Recent results from NA48/2 (LFV, DP) and NA62 (Neutral Pion Form Factor)

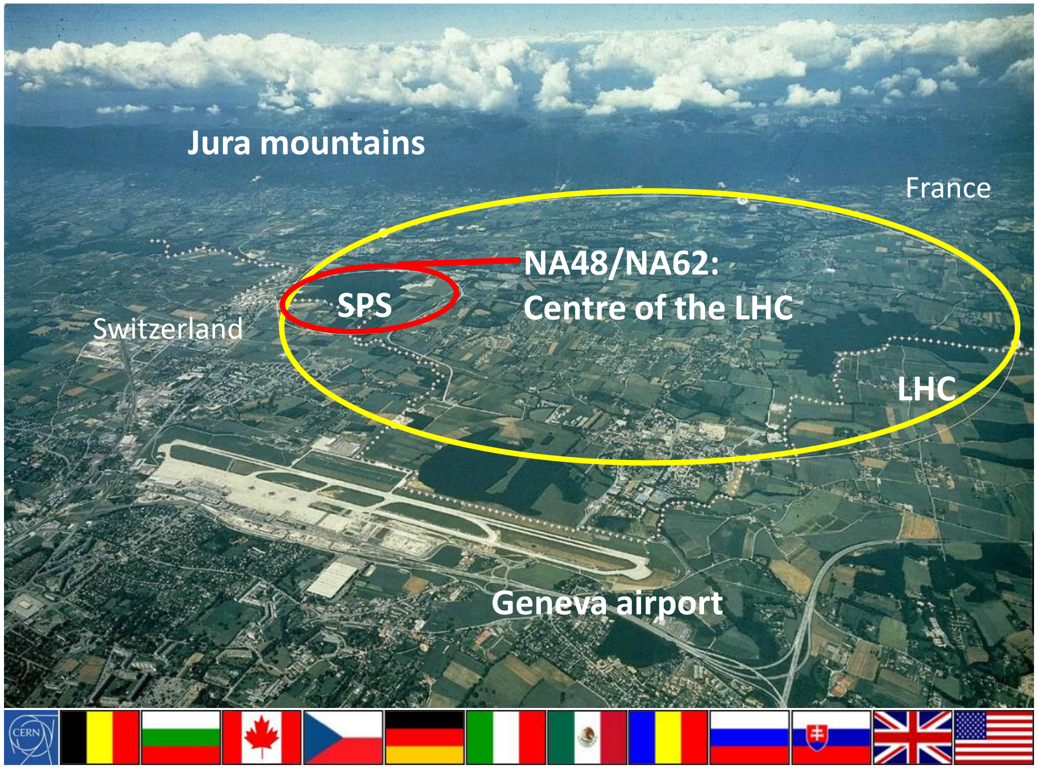
On behalf of the NA62 collaboration

Nicolas Lurkin
School of Physics and Astronomy, University of Birmingham
XIIIth International Conference on Heavy Quarks and Leptons, 24-05-2016

Outline

- NA48/2 - $\mathrm{NA62}_{\mathrm{R_K}}$ experiment
- Lepton Number Violating (LNV) decay $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$
- Search for resonances in $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ and $K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$
- Dark Photon (DP) searches in π^{0} decay
- π^{0} electromagnetic transition form factor (TFF) measurement

CERN NA48/NA62 experiments



Experiments history		
Earlier	NA31	
1997 ↓ 2001	NA48 (K_S/K_L)	$Re(\varepsilon'/\varepsilon)$ Discovery of direct CPV
2002	NA48/1 (K_S/hyperons)	Rare K_S and hyperon decays
2003 ↓ 2004	NA48/2 (K^+/K^-)	Direct CPV, Rare K^+/K^- decays
2007 ↓ 2008	$\mathrm{NA62}_{\mathrm{R_K}}$ (K^+/K^-)	$R_K = K^{\pm}_{e2}/K^{\pm}_{\mu 2}$
2014	NA62 (K^+)	$K^+ \to \pi^+ \nu\bar{\nu}$, Rare K^+ and π^0 decays

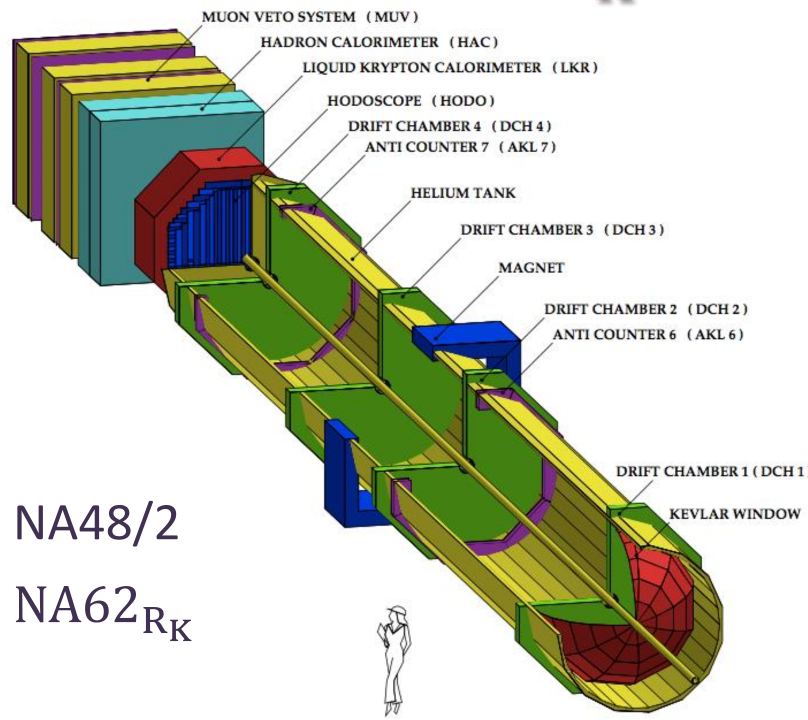
Kaon decay in flight experiment

NA62: currently ~200 participants, 29 institutions from 13 countries

Experimental Setup (NA48/2 – NA62$_{\mathrm{R_K}}$)

Principal subdetectors

- Scintillator hodoscope (HOD)
  - Low-level trigger,
    time measurement (150 ps)
- Magnetic spectrometer (4DHCs)
  - 4 views/DCH high efficiency
  - $\sigma_p/p = 1.02\% \oplus 0.044\% \cdot p$ [GeV/c] NA48/2
    $= 0.48\% \oplus 0.009\% \cdot p$ [GeV/c] NA62$_{\mathrm{R_K}}$
- Liquid Krypton EM calorimeter (LKr)
  - High granularity, quasi-homogeneous
  - $\sigma_E/E = \left(3.2/\sqrt{E} \oplus 9/E \oplus 0.42\right)\%$ [E in GeV]
  - $\sigma_x = \sigma_y = \left(4.2/\sqrt{E} \oplus 0.6\right)$ mm [E in GeV]
    (1.5 mm @ 10 GeV)



NA48/2
$P_K = 60 \pm 3$ GeV/c
3-track vertex trigger
Simultaneous K^+/K^- beam
NA62$_{\mathrm{R_K}}$
$P_K = 74 \pm 2$ GeV/c
K_{e2} trigger
Alternate K^+/K^- beam

LNV in the $K^{\pm} \to \pi\mu\mu$ decays

Majorana Neutrinos

- Asaka-Shaposhnikov model (νMSM) [PLB 620 (2005) 17]:
  three sterile neutrinos $\mathrm{N_i}$ in the SM to explain Dark Matter ($\mathrm{N_1}$, $\mathcal{O}$(keV))
  + Baryon Asymmetry and low ν mass ($\mathrm{N_{2,3}}$ $\mathcal{O}$(100 MeV – few GeV))
- Effective vertices with $W^{\pm}, Z$ and SM leptons with U mixing matrix
  - Production of $\mathrm{N_{2,3}}$ in $K^{\pm}$ decays and $\mathrm{N_{2,3}}$ decay for $m_{2,3} < m_K - m_\mu$
    $$K^{\pm} \to \mu^{\pm} N, \qquad N \to \pi^{\pm}\mu^{\mp}$$
  - $\mathrm{BR}(K^{\pm} \to \mu^{\pm} N) \times \mathrm{BR}(N \to \pi^{\mp}\mu^{\pm}) \sim |U_{\mu 4}|^4$

