



THE UNIVERSITY OF BRITISH COLUMBIA



# Searches for feebly interacting particles at non-LHC experiments

---

Christopher Hearty

U. British Columbia / IPP

June 7, 2021

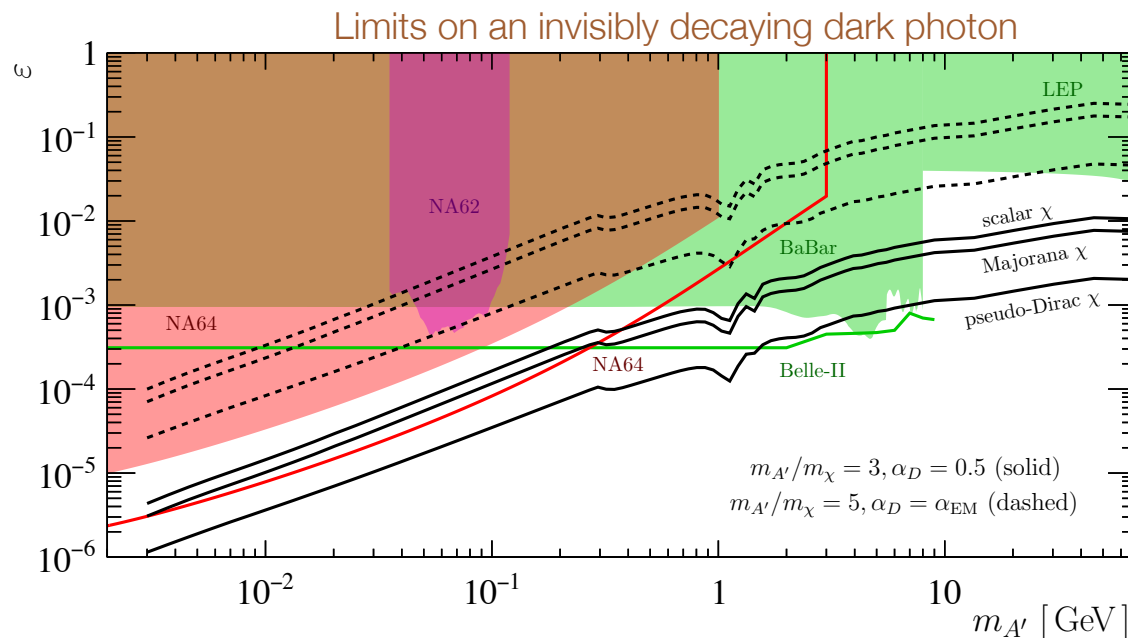
Ninth Annual Large Hadron Collider Physics Conference

*On behalf of the Belle II collaboration*



# The dark sector

- Considerable interest in models with new particles and interactions at low masses that interact minimally with the Standard Model. Explain dark matter, possible other phenomena (e.g., muon  $g-2$ ).
  - various “portals”: dark photons, scalars, neutrinos.



M. Graham, C. Hearty, M. Williams,  
Annu. Rev. Nucl. Part. Sci. 2021. 71:37

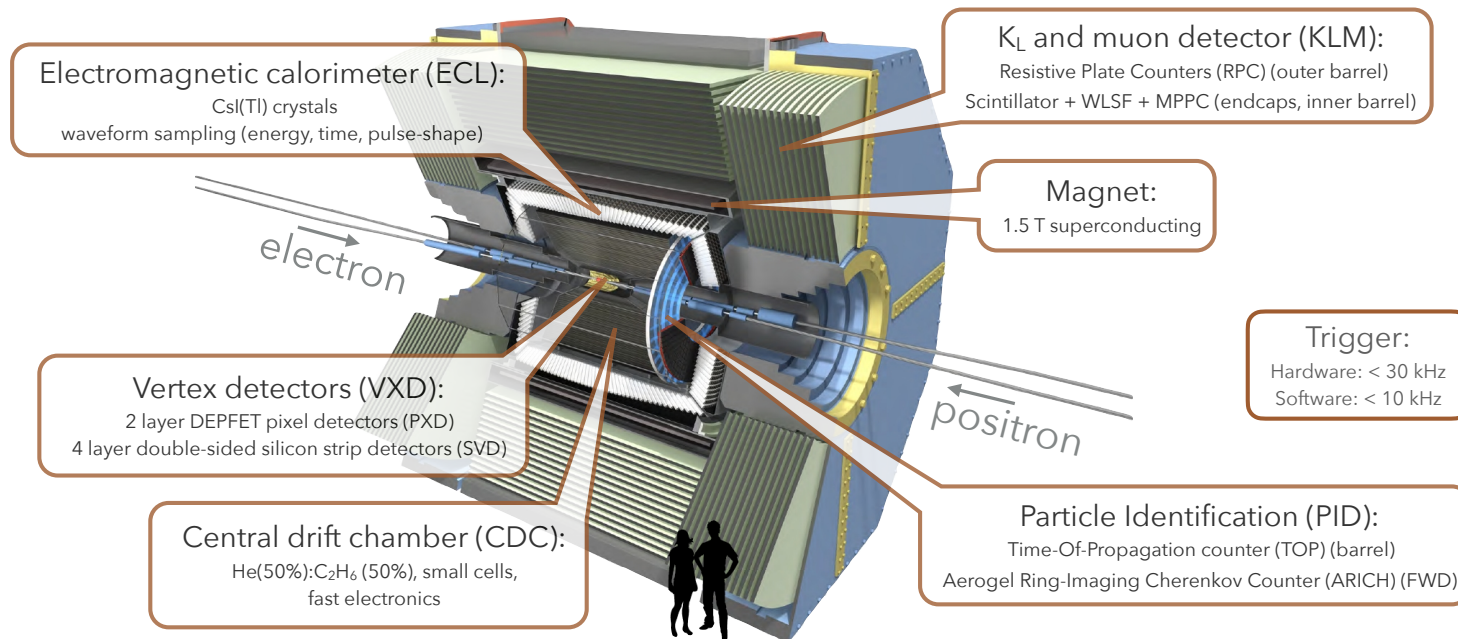
# Non-LHC accelerator-based experiments

---

- Different experimental approaches, but common features enable searches for low-mass, weakly coupled new particles:
  - low particle multiplicity;
  - well defined initial state
    - single electron, single meson,  $e^+e^-$  annihilation;
  - good acceptance  $\Rightarrow$  sensitive to small missing masses.
- Signatures: bumps in invariant mass or missing mass; displaced vertices.

