Search for invisible dark photon at NA62

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on behalf of the NA62 collaboration

Hidden sector searches: motivations

If DM is a thermal relic from hot early universe, can hunt for it in particle-physics:

search for non-gravitational interactions DM-SM

Mediators of a hidden sector might exist, inducing DM-SM field **(feeble)** interactions

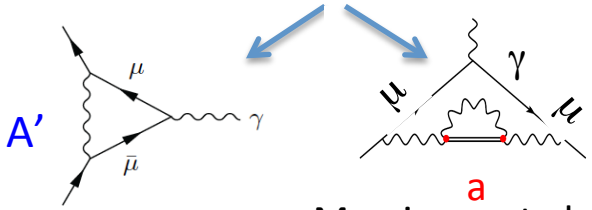
many possible dynamics: vector (A', aka dark photon), neutrino (HNL), axial (ALP, a), Higgs..

Various experimental hints for hidden sector at MeV-GeV: e.g., muon **g-2**

Feeble interaction:

suppressed production rate, long-lived states

fully profit of a high-intensity setup



Marciano, et al.
arXiv:1607.01022

Dark photon models

Model freedom, e.g. a vector **X** with coupling $\mathbf{g_X}$ $\mathbf{x_f}$ to SM fermions f + a hidden sector

See e.g., JHEP 1806 (2018) 004:

$$\mathcal{L} \subset g_X \sum_f x_f \bar{f} \gamma^\mu f X_\mu + \sum_\chi \mathcal{L}_{X\chi\bar{\chi}}$$

In the minimal A' scenario:

kinetic mixing with photon: $g_X = \varepsilon e$, $x_l = -1$, $x_\nu = 0$, $x_u = 2/3$, $x_d = -1/3$, etc.

model-dependent mixing with Z weak current

If $M_X > 2\ M_\chi$ for some χ → sizeable **invisible** width

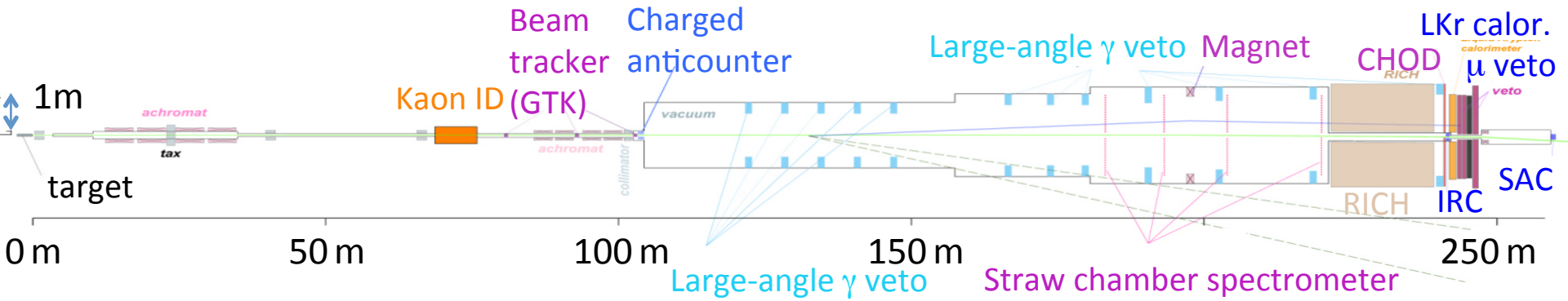
Model freedom (e.g.: A', B-L, B, proto-phobic, etc.) → be experimentally-driven

NA62: a high-intensity setup

High-intensity proton-produced charged hadron beam:

