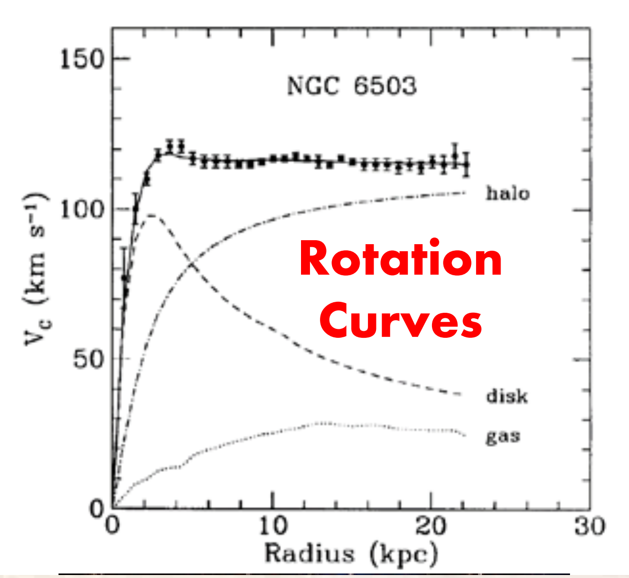
Search for Invisible Dark-Photon Decay at BABAR

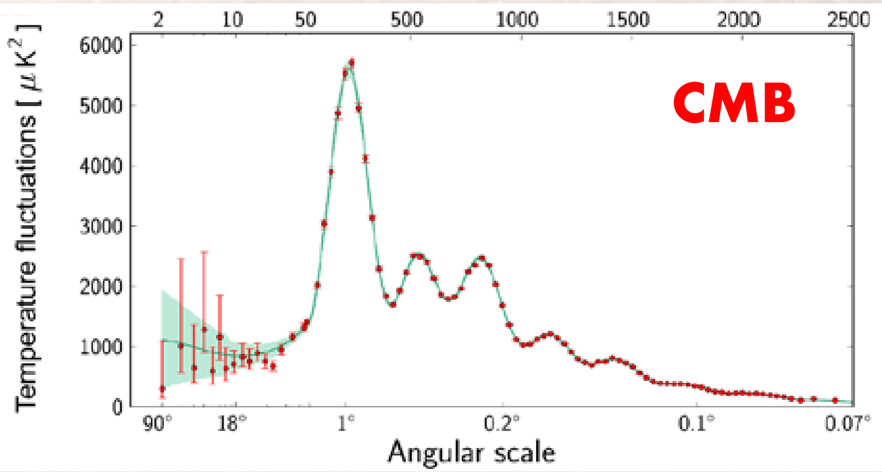
G. Eigen, University of Bergen

On behalf of the BABAR collaboration

Introduction

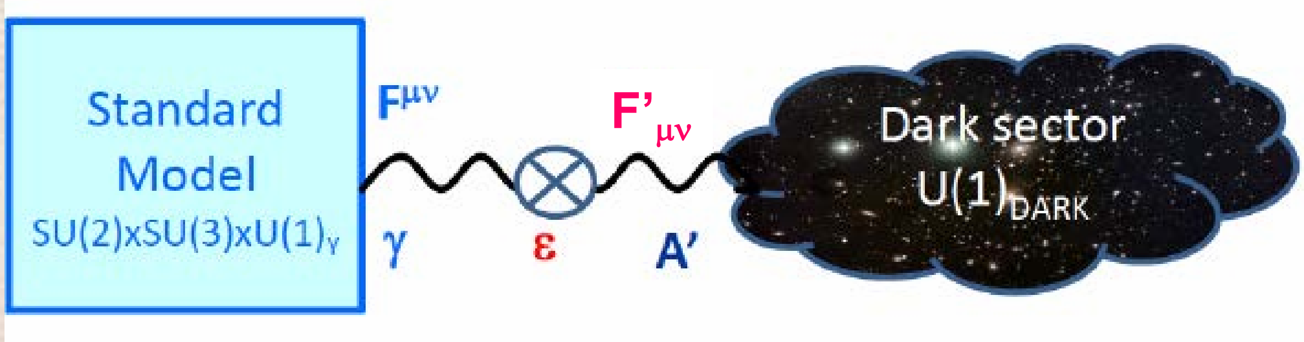
- What is dark matter?
  - New particle(s)?
  - A gravitational effect?
  - Black holes?
  - A combination of all?
- So far, we see only gravitational effects of dark matter
- No new particles have been observed
- Searches are ongoing at LHC and in astroparticle physics experiments





Access to the Dark Matter Sector

- In the past, dark matter particles have been associated with new heavy particles predicted in extensions of the Standard Model (SM), e.g. neutralinos
- Several dedicated WIMPs (weakly interacting massive particles) searches have not found any signal
- This has triggered theorists to consider light-mass dark-matter scenarios
- The SM may be connected to the dark sector through so-called portals, these links are the lowest-dimensional operators that may provide coupling of the dark sector to the SM (higher-dimensional operators are mass suppressed)
- At low-energy scales, the light vector portal is the most accessible portal
  - Vector: $\varepsilon F^{\mu\nu} F'_{\mu\nu}$ hidden photon (new U(1) symmetry
- Dark photons couple to the SM with mixing strength $\alpha' = \varepsilon^2 \alpha_{EM}$



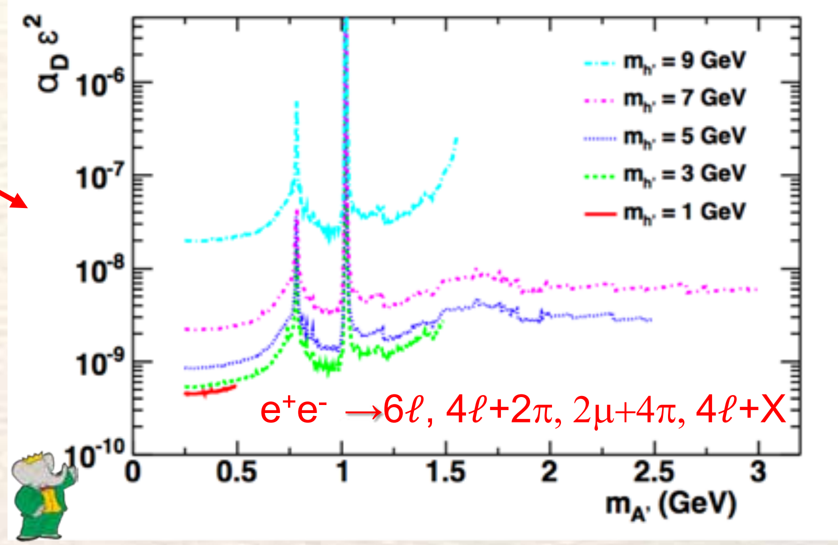
- BABAR has searched for dark photons in different final states

