

Searches for Light New-Physics Particles with BaBar Data

A Muonic Dark Force? New Results

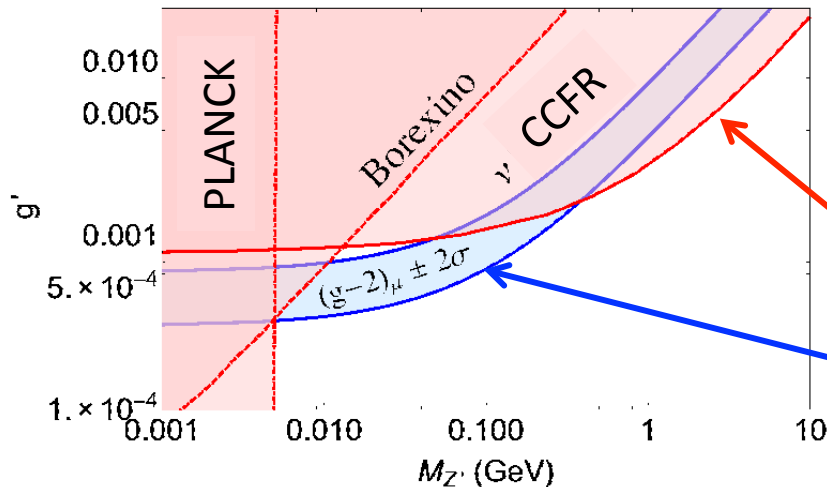
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PASCOS 2016

22nd International Symposium on Particles, Strings and Cosmology
XIIIth Rencontres du Vietnam, July 10-16, 2016, ICISE, Quy Nhon, Vietnam

Muonic Dark Force ?

- Astrophysics, cosmology: dark matter = ?
- Possible explanation: hidden sectors, with their own gauge bosons Z' , feebly coupled to SM
 - Z' kinetical mixing with SM bosons: couplings to light quarks and electrons proportional to SM, strongly constrained by existing searches
 - Z' directly coupled with SM fermions: may prefer heavy-flavour leptons; might explain $(g-2)_\mu$ measurements, proton radius in muonic atoms
- Example of a specific model: $L_\mu - L_\tau$ gauge interaction

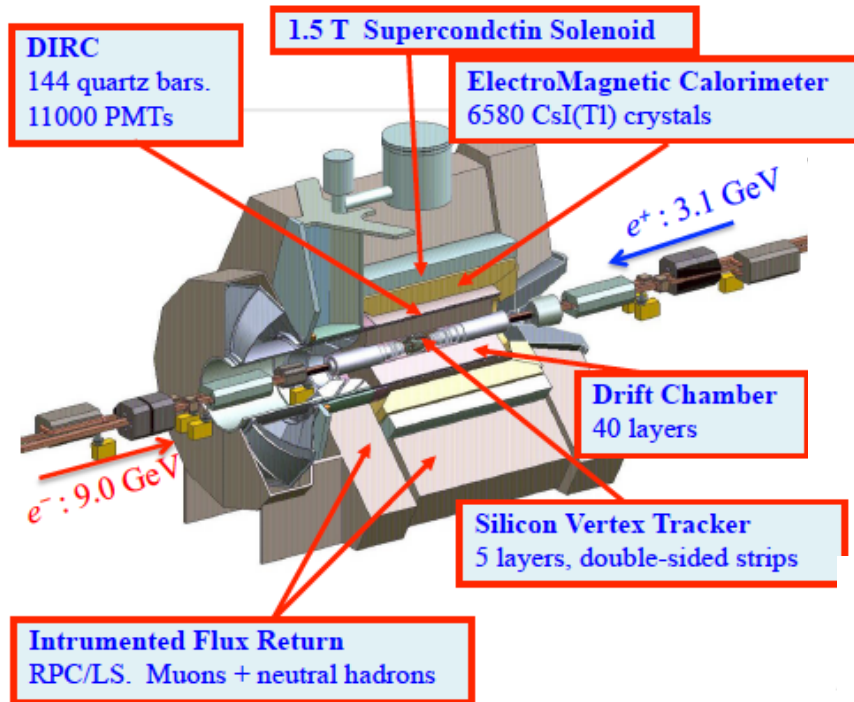


$$L_{Z'} = g' Z'_\alpha (\bar{\mu} \gamma^\alpha \mu + \bar{\nu}_{\mu L} \gamma^\alpha \nu_{\mu L} - \bar{\tau} \gamma^\alpha \tau + \bar{\nu}_{\tau L} \gamma^\alpha \nu_{\tau L})$$

Existing experimental constraints

Interesting region, favoured by $(g-2)_\mu$

BaBar Search for Z' : Data Sample



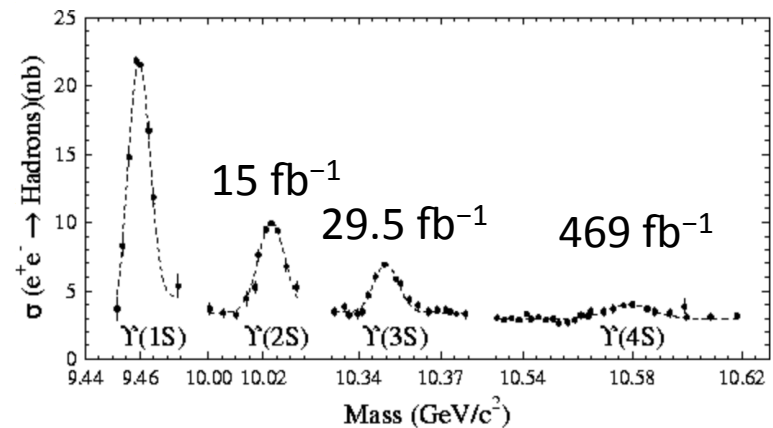
BaBar spectrometer NIM A729, 615(2014)

- Excellent momentum resolution
- Particle identification
- Large acceptance also for neutrals

PEP-II at SLAC (1999-2008)