For this result

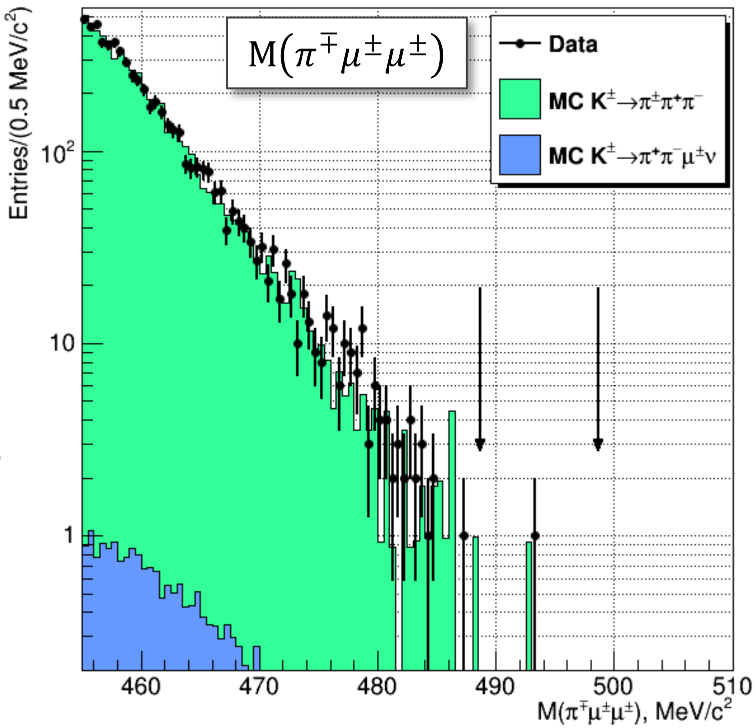
Inflatons

- Shaposhnikov-Tkachev model [PLB 639 (2006) 414]:
  νMSM + real scalar field (inflaton χ) with scale-invariant couplings to explain universe homogeneity and isotropy on large scales/structures on smaller scales
- χ-Higgs mixing (θ), χ-Higgs coupling → universe reheating, $\tau_\chi \sim (10^{-8} - 10^{-12})$
- Production in Kaon decays:
  $m_\chi < 354\ \mathrm{MeV}/c^2$ and $\mathrm{BR}(K^{\pm} \to \pi^{\pm}\chi) = 1.3 \times 10^{-3} \left(\frac{2|\vec{p}_\chi|}{M_K}\right)\theta^2$

LNV: Same-Sign Muon Sample

❑ Blind analysis:

- Selection based on simulation of $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ and $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ (background, similar topology)
  - 3-track vertex topology, 2 same-sign muons, 1 odd-sign pion, no missing momentum
  - First-order cancellation of systematic effects
- Control region: $M_{\pi\mu\mu} < 480\ \mathrm{MeV}/c^2$
- Signal region: $|M_{\pi\mu\mu} - M_K| < 5\ \mathrm{MeV}/c^2$



❑ Results:

- Event in Signal Region: $N_{obs} = 1$
- Expected background from MC:

$$N_{\exp} = 1.163 \pm 0.867_{stat} \pm 0.021_{ext} \pm 0.116_{syst}$$

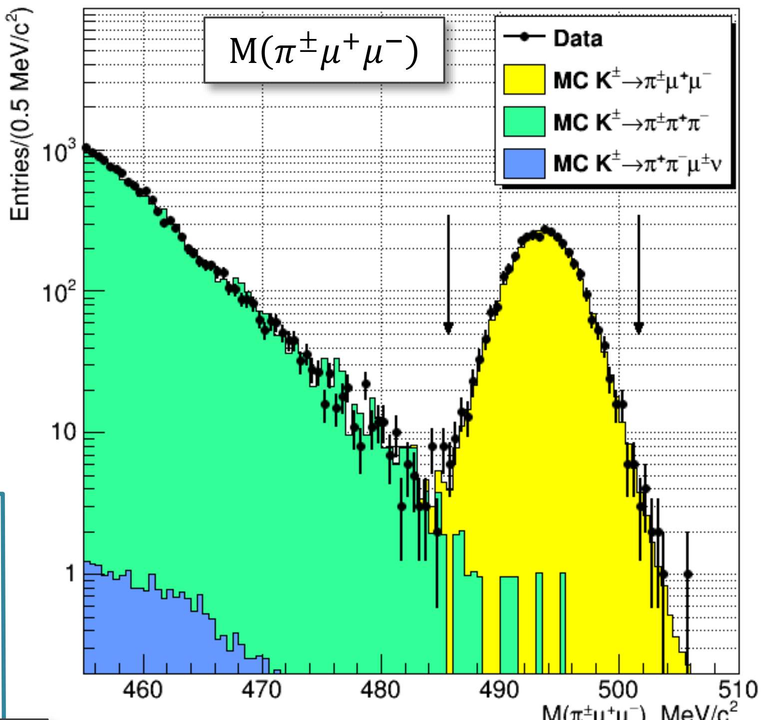
- From Rolke-Lopez statistical method:

$$BR\left(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}\right) < 8.6 \times 10^{-11}\ @\ 90\%\ \mathrm{CL}$$

LNC: Opposite-Sign Muon Sample

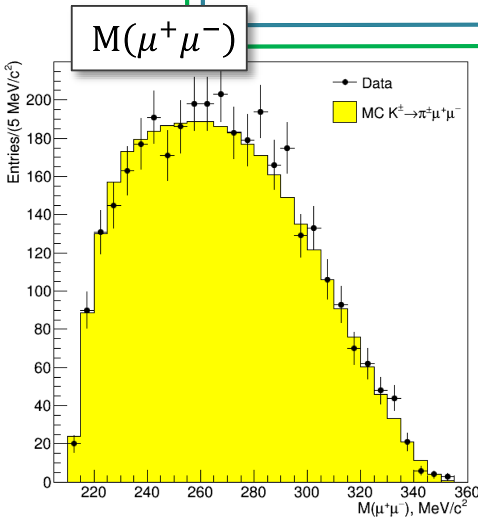
Selection

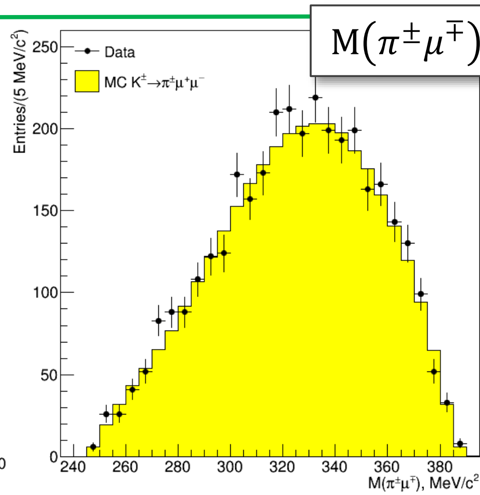
- Similar to same-sign
  - 3-track vertex, 2 opposite-sign muons, 1 pion, no missing momentum
  - First-order cancellation of systematic effects
  - Signal region: $|M_{\pi\mu\mu} - M_K| < 8\ \mathrm{MeV}/c^2$



