Search for the dark photon at NA48/2 and NA62

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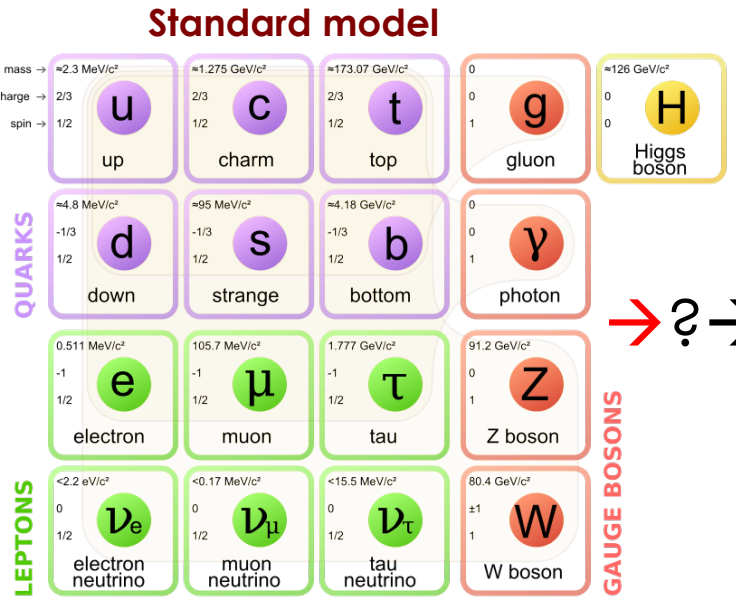
On behalf of the NA48/2 and NA62 collaborations

Light Dark Matter @ Accelerators La Biodola 24-28 Maggio 2017

What is the universe made of?



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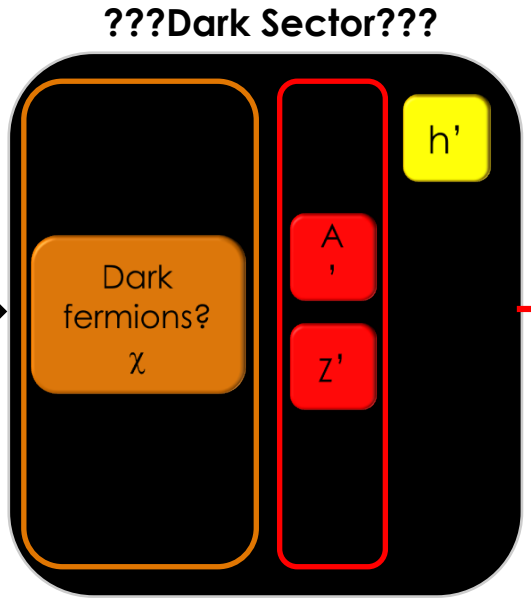

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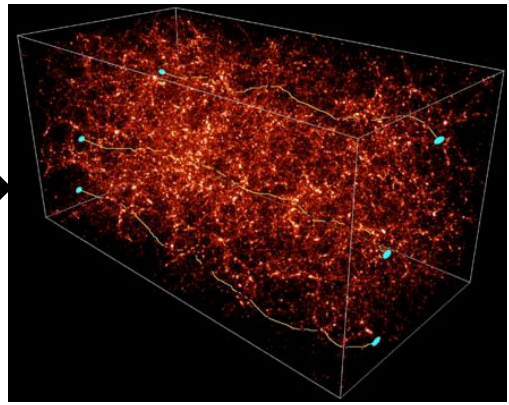
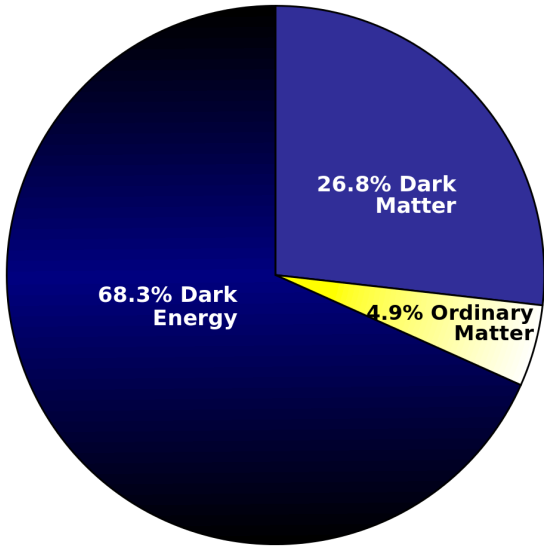


- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interacts gravitationally
- Many open questions
  - What is dark Matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the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

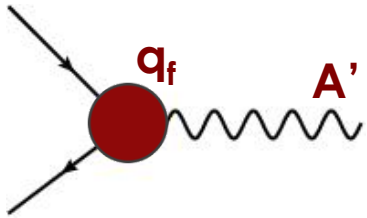
$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$

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.

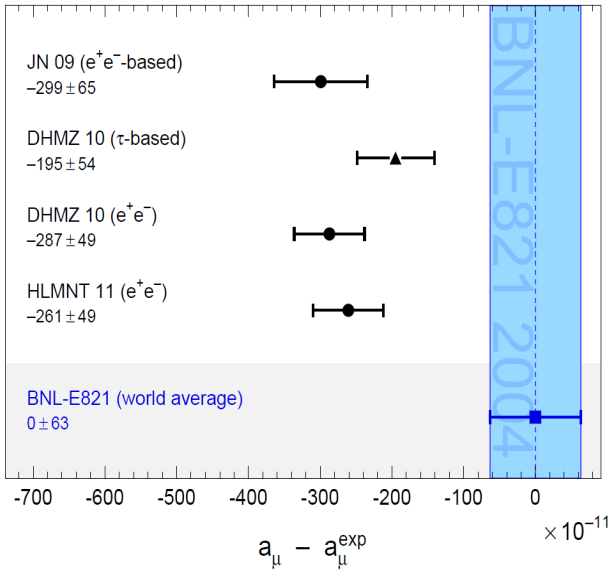
- **As in QED**, this will generate new interactions with SM fermions of type:

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

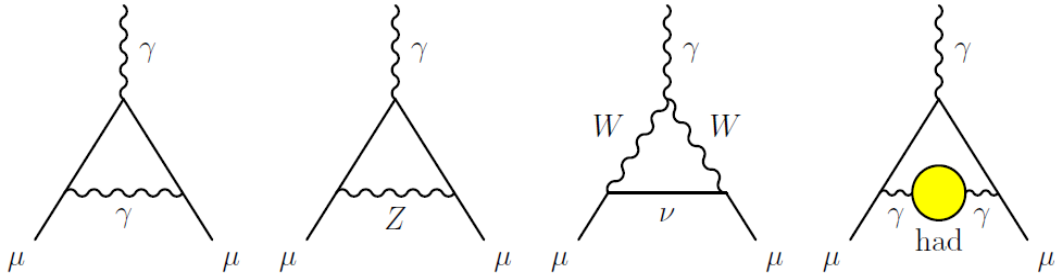


  - Not all the SM particles need to be charged under this new symmetry
  - In the **most general case q_f is different in between leptons and quarks** and can even be 0 for quarks. **P. Fayet, Phys. Lett. B 675, 267 (2009**)

Dark photon and g-2$_\mu$

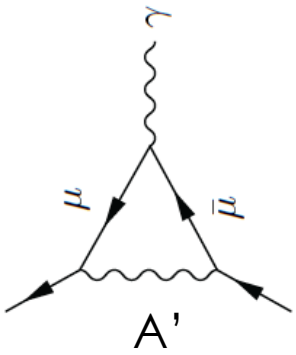


g-2 in the standard model

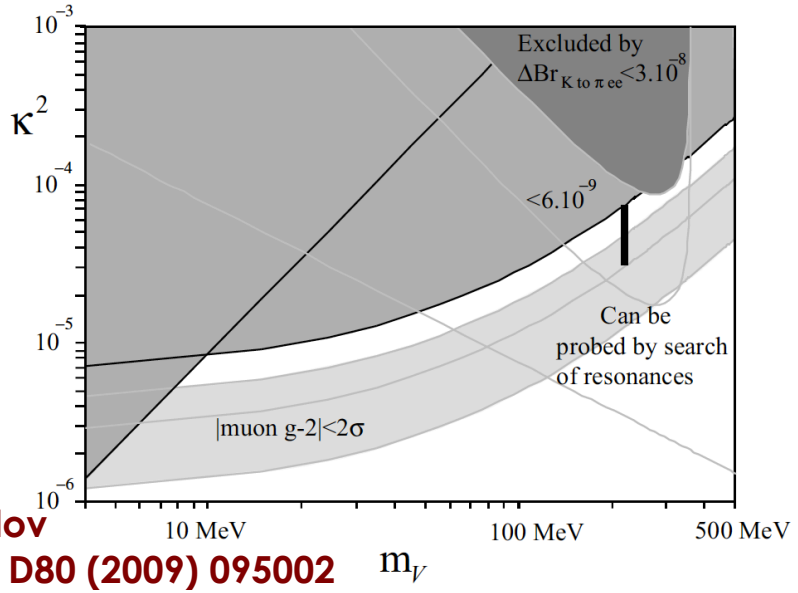


About 3s discrepancy between theory and experiment. Could be due to hadronic uncertainties on the Light by Light scattering?

g-2 and A'



