SEARCHES FOR HIDDEN SECTORS WITH *BABAR*

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on behalf of the *BABAR* Collaboration

HARVEY MUDD COLLEGE

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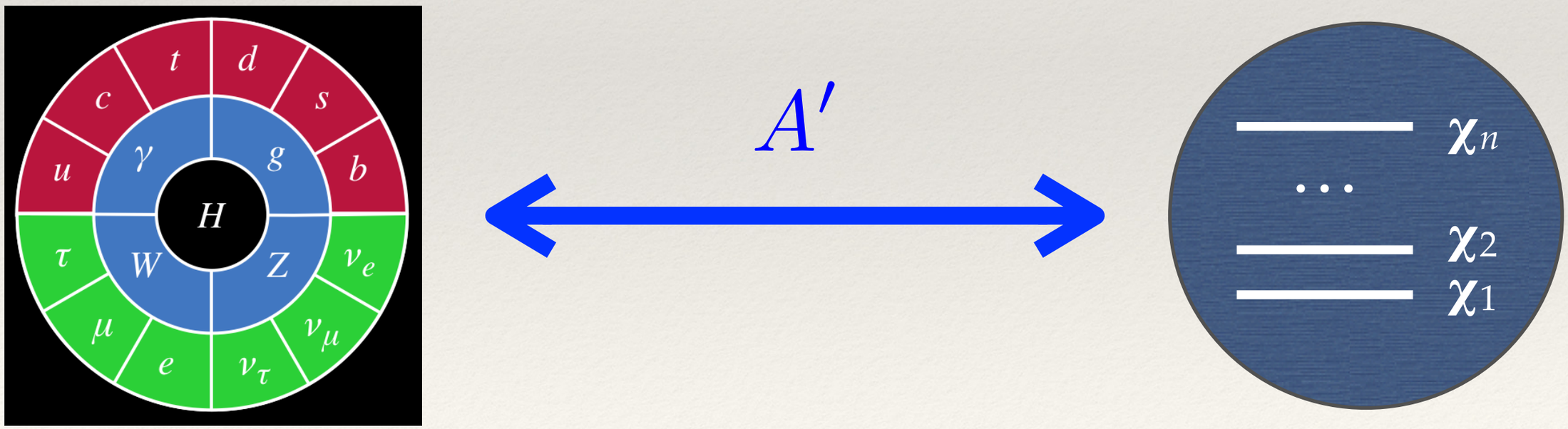
HIDDEN SECTORS

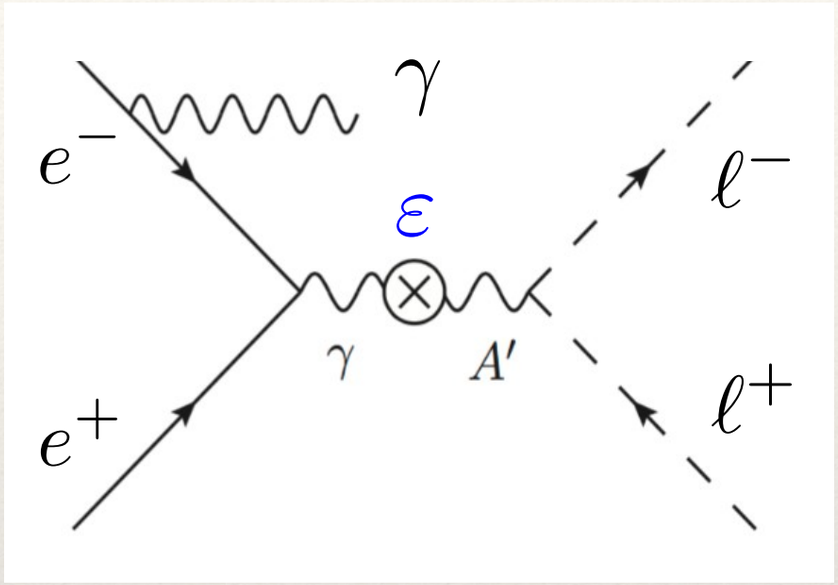
- Hidden-sector dark matter (DM): Dark matter interacts through a **new force**
    - Viable over DM mass range of keV - 100 TeV
    - Can give signatures very different from WIMPs for sub-GeV DM

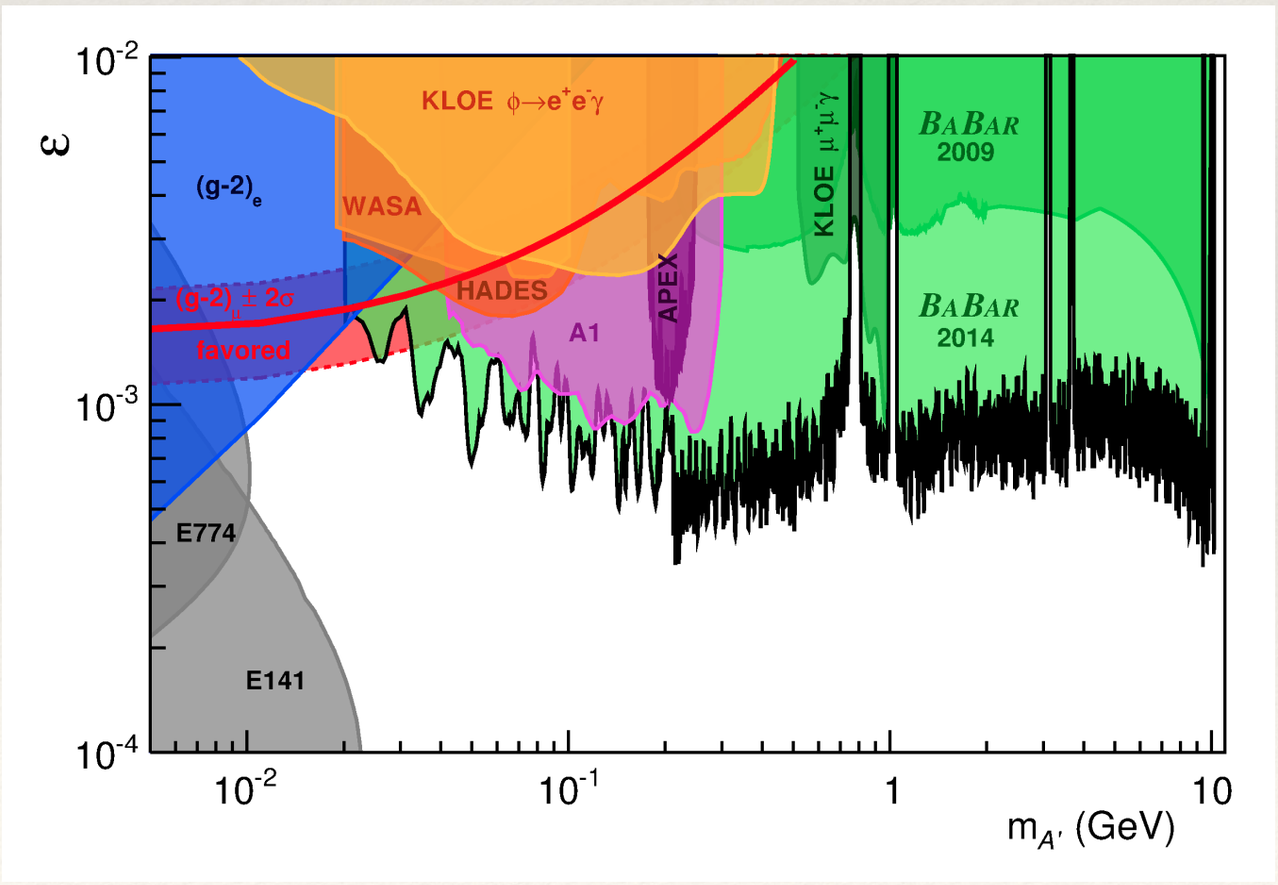


see *e.g.*, arXiv:1608.08632; arXiv:1707.04591

EARLIER SEARCHES

- In the minimal dark photon scenario, the dark photon decays into SM leptons
- *BABAR* search for $e^+e^- \to \gamma A', A' \to \ell^+\ell^-$ $(\ell = e,\ \mu)$ using 516/fb of data

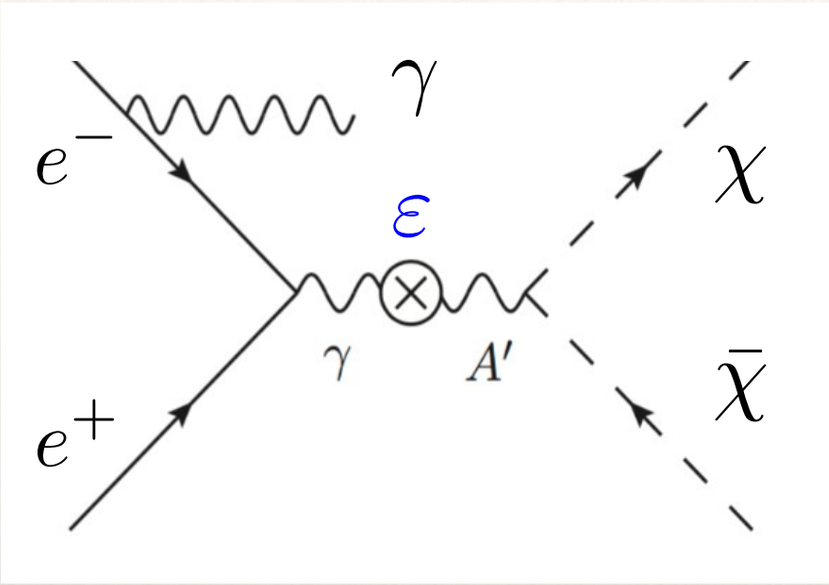




- 90% C.L. upper limit on kinetic mixing ε for dark photon masses 0.02-10.2 GeV

PRL 113 (2014) no. 20, 201801
arXiv:1406.2980

NEW SEARCHES

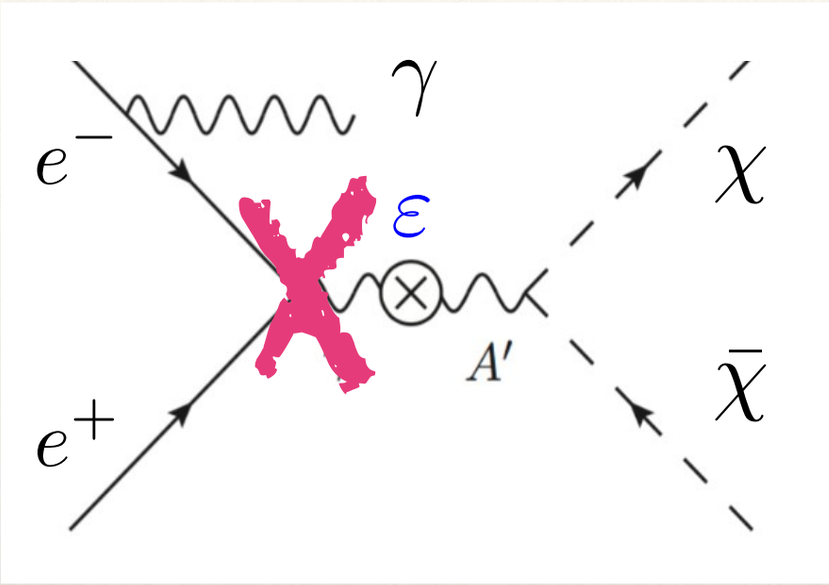


PRL 119 (2017) no. 13, 131804
arXiv:1702.0327

- If the dark photon decays into DM, we instead get a **monophoton + invisible** signature

