Search for light CP-odd Higgs boson and low mass New Physics at *B*A*B*AR

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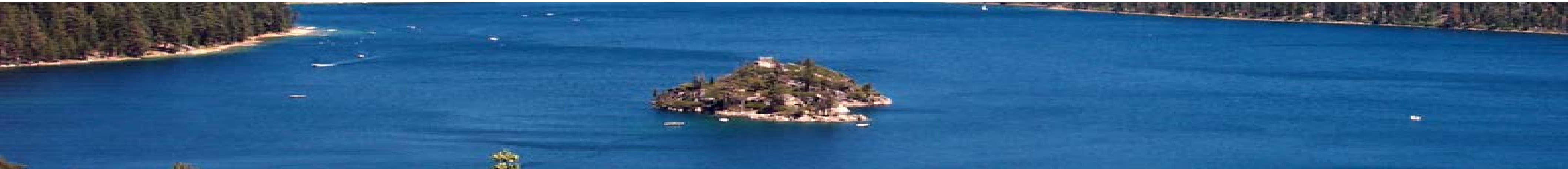
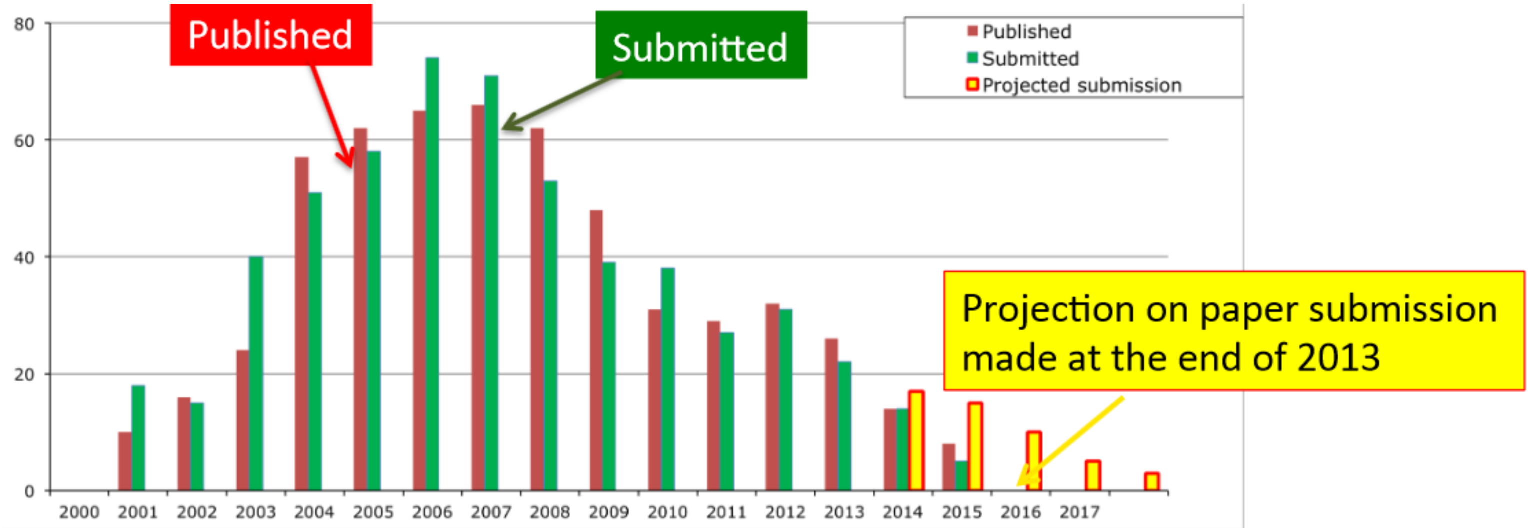
California Institute of Technology
on behalf of the *B*A*B*AR Collaboration

SUSY 2015 – Lake Tahoe





Continue harvesting scientific results from the *BABAR* dataset:

551 papers published (as of June 2015) and a significant number still in the pipeline

Recent highlights:

Indirect search for New Physics in precision measurements

Measurement of sin2β in $B^0 \to D^{(*)0}h^0$ (joint with Belle): arXiv:1505.04147, accepted by PRL

CPV in B mixing with dilepton events: PRL **114**, 081801 (2015)

Measurement of radiative tau decays: PRD **91**, 051103 (2015)

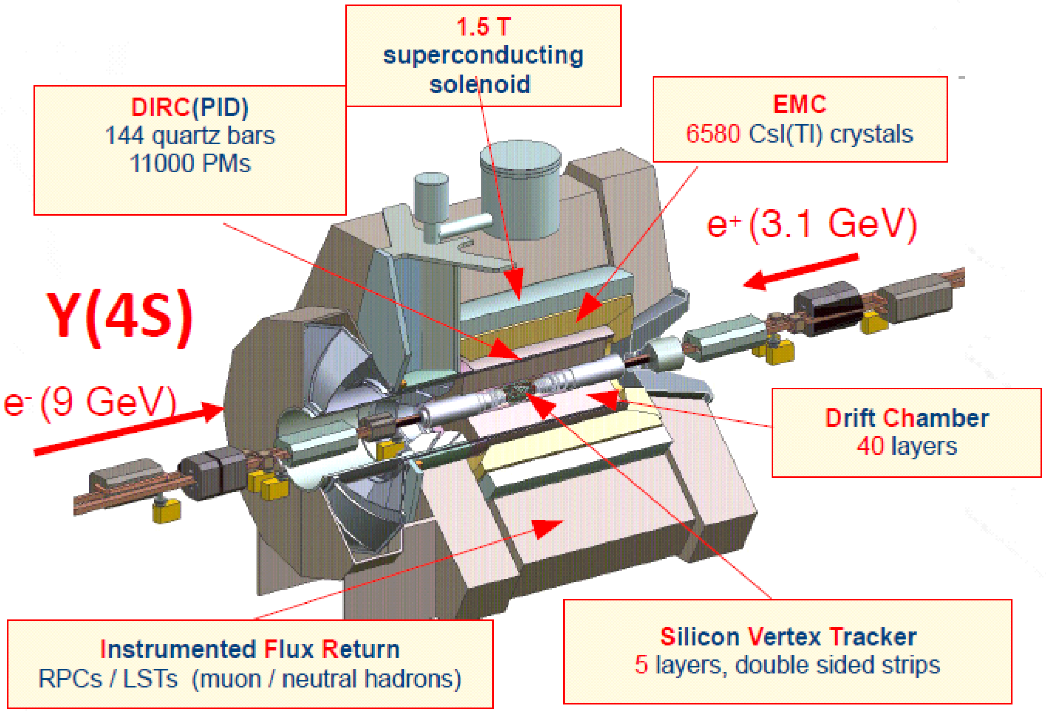
…

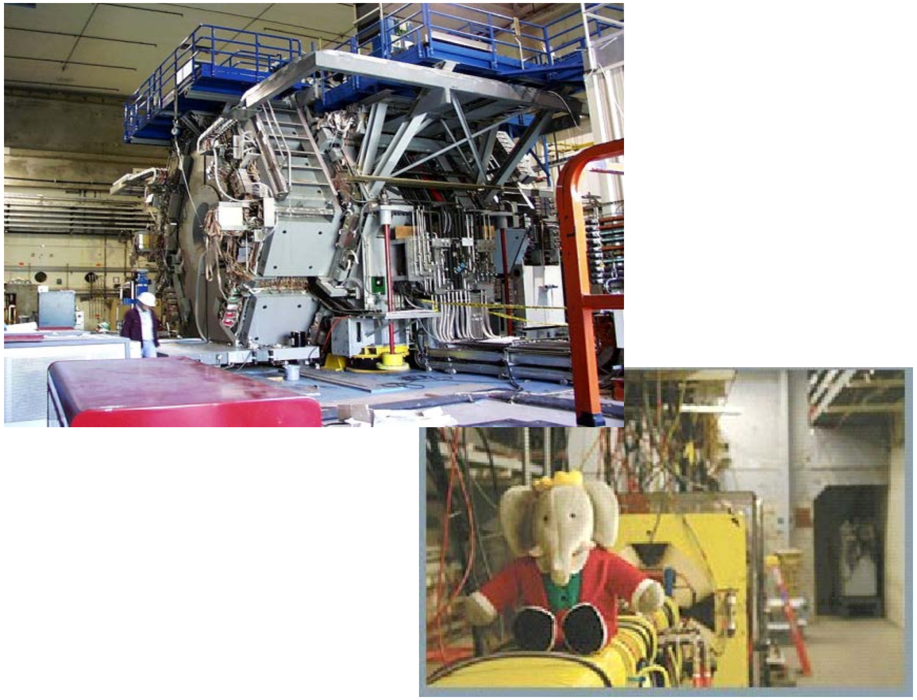
Direct search for low-mass New Physics – this talk

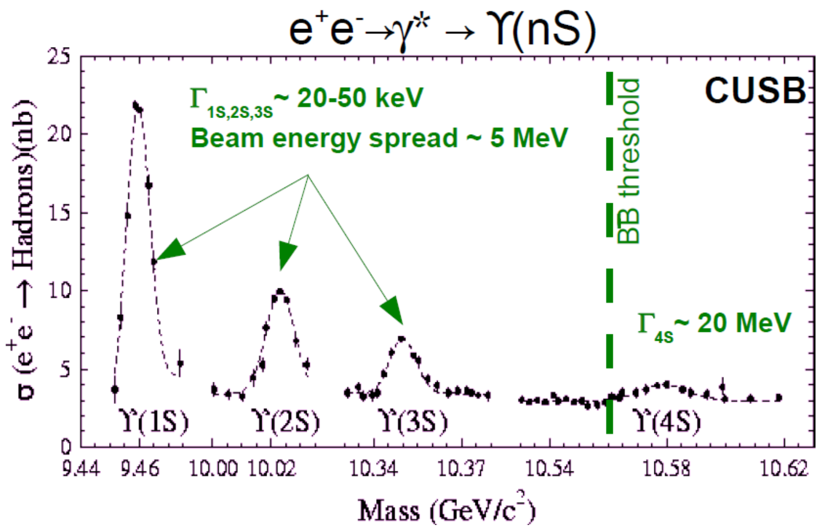
Search for a light Higgs resonance with a charm tag, PRD 91, 071102 (2015)

Search for exotic long-lived particles, PRL 114, 171801 (2015)

The BABAR detector







BABAR data sample contains

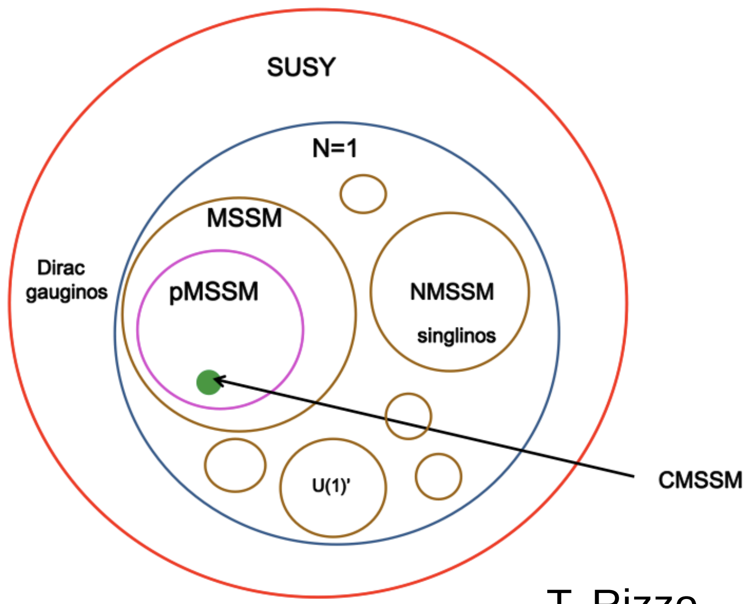
~470 x 10^6 Υ(4S)
~120 x 10^6 Υ(3S) (10x Belle)
~100 x 10^6 Υ(2S) (10x CLEO)
~ 18 x 10^6 $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$

Better sensitivity to direct production of light degrees of freedom at narrow resonances

A light CP-odd Higgs boson?