# Belle II

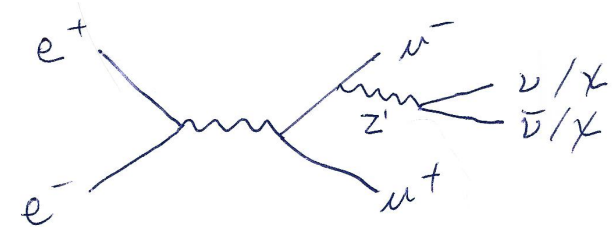
- Located at the SuperKEKB  $e^+e^-$  collider in Japan. Operates at  $\sqrt{s} = 10.58$  GeV ( $\Upsilon(4S)$ ).
- Collecting data since 2019. Luminosity goal is  $50 \text{ ab}^{-1}$  (50x Belle), but only  $0.2 \text{ ab}^{-1}$  so far.





# Belle II: Search for an invisibly decaying $Z'$

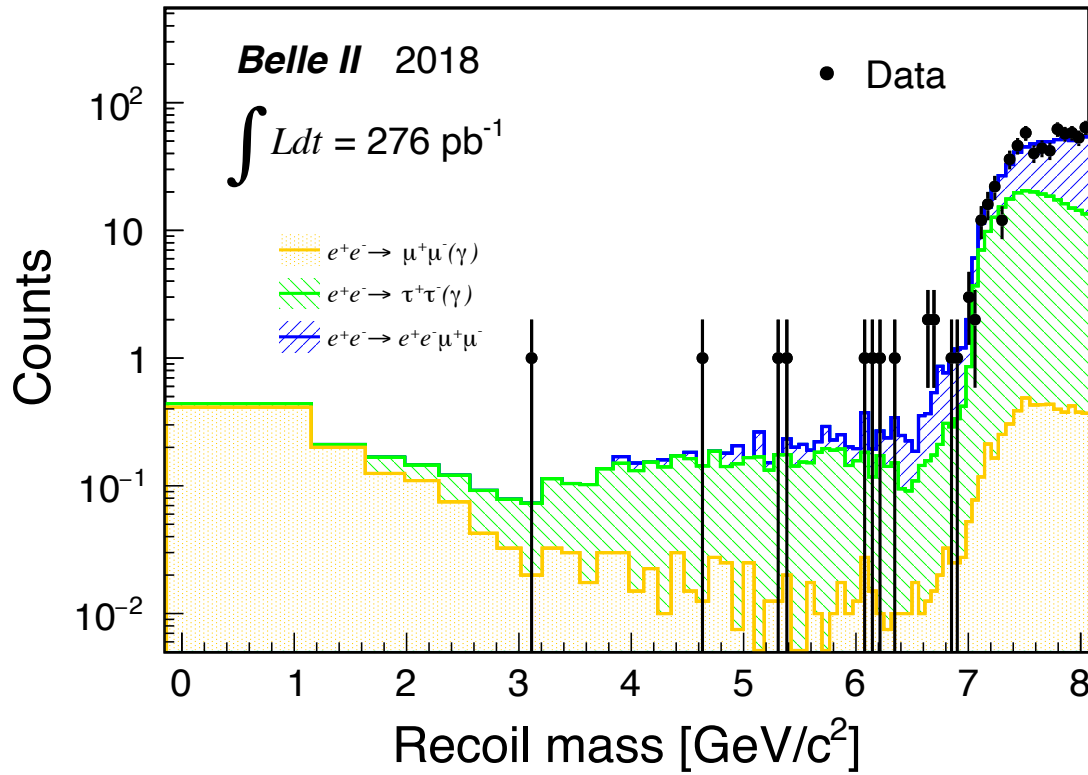
- New vector boson  $Z'$  with SM couplings only to  $\mu$ ,  $\tau$ ,  $\nu_\mu$ , and  $\nu_\tau$ . Could explain muon-related deviations from SM.



BaBar & CMS looked for  $Z' \rightarrow \mu^+\mu^-$

- Signature: pair of muons with peak in missing mass distributions.
- Backgrounds:  $e^+e^- \rightarrow \mu^+\mu^-\gamma$  at low mass,  $e^+e^- \rightarrow \tau^+\tau^-$ , with  $\tau \rightarrow \mu \nu \bar{\nu}$  otherwise.

