

Status of Dark Photon Searches

Suyong Choi

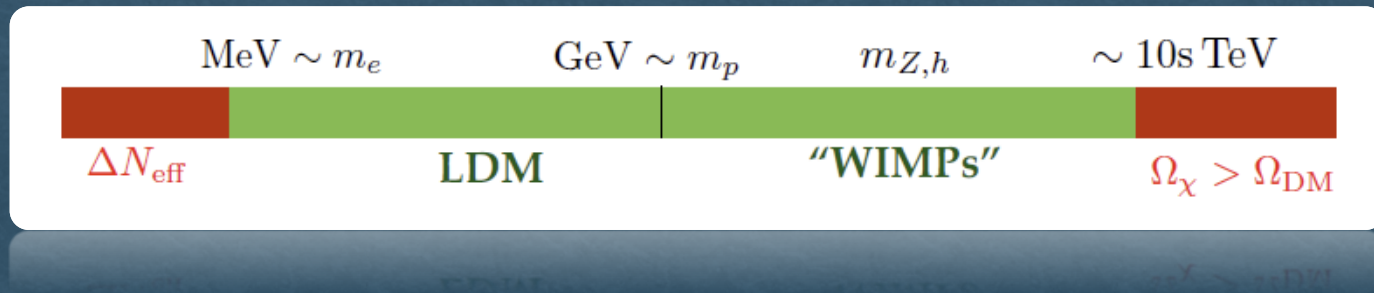
Korea University

Outline

- ◇ Introduction to Dark Photon
- ◇ Searches for dark photon in visible decays
- ◇ Searches for dark photon in invisible decays
- ◇ Summary and Outlook

Motivation for MeV-GeV dark photon

◇ Thermal DM candidate



◇ Vector portal DM models

- ◇ Small enough coupling to have evaded detection
- ◇ Large enough coupling for primordial (quasi-)thermal DM generation

Dark Photon

- ◊ Kinetic Mixing of Dark Photon and SM Photon (Arkani-Hamed et al., 2008)

$$\mathcal{L}_{\text{dark}} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_A^2 A'_\mu A'^\mu + \bar{\chi}(i\not{D} - m_\chi)\chi$$

- ◊ $U(1)_D$ gauge symmetry (vector portal)

- ◊ Coupling to charge of SM particles

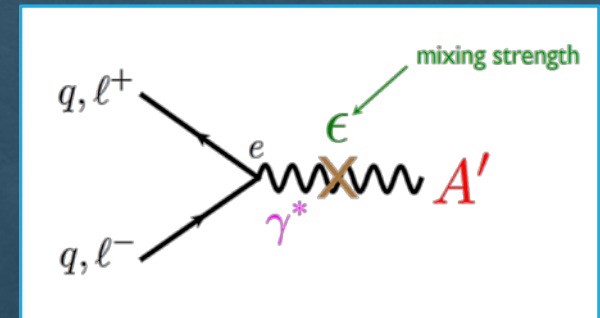
$$\mathcal{L}_{\text{int}} = -\epsilon e J_{em}^\mu A'_\mu$$

- ◊ Coupling of DM with dark photon

- ◊ Dark Z (Davoudiasl, Lee, Marciano, 2012)

- ◊ Couples to both photon and Z

- ◊ Parity violation



Experimental Signatures

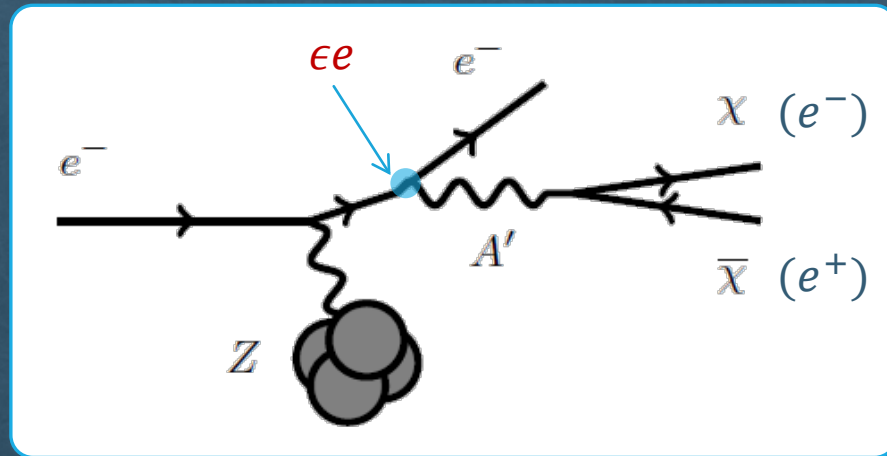
- Dark photons could be produced in processes where SM photons are produced

Process	SM process	Dark photon process	Experiments
Electron Bremsstrahlung	$e^- + N \rightarrow e^- + N + \gamma$	$e^- + N \rightarrow e^- + N + A'$	Electron fixed targets (E137, NA64, etc)
Annihilation	$e^+ + e^- \rightarrow \gamma + \gamma$	$e^+ + e^- \rightarrow \gamma + A'$	Babar, Belle, KLOE
Neutral meson decays	$\pi^0, \eta \rightarrow \gamma + \gamma$ $\phi \rightarrow \eta + \gamma$	$\pi^0, \eta \rightarrow \gamma + A'$ $\phi \rightarrow \eta + A'$	NA48, A1, APEX, HPS, SHiP, KLOE
Proton Bremsstrahlung	$p + N \rightarrow p + N + \gamma$	$p + N \rightarrow p + N + A'$	SHiP
Higgs decays	$h \rightarrow ZZ^*$	$h \rightarrow ZZ_D, Z_D Z_D$	LHC, Babar, Belle

Production and Decay of Dark Photons in Fixed Target Experiments

◇ Electron Bremsstrahlung process

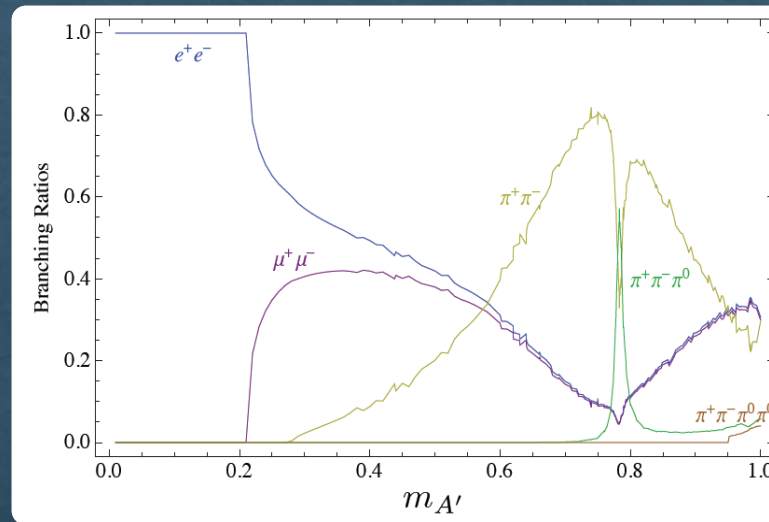
$$\sigma_{A'} \sim \frac{Z^2 \alpha^3 \epsilon^2}{m_{A'}^2}$$



$$\Gamma_{A'} \sim \alpha_D \text{ or } (\epsilon^2 \alpha)$$

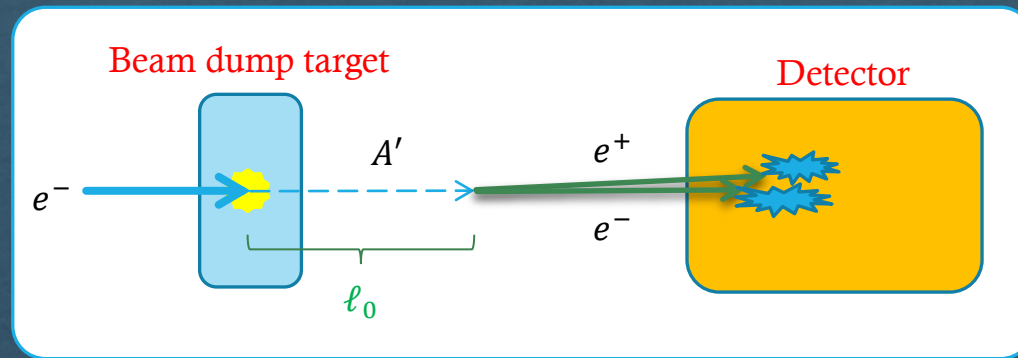
Decays of Dark Photon

◇ Decays into SM particles: $(m_{A'}, \epsilon^2)$



◇ Decays into DM: $(m_{A'}, m_\chi, \alpha_D, \epsilon^2)$

Fixed Target Experiment using Electron Beams



- ◇ $\ell_0 = c\tau\gamma \approx 0.8\text{cm} \left(\frac{E_{beam}}{10\text{ GeV}}\right) \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\text{ MeV}}{m_A}\right)^2$
- ◇ $E_{A'} \sim E_{beam}$ and $E_{e^-}, E_{e^+} \approx E_{beam}/2$
- ◇ Highly directional
- ◇ “Light shine through wall” type experiment

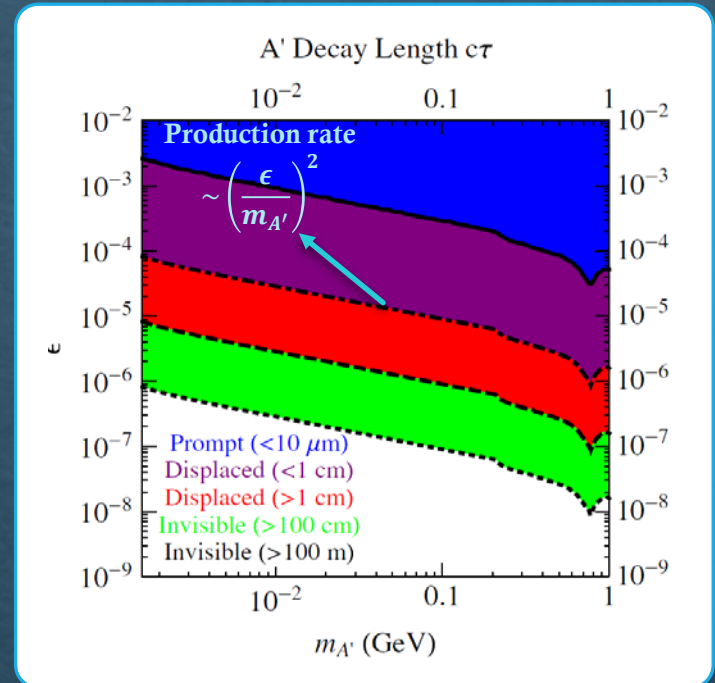
Experimental Considerations

- ◆ A' decay length

$$\gamma c\tau \sim \frac{E_{beam}}{(\epsilon m_{A'})^2}$$

- ◆ Production rate $\sim \left(\frac{\epsilon}{m_{A'}}\right)^2$

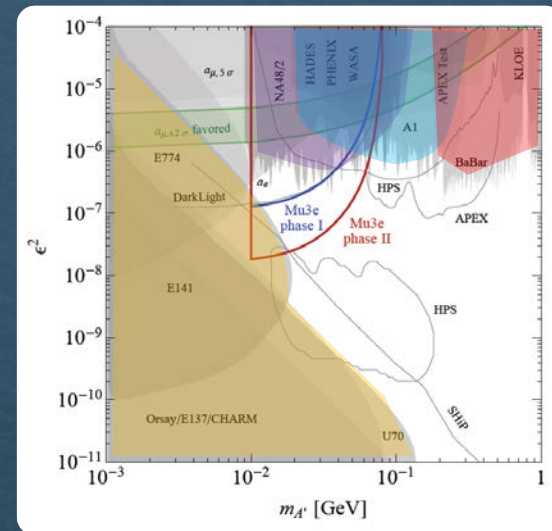
- ◆ Angular coverage: $\Delta\theta \sim \frac{m_{A'}}{E_{beam}}$



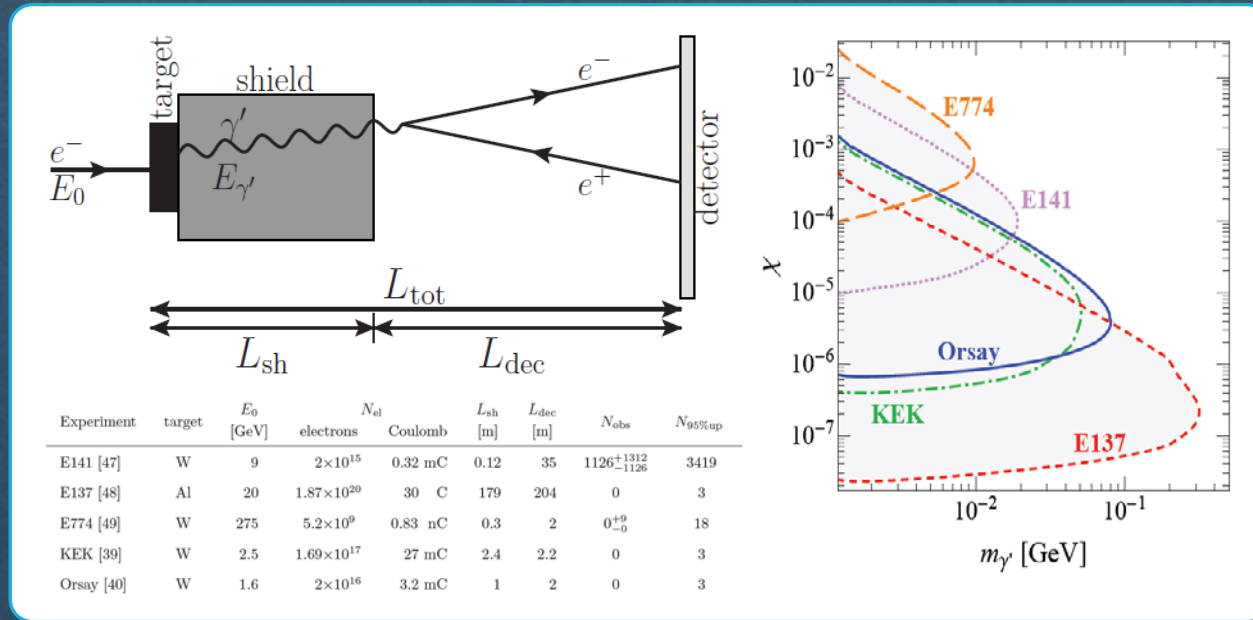
Dark Photons in Visible Mode

◆ Constraints

- ◆ Anomalous magnetic moments
- ◆ Electron/proton on beam dumps
- ◆ Electron on thin fixed targets
- ◆ e^+e^- colliders
 - ◆ $e^+e^- \rightarrow \gamma A' \rightarrow \gamma e^+e^-, \gamma \mu^+\mu^-$
 - ◆ $\phi \rightarrow \eta A'$
- ◆ $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+e^-$



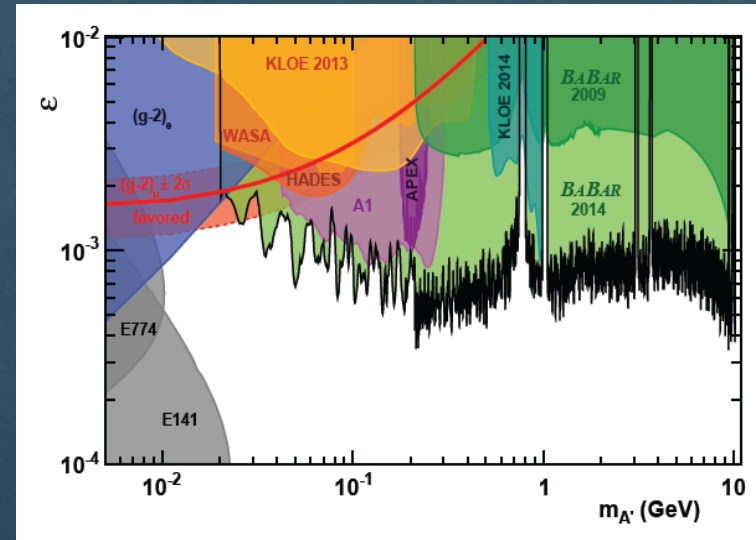
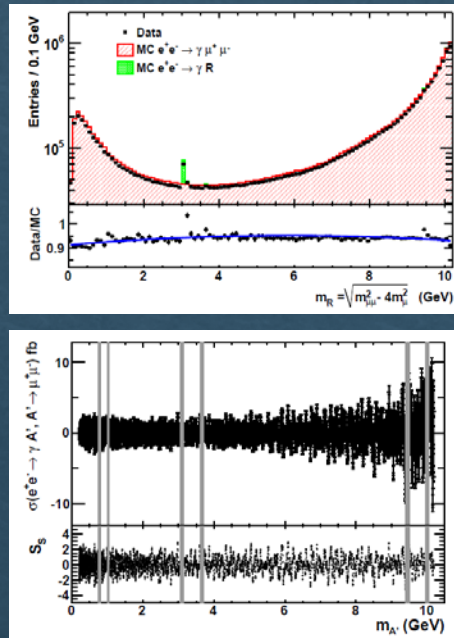
Exclusions from Past Electron Beam Dump Experiments



e^+e^- Collider – BaBar

◇ Channel: $e^+e^- \rightarrow \gamma A' \rightarrow \gamma e^+e^-, \gamma \mu^+\mu^-$

PRL 113, 201801 (2014)

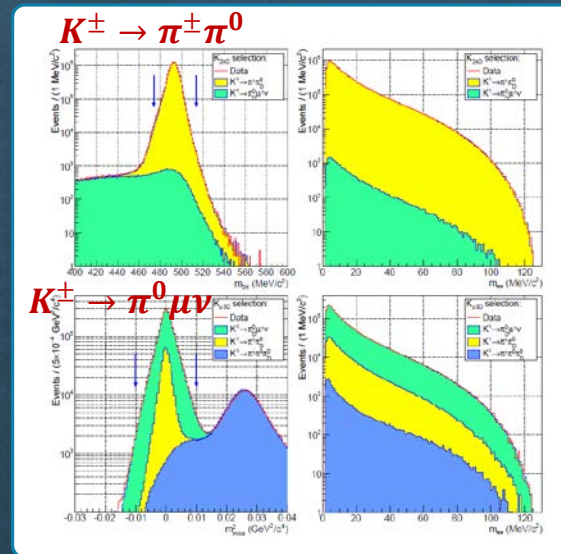
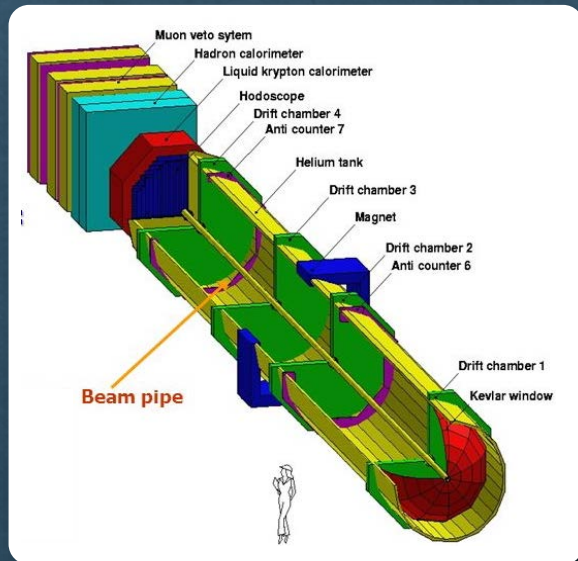


Excluding: $\omega, \rho, J/\psi, \psi(2s), \Upsilon(1s), \Upsilon(2s)$

NA48/2

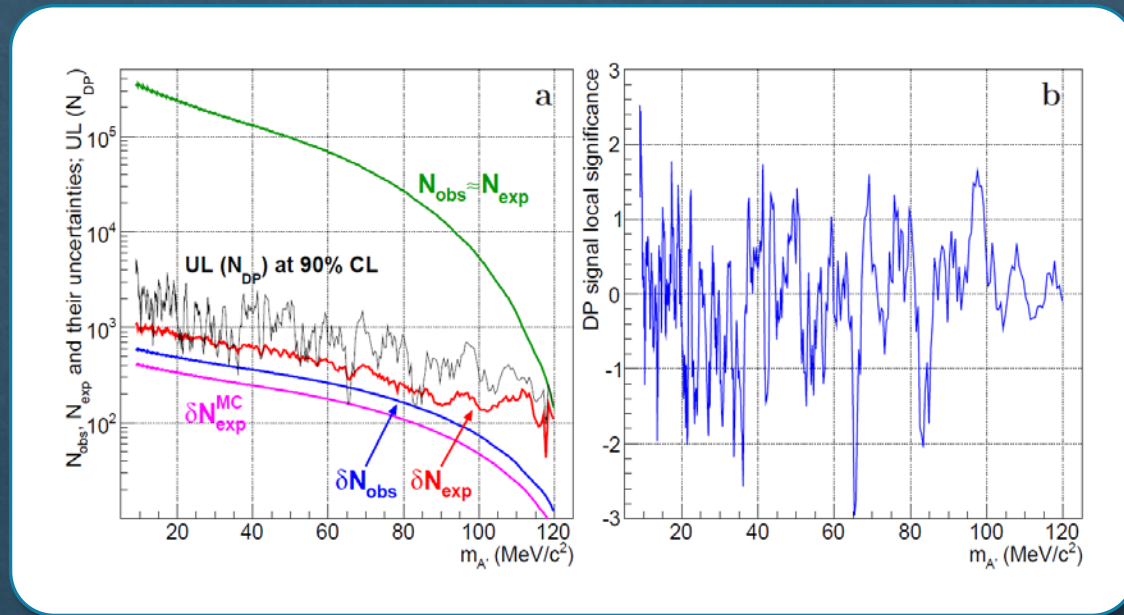
◇ Bump hunt in M_{ee} spectrum from $\pi^0 \rightarrow \gamma e^+ e^-$

Mass resolution:
0.16 ~ 1.3 MeV

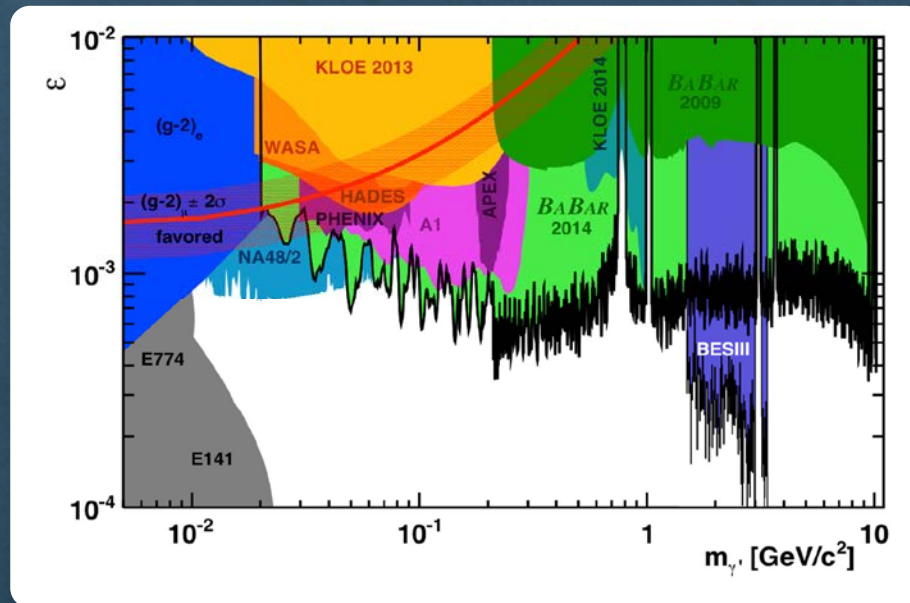


NA48/2

- ◇ Backgrounds from MC, corrected for trigger efficiencies



Visible Decays Summary of Dark Photon as of 2015

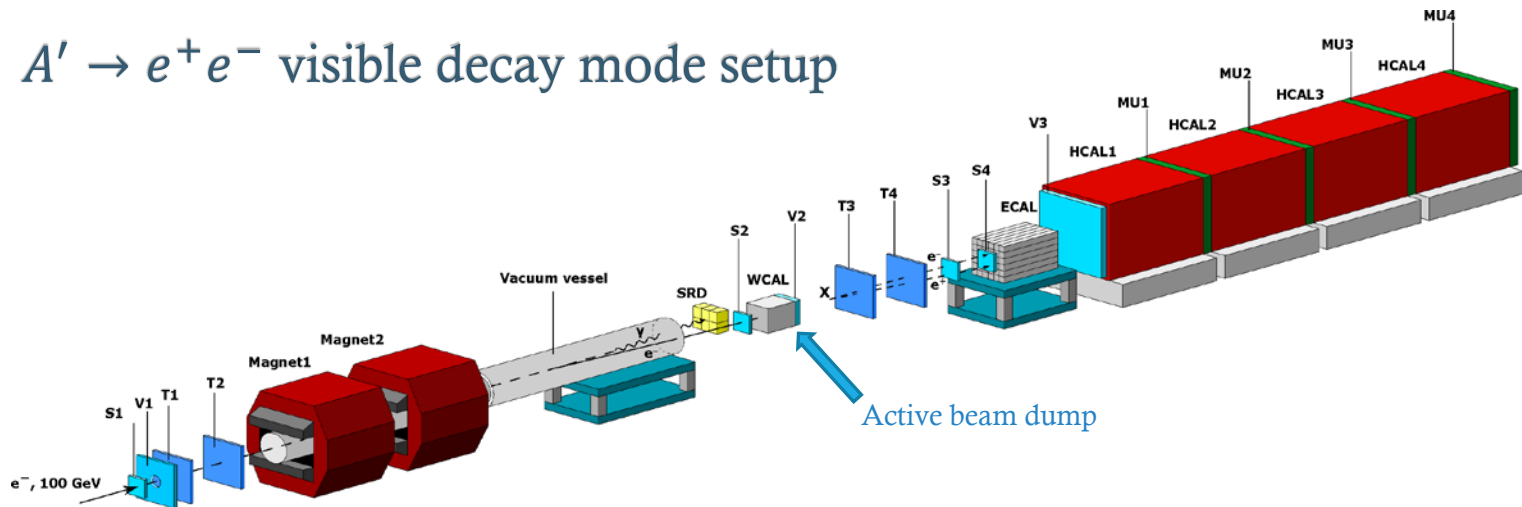


arXiv:1508.07659

NA64 at CERN

- ◇ Designed to search for light dark matter with “active” beam dump
- ◇ EM shower energy measured in the beam bump
- ◇ $E_{WCAL} + E_{ECAL} \approx E_{beam}$ with significant $E_{ECAL} > 25$ GeV

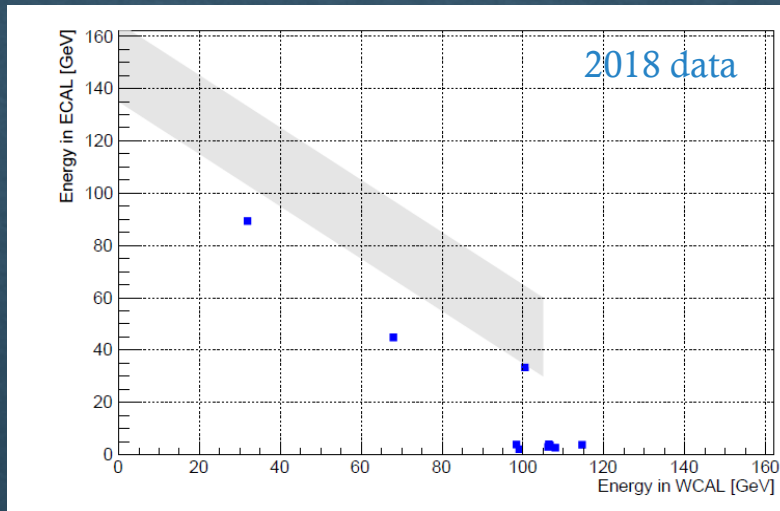
$A' \rightarrow e^+ e^-$ visible decay mode setup



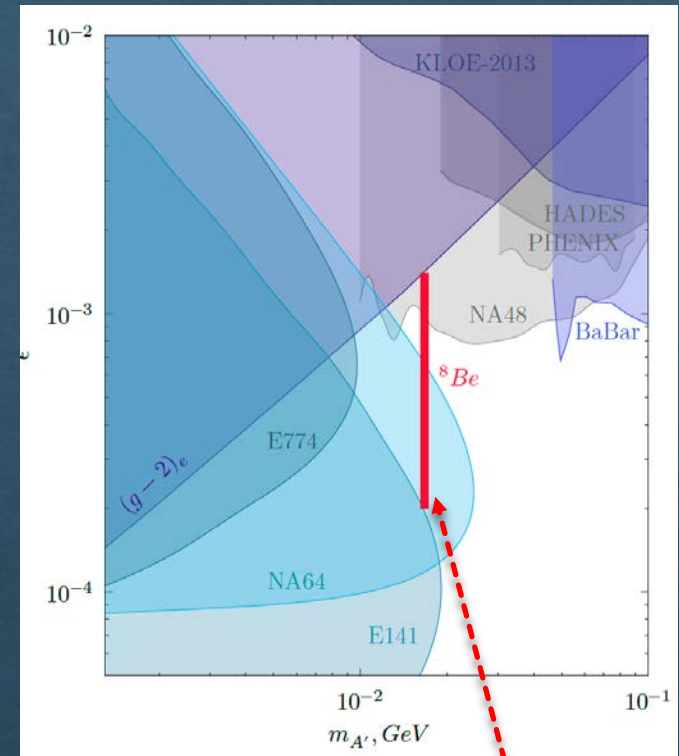
Dark Photon Search at NA64

CERN-SPSC-2019-024

- ◆ Preliminary result from 2017-2018 data
 - ◆ 100, 150 GeV e^- beam at CERN H4 line with $1.4 \sim 9 \times 10^6 e^-$ per 4.8s spill total of 2.8×10^{11} EOT



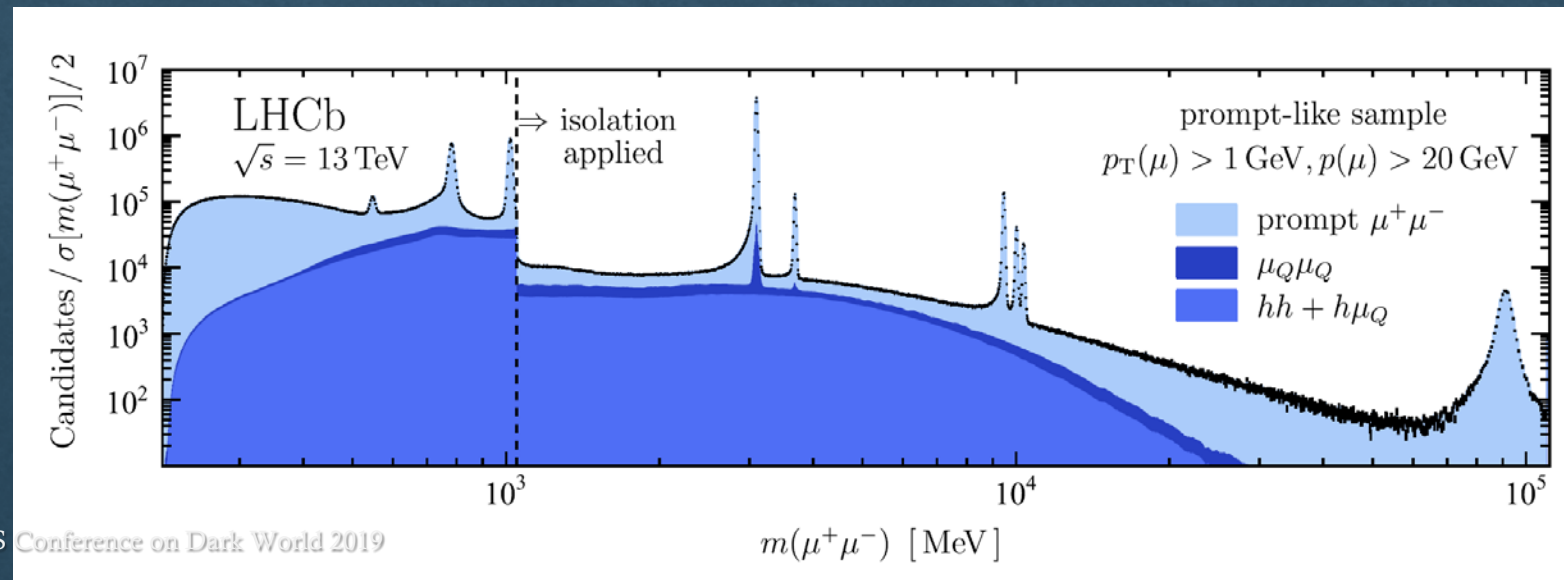
Source of background	2017 data	2018 data
punchthrough γ	< 0.001	< 0.0005
$K_S^0 \rightarrow 2\pi^0$	0.06 ± 0.034	0.005 ± 0.003
$\pi N \rightarrow (\geq 1)\pi^0 + n + \dots$	0.01 ± 0.004	0.001 ± 0.0004
$\pi, K \rightarrow e\nu, K_{e4}$ decays	< 0.0001	< 0.0001
$\pi, K \rightarrow e\nu, K_{e4}$ decays	< 0.001	< 0.001
$eZ \rightarrow eZ\mu^+\mu^-; \mu^\pm \rightarrow e^\pm\nu\nu$	< 0.001	< 0.001
Total	0.07 ± 0.035	0.006 ± 0.003



$> 5\sigma$ excess in e^+e^- mass spectrum at 17.6 MeV, PRL 116, 042501 (2016)

Dark Photon Search at LHCb

- ◆ LHCb searched for prompt and long-lived A' decaying to $\mu^+\mu^-$
 - ◆ Purely data-driven measurement
 - ◆ Same kinematics for A' and γ^* if $m(A') = m(\gamma^*)$ for prompt A' decays
- ◆ Data: pp collision at $\sqrt{s} = 13$ TeV 1.6 fb^{-1} (2016 data)



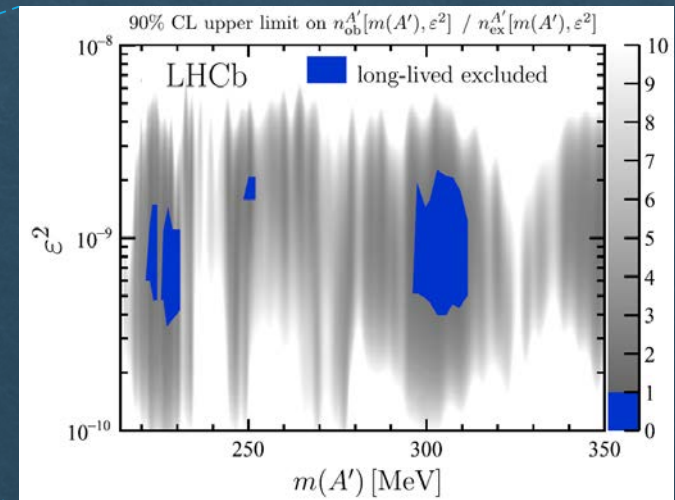
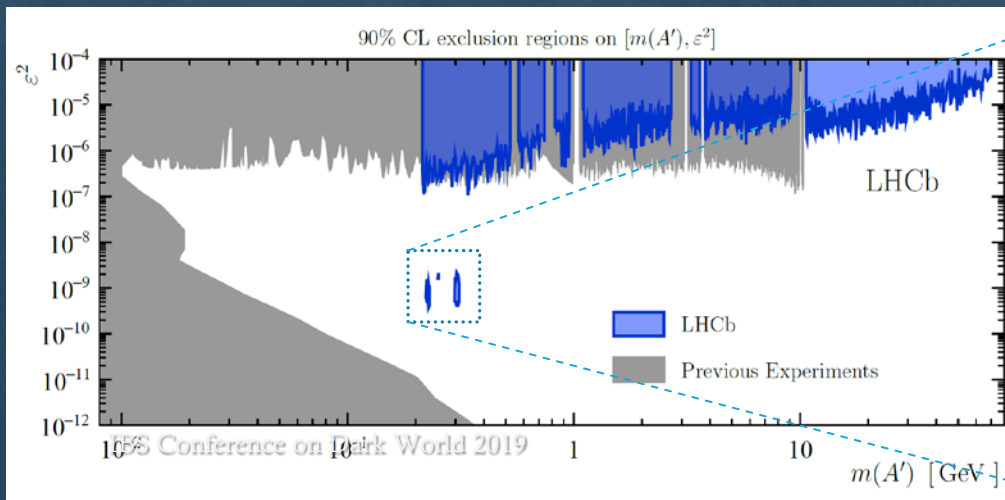
Dark Photon Searches at LHCb

◊ Sliding mass window

$$n_{ex}^{A'}(m_{A'}, \varepsilon^2) = \varepsilon^2 \frac{n_{ob}^{\gamma^*}(m_{A'})}{2 \Delta m} \mathcal{F}(m_{A'}) \epsilon_{\gamma^*}^{A'}(m_{A'}, \tau_{A'})$$

$\mathcal{F}$: phase space and other factors

$\epsilon_{\gamma^*}^{A'}$: Ratio of detection efficiencies ≈ 1 for prompt decays



Searches for Dark Photon in Invisible Mode

Dark Photon to DM Decays

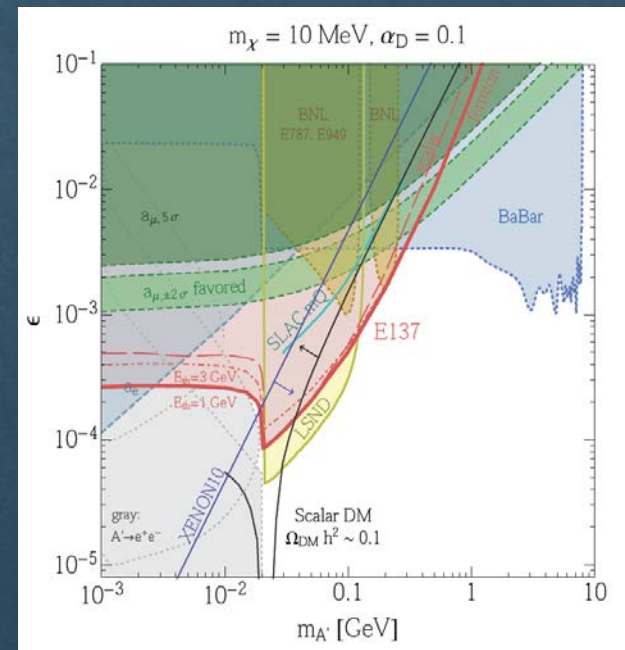
- ◇ A' decays into pair of DM particles
 - ◇ If $2m_\chi < m_{A'}$, then DM decays possible and could be dominant
 - ◇ To explain the DM relic density:

$$\alpha_D \simeq 0.02 f \left(\frac{10^{-3}}{\epsilon} \right)^2 \left(\frac{m_{A'}}{100 \text{ MeV}} \right)^4 \left(\frac{10 \text{ MeV}}{m_\chi} \right)^2$$

- ◇ Searches for $A' \rightarrow \chi\chi$
 - ◇ Indirect – missing energy or momentum. rate $\sim \epsilon^2$
 - ◇ Direct – $\chi - e$ or $\chi - N$ scattering events. rate $\sim \alpha_D \epsilon^4 \left(\frac{m_\chi}{m_{A'}} \right)^4$

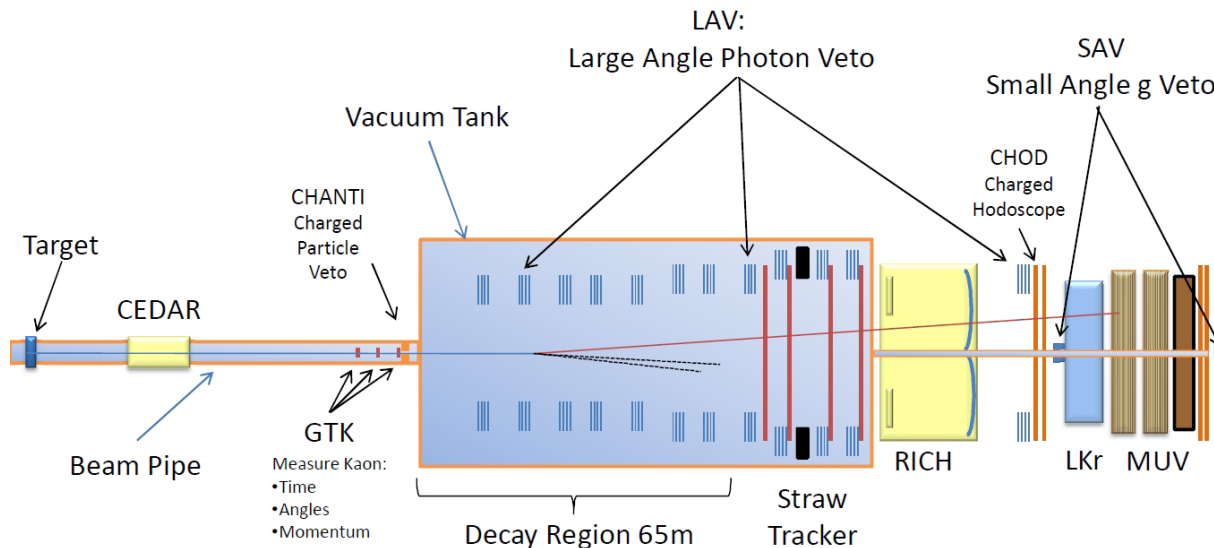
Searches for Dark Photon decaying into Light DM

- ◇ Rare Kaon decay
 - ◇ BNL E787, E949 limits on $\text{Br}(K^+ \rightarrow \pi^+ X)$ from analysis of search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.
 - ◇ Limited to $m'_A < m_K - m_\pi$
- ◇ Electron beam dump: E137
 - ◇ $\chi - e$ scattering in detector
- ◇ Electron-positron collider
 - ◇ $e^+ e^- \rightarrow \gamma A'$: mono-photon signature
- ◇ Neutrino experiments
 - ◇ If DM is long-lived and scatters in neutrino detectors limits from LSND applicable:
 $\pi^0 \rightarrow \gamma A'$



A' Search at NA62 at CERN

- Principal goal of this experiment is to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and determine $|V_{td}|$ with $\sim 10\%$ accuracy
- Dark photon is searched in $K^+ \rightarrow \pi^+ \pi^0$ with $\pi^0 \rightarrow A' \gamma$
 - Analyzed partial data of 2016. 1% of data collected in 2016-2018



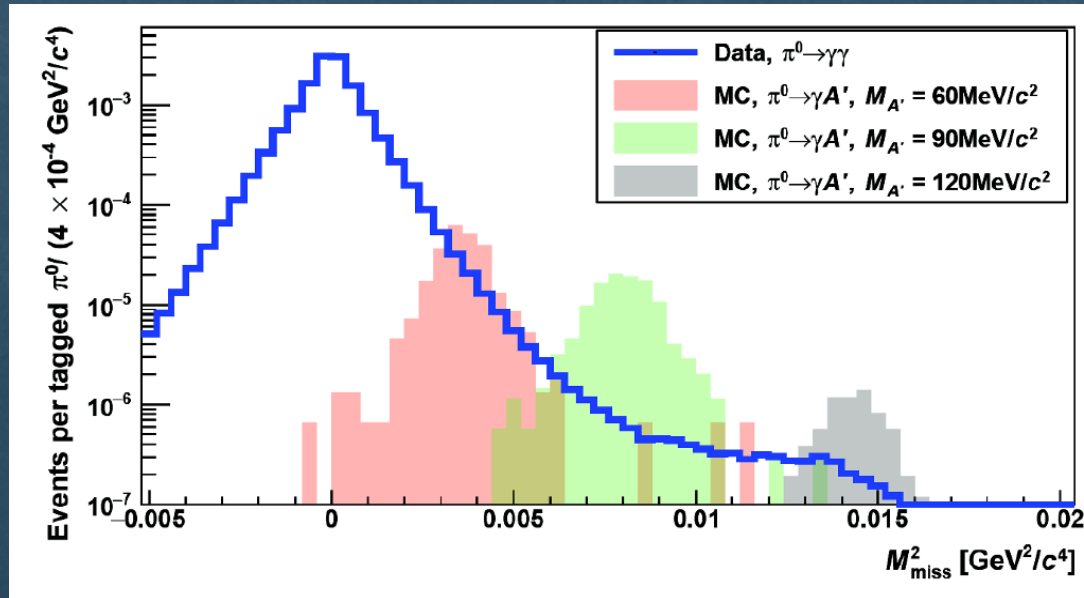
Specifications

K12 beam line:

- SPS primary protons @ 400 GeV/c
- 75 GeV/c ($\Delta P/P \approx 1\%$)
- Area @ beam tracker 16 cm^2
- Divergence $\approx 100 \mu\text{rad}$
- Kaon decays/year 4.8×10^{12}
- Unseparated secondary charged beam
- $p/\pi/K$ (positron free, $K \approx 6\%$, $p \approx 23\%$)
- Integrated average rate @ beam tracker 750 MHz

Invisible A' search at NA62

- Signature: $\pi^+ + \gamma + \text{Missing energy}$
- Sensitive variable: $M_{\text{miss}}^2 = (p_K - p_\gamma - p_\pi)^2$

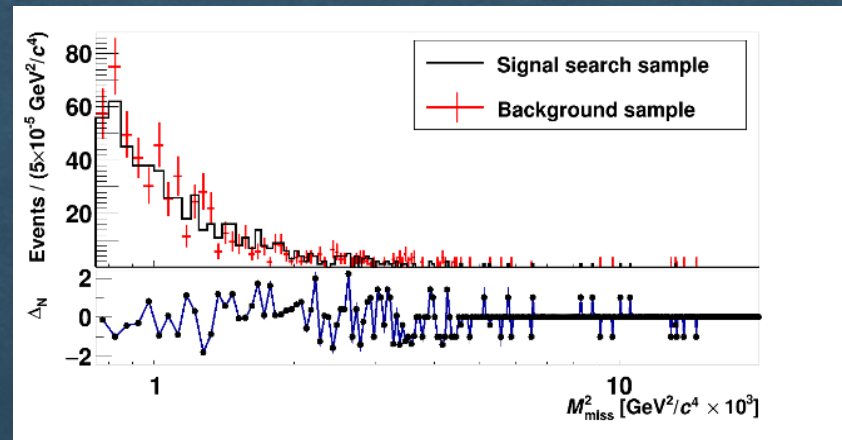
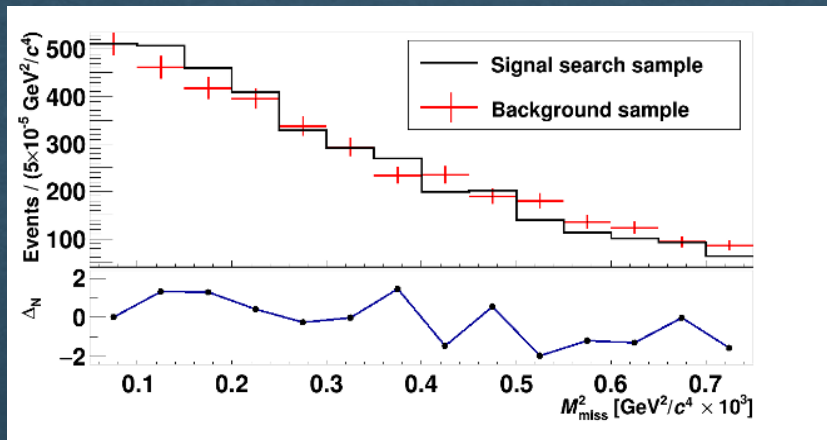


Invisible A' search at NA62

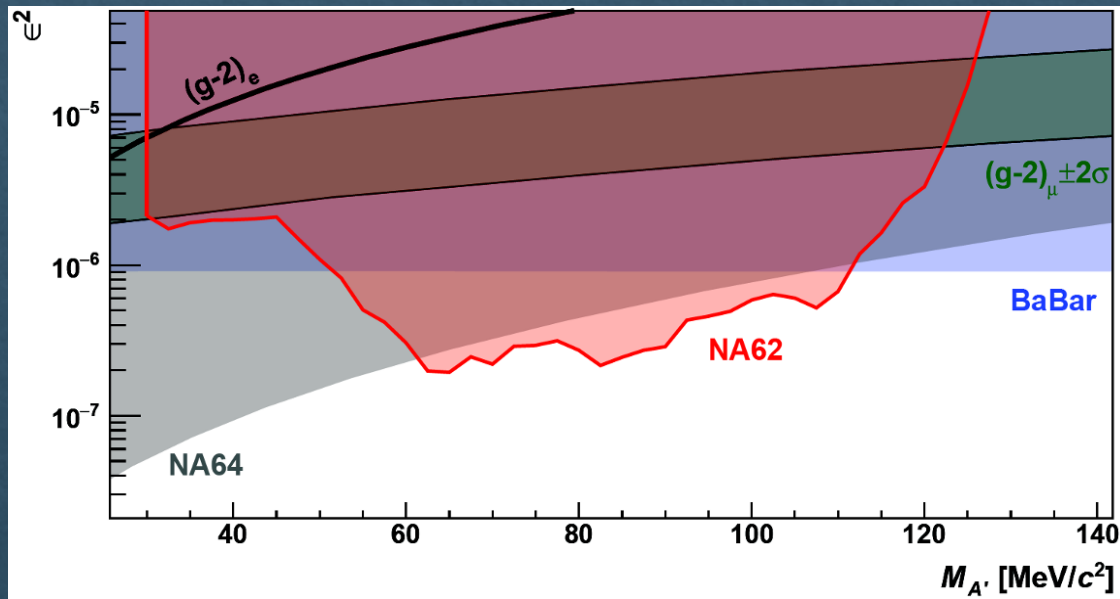
◇ Background normalization region

◇ $K^+ \rightarrow \pi^+ \pi^0 \rightarrow \pi^+ \gamma \chi$

◇ Signal region



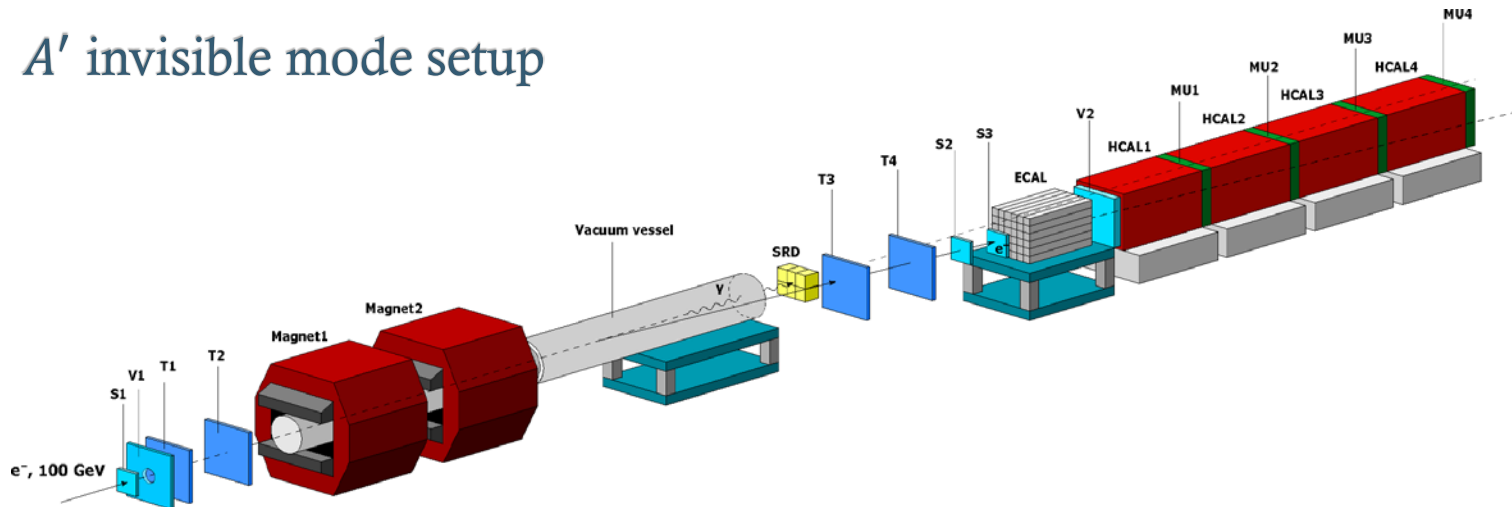
Invisible A' search at NA62



NA64

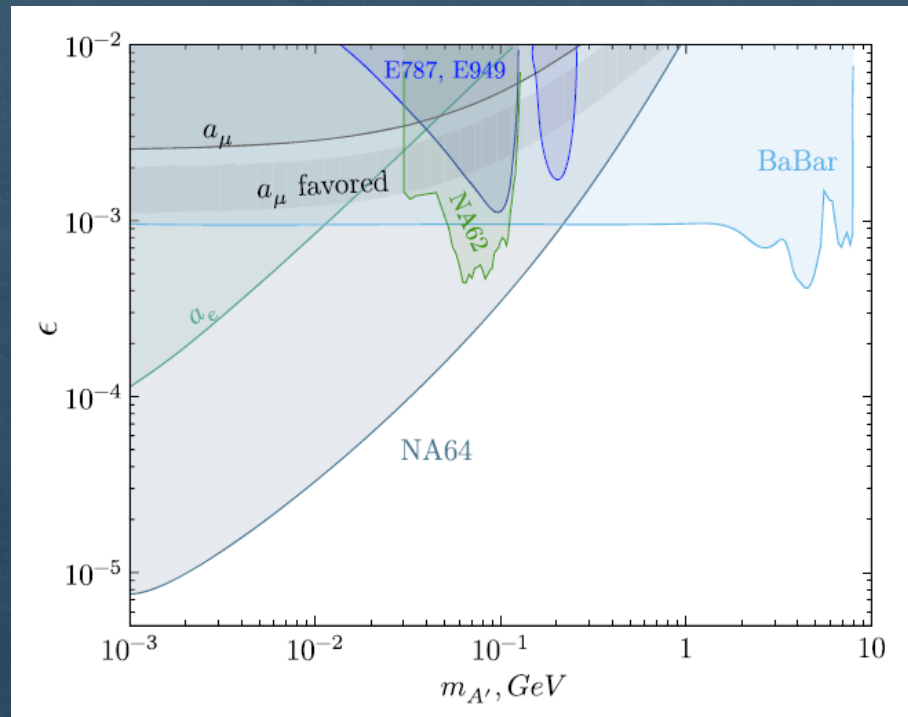
- ◇ Measure missing energy carried away by A' . Rate $\sim \epsilon^2$
 - ◇ $E_{beam} - E_{ECAL} > 50 \text{ GeV}$ and $E_{HCAL} < 1 \text{ GeV}$
 - ◇ Trying to measure $\chi - N$ interaction? $\propto \epsilon^2 \alpha_D$

A' invisible mode setup



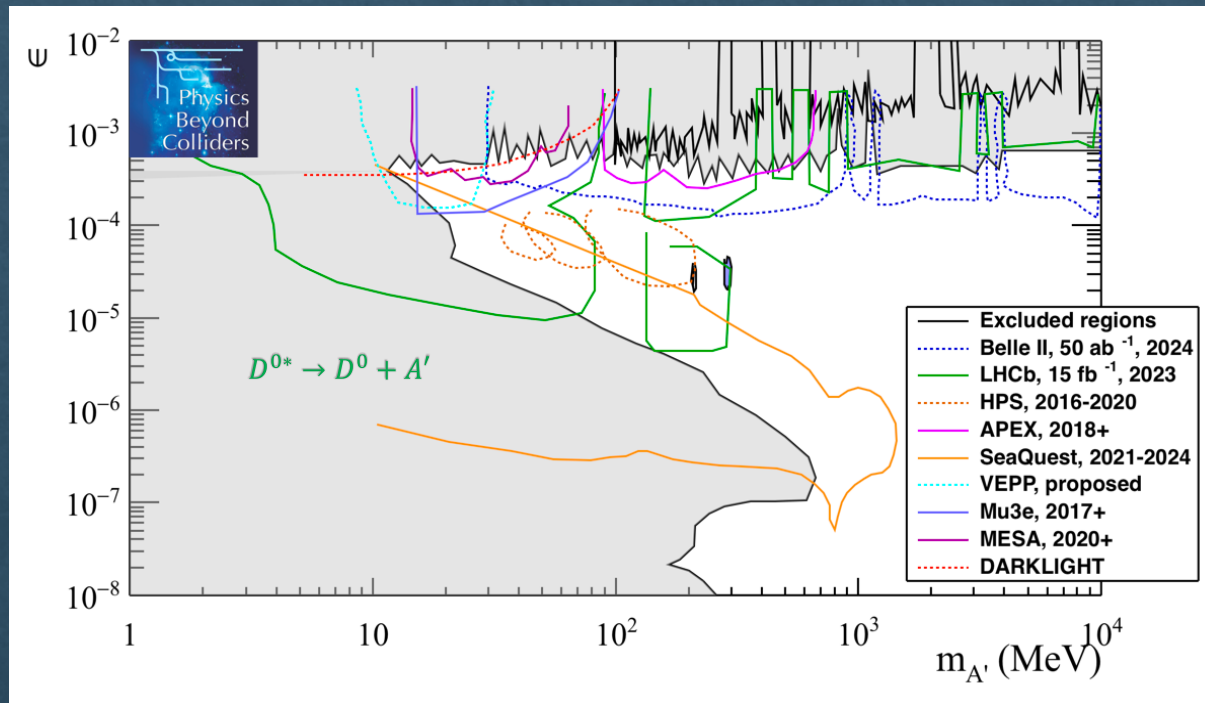
NA64 Dark Photon Search

◇ Assuming $Br(A' \rightarrow \chi\chi) \approx 100\%$

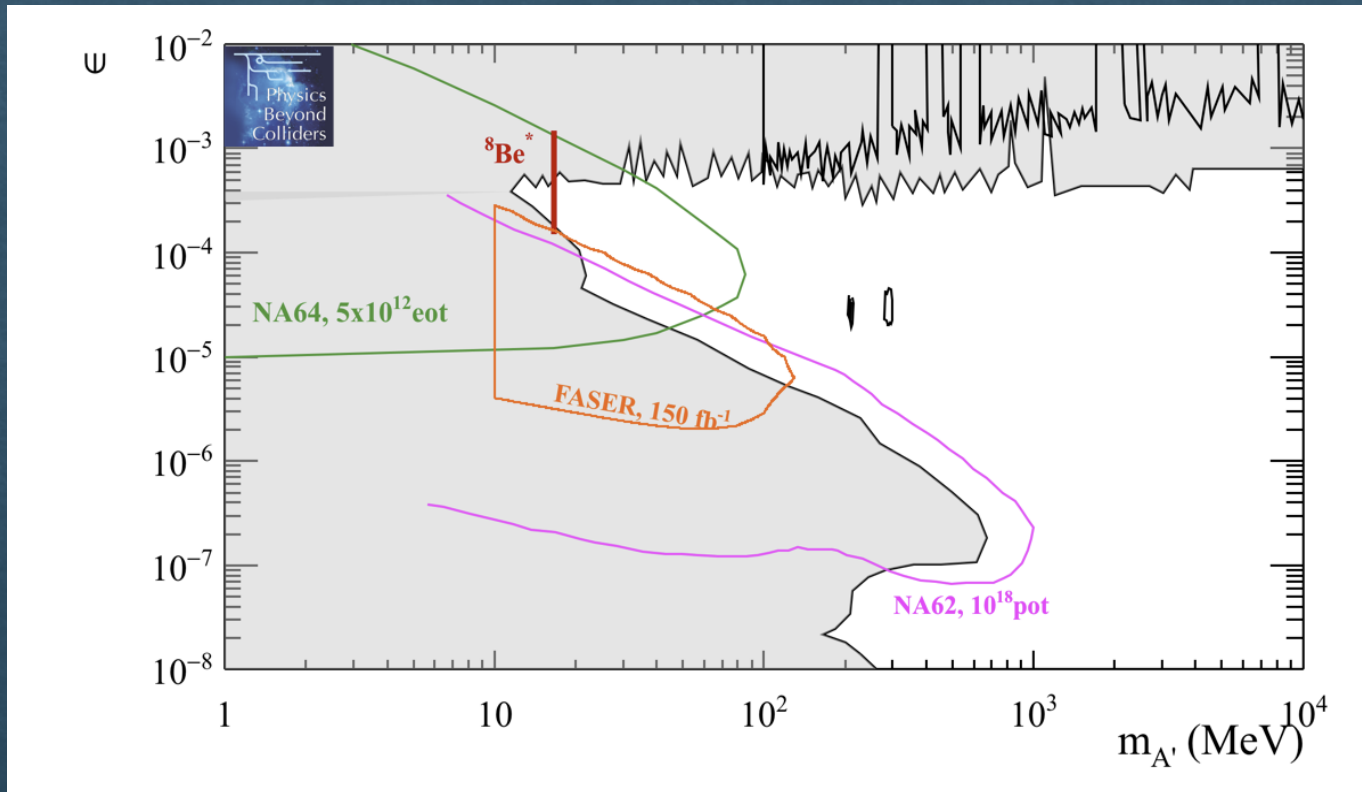


Dark Photon Searches Prospects

◇ Visible decays

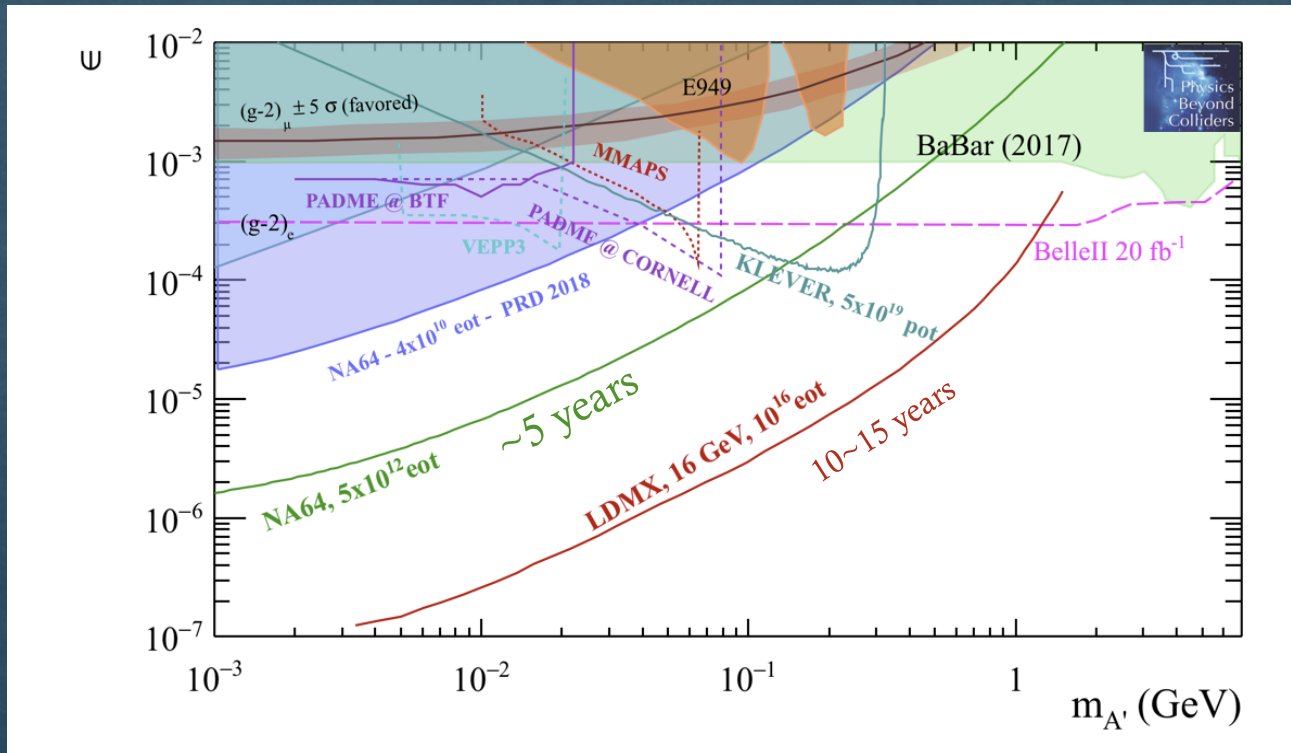


Future of Dark Photon Searches



Dark Photon Searches Prospects

◇ Invisible mode



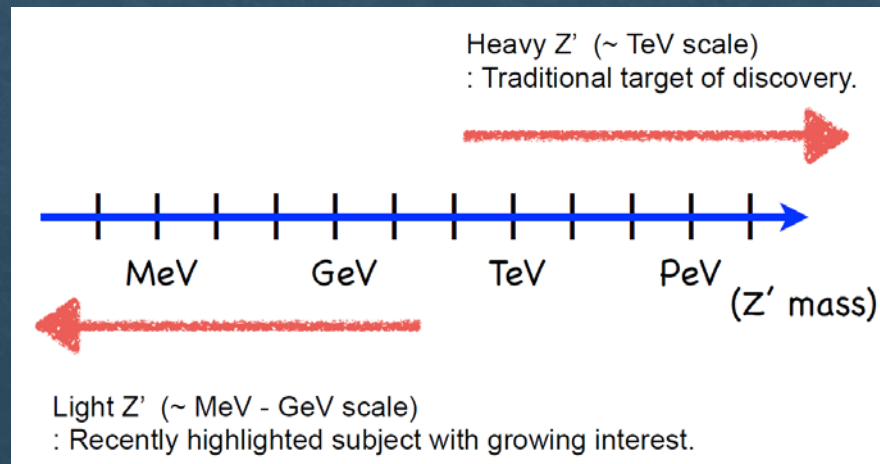
Summary and Outlook

- ◇ Variety of production modes and detection methods employed and $(g - 2)_\mu$ window closed
- ◇ Efforts for LDM search continues with ingenious detection concepts expanding the region that can be probed

Backup

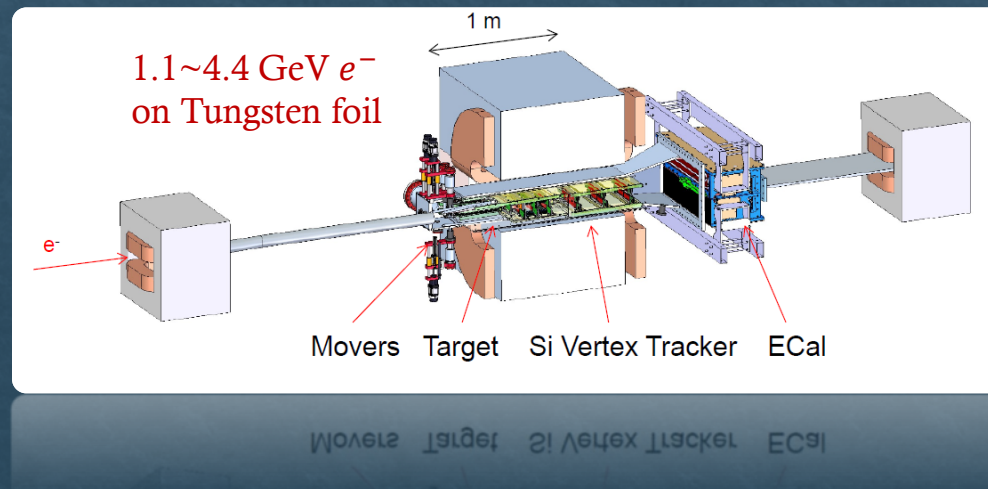
Dark Z

- ◇ Z' - Davoudiasl, Lee, Marciano (2012)
 - ◇ Couples to both photon and Z
 - ◇ Presence of additional terms can interfere and weaken limits from simple dark photon
 - ◇ Parity violation



HPS @ JLAB

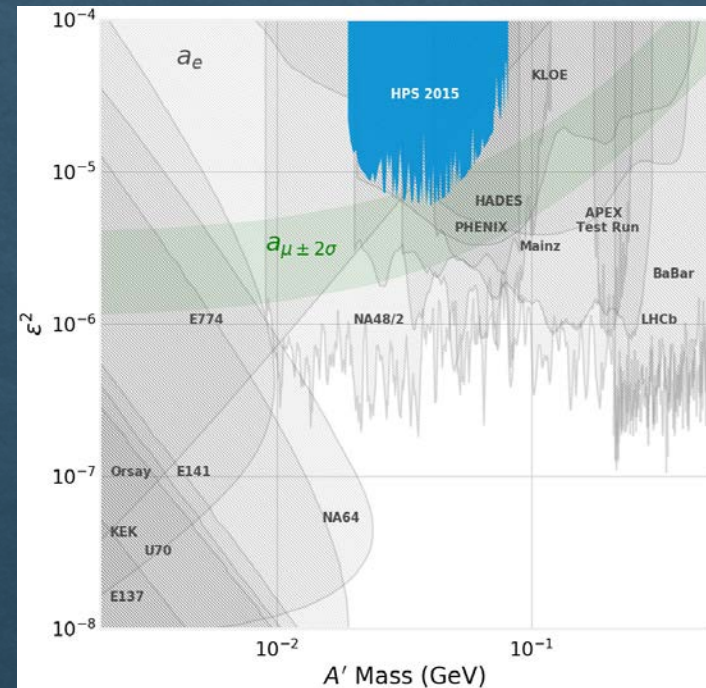
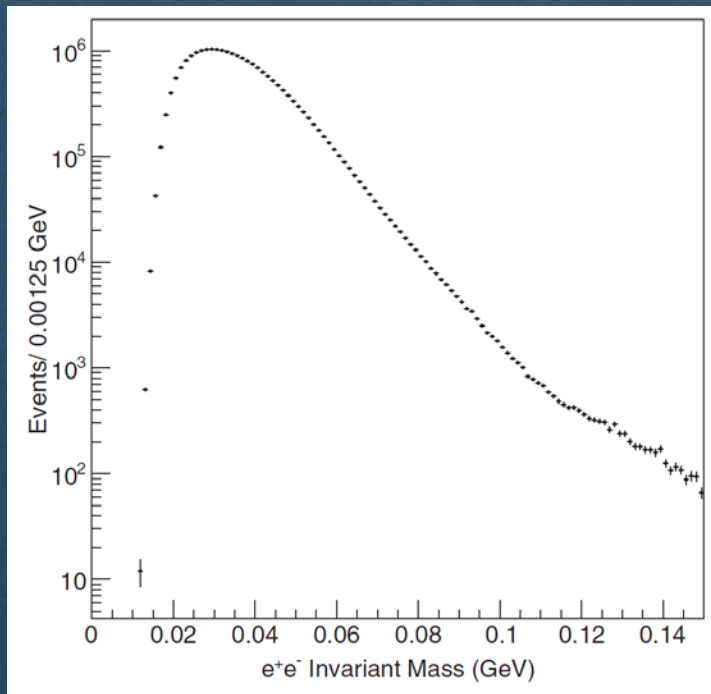
- ◇ Strategy: Bump hunt + displaced vertex
 - ◇ Silicon tracking detector + calorimeter
 - ◇ Good energy resolution ~ 1 MeV
 - ◇ Good vertex position resolution ~ 1 mm



Current Results

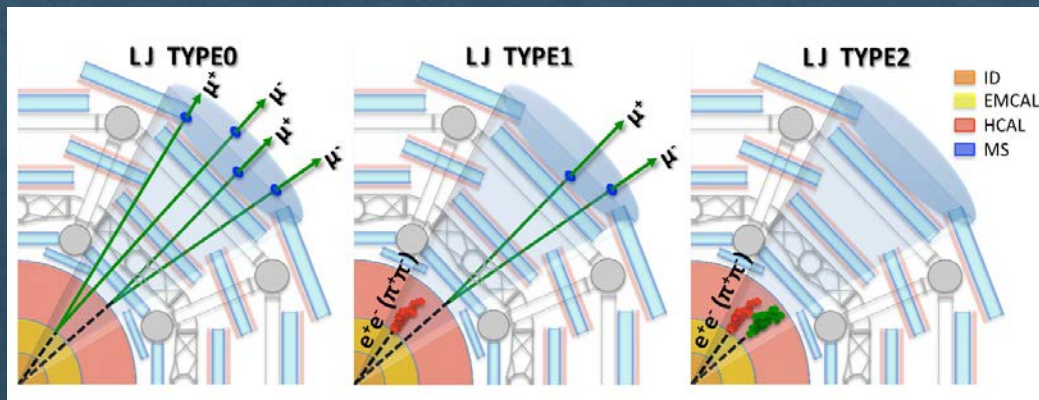
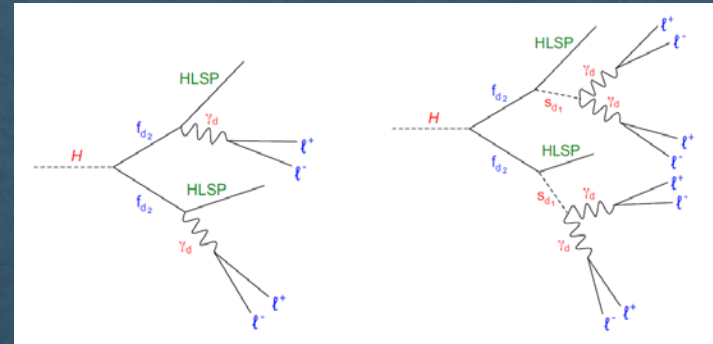
- ◆ Results with 1.7 days of engineering run data

Phys. Rev. D 98, 091101(R)

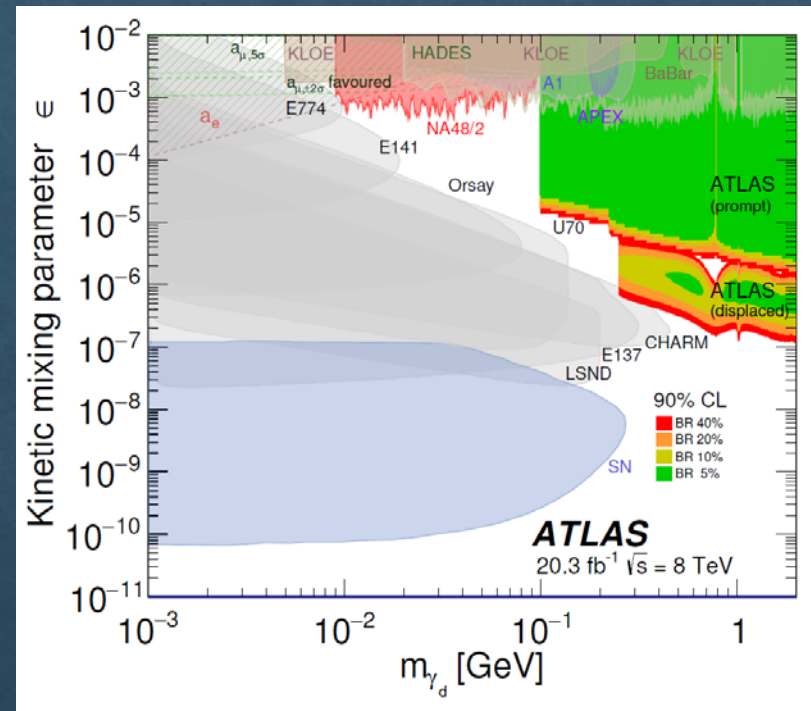
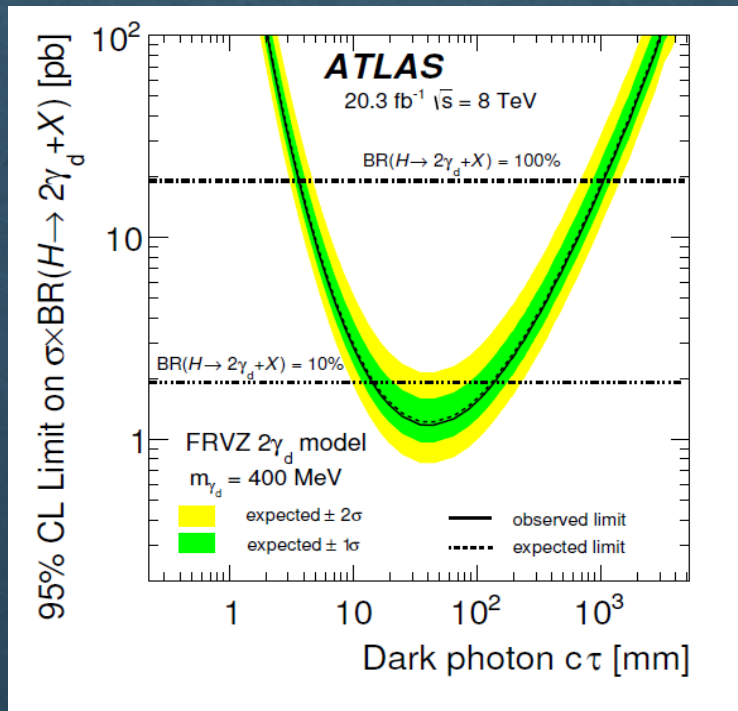


Dark Photon Search at LHC

- ◆ For light dark photons, the leptons from $A' \rightarrow \ell^+ \ell^-$ highly boosted – “lepton jets”
 - ◆ Prompt or non-prompt depending on parameters



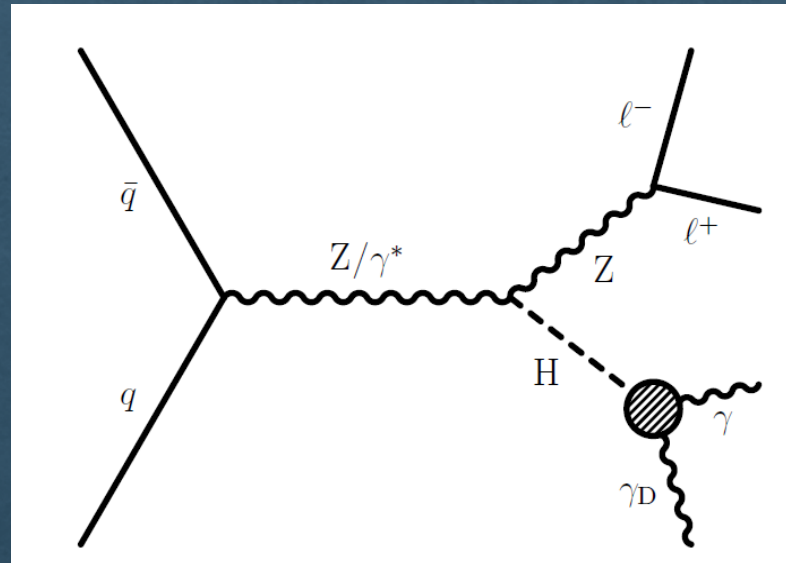
Dark Photon Search at LHC

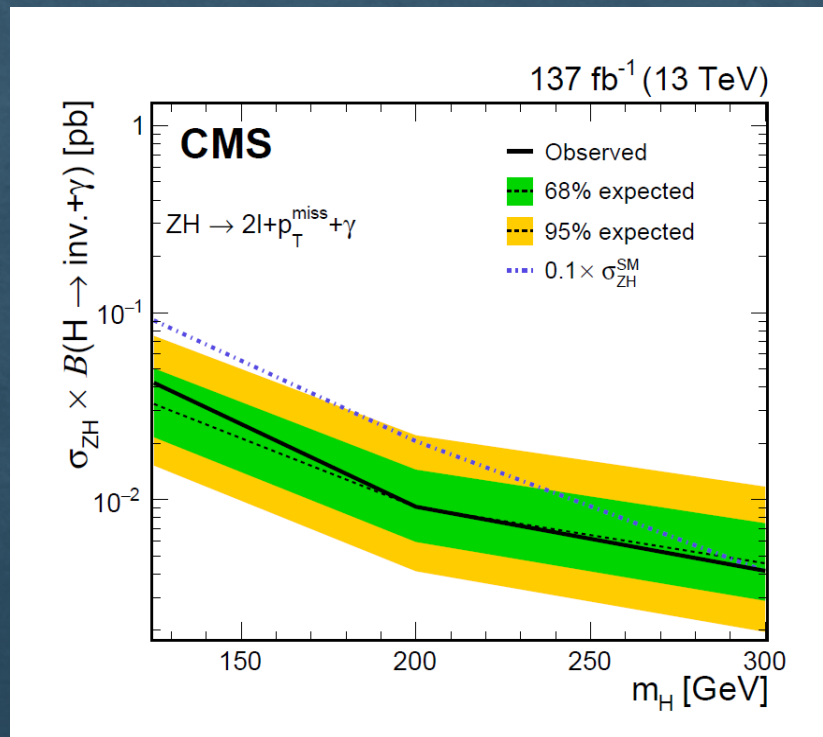
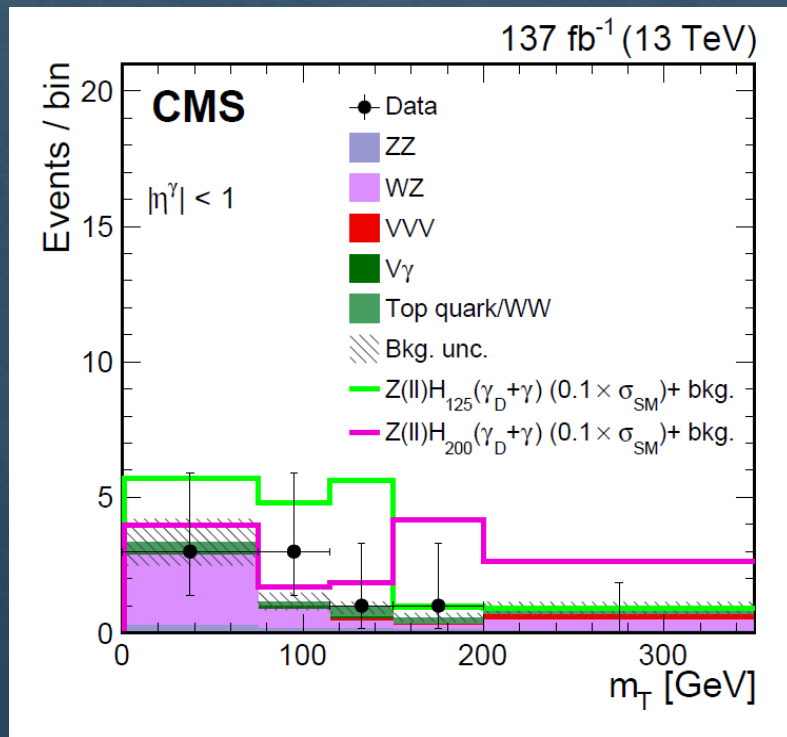


Dark Photon Search in CMS

JHEP 1910 (2019) 139

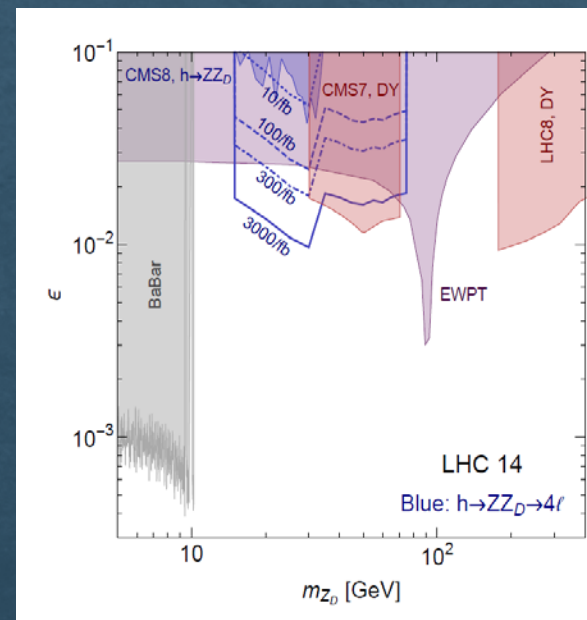
◇ ZH with $H \rightarrow \gamma\gamma_D$