$$(\alpha_{\mathrm{D}} > \varepsilon^2 \alpha)$$

NEW SEARCHES



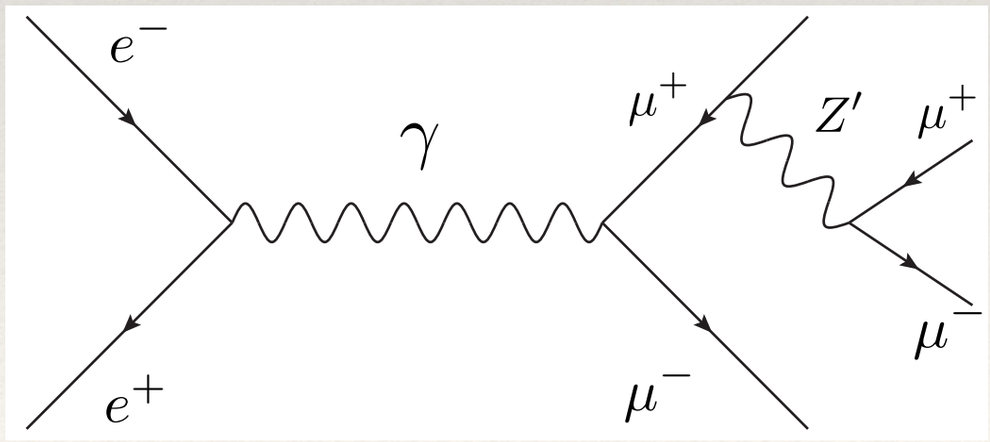
PRL 119 (2017) no. 13, 131804
arXiv:1702.0327

- If the dark photon decays into DM, we instead get a **monophoton + invisible** signature

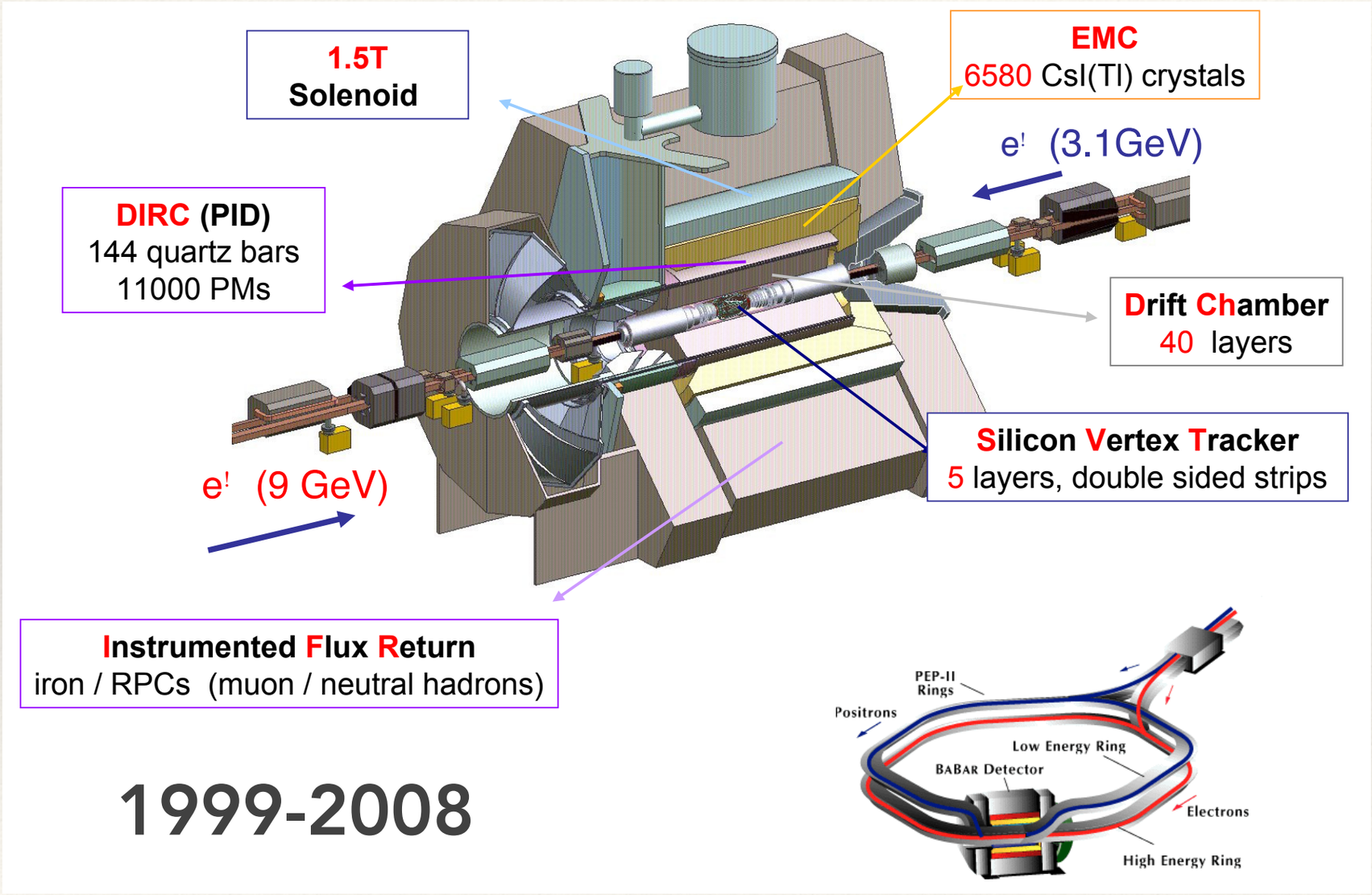
$$(\alpha_D > \varepsilon^2 \alpha)$$

- The dark force could couple predominantly to **heavy flavor leptons**

PRD 94 (2016) no. 1, 011102
arXiv:1606.03501



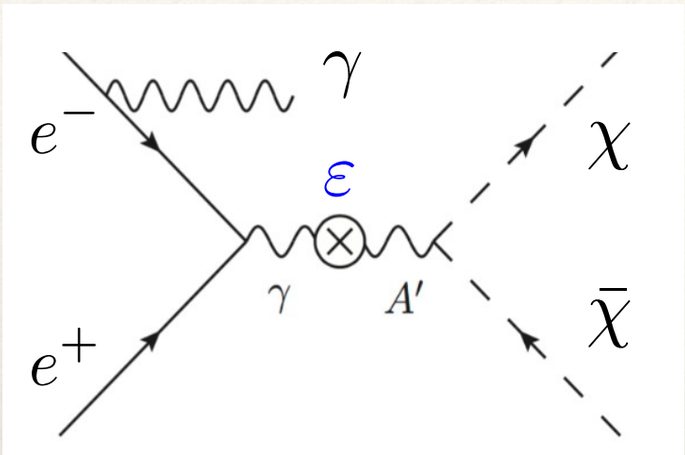
BABAR EXPERIMENT



- 432/fb $\Upsilon(4S)$ "on peak"
- 53/fb non-resonant "off peak"
- smaller samples at $\Upsilon(2S)/\Upsilon(3S)$

PRL 119 (2017) no. 13, 131804, arXiv:1702.0327

INVISIBLE DARK PHOTON



- Single photon trigger
- Only implemented in final running period!
- Largest samples are at $\Upsilon(2S)/\Upsilon(3S)$ energies

- L1 hardware trigger: 1 or more clusters with $E_{\rm lab} > 0.8$ GeV
- Two L3 software triggers, both veto tracks from interaction region:

(1) Low A' mass:

$$E^*_\gamma > 2 \text{ GeV}$$

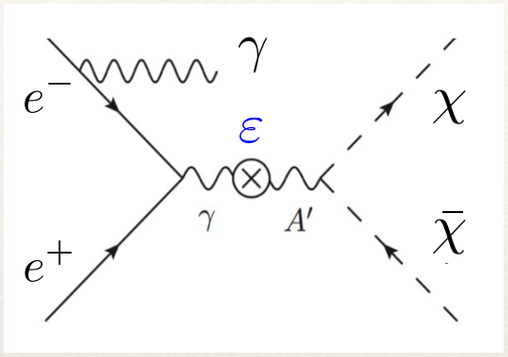
$$\mathcal{L}_{\rm int} = 53/\text{fb}$$

(2) High A' mass:

$$E^*_\gamma > 1 \text{ GeV}$$

$$\mathcal{L}_{\rm int} = 35.9/\text{fb}$$

OFFLINE SELECTION



- Signal: **missing mass** $M_X = M_{A'}$
- Backgrounds different at low/high missing mass

(1) Low A' mass:

$$4\ \mathrm{GeV}^2 < M_X^2 < 36\ \mathrm{GeV}^2$$

- $e^+e^- \to \gamma\gamma$ in which a photon escapes detection
- Require $E_\gamma^* > 3\ \mathrm{GeV}, |\cos\theta_\gamma^*| < 0.6$
- No drift chamber tracks with $p^* > 1\ \mathrm{GeV}$

(2) High A' mass:

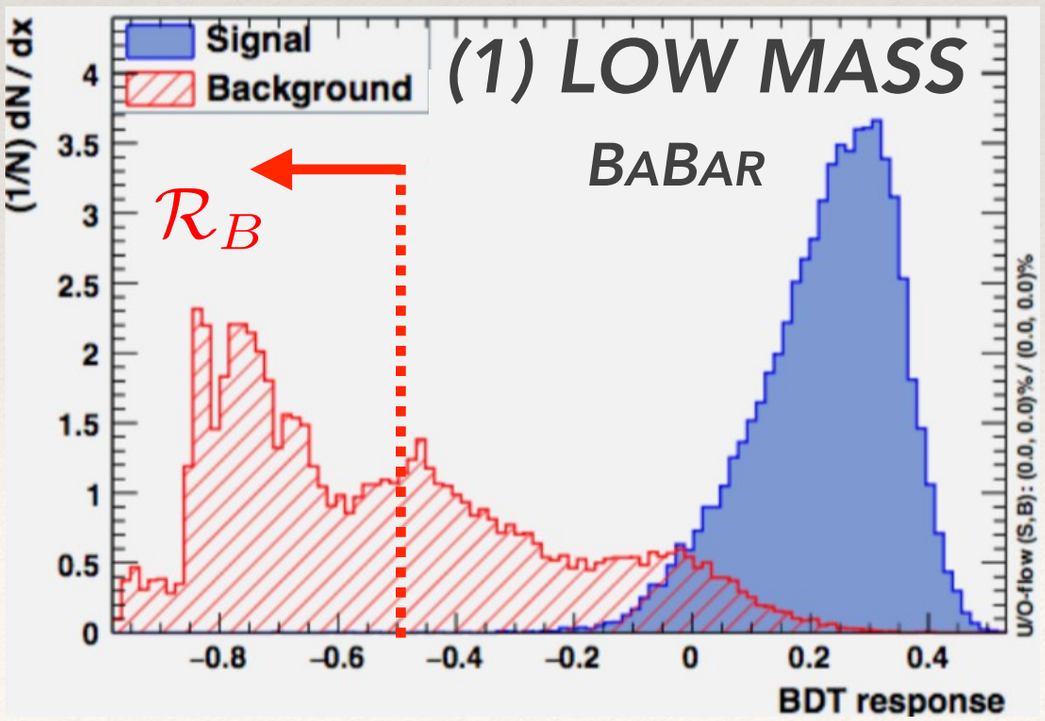
$$24\ \mathrm{GeV}^2 < M_X^2 < \begin{cases} 69.0\ \mathrm{GeV}^2 \\ 63.5\ \mathrm{GeV}^2 \end{cases}$$

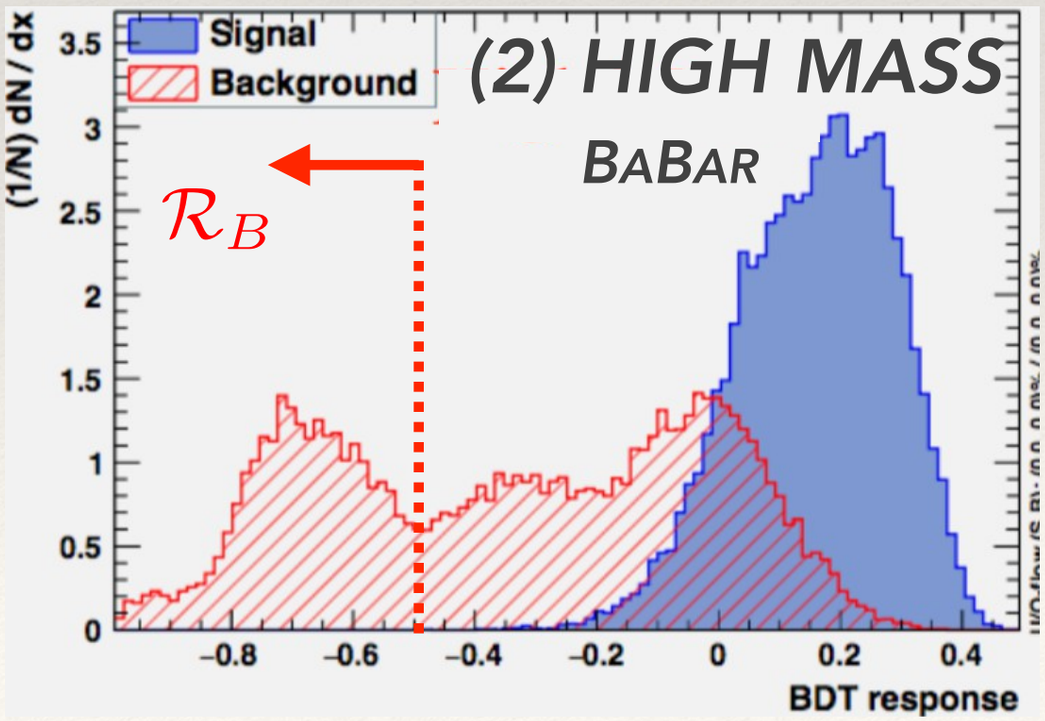
- $e^+e^- \to e^+e^-\gamma$ in which the e^+e^- escape detection
- Require $E_\gamma^* > 1.5\ \mathrm{GeV}, |\cos\theta_\gamma^*| < 0.6$
- No drift chamber tracks with $p^* > 0.1\ \mathrm{GeV}$

PRL 119 (2017) no. 13, 131804, arXiv:1702.0327

MULTIVARIATE ANALYSIS

- Train a Boosted Decision Tree (BDT) classifier on 12 observables
  - Cluster shape parameters for signal candidate EMC cluster
  - Energy & direction of other EMC clusters
  - Properties of IFR cluster(s) anti-aligned with signal cluster
- **Signal sample:** simulated sample with uniform A' mass distribution
- **Background sample:** Sample (~3/fb) of data from $\Upsilon(3S)$





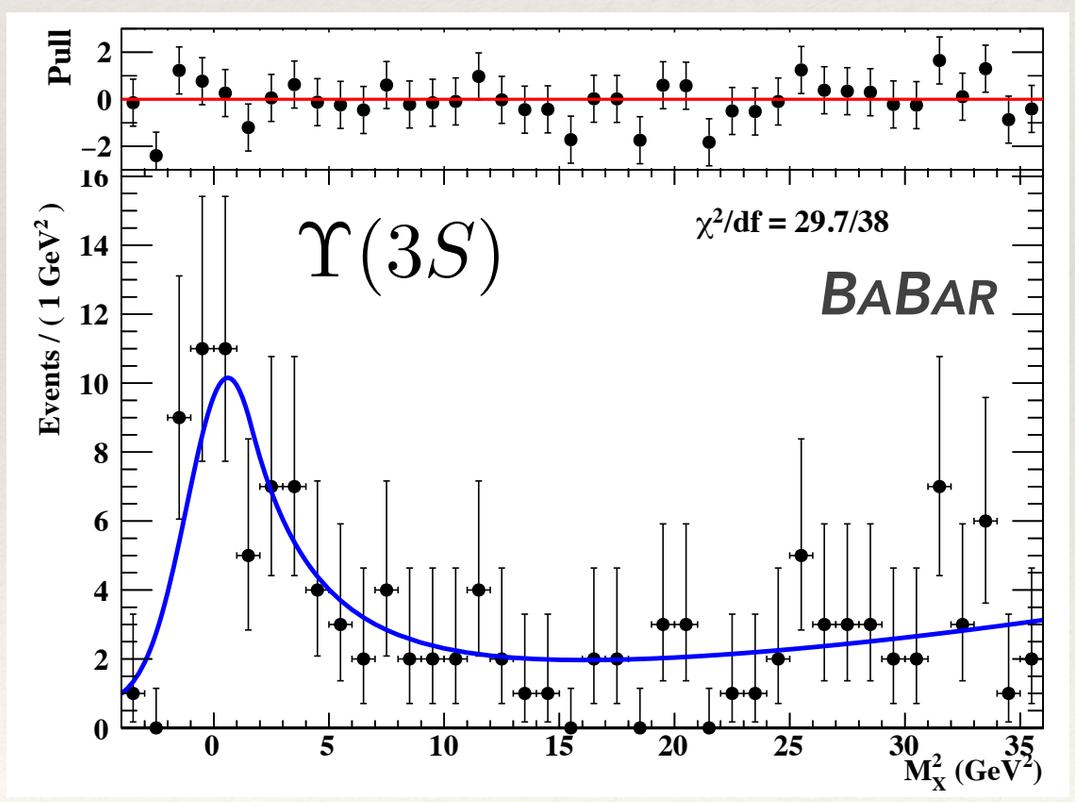
SELECTION & FITTING

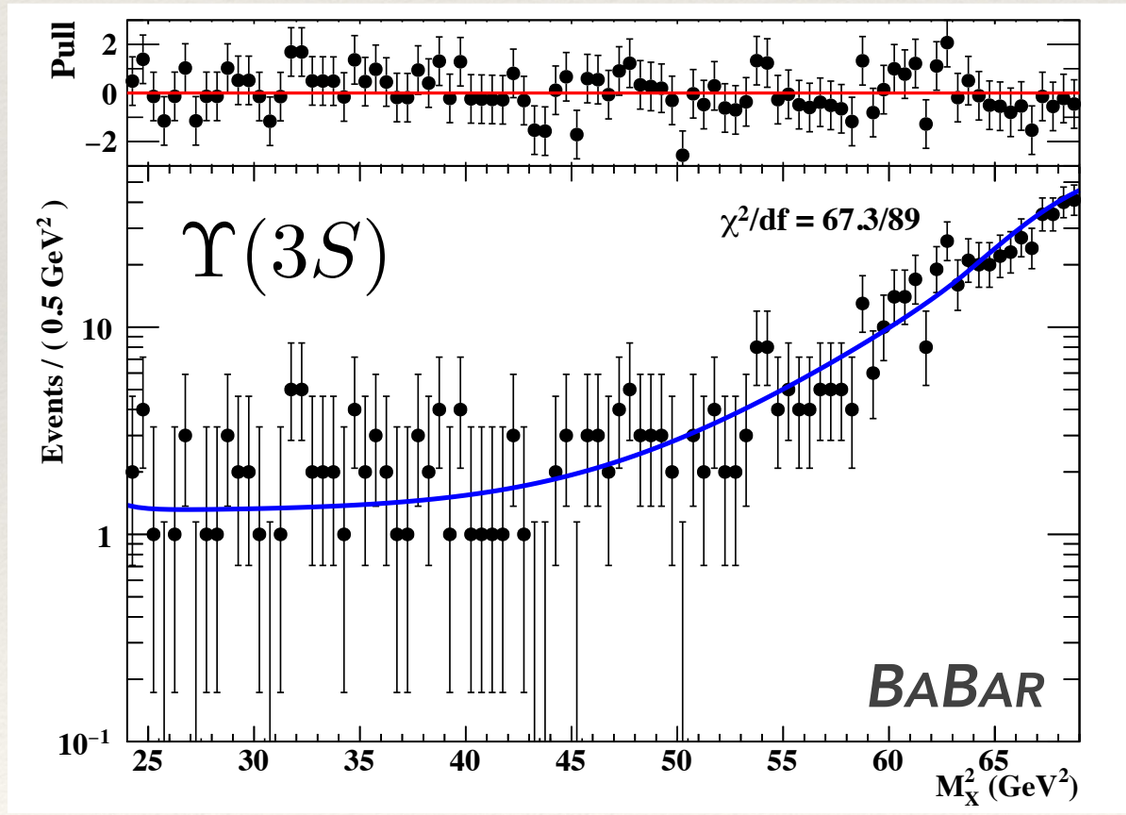
- We define two selection regions for BDT classifier
  - "Tight" ($\mathcal{R}_T$): optimizes ε_S/N_B (only for low-mass region where it is hard to reliably estimate bkd)
  - "Loose" ($\mathcal{R}_L$): optimizes $\varepsilon_S/\sqrt{N_B}$

