Dark Photon Search with NA48/2 and NA62 Experiments at CERN

Gia Khoriauli

JOHANNES GUTENBERG UNIVERSITÄT MAINZ   JG|U

Flavour and Dark Matter
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Content

❑ Theoretical framework of dark photon searches

❑ NA48/2 and NA62 experiments at CERN

❑ NA48/2 searches of dark photon, A'/X   *(published)*

◆ $\pi^0 \rightarrow \gamma A'$ and $A' \rightarrow e^+e^-$

   o $\pi^0 \rightarrow \gamma e^+e^-$ events selected from $K^\pm \rightarrow \pi^\pm \pi^0$ and $K^\pm \rightarrow \pi^0 \mu^\pm \nu$

◆ $K^\pm \rightarrow \pi^\pm X$ and $X \rightarrow \mu^+\mu^-$

❑ NA62 searches of dark photon, on-going studies

◆ Long-lived $A' \rightarrow \mu^+\mu^-$, data taking in beam dump mode

◆ $\pi^0 \rightarrow \gamma A'$ and $A' \rightarrow \chi\chi$ (invisible)

❑ Summary

Theory Framework

☐ Assume an extra U(1) gauge symmetry connected with the SM U(1) via kinetic mixing of their gauge fields

◆ The extra U(1) gauge boson, A' or dark photon, has a mass

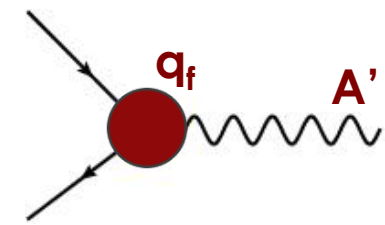◆ ε – mixing and $m_{A'}$ – mass are the theory free parameters

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

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

☐ Dark photon can couple with the SM fermions

◆ q_f – are shifts of electromagnetic charges and not necessarily the same for all SM fermions

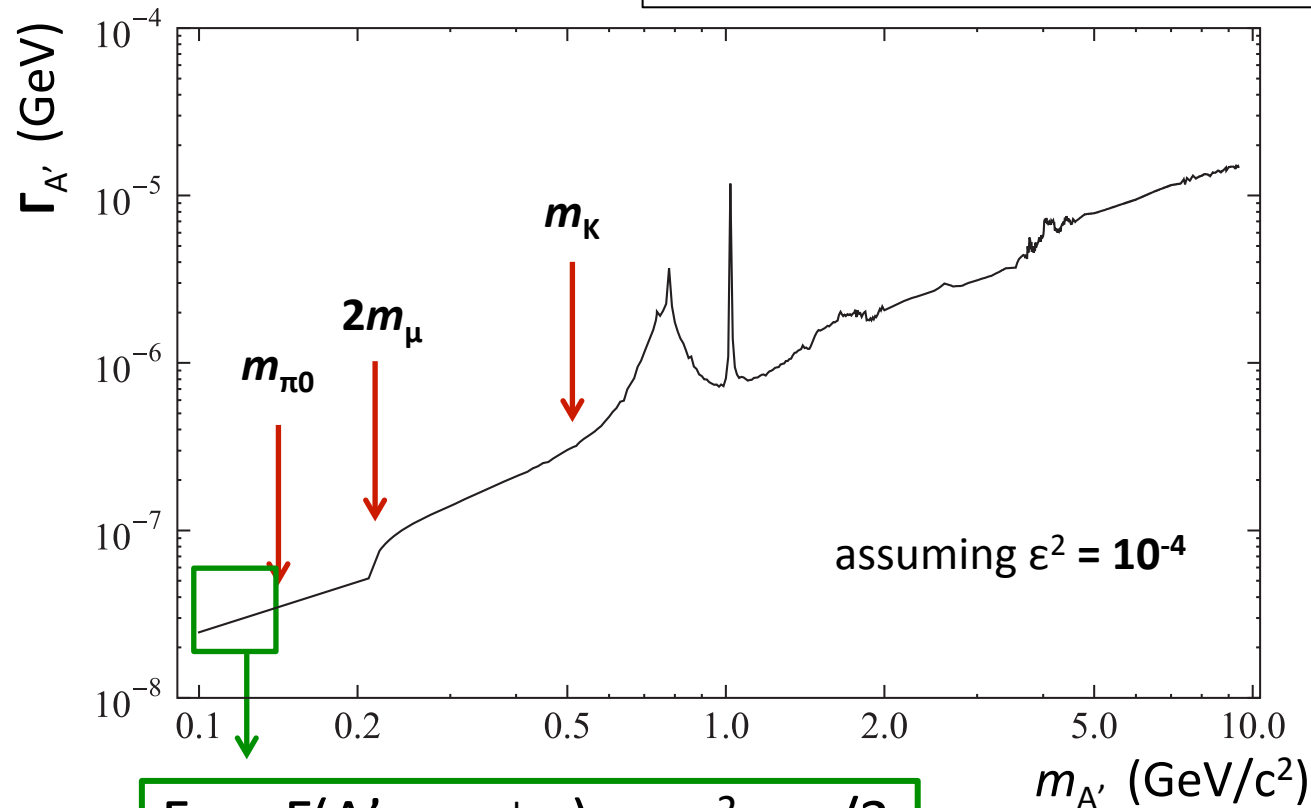$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

t. B 675 (2009) 267

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

Theory Framework

❑ Assume dark photon (DP) decays only into SM fermions

◆ DP decays only into an electron pair if $m_{A'} < m_{\pi 0}$
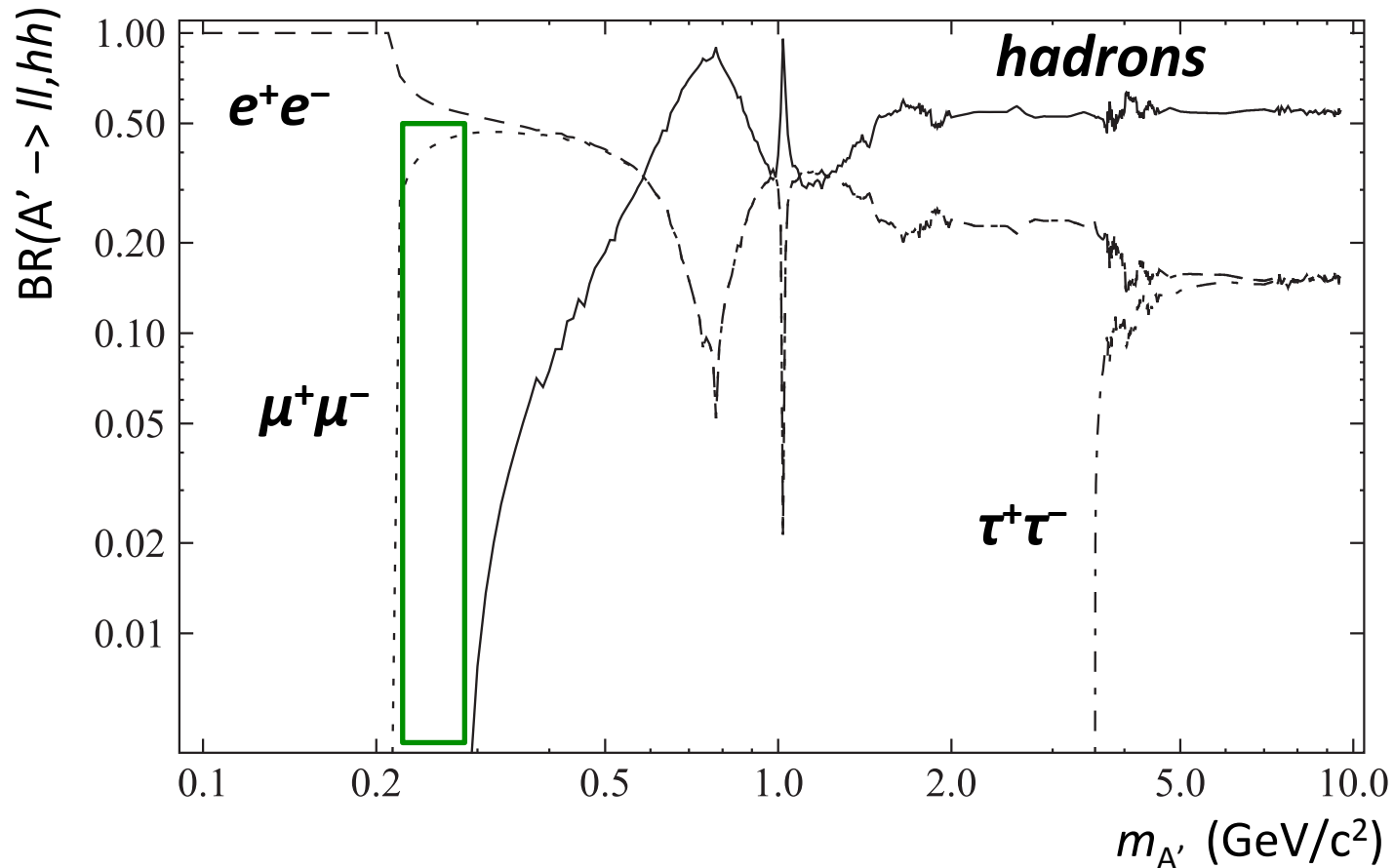
Batell, Pospelov and Ritz, PRD 79 (2009) 115008

assuming $\varepsilon^2 = 10^{-4}$

$\Gamma_{A'} \approx \Gamma(A' \to e^+ e^-) \approx \alpha \varepsilon^2 m_{A'} / 3$
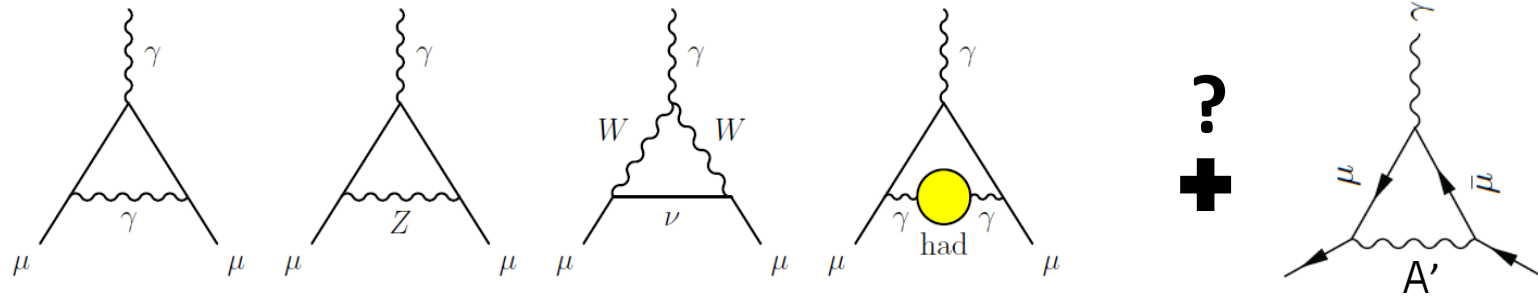
Theory Framework

