Dark photon studies at *BABAR*

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On behalf of the *BABAR* Collaboration

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Outline

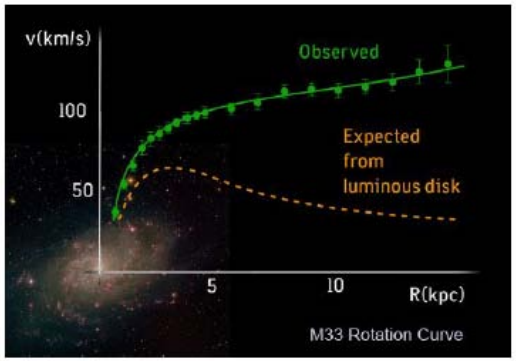
- Dark sectors: search for light dark matter at e^+e^- colliders (meson factories)
- Dark mediator searches at *BABAR*
  - Overview and first results
  - Latest results:
    - dark photon invisible decays
    - muonic dark forces
- Outlook and conclusions

The evidence for Dark Matter

- 1933, Zwicky: first suggestion for the existence of unseen “dark” matter after the analysis of the velocity dispersion of galaxies in the Coma cluster

- Since then: numerous astrophysical evidences collected for its existence – all based on gravity

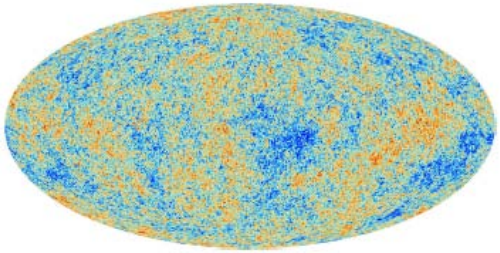
Galactic Rotation Curves



- But: its nature is still a mystery
- One possibility: formed by Weakly Interacting Massive Particles

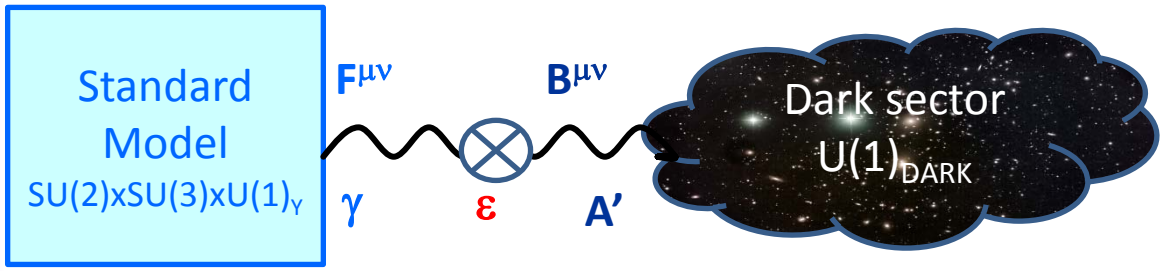
Gravitational Lensing

Structure of Cosmic Microwave Background



- So far null results from direct detection experiments and LHC
- New ideas needed to overtake the standard WIMP paradigm

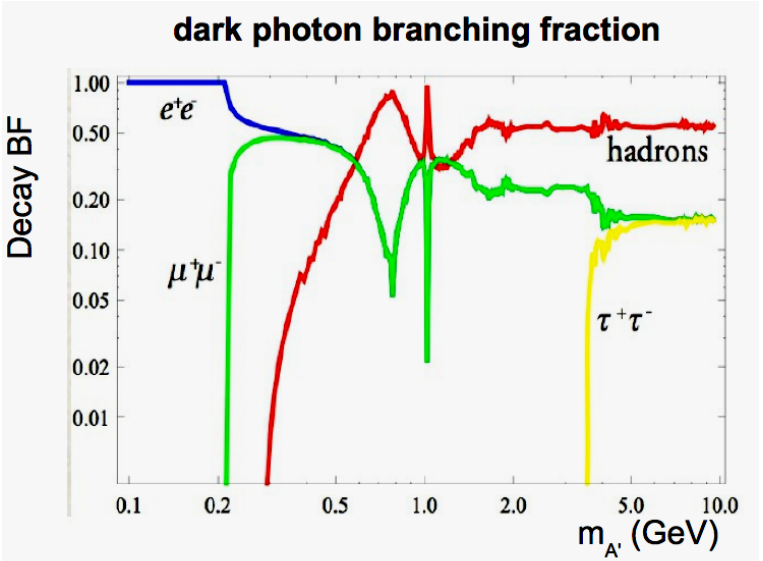
Dark sectors and gauge mediators: the vector portal



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

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

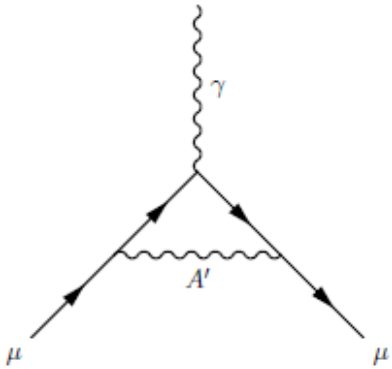
- After EWSB:
  - The mediator gets a mass, in the MeV-GeV scale
  - Dark gauge bosons couple to SM fermion pairs:
    - strength $\alpha' = \varepsilon_Y^2 \alpha$
  - The kinetic mixing is typically 10^{-5}-10^{-2} but could even be smaller
  - Dark sectors can contain a variety of dark particles χ, which couple to SM via this mediator



B. Batell et al, PR**D79** (2009), 115008

Any evidence for dark sectors yet?

- Some experimental observations from terrestrial and satellite searches suggest a departure from the minimal standard WIMPs paradigm
  - Able to explain the apparent $(g-2)_\mu$ discrepancy
  - Large local electron/positron excess reported by HEAT, PAMELA, PPB-BETS, ATIC, AMS (but no excess for proton/antiproton!)
  - 511 keV-line (INTEGRAL) + DAMA/LIBRA modulation signal



- Suitable mass range for the production/discovery at e^+e^- colliders
  - Cross sections: could be as large as ~0.1 fb

$$\sigma \sim \frac{\alpha \alpha_D \varepsilon^2}{s}$$

  - Sensitivity: $\mathscr{L}_{\text{int}}/s$
  - Any light charged DM state of the sector can be produced through an off-shell A' carrying the full center of mass energy of the e^+e^- collision
    - high particle multiplicity expected from decays or parton showers within the dark sector

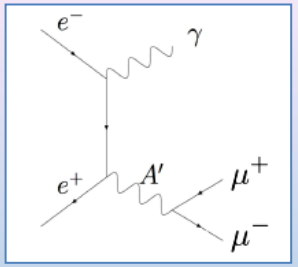
Light dark sectors searches at colliders

Particle physics experiments can produce dark photons, in the same processes in which photons are produced (with an extra ε^2 factor)

Is Dark Photon the lightest particle in the Dark Sector?

yes
DP decays to SM

Visible decays in di-leptons (light di-hadrons) final states
Search for narrow resonances ($\Gamma \sim m\varepsilon^2$)



Minimal decay

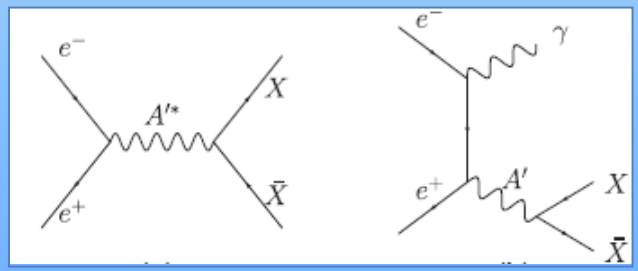
$\Gamma_{A'} << \sigma_m$

no
DP decays to DM

Are lighter dark sector χ stable?

yes

Invisible decay to lighter dark sector states

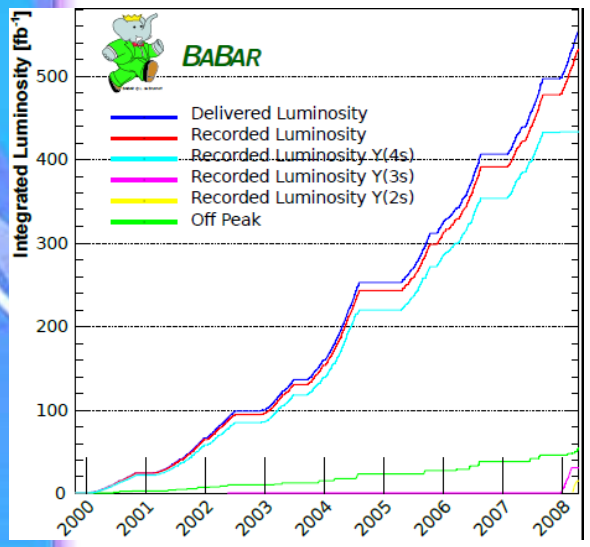


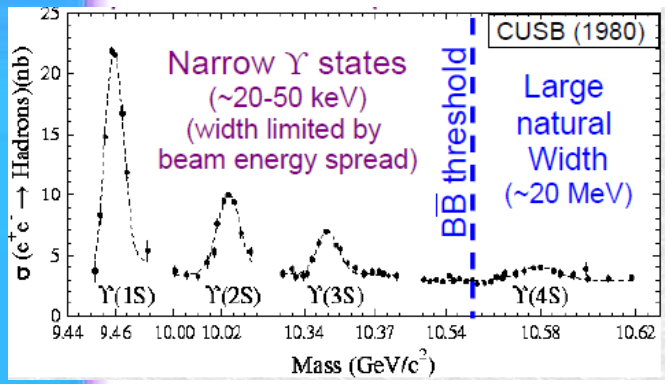
not ε suppressed, dominating!

