BaBar

TEL AVIV UNIVERSITY

Searches for a low-mass *CP*-odd Higgs boson at *BaBar*

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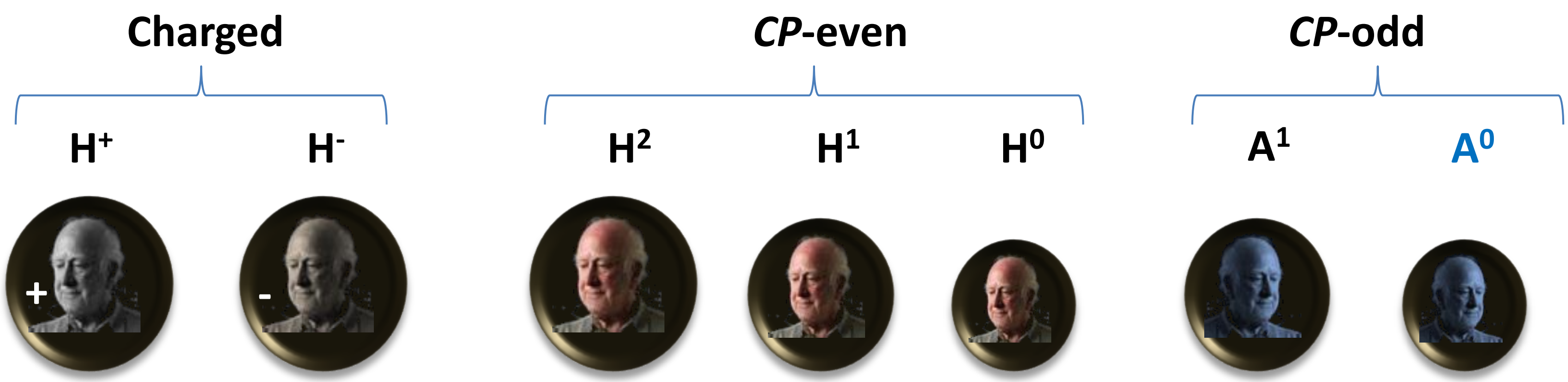
Higgs Hunting, July 2014

Possibility of a *CP*-odd light Higgs A^0

- Next-to-Minimal Supersymmetric Standard Model (NMSSM) predicts 7 Higgs bosons [Maniatis, Int. J. Mod. Phys. A25.3505]



- The lightest Higgs (**A^0**) in NMSSM may have $m_{A^0} < 2m_b$
  - Not excluded by LEP
  - Observed three anomalous events at Hyper-CP could be interpreted as an **A^0** $\rightarrow \mu^+\mu^-$ with mass 0.214 GeV

NMSSM Parameter Space

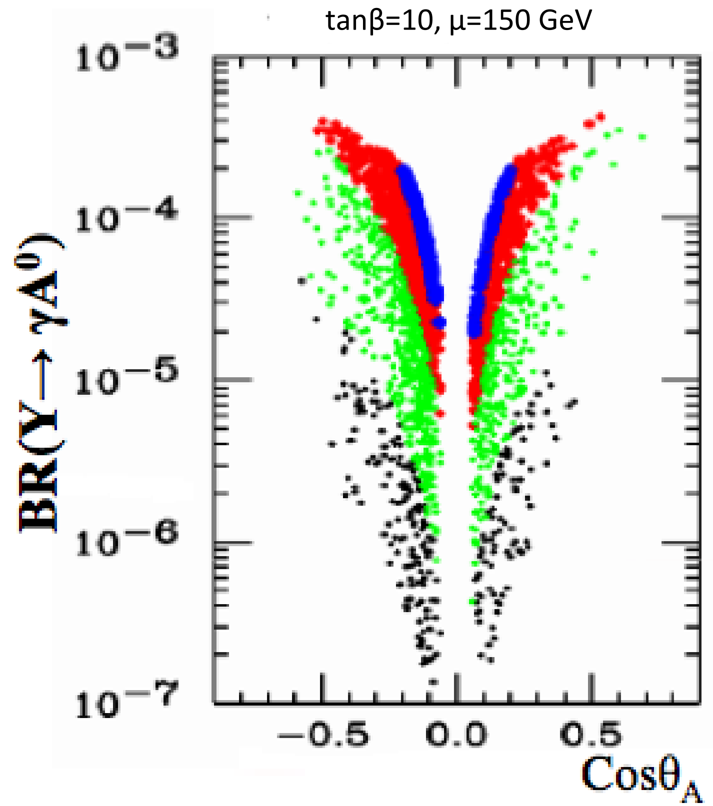
- BR($\Upsilon \rightarrow \gamma$ **A^0**) depends on several parameters, including
  - m_{A^0}
    - BF decreases as mass increases
  - The non-singlet fraction $\cos\theta_A$

  - The ratio of the VEV's of the up- and down-type MSSM Higgs doublets

$$\tan \beta = \frac{h_u}{h_d}$$

Dermisek, Gunion, McElrath
PRD 76:051105, 2007

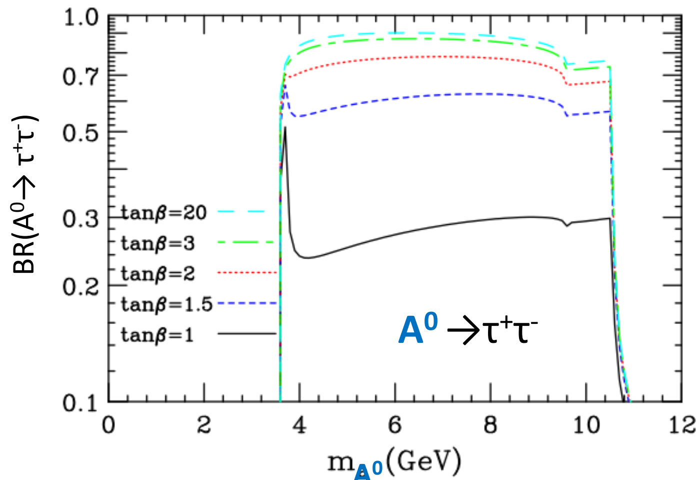
tanβ=10, μ=150 GeV

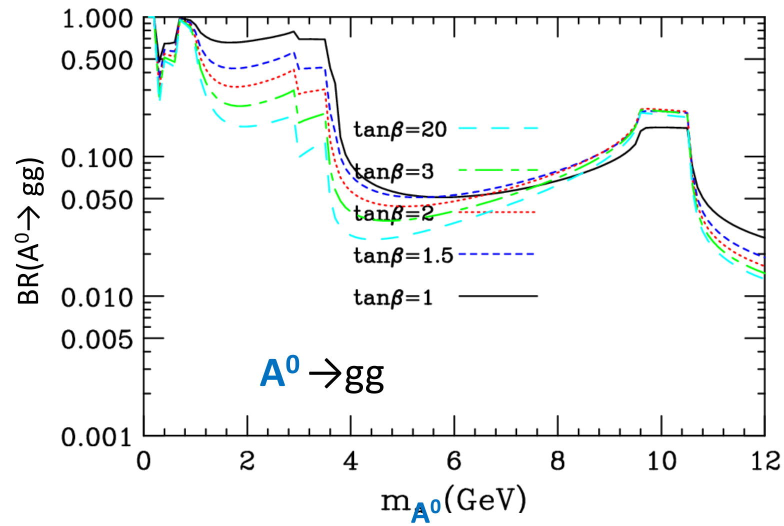


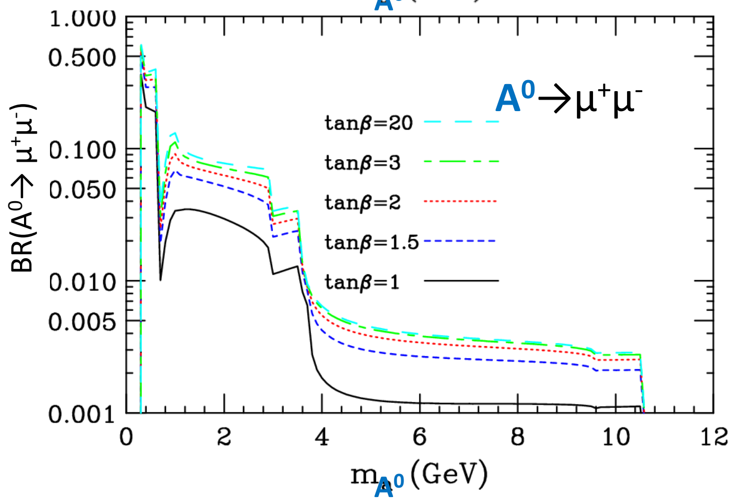
$0 < m_{A0} < 2m_\tau$
$2m_\tau < m_{A0} < 7.5$ GeV
$7.5 < m_{A0} < 8.8$ GeV
$8.8 < m_{A0} < 9.2$ GeV

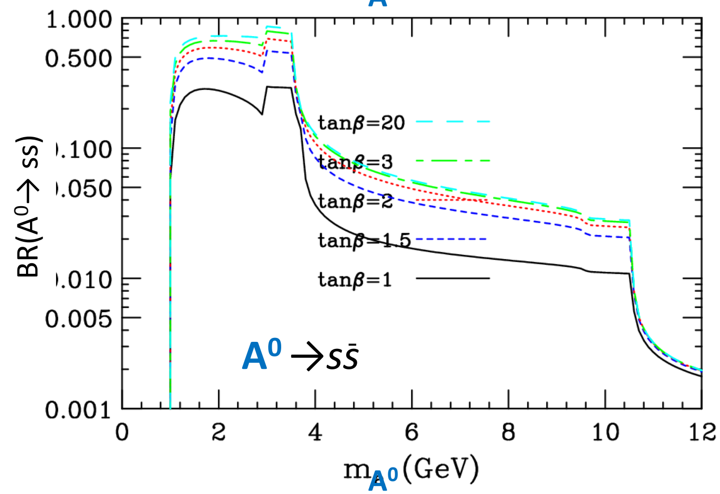
A^0 Branching Fractions

- The **A^0** branching ratios to lepton pairs or hadrons are dominant in different mass regions and tanβ values









