Search for invisible decay of a dark photon in e^+e^- collisions at *BABAR*

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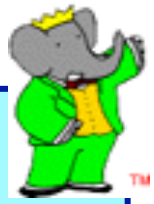
Motivation

- With the ~125 GeV/c^2 Higgs scalar, the Standard Model (SM) particle contents might be complete.
- However, big Beyond Standard Model (BSM) questions remain:
  - ***Dark matter***, *Neutrino masses, Baryon Asymmetry in the Universe, Inflation, Dark Energy*
- There are intriguing astrophysical observations: *Pamela, Fermi, AMS2, Dama…*

Could there be a hidden sector at low energy?

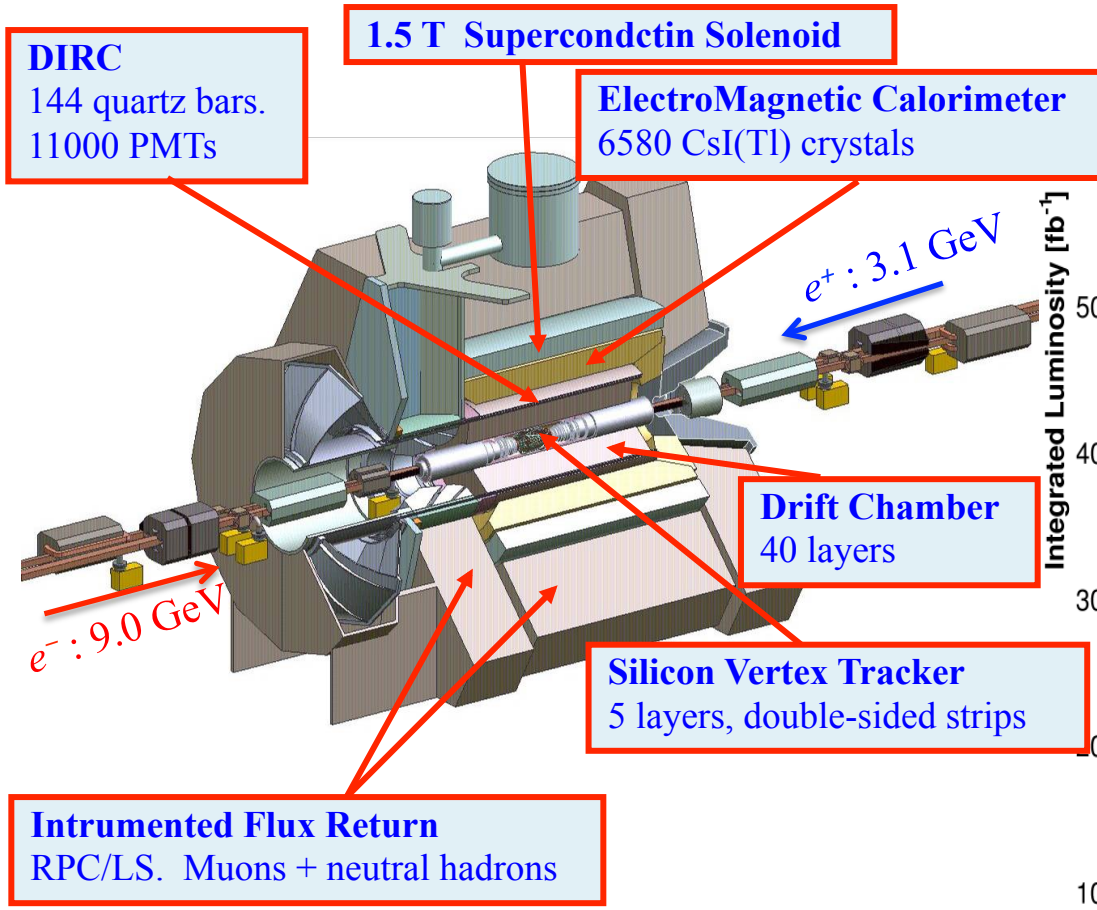
- A flurry of models include: SUSY models, portals/new effective scales:
  - *Vector, Scalar, Neutrino, axion-like…*
- An emerging experimental field at accelerators (colliders, beam dumps)

➢ Today: new preliminary results from *BABAR* at PEP-II

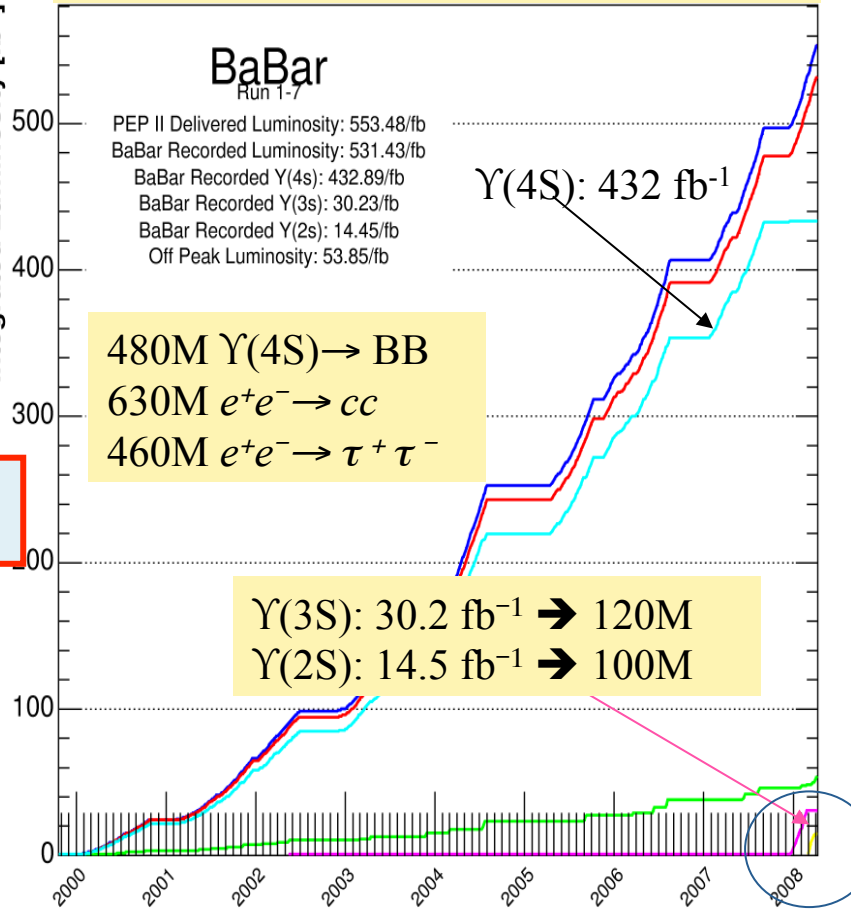


- Search for a dark photon decaying invisibly
  arXiv:1702.03327

BABAR detector and collected data sample



BABAR recorded luminosity and data set (1999-2008):