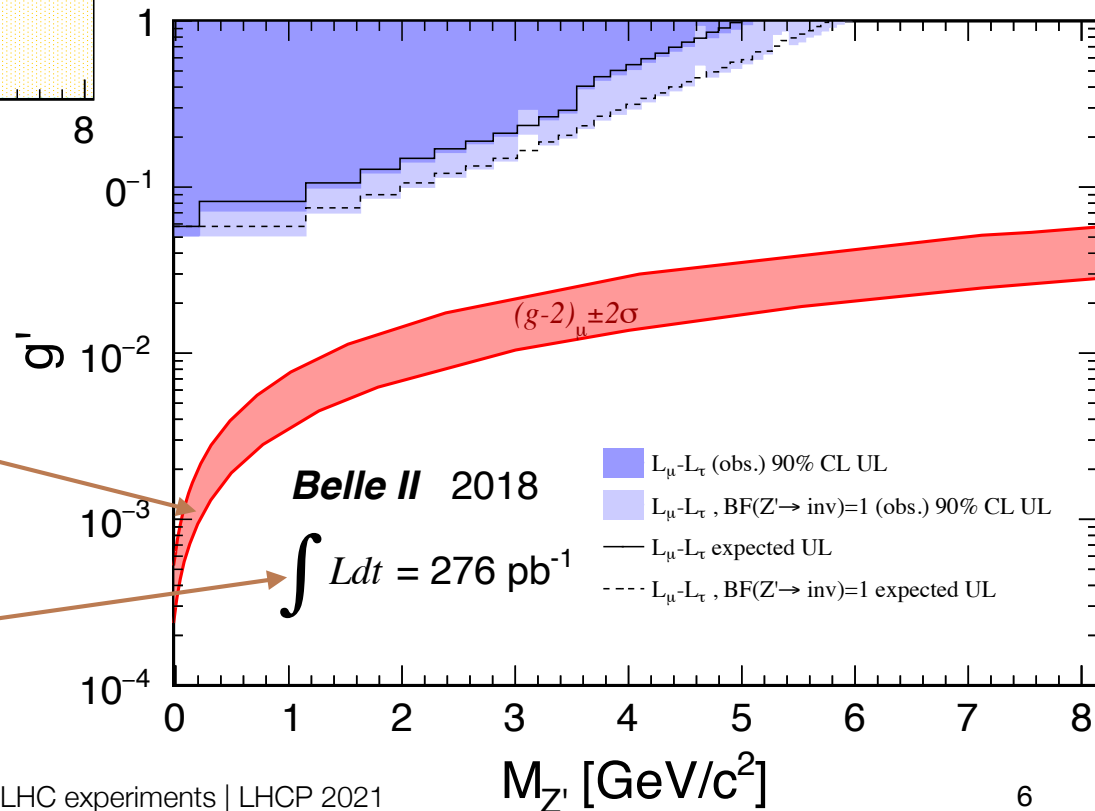
missed



observed events are consistent with expected tau pair background

parameter space that would explain muon  $g-2$

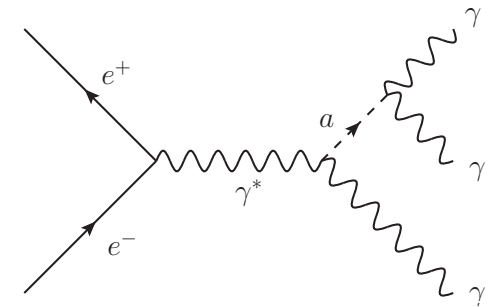
data from commissioning run only



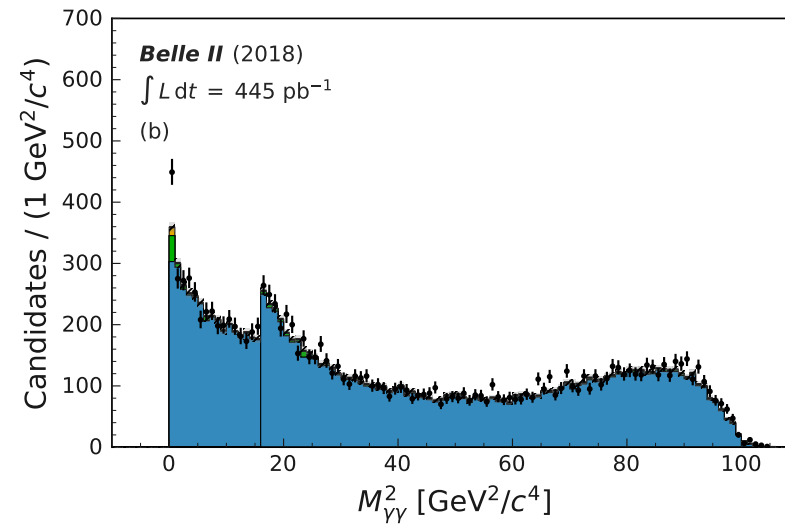
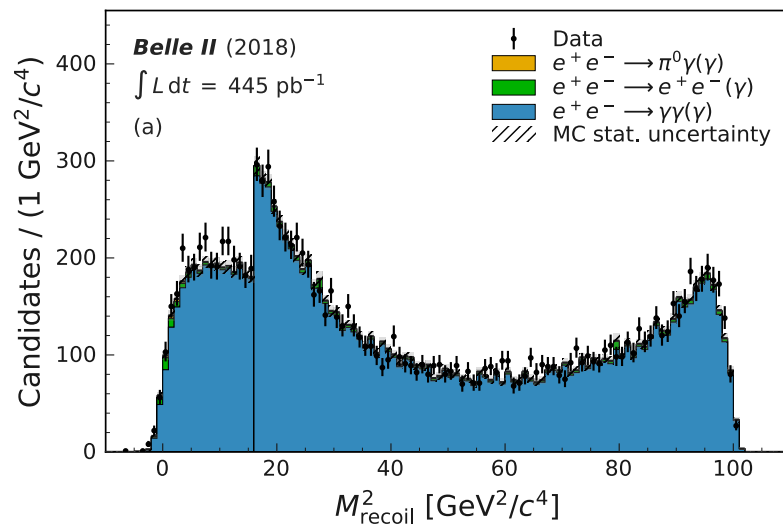


# Belle II: Search for axion-like particles

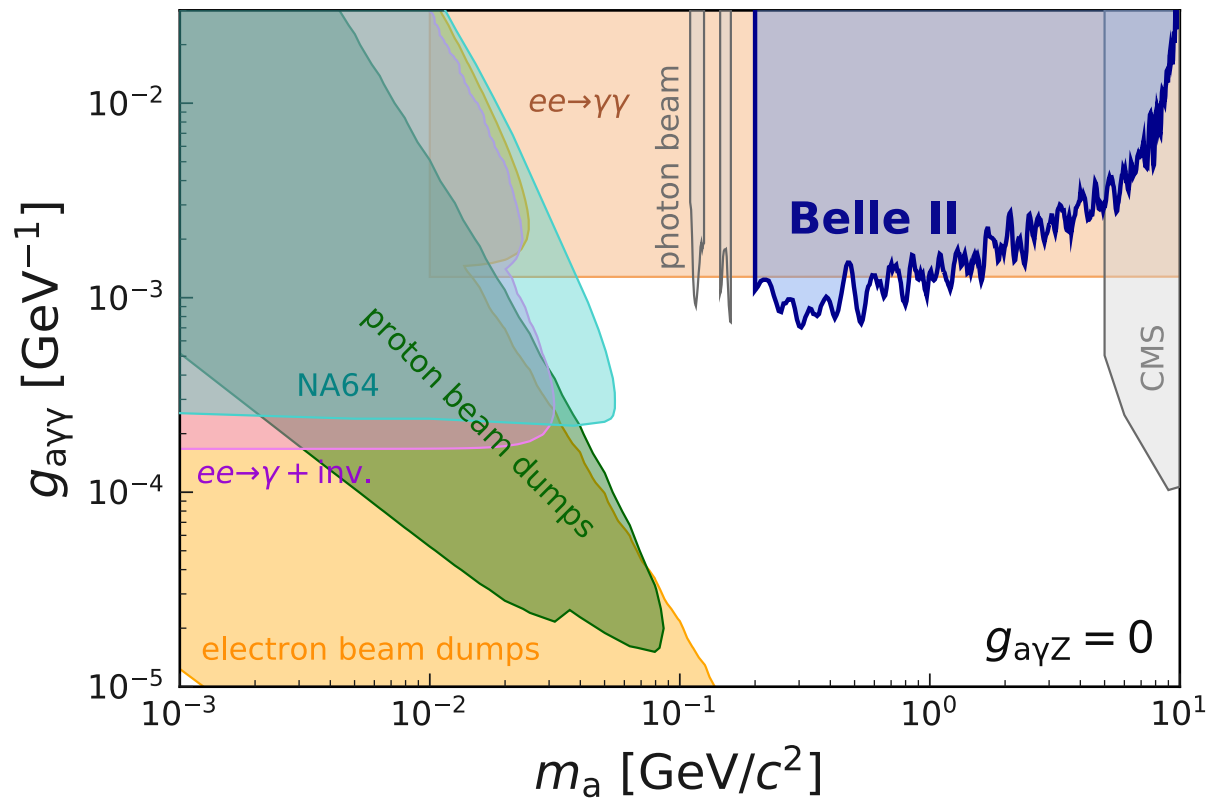
- Pseudoscalar, with couplings to gauge bosons. Photons, in this case.
- $3\gamma$  adding up to full center-of-mass energy; 2 of which add up to axion-like-particle mass. Large background from  $e^+e^- \rightarrow \gamma\gamma\gamma$ , but no  $2\gamma$  peak.



