Search for dark photon at NA48/2, and measurement of π^0 form factor

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On behalf of the NA48/2 collaboration

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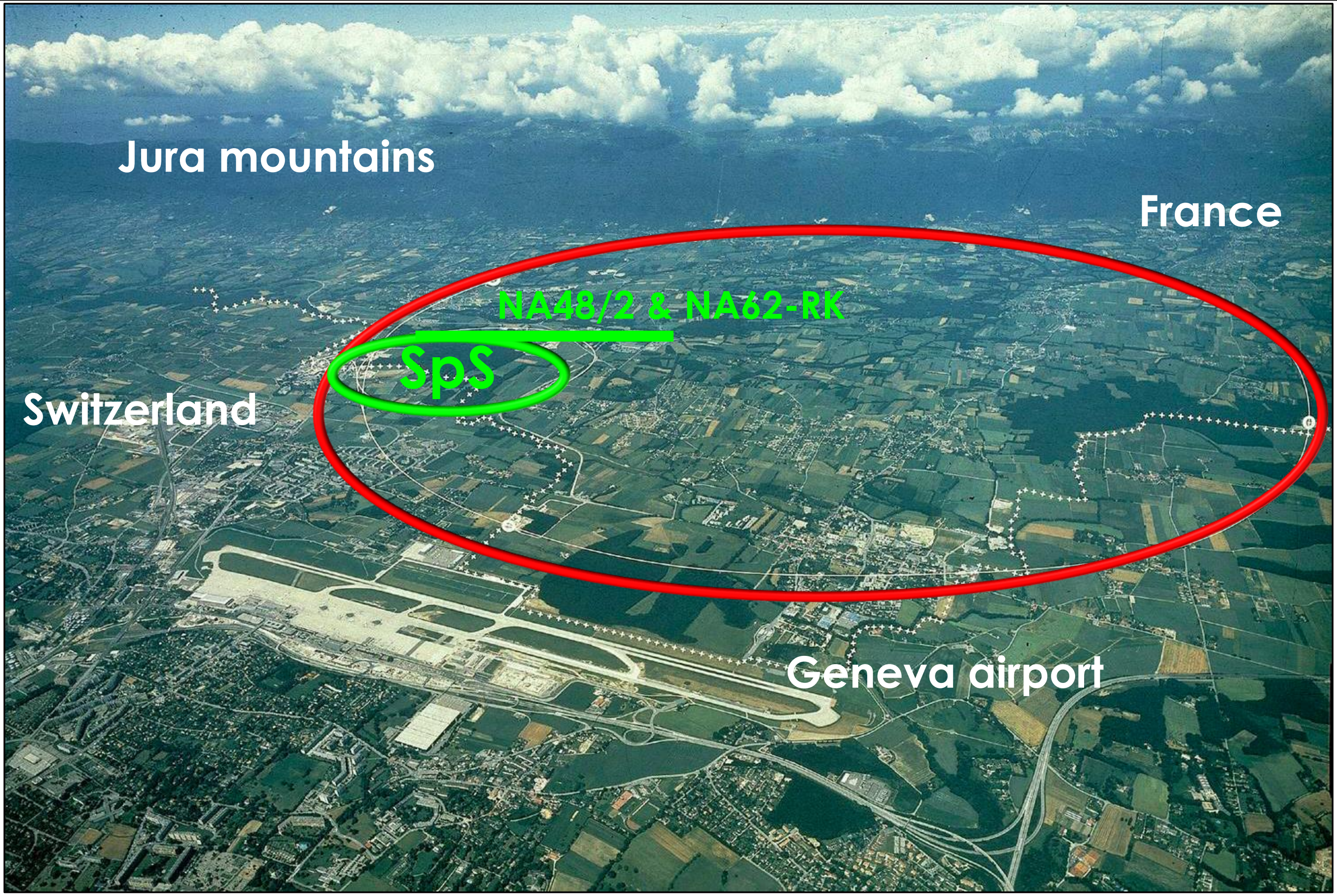
Outline

- NA48/2 experiments at CERN SPS
- Search for the dark photon in π^0 decays
- Measurement of π^0 form factor
- Conclusion and prospects

The NA48/2 and NA62 experiments @ SPS

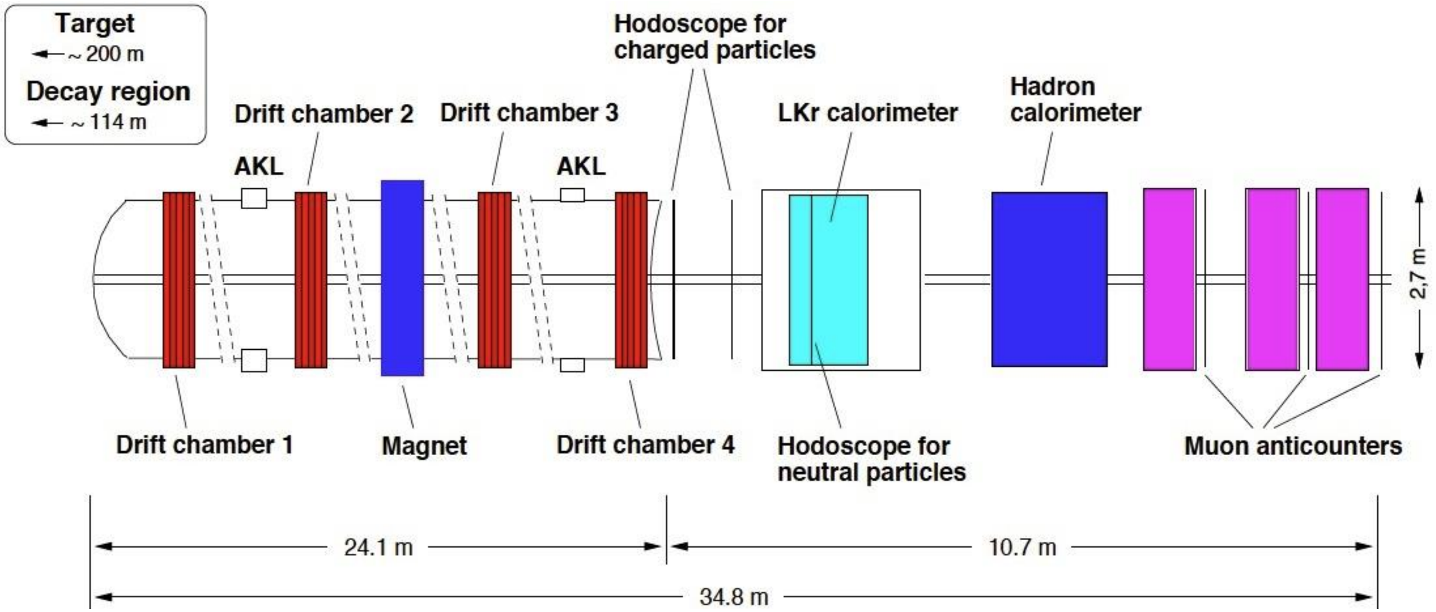


NA48/2 collaboration: 15 institutes from 8 countries:
NA62-RK collaboration: 30 institutes from 13 countries

NA48/2 (2003-04) NA62-RK (2007-08)

NA48/2 data taking : 4 months in 2003-04 ($K^{\pm}$) **60 GeV** Simultaneous $K^{\pm}$ beam

NA62-RK data taking: 4 months in 2007 (K^{+}) **74 GeV** mostly K^{+} only beam



Magnetic Spectrometer

- 4 drift chambers and a dipole magnet

$$\frac{s(p)}{p} = (1.02 \oplus 0.044p)\%$$ p in GeV/c

Liquid Krypton EM calorimeter (LKr)

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

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

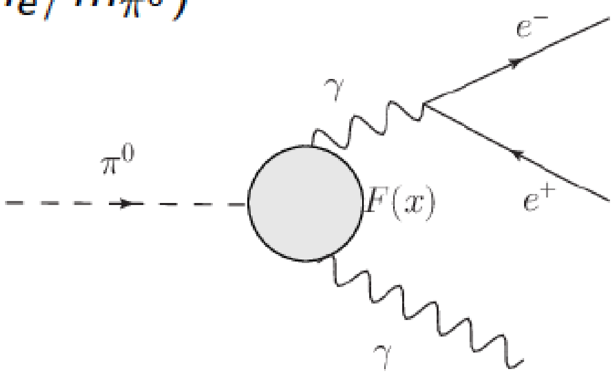
The π^0_D decay form factor | F(x) |

- π^0_D : π^0□$e^+e^-\gamma$ differential decay rate:

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

$$x = \frac{(p_{e^+}+p_{e^-})}{m^2_{\pi^0}} \qquad y = \frac{2p_{\pi^0}\cdot(p_{e^+}-p_{e^-})}{m^2_{\pi^0}(1-x)} \qquad r^2 = (2m_e/m_{\pi^0})^2$$

- First order Form Factor F(x):
  - | F(x) | ~1+***a***x ***a*** = FF slope parameter
  - Need sample with unbiased π^0 Dalitz decays.