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

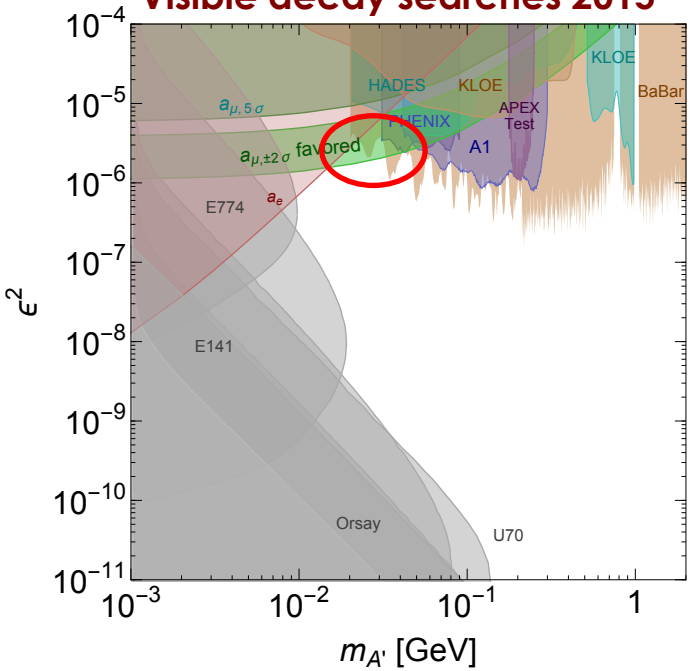


M. Pospelov
Phys.Rev. D80 (2009) 095002

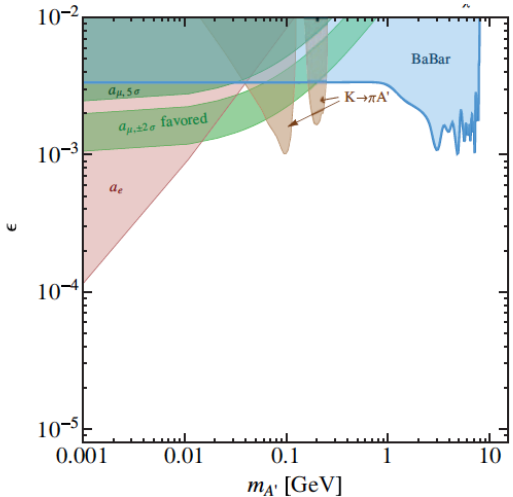
Dark photon searches status 2015

- 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 $M_\chi < M_{A'}/2$, $A' \rightarrow \chi\chi$, ε^2 suppression to all visible modes
  - No assumption on α_D and no kinetic mixing

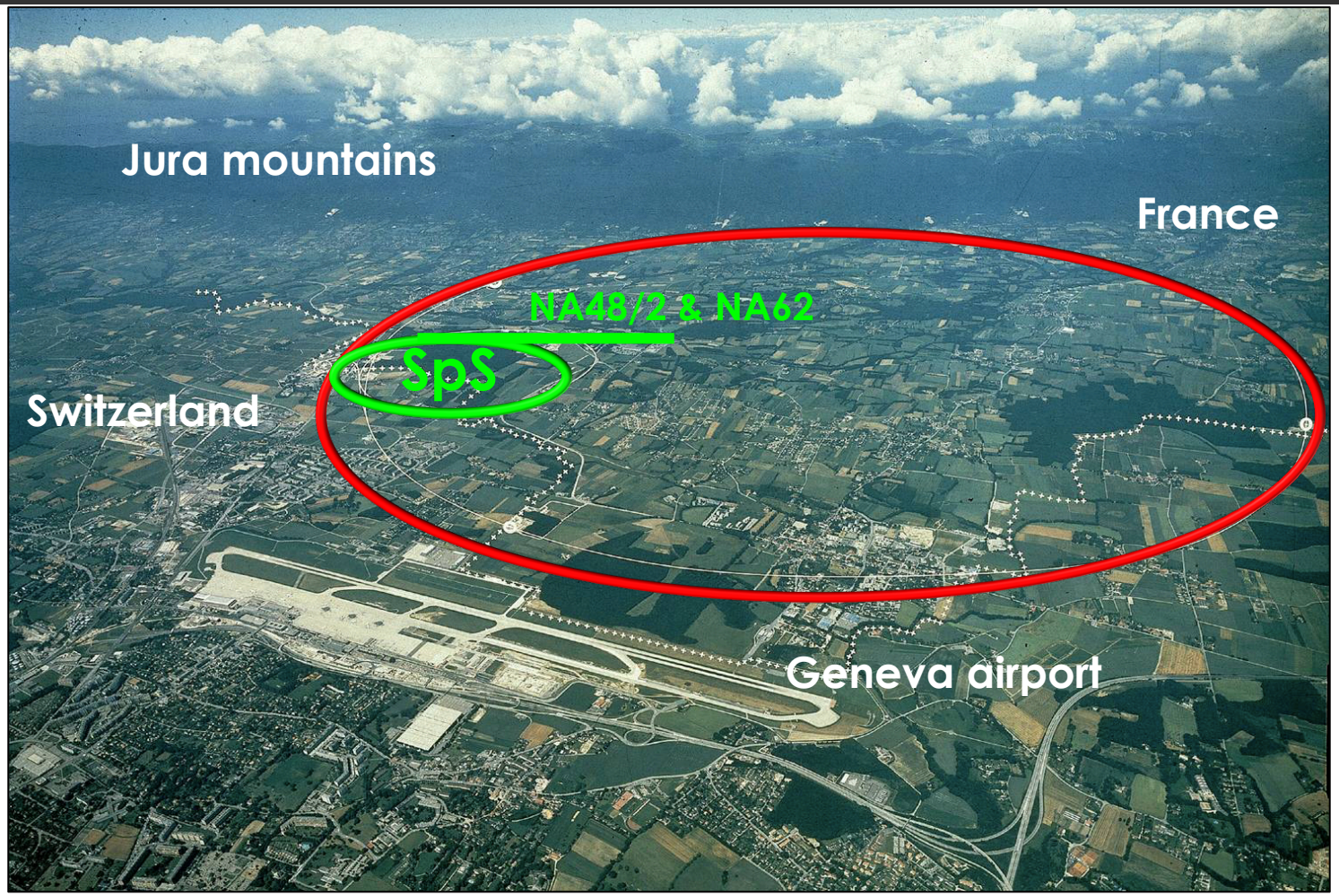
Visible decay searches 2015



Invisible decay searches



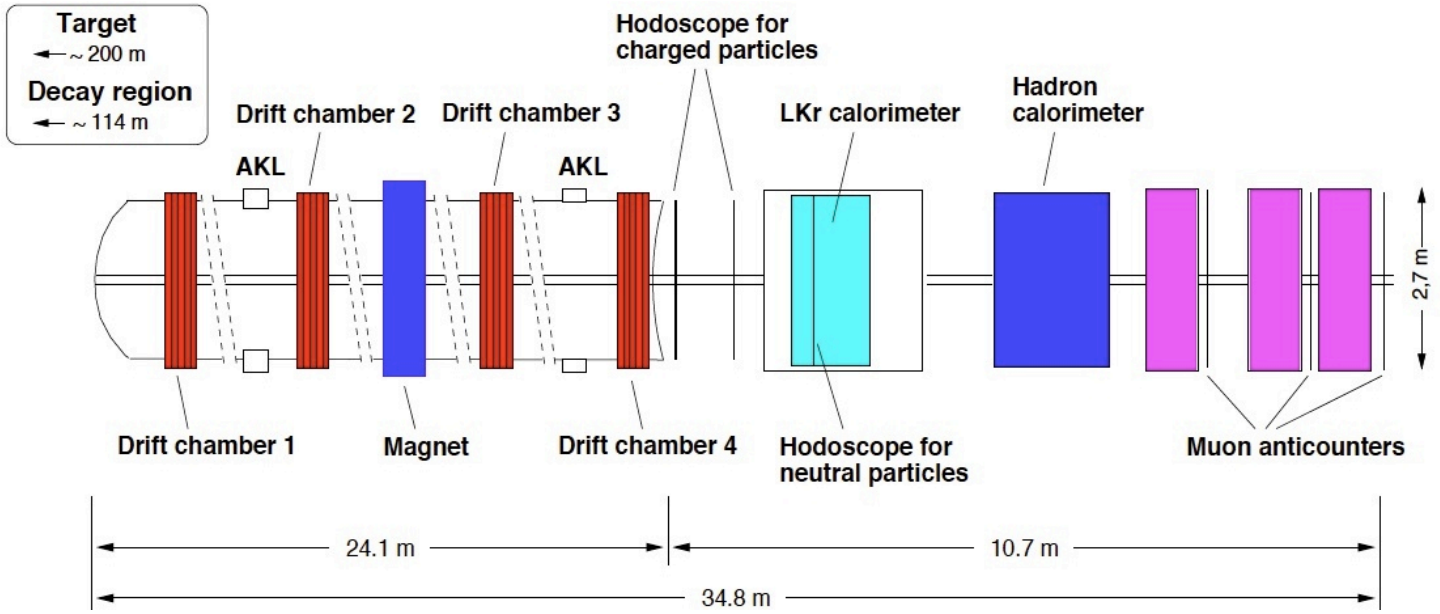
The NA48/2 and NA62 experiments @ SPS



NA48/2 collaboration: 15 institutes from 8 countries:
NA62 collaboration: 29 institutes from 13 countries

NA48/2 (2003-04)

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



Magnetic Spectrometer

- 4 drift chambers and a dipole magnet

$$\frac{\sigma(p)}{p} = (1.02 \oplus 0.044\,p)\%$$ 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)

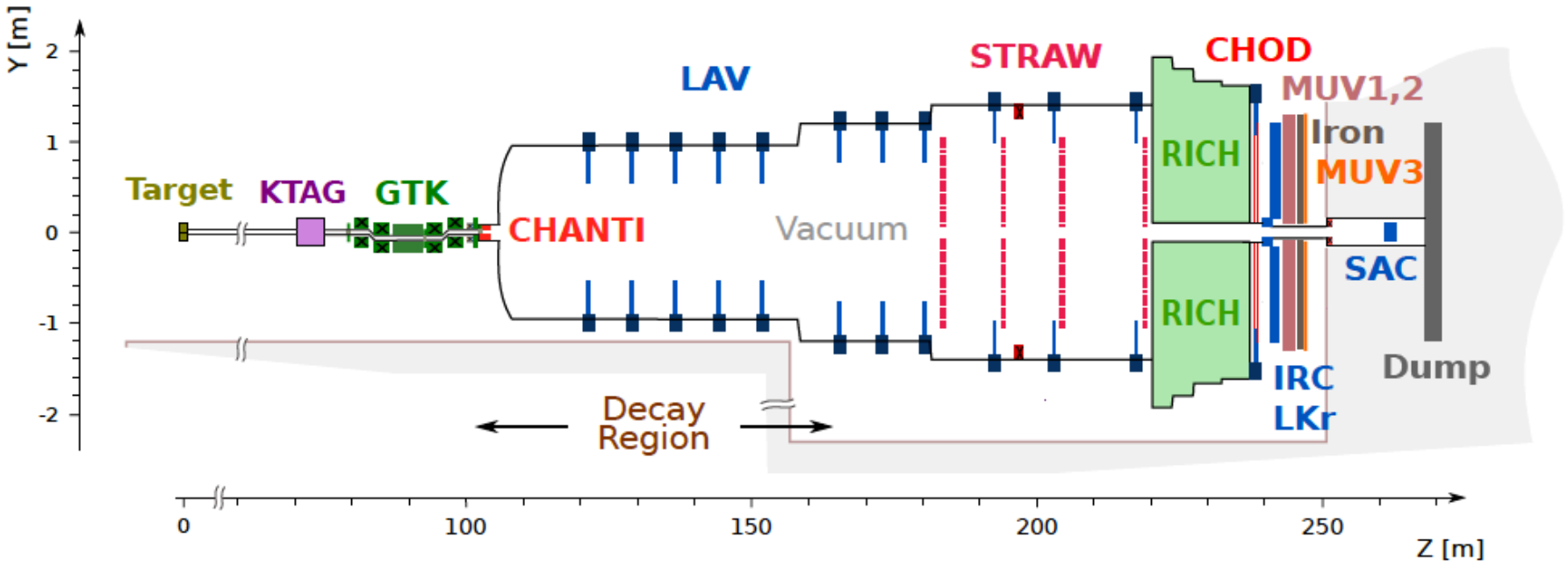
$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.4\%$$ E in GeV