10^{12} 400-GeV protons/s from ~3.5-s SPS spills onto a Be target

Secondary 75-GeV beam selected: 1% momentum bite, X,Y divergence < 100 μrad



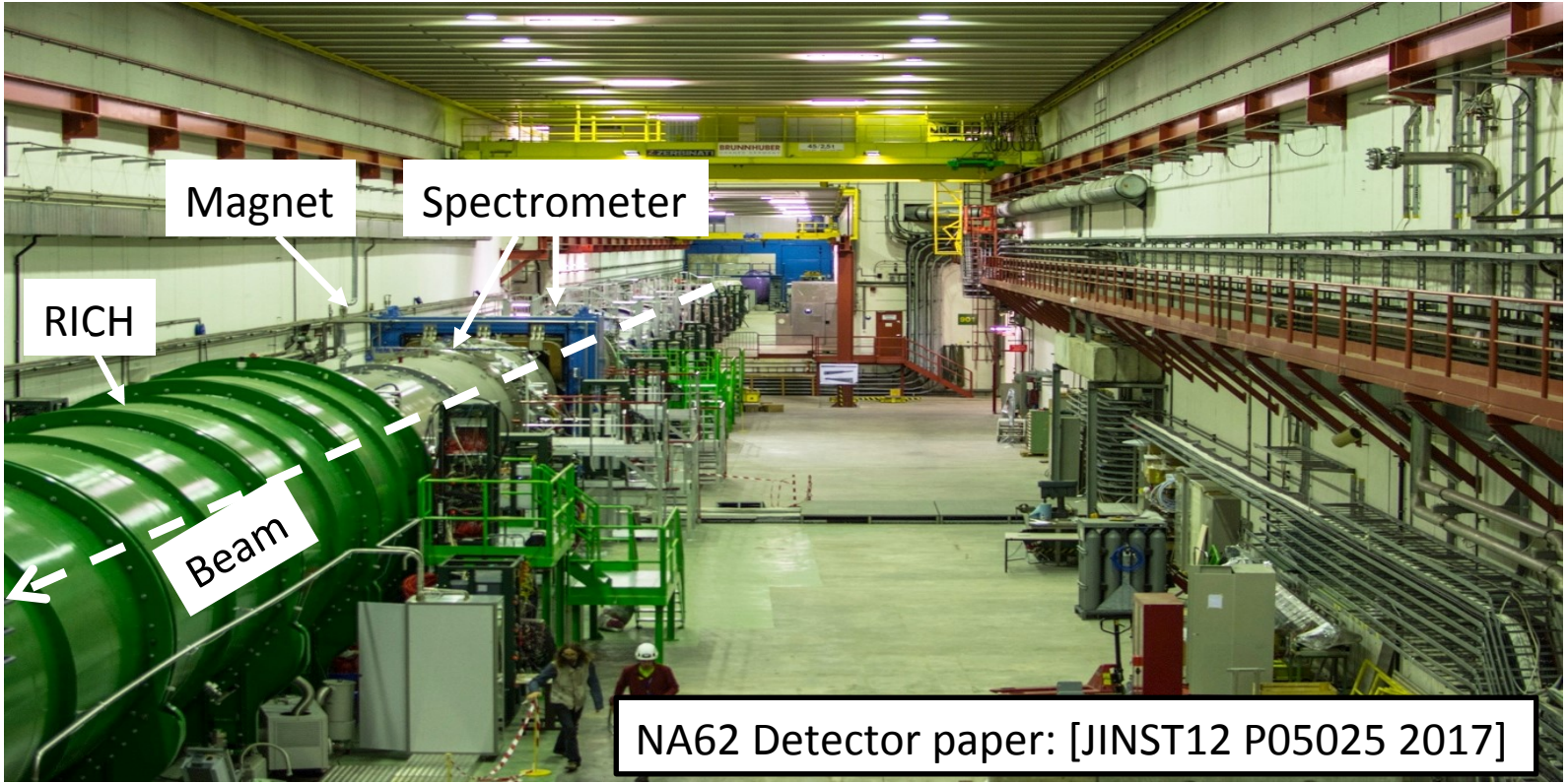
Can **track 750 MHz beam** (6% K^+) and sustain ~5 MHz K^+ decay in a **60-m long volume in vacuum**

Kinematics, rejection of main K modes 10^4—10^5 via kinematic reconstruction

PID capability, μ vs π rejection of $O(10^7)$ for $15 < p(\pi^+) < 35$ GeV

High-efficiency veto of additional photons, $O(10^8)$ rejection of π^0's for $E(\pi^0) > 40$ GeV

NA62: a high-intensity setup



NA62 Detector paper: [JINST12 P05025 2017]

