Search for a low-mass CP odd Higgs boson

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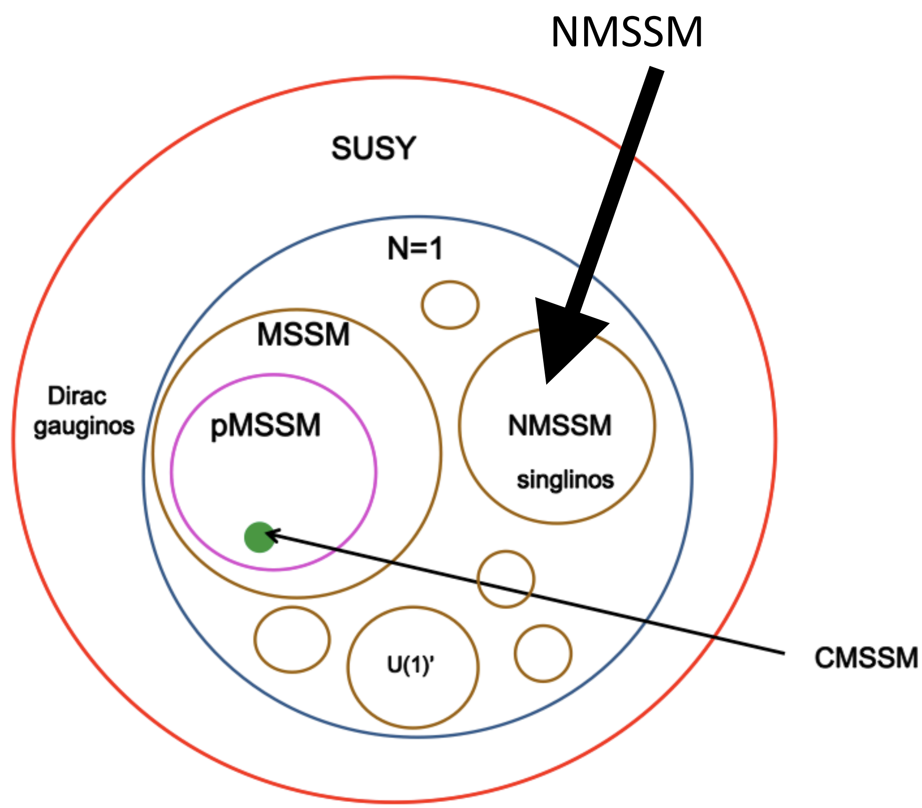
Possibility of a CP-odd light Higgs A^0

- Next-to-Minimal Supersymmetric Standard Model predicts 7 Higgs bosons
  - A^0, A^1, H^0, H^1, H^2, H^+, H^-
  - Phys. Rev. D 81, 075003 (2010)

- The lightest Higgs (A^0) in NMSSM can be lighter than 2 bottom quarks and is not excluded by LEP constraints

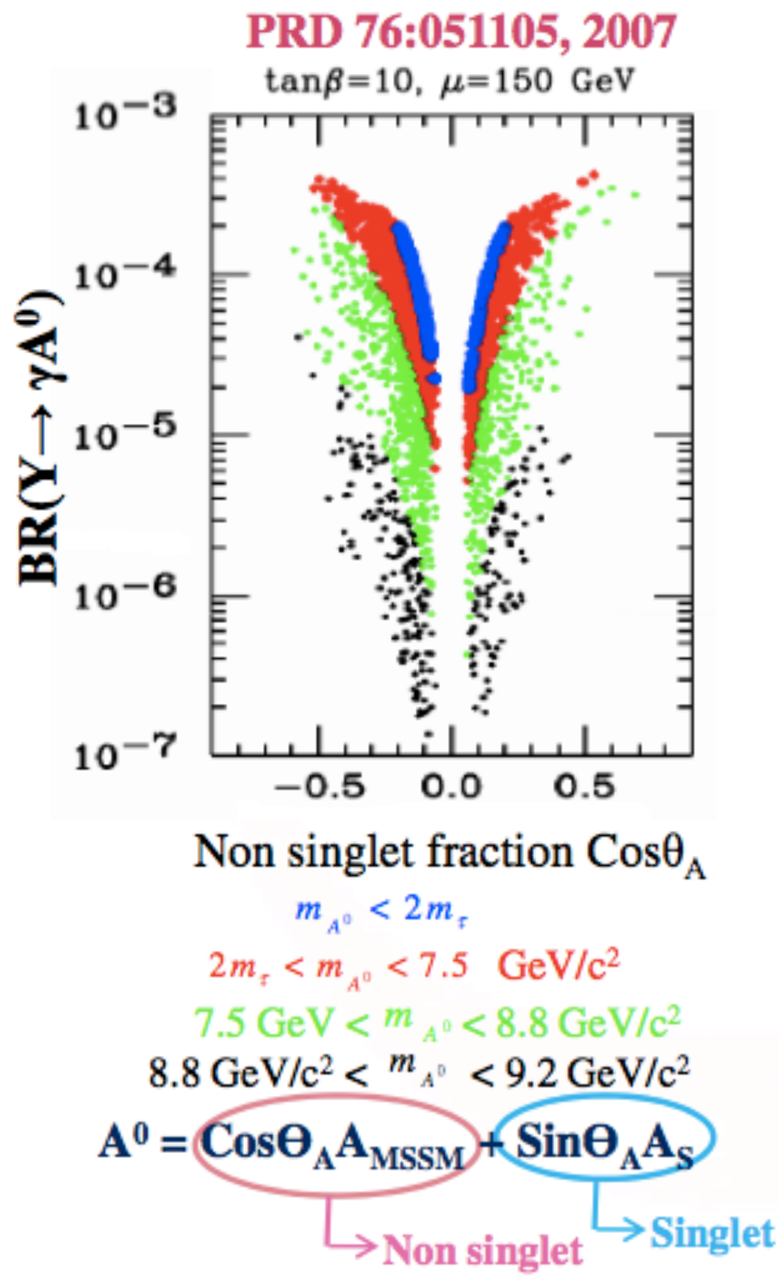
- The Higgs discovered at the LHC can be one of the heavier Higgs bosons