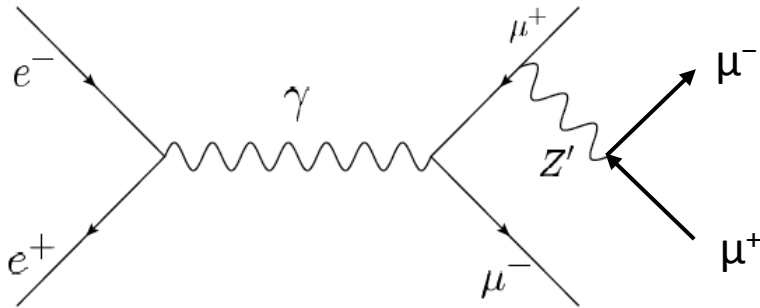
- 9.0 GeV e^- , 3.1 GeV e^+
- High luminosity
- Data samples at $\Upsilon(4S)$, $\Upsilon(3S)$, $\Upsilon(2S)$

Integrated luminosity
for this analysis: 514 fb^{-1}



Kinematics and Event Selection

$$e^+e^- \rightarrow \mu^+\mu^- Z', \quad \boxed{Z' \rightarrow \mu^+\mu^-}$$



Z' search:

$\mu^+\mu^-\mu^+\mu^-$ invariant mass $m_{4\mu}$

$\mu^+\mu^-$ invariant mass $m_{\mu^+\mu^-}$

$\mu^+\mu^-$ reduced mass m_R

$$m_R = \sqrt{m_{\mu^+\mu^-}^2 - 4m_\mu^2}$$

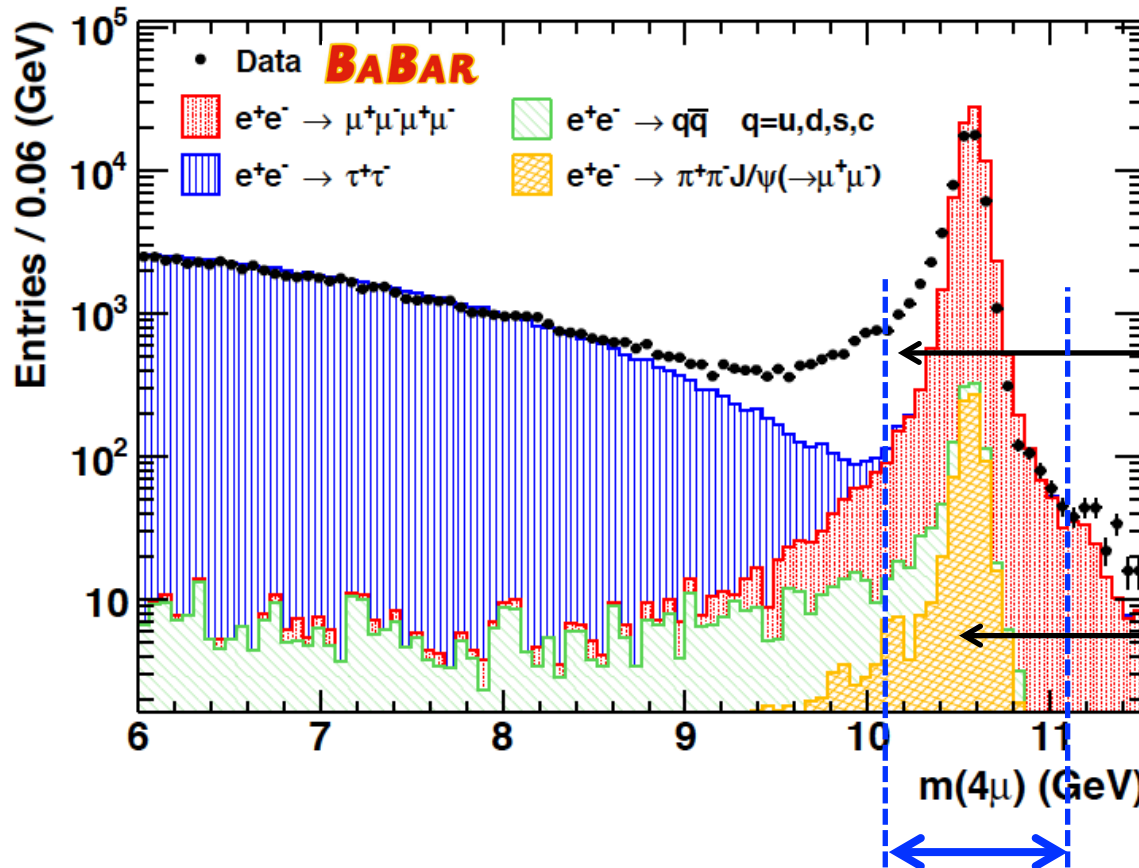
four Z' candidates per event

Selection criteria:

- 2 pairs of oppositely charged tracks
- sum of energy of e.m. clusters not associated to tracks < 200 MeV
- both positively OR both negatively charged tracks: loosely identified as muons
- Veto against $\Upsilon(2S, 3S) \rightarrow \Upsilon(1S) \pi^+\pi^-$, $\Upsilon(1S) \rightarrow \mu^+\mu^-$
- $E_{CM} - 500 \text{ MeV} < m_{4\mu} < E_{CM} + 500 \text{ MeV}$, E_{CM} = nominal CM energy

Standard Model Backgrounds

$\mu^+\mu^-\mu^+\mu^-$ invariant mass distribution: data and MC, $\Upsilon(4S)$ sample