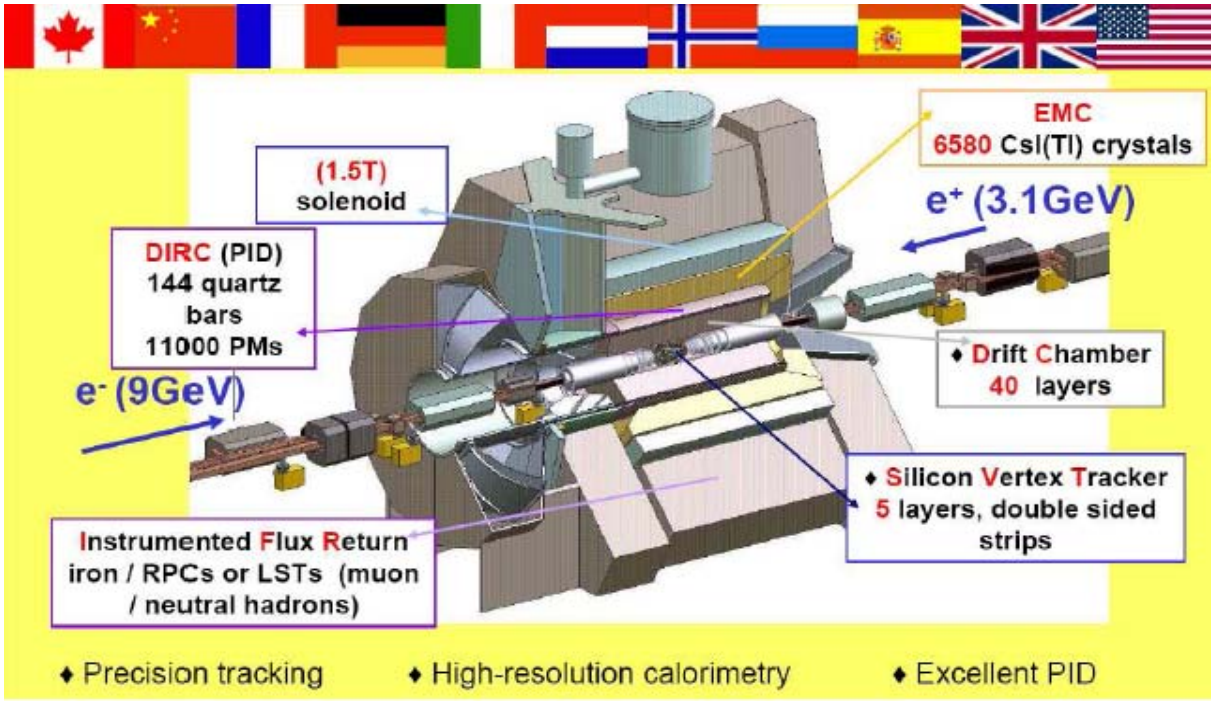
no

Multi-leptons and/or more complicated off-shell patterns involving Higgs, lepton/quark loops, …

The *BABAR* experiment at PEP-II, SLAC







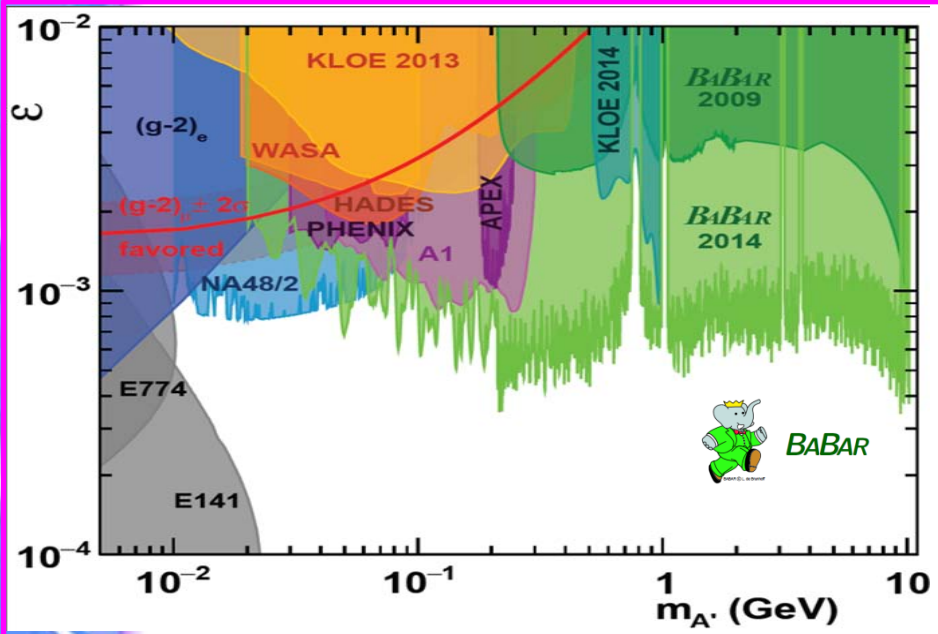
NIM **A479**, 1 (2002); NIM **A729**, 615 (2013)

PEP-II and *BABAR* operated from Oct 1999 to Apr 2008

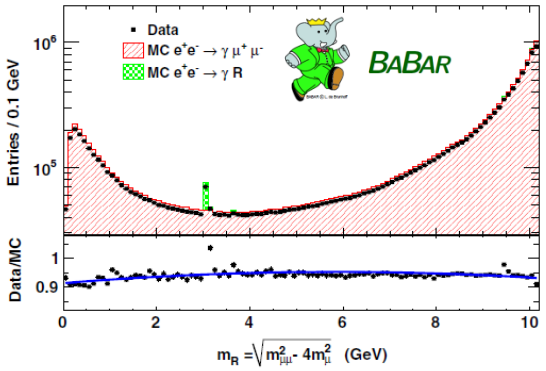
~ 500 fb^{-1} integrated luminosity

~470 ×10^6 Υ(4S)
~120 ×10^6 Υ(3S) (10x BELLE)
~100 ×10^6 Υ(2S) (10x CLEO)
~18 ×10^6 Υ(1S) from Υ(2S) →π$^+$π$^-$Υ(1S)

Dark sector searches in *BABAR*: a wide program

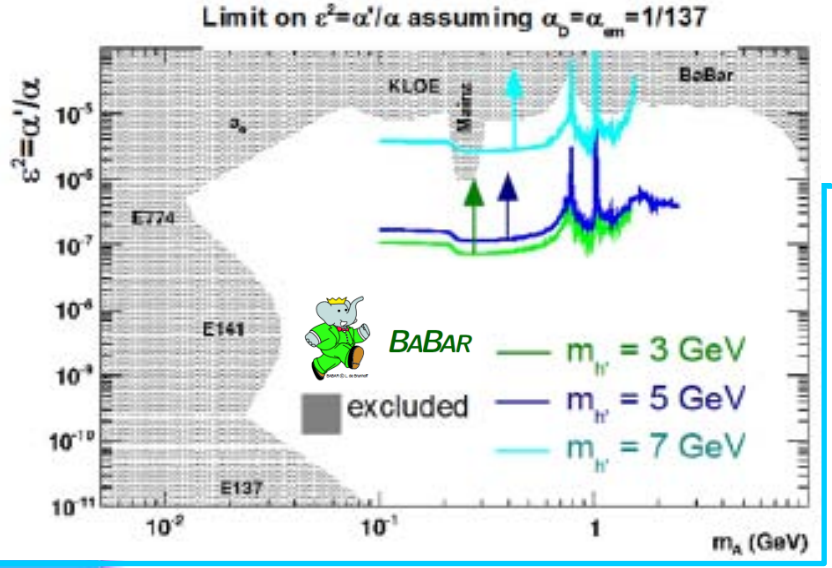


- **Dark photon searches:**
  - Production: $e^+e^- \rightarrow \gamma A'$
  - Decay in visible channels: $A' \rightarrow e^+e^-, \mu^+\mu^-$



*PRL**113** (2014), 201801*

PRL viewpoint



Dark Higgs boson:

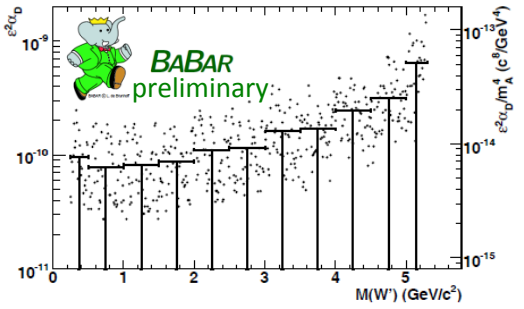
- Production: $e^+e^- \rightarrow hA'$
- Decay: $h \rightarrow A'A' \rightarrow 4\ell$

*PRL**108** (2012), 211801*

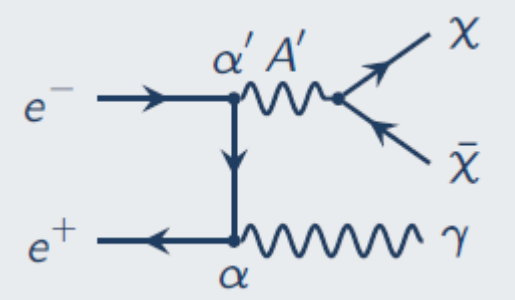
Dark gauge boson:

- Production: $e^+e^- \rightarrow \gamma A$
- Decay: $A' \rightarrow W'W'$
  $\rightarrow (\ell^+\ell^-)(\ell'^+\ell'^-)$

ArXiv: 0908.2821



Recent results from *BABAR*: Search for dark photon invisible decays

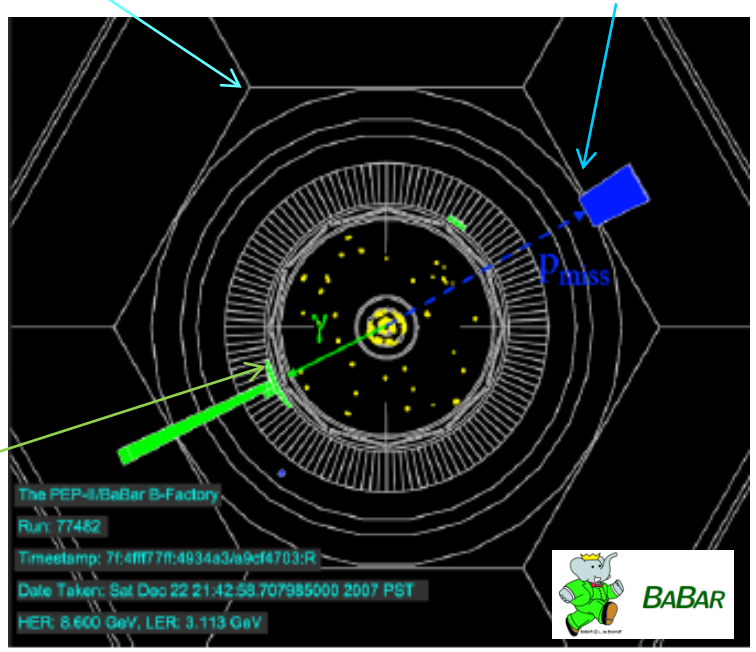


$$m^2_{A'} = s - 2\sqrt{s}E^*_\gamma$$

- $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow$ *invisible*
- Search for single photon events
- main experimental issues:
  - $2\gamma + \gamma e^+e^-$ backgrounds
  - Small holes in acceptance: hermeticity required

Problem: no efficiency along sector boundaries

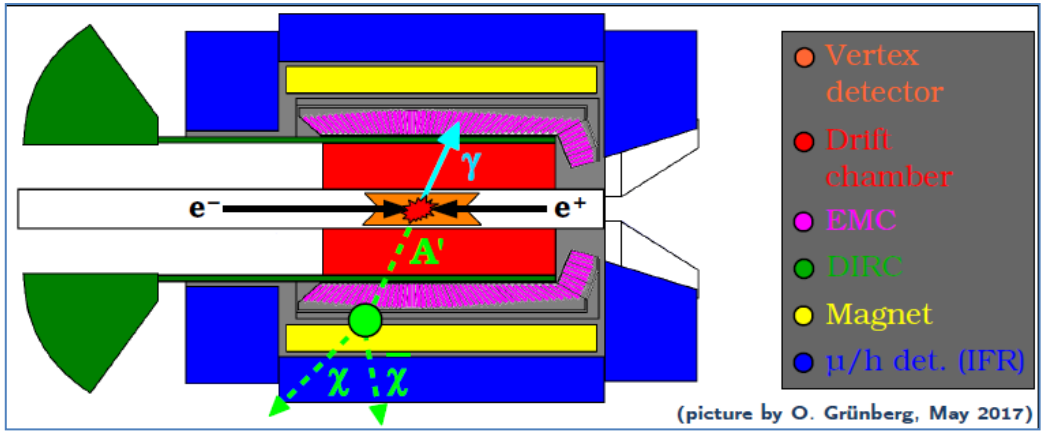
Photon signal in IFR



Problem: azimuthal gaps between crystals aligned with the interaction point

Triggering on single photon events in *BABAR*

- 53 fb^{-1} single photon trigger events collected mostly at $\Upsilon(2S)$ and $\Upsilon(3S)$ (5 fb^{-1} @ $\Upsilon(4S)$) in the final *BABAR* running period

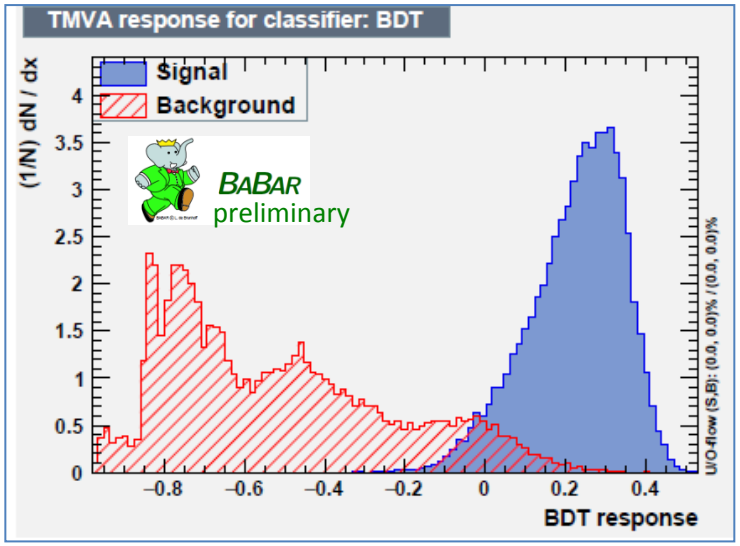


- Hardware trigger: $\geq$1 EMC cluster with $E_\gamma > 800$ MeV
- Software triggers: two lines $\Rightarrow$ two different analyses
  - High energy photon (low $m_{A'}$)
    - $E^*_\gamma > 2$ GeV
    - No track emitted from the interaction region
    - Active on the full data set
  - Low energy photon (high $m_{A'}$)
    - $E^*_\gamma > 1$ GeV
    - No track emitted from the interaction region
    - Active on ~36 fb^{-1} only

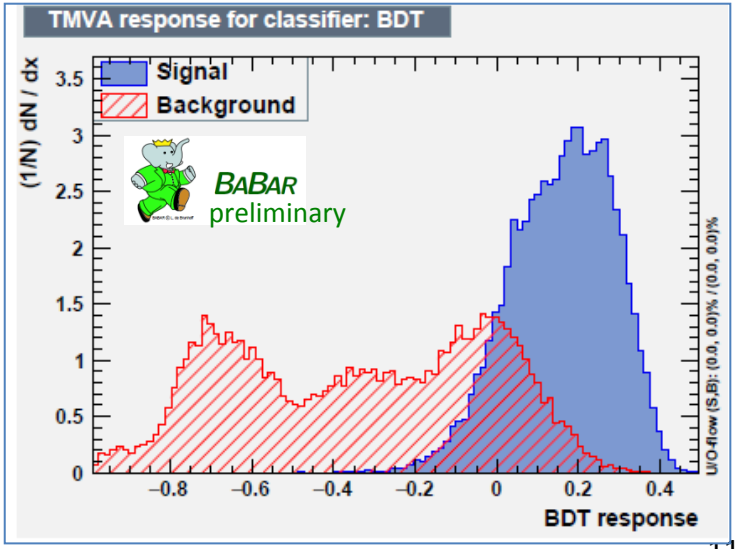
Invisible decay: analysis overview

- Signature: missing momentum
- Selections:
  - Photon: quality, energy, angle
  - Number of tracks: zero from IR
  - Cut on total extra calorimeter energy
  - Missing 4-vector:
    - Direction
    - Fiducial cuts: leakage, conversions, …
    - Angular distance from EMC crystal edges
    - Hadron/muon calorimeter (IFR) veto