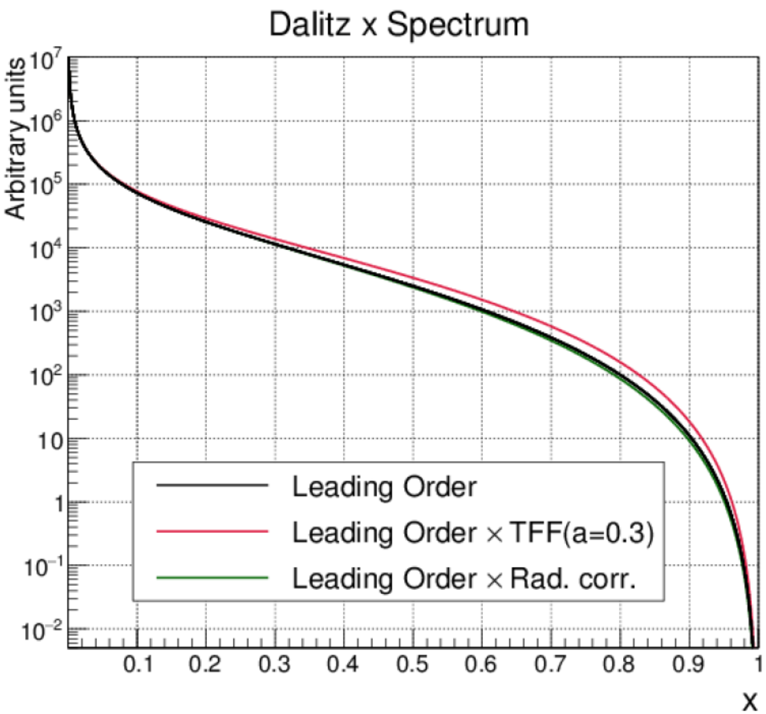
- A clean and large sample of π^0_D can be obtained at NA62-RK:
  - Source: $K^\pm\rightarrow\pi^\pm\pi^0$ tagged neutral pion (~10^9 π^0 □~10^7 π^0_D decays).
  - Avoid any trigger bias on the data sample (minimum bias trigger)
  - NA62-RK lower statistic but much better trigger conditions wrt to NA48/2

Measuring π^0_D transition FF slope

- Fit the differential decay width as function of x:

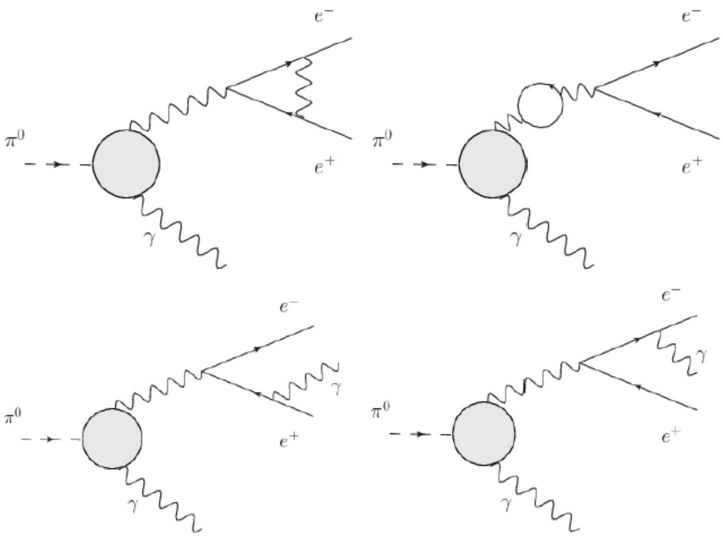
$$\frac{1}{\Gamma(\pi^0_{2\gamma})}\frac{d\Gamma(\pi^0_D)}{dx} = \frac{2\alpha}{3\pi}\frac{(1-x)^3}{x}(1+\frac{r^2}{x})\sqrt{1-\frac{r^2}{x}}(1+\delta(x,y))(1+ax)^2$$

- Theoretical expectation: ***a***~0.03 VMD models.
- FF is a tiny effect:
  - Need very precise measurement of x
  - Proper radiative corrections $\delta(x,y)$
- Relevant measurement to improve precision calculation of light by light scattering contribution to muon g-2.

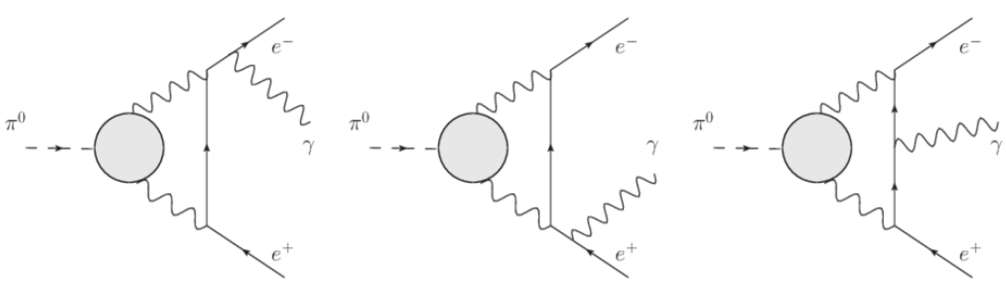


Computing π^0_D radiative correction $\delta(x,y)$

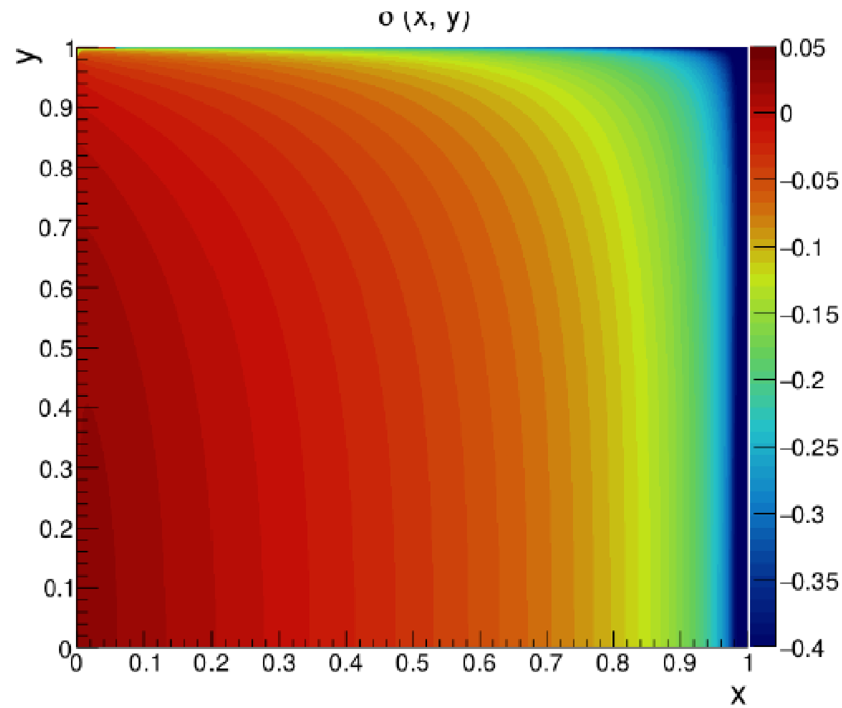
Original paper by **Mikaelian and Smith**:
Phys. Rev. D5(1972) 1763



Recent improvement **Husek, Kampf and Novotny**
Phys. Rev. D92(2015) 5, 054027



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

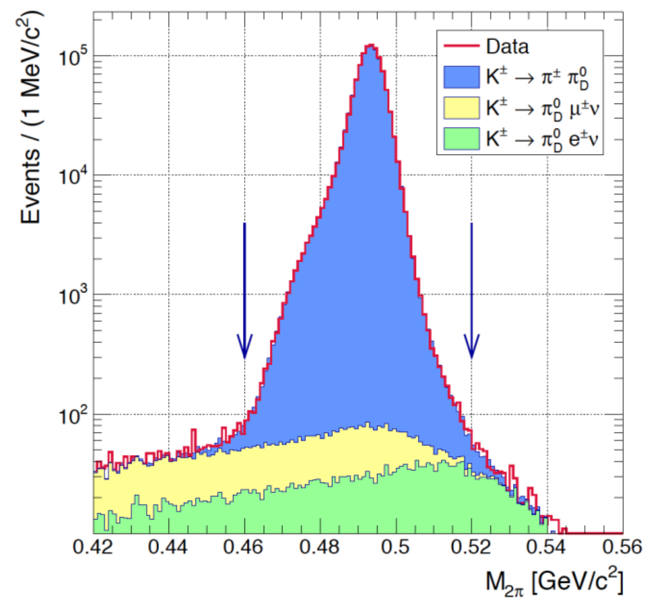


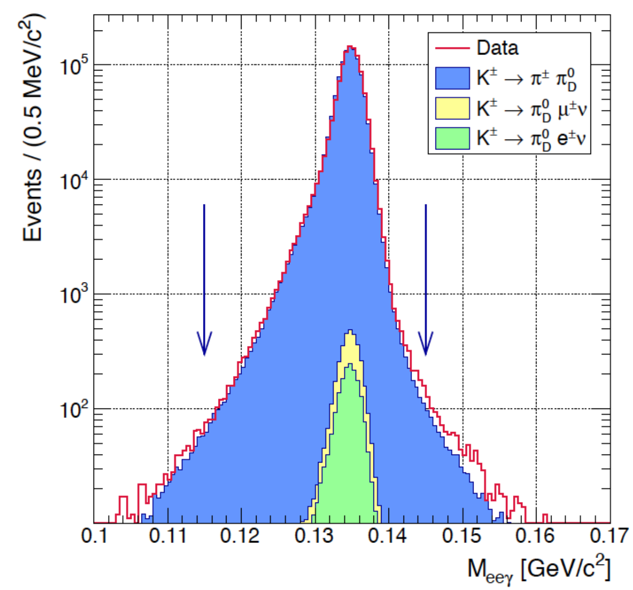
Husek, Kampf and Novotny
Parameterization introduced in MC to improve agreement with data.