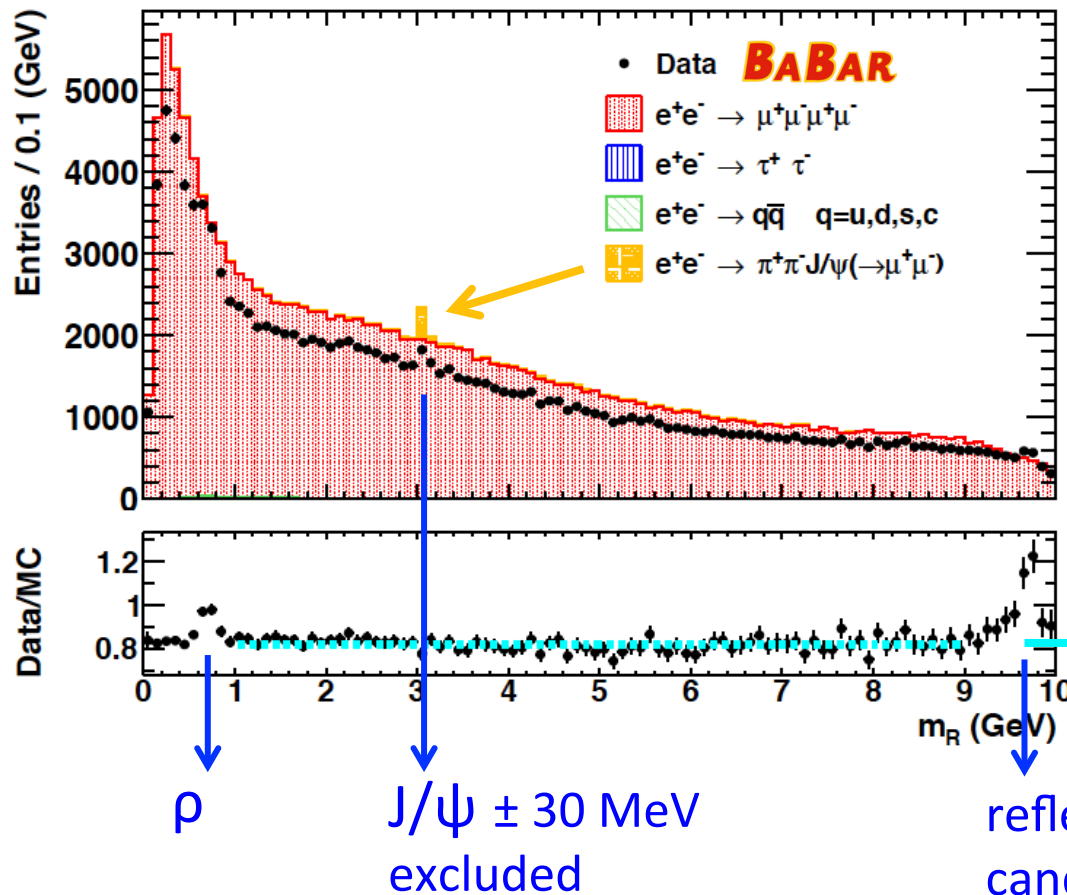
radiative tail from ISR
(not included in *Diag36*
generator for $\mu^+\mu^-\mu^+\mu^-$)
re-weighted later in MC

light quarks
and J/ψ

Selected interval: nominal CM energy ± 500 MeV

Reduced Mass, Data and MC

distribution of $\mu^+\mu^-$ reduced mass m_R for data and bkgd MC after refit with vertex and energy constraints to improve mass resolution



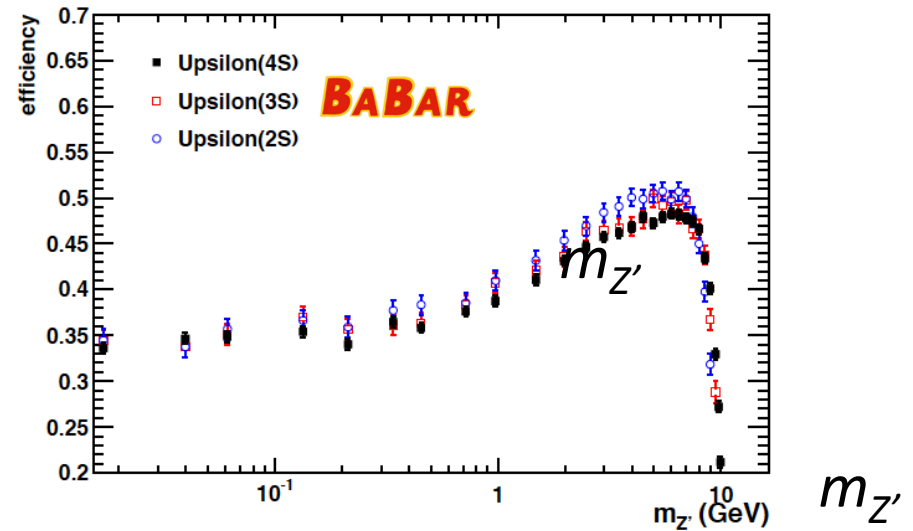
“optimistic” MC:
 correction factors
 (independent checks):
 0.86 ISR tail
 0.95 Tracking, PID



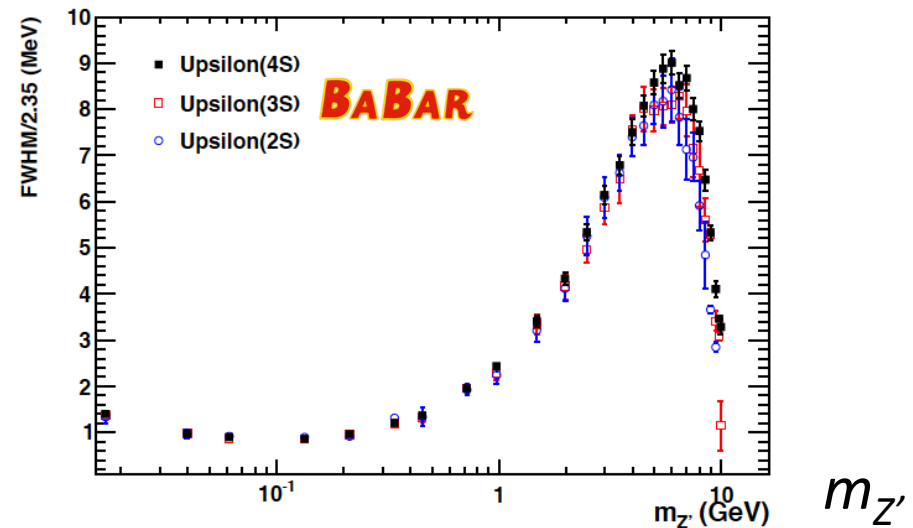
Data/MC = 0.82 ± 0.05

Signal Efficiency, Resolution vs $m_{Z'}$

Signal efficiency
35 to 50%



Mass resolution
1 to 9 MeV



Signal Yield and Cross Section

Signal yield N_{sig} from series of 2219 unbinned ML fits to m_R intervals (50 x resolution)

