Tau decays and dark-sector searches at BaBar

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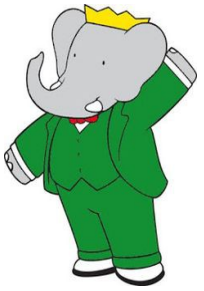
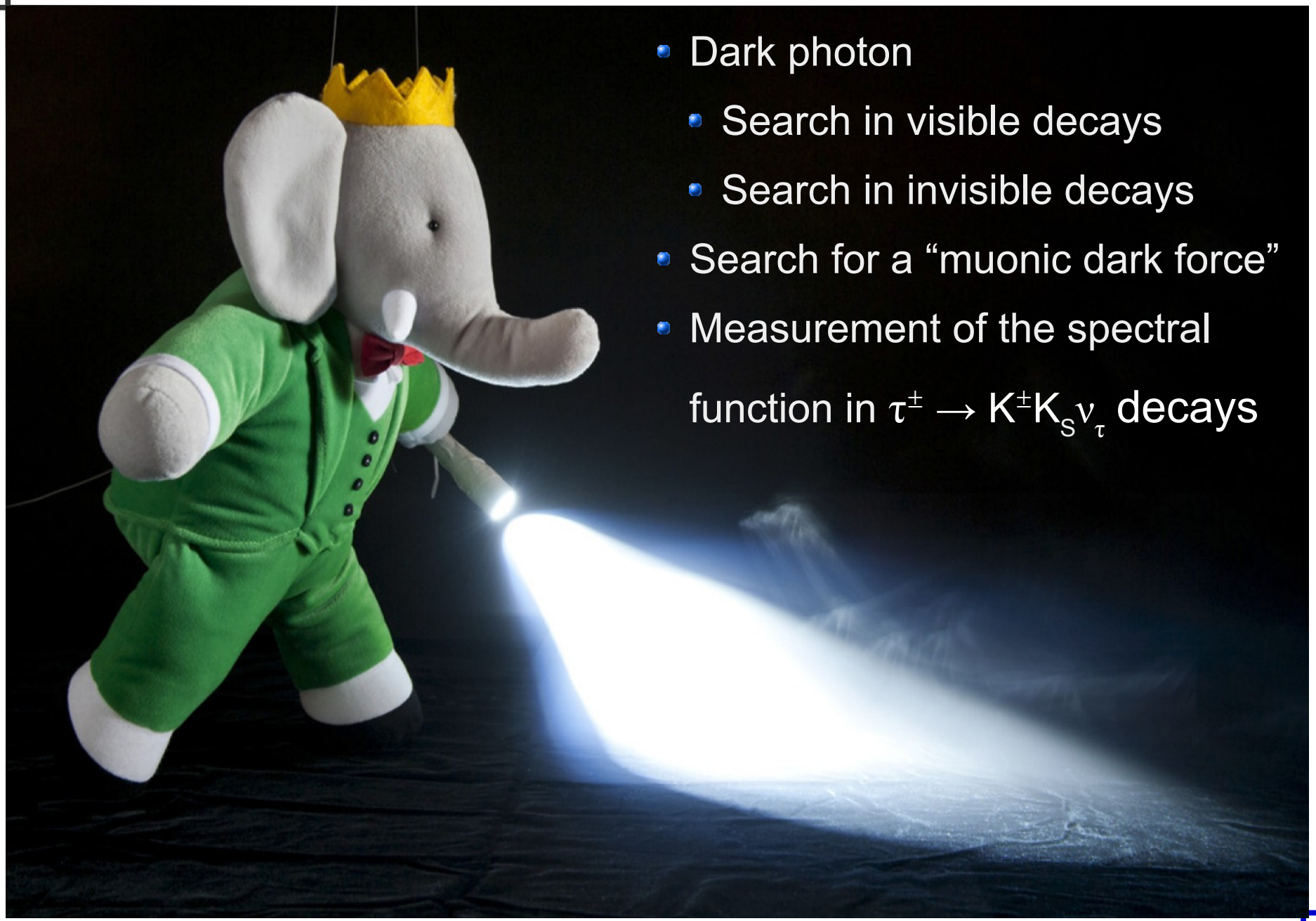
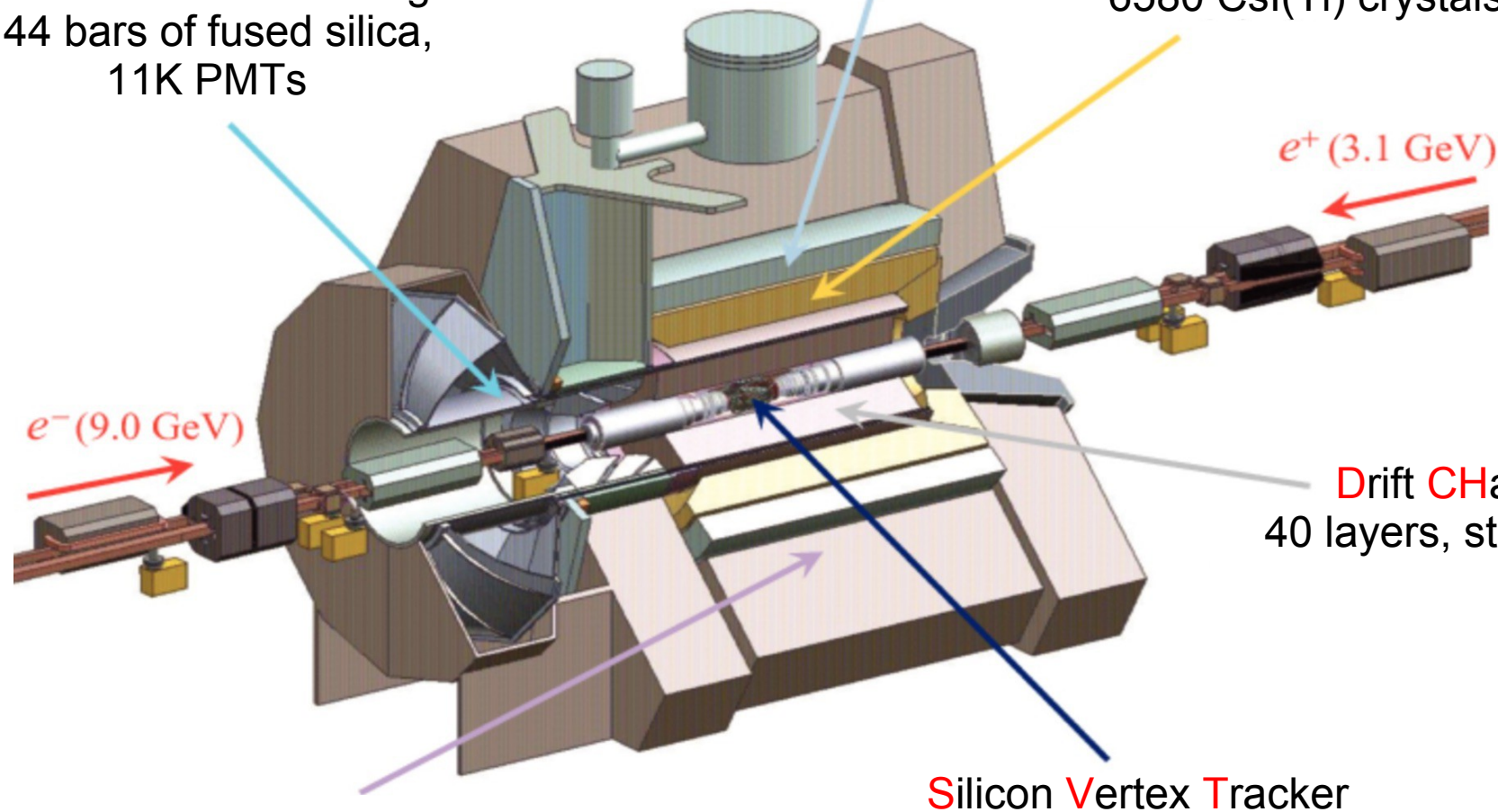


