Neutral Pion Form Factor Measurement by the NA62 Experiment

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On Behalf of the NA62 Collaboration

Outlook

- The CERN NA62 experiment
- The π^0 Form Factor (NA62 preliminary results)
- Search for Dark Photon in π^0 decays (NA48/2 final result)
- Conclusions

The NA62 Experiment

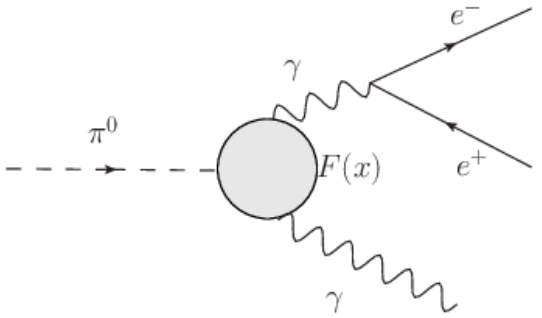
- **NA48** (1997-2001): K_L/K_S beams
  ➔Direct CPV Measurement
- **NA48/1** (2002): K_S beam
  ➔ K_S rare decays
- **NA48/2** (2003-4): K^+/K^- beams
  ➔ $K^\pm$ precise measurement
- **NA62** (2007-8): K^+/K^- beams
  ➔Lepton Universality $K_{e2}/K_{\mu 2}$
- **NA62** (2014-8): K^+ beam
  ➔BR($K^+ \to \pi^+ \nu\nu$), new physics, rare decays, etc

NA62: ≈ 200 participants, 30 Institutes

The Dalitz Decay $\pi^0 \to e^+e^-\gamma$

- Definition of *x* and *y* kinematic variables

$$x = \left(\frac{M_{e^+e^-}}{m_{\pi^0}}\right)^2 = \frac{\left(p_{e^+} + p_{e^-}\right)}{m_{\pi^0}^2}, \qquad y = \frac{2p_{\pi^0}\cdot\left(p_{e^+} - p_{e^-}\right)}{m_{\pi^0}^2}$$



- Differential Decay Rate ($r^2=(2m_e/m_{\pi 0})^2=x_{min}$)

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

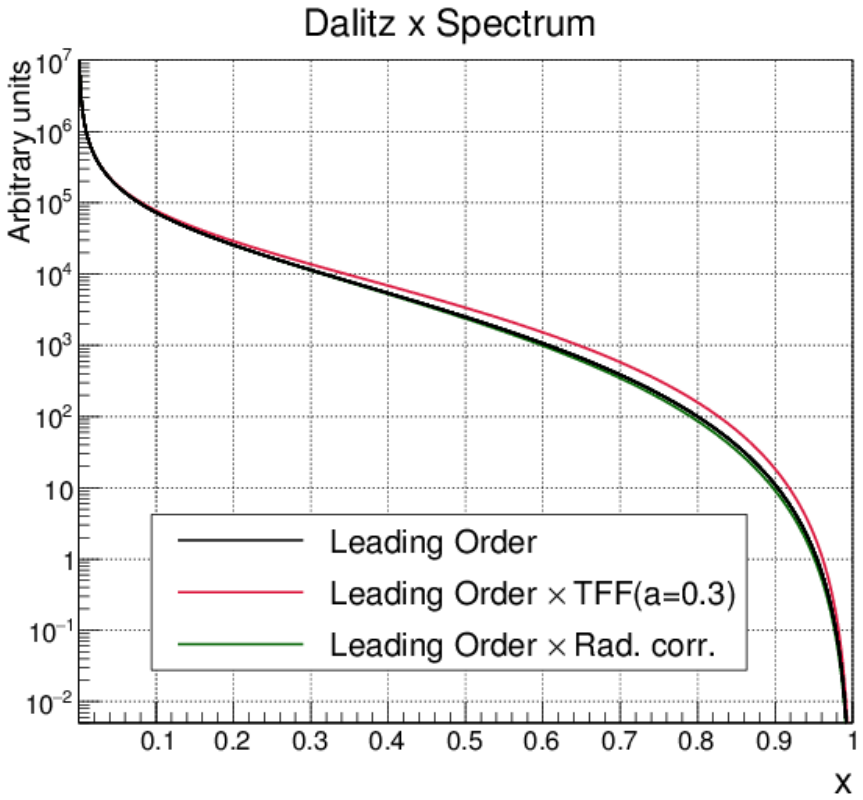
- The Transition Form Factor (TFF) *F(x)*

$$F\left(x\right) \approx 1 + ax, \qquad \text{a: TFF slope parameter}$$

- Radiative corrections: δ(x,y)

The π^0 Transition Form Factor (TFF)

- Comparison of TFF slope prediction with measurement: test of theoretical models
- π^0 TFF slope prediction from Vector Meson Dominance (VMD) model: a≈0.03
- The π^0 TFF can test models which predict:
  - ➢ Rate of rare decay $\pi^0 \rightarrow e^+e^-$
  - ➢ Hadronic light-by-light scattering contribution to $(g-2)_\mu$