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

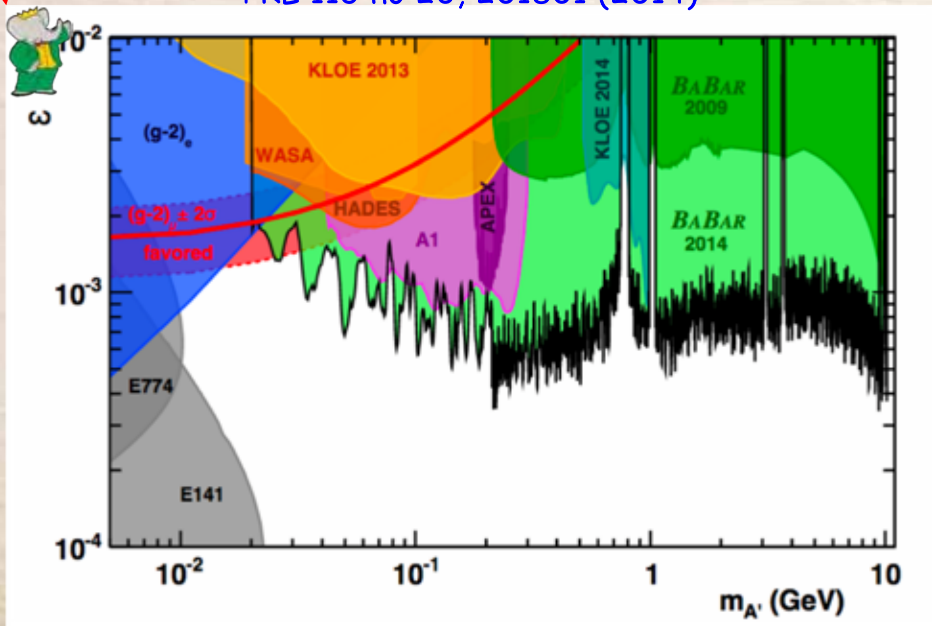
Previous BABAR Dark-Sector Searches

- Search for dark Higgs in $e^+e^- \rightarrow h'A', h' \rightarrow A'A'$
  ➔ set 90% confidence level (CL) upper limits on coupling $\alpha_D\,\varepsilon^2$
- Search for $e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-, \mu^+\mu^-$
  ➔ set 90% CL upper limits on mixing strength ε
- Search for dark sector muonic dark force in $e^+e^- \rightarrow \mu^+\mu^- Z', Z' \rightarrow \mu^+\mu^-$ ➔ set 90% CL upper limits on coupling parameter g'

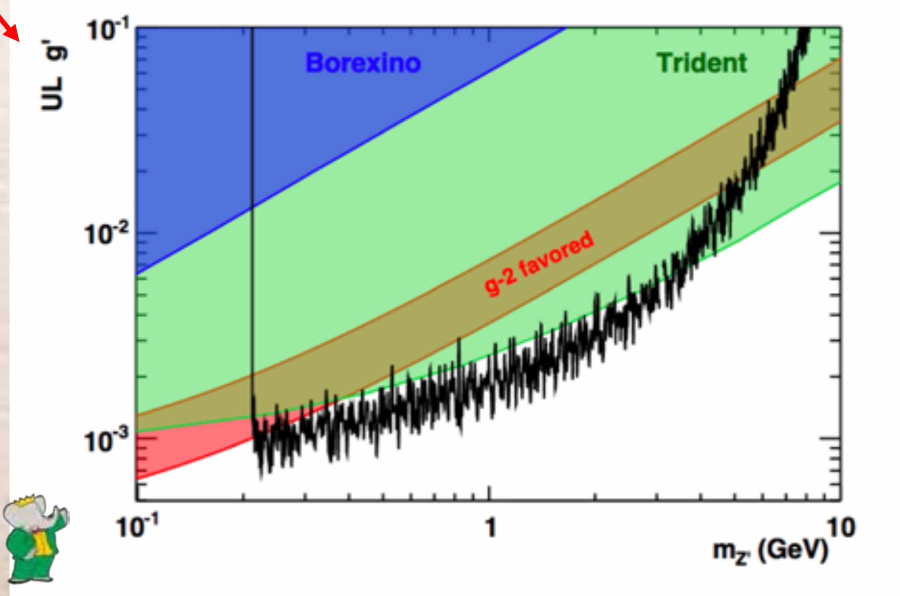
PRL 108, 211801 (2012)



PRL 113 no 20, 201801 (2014)

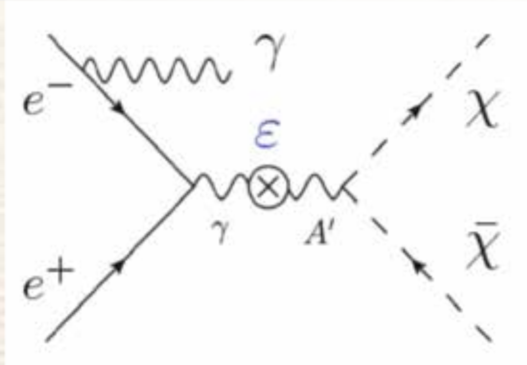


PRD 94 no 1, 011102 (2016)



BABAR Search for Invisible Dark Photons

- Dark photons are produced in $e^+e^- \to \gamma_{ISR} A'$, and decay via $A' \to \chi\chi$ (invisible) PRL 119 no13, 131804 (2017)



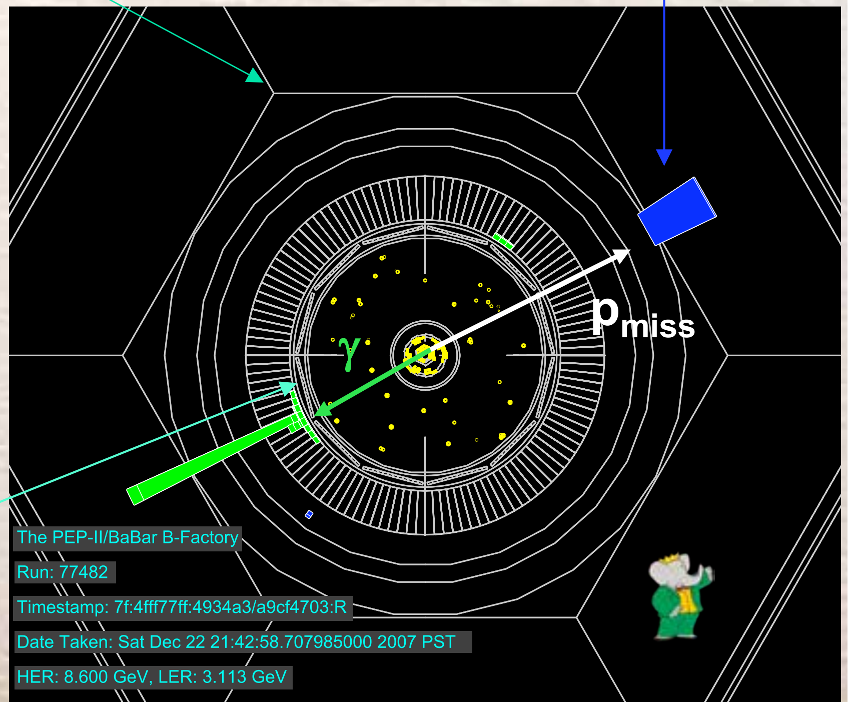
- Experimental signature: single photon plus missing energy & missing momentum in the recoil ➔ need single photon trigger
- This search is based on 53 fb^{-1} of BABAR data at the $\Upsilon(2S)$, $\Upsilon(3S)$ & $\Upsilon(4S)$ using a special single-photon trigger
- Special Hardware trigger, L1:
  - $\geq$1 EMC cluster, E>0.8 GeV
- Two special software triggers, L3:
  - High E^*_γ >2 GeV ➔ lower M_X 53 fb^{-1}
  - Low E^*_γ >1 GeV ➔ higher M_X 38 fb^{-1}