Outline



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

The BaBar experiment

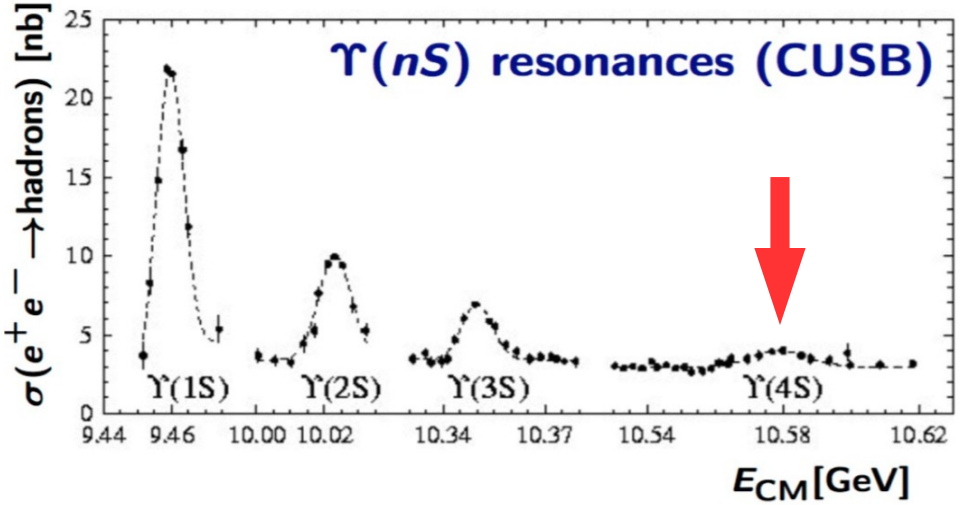


- Data taking from 1999 to 2008 at PEP-II asymmetric B-factory at SLAC

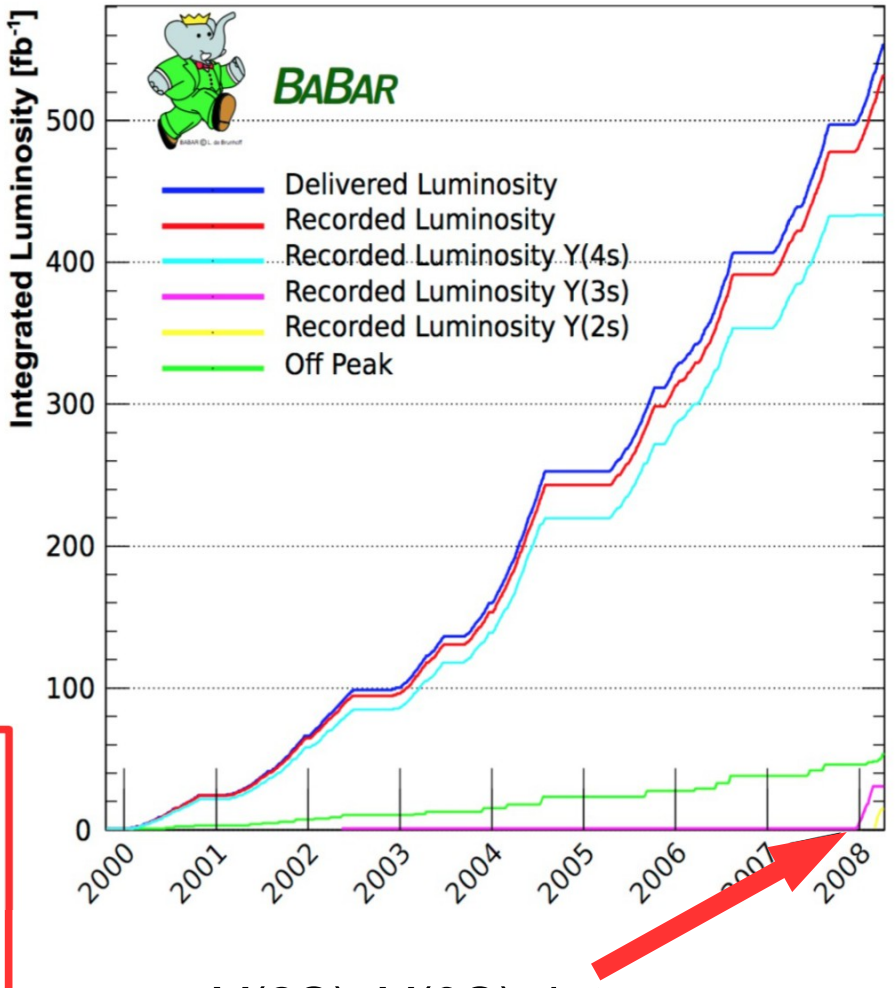
Nucl.Instrum.Meth. A 479, 1 (2002)
Nucl.Instrum.Meth. A 729, 615 (2013)

