Search for a light Higgs boson in single-photon decays of Υ(1S) using Υ(2S)→ $\pi^+\pi^-$Υ(1S) tagging method

$$[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S) \to \gamma A^0(\to \tau^+\tau^-/\mu^+\mu^-)]$$

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Motivation

Search for a light Higgs boson A^0:

- The standard model (SM) predicted only one scalar Higgs with a mass around 120 GeV/c^2, which has been discovered by ATLAS [1] and CMS [2].
- However, low-mass Higgs with mass of $\mathcal{O}$(10 GeV) are predicted in Next-to-Minimal Supersymmetric Standard Model (NMSSM) [3-7].
- The NMSSM contains two charged Higgs bosons, three neutral CP-even bosons, and two CP-odd bosons. The lighter CP-odd Higgs, denotes as A^0, has a mass below $b\bar{b}$ production threshold, which are suggested to be searched in Υ radiative decays [3-7].
- The branching fraction of $\Upsilon(nS) \rightarrow \gamma A^0$ reaches 10^{-4}, depending on the A^0 mass and couplings [4].

[1] PLB 716, 1 (2012) [2] PLB 716, 30 (2012) [3] PRD 70, 034018 (2004) [4] PRL 95, 041801 (2005) [5] PRD 76, 051105 (2007) [6] PRD 77, 015013 (2008) [7] PRD 81, 075003 (2010)

Motivation

The results of $\Upsilon(1S) \to \gamma A^0(\to \tau^+\tau^-/\mu^+\mu^-)$ from CLEO and BaBar:

Experiment	Data sample	Channel	$\mathcal{B}^{UL}(\Upsilon(1S) \to \gamma A^0)\times \mathcal{B}(A^0 \to \tau^+\tau^-/\mu^+\mu^-)$	A^0 mass range
CLEO [8]	21.5×10^6 $\Upsilon(1S)$	$\Upsilon(1S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	$(1-5)\times10^{-5}$	$2m_\tau < M(\tau^+\tau^-) <$7.5 GeV
BaBar [9]	92.8×10^6 $\Upsilon(2S)$	$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ $\Upsilon(1S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	$(0.9-13)\times10^{-5}$	$2m_\tau < M(\tau^+\tau^-) < 9.2$ GeV
CLEO [8]	21.5×10^6 $\Upsilon(1S)$	$\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	$(1-9)\times10^{-6}$	$0.201 < M(\mu^+\mu^-) < 3.565$ GeV
BaBar [10]	92.8×10^6 $\Upsilon(2S)$ 116.8×10^6 $\Upsilon(3S)$	$\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$ $\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	$(0.28-9.7)\times10^{-6}$	$0.212 < M(\mu^+\mu^-) < 9.2$ GeV

Search for dark matter (DM):

- One type of DM, often called the weakly interacting massive particle (WIMP), is generally expected to be in the mass region ranging from $\mathcal{O}(1)$ MeV to $\mathcal{O}(100)$ TeV [11, 12].
- The decay of $\Upsilon(nS) \to \gamma H$ followed by the H decaying into a lepton pair such as $\tau^+\tau^-$ and $\mu^+\mu^-$ is suggested to be searched for in the B factories, where H is the mediator having an interaction between the WIMP and SM particles [13, 14].

[8] PRL 101, 151802 (2008) [9] PRD 88, 071102 (2013) [10] PRD 87, 031102 (2013) [11] PRL 92, 101301 (2004) [12] JHEP 09, 162 (2016) [13] JHEP 07, 050 (2019) [14] PRD 105, 035035 (2022)

Datasets

$\Upsilon(1S, 2S, 3S)$ datasets at e^+e^- colliders [Front. Phys. 15 (2020) 6, 64301]:

Experiment	$\Upsilon(1S)$		$\Upsilon(2S)$		$\Upsilon(3S)$	
	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6
CLEO	1.2	21	1.2	10	1.2	5
BaBar	-	-	14	99	30	122
Belle	6	102	25	158	3	12

We used these data samples.