$$M^2_X = E^2_{miss} - \vec{p}^{\,2}_{miss}$$

- Note: $m_{A'} = M_X$

Problem: no efficiency along sector boundaries

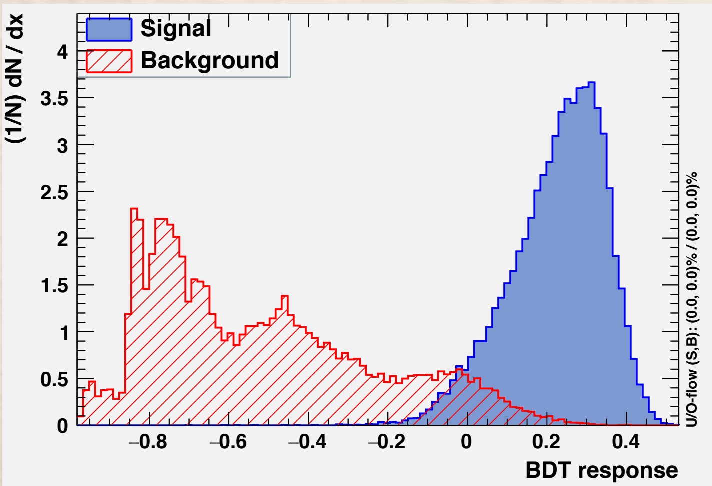
Photon signal in IFR



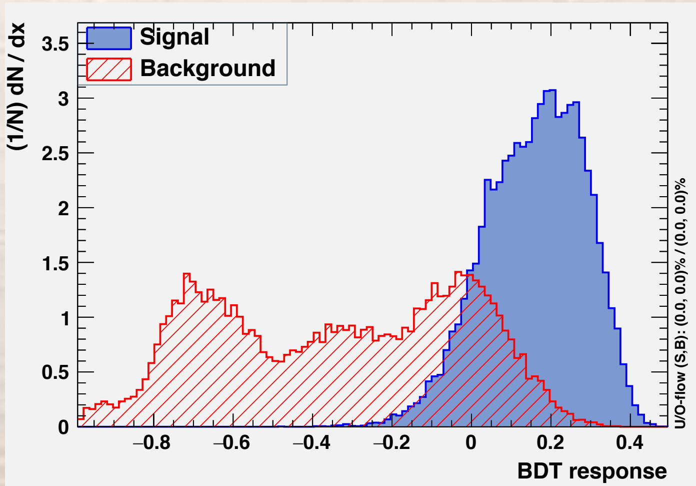
Problem: no efficiency along sector boundaries aligned with the IR

Signal Selection

- Low $m_{A'}$<5.5 GeV
- Main background: $e^+e^- \rightarrow \gamma\gamma$ as one photon may escape detection in CsI crystals due to their orientation to IR
- Single isolated γ shower with E^*_γ **> 3 GeV** & $|\cos\ \theta^*_\gamma| < 0.6$
- No drift chamber tracks p^***>1 GeV**
- Use multivariate **BDT** discriminant based on **12** discriminating variables



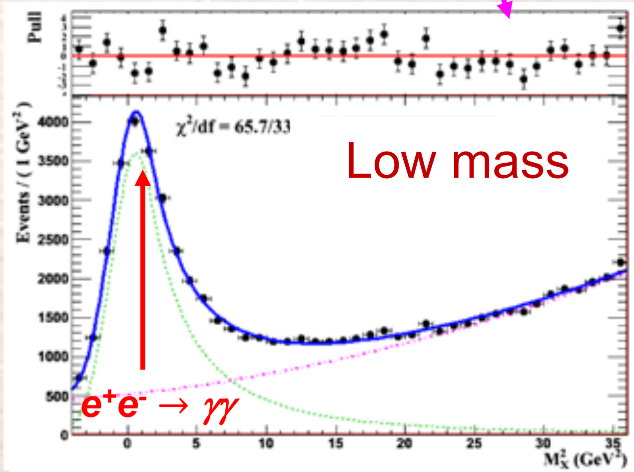
- High $m_{A'}$>5.5 GeV
- Main background: $e^+e^- \rightarrow e^+e^-\gamma$ in which e^+ and e^- escape detection
- Single isolated γ shower with E^*_γ **> 1.5 GeV** & $|\cos\ \theta_{*\gamma}| < 0.6$
- No drift chamber tracks p^***>0.1 GeV**
- Use multivariate **BDT** discriminant based on **12** discriminating variables

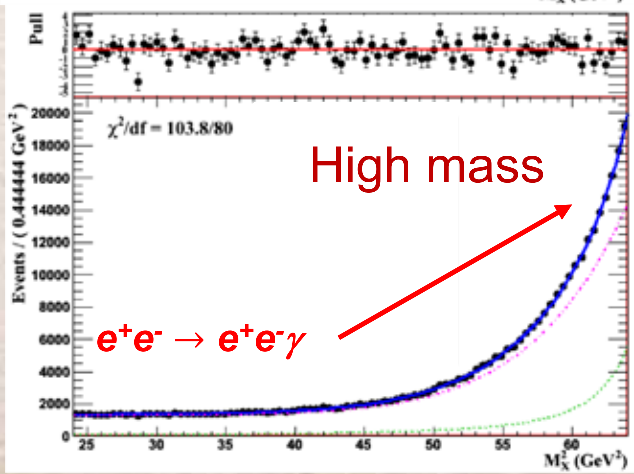


Fit Regions

- We define different selections:
  - $\mathfrak{R}_T$: for **low $m_{A'}$** use tight selection that maximizes ε_s/N_B for large N_B and $\varepsilon_s/2.3$ for $N_B \to 0$, since number of peaking $e^+e^- \to \gamma\gamma$ cannot be determined reliably
  - $\mathfrak{R}_L$: for **high $m_{A'}$** use loose selection that maximizes $\varepsilon_s/(N_B)^{0.5}$
  - $\mathfrak{R}'_L$: same as $\mathfrak{R}_L$ but for **low $m_{A'}$**, restricted to events not included in $\mathfrak{R}_T$
  - $\mathfrak{R}_B$: background selection -0.5 < BDT < 0,
- We measure the cross section $\sigma_{A'}$ as a function of $m_{A'}$ by performing a series of extended maximum likelihood fits to the distributions of M^2_X
- We vary $m_{A'}$ from zero to 8.0 GeV in 166 steps (half the mass resolution) and perform sets of simultaneous fits to to $\Upsilon(2S)$, $\Upsilon(3S)$, $\mathfrak{R}_L$ and $\mathfrak{R}_B$ for high M_X region and to $\Upsilon(2S)$,$\Upsilon(3S)$, $\Upsilon(4S)$, $\mathfrak{R}'_L$, $\mathfrak{R}_T$ and $\mathfrak{R}_B$ for low M_X

