# Direct Searches for New Physics Particles at BABAR

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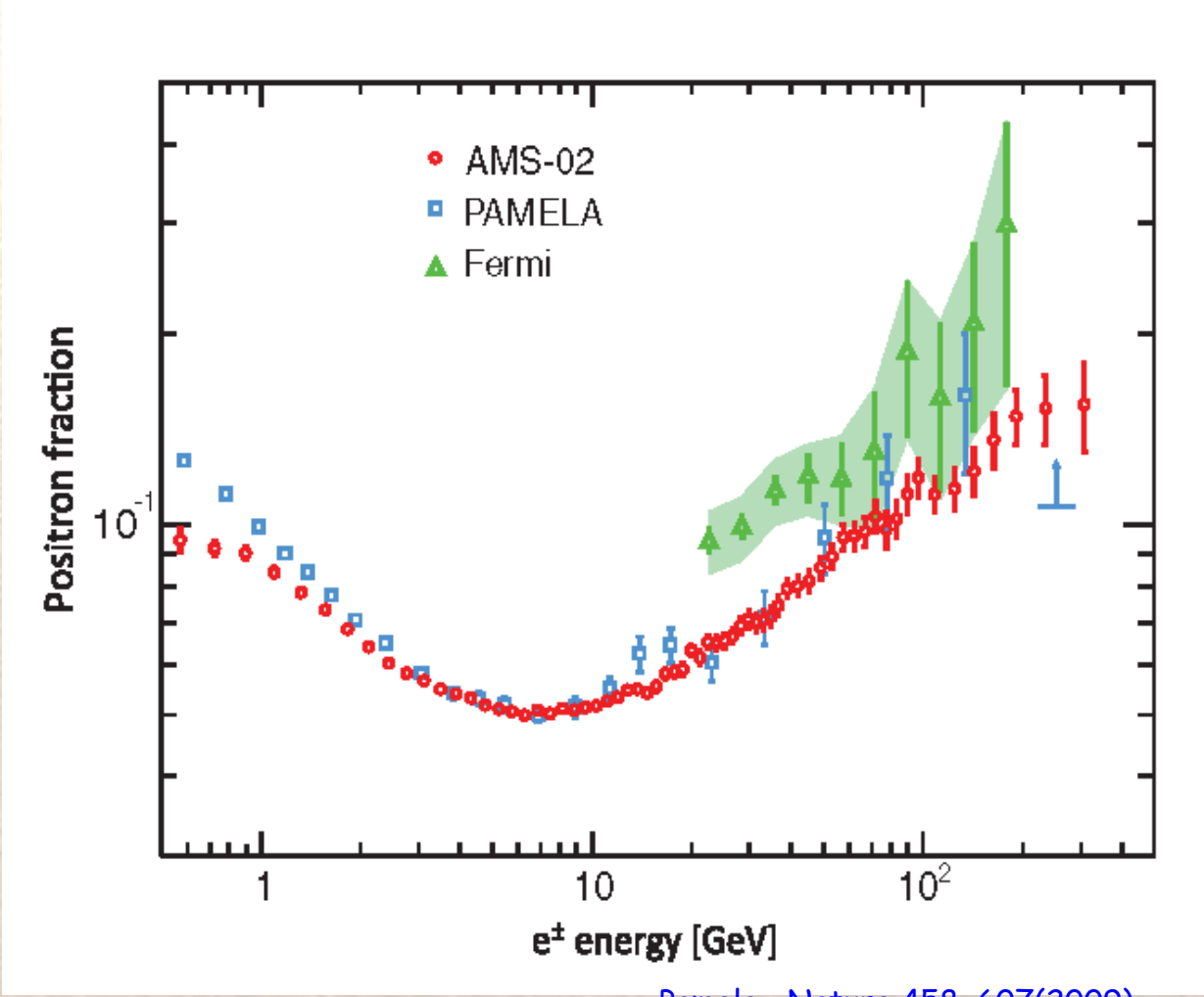
# Outline

- Motivation
- Search for dark photons
- Search for long-live particles
- Search for $\pi^0$-like new particles
- Conclusions and outlook

# Introduction: 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)

# Link between SM and Dark Matter

- In the past, dark matter particles have been associated with new heavy particles predicted in extensions of the Standard Model (SM), e.g. neutralinos
- There are several searches for WIMPs (weakly interacting massive particles)
- The observation by Pamela has triggered 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)
  - Vector: $\varepsilon F^{Y,\mu\nu} F'_{\mu\nu}$ hidden photon (new U(1) symmetry)
  - Axion: $f_a^{-1} F^{\mu\nu} F_{\mu\nu} a$ axion
  - Scalar: $\lambda H^2 S^2 + \mu H^2 S$ hidden scalar/exotic decays
  - Neutrino: $\kappa (H\ell) N$ sterile neutrino

    PLB 662, 53 (2008)
- At low energy scale, the light vector portal is the most accessible portal, but the scalar portal can be probed as well

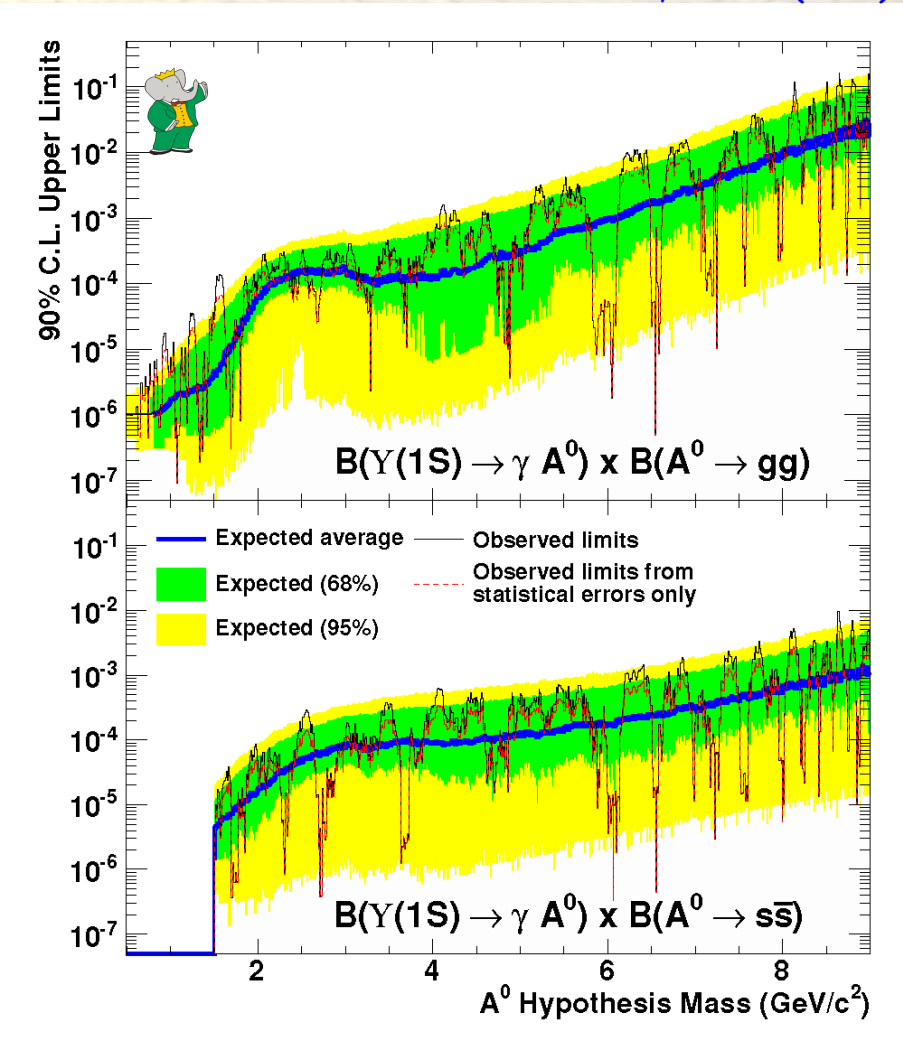
# Previous BABAR Searches

- Search for Higgsstrahlung in $e^+e^- \rightarrow h'A'$, $h' \rightarrow A'A'$ ➔ set 90% CL upper limit on $\alpha_D\varepsilon^2$ between $10^{-10}$ to $10^{-8}$ from $0.8<m_{h'}<10$ GeV and $0.25<m_{A'}<3$ GeV ($m_{h'}>2\,m_{A'}$)
  PRD 86, 051105 (2012)

- Search for $\Upsilon(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$
  ➔ set 90% CL upper limit on branching fraction at level of $(0.26\text{-}8.3)\times10^{-6}$ in $0.21<m_{A0}<10.1$ GeV PRD 87, 031102 (2013)

- Further Searches for $\Upsilon(2S, 3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$, hadrons, invisible
  ➔ set similar 90% CL upper limit on branching fractions
  PRD 88, 071102 (2013)
  PRL 107, 221803 (2013)
  PRD 86, 051105 (2011)
  PRL 107, 021804 (2011)

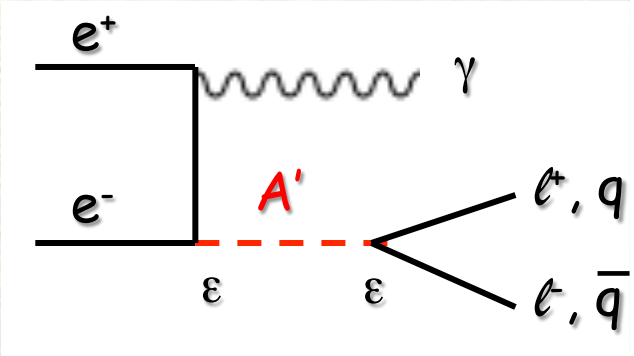
- Search for $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow gg$, $s\bar{s}$
  ➔ set 90% CL upper limit on branching fraction at level of $10^{-6}$ to $10^{-2}$ in $1.5.<m_{A0}<9.0$ GeV PRD 88, 031701 (2013)



