Search for Light Dark Sector at BaBar

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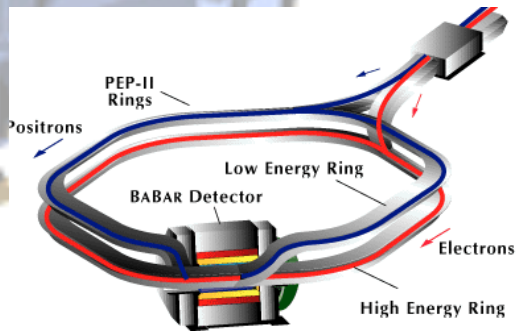
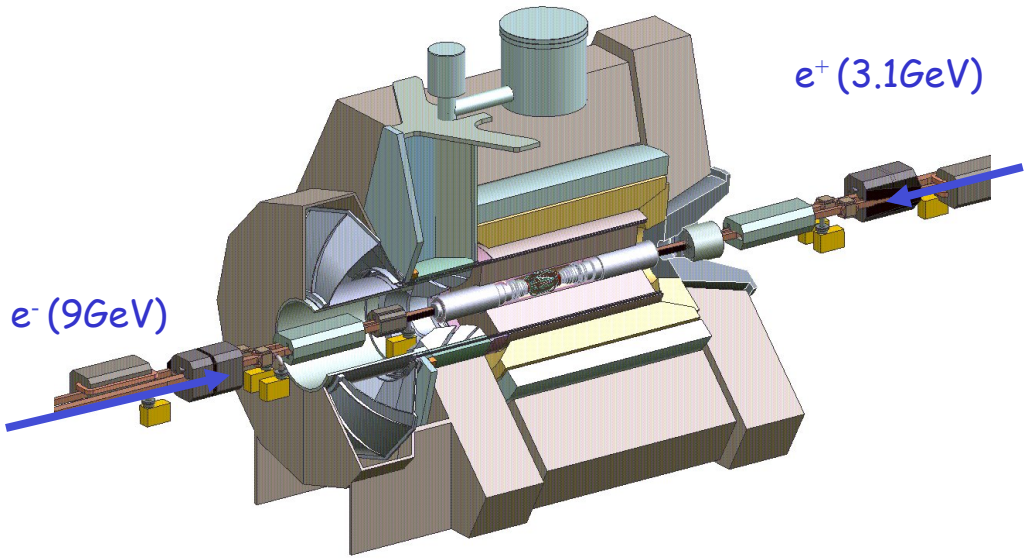
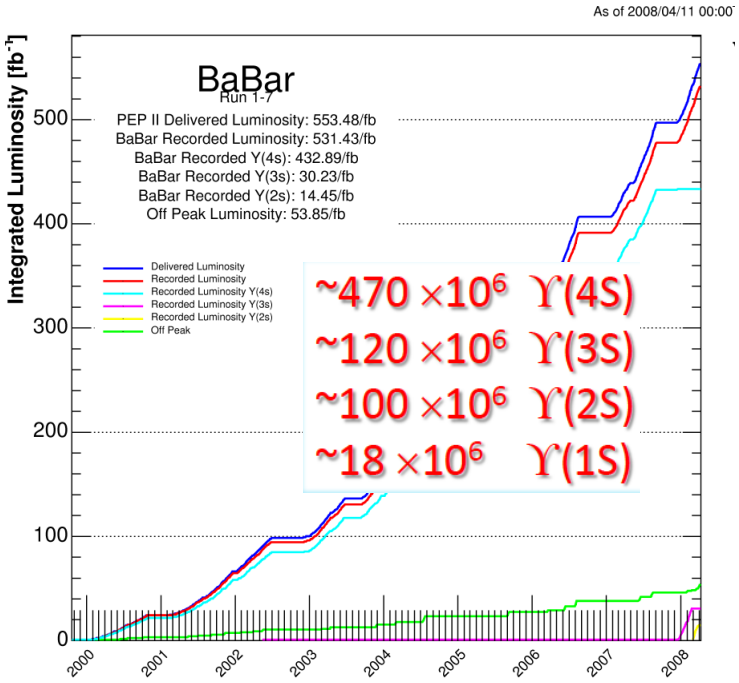


