Direct searches for low-mass new physics particles at BABAR

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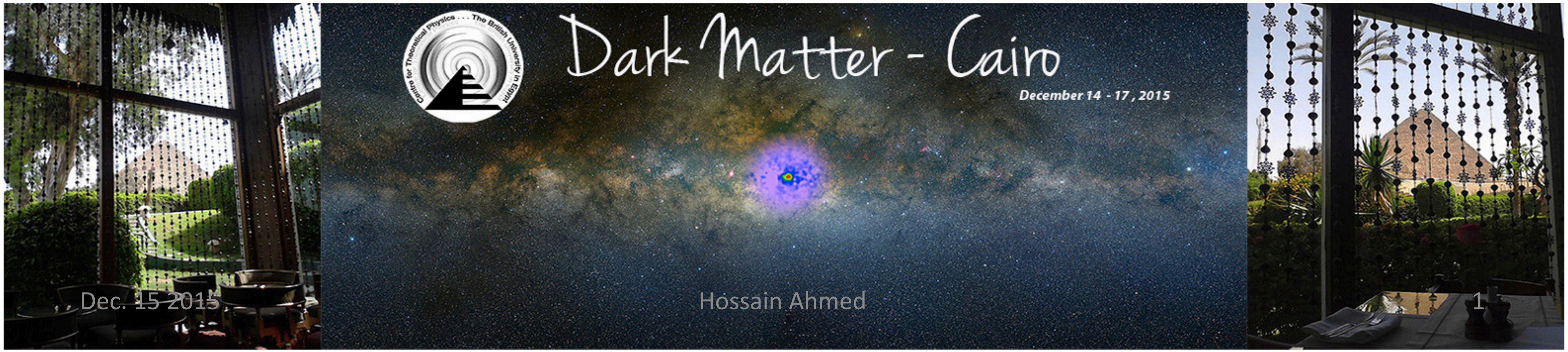
On behalf of the BABAR Collaboration



Direct searches for low-mass new physics particles at BABAR

✓ *Search for a light Higgs resonance in radiative decays of the $\Upsilon(1S)$ with a charm tag*

PRD 91 071102 (2015)

✓ *Search for a dark photon (→ e^+e^-, $\mu^+\mu^-$) in e^+e^- collisions at BABAR*

PRL 113 201801 (2014)

✓ *Search for Long-Lived Particles in e^+e^- Collisions*

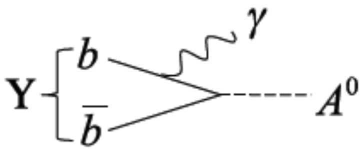
PRL 114 171801 (2015)

CP-odd Low-Mass Higgs

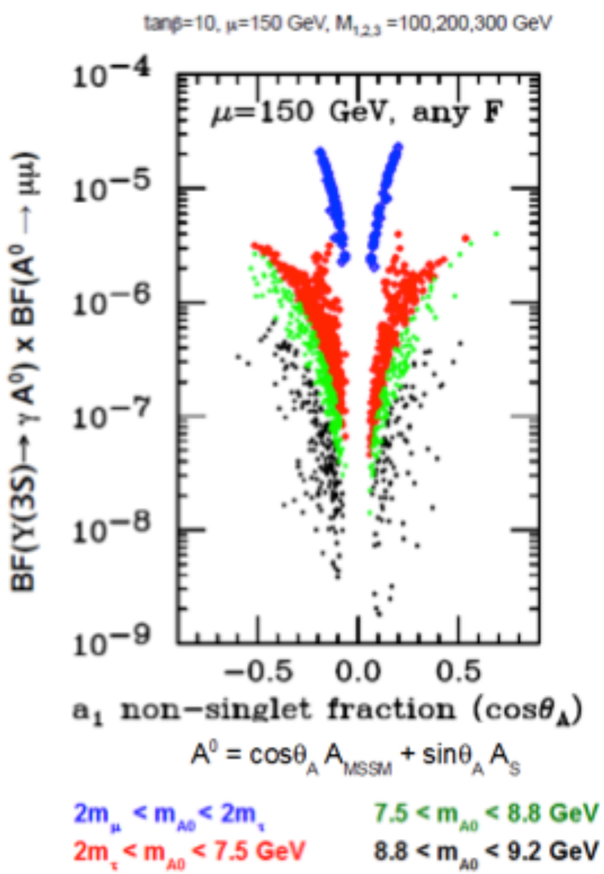
- An SM extensions, NMSSM, could solve the μ-problem of MSSM by adding one CP odd Higgs, one CP-even Higgs and one neutralino to MSSM content

- A light CP-odd Higgs A^0 with mass lower than $2m_b$ is not excluded by LEP constraints

- A CP-odd Higgs boson may be light enough to be produced at B-factories in bottonium decays



R. Dermisek et al., PRD 81, 075003 (2010)



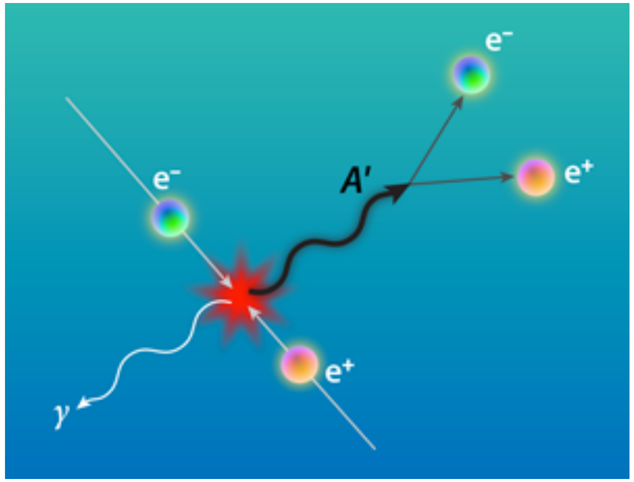
Dark Photon

- Success on SM urge more on BSM, e.g., Dark matter, Dark Energy etc.

- Dark matter might be a family of particles and forces—a so-called "dark sector" (e.g., Dark Force and Dark Photon)

- The Dark Photon $A^{/}$ may decays to the SM particles and may be light enough to observe in the low-energy e^+e^- colliders.

- Discoveries could bridge Astrophysics, Cosmology and Particle Physics.



APS/Alan Stonebraker

Long-Lived Particles (LLP)

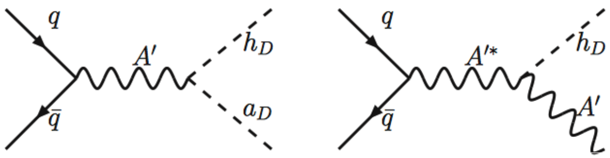
- Particles decaying in the detector far from interaction point are predicted by many extensions of the SM, e.g., split SUSY, hidden valley model etc.

- Many searches have been done already in different mass range, i.e., $m_{LLP} << GeV$, and $m_{LLP} \sim$ multi-GeV etc.

- Well suited search in the low-energy e^+e^- colliders, e.g., BABAR in $m_{LLP} \sim$ GeV mass range

- Long-Lived heavy neutrino search at BELLE (arXiv: 1301.1105)

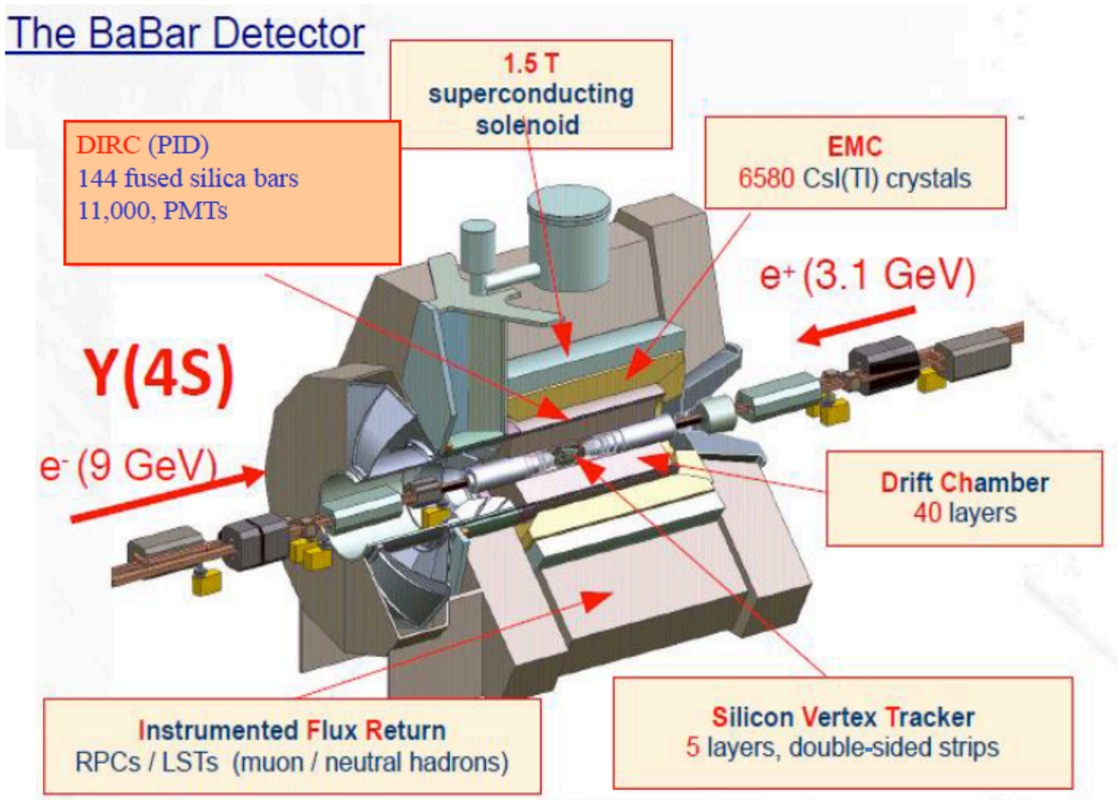
P Schuster: arxiv 0910.1602

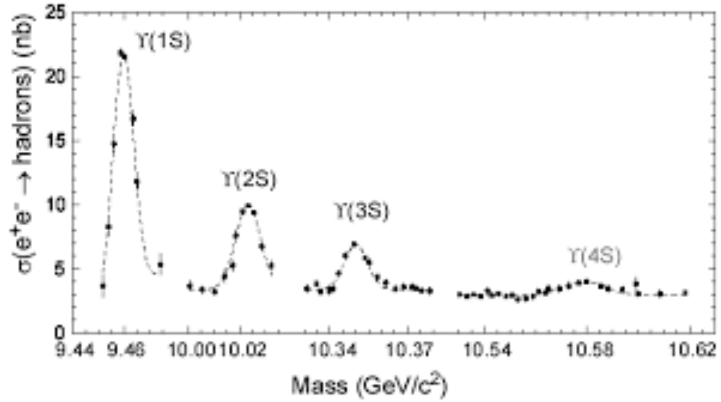


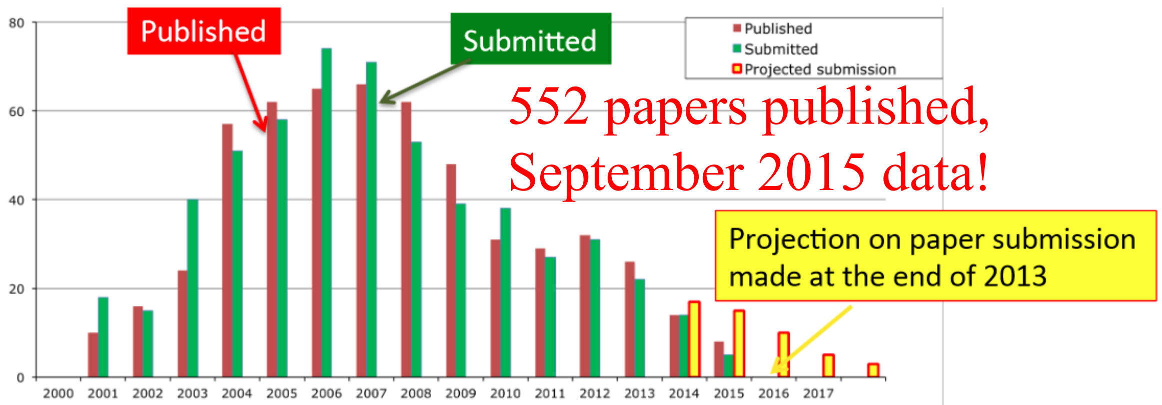
Analysis Modes

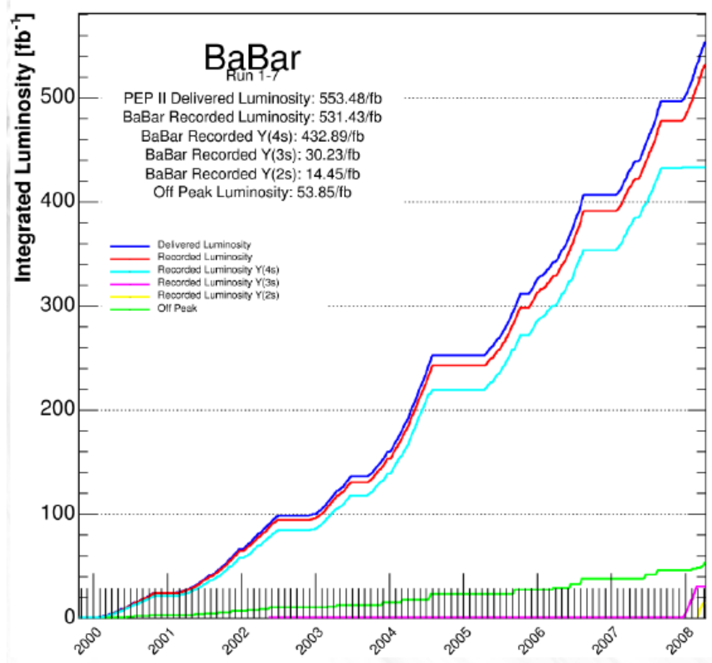
CP-Odd Low-Mass Higgs	Dark Photon	Long-Lived Particles
$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ $\Upsilon(1S) \to \gamma A^0, A^0 \to c\bar{c}$	$e^+e^- \to \gamma A', A' \to l^+l^-$ $l = e, \mu$	$f = e^+e^-, \mu^+\mu^-, e^\pm\mu^\pm$ $, \pi^+\pi^-, K^+K^-, K^\pm\pi^\pm$
13.6 fb^{-1} Υ(2S) on-resonance 1.4 fb^{-1} off-resonance (30MeV below of Υ(2S))	514 fb^{-1}	404 fb^{-1} Υ(4S) on-resonance 44 fb^{-1} Υ(4S) off-resonance (40 MeV below the on-resonance) 20 fb^{-1} Υ(4S) for validation 28 fb^{-1} Υ(3S) 14 fb^{-1} Υ(2S)

BABAR Detector





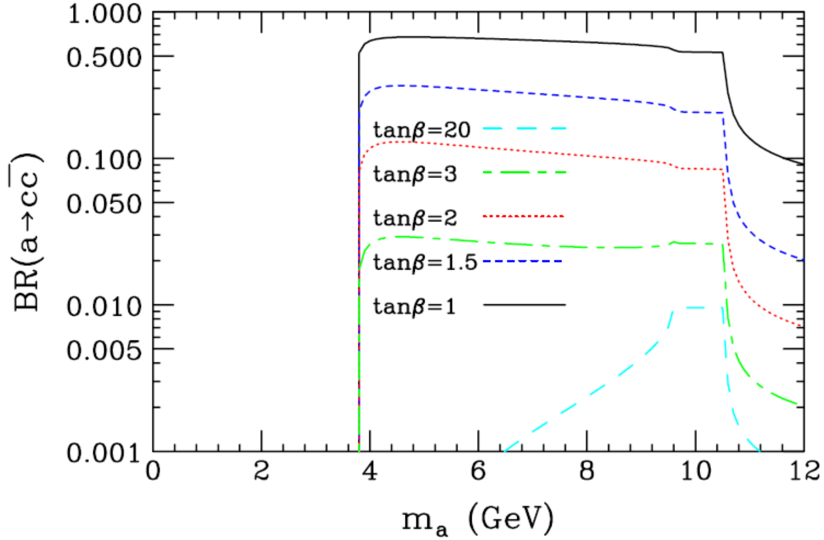




CP-odd Low-Mass Higgs Analysis

$\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible	arXiv:0808.0017 [hep-ex]
$\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	PRL 103, 181801 (2009)
$\Upsilon(2S, 3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	PRL 103, 081801 (2009)
$\Upsilon(2S, 3S) \to \gamma A^0, A^0 \to$ hadrons	PRL 107, 221801 (2011)
$\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible	PRL 107, 021804 (2011)
$\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	PRD 87, 031102 (2013)
$\Upsilon(1S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	PRD 88, 031102 (2013)
$\Upsilon(1S) \to \gamma A^0, A^0 \to gg, ss$	PRD 88, 031701 (2013)
$\Upsilon(1S) \to \gamma A^0, A^0 \to cc$	PRD 91, 071102 (2015)

R. Dermisek and J. Gunion, PRD 81, 075003 (2010)



BF depend on the final state particles and the model parameters, e.g., tanβ

Analysis Strategy

PRD 91 071102 (2015)

- Dipion (two oppositely charged track) + 1photon + hadron system (D (tag) +X)

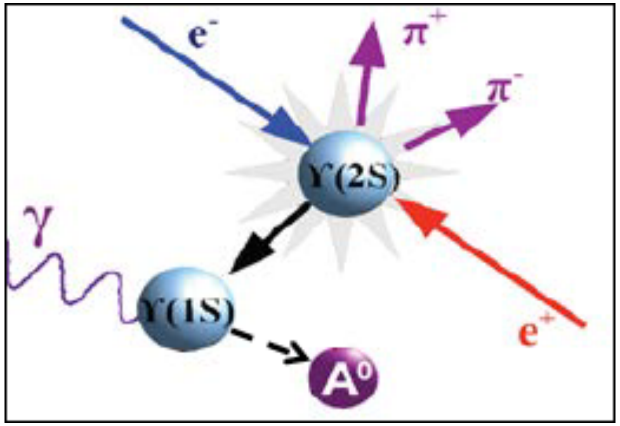
- The invariant mass, m_R for $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ is $m_R^2 = M_{\Upsilon(2S)}^2 + m_{\pi\pi}^2 - 2M_{\Upsilon(2S)}E_{\pi\pi}$

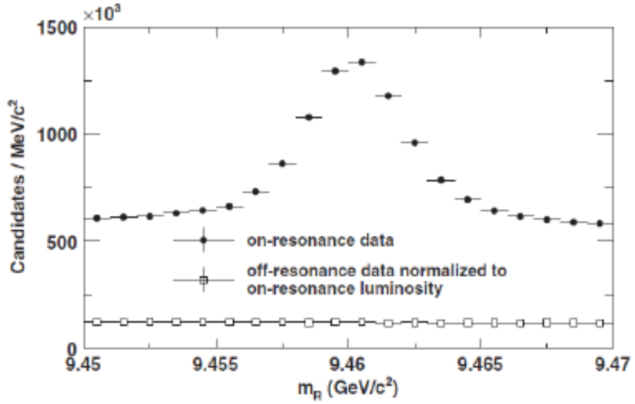
- EvtGen for signal event, Jetset for hadronization and GEANT4 for detector response

- Train 5 (charms) x 2 ($\pi\pi$ mass regions) BDT to discriminate signal from background using 24 variables (event shape, kinematics, vertex, D, photon, dipion)

- Reconstruct A^0 mass using

$$m_X^2 = (P_{e^+e^-} - P_{\pi^+\pi^-} - P_\gamma)^2$$





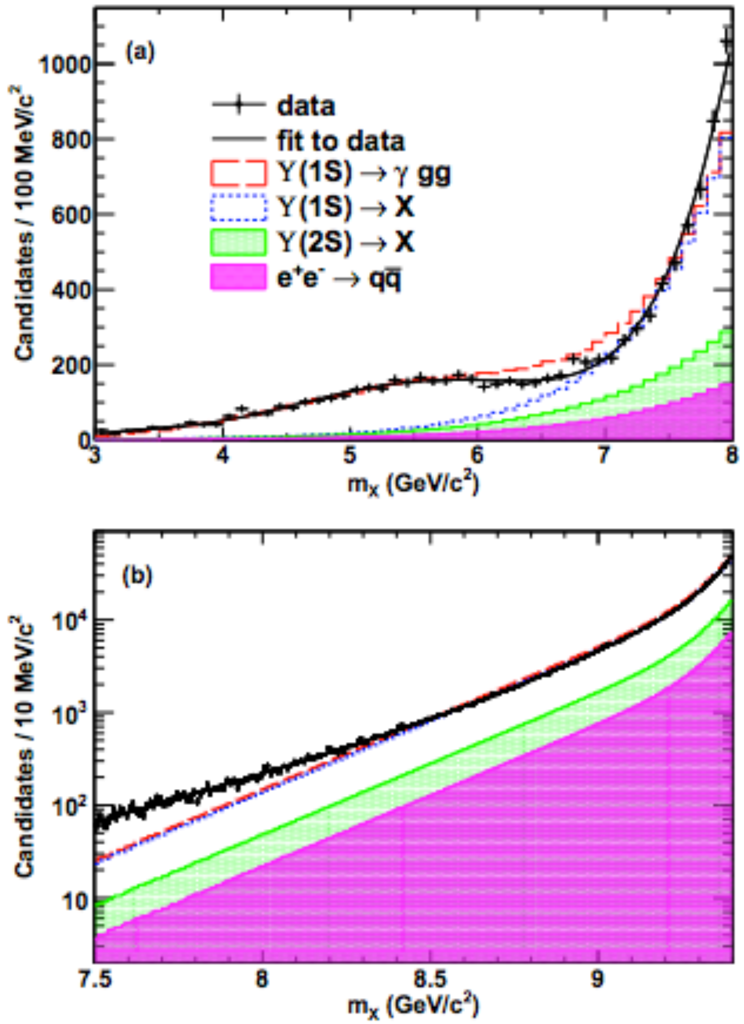
Backgrounds:
- $\Upsilon(1S) \rightarrow \gamma gg$
- $\Upsilon(1S) \rightarrow X$
- $\Upsilon(2S) \rightarrow X$
- qq continuum

Charm tag:
1. $D^0 \rightarrow K^- \pi^+$
2. $D^0 \rightarrow K^- \pi^+\pi^+\pi^-$
3. $D^0 \rightarrow K_S \pi^+\pi^-$
4. $D^+ \rightarrow K^- \pi^+\pi^+$
5. $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^- \pi^+ \pi^0$

Analysis Strategy

PRD 91 071102 (2015)

- 9800 and 7400000 candidates satisfy the selection criteria in low and high mass regions
- A^0 mass regions: low (4.00 – 8.00) GeV/c^2 and high (7.50 – 9.25) GeV/c^2
- Search for the A^0 resonance as a peak in the m_X distribution
- Signal m_X PDF modeled with the Crystal Ball function (Gaussian + Power Law)
- Background m_X PDF modeled with a 2nd order polynomials



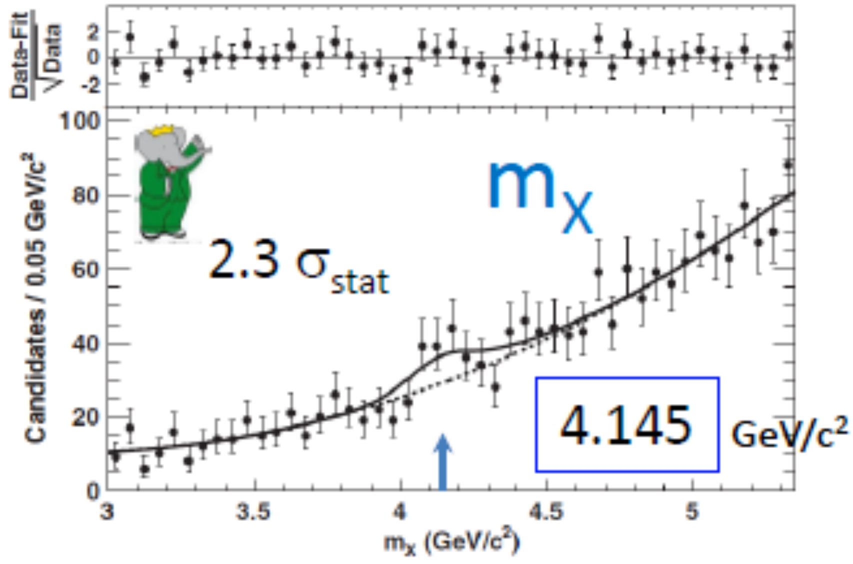
Exclude [8.95—9.1] GeV

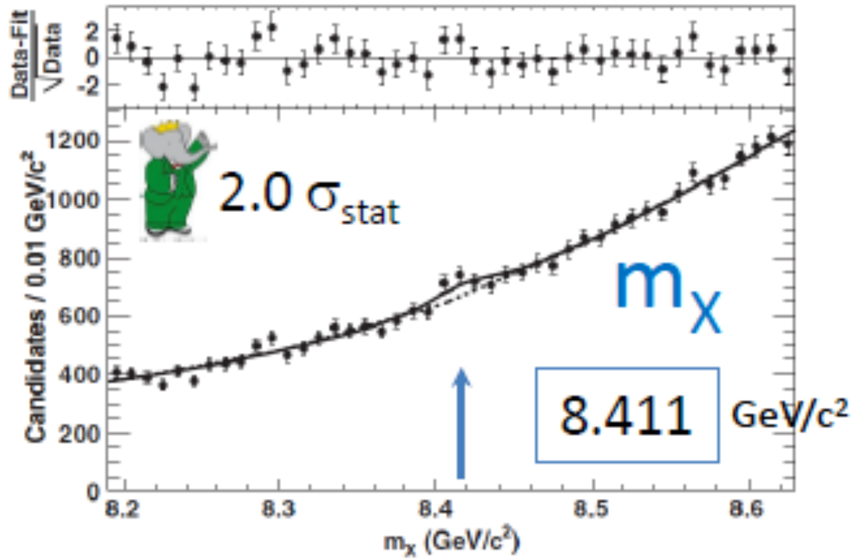
- avoid $\Upsilon(2S)\to\chi_b\to\Upsilon(1S)$ cascade

Analysis Strategy

PRD 91 071102 (2015)

- Reconstruction efficiencies ranges from 4.0% to 2.6%
- Local signal significance for low-mass region is 2.3σ
- Local signal significance for high-mass region is 2.0σ
- Systematic uncertainty dominated by ccbar hadronization ~10%, also signal PDF shape, D mass PDF, dipion BF & PDF, MC stats, γ efficiency, $N_{\Upsilon(2S)}$

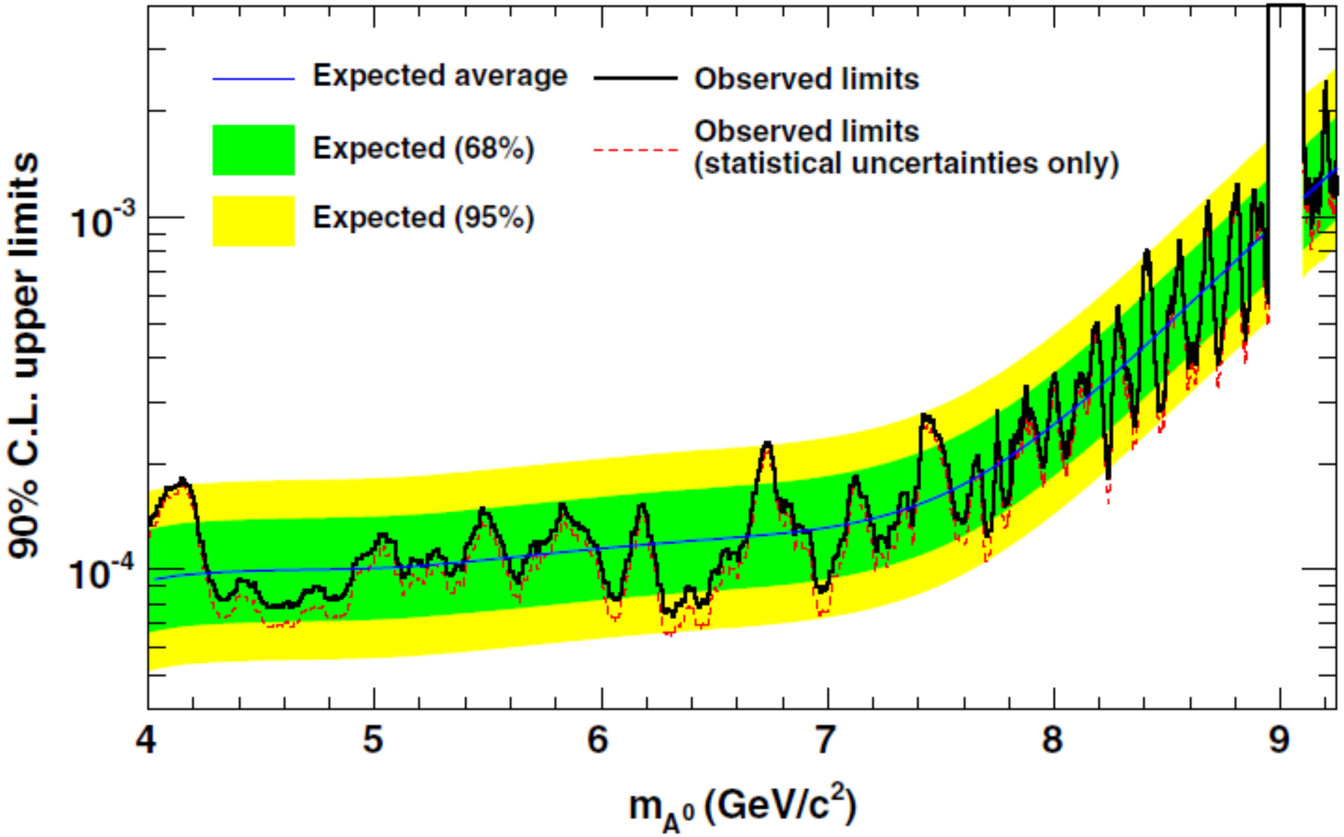




Result

PRD 91 071102 (2015)

- No significant signal



$$BF(\Upsilon(1S) \to \gamma A^0) \times BF(A^0 \to c\bar{c})$$

$$7.4 \times 10^{-5} - 2.4 \times 10^{-3} @ 90\% CL$$

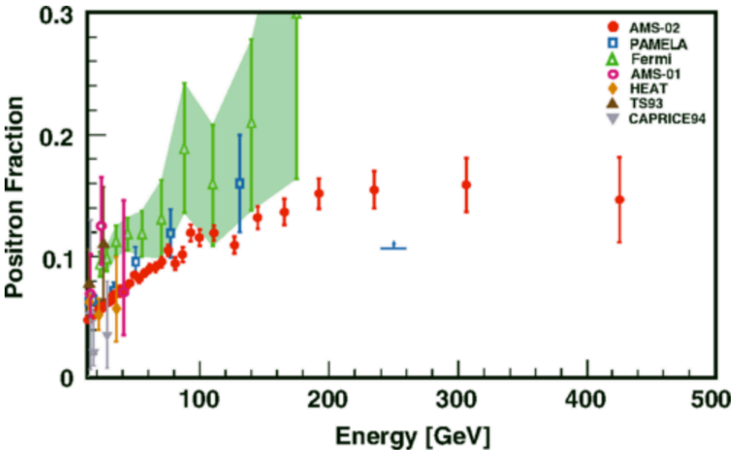
Dark Photon

• The dark photon ($A^{/}$) under a new gauge group $U(1)^{/}$ -- introduces by theory [arXiv:1311.0029, PRD 80 015003 (2009)]

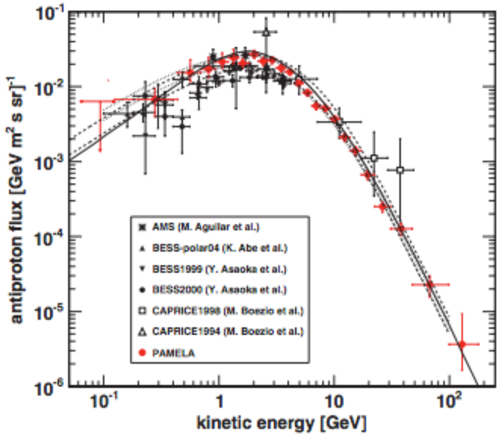
• Could be light (MeV-GeV mass range) and suitable for comparatively clean data from $e^{+}e^{-}$ collider, e.g. BABAR

• The excess of electrons and positrons, without a visible anti-proton excess, suggests dominantly leptonic decay or annihilation channels.

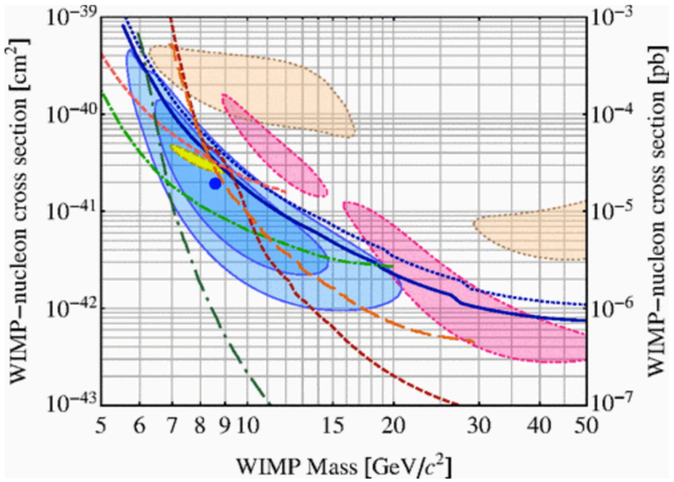
PRL 113 121101 (2014)



PRL 105 121101 (2010)



PRL 111 251301 (2013)



Dark Photon - Analysis

- Dark photon can be produced in

  $e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-, \mu^+\mu^-$

- Studied full BABAR dataset – 514fb^{-1}

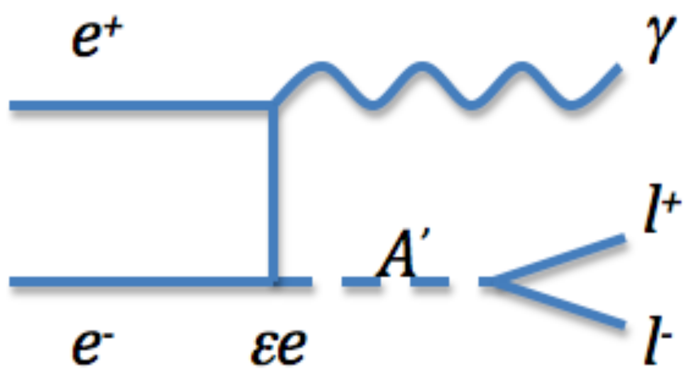
- Measure the cross-section of

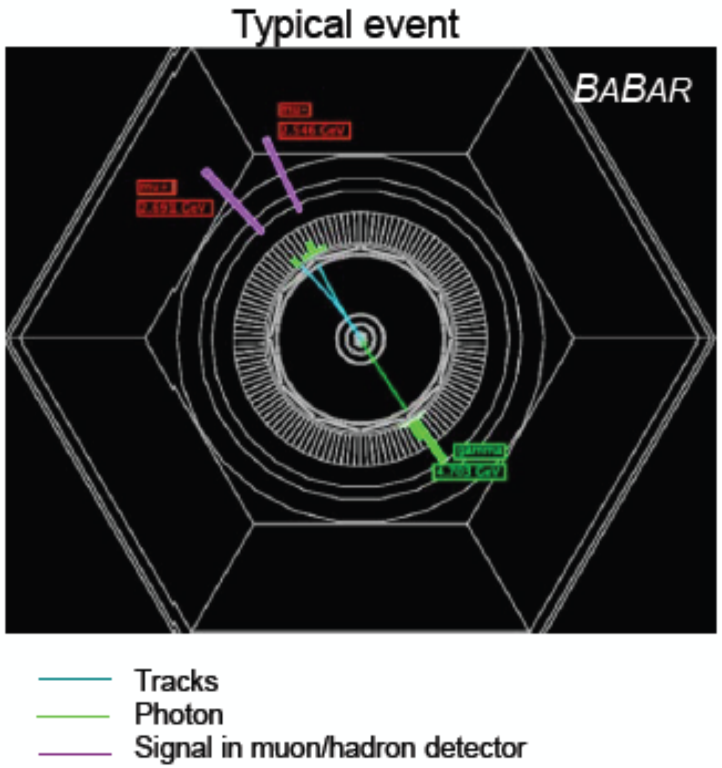
  $e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-, \mu^+\mu^-$

from 20 MeV to 10.2 GeV

- Look for a narrow peak in invariant mass (use reduced mass for dimuon channel)

- PRD 113 201801 (2014)





Dark Photon- Analysis

Event Selection

• Two tracks (oppositely charged) + 1 photon

• MadGraph for signal event, BHWIDE + KK for backgrounds and GEANT4 for detector acceptance

• Particle Identification (e/mu)

• Neural network to reduce the converted photons background

• Signal selection efficiencies are 15% (35%) for the dielectron (dimuon) channel

Signal Yield @ $m_{A'}$

Electron channel

• dielectron invariant mass spectra

• mass steps -> Gaussian fit -> simulated A'

• mass resolution: 1.5 -8 MeV

• 5704 fits : 0.02 – 10.2 GeV

Muon channel

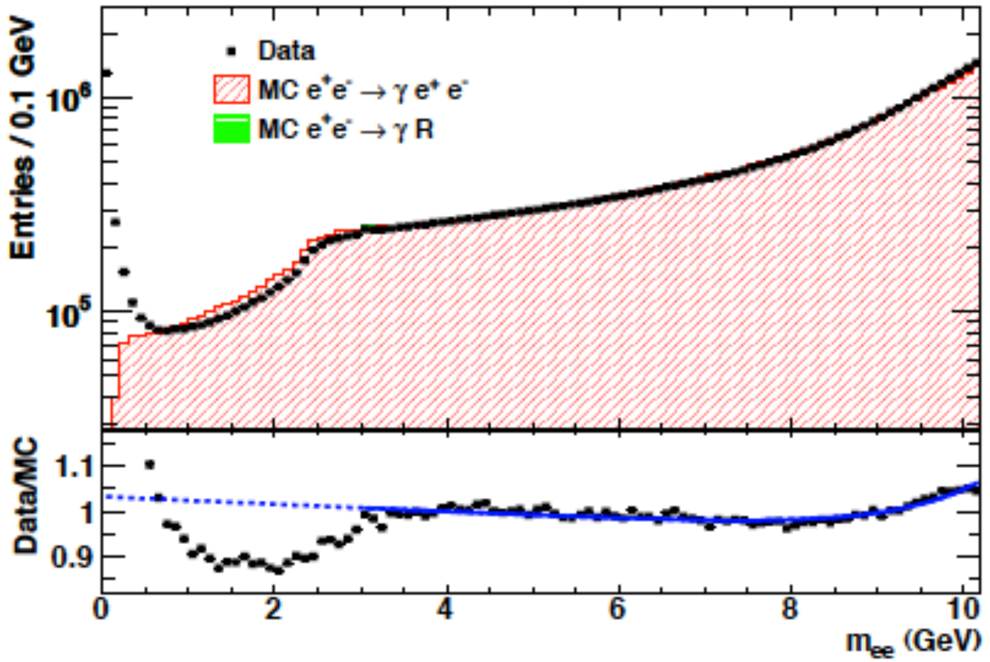
• reduced dimuon invariant mass spectra

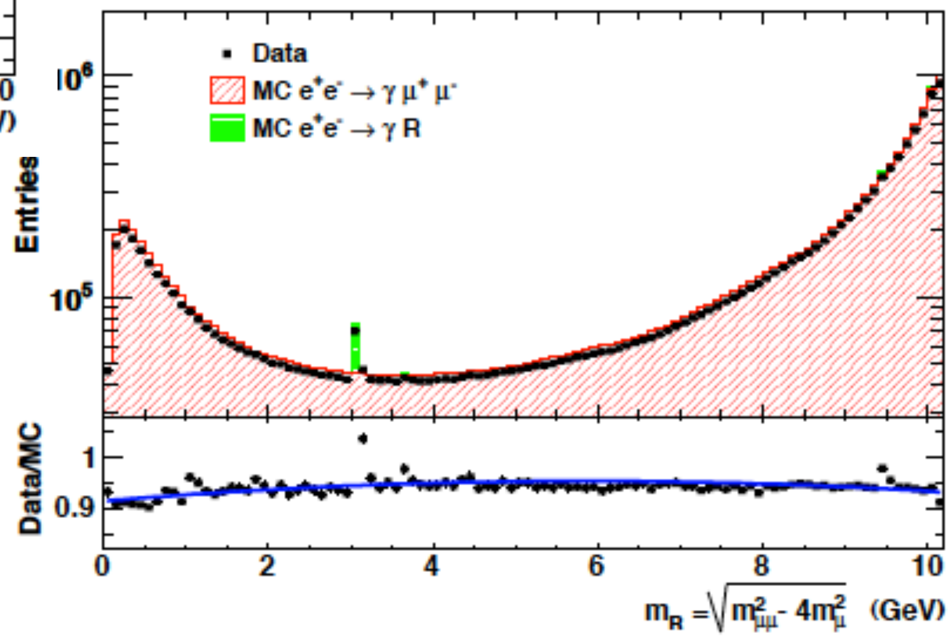
• mass steps -> Gaussian fit -> simulated A'

• mass resolution: 1.5 -8 MeV

• 5370 fits : 0.212 – 10.2 GeV

Dark Photon- Analysis





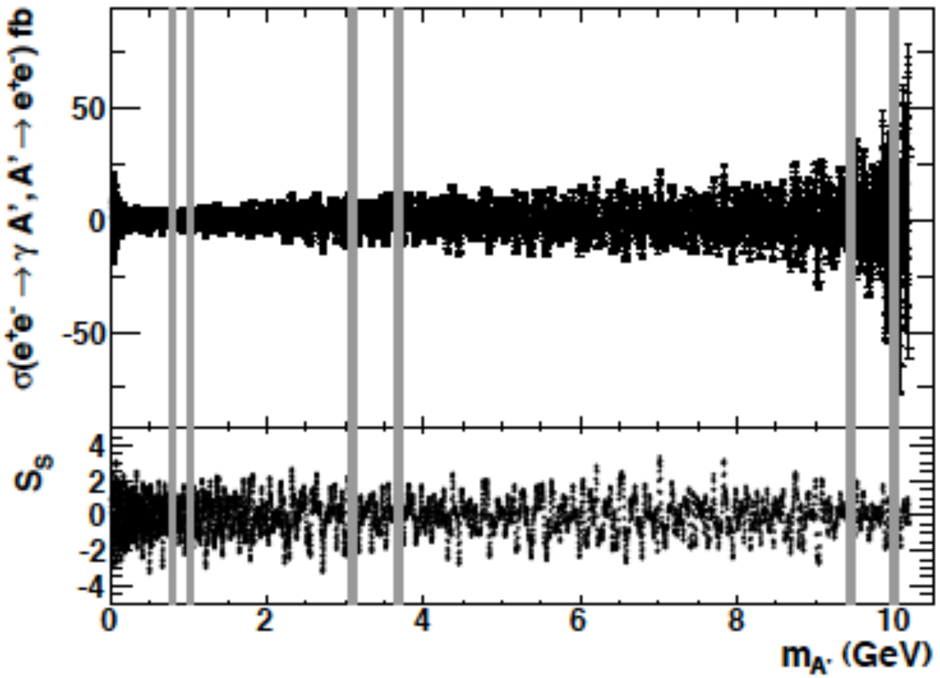
- Invariant mass distributions
- $R \approx J/\psi, \psi(2S), \Upsilon(1S), \rho$

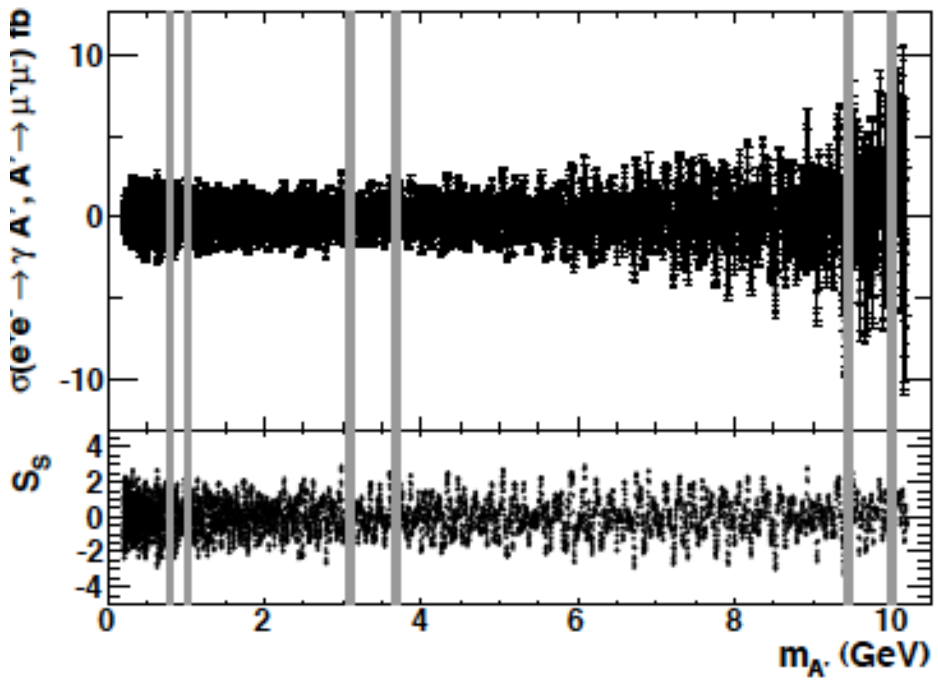
Dark Photon- Analysis

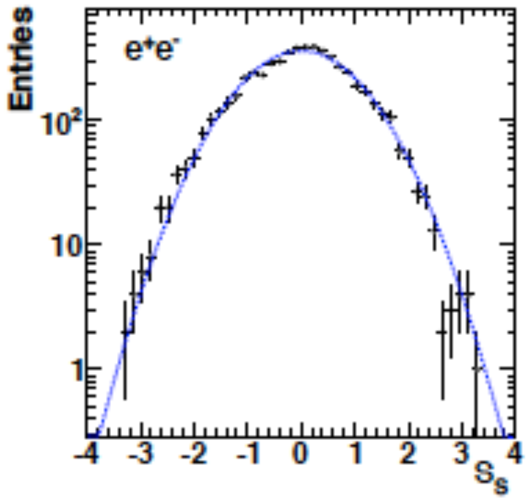
Cross-section of $e^{+}e^{-} \rightarrow \gamma A', A' \rightarrow l^{+}l^{-} (l = e, \mu)$

- Scan excludes the known resonances (gray bands in next page)
- Cross-section from the fitted signal yields (sum of signal yields/ efficiency x luminosity)
- Statistical significance of each fit $S_s = \sqrt{2\log(L/L_0)}$, where L and L_0 are the likelihood values for fits with a free signal and the pure background hypothesis respectively
- Dark photon BF, luminosity, and limited MC statistics propagates as systematic uncertainties

Dark Photon- Signal Significance

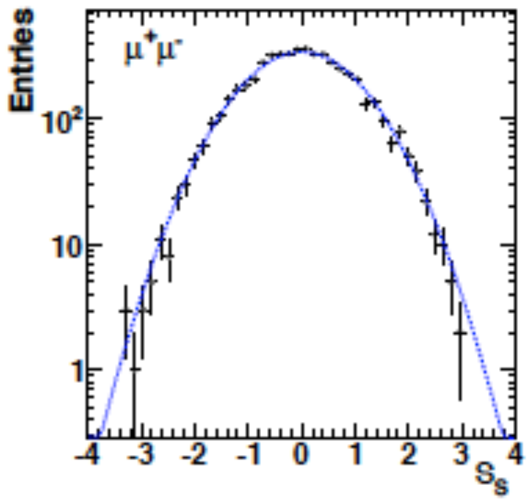






Largest fluctuation

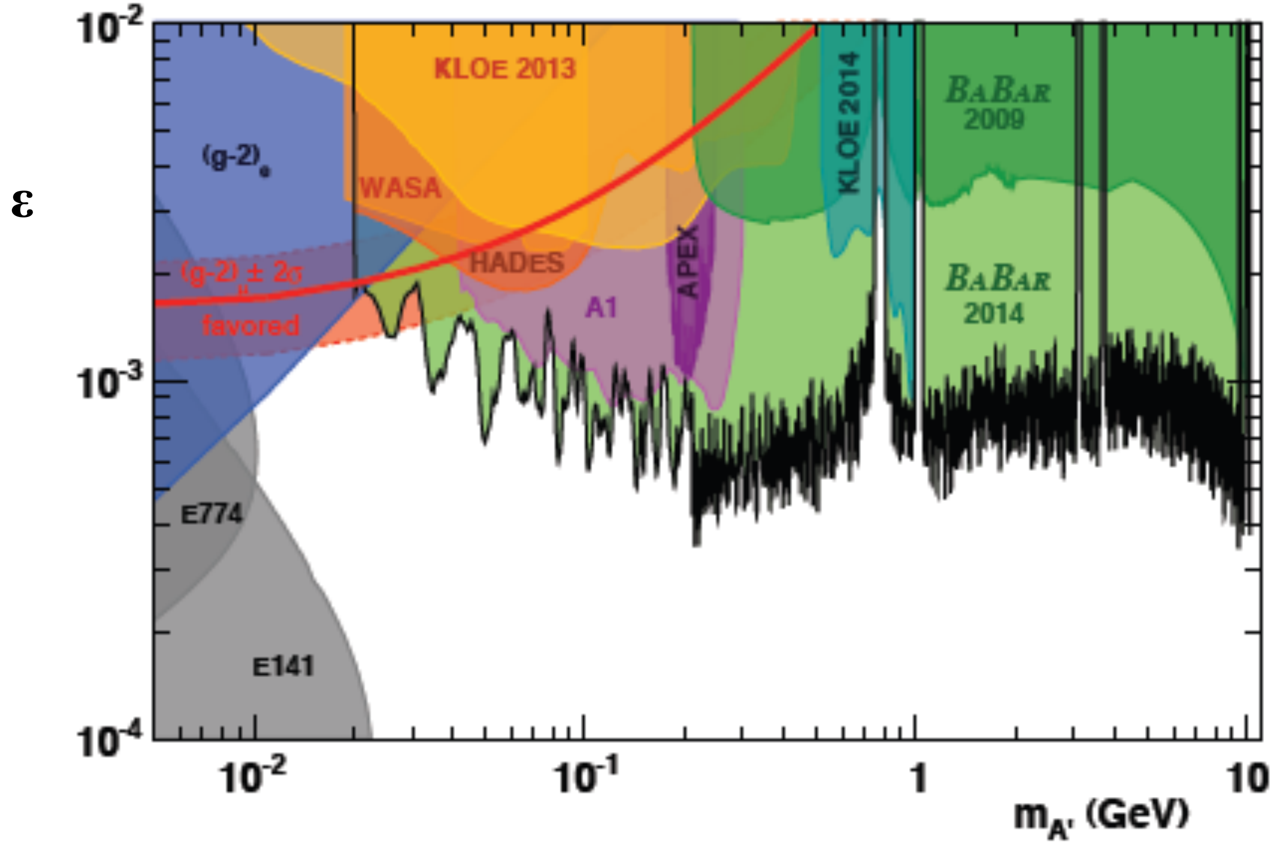
- 3.4 σ (e) M=7.02 GeV
- 2.9 σ (μ) M=6.09 GeV



Dark Photon- Results

- No significant signal

PRL 113 201801 (2014)



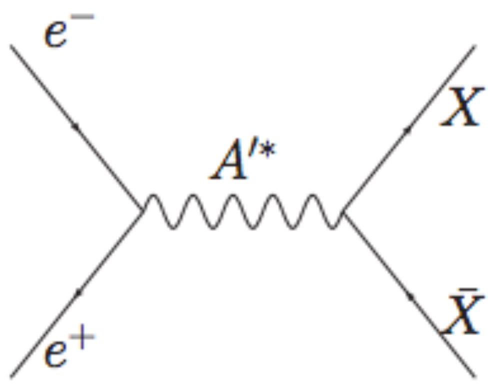
Upper limit on mixing strength at the level of 10^{-4} – 10^{-3} @ 90 % CL

Long-Lived Particles

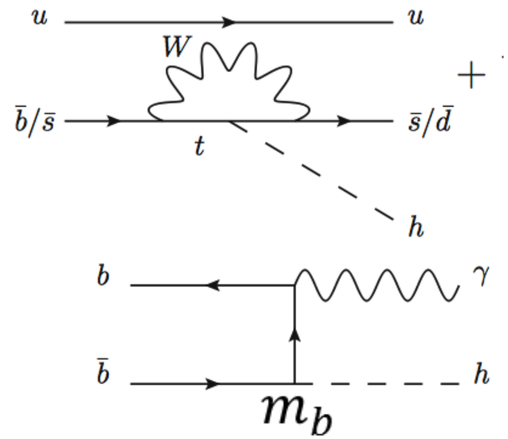
- GeV-scale hidden sector states that may be long-lived, have much attention from recent astrophysical observations (e.g., AMS, PAMELA, CDMS etc.) and theories (e.g., PRD 79 115008 (2009), PRD 80 015003 (2009) etc.)

- At B factories LLP can be produced via vector (dark photon) and/or scalar (Higgs) portal

R Essig, arXiv:0903.3941



Clarke, Foot, Volkas , JHEP 1402 (2014) 123



LLP Analysis

$$e^+e^- \rightarrow L \rightarrow f$$

$$f = e^+e^-, \mu^+\mu^-, e^\pm\mu^\pm, \pi^+\pi^-, K^+K^-, K^\pm\pi^\pm$$

L = neutral
L = long-lived (displaced vertex)
L = two-body decay (fit to the L candidate invariant mass)

Result Presentation

Model Independent (MI)

- *no assumption on L production mechanism*
- *present limit on the product of*

$$\sigma(e^+e^- \rightarrow LX) * BF(L \rightarrow f) * \varepsilon(f)$$

Model Dependent (MD)

$$BF(B \rightarrow X_s L) * BF(L \rightarrow f)$$

- X_s *– hadron system with strangeness -1*

LLP Analysis

MC production

→Model Independent

- EvtGen, L spin zero
- 11 masses (0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 9.5 GeV/c^2)
- for $m_0^{MC} \leq 4 GeV/c^2, e^+e^- \rightarrow B\overline{B}$ where one B decays to L+ Nπ (N =1,2,3) and other B decays generically
- At higher masses the production process is Y(4S)→ L + Nπ
- 20 cm transverse decay distance in both cases

→Model Dependent

- B→X_sL
- 7 masses (0.5, 1, 2, 3, 3.5, 4, and 4.5 GeV/c^2)
- 10% K, 25% K^*(892) and 65% K^*(1680)
- BTOXSLL model used with EvtGen for dimuon spectrum production (B→$X_s\mu^+\mu^-$)

→ Background MC

- EvtGen for $e^+e^- \rightarrow B\overline{B}$
- KK2f for $e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-$
- JETSET for $q\overline{q}$ and GEANT4 for detector acceptance

LLP Analysis

• Particle identification (PID) for oppositely charged track pairs

• $\frac{d_0}{\sigma_{d_0}} > 3$

• Two tracks are fit to a common vertex

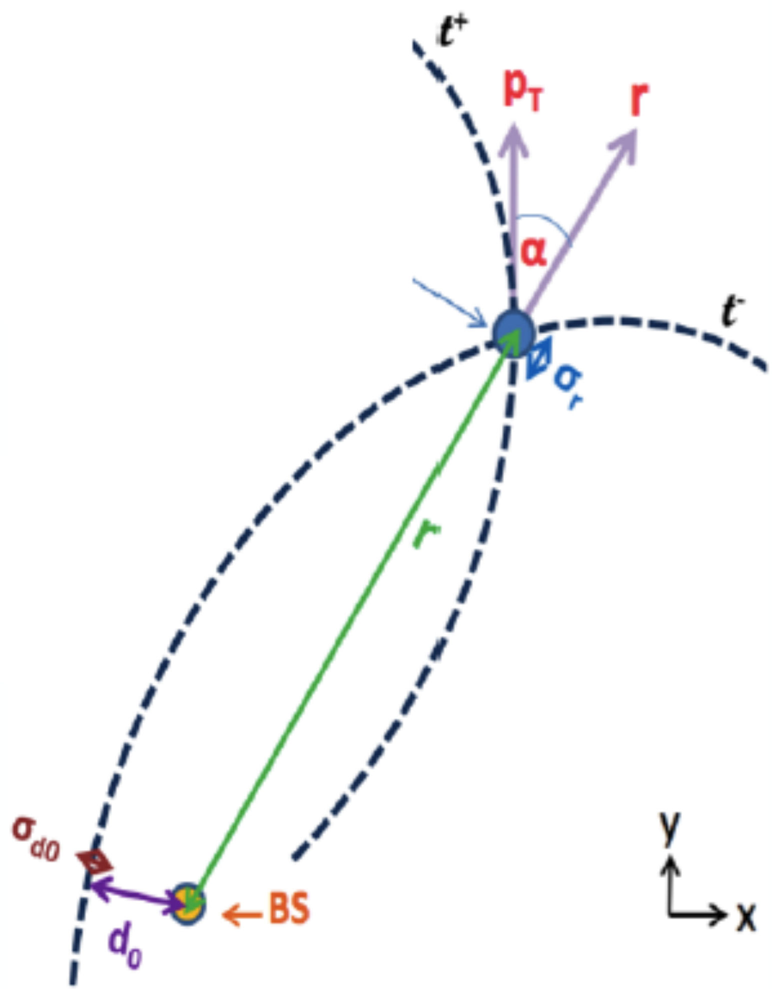
• $\chi^2 < 10$ (1 dof)

• $1 < r < 50\text{cm}$, $\sigma_r < 0.2\text{cm}$

• $\alpha < 0.01$ rad

• $\sigma_m < 0.2 \text{ GeV}/c^2$

• Remove K_s and Λ candidates (mass)

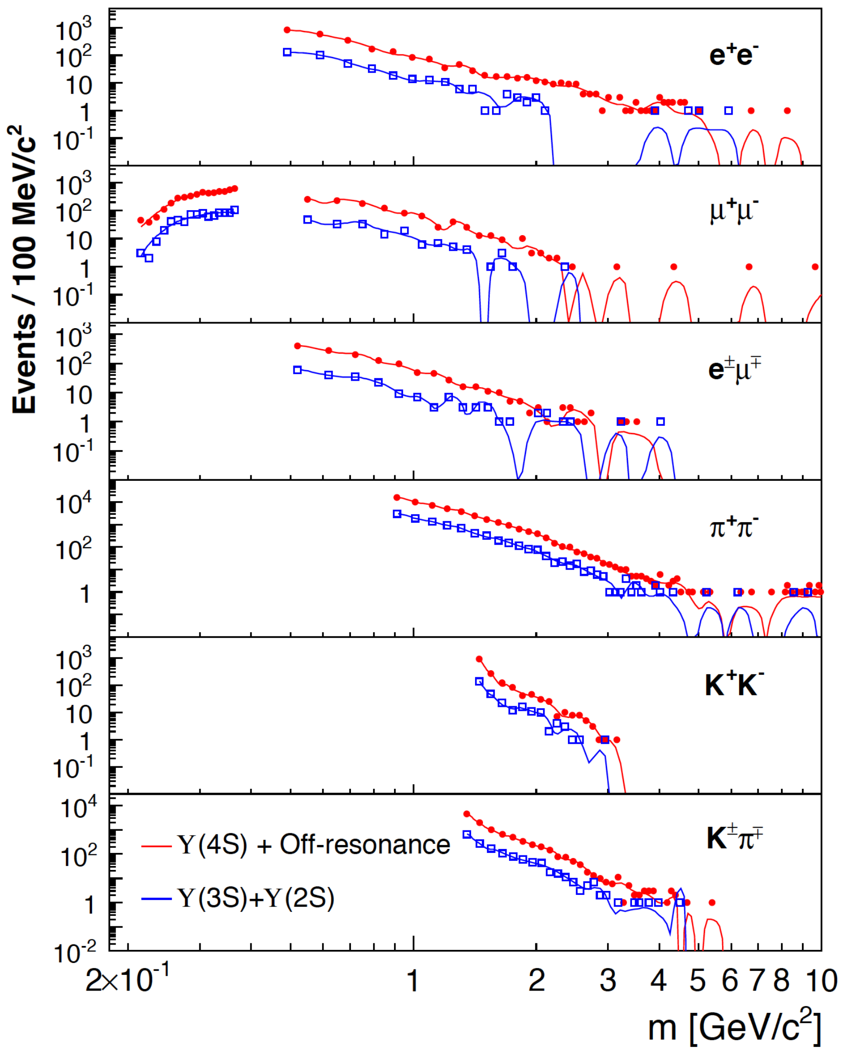


LLP Analysis - Signal Extraction

- Extract the signal yield for each final state as a function of L mass
- Performed unbinned extended maximum likelihood (UEML) fit
- Scan for a signal on top of background in 2MeV steps
- For each scan point the the statistical significance of signal is

$$S(m_0) = \pm\sqrt{2\log\frac{L(s+b)}{L(b)}}$$

- Two scan points have a significance > 3σ, in $\mu^+\mu^-$ mode
  - *one consistent with γ conversion,*
  - *the other is not significant, when accounting for the look elsewhere effect.*



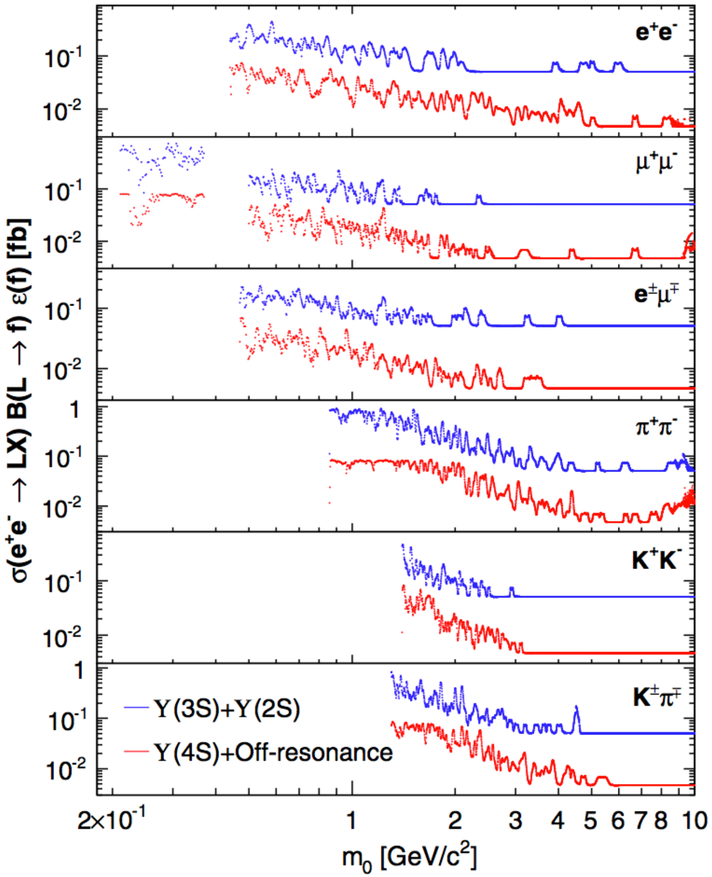
LLP -- Result

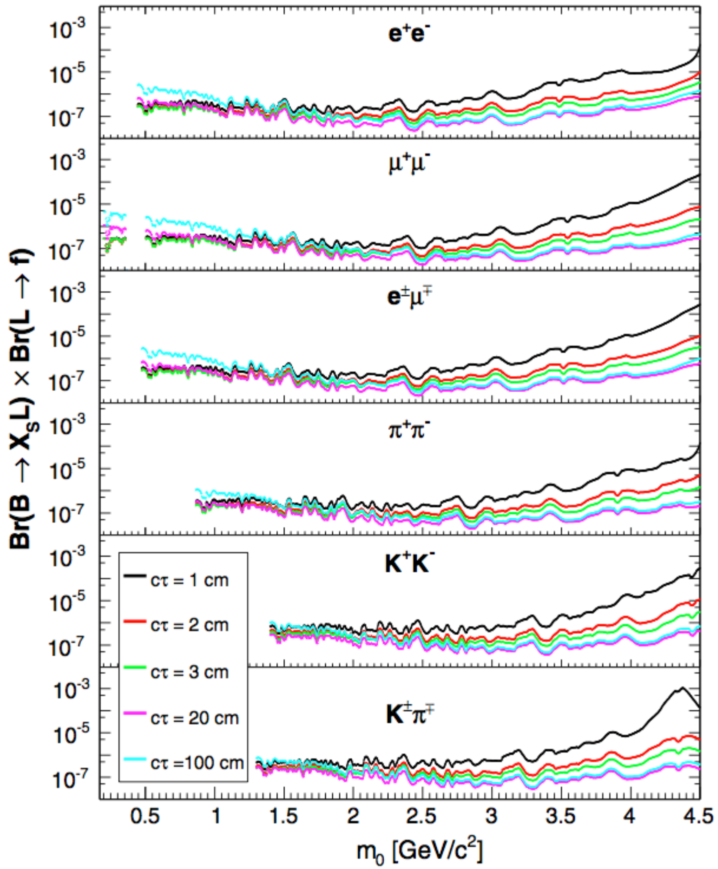
- No significant signal

MI

PRL 114 171801 (2015)

MD





Upper limit on both cases are set at 90 % CL for six 2-body final state

Summary

• BABAR has made a significant contribution on search for the low-mass new physics particles

-- Direct searches: unique sensitivity to low-mass new physics in high-statistics datasets

• No significant evidence for light new physics particle has been found and upper limits have been set

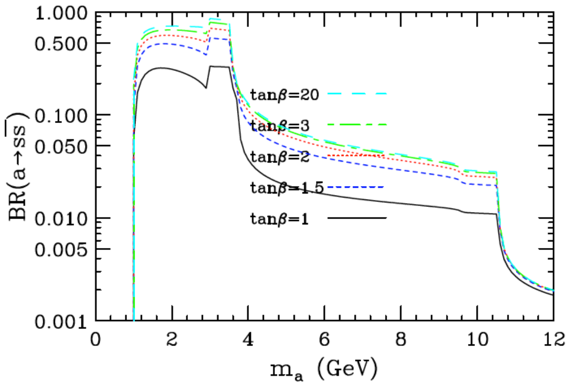
• Future B factories, e.g. BELLE-II will provide more statistics and improve the current limit (and/or new findings!)

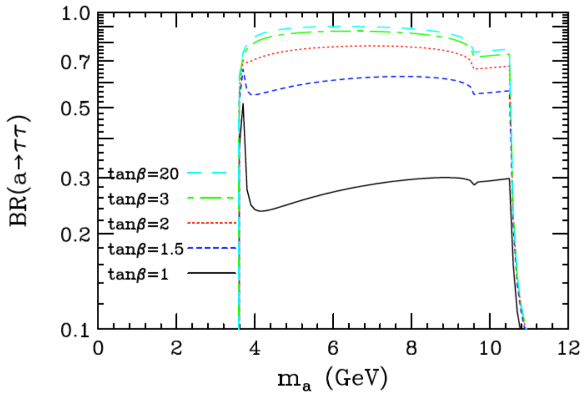
Summary

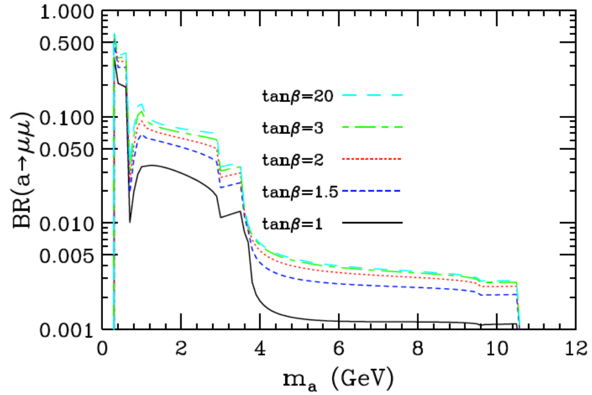
JAZAN invites any regional and global collaboration in particle physics field!

THANK YOU!

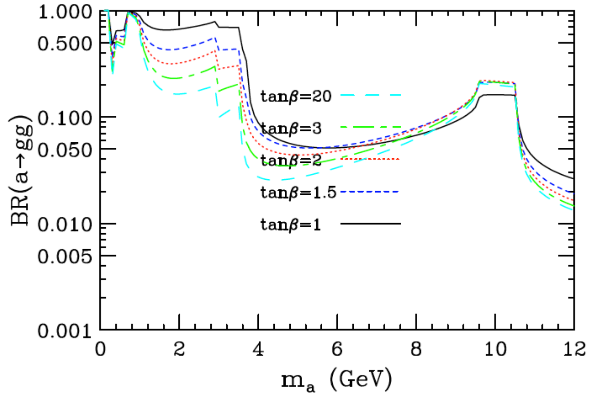
Backup Slides

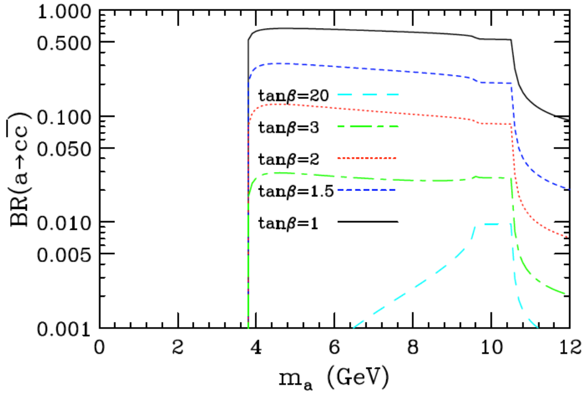


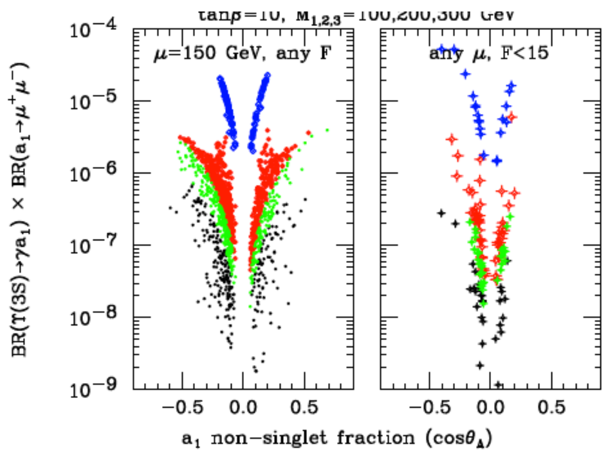




R. Dermisek and J. Gunion PRD 81 075003(2010)

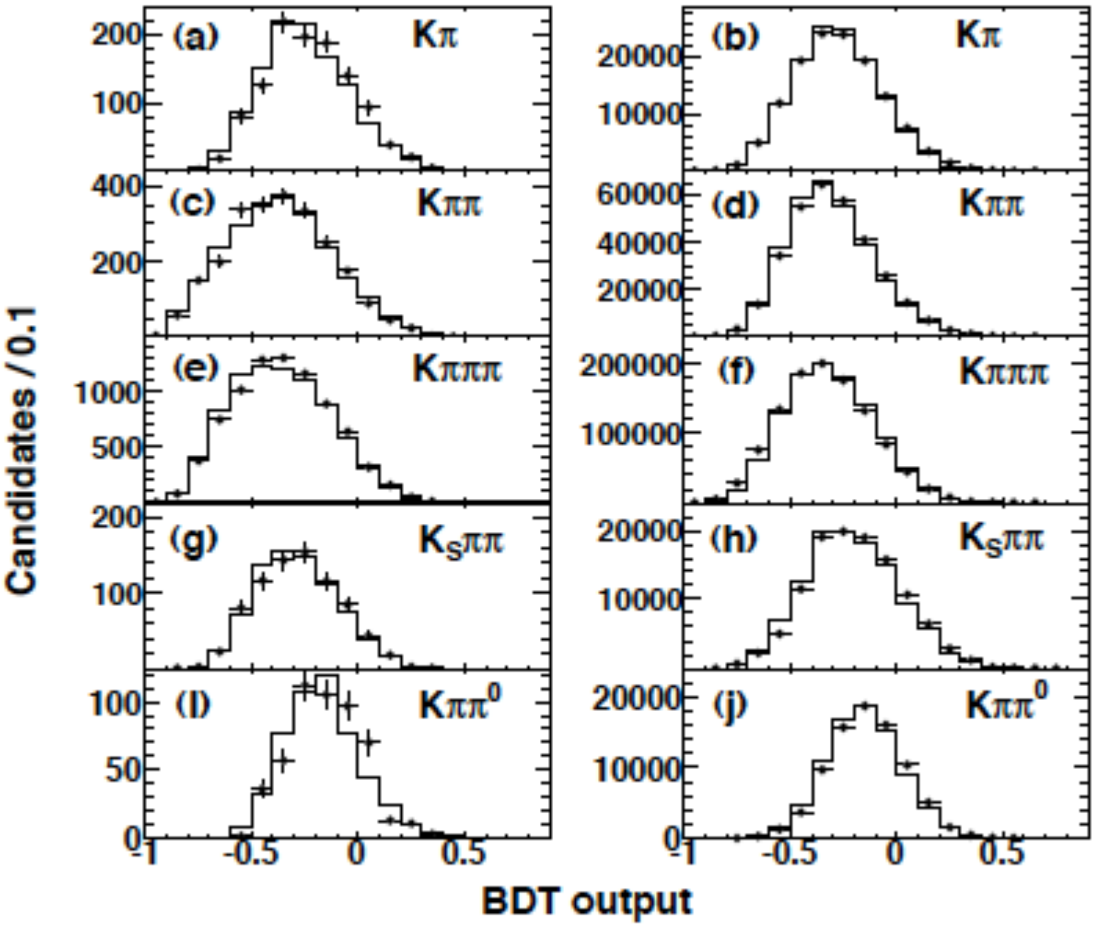






Backup Slides

PRD 91 071102 (2015)



Backup Slides

Richard Kass Talk in DPF 2015, Ann Arbor, MI

Highest-significance mass points

$m_{\mu\mu}$=0.212 GeV

S=4.7

13 signal events

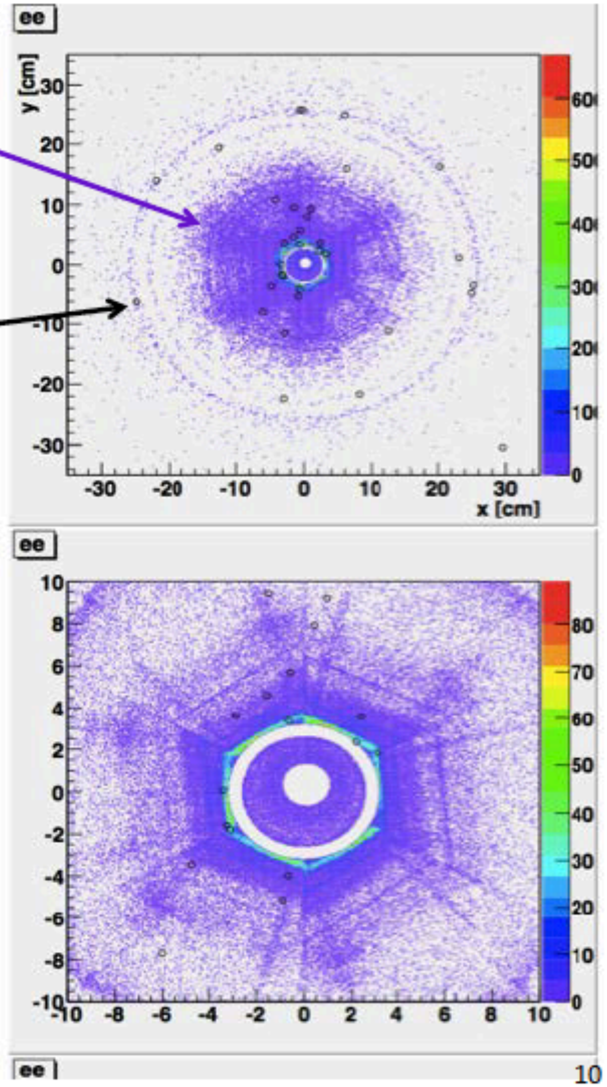
p-value=4×10^{-4} with look-elsewhere effect in $m_{\mu\mu} < 0.37$ GeV

More than 50% of the candidates are in or near material regions.

All have $0.2 < p < 0.3$ GeV where is e-μ discrimination is poor.

Consistent with γ-conversions

γ-conversion, $m_{ee} < 10$ MeV



$m_{\mu\mu}$=1.24 GeV

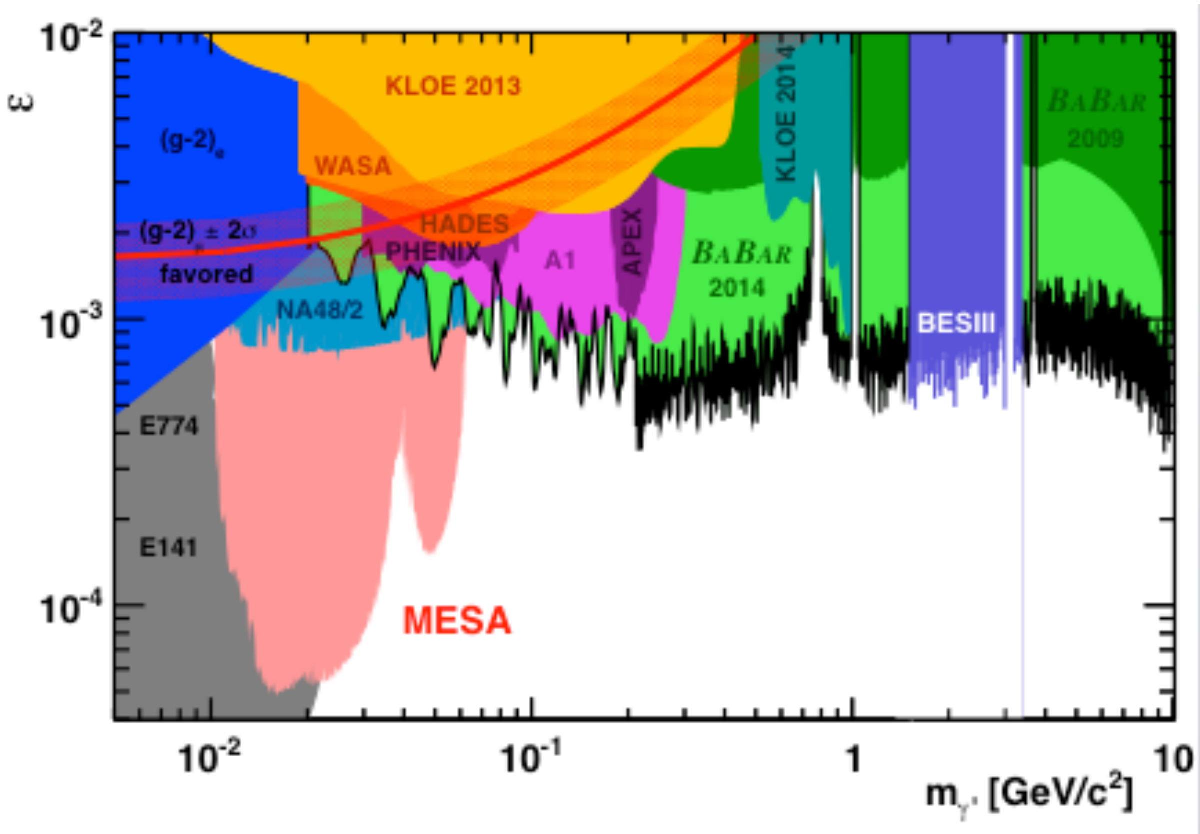
S=4.2

10 signal events

p-value=8×10^{-3} with look-elsewhere effect in $m_{\mu\mu} < 0.5$ GeV

8/5/2015 Richard Kass 10

Backup Slides



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International Workshop on e+e- Collisions from Phi to Psi
September 26, 2015
Hefei, China