Details in:
- NIM **A479**,1 (2002),
- NIM **A729**, 615 (2013)

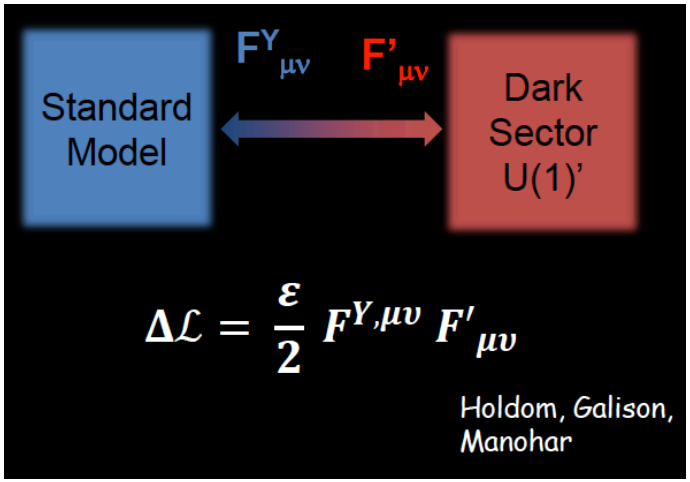
Dark photon A'

- Dark matter models introducing a new sector with a "dark" force mediated by a light gauge boson can accomodate anomalies observed in astrophysical research

$$\chi\chi \rightarrow A'A' \rightarrow (e^+e^-)(e^+e^-)$$

$m_\chi \sim$ TeV; $m_{A'} \sim$ MeV-GeV

Arkani-Hamed et al.
PRD 79, 015014 (2009)



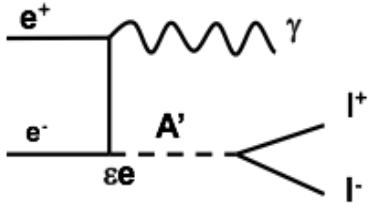
- Kinetic mixing of A′ with SM γ (*vector portal*)
  - mixing strength $\varepsilon \approx 10^{-5} - 10^{-2}$
- Dark photon – SM fermions coupling $\alpha' = \varepsilon^2 \alpha$

- A′ decay modes depend on its mass and coupling, as well as on particle spectrum of the dark matter
  - if lowest DM state $2m_\chi > m_{A'} \Rightarrow A' \rightarrow$ SM particles (in particular lepton pairs $A' \rightarrow e^+e^-, \mu^+\mu^-$)
  - if lowest DM state $2m_\chi < m_{A'} \Rightarrow A' \rightarrow$ invisible is the dominant decay ($A' \rightarrow \chi\chi$)

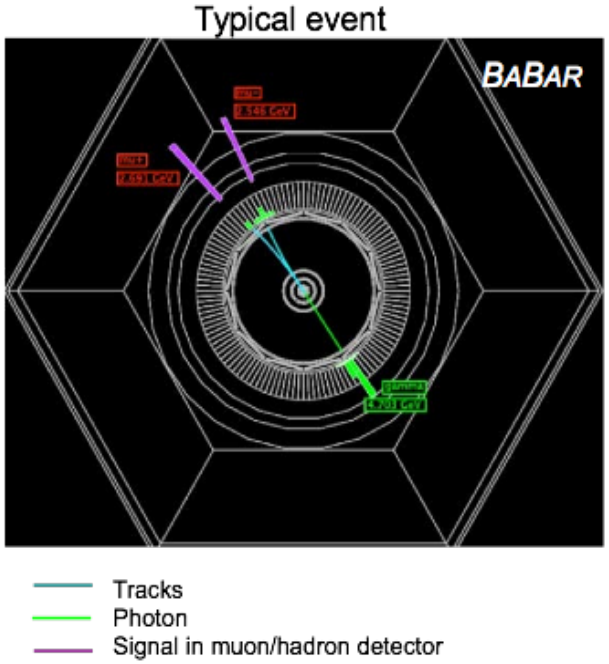
Searches at BABAR: $e^+e^- \to \gamma A'$; $A' \to e^+e^-, \mu^+\mu^-$

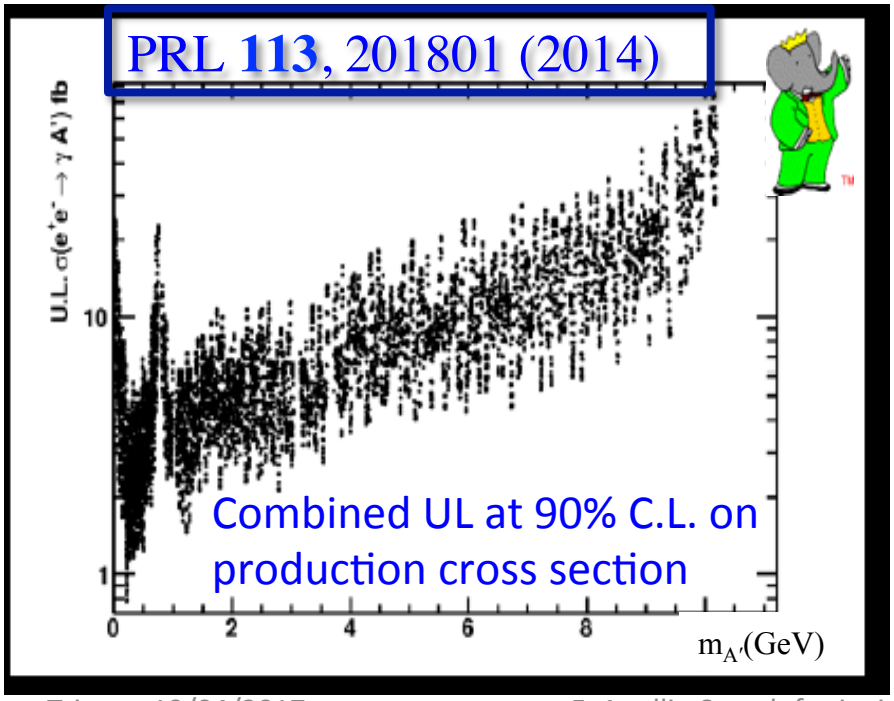
In *BABAR* a dark photon can be produced in
$e^+e^- \to \gamma A'$; $A' \to e^+e^-, \mu^+\mu^-$