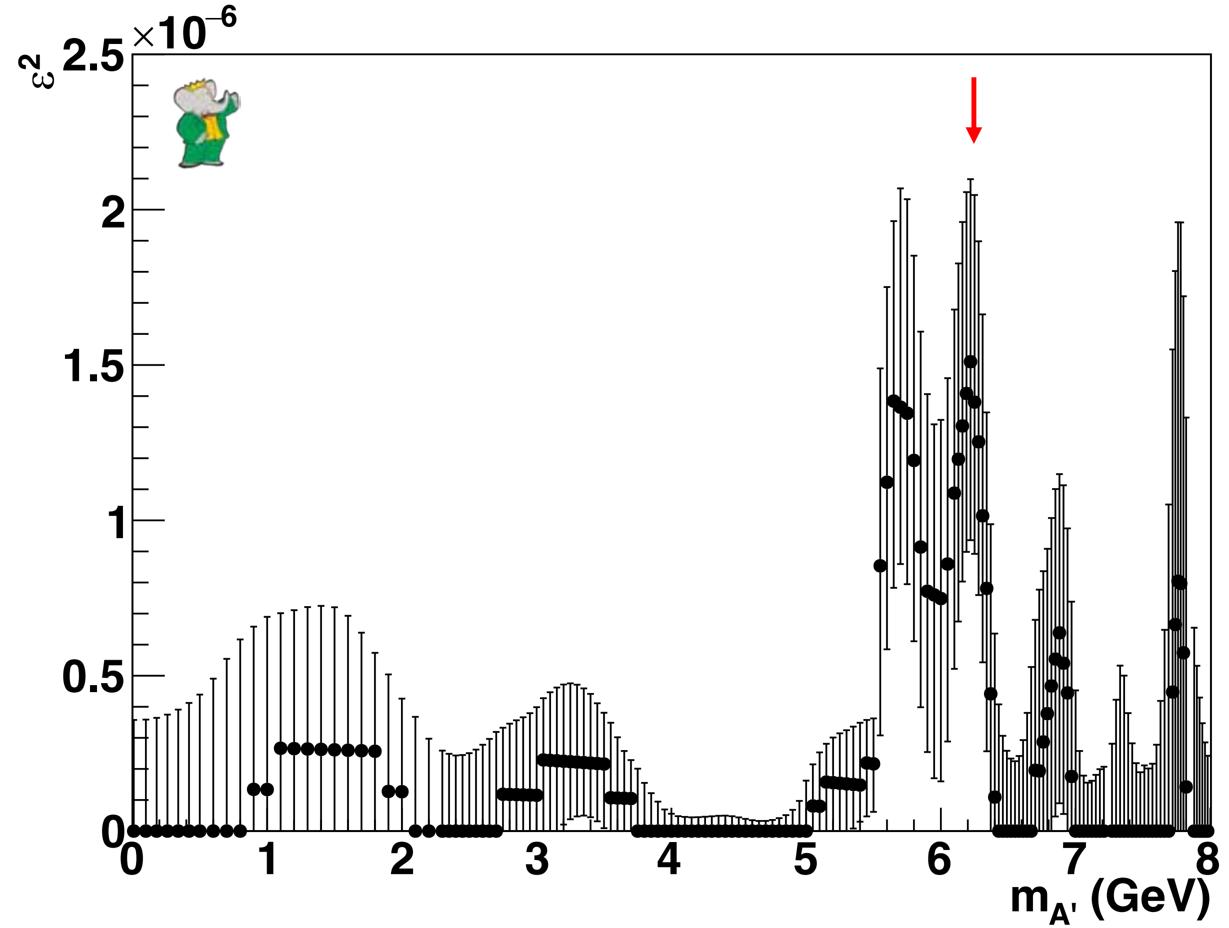
Dataset	"lowM"				"highM"		
Dataset	$\mathcal{L}$	Selection			$\mathcal{L}$	Selection	
		$\mathcal{R}_B$	$\mathcal{R}'_L$	$\mathcal{R}_T$		$\mathcal{R}_B$	$\mathcal{R}_L$
$\Upsilon(2S)$	$15.9\,\text{fb}^{-1}$	22,590	42	6	$15.9\,\text{fb}^{-1}$	405,441	324
$\Upsilon(3S)$	$31.2\,\text{fb}^{-1}$	68,476	129	26	$22.3\,\text{fb}^{-1}$	719,623	696
$\Upsilon(4S)$	$5.9\,\text{fb}^{-1}$	7,893	16	9			





Analysis Properties

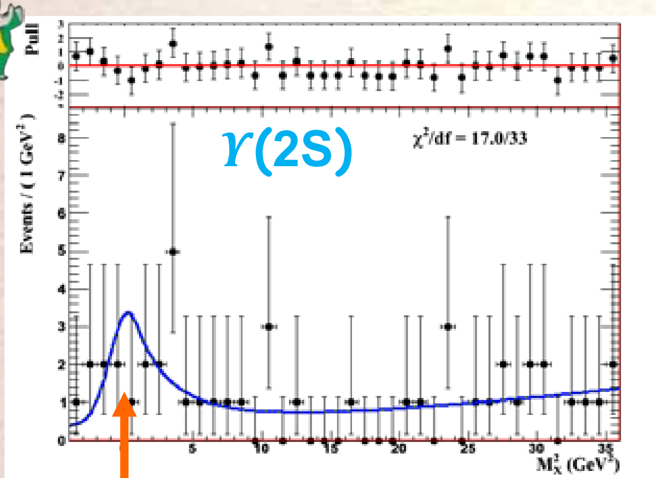
- Mass resolution varies from $\sigma(M^2_X)$: 1.5 GeV^2 to 0.7 GeV^2 for $m_{A'} \approx 0 - 8$ GeV^2
- Signal selection efficiency varies as a function of $m_{A'}$:
  - $\Re_T$ selection: 2.4-3.1%
  - $\Re'_L$ selection: 3.4-3.8%
  - $\Re_L$ selection: 2.0-0.2%
- Measured maximum likelihood values of the ***A'*** mixing strength squared, ε^2, as function of $m_{A'}$
- Largest systematic errors result from the shape of signal and background PDFs
- Total systematic error on signal cross section is 5%
- Most significant deviation from zero occurs at $m_{A'}$=6.21 GeV with significance of 3.1σ ➔ global significance of 2.6σ