T. Rizzo (SLAC Summer Institute 2012)

NMSSM Parameter Space

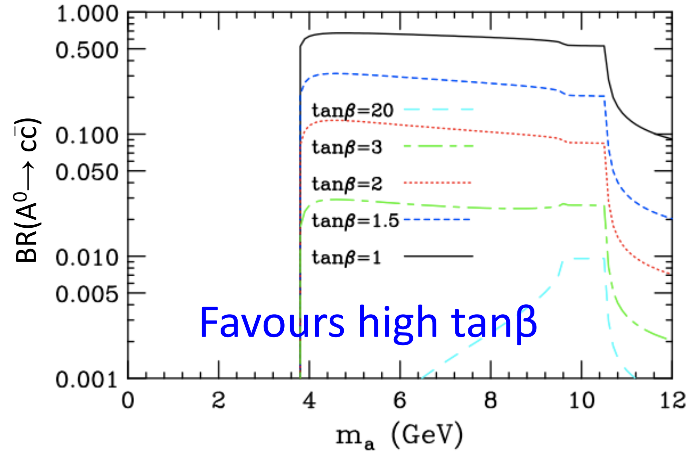
- BF($\Upsilon \rightarrow \gamma A^0$) depends on parameters such as the non-singlet fraction
  - BF decreases as mass increase
  - Difficult to exclude from 7.5 to 9.2 GeV/c^2 because of the low predictions

