



# Neutral pion form factor measurement at NA62

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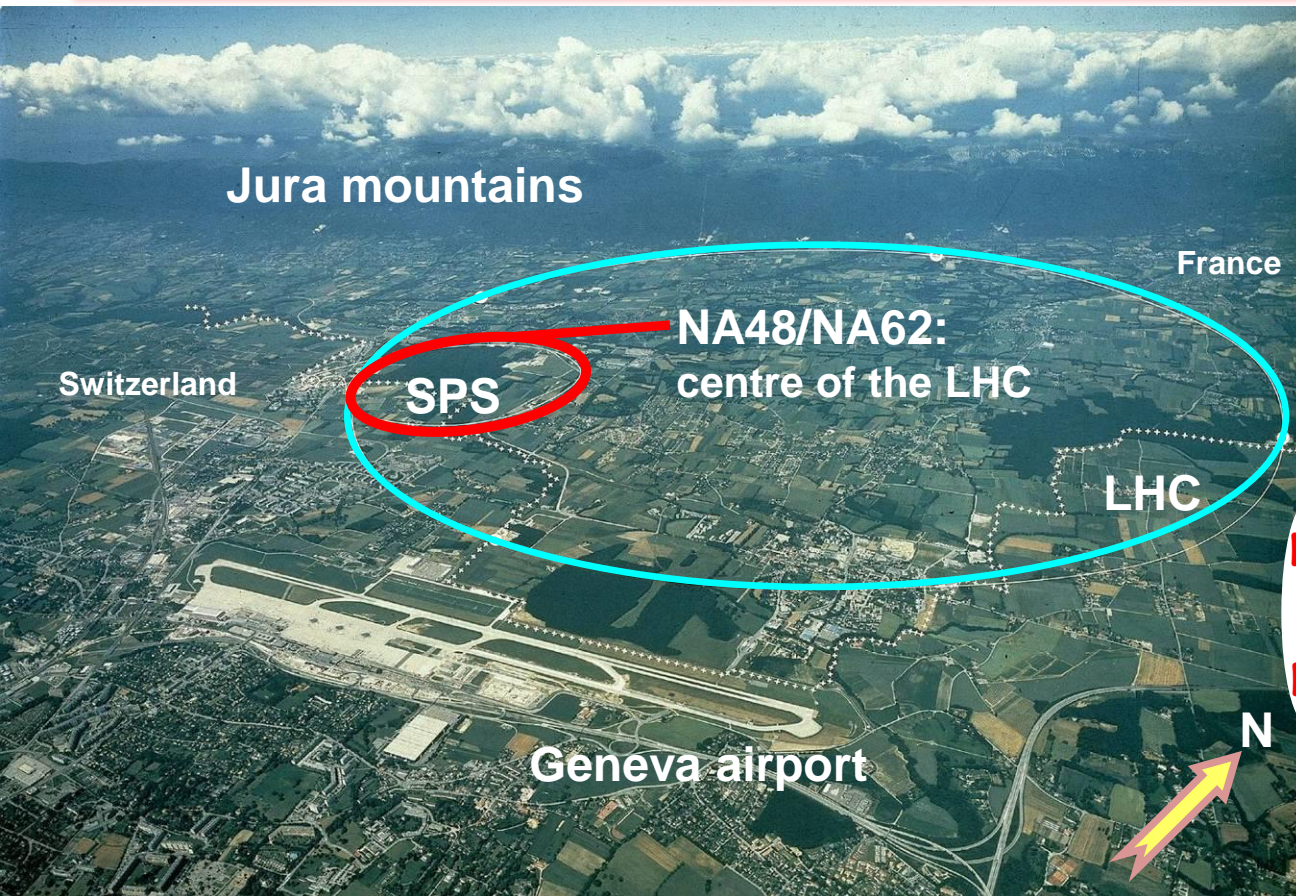
on behalf of the NA48/2 and NA62 collaborations

## Outline:

- 1) The NA48/2 and NA62- $R_K$  experiments at CERN
- 2)  $\pi^0$  transition form factor measurement from  $\pi^0$  Dalitz decays
- 3) A related result: search for the dark photon in  $\pi^0$  decays
- 4) Summary



# Kaon experiments at CERN



Kaon decay in flight experiments.  
 NA62: currently ~200 participants, ~30 institutions

## Earlier: NA31

1997:  $\epsilon'/\epsilon: K_L+K_S$

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**  
discovery of direct CPV

**NA48/1**

2002:  $K_S$ /hyperons

**NA48/2**

2003:  $K^+/K^-$

2004:  $K^+/K^-$

**NA62**  
 $R_K$  phase

2007:  $K_{e2}^{\pm}/K_{\mu2}^{\pm}$  | tests

2008:  $K_{e2}^{\pm}/K_{\mu2}^{\pm}$  | tests

**NA62**

2014: pilot run

2015–: data taking

# NA48/2 and NA62-R<sub>K</sub> experiments

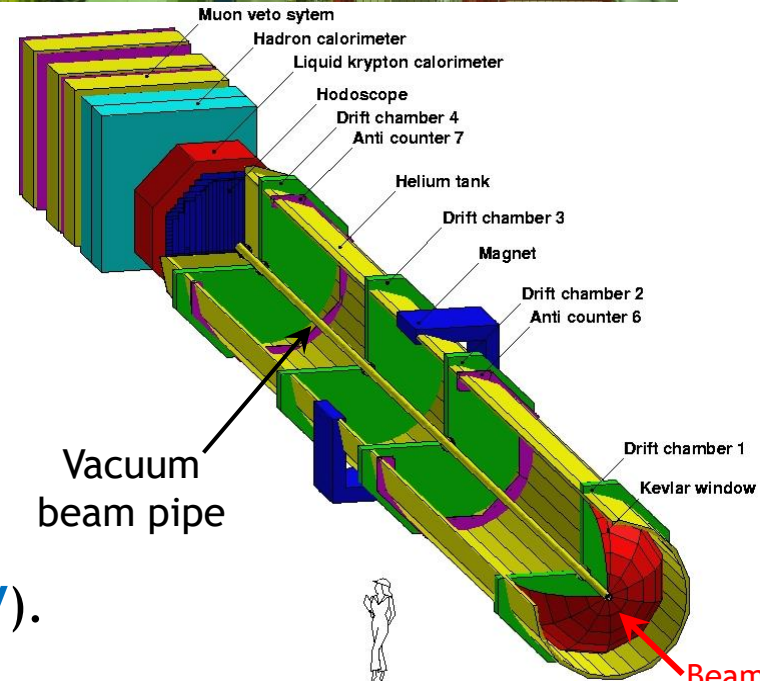
2003-2007: charged kaon beams,  
the NA48 detector

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

- ❖ Maximum  $K^\pm$  decay rate  $\sim 100$  kHz;
- ❖ **NA48/2**: six months in 2003–04;
- ❖ **NA62-R<sub>K</sub>**: four months in 2007.

## Principal subdetectors:

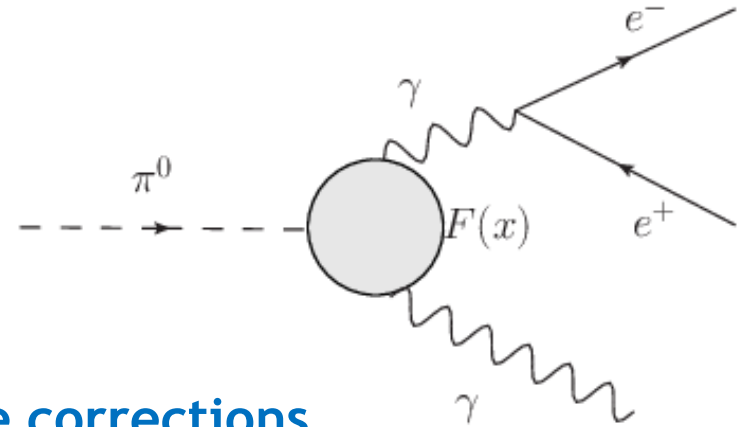
- ❖ **Magnetic spectrometer (4 DCHs)**  
4 views/DCH: redundancy  $\Rightarrow$  efficiency;  
 $\delta p/p = 0.48\% \oplus 0.009\% p$  [GeV/c] (in 2007)
- ❖ **Scintillator hodoscope (HOD)**  
Fast trigger, time measurement (**150ps**).
- ❖ **Liquid Krypton EM calorimeter (LKr)**  
High granularity, 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).



# $\pi^0$ Dalitz decay: $\pi^0_D \rightarrow e^+e^-\gamma$

Kinematic variables:

$$x = \frac{(p_{e^+} + p_{e^-})^2}{m_{\pi^0}^2}, \quad y = \frac{2 p_{\pi^0} \cdot (p_{e^+} - p_{e^-})}{m_{\pi^0}^2(1-x)}$$



**Radiative corrections**

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

**Transition form factor:**

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

$\pi^0$  decay studies at NA48/2 and NA62 experiments:

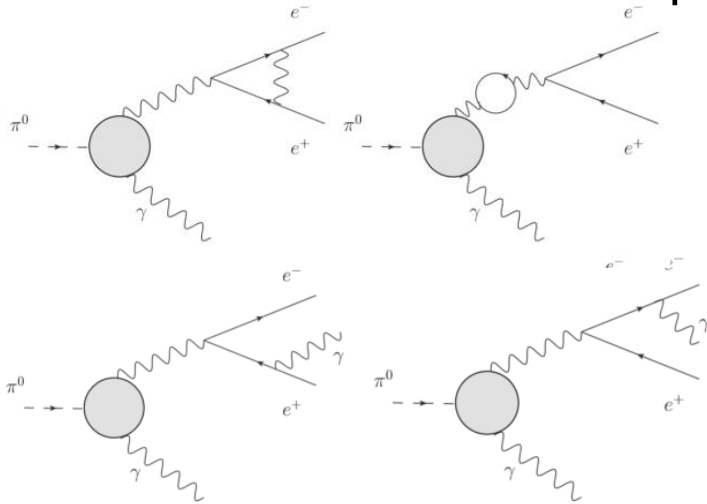
- ❖ High intensity  $K^\pm$  decay in flight experiments.
  - ❖ Intensive sources of tagged  $\pi^0$ , mainly via  $K^\pm \rightarrow \pi^\pm \pi^0$  decays (**BR=21%**).
  - ❖ **NA48/2**: three-track trigger; **NA62-R<sub>K</sub>**: electron ( $e^\pm$ ) trigger.
- Both experiments collected large samples of  $\pi^0_D$  decays.

# Radiative corrections

Radiative corrections are a key issue:  
larger correction to  $d\Gamma/dx$  spectrum than TFF

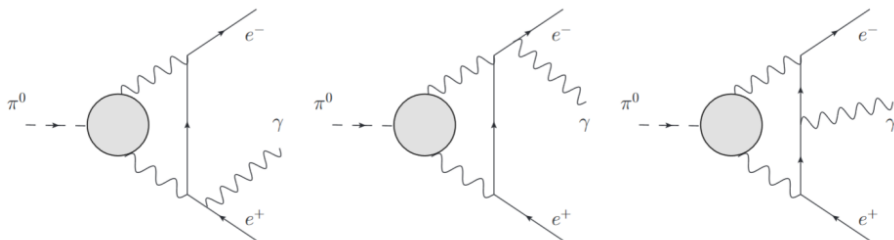
Mikaelian and Smith, PRD5 (1972) 1763:

~5% correction to  $d\Gamma/dx$  slope



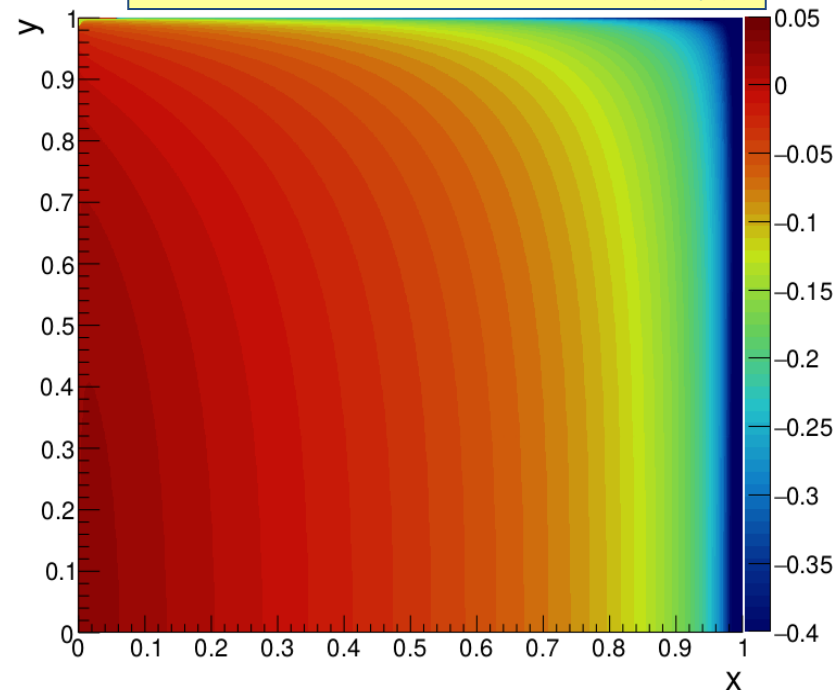
Husek, Kampf and Novotny,  
PRD92 (2015) 054027:

further ~0.5% correction to  $d\Gamma/dx$  slope



$$\frac{d^2\Gamma}{dx dy} = \left( \frac{d^2\Gamma}{dx dy} \right)_0 (1 + \delta(x, y))$$

Radiative corrections:  $\delta(x, y)$

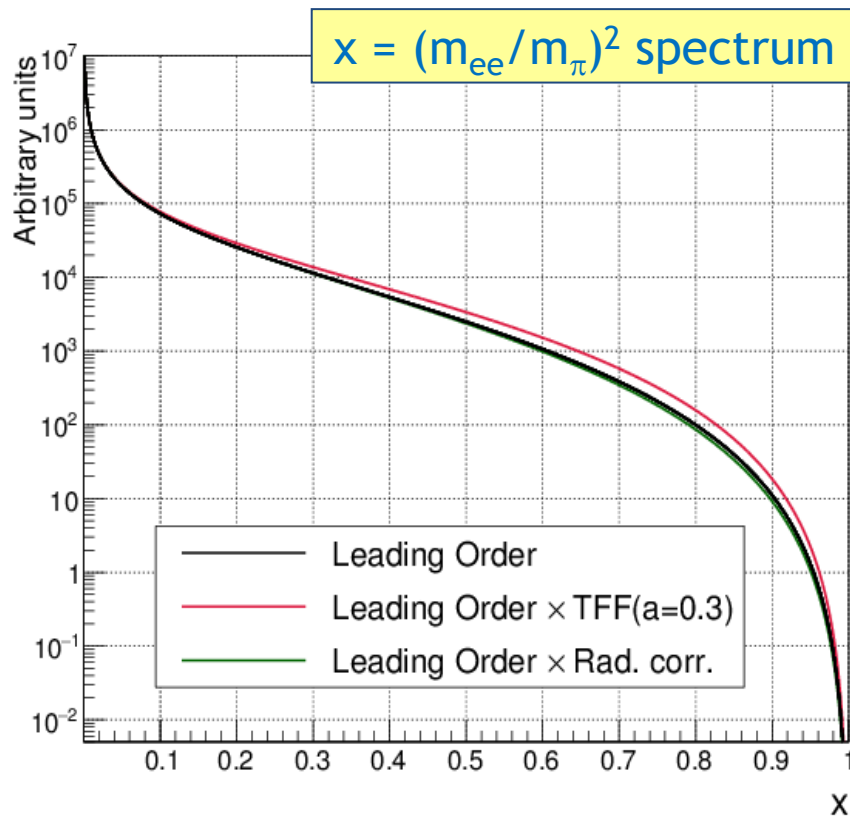


- ✓ Husek et al. (2015) computation is used in this analysis;
- ✓ Crucially, radiative photon emission is simulated.

# Transition form factor

Differential decay width:

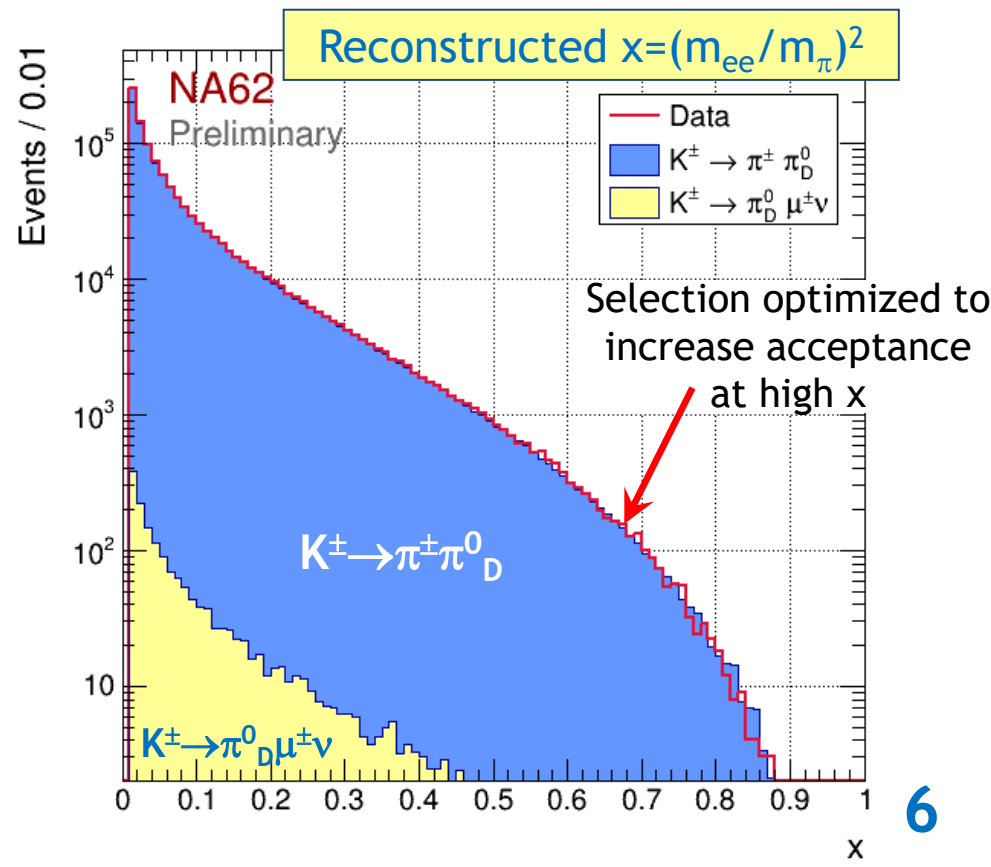
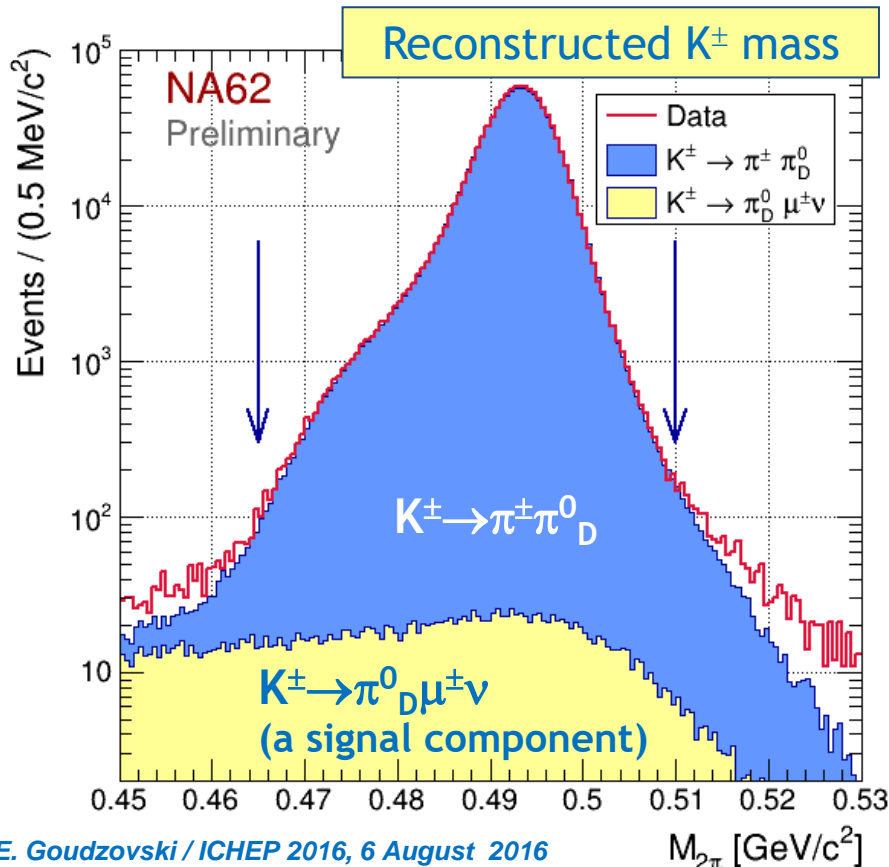
$$\frac{1}{\Gamma(\pi_{2\gamma}^0)} \frac{d\Gamma(\pi_D^0)}{dx} = \frac{2\alpha}{3\pi} \frac{(1-x)^3}{x} \left(1 + \frac{r^2}{2x}\right) \sqrt{1 - \frac{r^2}{x}} (1 + \delta(x)) (1 + ax)^2$$



- ❖ VMD expectation: TFF slope  $a \approx 0.03$   
[L.G.Landsberg, Phys.Rept 128 (1985) 301]
- ❖ Enters hadronic contribution to  $(g-2)_\mu$   
[Knecht, EPJ Web Conf. 118 (2016) 01017]  
[Nyffeler, arXiv:1602.03398]
- ❖ Influences the  $\pi^0 \rightarrow e^+e^-$  decay rate  
[Husek et al., EPJ C74 (2014) 3010]
- ❖ Comparison of TFF slope predictions to a model-independent measurement: important test of the models.
- ❖ A difficult measurement: narrow  $q^2$  region accessible  $\rightarrow$  small effect.