PRD **81** 075003 2010

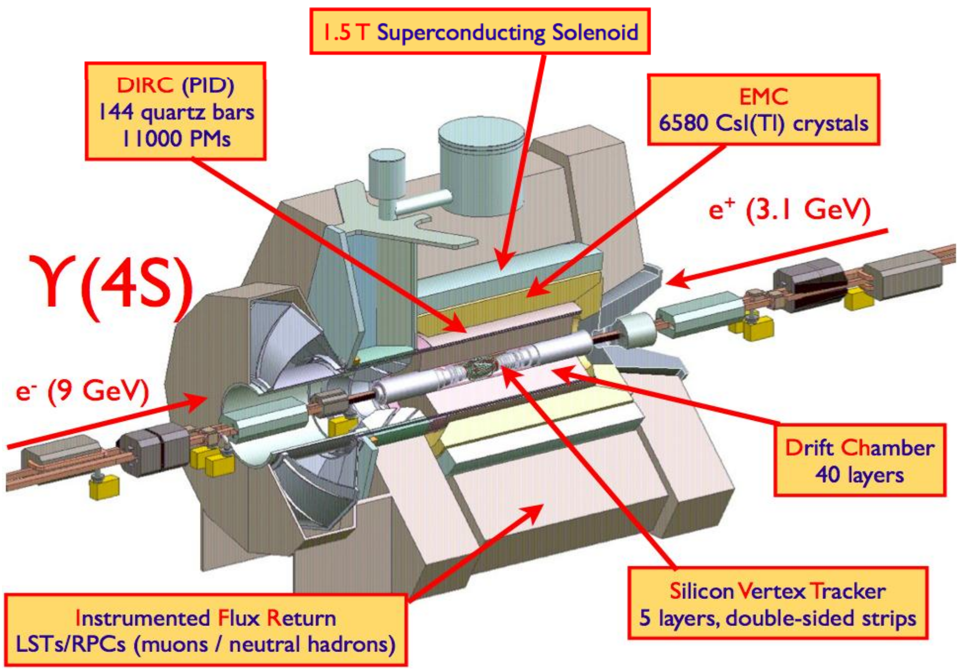
BABAR light Higgs searches

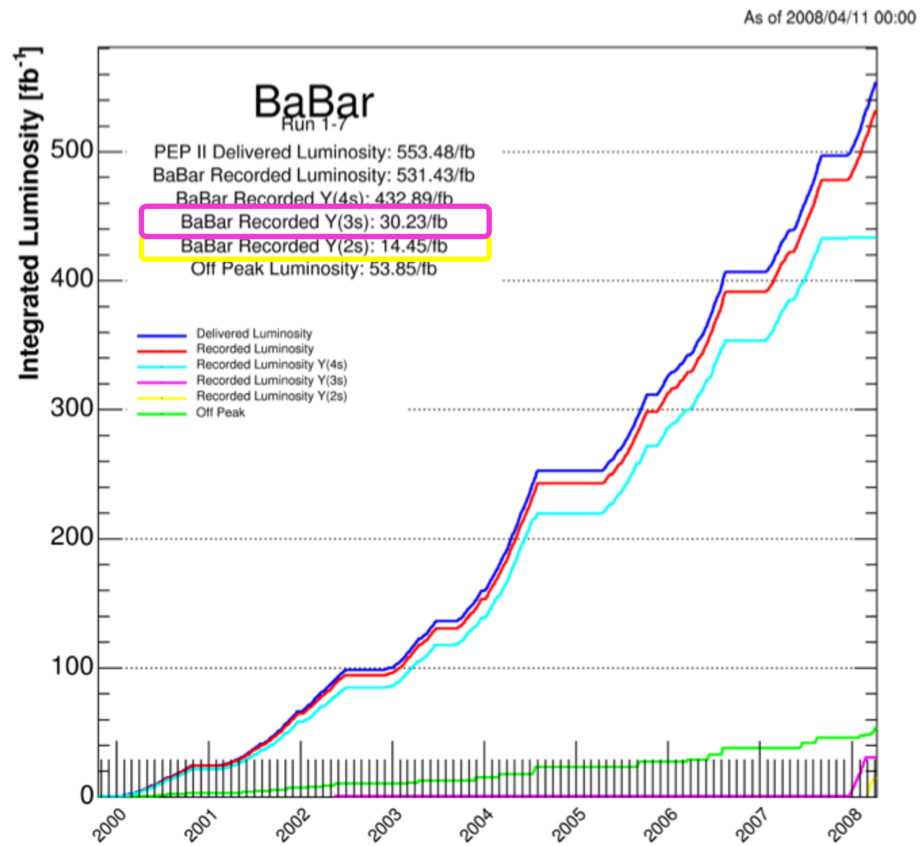
- Two main search types for **A^0** radiative decays
  - Direct from $\Upsilon(2S,3S)$
  - From $\Upsilon(1S)$, tagged from $\Upsilon(2S,3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$

Previous results	
$\Upsilon(2S,3S) \rightarrow \gamma$ **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)
$\Upsilon(2S,3S) \rightarrow \gamma$ **A^0**, **A^0** $\rightarrow$hadrons	PRL **107**, 221803 (2011)
Our newest results, and focus of today's talk:	
$\Upsilon(1S) \rightarrow \gamma$ **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)
$\Upsilon(1S) \rightarrow \gamma$ **A^0**, **A^0** $\rightarrow$gg or ss	PRD **88**, 031701(R) (2013)

The *BABAR* Experiment

Nucl.Instrum.Meth. A 479, 1 (2002)
Nucl.Instrum.Meth.A 729, 615 (2013)

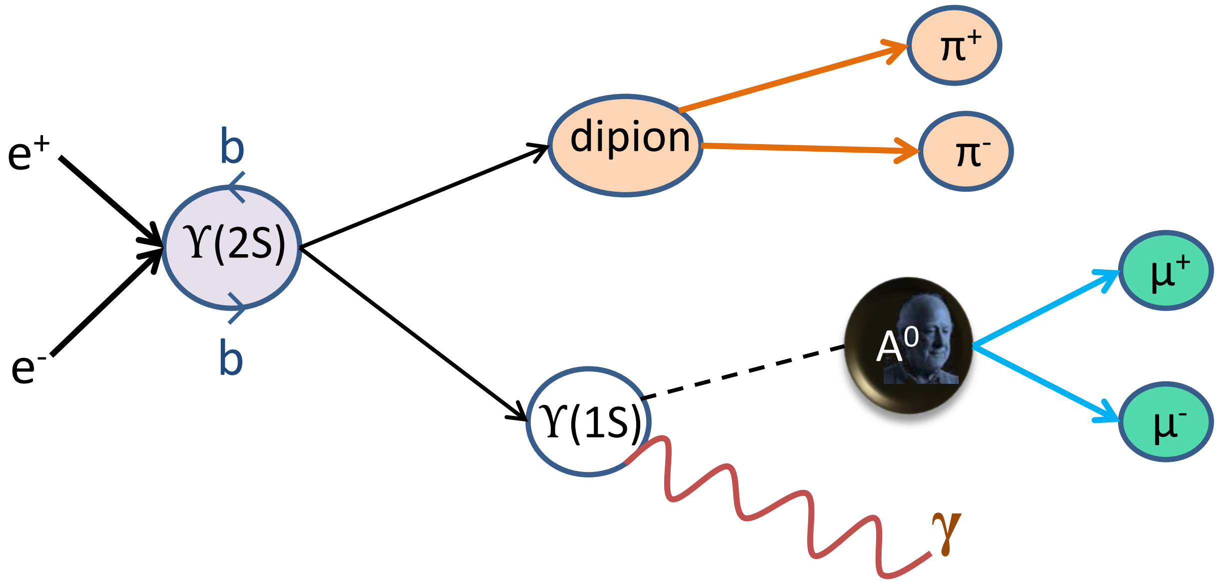




- The datasets used in the analyses described in this talk:
  - 117M $\Upsilon(3S)$
  - 99M $\Upsilon(2S)$
  - 23M $\Upsilon(1S)$
    - from $\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$

$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$

- Fully reconstruct the decay chain
  $\Upsilon(2S,3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma$ **A^0**, **A^0** $\rightarrow \mu^+\mu^-$



- The reduced mass is calculated for each **A^0** candidate:

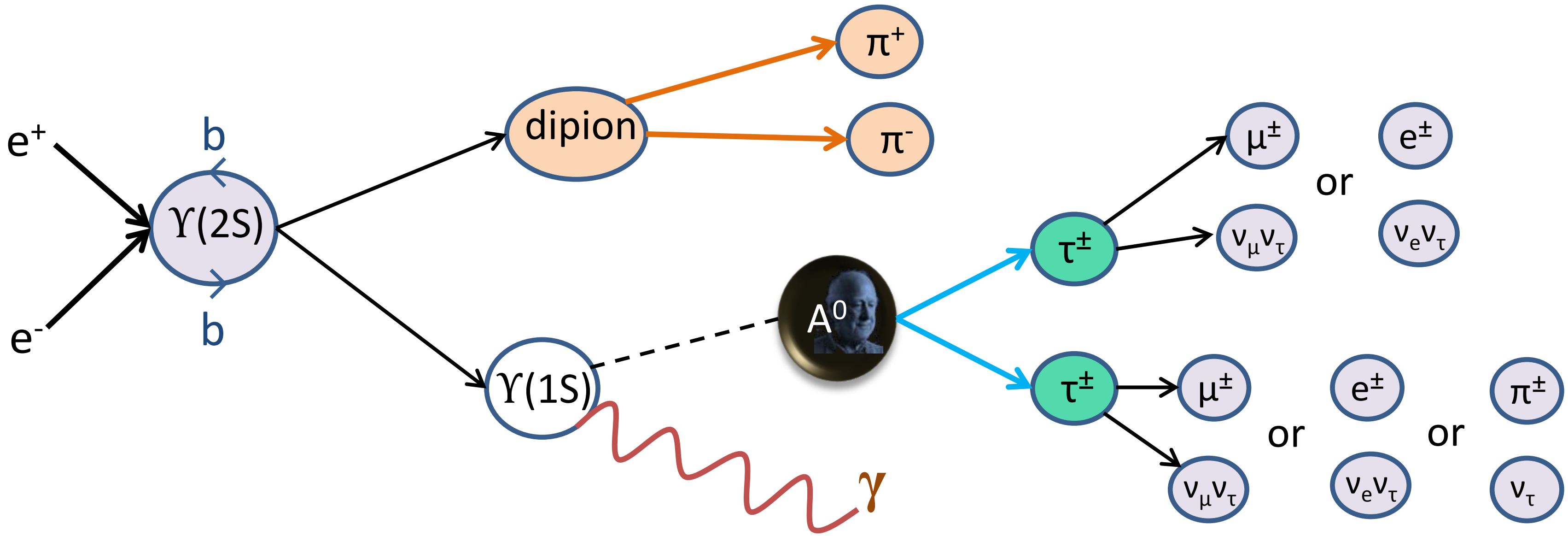
$$m_{red} = \sqrt{m^2_{\mu^+\mu^-} - 4m^2_\mu}$$