Low mass region



High mass region

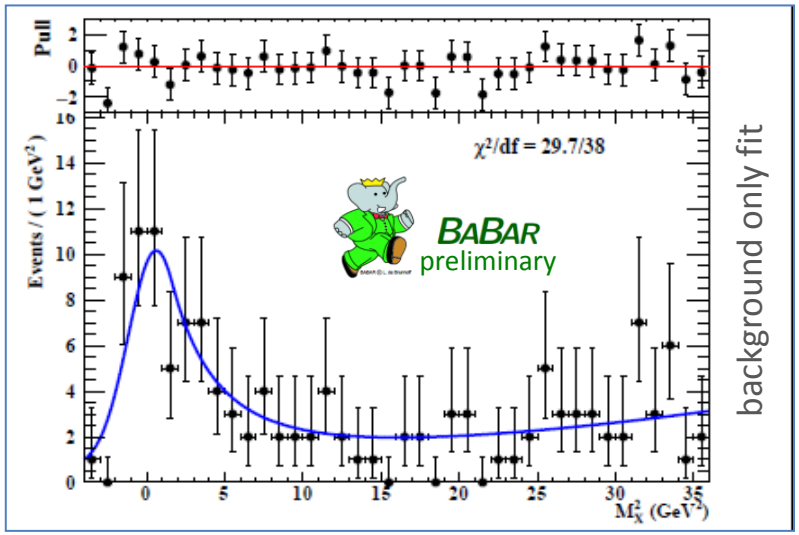


- BDT training to separate signal from background in two mass regions
  - Low mass: $-4 < m_{A'}^2 < 36$ GeV^2
  - High mass: $24 < m_{A'}^2 < 69$ GeV^2

- Good signal/background separation in both samples, same BDT response for the signal

Invisible decays: signal vs background

- Low mass selection:
  $0 < m_{A'} < 5.5$ GeV
- $E_\gamma^* > 3$ GeV
- Backgrounds:
  - $e^+e^- \to \gamma\gamma$ with a missing γ
    - Peaking at $m_X = 0$
  - Long tail away from $m_X = 0$
- Fit of missing mass spectrum in 89 mass slices with:
  - Crystal Ball function for the signal
  - 2nd order polynomial + CB for peaking background



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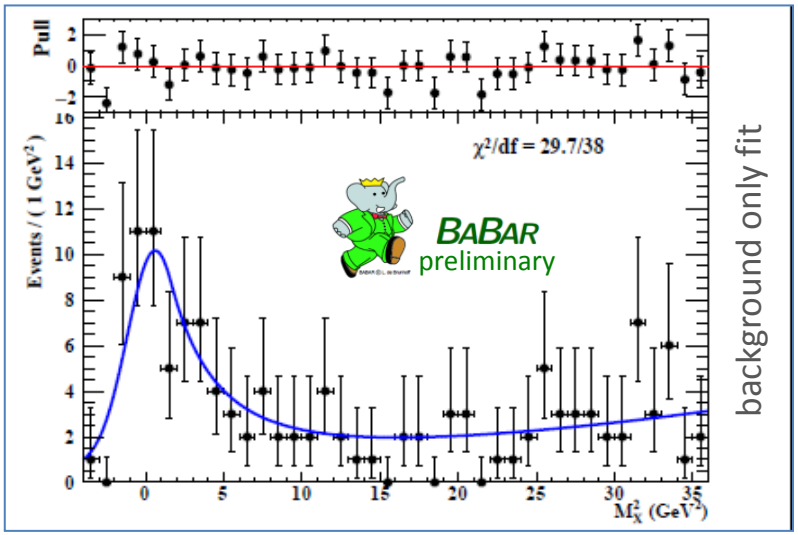
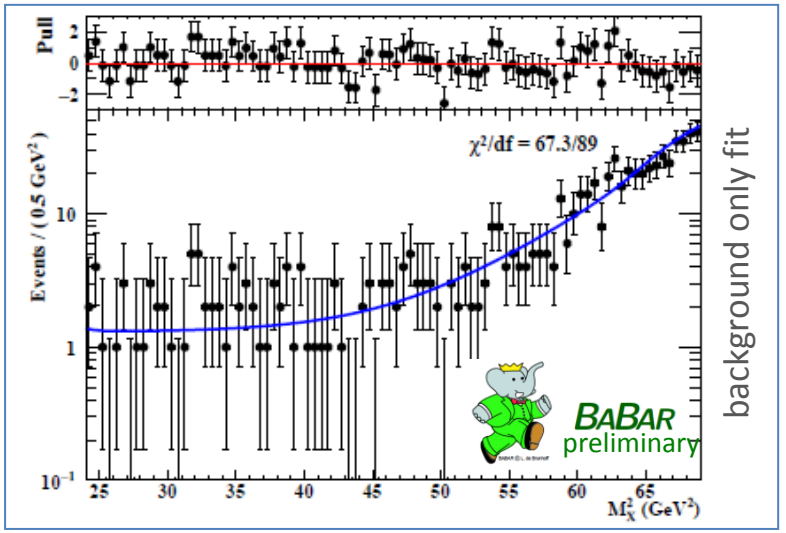


- High mass selection:
  $5.5 < m_{A'} < 8$ GeV
- $E_\gamma^* > 1.5$ GeV
- Backgrounds (smooth):
  - $e^+e^- \to e^+e^-\gamma$ with missing e^+e^-
  - tail of $e^+e^- \to \gamma\gamma$
- Fit of missing mass spectrum in 88 mass slices with:
  - Crystal Ball function for the signal
  - Exponentiated polynomial for the background



Signal extraction and results

- Simultaneous fits of m_X^2 for Υ(2S), Υ(3S) and Υ(4S) data, with tight and loose selections
  - 9 low mass + 4 high mass data sets
  - Fixed background shape
  - Floating yields for signal, peaking + continuum background

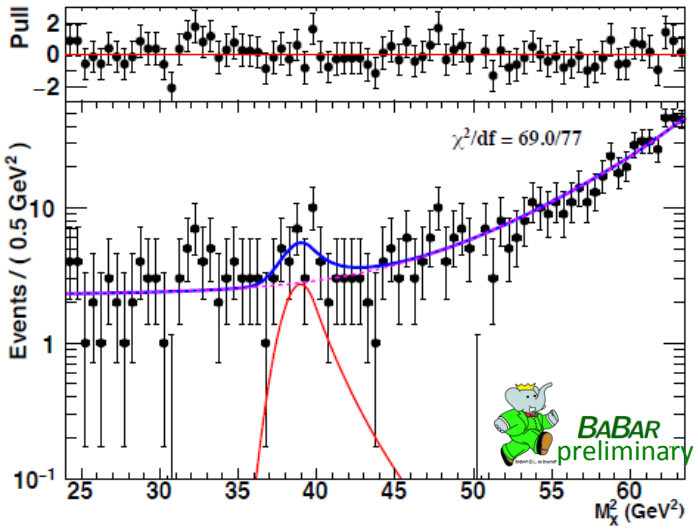
- Local significance from likelihood ratio:

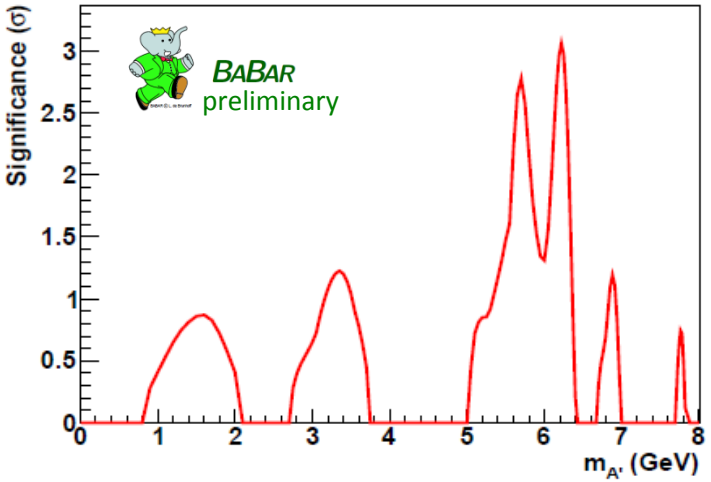
$$S = sign(N_{sig}) \cdot \sqrt{2 \ln \frac{\mathcal{L}}{\mathcal{L}_0}}$$