Simulation includes emission of radiative photons

NA62-RK π^0_D selection

- Source $K^{\pm} \rightarrow$ □±□0 and $K^{\pm} \rightarrow$ □0$\mu^{\pm}\nu$
  - Tag the π^0 and select its Dalits decay
- Main selection cuts:
  - Three good track candidates
  - One good gamma candidate
  - Reconstructed $e^+e^-\gamma$ invariant mass region: $115 MeV/c^2 < M_{ee\gamma} < 145 MeV/c^2$
  - Reconstructed □+□0 invariant mass region: 465 MeV/c^2 < M□+□0 < 510 MeV/c^2
  - Reconstructed Dalitz variable : 0.01<x<1
- Selected data sample NA62-RK 2007:
  - 1.05×10^6 π^0_D candidates



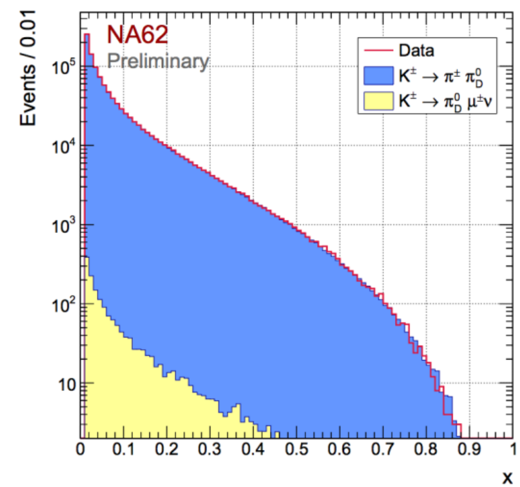


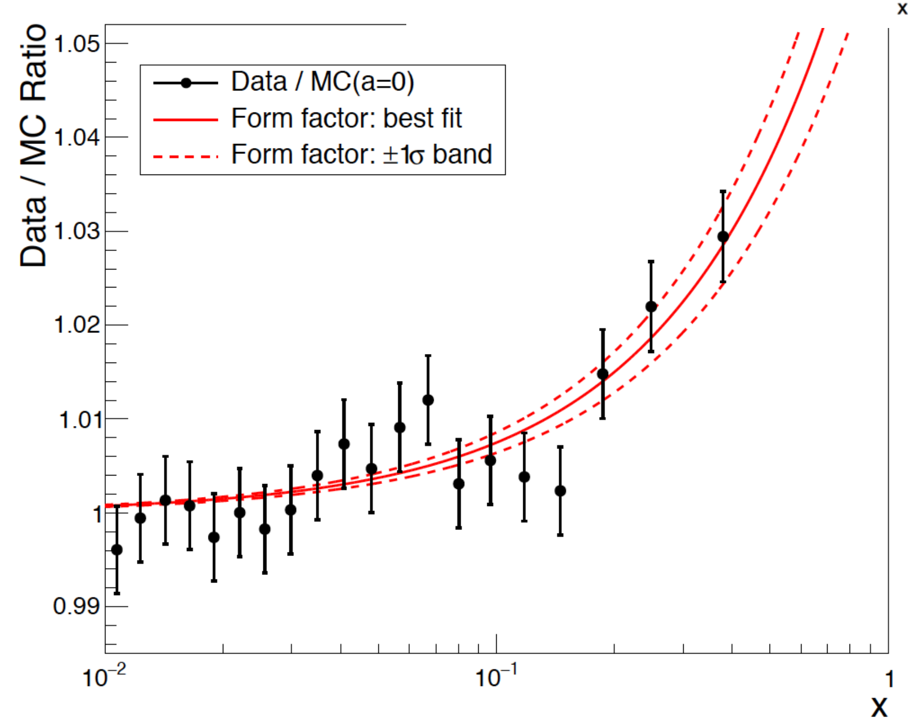
FF slope fit measurement

- Split the reconstructed Dalitz x data into 20 equi-populated bins
- Compare data with MC TFF slope ***a***= 0.032
- Re-weight MC events to get simulated distributions with different values of ***a***:

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

- Perform χ^2 test to extract best ***a***



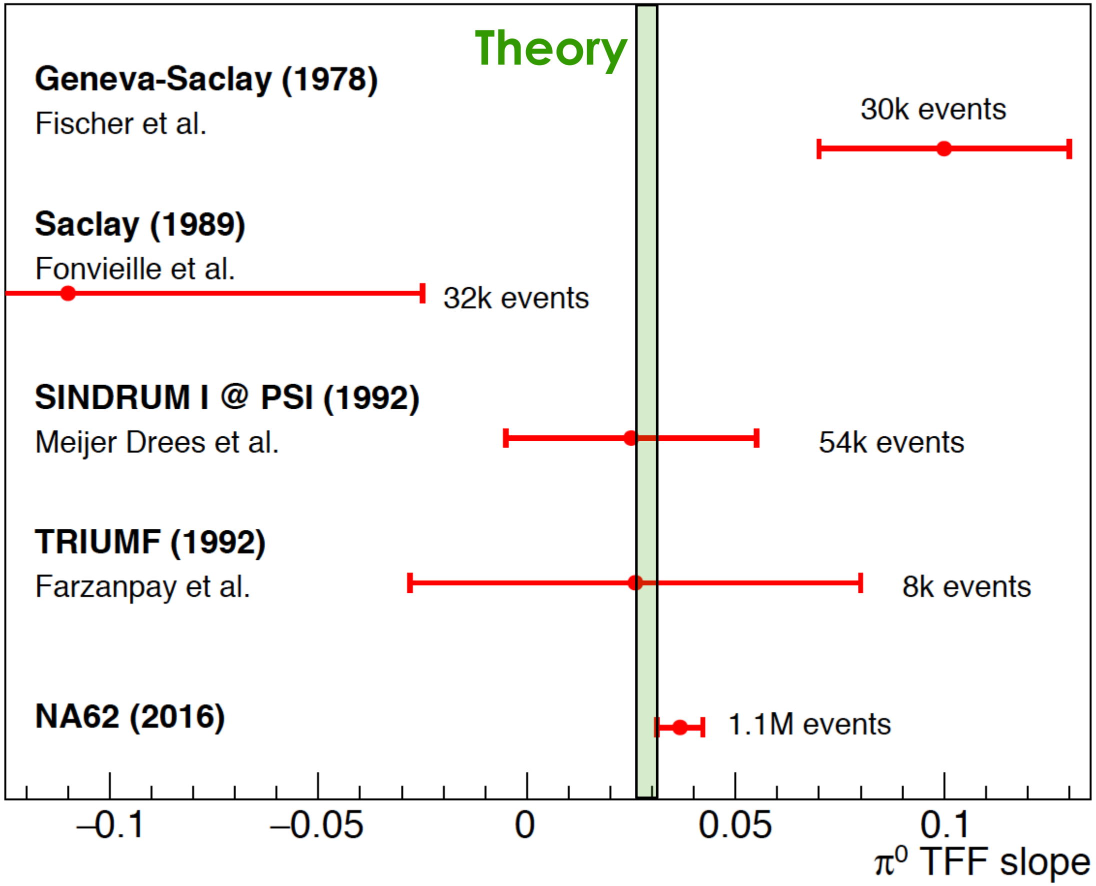


***NA62-RK* preliminary** fit result:

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

χ^2/d.o.f = 52.5/49

Comparison with other experiments



Theoretical expectation for FF

χPT
EPJ C46 (2006), 191
$a = (2.90 \pm 0.50)\times10^{-2}$

Dispersion theory
EPJ C74 (2014), 3180
$a = (3.07 \pm 0.06)\times10^{-2}$

Two-hadron saturation model
EPJ C75 (2015) 12, 586
$a = (2.92 \pm 0.04)\times10^{-2}$