Results

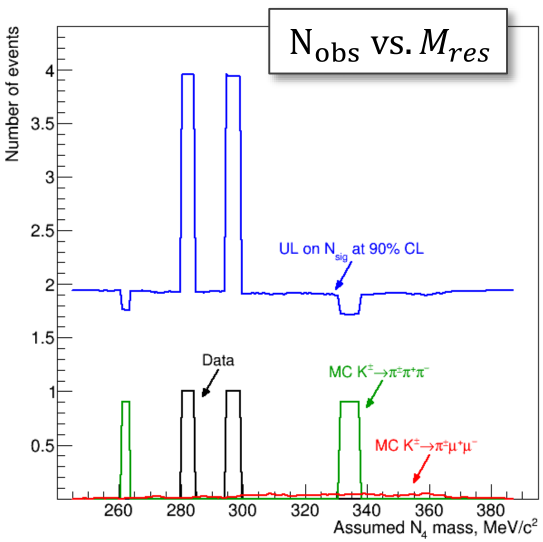
- Event in Signal Region:
  3489 $K^\pm \to \pi^\pm\mu^+\mu^-$ candidates
- Background: $(0.36 \pm 0.10)\%$
- See [Phys. Lett. B697 (2011) 107] for previous measurement of BR and FF
- Search for resonances in $M_{\pi\mu}$ and $M_{\mu\mu}$ invariant masses
  - step=$0.5\sigma(M_{res})$ and window=$\pm 2\sigma(M_{res})$
  - Limit using Rolke-Lopez from N_{obs} and N_{exp} for each hypothesis



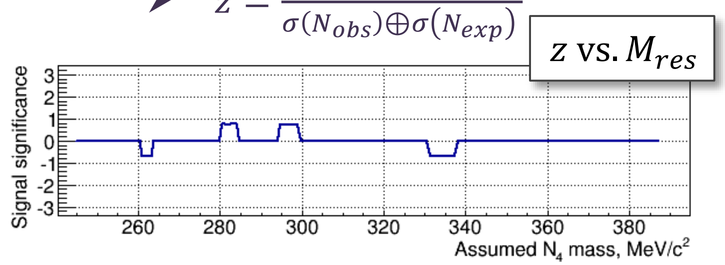


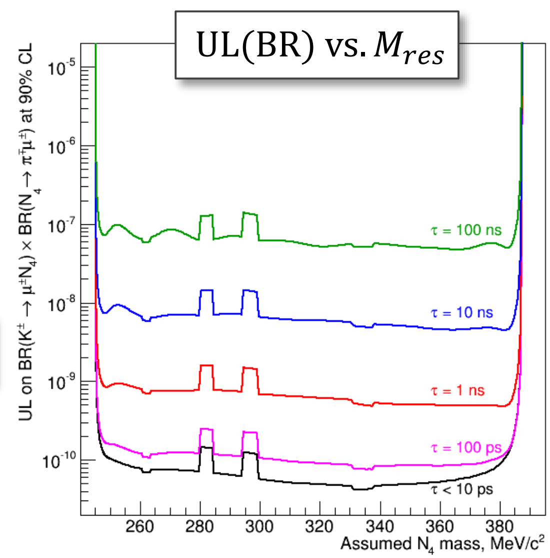
LNV and LNC: Resonances searches

- **Search for $K^{\pm} \rightarrow \mu^{\pm} N_4 \left(N_4 \rightarrow \pi^{\mp}\mu^{\pm}\right)$ decays,** 284 mass hypotheses
  - 2 possibilities for $M\left(\pi^{\mp}\mu^{\pm}\right)$, closest to M_{res} chosen
  - Never exceeds $+3\sigma$: no signal observed and $\mathrm{UL(BR)} \sim 10^{-10}$ for $\tau < 100$ ps



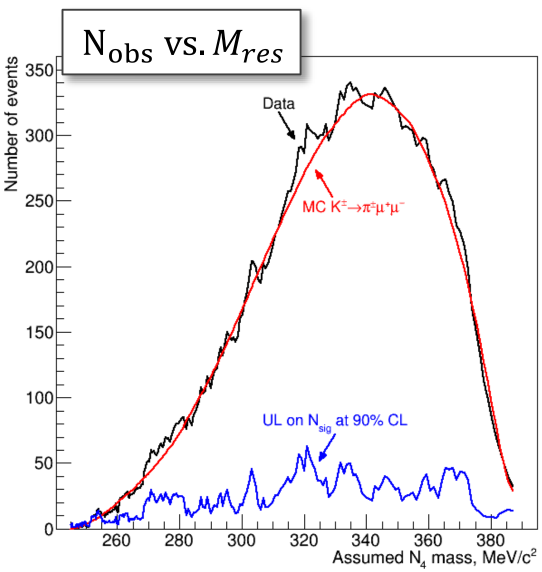
- **Upper limit on $\mathbf{BR}(K^{\pm} \rightarrow \mu^{\pm} N_4)\mathbf{BR}\left(N_4 \rightarrow \pi^{\mp}\mu^{\pm}\right)$**
  - $$UL(\mathrm{BR}) = \frac{\mathrm{UL}\left(N_{sig}\right)}{N_K * Acceptance}$$
- **Statistical significance**
  - $$z = \frac{\left(N_{obs} - N_{exp}\right)}{\sigma\left(N_{obs}\right) \oplus \sigma\left(N_{exp}\right)}$$



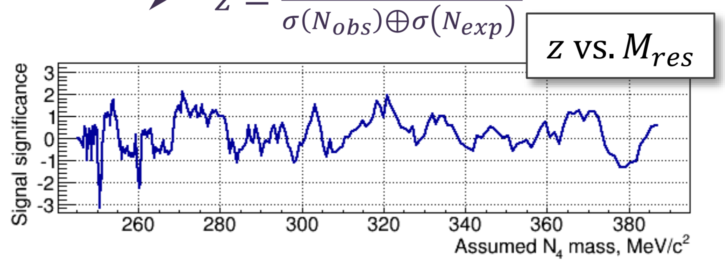


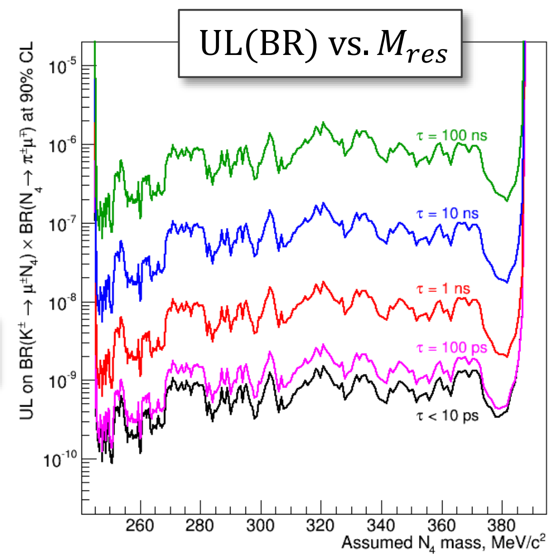
LNV and LNC: Resonances searches

- **Search for $K^{\pm} \rightarrow \mu^{\pm}N_4(N_4 \rightarrow \pi^{\mp}\mu^{\pm})$ decays,** 284 mass hypotheses
  - 2 possibilities for $M(\pi^{\mp}\mu^{\pm})$, closest to M_{res} chosen
  - Never exceeds $+3\sigma$: no signal observed and $\mathrm{UL(BR)}{\sim}10^{-10}$ for $\tau < 100$ ps
- **Search for $K^{\pm} \rightarrow \mu^{\pm}N_4(N_4 \rightarrow \pi^{\pm}\mu^{\mp})$ decays,** 280 mass hypotheses
  - Never exceeds $+3\sigma$: no signal observed and $\mathrm{UL(BR)}{\sim}10^{-9}$ for $\tau < 100$ ps