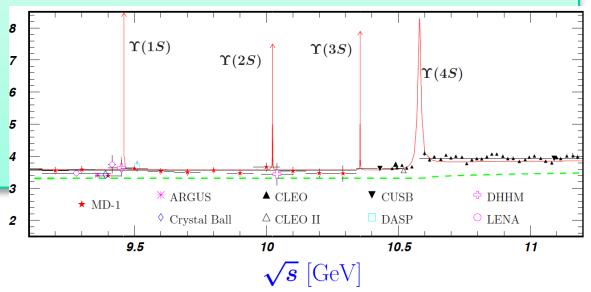
BaBar Experiment

Detail see: Nucl.Instrum.Meth.A479:1-116,2002

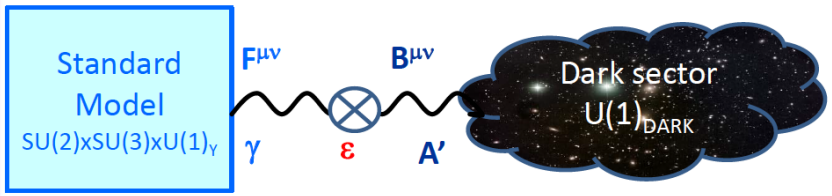




- A International experiment at SLAC to study CP violation in B meson decays: (1999 -2008)
  - ✓ A symmetric e^+e^- collisions at 10.58GeV: Υ(4S) resonance
  - ✓ Also at lower energy at Υ(3S), Υ(2S) resonances
  - ✓ Large samples of B and charm mesons, light quarks, tau and QED processes
- Typical 4π detector cover 96% solid angles: 1.5TB field, Silicon detector, drift chamber, Ecal, Particle ID)
  - ✓ Excellent tracking capability: reconstruct charged track with momentum as low as 60 MeV
  - ✓ PID eff (e: 0.96-0.99; μ: 0.6-0.88; K/π: 0.9 – 0.98)
  - ✓ Small fake rate (π→e: <1%; π→μ: <3%; π→K: ~2%)
  - ✓ All inclusive trigger: ~ 98% efficiency
  - ✓ Excellent detector simulation/calibration
  - ✓ Clean environment and well understood background components:



Dark Sector Searches at BaBar



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

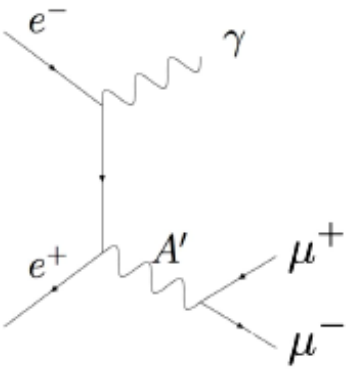
Kinetic mixing between the SM hypercharge and $U(1)_{DARK}$ field with mixing strength ε_Y

A mixing between the dark photon and the photon, i.e. a coupling between the dark photon and SM fermions with strength $\alpha\epsilon^2$

There are other portals possible (such as scalar or neutrino).

- Dark sector particles can be produced at lepton colliders
- Dark sector searches : One of most active analysis areas in BaBar post data taking era
- Typical analysis strategy:
  - ✓ Blind analysis, optimize background rejection using a small data sample
  - ✓ Reconstruct invariant mass of the dark sector particle
  - ✓ Scan mass spectrum for peaking structure from dark sector particle:
    - Signal PDF from MC simulation (assume small nature width)
  - ✓ Data driven method to estimate background
    - Smooth combinatorial background distribution
- A few selected analysis from BaBar without too much analysis details

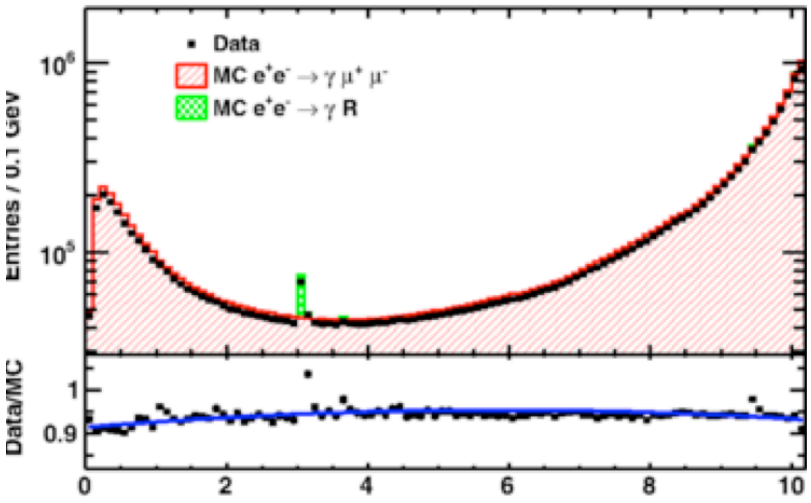
Visible Dark Photon Searches



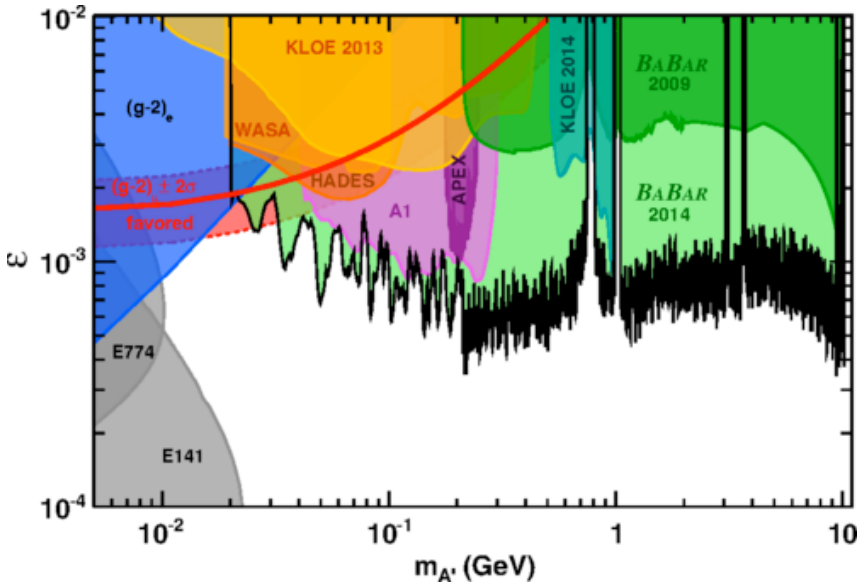
Production: $e^+e^- \rightarrow \gamma A'$