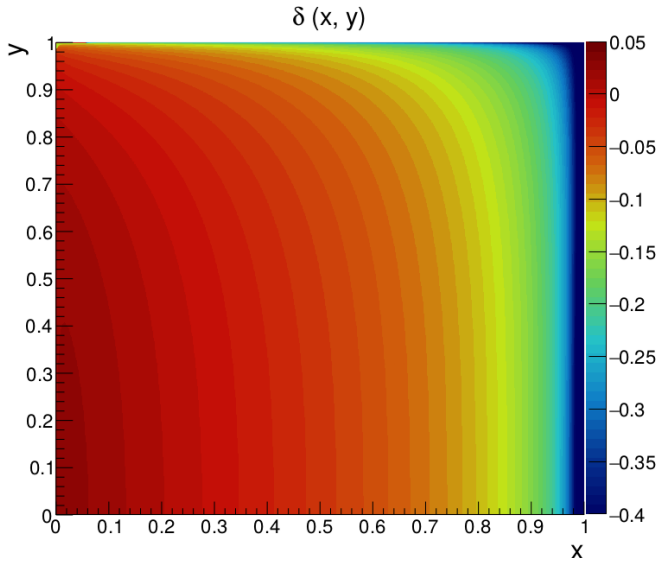


Radiative Corrections

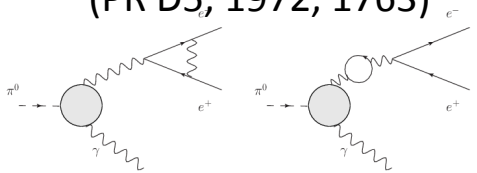
- Radiative Correction Factor $\delta(x,y)$

$$\frac{\partial\Gamma}{\partial x\partial y} = \left(\frac{\partial\Gamma}{\partial x\partial y}\right)_0 \left(1+\delta(x,y)\right)$$

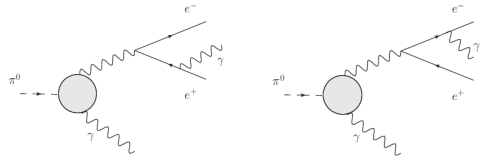
- Radiative corr. implemented in the MC π^0_D generator including inner bremsstrahlung γ's
- Use Mikaelian and Smith approach revisited by T.Husek et al



Mikaelian and Smith
(PR D5, 1972, 1763)