  - Twice the momentum of the muons in the **A^0** rest frame

$\Upsilon(1S) \to \gamma A^0,\ A^0 \to \tau^+\tau^-$

- The mass recoiling against the dipion system peaks at $\Upsilon(1S)$ for signal

$$m^2_{recoil} = M^2_{\Upsilon(2S)} + m^2_{\pi\pi} - 2M_{\Upsilon(2S)}E^{CM}_{\pi\pi}$$

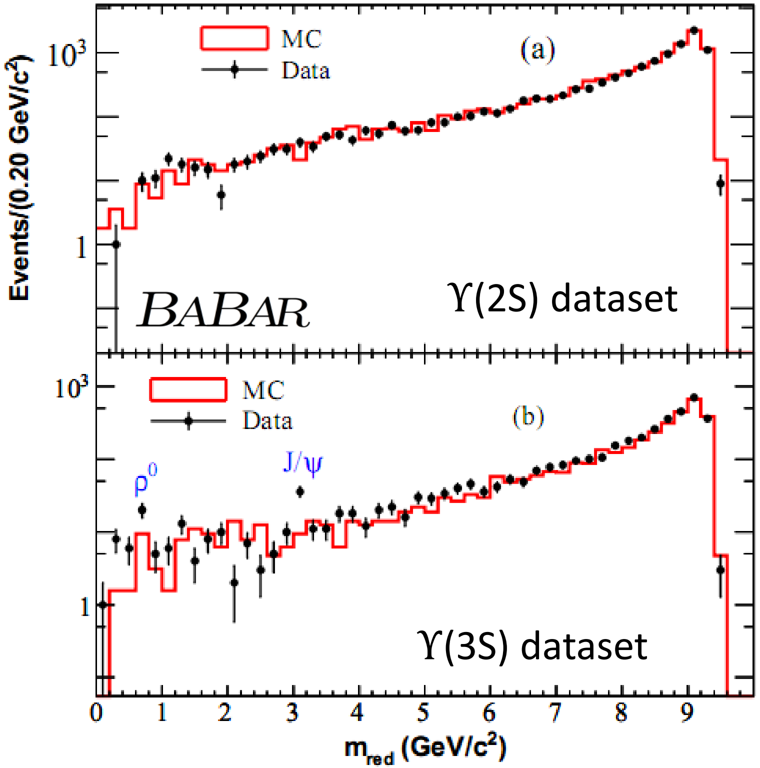


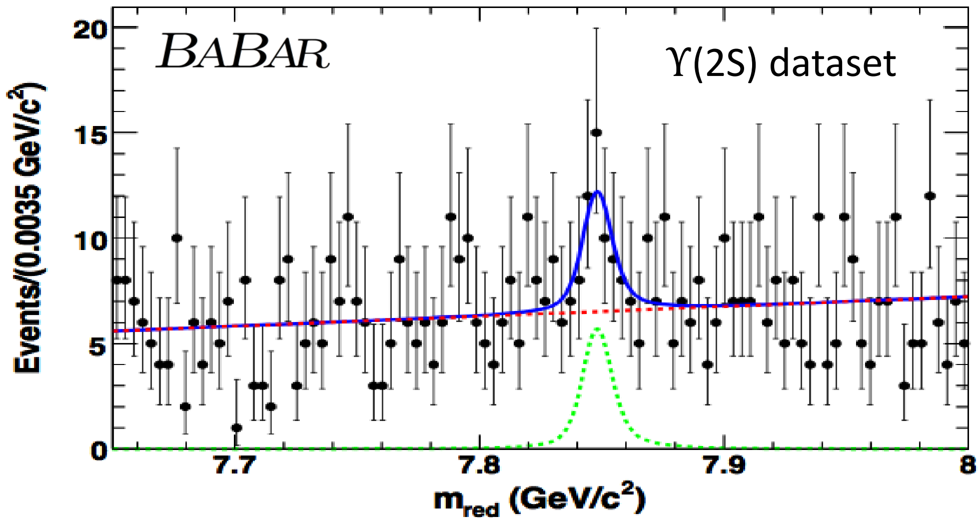
- The square of the mass recoiling against the photon, in the $\Upsilon(1S)$ frame is calculated for each **A^0** candidate:

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

$\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$

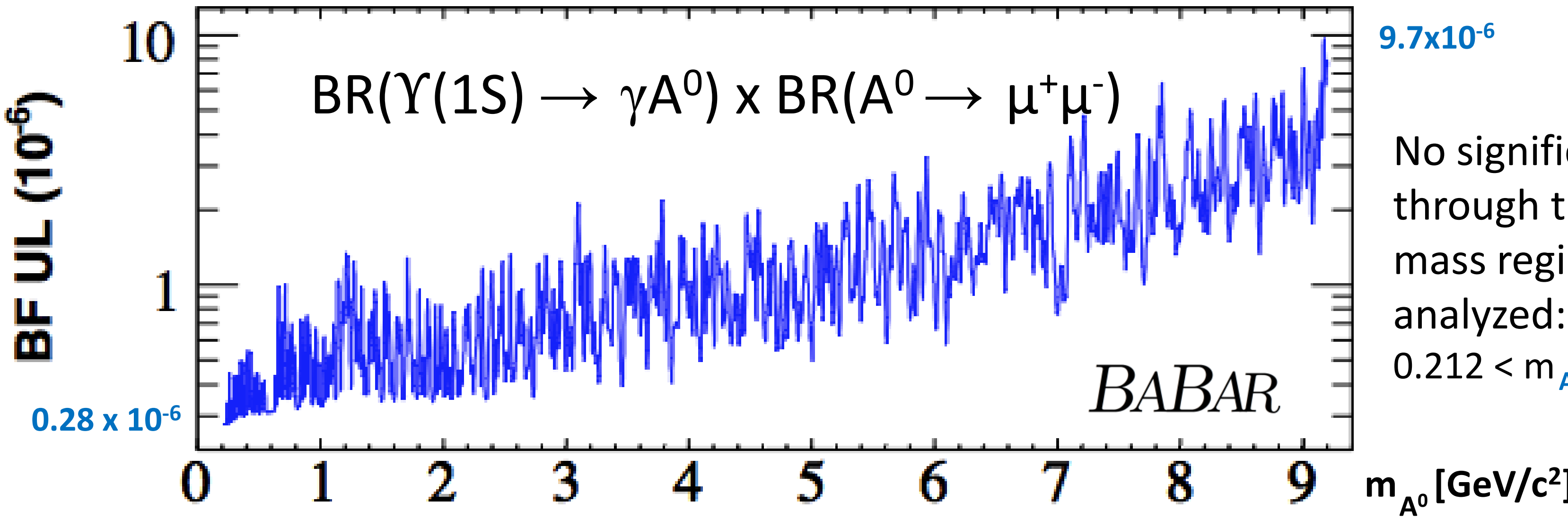
- The signal yield is extracted by performing a series of max likelihood fits for n_{sig}, n_{bkg}
  - Signal PDF determined by MC, Bkg PDF is a Chebyshev polynomial
  - Scan in steps of half the signal mass resolution (btw 2 and 9 MeV)
- Signal significance calculated according to likelihood ratio test $S_m = sign(n_{sig})\sqrt{-2\ln\left(\frac{L_0}{L_1}\right)}$



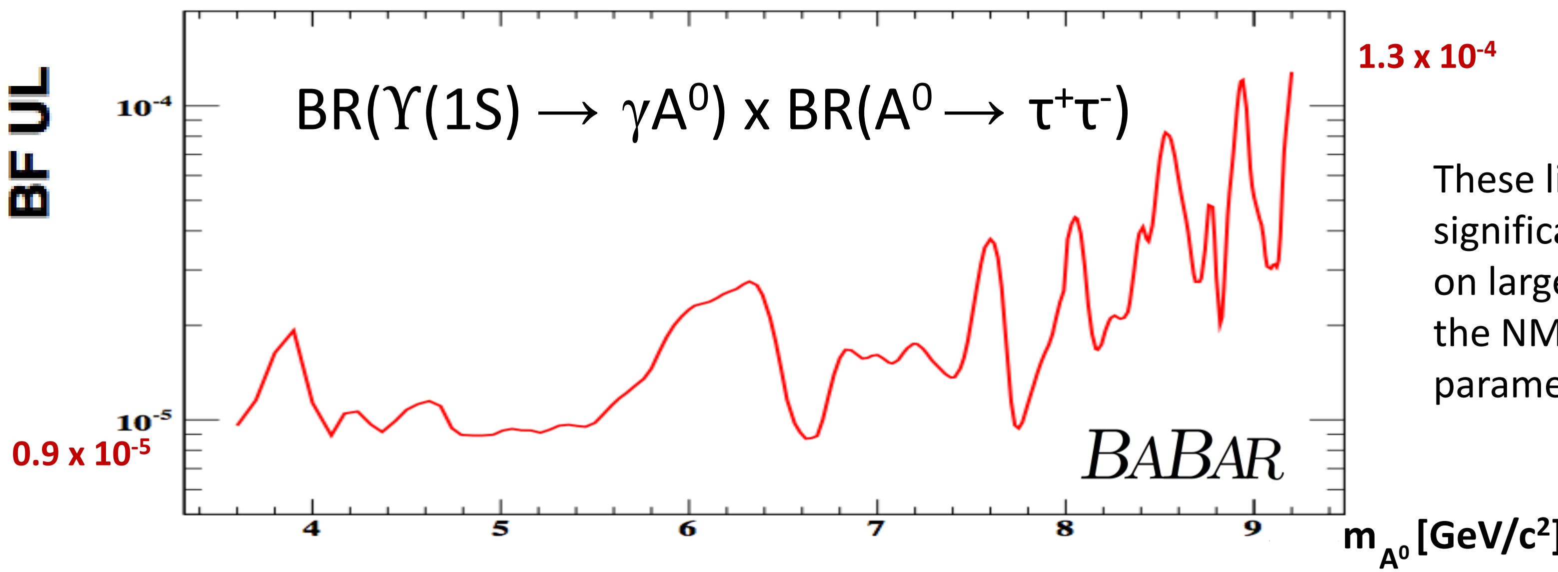


- Largest significance: 3.62σ at m_{A^0} = 7.85 GeV
- Using pseudo experiments, 18.1% probability of observing a 3.62σ+ fluctuation

90% CL UL for $A^0 \rightarrow \ell^+\ell^-$



No significant signal through the entire mass region analyzed:
$0.212 < m_{A^0} < 9.20$ GeV