- Shape of signal and background fixed prior to fitting
  - **Background:** shape determined by fits in $\mathcal{R}_B$
    - 2nd-order polynomial (low-mass continuum), sum of exponentiated polynomials (high-mass continuum), Crystal Ball function for low-mass peaking background
  - **Signal:** Crystal Ball with shape determined by fits to MC, validated with $e^+e^- \to \gamma\gamma$

SIGNAL EXTRACTION

- Perform unbinned max. likelihood fits to missing-mass distribution over $M_X = 0 - 8.0\ \mathrm{GeV}$ (simultaneously over all datasets)
    - Step size between signal hypotheses is half of resolution
- Sample background-only fits:



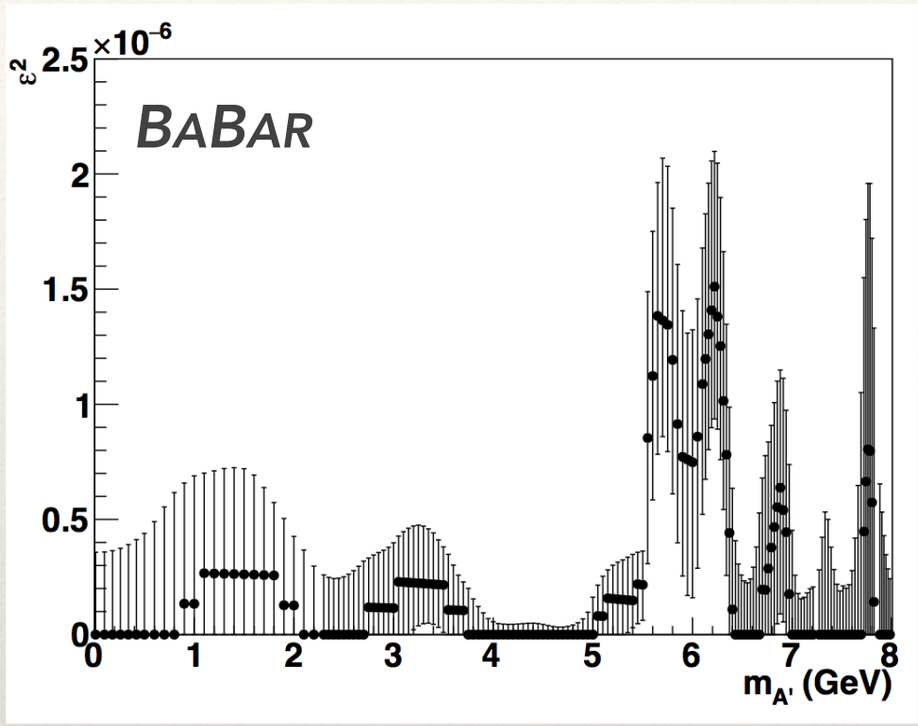


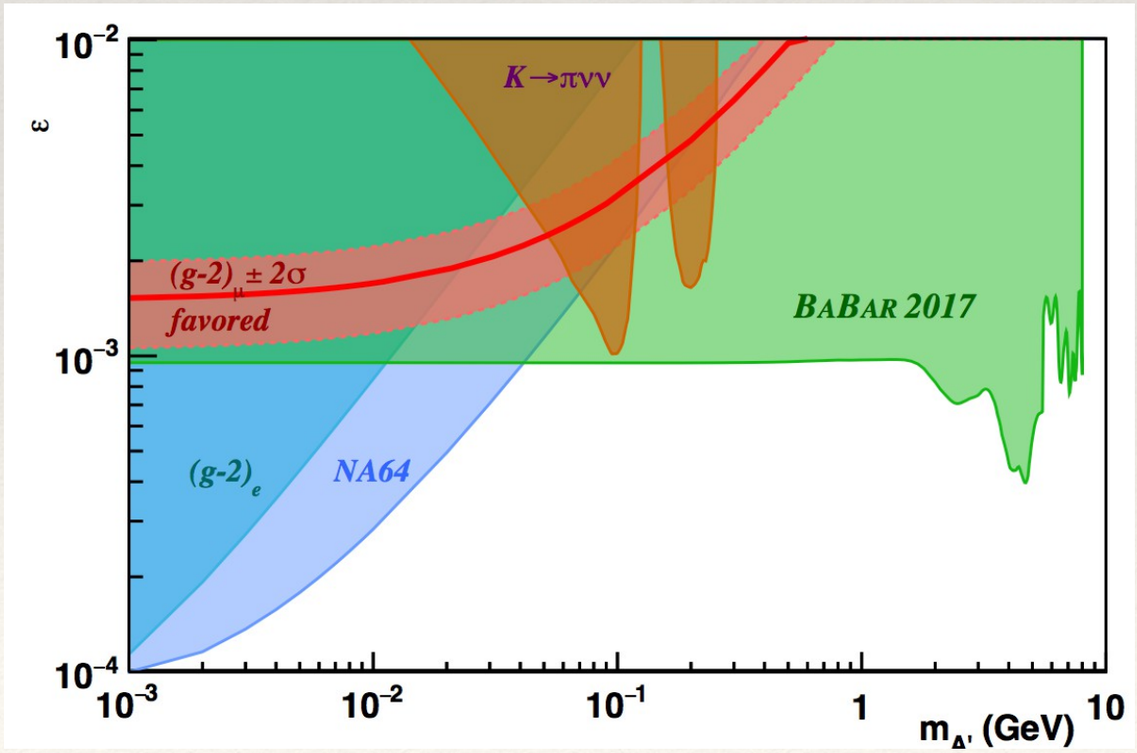
(loose selection)

PRL 119 (2017) no. 13, 131804, arXiv:1702.0327

DARK PHOTON: RESULTS

- No significant deviation from background-only hypothesis
  - Set 90% confidence level upper limit on ε^2





- Exclude the entire region favored by *g*-2 anomaly!

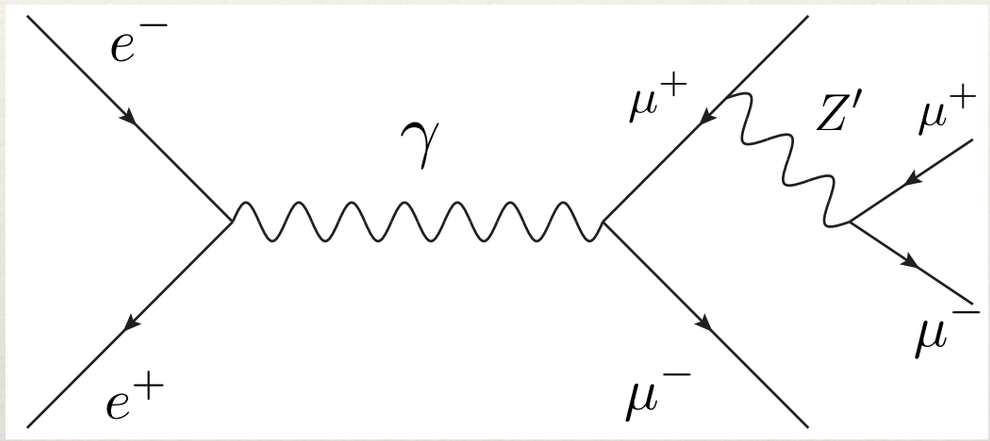
NA64: PRL 118 (2017) 011802
arXiv:1610.02988

DARK MUONIC FORCE

- The dark force could couple predominantly to **heavy flavor leptons**

  He *et* al., PRD 43 (1991), 22; and others

  - Example model: $L_\mu - L_\tau$ gauge model
    - Motivated by muon *g-2*, sterile neutrino DM, proton charge radius, etc.

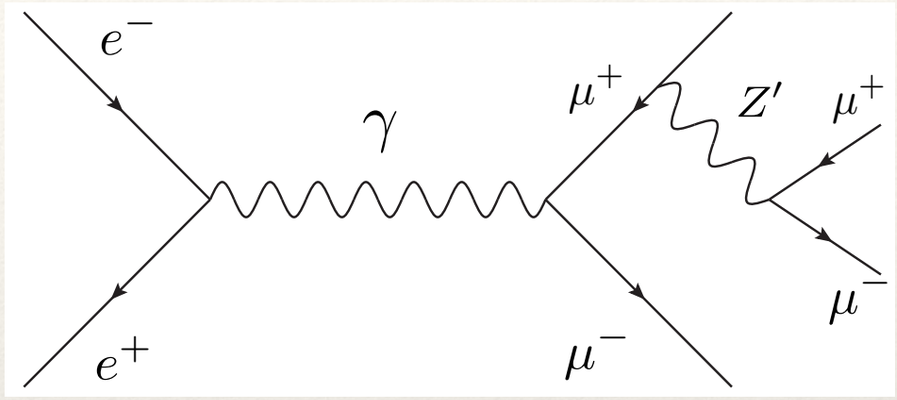


- Analysis looks for Z' final-state radiation, uses 514/fb of data (including at $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$ and non-resonant)
  - Small sample (5%) used for optimization/validation and then discarded