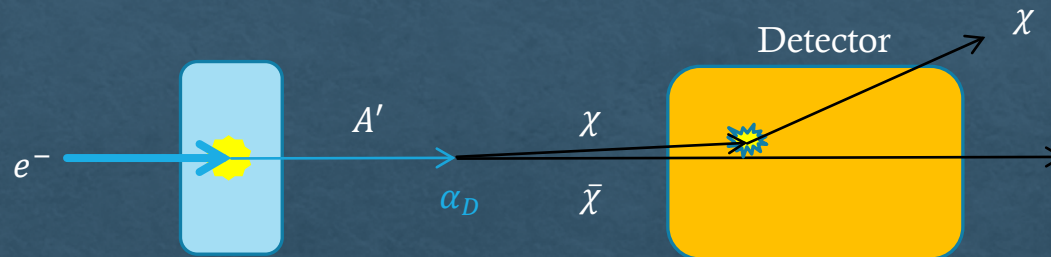
Dark Z Search at LHC

- ◇ $H \rightarrow ZZ_D \rightarrow 4\ell$
 - ◇ Reinterpretation of ZZ^* analysis
- ◇ DY-like $Z_D \rightarrow \ell^+ \ell^-$
 - ◇ Dilepton bump hunt
- ◇ Interesting to look for $H \rightarrow Z_D Z_D$
 - ◇ Experimentally challenging



Invisible Decay Mode

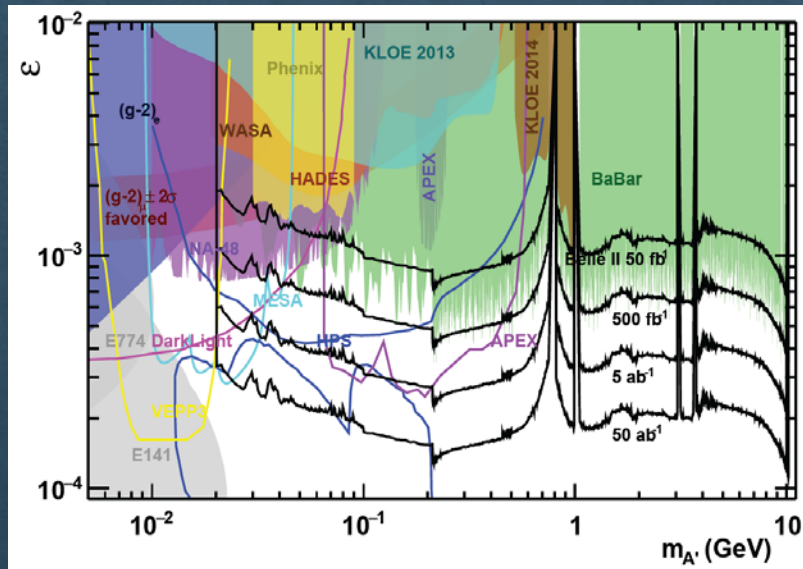
◇ $A' \rightarrow \chi \bar{\chi}$



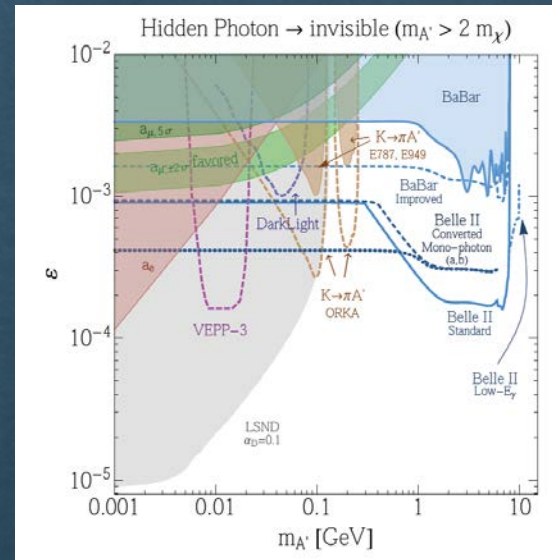
- ◇ If $\alpha_D \gg \alpha \epsilon^2$, A' decays mostly to $\chi \bar{\chi}$ and limits from $A' \rightarrow e^+ e^-$ experiments do not apply
- ◇ Look for weak recoil signal
- ◇ Short lifetime of A' not a problem
- ◇ Due to small $\chi - N$ cross section, detection probability $\sim$ length

Belle II

◇ Visible Mode

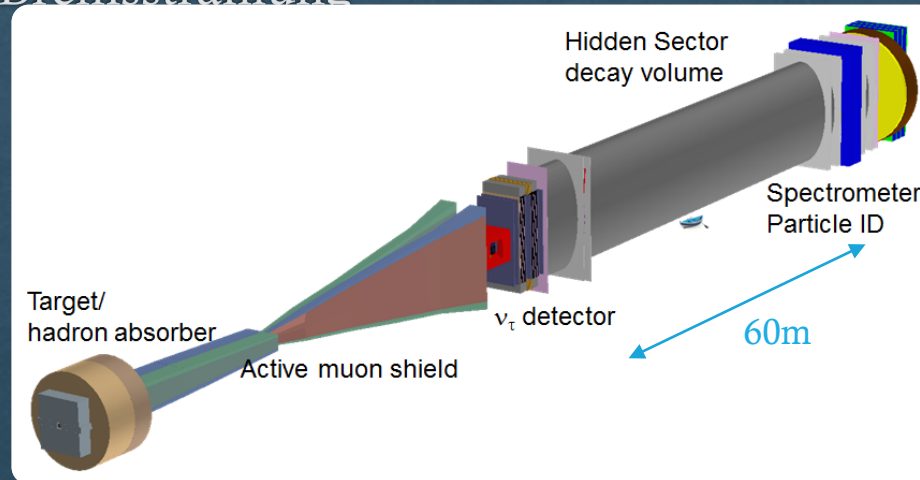


◇ Invisible Mode



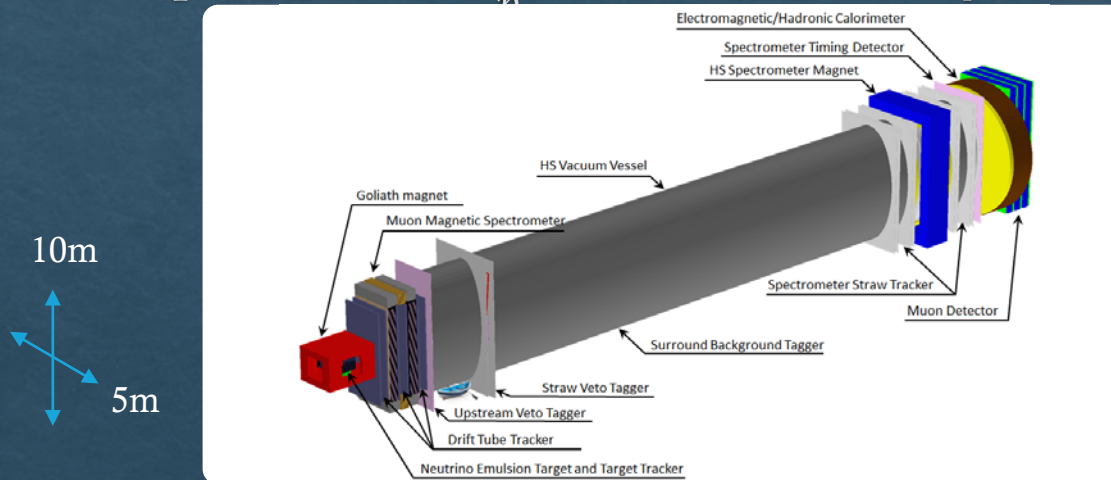
Search for Hidden Particles (SHiP) Experiment at CERN

- ◇ 2×10^{20} 400 GeV proton on target
- ◇ Mode for dark photon searches: $\pi^0, \eta, \eta' \rightarrow \gamma A'$,
p-Bremsstrahlung



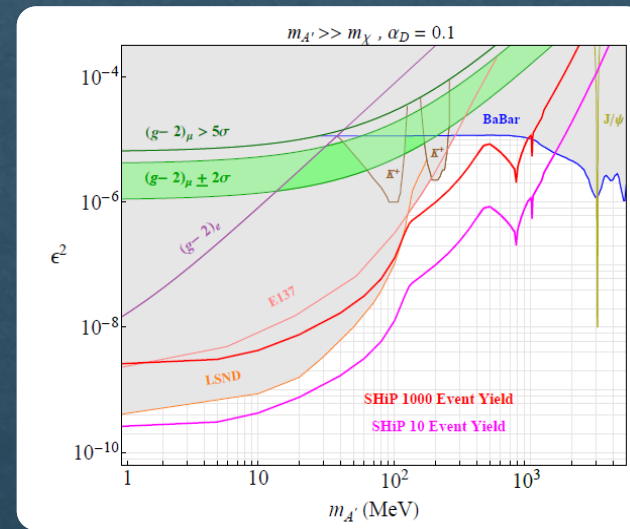
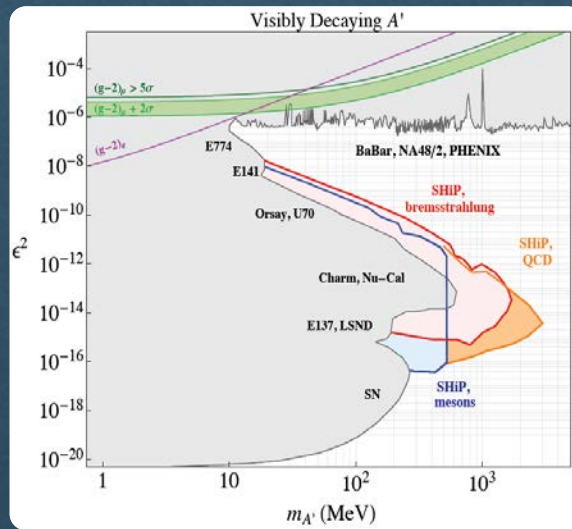
Search for Hidden Particles (SHiP) Experiment at CERN

- ◇ Shashlik EM Calorimeter – $\frac{\sigma_E}{E} \sim \frac{6\%}{\sqrt{E}}$
- ◇ Spectrometer – $\frac{\sigma_p}{p} \sim 0.5\% \oplus 0.022\% p$

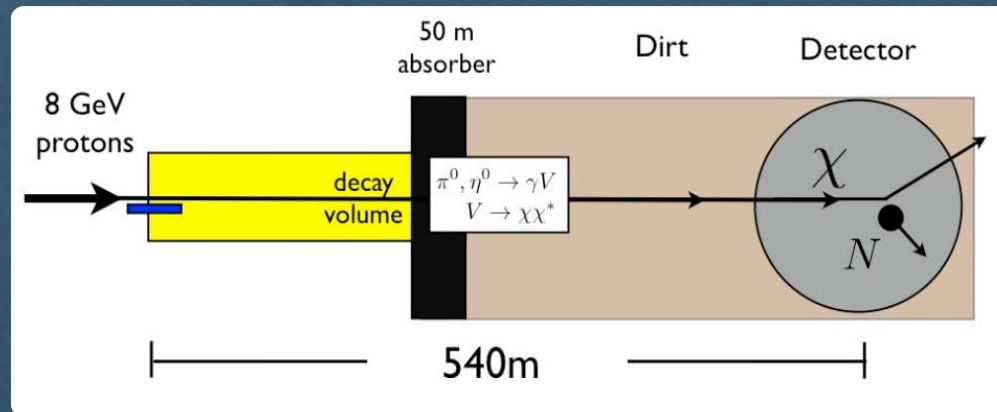


Visibly Decaying Dark Photon - SHiP

◇ Operation expected in 2026



MiniBoone DM



- ◇ Look for $e - \chi$ and $N - \chi$ scatterings
- ◇ Background reduction
 - ◇ Bypass Be target to reduce neutrino backgrounds
 - ◇ Timing information to reduce backgrounds
 - ◇ 10 MeV DM travels slower than neutrinos
- ◇ Run completed in 2014