with a cross section proportional to $\varepsilon^2 = \alpha'/\alpha$



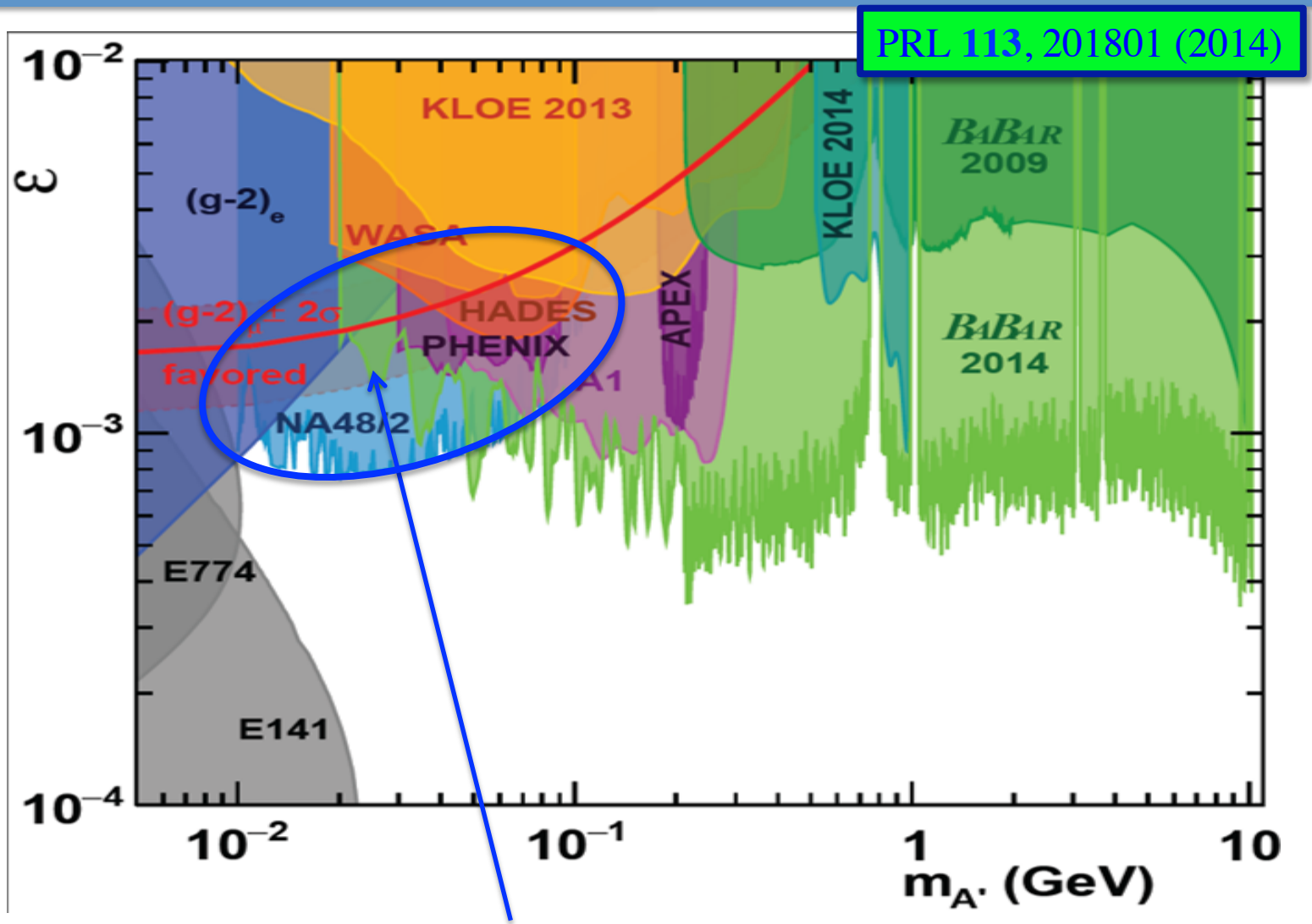
- Analysis performed on the full data sample of 514 fb^{-1}
- Look for a narrow peak in the invariant mass of the lepton pair
- Scan the energy range from 20 MeV to 10.2 GeV





- No significant eccess observed
- Largest significance 3.4σ at 7.02 GeV

Limits in the ε.*vs*.m plane

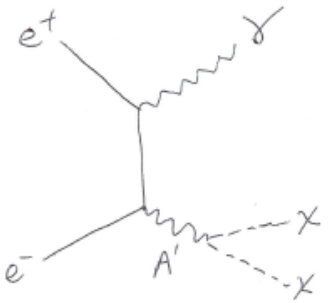


After *BABAR* and NA48/2 results the preferred region of phase space to explain the muon g-2 with visible decays of a dark photon is fully ruled out

Search for invisible decays of a dark photon

Search for single-photon final states:
- assume on-shell A' ($m_\chi < m_{A'}/2$), with negligible decay width w.r.t. experimental resolution
- assume that A' decays predominantly to DM

$$E_\gamma^* = \frac{s - M_X^2}{2\sqrt{s}}$$



- The analysis optimized for and interpreted in terms of a dark photon decaying invisibly
- Similar signature for other modes, e.g. axion production, light Higgs boson
  - The recoiling particle can be either a vector or a scalar