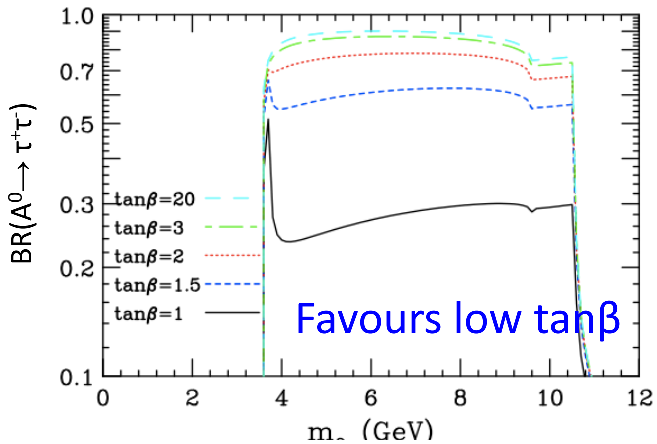


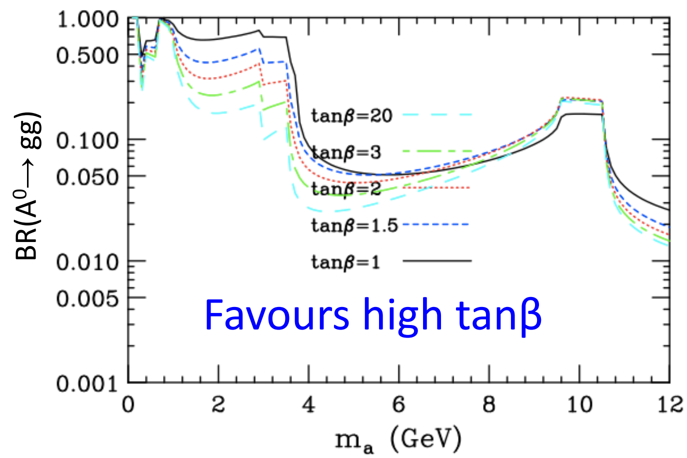
PRD **81** 075003 2010

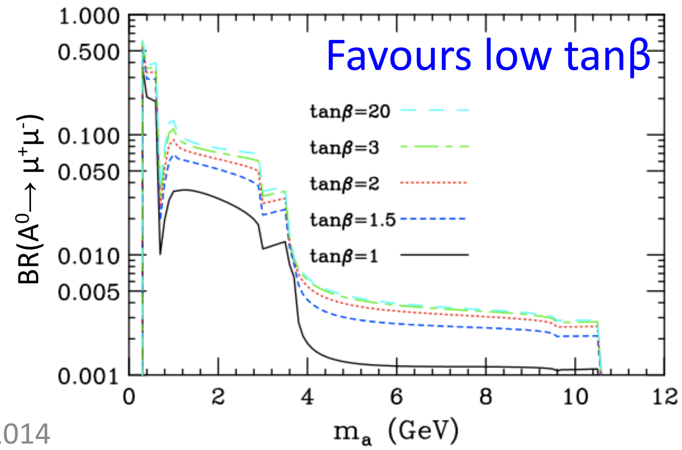
Higgs Branching Fractions

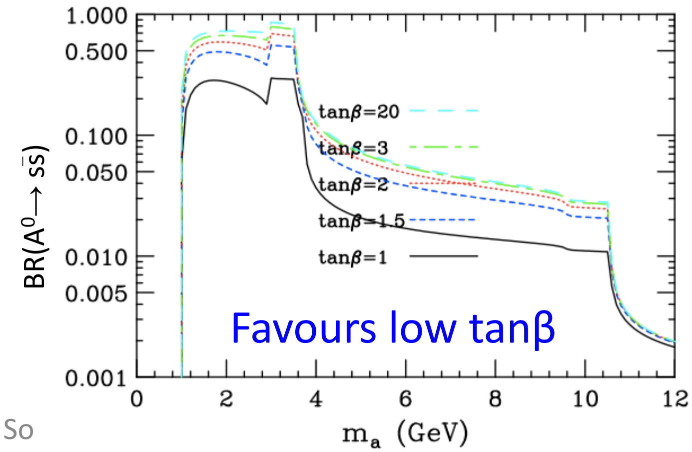
$$B\left(A^0 \to f\bar{f}\right) \propto m_f^2/\tan^2\beta \quad \text{up-type fermions}$$
$$B\left(A^0 \to f\bar{f}\right) \propto m_f^2 \tan^2\beta \quad \text{down-type fermions}$$











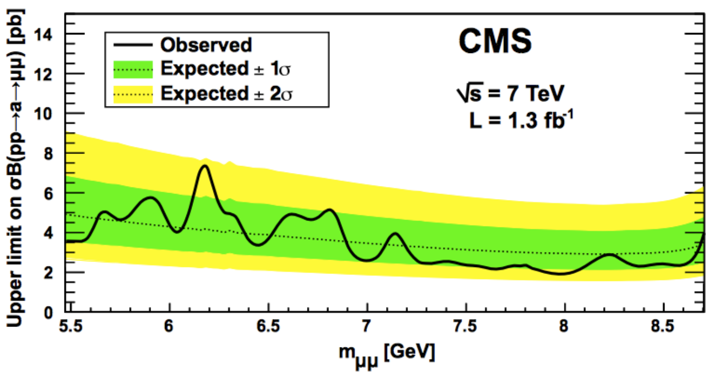
BABAR light Higgs searches

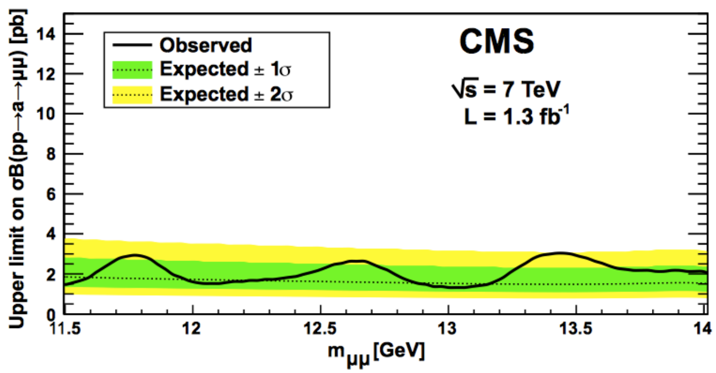
Two main types of search: direct from the $\Upsilon(2,3S)$ and using $\Upsilon(1S)$ from $\Upsilon(2,3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ events

Our previous results	
$\Upsilon(2,3S) \rightarrow \gamma\, A^0, A^0 \rightarrow \mu^+\mu^-$	PRL 103, 081803 (2009)
$\Upsilon(3S) \rightarrow \gamma\, A^0, A^0 \rightarrow \tau^+\tau^-$	PRL 103, 181801 (2009)
$\Upsilon(1S) \rightarrow \gamma\, A^0, A^0 \rightarrow$ invisible	PRL 107, 021804 (2011)
$\Upsilon(2,3S) \rightarrow \gamma\, A^0, A^0 \rightarrow$ hadrons	PRL 107, 221803 (2011)
$\Upsilon(1S) \rightarrow \gamma\, A^0, A^0 \rightarrow \mu^+\mu^-$	PRD 87, 031102(R) (2013)
$\Upsilon(1S) \rightarrow \gamma\, A^0, A^0 \rightarrow \tau^+\tau^-$	PRD 88, 071102 (2013)
Our newest result, focus of today's talk:	
$\Upsilon(1S) \rightarrow \gamma\, A^0, A^0 \rightarrow gg$ or $s\bar{s}$	PRD 88, 031701(R) (2013)

Other light Higgs searches

- CMS: gg $\longrightarrow$ $A^0 \longrightarrow \mu^+\mu^-$ (PRL **109** 121801 2012)
- Belle: Υ(1S,2S) $\longrightarrow \gamma$ A^0; $A^0 \longrightarrow \mu^+\mu^-$ (preliminary)
  and Υ(1S,2S) $\longrightarrow \gamma$ A^0; $A^0 \longrightarrow \tau^+\tau^-$ (preliminary)
- Neither has seen a significant signal