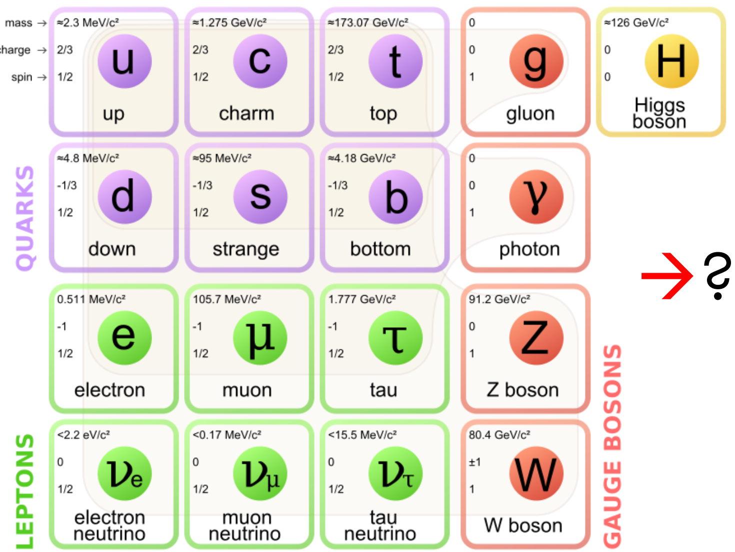
NA62-RK preliminary

$\boldsymbol{a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst})\times10^{-2}}$

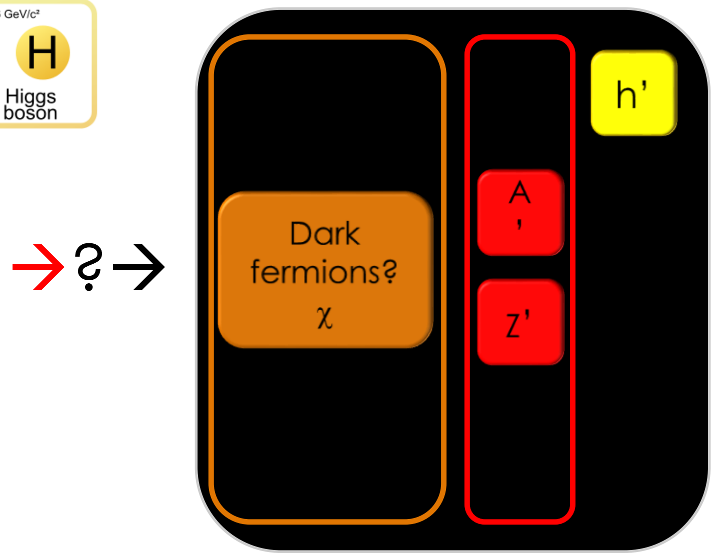
The NA62 preliminary measurement is the most precise FF measurement to-date
Final result and paper to come soon!

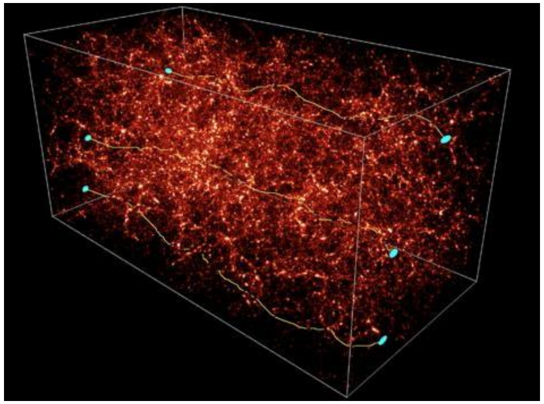
What is the universe made of?

Standard model

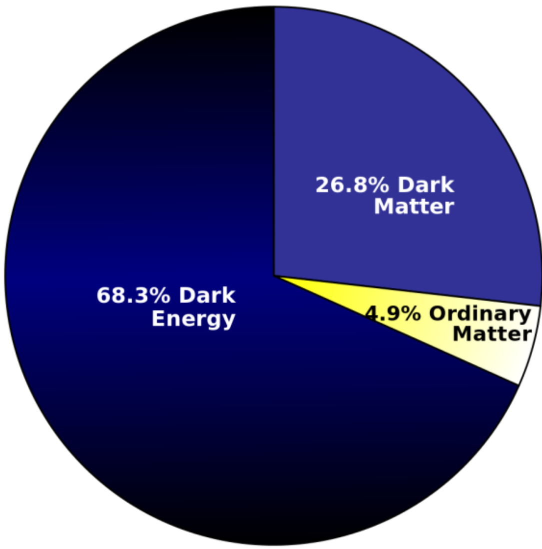


???Dark Sector???





- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interacts gravitationally
- Many open questions
  - What is dark Matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector spectrum?



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

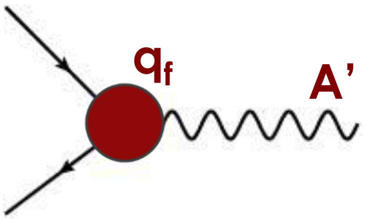
$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$

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.

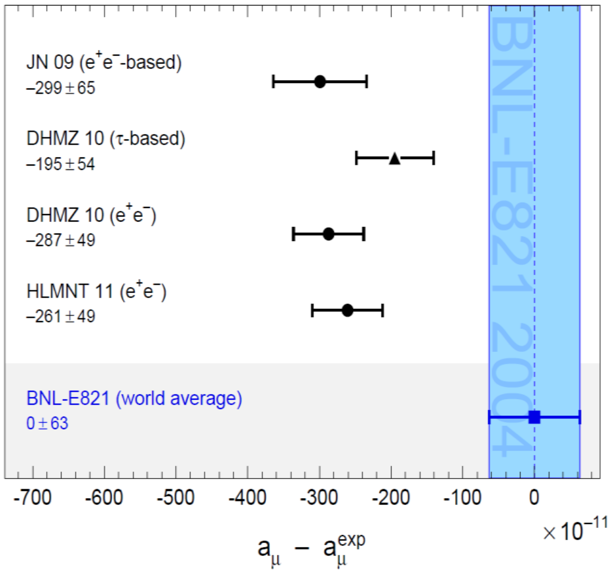
- **As in QED**, this will generate new interactions with SM fermions of type:

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

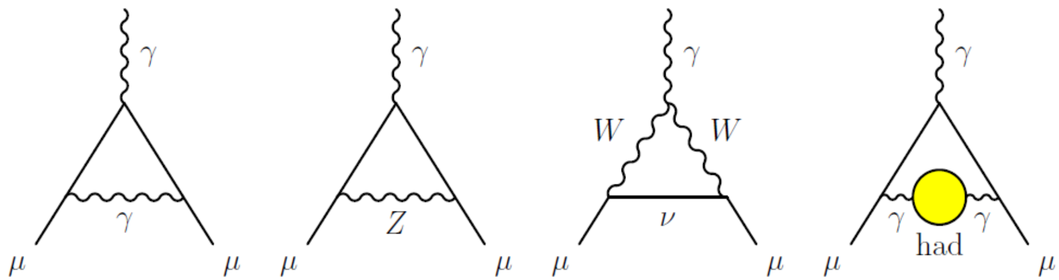


  - Not all the SM particles need to be charged under this new symmetry
  - In the **most general case q_f is different in between leptons and quarks** and can even be 0 for quarks. **P. Fayet, Phys. Lett. B 675, 267 (2009)**

Dark photon and g-2$_\mu$

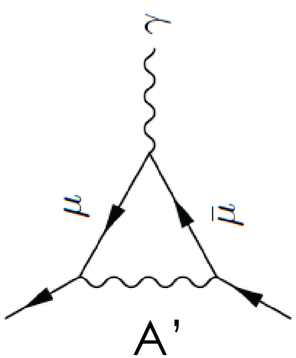


g-2 in the standard model

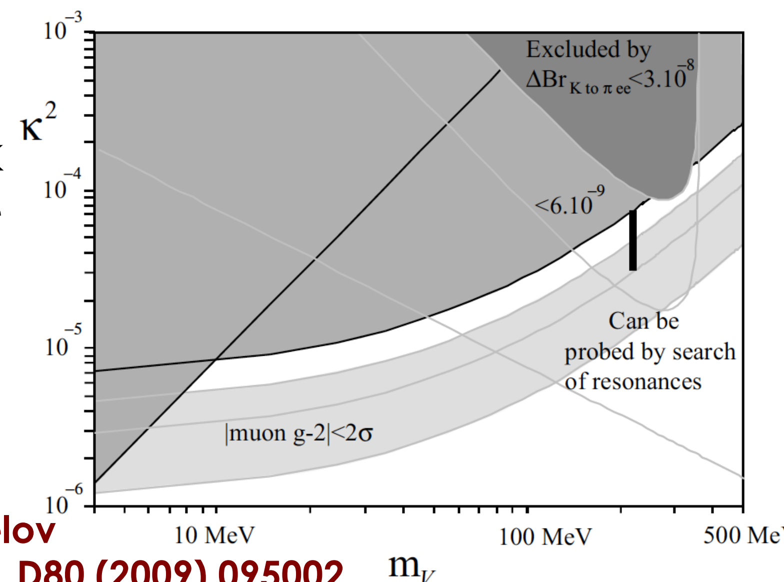


About 3s discrepancy between theory and experiment. Could be due to hadronic uncertainties on the Light by Light scattering?