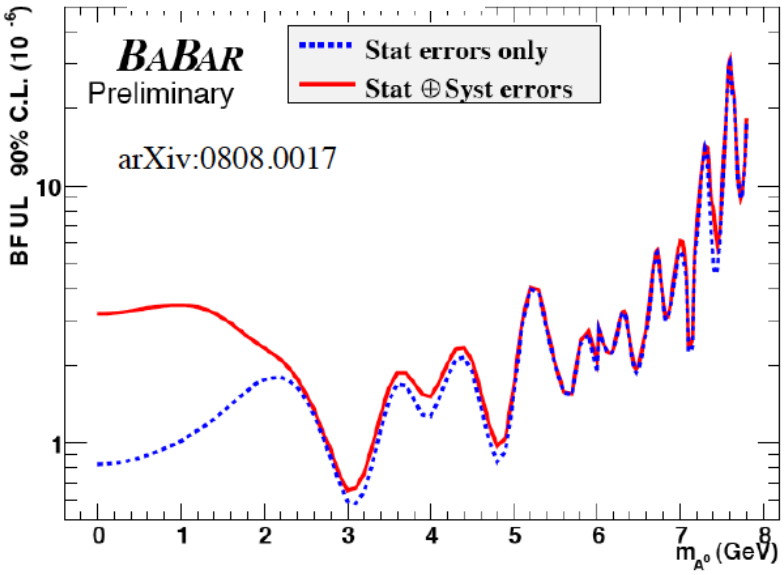
- Low-multiplicity final state: photon + nothing else
  - Missing energy and momentum is the best signature
  - Hermeticity and efficiency of the detector are the key
  - Strategy: select single-photon events, look for a bump in the missing mass or E_γ^*
  - Main backgrounds:
    - $e^+e^- \to \gamma\gamma$: peaking at $M_x^2 \sim 0$, hard to predict with simulation
    - $e^+e^- \to e^+e^-\gamma$: continuum distribution in M_x^2
    - machine background: do not mimic signal, but can be the second photon in a signal event

2007 analysis results: $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

Preliminary results: arXiv:0808.0017

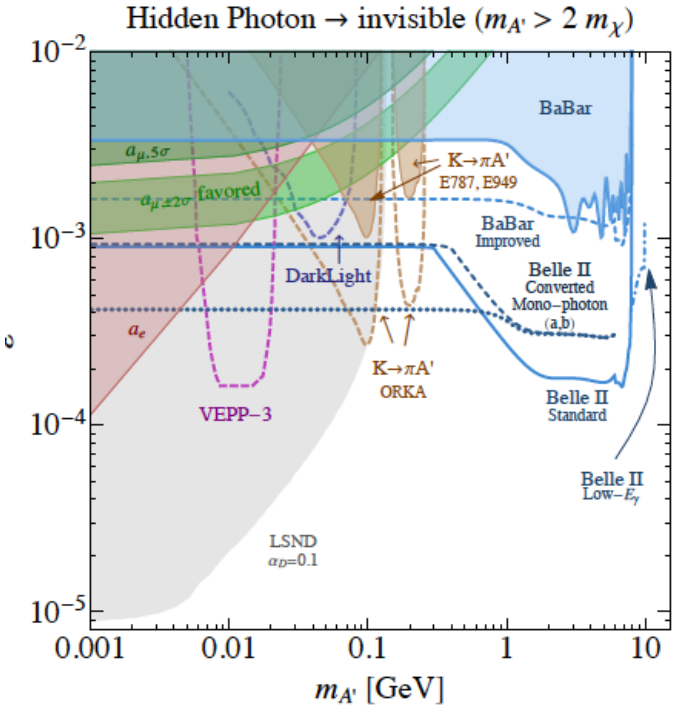
analysis optimized for search for a light CP-odd Higgs boson A0 -> invisible

No significant signal;
limits on BF constrain
NMSSM parameter
space



Unpublished. Nevertheless >90 citations!

Results reinterpreted by theorists in terms of other NP scenarios



R. Essig *et al.*,
JHEP **1311**, 167 (2013)

Search for $A' \rightarrow$invisible: Trigger

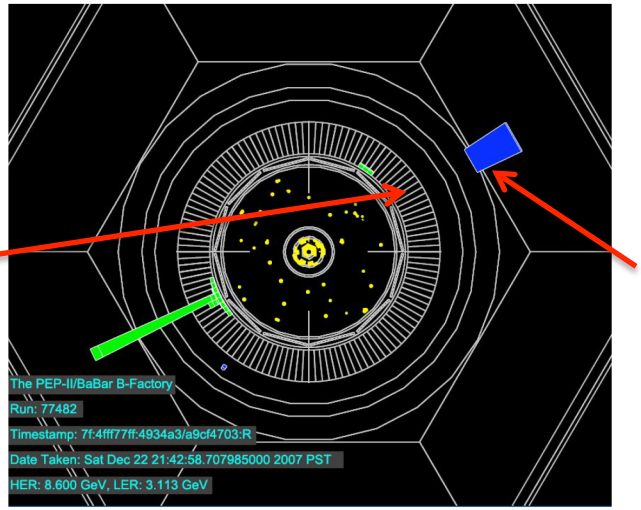
- Two single-photon software trigger algorithms, with different E_γ^* threshold, implemented at different times for the final BABAR running period
- Trigger lines further refined by software filters
  - high-energy photon filter line: $E_\gamma^* > 3$ GeV, no tracks with $p^* > 1$ GeV/c
    - data set: 53 fb-1, mostly at the Y(3S) and Y (2S), with a small sample at the Y(4S)
  - low-energy photon line: $E_\gamma^* > 1.5$ GeV, no tracks with $p^* > 0.1$ GeV/c, loose shower shape
    - data set: a subset of the previous one, with no Y(4S) sample

- This naturally split the selection into two broad $m_{A'}$ ranges
  - low mass (high E_γ^*): $-4 < m_{A'} < 36$ GeV^2
  - high mass (low E_γ^*): $24 < m_{A'} < 69.0$ GeV^2 for the Y(3S) data set
    $24 < m_{A'} < 63.5$ GeV^2 for the Y(2S) data set