M. Dolan et al, JHEP 12 (2017), 094



- Exclusion limits are complementary to those from NA64 (later)



Belle II limits using  
1/10,000th of  
final data set



# NA64 — electron beam fixed target experiment

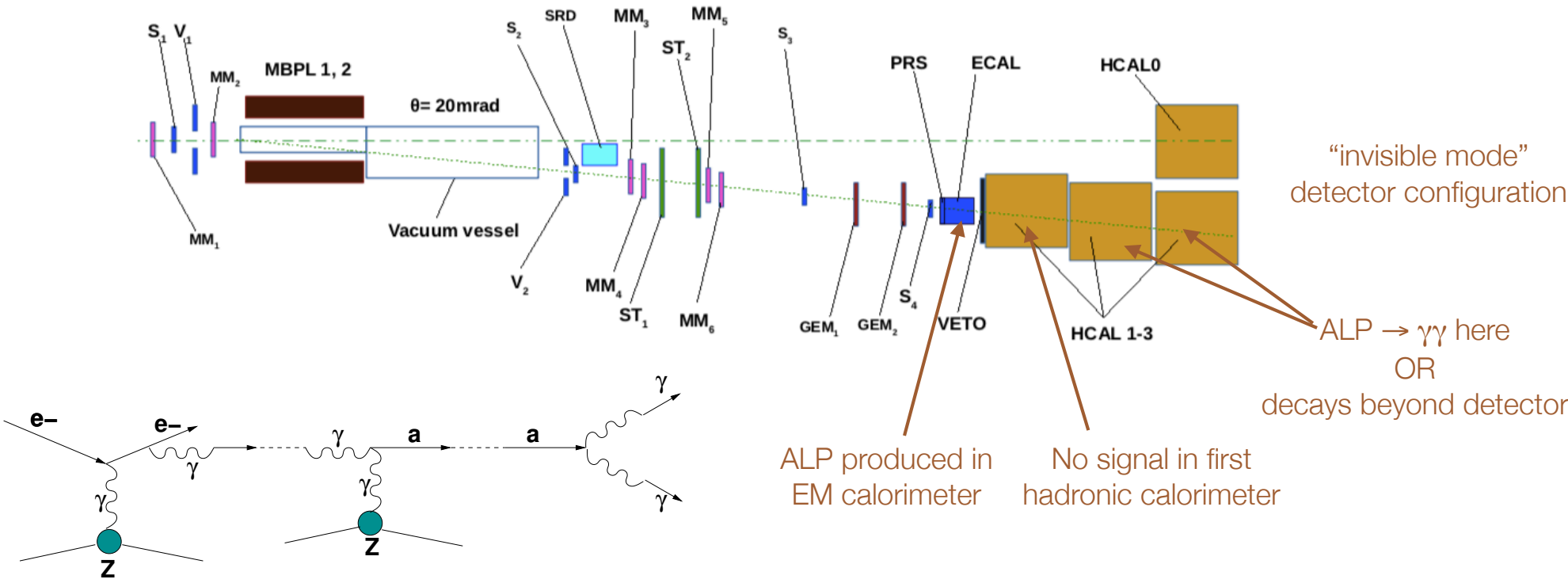


- Searches for new light particles produced in electron interactions in an active target.
- 100 GeV or 150 GeV  $e^-$  beam, CERN SPS; two detector configurations.
- Earlier results include unique limits on dark photons:
  - invisible decays [PRL 123, 121801 \(2019\)](#)
  - decays to  $e^+e^-$ , [PRD 101, 071101R \(2020\)](#)
    - relevant for ATOMKI anomaly (peak in  $e^+e^-$  spectrum in decays of  $^8\text{Be}^*$  nuclei).

# NA64: Search for axion-like particle (ALP) decaying to two photons



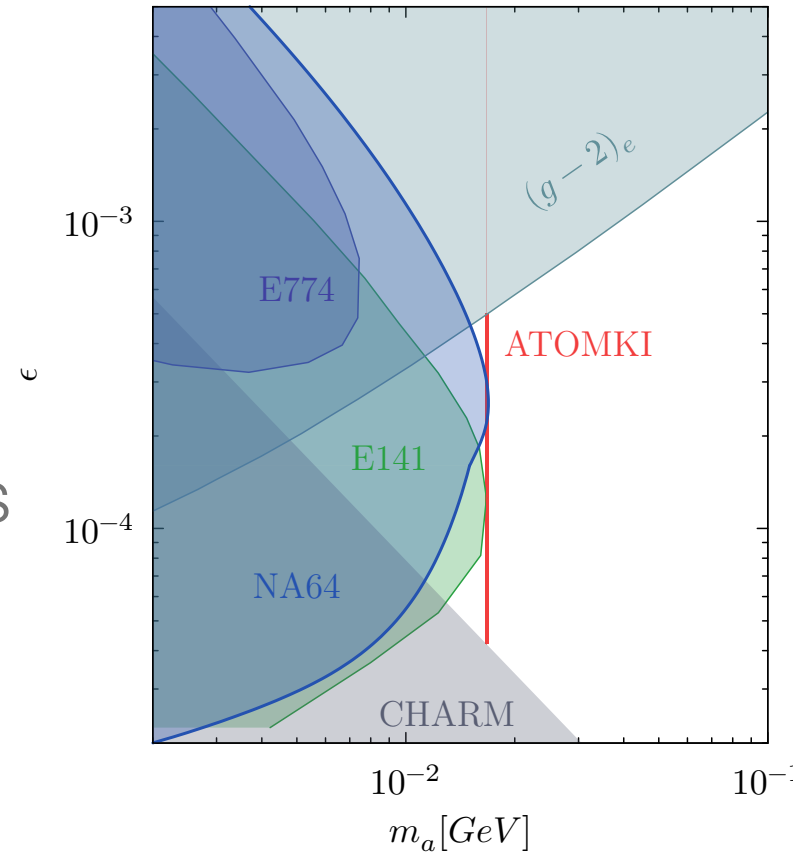
- $2.84 \times 10^{11}$  100 GeV  $e^-$  on target, 2016–2018.



- Expect  $<1$  event from  $K^0$  decays to  $\pi^0$  in HCAL; no events seen. See earlier Belle II plot for limits.



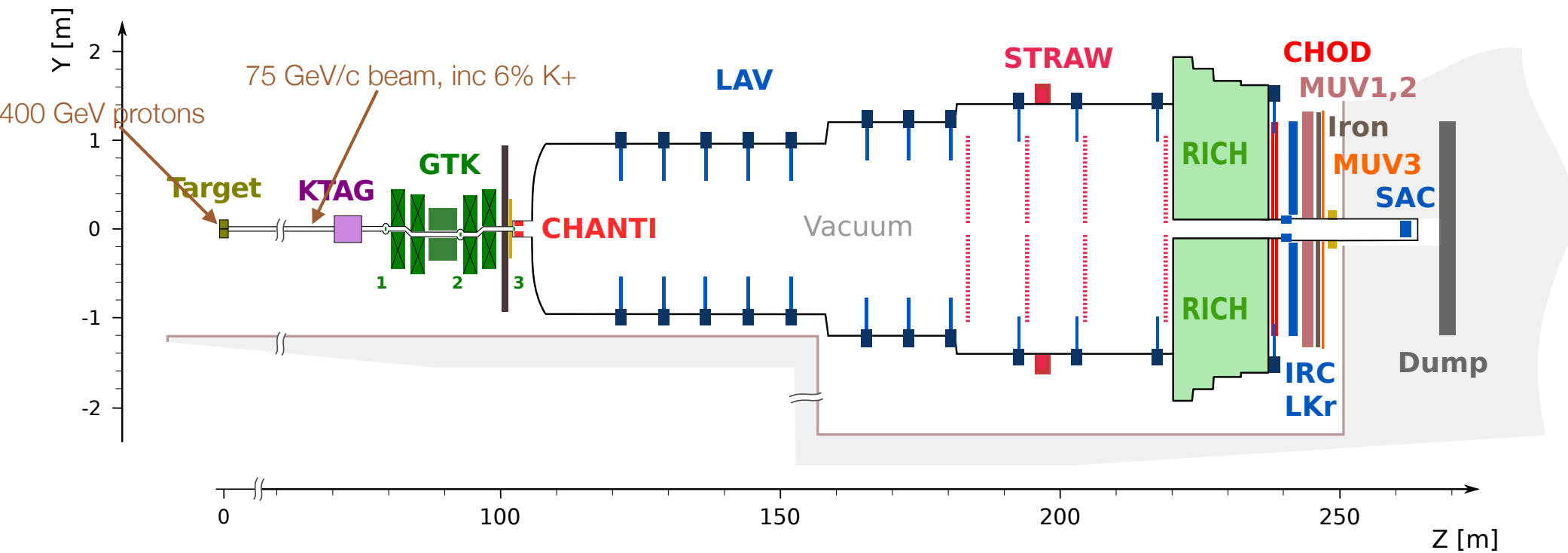
- Limits approaching ATOMKI region.
- Variety of improvements after LS2:
  - 200 GeV beam to increase boost, so that dark photon decays occur beyond the target;
  - thinner WCAL;
  - dipole magnet to separate  $e^+e^-$  decay products;
  - test running with muon beam.



# NA62



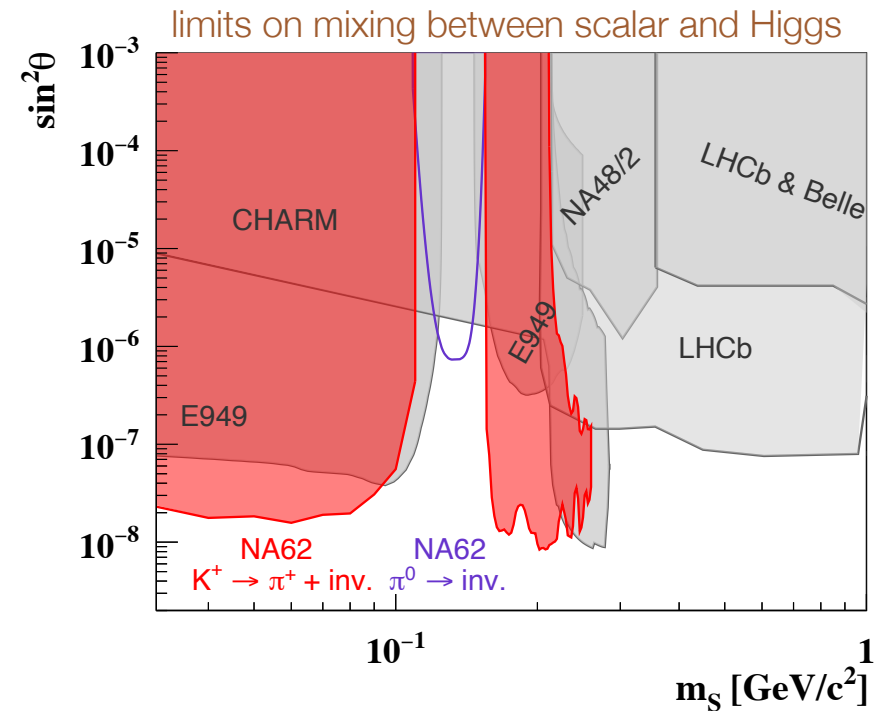
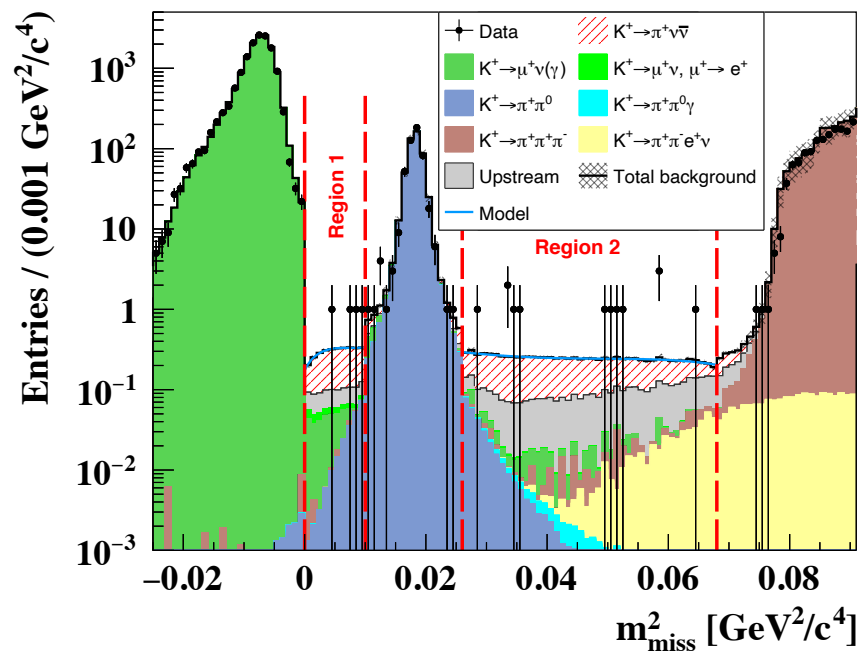
- Located in the CERN SPS; studies the ultra-rare decay  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ , but good sensitivity to new particles produced in decays of kaons or pions.



# NA62: $K^+ \rightarrow \pi^+ X$ , $X \rightarrow$ invisible scalar/pseudoscalar



- Single  $\pi^+$  (just like  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ), but monoenergetic in  $K^+$  rest frame  $\Rightarrow$  peak in  $m_{miss}^2$ .
  - largest background is  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ .
  - $2.7 \times 10^{12}$   $K^+$  in fiducial volume.



NA62:  $K^+ \rightarrow \pi^+ \pi^0$ ,  $\pi^0 \rightarrow$  invisible, or  
 $K^+ \rightarrow \pi^+ X$ ,  $X \rightarrow$  invisible

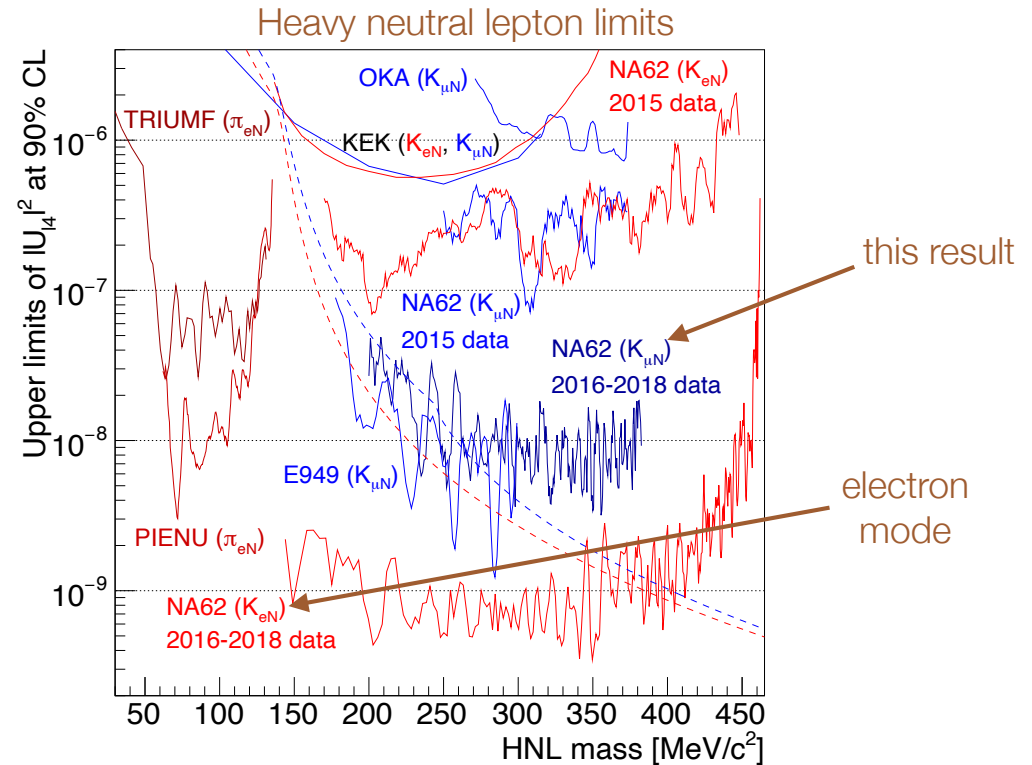
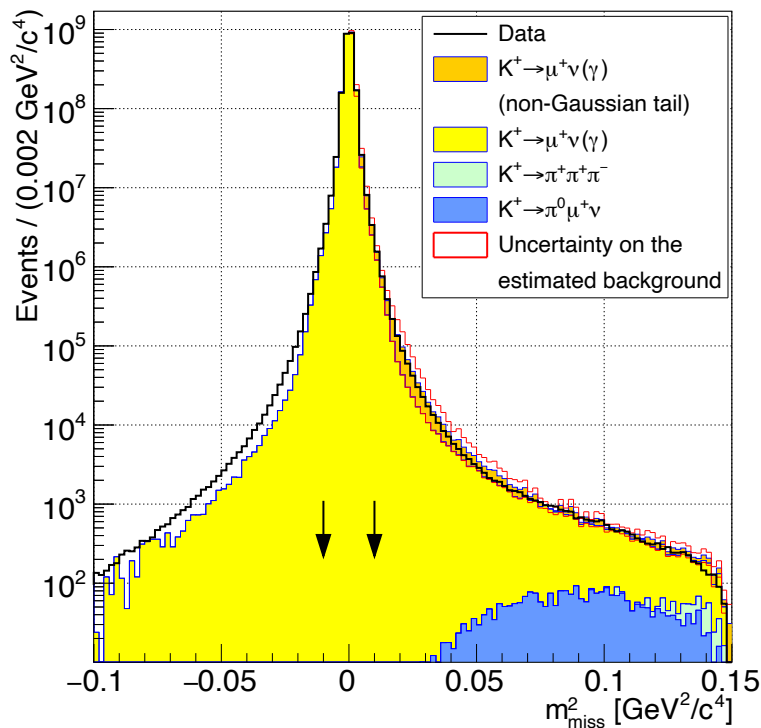


- 2017 data;  $4 \times 10^9$   $\pi^0$  tagged using  $\pi^+$  momentum.
- Excellent hermeticity: expect  $10_{-8}^{+22}$   $\pi^+ \pi^0$  events where the  $\pi^0$  decay is missed for  $25 < p_{\pi^+} < 40$  GeV/c; observe 12  
 $\Rightarrow B(\pi^0 \rightarrow \text{invisible}) < 4.4 \times 10^{-9}$ .



# NA62: $K^+ \rightarrow \mu^+$ invisible

- 2016–2018 data set, prescaled trigger:  $1.1 \times 10^{10} K^+$ .
- $K^+ \rightarrow \mu^+ \nu_\mu$        $K^+ \rightarrow \mu^+ N$       Heavy neutral lepton
- $K^+ \rightarrow \mu^+ \nu_\mu \nu \bar{\nu}$        $K^+ \rightarrow \mu^+ \nu_\mu X$       dark photon or scalar

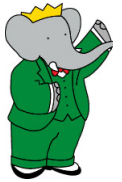




# BaBar

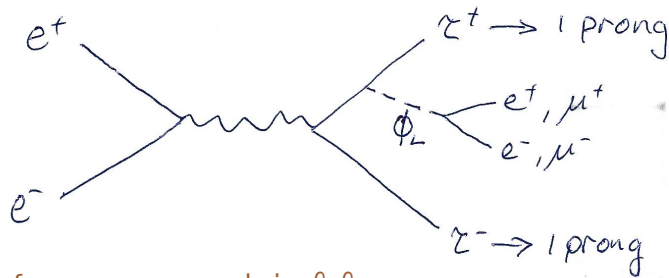


- 
- Recorded  $514 \text{ fb}^{-1}$  of data 1999–2008 at the PEP-II  $e^+e^-$  collider. Mostly  $Y(4S)$ , also  $Y(2S)$  and  $Y(3S)$ .
  - Still producing interesting and unique physics results.



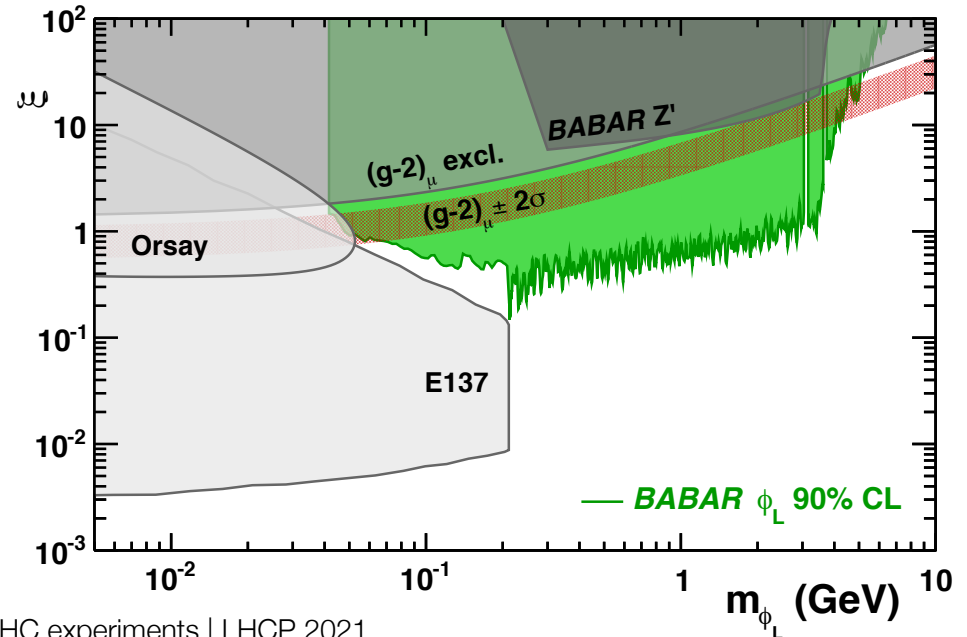
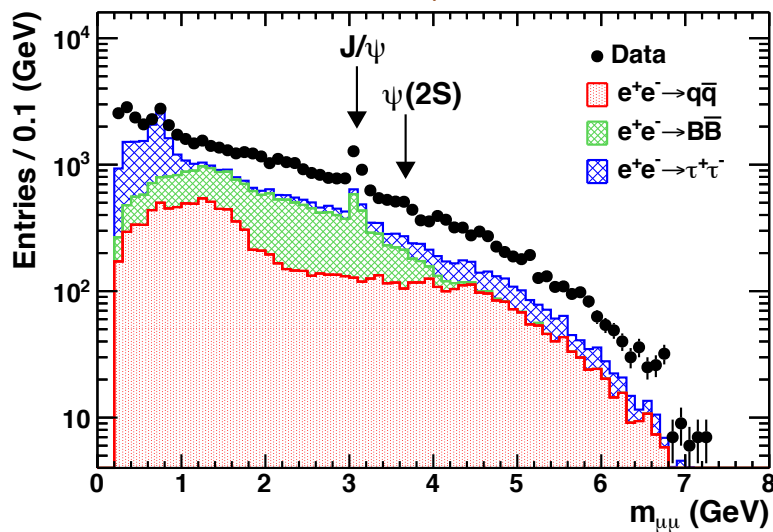
# BaBar: Search for a dark leptophilic scalar

- Dark scalar mixes with Higgs  $\Rightarrow$  couplings depend on mass. Suppress couplings to quarks to evade limits from flavour-changing neutral current processes  $B \rightarrow K X$ .

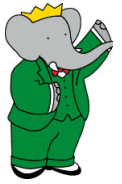


4 tracks and missing energy.  
Prompt decay to  $\mu \mu$ ;  
 $e e$  is possibly displaced.

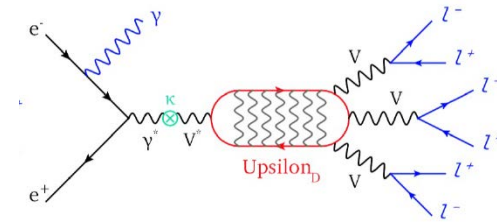
search for narrow peak in  $\ell \ell$  mass



# BaBar preliminary: search for darkonium in $e^+e^-$ collisions



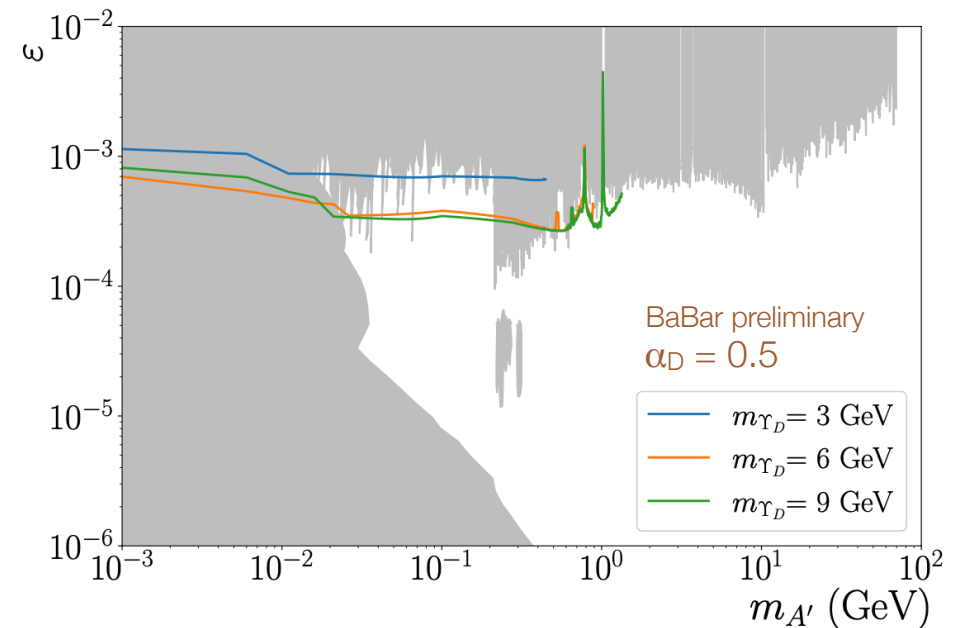
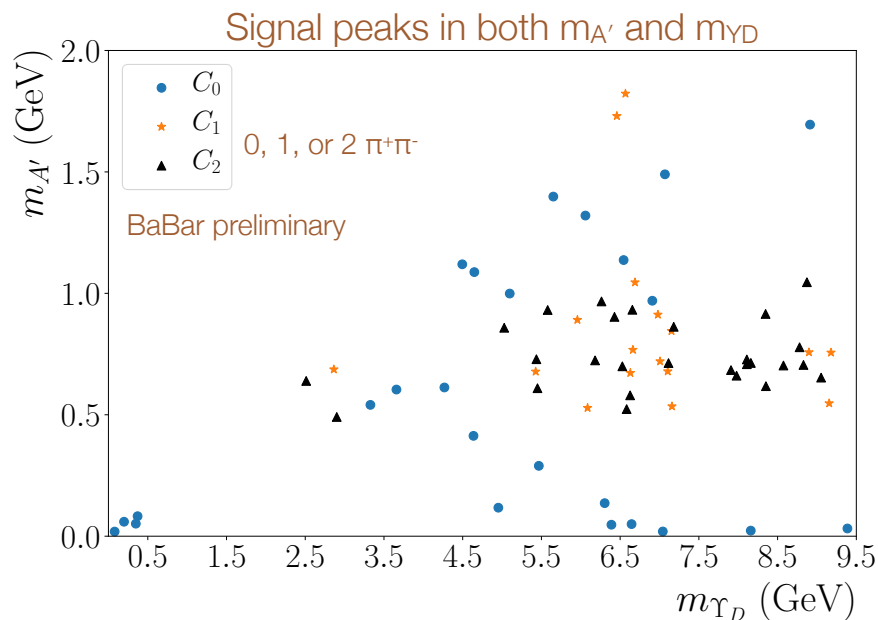
- Dark Dirac fermion  $\chi$  couples to dark photon  $A'$ . Sufficiently low  $m_{A'}$  and large enough coupling  $\Rightarrow \chi\bar{\chi}$  bound states  $\eta_D$  and  $Y_D$ .



An et al., PRL 116 (1026) 151801

$$e^+e^- \rightarrow \gamma Y_D, Y_D \rightarrow A'A'A', A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$$

may or may not be reconstructed



# Summary

---

- Very active and wide-ranging program of searches for feebly interacting particles at non-LHC experiments.
  - the nine papers I presented today are a subset of the results from the past year.
- These experiments are sensitive to regions of parameter space that would explain dark matter or other SM anomalies. Many new results over the next few years.

If you would like to talk during the upcoming coffee break:

<https://ubc.zoom.us/j/62966284139?pwd=Wjd5OWgxTkkvdlpTUlZLbkpiaUJXdz09>

Meeting ID: 629 6628 4139

Passcode: 671914