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Search for Darkonium at BaBar

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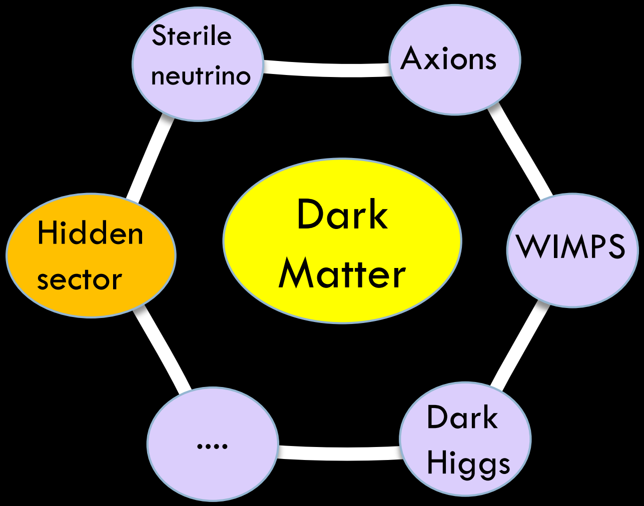
Hidden sector with vector portal

- Astrophysical and Cosmological observations support the existence of Dark Matter

- **Hidden Sector**: new particles that couple very weakly to the SM world via “portals”

↓

mass below electro-weak scale:
direct signature



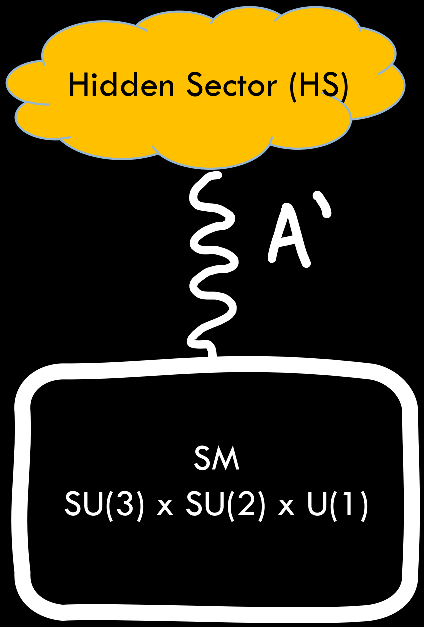
- Interaction Lagrangian in the so-called portal framework:

$$\mathcal{L}_{portal} = \sum O_{SM} \times O_{DS}$$

O_{SM}: operator composed from SM fields
O_{DS}: operator composed from dark sector fields

- One of lowest dimensional vector portal includes a new gauge boson: the Dark Photon (A’)

Hidden sector with vector portal



Hidden Sector (HS)

A'

SM

SU(3) x SU(2) x U(1)

- Vector portal model: includes interaction with light new vector particles. Such particles result from extra gauge symmetry of BSM physics

J. Phys. G **47**,010501

kinetic mixing parameter

Most Minimal Vector Portal interaction:

$$\mathcal{L}_{vector} = \mathcal{L}_{SM} + \mathcal{L}_{DS} - \frac{\epsilon}{2} F_{\mu\nu} A'^{\mu\nu}$$

Dark field Lagrangian that may include new matter fields χ charged under U(1) gauge group

field strength of A' which couples to the SM hypercharge field

- If $m_{A'} < 2m_{\chi}$, the A' decays visibly into a pair of SM particles
- Dark photon lifetime could be sufficiently large to produce displaced decay vertices:

$$l_{lab} = \gamma\beta c\tau = \frac{p}{m_{A'}^2} \cdot \frac{3\hbar c}{\alpha\epsilon^2}$$

if $m_{A'} = 10\,\mathrm{MeV}/c^2$ and $\epsilon = 10^{-4} \Longrightarrow l_{lab} = 0.2\mathrm{m}$

Dark Matter Bound States in Hidden Sector

- A specific minimal Dark Sector model contains a single Dirac fermion χ:

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\chi} i \gamma^{\mu} (\partial_{\mu} - i g_D A'_{\mu}) \chi - m_{\chi} \bar{\chi} \chi - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} - \frac{\epsilon}{2} F_{\mu\nu} A'^{\mu\nu} + \frac{1}{2} m^2_{A'} A'_{\mu} A'^{\mu}$$

coupling constant: $\alpha_D = \frac{g_D^2}{4\pi}$

PRL**116**, 151801

- g_D sufficiently large: the force between the dark fermions mediated becomes attractive, resulting in the formation of dark matter bound state $\chi\bar{\chi}$ (darkonium)
- The existence of stable bound states requires $1.68 m_{A'} \leq \alpha_D m_\chi$ Phys.Rev.A**1**, 1577
- Within this model, one of the lowest bound state is $\Upsilon_D(J^{PC} = 1^{--})$. Its quantum numbers suggest the following production and decay mechanisms at e^+e^- colliders *:

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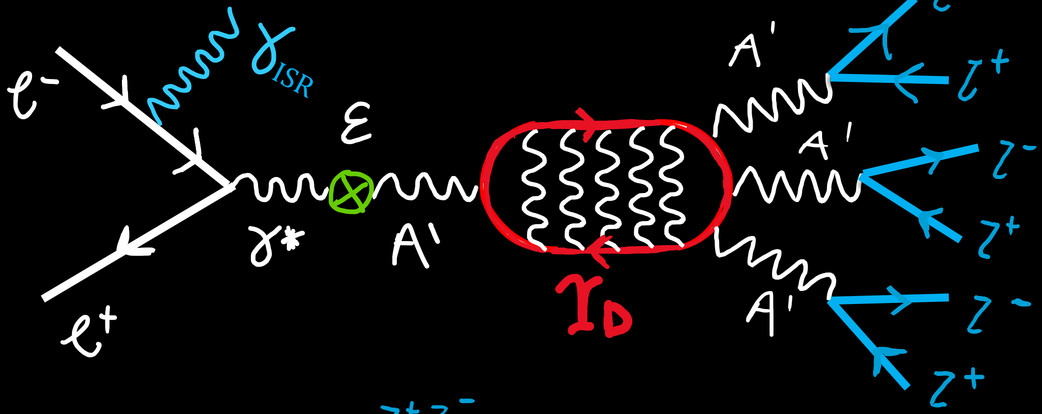
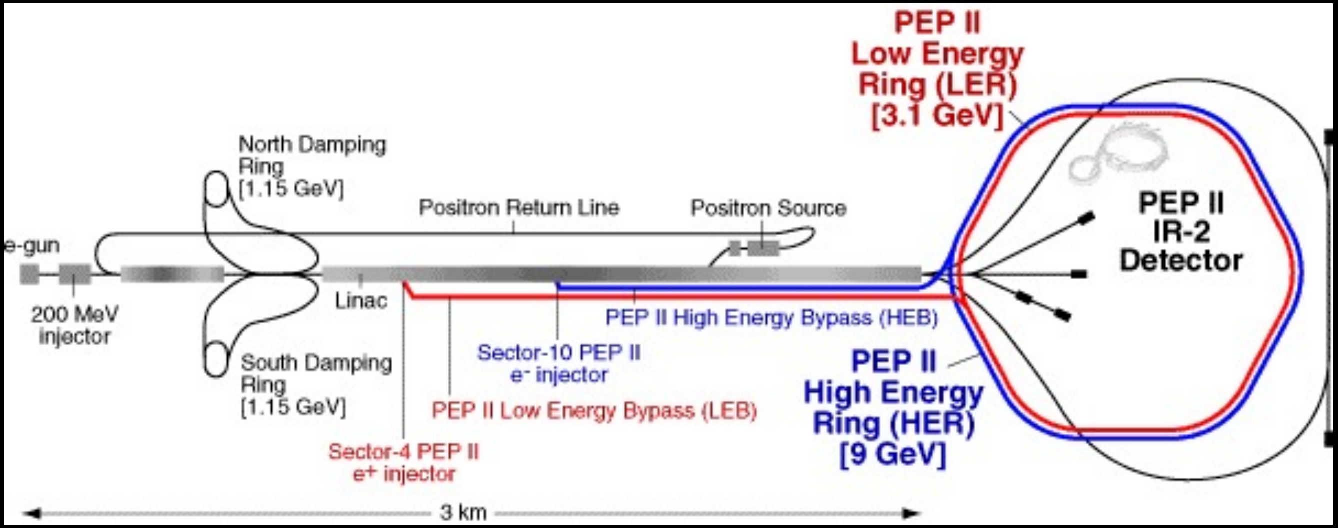
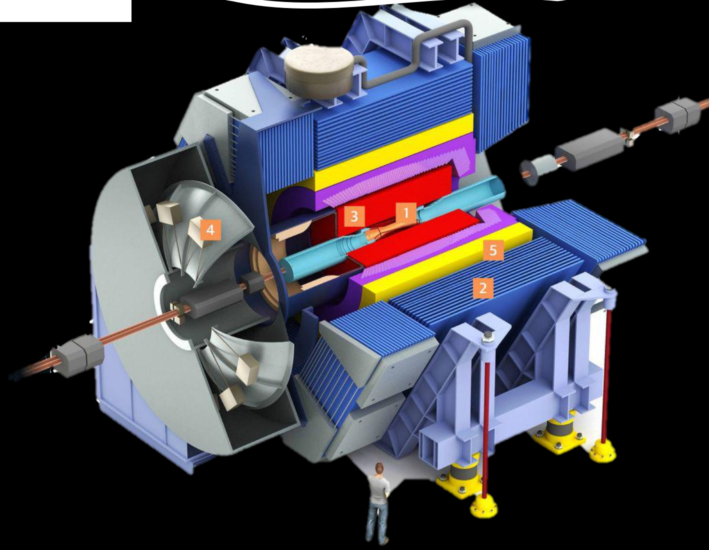


where $l^+ l^-$ pairs of leptons

PEP-II and the BaBar experiment



🟧 Vertex detector
🟦 Support tube
🟥 Tracking chamber
◼ Cherenkov Detector
🟪 EM Calorimeter
🟨 Magnet coil
🟦 Muon detector



- Asymmetric e^+e^- collider operating at center-of-mass (cms) energy $\sqrt{s}$ close to 10.58 GeV
- Total integrated luminosity of 514 fb^{-1} collected, mostly at the $\Upsilon(4S)$ resonance
  - Initial-State-Radiation (ISR): the emission of a photon in the initial state allows to exploit a lower cms energy range, from threshold to $\sqrt{s}$

Analysis Strategy

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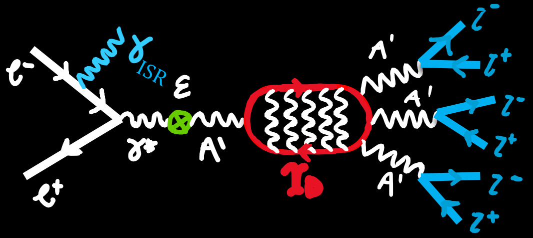

GOAL: search for the reaction

$$e^+e^- \rightarrow \gamma_{ISR}\Upsilon_D \rightarrow A'A'A'$$

with A' subsequently decays to e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$

- $0.001 \text{ GeV} < m_{A'} < 3.16 \text{ GeV}$ and $0.05 \text{ GeV} < m_{\Upsilon D} < 9.5 \text{ GeV}$

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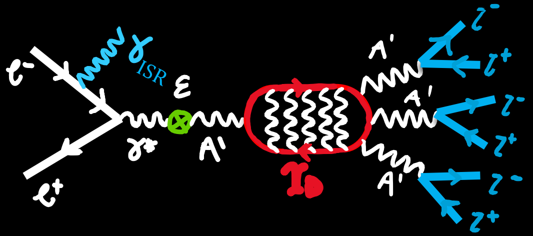

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- 0.001 GeV < $m_{A'}$<3.16 GeV and 0.05 GeV < $m_{\Upsilon D}$<9.5 GeV

- 6 charged tracks per event, identified as electrons, muons or pions
  - At least one lepton pair of opposite charge with the same flavour
- Υ_D candidate by combining three A' candidates
- The detection of γ_{ISR} is not explicitly required
  - We infer the kinematics of the particle recoiling against the Υ_D candidates

Background studies:

- Reconstruct same-sign combinations (combinatorial nature of the bkg)
- ~5% of the data

- Signal purity improved by training multiple machine learning models (Random Forest was chosen , Mach.Learn. 45, 5 (2001))

$(m_{\Upsilon D}, m_{A'})$ Mass Distribution

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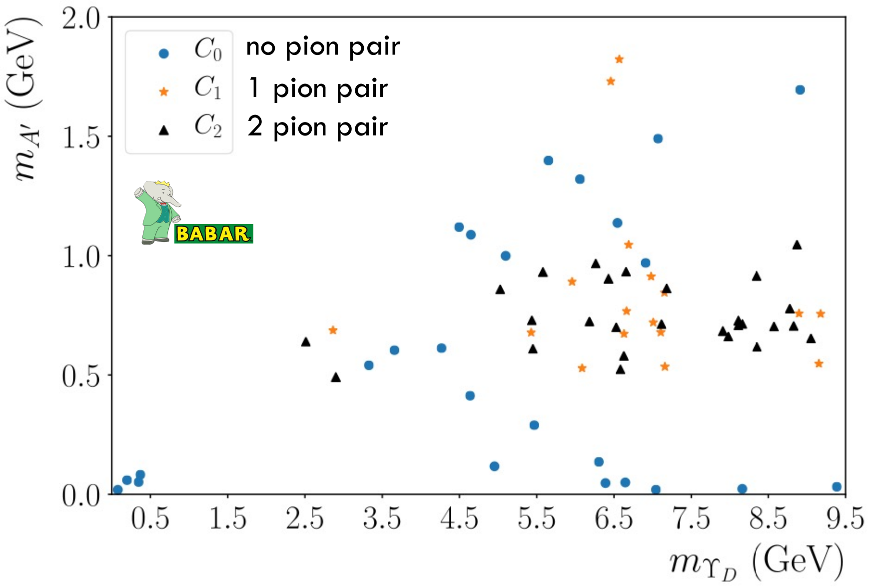
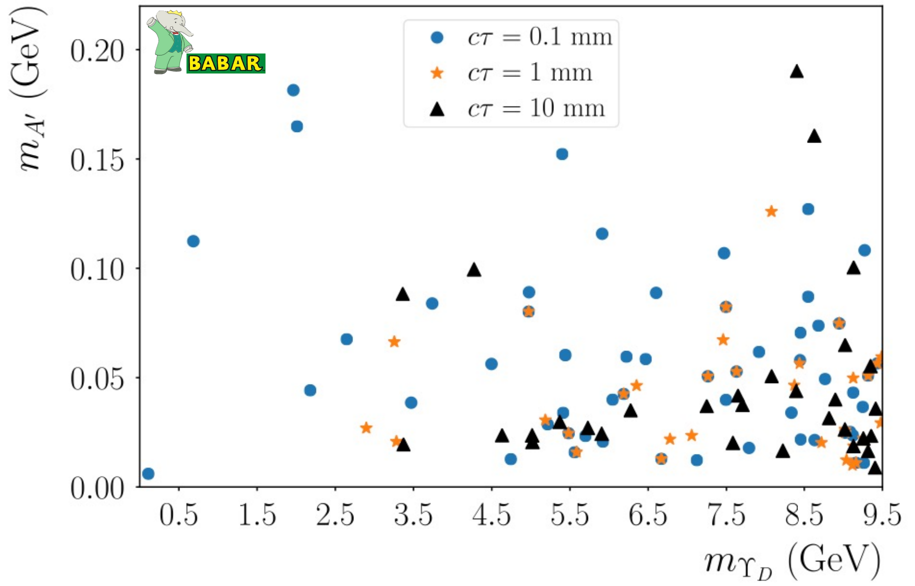
Prompt A' decay



Displaced A' decay vertex: $m_{A'}$<0.2 GeV



- Training done for each category, based on the number of pion pairs
- 69 events passed the selection criteria

- A' decays most exclusively to e^+e^- pair
- Training done for each $c\tau$
- 56, 33, 31 events selected for $c\tau = 0.1$, 1, 10 mm, respectively

No significant signal is observed

Results

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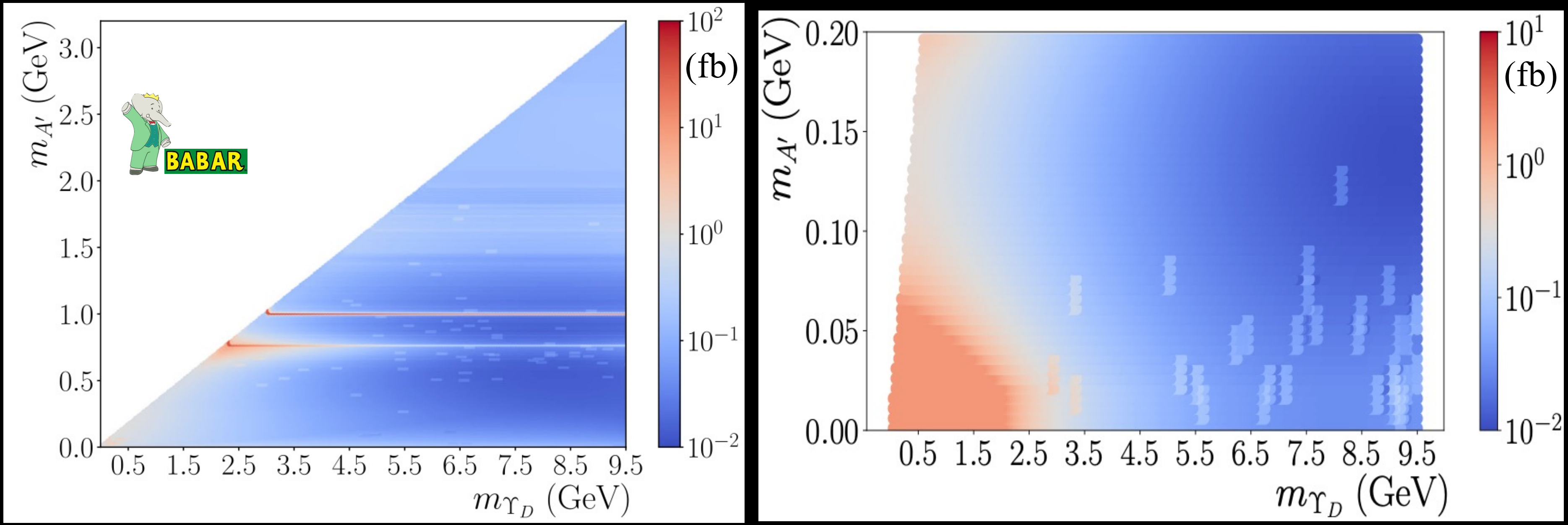
BABAR

90% C.L. upper limits on the $e+e-\rightarrow\gamma_{ISR}\Upsilon_D$ cross section for prompt dark photon decays (left) and for dark photon lifetime corresponding to $c\tau_{A'} = 1$ mm (right)

https://journals.aps.org/prl/supplemental/10.1103/PhysRevLett.128.021802/supplemental.pdf



Looser bounds around $m_{A'} \sim 0.8$ GeV and $m_{A'} \sim 1$ GeV, where the dark photons predominantly would decay into $\pi^+\pi^-\pi^0$ and K^+K^- near the ω and ϕ resonances, respectively (not considered in this analysis)

Results

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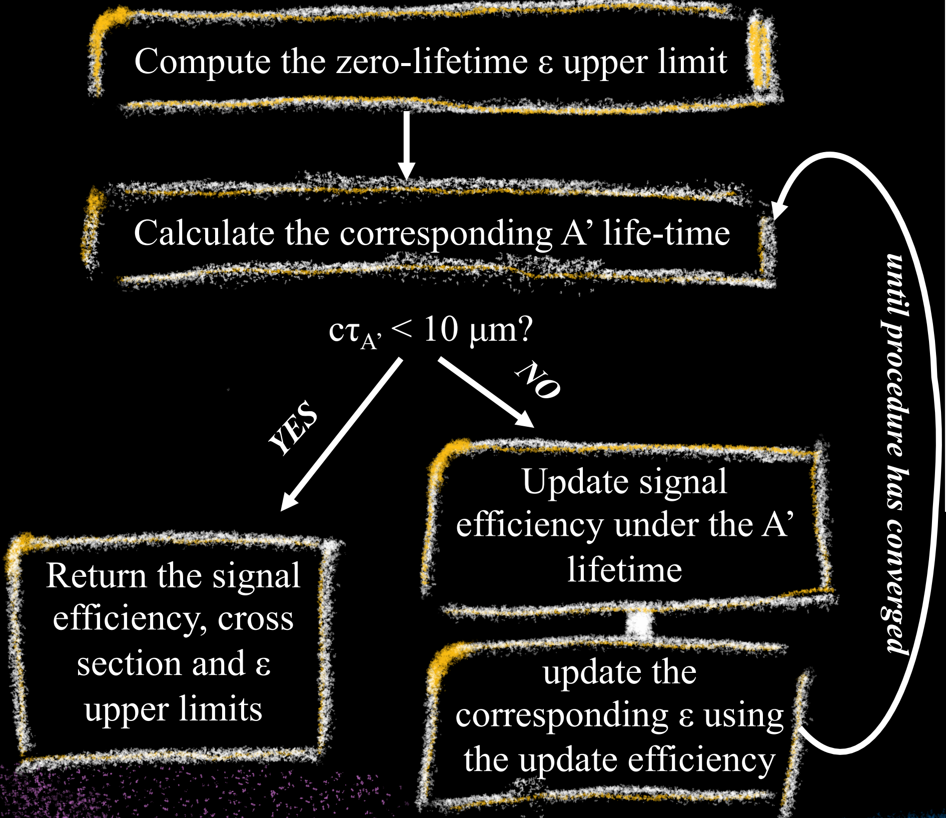
90% C.L. upper limits on the kinetic mixing ε^2 as a function of $m_{\Upsilon D}$ and dark photon mass $m_{A'}$, assuming $\alpha_D = 0.5$

Iterative procedure in order to take into account the A' lifetime:



Compute the zero-lifetime ε upper limit

Calculate the corresponding A' life-time

$c\tau_{A'} < 10$ μm?

YES

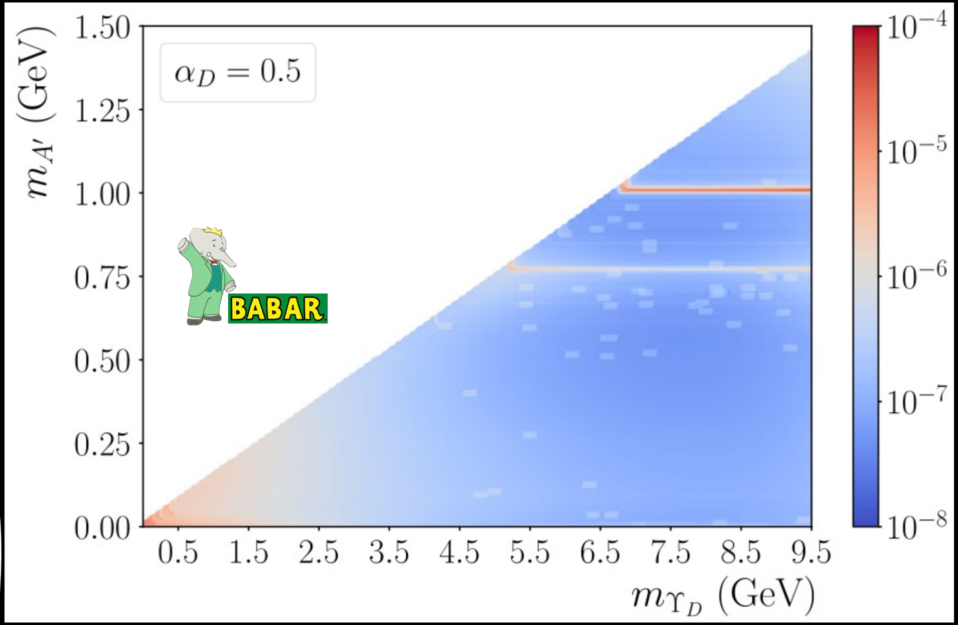
Return the signal efficiency, cross section and ε upper limits

NO

Update signal efficiency under the A' lifetime

update the corresponding ε using the update efficiency

until procedure has converged



α_D = 0.1,0.3, 0.5, 0.7, 0.9, 1.1; all the distributions in https://journals.aps.org/prl/supplemental/10.1103/PhysRevLett.128.021802/supplemental.pdf

Results

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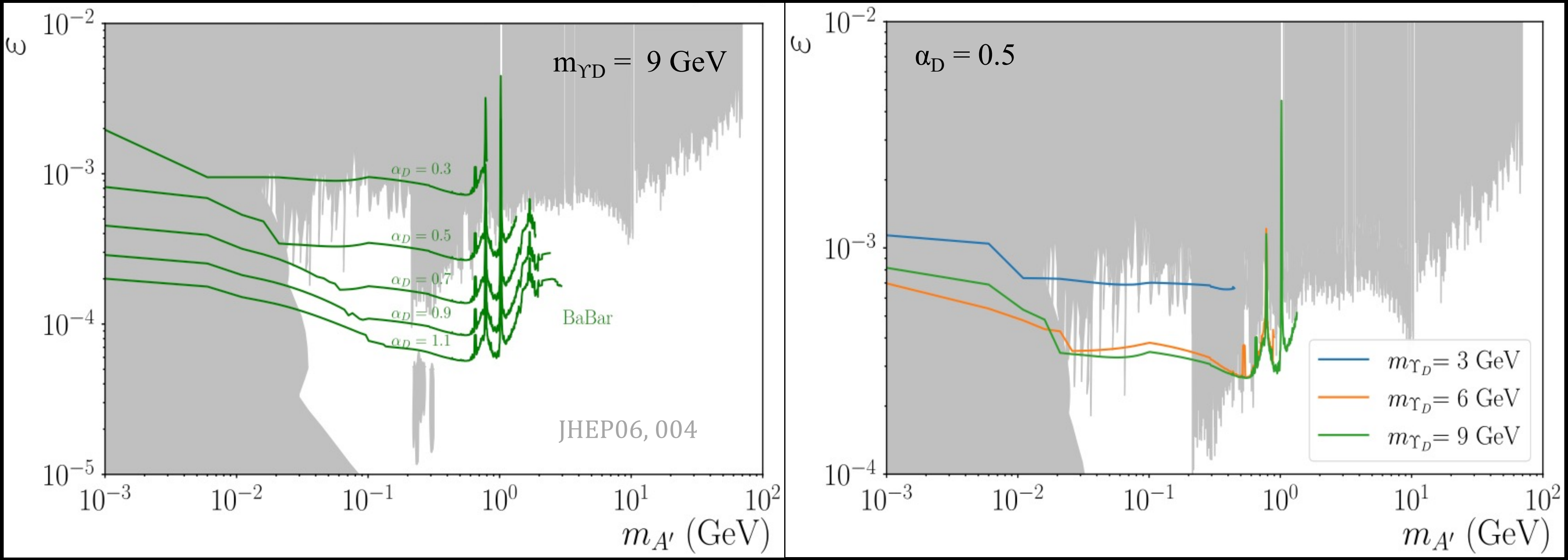
90% C.L. upper limits on the γ-A’ kinetic mixing ε for various α_D values assuming $m_{\Upsilon D}$ = 9 GeV (left) and for various Υ_D masses assuming α_D = 0.5 (right)



Depending on the value of the model parameters, the upper limit on the γ-A’ kinetic mixing ε ranges between 5×10^{-5} - 10^{-3}

Conclusions

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- We report the first search for a dark sector bound state decaying into three dark photons in the range 0.001 GeV < $m_{A'}$<3.16 GeV and 0.05 GeV < $m_{\Upsilon D}$<9.5 GeV

$$e^+e^- \to \gamma_{ISR}\Upsilon_D \to A'A'A'$$

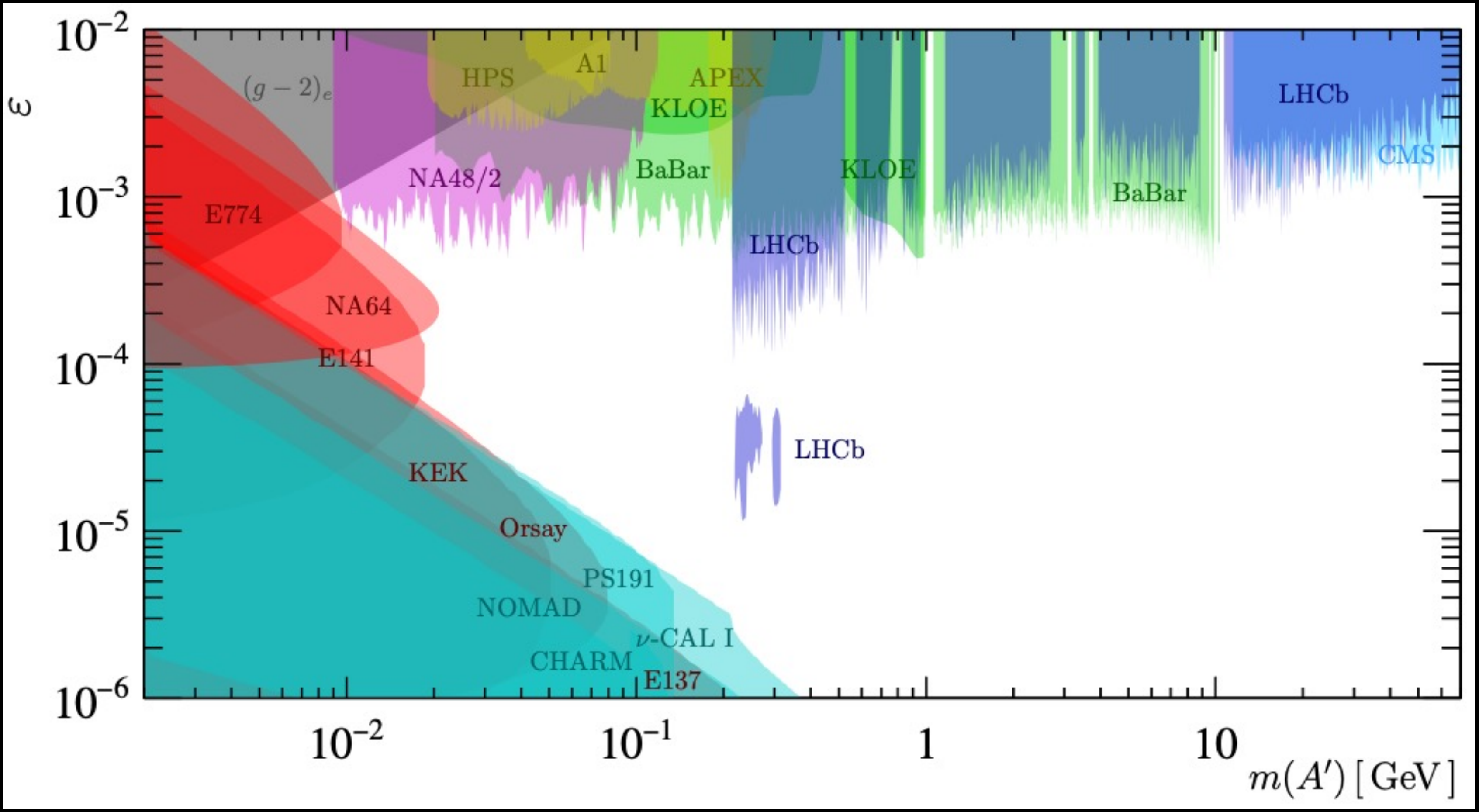
- Prompt and displaced dark photon decays are taken into account

- No significant signal is observed
  - we derive 90% C.L. upper limit on the γ-A' kinetic mixing ε at the level of 5×10^{-5} - 10^{-3}

- These measurements improve upon existing constraints up to one order of magnitude over a significant fraction of $m_{A'}$ below 1 GeV for large values of the dark sector coupling constant

- Other darkonium states could be searched for in order to improve the upper limit cross section (kinetic mixing ε) bkslide

JHEP06, 004


10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ε
$(g-2)_e$
HPS
A1
APEX
KLOE
NA48/2
BaBar
KLOE
LHCb
BaBar
LHCb
CMS
E774
NA64
E141
LHCb
KEK
Orsay
PS191
NOMAD
ν-CAL I
CHARM
E137
10^{-2}
10^{-1}
1
10
$m(A')$ [GeV]

$$\mathcal{L} = \mathcal{L}_{SM} + \chi i\gamma^{\mu}(\delta_{\mu} - i g_D A'_{\mu})\chi - m_{\chi}\bar{\chi}\chi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}A'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu}$$

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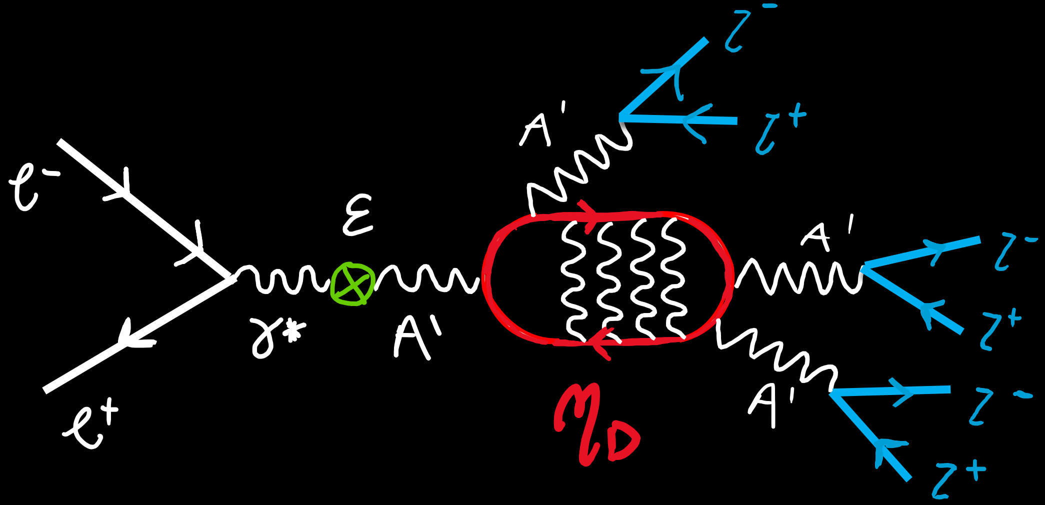

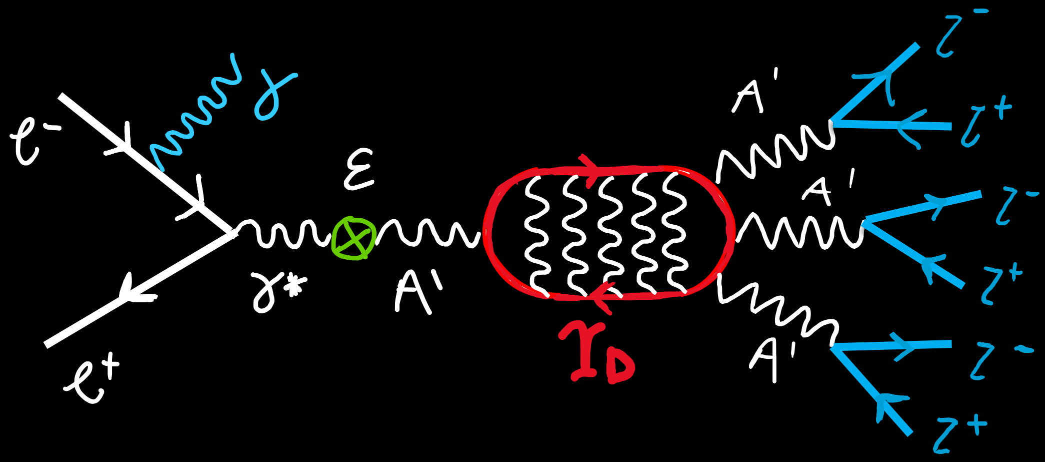

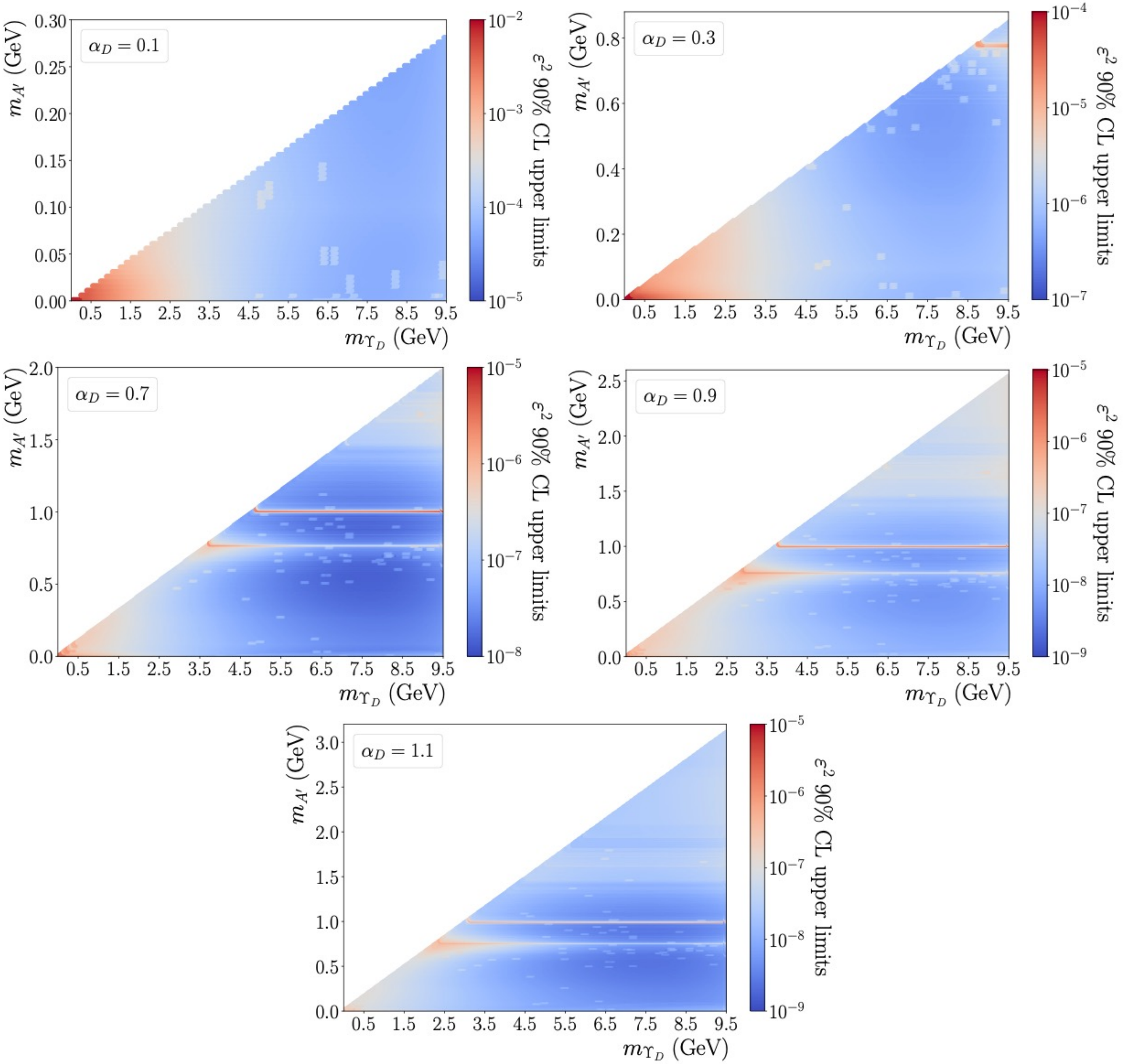

FIG. 4: The 90% CL upper limits on the kinetic mixing ε^2 as a function of the Υ_D mass, m_{Υ_D}, and dark photon mass, $m_{A'}$, assuming (top left) $\alpha_D = 0.1$, (top right) $\alpha_D = 0.3$, (middle left) $\alpha_D = 0.7$, (middle right) $\alpha_D = 0.9$, and (bottom) $\alpha_D = 1.1$.