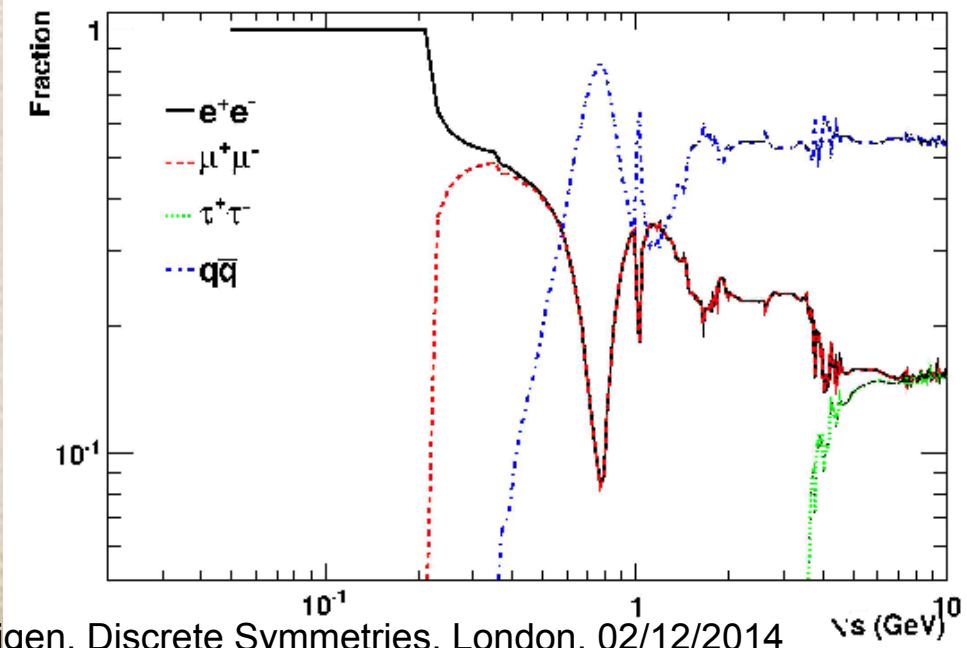
# Search for Dark Photons

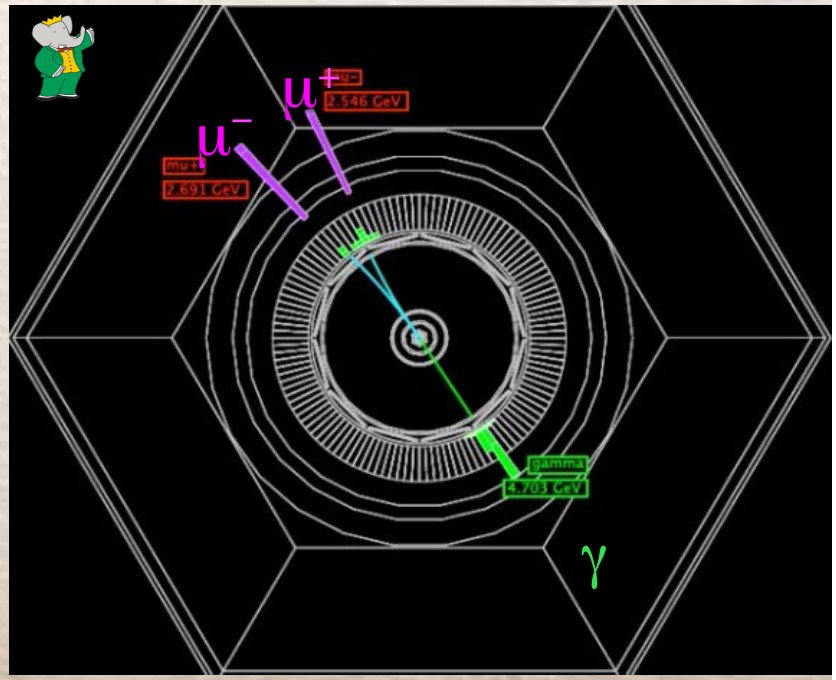
# Dark Photon Production in BABAR

- A dark photon $A'$ can be produced in $e^+e^- \to \gamma A' \to \gamma \ell^+\ell^-$ $(q\bar{q})$
- Cross section is reduced wrt $e^+e^- \to \gamma\gamma$; $\sigma \propto \varepsilon^2 \alpha^2 / E^2_{CM}$ where $\varepsilon$ lies in the range $10^{-5}$-$10^{-2}$
- BABAR looks for $e^+e^-$ or $\mu^+\mu^-$ and $\gamma$ with $E_{CM}$ >200 MeV
  - Apply constrained fit to beam energy & beam spot
  - Use kinematic constraints to improve purity
  - Require good quality on $\gamma$, e & $\mu$ and remove e conversions



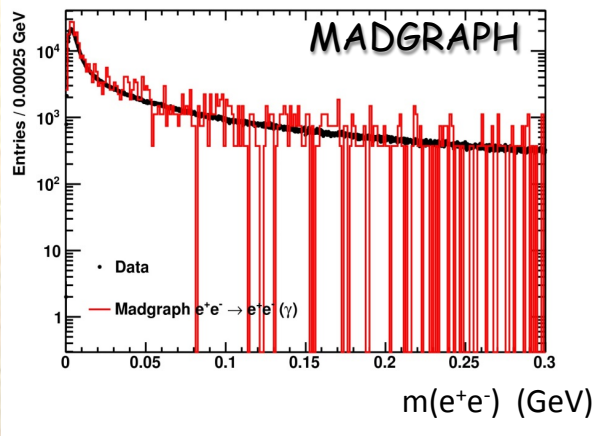

Batell et al., PRD 79, 225008 (2009)

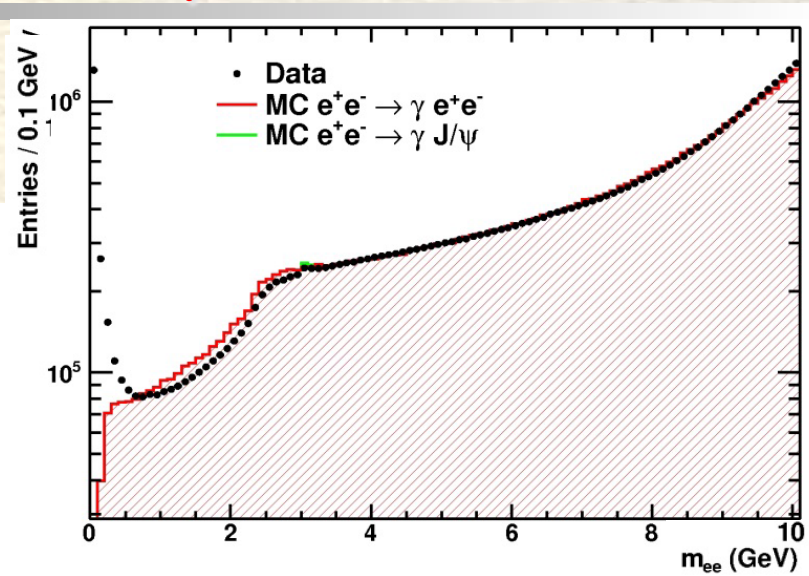


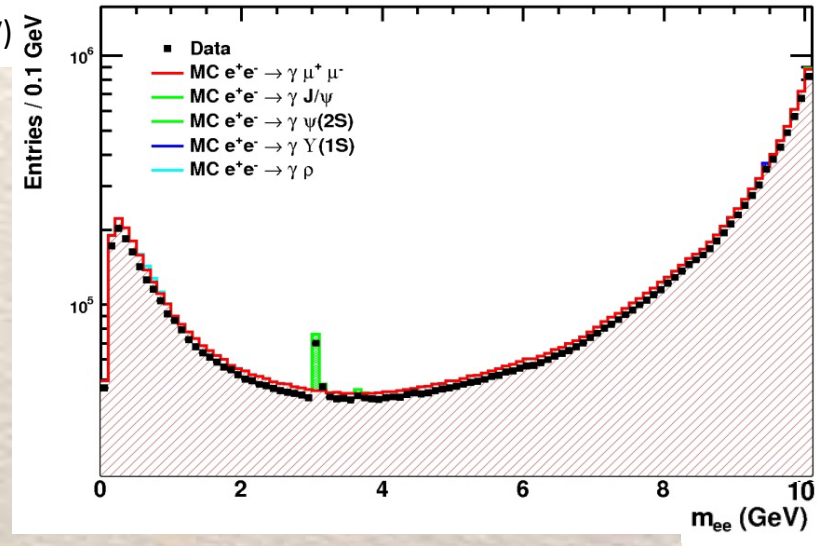
# Raw $e^+e^-$ and $\mu^+\mu^-$ Mass Spectra

- Generally, good data/MC agreement for $m_{ee}$
- BHWIDE generator fails to reproduce low $m_{ee}$ mass region
- MADGRAPH generator reproduces low $m_{ee}$ consistently, but has low statistics
  - ➔ Signal extraction does not rely on MC



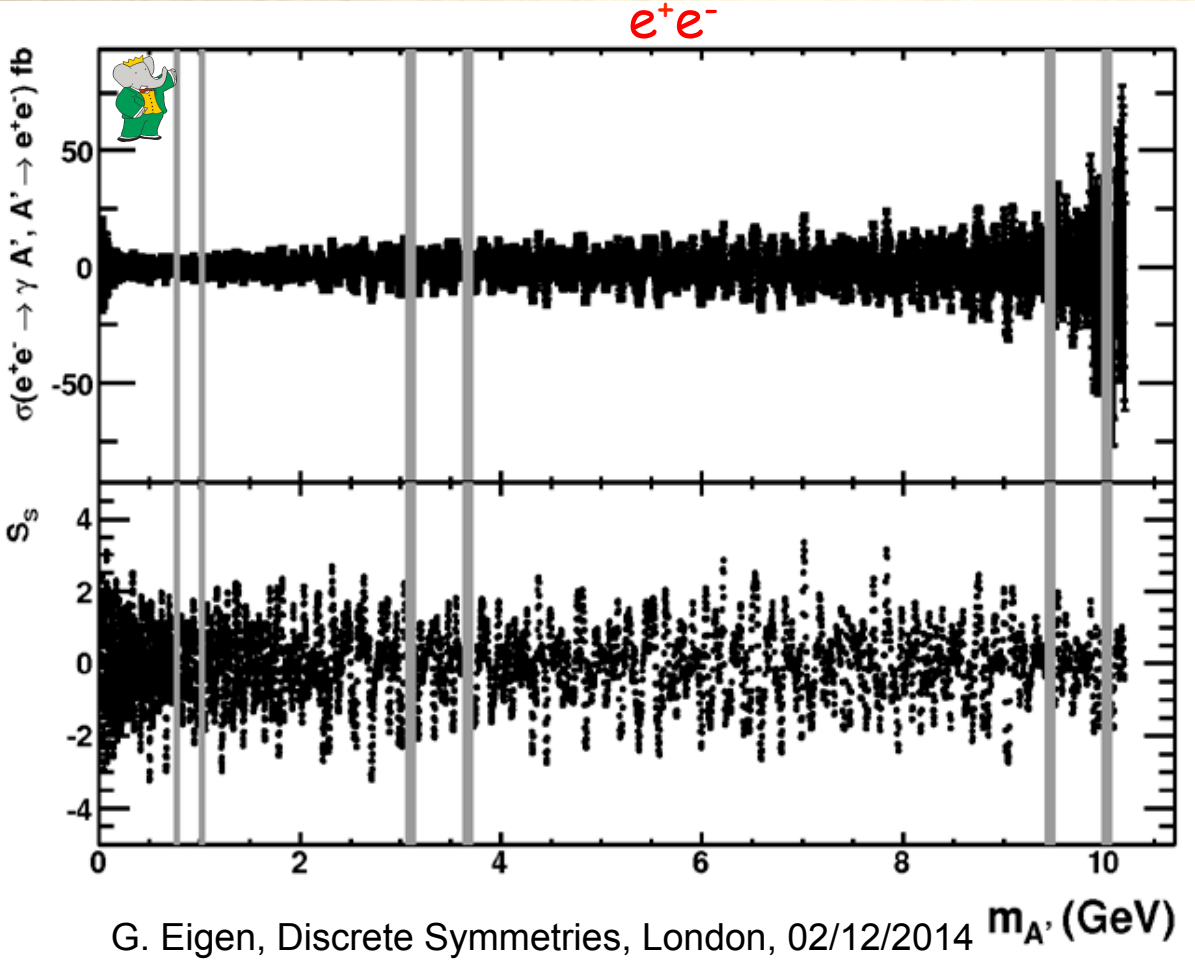

- For $\mu\mu$, define reduced mass $m_{red} = \sqrt{\left(m^2_{\mu\mu} - 4m^2_{\mu}\right)}$
  - ➔ smoother turn-on near threshold