Decay in visible channels: $A' \rightarrow e^+e^-, \mu^+\mu^-$

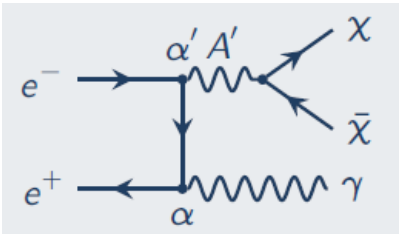
- Fit di-lepton mass spectrum to extract signals
- For each mass hypothesis:
  - ✓ Fit a mass window ~ 20 times signal resolution (σ)
  - ✓ Signal PDF: from MC simulation
  - ✓ Combinatorial bg: 3rd or 4th order polynomial
  - ✓ Peaking bg from resonance region (Eg: J/Ψ etc) included wherever appropriate
- No significant signal yields were seen.



PRL 113, 201801 (2014)



Invisible Dark Photon Searches



- Analysis using 53 fb^{-1} single photon trigger events
  - ✓ Collected in final BaBar running
  - ✓ Mostly at Υ(3S) and Υ(2S)
  - ✓ Small ~ $5fb^{-1}$ at Υ(4S)
- Trigger for such events not available in earlier data taking

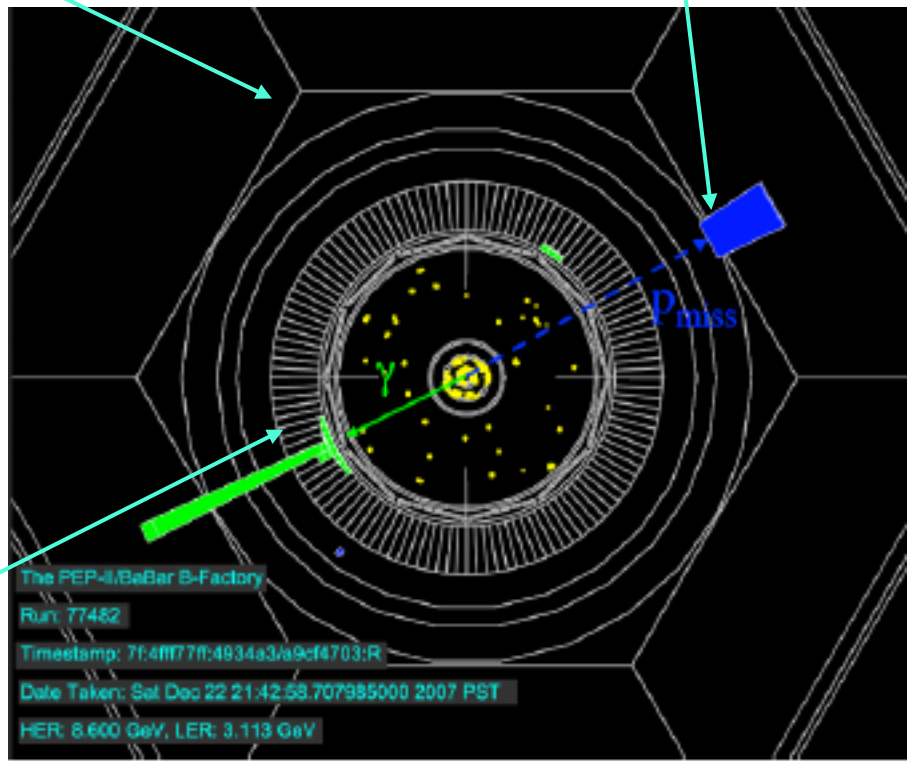
- Dark photon decay invisibly into dark matter
- Experimental signature:
  - ✓ Single photon final state
- Looking for a bump in missing mass

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

- Main backgrounds: $e^+e^- \to \gamma\gamma$, γe^+e^-
  - ✓ Particles outside detector acceptance
  - ✓ Azimuthal gaps between Ecal crystals not completely covered by IFR (not perfect alignment with the gap)