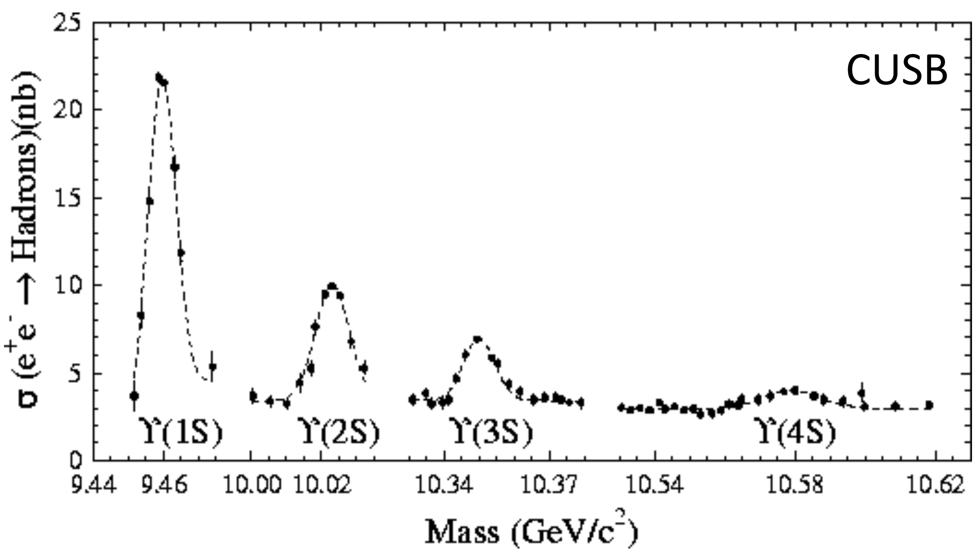


Belle's upper limits as presented at Lake Louise 2013

Mode	90% CL Upper Limit [$\times 10^{-6}$]	A^0 Mass [GeV]
$BF(\Upsilon(2S)\rightarrow\gamma A^0)\times BF(A^0\rightarrow\mu^+\mu^-)$	0.19 ~ 8.26	0.213~9.37
$BF(\Upsilon(1S)\rightarrow\gamma A^0)\times BF(A^0\rightarrow\mu^+\mu^-)$	0.01 ~ 11.86	0.212~9.27
$BF(\Upsilon(2S)\rightarrow\gamma A^0)\times BF(A^0\rightarrow \tau^+\tau^-)$	1.61 ~ 12.17	4.16~9.19
$BF(\Upsilon(1S)\rightarrow\gamma A^0)\times BF(A^0\rightarrow \tau^+\tau^-)$	0.91 ~ 45.37	3.84~9.16

Dataset

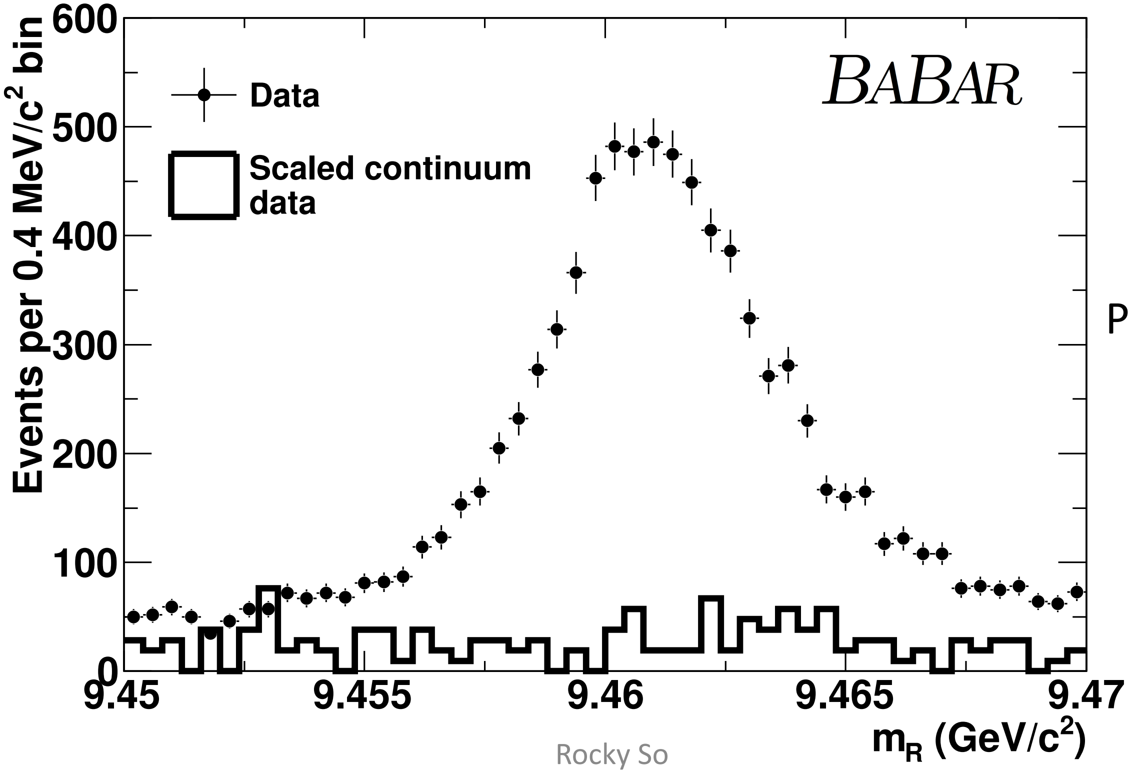
- 99M ϒ(2S)
  - 14/fb at 10.02 GeV e^+e^- center of mass energy
  - 1.4/fb at 9.99 GeV for backgrounds study
- 18M ϒ(1S) by tagging dipions $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$



