Dark Sector Searches at e^+e^- Colliders

Dark Interactions
Brookhaven National Lab
October 5, 2016

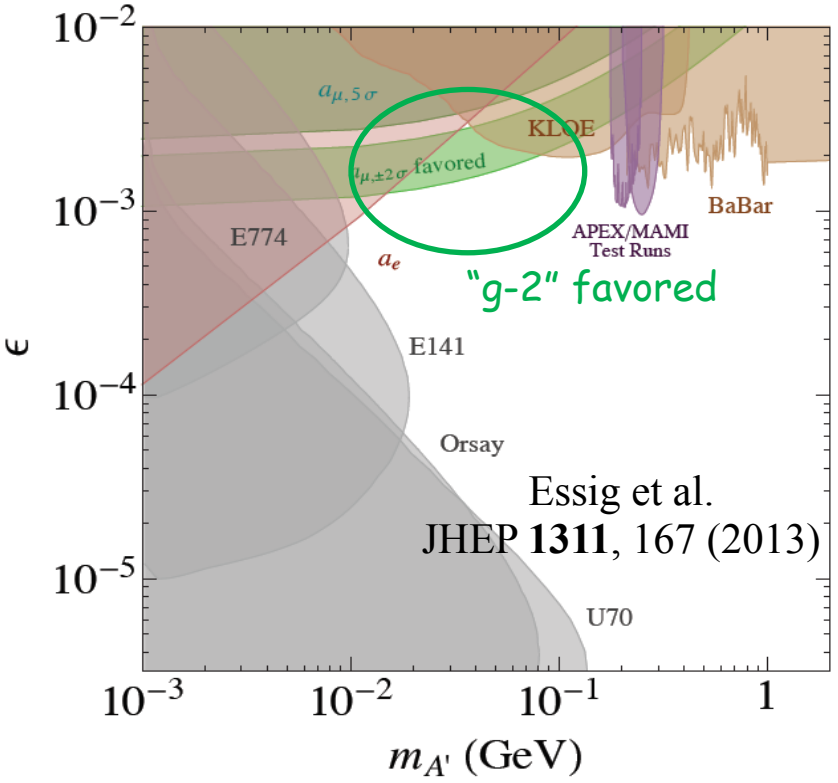
Yury Kolomensky
UC Berkeley/LBNL

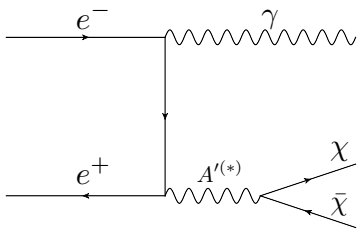
Outline

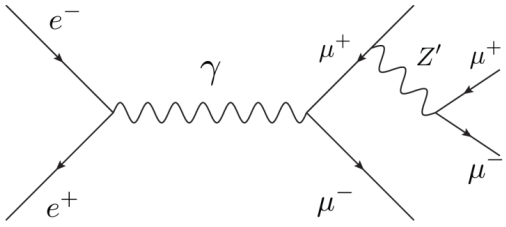
- KLOE results
  - A'$\rightarrow e^+e^-, \pi^+\pi^-, \mu^+\mu^-$
- New BaBar results
  - Muonic dark force
  - Preview of things to come
- Near future prospects (Belle-II)

Dark Sector Searches

- Coupling to SM particles proportional to $\varepsilon^2\alpha$
- Search for direct resonance production in e^+e^- annihilation.
- Multi-lepton final states, or radiative processes $e^+e^- \rightarrow \gamma$ +visible, γ+invisible
- Very large datasets allow for high-statistics searches







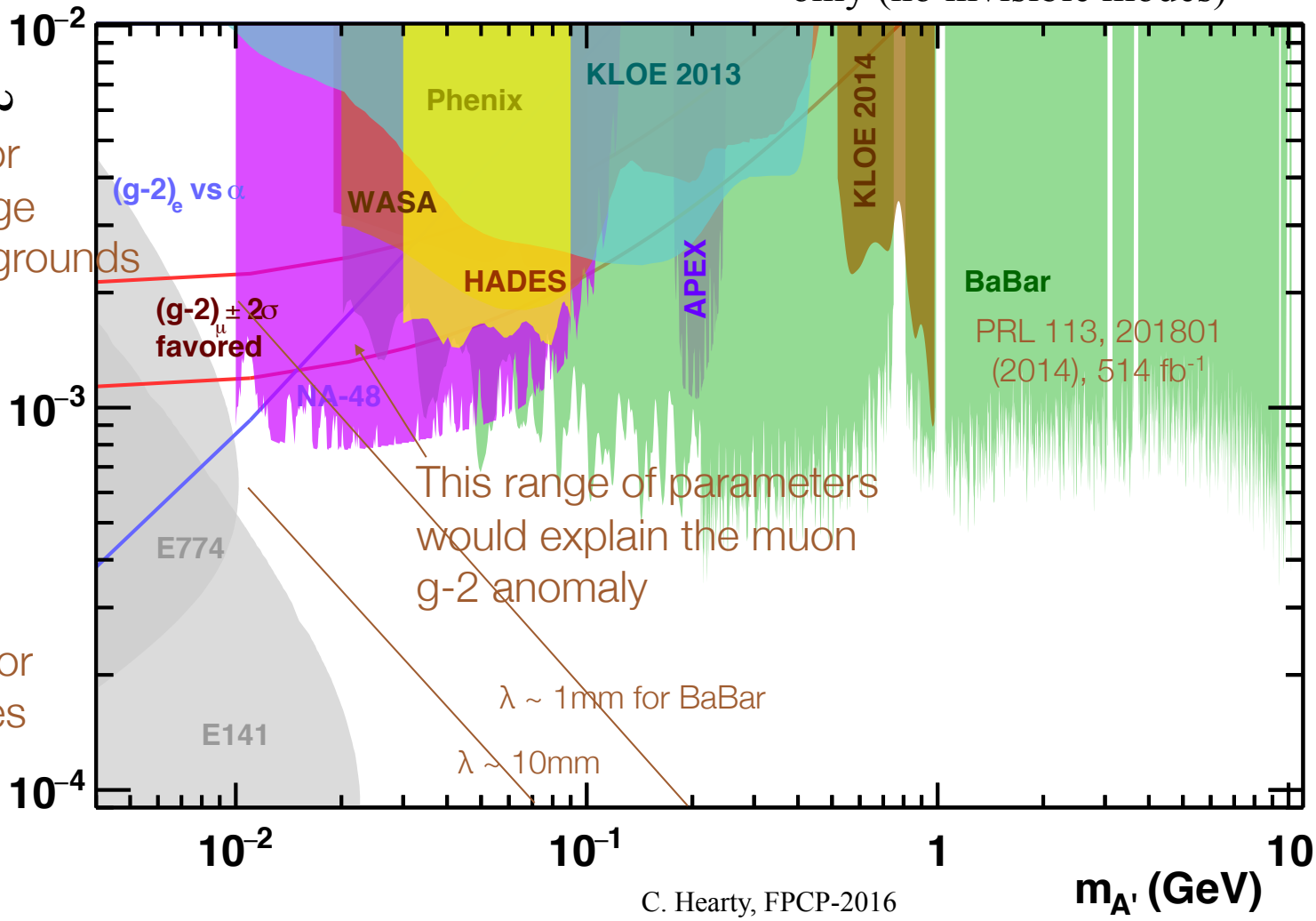
Pospelov;
Bjorken, Essig, Schuster, Toro
Andreas, Niebuhr, Ringwald
Batell, Pospelov, Ritz;
Essig, Harnik, Kaplan, Toro
Blumlein, Brunner;

Dent, Ferrer, Krauss
Essig Schuster, Toro, Wojtsekhowski
KLOE, APEX, MAMI/A1 Collab.
Davoudiasl, Lee, Marciano;
Endo, Hamaguchi, Mishima

Active Field

Status of the field as of 2015

Assume decays of A' to SM only (no invisible modes)