The BaBar data sample

Center of Mass Energy



Integrated luminosity

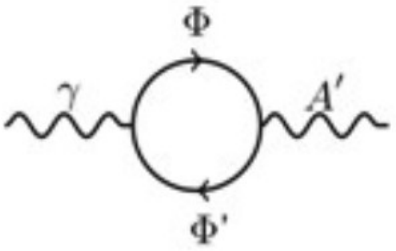


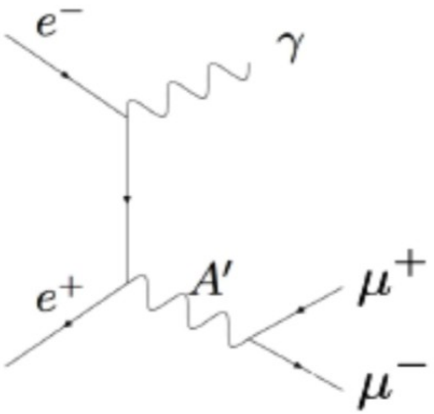
Y(2S), Y(3S) data

BaBar data samples

$(98.3 \pm 0.9) \times 10^6$	Y(2S)	(13.6 fb^{-1})
$(121.3 \pm 1.2) \times 10^6$	Y(3S)	(27.9 fb^{-1})
$(471.0 \pm 2.8) \times 10^6$	Y(4S)	(424.2 fb^{-1})

Dark photon searches





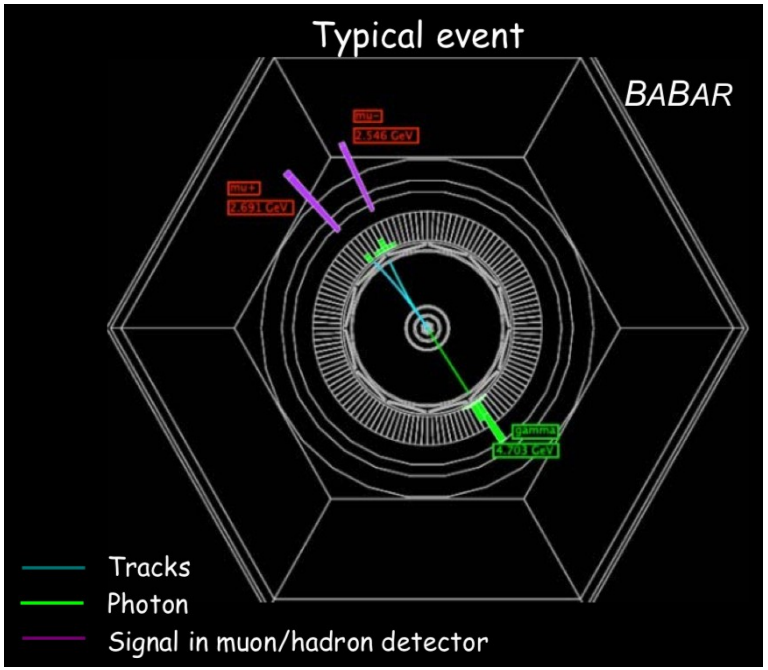
$$\Delta L = \frac{\varepsilon_Y}{2} F^{Y,\mu\nu} B_{\mu\nu}$$

B. Holdom, Phys. Lett. B 166, 196 (1986)

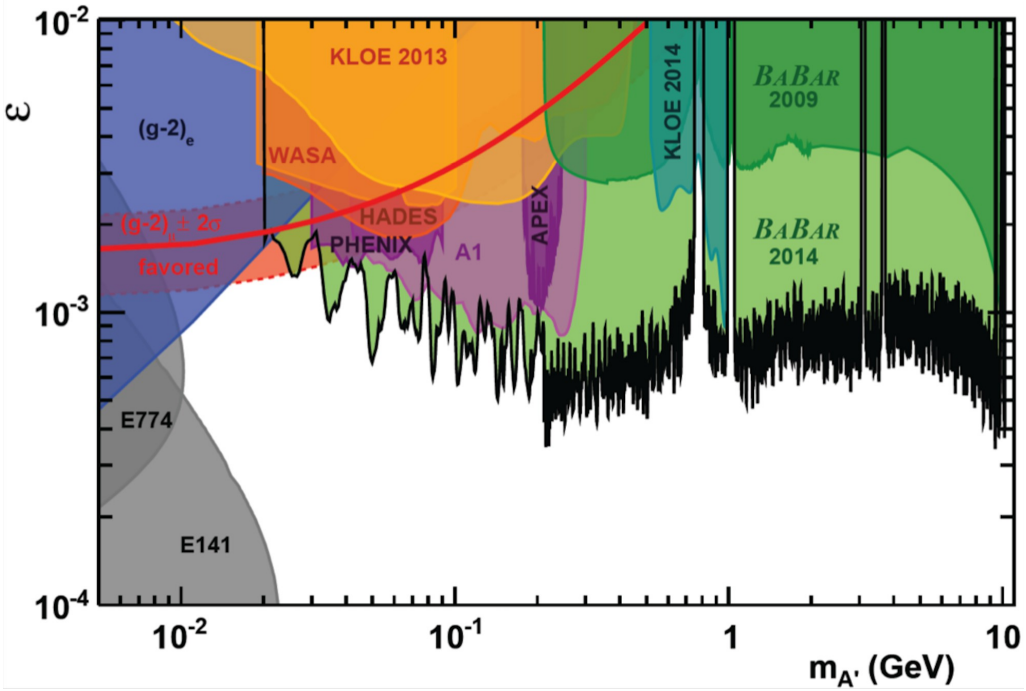
- Basic idea: kinetic mixing between the dark photon and the SM photon
- If the dark photon mass is low enough it could be be produced at B-factories → one of most active analysis areas in post data taking era
- General analysis strategy:
  - Search for $e^+e^- \rightarrow \gamma\gamma$, use first γ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

