Dark Sector Searches
at $e^+e^-$ Colliders

Dark Interactions
Brookhaven National Lab
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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, $\gamma$+invisible
- Very large datasets allow for high-statistics searches
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)

This range of parameters would explain the muon $g-2$ anomaly

$\lambda \sim 1\text{mm}$ for BaBar

$\lambda \sim 10\text{mm}$ for WASA

Limits on $\varepsilon$ and $m_{A'}$ as of FPCP 2015

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$\lambda \sim 1\text{mm}$ for BaBar

$\lambda \sim 10\text{mm}$ for WASA

PRL 113, 201801 (2014), 514 fb$^{-1}$

C. Hearty, FPCP-2016
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: $A' \rightarrow e^+e^-$

- **Fully-reconstructed final state**
  - $e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-$
  - $1.54 \text{ fb}^{-1}$ collected at $E_{cm}=1.019$ GeV (phi peak)
  - Select fully-reconstructed events with $e^+, e^-$, $\gamma$ at wide angles to suppress bhabha backgrounds

- **Look for narrow peak in $e^+e^-$ mass spectrum**
  - $5 \text{ MeV} < m_{A'} < 500 \text{ MeV}$

KLOE 2015

BabaYaga does a good job of describing data

No significant signal seen

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**KLOE:** $A' \rightarrow \pi^+ \pi^-$

- **Partially-reconstructed final state**
  - $e^+ e^- \rightarrow \gamma A', A' \rightarrow \pi^+ \pi^-$
  - 1.93 fb$^{-1}$ collected at $E_{cm} = 1.019$ GeV (phi peak)
  - Select events with ISR kinematics, $\pi^+, \pi^-$ at wide angles, undetected $\gamma$

- **Look for narrow peak in $\pi^+ \pi^-$ mass spectrum around $\rho$ and $\omega$ resonances**
  - Backgrounds dominated by hadronic events: $e^+ e^- \rightarrow \pi^+ \pi^- \gamma$ and phi decays
  - Look for narrow peak above smooth background, except for $\rho/\omega$ interference region where background needs to be modeled carefully (PHOKARA)

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Count events over interpolated background
No significant excess above 2σ local significance
KLOE Results

Significant improvement by KLOE at low $m_{A'}$ and in resonance region
Most $(g-2)_\mu$ parameter space excluded by $e^+e^-$ data

C. Hearty, FPCP-2016
KLOE: $A' \rightarrow \mu^+ \mu^-$ with Missing Energy

- Partially-reconstructed final state
  - Higgsstrahlung $e^+ e^- \rightarrow h' A'$, $A' \rightarrow \mu^+ \mu^-$ and long-lived $h'$
  - 1.86 fb$^{-1}$ collected at or below phi peak
  - Select events with reconstructed $\mu^+, \mu^-$ and missing momentum pointing to the calorimeter

- Look for narrow peak in $\mu^+ \mu^-$ mass in bins of $M_{\mu\mu}$ and $M_{\text{miss}}$

$\phi \rightarrow K^+ K^- \rightarrow \mu^+ \mu^- \nu \nu$
suppressed by cut on lifetime ($\lambda \sim 90$ cm)

$e^+ e^- \rightarrow \mu^+ \mu^-$

$e^+ e^- \rightarrow \pi^+ \pi^- \gamma$

$e^+ e^- \rightarrow \mu^+ \mu^- \gamma$

Fig. 2. Results for on-peak sample (left plot, 1.65 fb$^{-1}$ integrated luminosity) and off-peak sample (right plot, 0.206 fb$^{-1}$ integrated luminosity).

Fig. 3. Data–Monte Carlo comparison for the on-peak sample (top plots) and off-peak sample (bottom plots). Projections along the $M_{\mu\mu}$ axis (left plots); projections along the $M_{\text{miss}}$ axis (right plots). Also shown are the various contributing backgrounds.
KLOE: $A' \rightarrow \mu^+\mu^-$ with Missing Energy

- **Cut-n-count analysis**
  - Use events in sideband bins to predict the bin of interest
- **First constraints for** $m_{h'} < m_A'$

![Graphs showing the relationship between $m_U$ (MeV) and $\alpha_D \epsilon_2^2$ for different $m_h$ values.](https://example.com/graphics1)

![Graphs showing the relationship between $m_h$ (MeV) and $\alpha_D \epsilon_2^2$ for different $m_u$ values.](https://example.com/graphics2)

BaBar Search for Muonic Dark Force


- 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
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

$\rho$

$J/\psi$

$\psi(2S) \rightarrow \pi^+\pi^- J/\psi$

$\psi(2S) \rightarrow \pi^+\pi^- J/\psi$

$\psi(2S)$

$\Upsilon(2S)$

$\Upsilon(3S)$

uds

$e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

$e^+e^- \rightarrow \tau^+\tau^-$
Most significant signal at \( m_B = 0.79 \) GeV. 
4.3\( \sigma \)(1.6\( \sigma \)) local (global) significance

Distribution of local significance

(g-2)\( \mu \) region disfavored
BaBar Invisible Dark Photon Search

- $\gamma(3S) \rightarrow \gamma + \text{invisible}$ (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 $\varepsilon$ of order $O(10^{-3}-10^{-2})$
- Updated analysis in progress

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

Hidden Photon $\rightarrow$ invisible ($m_{A'} > 2 m_\chi$)

$\alpha_e$, $\alpha_{e,2\sigma}^{\text{favored}}$

Essig et al., arXiv:1309.5084

Several new initiatives will further probe this region.
Invisible Dark Photon: Limits

Hidden Photon → invisible ($m_{A'} > 2m_\chi$)

$10^{-3}$ 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: $E_\gamma > 0.8$ GeV
    - $300-400$ Hz @ $10^{34}$ cm$^{-2}$s$^{-1}$ luminosity (~40 nb cross section)
  - Level-3 trigger and offline filter
    - $\sim 100$ 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 $\varepsilon$ superscript 0 $\Rightarrow$ BaBar value

$$\frac{U_{\varepsilon}}{U_{\varepsilon}^0} = \left( \frac{\mathcal{L}^0}{\mathcal{L}} \frac{\Delta M}{\Delta \Delta M} \frac{\varepsilon_{\ell\ell}^0}{\varepsilon_{\ell\ell}} \right)^{0.25}$$

Bertrand Echenard
Chris Hearty

Lifetime is non-negligible here; requires some work E141

Projected Belle II sensitivity for visible $A'$ decays
Belle-II Sensitivity: Invisible Mode

Projected Belle II sensitivity for invisible $A'$ decays
• Extrapolating BaBar preliminary result, with corrections.
• Competitive measurement may be possible with Phase 2 commissioning data, maybe 20 fb$^{-1}$.

$$\epsilon \lesssim 10^{-3}$$

BaBar expected

$$\sigma \leq 50 \text{ fb}^{-1}$$

Belle II 50 fb$^{-1}$

$500 \text{ fb}^{-1}$

$5 \text{ ab}^{-1}$

$50 \text{ ab}^{-1}$

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
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

90% CL upper limit on $\alpha_D \varepsilon^2$

$\alpha_D \varepsilon^2$ vs $m_{A'}$ (GeV)

$\alpha_D \varepsilon^2$ vs $m_{h'}$ (GeV)

Substantial improvement over previous limits. Constrain model space.
Direct Search for Dark Sector

Look for $e^+e^- \rightarrow l^+l^-l'^+l'^-$ final states ($4e$, $2e2\mu, 4\mu$) as a function of two-lepton mass

Full BaBar dataset ($\sim 540 \text{ fb}^{-1}$)

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

$$\sigma(e^+e^- \rightarrow WW' \rightarrow l^+l^-l'^+l'^-)< (25 - 60) \text{ ab}$$

arXiv:0908.2821