Dipion tagging: $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

- Select on the invariant mass recoiling from the dipions
  $m_R^2 = M_{\Upsilon(2S)}^2 + M_{\pi\pi}^2 - 2M_{\Upsilon(2S)}E_{\pi\pi}$
- Dipion transitions peak at the $\Upsilon(1S)$ mass
  - The backgrounds are low after a selection of $9.45 < m_R < 9.47$ GeV/c^2

The signal PDF is a Gaussian with power law tail on both sides



PRD 88, 031701(R) (2013)

$\Upsilon(1S) \to \gamma A^0$; $A^0 \to$ gg or $s\bar{s}$

- Fully reconstruct gg using 26 channels
- Fully reconstruct $s\bar{s}$ using the subset that contains 2 or 4 kaons
- Require the hadronic system and a photon to be consistent with the mass of an $\Upsilon(1S)$

#	Channel	#	Channel
1	$\pi^+\pi^-\pi^0$	14	$K^+K^-\pi^+\pi^-$
2	$\pi^+\pi^-2\pi^0$	15	$K^+K^-\pi^+\pi^-\pi^0$
3	$2\pi^+2\pi^-$	16	$K^\pm K^0_S\pi^\mp\pi^+\pi^-$
4	$2\pi^+2\pi^-\pi^0$	17	$K^+K^-\eta$
5	$\pi^+\pi^-\eta$	18	$K^+K^-2\pi^+2\pi^-$
6	$2\pi^+2\pi^-2\pi^0$	19	$K^\pm K^0_S\pi^\mp\pi^+\pi^-2\pi^0$
7	$3\pi^+3\pi^-$	20	$K^+K^-2\pi^+2\pi^-\pi^0$
8	$2\pi^+2\pi^-\eta$	21	$K^+K^-2\pi^+2\pi^-2\pi^0$
9	$3\pi^+3\pi^-2\pi^0$	22	$K^\pm K^0_S\pi^\mp2\pi^+2\pi^-\pi^0$
10	$4\pi^+4\pi^-$	23	$K^+K^-3\pi^+3\pi^-$
11	$K^+K^-\pi^0$	24	$2K^+2K^-$
12	$K^\pm K^0_S\pi^\mp$	25	$p\bar{p}\pi^0$
13	$K^+K^-2\pi^0$	26	$p\bar{p}\pi^+\pi^-$

$\Upsilon(1S) \rightarrow \gamma A^0$; $A^0 \rightarrow gg$ or $s\bar{s}$

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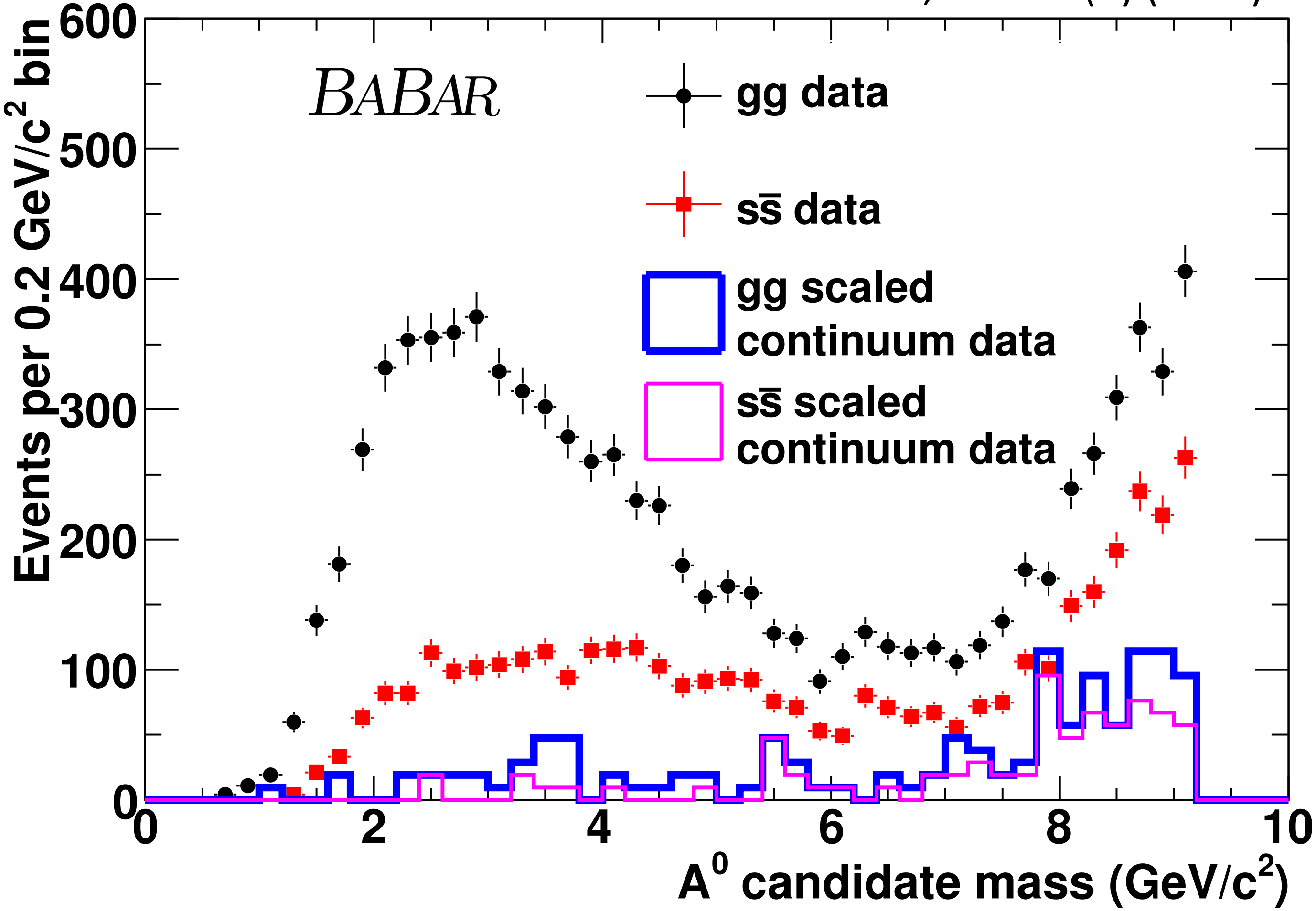


