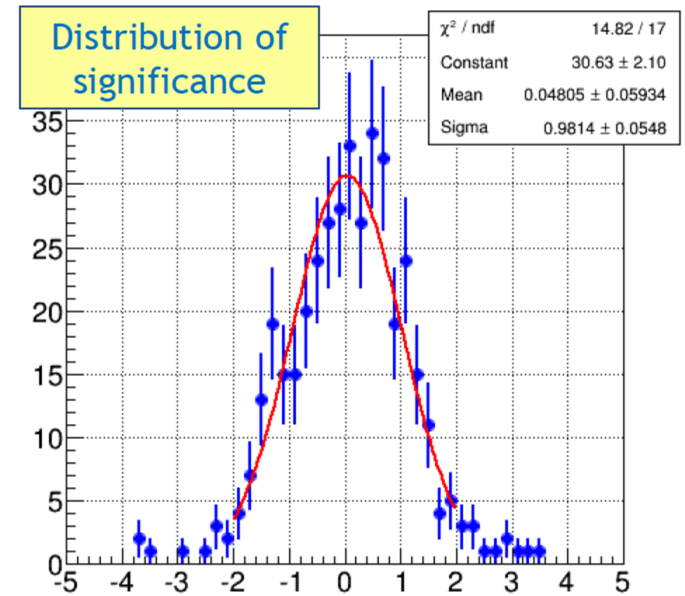
M_{ee}: data and MC

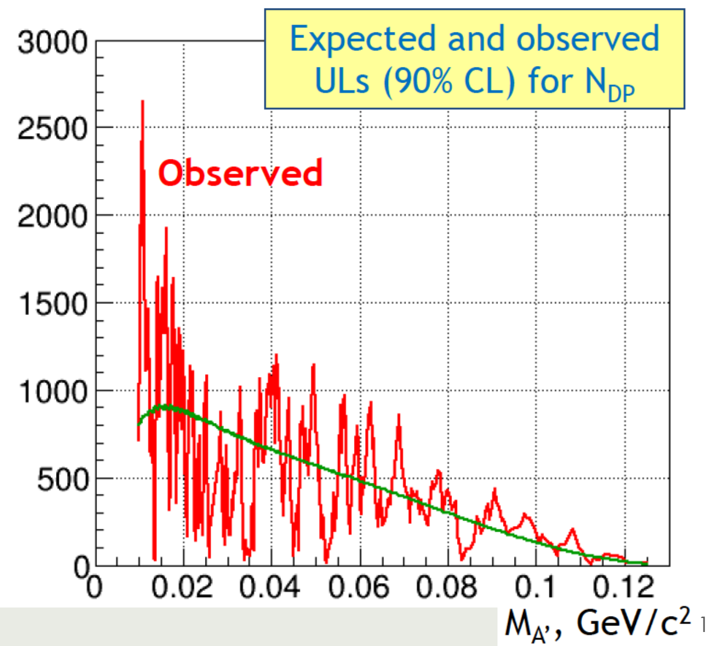


Selection optimized for $K_{2\pi D}$ (total P_T consistent to zero).
Candidates: $N(K_{2\pi D}, M_{ee}>10\text{MeV}/c^2)=4.687\cdot10^6$, $K_{\mu 3D}$ contribution: 0.15%.
Semileptonic $K^{\pm}$ decays ($K\to\pi^0_D l^{\pm}\nu$, large P_T) can be included.