$K^{\pm} \to \pi^{\pm}\pi^0$ $\pi^0 \to \gamma A'$ $A' \to e^+e^-$: PLB 746 (2015) 178

$K^{\pm} \to \pi^{\pm}A'$ $A' \to \ell^+\ell^-$ PLB 769 (2017) 67–76

Search for dark photons at NA62

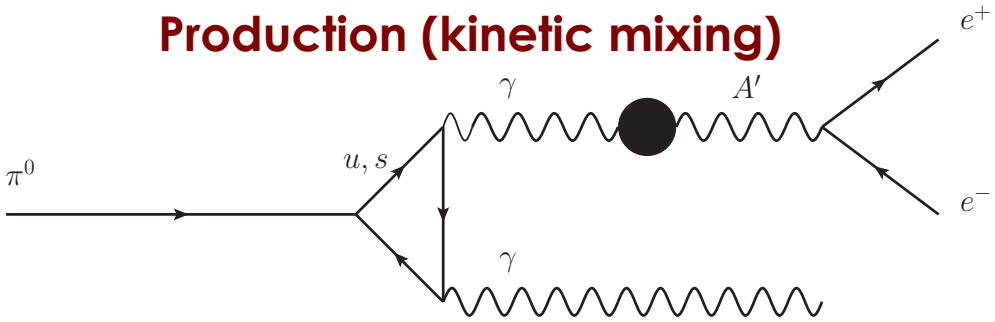
- NA62 has an high intensity hadron beam and can search for A' using different experimental techniques and production mechanisms
  - Meson decay and proton bremsstrahlung: dedicated dump mode
    - Dedicated talk by M. Mirra
  - Mesons decay (K and pions): parasitic to $\pi\nu\nu$ searches
    - $K^+ \to \pi^+\pi^0$ $\pi^0 \to \gamma A'$ $A' \to \chi\chi$ A' invisible decays.
    - $K^+ \to \pi^+ A'$ with $A' \to \chi\chi$ or $A' \to \ell^+\ell^-$ invisible and invisible



Dark photon in π^0 decays

Dark photon in π^0 decays

Production (kinetic mixing)

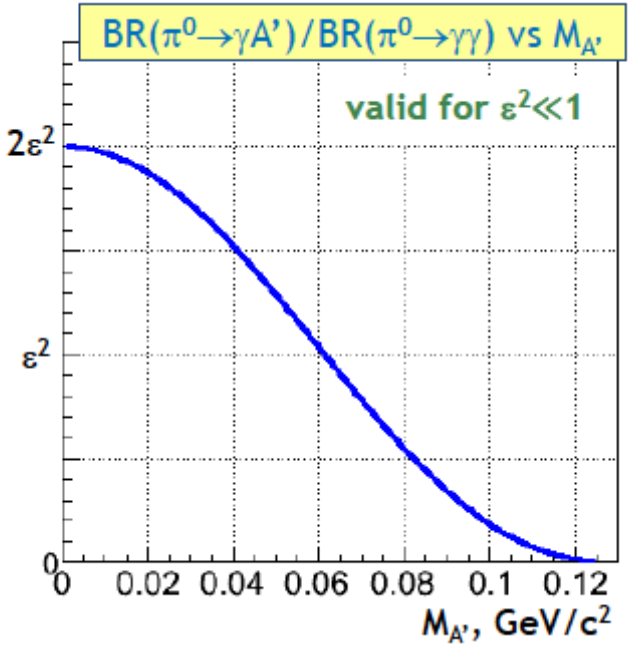


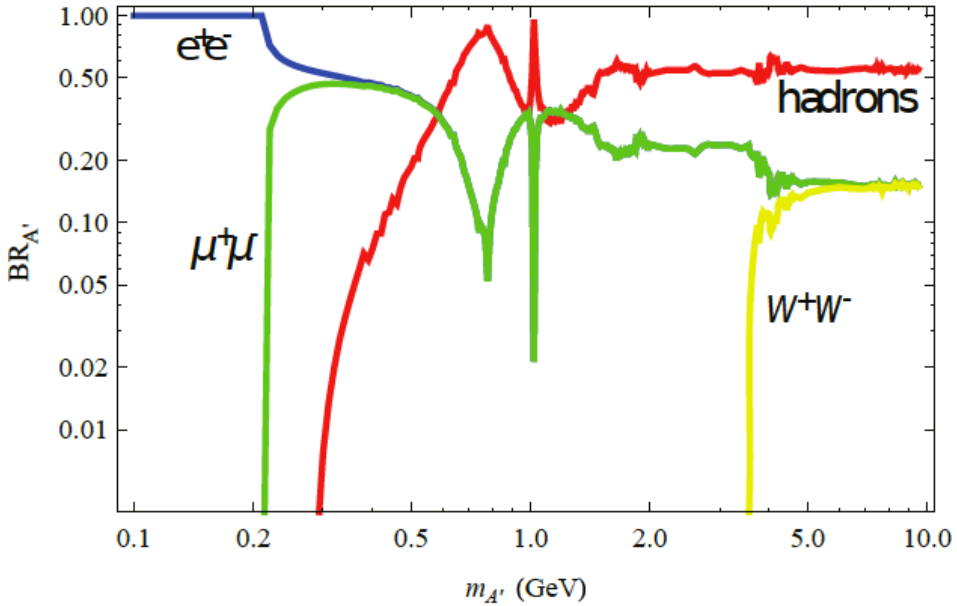
Decay (if no light dark sector)

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

$$\frac{BR(\pi^0 \to \gamma A')}{BR(\pi^0 \to \gamma\gamma)} \approx 2\varepsilon^2 \, |F(M_{A'}^2)|^2 \left(1-\frac{M_{A'}^2}{M_\pi^2}\right)^3$$

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





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

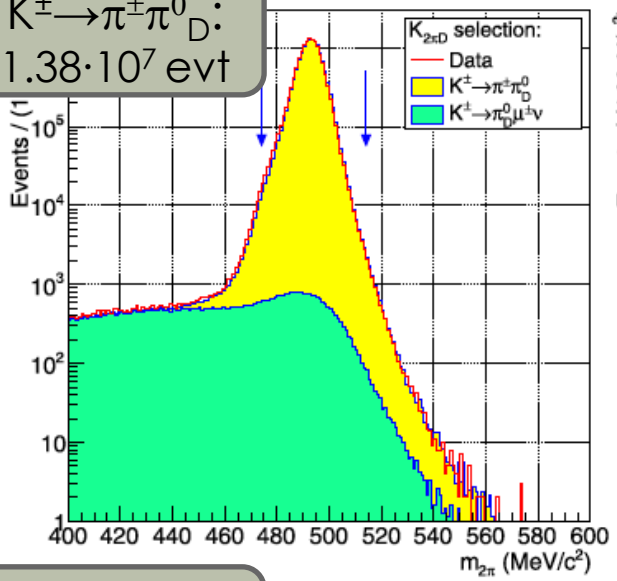
NA48/2 data sample

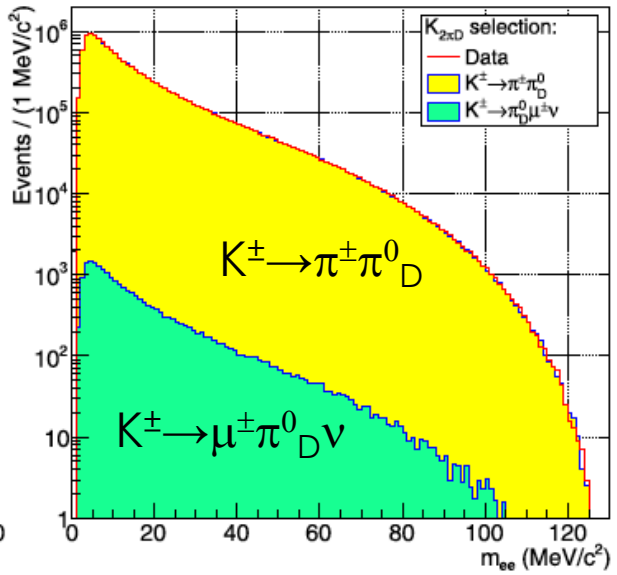
- Number of kaon decays in NA48/2 ('03/'04): $N_K \approx 2 \cdot 10^{11}$
  - $5 \cdot 10^{10}$ π^0 tagged decays from $K^{\pm} \to \pi^{\pm}\pi^0$ and $K^{\pm} \to \pi^0 \mu^{\pm} \nu$ decays
- Exclusive search for the **decay chain $\pi^0 \to \gamma A'$, $A' \to e^+e^-$**
  - Search for a narrow peak 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 $K^{\pm} \to \pi^{\pm}\pi^0_D$: $BR(K_{2pD}) = 2.4 \cdot 10^{-3}$
  - 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 **~1.7x10^7 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