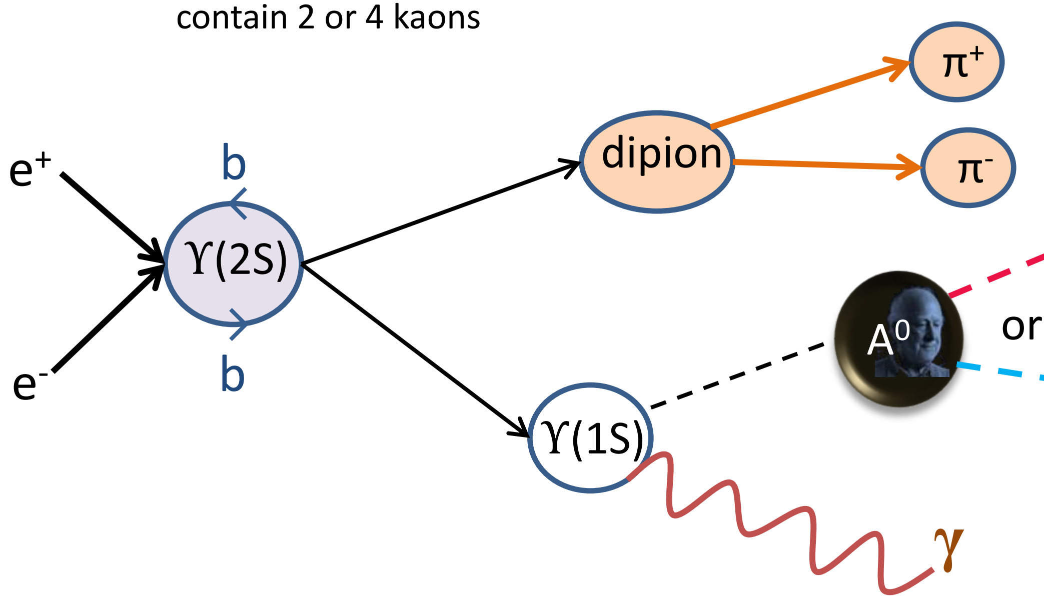
These limits set significant constraints on large sections of the NMSSM parameter space

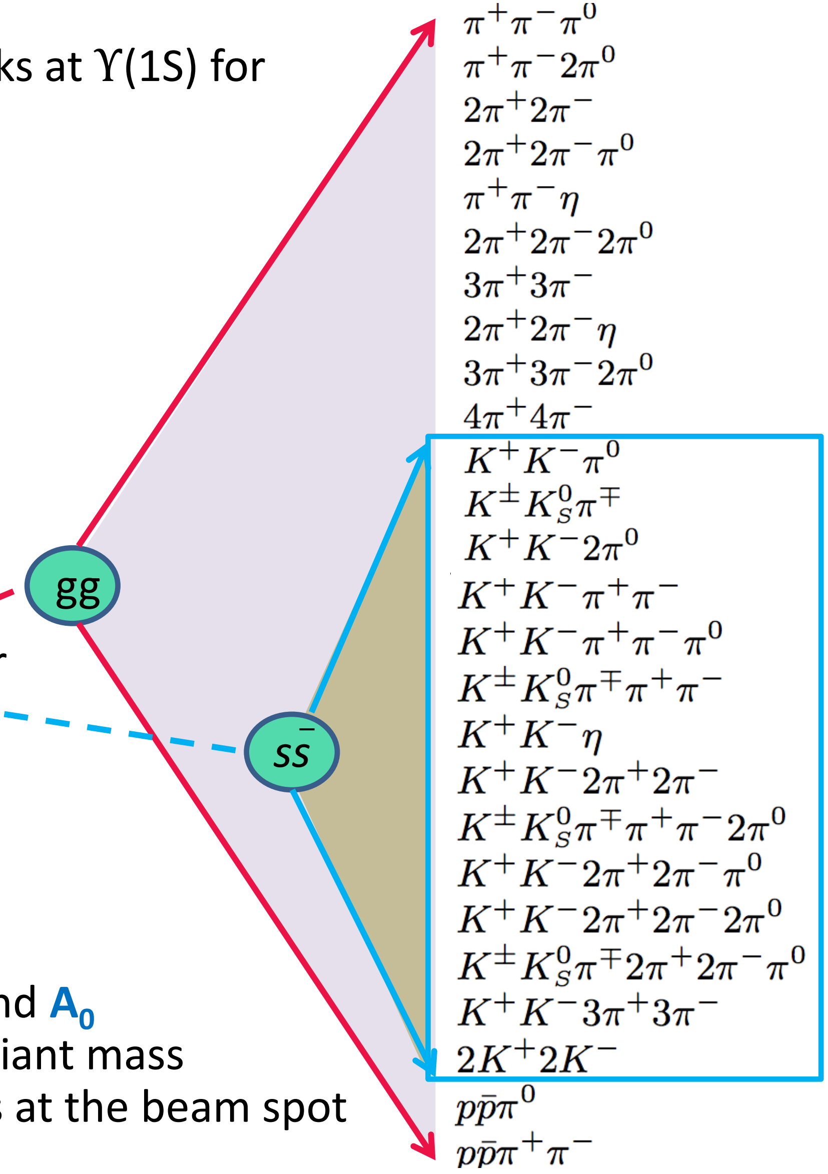
$\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow gg$ or $s\bar{s}$

- The mass recoiling against the dipion system peaks at $\Upsilon(1S)$ for signal

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

- 26 gg channels are fully reconstructed
  - Out of which the ss subset channels contain 2 or 4 kaons



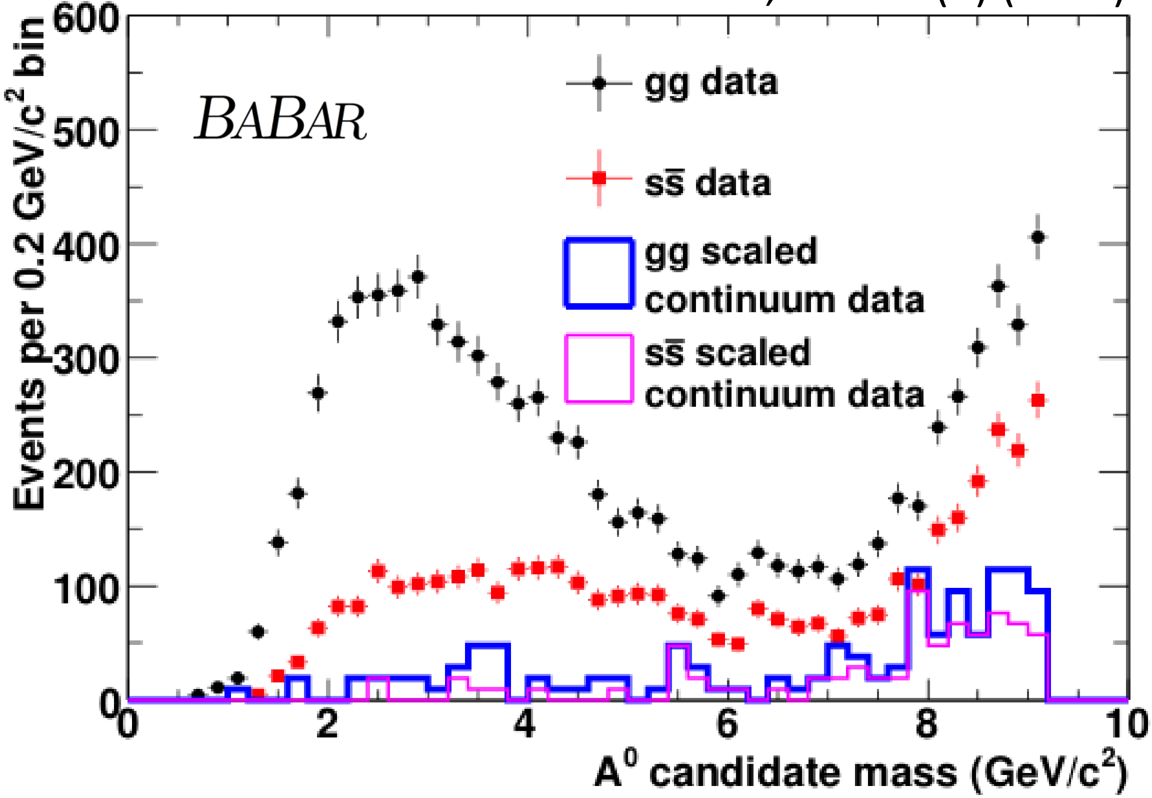


- To improve the A_0 mass resolution, the photon and A_0 candidates are constrained so that the total invariant mass equals the $\Upsilon(1S)$ mass, and the A_0 decay vertex is at the beam spot

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

- A^0 mass distribution after final selection

PRD 88, 031701(R) (2013)



- The main bkg source is from $\Upsilon(1S) \rightarrow \gamma gg$ and $\Upsilon(1S) \rightarrow ggg$, where the gluons hadronize to more than one daughter
  - A π^0 from the hadronization is mistaken as the radiative photon