- The discovery of the Higgs boson begs the question: is it the Higgs, or is it a Higgs?
- No sign of new heavy Higgs boson yet, but the night is still young…
- On the other hand, several SM extensions (NMSSM, 2HDM Type-II,…) include the possibility of additional light Higgs boson.
- NMSSM proposed to solve the "μ problem", adding one CP-odd Higgs, one CP-even Higgs and one neutralino to the MSSM content.

SUSY Cartography



T. Rizzo

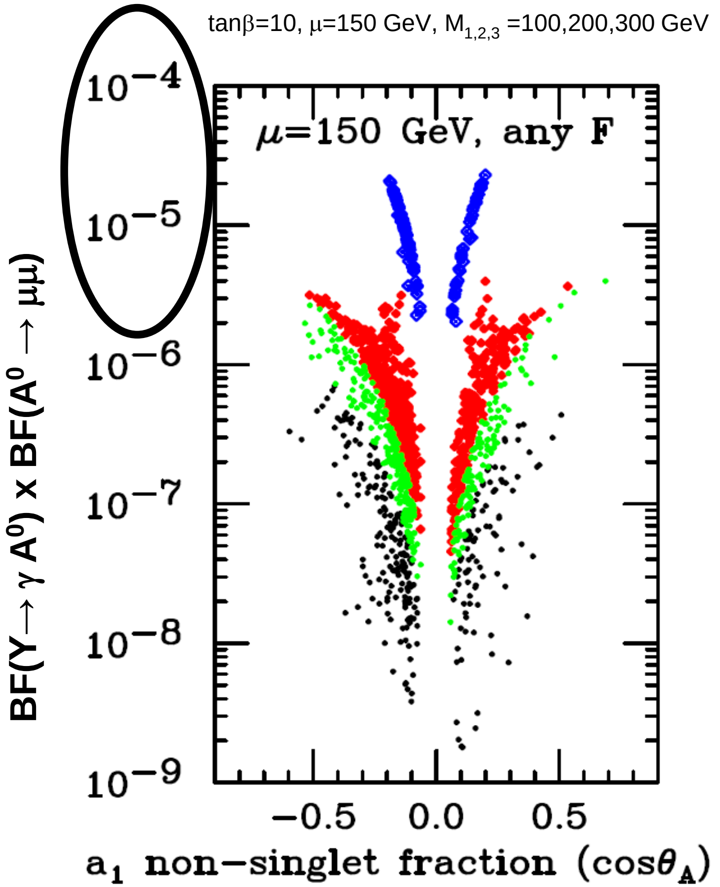
- The lightest CP-odd Higgs boson (A^0) with a mass below 2 m_b has not been excluded by LEP.
- Low masses might be difficult to access at the LHC, and low-energy high luminosity experiment might offer an ideal environment to probe for these possibilities → complementarity between low and high energies.

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

A light CP-odd Higgs

- Many SM extensions (NMSSM, 2HDM Type-II,…) include the possibility of additional Higgs boson, which could be light
- NMSSM proposed to solve the "μ problem", adding one CP-odd Higgs, one CP-even Higgs and one neutralino to the MSSM content
- Radiative decays $\Upsilon(nS) \rightarrow \gamma A^0$ (n=1,2,3) offer an ideal environment to search for light CP-odd Higgs, and more generally a light scalar.
- Possible connection with dark matter connection in $A^0 \rightarrow \chi\chi$ decays if $m_\chi < m_A / 2$.
- Branching fractions can be quite large!

Very active program at *BABAR* to search for these possibilities!



$$\boxed{A^0 = \cos\theta_A\, A_{MSSM} + \sin\theta_A\, A_S}$$

$0 < m_{A0} < 2m_\tau$
$2m_\tau < m_{A0} < 7.5$ GeV
$7.5 < m_{A0} < 8.8$ GeV
$8.8 < m_{A0} < 9.2$ GeV

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

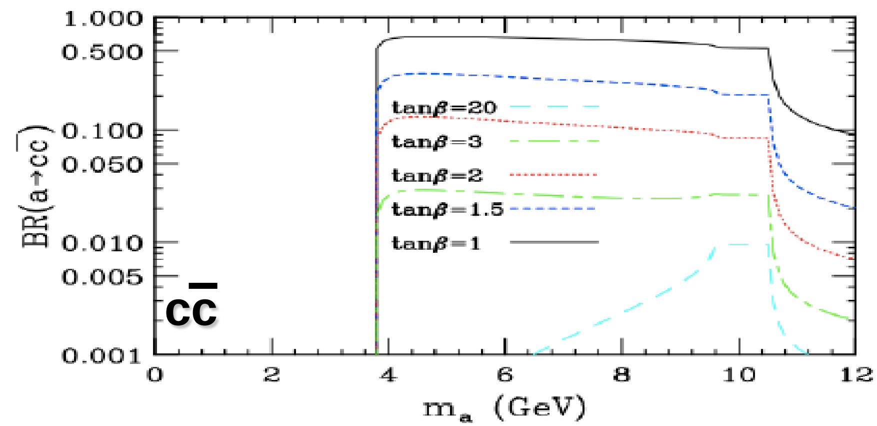
Branching fractions depend on final state and the model parameters

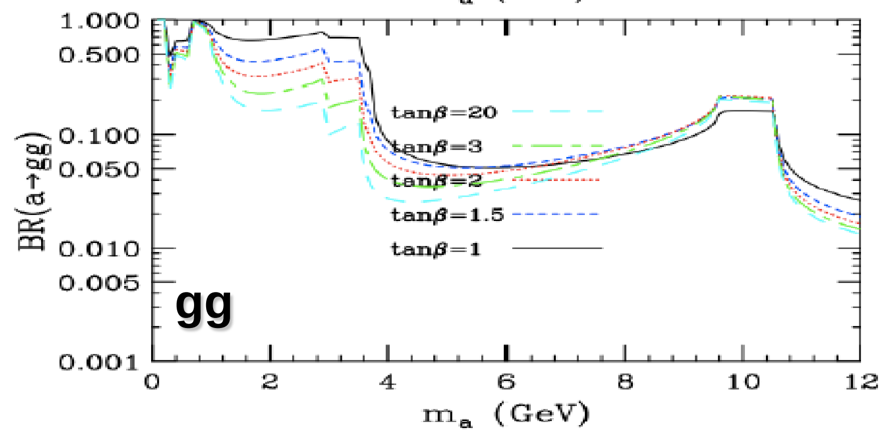
$$BR(A^0 \to f\bar{f}) \propto \cos\theta_A m_f^2 / \tan^2\beta$$ up-type fermions

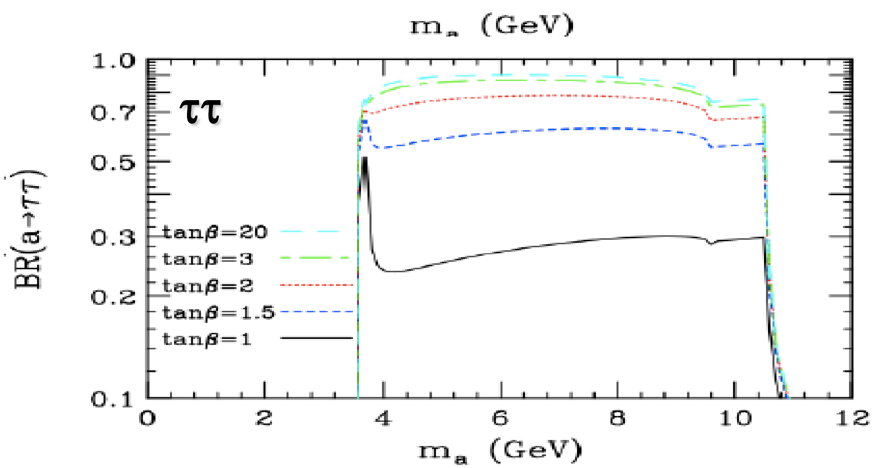
$$BR(A^0 \to f\bar{f}) \propto \cos\theta_A m_f^2 \tan^2\beta$$ down-type fermions

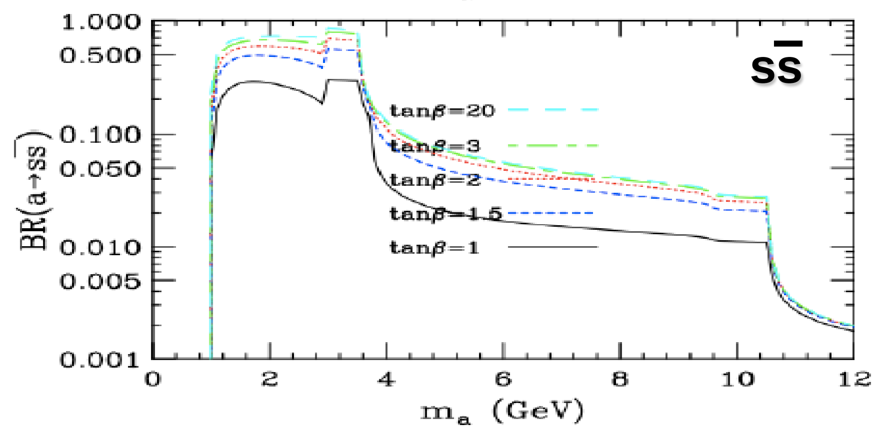
	Low tanβ	High tanβ
Low mass	**gg**	**$s\bar{s}$**
High mass	**$c\bar{c}$**	**ττ**

+ dimuon at lower masses / invisible in some scenarios



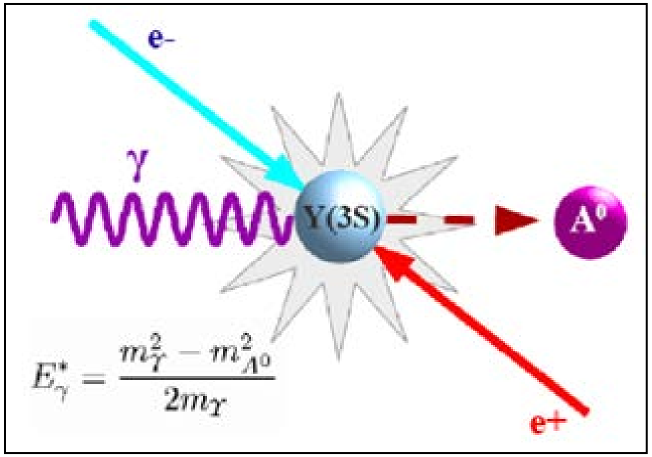






Radiative ϒ(2S,3S) decays

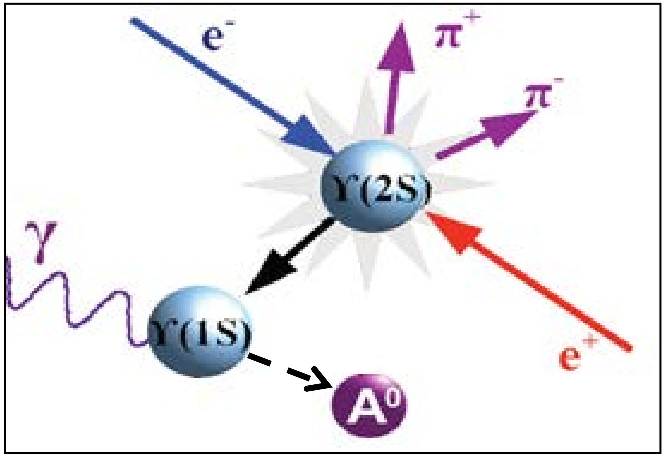
Large branching fraction, large bkg



- $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$
  PRL 103, 081803 (2009)
- $\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$
  PRL103, 181801 (2009)
- $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ hadrons
  PRL107, 221803 (2011)
- $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ invisible
  arXiv: 0808.0017