A^0 resolution is ~100MeV/c^2

Efficiencies from a few % at 0.5 GeV/c^2 to 10^{-4} at masses ~9GeV/c^2

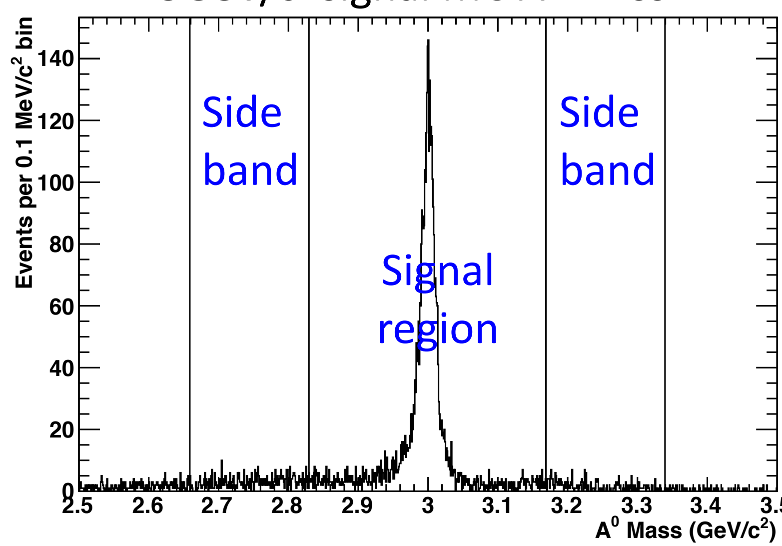
Signal Extraction

- Scan mass spectrum in 0.01 GeV/c^2 steps from 0.5 to 9.0 GeV/c^2 (gg) and 1.5 to 9.0 GeV/c^2 (ss)

- Calculate probability of seeing n_{signal} **or more** given that we see $n_{side\ band}$

- Use a Bayesian-frequentist hybrid (NIM A 595 (2008) 480)

3GeV/c^2 signal MC $A^0 \longrightarrow s\bar{s}$



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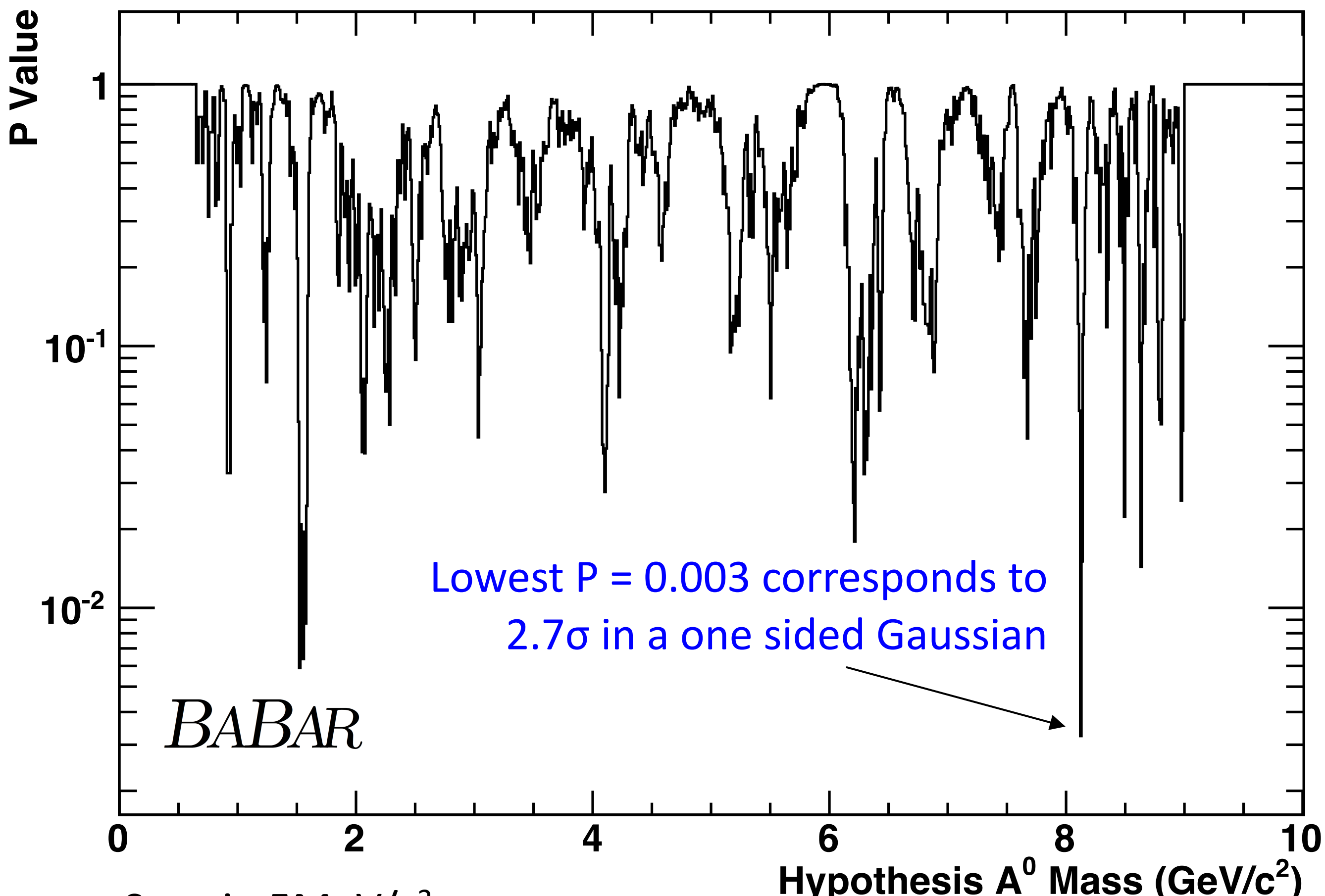
gg results



Scan in 5MeV/c^2 steps

The probability of seeing a 2.7σ fluctuation anywhere is 86% calculated using simulated experiments

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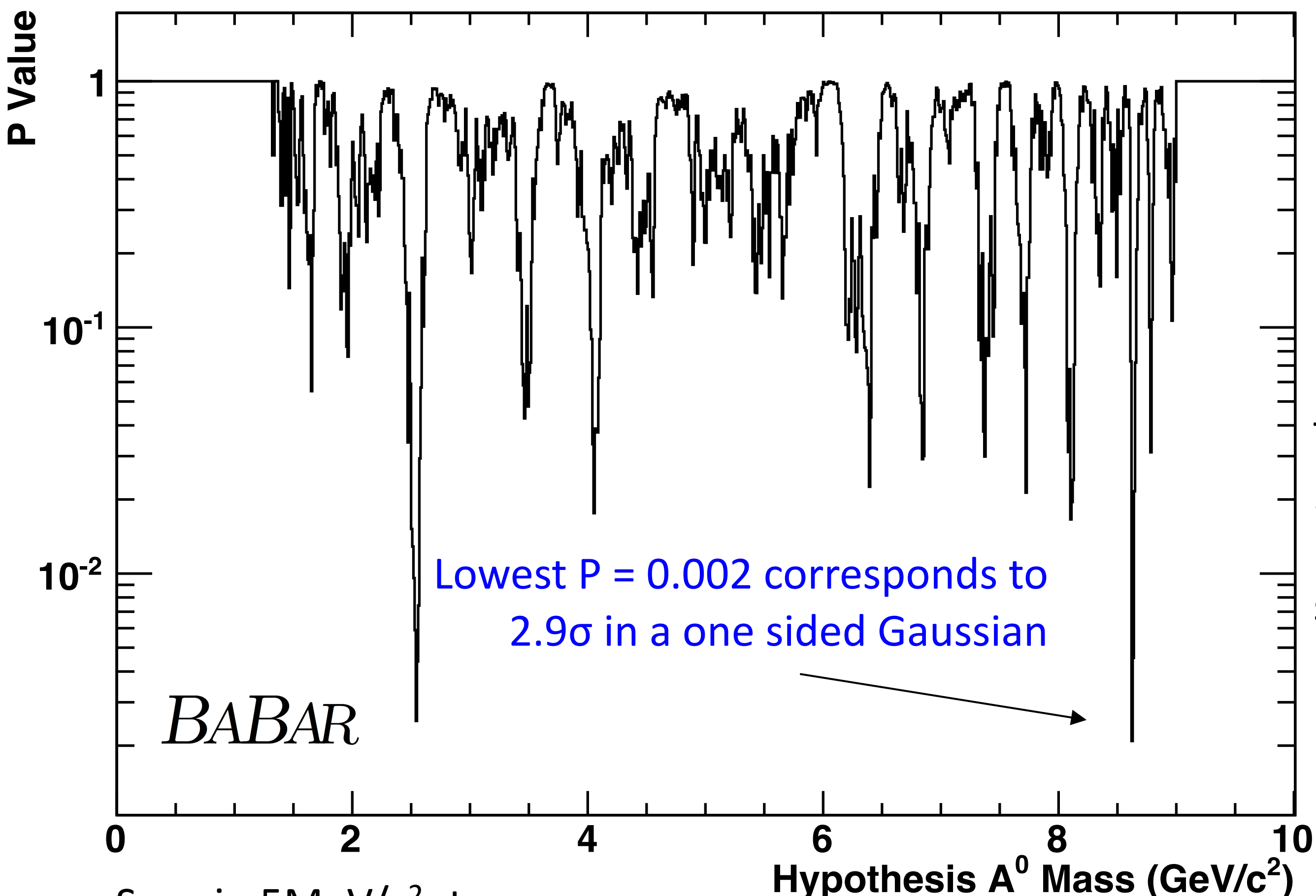
$s\bar{s}$ results