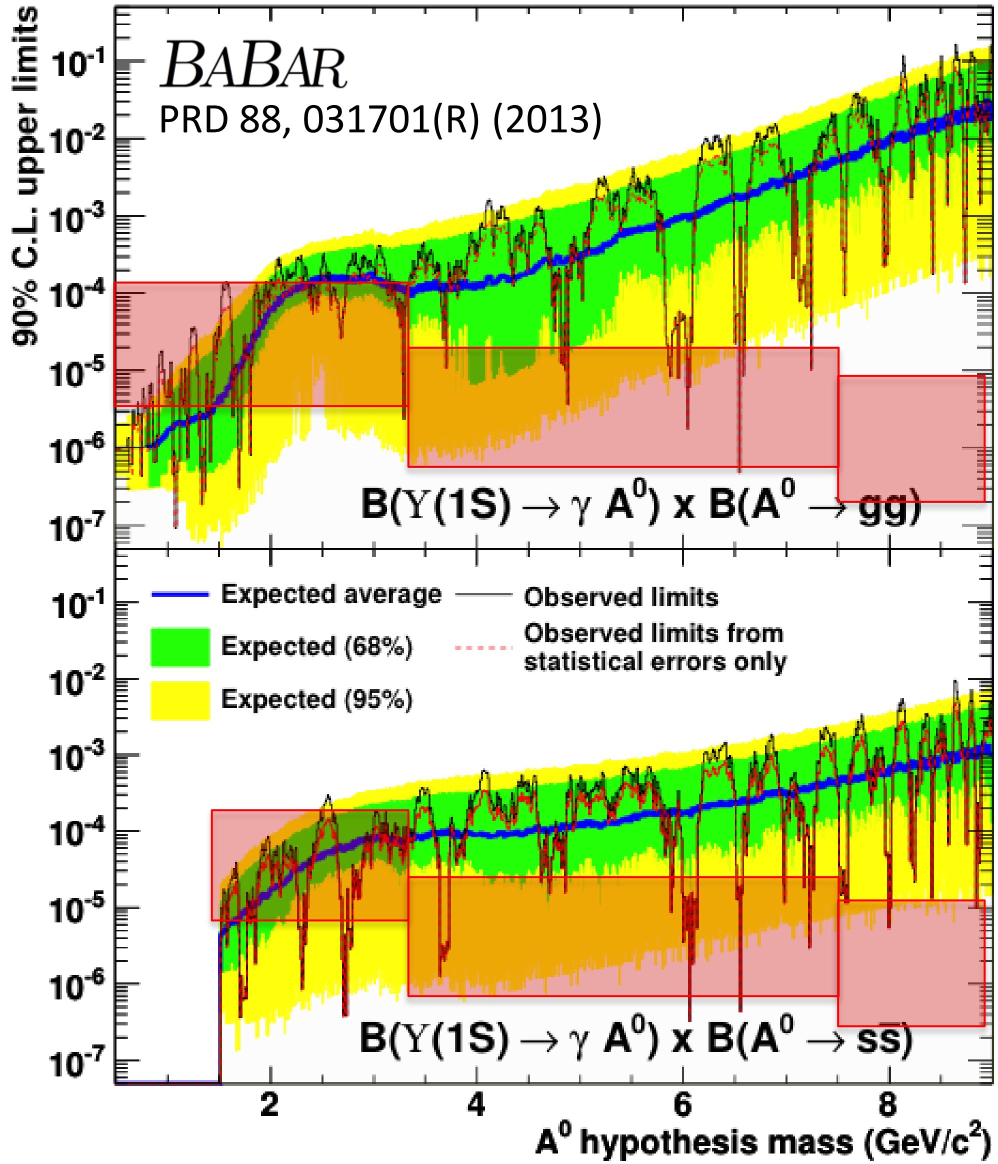
$\Upsilon(1S) \to \gamma A^0$, $A^0 \to gg$ or $s\bar{s}$

- 90% CL Upper limits are set on

  $BR(\Upsilon(1S) \to \gamma \mathbf{A^0}) \times BR(\mathbf{A^0} \to gg)$
  $BR(\Upsilon(1S) \to \gamma \mathbf{A^0}) \times BR(\mathbf{A^0} \to s\bar{s})$

- **The red boxes denote the approximate range of the NMSSM theory predictions [PRD 76 051105, 2007] [PRD 76 075003, 2010]**

- Our limits exclude some NMSSM parameter space, especially in the range $m_{A^0} < 2m_\tau$



Summary and Outlook

- *BABAR* has seen no evidence for a *CP*-odd light Higgs boson
  - We set limits which constrain a wide range of the NMSSM parameter space

- Analyses searching for $A^0 \longrightarrow c\bar{c}$ and $A^0 \longrightarrow \gamma\gamma$ in progress

- Other Higgs hunting analyses at *BABAR*
  - Search for dark Higgs in $e^+e^- \rightarrow h'A'$, $h' \rightarrow A'A'$ [PRL 108, 211801 (2012)]
    - The three A's are reconstructed in 11 combinations of leptonic and hadronic modes
  - Work in progress: search for long-lived particles decaying through the Higgs-portal, into lepton or hadron pairs

Backup Slides

NMSSM

- μ is the supersymmetric Higgs-mass parameter
- The NMSSM Higgs sector is characterized by 7 free parameters. Its potential is given by

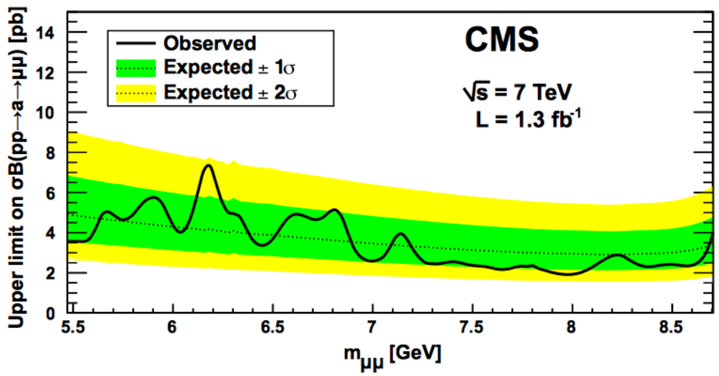
$$
\begin{aligned}
V_{Higgs} = & \left|\lambda\left(H_u^+ H_d^- - H_u^0 H_d^0\right) + \kappa S^2\right|^2 \\
& + \left(m_{H_u}^2 + |\lambda S|^2\right)\left(\left|H_u^0\right|^2 + \left|H_u^+\right|^2\right) \\
& + \left(m_{H_d}^2 + |\lambda S|^2\right)\left(\left|H_d^0\right|^2 + \left|H_d^-\right|^2\right) \\
& + \frac{1}{8}\left(g_1^2 + g_2^2\right)\left(\left|H_u^0\right|^2 + \left|H_u^+\right|^2 - \left|H_d^0\right|^2 - \left|H_d^-\right|^2\right)^2 \\
& + \frac{1}{2} g_2^2 \left|H_u^+ H_d^{0\star} + H_u^0 H_d^{-\star}\right|^2 \\
& + m_S^2 |S|^2 + \left[\lambda A_\lambda \left(H_u^+ H_d^- - H_u^0 H_d^0\right) S + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right].
\end{aligned}
$$

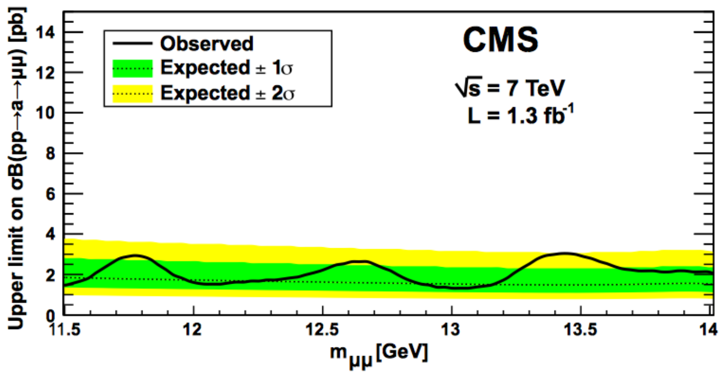
(taken from Pantelis Mitropoulos's thesis)

  - Where H_u and H_d are the two MSSM Higgs doublets, and S is the additional gauge singlet chiral field

Other light Higgs searches

- CMS: $gg \rightarrow A^0 \rightarrow \mu^+\mu^-$ (PRL **109** 121801 2012)
- Belle:
  - $\Upsilon(1S,2S) \rightarrow \gamma A^0$; $A^0 \rightarrow \mu^+\mu^-$ (preliminary)
  - $\Upsilon(1S,2S) \rightarrow \gamma A^0$; $A^0 \rightarrow \tau^+\tau^-$ (preliminary)



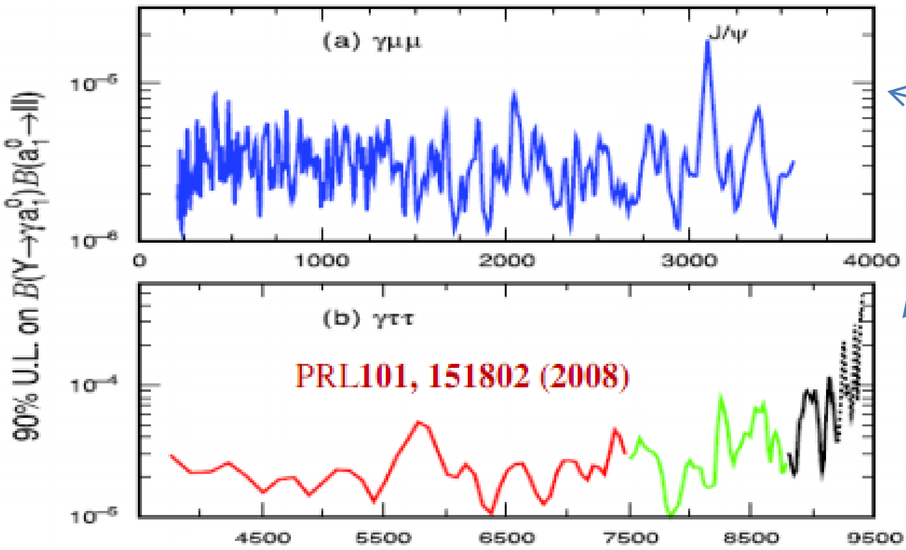


Belle's upper limits as presented at Lake Louise 2013

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

Other light Higgs searches

➢ CLEO collaboration

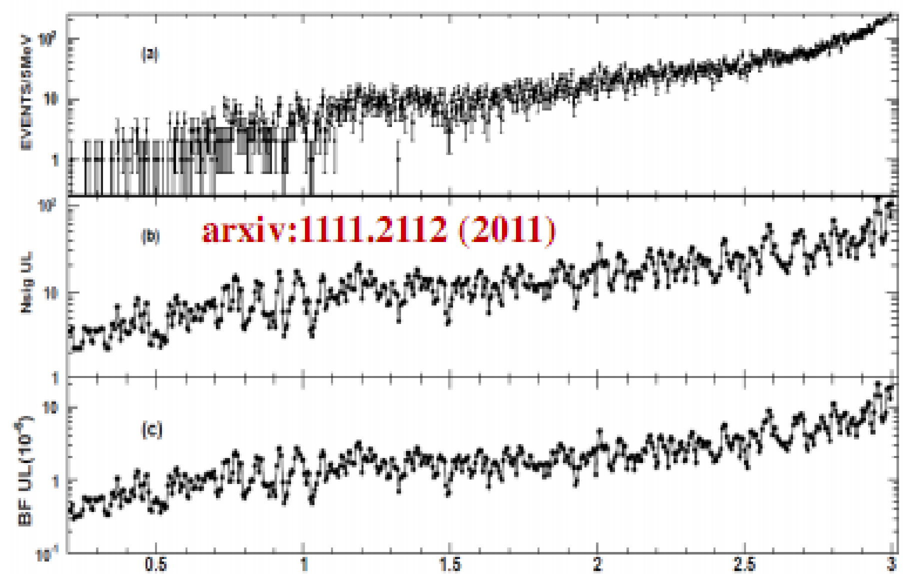


m_{A^0} [MeV/c^2]

- CLEO:
  - $\Upsilon(1S) \rightarrow \gamma$ **A^0**; **A^0** $\rightarrow \mu^+\mu^-$
  - $\Upsilon(1S) \rightarrow \gamma$ **A^0**; **A^0** $\rightarrow \tau^+\tau^-$