Search for dark photon in $\pi^0 \rightarrow \gamma$ invisible

Tag a pure, intense π^0 beam of known momentum from $K^+ \rightarrow \pi^+\pi^0$ decays

Contamination < 10^{-3} solely reconstructing $K^+ \rightarrow \pi^+$ decays + missing mass condition

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

Signal signature: π^0 tagging, one photon + missing momentum, no further activity

Signal trigger based on "1 track" + small forward energy ← same trigger line as $\pi\nu\nu$

Normalization based on minimum-bias triggered π^0-tagged events, $n_{\pi 0}$

$$\mathrm{BR}(\pi^0 \to A'\gamma) = \mathrm{BR}(\pi^0 \to \gamma\gamma)\frac{n_{\mathrm{sig}}}{n_{\pi^0}}\frac{1}{\varepsilon_{\mathrm{sel}}\varepsilon_{\mathrm{trg}}\varepsilon_{\mathrm{mass}}}$$

The efficiency for π^0 tagging cancels at first order

Search for dark photon in $\pi^0 \rightarrow \gamma$ invisible

Normalization based on minimum-bias triggered $K^+ \rightarrow \pi^+\pi^0$ decays selected as "$K_{2\pi}$":

- **A single K^+—π^+ vertex with**
  - **position $115 < z < 165$ m downstream the T10 target**
  - **$15 < p_\pi < 35$ GeV/*c*, thus ensuring at least ~40 GeV of missing energy**
  - **$0.013 < (P_K - P_\pi)^2 < 0.023$ GeV^2/c^4, compatible with π^0 mass to within ~ ± 20 MeV**
- **No conditions on π^0 photons**
- **Contamination < 10^{-3}**

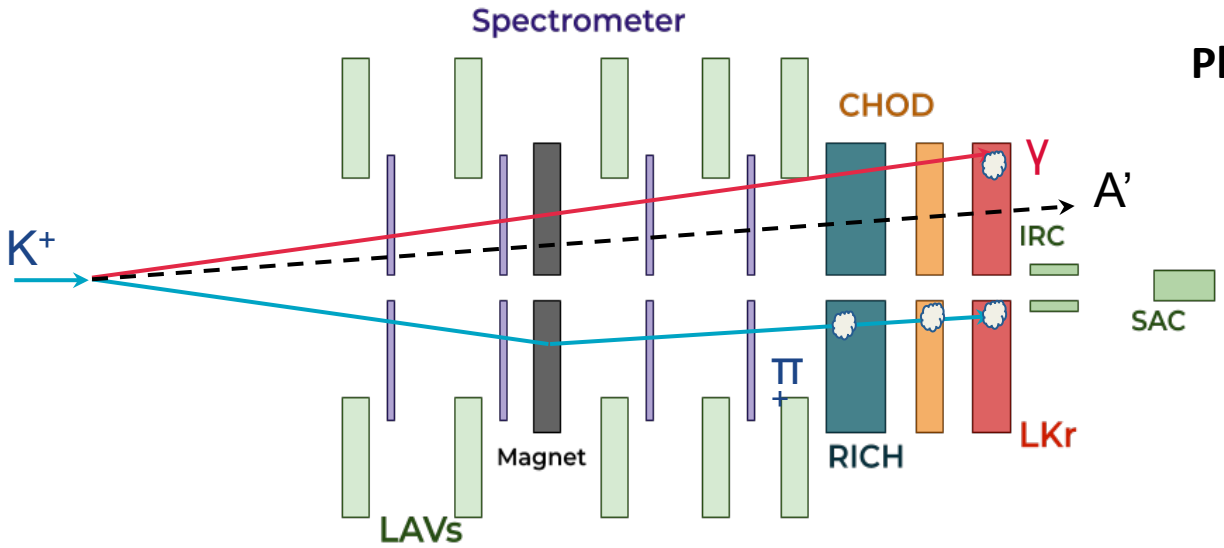
Data from 2016, $n_{\pi 0}$ ~ 412 M π^0s tagged from $K_{2\pi}$ decays (~1% of full data set)

Selection criteria for $\pi^0 \rightarrow \gamma$ invisible

Signal search starts from $K_{2\pi}$ selected (π^0 tagged) events:

One photon in LKr, missing momentum pointing to LKr, isolation condition, minimum E_{miss}

Veto on additional particles using CHOD, LAVs-IRC-SAC, RICH, LKr



Photon detection inefficiencies:

LAVs $O(10^{-3})$ for E_γ in 1—4 GeV; $< 10^{-3}$ for $E_\gamma > 4$ GeV

LKr $O(10^{-4})$ for E_γ in 10—20 GeV; $< 10^{-5}$ for $E_\gamma > 20$ GeV

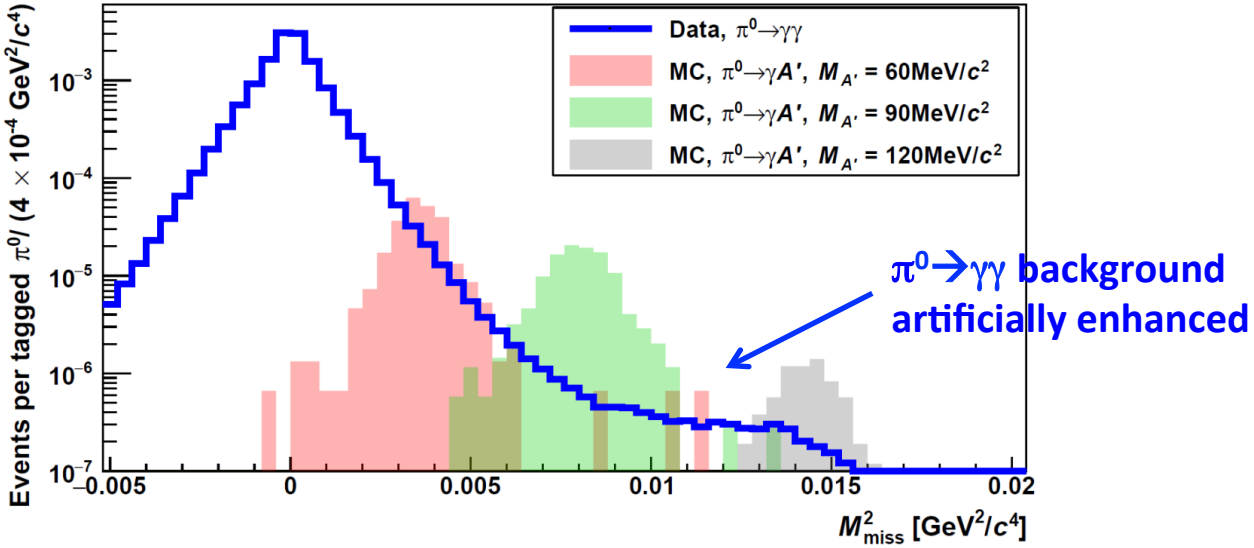
IRC $< 10^{-3}$ for $E_\gamma > 10$ GeV

SAC $O(10^{-3})$ for $E_\gamma > 10$ GeV

Search for $\pi^0 \rightarrow \gamma$ invisible

Search for a peak around $M_{A'}^2$ from $M_{miss}^2 = (p_K - p_{\pi+} - p_\gamma)^2$

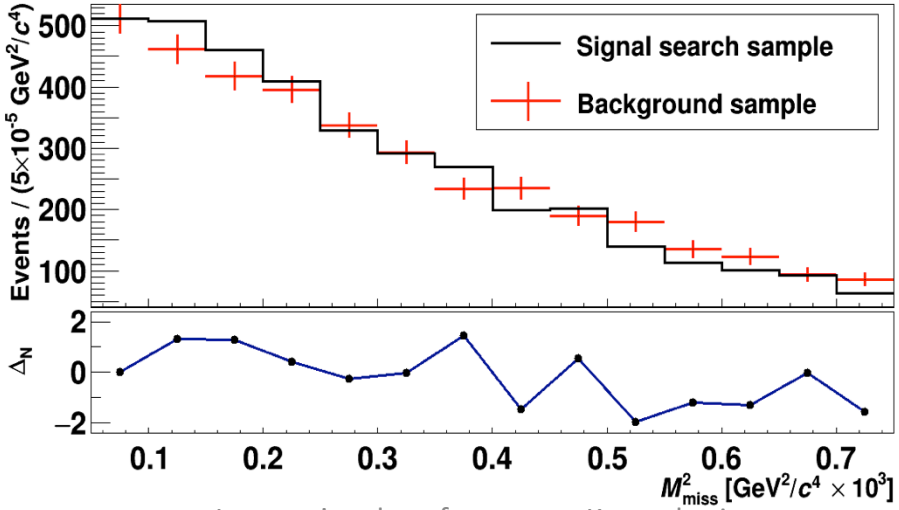
- **Signal M_{miss}^2 resolution 6—10 x 10^{-4} GeV^2/c^4 for $M_{A'}$ in 30—130 MeV/c^2 ← Search region**
- **Perform a counting experiment in ±1σ sliding M_{miss}^2 windows**