Scan in 5MeV/c^2 steps

The probability of seeing a 2.9σ fluctuation anywhere is 59% calculated using simulated experiments

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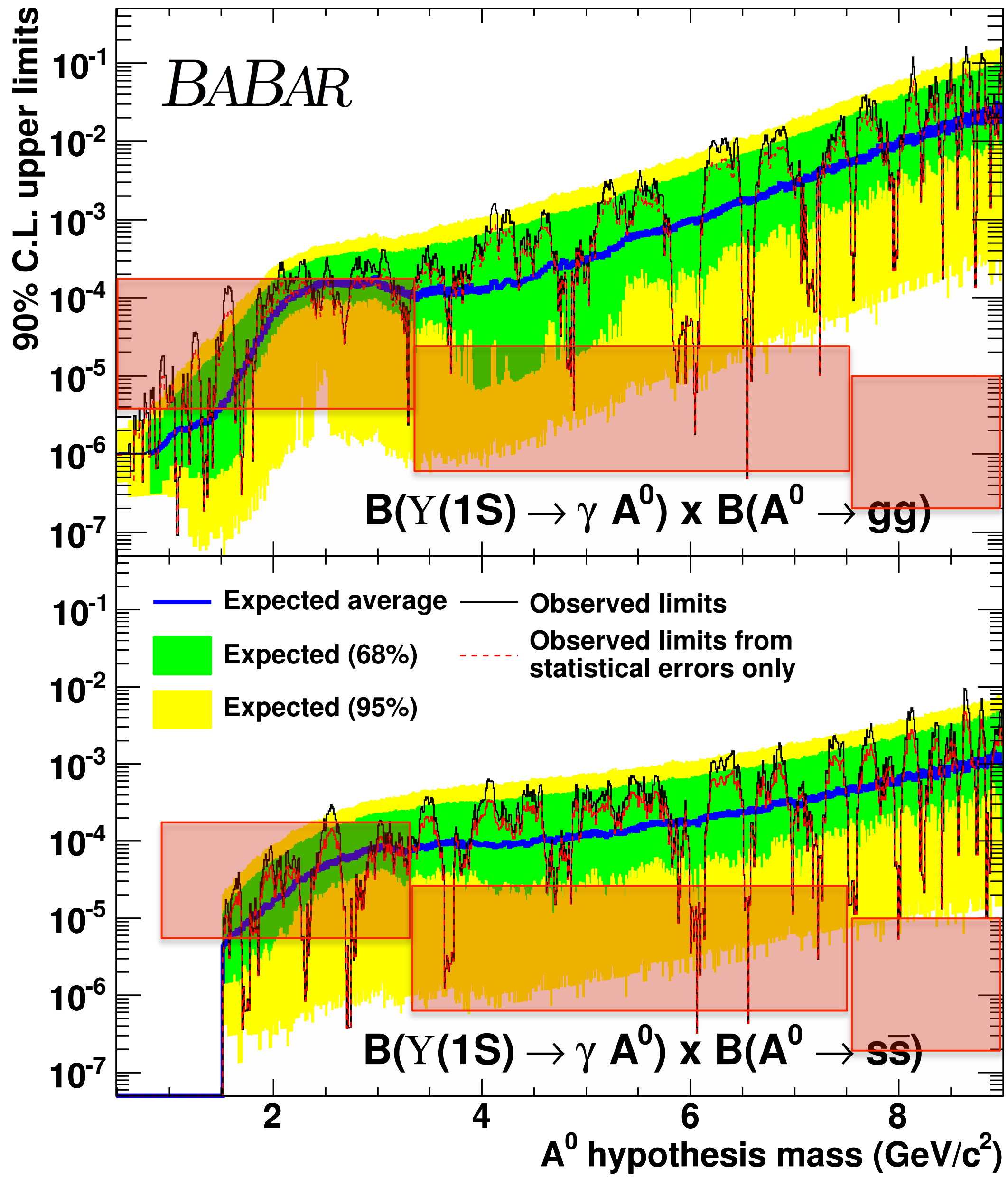
Branching Fraction Upper Limits



Our limits excludes some NMSSM parameters space for A^0 mass less than $\tau^+\tau^-$

Red box = approximate range of theory predictions
PRD 76 051105 2007
PRD 81 075003 2010

Summary and Outlook

- *BABAR* has seen no evidence for a CP-odd light Higgs boson
- We exclude some NMSSM parameter space below the charm/tau threshold
- Analyses searching for A^0 decaying into $\gamma\gamma$ or $c\bar{c}$ are in progress

Extra slide

p-value calculation

$$\mathcal{L}(\mu_b; n_{off}, \tau) = \frac{(\tau\mu_b)^{n_{off}}\ e^{-\tau\mu_b}}{n_{off}!}$$

$$p(\mu_b; n_{off}, \tau) = \mathcal{L}(\mu_b; n_{off}, \tau) \Big/ \int_0^\infty \mathcal{L}(\mu_b; n_{off}, \tau)\, d\mu_b$$

$$p_{\mathrm{P}}(\mu_b; n_{on}) = \sum_{j=n_{on}}^{\infty} e^{-\mu_b} \mu_b^j / j! = \Gamma(n_{on}, 0, \mu_b)/\Gamma(n_{on})$$

$$p_o(n_{on}, n_{off}, \tau) = \int_0^\infty p(\mu_b; n_{off}, \tau) \times p_{\mathrm{P}}(\mu_b; n_{on}) d\mu_b$$