➢ BESIII collaboration

$J/\psi \rightarrow \gamma A^0,\ A^0 \rightarrow \mu^+\mu^-$



m_{A^0} [GeV/c^2]

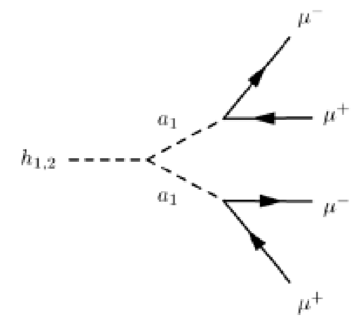
Other light Higgs searches

CMS results as presented yesterday by Felix

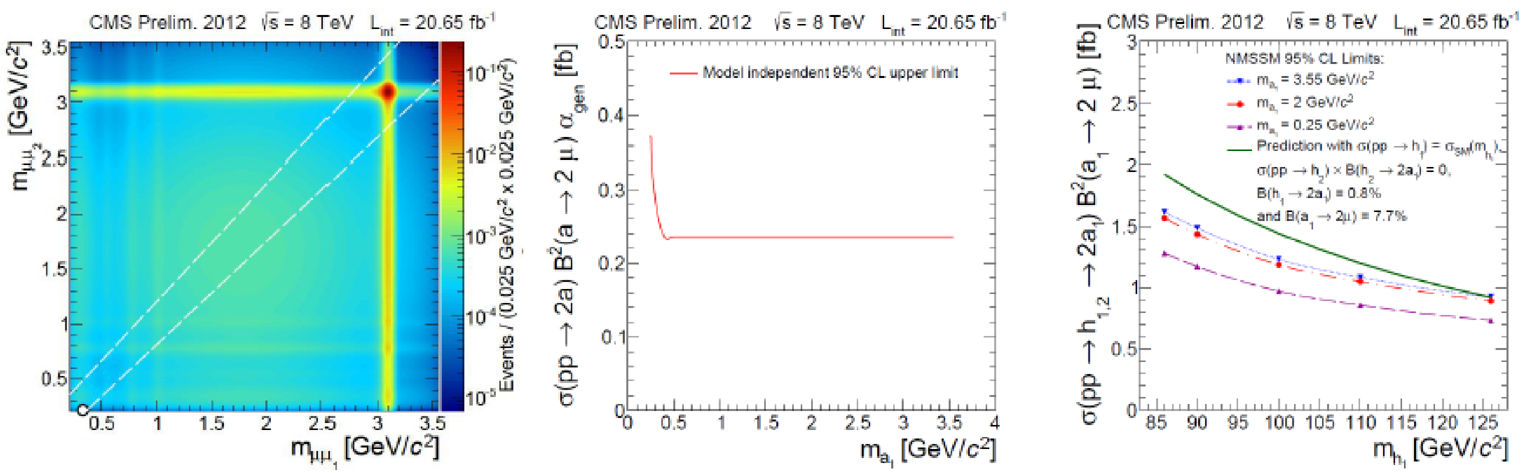
Neutral NMSSM Higgs Boson searches

CMS-PAS-HIG-13-010

$$h \rightarrow 2a + X \rightarrow 4\mu + X$$



- non-SM decay of h including two new light bosons
- NMSSM: substantial BR $a \rightarrow \mu\mu$ if $2m_\mu < m_a < 2m_\tau$
- background dominated by $b\bar{b}$ and J/ψ pair production
- 1 event observed in signal region, compatible with bkg. prediction 3.8 ± 2.1
- limit obtained for $0.25 < m_a < 3.55$ GeV, $m_h > 86$ GeV
- search interpreted for dark-SUSY models as well as model-independent



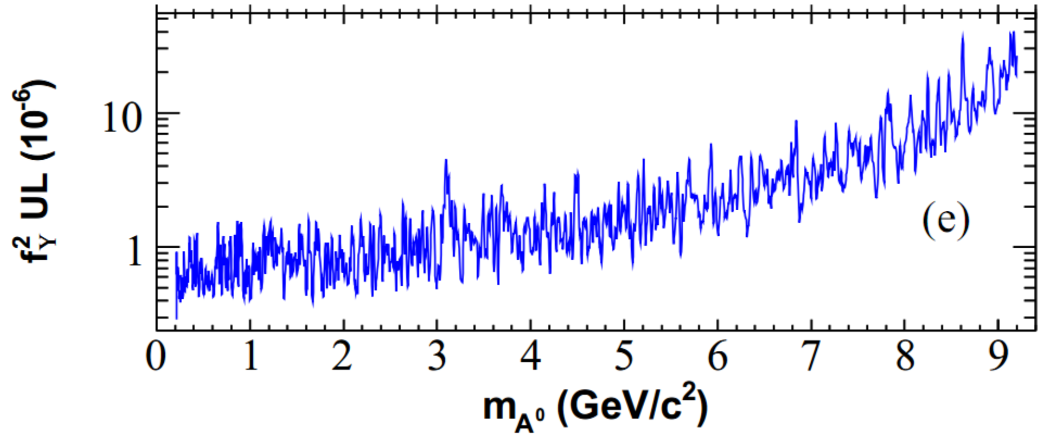
Felix Friedrich (TU Dresden) BSM Higgs searches at ATLAS and CMS 15 / 22

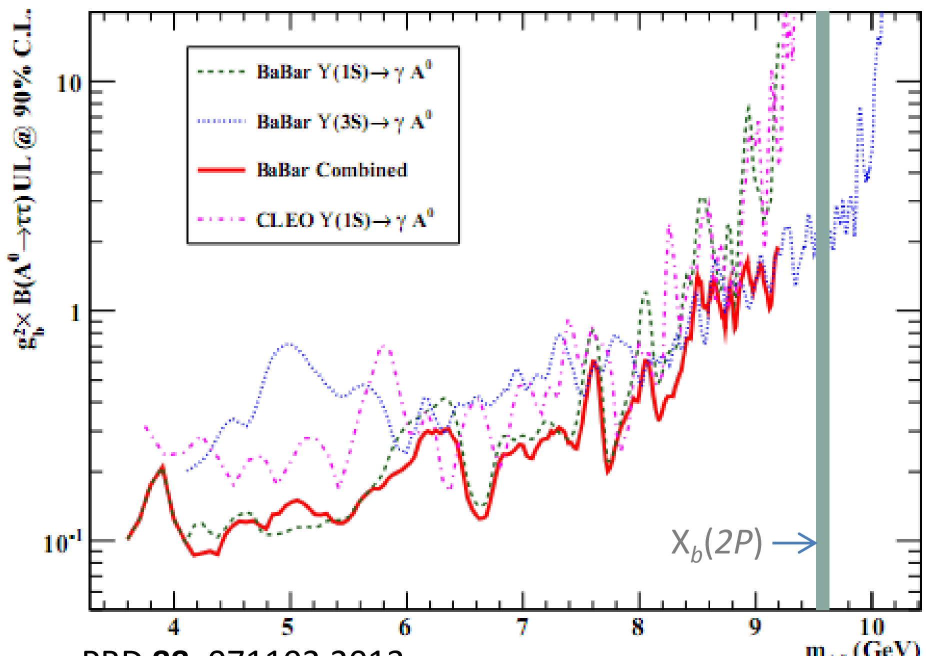
Limits on the Yukawa coupling

- Limits on the Yukawa coupling between **A^0** and the *b* quark are set when combining the results of the following *BABAR* searches:

  - $\Upsilon(1S) \rightarrow \gamma$ **A^0**; **A^0** $\rightarrow \mu^+\mu^-$
  - $\Upsilon(2S,3S) \rightarrow \gamma$ **A^0**; **A^0** $\rightarrow \mu^+\mu^-$

PRD **87**, 031102(R) 2013





PRD **88**, 071102 2013

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

- $\Upsilon(1S) \rightarrow \gamma$ **A^0**; **A^0** $\rightarrow \tau^+\tau^-$
- $\Upsilon(3S) \rightarrow \gamma$ **A^0**; **A^0** $\rightarrow \tau^+\tau^-$

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

$A^0 \longrightarrow \mu^+\mu^-$: Event selection 1

❖Track multiplicity, photon and muon selection variables:

- Number of tracks detected per event to be equal to four.

- Lateral moment of electromagnetic calorimeter (EMC) crystals associated with a photon shower to be in the range of 0.06 – 0.74.

- Zernike moment A_{42} should be less than 0.1.

- For $A^0 \rightarrow \mu^+\mu^-$ reconstruction, we require that either one of the charged track must be identified as muon (muBDTVeryLooseFakeRate (bit 20)).

- Apply a selection cut of the Υ(2S, 3S) kinematic fit χ^2 ($\chi^2_{\Upsilon(2S,3S)} < 300$), which are calculated after fitting the entire decay chain using the beam energy constraints on Υ(2S, 3S) and mass constraints on Υ(2S, 3S) and Υ(1S).

• Dipion selection variables:

- Cosine of angle between two pions in the laboratory frame.
- Transverse momentum of dipion in the laboratory frame.
- Azimuthal angle of pion
- Transverse momentum of pion.
- Dipion mass.
- Cosine of pion helicity angle.
- Transverse position of dipion vertex
- mass recoiling against the dipion system, m_{recoil}.

6

$A^0 \rightarrow \mu^+\mu^-$: Event selection 2

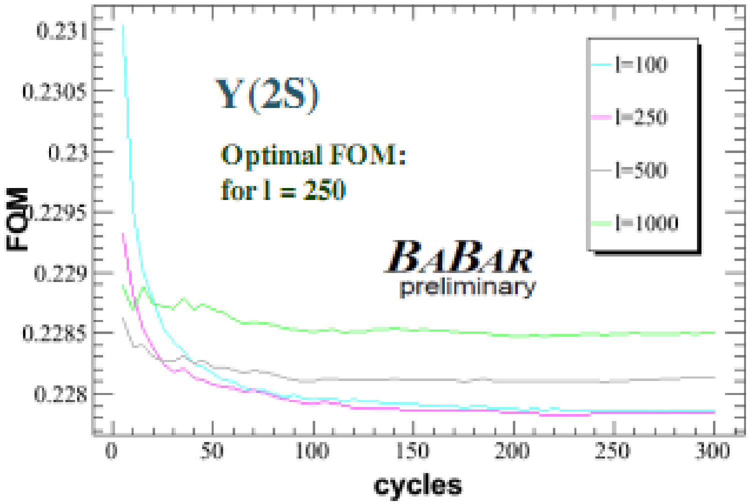
Cut optimization : Dipion variables

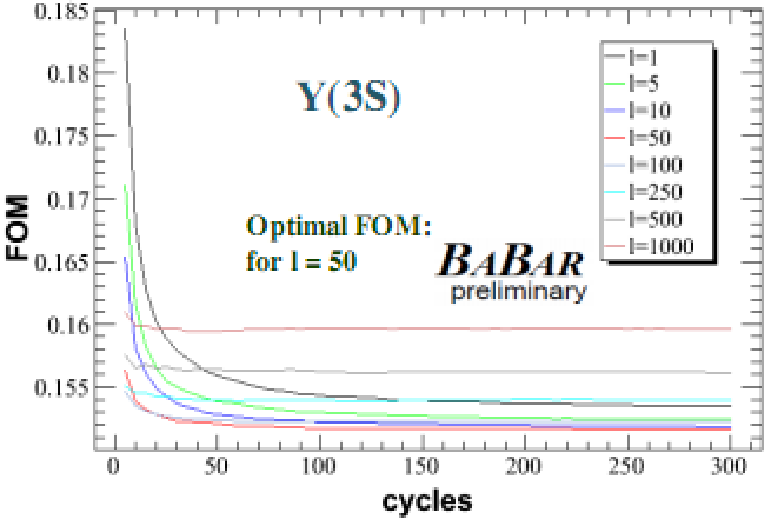
- Use a neural network based Random forest classifier included in StatPatternRecognition package to optimize the pion related variable.