Radiative ϒ(1S) decays

Lower branching fraction, less bkg



- $\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible
  PRL107, 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, 071102 (2013)
- $\Upsilon(1S) \to \gamma A^0, A^0 \to gg$ or $s\bar{s}$
  PRD 88, 031701 (2013)
- $\Upsilon(1S) \to \gamma A^0, A^0 \to c\bar{c}$ **New**
  PRD 91, 071102 (2015)

CLEO Y(1S) $A^0 \to \mu^+\mu^-$, $\tau^+\tau^-$, PRL 101, 151802 (2008)
BESIII J/ψ $A^0 \to \mu^+\mu^-$, PRD **85**, 092012 (2011)

CMS inclusive $A^0 \to \mu^+\mu^-$, PRL 109, 121801 (2012)
CMS $H(125) \to 2(A^0 \to \mu^+\mu^-)$, PLB 726, 564 (2013)

PRL103, 081803 (2009)
PRD 87, 031102 (2013)

Search for

$\Upsilon(2S,3S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$

Analysis highlights

Tag the $\Upsilon(1S)$: one photon with $E\gamma^* > 200$ MeV + 4 tracks with at least one identified as muon

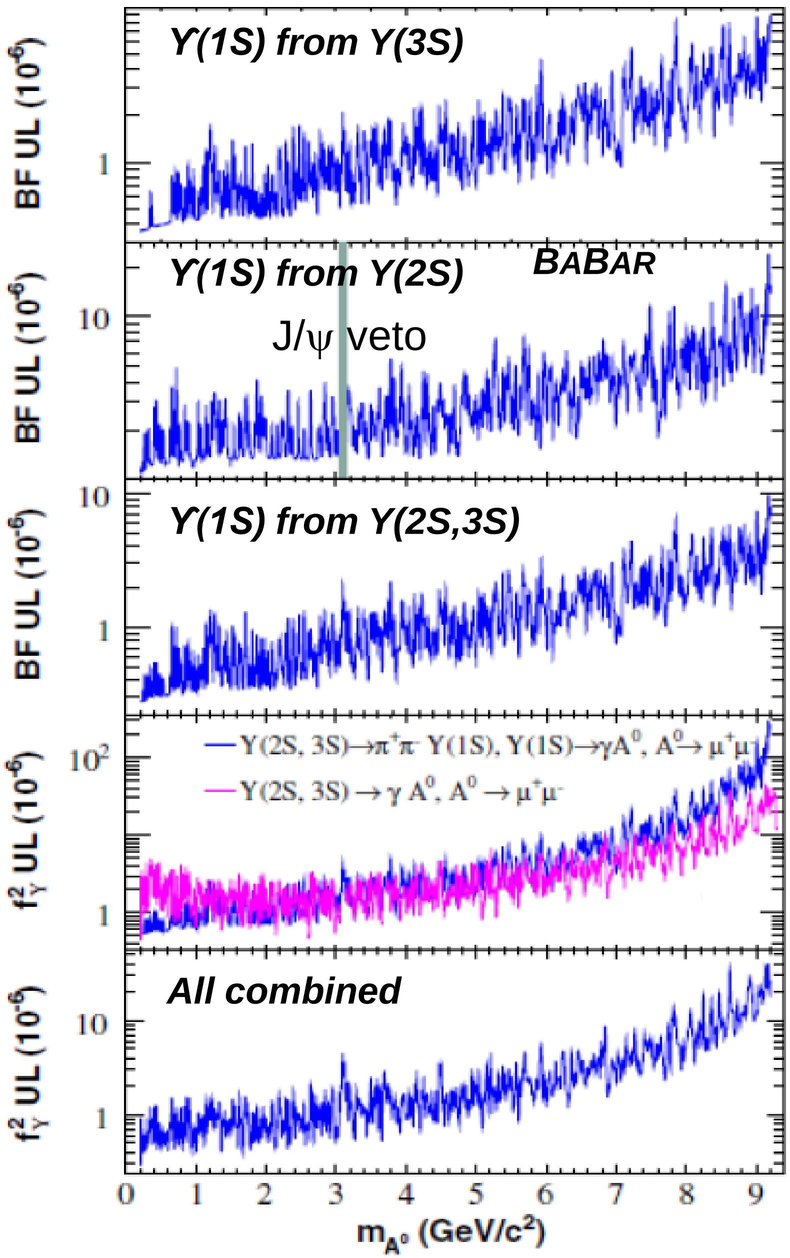
Require the $\gamma\mu\mu$ system to be compatible with a $\Upsilon(1S)$ meson, apply kinematic constraints to improve resolution

Scan reduced mass $m_r = (m^2_{\mu\mu} - 4m^2_{\mu})^{1/2}$

Combination with the results from $\Upsilon(2S,3S)$ decays to extract a limit on the effective Yukawa coupling (f_Υ) between A^0 – b-quark:

$$\frac{B(\Upsilon(nS) \to \gamma A^0)}{B(\Upsilon(nS) \to \ell^+\ell^-)} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(ns)}^2}\right)$$

$$f_\Upsilon^2 \times B(A^0 \to \mu^+\mu^-) = (0.3 - 40) \times 10^{-6}$$



* F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).
M. L. Mangano and P. Nason, Mod. Phys. Lett. A22, 1373 (2007).
P. Nason, Phys. Lett. B175, 223 (1986).

PRL103 , 181801 (2009)
PRD 88, 071102 (2013)

Search for

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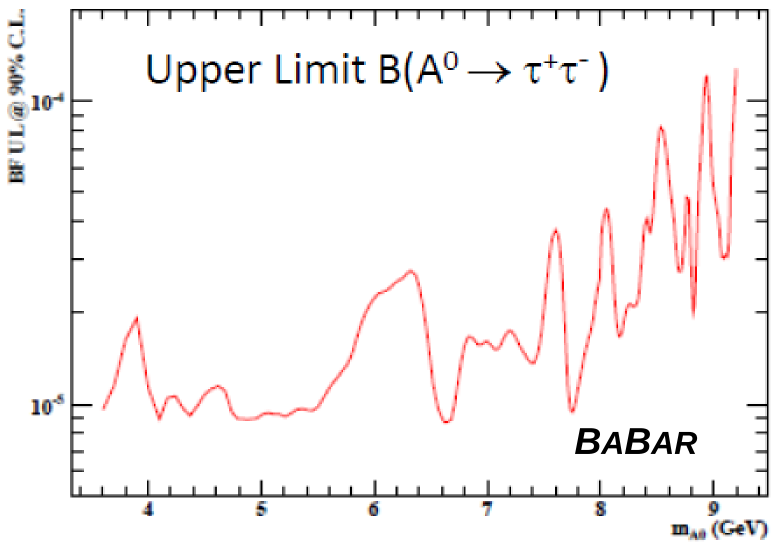


Analysis highlights

Tag the Y(1S) from the dipion transition

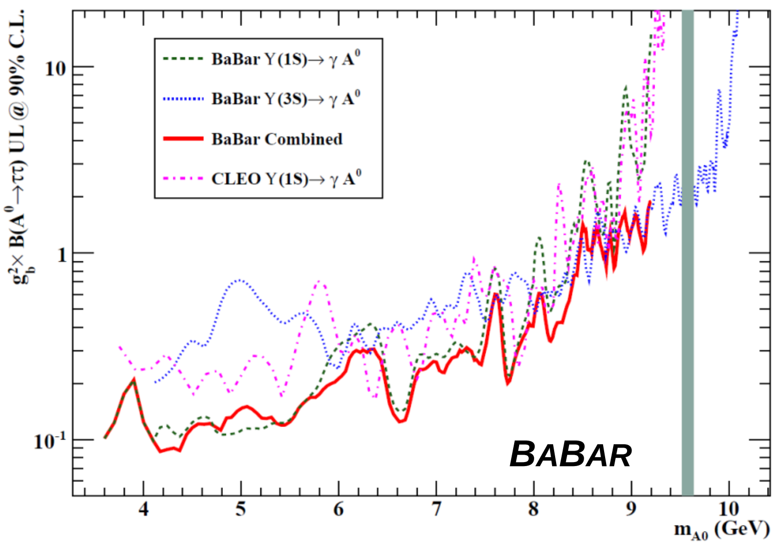
Tag 1-prong decay of tau ($\tau \to \mu\nu\nu$, $\tau \to e\nu\nu$, $\tau \to \pi\nu\nu$)

Optimize analysis in low mass $3.6 < m_A < 8.0$ GeV / high mass $8.0 < m_A < 9.2$ GeV regions

Fit for a narrow peak to the photon recoil mass in the Y(1S) system

Combination with the results from Y(2S,3S) decays to extract a limit on the effective Yukawa coupling (g_b) between A^0 – b-quark*:

$$\frac{B(\Upsilon(nS) \to \gamma A^0)}{B(\Upsilon(nS) \to \ell^+\ell^-)} = \frac{g_b^2 G_F m_b^2}{\sqrt{2\pi\alpha}} \mathcal{F}_{QCD}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(ns)}^2}\right)$$



$g_b^2 \times B(A^0 \to \tau^+\tau^-) = 0.1 – 1.9$ @ 90% CL

* F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).
M. L. Mangano and P. Nason, Mod. Phys. Lett. A22, 1373 (2007).
P. Nason, Phys. Lett. B175, 223 (1986).

PRD 88, 031701R (2013)

Search for

$\Upsilon(2S,3S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to gg, s\bar{s}$

Analysis highlights

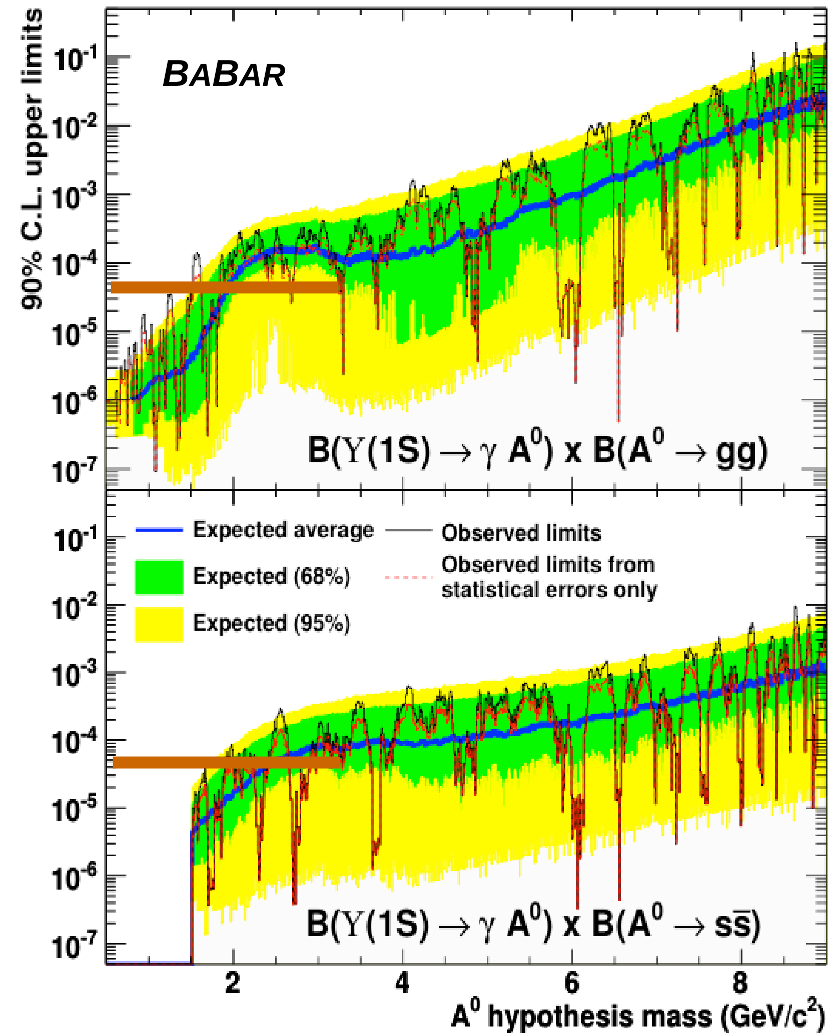
Exclusive reconstruction of A^0 in 26 / 14 different channels for gg / $s\bar{s}$

Two body decays excluded as CP-odd Higgs can not decay into two pseudo-scalars.