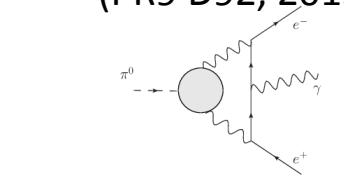


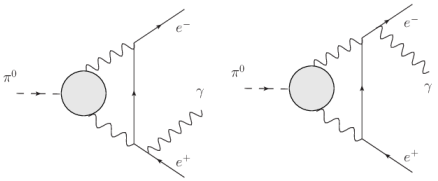
Virtual photon contributions



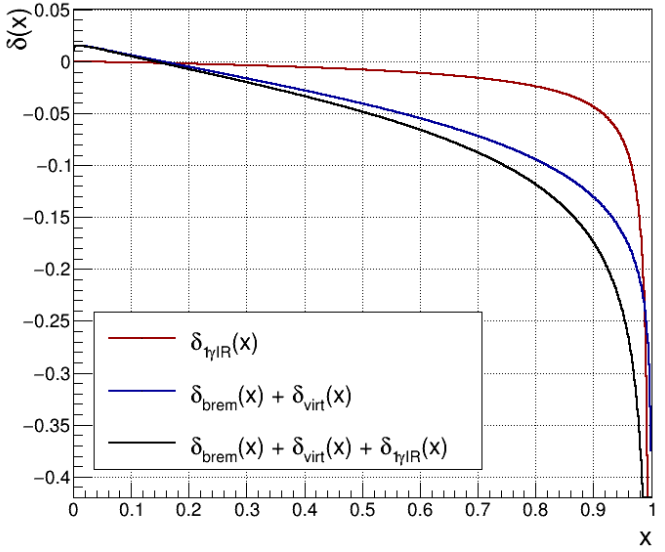
Bremsstrahlung contributions

T. Husek et al
(PR9 D92, 2015, 054027

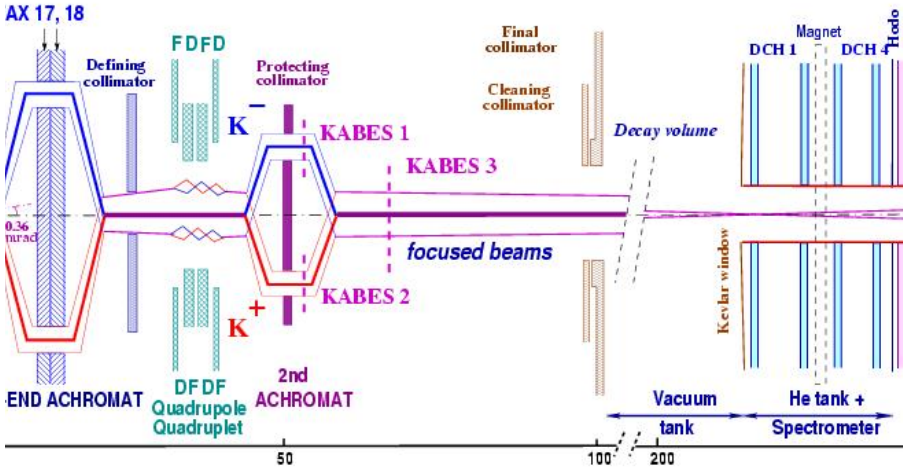




1-loop 1-γ irreducible contributions

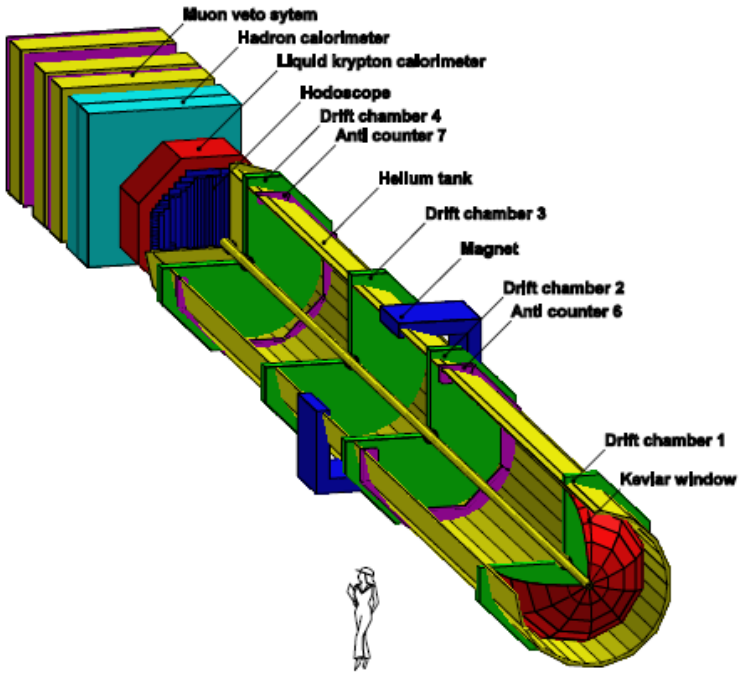


The NA62 layout in 2007



Beam Layout

- $K^{\pm}$ beams
- $p_K = 75 \pm 2$ GeV/c



Main Detectors

- Magnetic Spectrometer: 4 DCH + Dipole Magnet
  $\sigma(p)/p = (0.48 + 0.009\,p)\%\ \ (GeV/c)$
- Liquid Krypton e.m. Calorimeter (LKr)
  $\sigma(E)/E = (3.2/\sqrt{E} + 9/E + 0.42)\%\ \ (GeV)$
- Hodoscope: trigger and timing
  $\sigma_t \approx 150\ ps$

$$x = \left(\frac{M_{e^+e^-}}{m_{\pi^0}} \right)^2$$

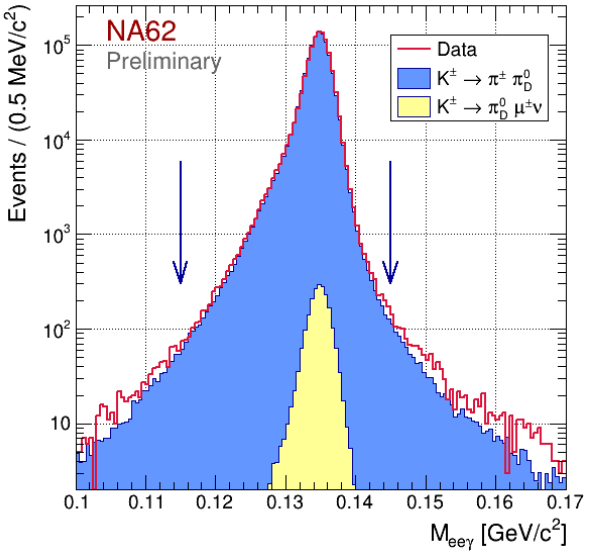
NA62 Data Sample

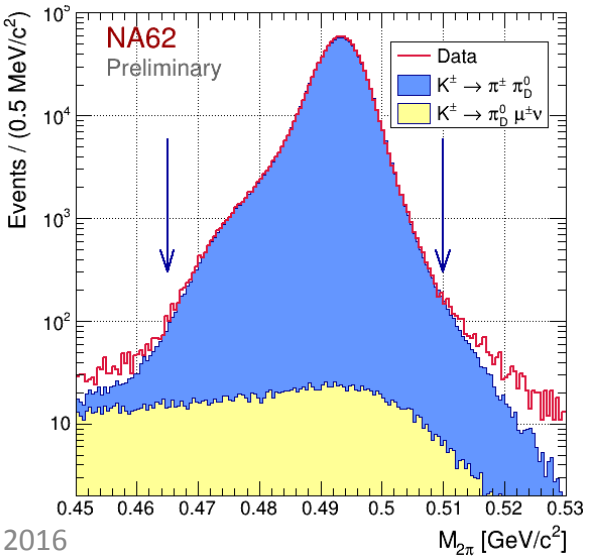
NA62 is a Kaon Factory

- Use $K^{\pm} \rightarrow \pi^{\pm}\pi^0$ ($K_{2\pi}$) as a source of tagged π^0
- NA62 data (2007) ≈ 2×10^{10} $K^{\pm}$ decays in fiducial region
- ≈5×10^9 π^0 from $K_{2\pi}$