Search for $A' \rightarrow$invisible: Event selection

- Detector hermeticity is a critical issue
- Require $|\cos\theta_\gamma^*|<0.6$ so that both γ's are within EMC acceptance
- Still possible that photons escape detection in the EMC
  - azimuthal gaps between crystals aligned with collision point

$e^+e^- \rightarrow \gamma\gamma$ event with no signal left by second photon in the EMC



photon shower detected in the muon system (IFR)

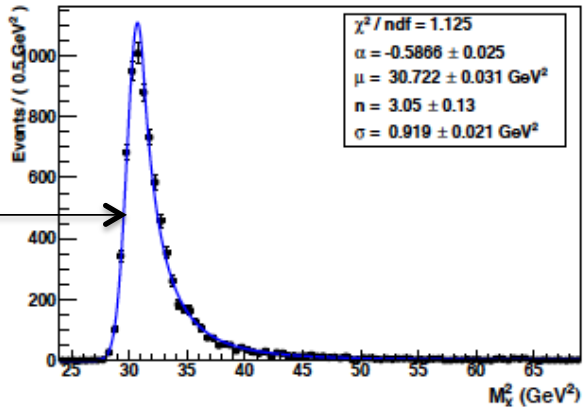
- Boosted Decision Tree selector to separate signal and background, based on 12 discriminating variables, including:
  - EMC cluster shape variables => photon quality
  - extra detected energy (besides the primary photon) in the LAB system
  - kinematics of the 2nd most-energetic photon, and its angular distance from the primary photon.
  - activity in the IFR around the missing momentum direction (very effective in suppressing the $e^+e^- \rightarrow \gamma\gamma$ background)
- BDT trained separately in Low- and High-mass regions by using 3 fb^{-1} of Y(3S) data, and simulated signal

Search for $A' \rightarrow$invisible: Fits to data

- Extract signal yields and ultimately set U.L. on A' coupling ε by simultaneous fits to M_X^2 distributions:
  - High-mass region: Υ(2S, 3S) data, with Loose BDT cut (2 data sets)
    - background dominated by radiative Bhabha, smooth in recoil mass M_x
  - Low-mass region: Υ(2S, 3S, 4S) data, with non-overlapping Loose and Tight selections (6 data sets)
    - both peaking (from $e^+e^- \rightarrow \gamma\gamma$) and smooth background is present

- Perform fits for 166 mass hypothesis

- For each fit:
  - Background PDFs fixed by fitting data in the background region -0.5< BDT <0
  - Signal PDF is a Crystal Ball with parameters fixed from MC
  - Float signal (actually the coupling squared ε^2), and number of background events separately for peaking and continuum

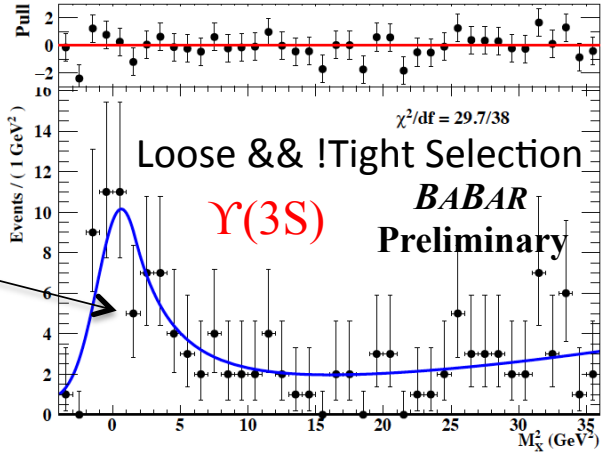


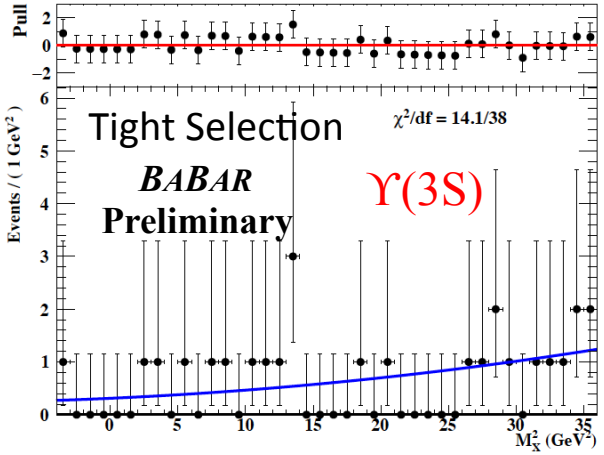
Search for $A' \rightarrow$invisible: Background-only fits

arXiv:1702.03327

- Example of data in the low-mass region

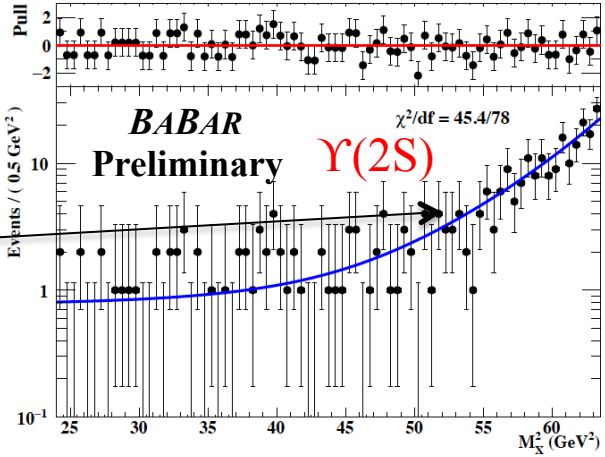
Irreducible peaking background from $e^+e^- \rightarrow \gamma\gamma$