g-2 and A'



Additional diagram with dark photon exchange can fix the discrepancy!
(with sub GeV A' masses ☺)

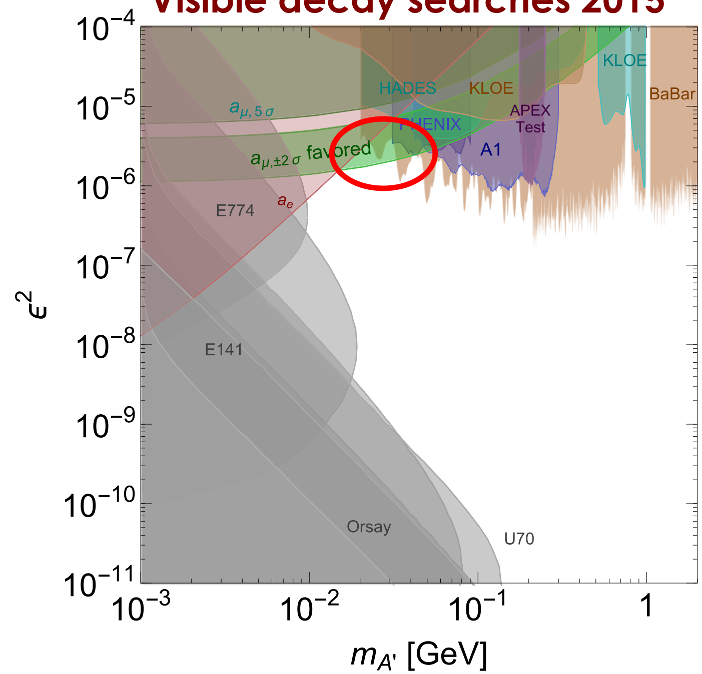


M. Pospelov
Phys.Rev. D80 (2009) 095002

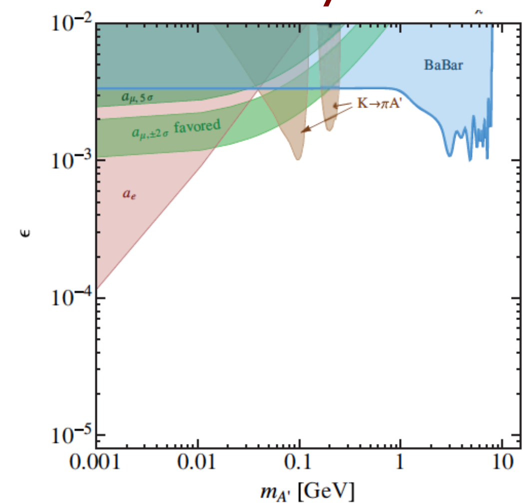
Dark photon searches status

- Visible decays: A'→ ee, μμ, ππ,
  - Kinetic mixed dark photons simplest model
- Favored parameters values explaining muon g-2 (**green** 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
  - Tight limit form α_{EM} (**red** filled area) **PhysRevD.86.095029**
- Much less constraints on "Invisible" decay mode
  - If $M_\chi<M_{A'}/2$, A'→χχ, ε^2 suppression to all visible modes
  - No assumption on α_D and no kinetic mixing

Visible decay searches 2015

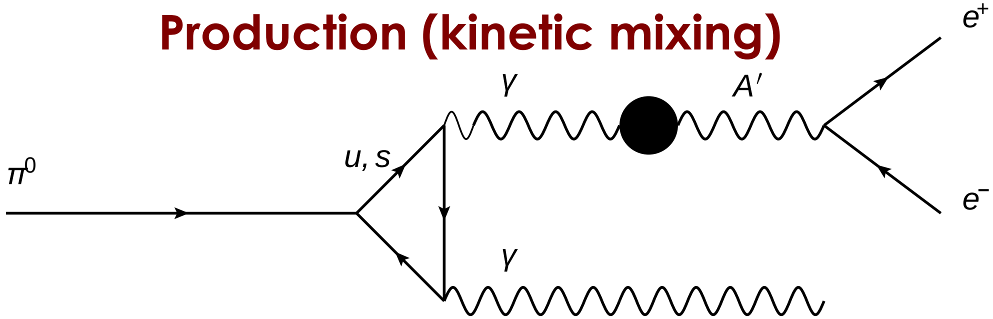


Invisible decay searches



Dark photon in π^0 decays

Production (kinetic mixing)

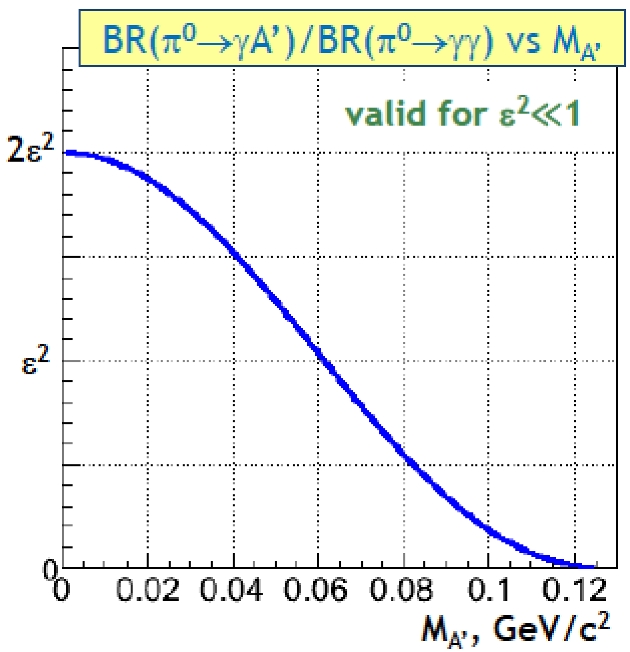


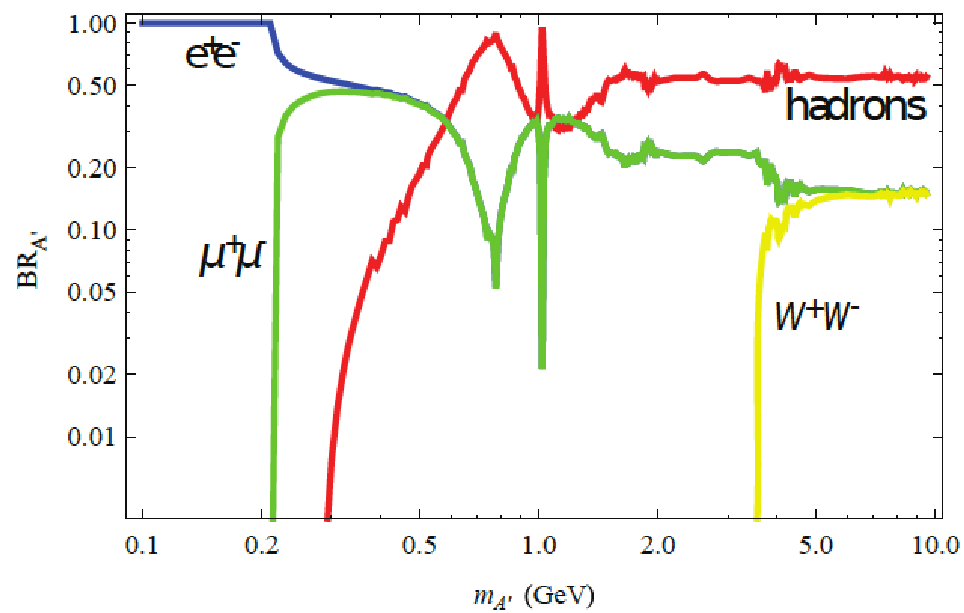
Decay (if no light dark sector)

$$G(A' \to e^+e^-) = \frac{a}{3} e^2 M_{A'} \sqrt{1 - \frac{4m_e^2}{M_{A'}^2}} \left(1 + \frac{2m_e^2}{M_{A'}^2}\right)$$

$$\frac{BR(p^0 \to gA')}{BR(p^0 \to gg)} \approx 2e^2 \, |F(M_{A'}^2)|^2 \left(1 - \frac{M_{A'}^2}{M_p^2}\right)^3$$