Selection of π^0 Dalitz decays

- 3 tracks, 1 γ
- $115 < M_{ee\gamma} < 145$ MeV/c^2
- $465 < M_{\pi\pm\pi0} < 510$ MeV/c^2
- $0.01 < x < 1$



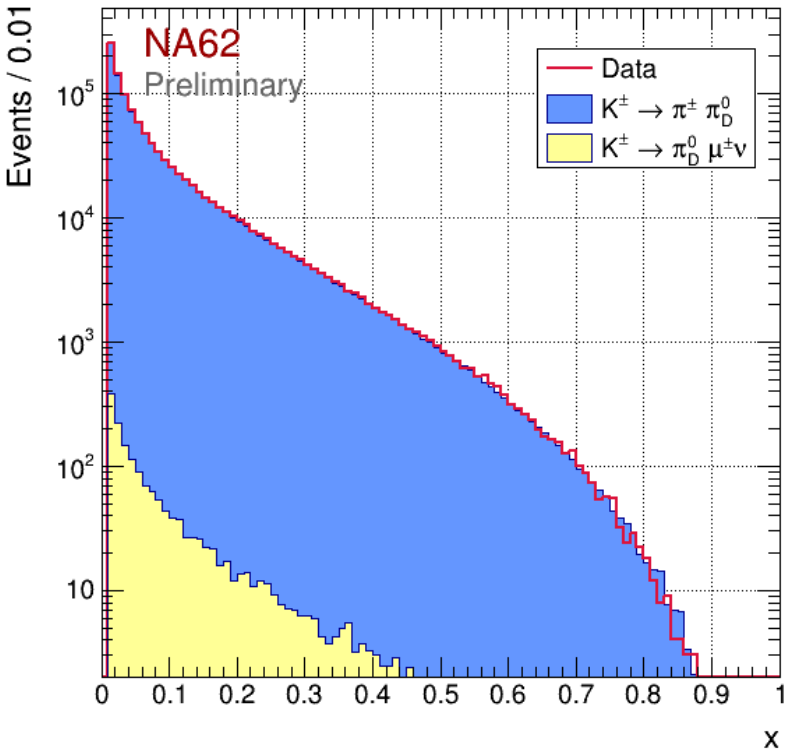


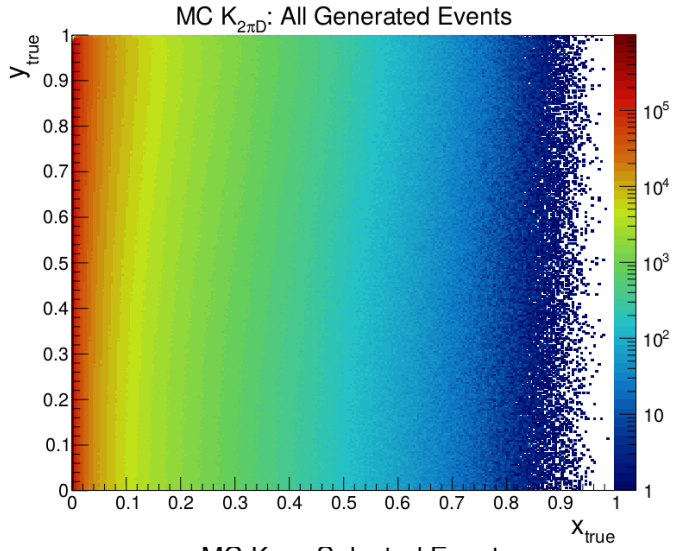
$$x = \left(\frac{M_{e^+e^-}}{m_{\pi^0}} \right)^2$$

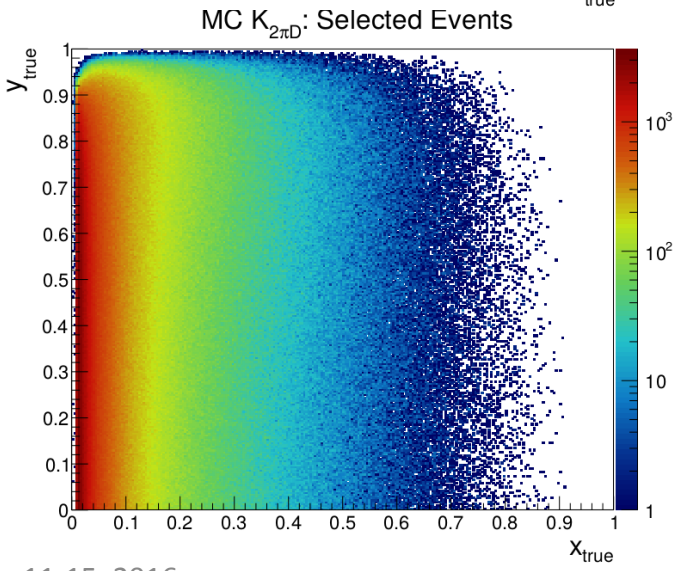
The π^0_D x spectrum

$$N_{\pi^0_D}\left(x > 0.01\right) = 1.05 \times 10^6$$

Adjust the MC to the data x spectrum with a χ^2 test ➔TFF slope







$$F(x) \approx 1 + ax$$

Fit of π^0_D TFF

- Data divided into 20 equi-populated x-bins
- MC generated with a constant TFF slope a_{sim}=0.032 (PDG world average)
- Re-weight MC events with different slopes