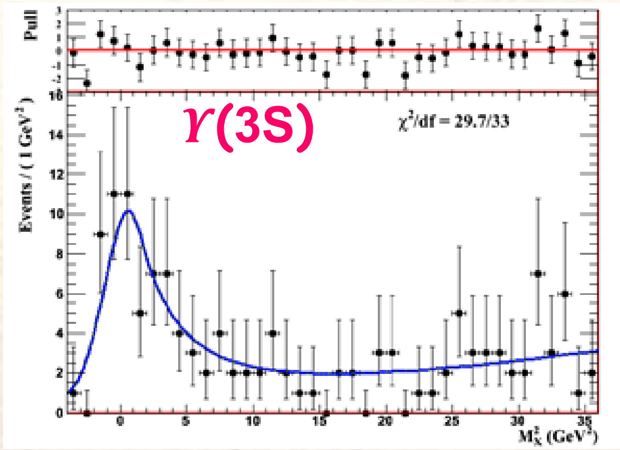


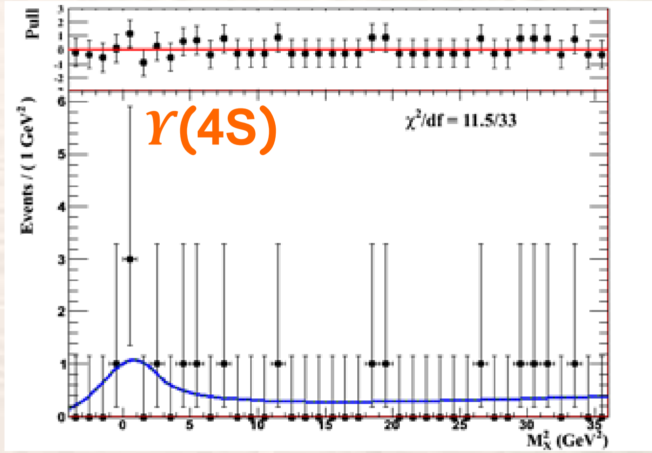
Observed Event Yields

- Fits to full unblinded data sets

Low-mass region

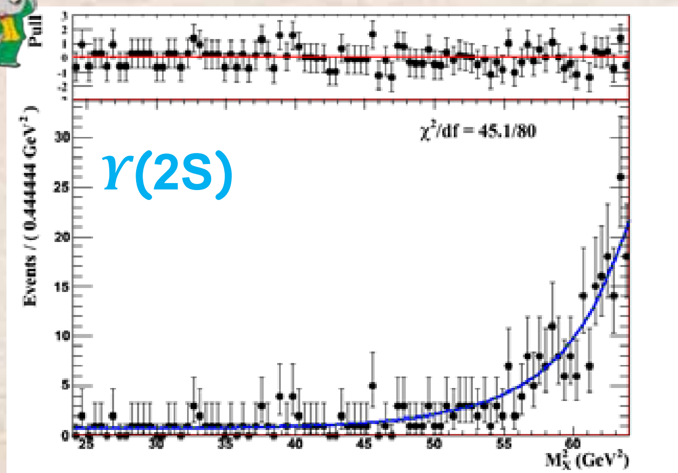


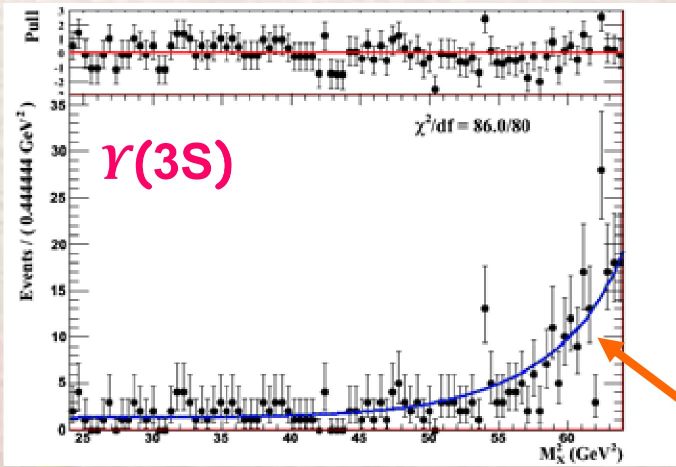




High-mass region

$e^+e^- \to \gamma\gamma$





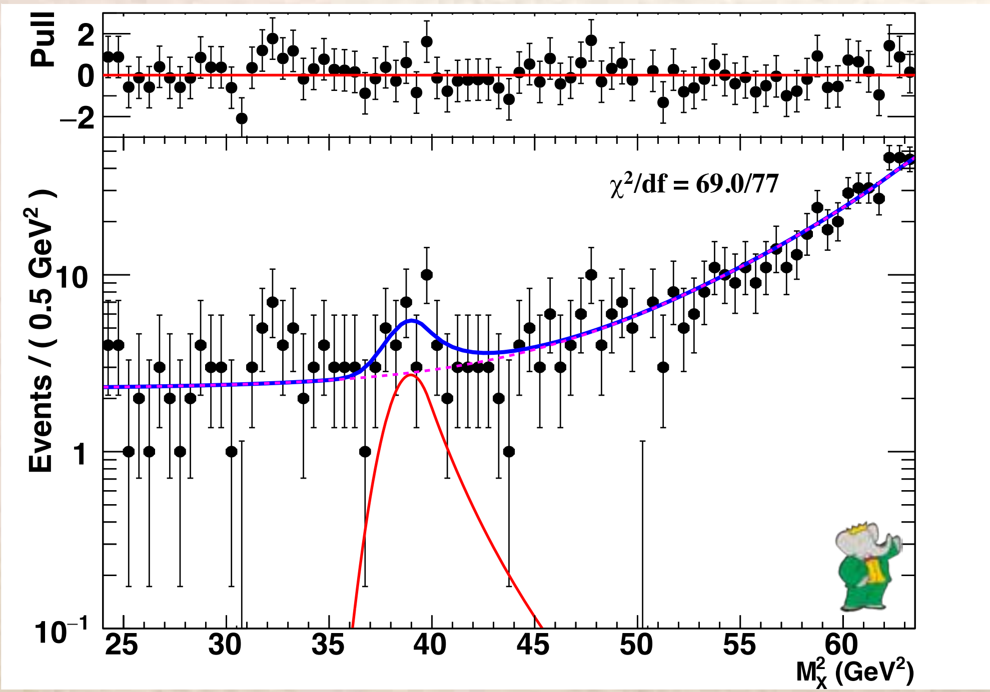
$e^+e^- \to e^+e^-\gamma$

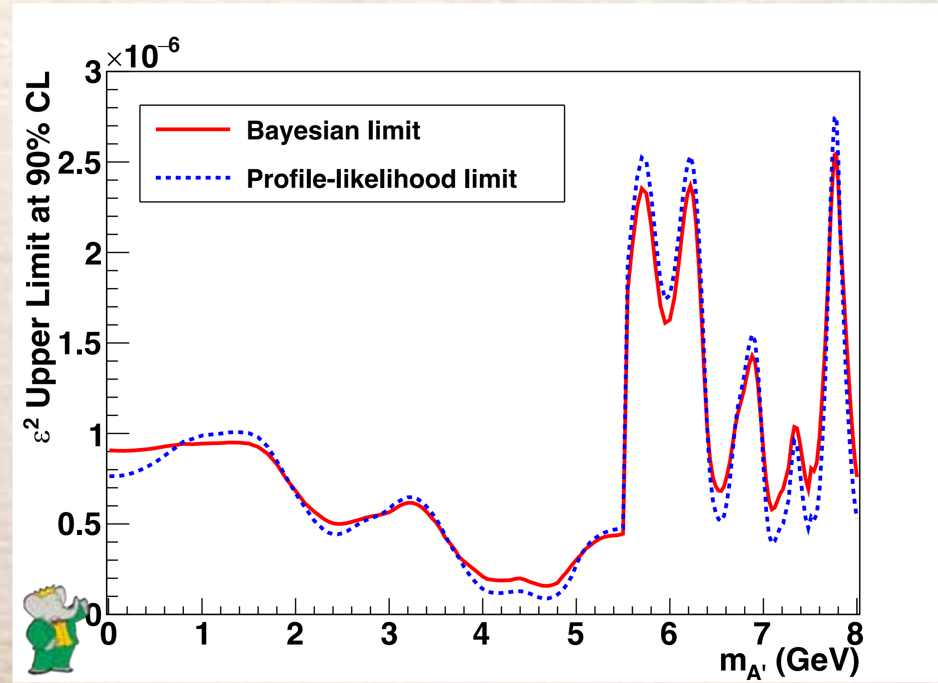
Results

- In the low-mass region, no mass points exceed a 2σ significance
- In the high-mass region, there are 2 points above 2σ
  - 2.8σ local significance for $m_{A'}$=5.70 GeV
  - 3.1σ local significance for $m_{A'}$=6.21 GeV ➔global significance: 2.6σ

$$S = \sqrt{2\mathrm{Log}\frac{\mathcal{L}_{max}}{\mathcal{L}_0}}$$

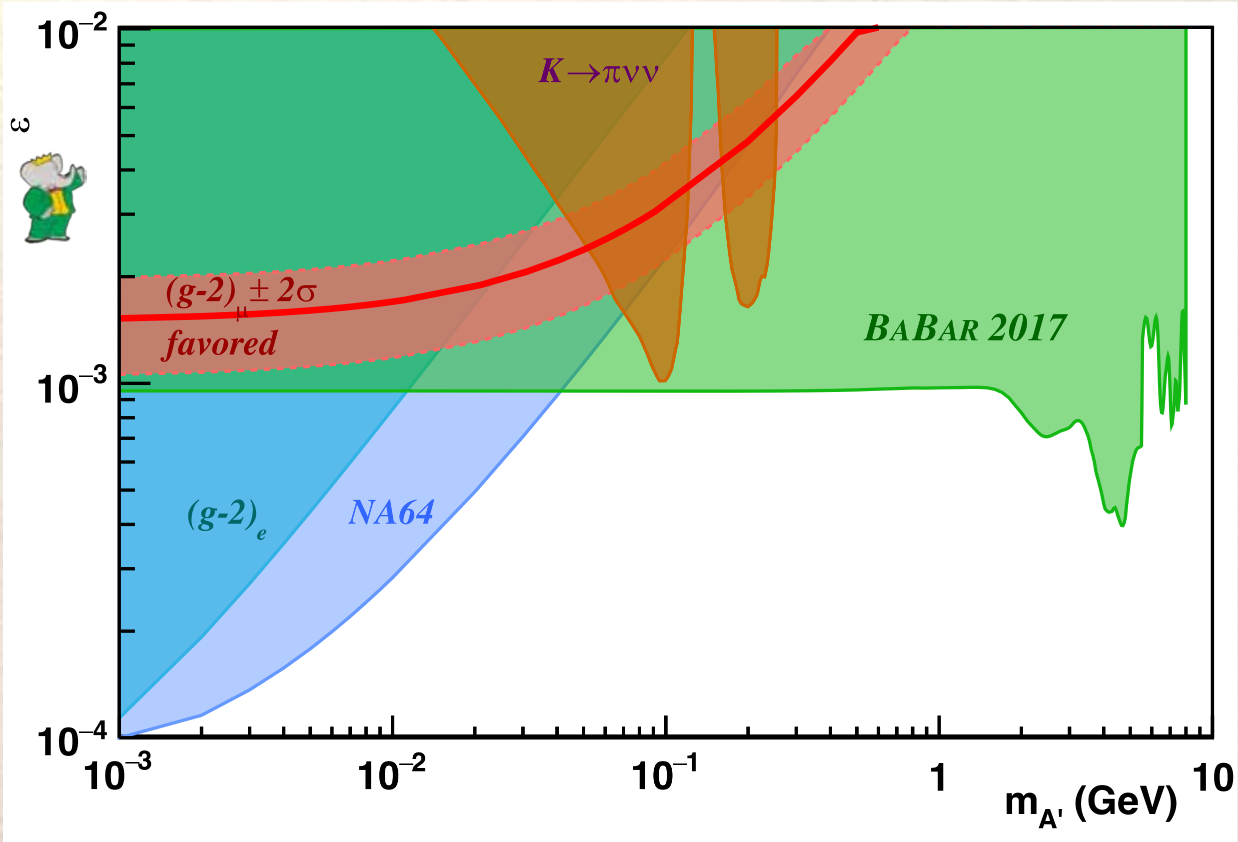
- Set 90%CL upper limit on mixing strength squared ε^2 in the $0<m_{A'}<8$ GeV mass range using both a Bayesian method with a uniform prior for ε^2>0 and a frequentist profile likelihood





Results on the Mixing Strength ε

- At each value of $m_{A'}$, we compute a Bayesian limit on ε as a square root of the Bayesian limits on ε^2
- Our results are shown in comparison to results from other experiments in which ***A'*** decays invisibly and to the region of parameter space consistent with the $(g\text{-}2)_\mu$ anomaly
- Our results rule out that the $(g\text{-}2)_\mu$ anomaly is due to dark photon models with invisible decays
- Our results place stringent constraints on dark-sector models over a broad range of parameter space
- Our results yield a significant improvement over previous results



Conclusions and Outlook

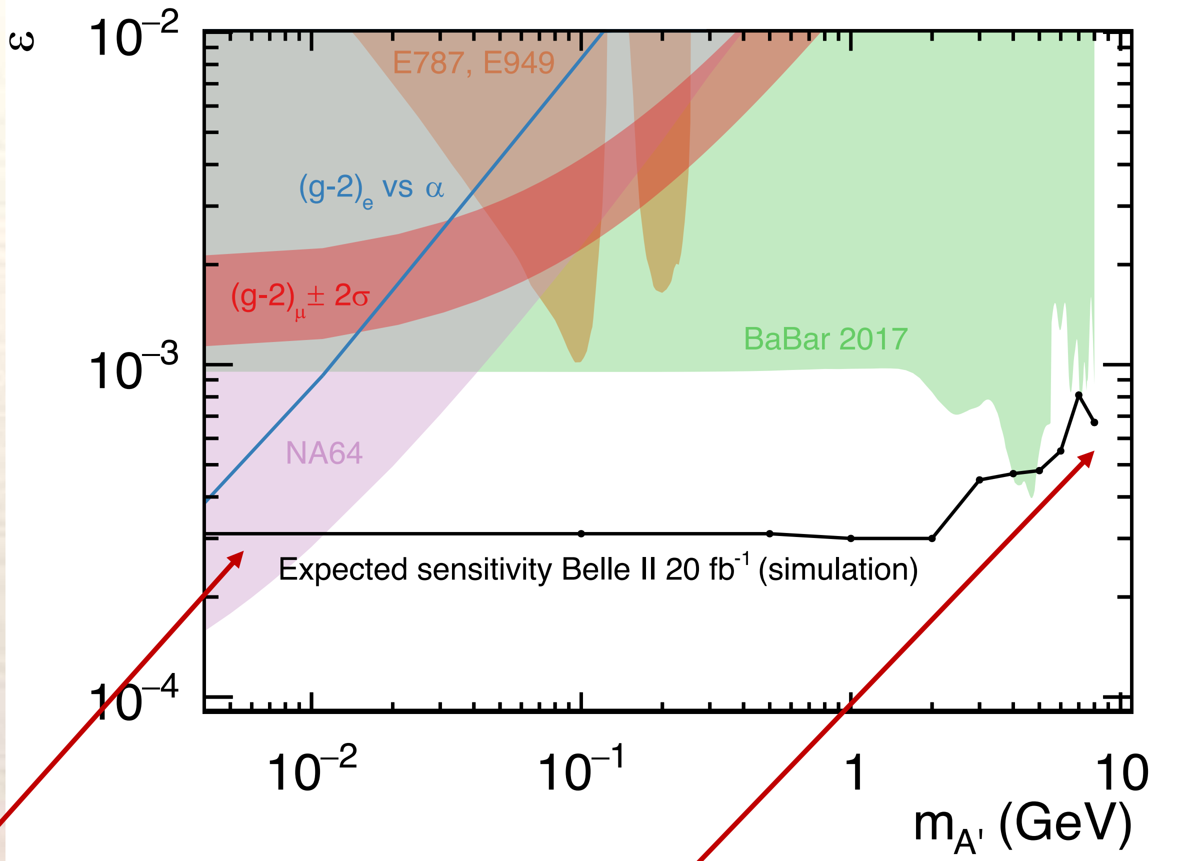
- We have searched for invisible decays of dark photons and see no signal
  - The largest fluctuation has a significance of 3.1σ locally and 2.6σ globally