- Use gini-index as a FOM to train the Random Forest classifier.

- Gini-index = 2pq; where p and q are fractions of correctly classified and misclassified events in each node. SPR uses negative Gini-index.

- We can control two parameters during the training process:
  - Number of trees grown (training cycles)
  - Number of events per terminal node "l"





$A^0 \longrightarrow \mu^+\mu^-$: Systematics

Source	Uncertainty	
	$\Upsilon(2S)$	$\Upsilon(3S)$
Additive uncertainties (events)		
N_s PDF	0.052	0.014
Fit Bias	0.093	0.073
Total	0.107	0.074
Multiplicative uncertainties (%)		
$\mathcal{B}(\Upsilon(nS) \rightarrow \pi^+\pi^-\Upsilon(1S))$	2.20	2.30
$N_{\Upsilon(nS)}$	1.10	1.10
Muon-ID	4.30	4.25
Di-pion efficiency	2.21	2.16
Photon efficiency	1.96	1.96
Charged tracks	3.73	3.50
$\Upsilon(nS)$ kinematic fit χ^2	1.52	2.96
Total	7.04	7.35

$A^0 \longrightarrow \tau^+ \tau^-$: Event selection 1

Pion MVA

Pion variables describe kinematics of $\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ transition
Since pions are slow, the discriminating power of the classifier is (weakly) correlated to dipion recoil mass (missing $\Upsilon(1S)$ mass)

Pion MVA Input Variables

Pion Variables	**Description**
UMass	Invariant mass of the dipion system
vDist	Vertex distance of the pions from the electron-positron beam
Pt	Transverse momentum of the dipion pair in CM
pAngle	Angle between two pions in the center of mass frame
piHelicity	Cosine of the helicity angle of the pions
UChi2Prob	Probability that the two pion tracks are consistent with coming from a common vertex, distributed between 0 and 1
p1MagPions	Highest-momentum charged pion track in CM
p1PCosTheta	Cosine of the angle of the highest-momentum pion track in CM
UPolarCosTh	Cosine of the angle between the dipion momentum and the beam direction

$A^0 \longrightarrow \tau^+ \tau^-$: Event selection 2

Tau MVA

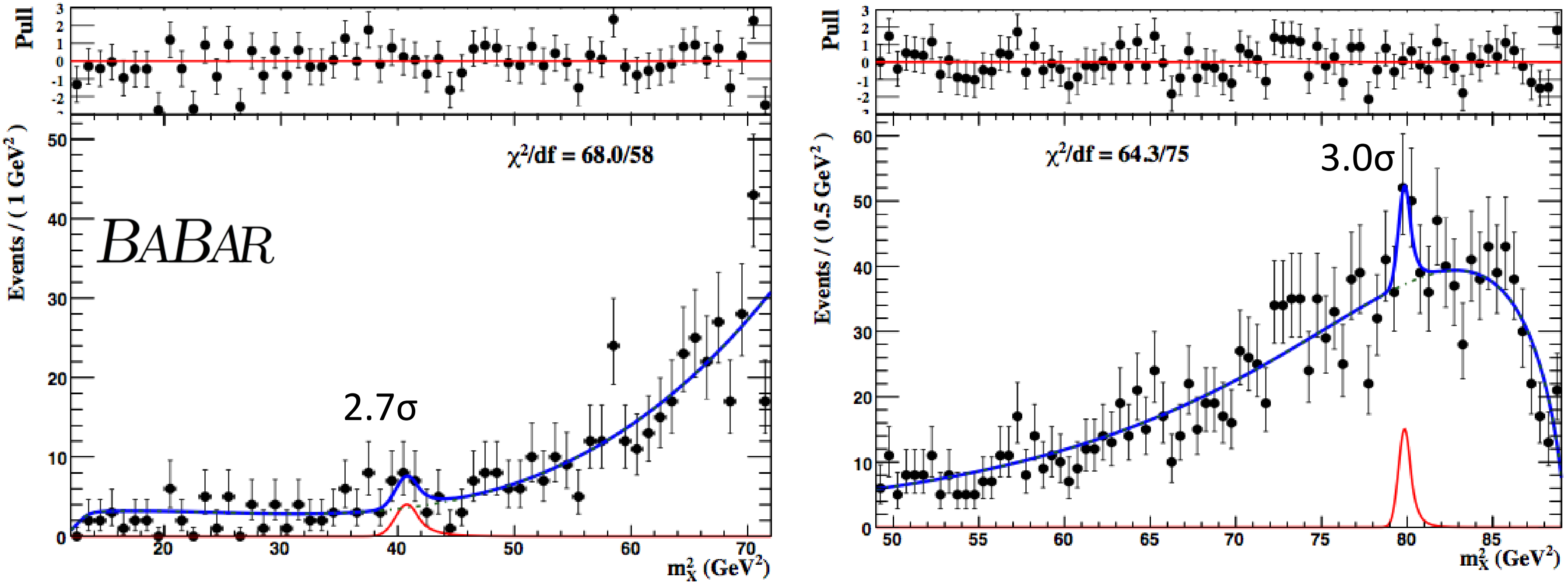
Take advantage of missing energy and momentum in the event

Tau MVA Input Variables

Tau Variables	Description
MissingEnergyCM	Missing energy of the entire event in the center of mass frame, which is calculated from the difference between initial and final four-vector momenta, i.e. $(\mathbf{p}_{ee} - (\mathbf{p}_{2\pi} + \mathbf{p}_{\gamma} + \mathbf{p}_{2\tau}), E_{ee} - (E_{2\pi} + E_{\gamma} + E_{2\tau}))$, where $\mathbf{p}$ is the three-vector momenta and E is the total energy of the beam, pions, gamma and τ daughter pair, respectively
PMissCosThCM	Cosine of the angle of the missing momentum in the center of mass frame
e2Mag	Second highest-momentum neutral particle in CM
eExtra	Total photon energy excluding the highest momentum photon
PTnet	Net transverse-momentum of the entire reaction in CM
lAngle	Angle between the two charged τ daughters in the center of mass frame
p1MagTau	Highest-momentum charged τ daughter
Aapl	Cosine of the angle between the photon and the plane formed by the τ tracks
p1TcosthCM	Cosine of the angle of the highest-momentum tau track in CM
p1TGamCMcosth	Cosine of the angle between the highest-momentum τ track and the highest momentum photon in CM
HChi2Prob	Probability that the two τ daughter tracks are consistent with coming from a common vertex, distributed between 0 and 1
p1PGamCMcosth	Cosine of the angle between the highest-momentum pion track and the highest momentum photon in CM
HMass	Invariant mass of the pair of the τ daughter tracks
vDistTau	Vertex distance of the τ daughters from the electron-positron beam

$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-$

- Used two mass regions in order to achieve a balanced selection efficiency
  - Differences in the kinematics of each range call for two sets of selection criteria
  - Signal yield extracted similarly to **A^0** → $\mu^+\mu^-$
  - Bkg PDF is a combination of Chebyshev polynomials and Err functions



- The largest obtained significance is 3.0σ at m_{A^0} = 8.93 GeV
- Using pseudo-experiments, 7.5% probability of observing a 3.0σ+ fluctuation

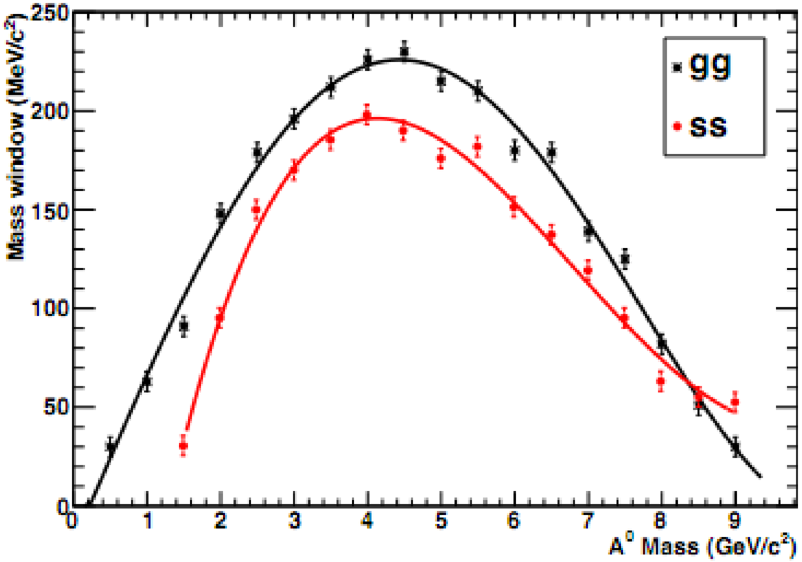
$A^0 \longrightarrow$ gg or *ss* : Event selection

- Recoil mass within 10MeV/c^2 of $\Upsilon(1S)$
- Dipion neural net output greater than 0