Likelihood function: pdfs for signal, continuum and peaking backgrounds

No evidence of excess over the backgrounds

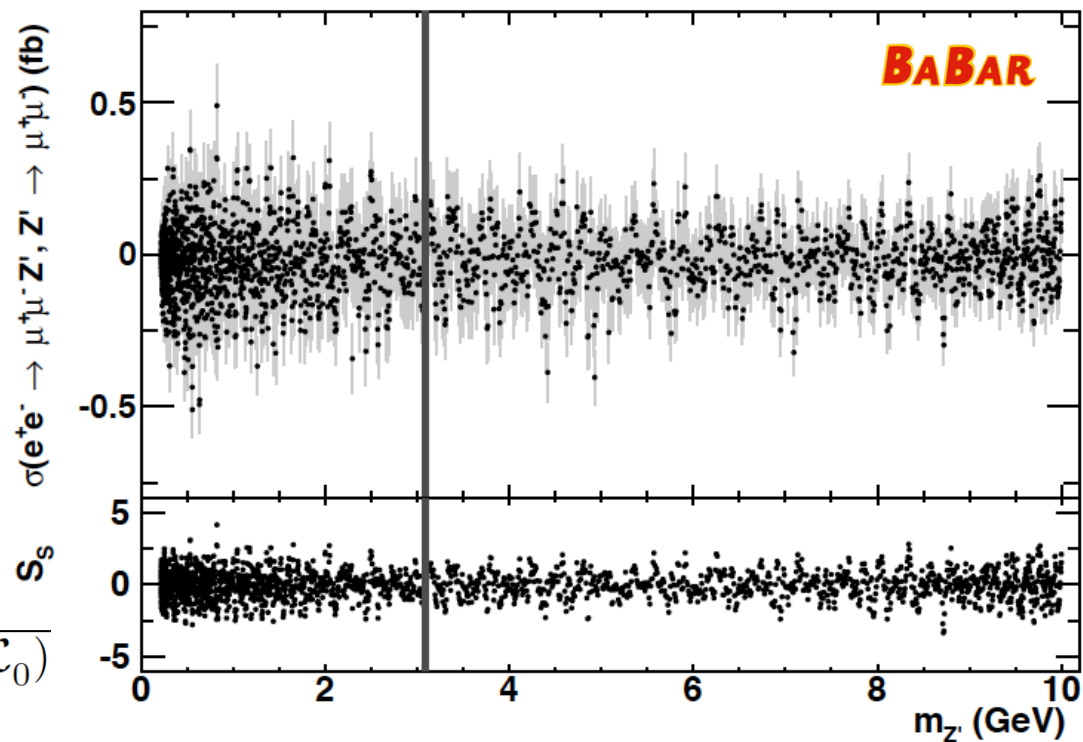
Cross section:

Compatible with zero

$$\sigma = \frac{N_{sig}}{eff \times Lumi}$$

Significance:

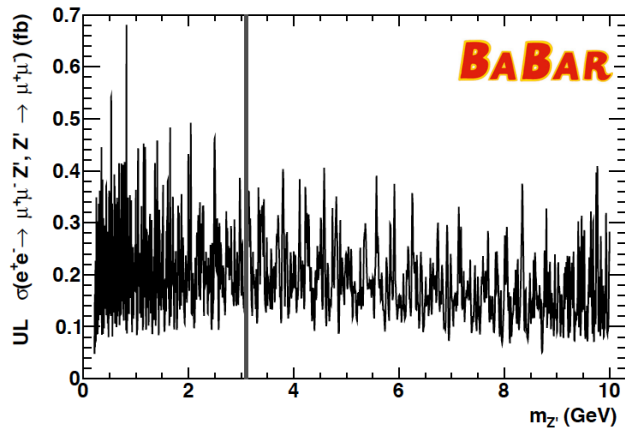
$$\mathcal{S}_S = \text{sign}(N_{sig}) \sqrt{2 \log(\mathcal{L}/\mathcal{L}_0)}$$



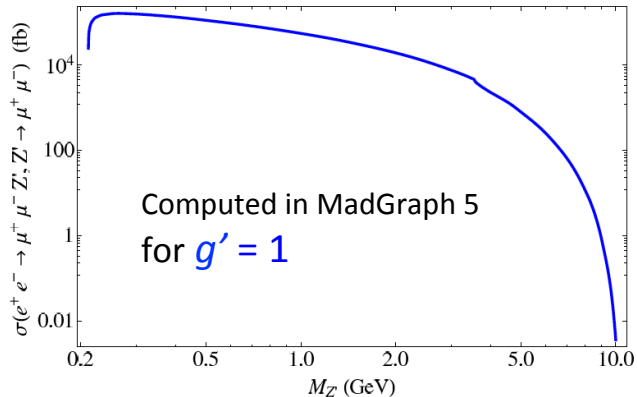
Main systematic uncertainties: efficiency + ISR 5%, luminosity 0.6%, MC stat. 1-3%

g' vs $M_{Z'}$ Upper Limits

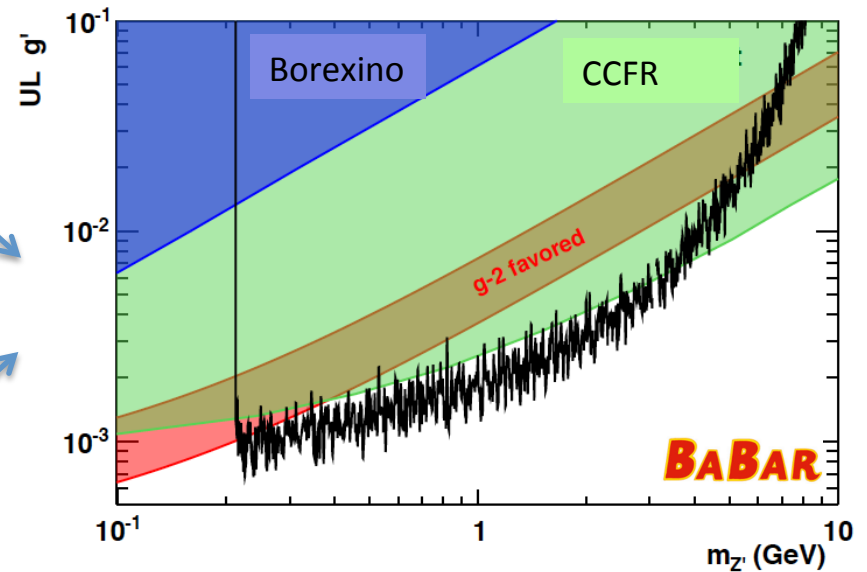
Bayesian 90% CL upper limit on σ [fb]