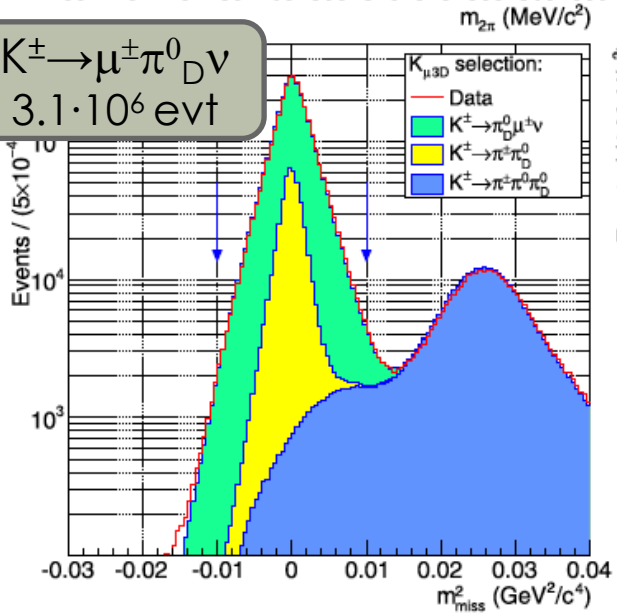
$K^{\pm}\to\pi^{\pm}\pi^{0}_{D}$: $1.38\cdot10^{7}$ evt

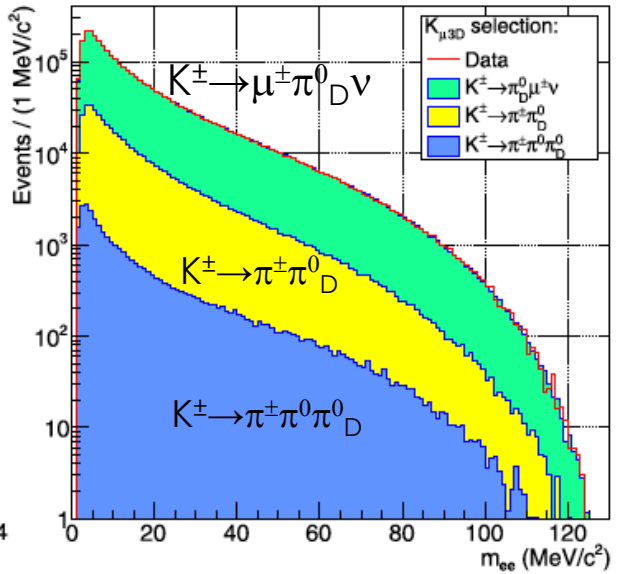




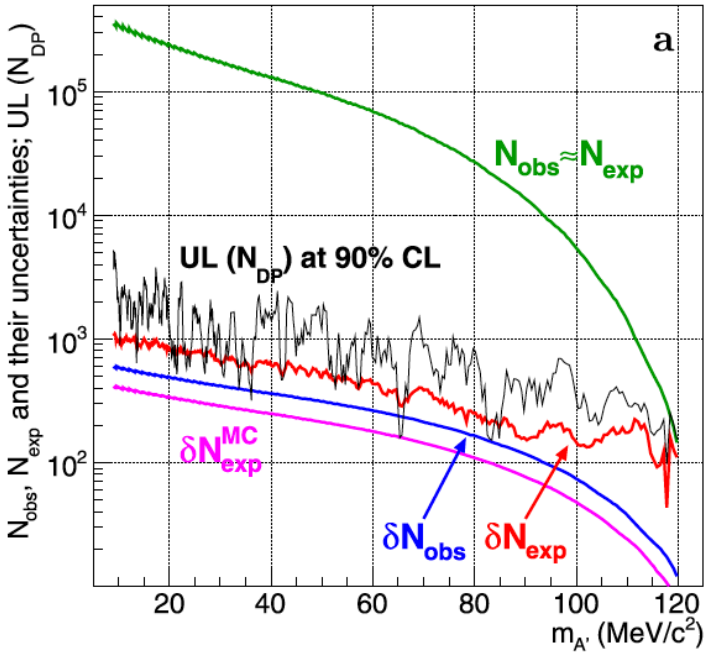
- $K^{\pm}\to\mu^{\pm}\pi^{0}_{D}$ selection
  - $|M_{ee\gamma}- M_{\pi 0}| <8$ MeV/c^2
  - $M^2_{miss} < 0.01$GeV^2/c^4
  - missing P_T due to neutrino: $5\cdot10^{-4} < P_T < 0.04$ GeV^2/c^2

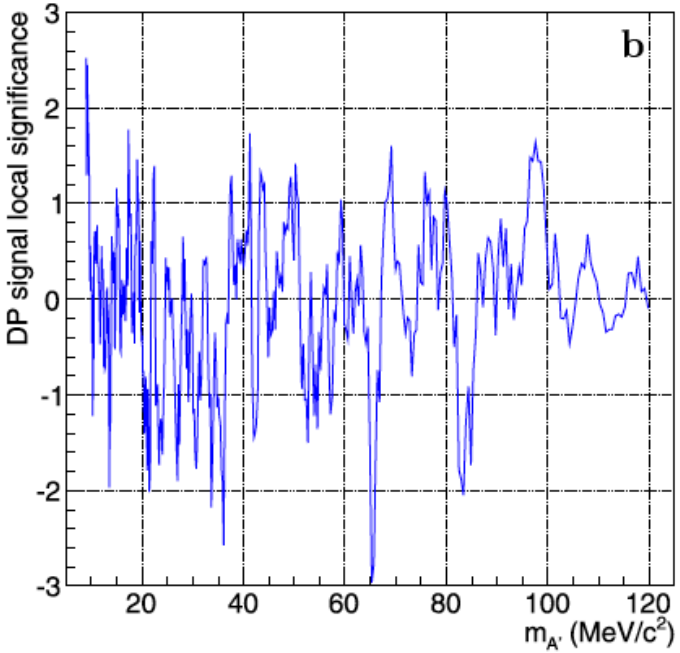
$K^{\pm}\to\mu^{\pm}\pi^{0}_{D}\nu$ $3.1\cdot10^{6}$ evt





Statistical significance



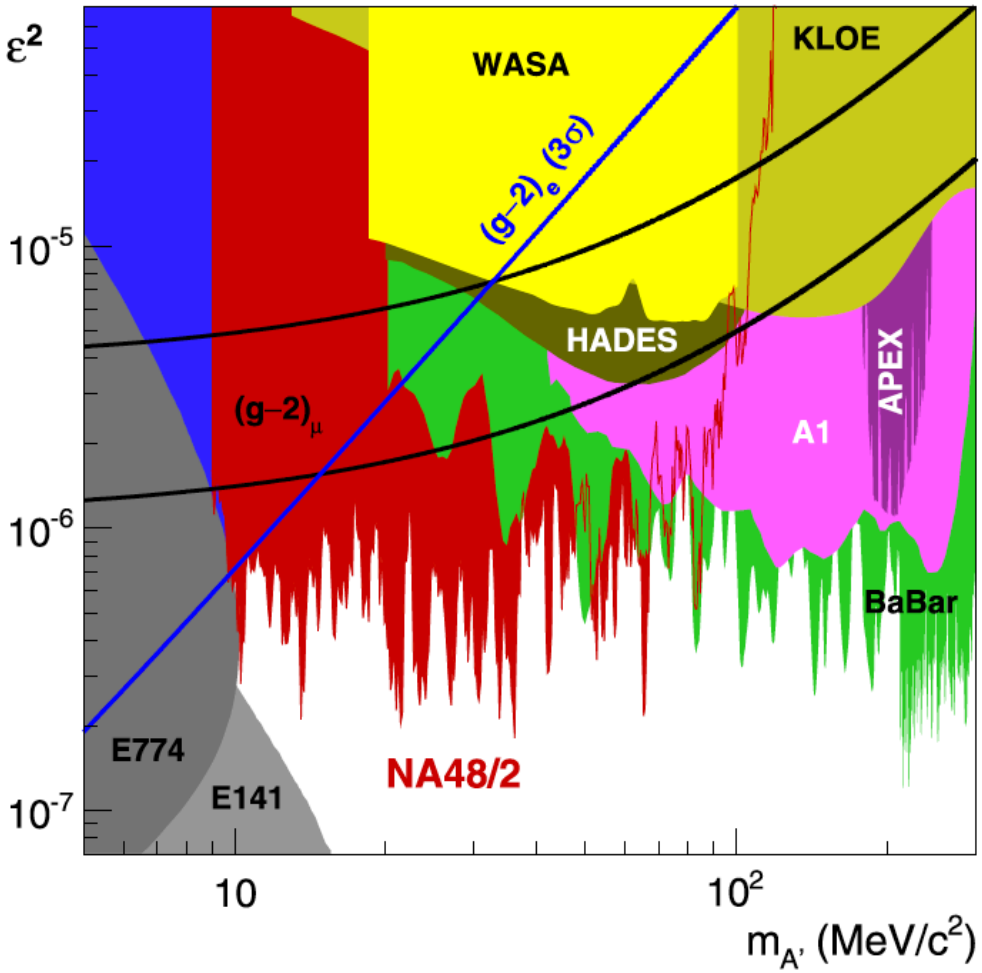


- Scanned DP mass range: 9 MeV/c^2<M_{DP}<120 MeV/c^2.
  - Variable DP mass step: ±1.5σ($M_{A'}$).
  - DP search window: ±0.5σ($M_{A'}$)
  - 404 DP mass hypothesis tested
- Confidence intervals for $N_{A'}$ are computed from:
  - N_{exp}, N_{obs} and δN_{obs} , δN_{exp} in the signal mass window
  -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

NA48/2 DP exclusion limit

DP exclusion summary

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



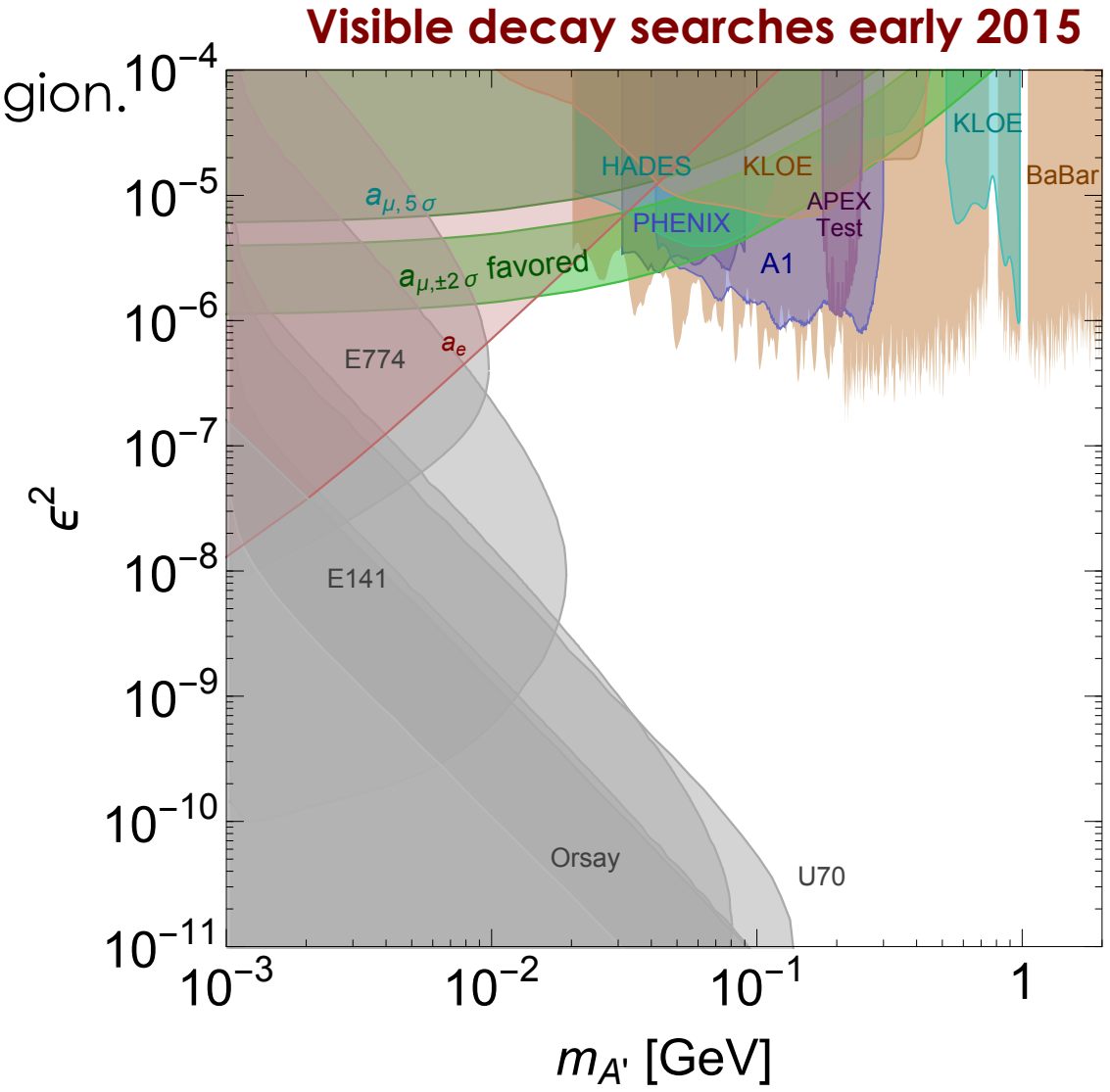
Improvement of the existing limits in the range 9-70 MeV/c^2.

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 π^0_D background: upper limit on ε^2 scales as $\sim(1/N_K)^{1/2}$, modest improvement with larger data samples.

Impact of NA48/2 measurement

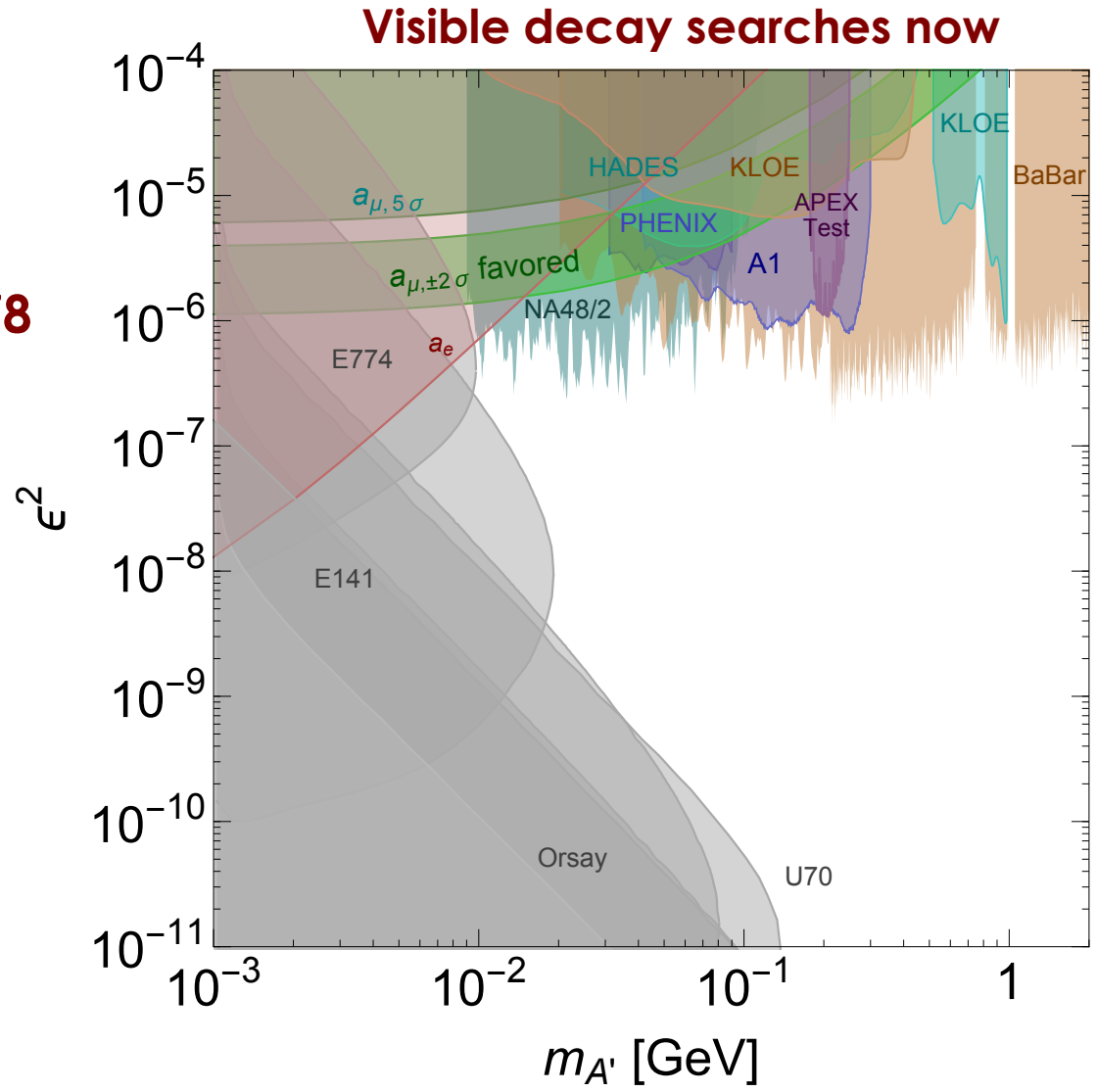
Favored region (g-2)μ still available in the low mass region.



Impact of NA48/2 measurement

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

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



Search for $\pi^0 \to \gamma A'$ $A \to \chi\chi$ at NA62

- Search for $K^{\pm} \to \pi^{\pm}\pi^0 \to \pi^{\pm}\gamma A' \to \pi^{\pm}\gamma\chi\chi$ searching for $\pi^{\pm}$ one γ and M_{miss}
  - Assuming BR(A' $\to\chi\chi$)=1

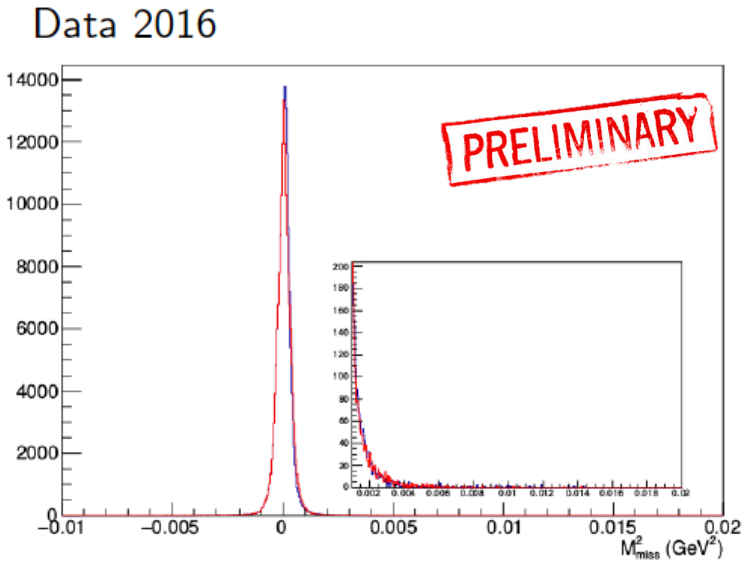
$$\mathrm{BR}\left(\pi^0 \to A'\gamma\right) = 2\epsilon^2 \left(1 - \frac{m_A^2}{m_{\pi^0}^2}\right)^3 \times \mathrm{BR}\left(\pi^0 \to \gamma\gamma\right)$$

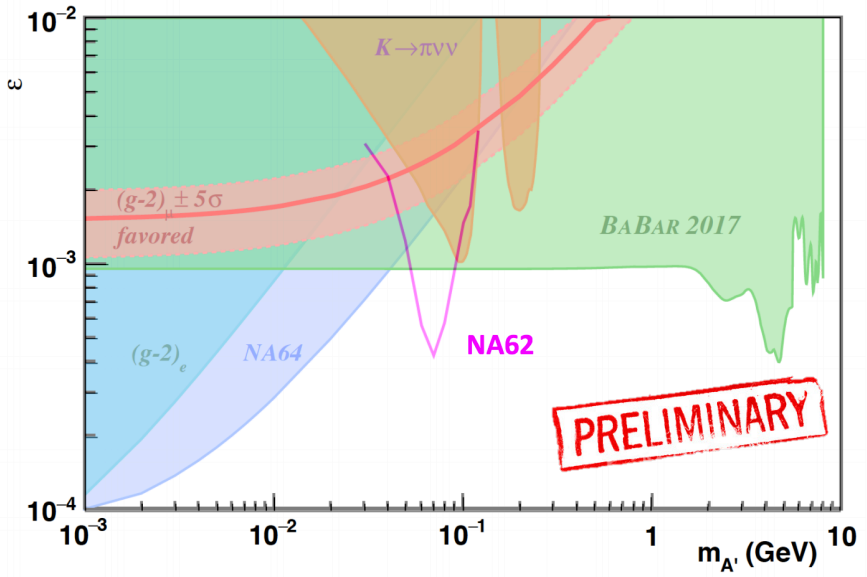
- Mass reach bounded from above to π^0 mass (~135 MeV)
  - Strong kinematic suppression near the mass limit
- Search for a peak in the missing mass $M^2_{miss} = (P_K - P_\pi - P_\gamma)^2$
- Extraction of limits comparing to BR($\pi^0 \to \gamma\gamma$)

$$\frac{n_{\mathrm{sig}}}{n_{\pi 0}} = \frac{\mathrm{BR}(\pi^0 \to A'\gamma)}{\mathrm{BR}(\pi^0 \to \gamma\gamma)} \varepsilon_{\mathrm{sel}} \varepsilon_{\mathrm{trg}} \epsilon_{\mathrm{mass}}$$

$$\frac{BR(\pi^0 \to \gamma A')}{BR(\pi^0 \to \gamma\gamma)} \approx 2\varepsilon^2 \, |F(M_{A'}^2)|^2 \left(1 - \frac{M_{A'}^2}{M_\pi^2}\right)^3$$