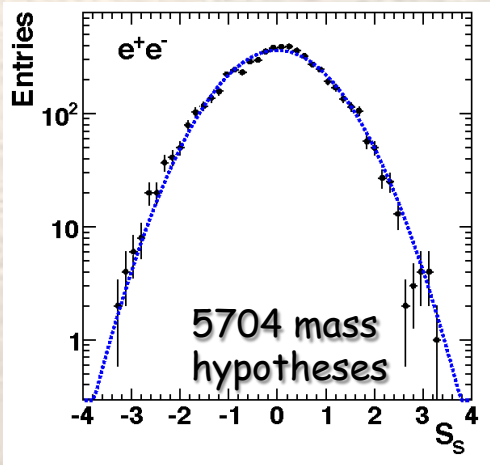

- KK2F generators reproduces $m_{red}$ well
- Sensitivity is dominated by $\mu\mu$ mode due to higher efficiency and lower backgrounds
- Exclude $\omega$, $\phi$, $J/\psi$, $\psi(2S)$, $\Upsilon(1S)$ & $\Upsilon(2S)$ mass regions

# Observed Cross Section for Dark Photons

- Results on $\sigma(e^+e^- \to \gamma A' \to \gamma \ell^+\ell^-)$ include all data at Υ(2S), Υ(3S) and Υ(4S)
- Largest deviations in $e^+e^-$ channel:
  3.4σ at 7.02 GeV ➔0.6σ with trial factor (determined from MC)




Significance

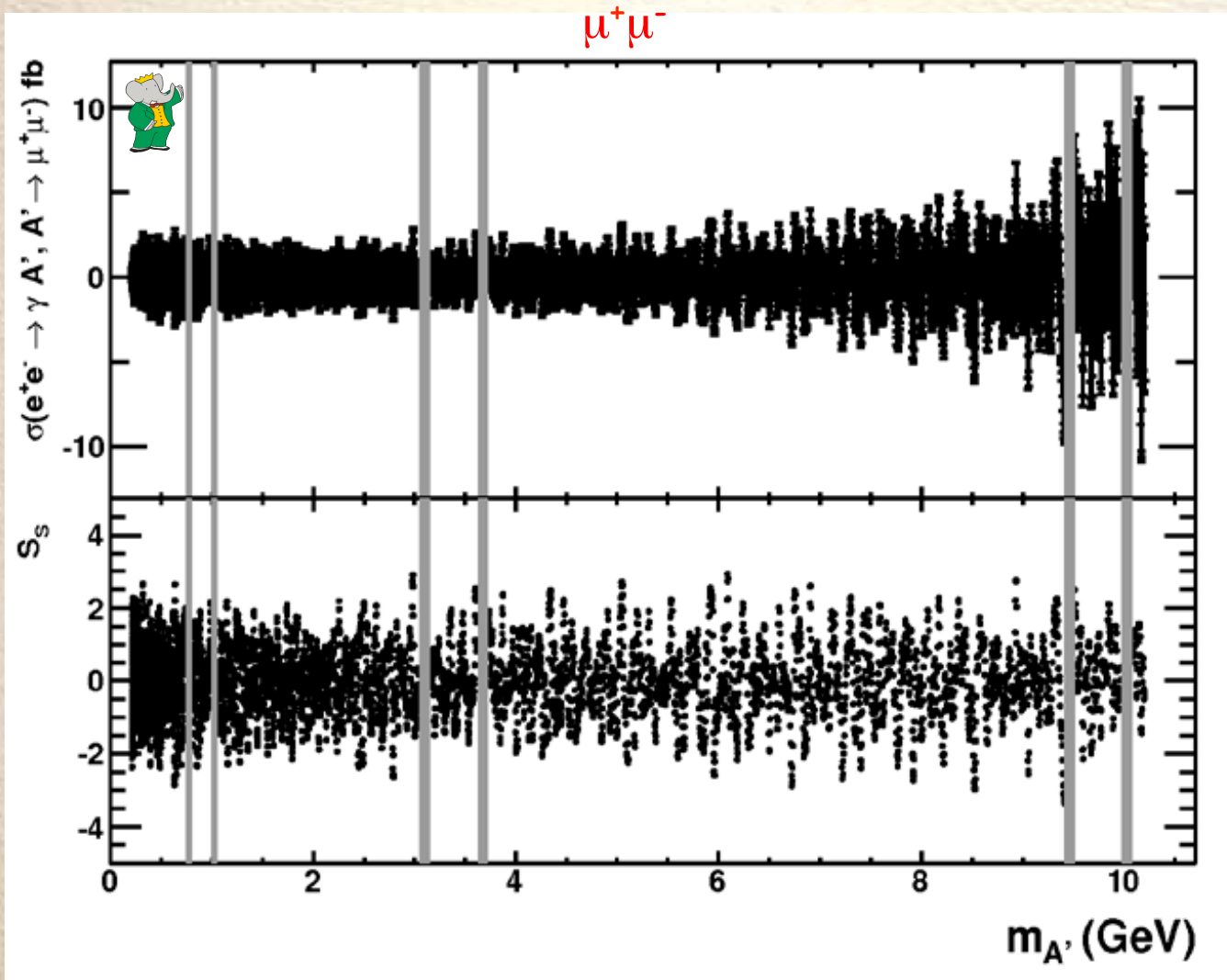



Significances are estimated as $[2 \log (\mathcal{L}/\mathcal{L}_0)]^{1/2}$

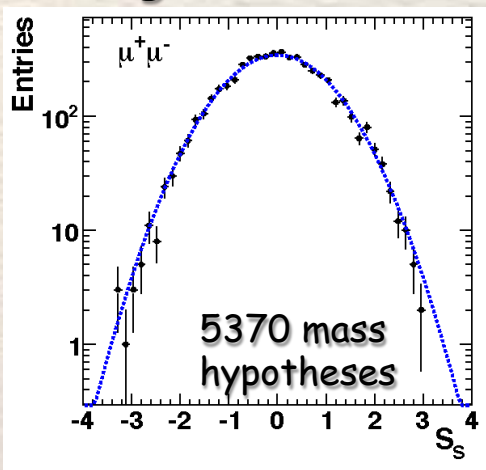
PRL 113, 201801 (2014)

# Observed Cross Section for Dark Photons

- Largest deviations: in $\mu^+\mu^-$ channel $2.9\sigma$ at 6.09 GeV ➔ $0.1\sigma$ with trial factors