First-order σ vs $m_{Z'}$ in the $L_\mu-L_\tau$ model



90% CL upper limit on g' vs $m_{Z'}$

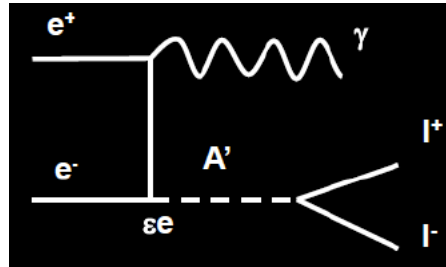


assumed in this plot: equal magnitude couplings to muons, taus and corresponding neutrinos

Other Light-Particles Searches in BaBar

Dark photons

more results expected
decays to invisible
single-photon trigger!



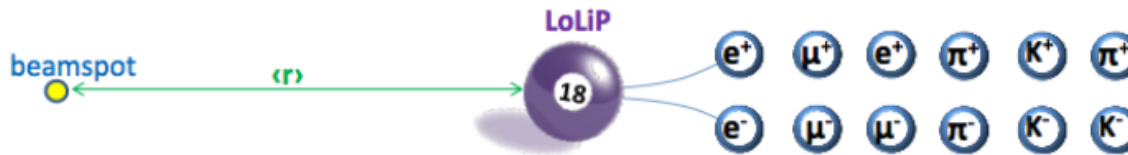
coupling to SM fermions

$$\alpha' = \epsilon^2 \alpha$$



mixing strength $\epsilon < 10^{-3}$

Long Lived Particles

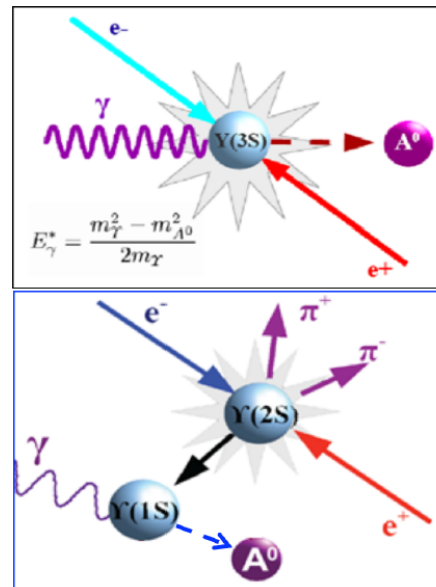


“vector portal”
dark photons
“scalar portal”
Higgs, inflaton

Next-to-MSSM, 7 scalar fields
visible CP-odd component A^0

Light Higgs

more results expected
decays to invisible
single-photon trigger!

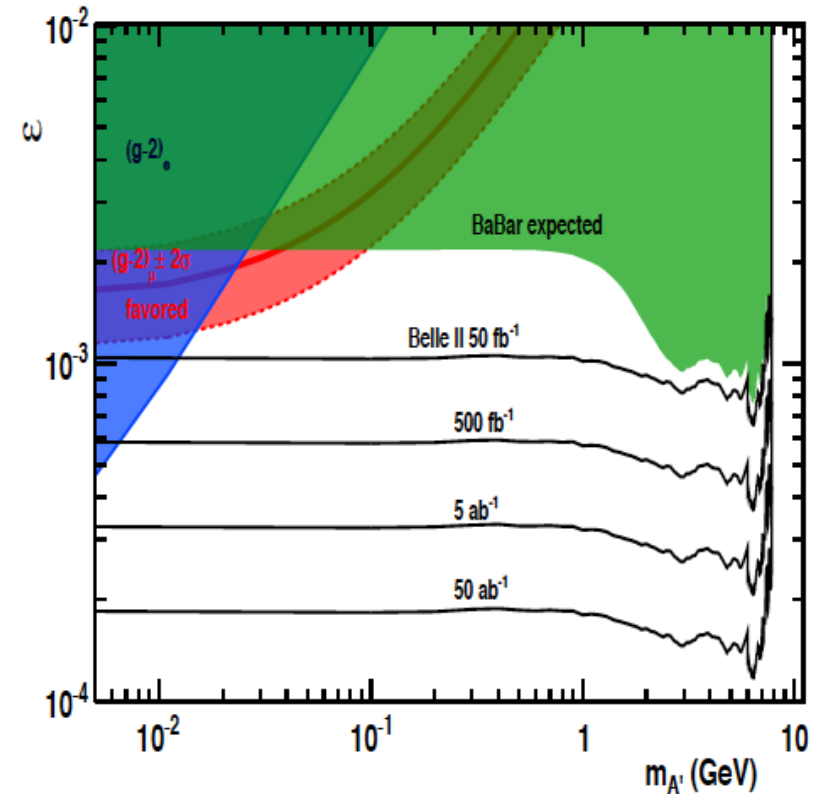
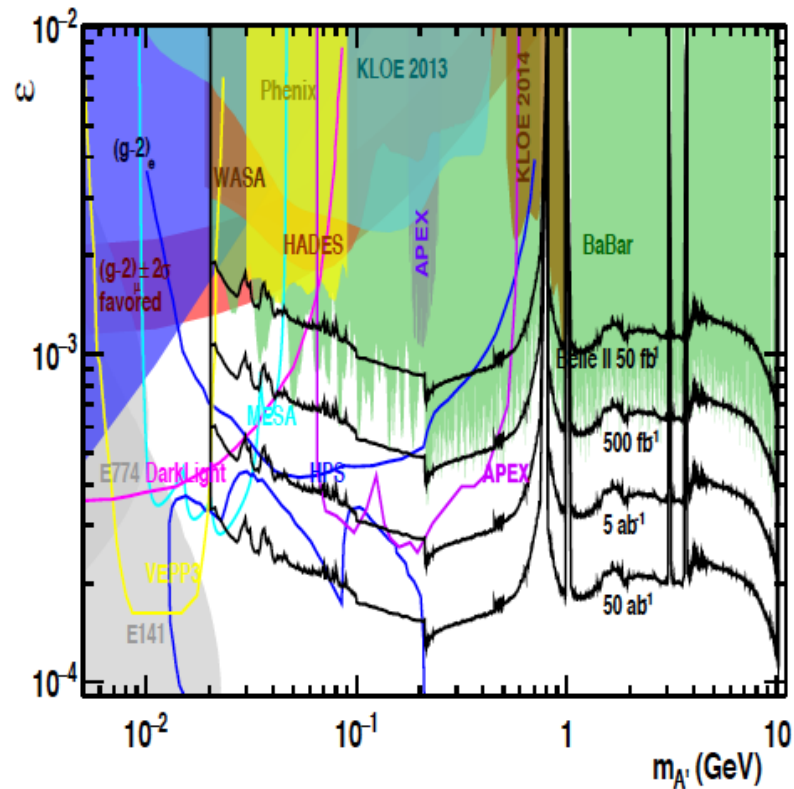


Not constrained by LEP below m_{bb}
 $\text{BF}(Y \rightarrow \gamma A^0) \approx 10^{-7} \div 10^{-4}$ accessible

Future Reach: Two Examples

$$e^+e^- \rightarrow \gamma A', A' \rightarrow l^+l^-, \text{ with } l = e \text{ or } \mu$$

$$e^+e^- \rightarrow \gamma A', A' \rightarrow \chi\chi$$



Predicted Upper Limits for Belle II
extrapolated from BaBar by C.Hearty (B2TIP 2014)

Searching in the Dark

PRESENT

low masses (< 10 GeV)

interesting constraints
from B-factories

BaBar (& Belle)

More analyses ongoing
on existing data

Standard Model

FUTURE

low masses (< 10 GeV)

SuperKEKB: Lumi x 40

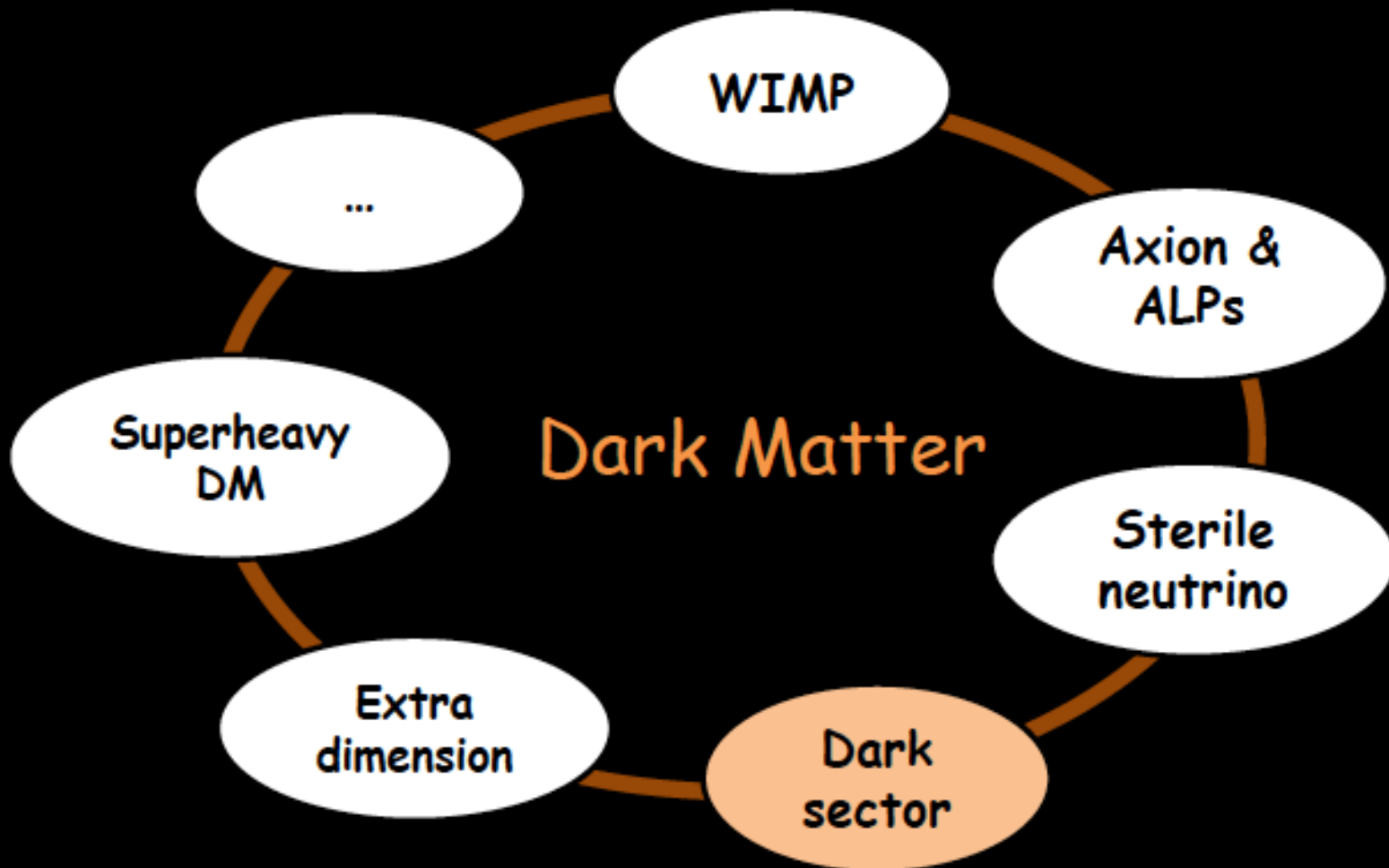
Belle II

Significant improvements
expected!