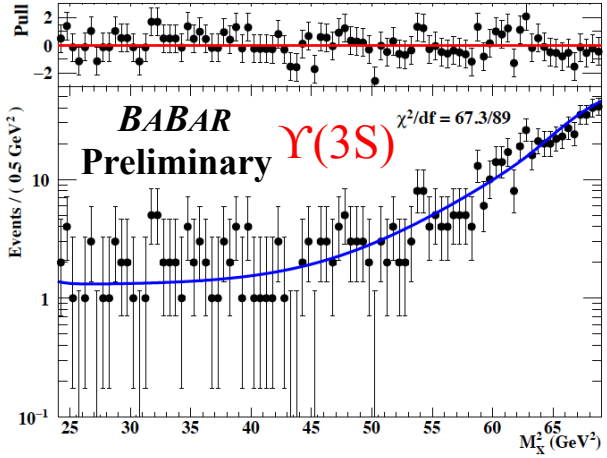




- Example of data in the high-mass region

Smooth rise due to radiative Bhabha

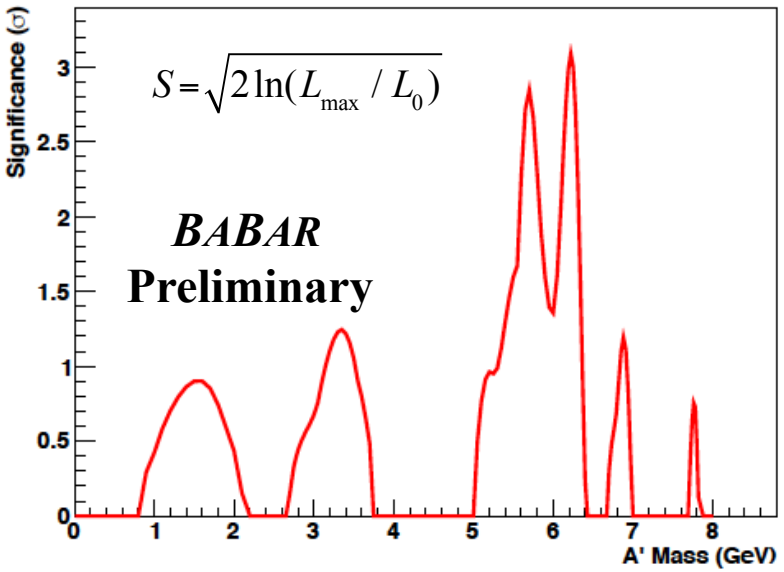




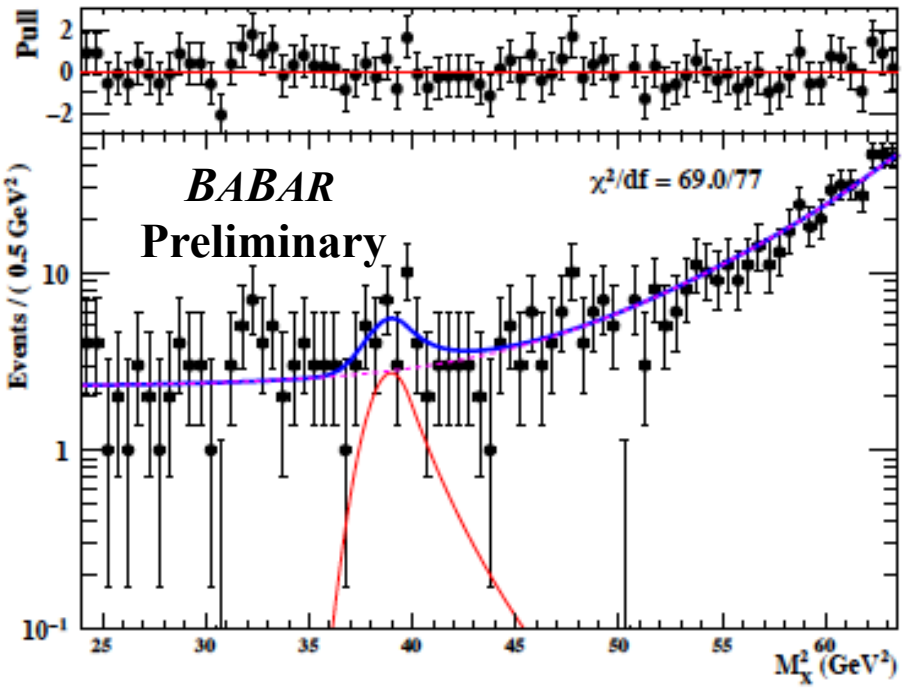
- Background-only fits show good agreement with data in all signal regions