Statistical significance

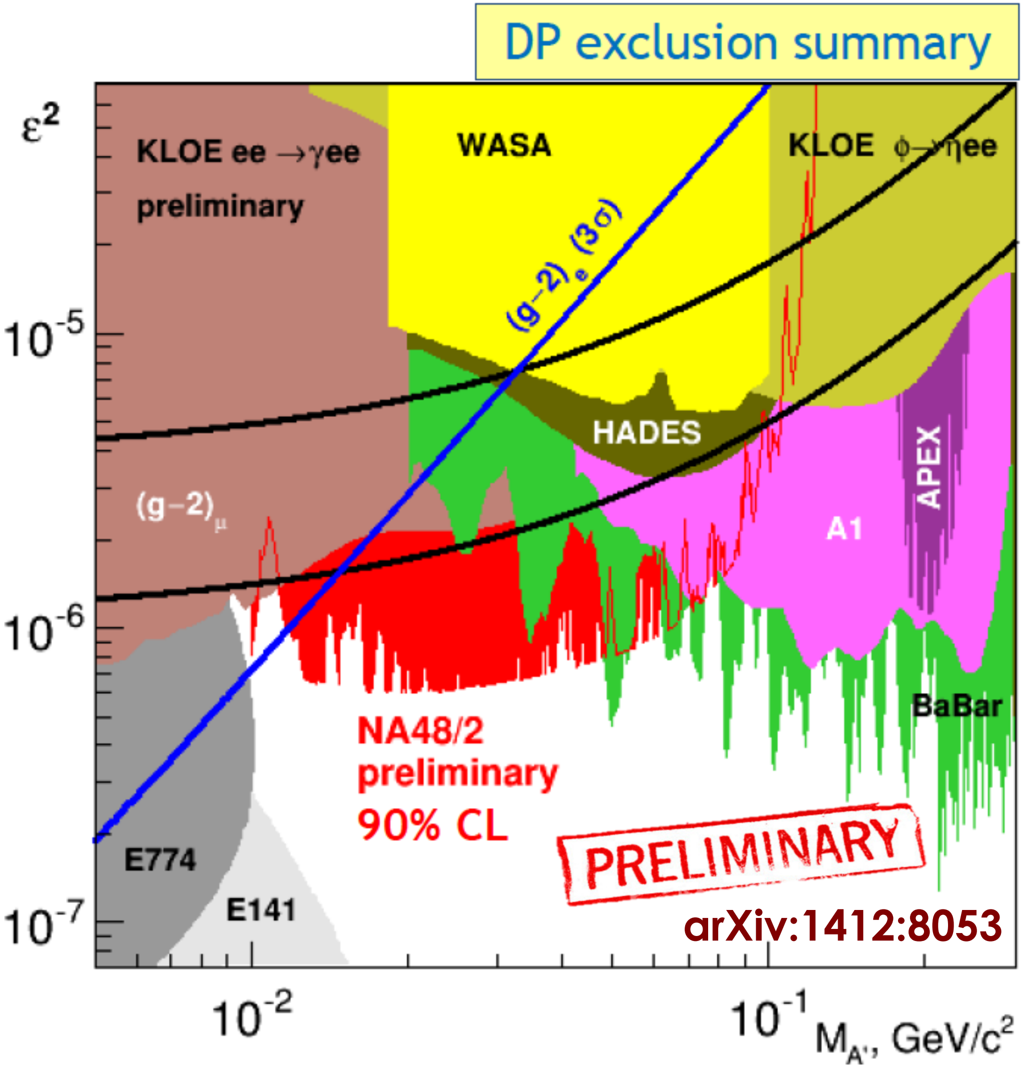






- Scanned DP mass range: 10 MeV/c^2<M_{DP}<125 MeV/c^2.
  - Variable DP mass step: $\approx 0.5\sigma M_{ee}$.
  - DP mass hypotheses tested: 398
- Confidence intervals for $N_{A'}$ are computed from:
  - N_{exp}, N_{obs} and δN_{obs} in the signal mass window
  - The Rolke-Lopez method.

NA48/2 preliminary exclusion limit



We conservatively assume $N_{obs}=N_{exp}$ in cases when $N_{obs}<N_{exp}$. Therefore there are no downward spikes

Improvement of the existing limits in the range 10-60 MeV/c².

If **DP couples** to SM through **kinetic mixing** and **decays only to electrons**, it **is ruled out** as the explanation for anomalous **(g-2)μ.**

Conclusions

- NA48/2 reported **the first observation** of the decay **$K^{\pm}\rightarrow\pi^{\pm}\pi^{0}e^{+}e^{-}$**
  - Based on 1860 candidates the **preliminary** value of the **BR** is:

$$BR(ppee) = \frac{N_{ppee} - N_{BG}}{K_{Flux} \cdot Acc^{TOT}_{ppee} \cdot \varepsilon_{ppee}} = (4.06 \pm 0.10_{stat} \pm 0.06_{sys} \pm 0.13_{ext}) \cdot 10^{-6}$$

PRELIMINARY

  - Statistical precision can be reduced significantly including 2004 data
  - Observation of DE and INT components requires radiative correction in theoretical model. Final result expected for the end of the year.

- NA48/2 presented a preliminary limit on the dark photon searches
  - Improvement of the existing limits in the range 10-60 MeV/c^2.
  - Allowed value of ε^2 has been pushed well below 10^{-6} at 90% CL
  - Assuming **kinetic mixing** and dark photon **decaying to lepton pairs** the whole favored by **$(g-2)_\mu$ region has been excluded**
  - Further improvements can be obtained by including semi-leptonic decays
  - Final result draft paper in preparation

Spare slides