Sensitivity: preliminary estimate





- Data-driven BG estimate (peak resolution mostly left-right-symmetric)
- Limited amount of statistics used 1.5×10^{10} K^+ (6.5% of 2016 sample).
- Promising preliminary limit at 90% CL on invisible A' decay

Dark photon in $K^{\pm} \to \pi^{\pm} A'$ $A' \to \ell^+ \ell^-$

Dark photon in $K^{\pm}\to\pi^{\pm}A'$ $A'\to\ell^{+}\ell^{-}$

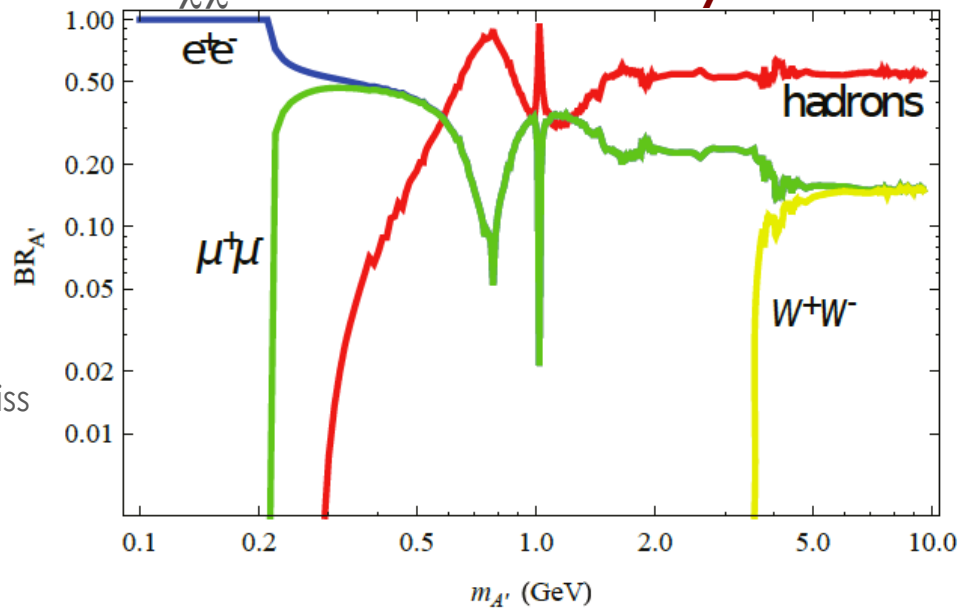
- Mixing from $K\to\pi^{\pm}\gamma^{*}$ with γ^{*} mixing to A'

$$\Gamma_{K\to\pi V}=\frac{\alpha\kappa^2}{2^{10}\pi^4}\frac{m_V^2W^2}{m_K}f(m_V,m_K,m_\pi)\implies \mathrm{Br}_{K\to\pi V}\simeq 8\times10^{-5}\times\kappa^2\left(\frac{m_V}{100\ \mathrm{MeV}}\right)^2.$$

PHYS. REV. D 80, 095024 (2009)

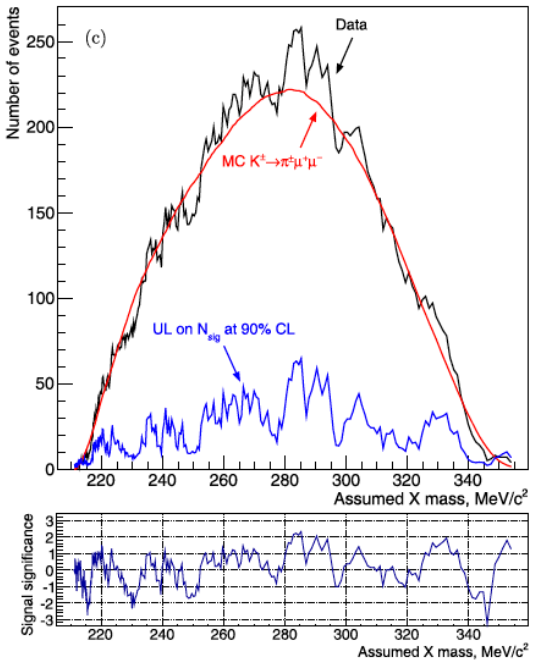
- Depending on A' the decay type can end up in different final states similar to kaon decays:
  - Visible: $K\to\pi^{\pm}e^{+}e^{-}$ can hide $K\to\pi^{\pm}A'$ $A'\to e^{+}e^{-}$
  - Visible: $K\to\pi^{\pm}\mu^{+}\mu^{-}$ can hide $K\to\pi^{\pm}A'$ $A'\to\mu^{+}\mu^{-}$ PLB 769 (2017) 67–76
  - Invisible: $K\to\pi^{\pm}\nu\nu$ can hide $K\to\pi^{\pm}A'$ $A'\to\chi\chi$

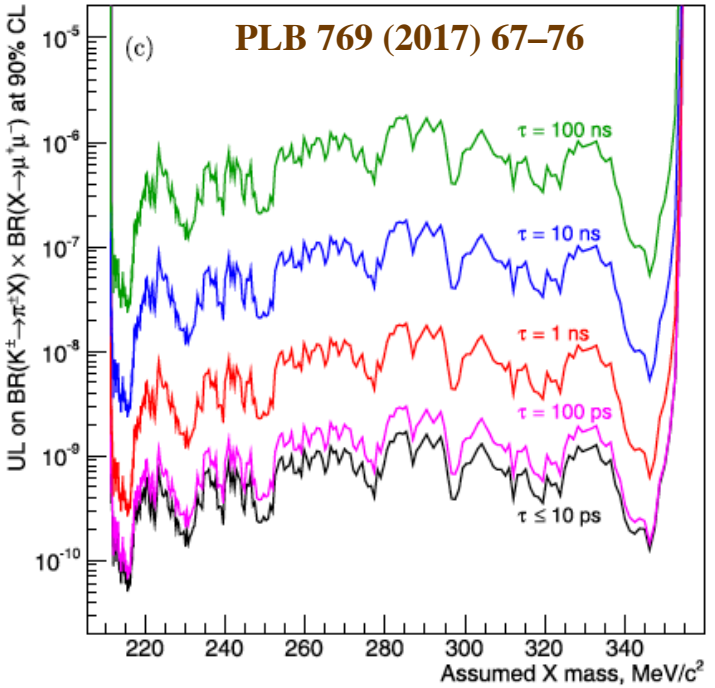
- All of this mode are accessible in NA48/2+NA62 experiments!
- Signature being narrow mass peak in $\ell^{+}\ell^{-}$ invariant mass or M_{Miss}



NA48/2 search for $K^{\pm}\to\pi^{\pm}\mu^{\pm}\mu^{\mp}$

- NA48/2 search resonances in decays $K^{\pm}\to\pi^{\pm}\mu^{\pm}\mu^{\mp}$:
  - Sample of 2×10^{11} $K^{\pm}$ decays collected in 2003–04.
  - Can be reinterpreted as: $K^{\pm}\to\pi^{\pm}A'$ $A'\to\mu^{\pm}\mu^{\mp}$
  - Limits on $BR(K^{\pm}\to\pi^{\pm}A')BR(A'\to\mu^{\pm}\mu^{\mp})$ in the mass region:
    - 210 MeV < $M_{A'}$<350 MeV as function of the lifetime
    - A' lifetime <10^{-12} for explored region ($\varepsilon^2<10^{-5}$)
    - Upper Limit on $BR(K^{\pm}\to\pi^{\pm}X)BR(X\to\mu^{\pm}\mu^{\mp})$ in 10^{-9}-10^{-10} region





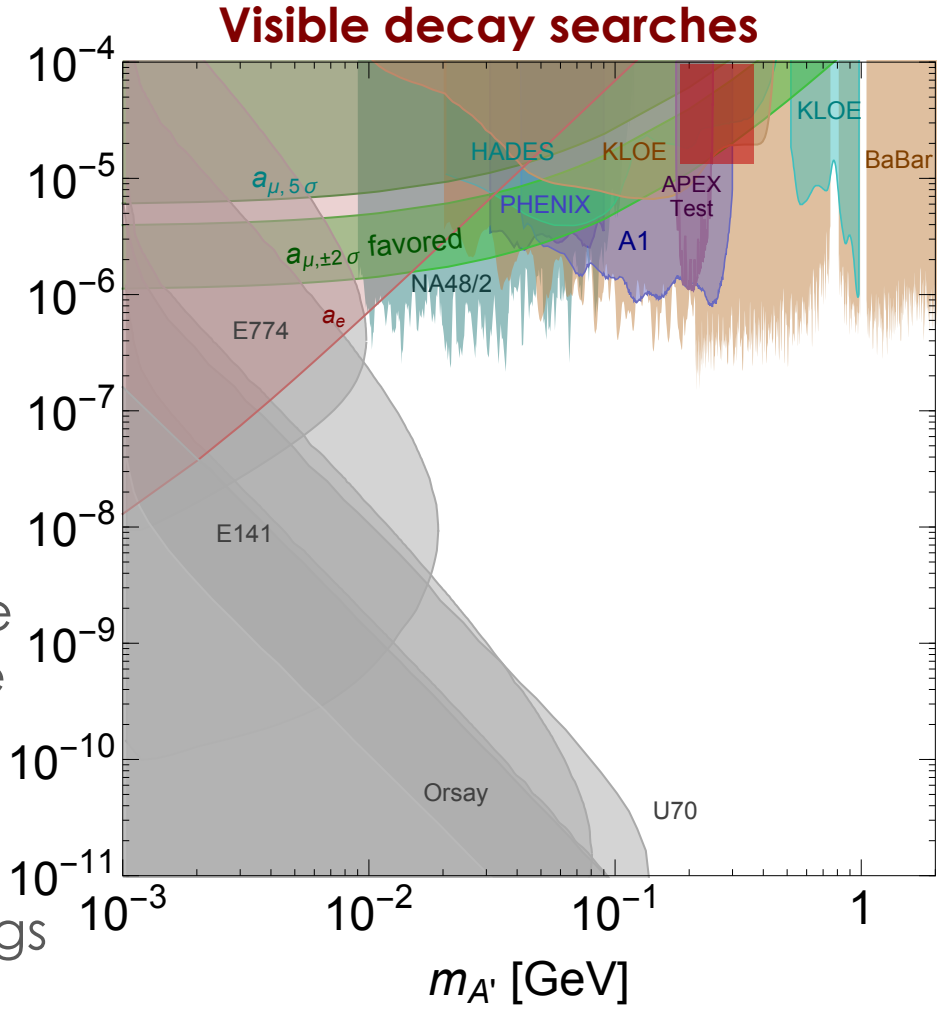
NA48/2 $K^{\pm}\to\pi^{\pm}\mu^{\pm}\mu^{\mp}$ and A' bounds

$$UL(\varepsilon^2) = \frac{UL(\mathrm{BR}(K^{\pm}\to\pi^{\pm}X)\mathrm{BR}(X\to\mu^{\pm}\mu^{\mp}))}{\mathrm{BR}(K^{\pm}\to\pi^{\pm}X)\mathrm{BR}(X\to\mu^{\pm}\mu^{\mp})}$$

$$\Gamma_{K\to\pi V} = \frac{\alpha\kappa^2}{2^{10}\pi^4}\frac{m_V^2 W^2}{m_K} f(m_V, m_K, m_\pi) \implies$$

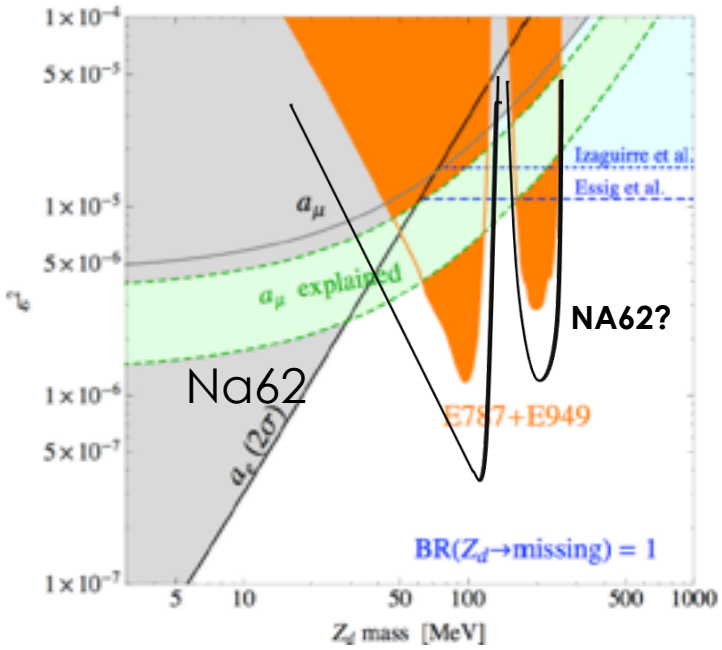
$$\mathrm{Br}_{K\to\pi V} \simeq 8\times 10^{-5}\times\kappa^2\left(\frac{m_V}{100\ \mathrm{MeV}}\right)^2.$$

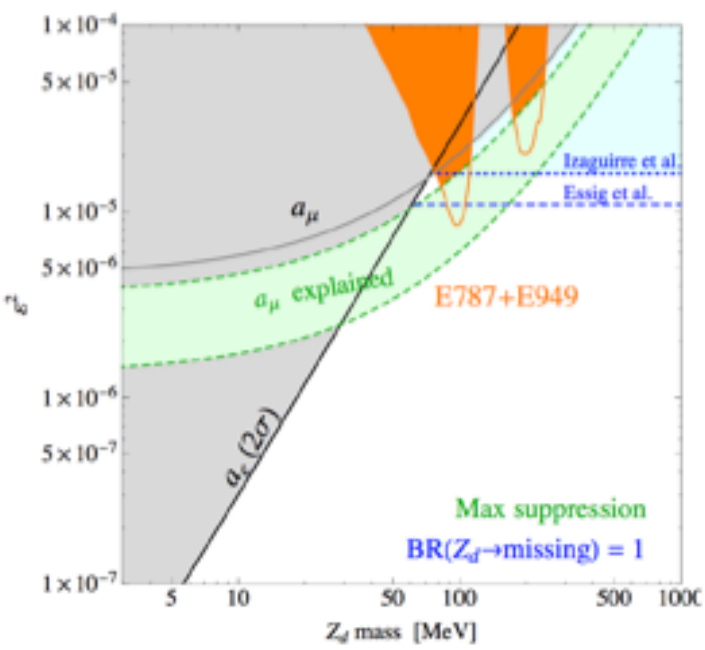
$$Br(X\to\mu^{\pm}\mu^{\mp}) = \frac{\Gamma(\mu^{\pm}\mu^{\mp})}{\Gamma(\mu^{\pm}\mu^{\mp})+\Gamma(e^{\pm}e^{\mp})} \sim 0.5$$



- Bound in the A' parameter space not competitive with Babar in the kinetic mixing scenario
  - Universal lepton coupling
- What about if we modify couplings to leptons (L_μ-L_τ)?
  - Muon dominated coupling factor 2 more stringent limit ~5E-6

$K^+ \to \pi^+ \nu\nu$ and the A' invisible decays



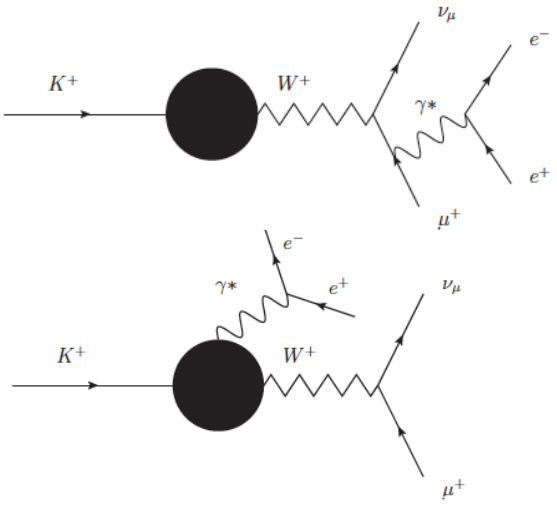


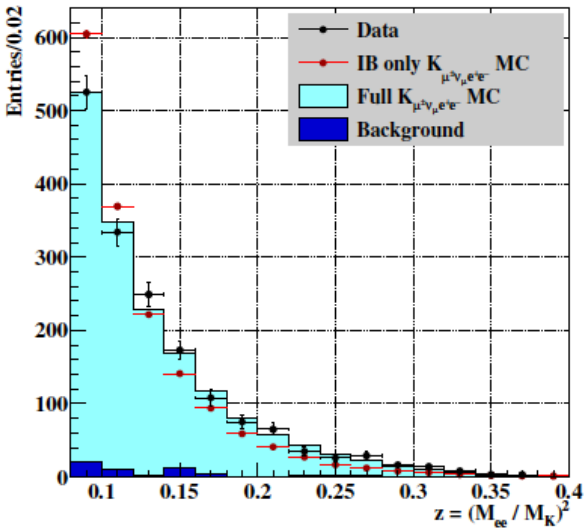
In models assuming that the dark photon couples to SM through kinetic mixing eq≠0 $K^\pm \to \pi^\pm \nu\nu$ can be used to constrain $K^\pm \to \pi^\pm$A' A' $\to \chi\chi$:

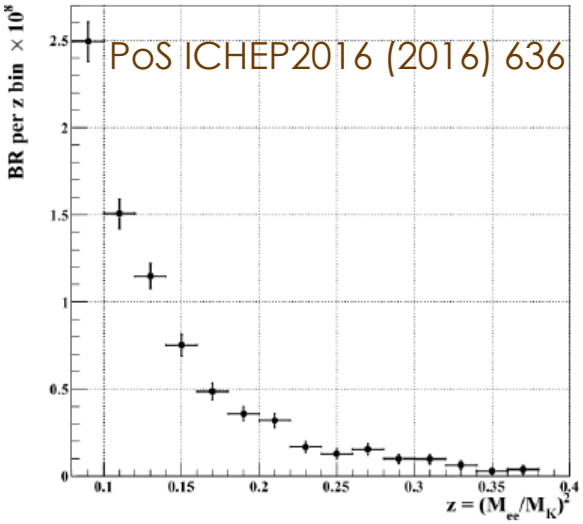
$$\Gamma(K^\pm \to \pi^\pm Z_d)|_\varepsilon = \frac{\varepsilon^2 \alpha W^2 m_{Z_d}^2}{2^{10}\pi^4 m_K^7} \sqrt{\lambda(m_K^2, m_\pi^2, m_{Z_d}^2)} \times [(m_K^2 - m_\pi^2)^2 - m_{Z_d}^2(2m_K^2 + 2m_\pi^2 - m_{Z_d}^2)],$$

Depending on how the model is built the limit can change significantly for example allowing the mass mixing with SM Z.