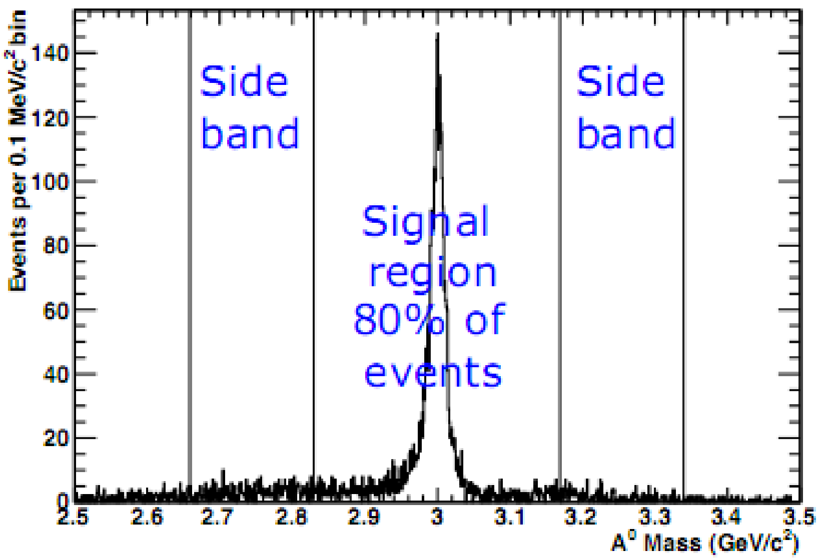
- Probability χ^2 $\Upsilon(1S)$ mass constrained fit is greater than 0.001
- π^0 veto of radiative photon with other photon within 50MeV/c^2 of π^0 mass
- A42 moment of radiative photon less than 0.1
- Select the channel that has the highest (MLP output X Probability χ^2)

$A^0 \to gg$ or ss : Signal region and sidebands

- Use signal MC to determine signal region mass window and side band, then interpolate



3GeV/c^2 signal MC $A^0 \to ss$

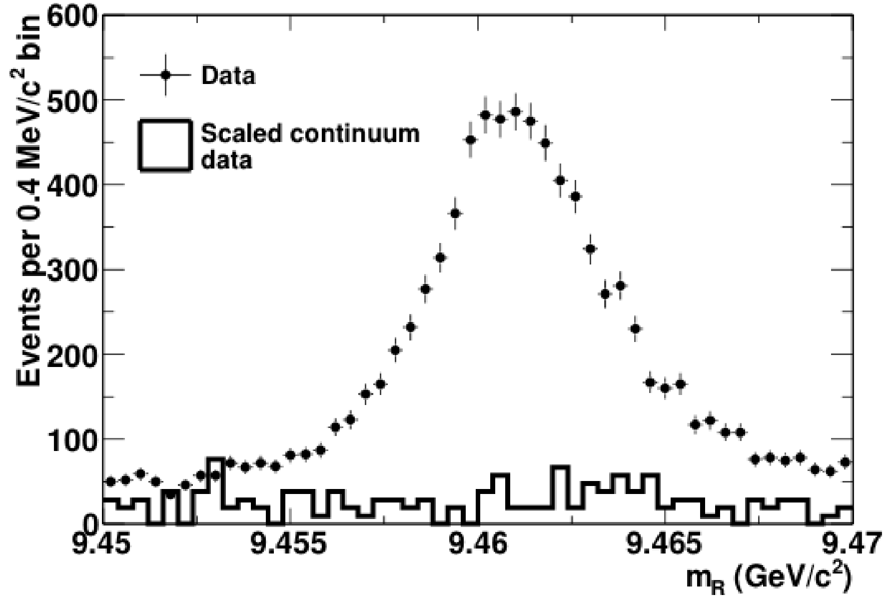


$A^0 \longrightarrow$ gg or ss : Dipion tagging

- $\Upsilon(1S)$ dataset
- Dipion tagging is done by:
  - Leptonic modes: full reconstruction of the decay process
  - Hadronic modes: selecting on the invariant mass recoiling from the dipions

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

- Peaks at the $\Upsilon(1S)$ mass
- The backgrounds are low after a selection of $9.45 < m_R < 9.47$ GeV/c^2



mY(1S)=9.4603 GeV

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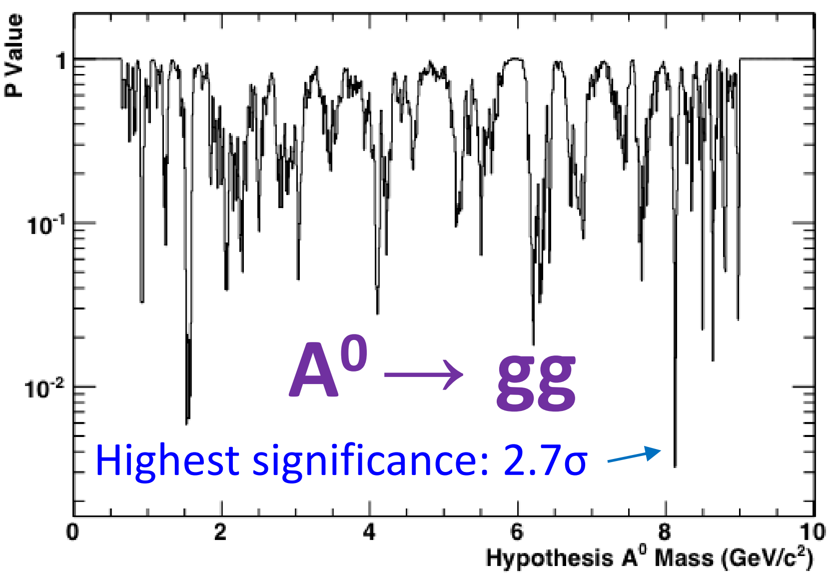
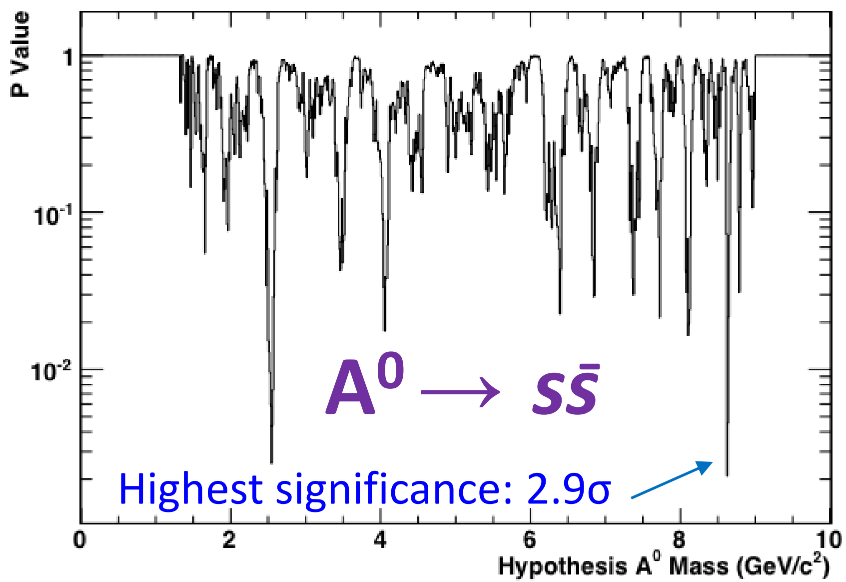
$\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow gg$ or $s\bar{s}$

- Mass windows are defined, centered at the hypothesis A_0 mass, that contain 80% of the signal events.
  - Sideband regions are half of the mass window size adjacent to both sides of the mass window
- The mass spectrum is scanned in 10 MeV steps, $n_{sig} = n_{window} - n_{sidebands}$
- The probability of seeing n_{sig} or more, given $n_{sidebands}$:

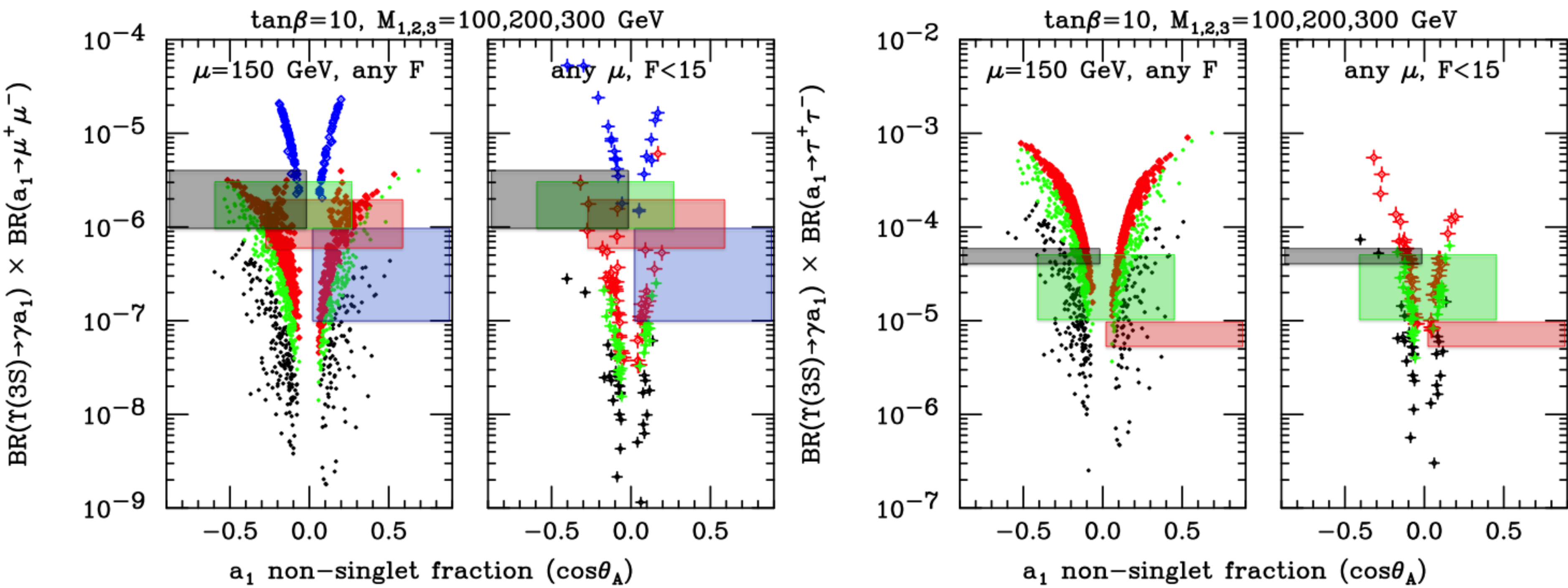




The probability of seeing a 2.9σ fluctuation anywhere is 59%, calculated using simulated experiments

Parameter space excluded by data

$\mu^+\mu^-$ PRD 81, 075003 (2010) $\tau^+\tau^-$



$0 < m_A < 2m_\tau$

$7.5 < m_A < 8.8\text{GeV}$

$2m_\tau < m_A < 7.5\text{GeV}$

$8.8 < m_A < 9.2\text{GeV}$

Dots = prediction at different masses
Box = range of exclusion by data at different masses

We reject the space above the boxes
(horizontal location of boxes separated for visual purposes)