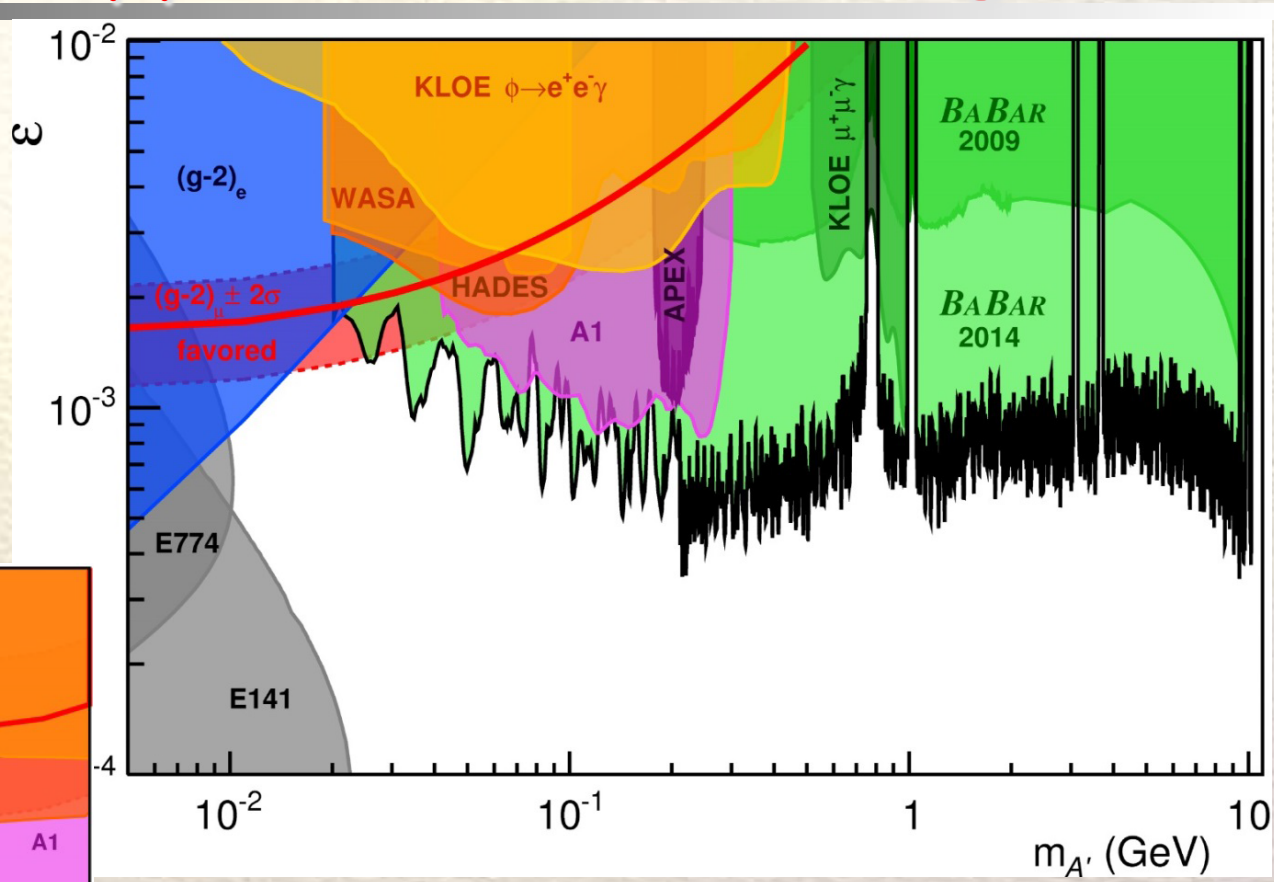

significance

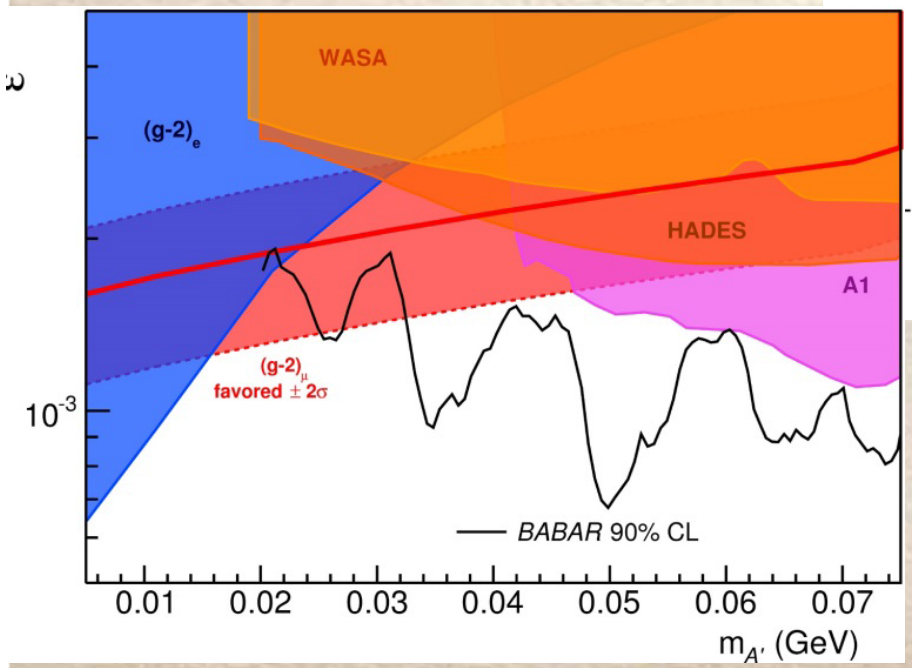



PRL 113, 201801 (2014)

# Mass-dependent Upper Limit on Mixing ε

- BABAR pushes exclusion region on ε in the mass range 0.03- ~10 GeV substantially lower
- Most of the region favored by g-2 is now excluded




- Region near ρ mass can be further probed by analyzing $A' \to \pi^+\pi^-$ channel

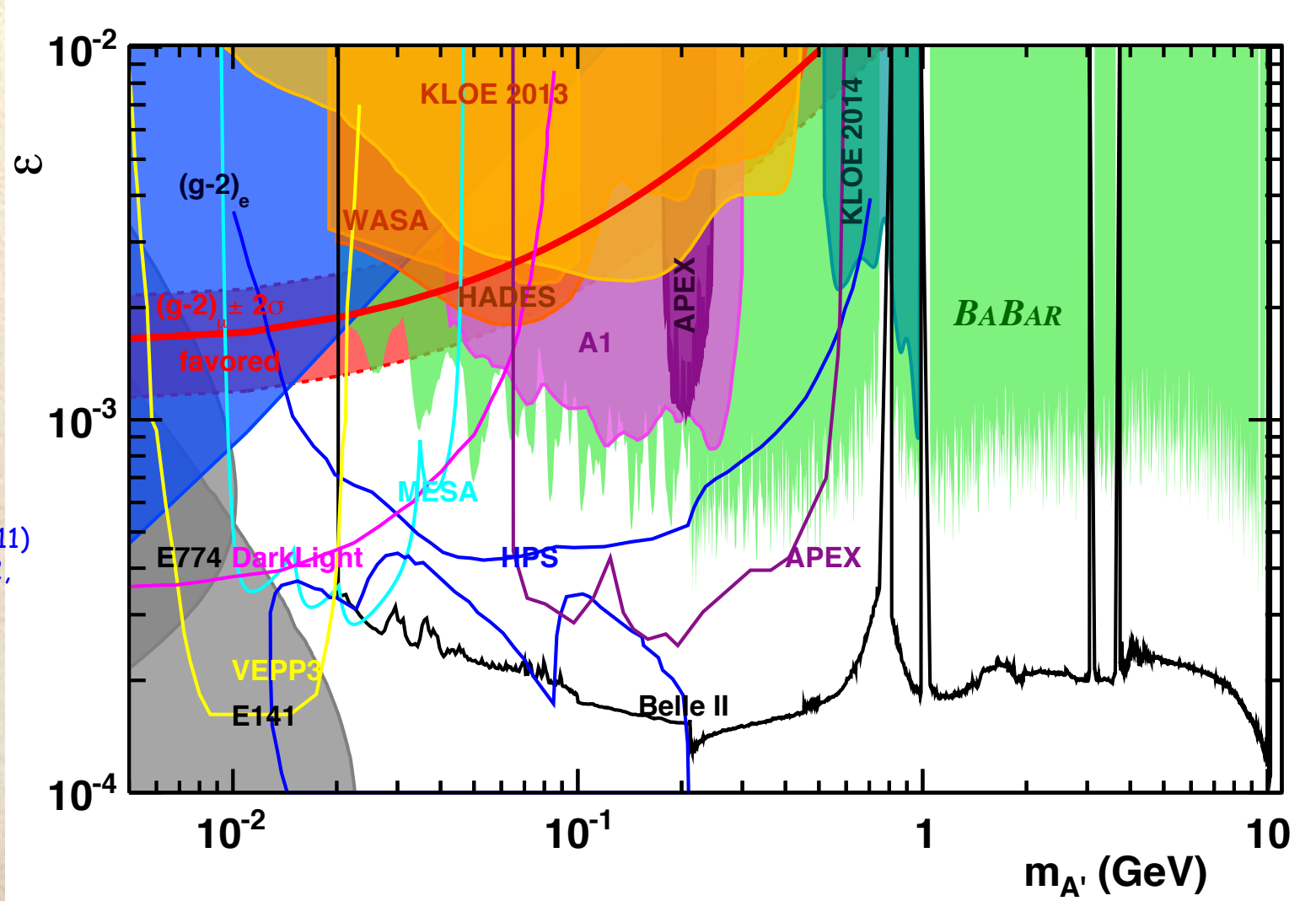
PRL 113, 201801 (2014)

# 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 ~$10^{-4}$

- New dedicated experiments:
  APEX
  Dark Light
  HPS
  MESA
  VEPP3

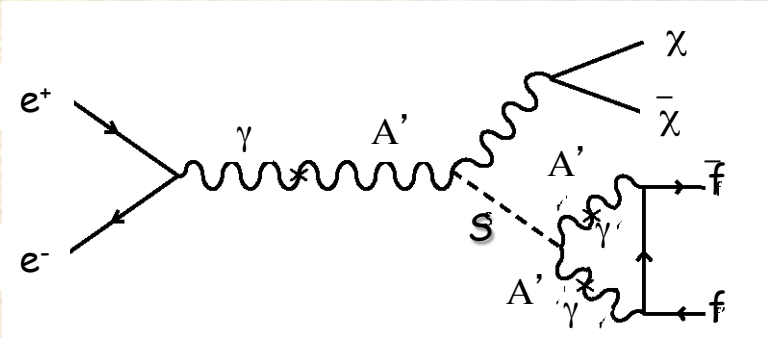
APEX, PRL 107, 191804 (2011)
HPS, J. Phys. Conf. Ser. 382, 012008 (2012)
MESA, AIP Conf. Proc. 1563 140 (2013)



# Search for Long-Lived Particles

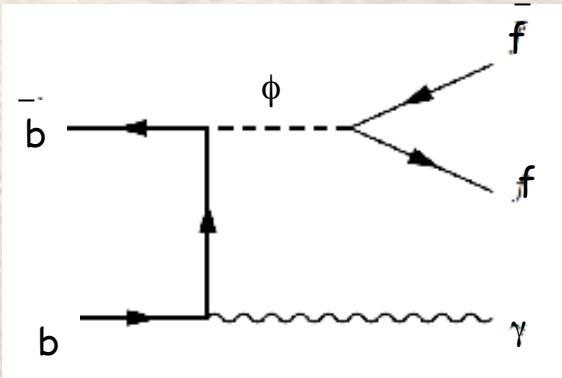
# Production Mechanisms for Long-Lived Particles

- The simplest way to produce a long-lived dark particle is via mixing of a photon from $e^+e^-$ annihilation with a dark photon A'
  - ➔ the dark photon emits a dark scalar S and decays to 2 dark fermions $\chi$ (not seen)
  - ➔ the dark scalar decays to 2 dark photons that mix with real photons that in turn decay to a pair of fermions




- The mass is limited to $m_S < 2m_\chi$ since $m_{A'} > 2m_\chi$
  - ➔ prediction lies around 1 GeV

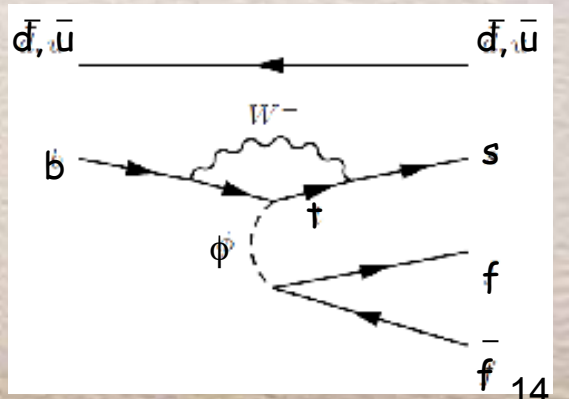
Arkani_Hamed et al., Phys.Rev.D.79, 015014 (2009)




- Another production mechanism originates from the coupling of the SM Higgs field to one new scalar field $\phi$
  - ➔ so $\phi$ can be produced in SM processes like $\Upsilon$(nS) or B decay and can decay to 2 fermions

Bezrukov and Gorbunov, JHEP 1307, 140 (2013)

Batell et al., PRD 79, 115008 (2009)
Essig et al., PRD 80, 015003 (2009)
Schuster et al., PRD 81, 016002 (2010)
Bossi Adv.HEP 2014, 891820 (2014)




- The mass range is $0.1 < m_\phi < 10$ GeV

Clarke et al., JHEP 1402, 123 (2014)