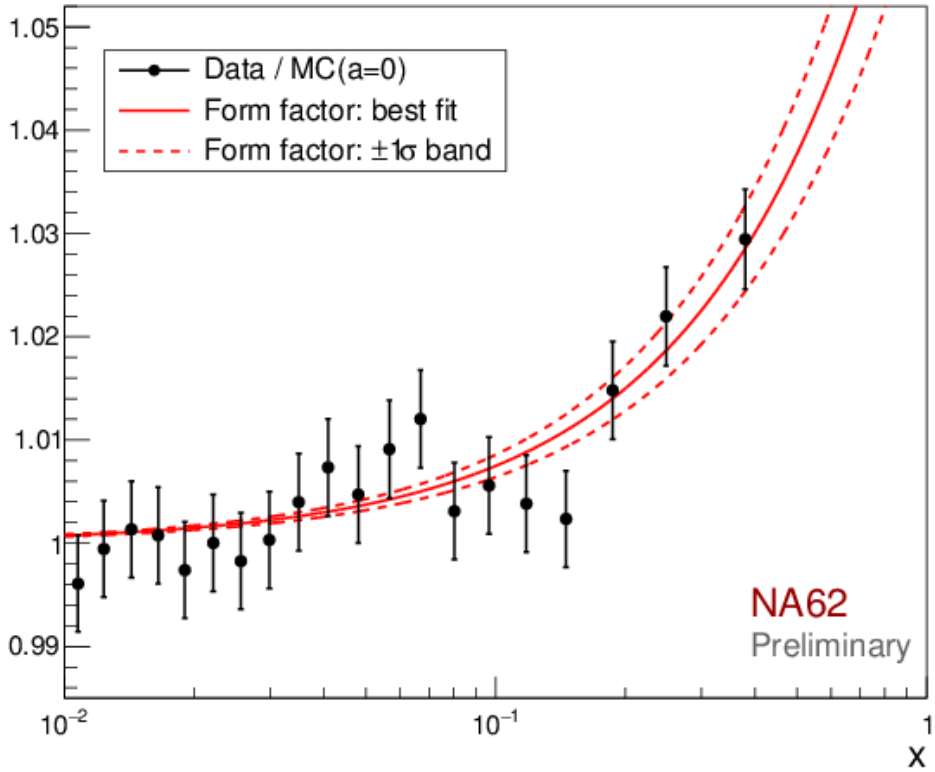
$$w(a) = \frac{(1 + a\, x_{true})^2}{(1 + a_{sim}\, x_{true})^2}$$

- Find the slope with the best data/MC agreement

(lowest $\chi^2(a)$: χ^2/d.o.f. = 52.5/49)

$$a = (3.70 \pm 0.53_{stat}) \times 10^{-2}$$

Statistical uncertainty include data (main contribution) and MC statistics



$$F(x) \approx 1 + ax$$

Preliminary Results of π^0_D TFF

Source	Uncertainty δa (x10²)
Total Statistical = 0.53 x 10^{-2}	
Statistical: Data	0.49
Statistical: MC	0.20
Total Systematics = 0.36 x 10^{-2}	
Beam momentum spectrum simulation	0.30
Spectrometer momentum scale	0.15
Spectrometer resolution	0.05
LKr non-linearity and energy scale	0.04
Accidental background	0.08
Particle mis-ID	0.08
Neglected π^0 Dalitz sources in MC	0.01

$$a = \left(3.70 \pm 0.53_{stat} \pm 0.36_{syst}\right) \times 10^{-2} = \left(3.70 \pm 0.64\right) \times 10^{-2}$$

Comparison with other Experiments

- Only measurements which took rad.corr. into account are considered

TFF slope theory expectation:

- Chiral Perturbation Theory

$$a = (2.90 \pm 0.50) \times 10^{-2}$$

[K. Kampf et al. EPJ C46 (2006), 191]