  - Max @ 6.21 GeV: 3.1σ

- Overall global significance: 2.6σ
  ⇒ No significant signal

- Evaluation of upper limit at 90% C.L., with flat prior

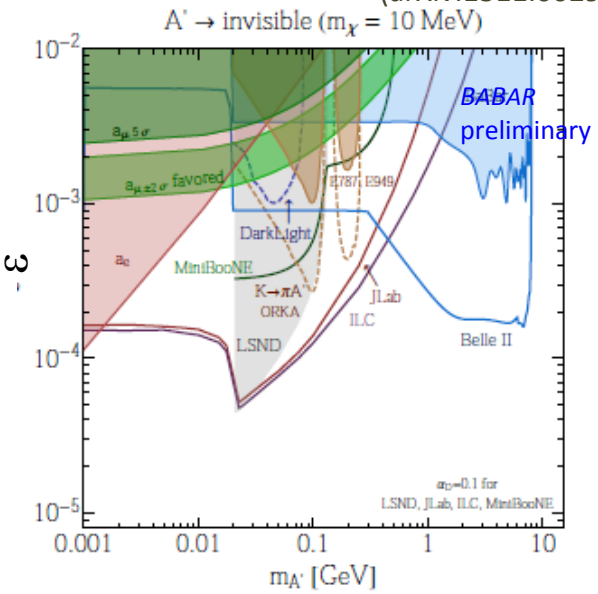




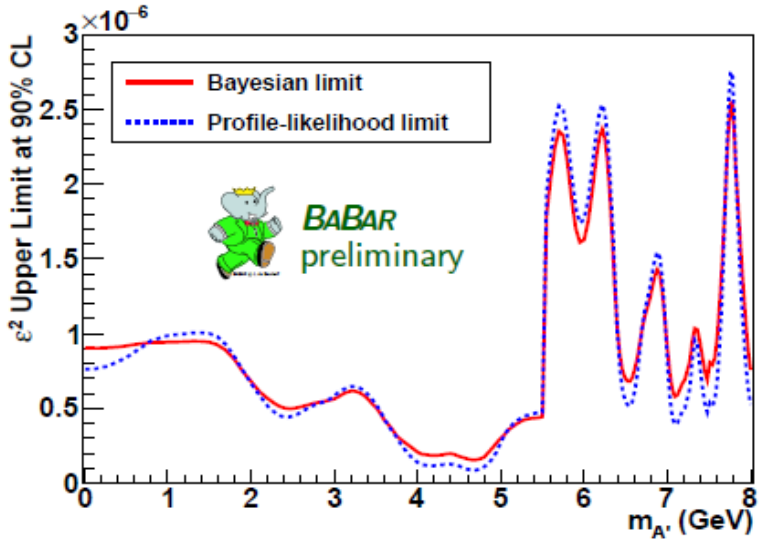
Invisible decays: limits on coupling vs $m_{A'}$

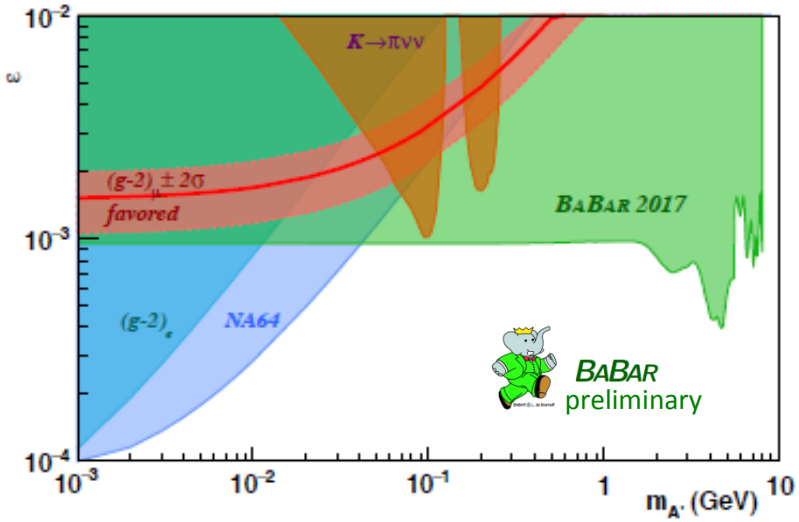
- Sizeable improvement with respect to previous results
  - Old results by *BABAR* on low mass Higgs search in invisible channels (arXiv:0808.0017), reinterpreted for a vector gauge boson (R. Essig, arXiv:1311.0029): superseded
  - Recent results from NA64, NA48/2

(arXiv:1311.0029)



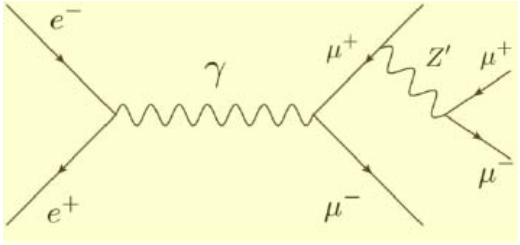
- Total exclusion of $(g-2)_\mu$ anomaly favored region
- Paper submitted to PRL, *arXiv:1702.03327*





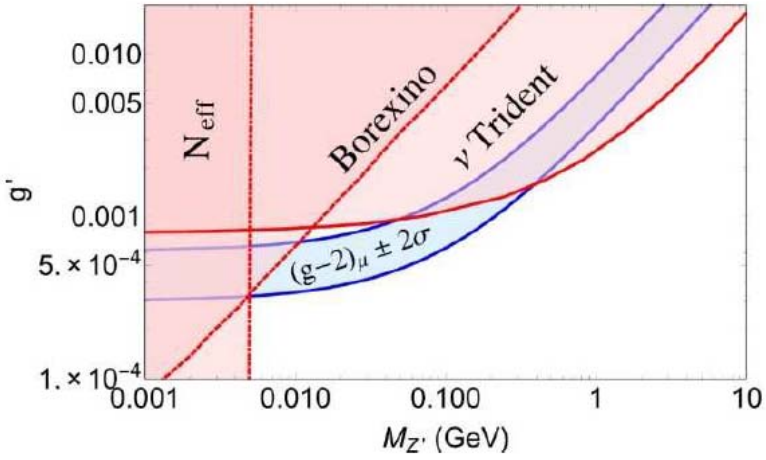
Recent results from *BABAR*: Search for dark muonic forces

$e^+e^- \to \mu^+\mu^- Z', Z' \to \mu^+\mu^-$ (4μ final states)



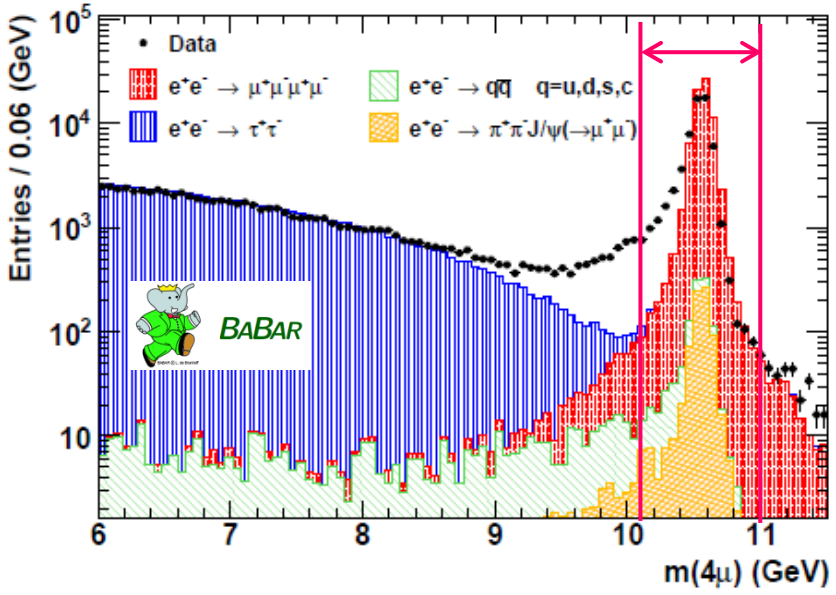
- L_μ–L_τ gauge interaction
  - Can explain several anomalies:
    - $(g-2)_\mu$
    - SM vs sterile neutrinos abundance
    - proton radius discrepancy
- Minimal model: new gauge boson Z'
  - Produced from heavy-flavor lepton radiation: μ, τ
  - Could have low mass (*arXiv:1401.2459*)
  - No observations so far (neutrino experiments only)

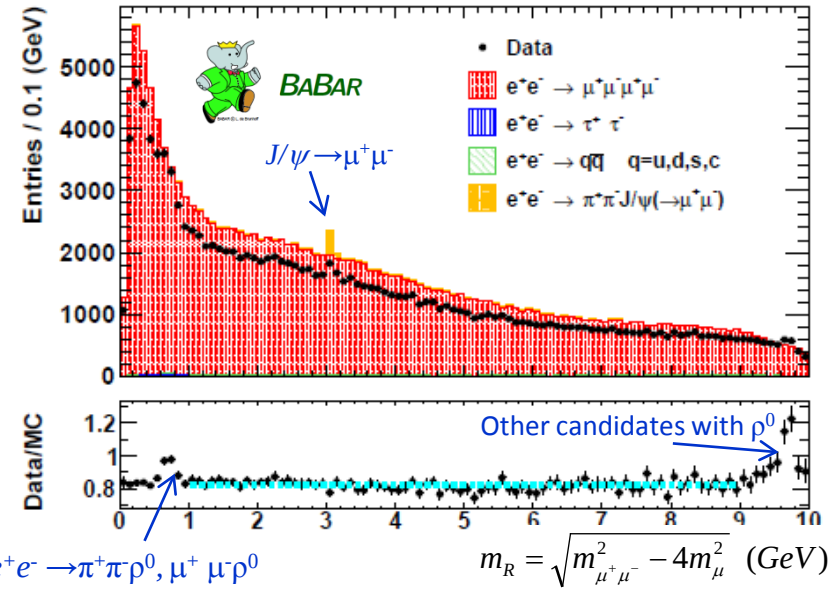
From: W Altmannhofer et al, PRL **113** (2014), 091801
A Kamada et al, PR**D92** (2015), 113004