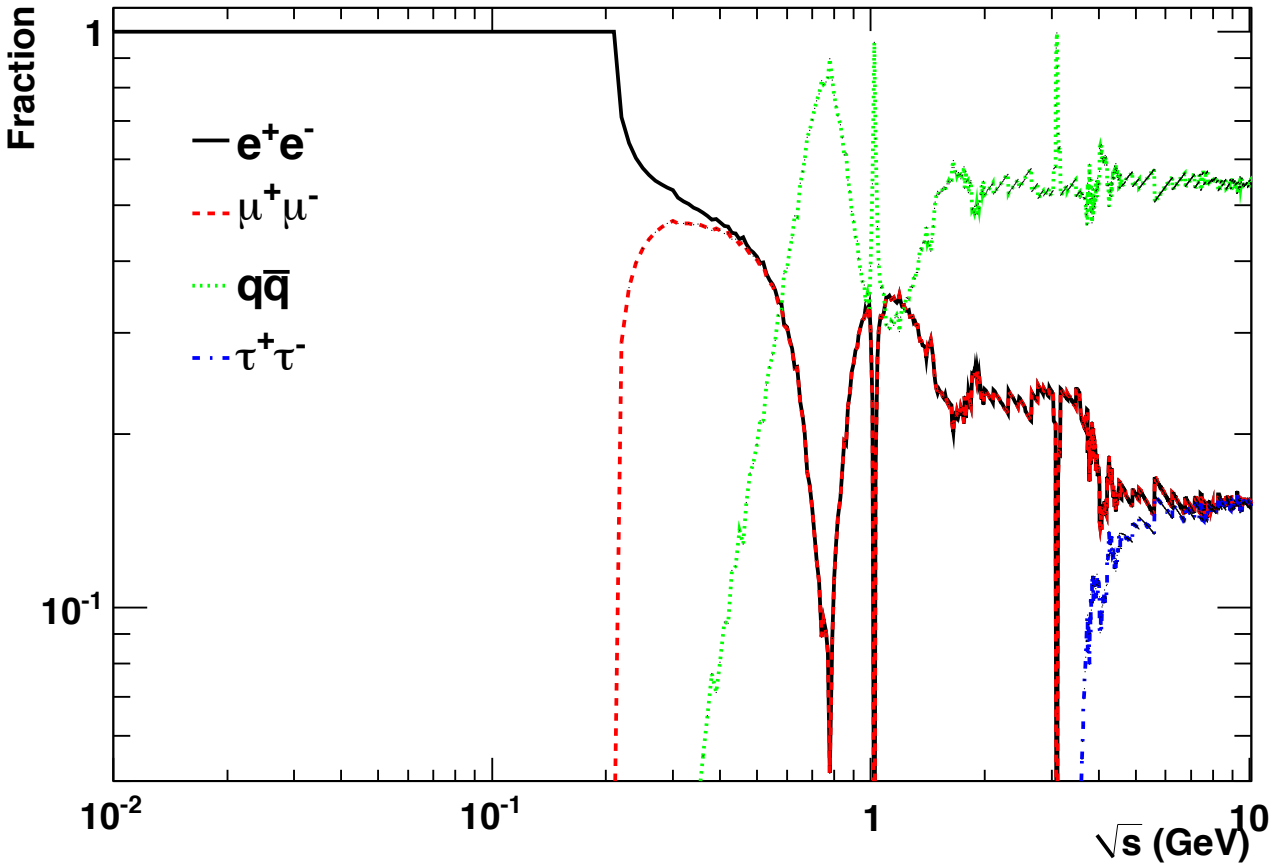


Colored: searches for narrow peaks on large prompt-decay backgrounds

Grey: searches for displaced vertices (beam dumps)

C. Hearty, FPCP-2016

Dark Photon Branching Ratios



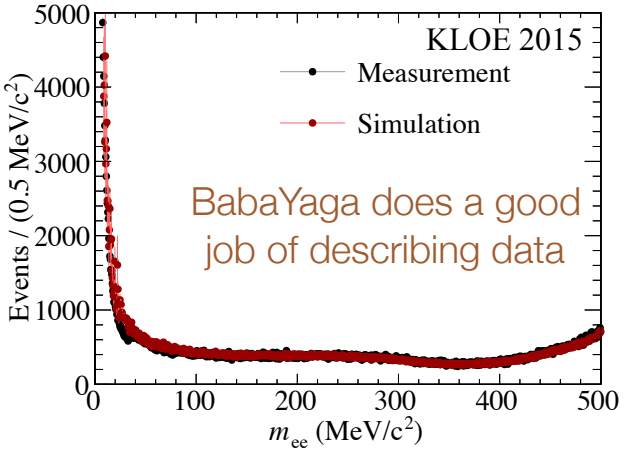
B. Echenard

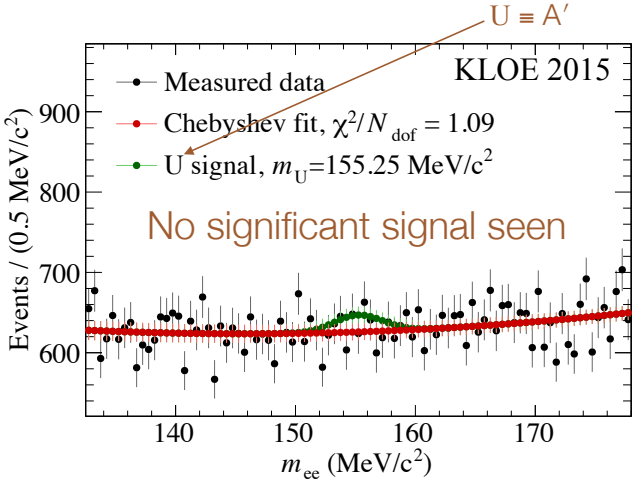
Same BRs as for virtual photon of mass $m_{A'}$
Assumes no invisible degrees of freedom
Lepton modes are simplest, but important to cover all bases

KLOE: $A' \to e^+e^-$

Phys. Lett. **B750**, 633 (2015)

- Fully-reconstructed final state
  - $e^+e^- \to \gamma A'$, $A' \to e^+e^-$
  - 1.54 fb^{-1} collected at E_{cm}=1.019 GeV (phi peak)
  - Select fully-reconstructed events with e^+, e^-, γ at wide angles to suppress bhabha backgrounds
- Look for narrow peak in e^+e^- mass spectrum
  - 5 MeV < $m_{A'}$ < 500 MeV



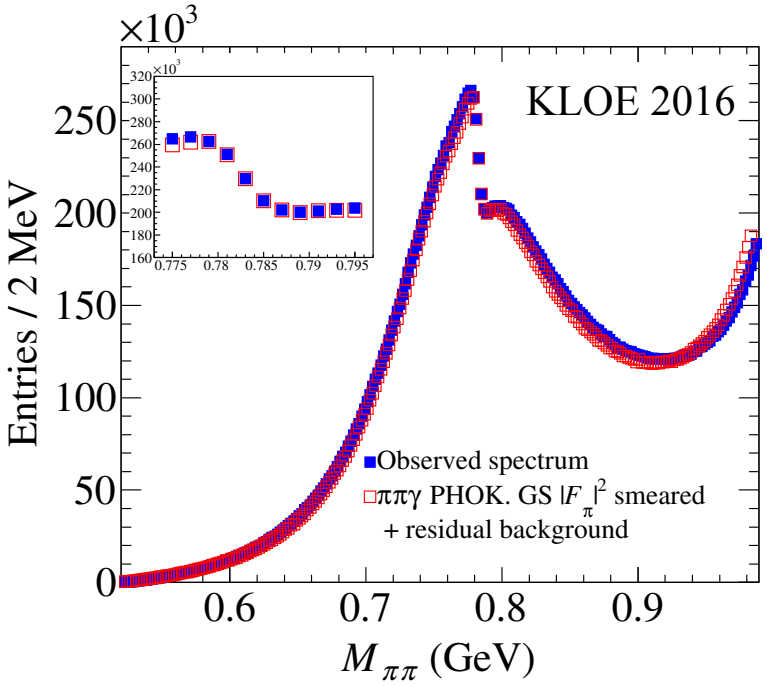


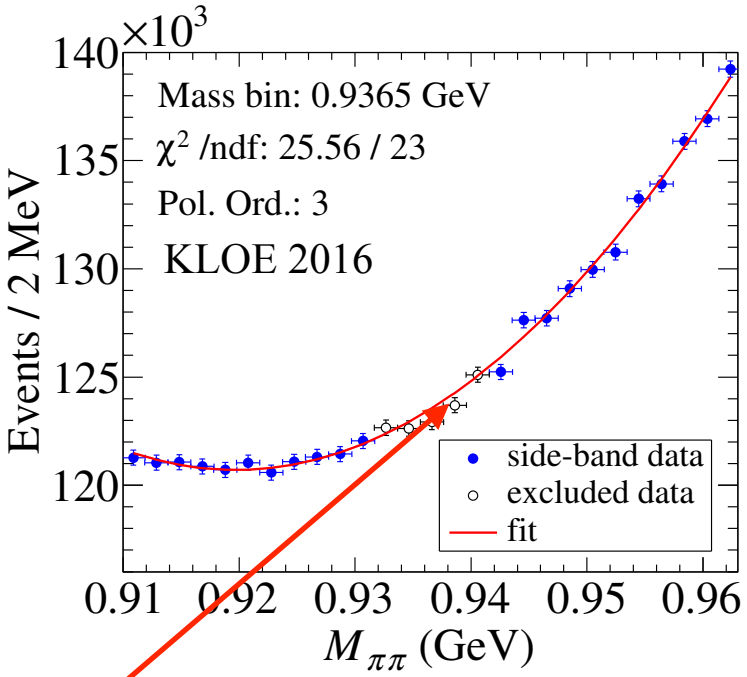
KLOE: $A' \to \pi^+\pi^-$

Phys. Lett. **B757**, 656 (2016)

- Partially-reconstructed final state
  - $e^+e^- \to \gamma A'$, $A' \to \pi^+\pi^-$
  - 1.93 fb^{-1} collected at E_{cm}=1.019 GeV (phi peak)
  - Select events with ISR kinematics, π^+, π^- at wide angles, undetected γ
- Look for narrow peak in $\pi^+\pi^-$ mass spectrum around ρ and ω resonances
  - Backgrounds dominated by hadronic events: $e^+e^- \to \pi^+\pi^-\gamma$ and phi decays
  - Look for narrow peak above smooth background, except for ρ/ω interference region where background needs to be modeled carefully (PHOKARA)

KLOE: $A' \to \pi^+\pi^-$

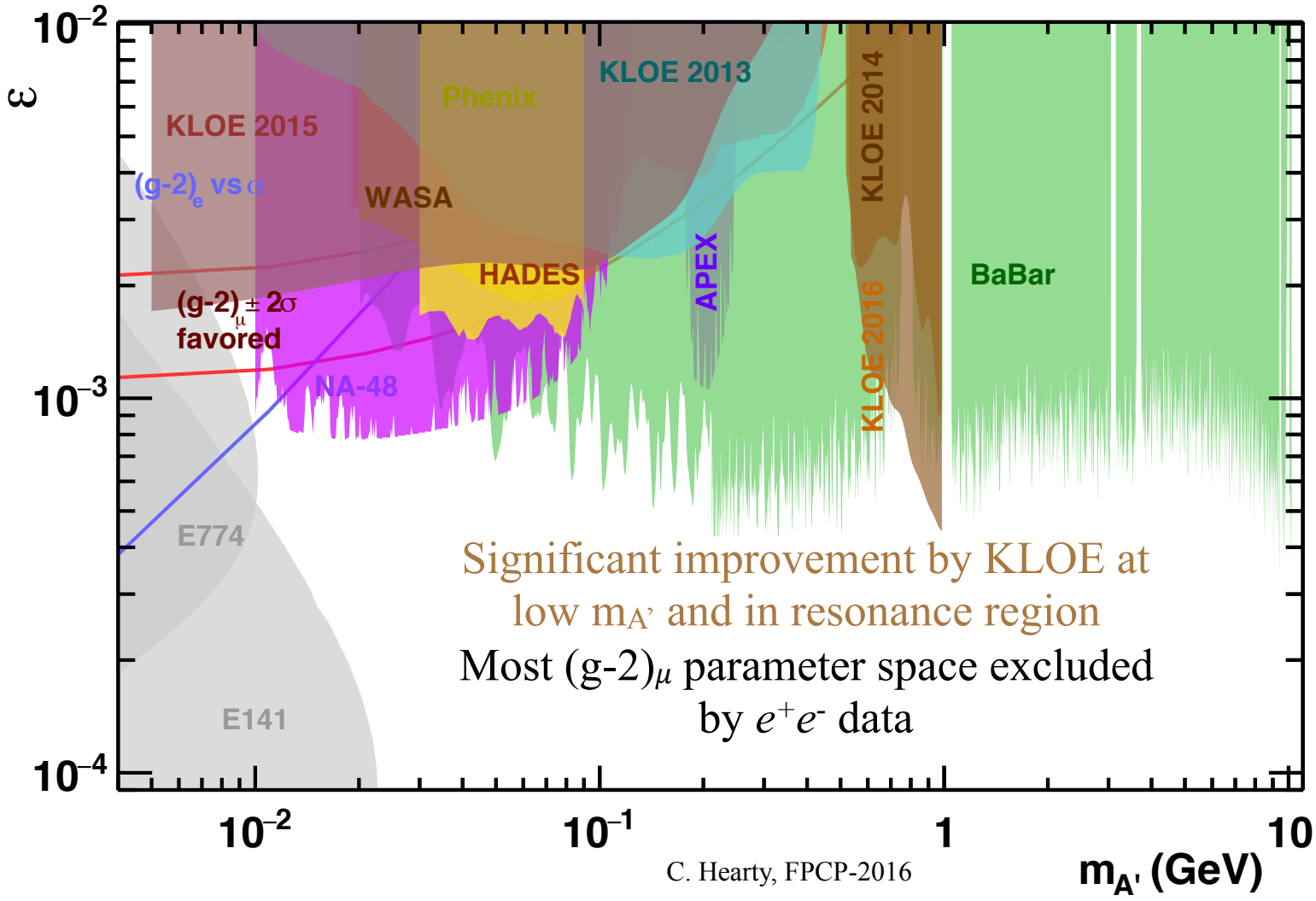




Count events over interpolated background

No significant excess above 2σ local significance

KLOE Results



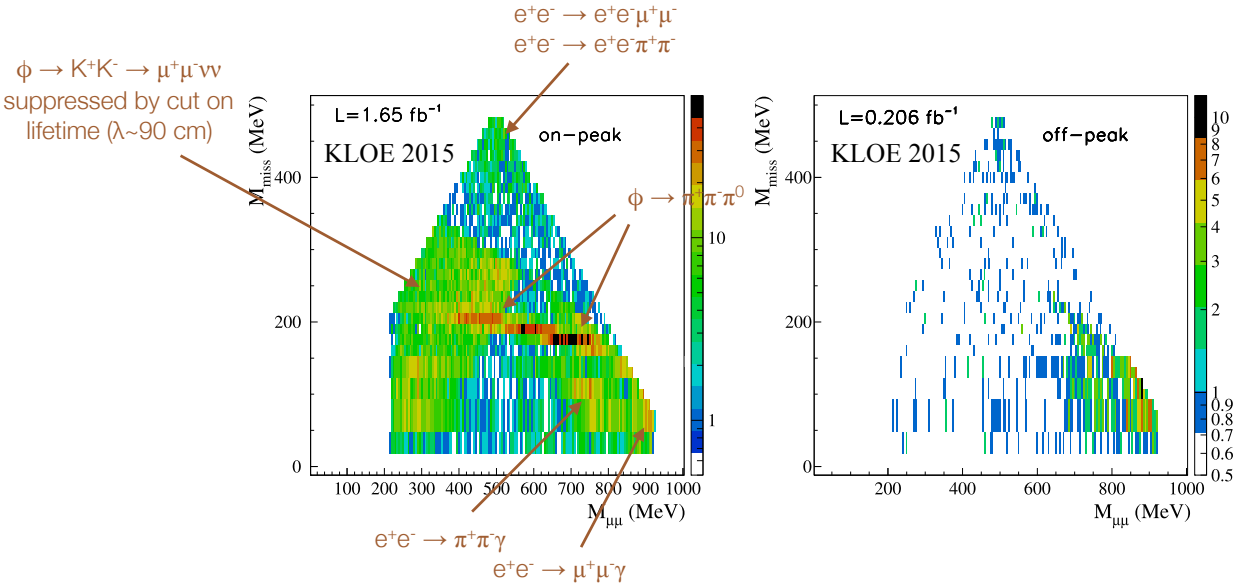
C. Hearty, FPCP-2016

KLOE: $A' \to \mu^+\mu^-$ with Missing Energy

- Partially-reconstructed final state

  Phys. Lett. **B747**, 365 (2015)

  - Higgsstrahlung $e^+e^- \to h'A'$, $A' \to \mu^+\mu^-$ and long-lived h'
  - 1.86 fb^{-1} collected at or below phi peak
  - Select events with reconstructed μ^+, μ^- and missing momentum pointing to the calorimeter
- Look for narrow peak in $\mu^+\mu^-$ mass in bins of $M_{\mu\mu}$ and M_{miss}



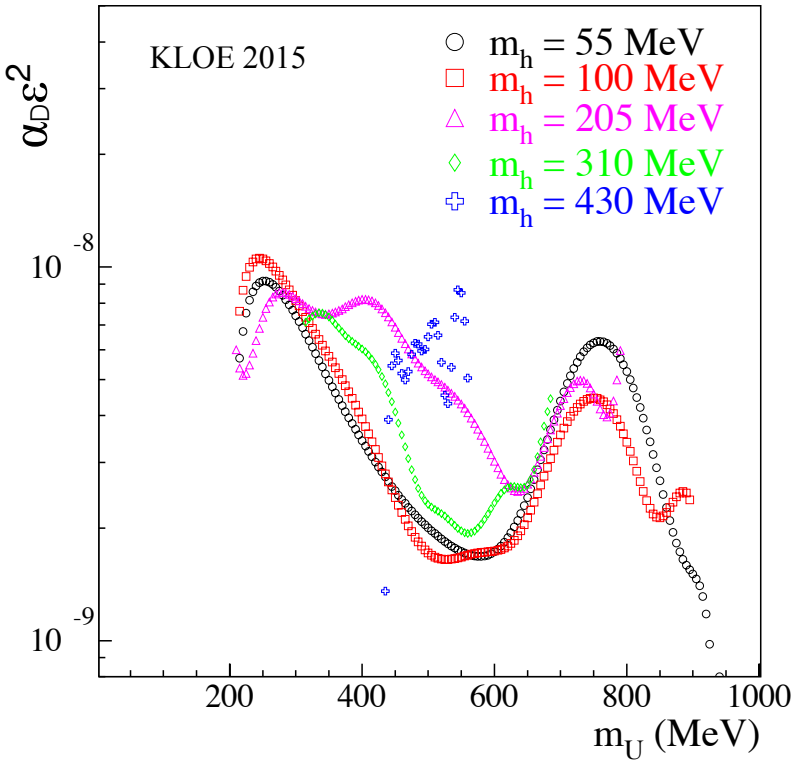
KLOE: $A' \to \mu^+\mu^-$ with Missing Energy

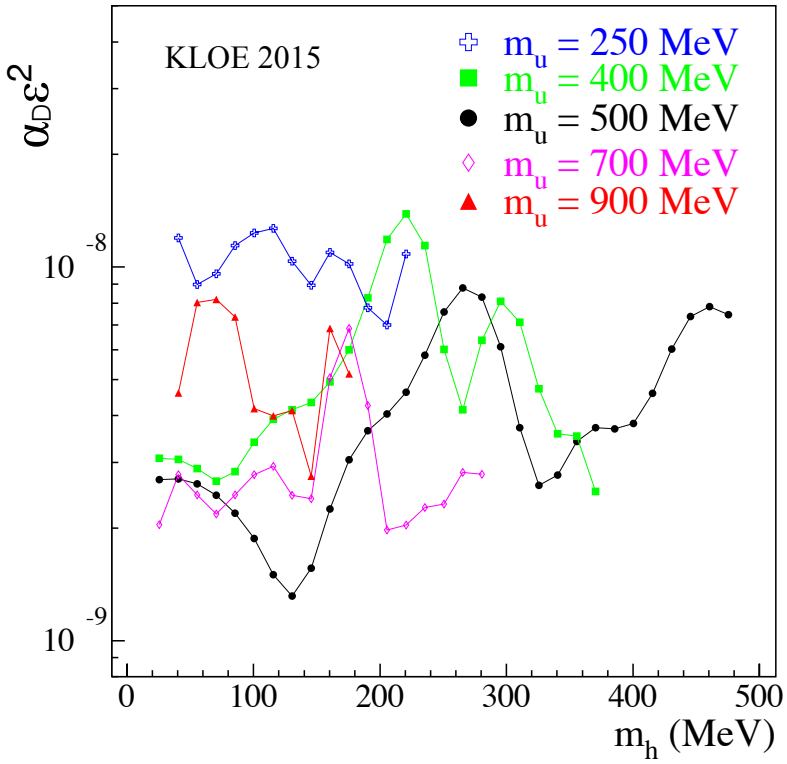
- Cut-n-count analysis

Phys. Lett. **B747**, 365 (2015)

  - Use events in sideband bins to predict the bin of interest

- First constraints for $m_{h'} < m_{A'}$

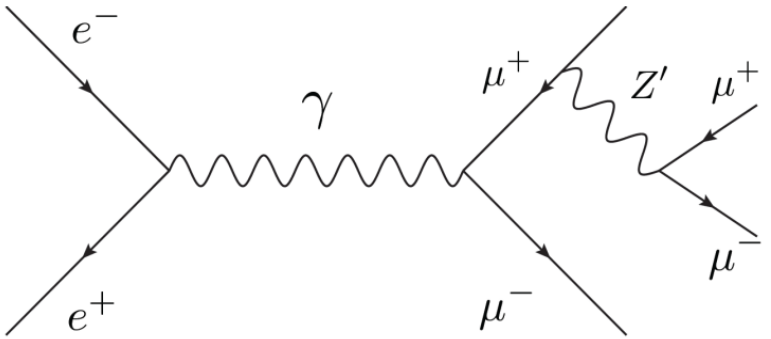




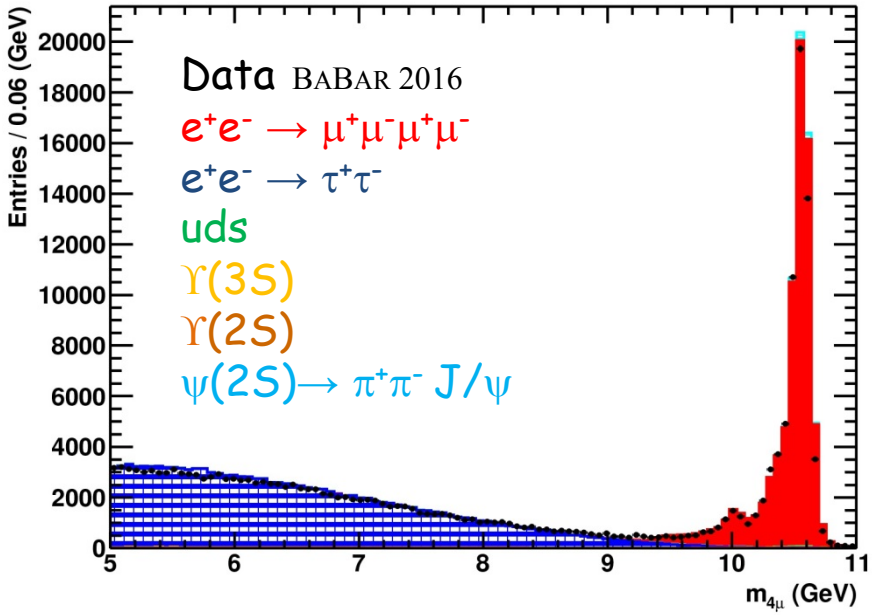
BaBar Search for Muonic Dark Force

Phys.Rev. D94, 011102 (2016)

- Dark Z' that couples to 2nd (and 3rd) generations
  - Avoids constraints from previous multi-lepton searches
  - Could potentially explain (g-2)μ
- Fully reconstructed 4μ final state (2 identified muons)
  - Full 514 fb^{-1} dataset

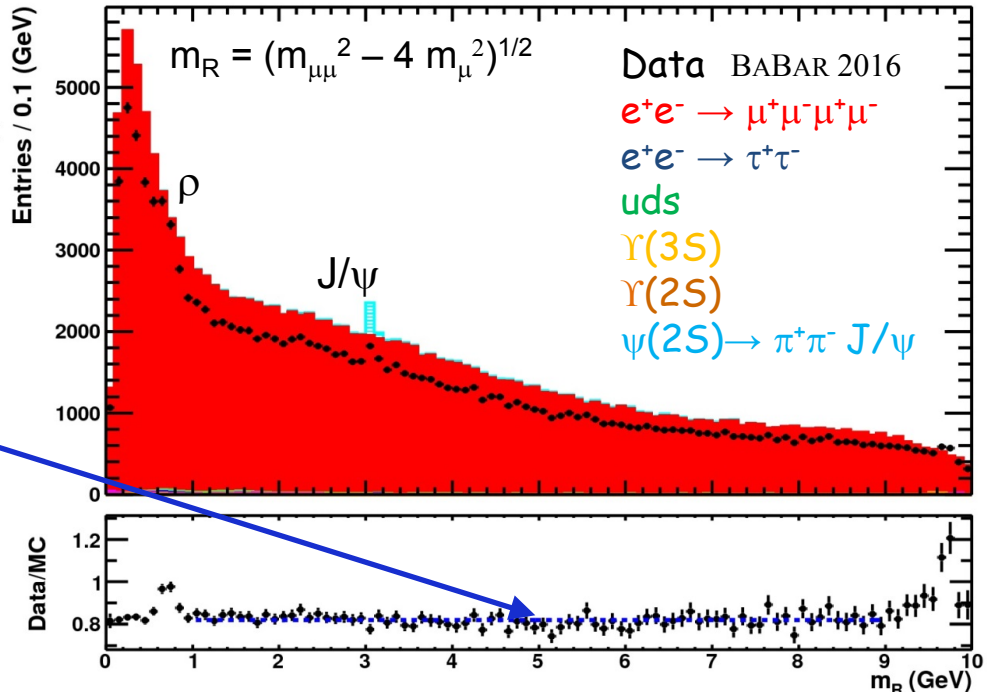


BaBar Search for Muonic Dark Force

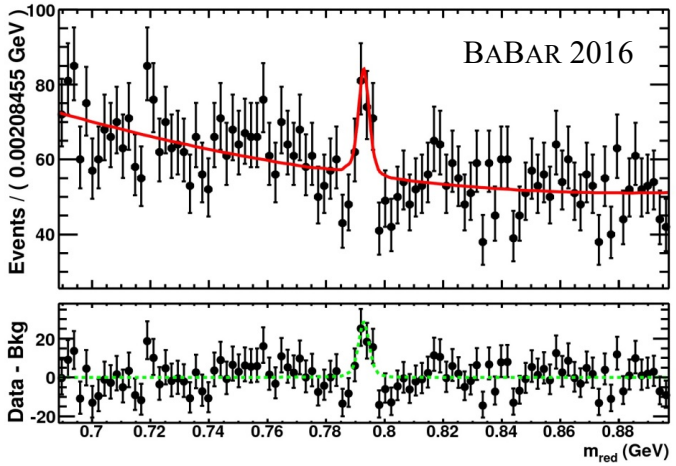


Accept events within 500 MeV of E_{cm}
ISR tail added to simulation reproduces data reasonably well

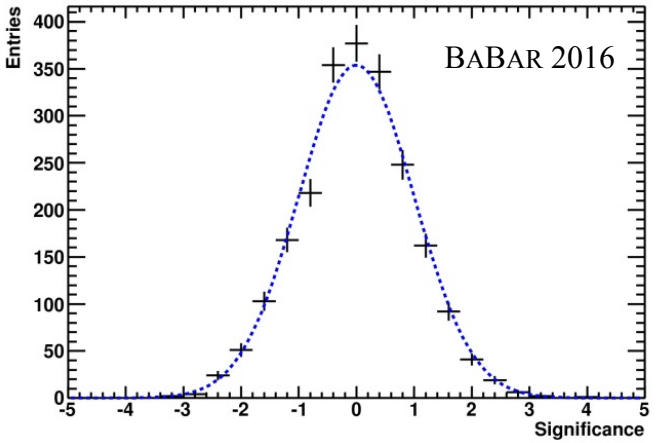
MC efficiency corrected for data/ MC (dis)agreement
Look for narrow peaks in $\mu\mu$ invariant mass, avoiding known resonances



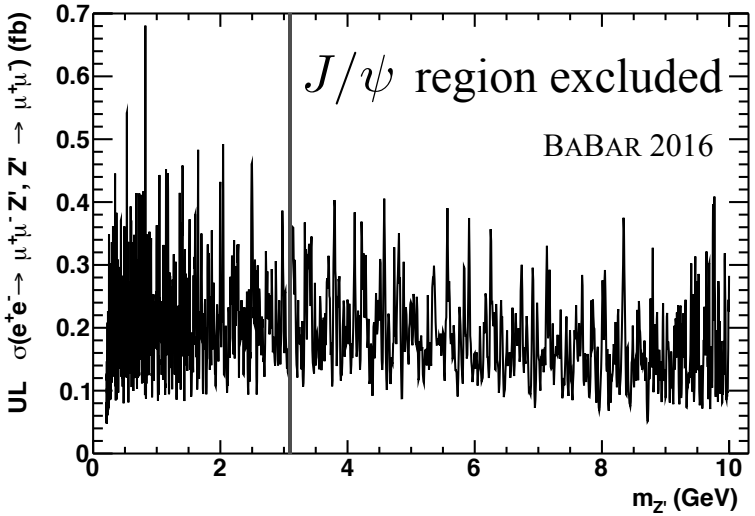
BaBar Search for Muonic Dark Force

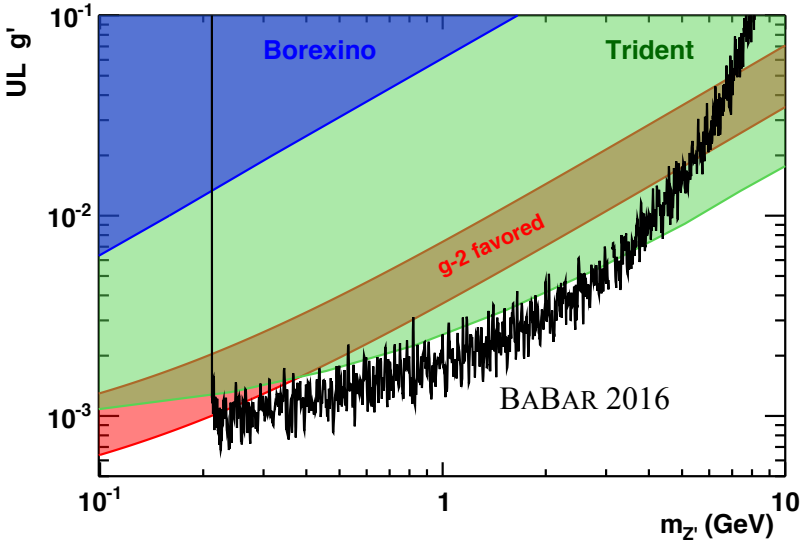


Most significant signal at $m_{Z'}$=0.79 GeV.
$4.3\sigma(1.6\sigma)$ local (global) significance



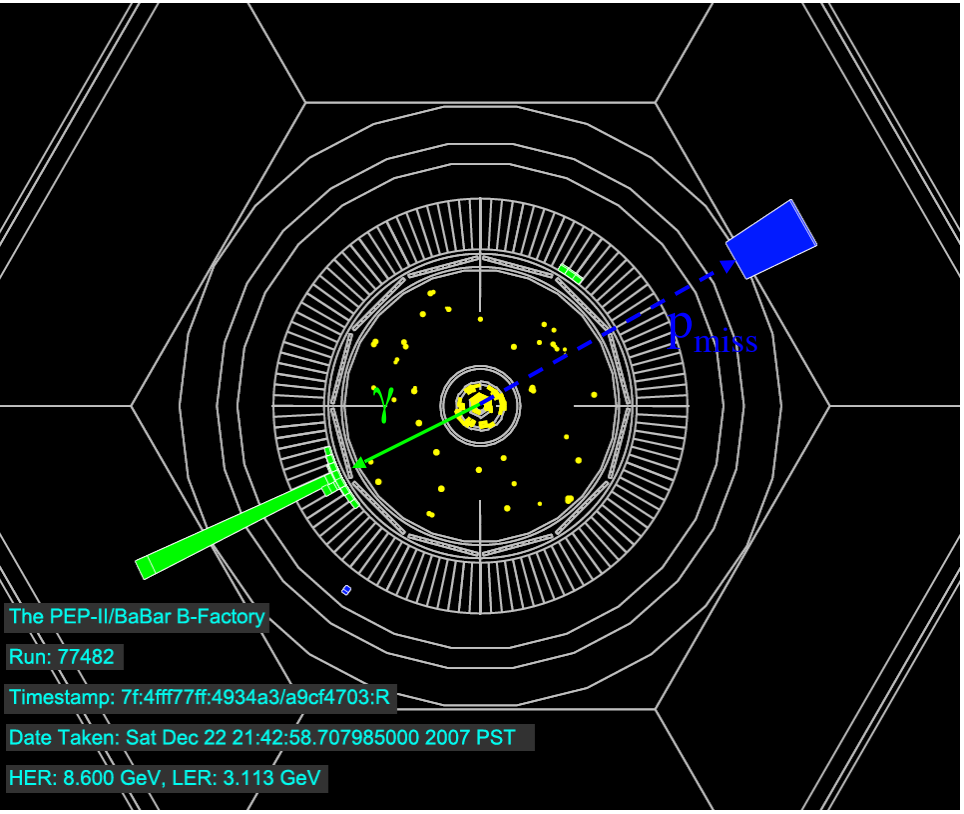
Distribution of local significance





$(g\text{-}2)_\mu$ region disfavored

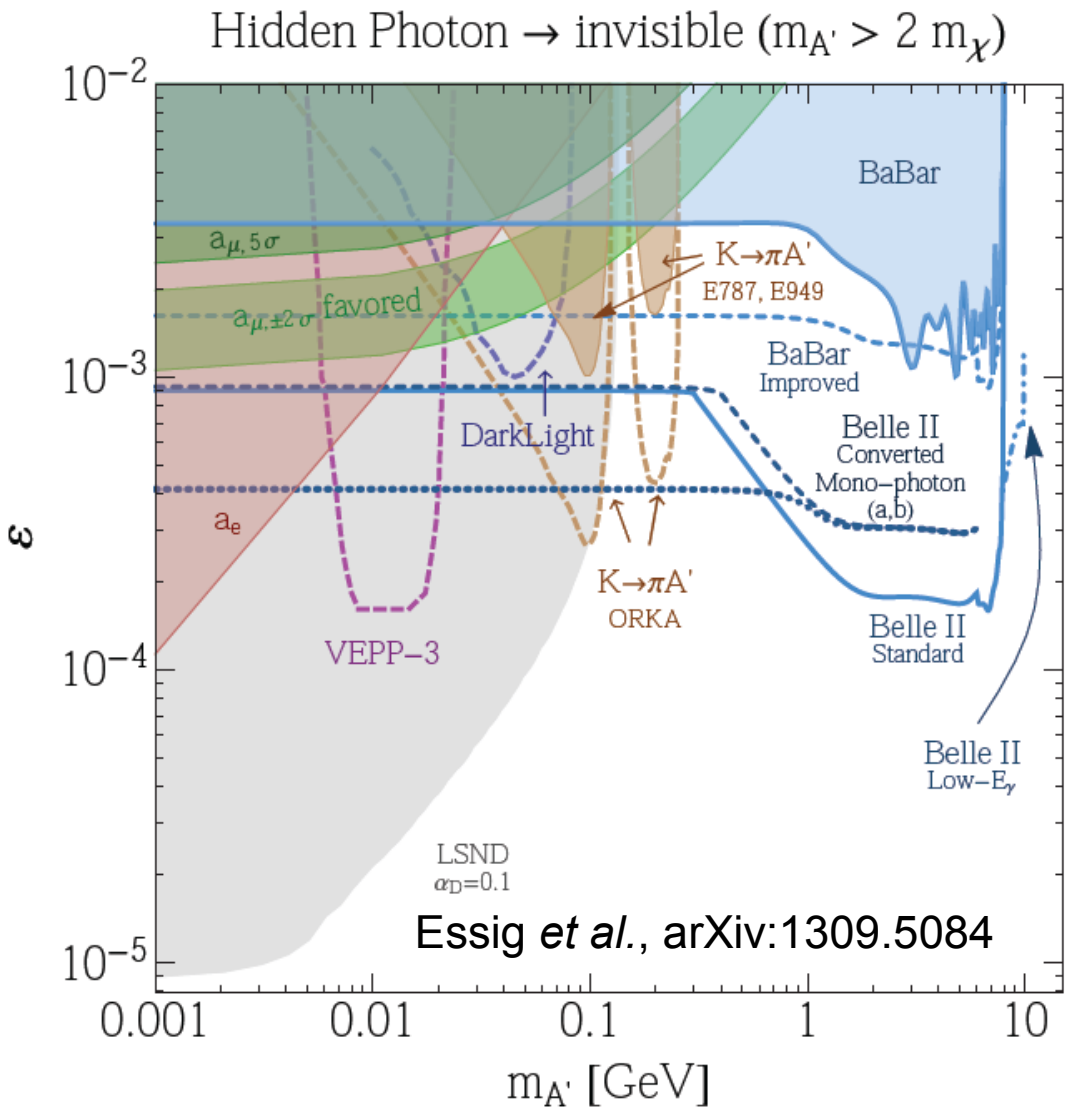
BaBar Invisible Dark Photon Search



Peaking background from $e^+e^- \to \gamma\gamma$, with one of the photons missing the EM calorimeter. Veto such events by detecting activity in the muon detector (IFR).

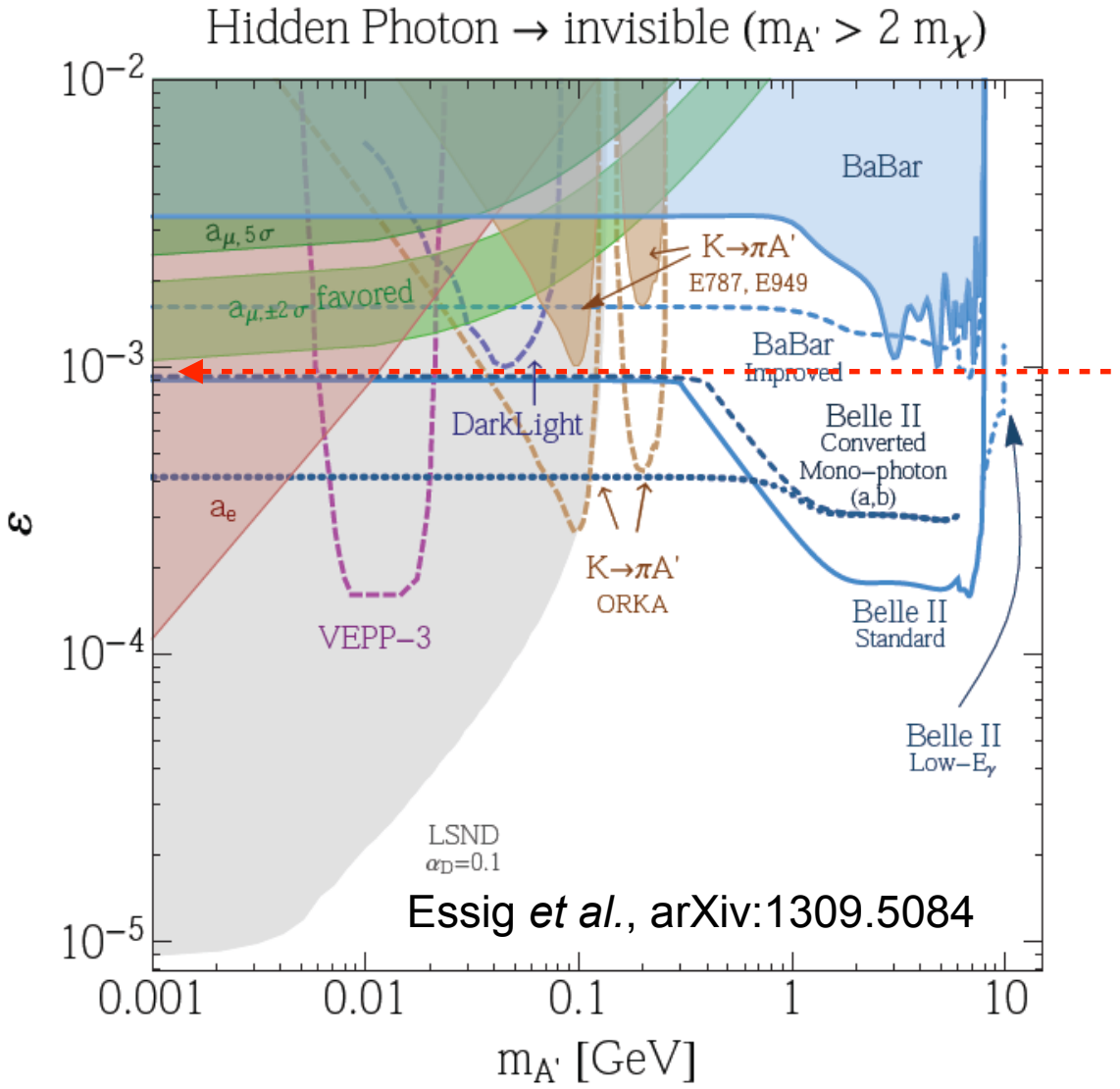
- $\Upsilon(3S) \to \gamma$+invisible (arXiv:0808.0017)
- Require a single photon with $E^*_\gamma > 2.2$ GeV
- No charged tracks, small excess calorimeter energy
- Missing momentum points to calorimeter
- No activity in IFR aligning with missing momentum
- No signal found: limits on ε of order $O(10^{-3}\text{-}10^{-2})$
- Updated analysis in progress

Invisible Dark Photon: Limits



Essig *et al.*, arXiv:1309.5084

Invisible Dark Photon: Limits



10^{-3} should be possible with updated analysis

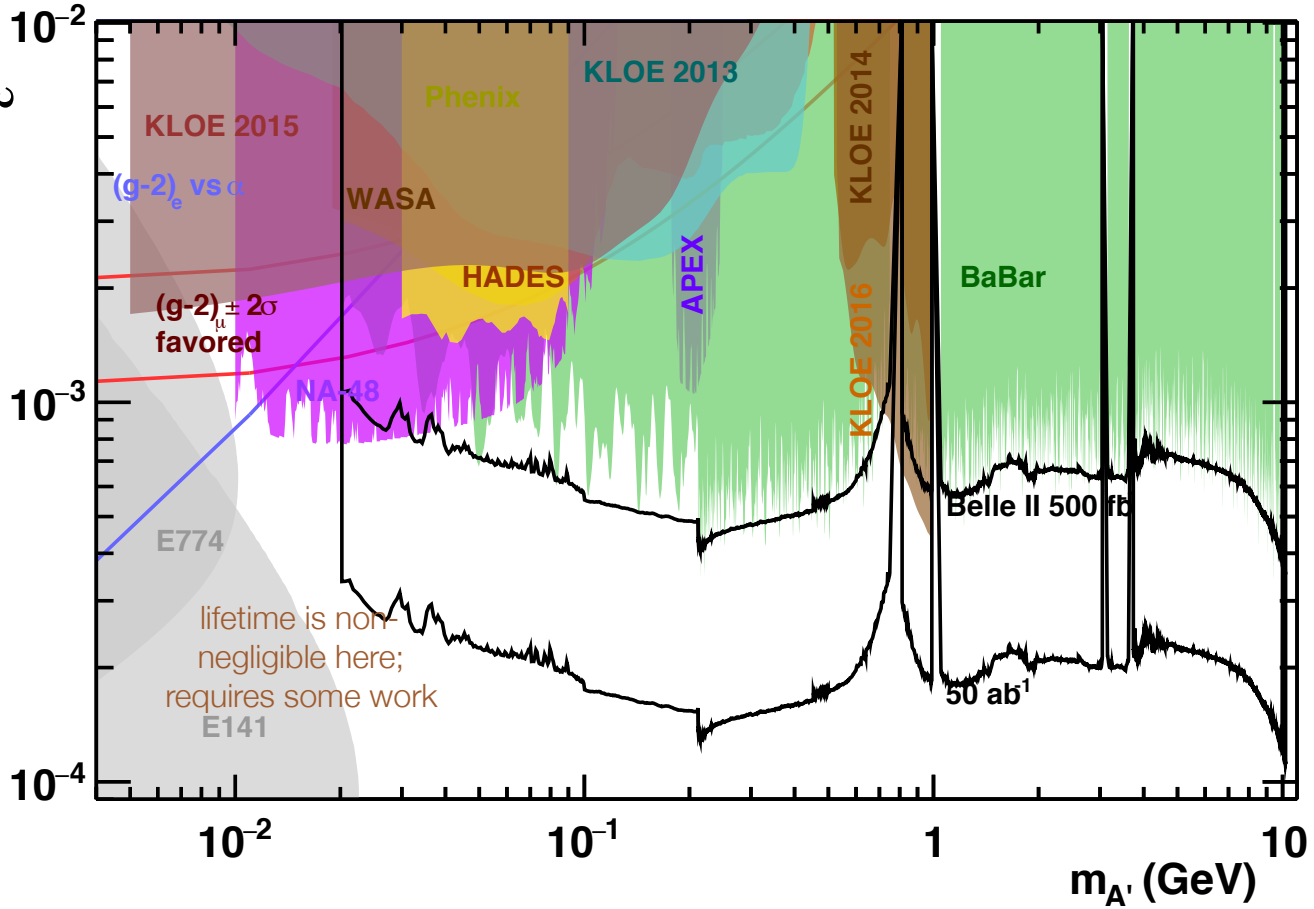
Implications for Belle-II

- Low-multiplicity triggers are key
- Single-photon triggers implemented in BaBar in 2007-2008:
  - Level-1 trigger: E_γ>0.8 GeV
    - ☞ 300-400 Hz @ 10^{34} $cm^{-2}s^{-1}$ luminosity (~40 nb cross section)
  - Level-3 trigger and offline filter
    - ☞ ~100 Hz rate
- High rate: early (low-lumi) analyses. May need to tighten selection at high luminosity
- Better (non-projective) calorimeter for invisible analysis
- For visible analyses, mass resolution may improve (larger drift chamber)

Belle-II Sensitivity: Visible Modes

Upper limit on ε
superscript 0 ⇒ BaBar value

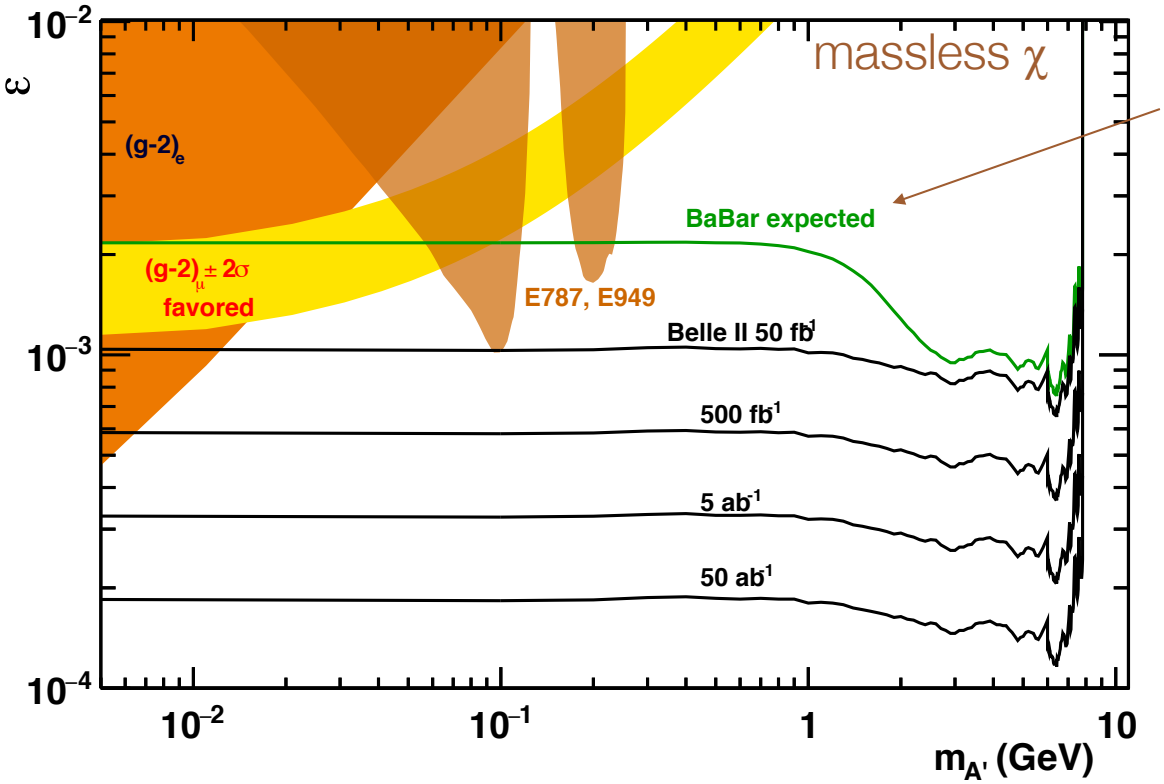
$$\frac{U_\epsilon}{U_\epsilon^0} = \left(\frac{\mathcal{L}^0}{\mathcal{L}} \frac{\Delta_M}{\Delta_M^0} \frac{\epsilon_{\ell\ell}^0}{\epsilon_{\ell\ell}} \right)^{0.25}$$



Bertrand Echenard
Chris Hearty

Belle-II Sensitivity: Invisible Mode

limit on ε improves as $\mathscr{L}^{0.25}$



C. Hearty | Light Higgs, Dark Sector | FPCP2016

Possible results as early as 2017-2018 ?

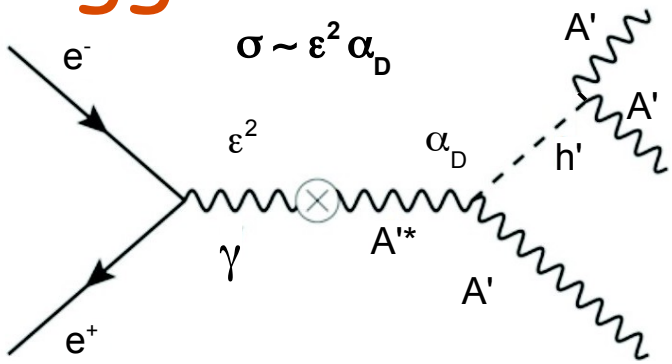
Summary and Outlook

- B Factories provide significant constraints on new physics models with low-mass degrees of freedom
  - Direct searches: unique sensitivity to low-mass new physics in high-statistics datasets
- Belle-II will increase statistics by orders of magnitude
  - Combined with LHC and direct detection dark matter searches, these measurements will provide unique information on the dynamics and flavor structure of new physics

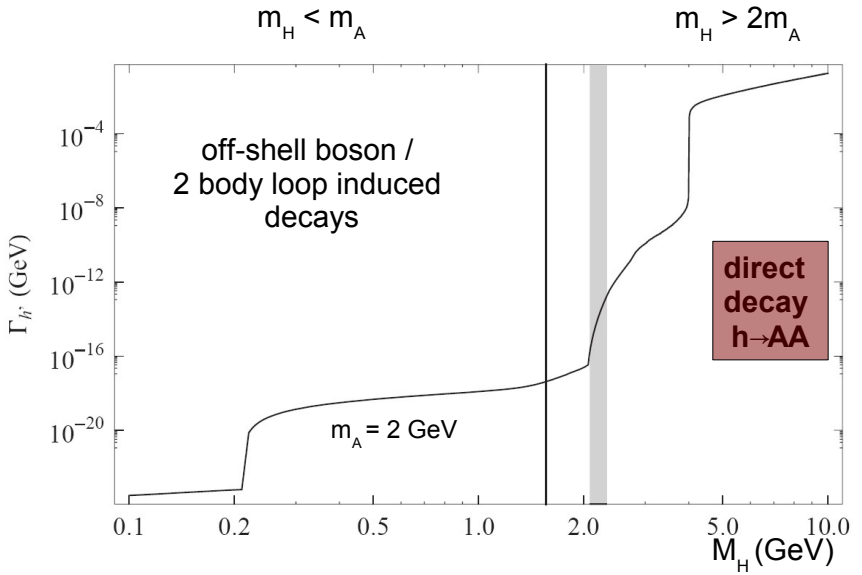
Backup

Search for Dark Higgs

- Extension of the dark sector models: dark Higgs
  - Mass generation in dark sector
  - Mass can be low
  - Detect by Higgs-strahlung process $e^+e^- \rightarrow A'h'$
  - Decays to A' pairs
    - ☞ Multi-particle (multi-lepton) final state
    - ☞ Clean detection, virtually no QED background



Higgs decay topology



displaced / invisible decay — prompt decay

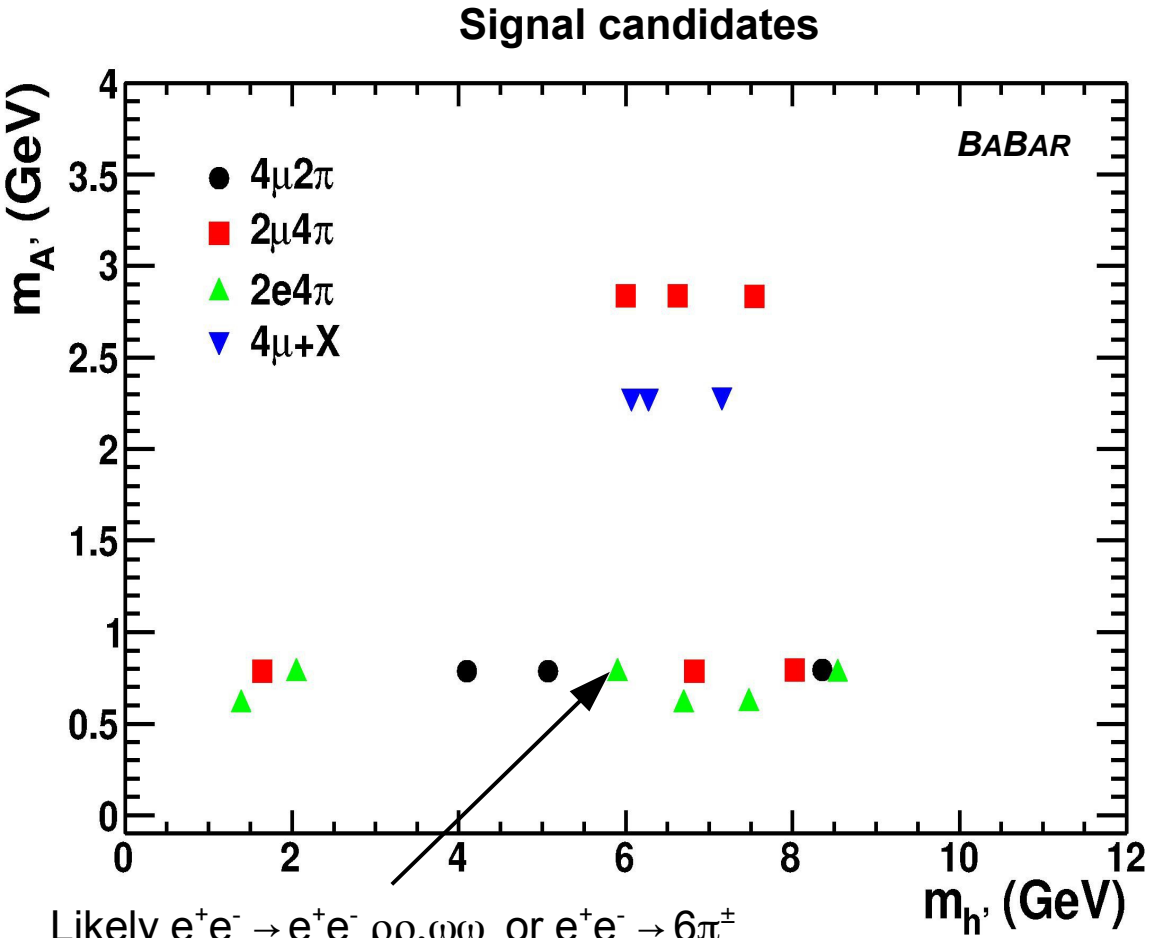
Dark Higgs Search

Focus on direct decay topology: $e^+e^- \rightarrow A'h'$; $h' \rightarrow A'A'$
Look for A' decays to a pair of oppositely-charged tracks, or to invisible final state ($A' \rightarrow e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$, X)

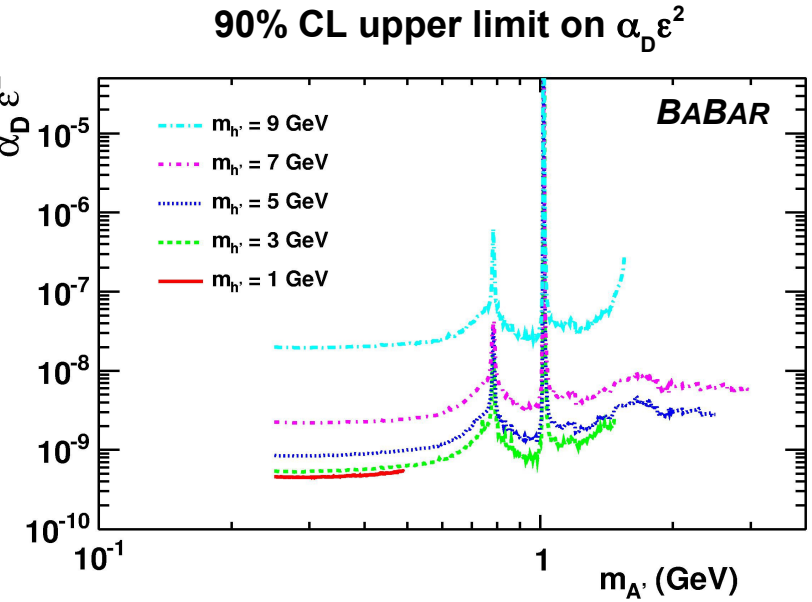
Require same mass for each pair

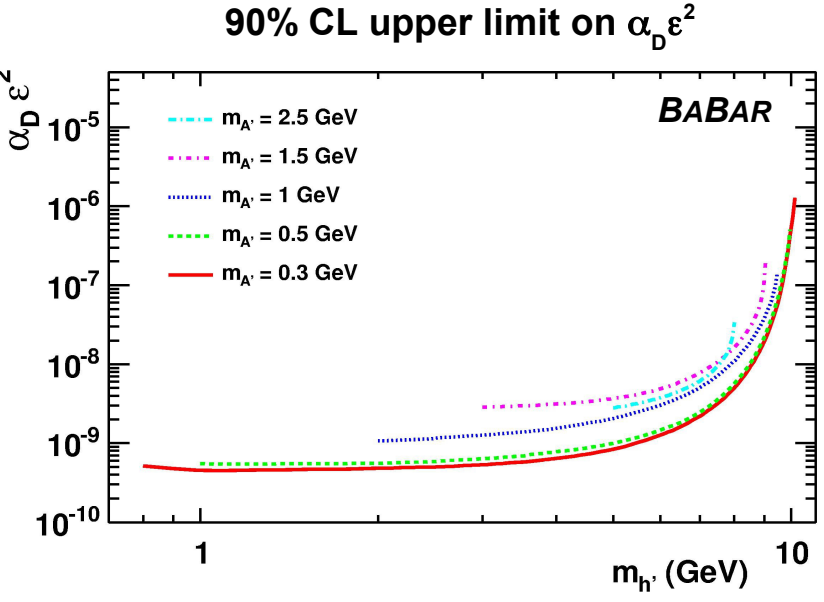
6 events selected
(18 combinations)

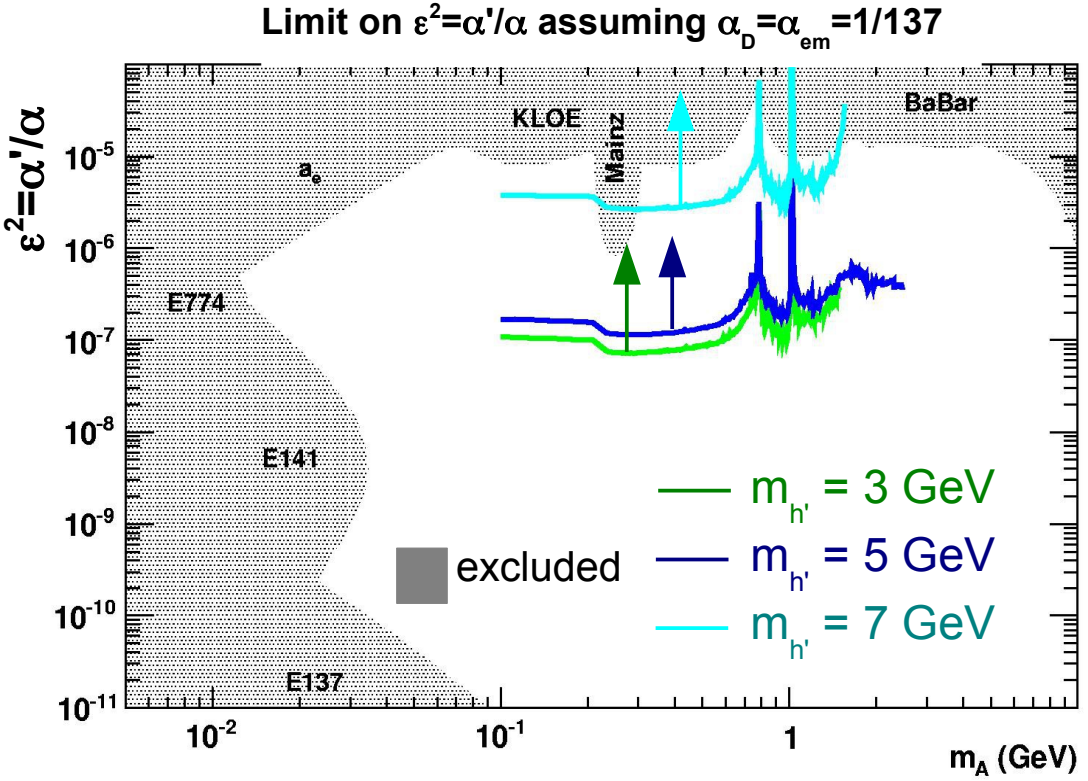
Consistent with background estimates



Dark Higgs Limits







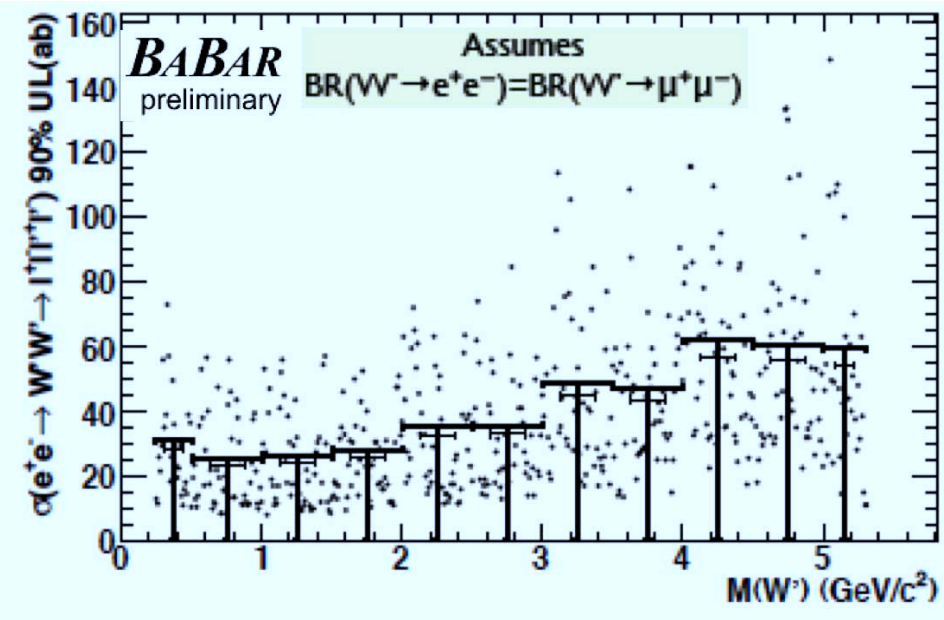
PRL **108**, 211801 (2012)

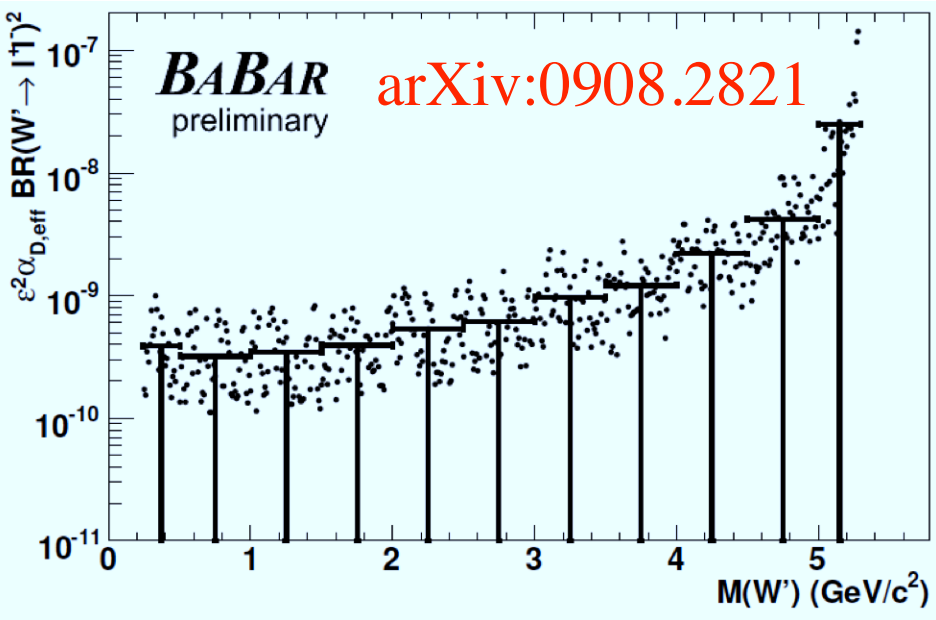
Substantial improvement over previous limits. Constrain model space

Direct Search for Dark Sector

Look for $e^+e^- \to l^+l^-l^+l^-$ final states (4e, 2e2μ,4μ) as a function of two-lepton mass

Full BaBar dataset (~540 fb^{-1})





$$\sigma(e^+e^- \to W'W' \to l^+l^-l'^+l'^-) < (25-60)\,\text{ab}$$

Some of the smallest cross section ULs measured @ B-Factories