- Dispersion Theory

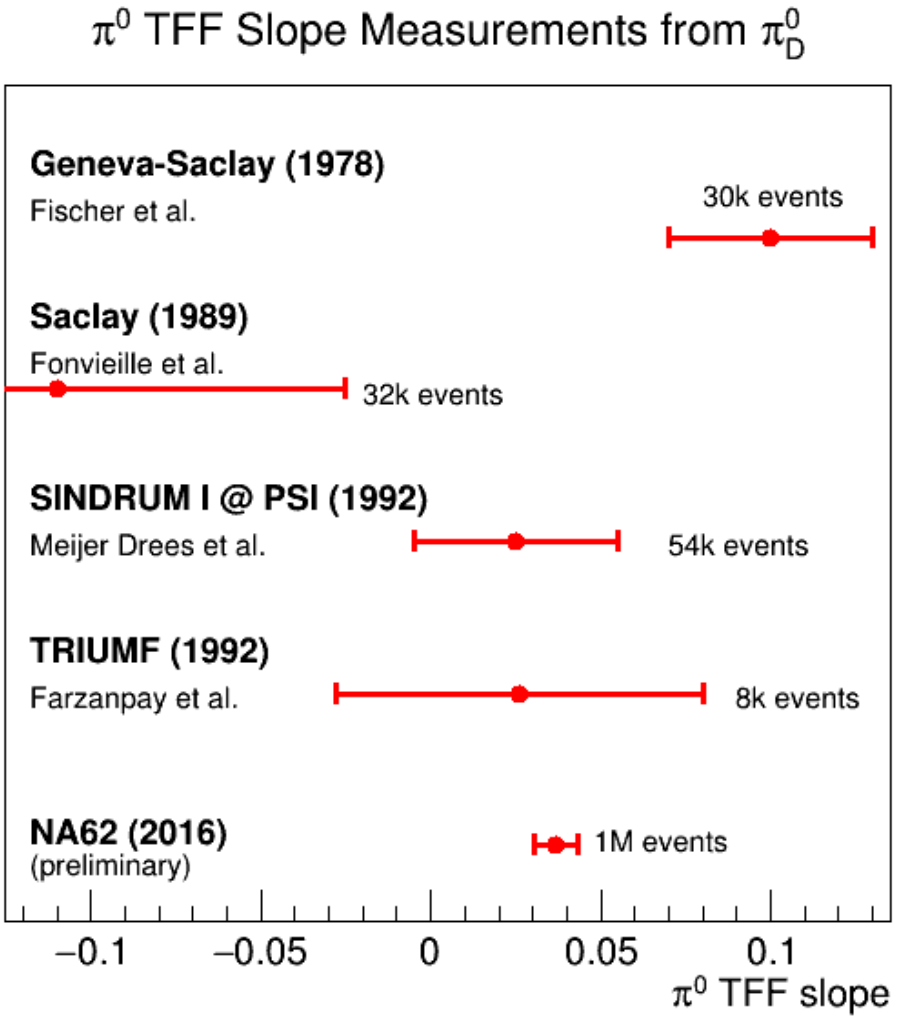
$$a = (3.07 \pm 0.06) \times 10^{-2}$$

[M. Hoferichter et al. EPJ C74 (2014), 3180]

- Two-Hadron Saturation Model

$$a = (2.92 \pm 0.04) \times 10^{-2}$$

[T. Husek et al. EPJ C75 (2015), 586]



Dark Photon

- Simple extension of the SM: **extra U(1)** gauge symmetry with one extra gauge boson, the **dark photon** A' with mass $m_{A'}$
- Assume QED-like interaction with fermions
- Assume mixing between QED and the new U(1) gauge boson (**ε** is the mixing parameter)

➢ Possible explanation for positron excess in cosmic rays (PAMELA, FERMI, AMS-02) by dark matter annihilation

➢ Possible solution for the muon g−2 anomaly

▪ Search for $\pi^0 \rightarrow \gamma A'$ with $A' \rightarrow e^+e^-$ (**similar to Dalitz decay**)

NA48/2 data sample

- 2003-2004 data taking
- Simultaneous K^+/K^- beams with $p_K=(60\pm3)$ GeV/c
- Detector setup similar to NA62(2007) but reduced dipole magnetic field

$$\sigma(p)/p = (1.02 + 0.044p)\% \quad (GeV/c)$$

- 2×10^{11} $K^\pm$ decays in the fiducial volume
- 5×10^{10} tagged π^0 decays (use $K^\pm \rightarrow \pi^\pm\pi^0$, $K^\pm \rightarrow \pi^0\mu^\pm\nu$)
- Search for a narrow peak in the e^+e^- invariant mass
- Very good e^+e^- mass resolution: about 1.1%