(same mass range,
smaller couplings)



Searching in the Dark



Searching in the Dark

with the help of some light



BACK-UP SLIDES

References

- Z' kinetic mixing

models

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

Experimental constraints

R. Essig et al., arXiv:1311.0029 [hep-ph] and references therein.

D. Babusci et al. [KLOE-2 Collaboration], Phys. Lett. B 736, 459 (2014).

H. Merkel et al. [A1 Collaboration], Phys. Rev. Lett. 112, 221802 (2014).

J. P. Lees et al. [BABAR Collaboration], Phys. Rev. Lett. 113, 201801 (2014).

J. R. Batley et al. [NA48/2 Collaboration], Phys. Lett. B 746, 178 (2015).

A. Anastasi et al. [KLOE Collaboration], Phys. Lett. B 750, 633 (2015).

A. Anastasi et al. [KLOE-2 Collaboration], Phys. Lett. B 757, 356 (2016).

- Z' coupled to heavy leptons

models

X. G. He, G. C. Joshi, H. Lew and R. R. Volkas, Phys. Rev. D 43, 22 (1991)

X. G. He, G. C. Joshi, H. Lew and R. R. Volkas, Phys. Rev. D 44, 2118 (1991)

B. Batell, D. McKeen and M. Pospelov, Phys. Rev. Lett. 107, 011803 (2011).

Experimental constraints

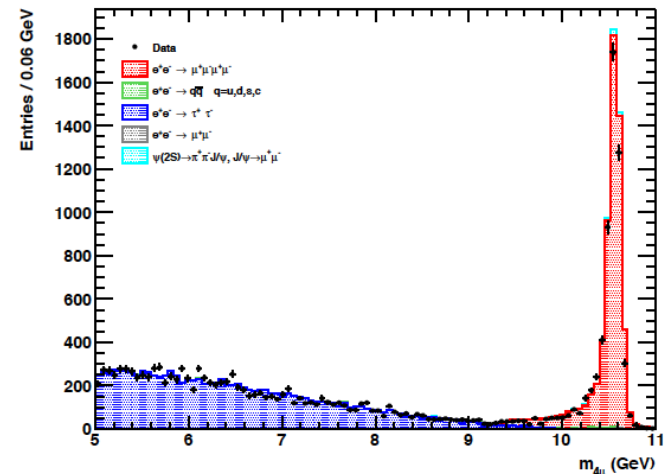
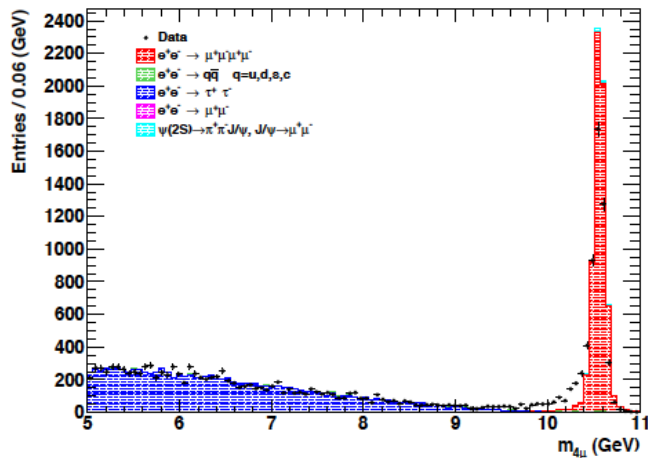
W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin, Phys. Rev. Lett. 113, 091801 (2014).

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

ISR Radiative Tail re-weighting

(describe method)

MC re-weighting effect compared the 5% data sample used for analysis optimisation



Other Searches in BaBar (published)

Review by F. Anulli, PASCOS 2015

PRL 113, 201801 (2014) dark photons A'

$$e^+e^- \rightarrow \gamma A', \quad A' \rightarrow e^+e^-, \mu^+\mu^-$$

PRL 114, 171801 (2015) light long-lived particles (LoLiP) L

$$e^+e^- \rightarrow LX, \quad L \rightarrow ee, \mu\mu, e\mu, \pi\pi, KK, K\pi$$

PRD 91, 071102 (2015) low mass CP-odd Higgs boson A^0

$$\Upsilon(1S) \rightarrow \gamma A^0, \quad A^0 \rightarrow c\bar{c}$$

PRD 88, 031701 (2013) $\Upsilon(1S) \rightarrow \gamma A^0, \quad A^0 \rightarrow gg, s\bar{s}$

PRD 88, 031102 (2013) $\Upsilon(1S) \rightarrow \gamma A^0, \quad A^0 \rightarrow \tau^+\tau^-$

PRD 87, 031102 (2013) $\Upsilon(1S) \rightarrow \gamma A^0, \quad A^0 \rightarrow \mu^+\mu^-$

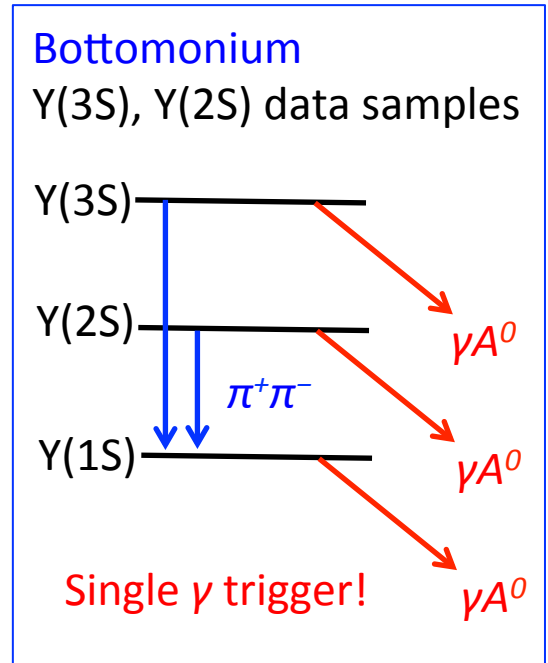
PRL 107, 021804 (2011) $\Upsilon(1S) \rightarrow \gamma A^0, \quad A^0 \rightarrow \text{invisible}$

PRL 107, 221801 (2011) $\Upsilon(2S, 3S) \rightarrow \gamma A^0, \quad A^0 \rightarrow \text{hadrons}$

PRL 103, 081801 (2009) $\Upsilon(2S, 3S) \rightarrow \gamma A^0, \quad A^0 \rightarrow \mu^+\mu^-$