Background dominated by $\Upsilon(1S) \to \gamma gg$ (low masses) and $\Upsilon(1S) \to ggg$ (high masses)

Extract yield from mass spectrum in the range $0.5 < m_A < 9$ GeV, use cut and count method with bkg estimated from sidebands.

Large systematic uncertainty from hadronization (~50%)



$B(\Upsilon(1S) \to \gamma A^0, A^0 \to gg) < 10^{-6} - 10^{-2}$
$B(\Upsilon(1S) \to \gamma A^0, A^0 \to s\bar{s}) < 10^{-5} - 10^{-3}$

Brown line = approximate predictions

PRL107, 021804 (2011)

Search for

$\Upsilon(2S,3S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to$ invisible

Analysis highlights

Tag the Y(1S) from the dipion transition

Require two tracks + one high-energy photon and no additional activity

Missing energy and momentum

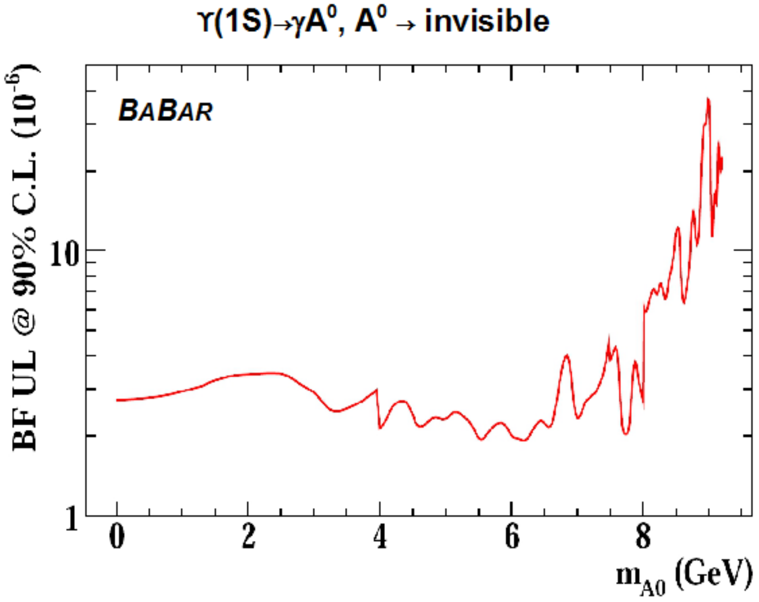
Consider both $\Upsilon(1S) \to \gamma A^0$ (two-body) and $\Upsilon(1S) \to \gamma\chi\chi$ (multi-body) decays

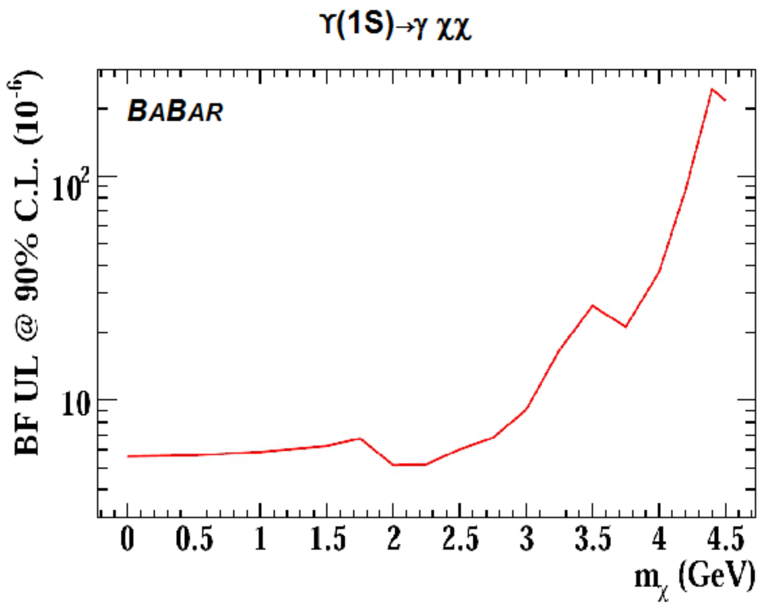
Fit the the recoil mass squared (M^2_{recoil}) and missing mass (M^2_x) squared

$B(\Upsilon(1S) \to \gamma A^0, A^0 \to invisible) < (1.9 - 37) \times 10^{-6}$

$B(\Upsilon(1S) \to \gamma\chi\chi) < (0.5 - 25) \times 10^{-5}$

Significant constraints on theoretical models[1,2]





1) PRD 76, 051105 (2007) 2) PRD 80,115019 (2009)

PRD 91, 071102R (2015)

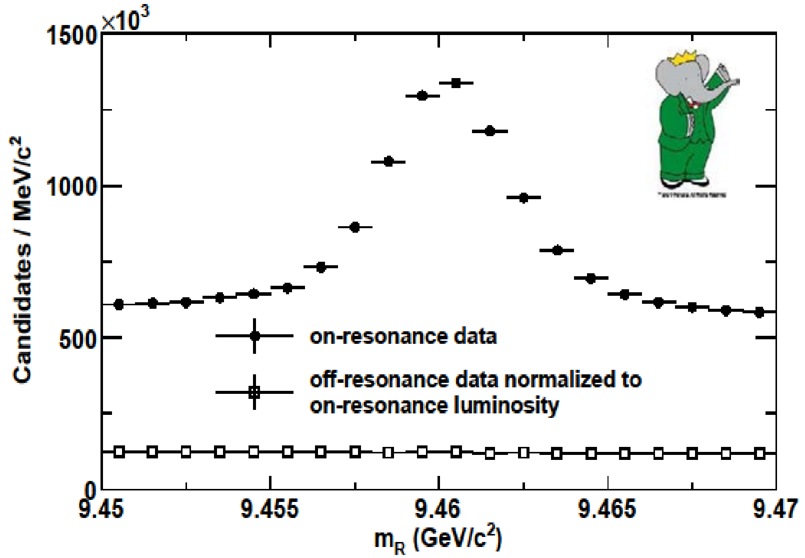
Search for

$\Upsilon(2S,3S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to c\bar{c}$

Analysis highlights

Require two tracks + one photon + hadronic system

Tag the Y(1S) from the dipion transition requiring $|m_R - m_{Y(1S)}| < 10$ MeV



$$m_R^2 = M_{\Upsilon(2S)}^2 + m_{\pi\pi}^2 - 2M_{\Upsilon(2S)}E_{\pi\pi}$$

Reconstruct D decay to tag $c\bar{c}$ system:

$D^0 \to K\pi$, $D^0 \to K\pi\pi\pi$, $D^0 \to K_s\, \pi\pi$,
$D^+ \to K\pi\pi$
$D^{*+} \to D^0\pi$, $D^0 \to K\pi\pi^0$

Reconstruct A^0 mass using $m_x^2 = (P_{ee} - P_{\pi\pi} - P_\gamma)^2$

Two mass regions:

Low mass 4.00 – 8.00 GeV

High mass 7.5 – 9.25 GeV

Veto 8.95 – 9.1 GeV range to remove $\Upsilon(2S) \to \chi_b \to \Upsilon(1S)$ photon cascade

PRD 91, 071102R (2015)

Search for

$\Upsilon(2S,3S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to c\bar{c}$

Analysis highlights

Require two tracks + one photon + hadronic system

Tag the Y(1S) from the dipion transition requiring $|m_R - m_{Y(1S)}| < 10$ MeV

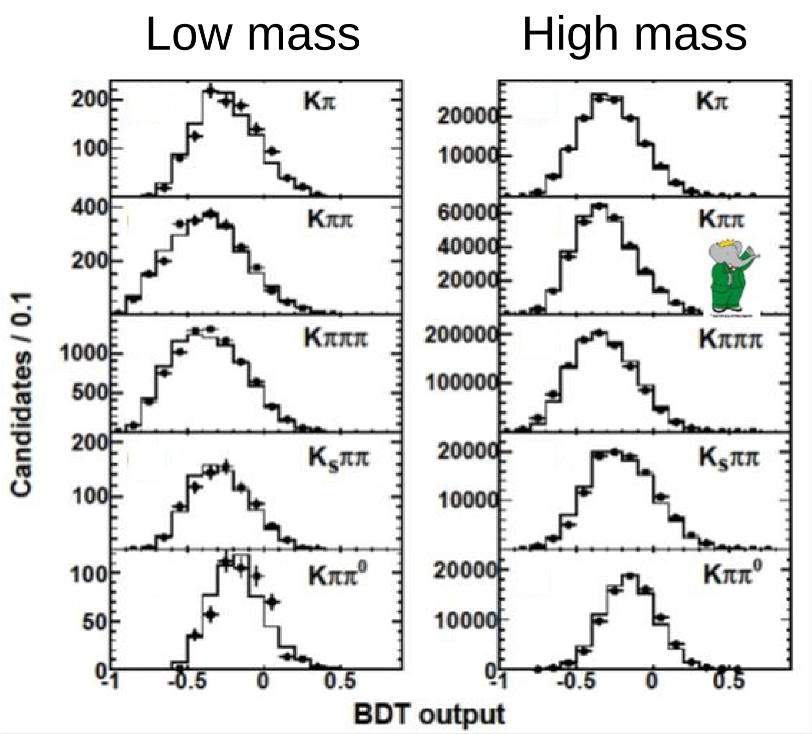
Reconstruct D decay to tag $c\bar{c}$ system:

$D^0 \to K\pi$, $D^0 \to K\pi\pi\pi$, $D^0 \to Ks\,\pi\pi$,
$D^+ \to K\pi\pi$
$D^{*+} \to D^0\pi$, $D^0 \to K\pi\pi^0$

Reconstruct A^0 mass using $m_x^2 = (P_{ee} - P_{\pi\pi} - P_\gamma)^2$

Train 5 (charm) x 2 (mass) BDT to separate signal from background using 24 variables (event shape, kinematics, vertex, D, photon, dipion)

Off-resonance data (pts)
vs
ee → qq MC (hist)



Very good agreement

PRD 91, 071102R (2015)

Signal extraction

Perform binned extended maximum likelihood fits in the low & high mass regions in 20σ mass window:

10 MeV steps for low mass
2 MeV steps for high mass

Fit function:

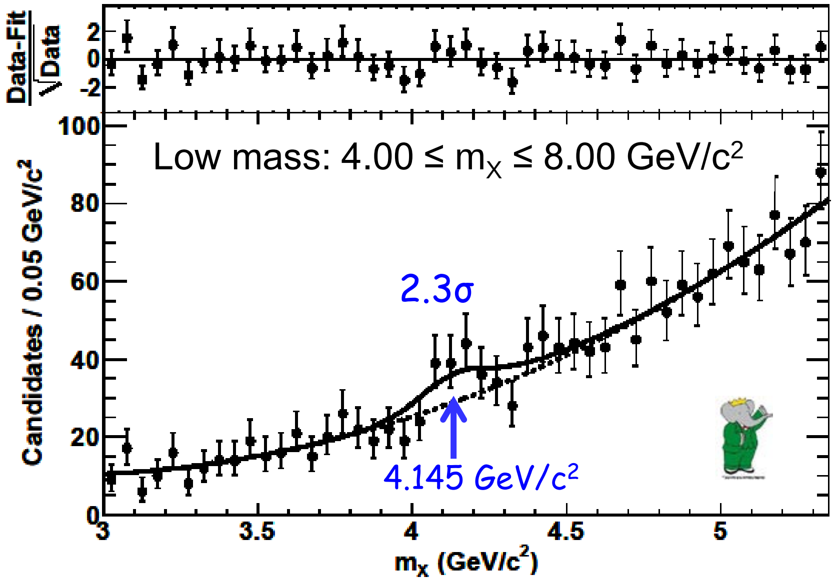
Signal PDF (fixed): Crystal Ball modelled from MC
Background PDF (float): 2nd order polynomial

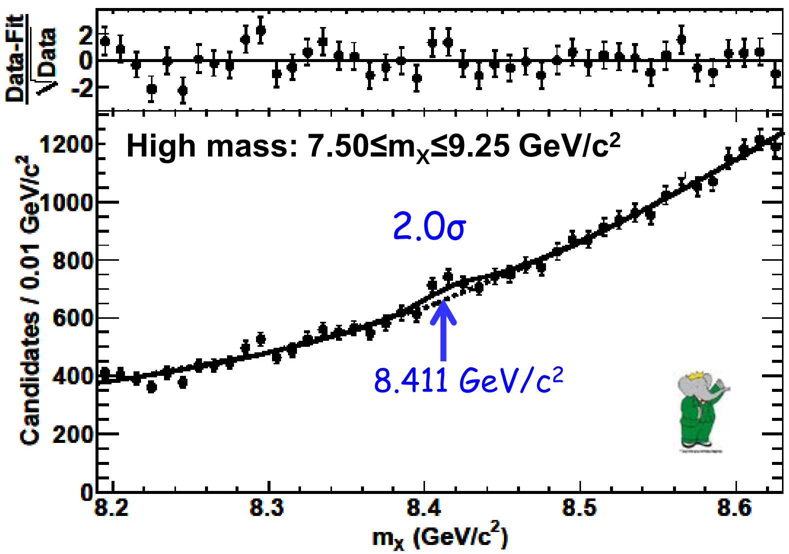
Largest local significance:
2.3σ @ 4.145 GeV - 2.0σ @ 8.411 GeV

Reconstruction efficiency:
4%.0 @ 4.00 GeV - 2.6% @ 9.25 GeV

Systematic uncertainty dominated by $c\bar{c}$ hadronization ~10%, also signal PDF shape, D mass PDF, dipion BF & pdf, MC stats, γ efficiency, $N_{\Upsilon(2S)}$

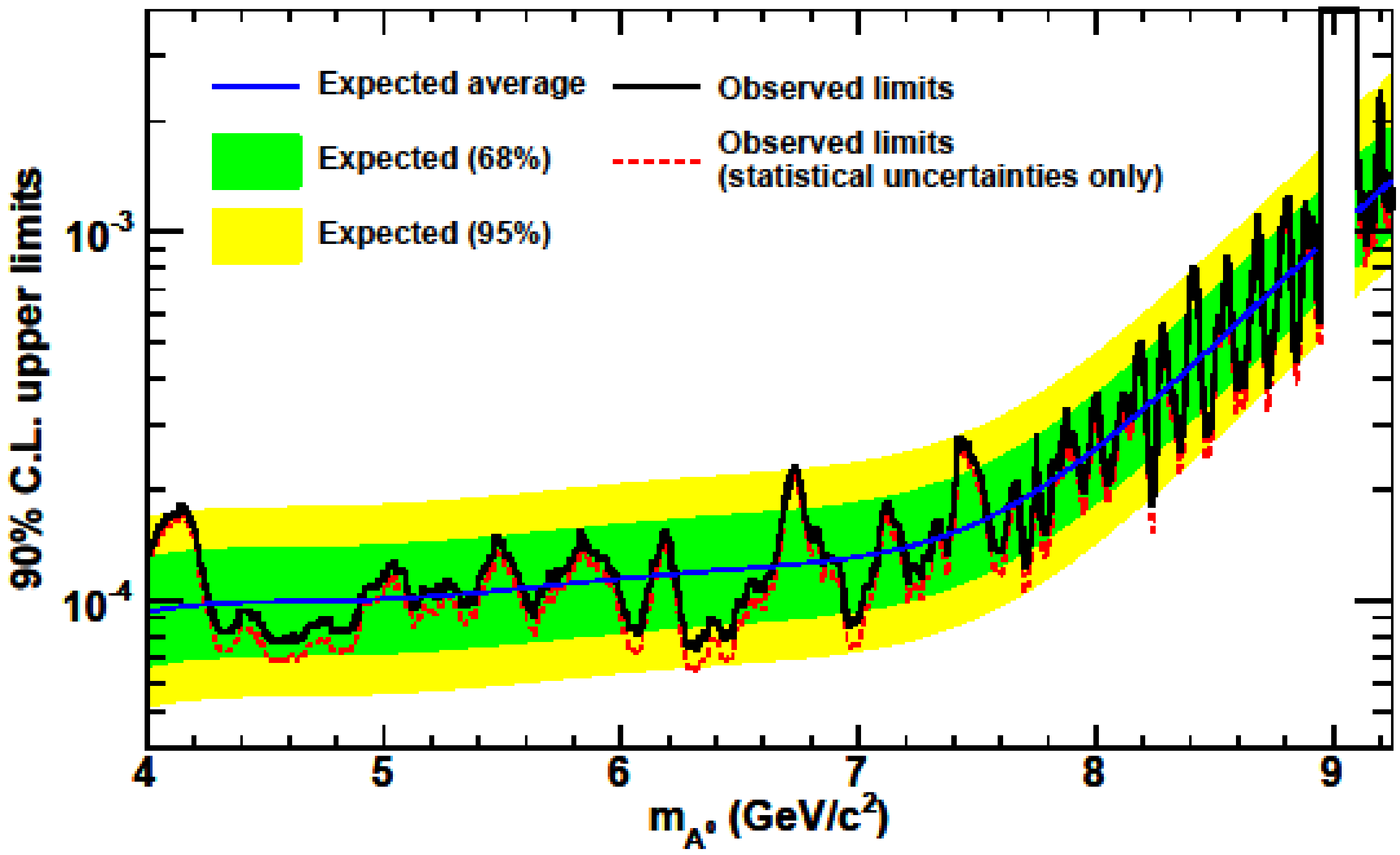
No significant signal



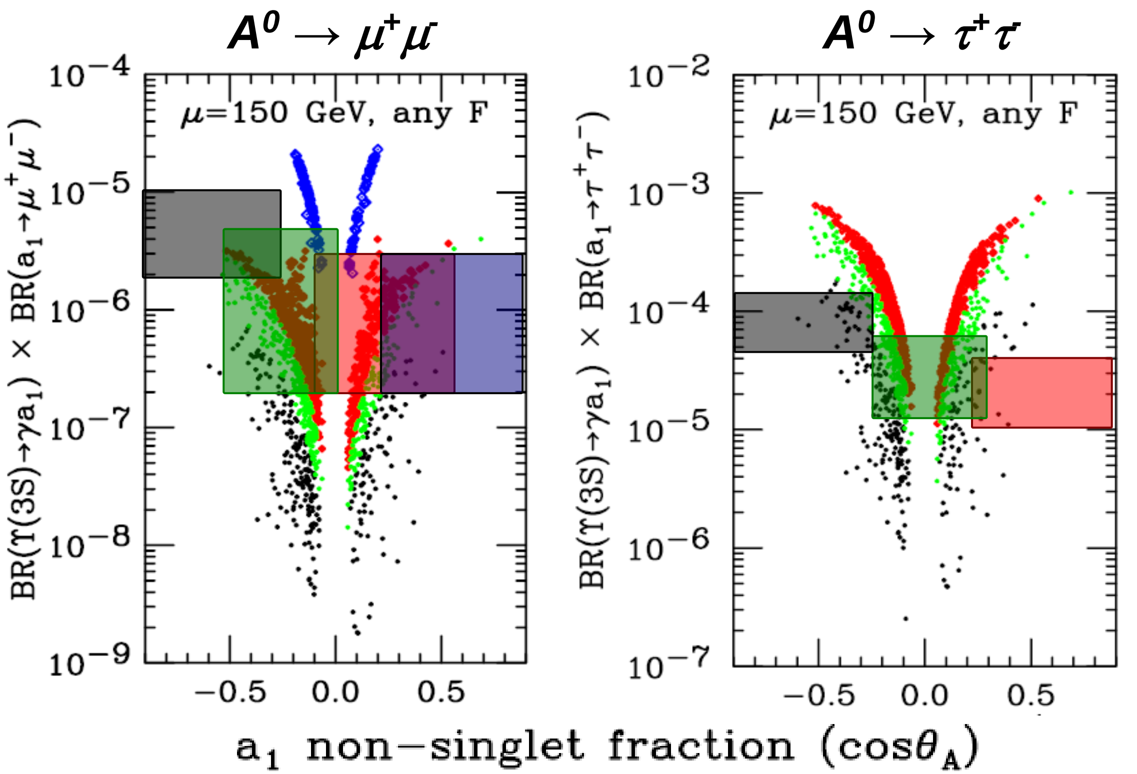


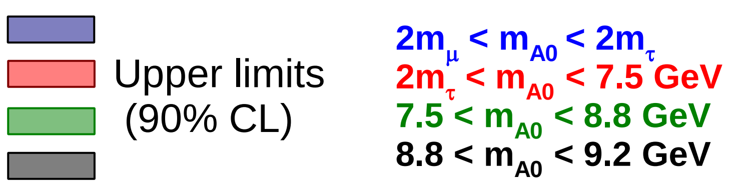
PRD 91, 071102R (2015)