Visible decays

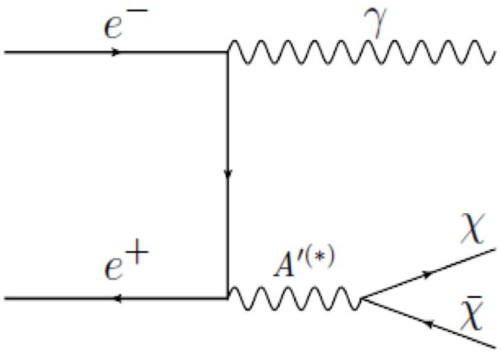
- Search for $e^+e^- \to \gamma A'$, $A' \to e^+e^-$, $\mu^+\mu^-$ on whole Y(2S, 3S, 4S) dataset
- Fit dilepton mass spectrum to extract signals for each mass hypothesis
- Fit a mass window ~20 times signal resolution (σ)
- Combinatorial background → 3rd or 4th order polynomial, peaking bkg inc.
- Regions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



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



Invisible decays



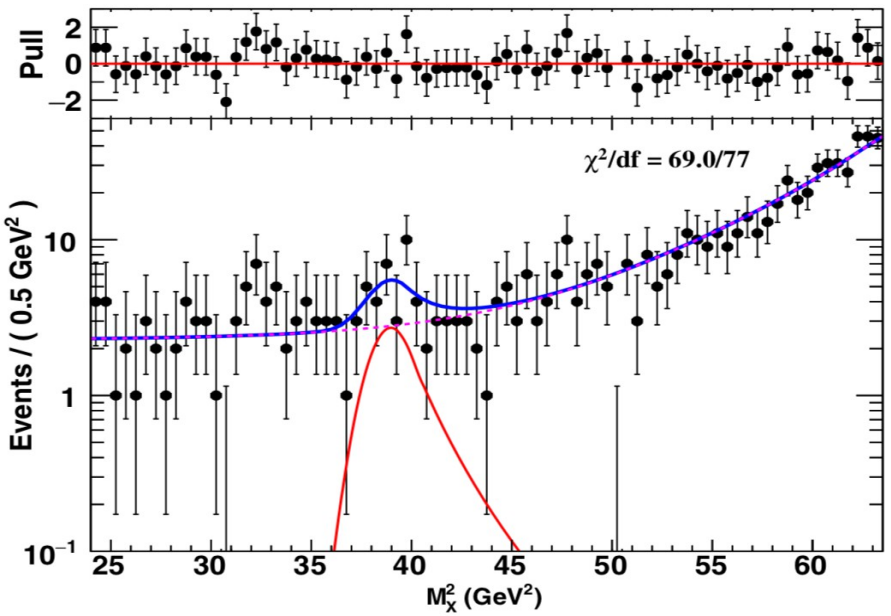
- Dark photon decays invisibly into dark matter → single photon trigger
- Analysis using 53 fb^{-1} of data collected in final BaBar running as such trigger was not available in earlier data-taking era
- Mostly at Y(3S) and Y(2S), small ~ $5fb^{-1}$ at Y(4S)
- Single photon final state → we look for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

$$m^2_{A'} = s - 2\sqrt{s}E^*_\gamma$$

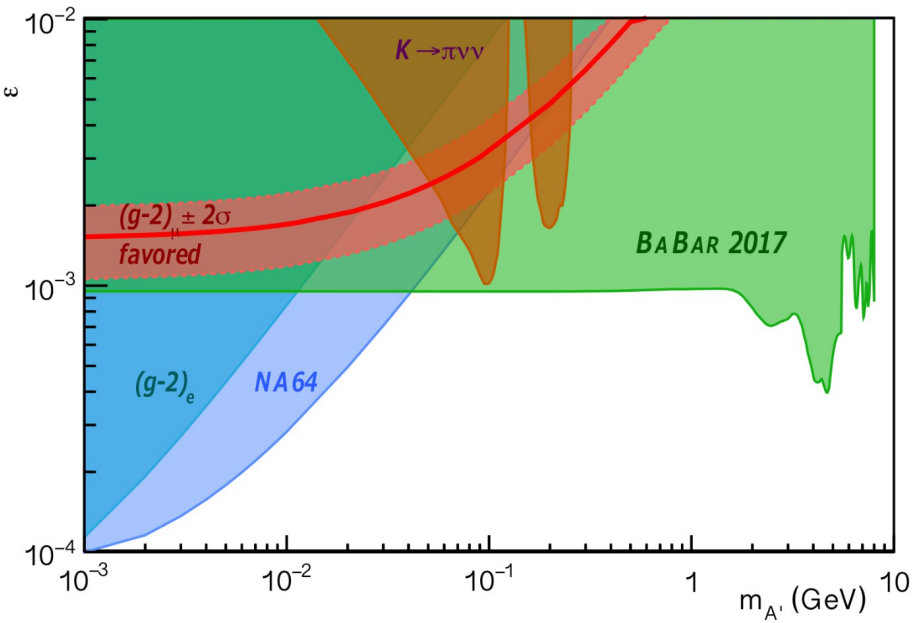
- Main backgrounds: $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow \gamma e^+e^-$
- Main issue: photons which go undetected because of azimuthal gaps between the EMC crystals which are not covered by IFR

Invisible decays

- Scan missing mass spectrum with different signal mass hypotheses
- Signal PDF: Crystal Ball function, background PDFs:
  - $m_{A'} < 5.5$ GeV: 2nd 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^2 → local (global) significance = 3.1 (2.6) sigma, global p-value ~ 1% → no significant signal



J.P. Lees *et al.* PRL 119, 131804 (2017)

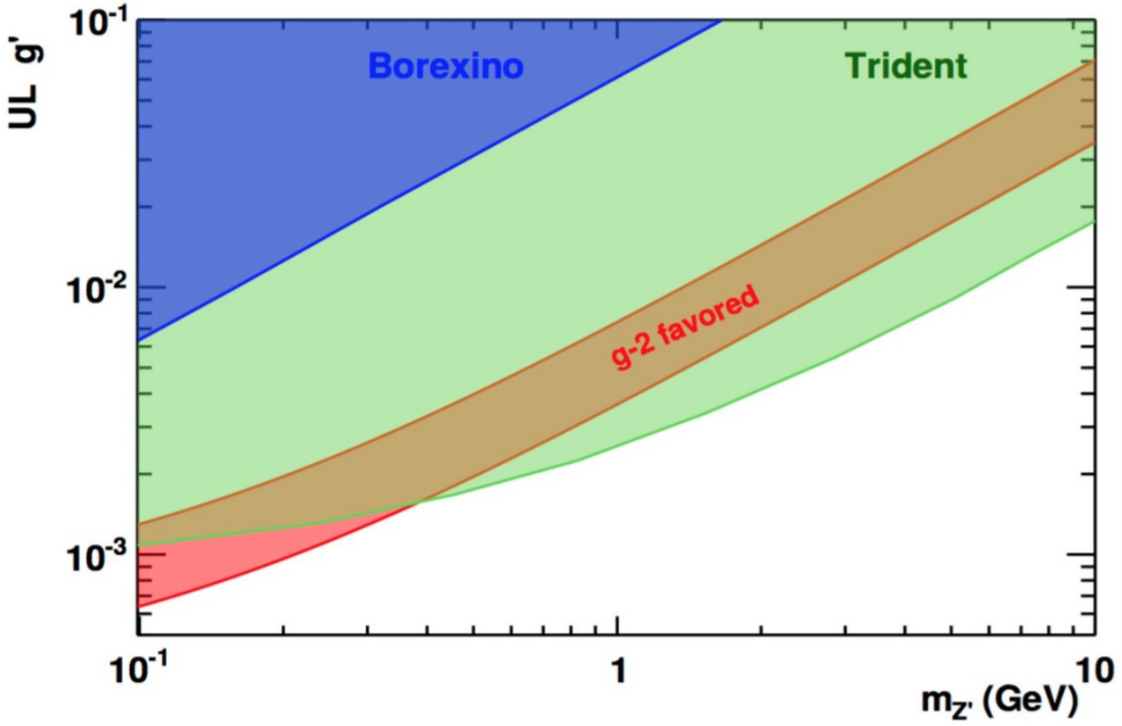


Muonic dark force

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

X. G. He *et al.*, Phys. Rev. D 43, 22 (1991).
X. G. He *et al.*, Phys. Rev. D 44, 2118 (1991).

- Simplified model: SM plus new gauge boson Z′ with mass $M_{Z'}$ and gauge coupling g'



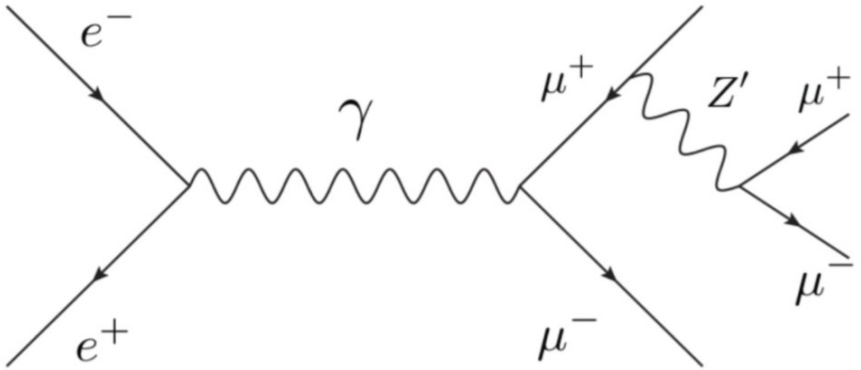
Trident: W. Altmannshofer *et al.*, Phys. Rev. Lett. 113, 091801 (2014).