Search for muonic dark forces: method

- Purpose: search for Z' production ($m_{Z'} > 2m_{\mu}$) in 4 muon final states with full beam energy
- Data: 514 fb^{-1} taken mostly at $\Upsilon(4S)$ + $\Upsilon(3S)$, $\Upsilon(2S)$ + 40 MeV off-peak
- Selection:
  - 4 tracks, small extra energy from neutrals (< 200 MeV)
  - Two tracks of same sign identified as muons
  - 4μ invariant mass within 500 MeV from CM energy
  - Events from $\Upsilon(2S, 3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ excluded
- Signal region dominated by $e^+e^- \to 4\mu$ QED background
- Overestimation of data by MC: ISR, tracking, PID corrections needed





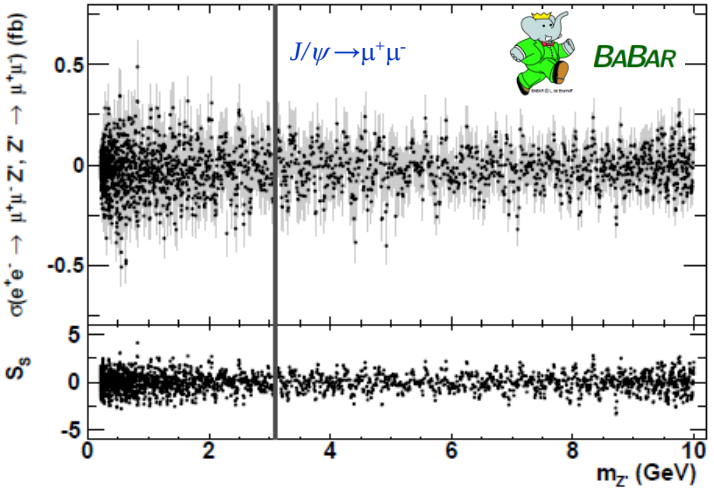
Cross section evaluation and upper limits

- Look for a narrow peak over a smooth background: scan over di-muon reduced mass, fits in $50\sigma_m$ wide windows
  - Separate evaluation for the three Υ(4S, 3S, 2S) data sets, final combination of likelihoods
  - Systematics (signal, modelling) taken into account
- Signal significance evaluated from likelihood ratio

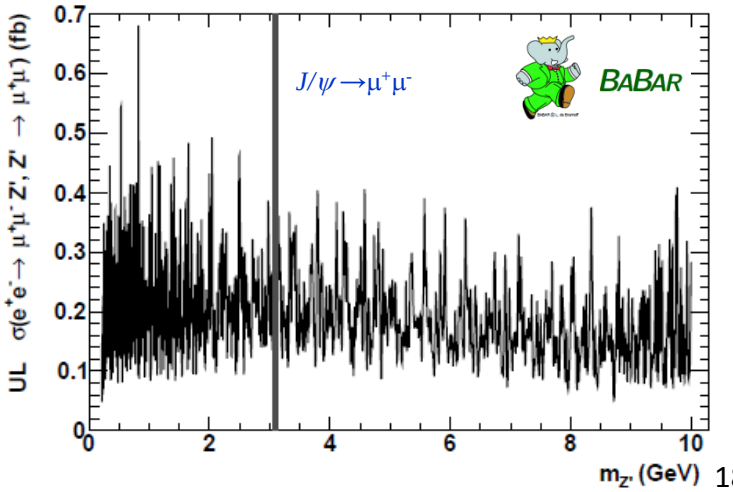
$$S = sign(N_{sig}) \cdot \sqrt{2 \ln \frac{\mathcal{L}}{\mathcal{L}_0}}$$

  - No significant signal in the mass range $0.212 < m_{Z'} < 10$ GeV
  - Largest local significance: 4.3σ @ $m_{Z'} = 0.83$ GeV
  - Global significance: 1.6σ
- Cross section Bayesian upper limit derivation at 90% C.L. with flat prior

$$\sigma(e^+e^- \to \mu^+\mu^+ Z' \to 2\mu^+ 2\mu^-) = \frac{N_{sig}}{\mathcal{L} \cdot \varepsilon}$$

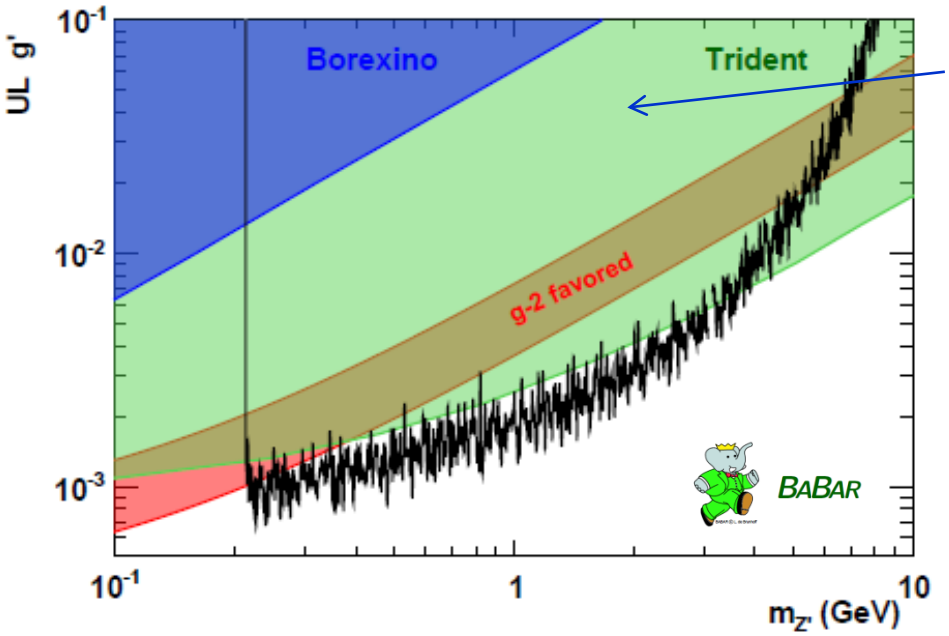


Region around J/ψ signal excluded (±30 MeV)



Results: limits on new gauge coupling g' vs $m_{Z'}$

- Improved excluded areas compared to neutrino experiments
- Upper limit for g' down to ~7×10^{-4} near to di-muon threshold
- Most of the favored $(g-2)_\mu$ region is ruled out
- Powerful constraints for new vector bosons coupling exclusively with muons



CCFR: $\mu^+\mu^-$ production in ν_μ N scattering

BABAR hypothesis: equal coupling to μ, ν_μ, τ and ν_τ

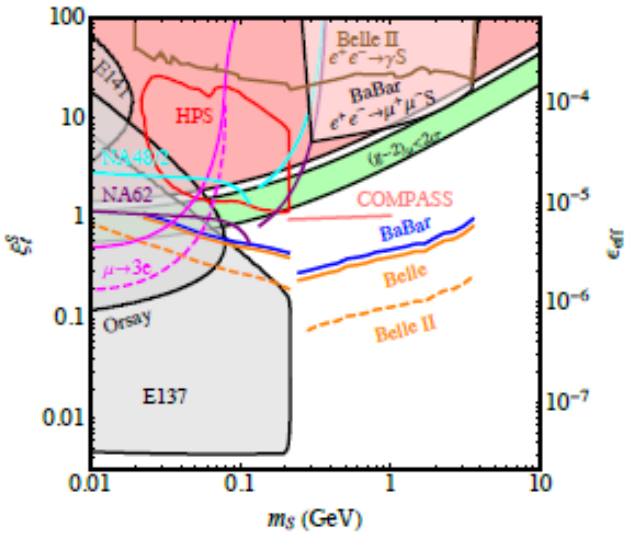
- Published: *BABAR* Coll., J.P. Lees *et al.*, Phys. Rev. **D94** (2016), 0111012
- New results awaited shortly from *BABAR* and Belle in the channel $e^+e^-\to\mu^+\mu^-Z'$, $Z' \to$ *invisible*

Outlook

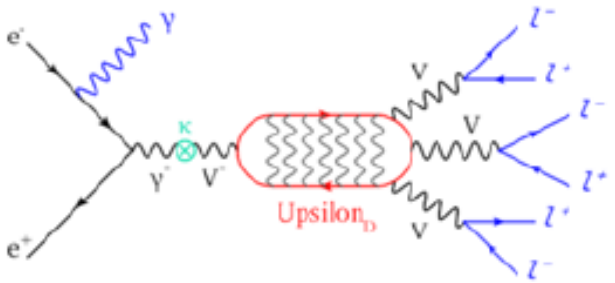
- Several efforts still ongoing to exploit *BABAR* data on related topics

- Search for light dark scalars (ϕ):
  - Can couple to SM via Higgs mixing
  - Couplings proportional to the mass
  - Look for di-lepton resonances in $e^+e^- \to \tau^+\tau^-\phi,\ \phi \to \mu^+\mu^-,\ e^+e^-$
  - Could help probing the remaining $(g\text{-}2)_\mu$ region at low masses

Batell et al.. arXiv: 1606.04943



- Search for self-interacting DM
  - Strong Dark Sector coupling: darkonium $\Rightarrow$ DM bound states
  - Multi-muon final states, striking signature

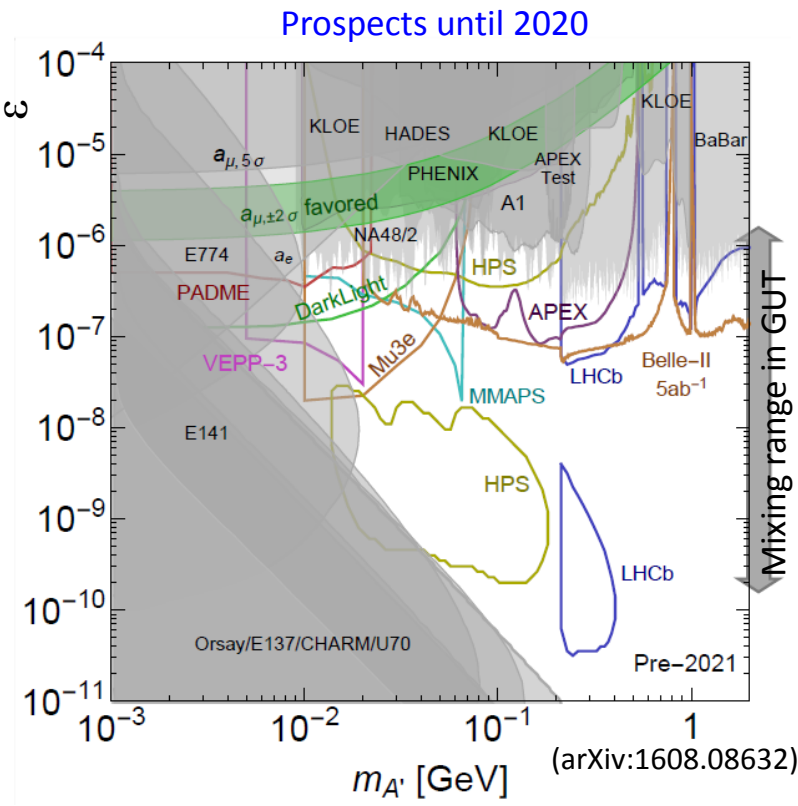


An et al., PRL**116** (2016), 151801

Conclusions

- Light dark sectors represent a new possibility for Dark Matter interpretation alternative to the WIMP paradigm, with a wealth of new viable candidates in the MeV-GeV mass range

- Low energy, high intensity e^+e^- colliders are ideal places where to study their interactions and decays



- *BABAR* has conducted an extensive program for searches and set stringent limits in the mass-coupling plane: no evidence of signals so far
  - *BABAR* single photon search excludes the $(g-2)_\mu$ favored region and rules out the mass range down to 1 MeV for invisible decays
  - At the moment it presents the best LDM sensitivity among experiments at colliders
  - Belle II is ready to step in and improve data accuracy

- Very lively field, with many complementary new initiatives risen in the latest years, and more yet to come

backup slides

$A' \to e^+e^-, \mu^+\mu^-$ (PRL**113** (2014), 201801)

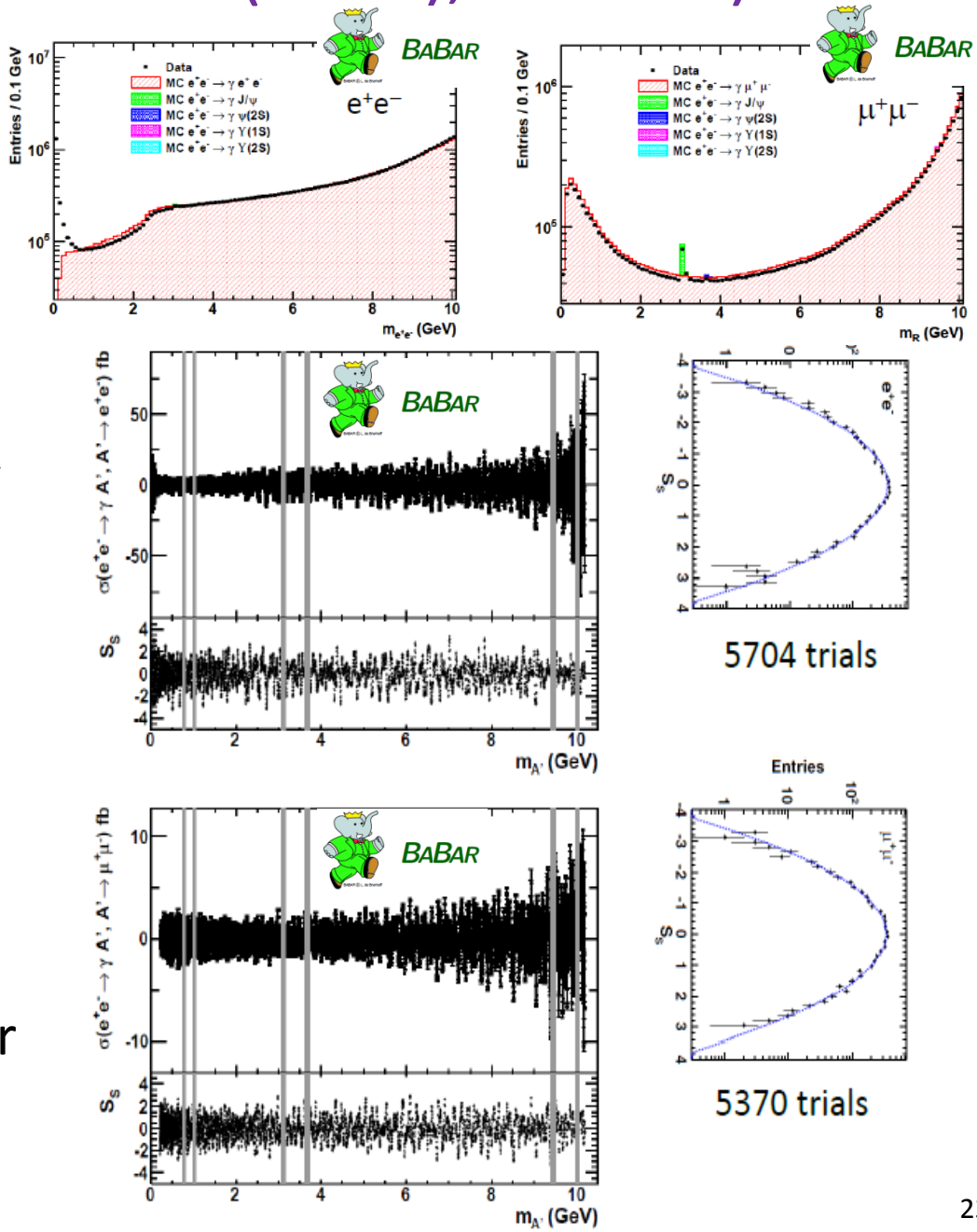
- Extract cross sections with fits over sliding windows covering the range

  $0.02_e, (0.212_\mu) <$

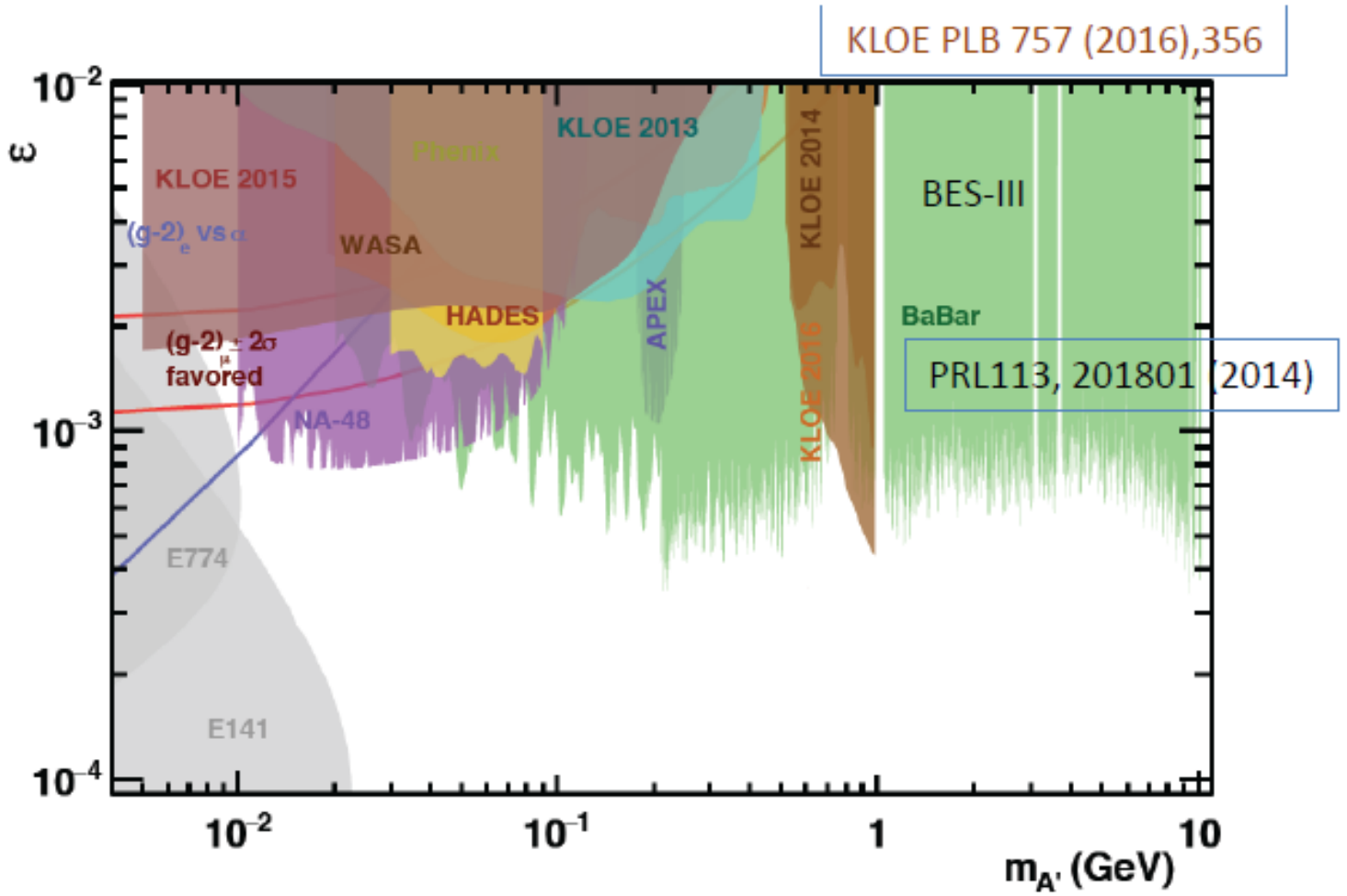
  $< m_{A'} < 10.2$ GeV

- Highest significances:
  - Electron channel:
    - 3.4σ @ m = 7.02 GeV
  - Muon channel:
    - 2.9σ @ 6.09 GeV

- Bayesian 90% C.L. upper limits on the cross section: from 1 to 10 fb

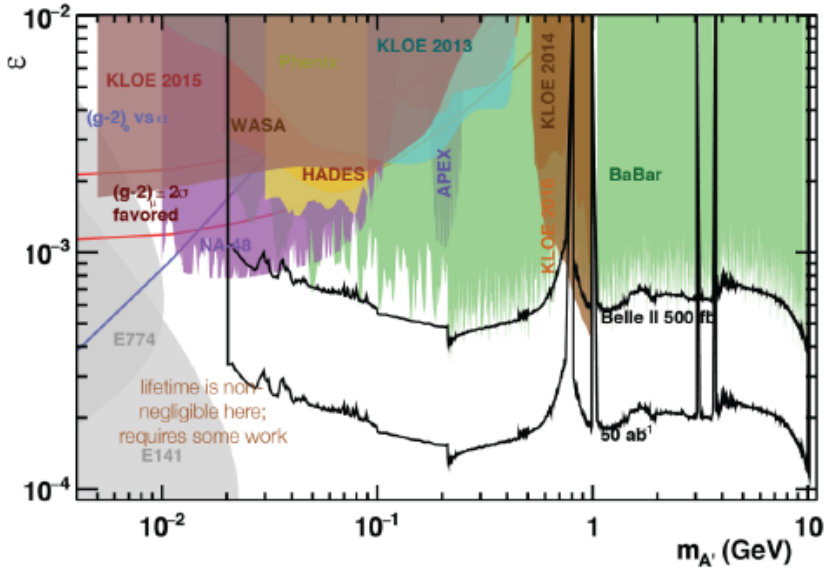


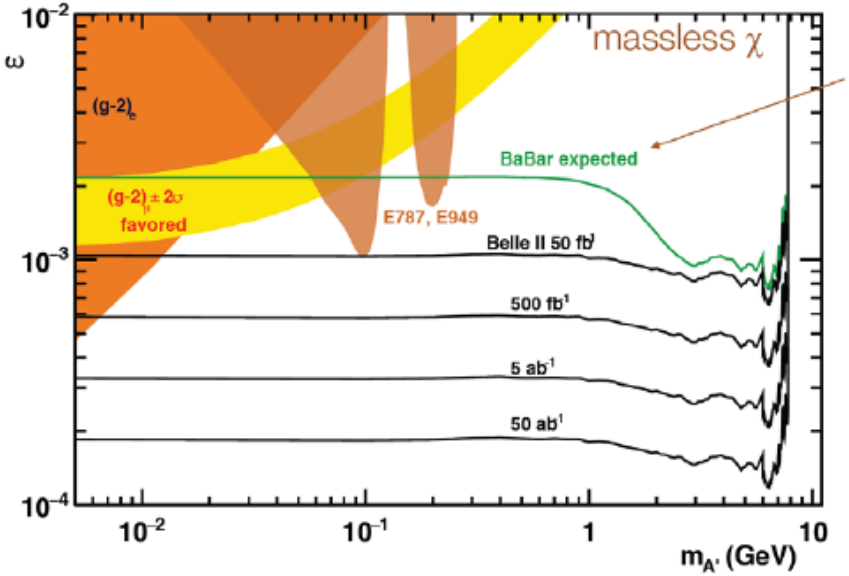
Dark photon visible decays, FPC2016



Dark photon sensitivities for new experiments (FPCP2016)

C. Hearty, FPCP2016,
"Light Higgs, Dark Sectors"



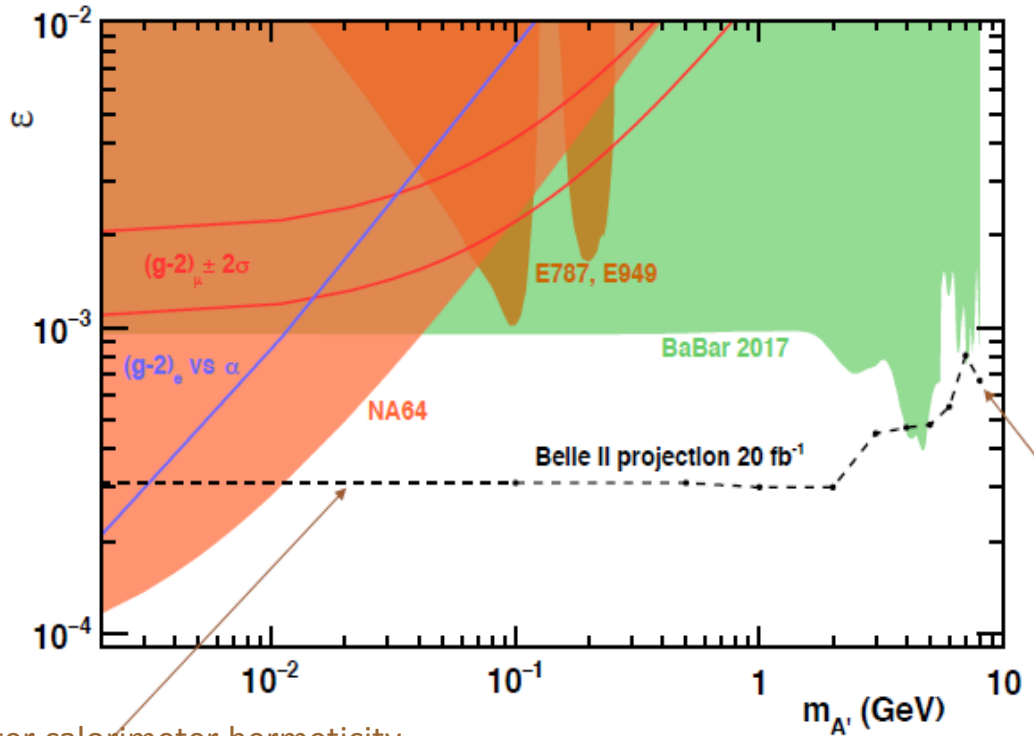


Visible decays in two bodies:
$e^+e^- \rightarrow \gamma A', A' \rightarrow \ell^+\ell^-$

Invisible decays:
$e^+e^- \rightarrow \gamma A', A' \rightarrow invisible$

Search for invisible decays at BelleII

- Better sensitivity already with 20 fb^{-1} of data only :
  - Better calorimeter hermeticity
  - Improved trigger thresholds



Reach masses of 9.1–9.5 GeV/c^2 with lower trigger threshold (vs 8 GeV/c^2 for BaBar)

Better calorimeter hermeticity to suppress $e^+e^- \to \gamma\gamma$