Background to $\pi^0 \rightarrow \gamma$ invisible

Dominant background: $\pi^0 \rightarrow \gamma\gamma$ with 1 photon missing, reduced by ~10^{-4} -- 10^{-5} by γ-vetoes

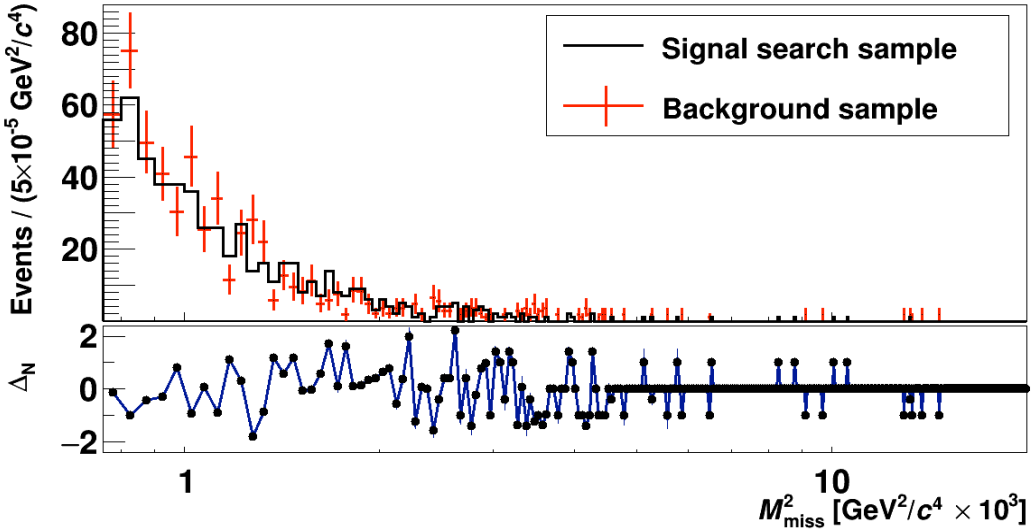
- **Inefficiency dominated by photon conversions upstream the LKr**
- **Data-driven background evaluation by inverting CHOD-based veto conditions**
- **Background normalized to data in side-band region (A' excluded by past experiments)**



Signal region for $\pi^0 \rightarrow \gamma$ invisible

Compare observed counts to expected background in the signal region, $30 < M_{A'} < 120$ MeV/c^2

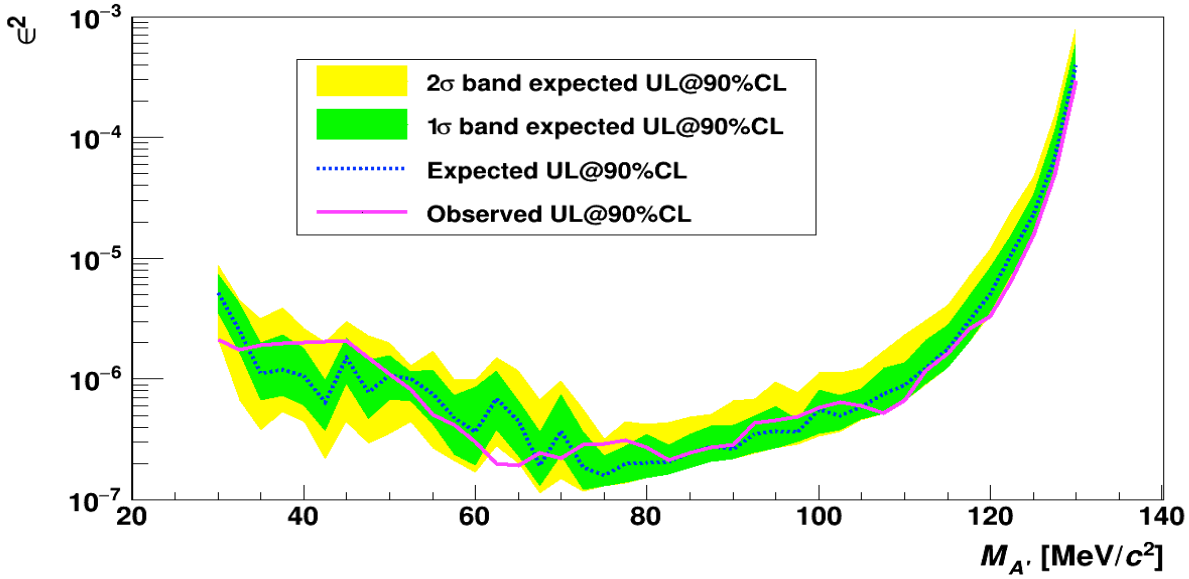
From a sample of 4×10^8 π^0's, background at O(1) event for $M_{A'} > 60$ MeV/c^2



Result for $\pi^0 \rightarrow \gamma$ invisible

Compare observed event counts to expected background: CLs method, counting experiment

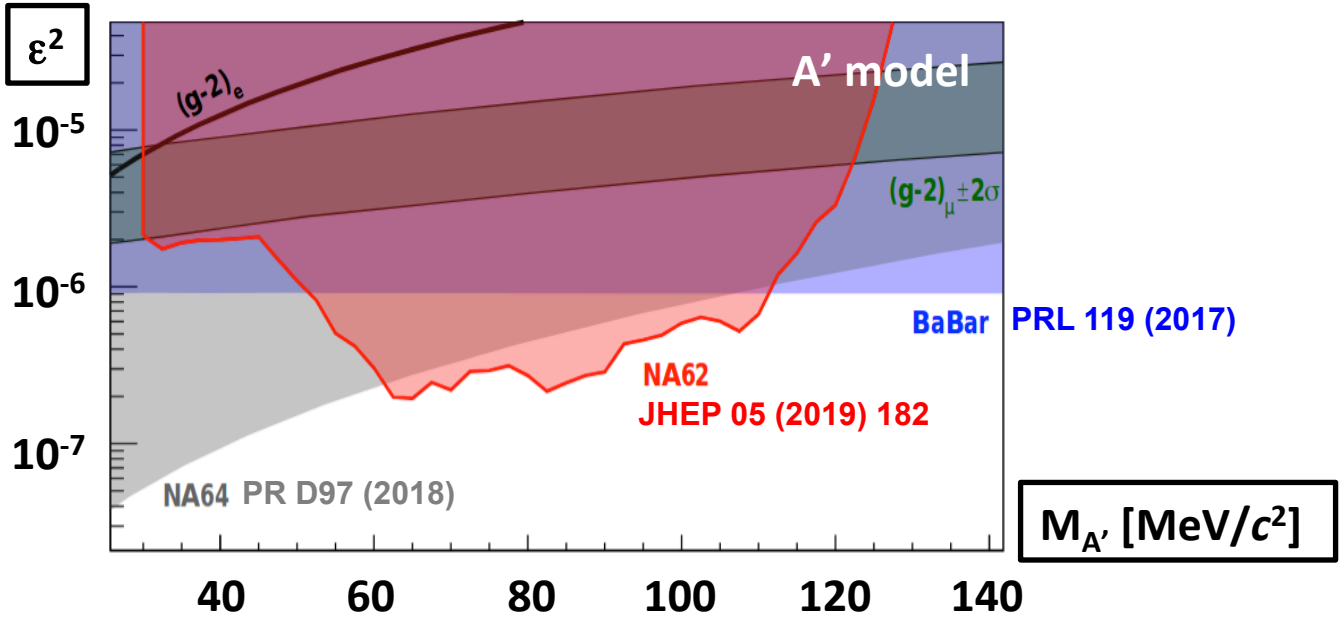
Observation compatible with expected fluctuations of pure background → set 90%CL UL



Implications for A' dark-photon model

Interplay of results from different techniques: $e^+e^- \rightarrow \gamma$ A' [BaBar], e^- dump + E_{miss} [NA64]

Published most stringent exclusion for $60 < M_{A'} < 110$ MeV/c^2



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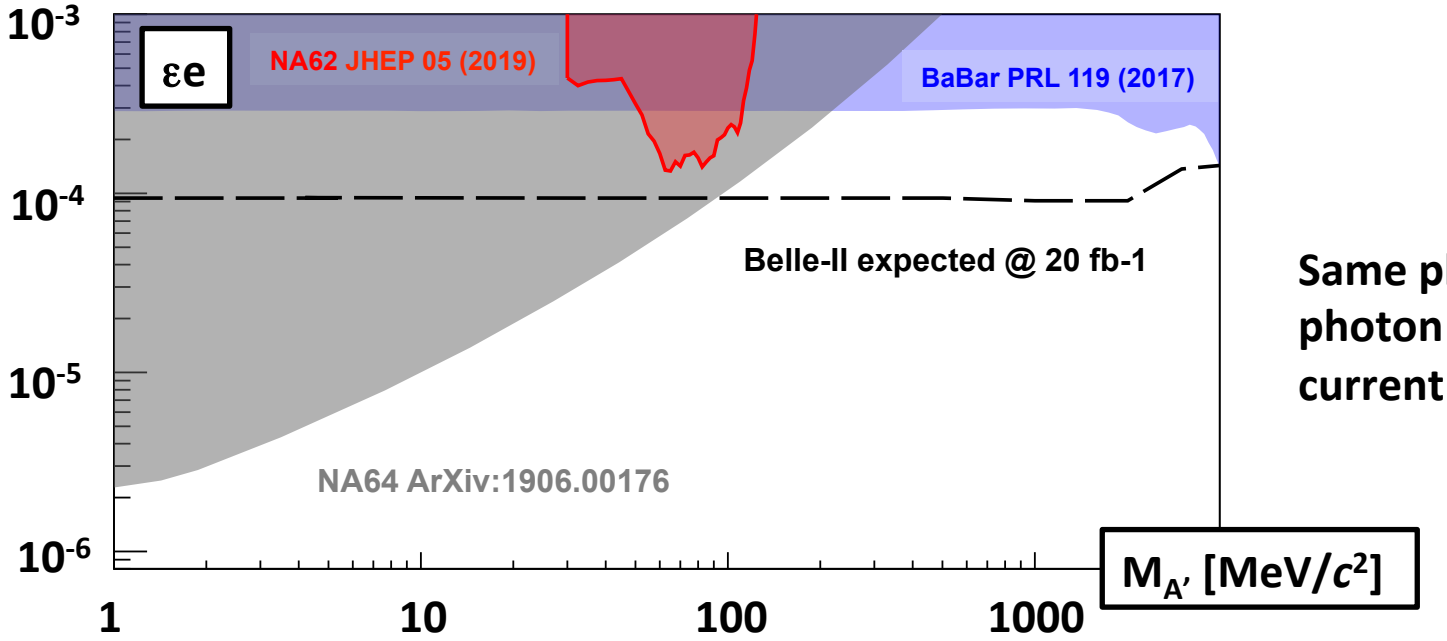
Interplay of results from different techniques: $e^+e^- \rightarrow \gamma$ A' [BaBar], e^- dump + E_{miss} [NA64]

Published most stringent exclusion for $60 < M_{A'} < 110$ MeV/c^2, covered by new NA64 result

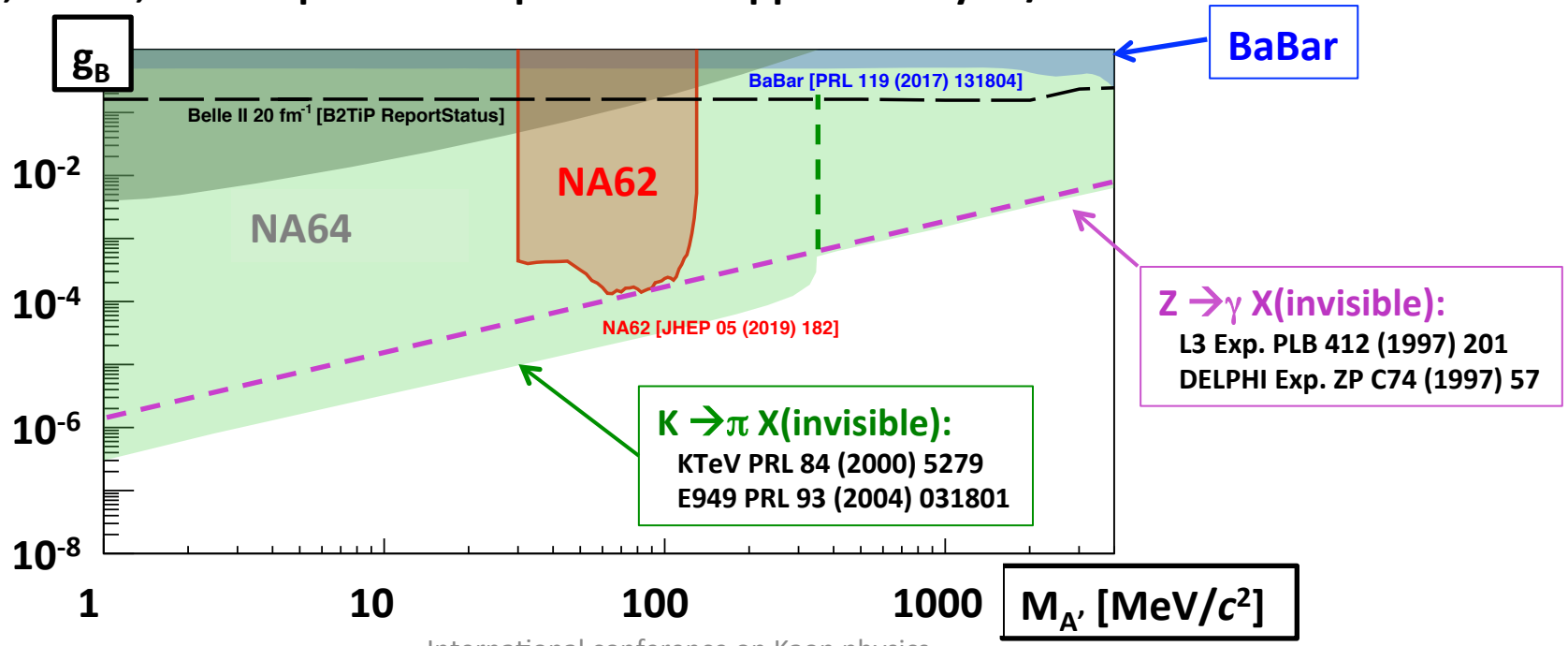


Same plot holds for dark photon coupled to B-L current if $\varepsilon e \rightarrow g_{B-L}$

and for B-current-coupled dark-photon

Different scenario for dark photon coupled to Baryonic current [see PRL 119 (2017) 141803]

NA64, BaBar, Belle-II production processes suppressed by $\alpha^2/4\pi^2$



Conclusions and outlook

A first search for an invisible particle in $\pi^0 \rightarrow A' \gamma$ has been presented

- **Competitive limits on A', B-L dark photon models by using ~1% of NA62 data set**
- **Models with unsuppressed FCNCs (e.g. B-model) dominated by $K \rightarrow \pi\nu\bar{\nu}$**

Analysis by-product: search for $\pi^0 \rightarrow \gamma\nu\bar{\nu}$ decay (SM expected BR ~ 10^{-18}):

- **BR < 1.9×10^{-7}@90% CL, improving x1000 over previous results**

Perspectives from analysis of full NA62 data set:

- **Expected yield increase by O(100)**
- **Background to be kept under control → possible through kinematic fitting**

Spare slides

Systematic checks: discovery potential

Signal with $M_{A'}$ = 80 MeV/c^2 and various ε^2 values added to data

Account for full selection and trigger efficiency with related uncertainties