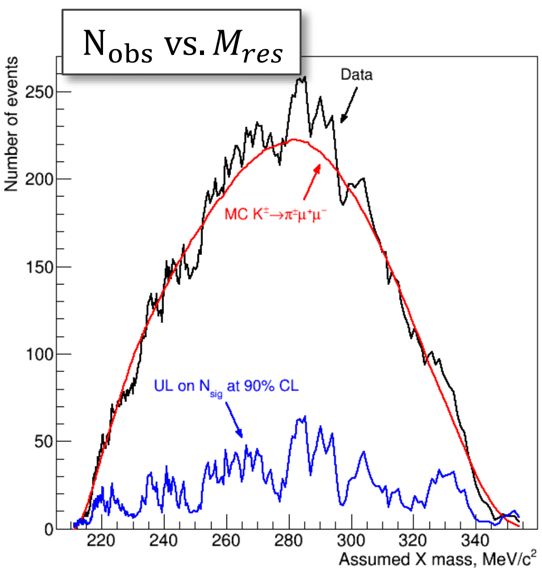
- **Upper limit on $\mathrm{BR}(K^{\pm} \rightarrow \mu^{\pm}N_4)\mathrm{BR}(N_4 \rightarrow \pi^{\mp}\mu^{\pm})$**
  - $$UL(\mathrm{BR}) = \frac{\mathrm{UL}(N_{sig})}{N_K * Acceptance}$$
- **Statistical significance**
  - $$z = \frac{(N_{obs} - N_{exp})}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$$



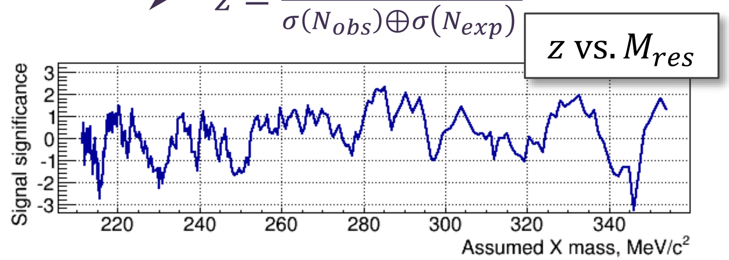


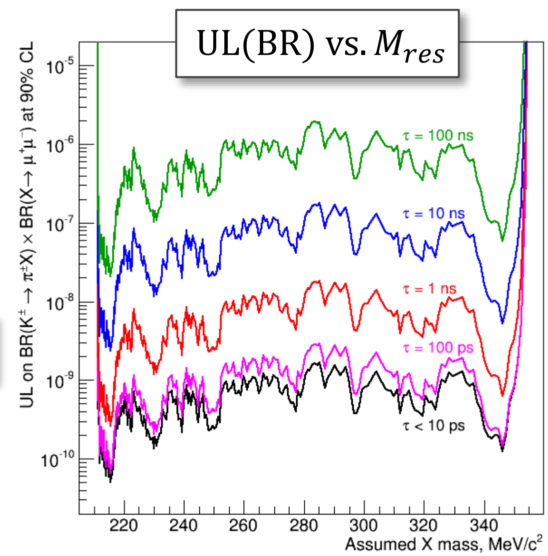
LNV and LNC: Resonance searches

- **Search for $K^{\pm} \to \mu^{\pm} N_4 (N_4 \to \pi^{\mp} \mu^{\pm})$ decays,** 284 mass hypotheses
  - 2 possibilities for $M(\pi^{\mp}\mu^{\pm})$, closest to M_{res} chosen
  - Never exceeds $+3\sigma$: no signal observed and $\mathrm{UL(BR)} \sim 10^{-10}$ for $\tau < 100$ ps
- **Search for $K^{\pm} \to \mu^{\pm} N_4 (N_4 \to \pi^{\pm} \mu^{\mp})$ decays,** 280 mass hypotheses
  - Never exceeds $+3\sigma$: no signal observed and $\mathrm{UL(BR)} \sim 10^{-9}$ for $\tau < 100$ ps
- **Search for $K^{\pm} \to \pi^{\pm} X (X \to \mu^{+} \mu^{-})$ decays,** 267 mass hypotheses
  - Never exceeds $+3\sigma$: no signal observed and $\mathrm{UL(BR)} \sim 10^{-9}$ for $\tau < 100$ ps



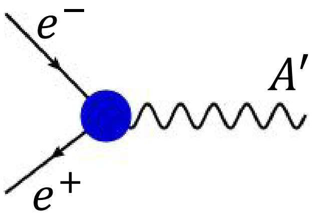
- **Upper limit on $\mathrm{BR}(K^{\pm} \to \mu^{\pm} N_4)\mathrm{BR}(N_4 \to \pi^{\mp}\mu^{\pm})$**
  - $$UL(\mathrm{BR}) = \frac{\mathrm{UL}(N_{sig})}{N_K * Acceptance}$$
- **Statistical significance**
  - $$z = \frac{(N_{obs} - N_{exp})}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$$



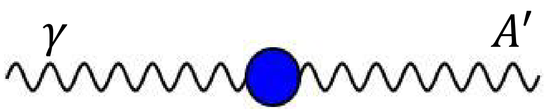


Dark Photon Searches

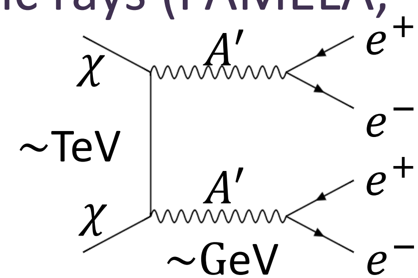
- **Simplest hidden sector model: Extra U(1) symmetry with gauge boson A'** [B.Holdom, Phys. Lett. B166 (1986) 196]
- **QED-like interactions with SM fermions**
  - $\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^{\mu} \psi_f U'_{\mu}$



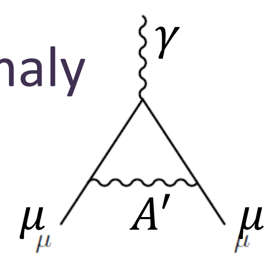
- **Coupling constants and charges generated through kinetic mixing between QED and the new U(1) gauge bosons**
  - $\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$



- **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

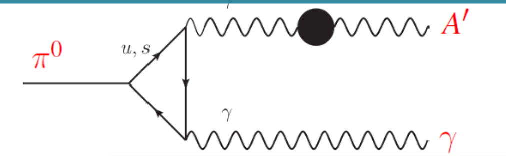


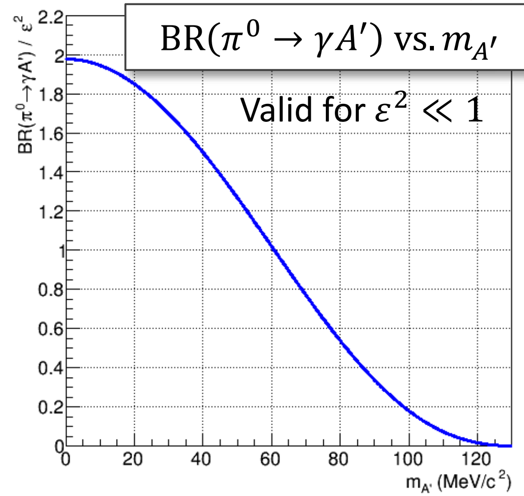
DP: $\pi^0 \to \gamma A'$ Decay

- **Production** Batell, Pospelov and Ritz, [PRD80 (2009) 095024]
  - $\mathrm{BR}(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathrm{BR}(\pi^0 \to \gamma\gamma)$
  - Mixing parameter ε and dark photon mass $m_{A'}$
  - Loss of sensitivity as $m_{A'}$ approaches the m_{π^0} threshold
  - For $\varepsilon^2 > 10^{-7}$ and $m_{A'} > 10\ \mathrm{MeV}/c^2$ mean free path is negligible and prompt decay is assumed
    - Signature similar to π_D^0