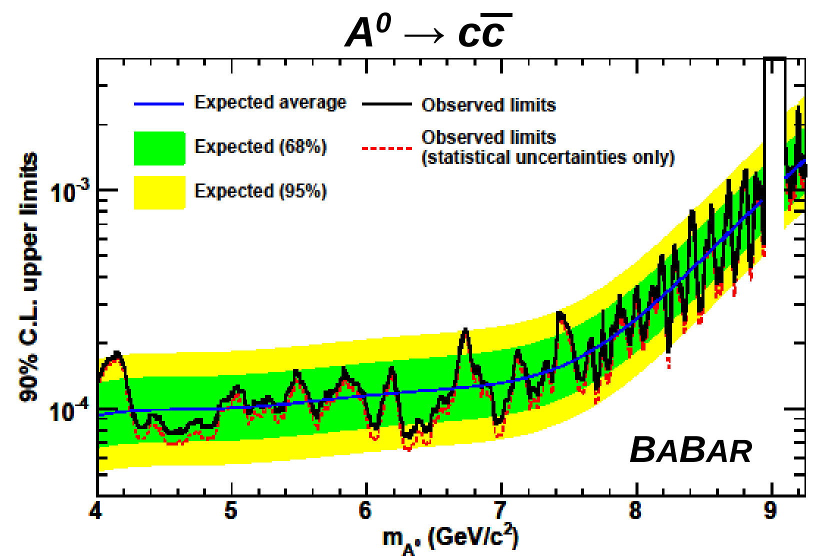
Upper limits at 90% CL

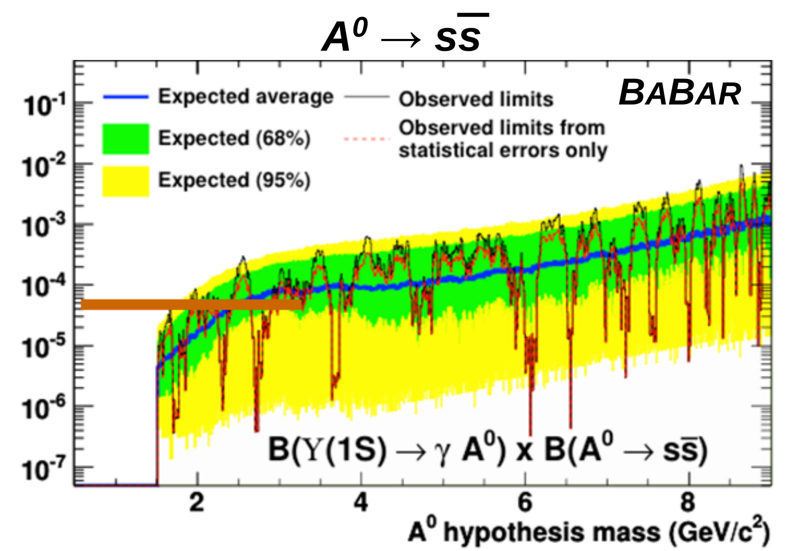


$B(\Upsilon(1S) \to \gamma A^0, A^0 \to c\bar{c}) < 7.4\text{x}10^{-5} - 2.4\text{x}10^{-3}$



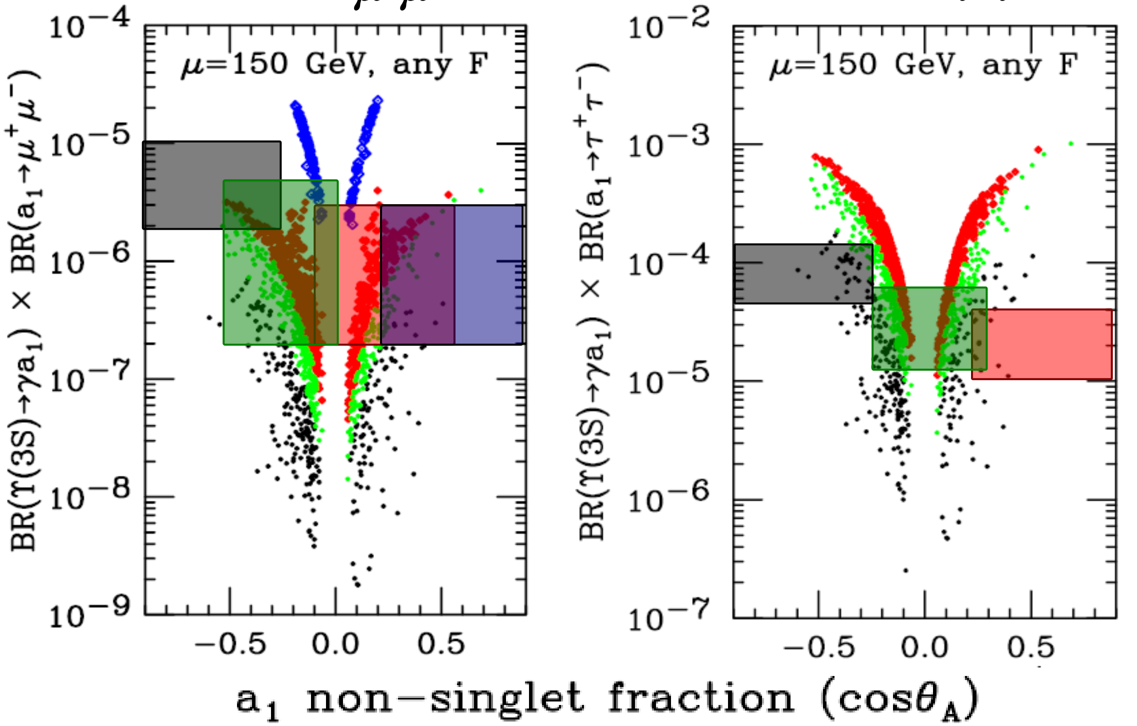






Substantial fraction of the parameter space (up to 7-8 GeV) is excluded

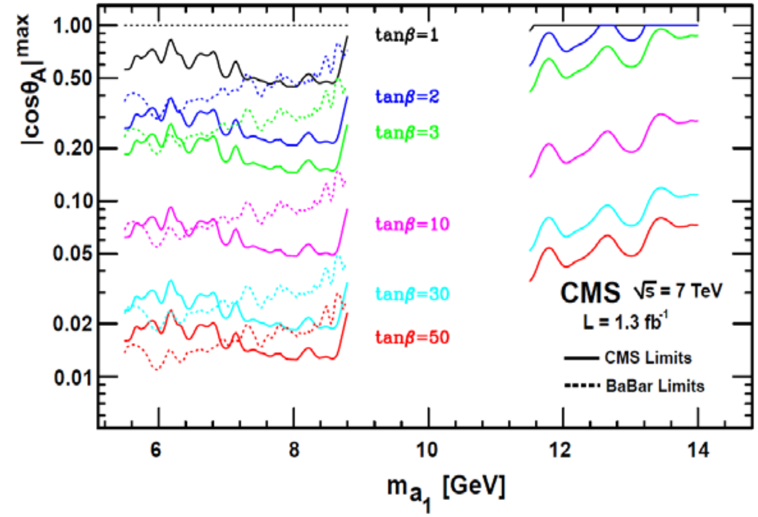
$A^0 \rightarrow \mu^+\mu^-$ ***$A^0 \rightarrow \tau^+\tau^-$***



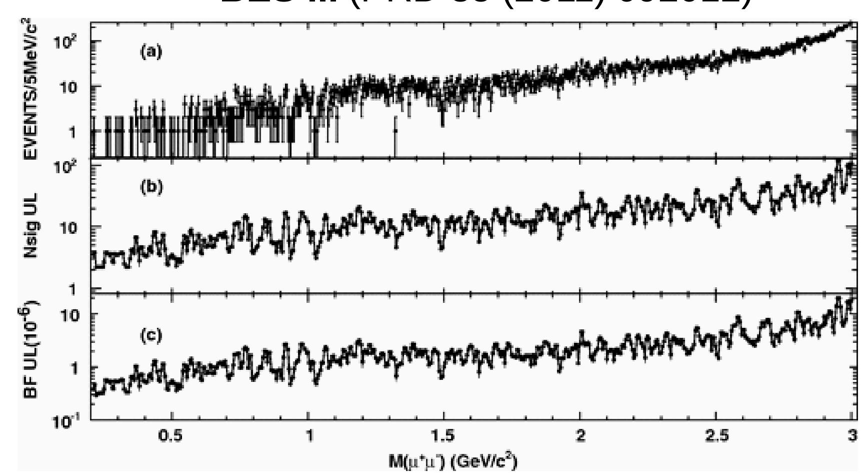
Upper limits (90% CL)

$2m_\mu < m_{A0} < 2m_\tau$
$2m_\tau < m_{A0} < 7.5$ GeV
$7.5 < m_{A0} < 8.8$ GeV
$8.8 < m_{A0} < 9.2$ GeV

$A^0 \rightarrow \mu^+\mu^-$
CMS (PRL 109 (2012) 121801)



$A^0 \rightarrow \mu^+\mu^-$
BES III (PRD 85 (2011) 092012)



CLEO Y(1S) $A^0 \rightarrow \mu^+\mu^-$, $\tau^+\tau^-$, PRL 101, 151802 (2008)

CMS $H(125) \rightarrow 2(A^0 \rightarrow \mu^+\mu^-)$, PLB 726, 564 (2013)

+ Bes III update coming soon

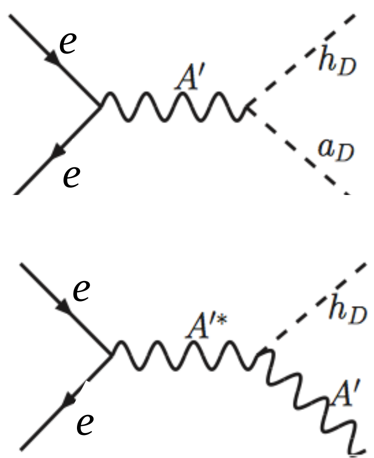
Search for long-lived particles at many scales

Sub-GeV scale:	$O(1\ \mathrm{GeV}/c^2)$ scale:	Multi-GeV scale:
e.g. :NuTeV	BaBar	e.g.: ATLAS, CDF, D0,CMS
Phys.Rev.Lett., 87, 041801 (2001)	Phys. Rev.Lett. 114 17, 171801 (2015)	Phys. Lett. B 719 280 (2013)

LoLiPs scenarios at *BABAR*:

Smoking gun signature: displaced decay vertex

Vector portal (dark photon)

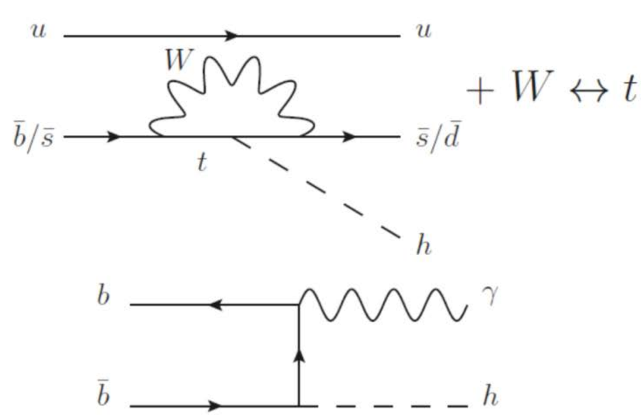


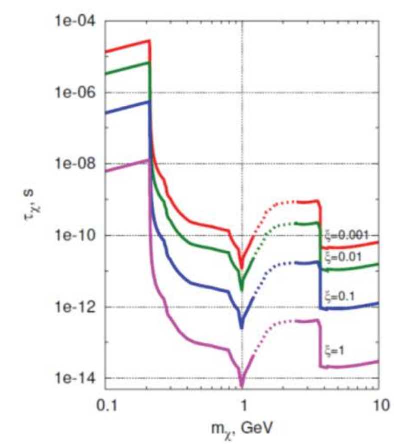
Schuster et al, PRD 81, 016002 (2009)
Essig et al, PRD 80, 015003 (2009)

Higgs portal : scalar inflaton mixes with Higgs

$$\mathcal{L}_{XN} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2}m_X^2 X^2 - \frac{\beta}{4}X^4 - \lambda\left(H^\dagger H - \frac{\alpha}{\lambda}X^2\right)^2$$

$$\mathcal{L}_{\text{grav}} = -\frac{M_P^2 + \xi X^2}{2}R,$$





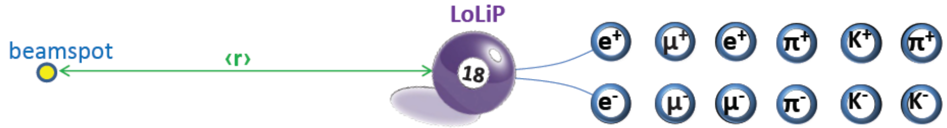
J.D. Clarke, R. Foot, R. Volkas, PRD 80, 015003 (2009)
F. Bezrukov, D. Gorbunov JHEP 1307 (2013) 140