Search for $A' \rightarrow$invisible: Signal extraction

(Local) signal significance vs $m_{A'}$



Most significant fit at $m_{A'}$= 6.21 GeV



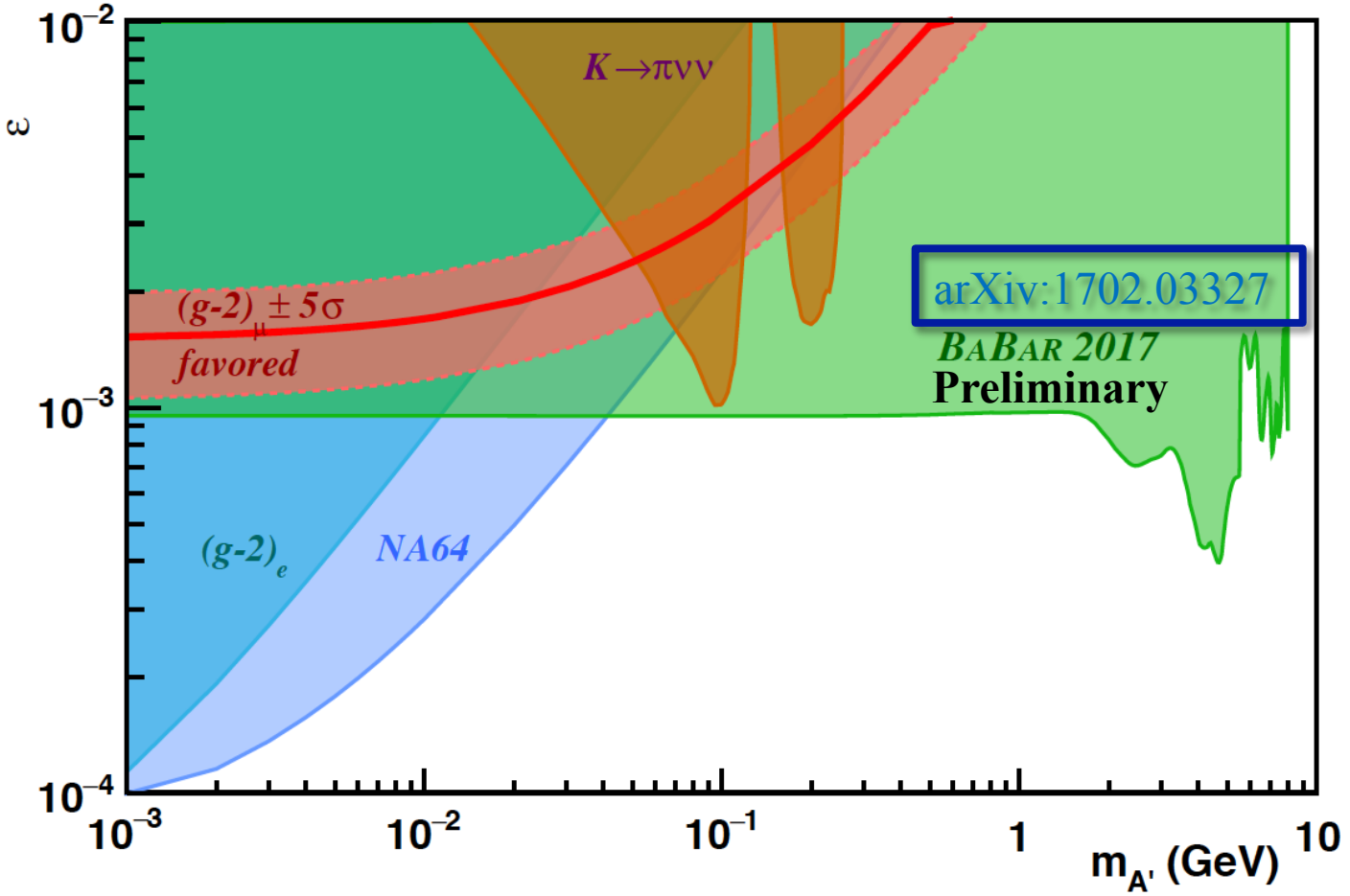
arXiv:1702.03327

- Local (global) significance of 3.1σ (2.6σ)
  - global p-value: ~1%
- Slightly smaller fluctuation at at $m_{A'}$= 5.70 GeV (2.8σ)

- No significant signal observed => set U.L. on mixing parameter ε as a function of dark-photon mass $m_{A'}$

Search for $A' \rightarrow$invisible: Results

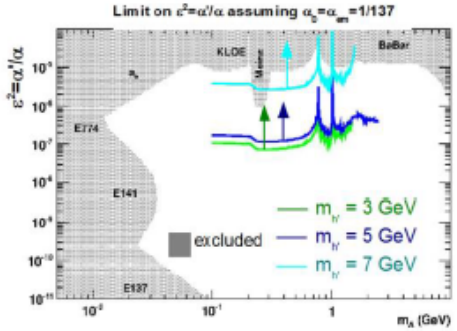
- Exlcusion regions for invisible decays of a dark photon after *BABAR* results



- Preferred region to explain $(g\text{-}2)_\mu$ entirely excluded

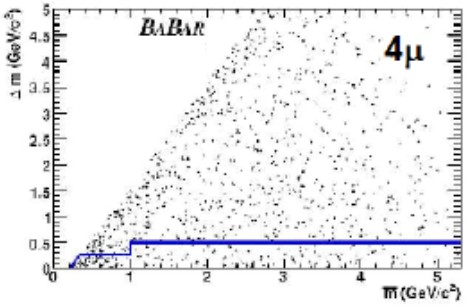
Further DM-related searches at *BABAR*

Search for dark Higgs bosons in $e^+e^- \to h' A', h' \to A' A'$



PRL 108 (2012) 211801

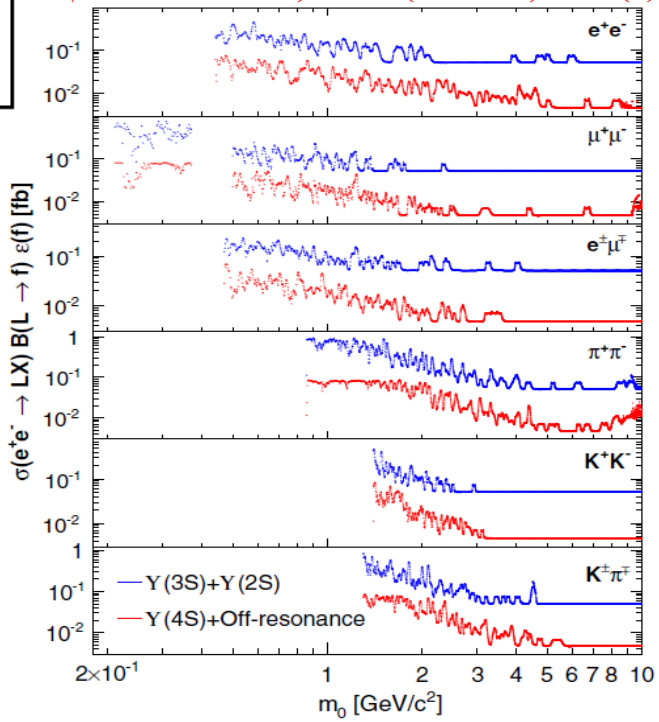
Search for dark bosons in $e^+e^- \to \gamma A' \to W' W'$



arXiv:0908.2821

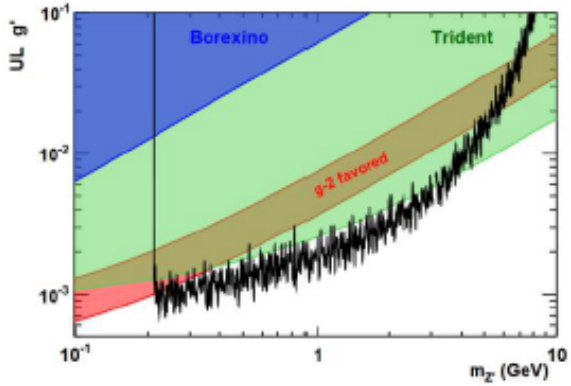
Search for long-lived particles in $e^+e^- \to L X$

$\sigma(e^+e^- \to X L) \times \mathcal{B}(L \to f) \times \varepsilon(f)$



PRL **114**, 171801 (2015)