NA48/2 π^0_D sample

- $K^{\pm} \rightarrow \pi^{\pm}\pi^0_D$ selection

$$\left|m_{\pi\gamma ee} - m_K\right| < 20 \text{ MeV/c}^2;$$

$$\left|m_{\pi\gamma ee} - m_{\pi^0}\right| < 8 \text{ MeV/c}^2;$$

no missing momentum

➢ $N(K_{2\pi D}) = 1.38 \times 10^7$

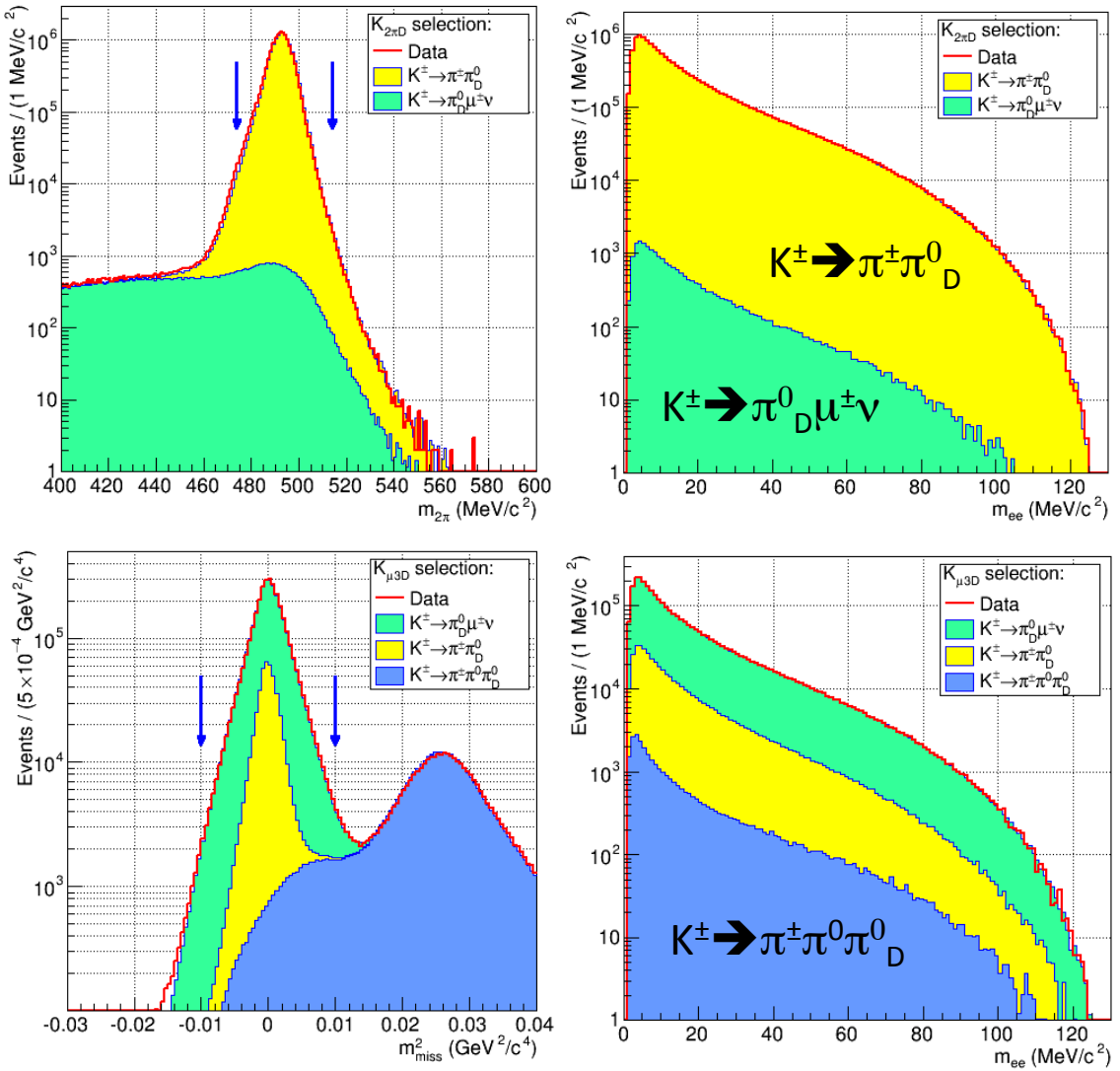
- $K^{\pm} \rightarrow \pi^0_D \mu^{\pm}\nu$ selection

$$m^2_{miss} = \left(P_K - P_\mu - P_{\pi^0}\right)^2$$

compatible with zero;

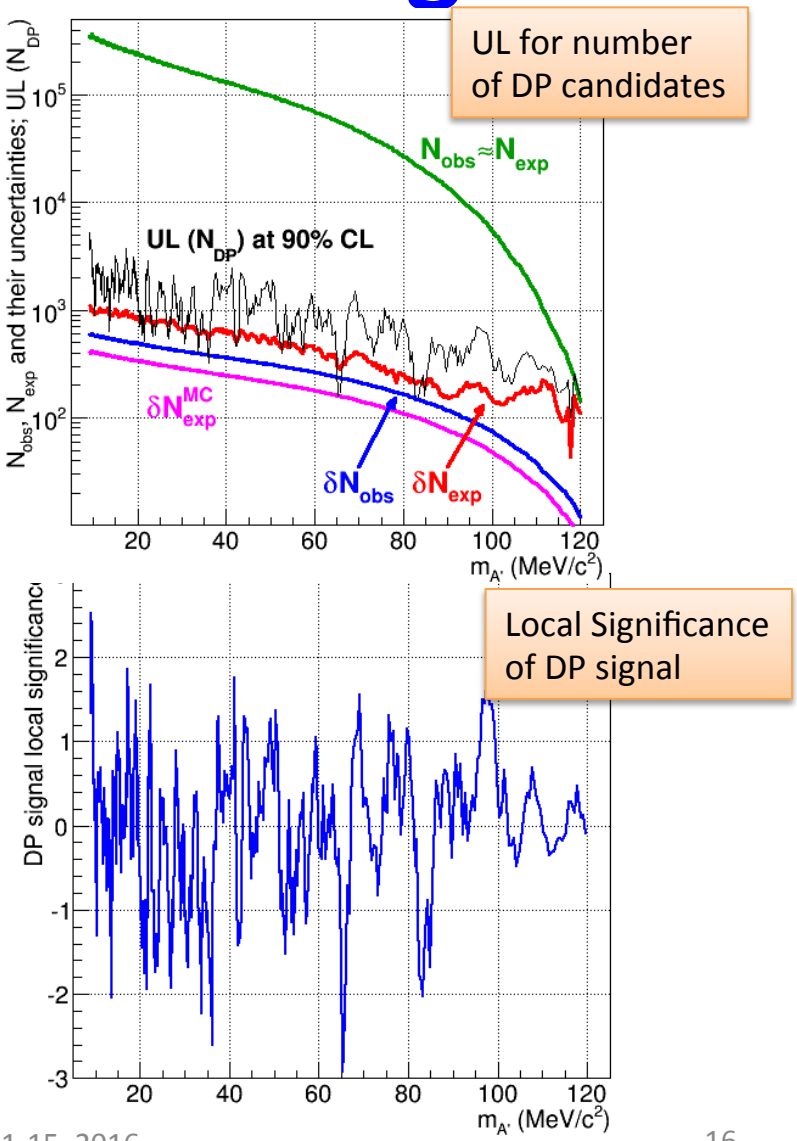
$$\left|m_{\pi\gamma ee} - m_{\pi^0}\right| < 8 \text{ MeV/c}^2;$$