      $\pi_D^0 \to \gamma e^+ e^-$; $\pi^0 \to \gamma A'$

      $\quad\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow e^+e^-$

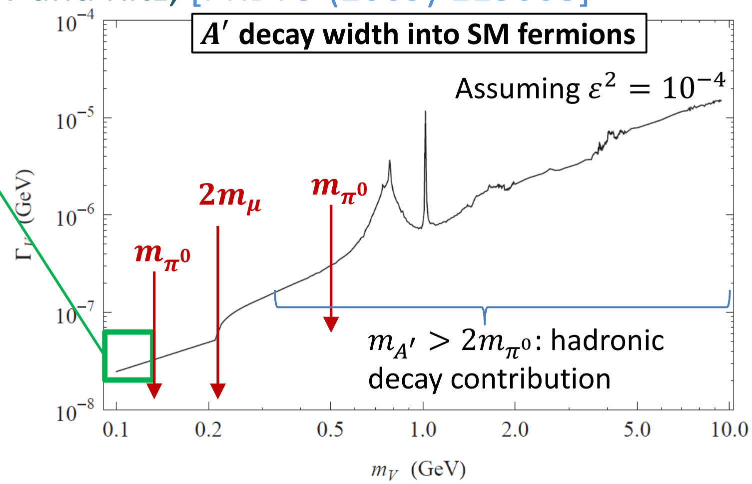


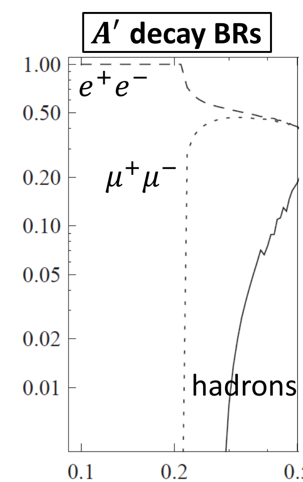


- **Decay** Batell, Pospelov and Ritz, [PRD79 (2009) 115008]
  - Accessible in π^0 decay, assuming only into SM fermions

    $\Gamma_{A'} \approx \Gamma(A' \to e^+e^-)$

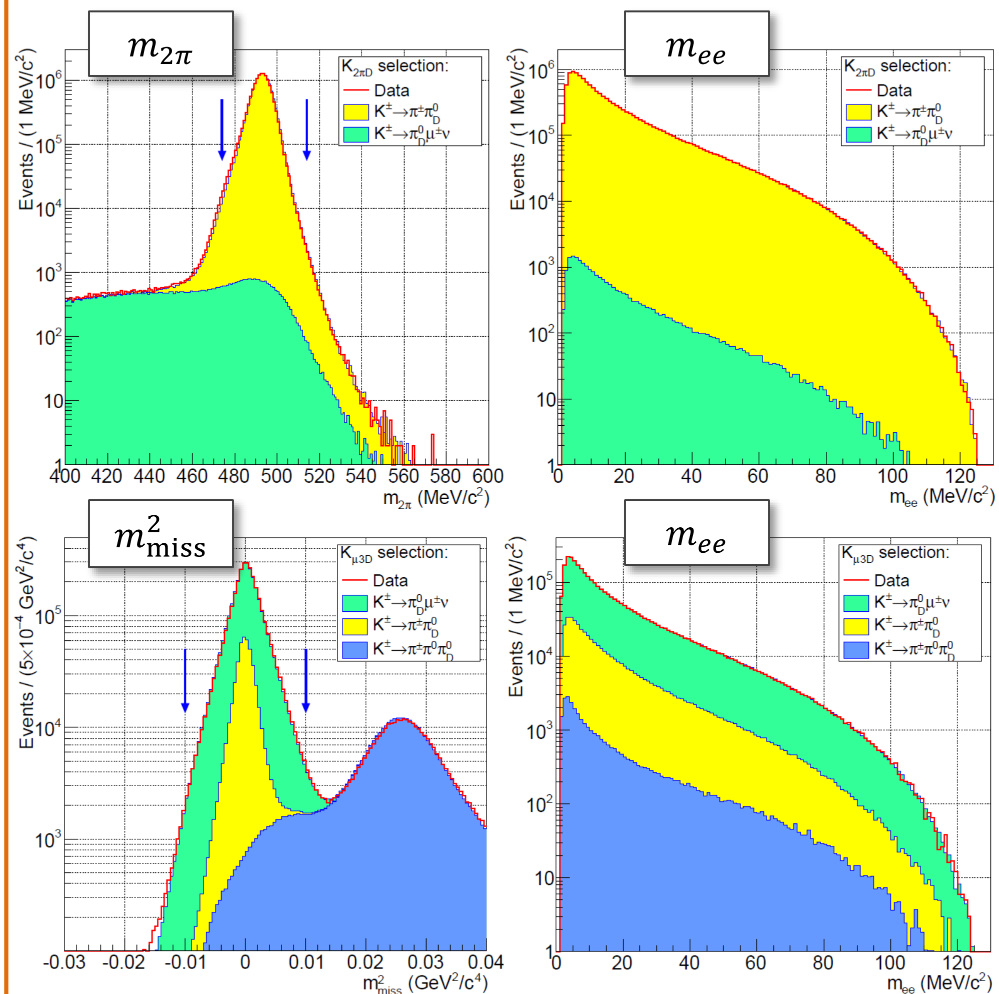
    $\approx \alpha\varepsilon^2 m_{A'}/3$





DP: NA48/2 Data Sample

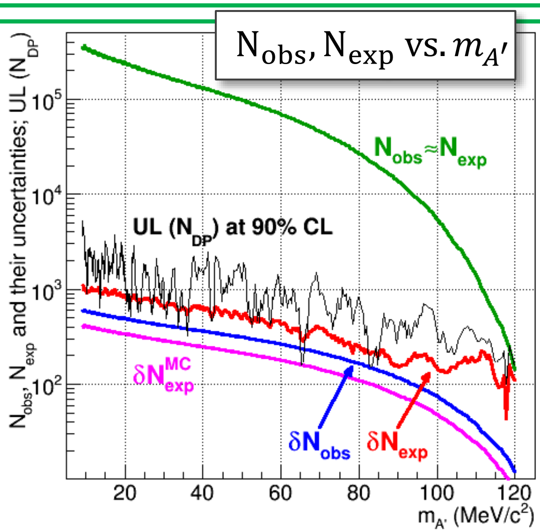
- NA48/2 data: $\sim 2 \times 10^{11}$ $K^{\pm}$ decays in the fiducial region
- $\pi/\mu/e$ separation using E/p
- Selection for $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D}$
  - Three-track vertex topology
  - $|m_{\pi\gamma eee} - m_K| < 20\ \mathrm{MeV}/c^2$
  - $|m_{\gamma ee} - m_{\pi^0}| < 8\ \mathrm{MeV}/c^2$
  - No missing momentum
- Selection for $K^{\pm} \rightarrow \pi^{0}_{D}\mu^{\pm}\nu$
  - $|m_{\gamma ee} - m_{\pi^0}| < 8\ \mathrm{MeV}/c^2$
  - No missing mass

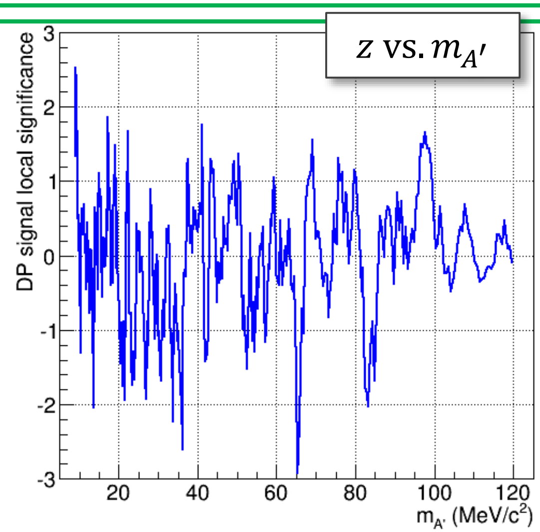


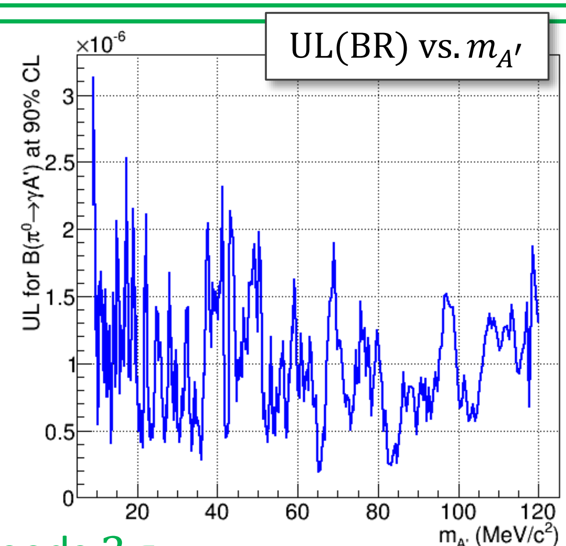
- Sensitivity determined by irreducible π^0 Dalitz decay (1.2%)
- Acceptance for both signature depending on $m_{A'}$ up to 4.5%

DP: Signal Search

- **Scan for narrow peaks in e^+e^- invariant mass spectrum**
  - $\sigma_{m_{ee}} = 0.011 \times m_{ee}$
  - Range: $9\ \mathrm{MeV}/c^2 \leq m_{A'} < 120\ \mathrm{MeV}/c^2$
  - Variable DP mass step: $\approx 0.5\sigma(m_{A'})$
  - mass-window: $\pm 1.5\sigma(m_{A'})$
  - Limits from N_{obs} and N_{exp} for each of the 404 $m_{A'}$ hypotheses



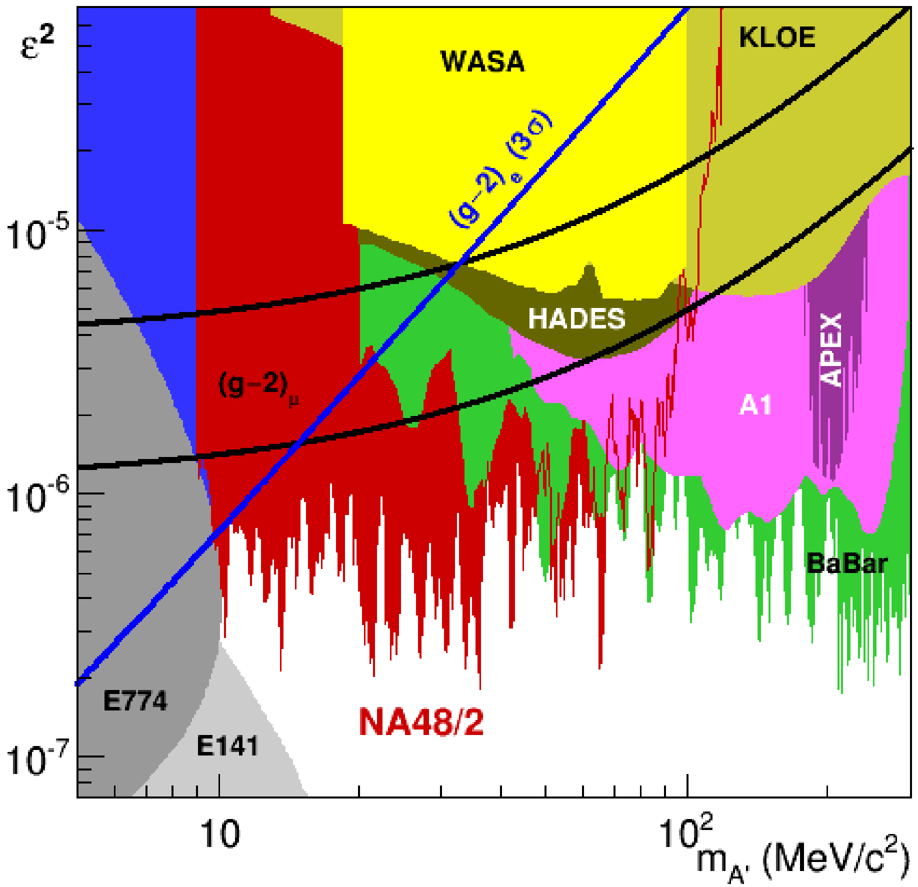




Local signal significance never exceeds 3σ:

- **no DP signal is observed.**

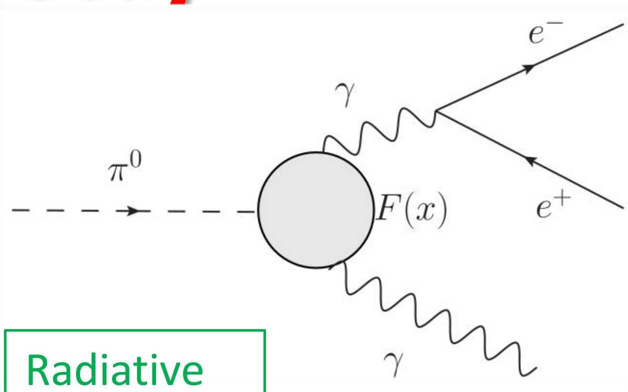
DP: Final NA48/2 Result



- [Phys.Lett. B746 (2015) 178]
  - Improvement on the existing limits in the $m_{A'}$ range $9 - 70\ \mathrm{MeV}/c^2$
  - Most stringent limits are at low $m_{A'}$ (kinematic suppression is weak)
  - Sensitivity limited by the irreducible π_D^0 background, ULs are 2-3 orders of magnitude above SES.
  - Upper limit on ε^2 scales as $\sim (1/NK)^{\frac{1}{2}}$: modest improvement with larger samples
  - If DP couples to quarks and decays mainly to SM fermions, it is ruled out as the explanation for the anomalous $(g-2)_\mu$

π^0 TFF: Dalitz Decay

$$\pi^0 \to e^+ e^- \gamma$$



- **Kinematic variables**
  - $x = \frac{(p_{e^+}+p_{e^-})^2}{m_{\pi^0}^2}, \quad y = \frac{2p_{\pi^0}\cdot(p_{e^+}-p_{e^-})}{m_{\pi^0}^2(1-x)}$
- **Differential decay width**
  - $\frac{1}{\Gamma(\pi^0_{2\gamma})}\frac{d^2\Gamma(\pi^0_D)}{dxdy} = \frac{\alpha}{4\pi}\frac{(1-x)^3}{x}\left(1+y^2+\frac{r^2}{x}\right)\left(1+\delta(x,y)\right)|F(x)|^2$