Search for muonic dark force in $e^+e^- \to \mu^+\mu^- Z', Z' \to \mu^+\mu^-$



PRD 94 (2016) 011102

Further analyses ongoing or planned

Conclusions

- Light dark sectors have recently emerged as a possibility for dark matter and provide a rich phenomenology

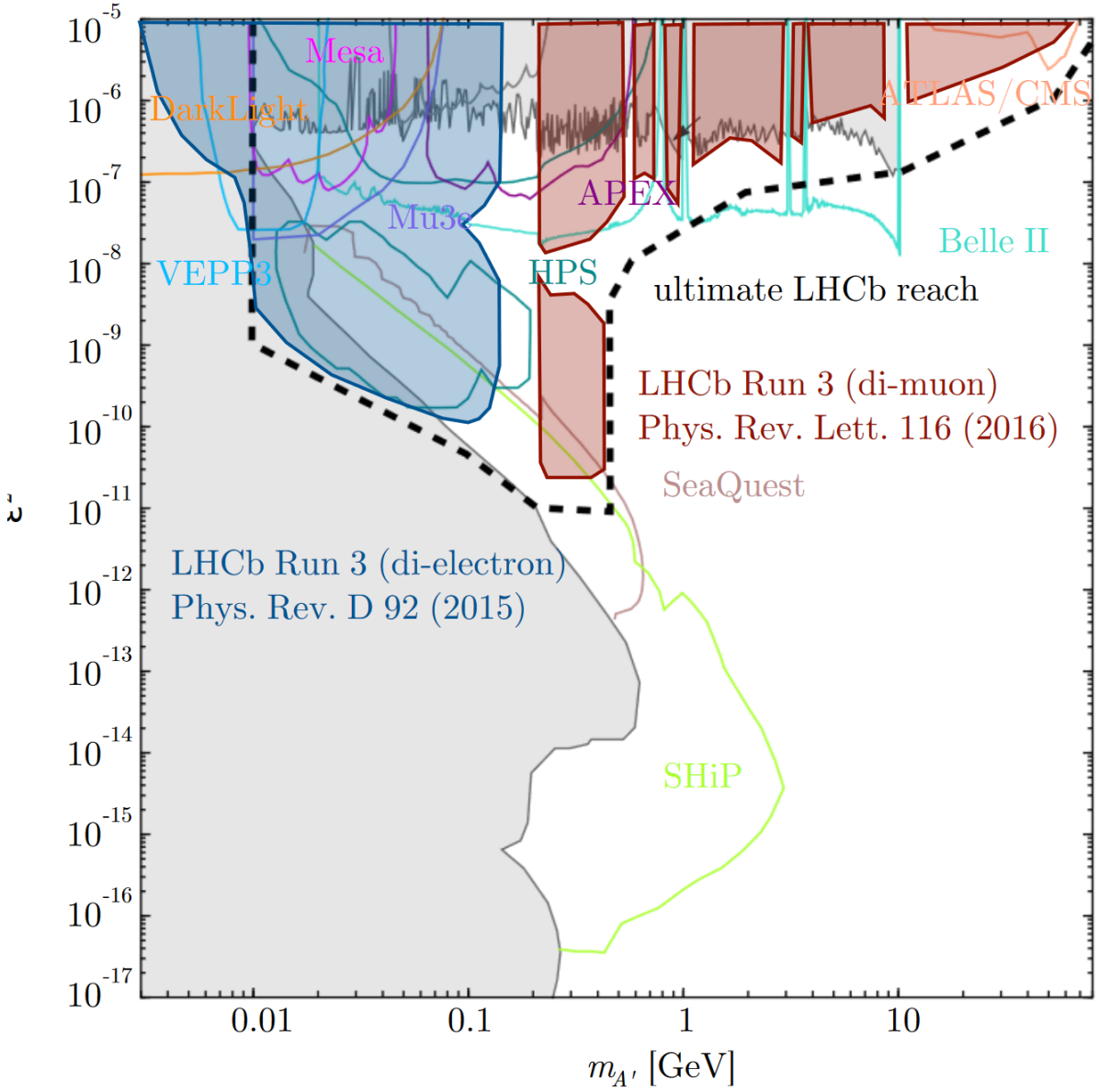
- *BABAR* pioneered the low-energy, high-intensity collider searches putting stringent limits on the parameter space of various dark sector models
  - Direct searches: unique sensitivity to low-mass new physics in high-statistics datasets
  - Complementary to results from fixed targets experiments and hadron colliders

- *BABAR* searches for invisible decays and for $A' \rightarrow l^+l^-$ excludes the region of parameter space preferred by the $(g\text{-}2)_\mu$ value

- More analyses in progress at *BABAR*

Backup Slides

Expected reach in the “near” future

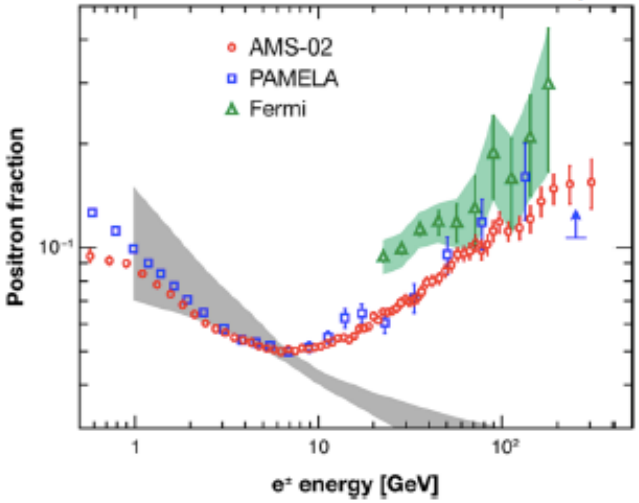


Astrophysical interest

PRD 79, 015014 (2009) Arkani-Hamed et al.

- ~TeV DM: $\chi\chi \to A'A' \to (e^+e^-)(e^+e^-)$
- Initial lack of antiproton excess
  → $m_{A'} <$ few GeV

PRL 110, 141102 (2013)
Nature 458, 607 (2009)
PRL 108, 011103 (2012).



- Possible antiproton excess now observed: