Neutral pion form factor by the NA62 experiment

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*on behalf of the NA62 collaboration:
Birmingham, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Mainz, Merced, Moscow, Naples, Perugia, Pisa, Protvino, Rome I, Rome II, Saclay, San Luis Potosí, Stanford, Sofia, Turin, Vancouver

New Trends in High-Energy Physics

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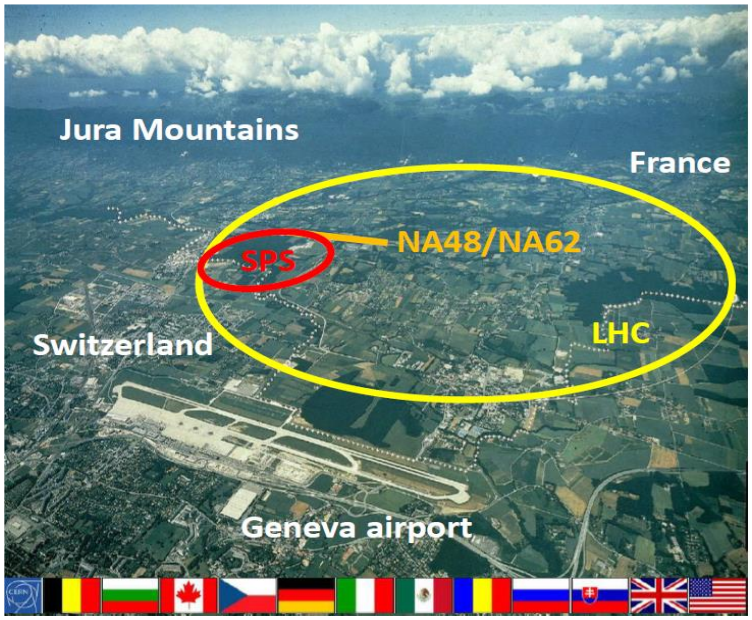
Outline

- **North area experiments**
- **The π^0 form factor measurement from π^0 Dalitz decays**
- **A related research for dark photon in π^0 decay**
- **Conclusions**

North Area experiments



Kaon Physics at CERN:

- ✓ **Fixed target experiments at CERN SPS**
- ✓ **Kaon decay-in-flight**

Currently in NA62:
~200 participants
29 institutions from 13 countries

NA48: K_L and K_S
ε'/ε and
Search for direct CPV
1997-2001

2002
NA48/1: K_S
K_s rare decay studies

2003-2004
NA48/2: K^+ and K^-
Search for direct CPV,
Charge asymmetry measurement

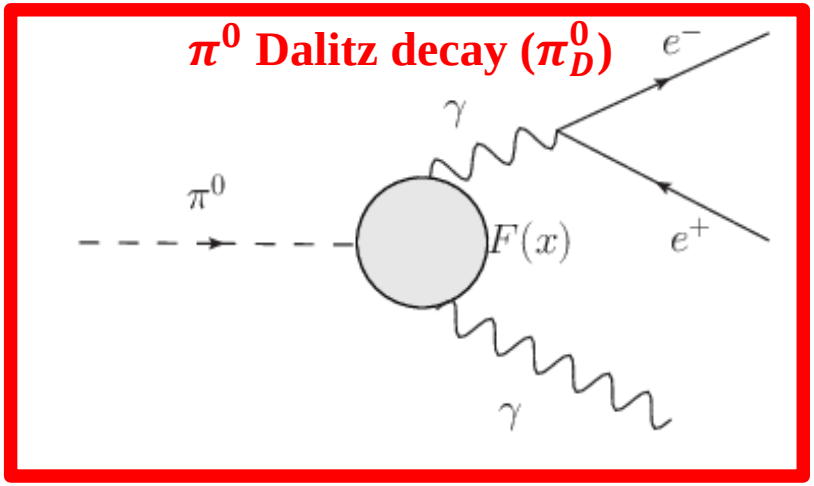
2007-2008
NA62-R_K: K^+ and K^-
Lepton universality:
$K_{e2}/K_{\mu 2}$

2014-
NA62: K^+
Main goal: BR($K^+ \to \pi^+ \nu\bar{\nu}$)

π^0 Dalitz decay: $\pi^0 \to \gamma e^+ e^-$

π^0 decay mode

Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
2γ	(98.823 ± 0.034) %	S=1.5
$e^+ e^- \gamma$	(1.174 ± 0.035) %	S=1.5
γ positronium	$(1.82 \pm 0.29) \times 10^{-9}$	
$e^+ e^+ e^- e^-$	$(3.34 \pm 0.16) \times 10^{-5}$	
$e^+ e^-$	$(6.46 \pm 0.33) \times 10^{-8}$	



Kinematic variables

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

with $r^2 = 4m_e^2/m^2_{\pi^0} \leq x \leq 1$

$$y = \frac{2p_{\pi^0}(p_{e^+} - p_{e^-})}{m^2_{\pi^0}(1-x)}$$

with $-\sqrt{1-r^2/x} \leq y \leq \sqrt{1-r^2/x}$

Differential decay width

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

Radiative correction

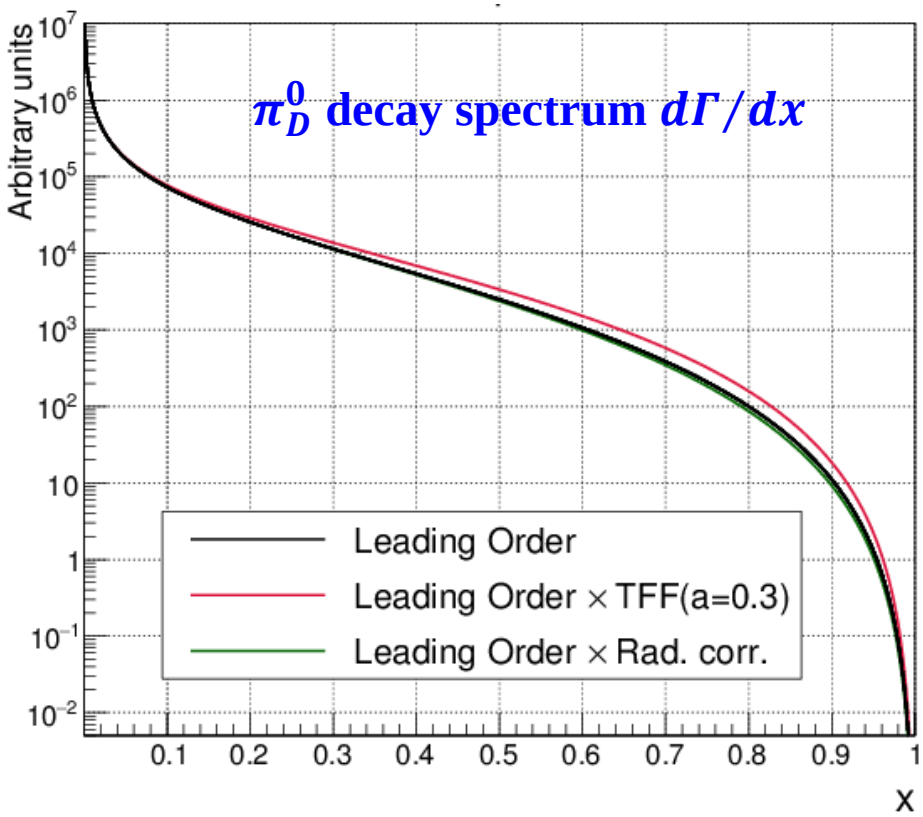
Transition Form Factor
$F(x) \approx 1 + ax$
a is the TFF slope

π^0 Dalitz decay: transition form factor

TFF slope can be extracted from the distribution of the of x Dalitz variable.