❑ Assume dark photon (DP) decays only into SM fermions

◆ Region for DP search in $\mu^+\mu^-$ channel: $2m_\mu < m_{A'} < 2m_{\pi0}$

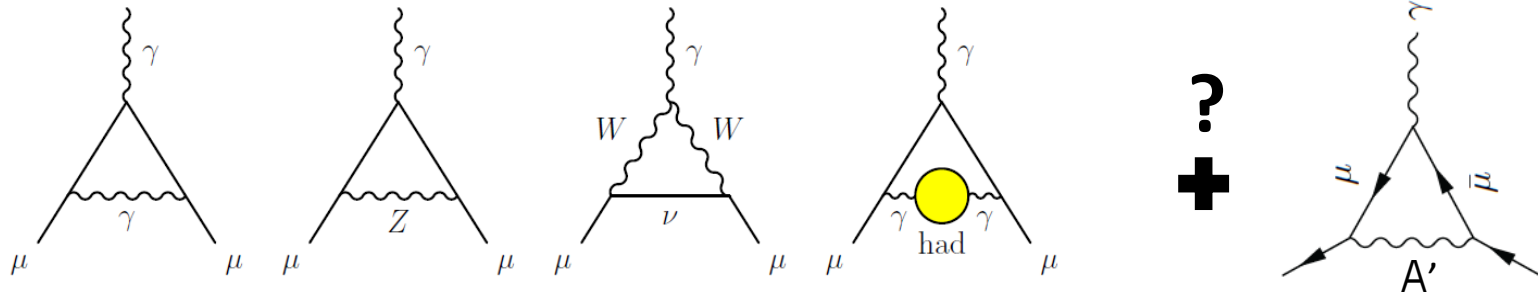*Batell, Pospelov and Ritz, PRD 79 (2009) 115008*

Theory Motivation

☐ Dark photon as a possible explanation of the **g-2** puzzle

$\times 10^{-11}$

DP mass in sub GeV range

Theory Motivation

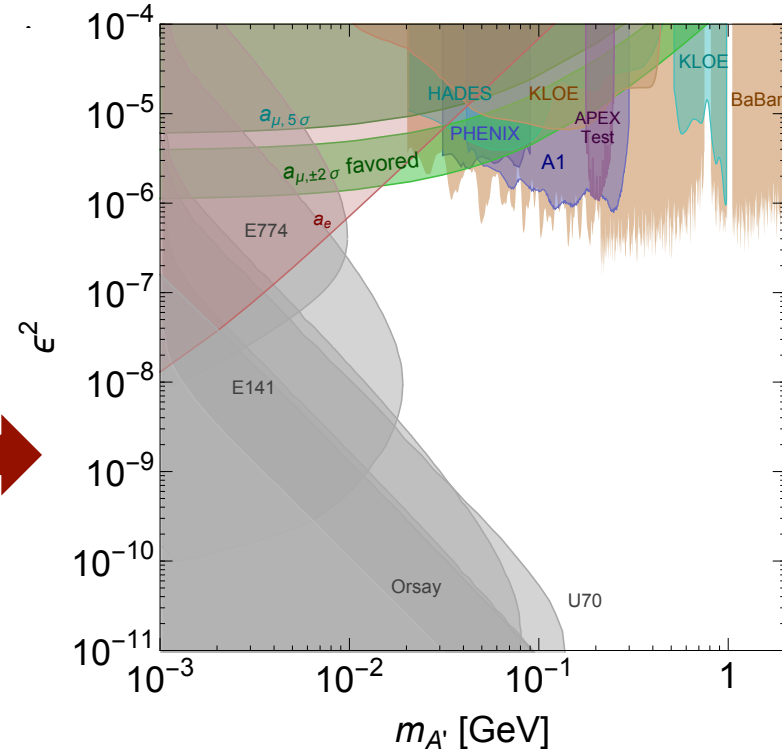☐ Dark photon as a possible explanation of the **g-2** puzzle
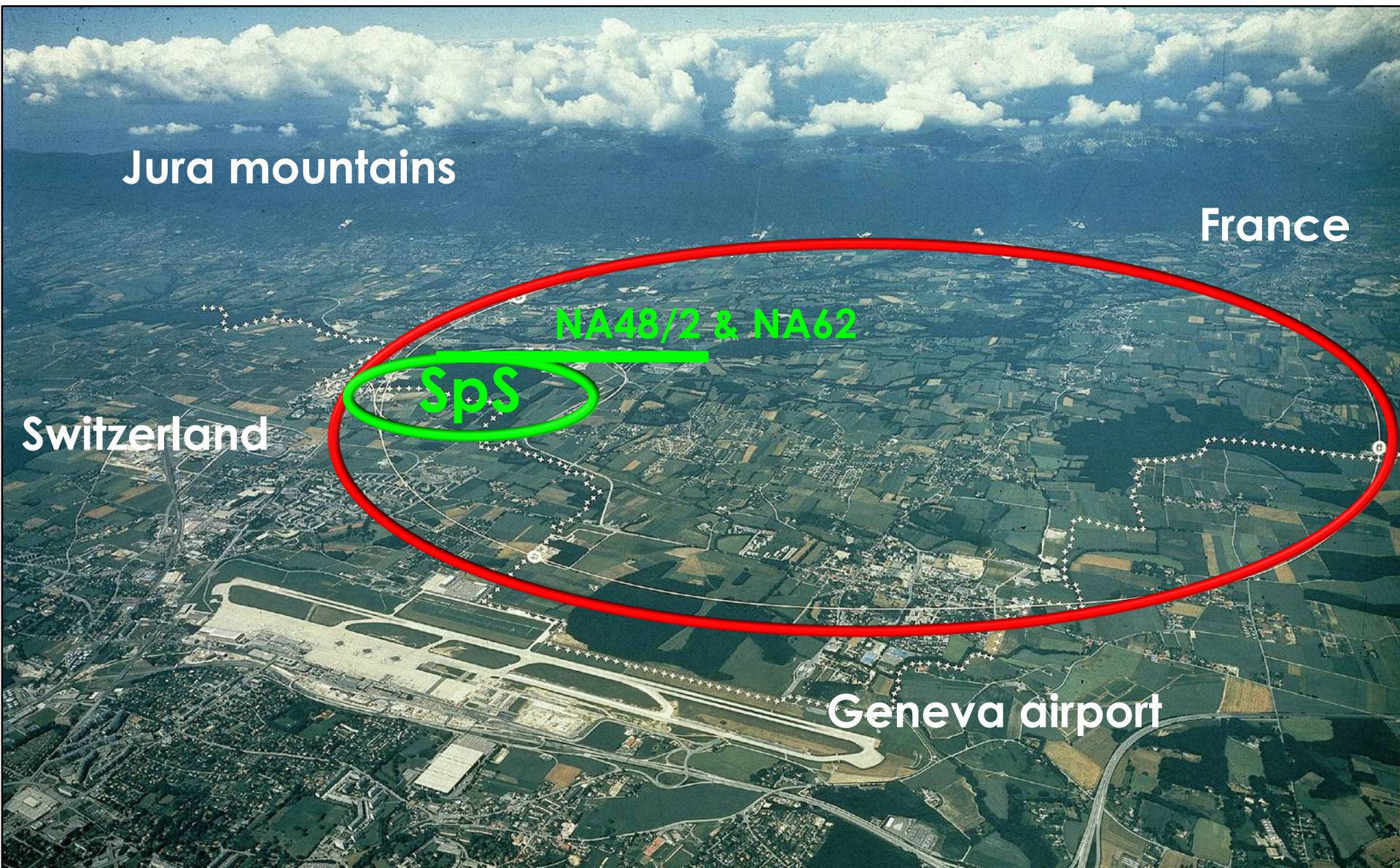

DP mass in sub GeV range

☐ Status of searc...

◆ Favoured ε and
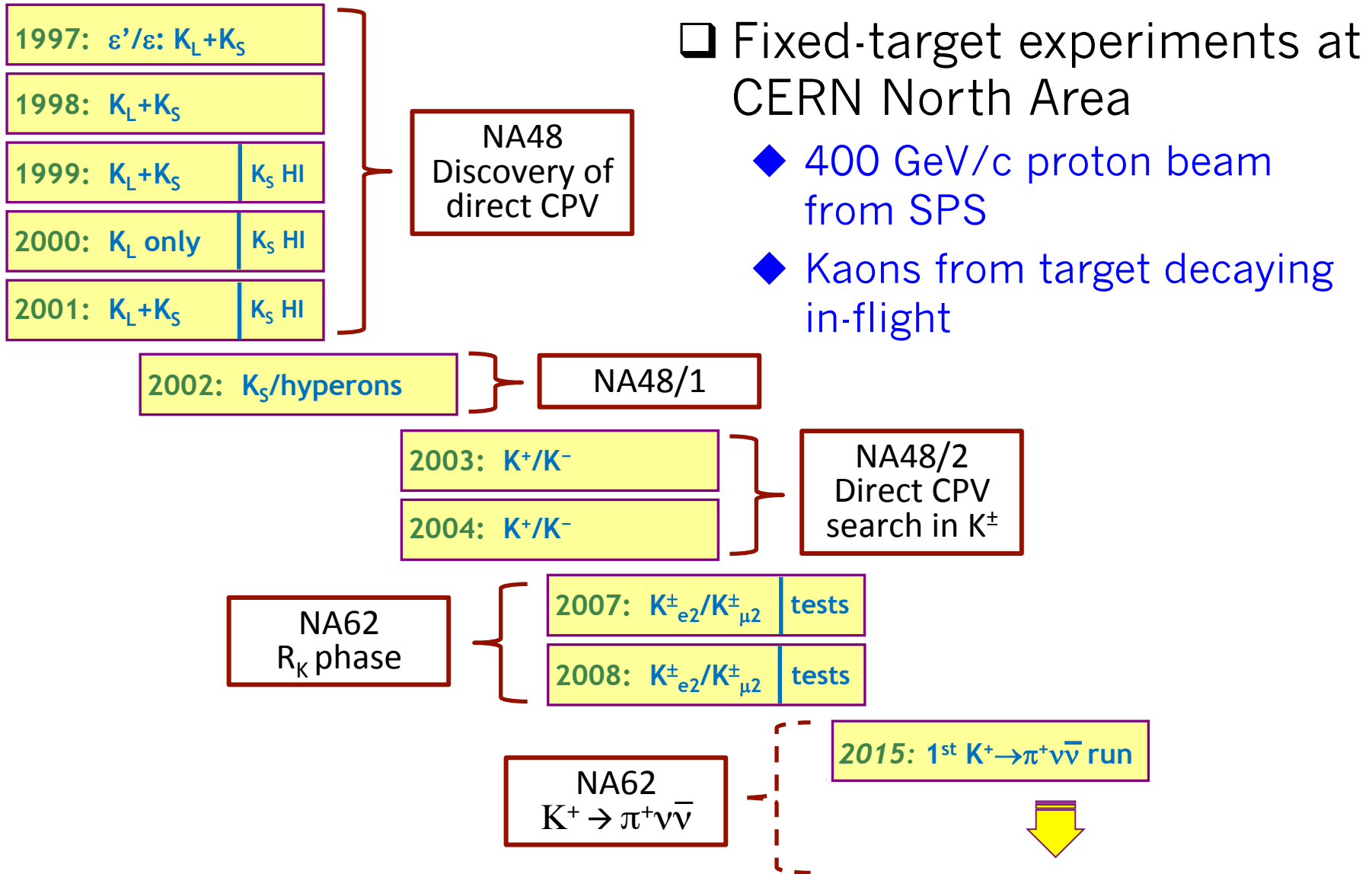(green band)

◆ Still not ruled

○ ~ 15 – 30 M

NA48/2 & NA62 Experiments

Jura mountains

France

NA48/2 & NA62

SpS

Switzerland

Geneva airport

NA48/2 & NA62 Experiments

1997: ε'/ε: 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

2002: K_S/hyperons

NA48/1

2003: K^+/K^-

2004: K^+/K^-

NA48/2 Direct CPV search in $K^\pm$

2007: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests

2008: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests

NA62 R_K phase

2015: 1st $K^+\rightarrow\pi^+\nu\bar{\nu}$ run

NA62 $K^+ \rightarrow \pi^+\nu\bar{\nu}$

❑ Fixed-target experiments at CERN North Area

◆ 400 GeV/c proton beam from SPS

◆ Kaons from target decaying in-flight

NA48/2 Detector and Beam

❑ Simultaneous K$^\pm$ beam

  ◆ p_K=60 GeV/c

  ◆ $\Delta p_K/p_K$=4%

  ◆ Total K$^\pm$ decays: ~10^{11}

  ◆ Main triggers:

    ○ Three-tracks

    ○ K$^\pm$ → π$^\pm$π^{0}π^0

Muon veto sytem

Hadron calorimeter

Liquid krypton calorimeter

Hodoscope

Drift chamber 4
Anti counter 7

Helium tank

Drift chamber 3

Magnet

Drift chamber 2
Anti counter 6

Drift chamber 1

Kevlar window
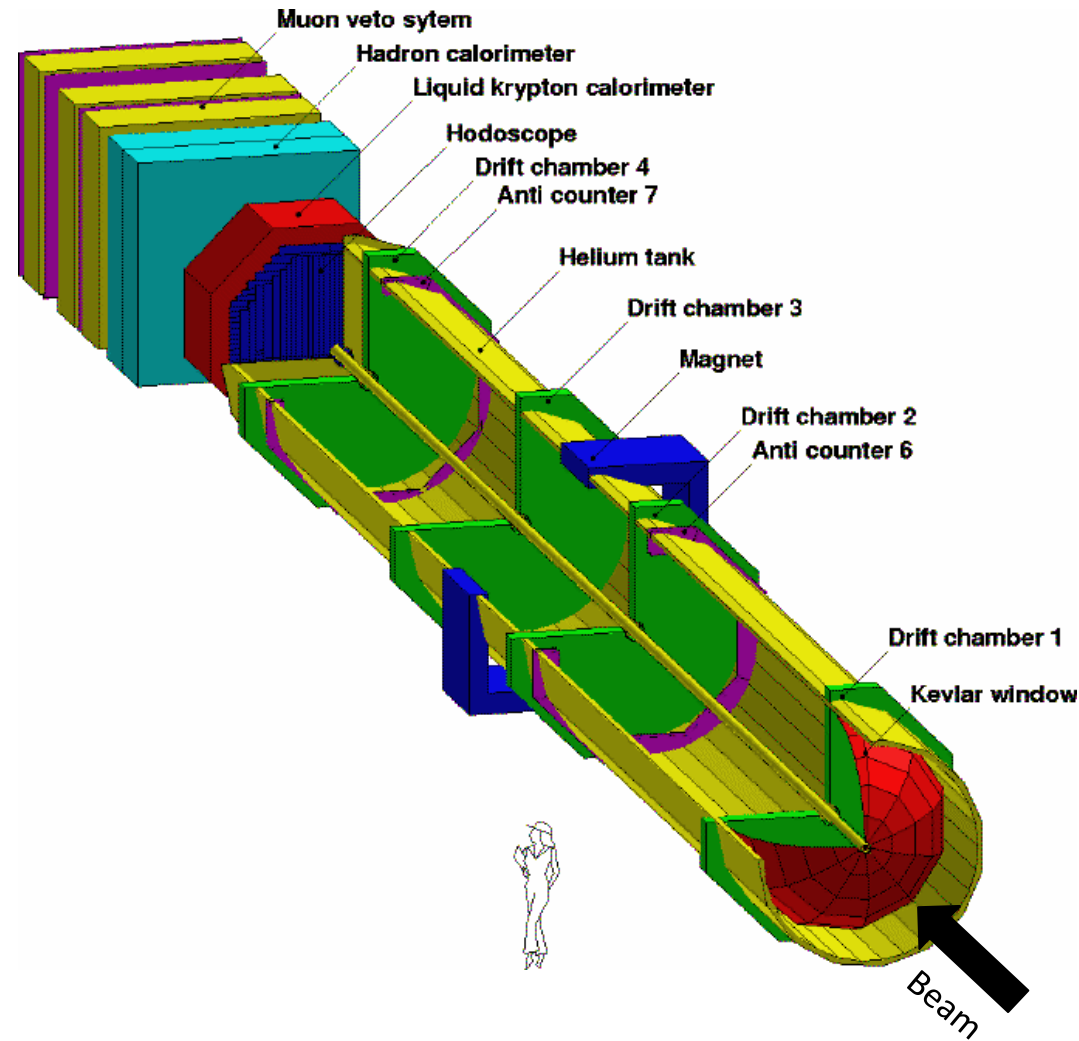
Beam

NA48/2 Detector and Beam

❑ Simultaneous K$^\pm$ beam

   ◆ p_K=60 GeV/c

   ◆ $\Delta p_K/p_K$=4%

   ◆ Total K$^\pm$ decays: ~10^{11}

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     ○ Three-tracks

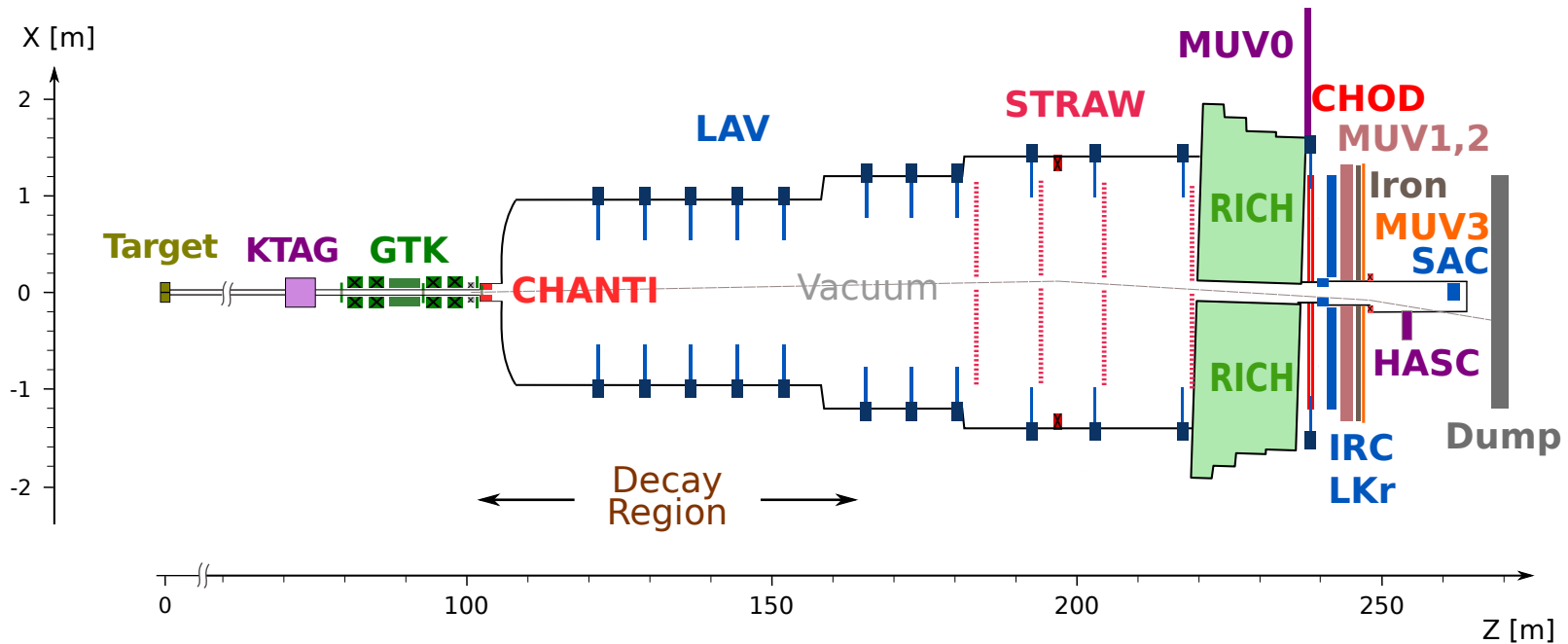   ○ K$^\pm$ → $\pi^\pm \pi^0 \pi^0$
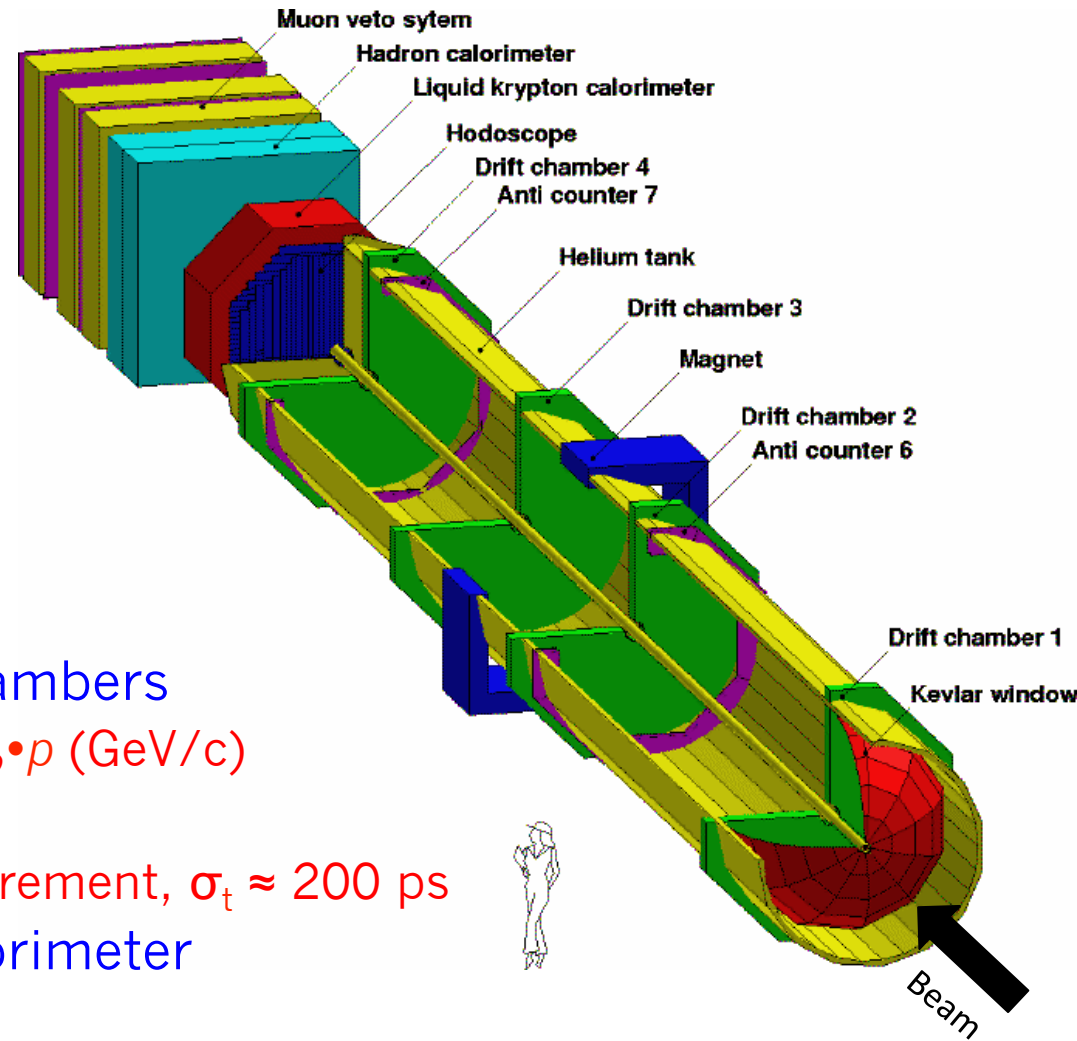
❑ Major sub-detectors

   ◆ Spectrometer, 4 drift chambers

     ○ σ_p/p = 1.02% + 0.044%•p (GeV/c)

   ◆ Scintillator hodoscope

     ○ Fast trigger, time measurement, σ_t ≈ 200 ps

   ◆ LKr electromagnetic calorimeter

     ○ σ_E/E = 1.4% @ 10 GeV

     ○ σ_x = σ_y = 1.5mm @ 10 GeV

Muon veto sytem
Hadron calorimeter
Liquid krypton calorimeter
Hodoscope
Drift chamber 4
Anti counter 7
Helium tank
Drift chamber 3
Magnet
Drift chamber 2
Anti counter 6
Drift chamber 1
Kevlar window
Beam

NA62 Detector and Beam

□ K⁺ beam

- ◆ 6% of the secondary beam
- ◆ p_{Kaon} = 75 GeV/c
- ◆ Δp_K = 1 GeV/c (RMS)
- ◆ Total Kaon decays: ~10^{13}
  - o To be recorded by 2018

□ Many new sub-detectors compared to NA48
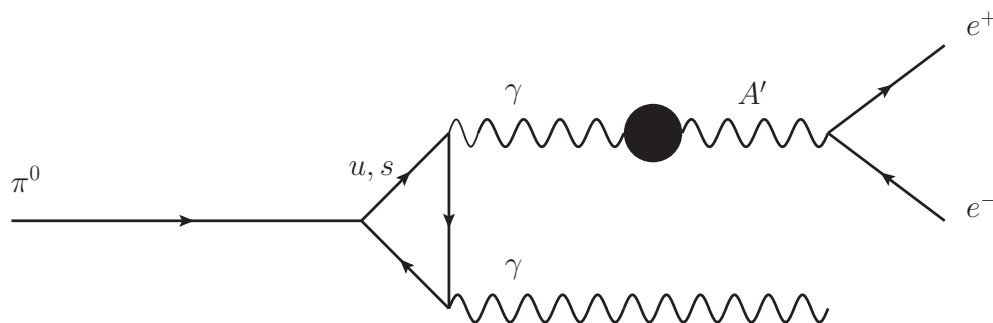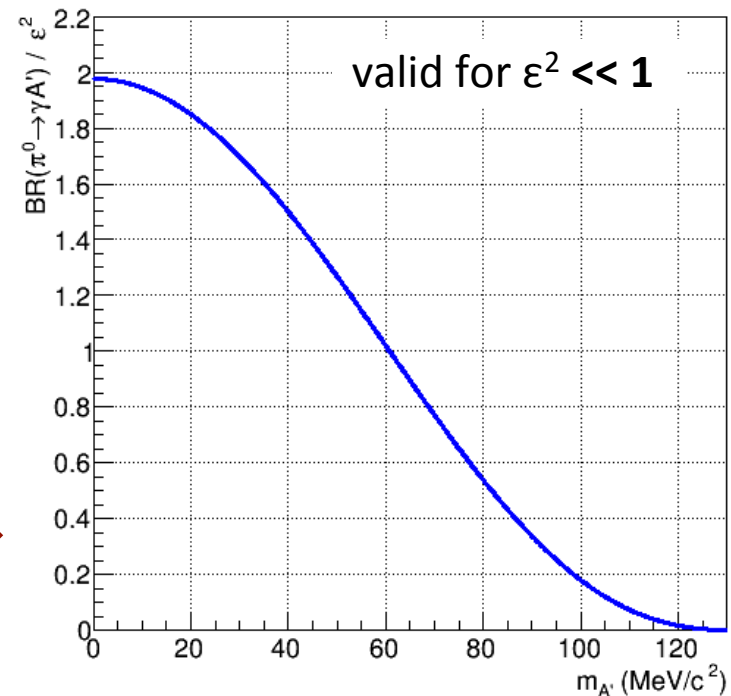
□ Advanced trigger (FPGA based) and data acquisition systems

❑ Assuming the model of coupling only with SM fermions

◆ Only $A' \to e^+e^-$ is allowed for $m_{A'} < m_{\pi^0}$

Batell, Pospelov and Ritz, PRD 79 (2009) 115008

$$\text{BR}(\pi^0 \to \gamma A') \cong 2\varepsilon^2 \left(1 - m_{A'}^2 / m_{\pi 0}^2\right)^3$$

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

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

BR($\pi^0 \to \gamma A'$)/BR($\pi^0 \to \gamma\gamma$) vs $M_{A'}$

valid for $\varepsilon^2 \ll 1$

$2\varepsilon^2$
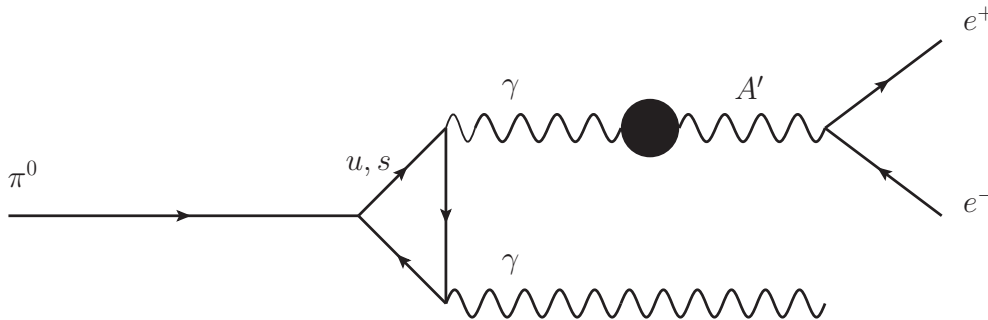
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Batell, Pospelov and Ritz, PRD 79 (2009) 115008

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valid for $\varepsilon^2 \ll 1$

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

❑ Analysis region

◆ 9 MeV/c² < $m_{A'}$ < 120 MeV/c²

No sensitivity for ε in region $m_{A'}$ >120 MeV/c²

NA48/2 Study of $\pi^0 \rightarrow \gamma (A' \rightarrow e^+ e^-)$

❑ DP proper lifetime below the di-muon threshold:

$$c\tau_{A'} = \hbar c / \Gamma_{A'} \approx 0.8 \ \mu\text{m} \times \left(\frac{10^{-6}}{\varepsilon^2} \right) \times \left(\frac{100 \ \text{MeV}/c^2}{m_{A'}} \right)$$

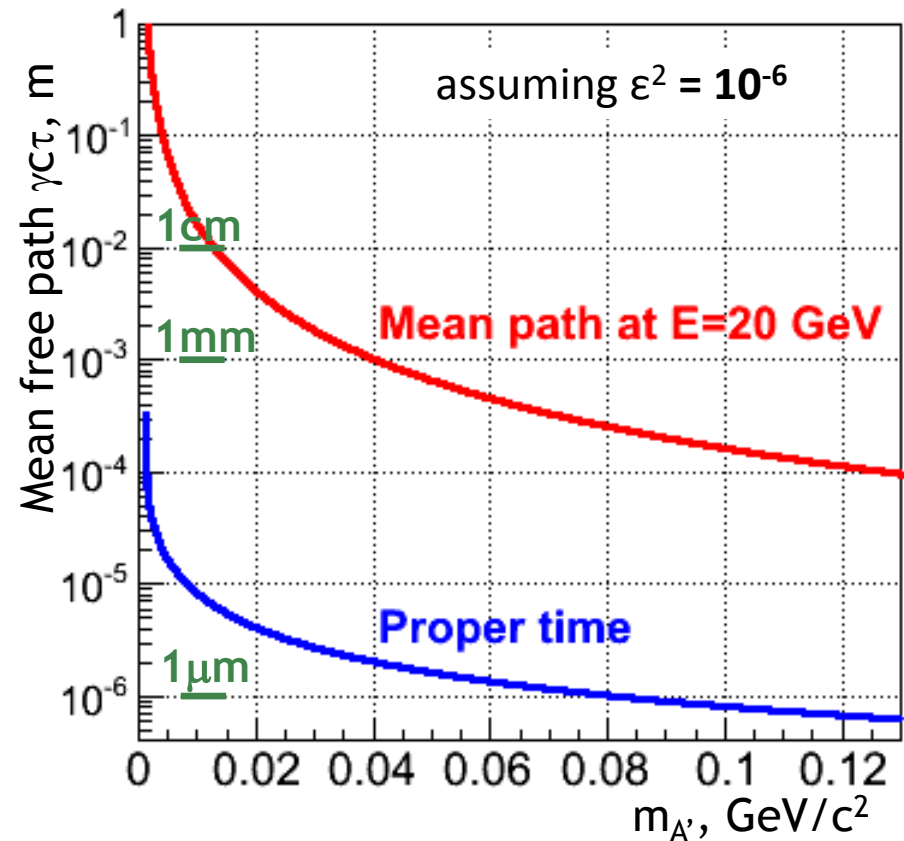❑ $m_{A'} > 10$ MeV/c^2 and $\varepsilon^2 > 10^{-7}$

◆ A' decay length << 1 m (resolution of z-coordinate)

❑ A' prompt decay

◆ Analysis channel has the same signature as π^0 Dalitz decay

○ $\pi^0 \rightarrow \gamma A'$ and $A' \rightarrow e^+ e^-$
○ $\pi^0_D \rightarrow \gamma e^+ e^-$

assuming $\varepsilon^2 = 10^{-6}$

Mean path at E=20 GeV

Proper time

Mean free path $\gamma c \tau$, m

1cm

1mm

1μm

$m_{A'}$, GeV/c^2

NA48/2 Study of $\pi^0 \rightarrow \gamma\,(A' \rightarrow e^+e^-)$

❑ NA48/2 data set: 2×10^{11} Kaon decays

❑ Source decays of π^0: $K^\pm \rightarrow \pi^\pm \pi^0$ (BR=20.7%) and $K^\pm \rightarrow \pi^0 \mu^\pm \nu$ (BR=3.4%)

❑ Signal event selection
- ◆ Three-track topology
- ◆ Search for narrow e^+e^- mass peak
  - ○ Excellent mass resolution: $\sigma_m = 0.067 + 0.0105 \times m_{ee}$
- ◆ Limitation on sensitivity: π^0 Dalitz decay background

❑ Acceptance from 4.5% down to 0.5% depending on $m_{A'}$

❑ Final selection: 1.69×10^7 reconstructed $\pi^0 \rightarrow \gamma\, e^+e^-$ events

NA48/2 Study of $\pi^0 \rightarrow \gamma (A' \rightarrow e^+ e^-)$
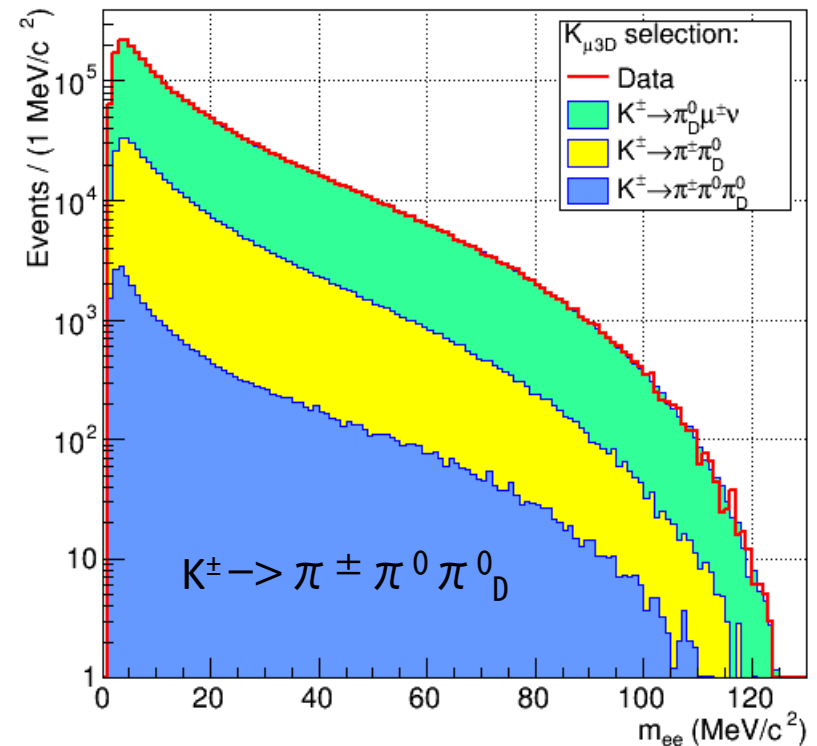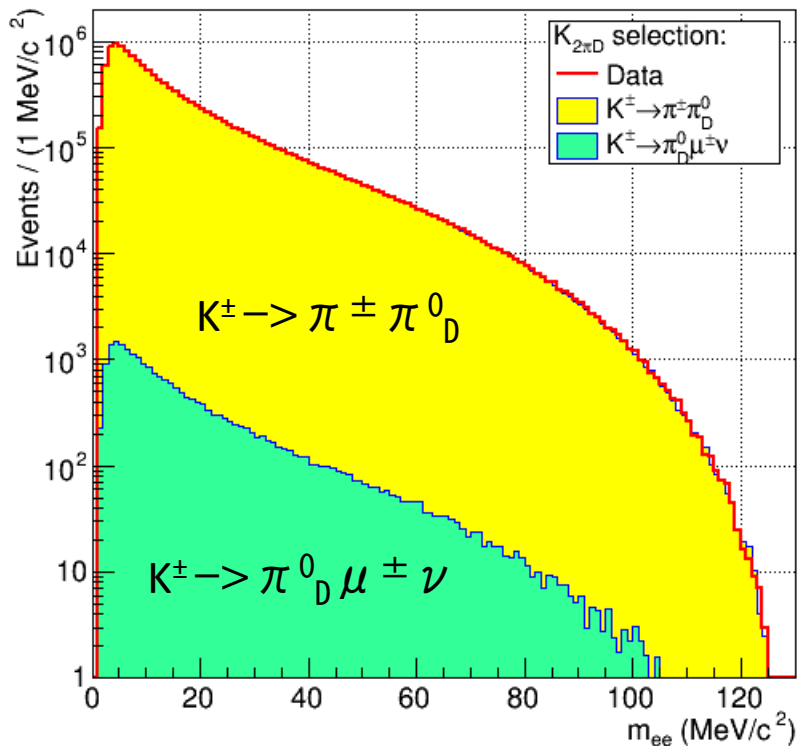
❑ $K^\pm \rightarrow \pi^\pm \pi^0_D$ selection

◆ $|m_{\pi \gamma ee} - m_K| < 20$ MeV/c^2

◆ $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/c^2

◆ No missing momentum

◆ 1.38×10^7 events selected
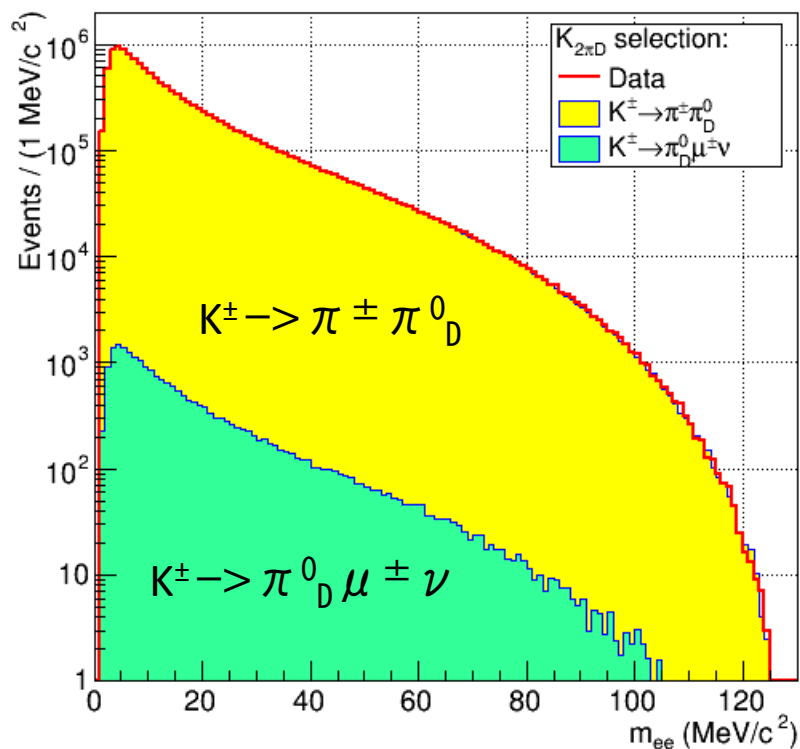
NA48/2 Study of $\pi^0 \to \gamma (A' \to e^+ e^-)$

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- ◆ $|m_{\pi\gamma ee} - m_K| < 20$ MeV/c^2
- ◆ $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/c^2
- ◆ No missing momentum
- ◆ 1.38×10^7 events selected

❑ $K^\pm \to \pi^0_D \mu^\pm \nu$ selection

- ◆ $m^2_{miss} = (P_K - P_\mu - P_{\pi 0})^2 \approx 0$
- ◆ $|m_{\gamma ee} - m_{\pi 0}| < 8$ MeV/c^2
- ◆ Missing momentum
- ◆ 0.31×10^7 events selected

NA48/2 Study of $\pi^0 \to \gamma(A' \to e^+e^-)$

❑ MC simulation of the π^0 Dalitz decay background

◆ Differential decay width at the lowest order

$$\frac{d^2\Gamma}{dxdy} = \Gamma_0 \frac{\alpha}{\pi} |F(x)|^2 \frac{(1-x)^3}{4x} \left(1 + y^2 + \frac{r^2}{x} \right)$$

$$r = 2m_e/m_{\pi^0} \qquad x = \frac{(Q_1 + Q_2)^2}{m_{\pi^0}^2} = (m_{ee}/m_{\pi^0})^2 \qquad y = \frac{2P(Q_1 - Q_2)}{m_{\pi^0}^2(1-x)}$$

◆ Radiative corrections are applied (no real photon emission)

K.O. Mikaelian and J. Smith, Phys. Rev. **D**5 (1972) 1763

T. Husek, K. Kampf and J. Novotny, arXiv:1504.06178

NA48/2 Study of π⁰ −> γ (A'−>e⁺e⁻)

❏ MC simulation of the π^0 Dalitz decay background

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$$\frac{d^2\Gamma}{dxdy} = \Gamma_0 \frac{\alpha}{\pi} |F(x)|^2 \frac{(1-x)^3}{4x} \left(1 + y^2 + \frac{r^2}{x} \right)$$

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T. Husek, K. Kampf and J. Novotny, arXiv:1504.06178

◆ π^0 transition form-factor (TTF) $F(x) \;=\; 1 + ax$

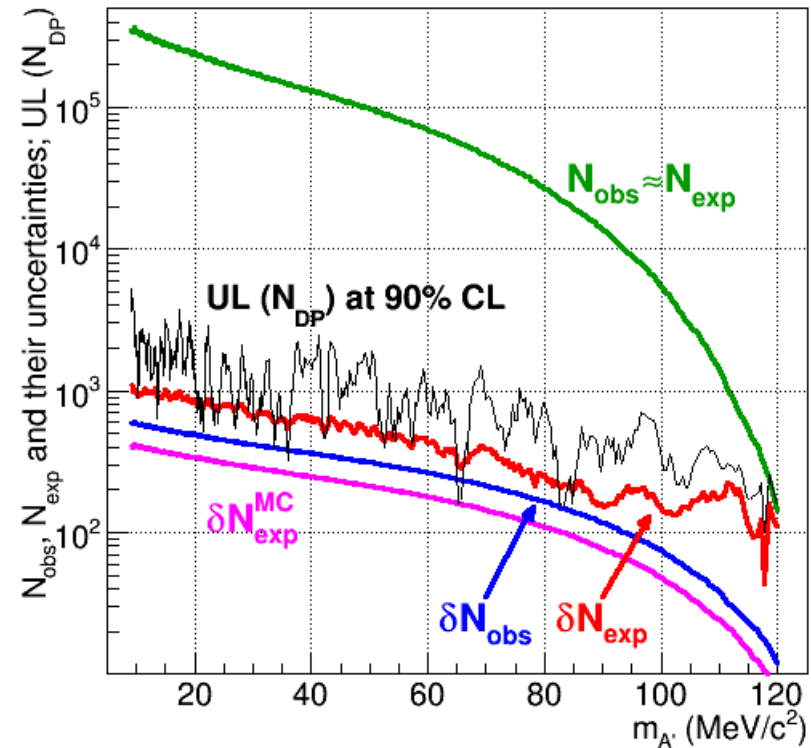◆ TTF slope parameter, a, obtained from the measured m_{ee} spectrum of the π^0 Dalitz decay itself
  ○ Insufficient precision from theoretical calculations or from previous measurements (PDG)

NA48/2 Study of $\pi^0 \to \gamma\,(A' \to e^+e^-)$

❑ DP mass scan in region 9 MeV/c² - 120 MeV/c²

- ◆ Mass window: $\pm 1.5 \times \sigma_m$
- ◆ Mass step: $0.5 \times \sigma_m$
- ◆ Variable $\sigma_m = 0.067 + 0.0105 \times m_{ee}$
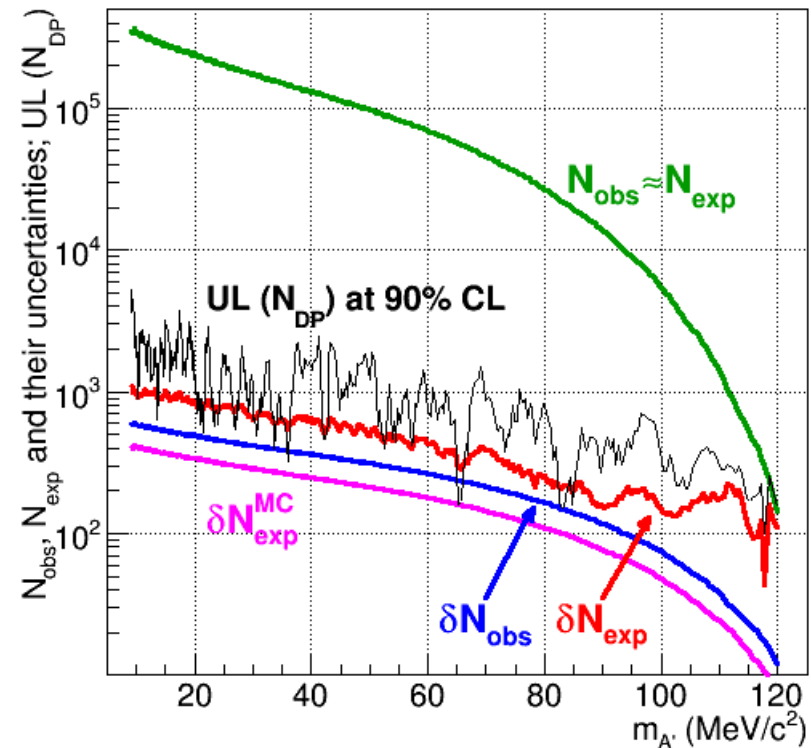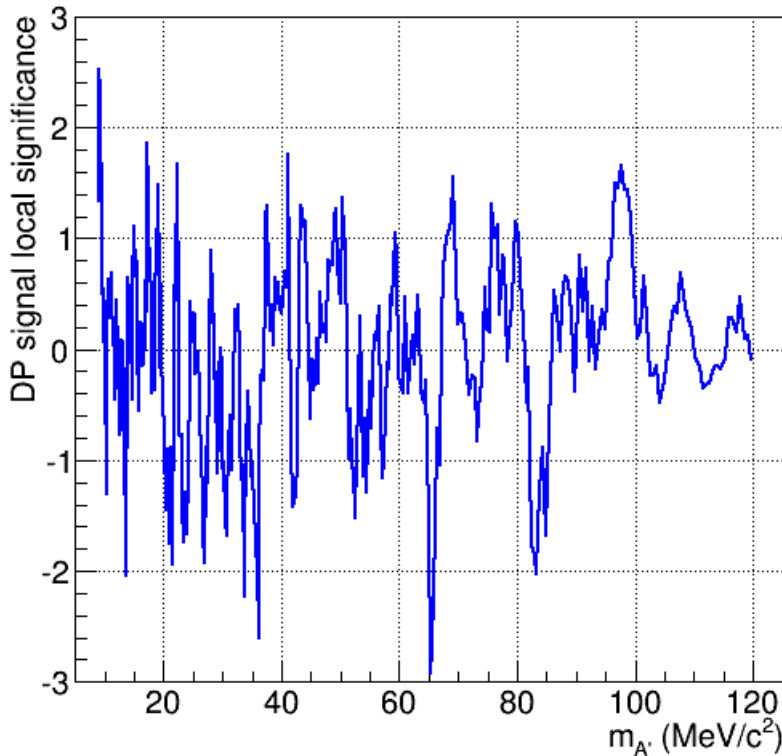- ◆ 404 mass hypothesis in total

NA48/2 Study of $\pi^0 \rightarrow \gamma(A' \rightarrow e^+ e^-)$

□ DP mass scan in region 9 MeV/c^2 - 120 MeV/c^2

- ◆ Mass window: $\pm 1.5 \times \sigma_m$
- ◆ Mass step: $0.5 \times \sigma_m$
- ◆ Variable $\sigma_m = 0.067 + 0.0105 \times m_{ee}$
- ◆ 404 mass hypothesis in total

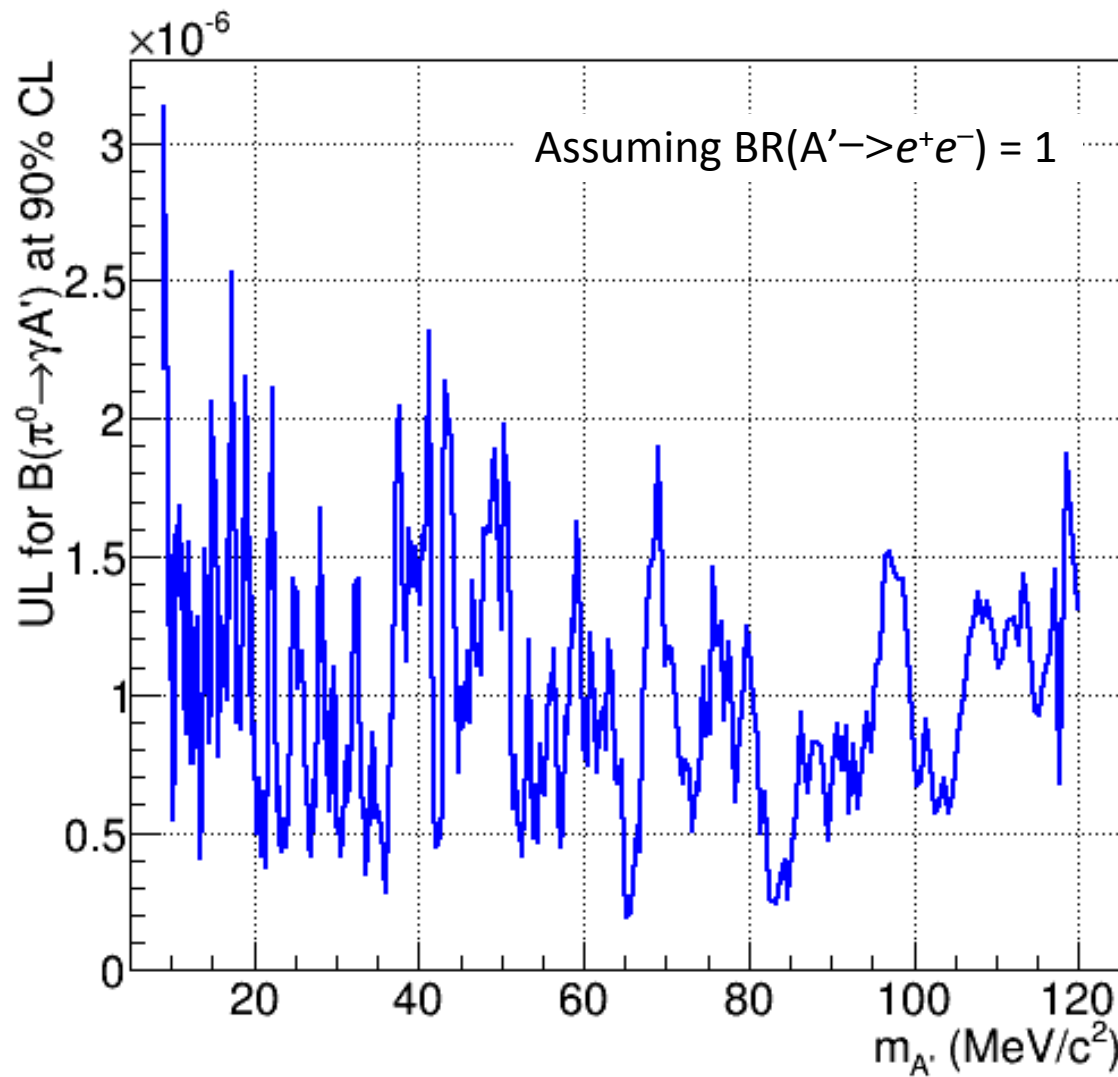□ No >3σ local significant excess, UL(N$_{DP}$), of N$_{obs}$ over N$_{exp}$

- ◆ No dark photon signal

NA48/2 Study of π⁰ –> γ (A'–>e⁺e⁻)

❑ Upper limit on BR($\pi^0 \to \gamma$ A') at 90% CL

Assuming BR(A'–>e^+e^-) = 1

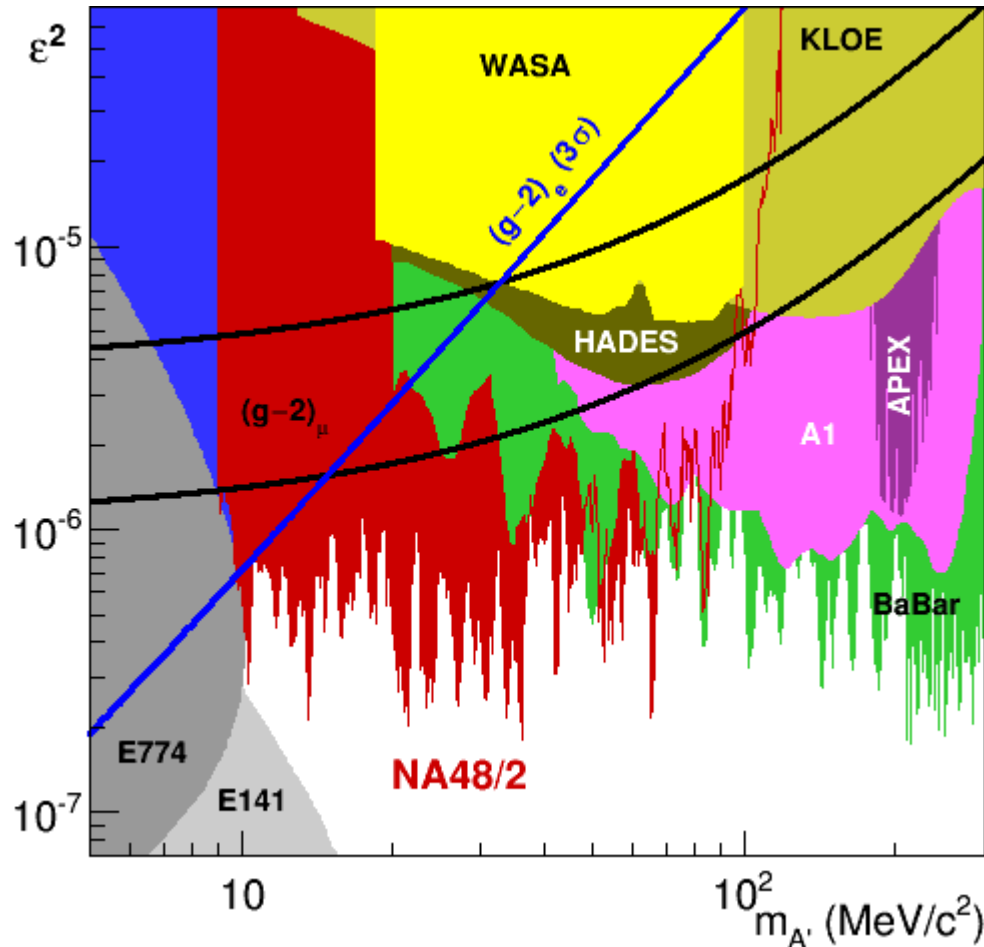# NA48/2 Study of $\pi^0 \to \gamma\,(A' \to e^+e^-)$

□ Final result: exclusion limits on ε and $m_{A'}$

$BR(\pi^0 \to \gamma\,A') \cong 2\varepsilon^2\,(1 - m_{A'}^2/m_{\pi0}^2)^3$

□ Improved limits in region 9 MeV/c^2 < $m_{A'}$ < 70 MeV/c^2

□ **g-2** preferred region completely ruled out

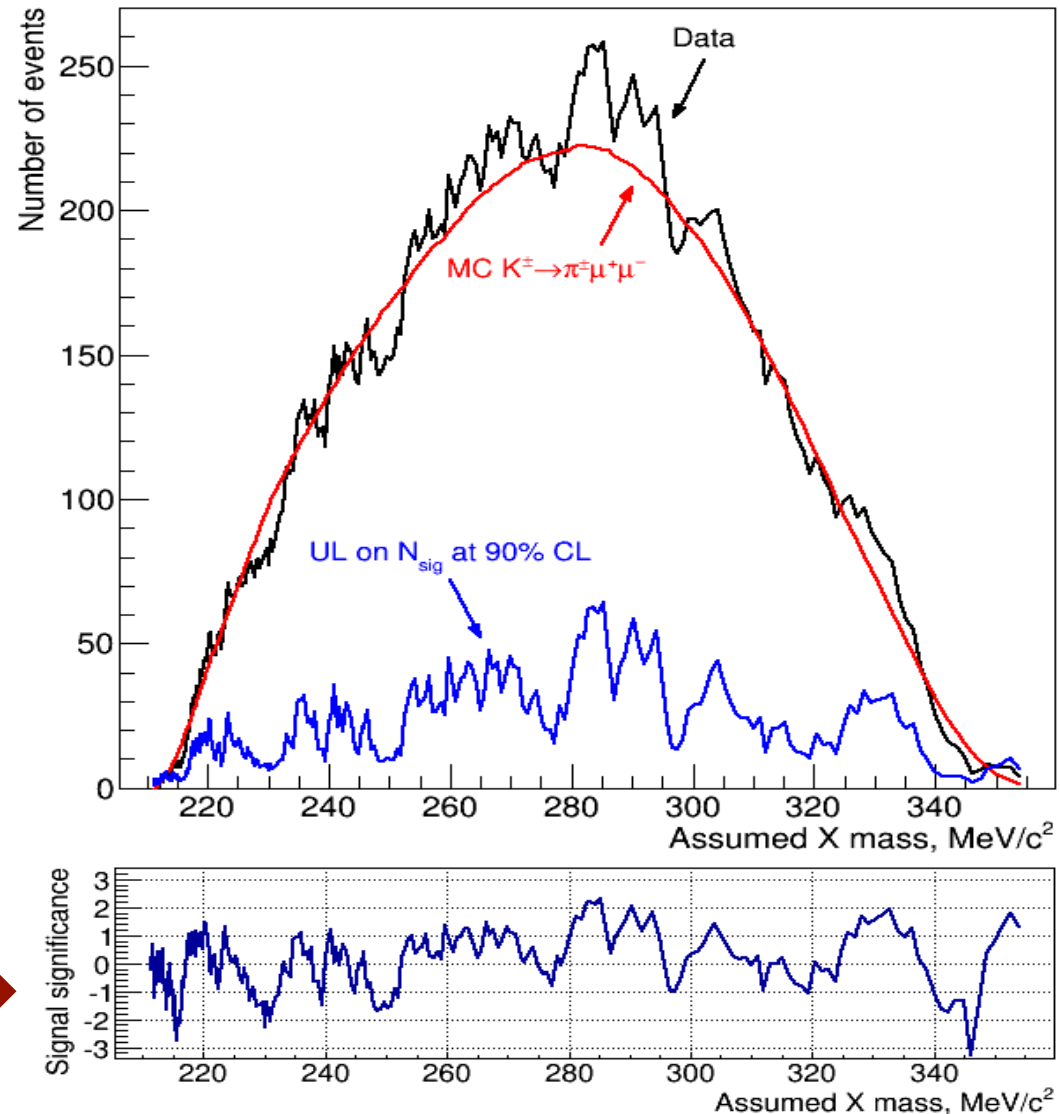   ◆ Under the assumption that A' couples only with SM fermions

