Tau decays and dark-sector searches at BaBar

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Outline

- Dark photon
- Search in visible decays
- Search in invisible decays
- Search for a “muonic dark force”
- Measurement of the spectral function in $\tau^{\pm} \rightarrow K^{\pm}K_{S}^{0}\nu_{\tau}$ decays
The BaBar experiment

- Data taking from 1999 to 2008 at PEP-II asymmetric B-factory at SLAC

- Silicon Vertex Tracker
  - 5 layers double-sided Si strips

- ElectroMagnetic Calorimeter
  - 6580 CsI(Tl) crystals

- Drift CHamber
  - 40 layers, stereo view

- 1.5 T solenoid

- Detector of Internally Reflected Cherenkov Light
  - 144 bars of fused silica, 11K PMTs

- Instrumented Flux Return iron / RPC / LSTs


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The BaBar data sample

Center of Mass Energy

\[ \sigma(e^+ e^- \rightarrow \text{hadrons}) \text{ [nb]} \]

\[ E_{CM}\text{[GeV]} \]

\( \Upsilon(nS) \) resonances (CUSB)

BaBar data samples

\[(98.3 \pm 0.9) \times 10^6 \ \ \Upsilon(2S) \ (13.6 \text{ fb}^{-1})\]

\[(121.3 \pm 1.2) \times 10^6 \ \ \Upsilon(3S) \ (27.9 \text{ fb}^{-1})\]

\[(471.0 \pm 2.8) \times 10^6 \ \ \Upsilon(4S) \ (424.2 \text{ fb}^{-1})\]

Integrated luminosity

Y(2S), Y(3S) data

Delivered Luminosity

Recorded Luminosity

Recorded Luminosity Y(4s)

Recorded Luminosity Y(3s)

Recorded Luminosity Y(2s)

Off Peak

BaBar data samples
Dark photon searches

- Basic idea: kinetic mixing between the dark photon and the SM photon
- If the dark photon mass is low enough it could be produced at B-factories → one of most active analysis areas in post data taking era
- General analysis strategy:
  - Search for $e^+e^- \rightarrow \gamma\gamma$, use first $\gamma$ as tag
  - Blind analysis, optimize background rejection using a small data sample
  - Scan mass spectrum for peaking structure from dark sector particle

$$\Delta L = \frac{\varepsilon_Y}{2} F^{Y,\mu\nu} B_{\mu\nu}$$

Visible decays

- Search for $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow e^+e^-, \mu^+\mu^-$ on whole $Y(2S, 3S, 4S)$ dataset
- Fit dilepton mass spectrum to extract signals for each mass hypothesis
- Fit a mass window $\sim$20 times signal resolution ($\sigma$)
- Combinatorial background $\rightarrow$ 3rd or 4th order polynomial, peaking bkg inc.
- Regions around resonance ($\rho, \phi, J/\psi, \psi(2S)$) are excluded
- No significant signal observed

J.P. Lees et al. PRL 113, 201801 (2014)
Invisible decays

- Dark photon decays invisibly into dark matter → single photon trigger
- Analysis using 53 fb\(^{-1}\) of data collected in final BaBar running as such trigger was not available in earlier data-taking era
- Mostly at \(\Upsilon(3S)\) and \(\Upsilon(2S)\), small \(\sim 5\text{fb}^{-1}\) at \(\Upsilon(4S)\)
- Single photon final state → we look for a peak in missing mass:

\[
m_{A'}^2 = s - 2\sqrt{s}E_{\gamma}^*
\]

- Main backgrounds: \(e^+e^- \rightarrow \gamma\gamma\), \(e^+e^- \rightarrow \gamma e^+e^-\)
- Main issue: photons which go undetected because of azimuthal gaps between the EMC crystals which are not covered by IFR
Invisible decays

- Scan missing mass spectrum with different signal mass hypotheses
- Signal PDF: Crystal Ball function, background PDFs:
  - $m_{A'} < 5.5$ GeV: 2\textsuperscript{nd} order polynomial + Crystal Ball for peaking ($e^+e^- \rightarrow \gamma\gamma$)
  - $5.5 < m_{A'} < 8$ GeV: exponential polynomial
- Most significant fit at $m_{A'} = 6.22$ GeV/c\textsuperscript{2} $\rightarrow$ local (global) significance = 3.1 (2.6) sigma, global p-value $\sim 1\%$ $\rightarrow$ no significant signal

J.P. Lees et al. PRL 119, 131804 (2017)
Muonic dark force

- Some dark matter models postulate $L_\mu - L_\tau$ gauge interaction: new gauge boson, $Z'$ may be produced from radiation of the heavy-flavor leptons
- Could account for $(g-2)_\mu$ discrepancy
- Simplified model: SM plus new gauge boson $Z'$ with mass $M_{Z'}$ and gauge coupling $g'$

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Current limits rely on $Z'$--neutrinos coupling, absent in some models
Muonic dark force at BaBar

- Very clean channel to search for \(Z'\) at BaBar: \(e^+e^- \rightarrow \mu^+\mu^- Z', Z' \rightarrow \mu^+\mu^-\)

- Use full dataset of 514 fb\(^{-1}\): Y(4S), Y(3S) and Y(2S)
- Select exactly 4 tracks in two oppositely charged pairs \(t_1^+, t_2^+, t_1^-, t_2^-\)
- Excess neutral energy less than 200 MeV
- Muon ID on either same-sign track pair \((t_1^+t_2^+ \text{ or } t_1^-t_2^-)\)
- Invariant mass within 500 MeV of event center-of-mass energy
- To suppress events with \(Y(2S, 3S) \rightarrow \pi^+\pi^-Y(1S), Y(1S) \rightarrow \mu^+\mu^-\) we reject candidates with any \(t^+t^-\) invariant mass within 10MeV of \(Y(1S)\) mass
Muonic dark force: event selection

- Four Z' candidates per event
- Background dominated by $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$, contributions from $e^+e^- \rightarrow q\bar{q}$ and $e^+e^- \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow \mu^+\mu^-$
- MC generator used to produce $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ (Diag36) does not have ISR simulation → data has 30% lower peak and ISR radiation tail → does not affect this search, as background is fit on $m(Z')$ data sidebands
Muonic dark force: results

- 2219 un-binned fits for $0 < \, m_{Z'} < 10 \text{ GeV/c}^2$ on $m_{Z'}$ intervals $\sim 50 \times \sigma(m_{Z'})$
- Signal modeled with MadGraph5 + Pythia6
- Maximum local significance is $4.3 \sigma$ at $m_{Z'} = 0.82 \text{ GeV/c}^2$, global significance of 1.6 (null hypothesis) for $Z'$ mass from 0.212 to 10 GeV/c$^2$
- Can set 90% CL limits on new gauge coupling $g'$ as a function of $Z'$ mass

The spectral function $V(q)$ for $\tau^{-} \rightarrow K^{-} K_{S} \nu_{\tau}$ is defined as:

$$V(q) = \frac{m_{\tau}^{8}}{12\pi C(q)|V_{ud}|^{2}} \frac{B(\tau^{-} \rightarrow K^{-} K_{S} \nu_{\tau})}{B(\tau^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\tau})} \frac{1}{N} \frac{dN}{dq} \quad q = M_{K_{S}}^{2}$$

$$C(q) = q(m_{\tau}^{2} - q^{2})^{2}(m_{\tau}^{2} + 2q^{2})$$

- $BF(\tau^{-} \rightarrow K^{-} K_{S} \nu_{\tau})$ has been measured by **Belle** = $(7.40 \pm 0.07 \pm 0.27) \times 10^{-4}$
- $V(q)$ is related to the iso-vector part of $e^{+}e^{-} \rightarrow K\bar{K}$ recently measured by **BaBar** (both $e^{+}e^{-} \rightarrow K^{+}K^{-}$ and $e^{+}e^{-} \rightarrow K_{L}K_{S}$) and **SND** ($e^{+}e^{-} \rightarrow K^{+}K^{-}$)
- $M_{K-K_{S}}$ measurement performed by **CLEO** with $O(10^{3})$ less data
- $V(q)$ never measured before, important for MC tuning:
  - $BF(\tau^{-} \rightarrow K^{-} K^{0} \nu_{\tau})$ (PDG2016) = $(0.740 \pm 0.025) \times 10^{-3}$
  - $BF(\tau^{-} \rightarrow K^{-} K_{S} \nu_{\tau})$ (MC) = $(0.8255(1)(\text{stat})) \times 10^{-3}$

- $11.5\%$ difference!
Spectral function in $\tau^- \rightarrow K^- K_S \nu_{\tau}$

- Cut based analysis:
  - $N(\text{tracks}) = 4$
  - $N(K_S) = 1$, $K_S \rightarrow \pi^+ \pi^-$
  - $d(K_S) = 1 - 70 \text{ cm}$
  - Thrust $> 0.875$
  - $K^- : p_{LAB} = 0.4 - 5 \text{ GeV/c}$
  - lepton: $p_{LAB} > 1.2$, $p_{CM} < 4.5 \text{ GeV/c}$
  - $\theta_{CM, \text{lepton} - KK} > 110^\circ$
  - Neutral E $< 2 \text{ GeV}$
  - data/MC efficiency correction based on PID
  - sig/bkg $\sim 1$, bkg almost entirely from non-signal $\tau$
  - $\tau$-bkg: 79% $\tau^- \rightarrow K^- K_S \pi^0 \nu_{\tau}$, 10% $\tau^- \rightarrow \pi^- K_S \nu_{\tau}$,
    3% $\tau^- \rightarrow \pi^- K_S \pi^0 \nu_{\tau}$, remaining mainly mis-tag

Efficiency correction

BaBar Preliminary

BaBar Preliminary

$\text{m}_{KK} (\text{GeV/c}^2)$
Spectral function in $\tau^- \rightarrow K^- K_S \nu_\tau$

- Background subtraction for $\tau^- \rightarrow K^- K_S \pi^0 \nu_\tau$ based on data

- $BF(\tau^- \rightarrow K^- K_S \nu_\tau) = (0.739 \pm 0.011 \pm 0.020) \times 10^{-3}$ in agreement with Belle

- $m_{KKs}$ spectrum in agreement with CLEO, far more precise

*First measurement of $V(q)$!*

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**BaBar Preliminary**

1/N dN/dq ($1000$)

$V(1000)$

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Summary

- B-factories can still provide significant constraints on new physics models

- We searched for a dark photon mixing with the SM photon both in visible and invisible final states and set new constraints on the parameter space

- We performed a search for a new gauge boson, Z' coupling primarily to heavy flavor leptons setting limits on the new gauge coupling constant and excluding most of the (g-2)_{\mu} anomaly preferred parameter space

- We measured for the first time the spectral function V(q) for \( \tau^{-} \rightarrow K^{-} K_{s} \nu_{\tau} \) decay, as well as the BFs and the mass spectra which are in agreement and partially improve previous experimental results
Thanks for your attention!