In this analysis, we search for $A^0(\to \tau^+\tau^-/\mu^+\mu^-)$ in $\Upsilon(1S)$ radiative decays using $\Upsilon(2S)\to \pi^+\pi^-\Upsilon(1S)$ tagging method:

- To suppress continuum and ISR backgrounds
- To increase trigger efficiency

Selection criteria

$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$

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

In $A^0 \to \tau^+\tau^-$, to suppress backgrounds:

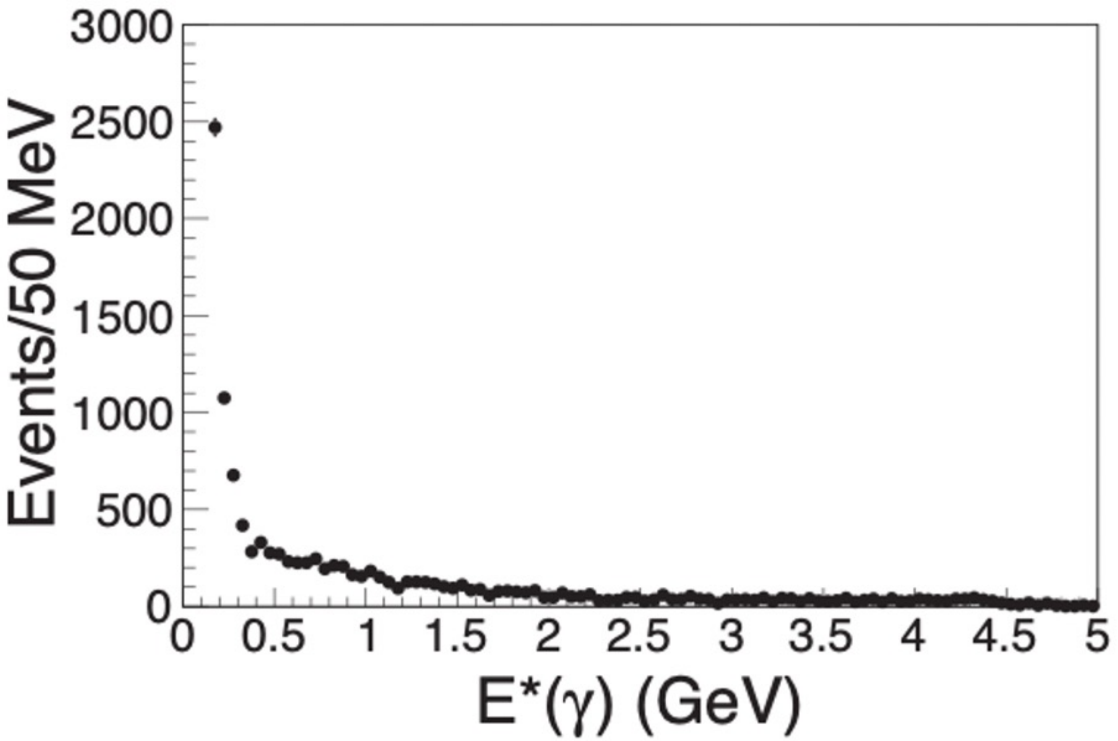
- $\tau\tau \to ee, \mu\mu, e\mu, \mu\pi, e\pi$
- The number of charged tracks N_{trk} == 4.
- The missing energy > 2.0 GeV, and missing polar angle within [30, 150] degrees
- We combine the signal photon with any other photon and then reject both photons of a pair whose π^0 likelihood is larger than 0.3 [PRL 93, 061803 (2004)].
- $\cos(\gamma\pi) < 0.4$ to suppress $\rho \to \pi\pi^0$
- $\cos(\gamma e) < 0.8$ and $\cos(\gamma\mu) < 0.8$ to suppress FSR and $\Upsilon(1S) \to \mu^+\mu^-(\gamma)/e^+e^-(\gamma)$ backgrounds