The NA48/2 Collaboration, Phys. Lett. B 746 (2015) 178

NA48/2 Study of K⁺−>π⁺μ⁺μ⁻

- ❑ Search for resonances → can be interpreted as decays of dark photon, **X**

  - ◆ $K^{\pm} \rightarrow \pi^{\pm}X$, where $X \rightarrow \mu^{+}\mu^{-}$

  - ◆ Coupling only with the SM fermions

  - ◆ 210 MeV/c² $< m_X < 350$ MeV/c²

- ❑ No significant excess above the expected background events

- ❑ Upper limit on BR(K± –> π±X)BR(X–> µ+µ−) at 90% CL
  - ◆ As a function of m_X and resonance lifetime

- ❑ Different lifetimes of DP assumed

  BR(K–>πA') ≈
  8×10⁻⁵ ε² ($m_{A'}$/100 MeV/c²)²

- ❑ Best limits at τ$_{A'}$ < 10⁻¹¹ s (black curve): ε² >10⁻⁵
  - ◆ Assumed BR(X–> µ+µ−) ~0.5
  - ◆ Not competitive to existing limits
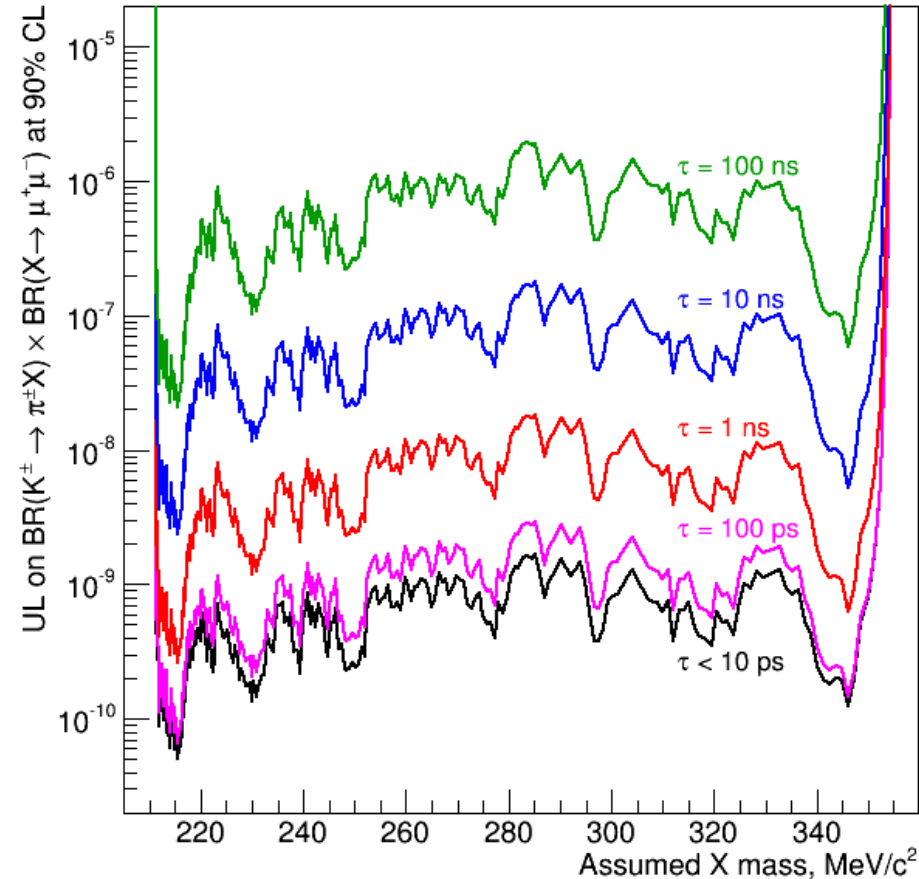
The NA48/2 Collaboration, Phys. Lett. B 769 (2017) 67-76

Dark Photon Visible Decays
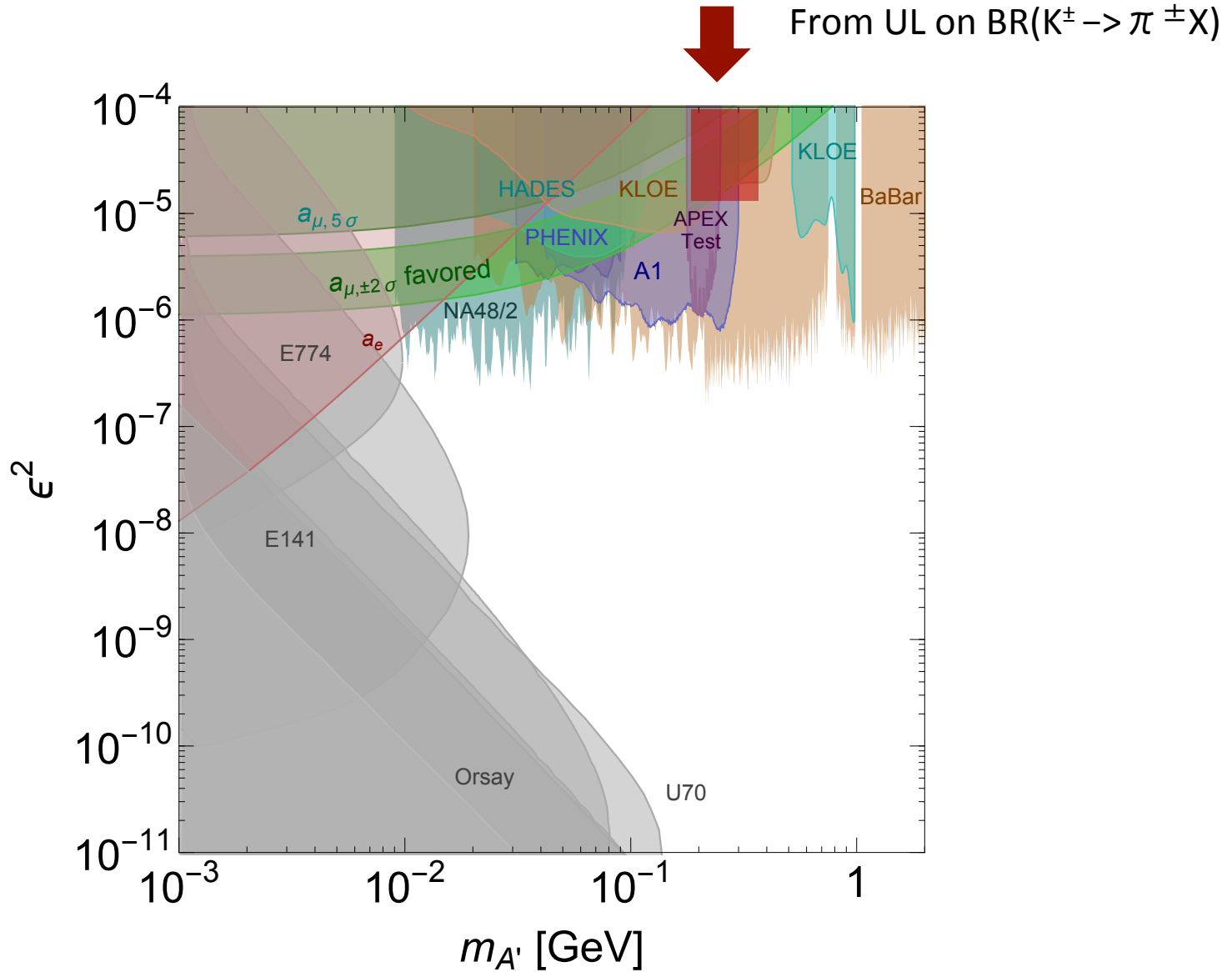
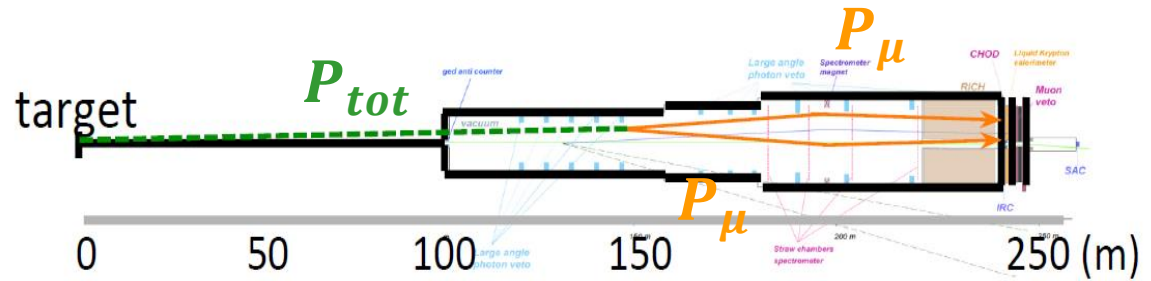From UL on BR($K^\pm \to \pi^\pm X$)

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

$$\dots \frac{m_V}{0 \text{ MeV}} \right)^2 .$$

NA62 Study of Long-lived A'−>µµ

□ Run in proton beam dump mode

◆ No electromagnetic and hadronic background

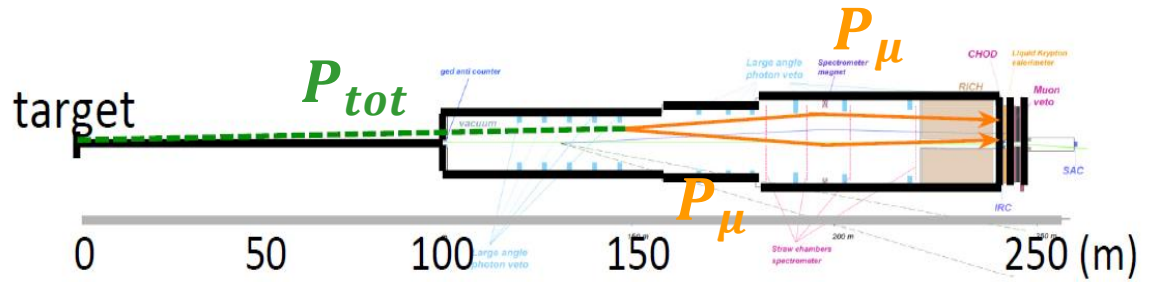□ Long lived A'−> $\mu^+\mu^-$ decays in detector fiducial volume