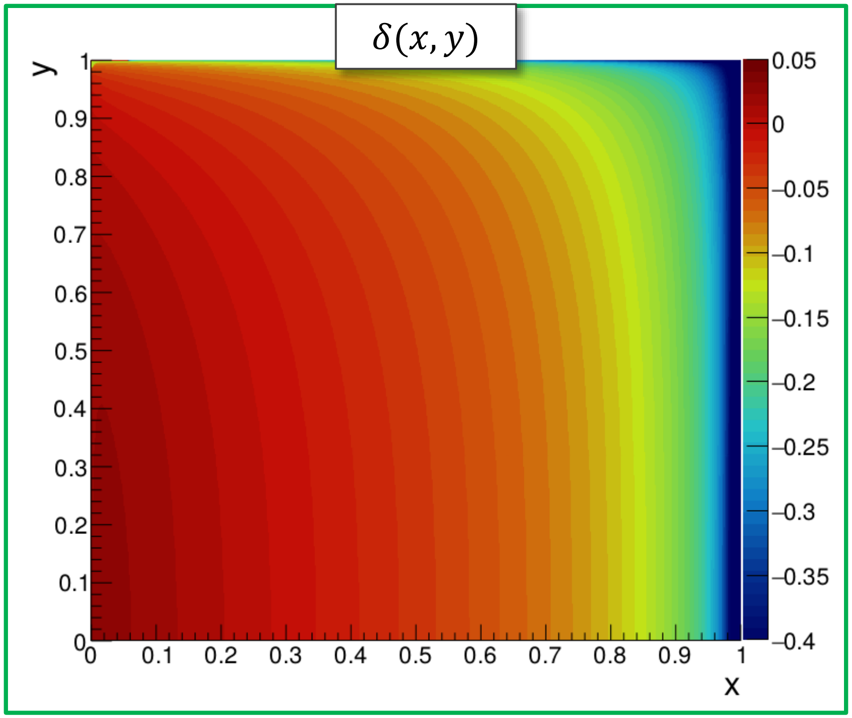
Radiative corrections

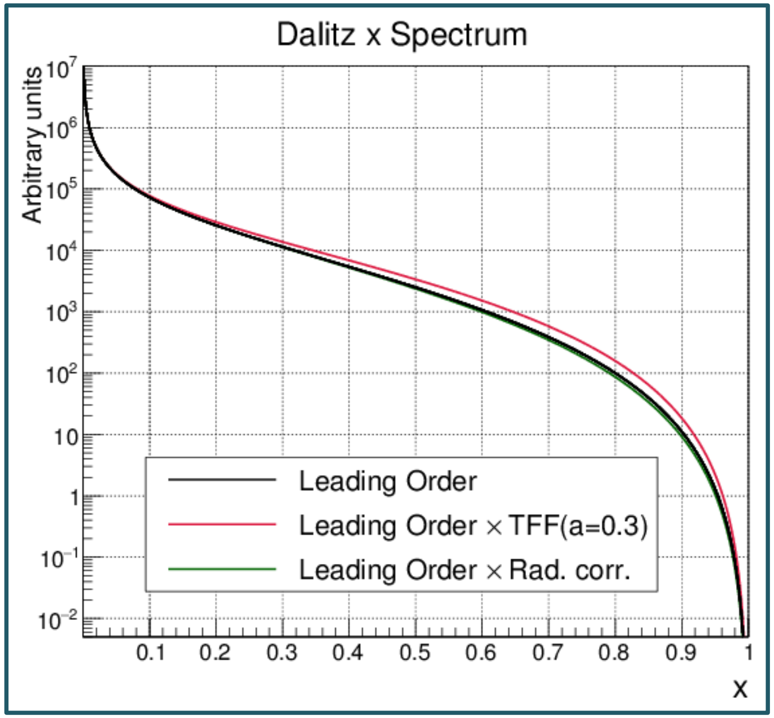
Electromagnetic Transition Form factor

- **Form factor varies slowly:**
  - Approximation $F(x) \approx 1 + ax$
- **Slope measured from Dalitz decays from $K^\pm \to \pi^\pm \pi^0_D$**
  - Expectation from VMD: $a \approx 0.03$
  - Enters hadronic light-by-blight scattering contribution to $(g-2)_\mu$
    A. Nyffeler [arXiv:1602.03398]
  - Model independent measurement: important test of the theory models

π^0 TFF: Radiative Corrections

- Corrections from NLO differential width encoded in $\delta(x, y)$
  - Mikaelian and Smith [Phys.Rev. D5 (1972) 1763]
  - Husek, Kampf and Novotny [Phys.Rev. D92 (2015) 5, 054027]
- Corrections of same magnitude as TFF
- New generator with radiative correction and simulation of bremsstrahlung photon.



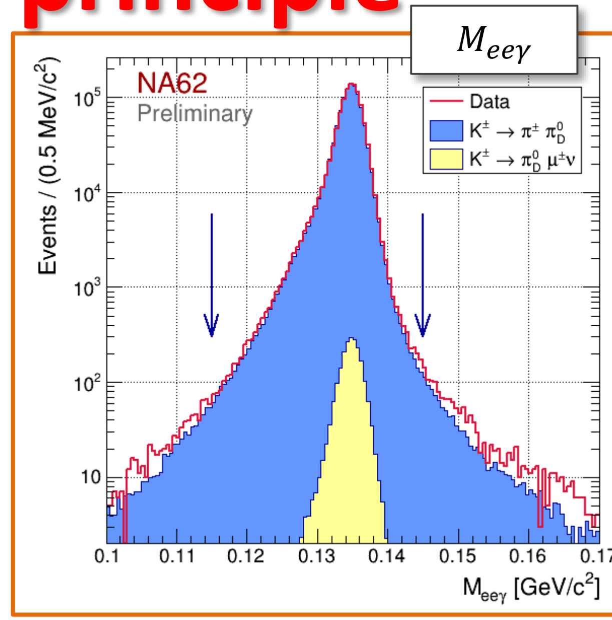


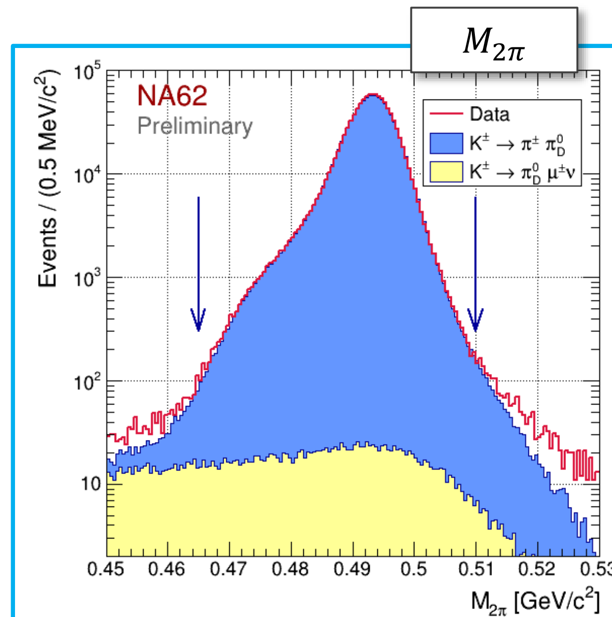
π^0 TFF: Measurement principle

- **Select pure π^0_D sample from**
  - 3-track vertex topology
  - One photon candidate and max three well reconstructed tracks
  - Identification by reconstructed kinematics
    $115\ \mathrm{MeV}/c^2 < M_{ee\gamma} < 145\ \mathrm{MeV}/c^2$
    $465\ \mathrm{MeV}/c^2 < M_{\pi^+\pi^0} < 510\ \mathrm{MeV}/c^2$
    Dalitz variable $\mathrm{y} < 1$; $0.01 < x < 1$
  - Reconstructed Kaon compatible with beam properties and offline L2 and L3 trigger conditions
- **Build x Dalitz distribution for data and MC (equal population bins)**
- **For each TFF slope value hypothesis, reweight simulated events ($a_{sim} = 0.032$)**

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

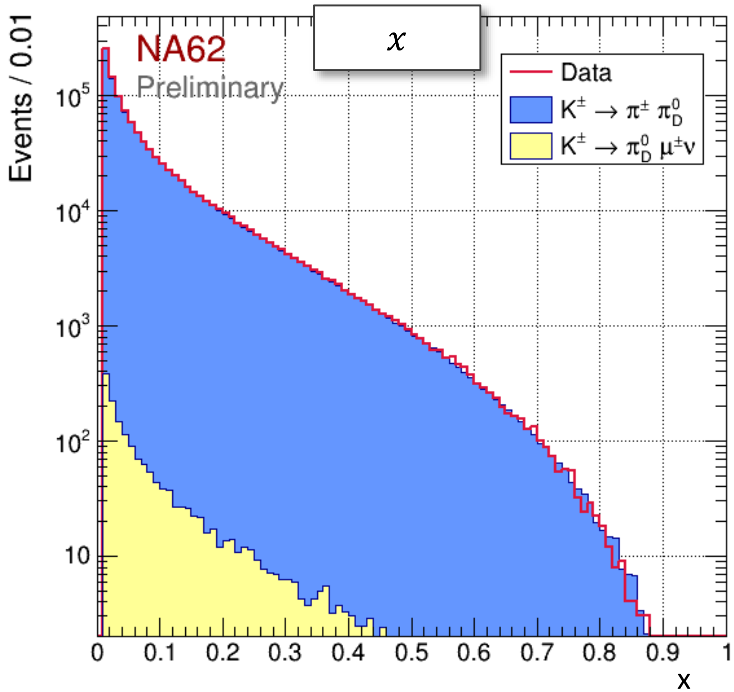
- **Minimise $\chi^2(a)$ of Data/Simulation wrt. a**