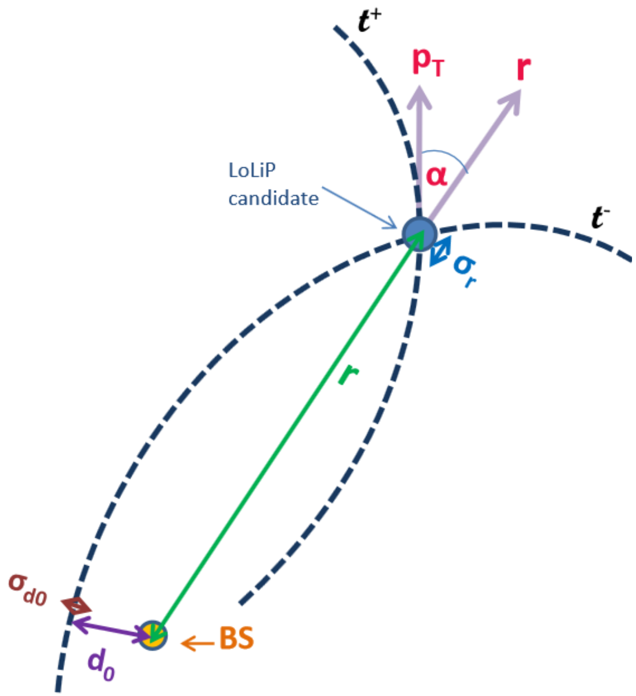
Search for neutral LoLips (L)

Long lived → displaced vertex: r > 1 cm

Reconstructed in two-body charged decays

$$e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$$
$$\pi^+\pi^-, K^+K^-, \pi^\pm K^\mp$$





PRL 114 (2015) 171801

Search for neutral LoLips (L)

Long lived → displaced vertex: r > 1 cm

Reconstructed in two-body charged decays

$$e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$$
$$\pi^+\pi^-, K^+K^-, \pi^\pm K^\mp$$

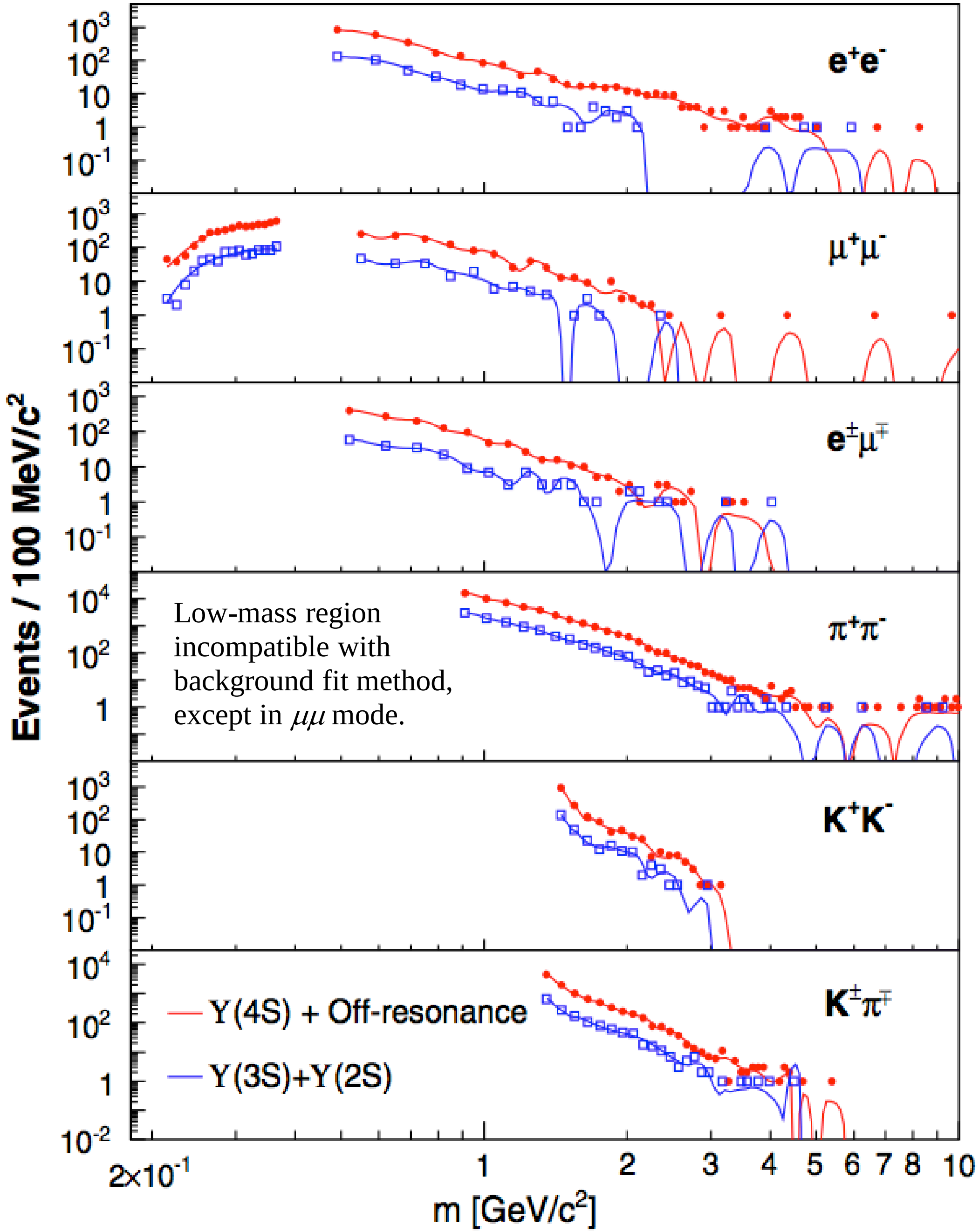
Search for peak in the invariant mass spectra

Scan each mass spectrum in 2 MeV steps, perform UML fits at each step

Fit background on data with spline assuming no signal

Signal PDF extracted from MC (fixed)

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

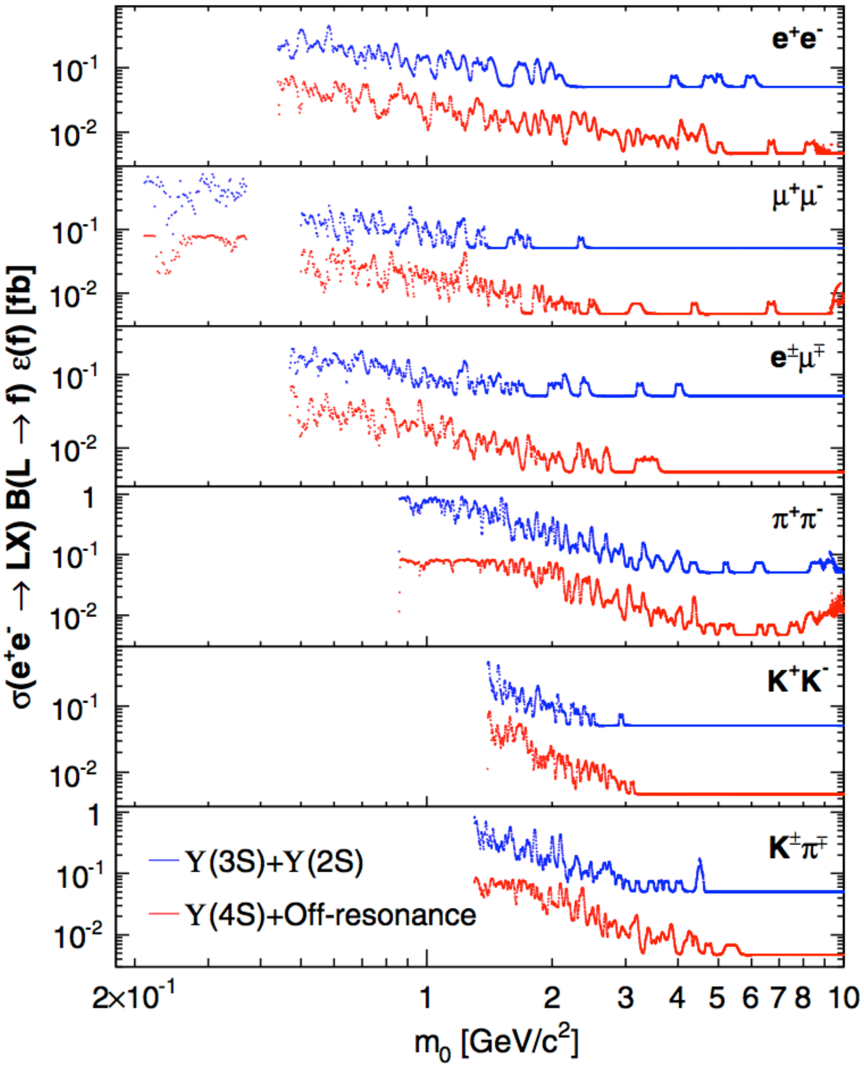


No significant signal

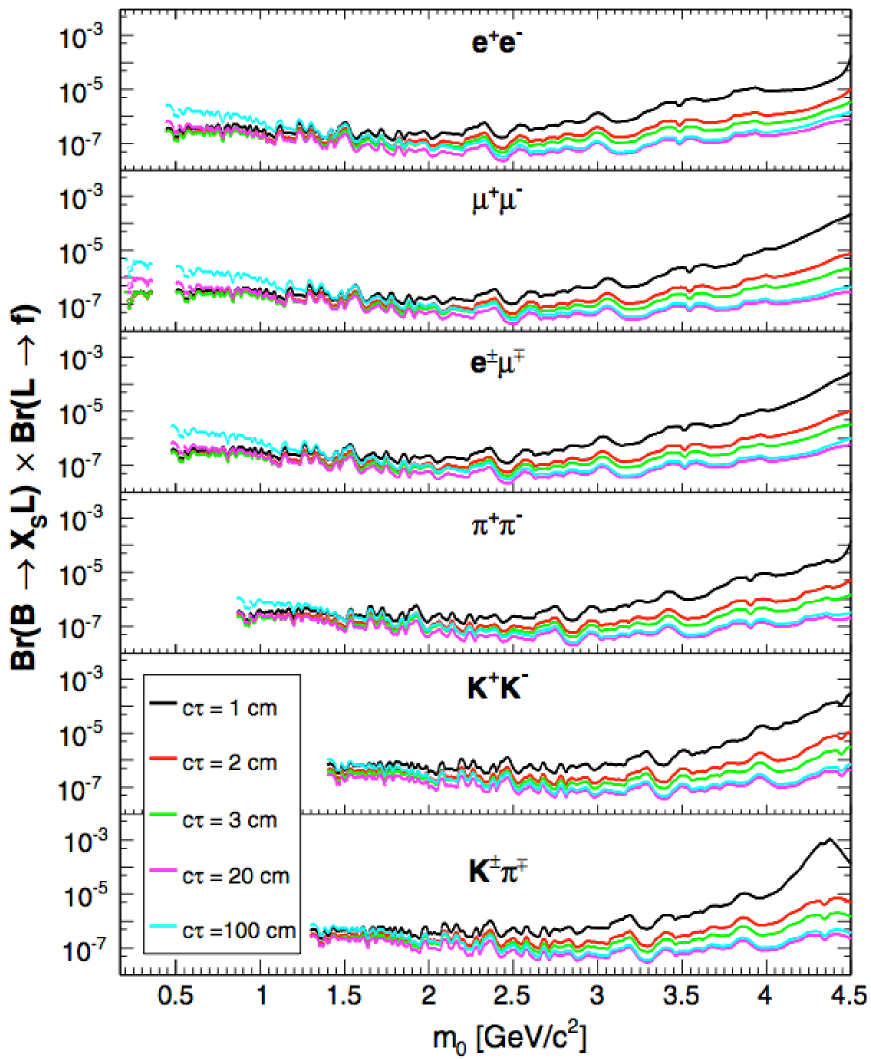
*PRL 114 (2015) 171801 **

Model-independent limits on $\sigma(ee \rightarrow LX)\ \mathrm{Br}(L \rightarrow f)\ \varepsilon(f)$