A. Kamada and H. B. Yu, Phys. Rev. D 92, 113004 (2015).

Current limits rely on Z′−neutrinos coupling, absent in some models

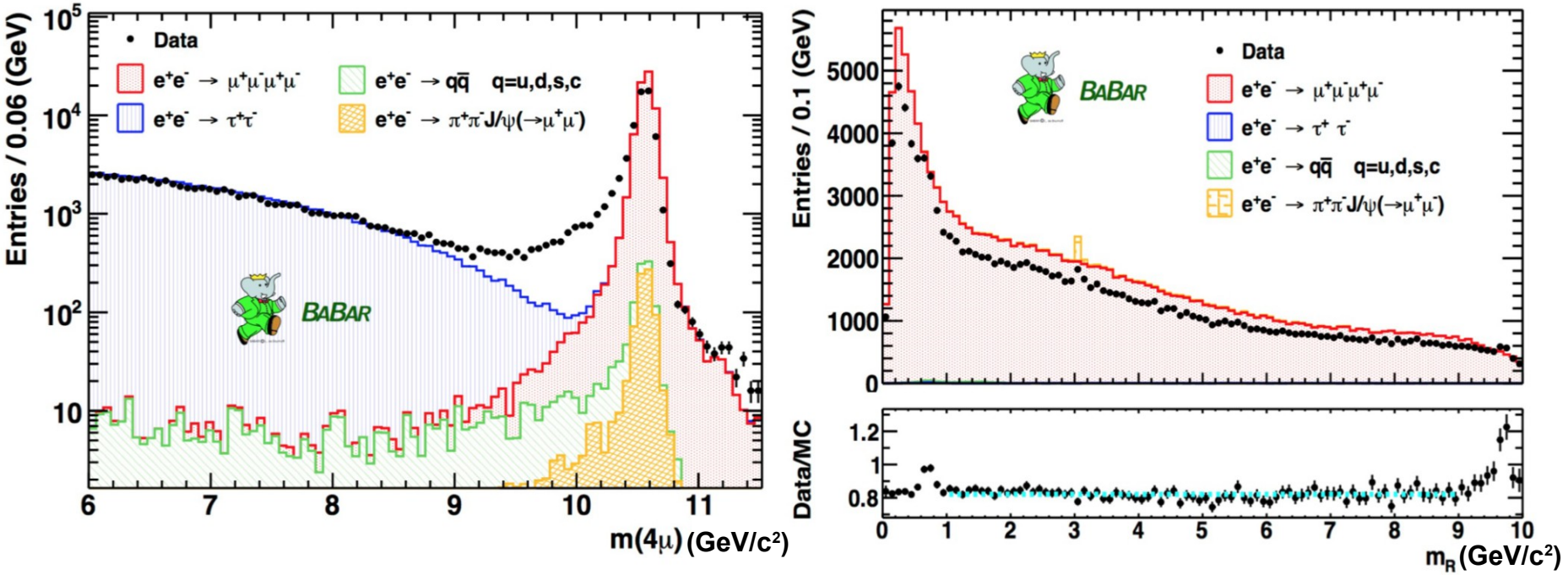
Muonic dark force at BaBar

- 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 ($t_1^+ t_2^+$ 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

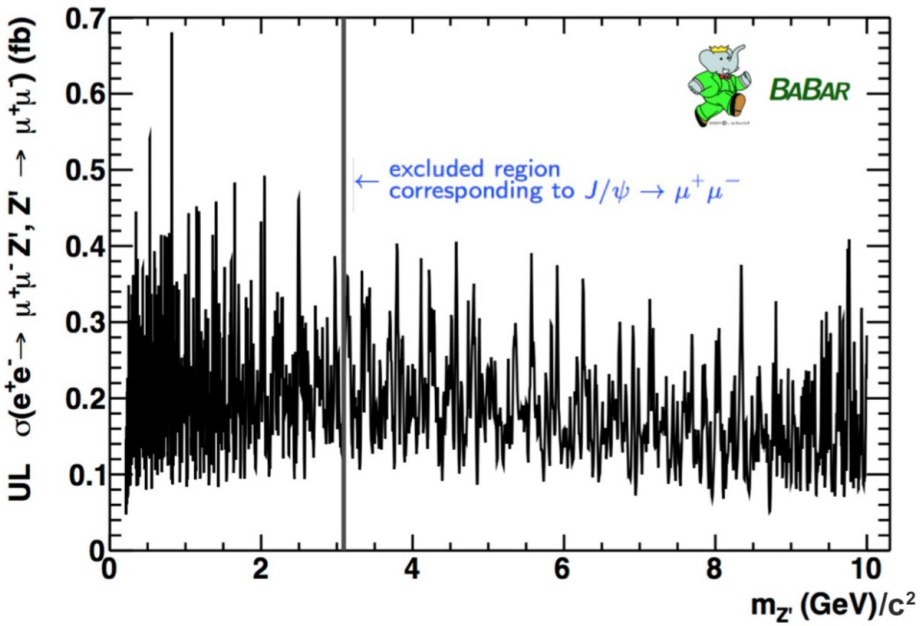


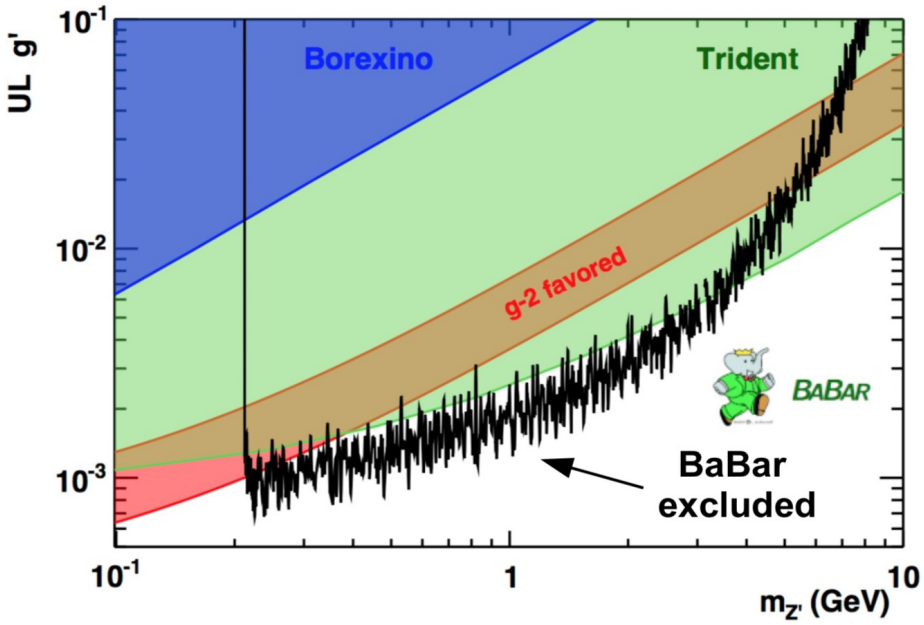
- Four Z' candidates per event
- Background dominated by $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$, contributions from $e^+e^- \to q\bar{q}$ and $e^+e^- \to \pi^+\pi^- J/\psi$, $J/\psi \to \mu^+\mu^-$
- MC generator used to produce $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ (Diag36) does not have ISR simulation → data 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 $0 < m_{Z'} < 10$ GeV/c^2 on $m_{Z'}$ intervals ~50 × $\sigma(m_{Z'})$
- Signal modeled with MadGraph5 + Pythia6
- Maximum local significance is 4.3 σ at $m_{Z'}$ = 0.82 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