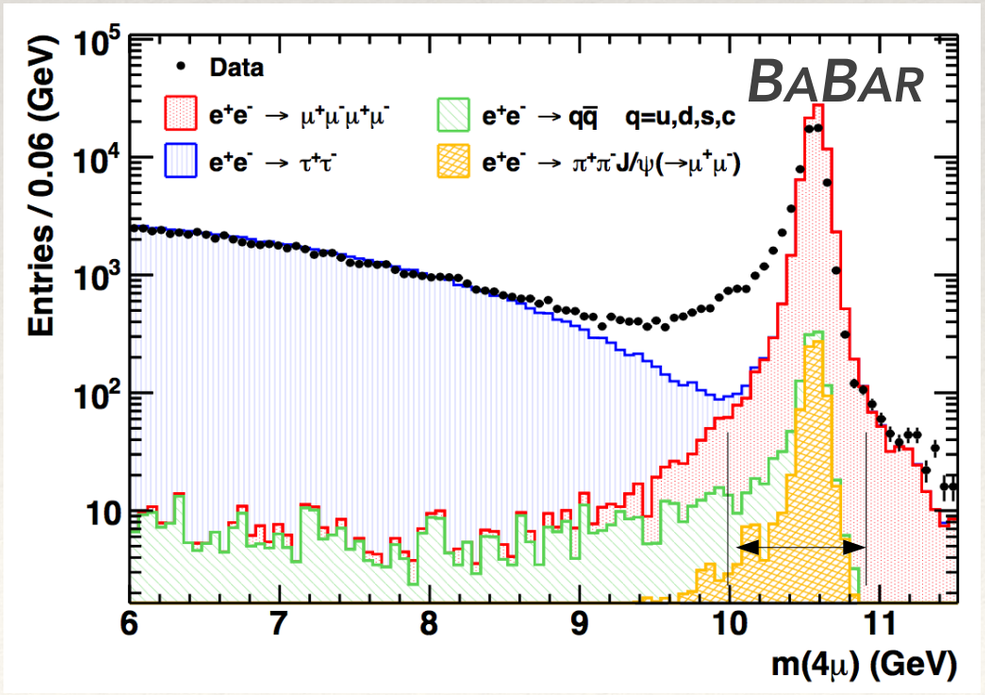
PRD 94 (2016) no. 1, 011102, arXiv:1606.03501

SIGNAL SELECTION

- Require events with exactly 4 tracks and at least 2 same-sign identified muons
    - Veto events with additional calorimeter energy > 200 MeV



- Veto events with 2-track mass within 100 MeV of $\Upsilon(1S)$ for candidate decays $\Upsilon(2S)/\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$



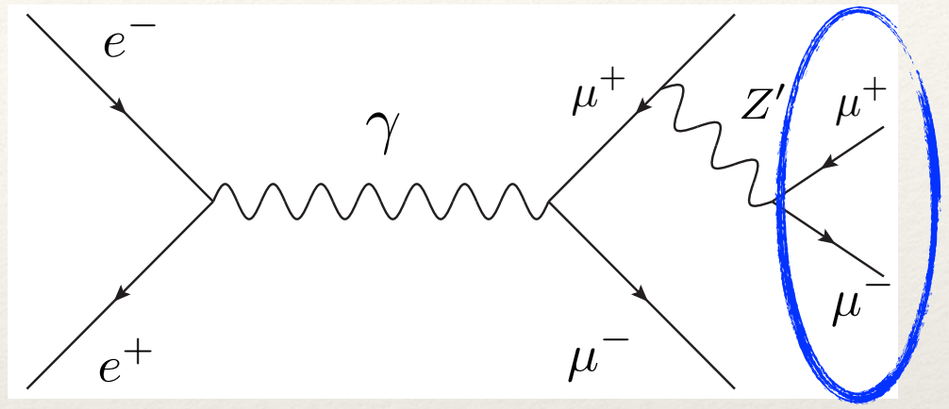
- ISR not in MC, corrected at analysis level
- Retain events with 4-muon mass within 500 MeV of nominal $E_{\rm CM}$

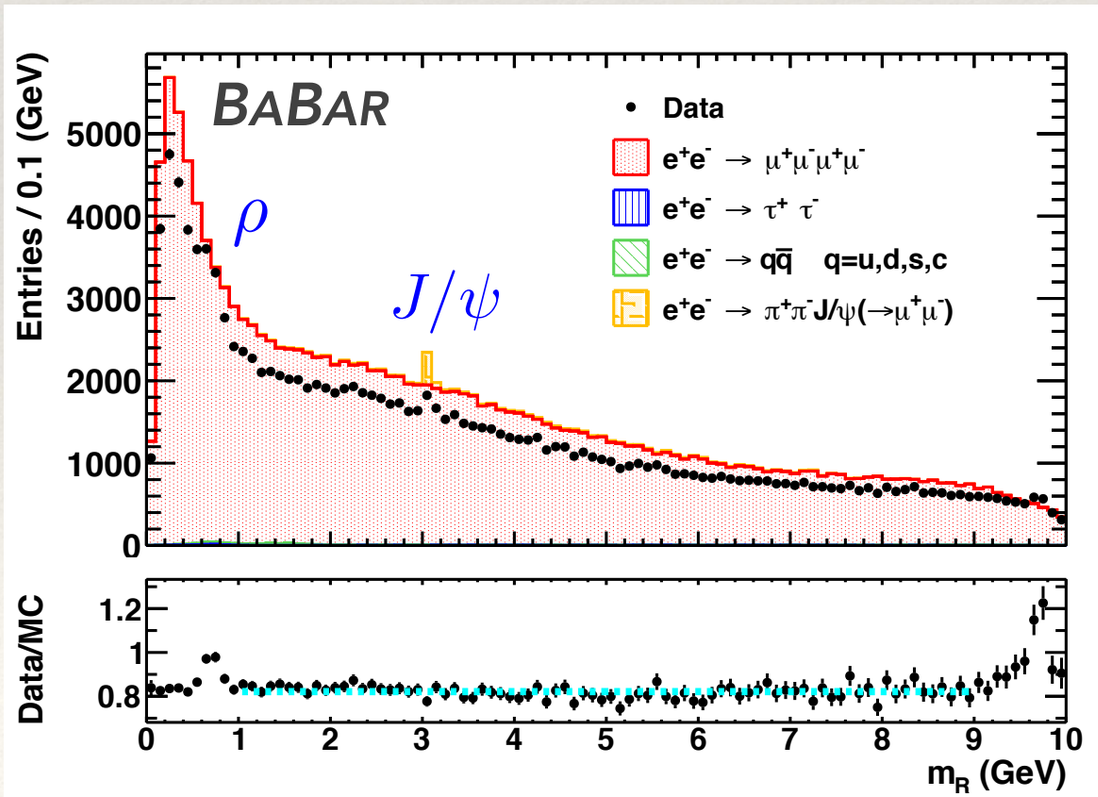
PRD 94 (2016) no. 1, 011102, arXiv:1606.03501

DI-MUON RECONSTRUCTION

- Consider all di-muon combinations
- Use **reduced di-muon mass:**

$$m_{\mathrm{R}} = \sqrt{m_{\mu\mu}^2 - 4m_{\mu}^2}$$





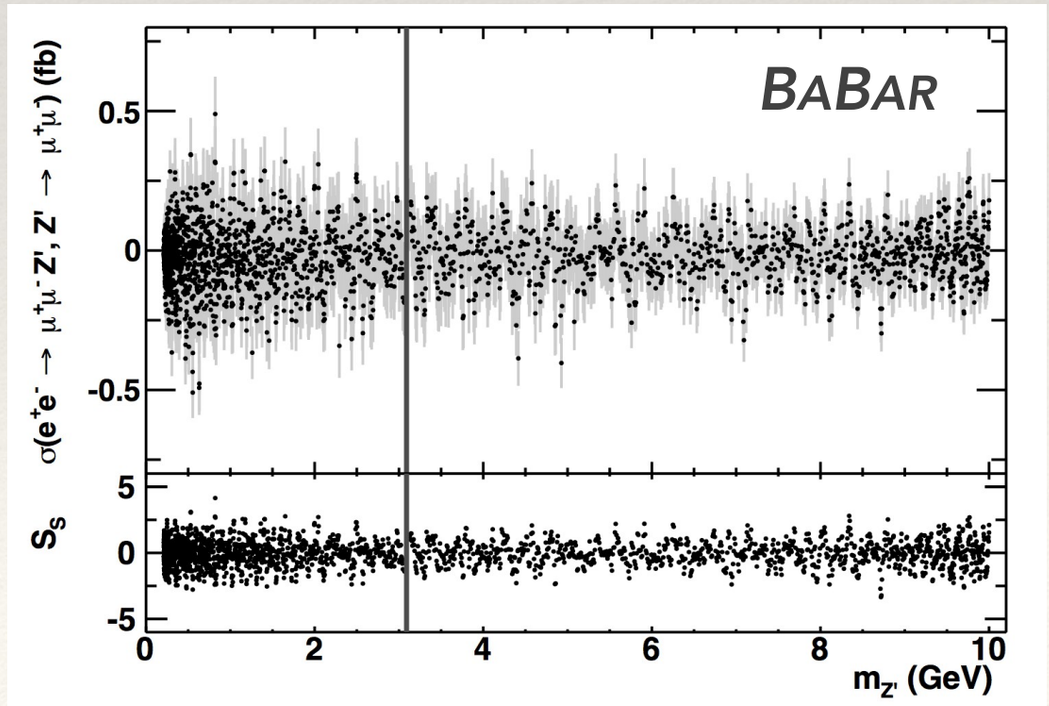
- Data/MC discrepancy due to ISR, particle ID & tracking efficiency

- Re-scale signal efficiency by same factor

PRD 94 (2016) no. 1, 011102, arXiv:1606.03501

SIGNAL EXTRACTION

- Perform series of unbinned maximum likelihood fits in windows of reduced di-muon mass of width 50σ and steps of 1σ
    - Signal shape modeled using non-parametric kernel density function derived from MC, validated on J/ψ
    - Background includes continuum (polynomial or arctan functions based on mass) and peaking J/ψ
- Signal extracted separately for each data set, results combined to give cross section
    - No significant deviation from background-only hypothesis
    - Set 90% confidence level upper limit on cross section

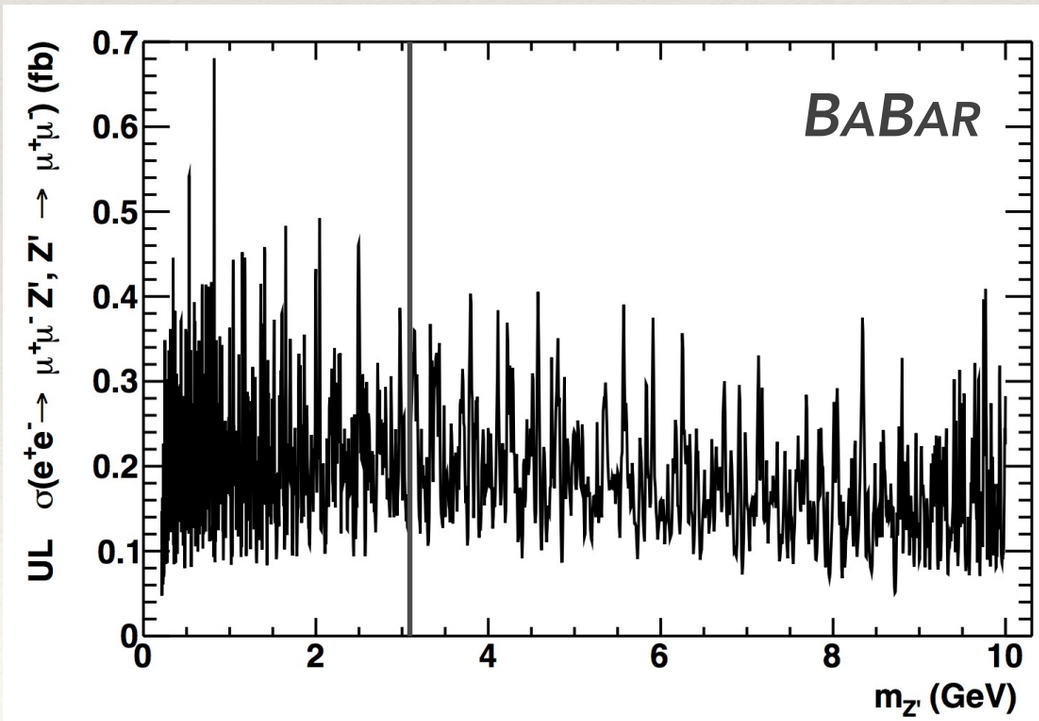


PRD 94 (2016) no. 1, 011102, arXiv:1606.03501

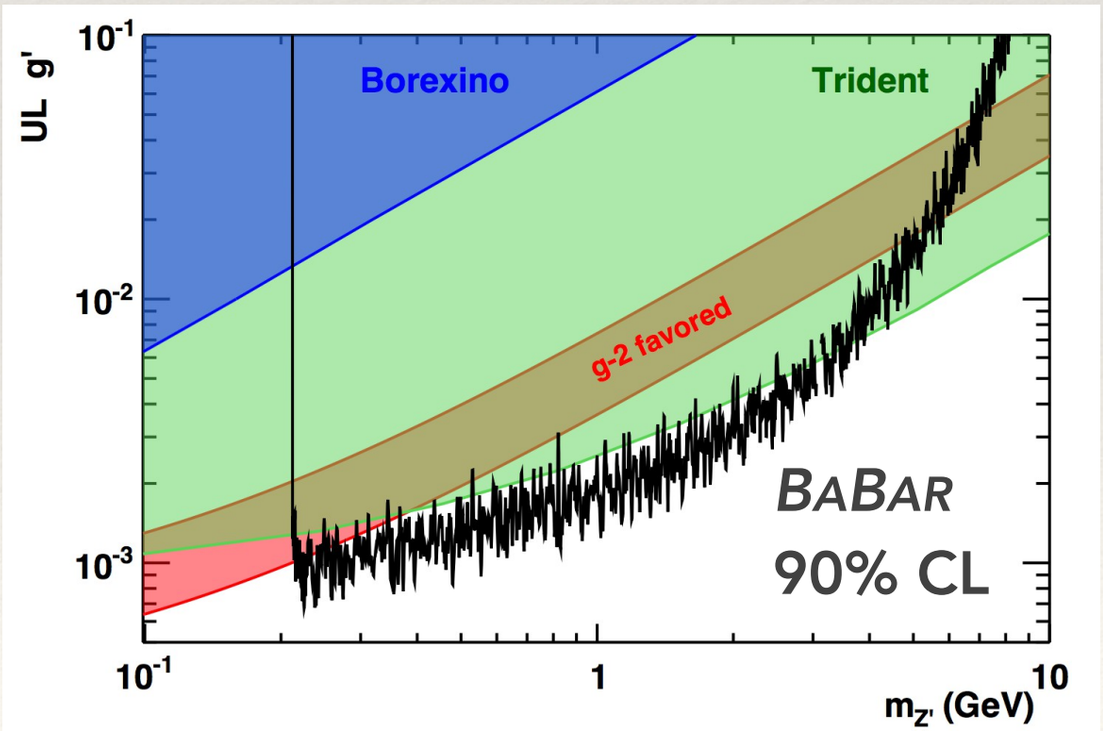
MUONIC FORCE: RESULTS

- First **direct** limits on muonic Z' in mass range, improves upon earlier indirect neutrino-experiment limits
- Limits on cross section can be applied to other models with couplings to muons

neutrino "trident": PRD 89 (2014) 095033, arXiv:1403.1269



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



Limits (90% C.L.) on Z' coupling

SUMMARY

- *BABAR* is an excellent experiment for discovering and constraining new low-mass particles due to clean environment and high-statistics sample

- Excluded entire parameter space of invisibly decaying dark photon motivated by muon *g-2*

- Put limits on production of a force that couples to 2nd-generation leptons, constrained muon *g-2* motivated parameters

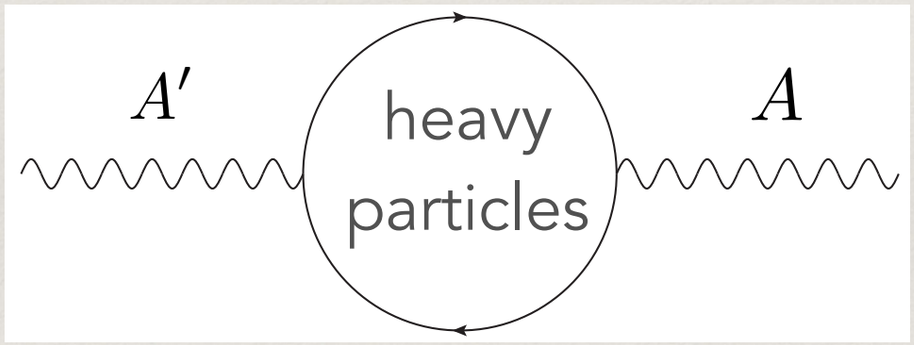
- We are only scratching the surface of hidden sectors: more to come!

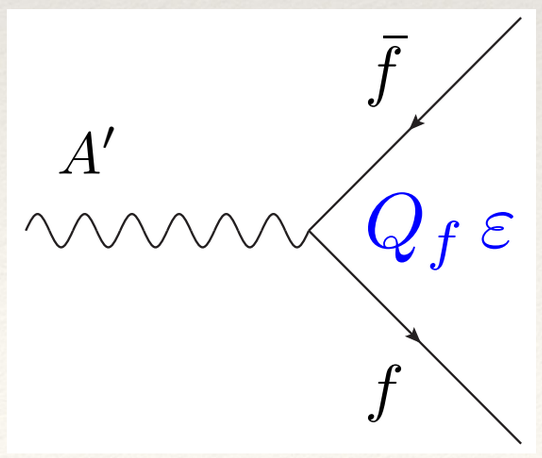
BACKUP SLIDES

DARK FORCES

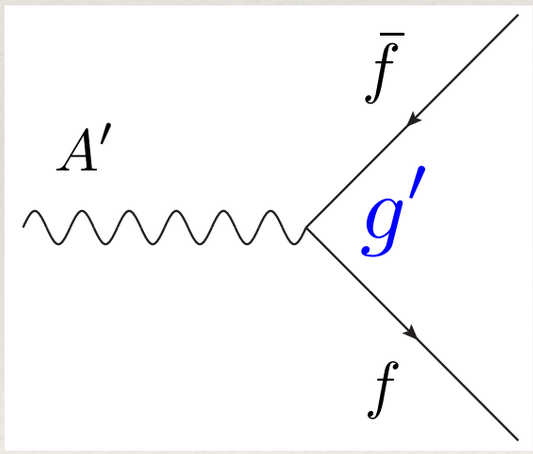
- Dark forces can interact with the Standard Model in two ways:

1. **Kinetic mixing ("dark photon"):**





2. **SM directly charged under new force:**

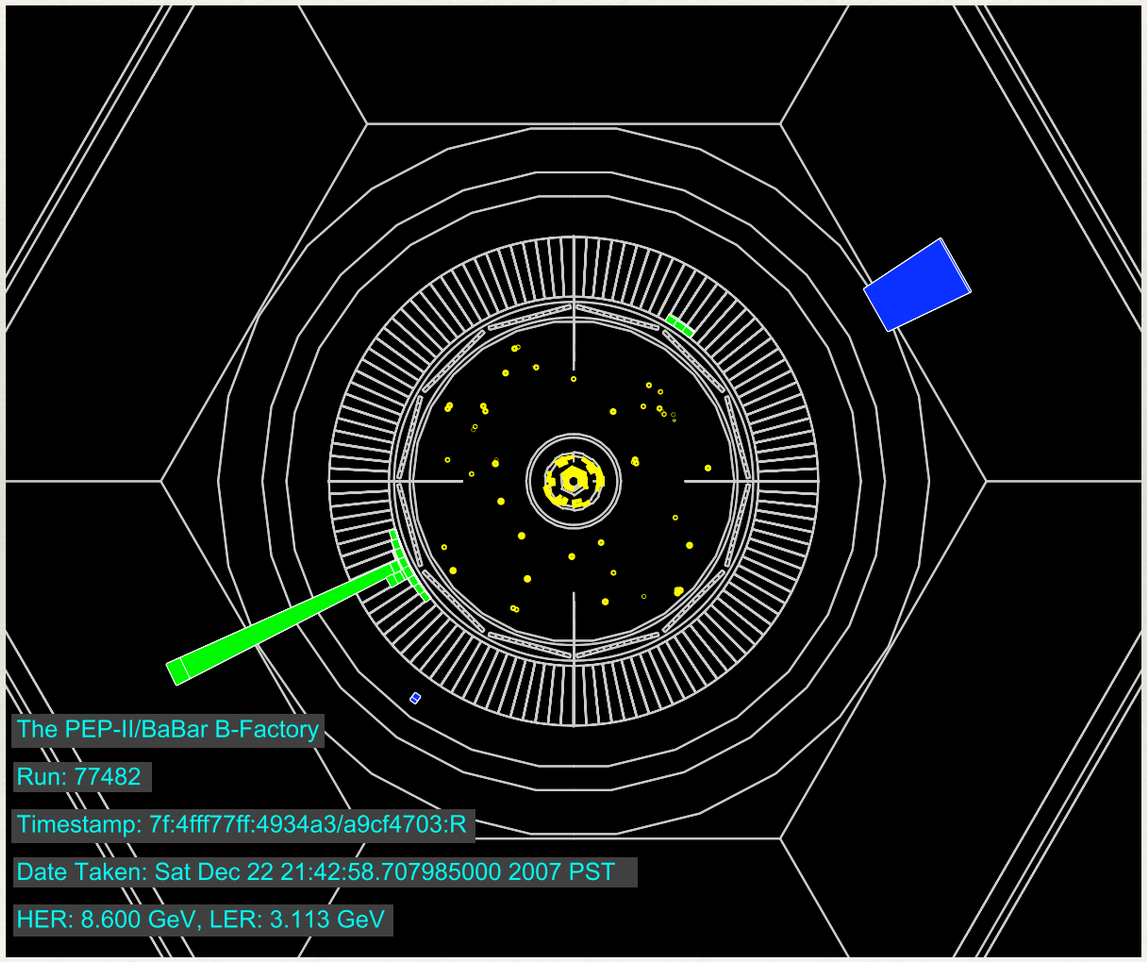


$$B - L,\ L_\mu - L_\tau,\ \ldots$$

PRL 119 (2017) no. 13, 131804, arXiv:1702.0327

INVISIBLE DARK PHOTON

- Monophoton event display, with anti-aligned energy deposit in IFR



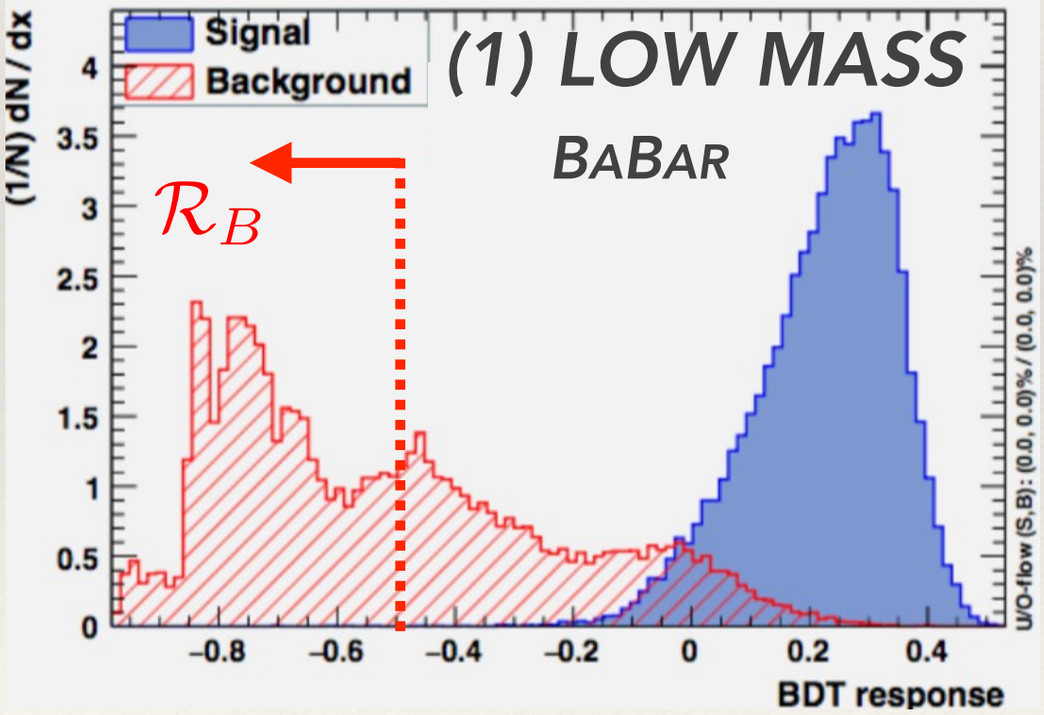
MULTIVARIATE ANALYSIS

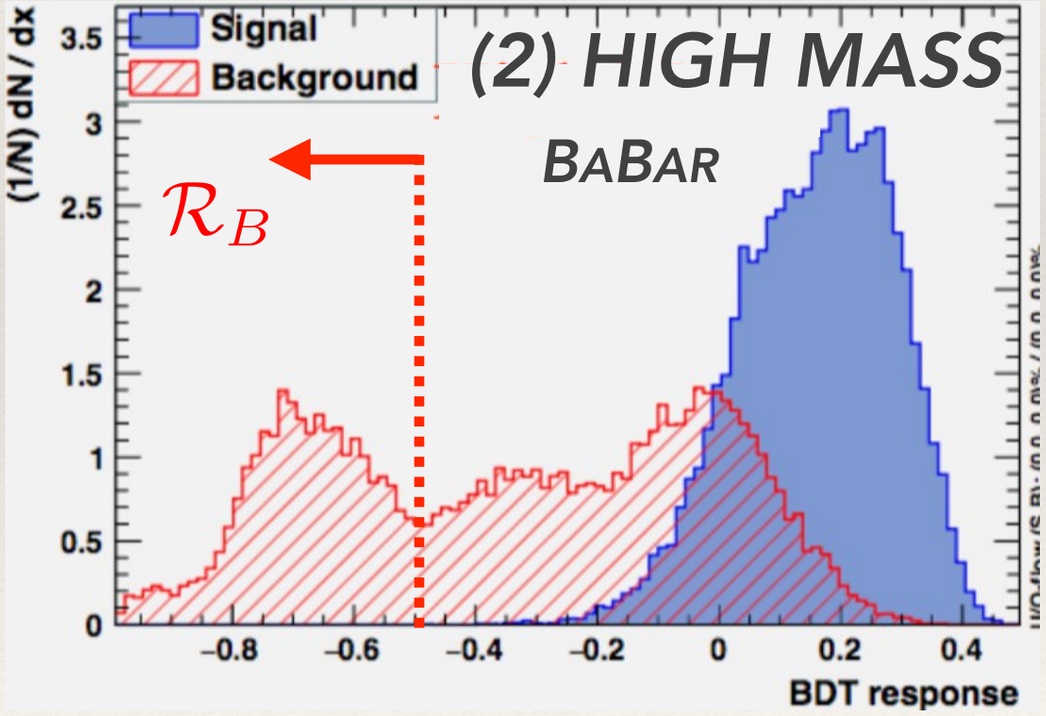
- Significant backgrounds remain, but many discriminating observables!

- After loose preselection cuts, train a Boosted Decision Tree (BDT) classifier based on 12 discriminating observables
  - Cluster shape parameters for signal candidate EMC cluster
  - Total calorimeter energy **excluding** signal candidate cluster
  - Properties of the second most energetic cluster (energy, polar angle, direction relative to signal candidate cluster)
  - Properties of the IFR cluster closest to missing momentum direction

MULTIVARIATE ANALYSIS

- BDT trained using the following samples:
    - Signal: simulated sample with uniform A' mass distribution
    - Background: Sample (~3/fb) of data from $\Upsilon(3S)$





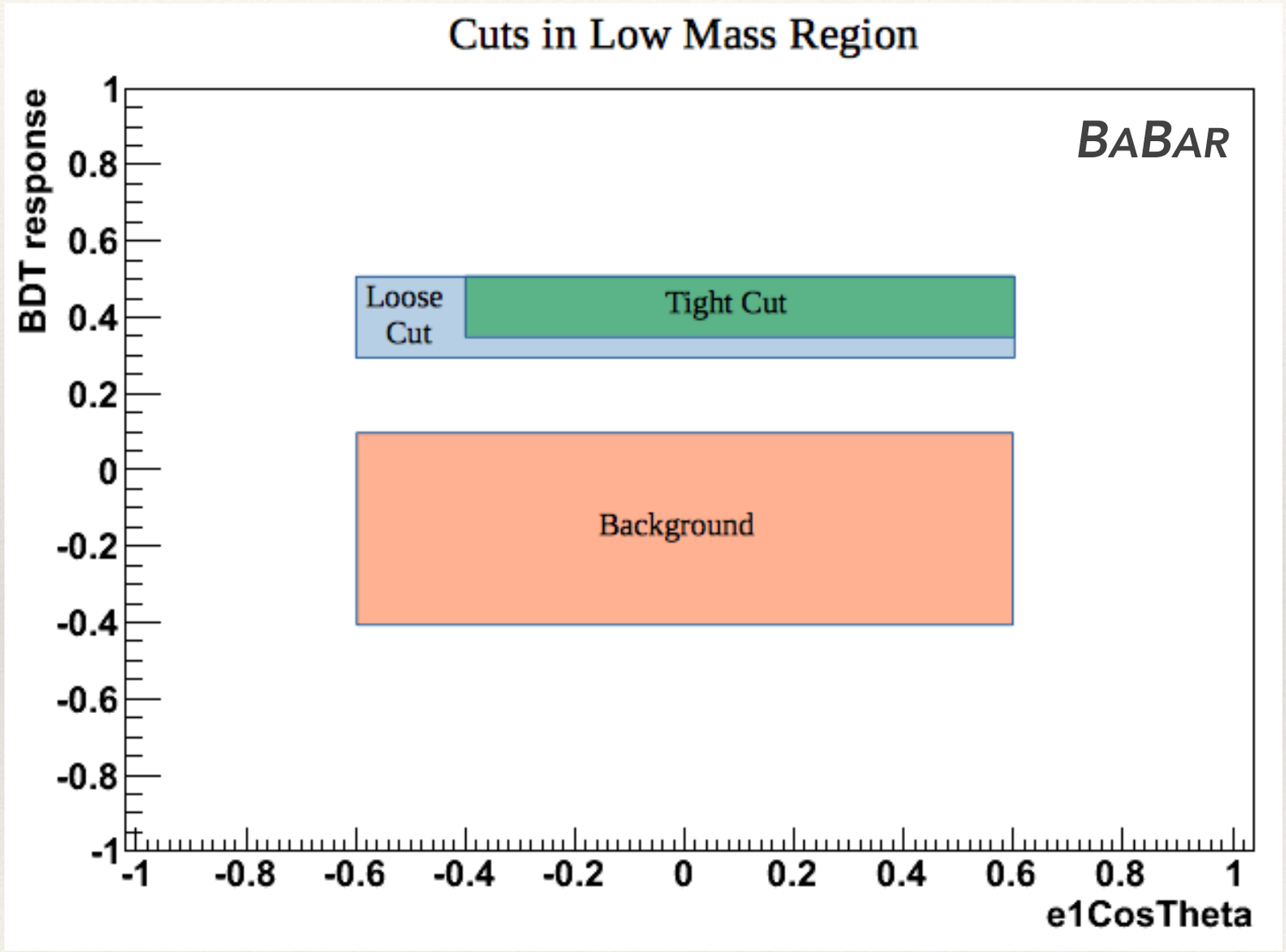
- "Background" ($\mathcal{R}_B$): defined as **BDT response < -0.5**