- We set 90% confidence level upper limits on the mixing strength ε^2

- We exclude that the **$(g\text{-}2)_\mu$** anomaly originates from dark-photon models with invisible decays

- Belle II will improve on the the BABAR results

- For 20 fb^{-1} the Belle II the 90% CL upper limit will be improved by nearly an order of magnitude



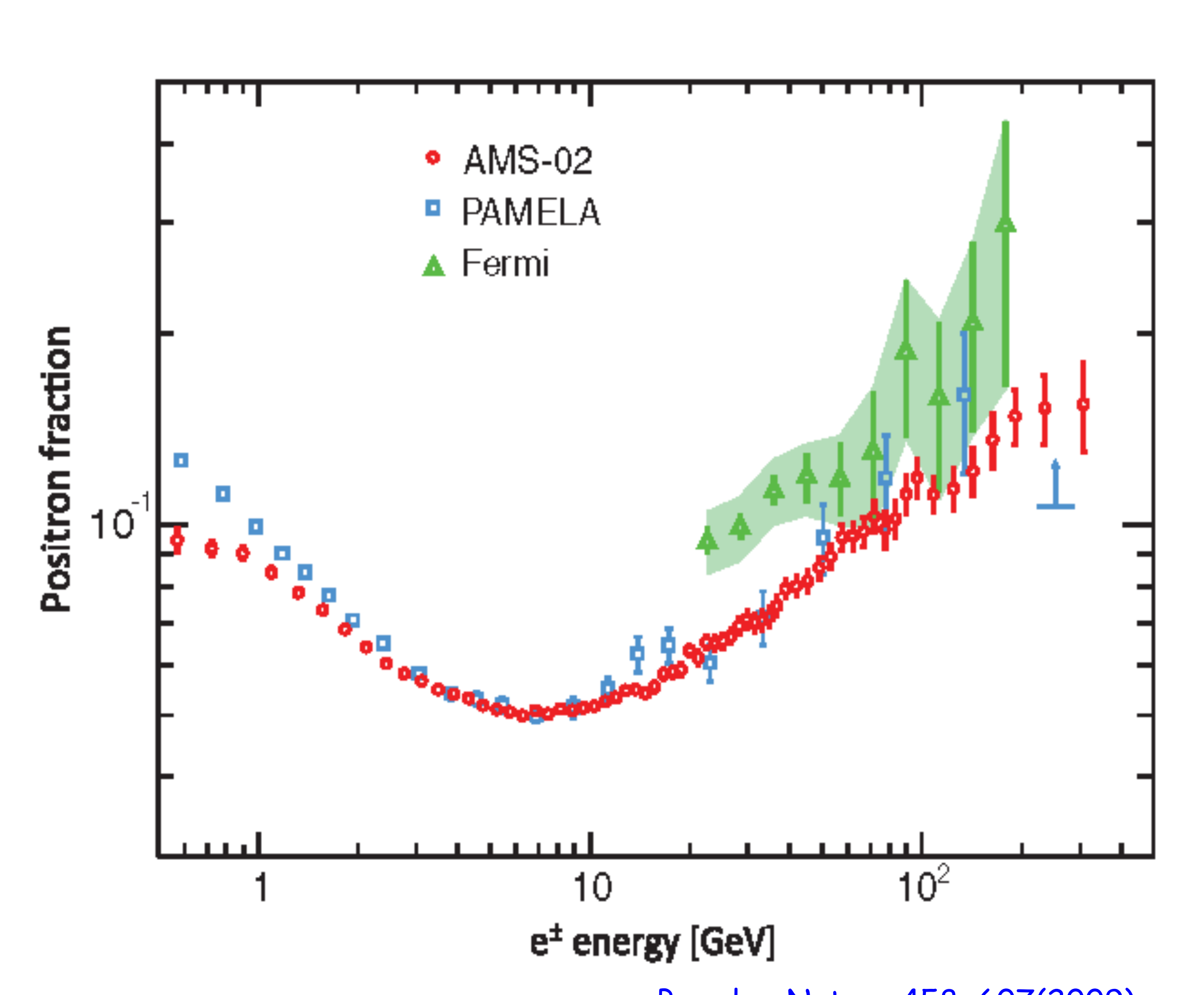
better calorimeter hermeticity to suppress $e^+e^- \to \gamma\gamma$

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

Backup Slides

Astrophysics Results

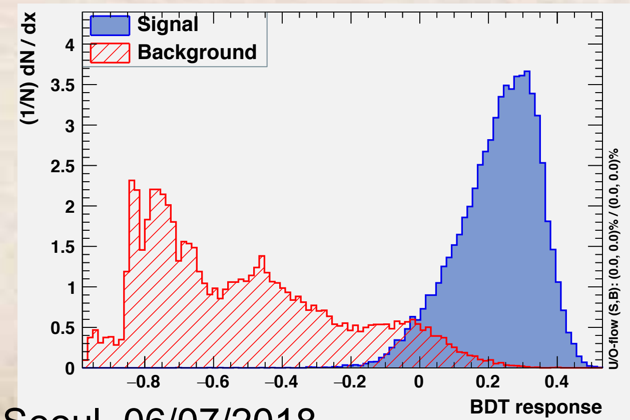
- In 2010, the Pamela experiment reported a positron excess that is increasing with energy above 10 GeV
- This was confirmed in 2012 by the Fermi LAT
- In 2014, AMS showed more higher precision data up to 300 GeV confirming an increase in e^+ fraction in the 10 -250 GeV energy range
- AMS has not observed an excess of anti-protons in the same energy range
- Though an astrophysical explanation is possible, theorists have come up with new dark matter scenarios favoring light particles



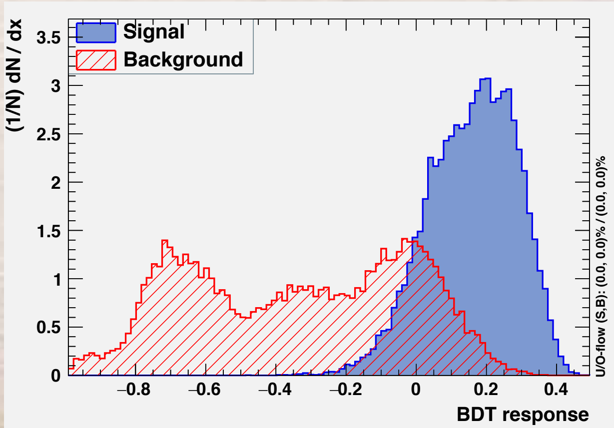
Pamela., Nature 458, 607(2009)
Fermi, PRL 108, 011103 (2012)
AMS, PRL 110, 141102 (2013)