J.P. Lees *et al.* Phys. Rev. D. 94, 011102 (2016)





Spectral function in $\tau^- \to K^- K_S \nu_\tau$

- The spectral function *V(q)* for $\tau^- \to K^- K_S \nu_\tau$ is defined as:

$$V(q) = \frac{m_\tau^8}{12\pi C(q)|V_{ud}|^2} \frac{\mathcal{B}(\tau^- \to K^- K_S \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \frac{1}{N} \frac{dN}{dq}$$

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

NEW

$q = M_{K\text{-}Ks}$

Phys. Rev. D4 2821 (1971)
[Erratum-ibid. D13, 771 (1976)]

Belle: Phys. Rev. D 89, 072009 (2014)

- BF($\tau^- \to K^- K_S \nu_\tau$) 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 $e^+e^- \to K\bar{K}$ recently measured by BaBar (both $e^+e^- \to K^+K^-$ and $e^+e^- \to K_L K_S$) and SND ($e^+e^- \to K^+K^-$)

$$\sigma^{I=1}_{e^+e^- \to K\bar{K}}(q) = \frac{4\pi^2\alpha^2}{q^2} V(q)$$

BaBar: Phys. Rev. D88, 3, 032013 (2013)

BaBar: Phys. Rev. D89, 9, 092002 (2014)

SND: Phys. Rev. D94, 112006 (2016)

- $M_{K\text{-}Ks}$ measurement performed by CLEO with O(10^3) less data

CLEO: Phys. Rev. D 53, 6037 (1996)

- *V(q)* never measured before, important for MC tuning:

BF($\tau^- \to K^- K^0 \nu_\tau$) (PDG2016) = $(0.740 \pm 0.025) \times 10^{-3}$

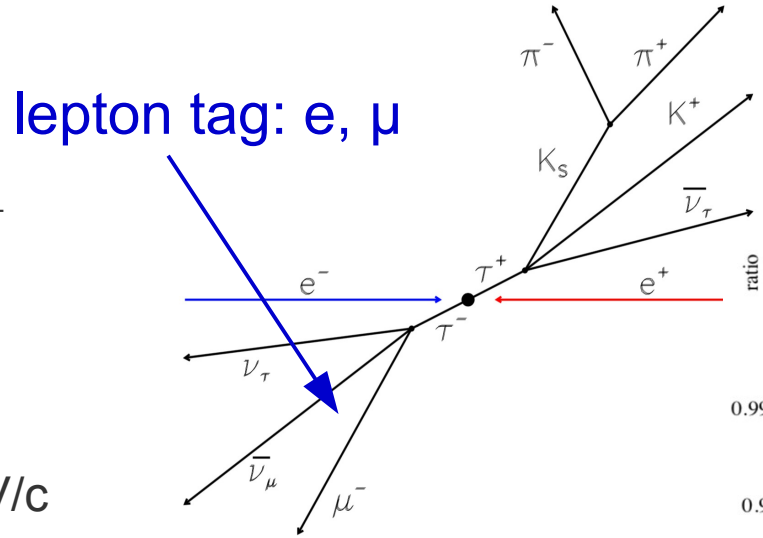
BF($\tau^- \to K^- K_S \nu_\tau$) (MC) = $(0.8255(1)(\text{stat})) \times 10^{-3}$

11.5% difference!

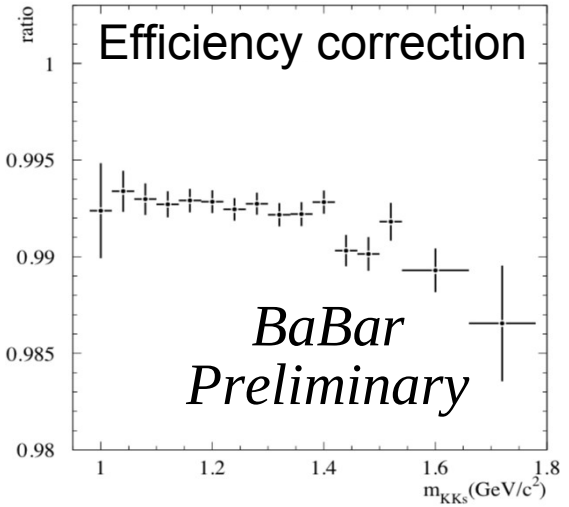
Spectral function in $\tau^- \to K^- K_S \nu_\tau$

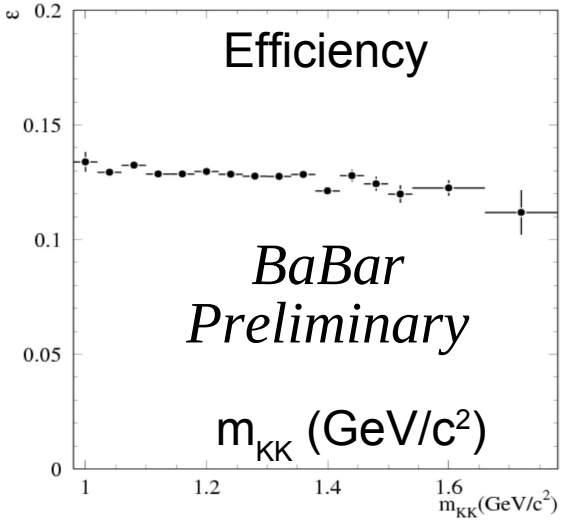
- Cut based analysis:
  - N(tracks) = 4
  - N(K_S) = 1, $K_S \to \pi^+\pi^-$
  - d(K_S) = 1 – 70 cm
  - Thrust > 0.875
  - K^- : p_{LAB} = 0.4 - 5 GeV/c
  - lepton: $p_{LAB} > 1.2$, $p_{CM} < 4.5$ GeV/c
  - $\theta_{CM,\ lepton\ -\ KKs} > 110^o$
  - Neutral E < 2 GeV
- data/MC efficiency correction based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