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





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

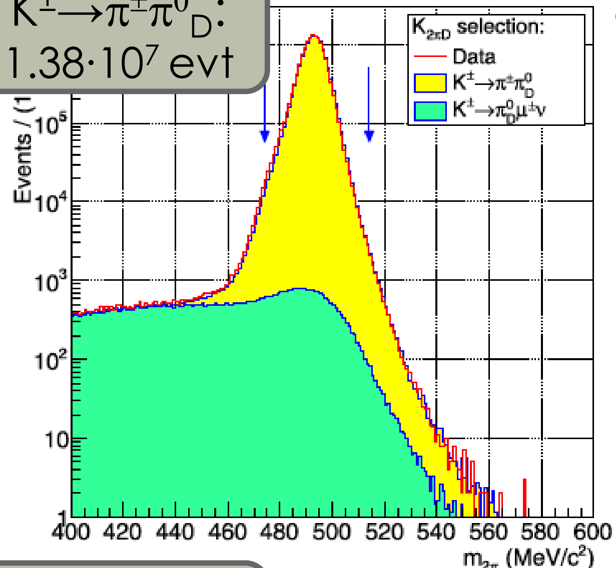
NA48/2 data sample

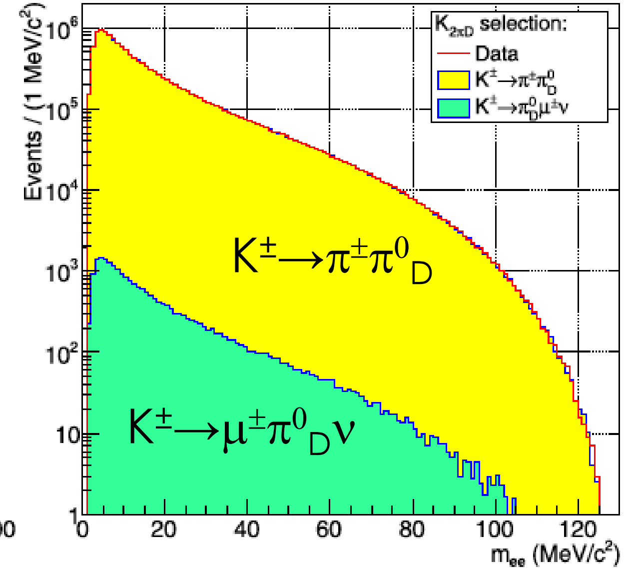
- Number of kaon decays in NA48/2 ('03/'04): $N_K \approx 2 \cdot 10^{11}$
  - $5 \cdot 10^{10}$ π^0 tagged decays from $K^\pm \to \pi^\pm\pi^0$ and $K^\pm \to \pi^0\mu^\pm\nu$ decays
- Exclusive search for the **decay chain $\pi^0 \to \gamma A'$, $A' \to e^+e^-$**
  - Search for a narrow peak in the e^+e^- invariant mass.
  - High efficiency trigger chain for 3-track vertices throughout all the data taking
  - Very good spectrometer mass resolution: $\sigma_{Mee} \approx 0.012 \times M_{ee}$
- DP final state $\pi^0 \to \gamma A'$, $A' \to e^+e^-$ identical to $\pi^0_D \to \gamma e^+e^-$;
  - Main background is $K^\pm \to \pi^\pm\pi^0_D$: $BR(K_{2pD})=2.4\rfloor 10^{-3}$
  - Sensitivity is limited by the irreducible K_{2pD} background.
- Signal acceptance:
  - depending on $M_{A'}$ from 4.5% down to 0.5% for high values $M_{A'}$.
- A total of **~1.7×10^7 candidates** collected during 2003-04 data taking

Data sample: $K_{2\pi D}$ + $K_{\mu 3D}$ selection

- $K^\pm \to \pi^\pm \pi^0_D$ selection
  - $|M_{ee\gamma} - M_{\pi 0}| < 8$ MeV/c^2
  - $|M_{\pi ee\gamma} - M_K| < 20$ MeV/c^2
  - No missing P_T: $< 5\cdot10^{-4}$ GeV^2/c^2

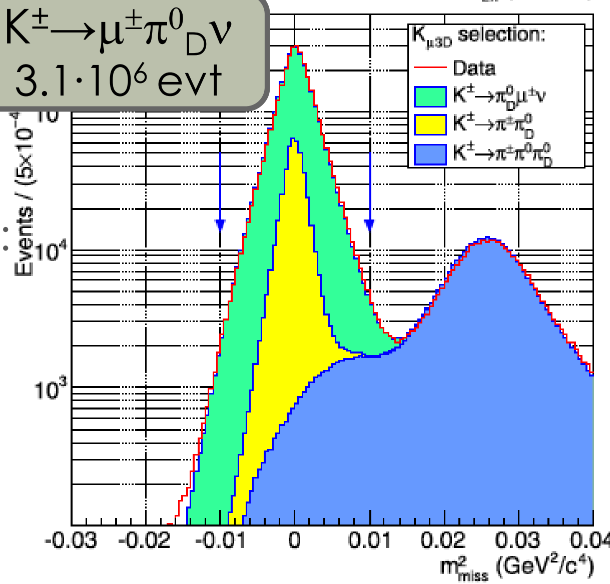
$K^\pm \to \pi^\pm \pi^0_D$: $1.38\cdot10^7$ evt

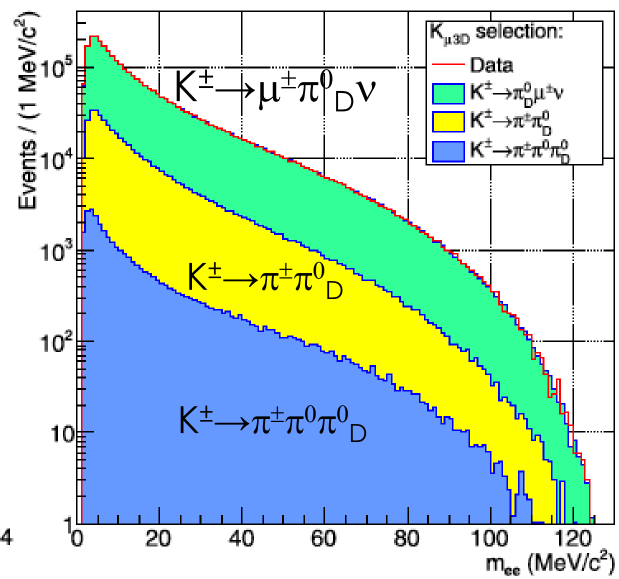




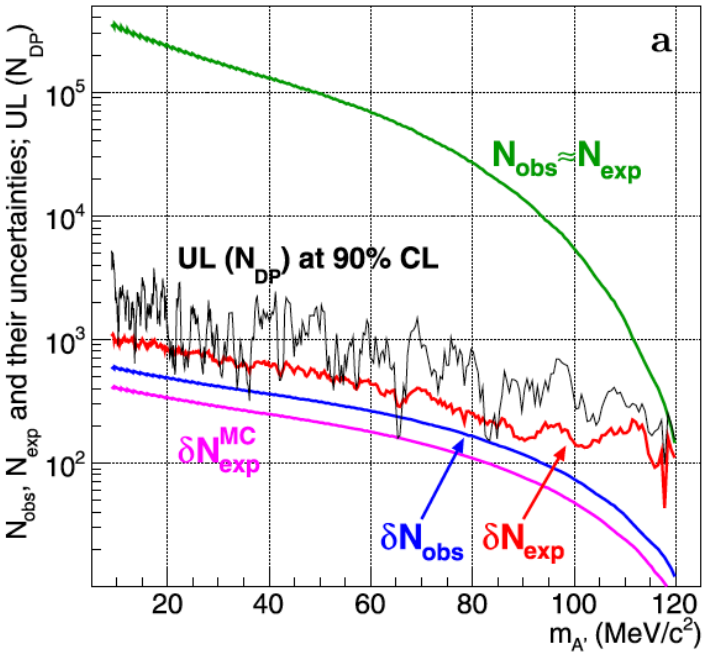
- $K^\pm \to \mu^\pm \pi^0_D$ selection
  - $|M_{ee\gamma} - M_{\pi 0}| < 8$ MeV/c^2
  - $M^2_{miss} < 0.01$ GeV^2/c^4
  - missing P_T due to neutrino: $5\cdot10^{-4} < P_T < 0.04$ GeV^2/c^2

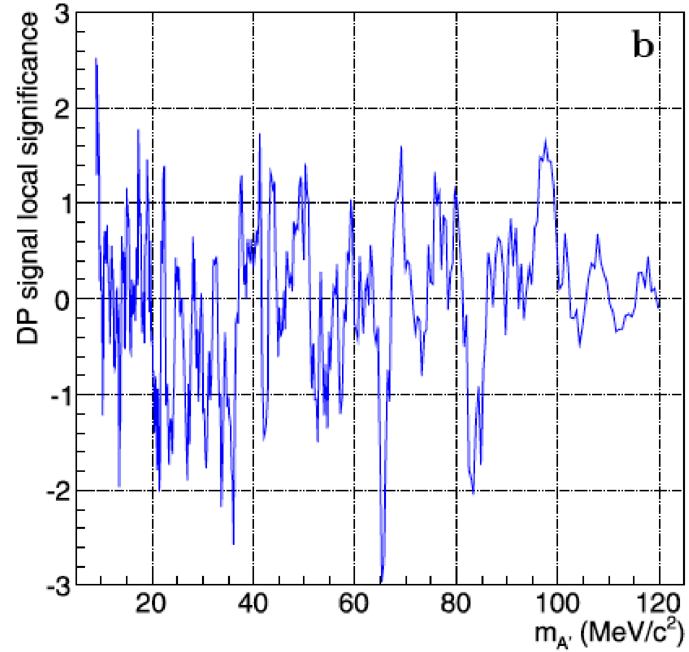
$K^\pm \to \mu^\pm \pi^0_D \nu$ $3.1\cdot10^6$ evt





Statistical significance



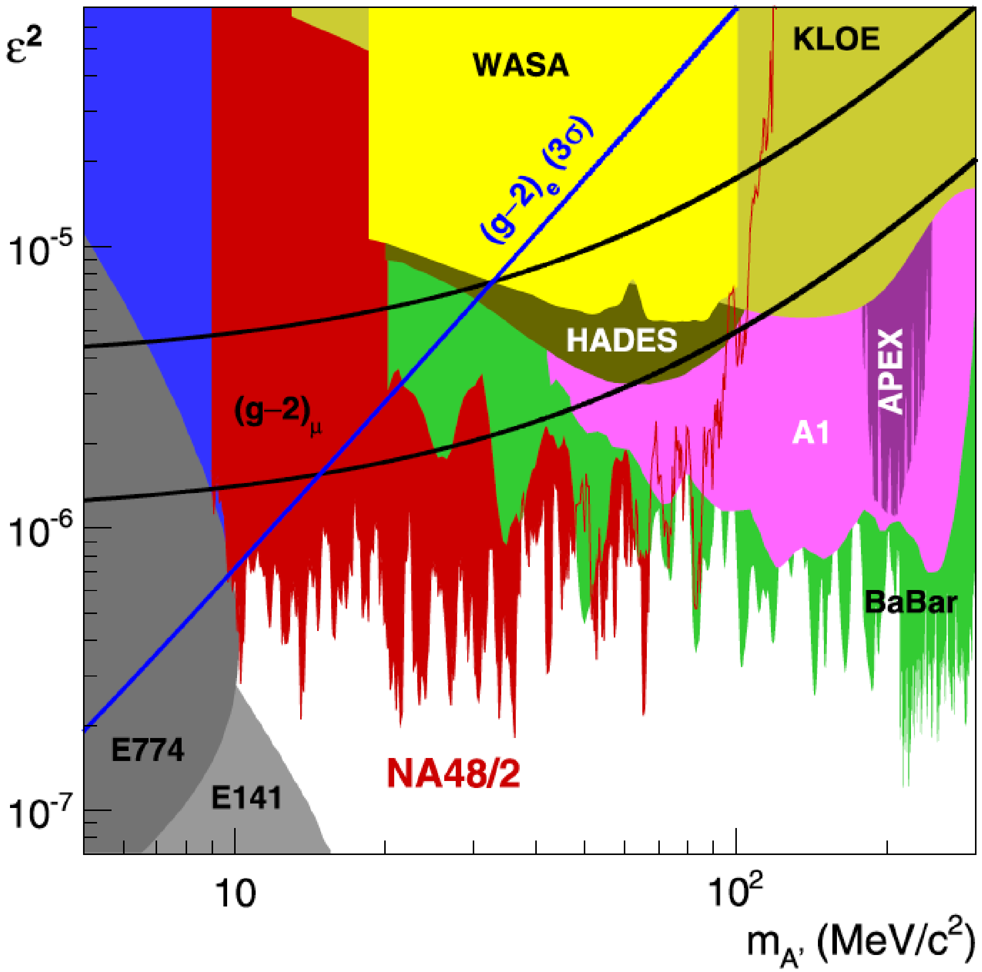


- Scanned DP mass range: 9 MeV/c^2<M_{DP}<120 MeV/c^2.
  - Variable DP mass step: □1.5□($M_{A'}$).
  - DP search window: □0.5□($M_{A'}$)
  - 404 DP mass hypothesis tested
- Confidence intervals for $N_{A'}$ are computed from:
  - N_{exp}, N_{obs} and □N_{obs} , □N_{exp} in the signal mass window
  - Frequentist confidence intervals Rolke-Lopez method.
- Local significance never exceeds 3 ⌠: no dark Photon signal observed

NA48/2 DP exclusion limit

DP exclusion summary

Final result: **PLB746 (2015) 178**



Improvement of the existing limits in the range 9-70 MeV/c^2.

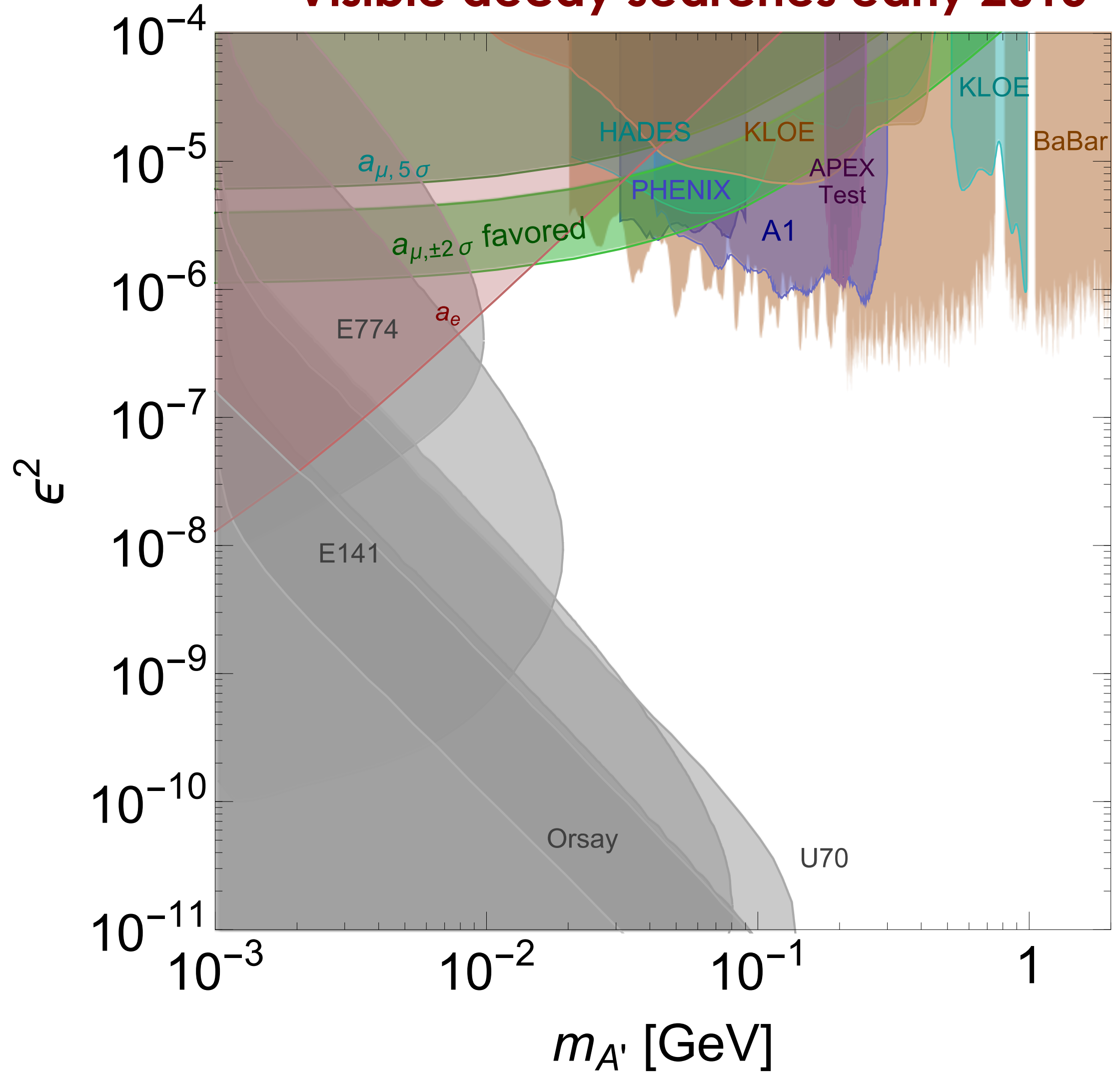
If **DP couples** to SM through **kinetic mixing** and **decays only to SM fermions**, it **is ruled out** as the explanation for anomalous **(g-2)μ.**

Sensitivity limited by irreducible □^0_D background: upper limit on □^{2} scales as ~$(1/N_K)^{1/2}$, modest improvement with larger data samples.

Impact of NA48/2 measurement

Favored region (g-2)μ still available in the low mass region.