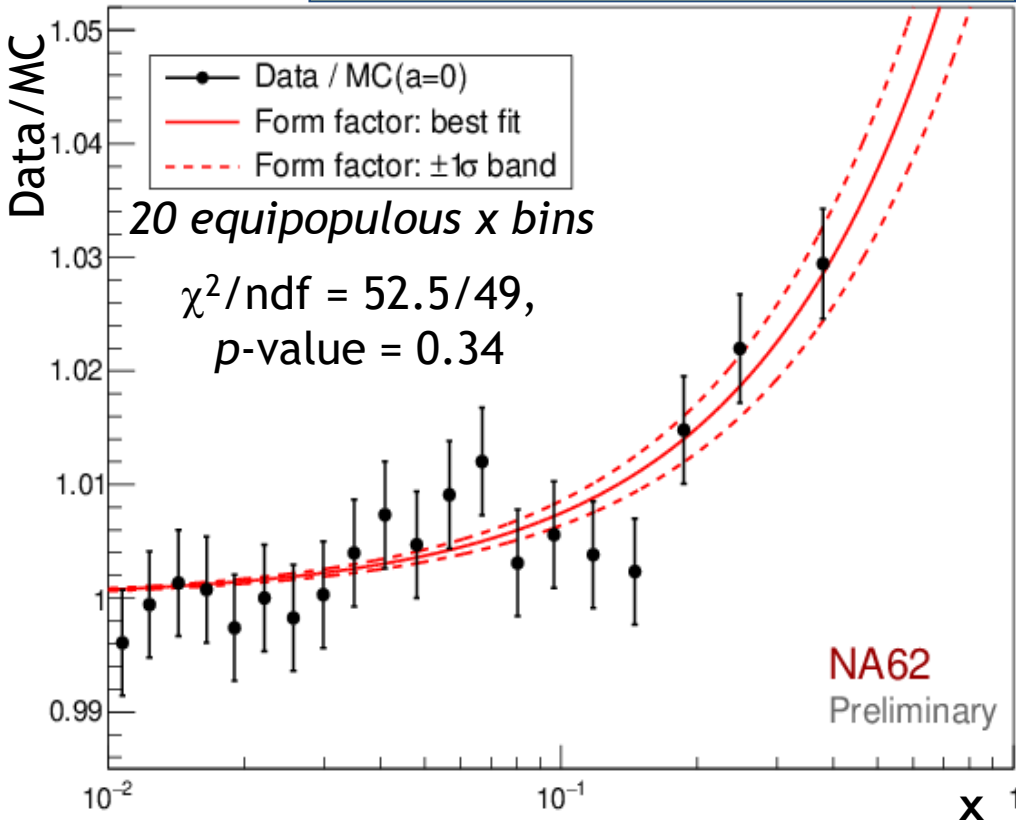
# $\pi^0 \rightarrow \gamma e^+ e^-$ sample: NA62-R<sub>K</sub>

- ❖ Kaon decays in the fiducial decay region:  $\sim 2 \times 10^{10}$ .
- ❖ Source of  $\pi^0$  considered:  $K^\pm \rightarrow \pi^\pm \pi^0$  decay (BR=21%).
- ❖ Reconstructed  $\pi^0_D$  decay candidates,  $x = (m_{ee}/m_\pi)^2 > 0.01$ :  $N(K_{2\pi D}) = 1.05 \times 10^6$ .
- ❖ Despite  $\sim 10$  times smaller sample wrt NA48/2, good for **spectrum study**:
  - ✓ minimum bias trigger: low systematics due to trigger efficiency;
  - ✓ low beam intensity: low systematics due to accidentals.



# TFF slope: preliminary result

Fit illustration: Data/MC(a=0)



Uncertainty	$\delta a \times 10^2$
Statistical: data	0.49
Statistical: MC	0.20
Beam spectrum simulation	0.30
Spectrometer momentum scale	0.15
Spectrometer resolution	0.05
LKr calorimeter non-linearity and energy scale	0.04
Particle mis-identification	0.08
Accidental background	0.08
Neglected $\pi^0$ sources	0.01
<b>Total</b>	<b>0.64</b>

NA62- $R_K$  preliminary result:

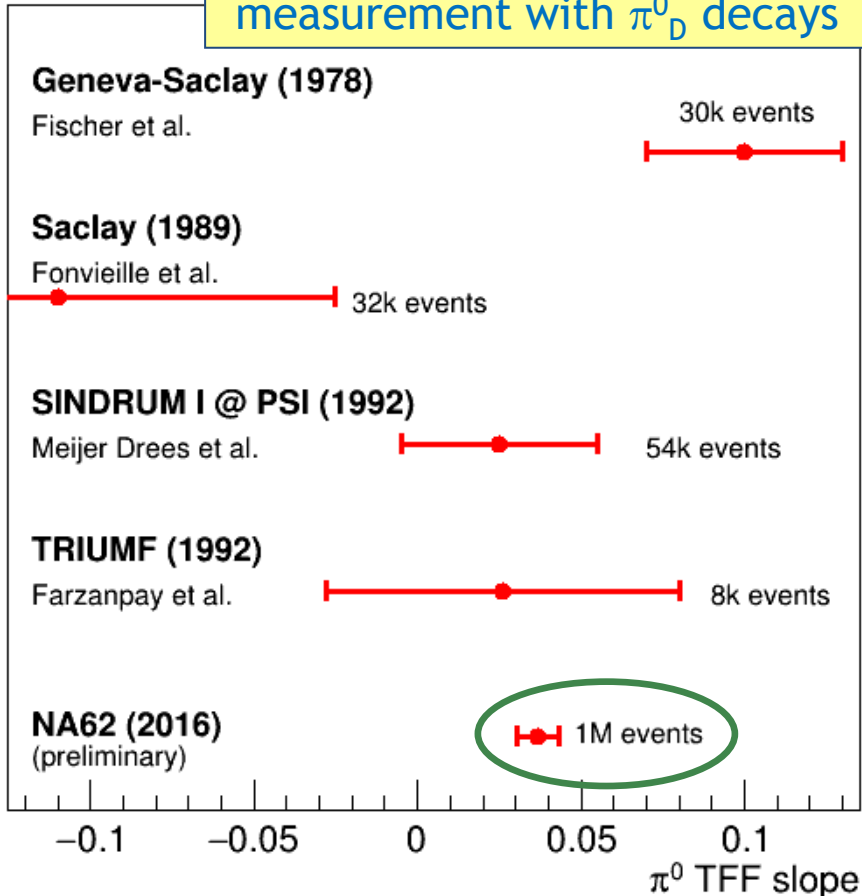
$$a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2}$$

[final result & paper in preparation]