NA48/2 $K^{\pm}\to\mu^{\pm}\nu e^{+}e^{-}$ decay

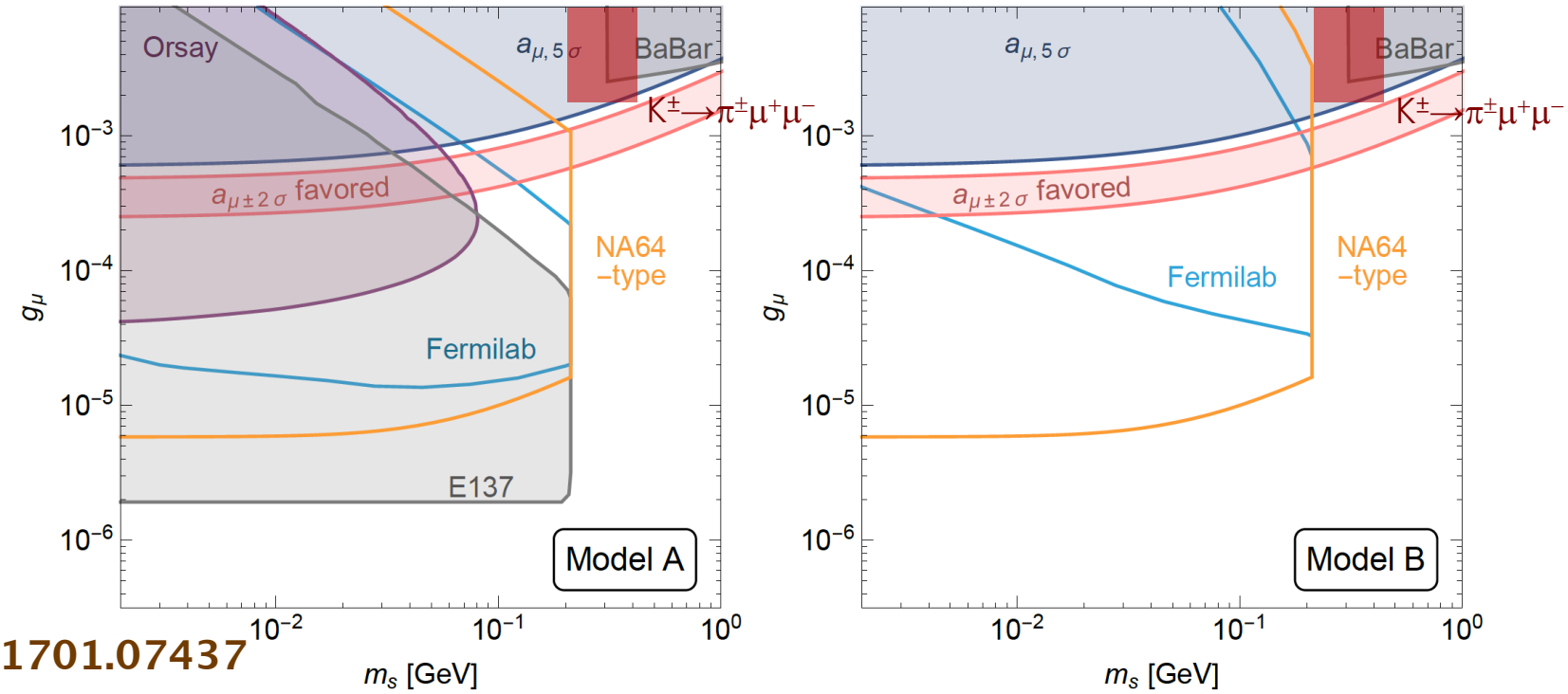






- Can exchange the radiated γ^* with A' decaying in e^+e^-
  - $K^{\pm}\to\mu^{\pm}\nu A'$ with $A'\to e^+e^-$
  - Mee spectrum can be searched for Mee resonance (in progress)
  - Measured limits on BR($M_{A'}$)10^{-8}-10^{-9} range
  - No need for coupling to electrons! Can explore A' coupling to only μ models!
- Can exchange the radiated γ^* with scalar ϕ decaying in e^+e^-
  - Enhanced expected wrt by the coupling to m_μ^2
  - Batell,Lange, McKeen,Pospelov, Ritz ArXiv 1606.04943v1
- Measurement ongoing in NA48/2: PoS ICHEP2016 (2016) 636

Muon dominated couplings?



arXiv:1701.07437

Model A: Mass proportionality, $g_\ell \propto m_\ell$. In particular, it implies that the couplings between the scalar S and electrons are 200 times smaller than those with muons. Despite this, the dominant decay channel for S below the di-muon threshold is S e+e-.

Model B: Coupling exclusively to muons, $g_\mu > 0$ and $g_e = g_\tau = 0$.

$K^{\pm}\to\pi^{\pm}\mu^{+}\mu^{-}$ needs quark related production mechanism.

$K^{\pm}\to\mu^{\pm}\nu\mu^{+}\mu^{-}$ is also very interesting in this scenario pure muon coupling!

Recent results on dark sector search

- Search for Heavy Neutrinos in $K^+ \to \mu^+ \nu$ Decays.
  - ArXiv 1705.07510v1 **NA62**
  - Can be recast as $K^+ \to \mu^+ \nu A'$ with $A' \to \chi\chi$
- Searches for lepton number violation and resonances in $K^\pm \to \pi^\pm \mu^+ \mu^-$ decays
  - Phys.Lett. B769 (2017) 67-76 **NA48/2**
  - Can be recast as $K^+ \to \pi^+ A'$ with $A' \to \mu^+ \mu^-$
- Model independent measurement of the leptonic kaon decay $K^\pm \to \mu^\pm \nu e^+ e^-$ with the NA48/2 experiment
  - PoS ICHEP2016 (2016) 636 **NA48/2**
  - Can be recast as $K^+ \to \mu^+ \nu A'$ with $A' \to e^+ e^-$
- Search for the dark photon in π^0 decays
  - Phys.Lett. B746 (2015) 178-185 **NA48/2**

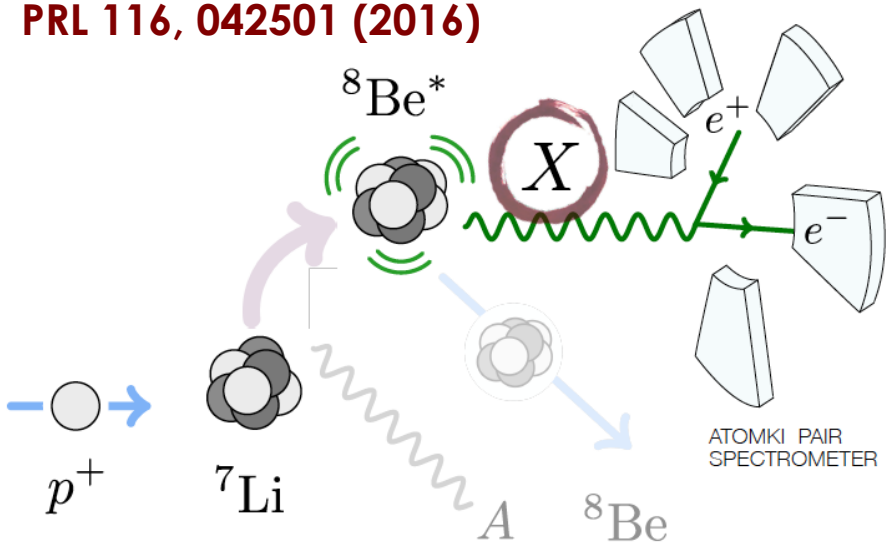
Conclusions

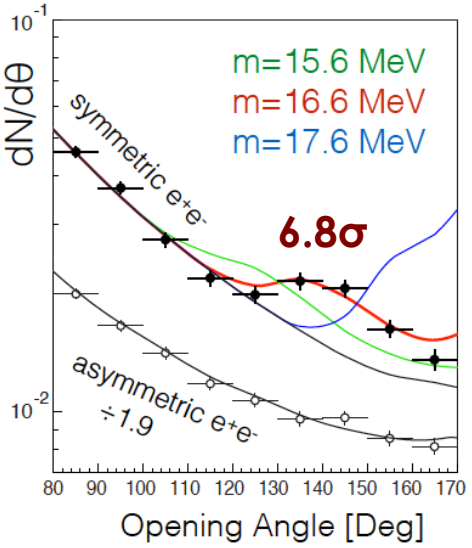
- **NA48/2** set a limit on the A' decays to e^+e^- (PLB746 (2015) 178)
  - Improvement of the existing limits for visible decays in the range 9-70 MeV/c^2.
  - Assuming **kinetic mixing** and dark photon **decaying to lepton pairs only** the whole favored by **(g-2)μ region has been excluded**
- **NA48/2** limit on A' decays to $K^{\pm}\to\pi^{\pm}X$ $X\to\mu^+\mu^-$ (PLB 769 (2017) 67–76)
  - The limit is not competitive as bound on kinetic mixing models
  - Being the only one in the region 210-350 MeV not obtained with electrons can be relevant in non universal coupling models.
- **NA62 is able to investigate dark sector physics in kaon decays**
  - Advanced analysis of $K^{\pm}\to\pi^{\pm}\pi^0$ $\pi^0\to\gamma A'$ $A'\to\chi\chi$ for invisible A' decays
  - Decays of $K^{\pm}\to\pi^{\pm}X$ $X\to\mu^+\mu^-$ and $X\to\chi\chi$
  - Dark sector search in Dump more also very promising (A', ALPs HNL)
  - NA62 implemented a dedicated di-lepton trigger for dark sectors studies!

Kaons are an exiting field to search for dark sectors candidates!

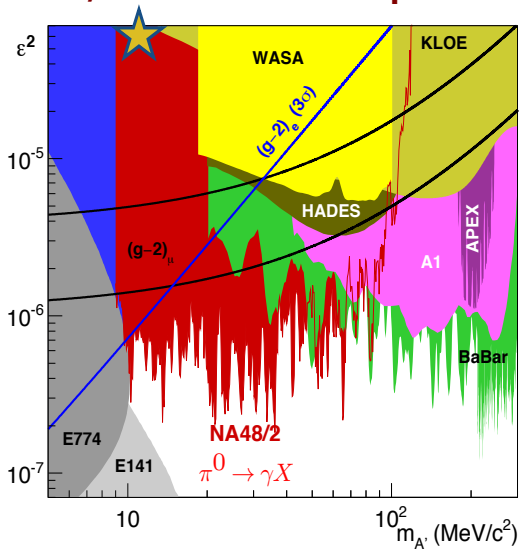
The Be^8 anomaly and the proto-phobic fifth force

PRL 116, 042501 (2016)



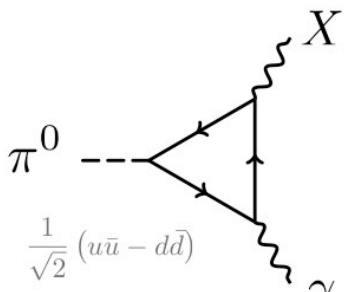


NA48/2 it's not a dark photon!



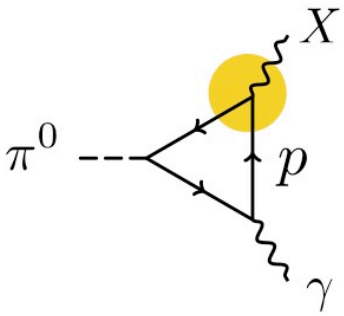
π⁰-phobia = p^+-phobia

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