Problem: no efficiency along sector boundaries

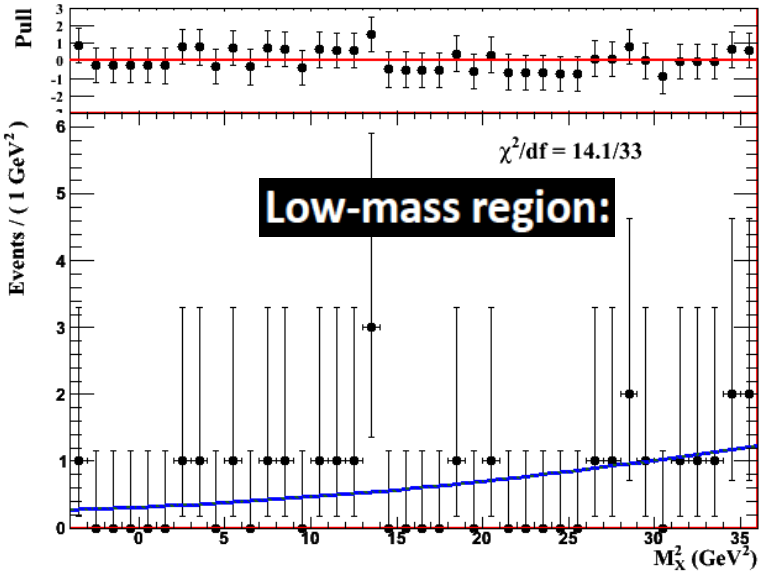
Photon signal in IFR

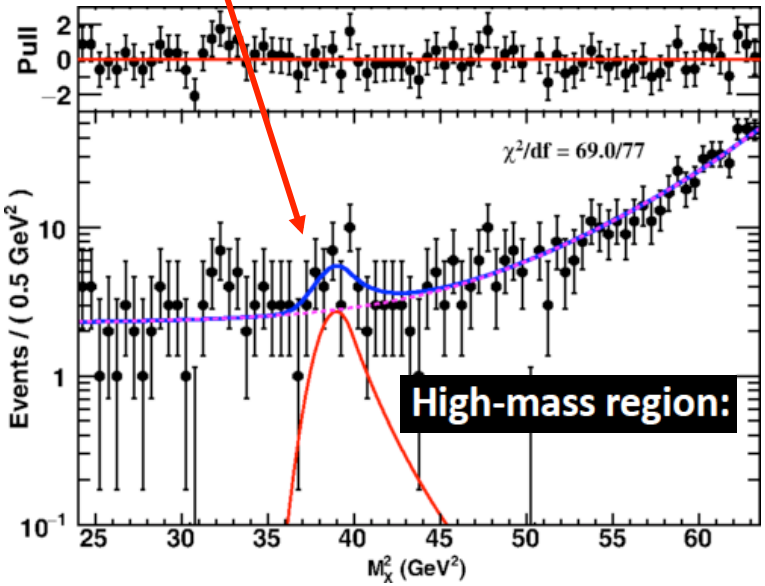


Problem: azimuthal gaps between crystals aligned with the interaction point

Invisible Dark Photon Searches

- Scan missing mass spectrum with different hypothesis of signal mass value
- Signal PDF: crystal ball function
  - ✓ Parameters taken from MC simulation, calibrated using data
- Background PDF: $m_{A'}$<5.5GeV
  - ✓ $m_{A'}$<5.5 GeV: 2nd order polynomial + Crystal ball for peaking background ($e^+e^-\rightarrow\gamma\gamma$)
  - ✓ 5.5<$m_{A'}$<8 GeV: Exponential polynomial
- Data consistent with background distribution
  - ✓ Most significant fit at $m_{A'}$=6.22GeV:
    - Local (global) significance = 3.1 (2.6) sigma
    - Global p-value ~ 1%

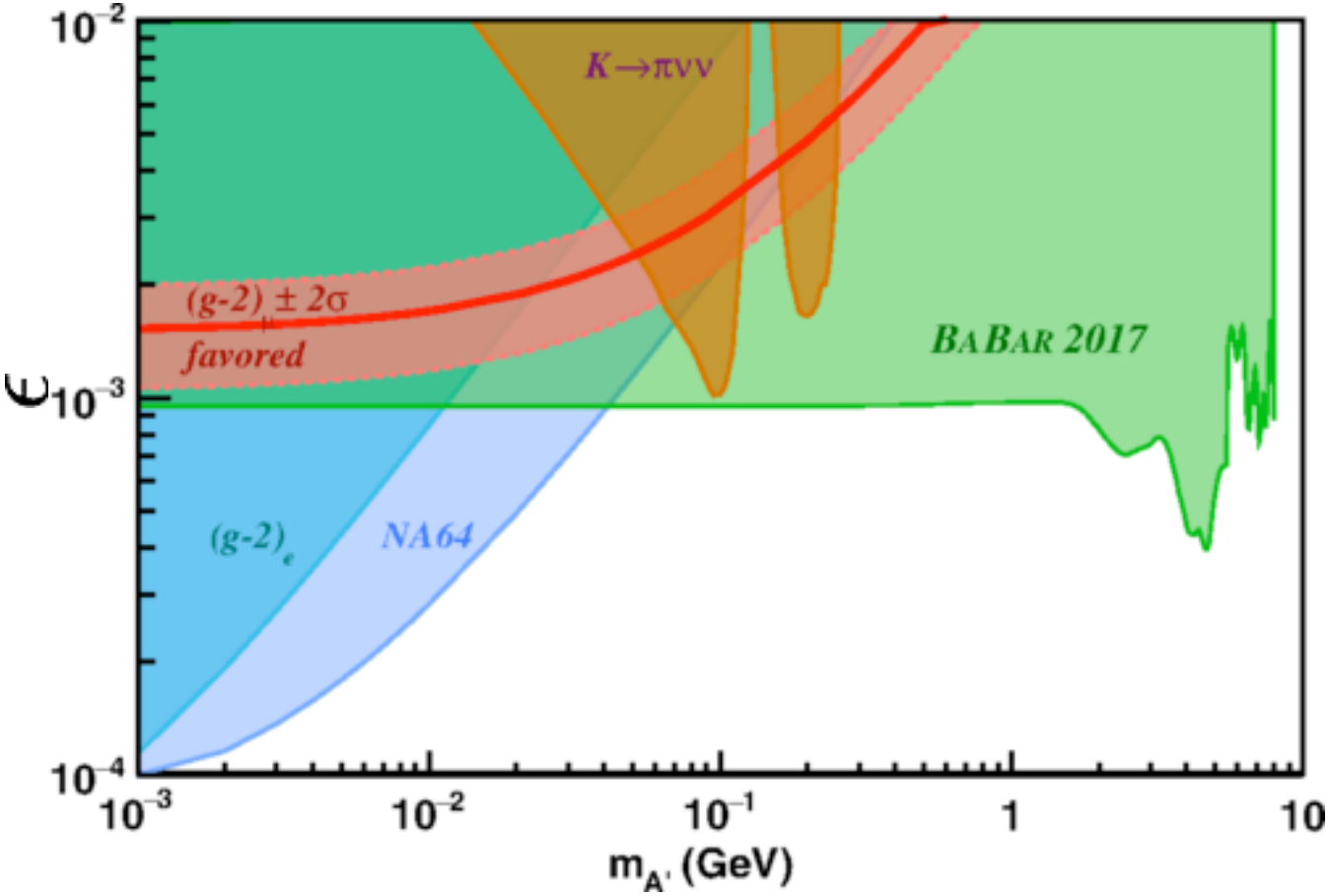




PRL 119, 131804 (2017)

Invisible Dark Photon Searches

PRL 119, 131804 (2017)

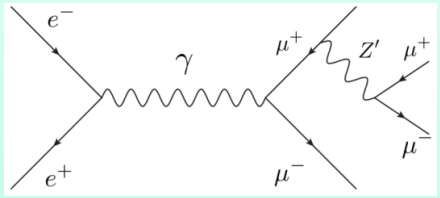


Completely exclude (90% CL) the favorable phase space by the g-2 anomaly

Search for dark muonic forces

- Muonic dark force: a new force coupling only to the second and third generation leptons with a gauge boson Z' (arXiv:1401.2459)
  - ✓ Explain g-2 anomaly,
  - ✓ Account for a dark matter as sterile neutrinos by increasing their cosmological abundances via new interaction with SM neutrinos
  - ✓ At Babar we can search for

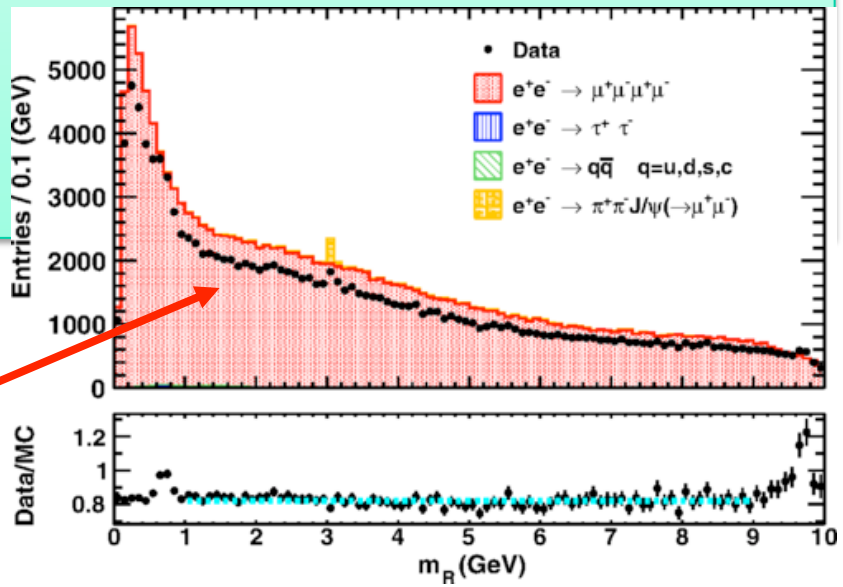
$$e^+e^- \rightarrow \mu^+\mu^- Z',\ Z' \rightarrow \mu^+\mu^-$$



- Fit reduced di-muon mass (m_R) to extract signals

- For each mass hypothesis, we fit over a mass window
  - ✓ 0-0.3 GeV for m_R<0.2GeV or a mass window ~ 50 times signal resolution (σ) for m_R>0.2GeV
  - ✓ Exclude J/Ψ resonance
  - ✓ Signal PDF: from MC simulation
  - ✓ Combinatorial bg: 3rd order polynomial

- No significant signal yields were seen.

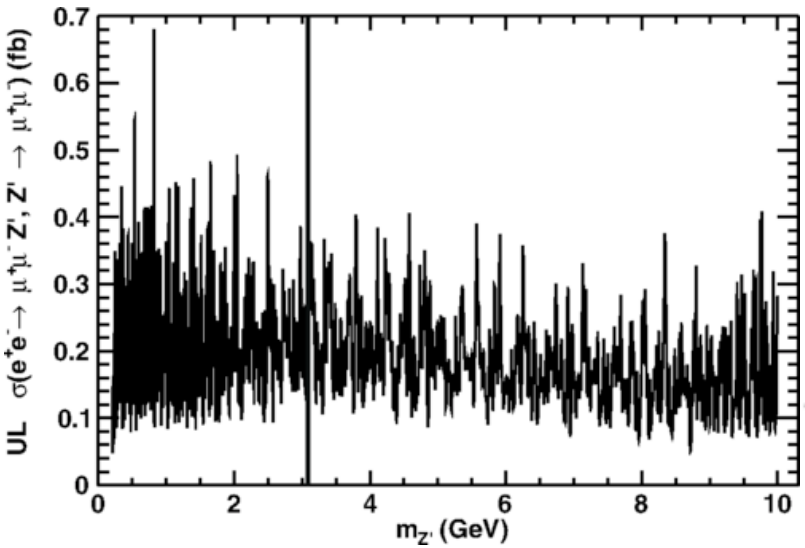


Dominant background are from $e^+e^-\rightarrow 4\mu$. The data/MC discrepancy arise primarily from ISR (absent from MC generator)

$$m_R = (m_{\mu\mu}^2 - 4\, m_\mu^2)^{1/2}$$

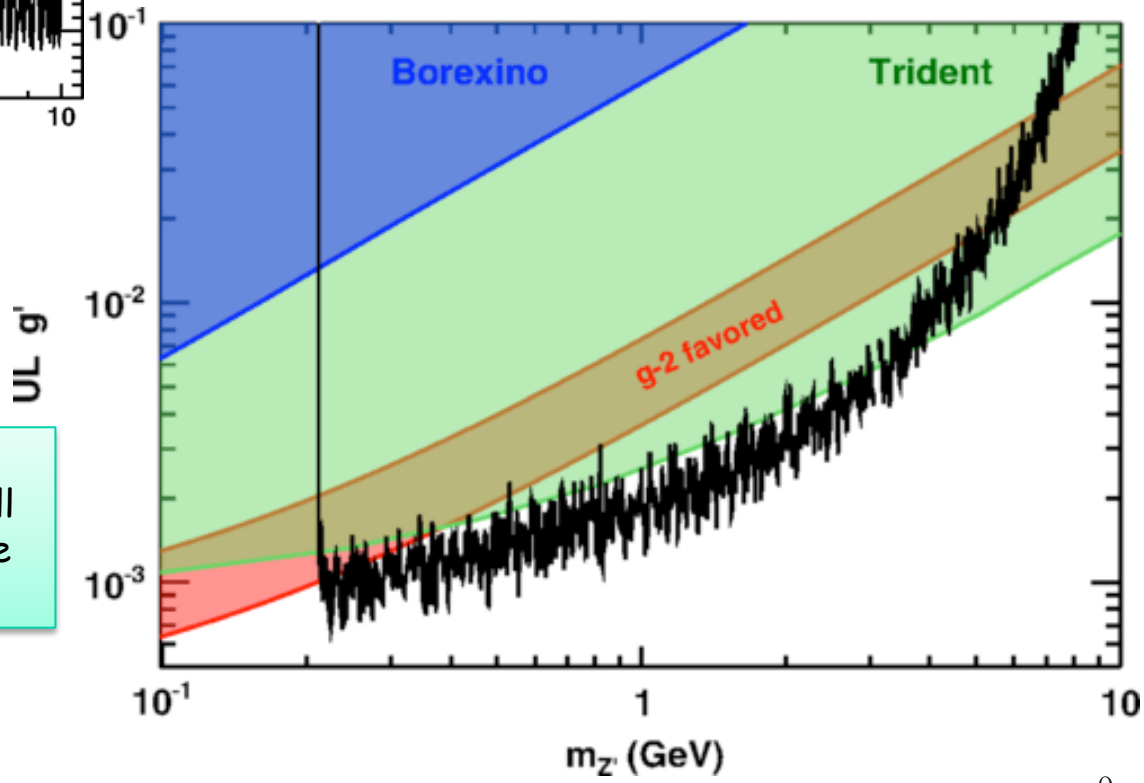
Search for dark muonic forces

Limit on $\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to \mu^+\mu^-)$



PRD 94, 011102(R) (2016)

Limits (90% CL) on Z' coupling



Improve the previous constraints from the neutrino experiments and exclude all but a sliver of the region favored by the "g-2" anomaly.

Search for long-lived neutral particles

- Searches for neutral long-lived particle L:

$$L \to f \quad (f = e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp, \pi^+\pi^-, K^+K^-, \text{or } K^\pm\pi^\mp)$$

- Event selection:
  - ✓ Two oppositely charged tracks
  - ✓ Passing PID requirement
  - ✓ Transverse decay length: 1< L_{xy} <50 cm
  - ✓ Reject bg from $K_S^0 \to \pi^+\pi^-$; $\Lambda \to p\pi^-$

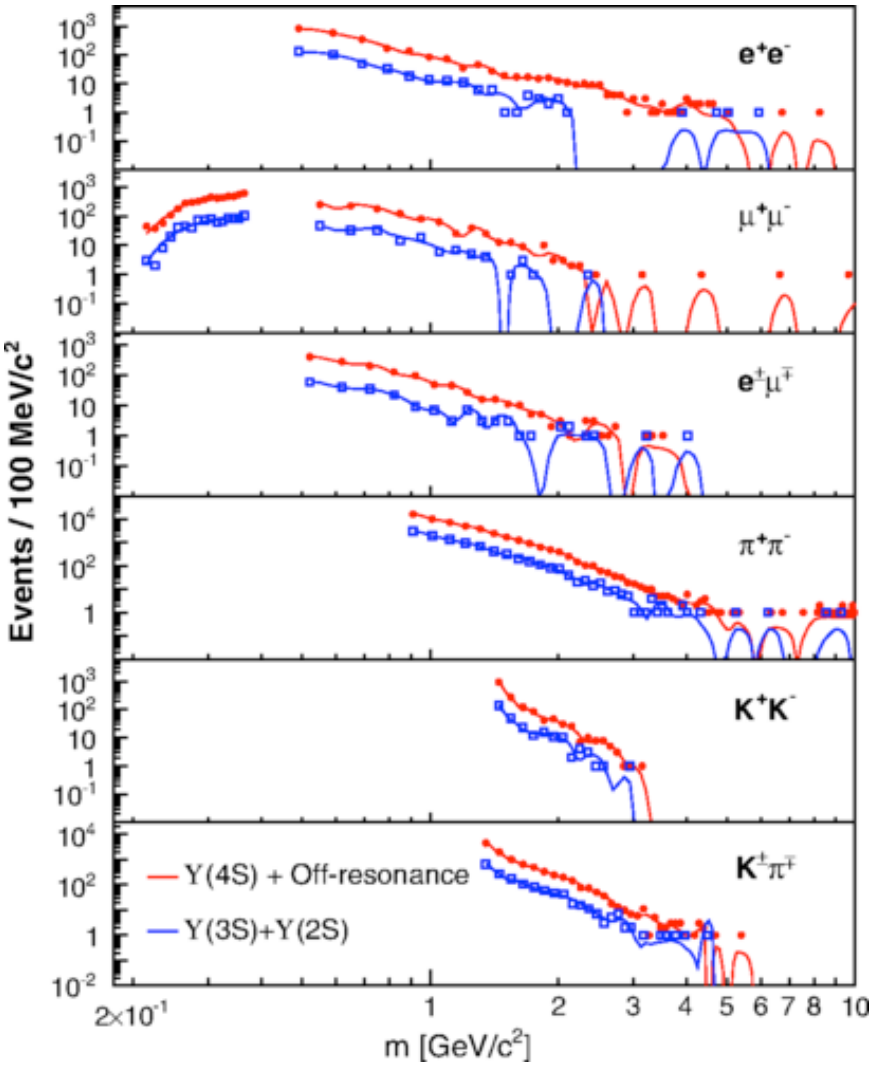
- Fit invariant mass of L to extract signals
  - ✓ Dominant bg from hadronic events with high track multiplicity, material interaction

- Signal PDF: MC simulation, assuming narrow width

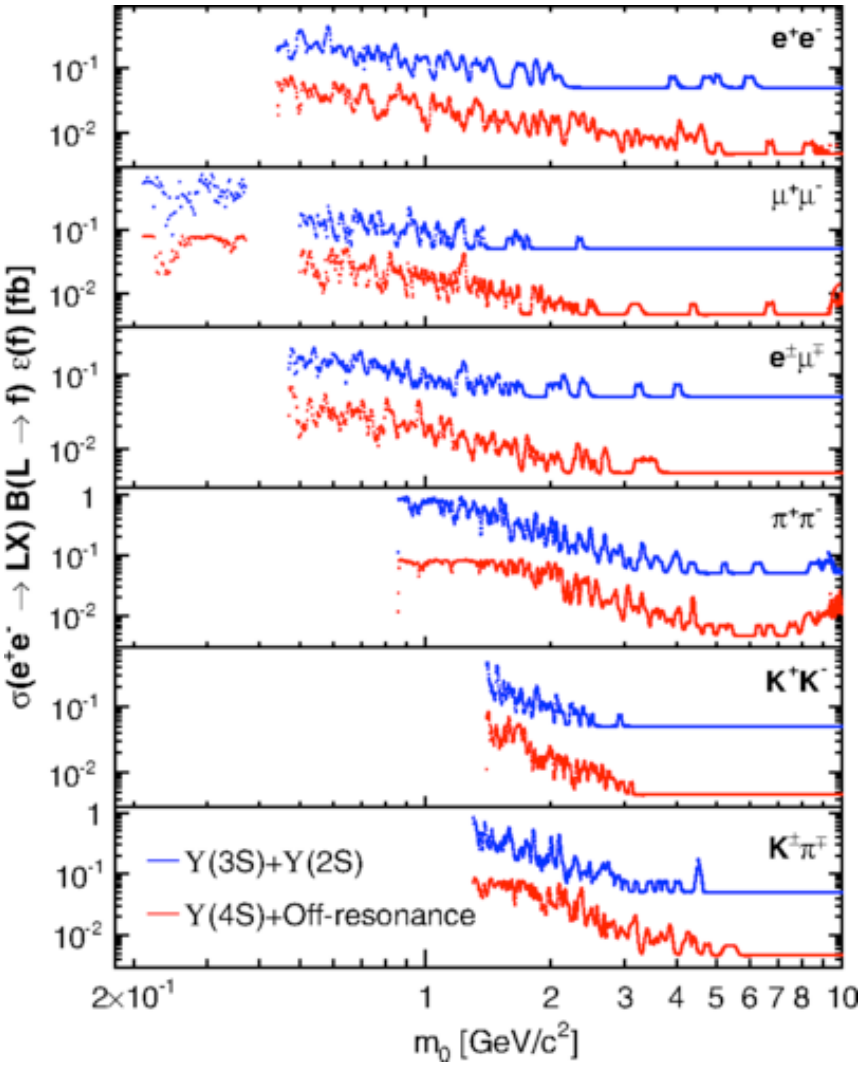
- Background PDF: Data driven
  - ✓ Assuming bg variation is very slow
  - ✓ Create a variable-bin-width histogram with w=nR, R is signal mass resolution (σ), n=15
  - ✓ n=15 chosen from MC to prevent conforming signal (largest source of sys errors)
  - ✓ Fit the histogram with 2nd order polynomial spline as background PDF

- No significant signal yield when scanning mass spectrum

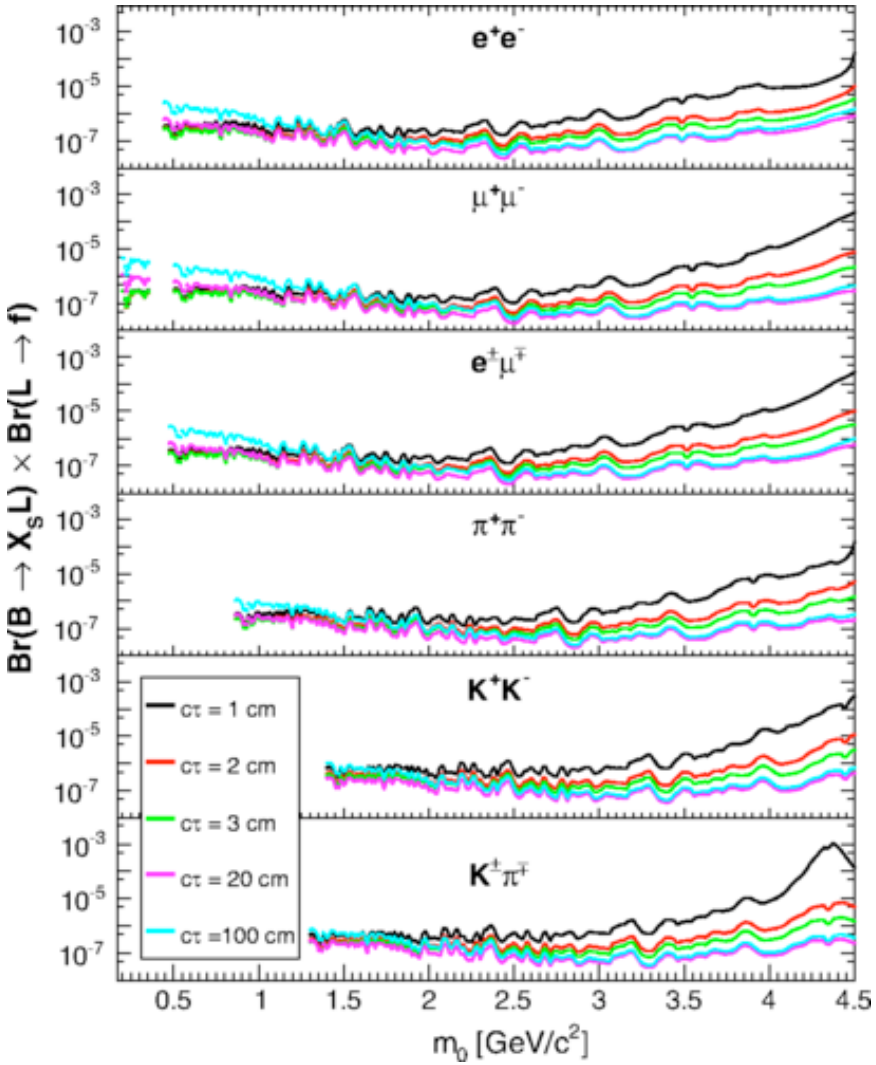
PRL 114, 171801 (2015)



Search for long-lived neutral particles



Details information including efficiency table available in the supplements of PRL 114, 171801 (2015)



Assuming B->X_s L, with Xs= 10%K, 25% K*(892) and 65% K*(1680)

Summary and Conclusion

- Dark sector: **one of most active analysis areas in BaBar nowadays**
  - ✓ Good acceptance of dark particles
    - they decay into SM
    - Invisible decays
  - ✓ Model dependent and independent searches
  - ✓ Data driven analysis
  - ✓ Complementary to other searches: <10 GeV new particles
  - ✓ **Only showed a few selected analysis**
    - PRL 113, 201801 (2014), PRL 119, 131804 (2017)
    - PRD 94, 011102(R) (2016), PRL 114, 171801 (2015)
  - ✓ **There are more ongoing searches for dark sectors**

- Some lessons and wish lists
  - ✓ Better MC generators are always helpful
  - ✓ Consider dark sector scenario during experiment R&D
    - Optimize detector for Unique/unconventional signals