PRL 103, 181801 (2009) $\Upsilon(3S) \rightarrow \gamma A^0, \quad A^0 \rightarrow \tau^+\tau^-$

arXiv:0808.0017 [hep-ex] $\Upsilon(3S) \rightarrow \gamma A^0, \quad A^0 \rightarrow \text{invisible}$



Other Searches in BaBar

On-going / published
Preliminary studies

Extensive program conducted at BABAR these last years

Search for dark photon

$$\begin{aligned} e^+e^- &\rightarrow \gamma A', \quad A' \rightarrow e^+e^-, \mu^+\mu^- \\ e^+e^- &\rightarrow \gamma A', \quad A' \rightarrow \text{invisible} \\ \pi^0 &\rightarrow \gamma l^+l^-, \quad \eta \rightarrow \gamma l^+l^-, \quad \phi \rightarrow \eta l^+l^-, \dots \end{aligned}$$

Search for dark Higgs boson

$$e^+e^- \rightarrow h' A', \quad h' \rightarrow A' A'$$

Search for dark boson(s)

$$e^+e^- \rightarrow \gamma A' \rightarrow W' W''$$

Search for dark hadrons

$$e^+e^- \rightarrow \pi_D + X, \quad \pi_D \rightarrow e^+e^-, \mu^+\mu^-$$

Search for dark scalar (s) and dark pseudoscalar (a)

$$\begin{aligned} B &\rightarrow K^{(*)} s \rightarrow K^{(*)} l^+l^- / \quad B \rightarrow K^{(*)} a \rightarrow K^{(*)} l^+l^- \\ B &\rightarrow ss \rightarrow 2(l^+l^-) \end{aligned}$$

Search for “muonic dark force”

$$e^+e^- \rightarrow \mu^+\mu^- Z', \quad Z' \rightarrow \mu^+\mu^-$$

Search for leptophilic dark scalar

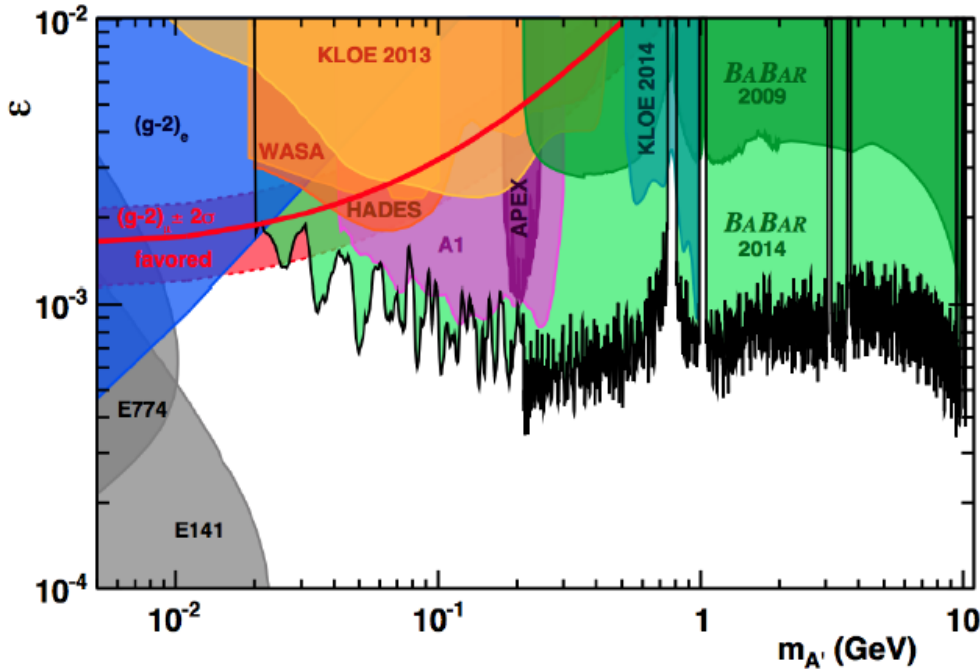
$$e^+e^- \rightarrow \tau^+\tau^- h', \quad h' \rightarrow \mu^+\mu^- \quad (4 \text{ leptons} + \text{MET})$$

Search for self-interacting dark matter

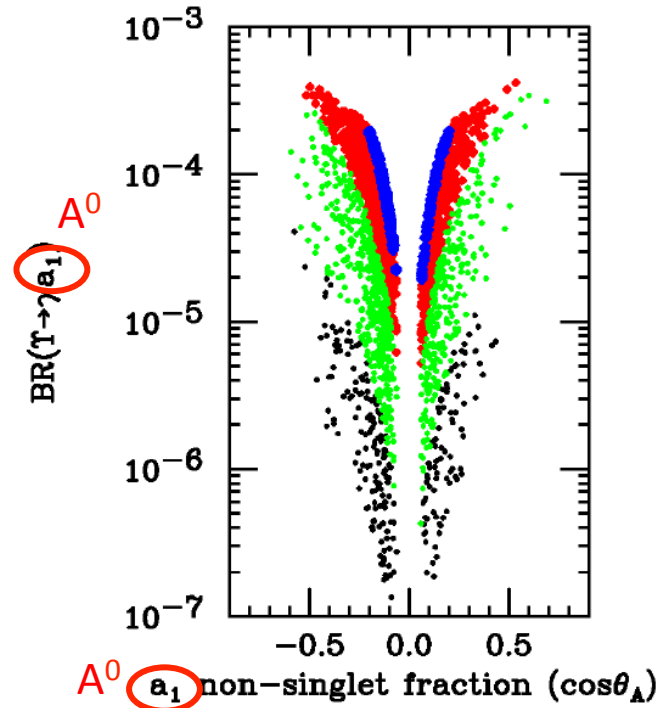
$$e^+e^- \rightarrow \gamma A' A' A', \quad A' \rightarrow l^+l^-, \pi^+\pi^-$$

From B.Echenard, seminar at CalTech, 2015

Work in Progress in BaBar



coupling strength ϵ of dark photons A' , present U.L.



NMSSM predictions for $BR(Y \rightarrow \gamma A^0)$
light Higgs A^0 in different scenarios

Dominant decays might be
 $A', A^0 \rightarrow$ invisible



Ongoing analysis
data taken after Sept. 2007
single-photon trigger and filters