Give tables of $\varepsilon(m, c\tau, p_T)$



Model-dependent limit on $\mathrm{Br}(B \rightarrow LX_s)\ \mathrm{Br}(L \rightarrow f)$ constrain inflaton model

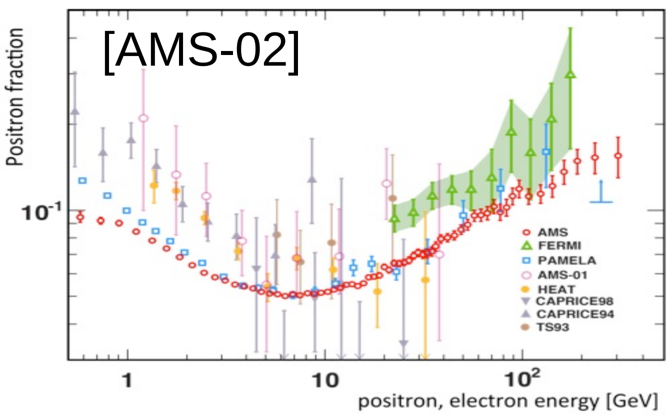


*See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.114.171801

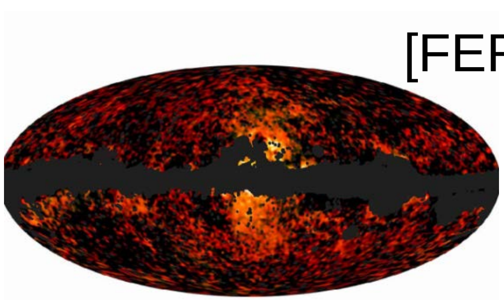
Models introducing a **new 'dark' force** mediated by a **new gauge boson with a mass around a GeV** have been proposed to explain various anomalies recently observed.

Wimp-like TeV-scale dark matter particles can **annihilate into pairs of dark bosons**, which subsequently decay to lepton pairs (protons are kinematically forbidden).

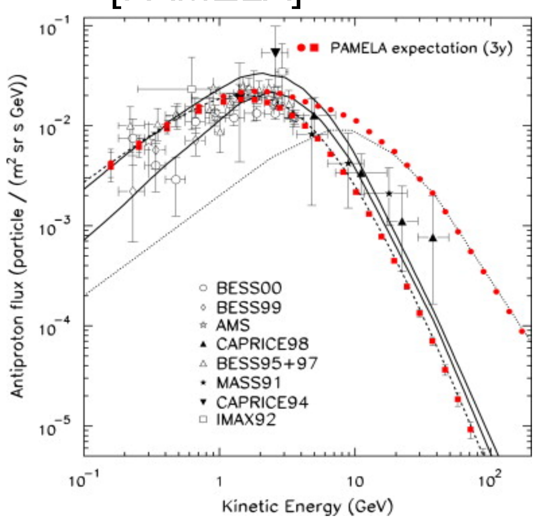
Other explanations of these anomalies have been proposed (e.g arXiv:1305.1324, 1502.01236), but it made us realize the **amazing possibilities at the GeV-scale that could be probed in laboratory!**

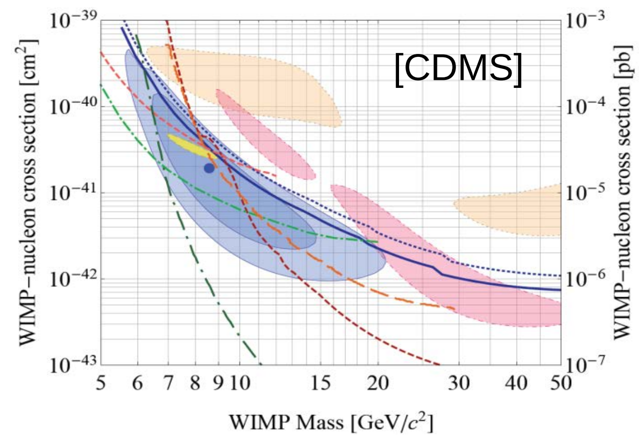


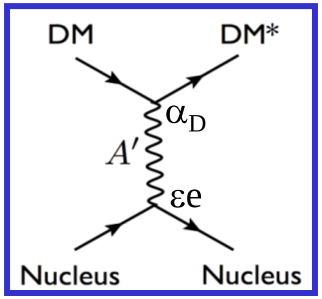
[FERMI]



[PAMELA]







[Slatyer,Schuster&Toro,...]

PRL 113 (2014) 201801

Search for dark photon

A dark photon can be produced in

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

Select events containing a photon and a pair of leptons, and search for a narrow resonance in the dilepton mass spectra

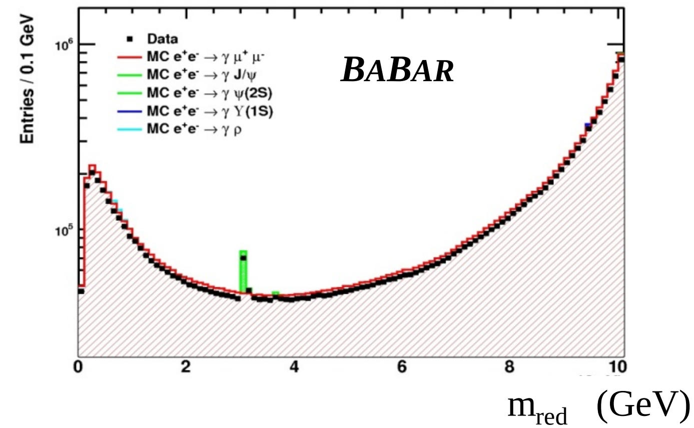
No significant signal is observed

Limits on the mixing parameter ε at the level of 10^{-3} is extracted for $0.02 < m_{A'} < 10$ GeV.

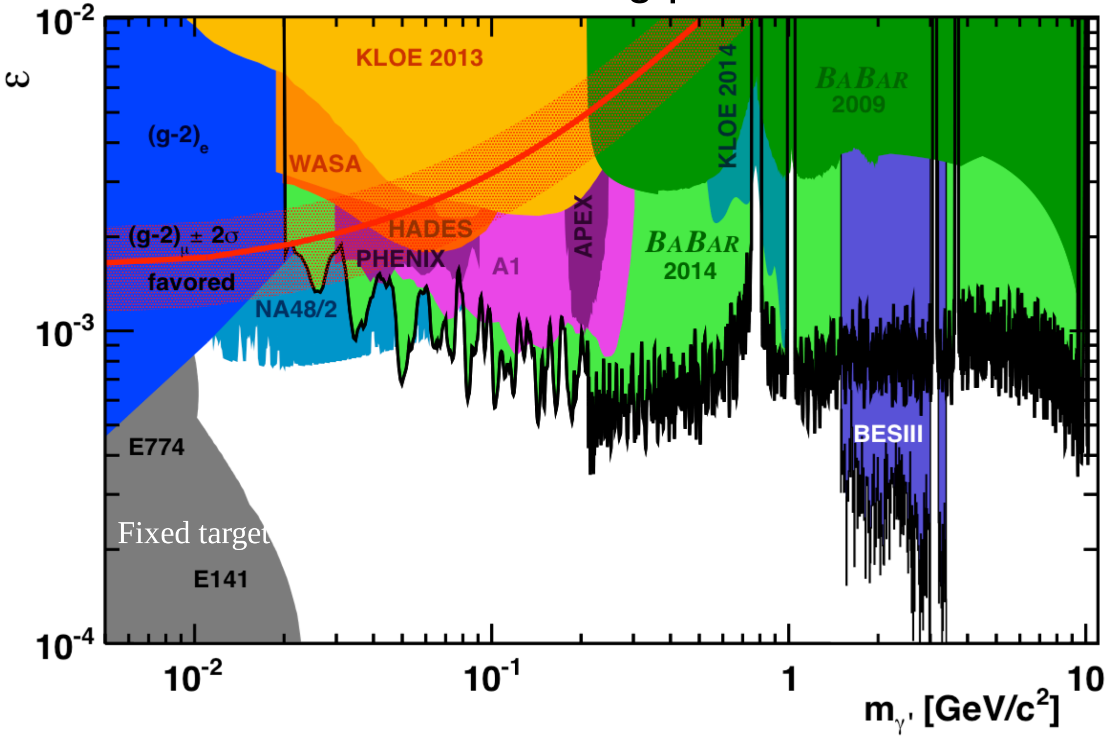
On-going measurements:

- Search for dipion decay of dark photon
- Search for invisible decay of dark photon
- Search for muonic / tauonic dark force

Dimuon reduced mass spectrum



Limits on mixing parameter ε



BABAR provides significant constraints on new physics models with low-mass degrees of freedom in high-statistics datasets.

No significant evidence for light new Physics has been found and upper limits have been set with a sizable improvement over previous measurements.

Ruled out significant fraction of “interesting” parameter space for dark photon, long-lived particles and low-mass Higgs models. New results on dark sector are coming soon, stay tuned!

The next generation of B-factories (Belle-II) will increase the available statistics by orders of magnitude.

Combined with LHC and direct detection dark matter searches, these measurements will provide unique information on the dynamics and flavor structure of new physics.

Happy hunting and good luck…

EXTRA MATERIAL

PRD 91, 071102R (2015)

Search for

$\Upsilon(2S,3S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to c\bar{c}$

Analysis highlights

Require two tracks + one photon + hadronic system

Tag the $\Upsilon(1S)$ from the dipion transition requiring $|m_R - m_{\Upsilon(1S)}| < 10$ MeV

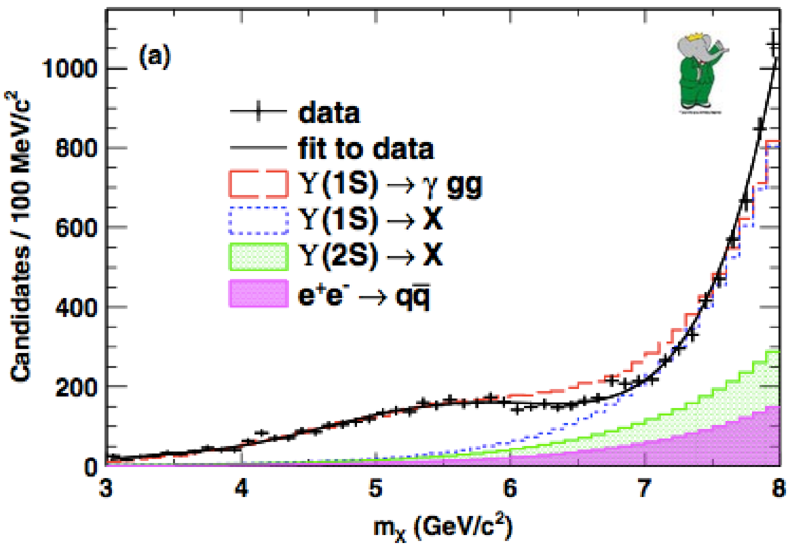
Reconstruct D decay to tag $c\bar{c}$ system:

$D^0 \to K\pi$, $D^0 \to K\pi\pi\pi$, $D^0 \to K_S\,\pi\pi$,
$D^+ \to K\pi\pi$
$D^{*+} \to D^0\pi$, $D^0 \to K\pi\pi^0$

Reconstruct A^0 mass using $m_x^2 = (P_{ee} - P_{\pi\pi} - P_\gamma)^2$

Train 5 (charm) x 2 (mass) BDT to separate signal from background using 24 variables (event shape, kinematics, vertex, D, photon, dipion)

Low mass: $4.00 \le m_X \le 8.00$ GeV



High mass: $7.50 \le m_X \le 9.25$ GeV