➢ $N(K_{\mu 3D}) = 0.31 \times 10^7$



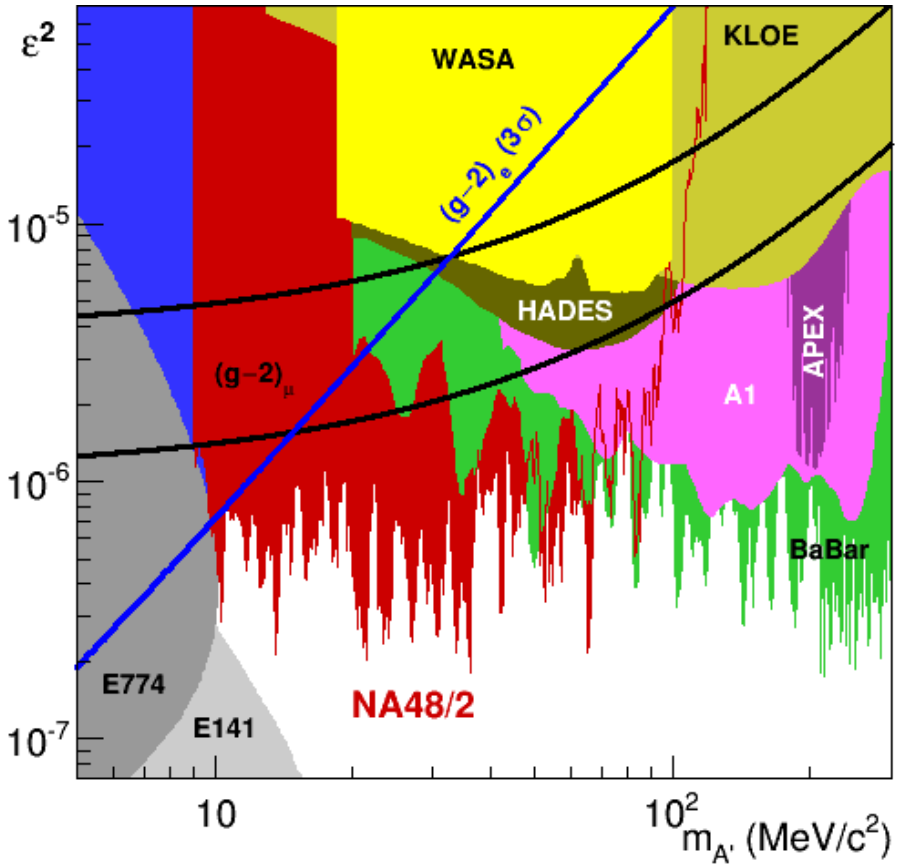
Search for Dark Photon signal

- Look for a narrow peak in m_{ee}
- Do a mass scan $9 < m_{A'} < 120$ MeV/c^2
- 404 DP mass hypothesis tested
- 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 significance never exceeds 3 σ: <u>no dark photon signal</u> is observed



Dark Photon exclusion

- NA48/2 final result
- Improve existing limits in $9<m_{A'}<70$ MeV/c^2
- Limited by irreducible π^0_D background
- If DP couple to quarks and decays mainly to SM fermions, it is ruled out as explanation for anomalous (g-2) of the muon



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Conclusions

- NA62 (2007) π^0 transition form factor slope preliminary measurement

$$a = \left(3.70 \pm 0.53_{stat} \pm 0.36_{syst}\right) \times 10^{-2} = \left(3.70 \pm 0.64\right) \times 10^{-2}$$

- Na48/2 (2003-4) final result on search for dark photon: Phys. Lett. B746 (2015) 178