  3% $\tau^- \to \pi^- K_S \pi^0 \nu_\tau$, remaining mainly mis-tag



NEW



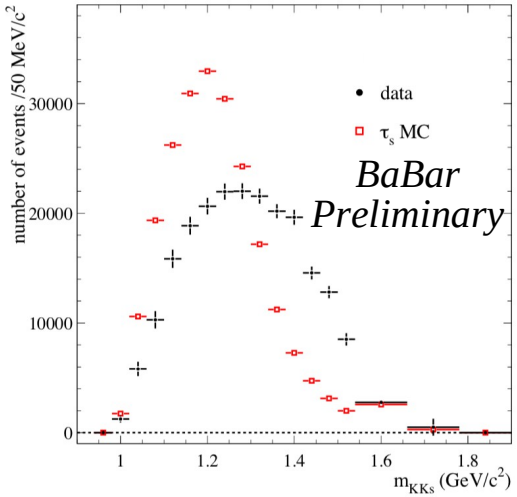


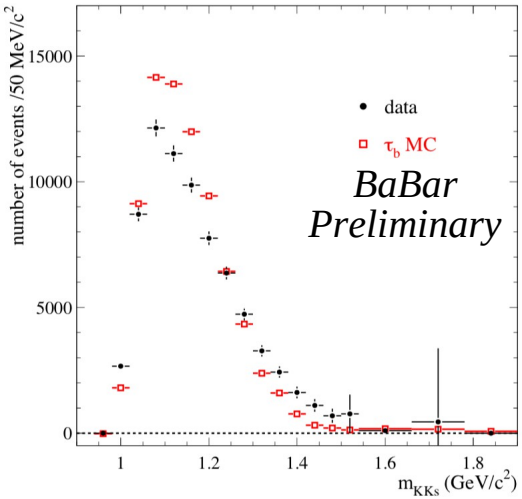
Spectral function in $\tau^- \to K^- K_S \nu_\tau$

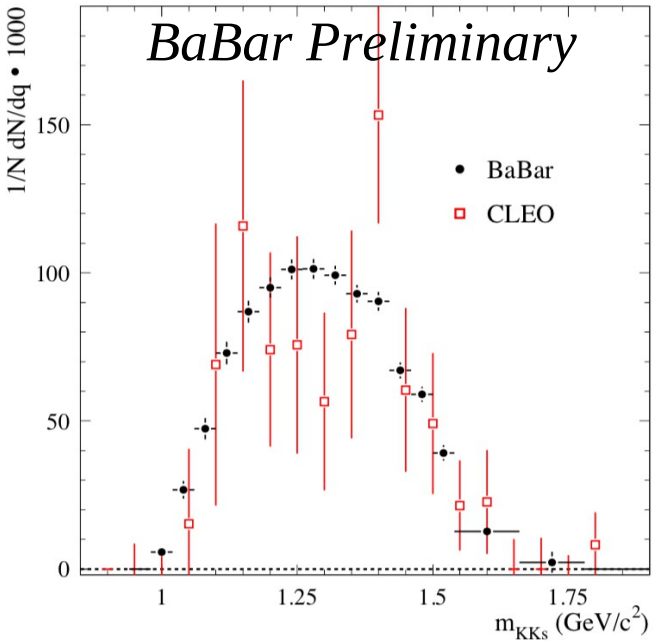
- Background subtraction for $\tau^- \to K^- K_S \pi^0 \nu_\tau$ based on data
- BF($\tau^- \to K^- K_S \nu_\tau$ is) = (0.739 ± 0.011 ± 0.020) x 10^{-3} in agreement with Belle
- m_{KKs} spectrum in agreement with CLEO, far more precise

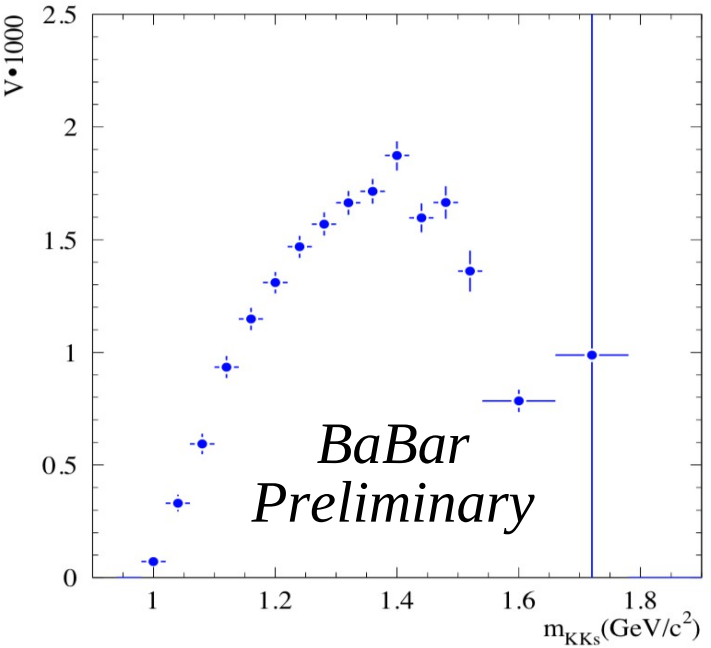
NEW

First measurement of V(q)!









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!