Signal Selection

- Low missing mass
  $-4 < M^2_x < 36\ \mathrm{GeV}^2$
- Main background: $e^+e^- \to \gamma\gamma$ as one photon may escape detection in CsI crystals due to their orientation to IR
- Single isolated γ shower with
  $E^*_\gamma > 3$ **GeV** & $|\cos\theta^*_\gamma| < 0.6$
- No drift chamber tracks **$p^*>1$ GeV**
- Use multivariate **BDT** discriminant based on **12** discriminating variables (e.g.: EM shower shape, extra EMC energy, $\Delta\phi_{12}$, distance of $\vec{p}_{miss}$ to EMC face, E in IFR, $\Delta\phi_{NH}$, ϕ_{miss}, $\cos\theta^*_\gamma$)



- High missing mass
  $24<M^2_x<69$ (63.5) GeV^2 for $\Upsilon(3S)$,($\Upsilon(2S)$)
- Main background: $e^+e^- \to e^+e^-\gamma$ in which e^+ and e^- escape detection
- Single isolated γ shower with
  $E^*_\gamma > 1.5$ **GeV** & $|\cos\theta_{*\gamma}| < 0.6$
- No drift chamber tracks **$p^*>0.1$ GeV**
- Use multivariate **BDT** discriminant based on **12** discriminating variables (e.g.: EM shower shape, extra EMC energy, $\Delta\phi_{12}$, distance of $\vec{p}_{miss}$ to EMC face, E in IFR, $\Delta\phi_{NH}$, ϕ_{miss}, $\cos\theta^*_\gamma$)



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  - $\mathfrak{R}_L$: loose selection at higher M_X that maximizes $\varepsilon_S/\sqrt{N_B}$ for $5.5 < m_{A'} < 8.0$ GeV
  - $\mathfrak{R}'_L$: same as $\mathfrak{R}_L$ but for $m_{A'} < 5.5$ GeV, restricted to events not included in $\mathfrak{R}_T$
  - $\mathfrak{R}_B$: background selection $-0.5 < \mathrm{BDT} < 0$,
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- For fits to $\mathfrak{R}_B$ set S=0
- For fits to $\mathfrak{R}_T$ and $\mathfrak{R}'_L$ fix background PDF, vary N_B, # peaking bkg, ε^2
- Signal PDF: Crystal Ball function

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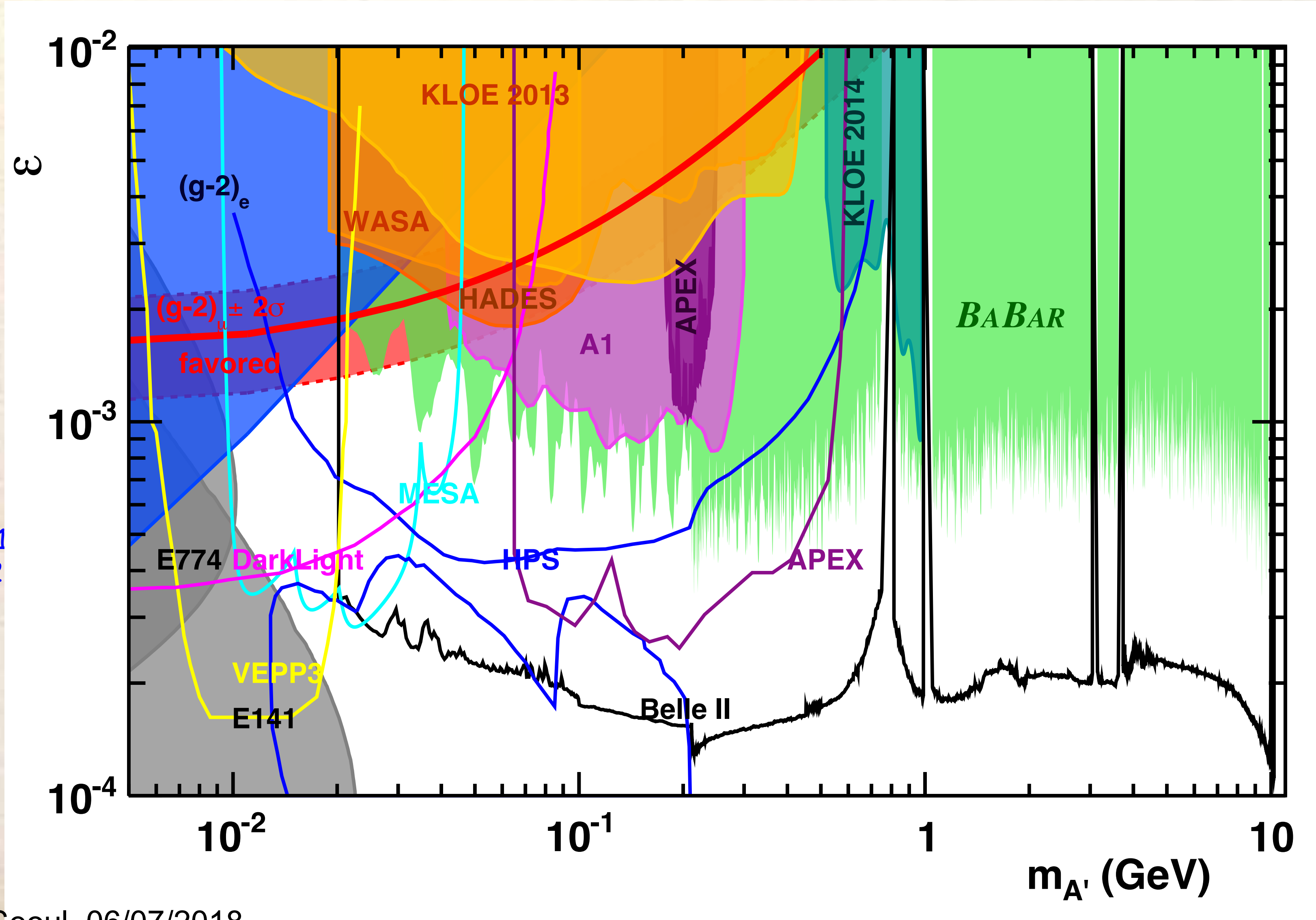
- Background PDF: Crystal Ball +2nd-order polynomial for $m_{A'} < 5.5$ GeV for $e^+e^- \to \gamma\gamma$ sum of exponentiated polynomials for $m_{A'} > 5.5$ GeV for $e^+e^- \to e^+e^-\gamma$

Reach of Future Experiments

- In the next few years, several dedicated experiments and Belle II will push the limit on ε further down nearly to $\sim 10^{-4}$
- New dedicated experiments: APEX Dark Light HPS MESA VEPP3



APEX, PRL 107, 191804 (201
HPS, J. Phys. Conf. Ser. 382
012008 (2012)
MESA, AIP Conf. Proc. 1563
140 (2013)