NA62 Study of Long-lived A'–>µµ

- Run in proton beam dump mode
  - No electromagnetic and hadronic background

P_{tot} — target — P_μ — P_μ

- Long lived A'–>$\mu^+\mu^-$ decays in detector fiducial volume

- Search for di-muon parent particle originated at target
  - Work in progress
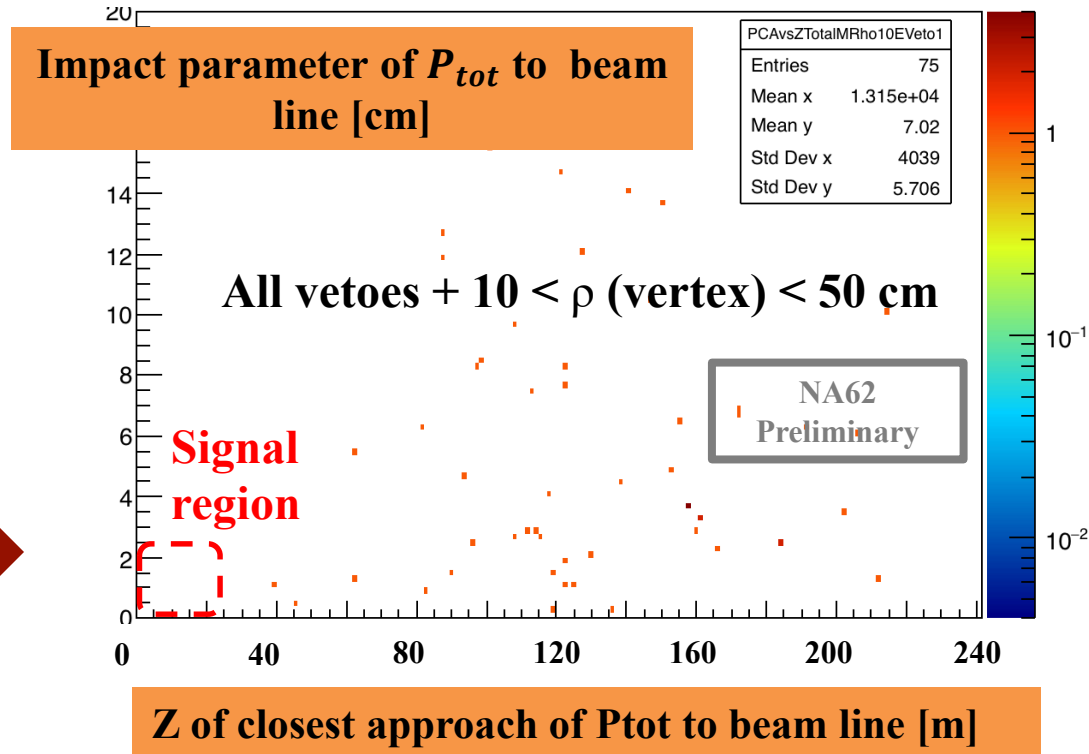
Impact parameter of P_{tot} to beam line [cm]

PCAvsZTotalMRho10EVeto1	
Entries	75
Mean x	1.315e+04
Mean y	7.02
Std Dev x	4039
Std Dev y	5.706

All vetoes + 10 < ρ (vertex) < 50 cm

NA62 Preliminary

Signal region

Z of closest approach of Ptot to beam line [m]

NA62 Study of $\pi^0 \to \gamma \, (A' \to \chi\chi)$

❏ Large sample of $K^+ \to \pi^+ \pi^0$

 ◆ NA62 main trigger: single track, no photons

 ◆ Search for decay chain: $\pi^0 \to \gamma A'$ and $A' \to \chi\chi$ (invisible)

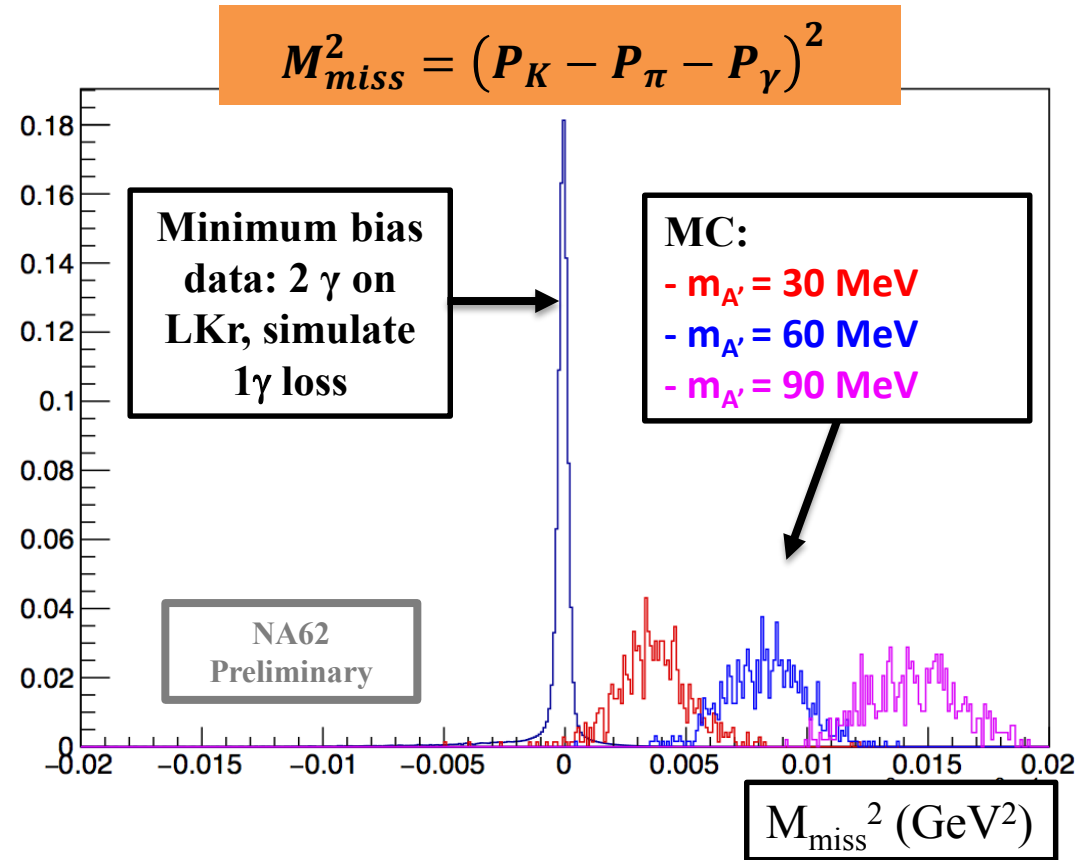# NA62 Study of $\pi^0 \to \gamma\,(A' \to \chi\chi)$

- ❑ Large sample of $K^+ \to \pi^+ \pi^0$
  - ◆ NA62 main trigger: single track, no photons
  - ◆ Search for decay chain: $\pi^0 \to \gamma A'$ and $A' \to \chi\chi$ (invisible)

- ❑ Signal event topology
  - ◆ Single π^+ track
  - ◆ Single photon
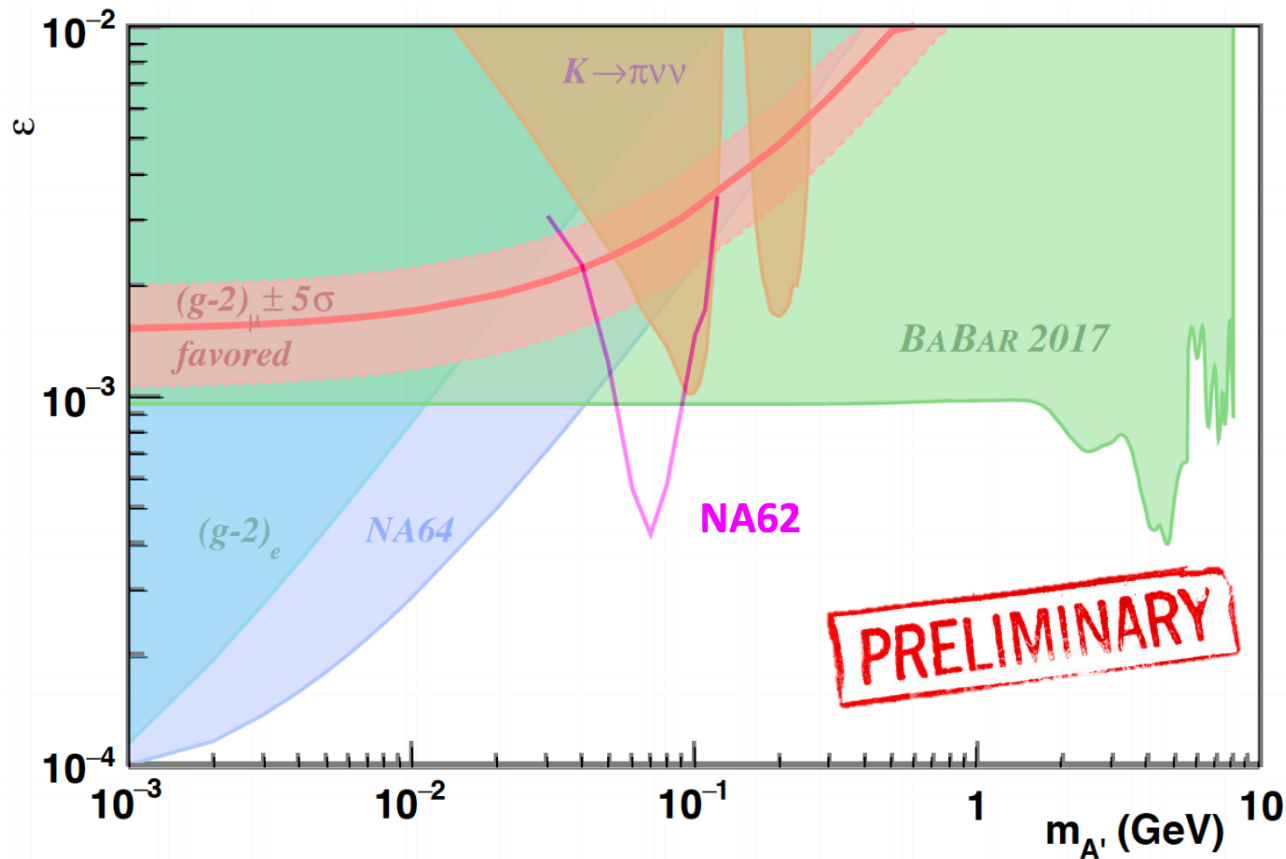 - ◆ Missing energy and momentum
    - ○ $M_{miss}^2 (m_{A'})$

- ❑ Excellent energy and momentum resolution of NA62 detector

$$M_{miss}^2 = (P_K - P_\pi - P_\gamma)^2$$

Minimum bias data: 2 γ on LKr, simulate 1γ loss

MC:
- $m_{A'}$ = 30 MeV
- $m_{A'}$ = 60 MeV
- $m_{A'}$ = 90 MeV

NA62 Preliminary

M_{miss}^2 (GeV^2)

NA62 Study of $\pi^0 \to \gamma\,(A' \to \chi\chi)$

❑ Improved limits at 90% CL (preliminary)

◆ DP mass range: ~ 50 MeV/c^2 < $m_{A'}$ < 90 MeV/c^2

◆ Data used: 1.5×10^{10} K$^+$ decays (6.5% of 2016 sample)

Summary

❑ Extra U(1) gauge symmetry and its gauge boson with non-zero mass: dark photon (**DP**)

 ◆ Kinetic mixing with the SM photon

 ◆ Coupling with SM fermions (visible) or/and possible new particles (invisible), mediator with dark sector

❑ NA48/2 and NA62: factories of large samples of charged Kaon decays for competitive **DP** searches

❑ NA48/2 analysis of **DP** decay into e^+e^- pair: improved limits finally ruled out **g-2** preferred parameter region

 ◆ Assumption: dark photon couples only with the visible matter

❑ NA62 on-going searches for **DP** in K^+ beam/dump mode