*First observation ( $5.8\sigma$ ) of non-zero TFF slope in the time-like momentum transfer region.*

# NA62 result & world data

World data:  $\pi^0$  TFF slope measurement with  $\pi_D^0$  decays



NA62- $R_K$  preliminary result:

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

## TFF expectations from theory:

- ❖ Chiral perturbation theory  
[Kampf et al., EPJ C46 (2006) 191]  
 $a = (2.90 \pm 0.50) \times 10^{-2}$
- ❖ Dispersion theory  
[Hoferichter et al., EPJ C74 (2014) 3180]  
 $a = (3.07 \pm 0.06) \times 10^{-2}$
- ❖ Two-hadron saturation model  
[Husek et al., EPJ C75 (2015) 586]  
 $a = (2.92 \pm 0.04) \times 10^{-2}$

## CELLO measurement:

[Behrend et al., Z. Phys. C49 (1991) 401]

Extrapolation of space-like momentum ( $\gamma\gamma \rightarrow \pi^0$ ) region data fit to VMD model:

$$a = (3.26 \pm 0.26_{\text{stat}}) \times 10^{-2}$$

# The NA48/2 $\pi^0 \rightarrow \gamma e^+ e^-$ sample

## Two exclusive selections

### $K^\pm \rightarrow \pi^\pm \pi_D^0$ selection:

- $|m_{\pi\gamma ee} - m_K| < 20 \text{ MeV}/c^2$ ;
- $|m_{\gamma ee} - m_{\pi^0}| < 8 \text{ MeV}/c^2$ ;
- no missing momentum.

### $K^\pm \rightarrow \pi_D^0 \mu^\pm \nu$ selection:

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

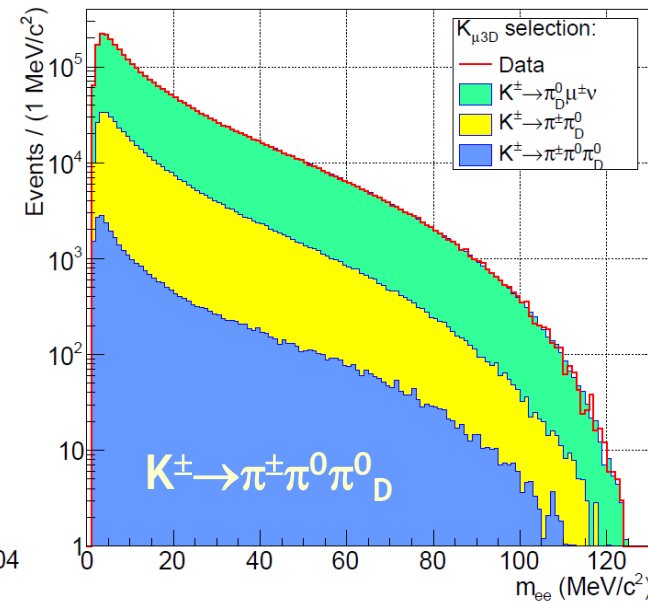
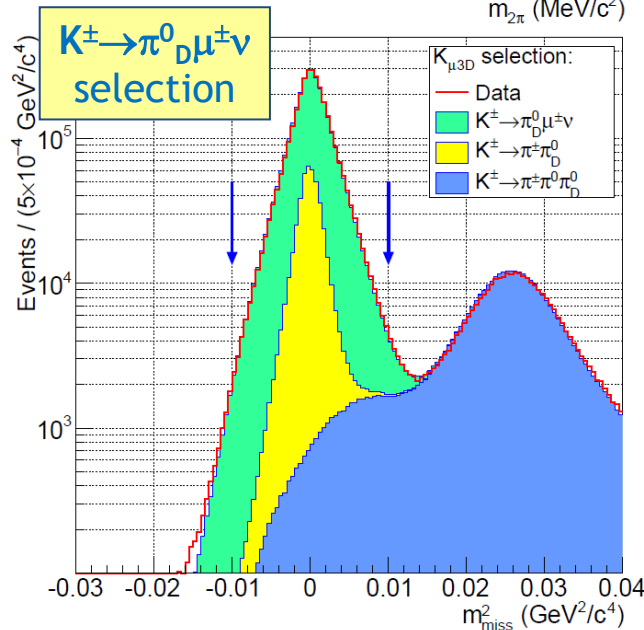
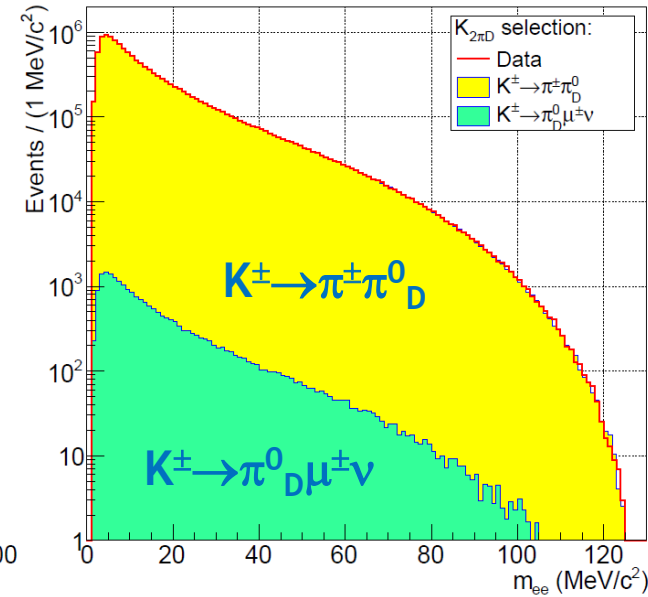
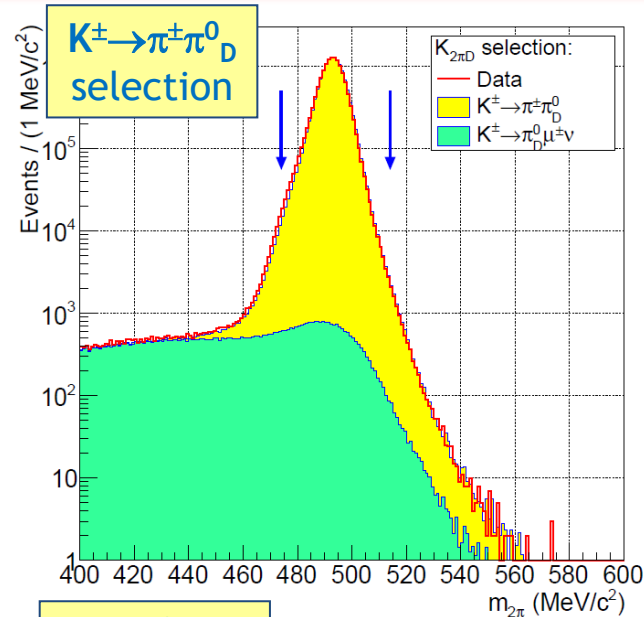
## Reconstructed

### $\pi_D^0$ decay candidates:

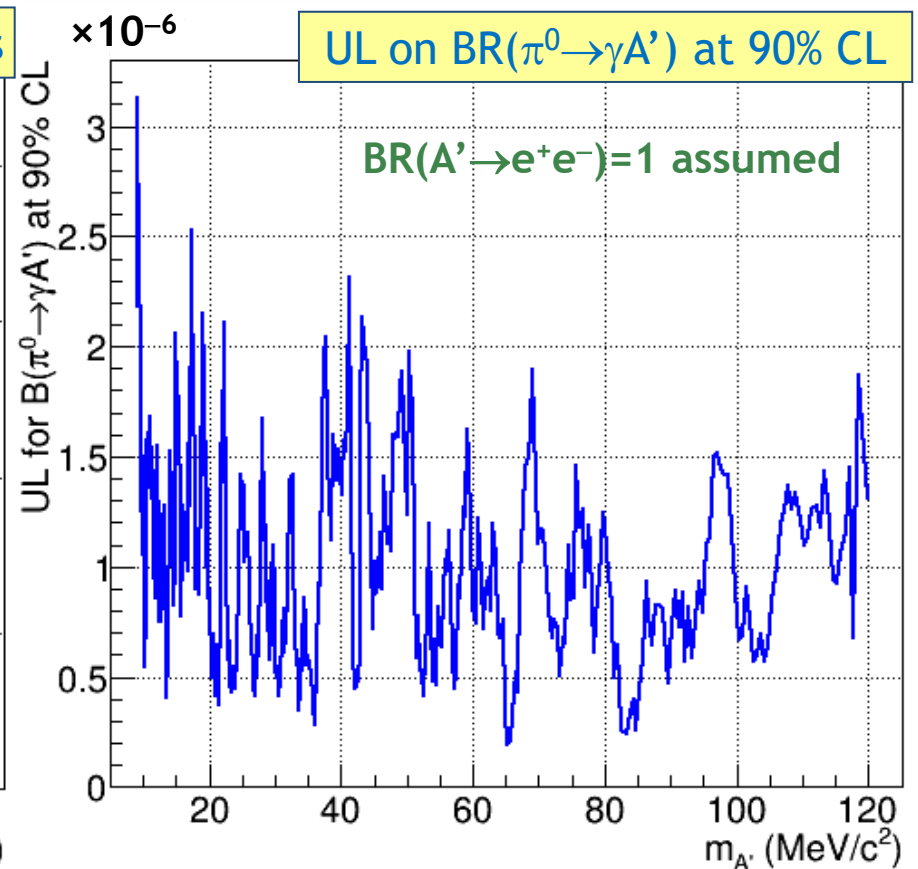
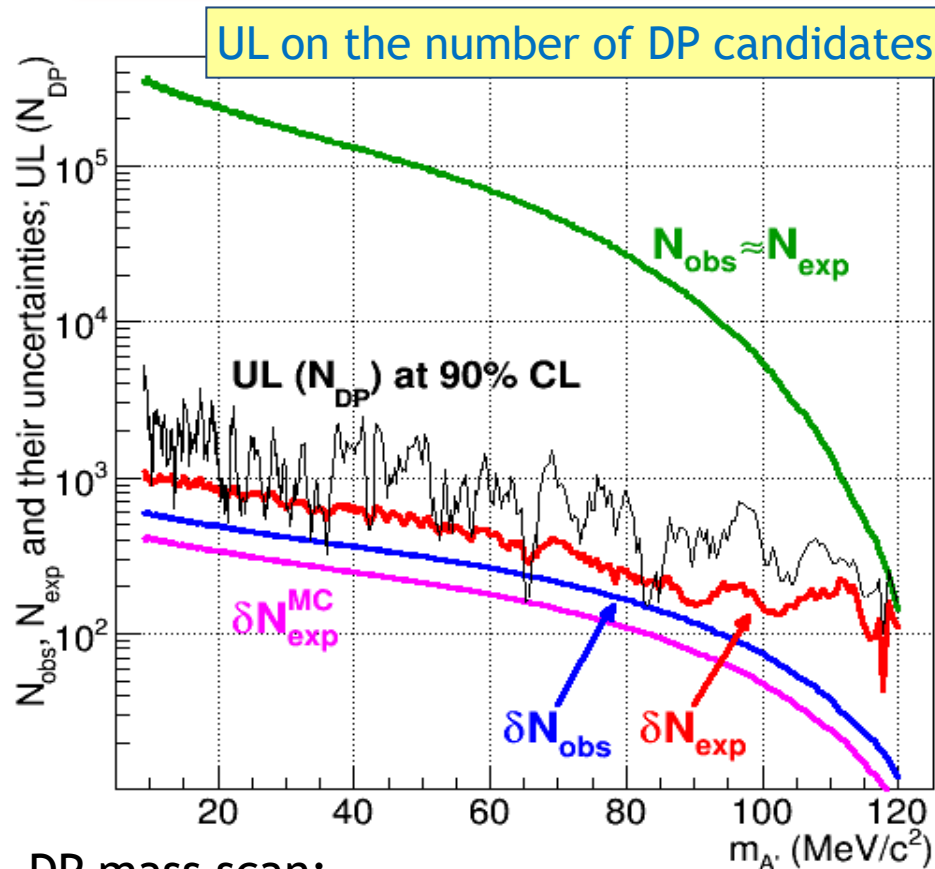
- $N(K_{2\pi D}) = 1.38 \times 10^7$ ,
- $N(K_{\mu 3D}) = 0.31 \times 10^7$ ,
- total =  $1.69 \times 10^7$ .

### $K^\pm$ decays in fiducial region:

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



# NA48/2: search for DP signal



DP mass scan:

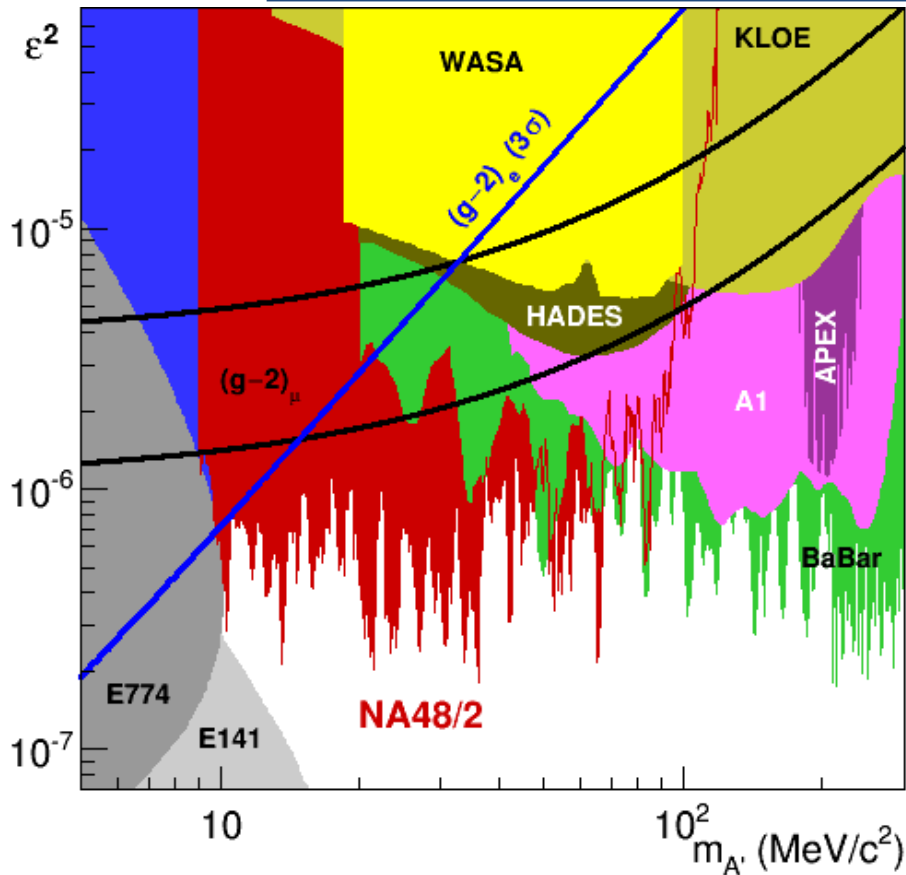
- prompt decay chain  $\pi^0 \rightarrow \gamma A'$ ,  $A' \rightarrow e^+e^-$ ;
- range:  $9 \text{ MeV}/c^2 \leq m_{A'} < 120 \text{ MeV}/c^2$ ;
- mass step  $0.5\sigma_m$ , signal window  $\pm 1.5\sigma_m$ ;
- DP mass hypotheses tested: 404;
- global fit for the background shape.

- ✓ Local signal significance never exceeds  $3\sigma$ : **no DP signal** observed.
- ✓ The obtained limits are background limited: 2–3 orders of magnitude above single event sensitivity.

# NA48/2: dark photon exclusion

PLB746 (2015) 178

DP exclusion summary: all results published by 2015



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

- ❖ Improvement on the existing limits in the  $m_{A'}$  range **9–70 MeV/c<sup>2</sup>**.
- ❖ Most stringent limits are at low  $m_{A'}$ , (kinematic suppression is weak).
- ❖ Sensitivity limited by irreducible  $\pi^0_D$  background: upper limit on  $\varepsilon^2$  scales as  $\sim(1/N_K)^{1/2}$ , modest improvement with larger data samples.
- ❖ If DP couples to quarks and decays **mainly to SM fermions**, it is ruled out as the explanation for the anomalous  $(g-2)_\mu$ .
- ❖ Sensitivity to smaller  $\varepsilon^2$  with displaced vertex analysis: to be investigated.

- ❖ Kaon decay in flight experiments at CERN provide large samples of tagged neutral pions.
- ❖ A preliminary result: *[paper in preparation]*
  - ✓ TFF slope:  $a = (3.70 \pm 0.64) \times 10^{-2}$ .
  - ✓ First observation of non-zero TFF slope in the time-like region.
  - ✓ Triggered progress in radiative corrections to  $\pi^0_D$  decays, which is crucial for this measurements.  
*[Husek et al., PRD92(2015)054027]*
- ❖ Final result: dark photon search in  $\pi^0$  decays *[PLB746 (2015) 178]*
  - ✓ Improved limits (down to  $\epsilon^2 = 2 \times 10^{-7}$ ) in the **9–70 MeV/c<sup>2</sup>** mass range.
  - ✓ The whole region favoured by  $(g-2)_\mu$  is excluded now, assuming DP decays into SM fermions only.