# Strategy for Long-Lived Particle Search

- We perform the first search for a long-lived particle *L* in the process $e^+e^- \to LX$ where X is any set of particles and L decays to $e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp, \pi^+\pi^-$, $K^+K^-$ and $K^\pm\pi^\mp$
- We present the results in 2 interpretations
  - First we use all data except for a 20 $fb^{-1}$ validation sample at $\Upsilon(4S)$ (404 $fb^{-1}$ at $\Upsilon(4S)$, 44 $fb^{-1}$ below $\Upsilon(4S)$, 28 $fb^{-1}$ at $\Upsilon(3S)$ and 14 $fb^{-1}$ at $\Upsilon(2S)$)
    ➔ results in a model-independent interpretation
  - Second, we select the $B \to LX_s$ decays from this data sample where $X_s$ is a hadronic system with strangeness -1
    ➔ results in a model-dependent interpretation
- We reject background from $K^0_S$ and $\Lambda$ as well low-mass peaking structures in the background by imposing mass thresholds:
  $m_{ee} > 0.44$ GeV, $m_{e\mu} > 0.48$ GeV, $m_{\mu\mu} > 0.50$ GeV and $m_{\mu\mu} > 0.37$ GeV
  $m_{\pi\pi} > 0.86$ GeV, $m_{K\pi} > 1.05$ GeV, $m_{KK} > 1.35$ GeV
- The efficiency varies from 47% for m=1 GeV at $2 < p_T < 3$ GeV & $c\tau = 3$ cm to a few per mil for large m and $c\tau$

# Signal Extraction

- Using unbinned extended ML fits of the mass distributions, we extract the signal yield for each final state as a function of mass m
- We divide the mass distribution of each mode into 13 regions straddling each of the signal MC samples
- We define signal PDFs in each region:

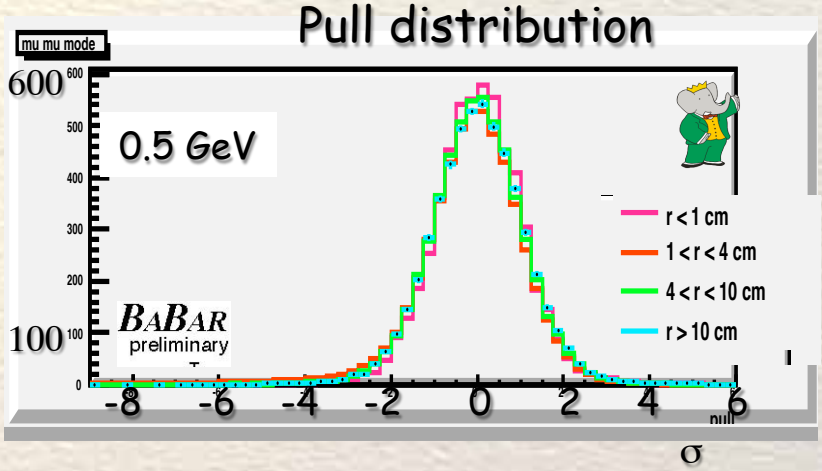
$$P_s(m) = H\left(\frac{m - m_t}{\sigma_m}\right)$$

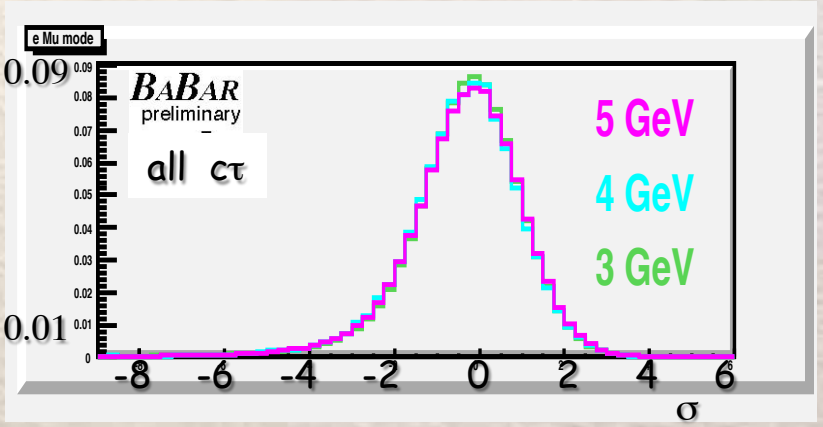
where H(x) is the pull histogram produced from masses closest to the true mass $m_t$ and m & $\sigma_m$ are measured mass and its error

- The background PDF is a 2nd-order polynomial spline interpolated between bin midpoints
- The histogram bin width in mass region i is $w_i = 15 * \sigma_{mi}$; $\sigma_{mi}$ increases from 4 MeV at $m_t$=0.2 GeV to ~180 MeV at $m_t$=9.5 GeV

➔ note, the factor n=15 is large enough to provide high sensitivity but small enough to prevent fluctuations to appear as significant signal peaks

Pull distribution



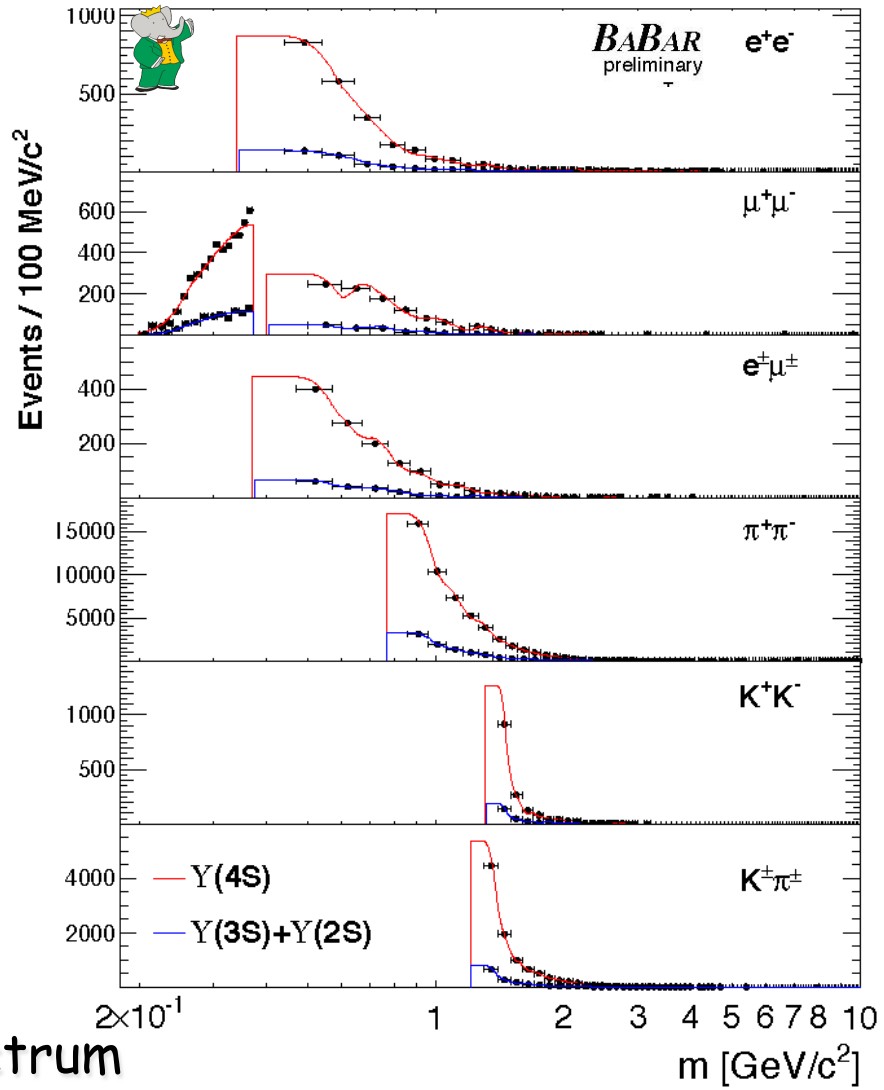
# Observed Signal Yields

- We scan the data in steps of $m_\dagger$=2 MeV
- We use the PDF $n_s P_s(m)+n_B P_B(m)$, where $n_s$ (signal) and $n_B$ (background) yields are determined from the fit
- We define the statistical significance

$$S = sign(n_s)\sqrt{-2\ln\left(\mathcal{L}_0/\mathcal{L}_s\right)}$$

where $\mathcal{L}_s$ is the ML of the fit and $\mathcal{L}_0$ is the ML for $n_s$=0

- Observe S=4.7 at $m_\dagger(\mu\mu)$=0.212 MeV, but most of vertices lie inside detector material and $\mu$ tracks have low momenta that are poorly separated from e and $\pi$
- Next highest S=4.2 at $m_\dagger(\mu\mu)$=1.24 GeV
  ➔ P=0.8% to see S≥4.2 in entire $\mu\mu$ mass spectrum



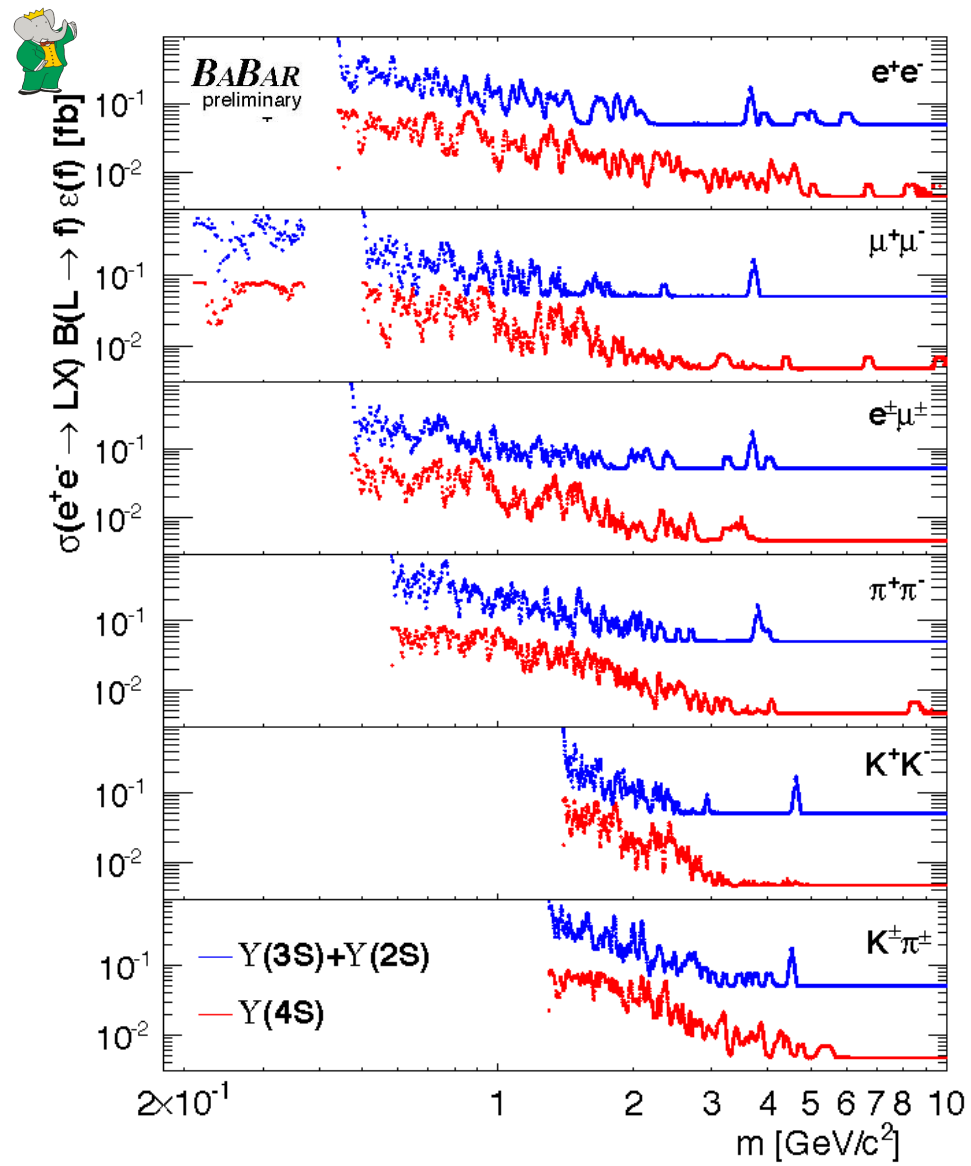

- Data are consistent with background expectation

# Results for Model-Independent Interpretation

- We determine the systematic error on the signal yield for each scan fit
- The dominant systematic error results from the background PDF
- We estimate systematic errors due to mass resolution, luminosity, particle ID (<1%) and # MC signal events
- We convolve $\mathcal{L}_S$ (normal distributed) with Gaussian representing total $\sigma_{sys}$
- We determine uniform-prior Bayesian upper limits at 90% CL on the product

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

➔ with efficiency tables limits can be applied to any production model



# Results for Model-Dependent Interpretation

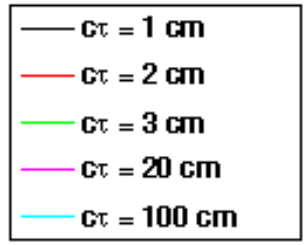
- For the model-dependent interpretation, we set Bayesian upper limits @90%CL on the product of branching fractions

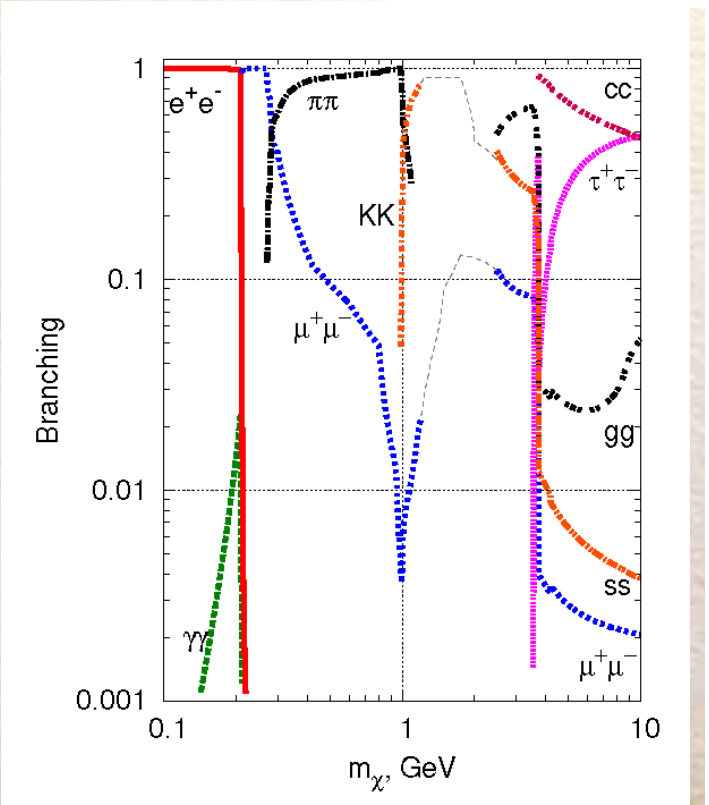
$$\mathcal{B}\left(B \to X_s L\right) \times \mathcal{B}\left(L \to f\right)$$

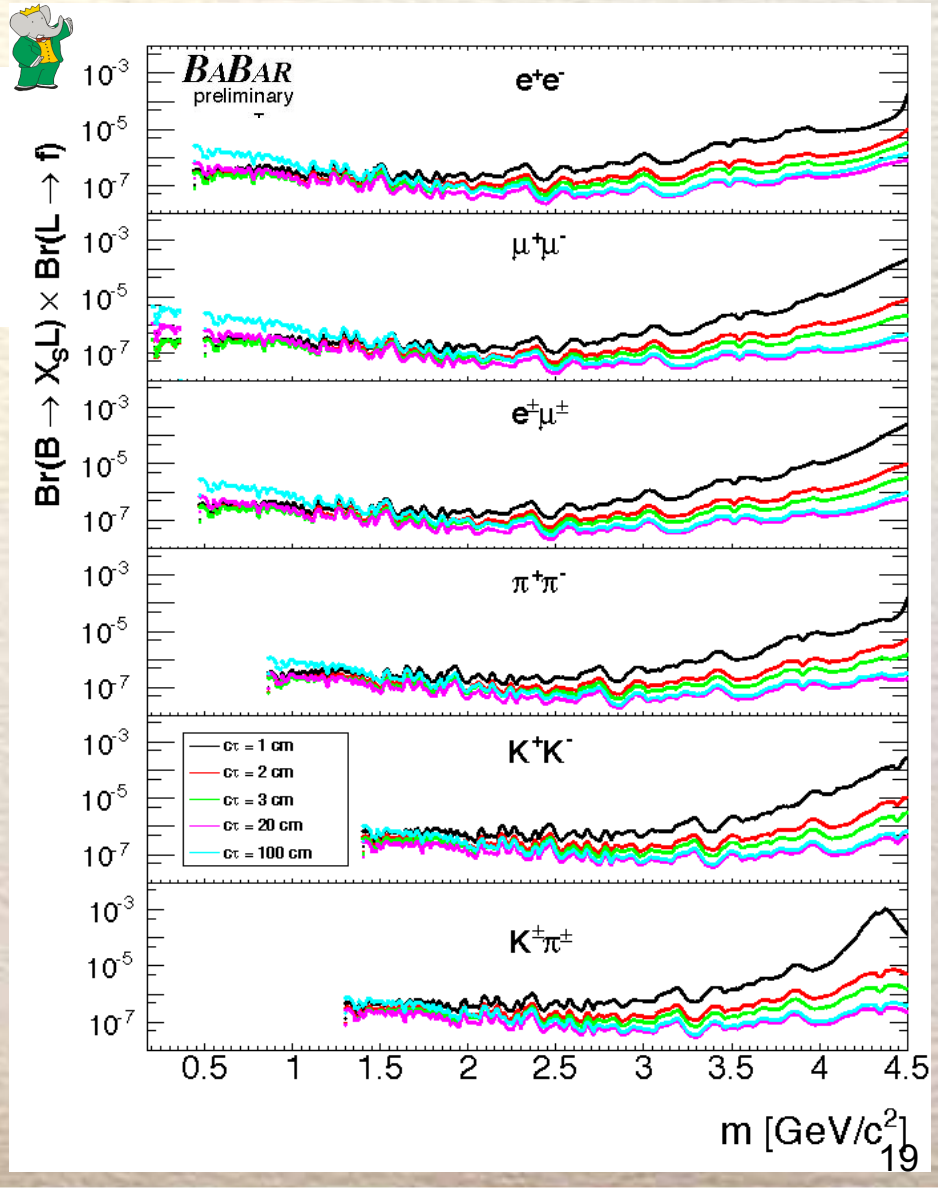
for each final state f and different cτ

- These limits exclude a significant region of the parameter space of the inflaton model

Bezrukov and Gorbunov, JHEP 1307, 140 (2013)



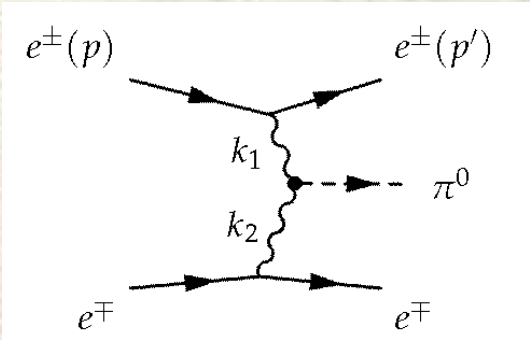



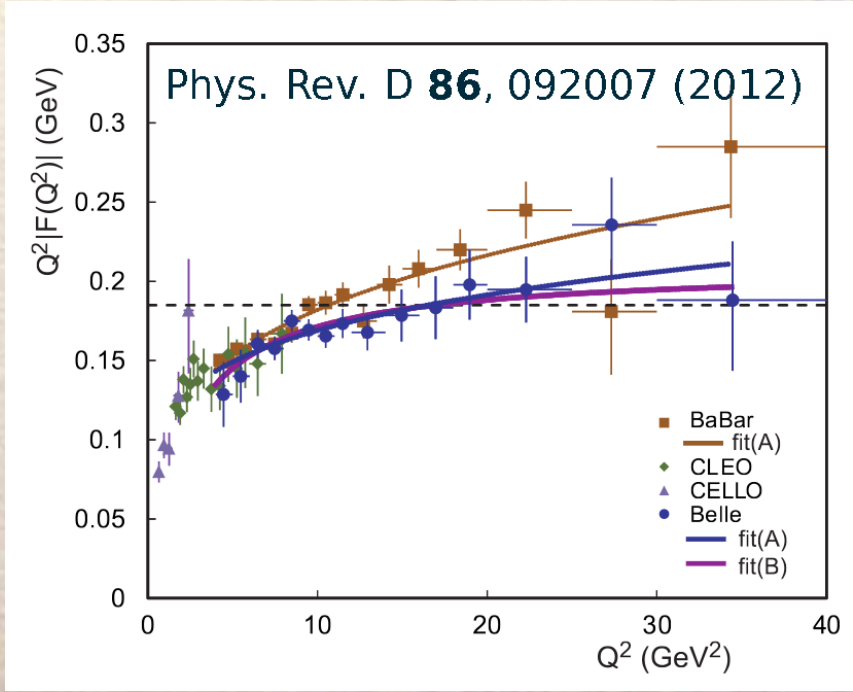
# Search for $\pi^0$-like Particles

# Motivation for $\pi^0$-like Particle Search

- Two-photon collisions were used by BABAR to measure the $\pi^0$ form factor
- At sufficiently high $Q^2$, the pion form factor should approach the Brodsky-Lepage limit of $\sqrt{2}\, f_\pi/Q^2 \approx 185\ \mathrm{MeV}/Q^2$ Brodsky et al., PRD 28, 228 (1983) )
- At $Q^2 > 15\mathrm{GeV}^2$, the prediction is highly reliable well beyond the non-perturbative QCD regime
- BABAR data show no sign of convergence towards the Brodsky-Lepage limit
- So maybe there is a new particle with a mass close to the $\pi^0$ mass decaying to $\gamma\gamma$ that causes this behavior
- The new particle may be a scalar ($\phi_S$), pseudoscalar ($\phi_P$) or hard-core pion ($\pi^0_{HC}$)

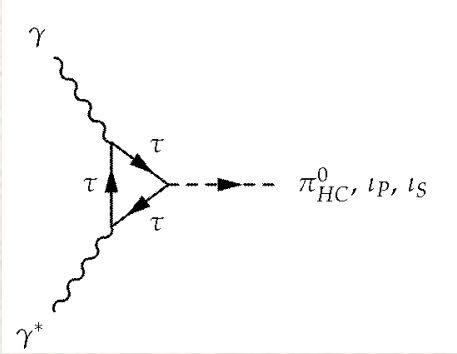
  Bakulev et al., PRD 86, 031501 (2012)
  Dorokhov, JETP let. 91, 163 (2010)
  Lucha et al., J. Phys D 39, 045003 (2012)
  Noguera et al., EPJ A 46, 197 (2010)



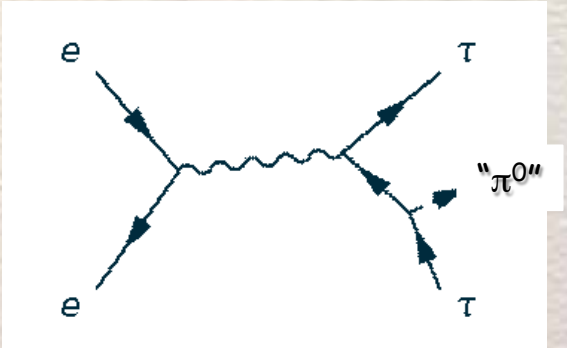
# Production of $\pi^0$-like Particles

- New particles may couple to $\tau$ leptons (other couplings are constrained by theory or experiments)




- So we focus on $\pi^0$-like particles in associated $\tau^+\tau^-$ pair production

- Cross sections for $\pi^0$-like particle production in $e^+e^- \to \tau^+\tau^-$ "$\pi^0$" processes, are predicted to be large (for $Q^2 > 8$ GeV$^2$)
  $\sigma_{\text{hard-core-pion}} = 0.25$ pb, $\sigma_{\text{pseudoscalar}} = 2.5$ pb and $\sigma_{\text{scalar}} = 68$ pb

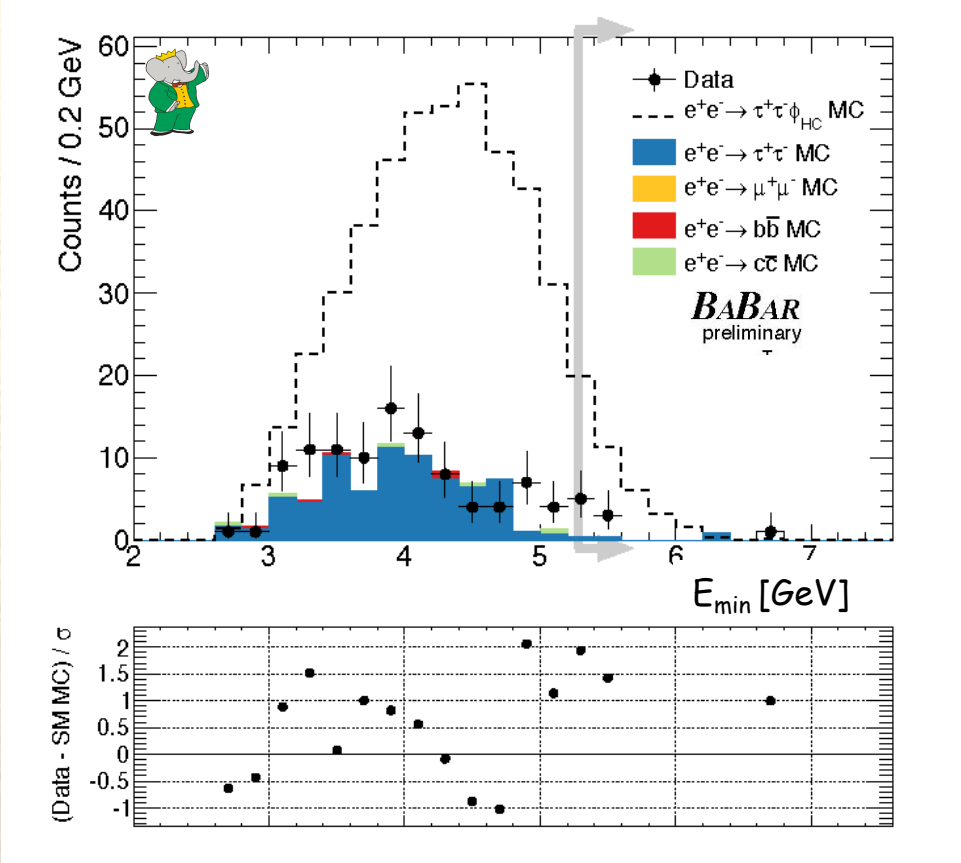



  ➔ Expect large samples at $\Upsilon(4S)$ in BABAR data set
  $N_{hcp} = 1.2\times10^5$, $N_{\text{pseudoscalar}} = 1.2\times10^6$ and $N_{\text{scalar}} = 3.2\times10^7$

- However, backgrounds are large as well

# Strategy for $\pi^0$-like Particle Search

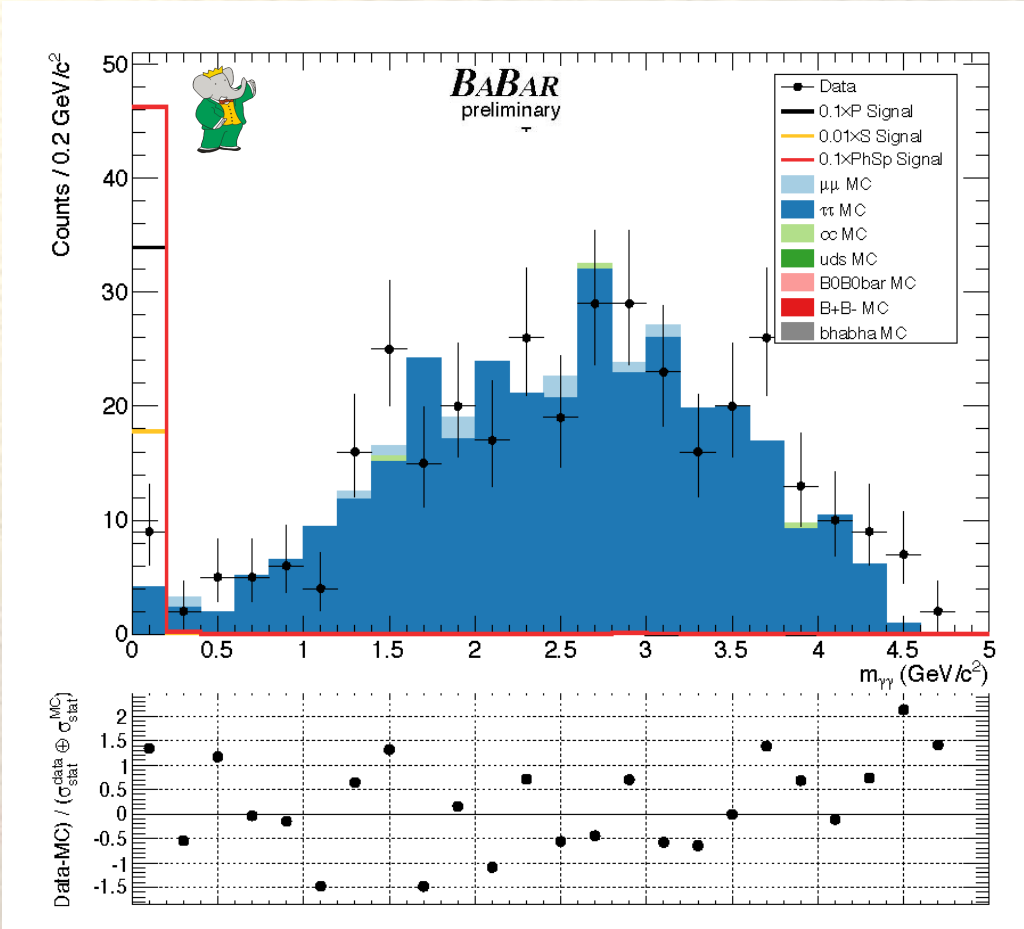
- BABAR study uses full $\Upsilon(4S)$ data set (468 $fb^{-1}$ ➔$4.3\times10^8$ $\tau$ pairs)
  - Select $\tau\tau$ events in the $\mu e$ decays with $p_T$>0.3 GeV for each lepton
  - Require exactly 1 $\pi^0 \rightarrow \gamma\gamma$ with $2.2 < E_{\pi 0} < 4.7$ GeV
  - Require $E_{extra} < 0.3$ GeV (total energy in the em calorimeter excluding $\gamma$,s from $\pi^0$ decay)
  - Reduce background from radiative e's: $E_\gamma$>0.25 GeV, $30° < \theta(e,\gamma) < 150°$
  - Reduce background from semi-leptonic + hadronic ($\pi^\pm\pi^0$) decays: $E_{min} = \min(E_l, E_\pi) + E_{\pi 0} > 0.5\ E_{CM}$; $m_{\pi\pm\pi 0} > m_\tau$




- $E_{min}$ spectrum before the requirement of $E_{min}$> 0.5 $E_{CM}$ is consistent with the expected $e^+e^- \rightarrow \tau^+\tau^-$ spectrum

# Signal Extraction for $\pi^0$-like Particles

- Fit $m_{\gamma\gamma}$ invariant-mass spectrum with Gaussian signal and linear background; $n(m_{\gamma\gamma}) = N_{lin}(1+a_{lin}\, m_{\gamma\gamma}) + N_g\ G(\mu_g, \sigma_g)$
  - Use unbinned maximum log-likelihood fit to extract $N_{lin}$, $N_g$ and $a_{lin}$
  - Get $\sigma_g$ from control study samples
  - Scan mass hypotheses $m_g$ between 110 MeV and 160 MeV
  - Extract highest yields in range

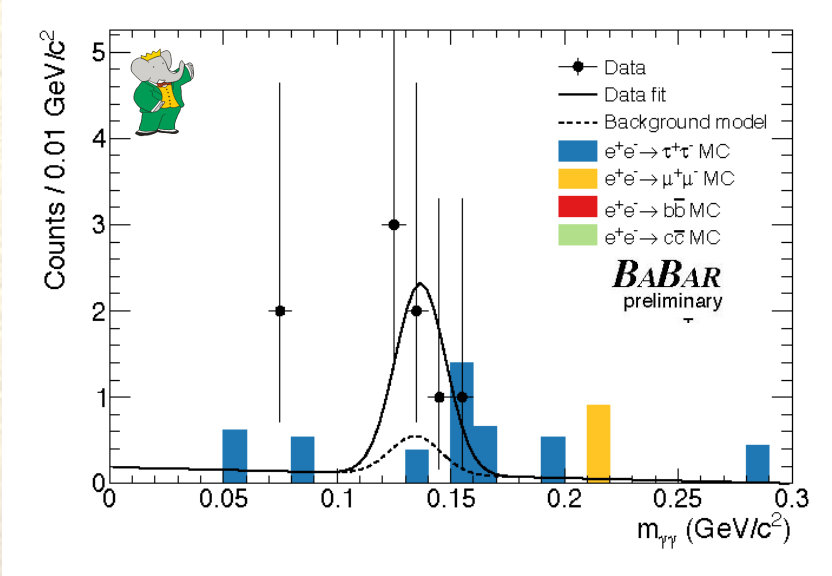


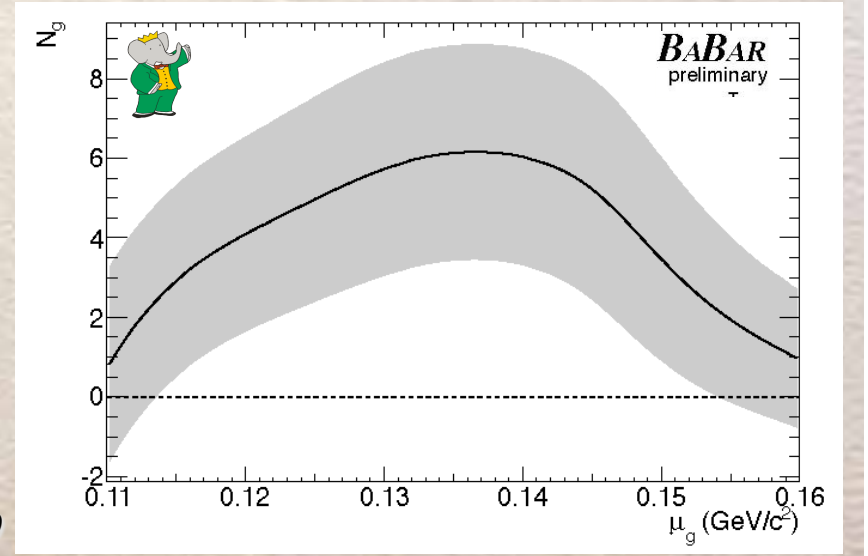

- Correct for peaking background: 1.24±0.37 events

- Correct for fit bias: -0.06±0.02 events

# Results for $\pi^0$-like Particle Search

- Perform extended maximum likelihood fit and scan over $\pi^0$ mass region
- Observe $N_g$= 6.2±2.7±0.06 events @137 MeV/$c^2$
  ➔ $N_{sig}=N_g-N_{bg}$= 5.0±2.7±0.4 events
- Efficiencies:
  $\varepsilon_{HCP,P}$=(0.455±0.019)% for $\pi^0_{HC}$ & $\phi_P$
  $\varepsilon_S$ =(0.090±0.004)% for $\phi_S$
- Cross sections:
  $\sigma_{HCP,P}$=(37.7±20.5$_{stat}$±3.2$_{sys}$) fb for $\pi^0_{HC}$ & $\phi_P$
  $\sigma_S$ =(191±104$_{stat}$±17$_{sys}$) fb for $\phi_S$
- Cross section upper limits @90%CL
  $\sigma_{HCP,P} \leq$ 73 fb ➔ (prediction: 270-820 fb)
  $\sigma_S \leq$ 370 fb ➔ (prediction: 68-1850 nb)
- Compatibility with theory (p-value)
  $\pi^0_{HC}$: p=5.9×10$^{-4}$; $\phi_P$:: p=8.8×10$^{-10}$; $\phi_S$:2.2×10$^{-9}$



# Conclusions and Outlook

- B factories are an excellent laboratory to search for light dark matter
- See no dark photons in 0.03- 10 GeV mass region ➔ push limit on the mixing parameter $\varepsilon$ at a level $10^{-4}$ to $10^{-3}$ depending on the dark photon mass
- Observe no long-lived particle in the $0.2 < m < 10$ GeV mass range and average flight length $0.5 < c\tau < 100$ cm
  ➔ this is the first search for long-lived particles at a high-luminosity $e^+e^-$ collider and the first search in a heavy-flavor environment
- The upper limit on the cross section for the production of $\pi^0$-like particles in association with a $\tau^+\tau^-$ pair is $\sigma < 73$ fb at 90% CL ➔ the hypothesis that $\pi^0$-like particles cause the non convergence of the pion form factor has a p-value of $5.9\times10^{-4}$ and thus is unlikely
- Belle II can improve on these limit by a factor of 3 to 2 orders of magnitude depending on the final state

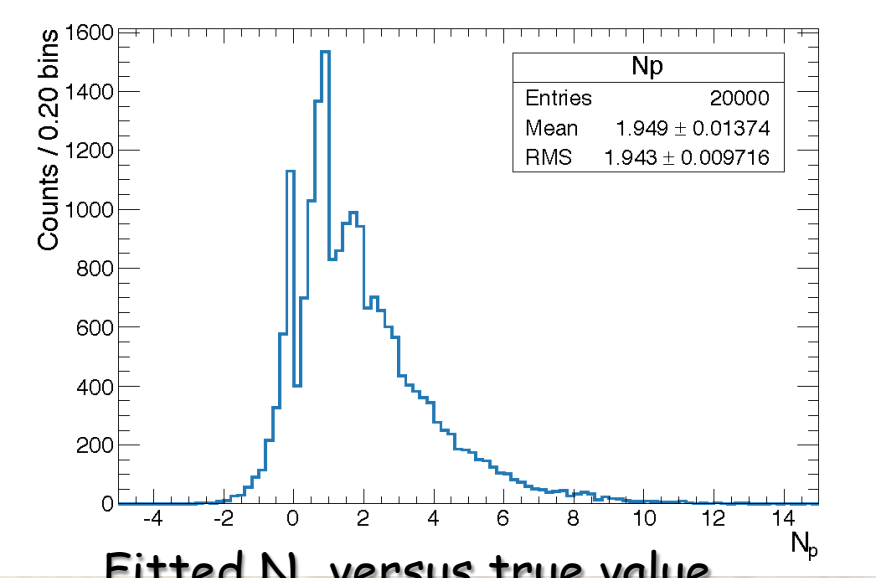
# Backup Slides

# Search for $\pi^0$-like Particles

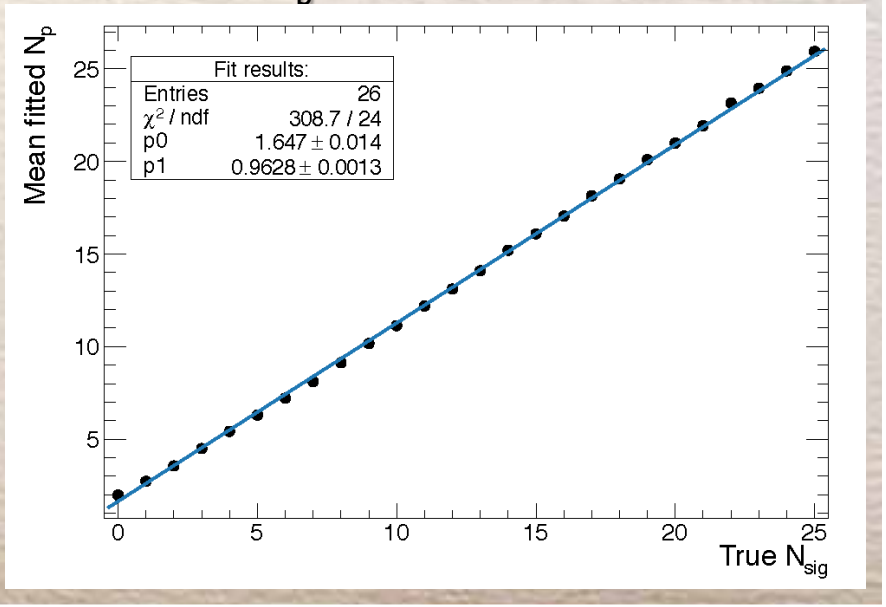
- Background studies
  - Extract combinatorial background from the fit
  - Simulate $e^+e^- \to \tau^+\tau^-$ ➔0.38±0.09 events
  - Estimate $\gamma\gamma$ contribution from data $e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$ ➔0.86=0.36 events
  - Total background: 1.24±0.37 events
- Fit bias study
  - Repeat fit after adding 0 to 25 signal events
  - Correct for the average fit error (bias): -0.06±0.02

➔ these results give the p-value of the background hypothesis ($p_0$)

Background-only distribution




Fitted $N_p$ versus true value



# Search for $\pi^0$-like Particles

- Generate $e^+e^- \to \tau^+\tau^-\pi^0$ with a 3-body phase space model
- Reweight according to the matrix element of the "$\pi^0$" like process (HCP, p,s)
- Fit using linear signal + linear background model
- Determine efficiencies:
  $\varepsilon_{P,HCP}$=(0.455±0.019)%
  $\varepsilon_S$ =(0.090±0.004)%
- Dominant systematic uncertainties come from the simulation statistics and the energy scale

| | $\varepsilon_{\iota_{P,}\pi^0_{HC}}$ | $\varepsilon_{\iota_S}$ |
|---|---|---|
| Nominal value | 0.455% | 0.0896% |
| Relative uncertainties | | |
| SP statistics | 3.5% | 3.7% |
| $\pi^0$ efficiency | 1.03% | 1.06% |
| PID Weighting | 0.5% | 0.5% |
| Momentum scale | 0.21% | 0.24% |
| Momentum resolution | 0.09% | 0.02% |
| Energy scale | 1.95% | 1.95% |
| Energy resolution | 0.55% | 0.55% |
| Combined uncertainty | 4.2% | 4.4% |