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

- **VMD expectation: TFF slope $a = 0.03$**
  [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 decay rate $\pi^0 \to e^+e^-$**
  [Husek et al., EPJ C74 (2014) 3010]
- **Comparison of the TFF slope predictions with model independent measurements is a remarkable test of the theoretical models**



TFF is a very tiny effect and it needs very precise measurement of x and proper treatment of the radiative corrections

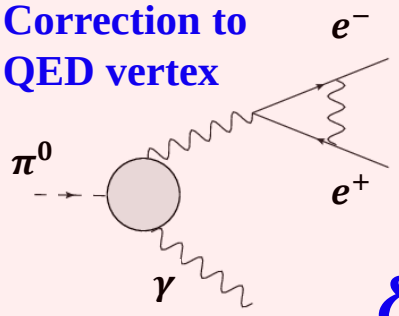
π^0 Dalitz decay: radiative corrections

They are essential because their contibution to the $d\Gamma/dx$ spectrum is larger than TFF

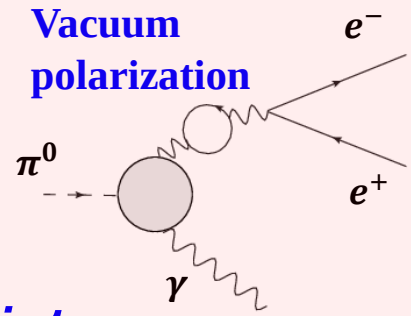
$$\delta = \delta_{virt} + \delta_{brem} + \delta_{1\gamma IR}$$

Original paper by *Mikaelian and Smith, PRD5 (1972) 1763*: ~5% correction to $d\Gamma/dx$ slope

Correction to QED vertex

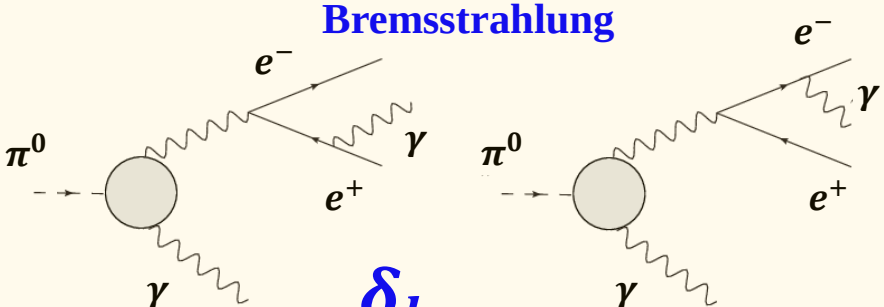


Vacuum polarization



δ_{virt}

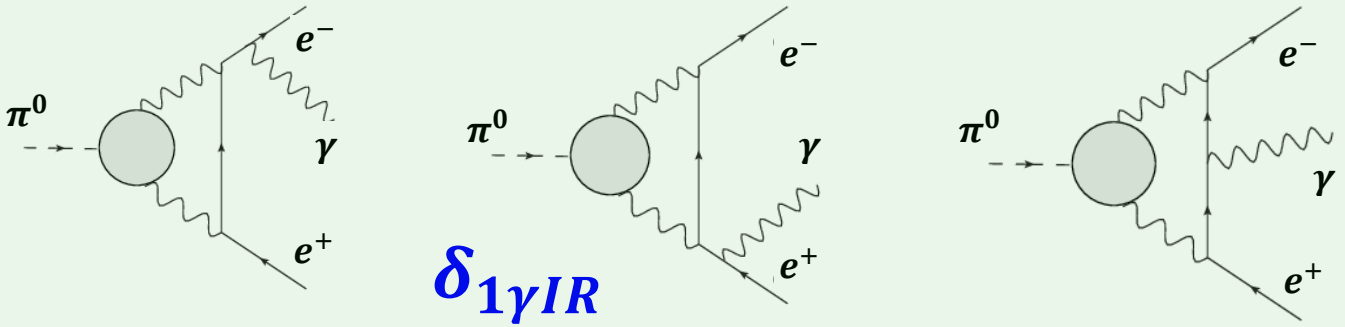
Bremsstrahlung



δ_{brem}

Recent improvement by *Husek, Kampf and Novotny, PRD92 (2015) 054027*: further 0.5% correction to the $d\Gamma/dx$ slope

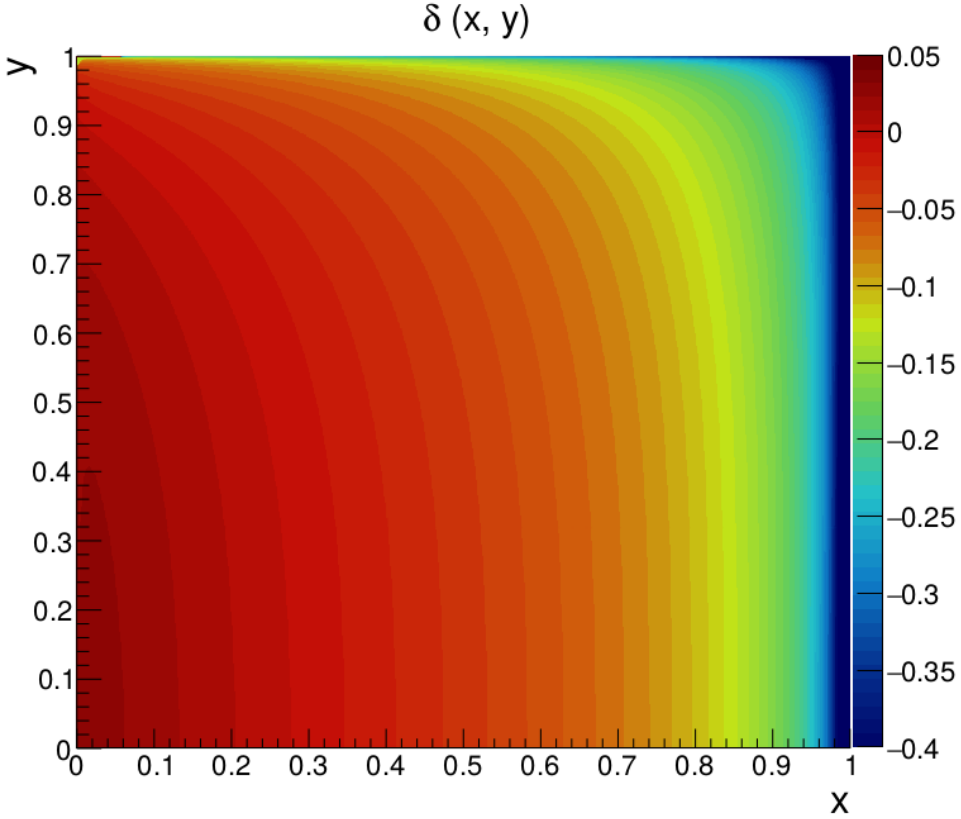
One-loop one-photon irreducible contribution

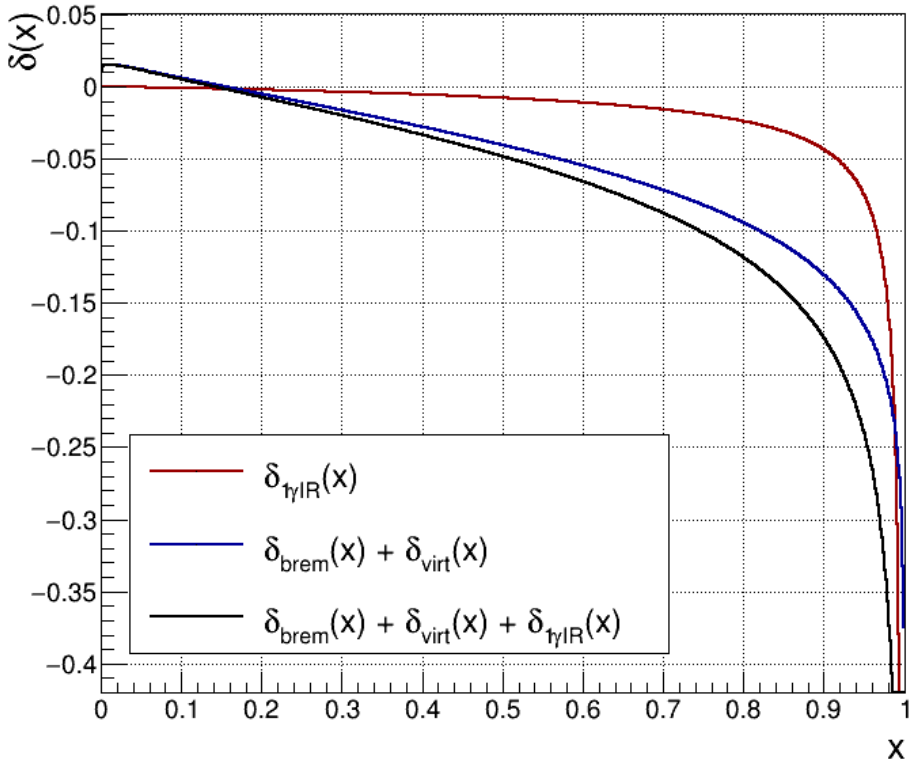


$\delta_{1\gamma IR}$

π^0 Dalitz decay: radiative correction

Size of the radiative corrections to π^0_D Decay

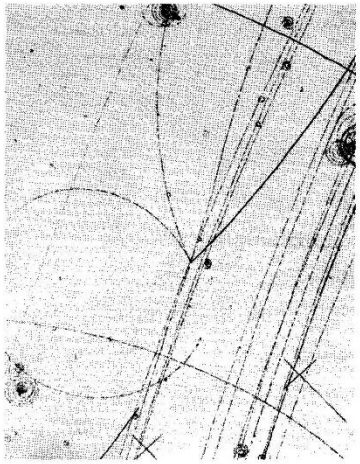


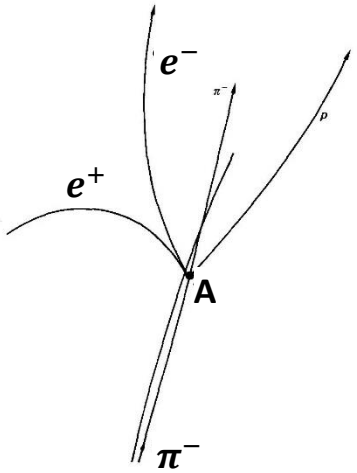


The radiative corrections introduce an effective negative slope to the LO *x* spectrum, which is about two times larger in absolute terms than the expected effect of the TFF.

π^0 Dalitz decay at NA62

π_D^0 decay spectrum $d\Gamma/dx$ is sensitive to the TFF mostly in the $x > 0.1$ region, so a large fraction of events lies in the region which is not sensitive to the TFF.





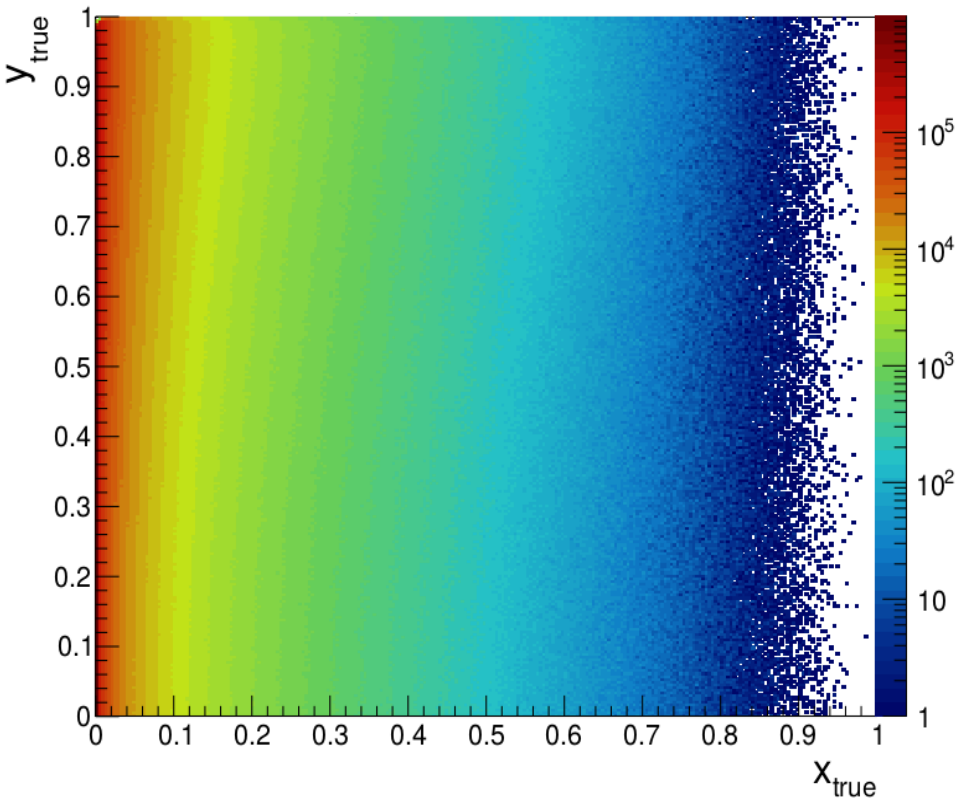
$\pi^- p$ inelastic interaction in point A, generating π^0 decaying Dalitz
Too low statistics…

- **A clean and large sample of π_D^0 can be obtained at NA62-R_K, that is not only a Kaon Factory but also a Pion Factory: production of a large sample of π^0 mesons mainly via the $K^+ \to \pi^+\pi^0$ (BR ~ 21%)**

- **NA62 data (2007): ~ 2×10^{10} $K^\pm$ decays in the fiducial region**
  Data taking optimized for the R_K measurement: identification of $e^\pm$ from $K^\pm \to e^\pm\nu$
  Factor 10 reduction of beam intensity w.r.t. NA48/2:
  - **➜ efficient minimum bias trigger configuration**
  - **➜ minimum accidental background**

π^0 Dalitz MC production

MC $K_{2\pi D}$: all generated events



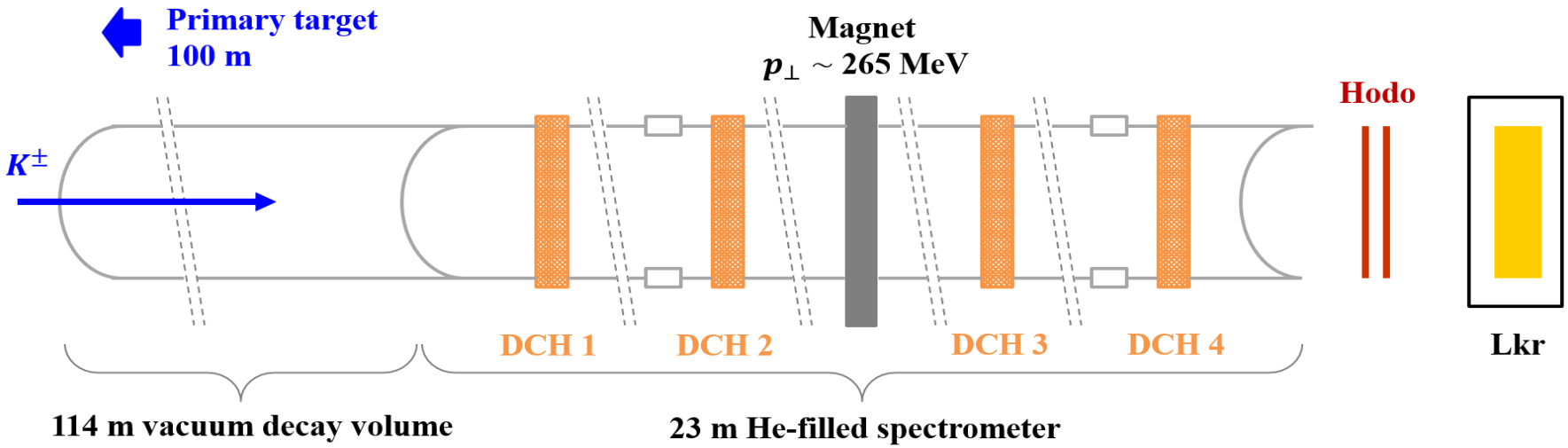
- ***Husek et al. (2015)*** **computation is used in this analysis; radiative corrections implemented in the MC π^0_D event generator, including inner bremsstrahlung photons**

- **3 MC samples used in this analysis:**
  - $K^{\pm} \to \pi^0_D \pi^{\pm}$ **($K_{2\pi D}$)**
  - $K^{\pm} \to \pi^0_D \mu^{\pm} \nu$ **($K_{\mu 3D}$)**
  - $K^{\pm} \to \pi^0_D e^{\pm} \nu$ **(K_{e3D})**

- **At the generator level a constant value for the TFF slope is used: $a_{sim} = 0.032$ (central value of the PDG world average)**

NA62-R_K experimental setup

NA62-R_K data taking: 4 months in 2007 (K^+) **74 GeV/c** mostly K^+ only beam



At 10 GeV

Drift chambers	$\sigma(p)/p = 0.48\% \oplus 0.009\%\ p$ [GeV] $\sigma_{x,y} = 90$ μm	0.48%
LKr calorimeter	$\sigma_E/E = 3.2\%/\sqrt{E}$ [GeV] $\oplus$ $9\%/E$ [GeV] $\oplus$ 0.42% $\sigma_x = \sigma_y = 4.2$ mm$/\sqrt{E} \oplus 0.6$ mm	1.4% 1.5 mm
Hodoscope	Fast trigger, good time resolution (150 ps)	

π^0 Dalitz selection at NA62-R_K

The NA62-R_K data sample:

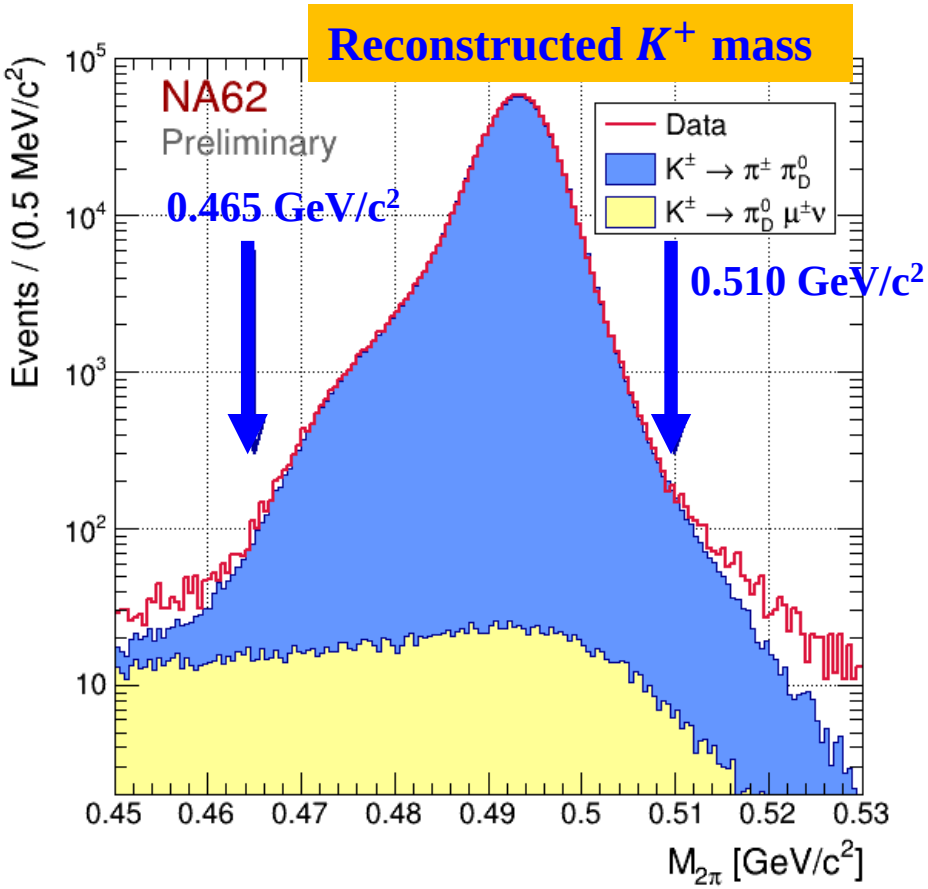
- **≈ 2 x 10^{10} kaon decays in the fiducial region**
- **≈ 5 x 10^9 π^0 mesons from $K^+ \rightarrow \pi^+\pi^0$**
- **negligible mean free path (few μm): prompt decay**

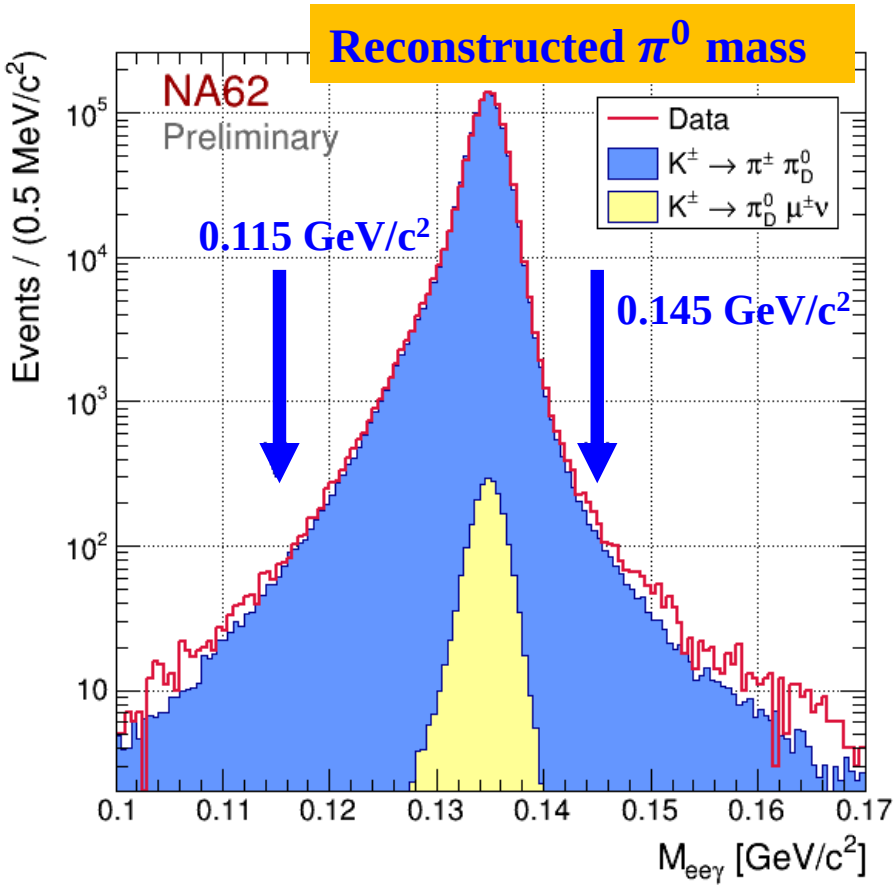
Main selection criteria:

- **events with exactly one reconstructed 3-tracks vertex**
- **position of the reconstructed vertex inside the fiducial decay region**
- **1 γ candidate isolated in the LKr e.m. calorimeter (not geometrically associated to any track by the reconstruction software)**

π^0 Dalitz sample at NA62-R_K

- Cut on $\pi^+\pi^0$ invariant mass (reconstructed K^+ mass)
- Cut on $e^+e^-\gamma$ invariant mass (reconstructed π^0 mass)
- Full kinematic closure





π^0 Dalitz sample at NA62-R_K

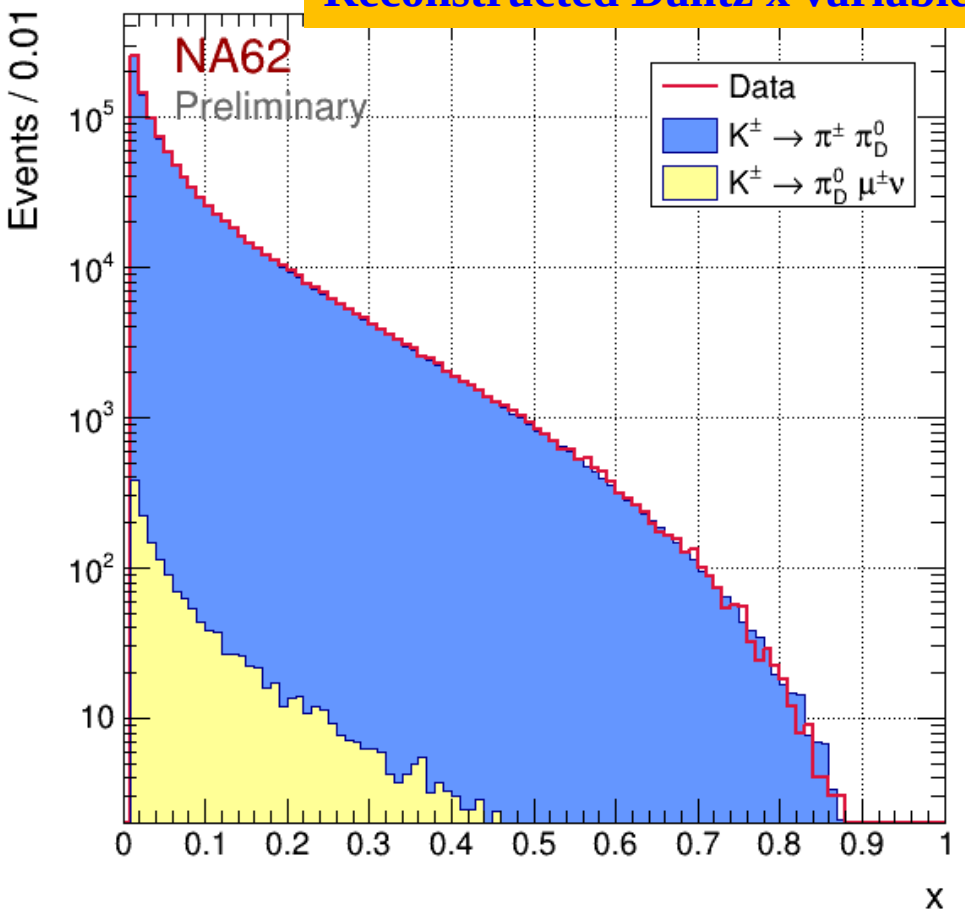
- **Signal region:**

$$0.01 < x = \left(\frac{M_{ee}}{m_{\pi^0}}\right)^2 < 1$$

Due to minimum distance of the $e^{\pm}$ tracks in DCH1.
Distribution not sensitive to the TFF in the x<0.01 region

Number of of fully reconstructed π^0_D events: 1.05 x 10^6
small contribution from $K_{\mu 3D}$

Reconstructed Dalitz x variable



The TFF slope is obtained by adjusting the simulation to the data x spectrum

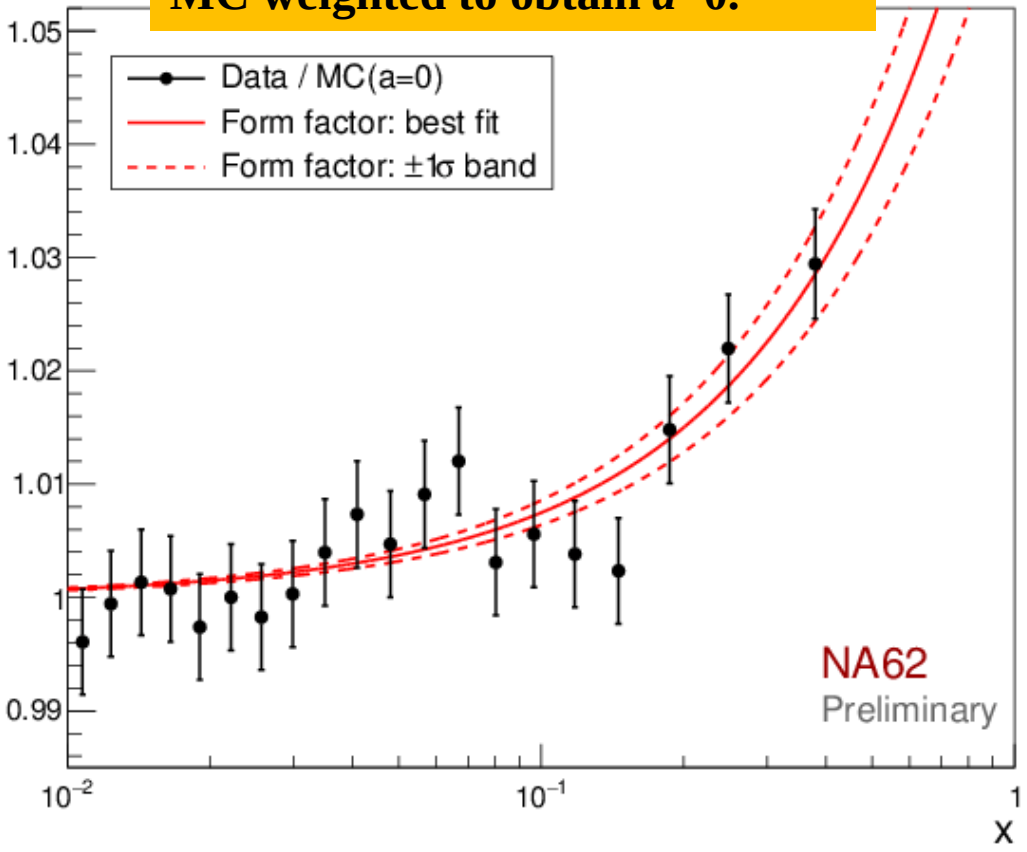
π^0 Dalitz: TFF slope fit

- Split the reconstructed Dalitz x data into 20 equi-populated bins
- Compare data with MC events generated using a constant TFF slope given by the central value of the PDG world average $\mathbf{a_{sim} = 0.032}$
- Re-weight MC events to get simulated distributions with different values of the slope from the same MC sample:

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

- Fit result: slope value from the best data/MC agreement with χ^2 test

Data/MC distributions, with the MC weighted to obtain a=0.



NA62-R_K preliminary fit result:

$a = (3.70 \pm 0.53_{stat}) \times 10^{-2}$ **with** χ^2**/ndf = 52.5/49**

π^0 TFF slope uncertaint

SOURCE	$\delta a \times 10^2$
Statistical - Data	0.49
Statistical - MC	0.20
TOTAL STATISTICAL	**0.53**
Beam momentum simulation	0.30
Spectrometer momentum scale	0.15
Spectrometer resolution	0.05
LKr non-linearity and energy scale	0.04
Particle mis-ID	0.08
Accidental background	0.08
Neglected $\boldsymbol{\pi^0_D}$ sources in MC	0.01
TOTAL SYSTEMATICS	**0.36**

NA62-R_K preliminary result:

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

NA62-R_K π^0 TFF preliminary result

NA62-R_K preliminary result:

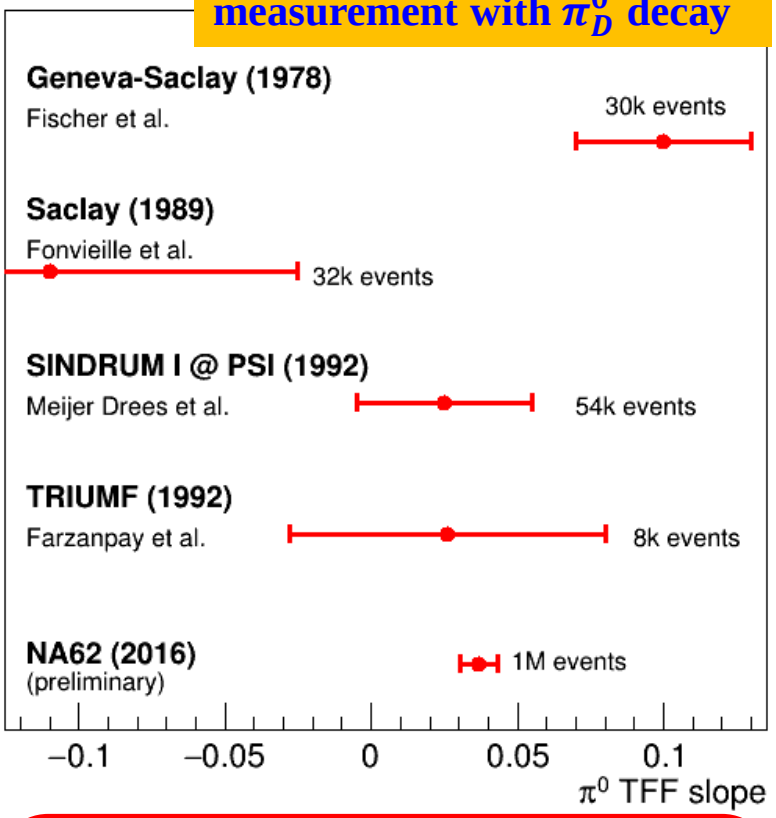
$$a = \left(3.70 \pm 0.53_{stat} \pm 0.36_{syst}\right) \times 10^{-2}$$

[final result and paper in preparation]

- ✓ **TFF slope measurement in the time-like momentum transfer region with a precision of ~15-20 %.**
- ✓ **The NA62 (2007 data) preliminary measurement of TFF slope is the most precise to date in the time-like region of momentum transfer**

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

World data π^0 TFF slope measurement with π^0_D decay



CELLO measurement:
Extrapolation of space-like momentum region data fit to VMD model *[Z. Phys. C49 (1991), 401]*

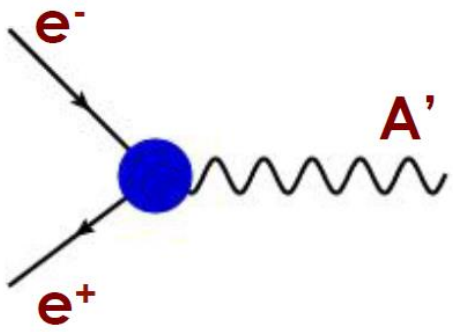
$$a = (3.26 \pm 0.26_{stat}) \times 10^{-2}$$

A related research: dark photon

Simplest hidden sector model: one extra U(1) gauge symmetry with one extra gauge boson, the dark photon A' with mass $m_{A'}$

- **QED-like interactions with SM fermions**

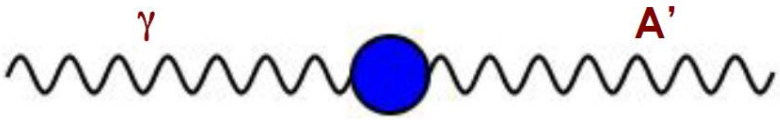
$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$



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

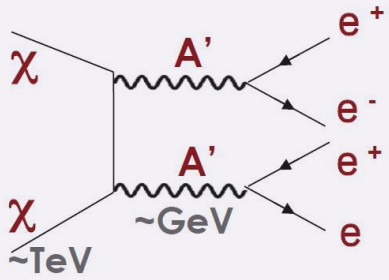
- **Interaction with the visible sector proceed through kinetic mixing between QED and the new U(1) gauge boson**

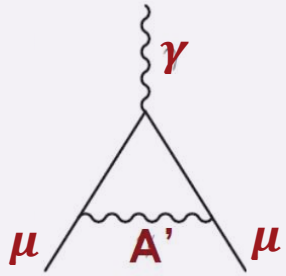
$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$



Motivations:

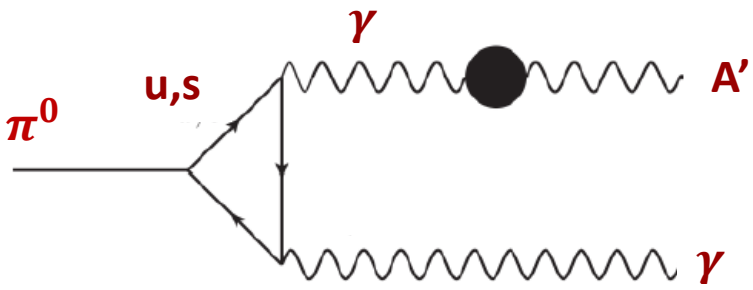
- **Possible explanation for positron excess in cosmic rays (PAMELA, FERMI, AMS-02) by dark matter annihilation**
- **Possible solution to the muon g-2 anomaly**





Dark photon at NA48/2

Search for the decay chains $K_{2\pi}/K_{\mu 3}$ followed by prompt $\pi^0 \to \gamma A', A' \to e^+e^-$



Same signature as $K_{2\pi D}$ and $K_{\mu 3D}$ for the the Dalitz π^0 decay study

NA48/2 data used:

- Detector setup similar to NA62-R_K but reduced dipole magnetic field (p_{t_kick} = 120 MeV/c)
- **2×10^{11} $K^{\pm}$ decays** in the fiducial volume
- **5×10^{10} tagged π^0** decays from $K_{2\pi}$ (BR=20.7%), $K_{\mu 3}$ (BR=3.4%)
- Excellent trigger for 3-track vertices
- Very good e^+e^- **invariant mass ($m_{e^+e^-}$) relative resolution ~1.1%**
- Sensitivity determined by irreducibile : **$\pi^0 \to \gamma e^+e^-$ background**
- Acceptance for both signal chains up to 4.5% depending on $m_{A'}$
- **Search for a narrow peak in the $m_{e^+e^-}$ spectrum**

$\pi^0 \to \gamma e^+ e^-$ sample at NA48/2

Two exclusive selections:

$K_{2\pi D}$ selection

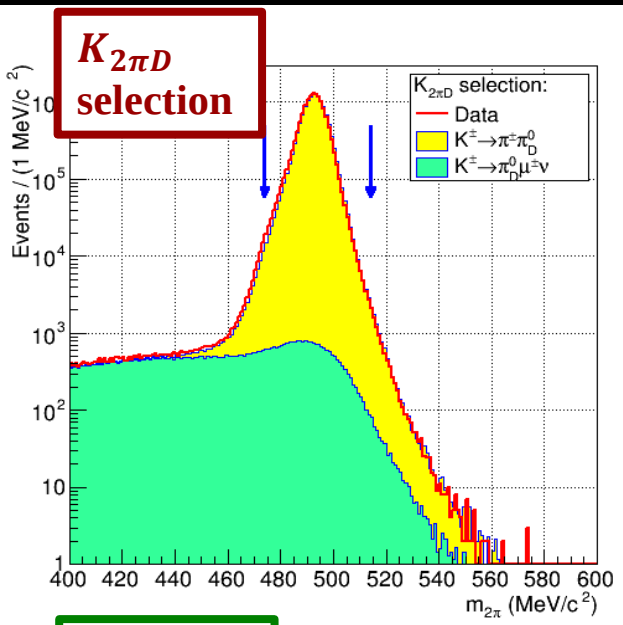
- $|m_{\pi\gamma ee} - m_K| < 20$ Mev/c^2
- $|m_{\gamma ee} - m_{\pi^0}| < 8$ Mev/c^2
- No missing momentum

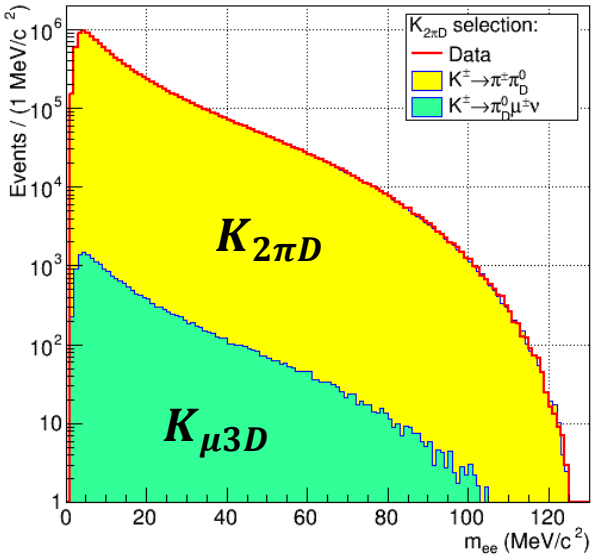
N($K_{2\pi D}$) = 1.38 x 10^7

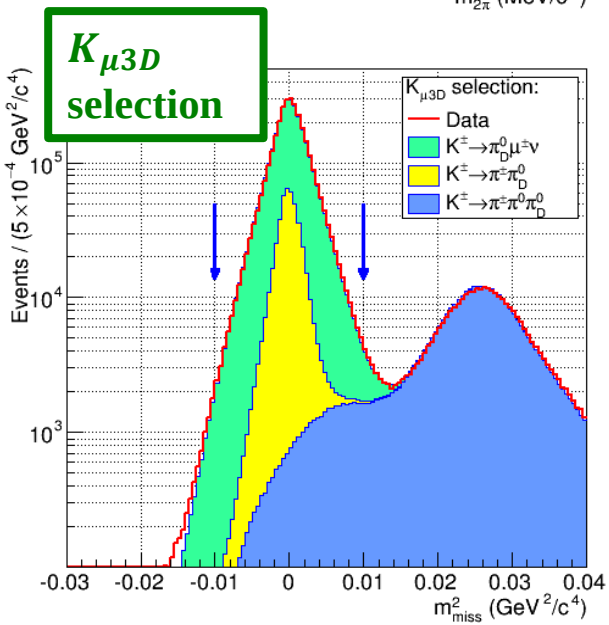
$K_{\mu 3D}$ selection

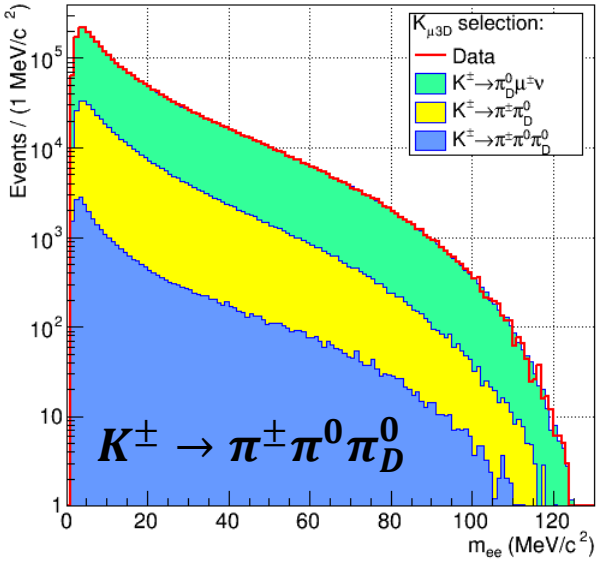
- $m^2_{miss} = (P_K - P_\mu - P_{\pi^0})^2$ compatible with 0
- $|m_{\gamma ee} - m_{\pi^0}| < 8$ Mev/c^2
- Missing total and transverse momentum

N($K_{2\pi D}$) = 0.31 x 10^7



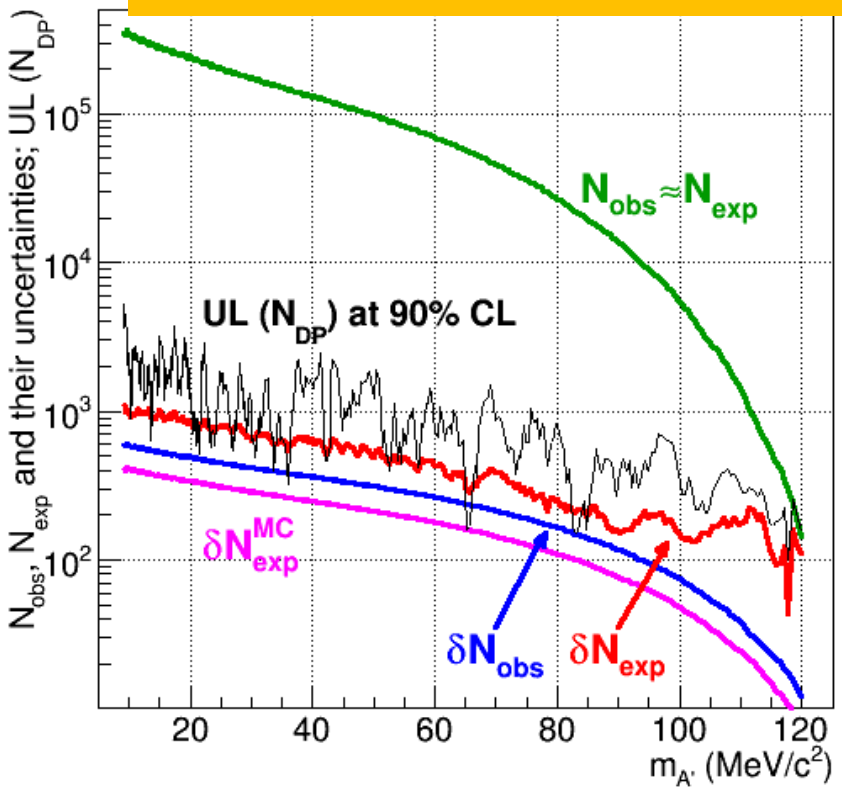




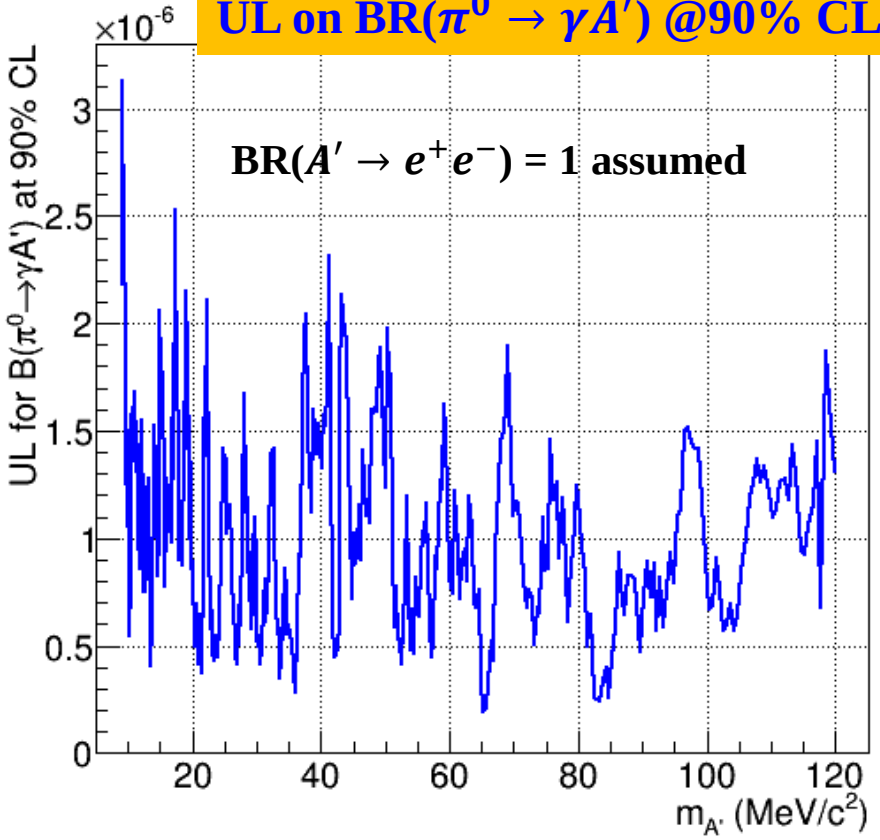


Search for dark photon at NA48/2

UL on the number of DP candidates



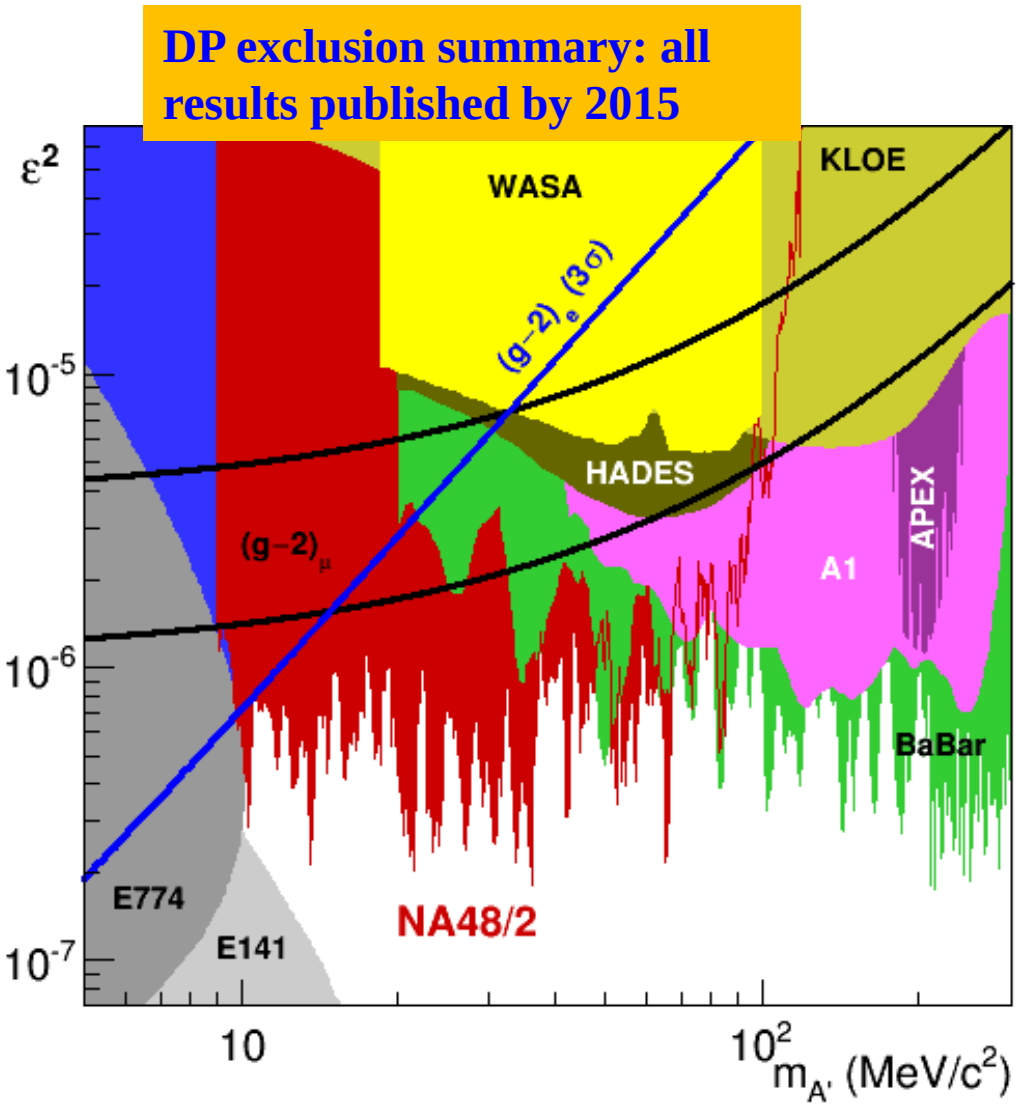
UL on BR($\pi^0 \to \gamma A'$) @90% CL



- **Scan for DP signal in the mass range: 9 MeV/$c^2 \leq m_{A'} <$120 MeV/c^2**
- **Mass step 0.5σ_m , signal window ±1.5σ_m**
- **DP mass hypotesis tested: 404**
- **Global fit for the background shape.**

Local significance never exceeds 3σ no DP signal observed

Dark photon exclusion at NA48/2



Improvement on the existing limits in the $m_{A'}$ range 9-70 MeV/c^2

- Sensitivity limited by irreducible π^0_D background
- Most stringent limits on ε^2 at low $m_{A'}$
- Upper limit on ε^2 scales with $(1/N_K)^{1/2}$, so a modest improvement achievable with larger $K^{\pm}$ data sample
- If dark photon couples to quarks and decays mainly to SM fermions, it is ruled out as explanation for anomalous $(g-2)_\mu$

Phys. Lett. B746 (2015) 178

Conclusion

Kaon decay in flight experiments at CERN provide large samples of tagged neutral pions.

NA62-R_K preliminary results:

- ✓ measurement of the π^0 Transition Form Factor slope parameter:
$$a = \left(3.70 \pm 0.53_{stat} \pm 0.36_{syst}\right) \times 10^{-2}$$
- ✓ the precision of the TFF measurement has been improved in the time-like momentum region.
- ✓ paper in preparation

NA48/2 final result on Dark Photon search [Phys. Lett. B746 (2015) 178]:

- ✓ existing limits on ε^2 in the 9 - 70 MeV/c^2 mass range are improved
- ✓ DP excluded as explanation for $(g-2)_\mu$ anomaly if it decays mainly to SM fermions

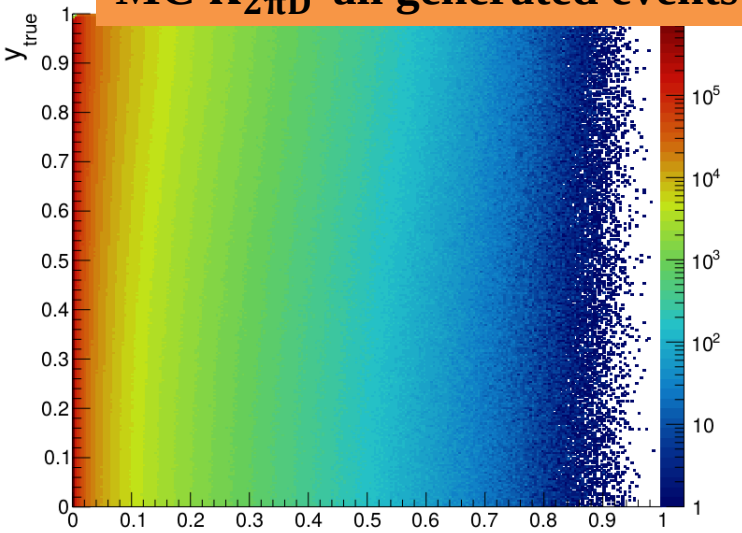
Backup

$K_{2\pi D}$ MC selection

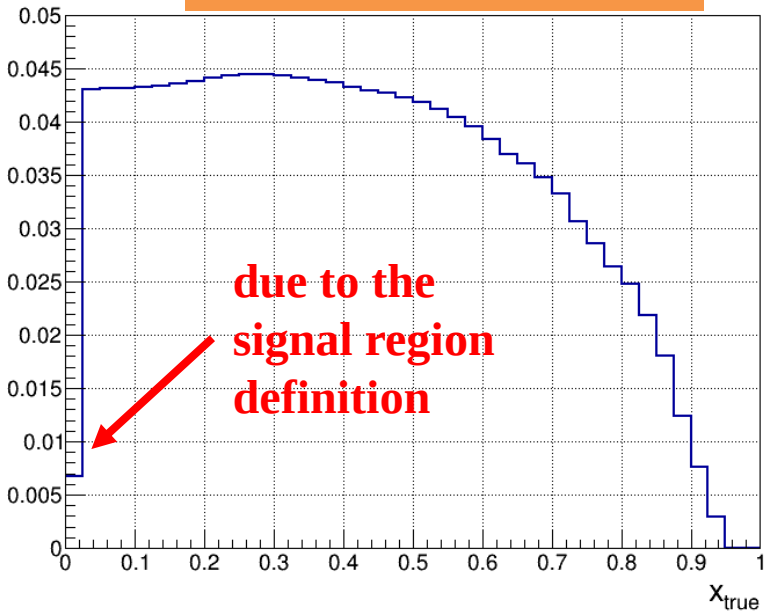
Selected events from MC

MC sample	Generated events	Acceptance
$K_{2\pi D}$	386268415	1.9 %
$K_{\mu 3D}$	105196033	0.020 %
K_{e3D}	103672720	0.013 %

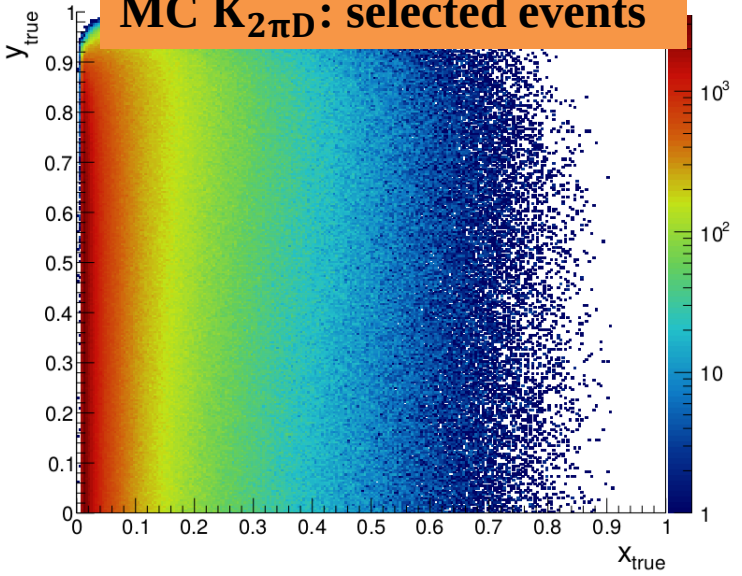
MC $K_{2\pi D}$: all generated events



MC $K_{2\pi D}$: acceptance



MC $K_{2\pi D}$: selected events



NA62-R_K trigger

- ***Q*1: a coincidence of at least one hit in each of the HOD planes, both hits belonging to the same quadrant.**
- ***ELKr* (10 GeV): a total energy deposition >10 GeV in the LKr calorimeter.**
- **1 TRKLM: at least one hit in at least two views and less than 15 hits in any of the views in the DCHs.**
- ***L*3(*Ke*2): at least one track with LKr energy / momentum (*E*/*p*) ratio larger than 0.6 and momentum in the range (5-90) GeV/c.**