π^0 TFF: Preliminary Result

- **Data sample**
  - Kaon decays: $\sim 2 \times 10^{10}$
  - Fully reconstructed π_D^0 events in the signal region ($x > 0.01$): 1.05×10^6



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

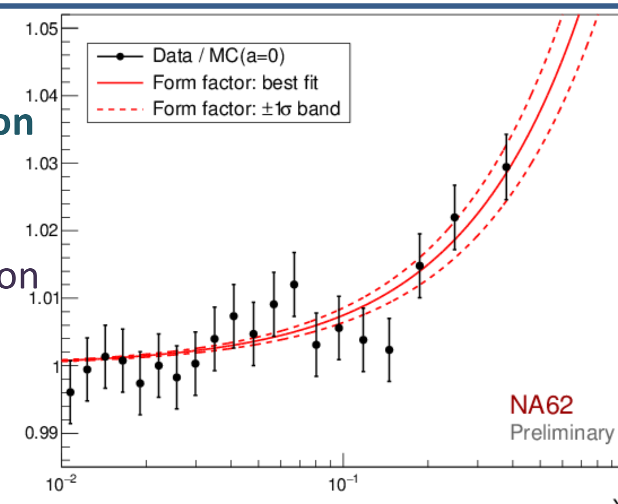
$$= (3.70 \pm 0.64) \times 10^{-2}$$

Preliminary

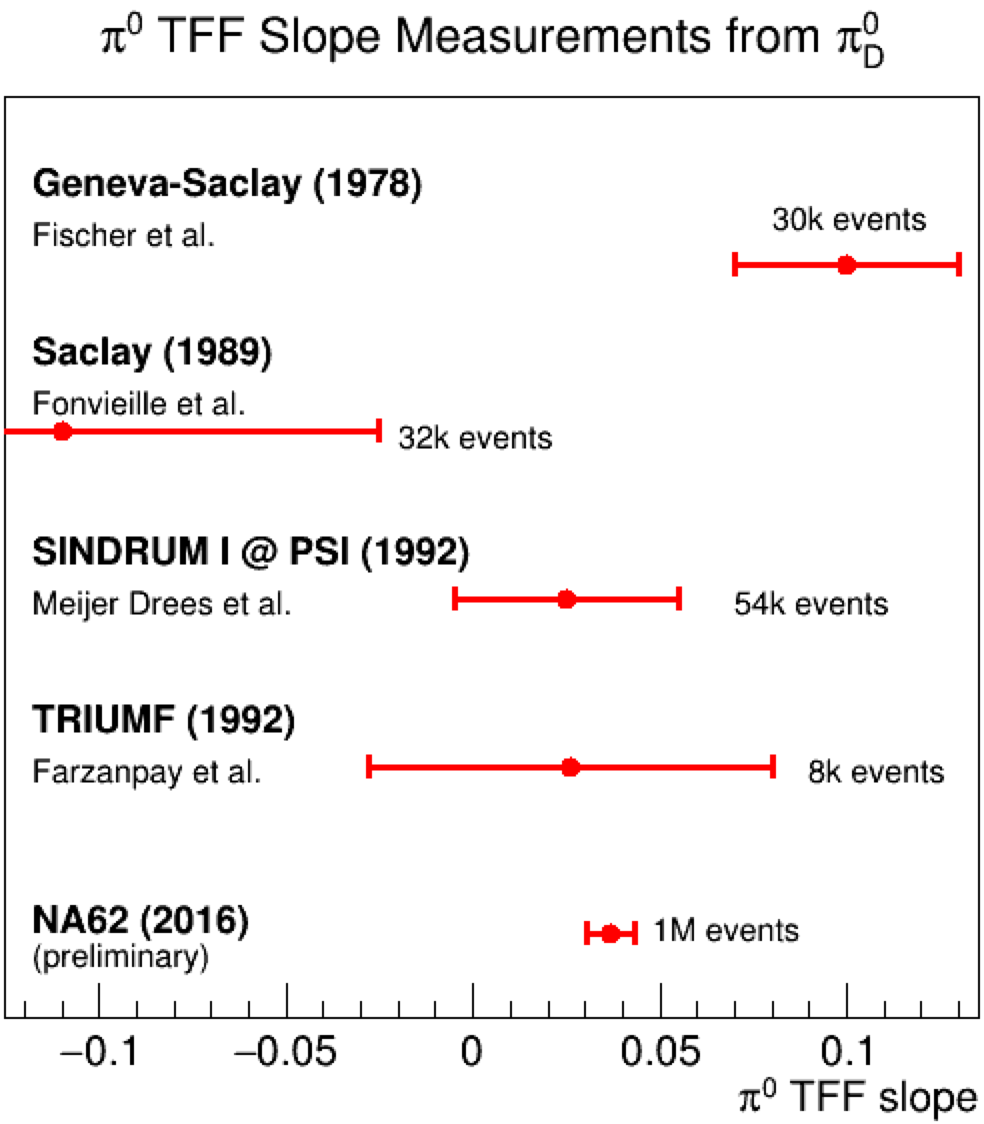
(χ^2/n.d.f: 52.5/49, p-value: 0.34)

Uncertainties	
Source	$\delta a (\times 10^{-2})$
Statistical – Data	0.49
Statistical – MC	0.20
Beam momentum spectrum 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 π_D^0 sources in MC	0.01

- **Fit result illustration**
  - Data / MC(a=0) ratio
  - 20 equal population bins
  - Points in bin barycenters



π^0 TFF: World Data



- **Theory expectations**
  - K. Kampf et al., EPJ C46 (2006), 191.
    Chiral perturbation theory:
    $a = (2.90 \pm 0.50) \times 10^{-2}$
  - M. Hoferichter et al., EPJ C74 (2014), 3180.
    Dispersion theory:
    $a = (3.07 \pm 0.06) \times 10^{-2}$
  - T. Husek et al., EPJ C75 (2015) 12, 586.
    Two-hadron saturation (THS) model:
    $a = (2.92 \pm 0.04) \times 10^{-2}$
- **CELLO measurement:**
  - H. J. Behrend et al., Z. Phys. C49 (1991), 401.
    Extrapolation of space-like momentum region data fit to VMD model:
    $a = (3.26 \pm 0.26_{stat}) \times 10^{-2}$

Summary

- **LNV decay @ NA48/2**
  - $BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 8.6 \times 10^{-11}$ @ 90% CL
- **Majorana Neutrinos and Inflaton @ NA48/2**
  - $K^{\pm} \to \mu^{\pm}N_4(N_4 \to \pi^{\mp}\mu^{\pm})$: UL(BR) of the order of 10^{-10} for $\tau < 100$ ps
  - $K^{\pm} \to \mu^{\pm}N_4(N_4 \to \pi^{\pm}\mu^{\mp})$: UL(BR) of the order of 10^{-9} for $\tau < 100$ ps
  - $K^{\pm} \to \pi^{\pm}\chi(\chi \to \mu^{+}\mu^{-})$: UL(BR) of the order of 10^{-9} for $\tau < 100$ ps
- **Dark Photon searches @ NA48/2**
  - Phys.Lett. B746 (2015) 178
  - Improved limits on DP mixing ε^2 in the mass range $9 - 70\ \mathrm{MeV}/c^2$
  - The whole region favoured by $(g-2)_{\mu}$ is excluded
- **π^0_D electromagnetic TFF slope @ $\mathrm{NA62_{R_K}}$**
  - $a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2}$
    - Preliminary model independent result
    - $\sim$1 million fully reconstructed π^0_D decays
    - Improves TFF precision in the time-like momentum region

First 6σ observation of non zero slope in time-like region