SELECTION OPTIMIZATION

- We define two selection regions that are optimized with respect to different figures of merit
  - "Tight" ($\mathcal{R}_T$): optimizes ε_S/N_B (only for low-mass region, hard to reliably estimate bkd)
  - "Loose" ($\mathcal{R}_L$): optimizes $\varepsilon_S/\sqrt{N_B}$ (applicable where bkd can be fit by a featureless continuum distribution)

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

SELECTION OPTIMIZATION

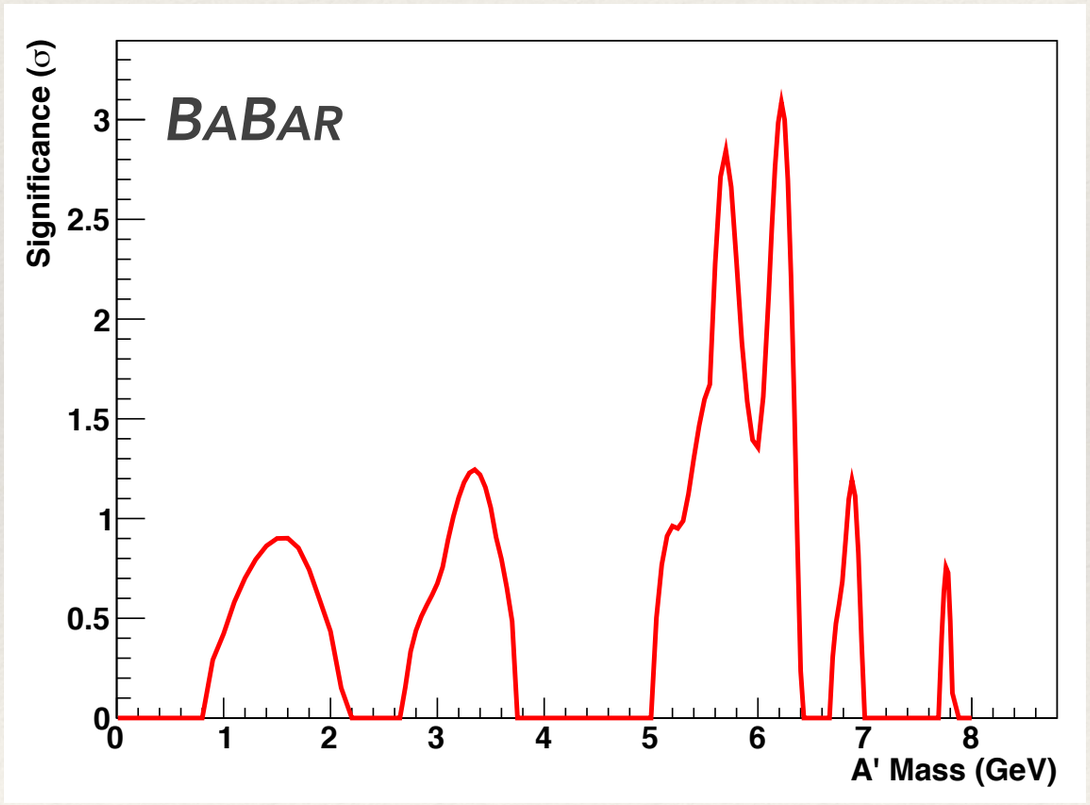


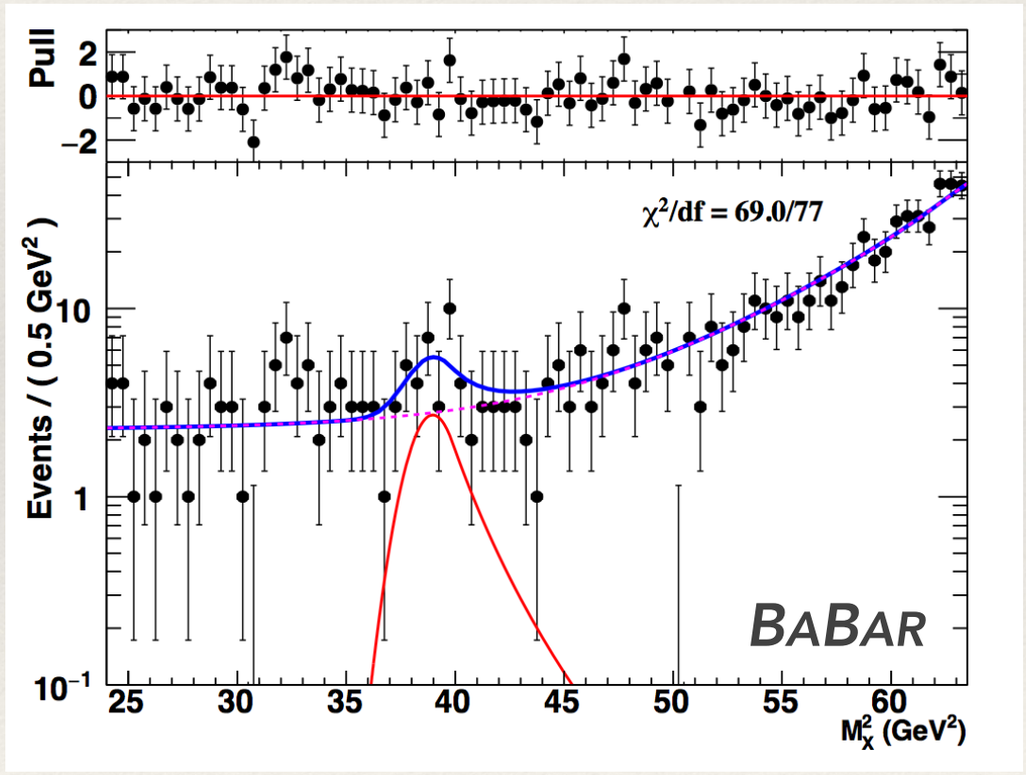
PRL 119 (2017) no. 13, 131804, arXiv:1702.0327

INVISIBLE DARK PHOTON

- Signal Efficiency: 2.4-3.8% (low mass), 0.2-2% (high mass)
- Signal Resolution: $0.7 - 1.5\ \mathrm{GeV}^2$
- Most significant fit:

$$M_{A'} = 6.21\ \mathrm{GeV}$$





$$\mathrm{local} : 3.1\sigma$$
$$\mathrm{global} : 2.6\sigma$$

DARK PHOTON SYSTEMATICS

- Signal shape: half of correction between data and MC in control sample of $e^+e^- \to \gamma\gamma$

- Trigger efficiency: 0.1-0.4%, evaluated using pre-scaled sample

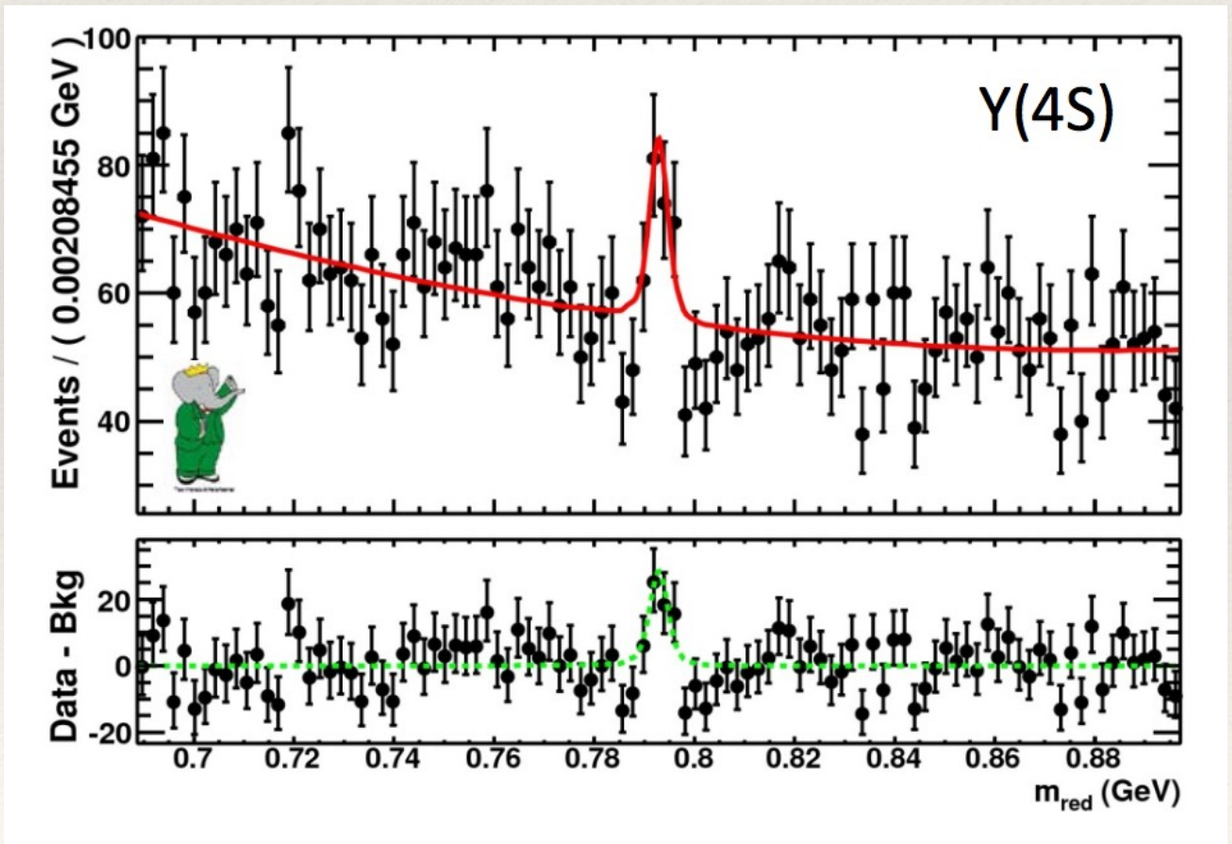
- Signal efficiency: 5%, dominated by differences between data and MC in gamma reconstruction

PRD 94 (2016) no. 1, 011102, arXiv:1606.03501

DARK MUONIC FORCE

- Signal Efficiency: 35-50%
- Signal Resolution: 1-9 MeV
- Most significant fit:

$$M_{Z'} = 0.82 \text{ GeV}$$



$$\text{local} : 4.3\sigma$$
$$\text{global} : 1.6\sigma$$

MUONIC FORCE SYSTEMATICS

- Background shape: difference between using different fit functions for continuum di-muon spectrum

- Signal efficiency corrections: 5%, dominated by uncertainties in modelling effects of ISR on efficiency, as well as data/MC differences in PID, tracking efficiencies

- Signal PDF interpolation: use next-to-nearest neighbor to interpolate signal shape and take difference as systematic

- Luminosity: 0.6%