Visible decay searches early 2015

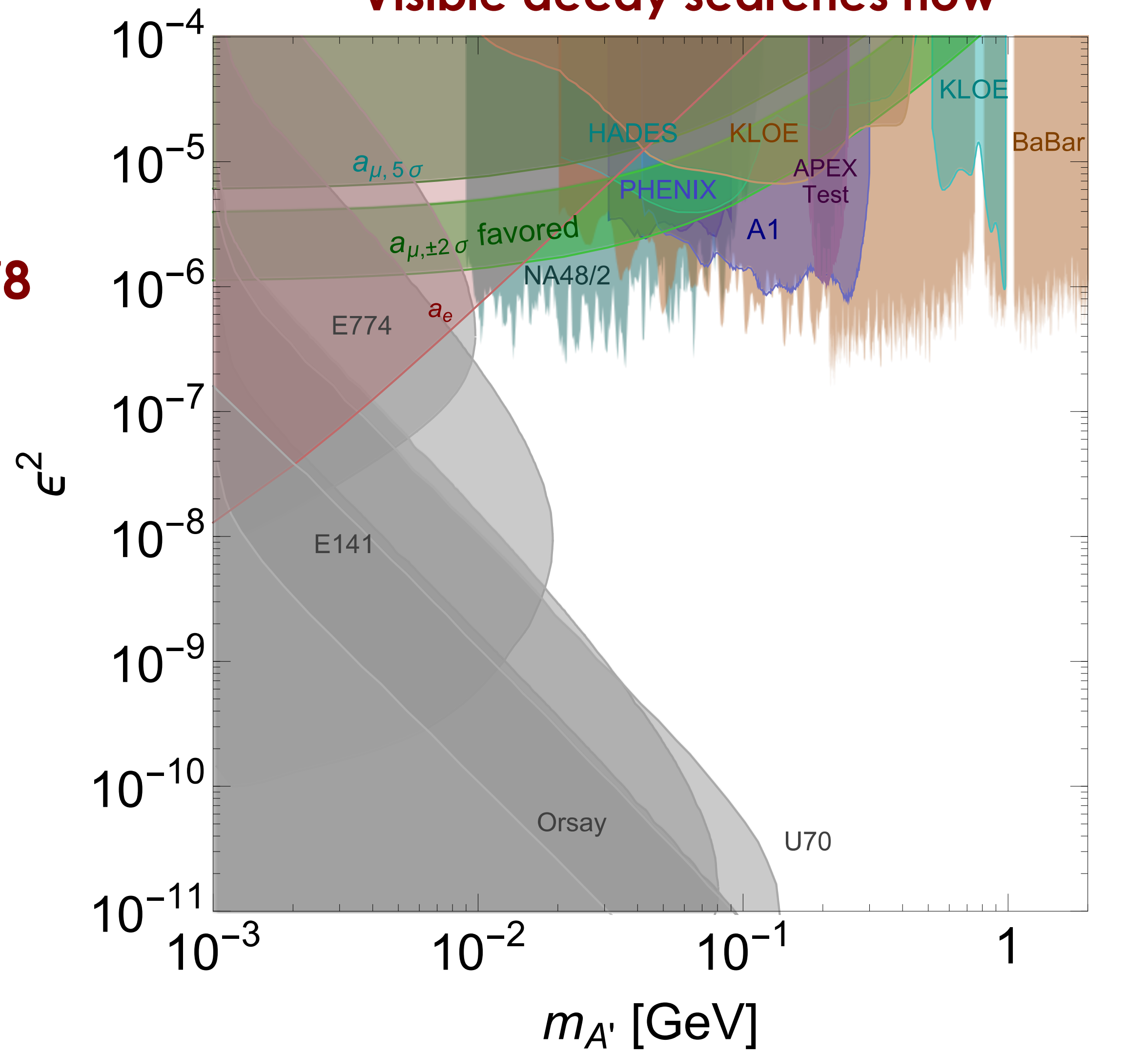


Impact of NA48/2 measurement

Favored region (g-2)μ completely excluded by NA48/2 measurement!

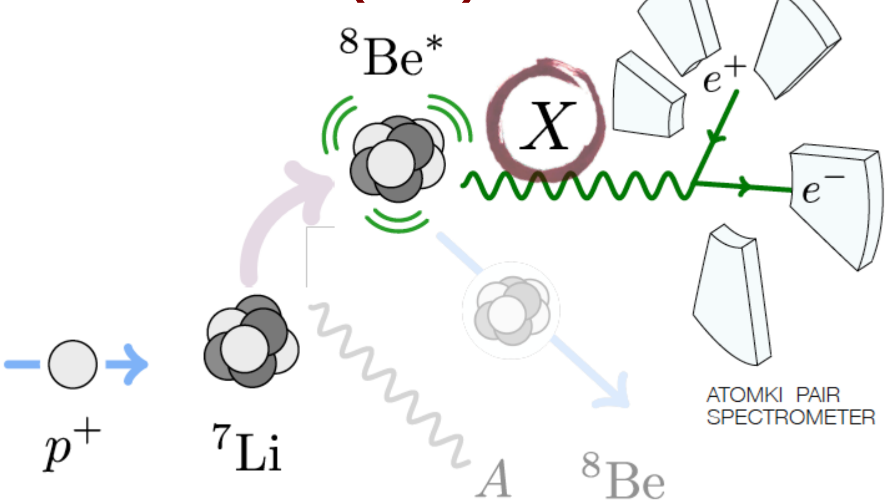
Final result: **PLB746 (2015) 178**

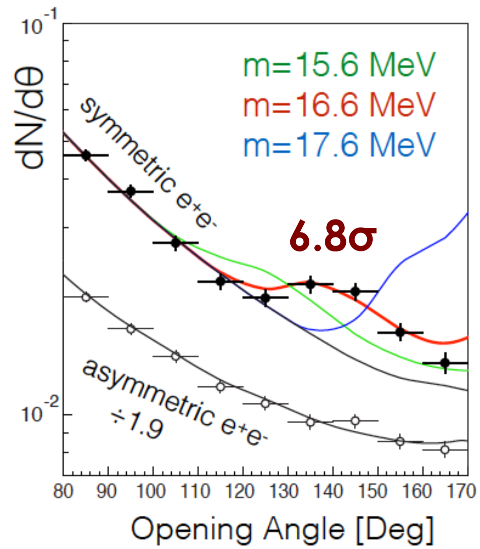
Visible decay searches now



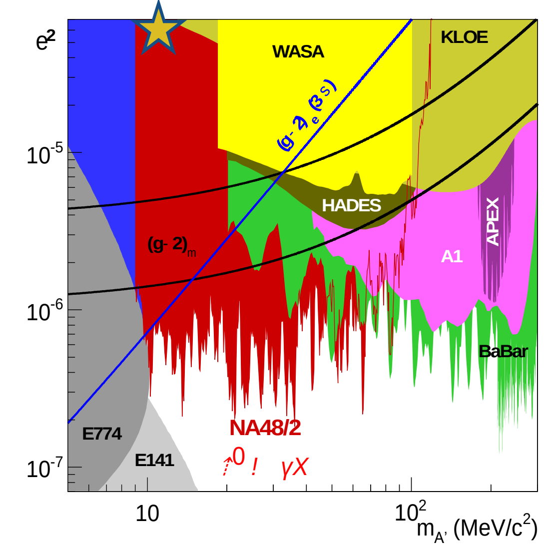
The Be^8 anomaly and the proto-phobic fifth force

PRL 116, 042501 (2016)





NA48/2 it's not a dark photon!



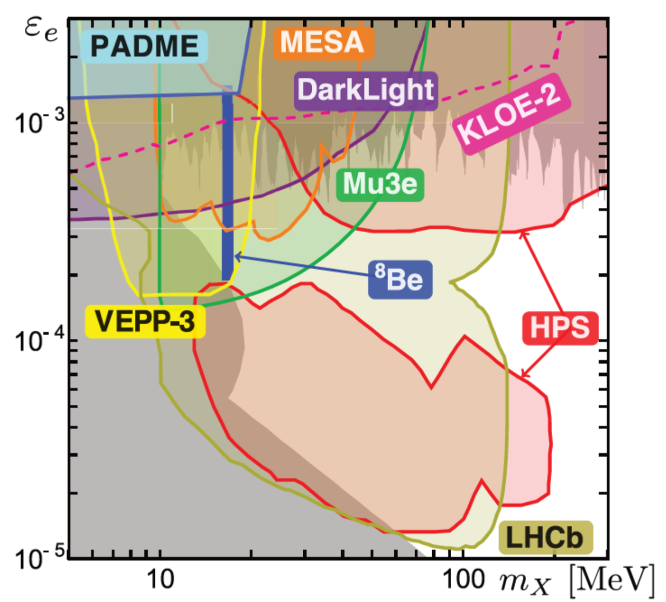
π^0-phobia = p^+-phobia

To avoid NA48/2, prohibit π^0 decay to Xγ

FROM QUARK CONTENT

$Q_u Q'_u - Q_d Q'_d = 0$ $\quad Q'_d = -2Q'_u$

ProtoPhobic coupling



Conclusions

- **NA62-RK** performed the most precise measurement of the π^0 **TFF**
  - $a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst})\times10^{-2}$ **PRELIMINARY**
  - Can be used to reduced uncertainties in the light by ligth scattering contribution to the $(g-2)\mu$
  - Final results and paper in preparation

- **NA48/2** set a limit on the dark photon searches (PLB746 (2015) 178)
  - Improvement of the existing limits for visible decays in the range 9-70 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 only** the whole favored by **$(g-2)\mu$ region has been excluded**
  - Several new physics models constrained by the NA48/2 measurement