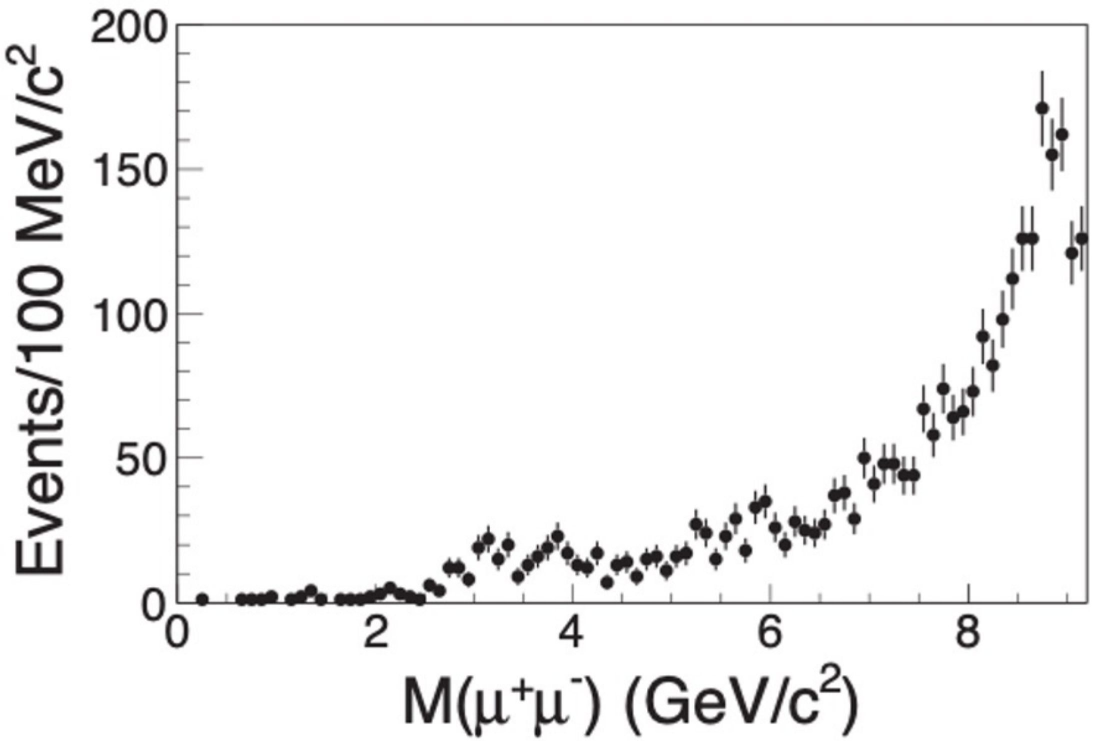
In $A^0 \to \mu^+\mu^-$, to suppress backgrounds:

- The number of charged tracks N_{trk} == 4.
- Four C constraint fit is applied for $\pi^+\pi^-\gamma\mu^+\mu^-$ final state and $\chi^2 < 50$.

The $E^*(\gamma)$ and M($\mu^+\mu^-$) distributions in data

For $A^0 \to \tau^+\tau^-$, we identify A^0 signal using the photon energy in Υ(1S) rest frame:
For $A^0 \to \mu^+\mu^-$, we identify A^0 signal using the invariant mass of di-muon. $E^*(\gamma) = \frac{m^2(\Upsilon(1S)) - M^2(\tau^+\tau^-)}{2m(\Upsilon(1S))}$





- No significant signals are seen.
- The dominant backgrounds come from $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)[\to \ell^+\ell^-(\gamma)]$ ($\ell =$ e, μ, or τ).

Fitting method

A series of two-dimensional (2D) unbinned extended maximum-likelihood fits to the $E^*(\gamma)/M(\mu^+\mu^-)$ and $M_{rec}(\pi^+\pi^-)$ distributions are performed.

- Parameterization of signal

We fit $E^*(\gamma)$ and $M(\mu^+\mu^-)$ distributions by modelling A^0 with the CB function and double Gaussian function. The Υ(1S) signal shape is described by the BW function convolved with a Gaussian function. The values of signal parameters are fixed according to signal MC simulations.

- Parameterization of background

The background shapes are described by a polynomial function. All parameters are float in the fits. We choose the order of the polynomial to minimize the Akaike information test (AIC) [Statistics and Probability Letters 33, 201 (1997)].

- Fitting step

About the half of photon resolution [724 points for $A^0 \to \tau^+\tau^-$ and 2671 for $A^0 \to \mu^+\mu^-$]

- Fitting range

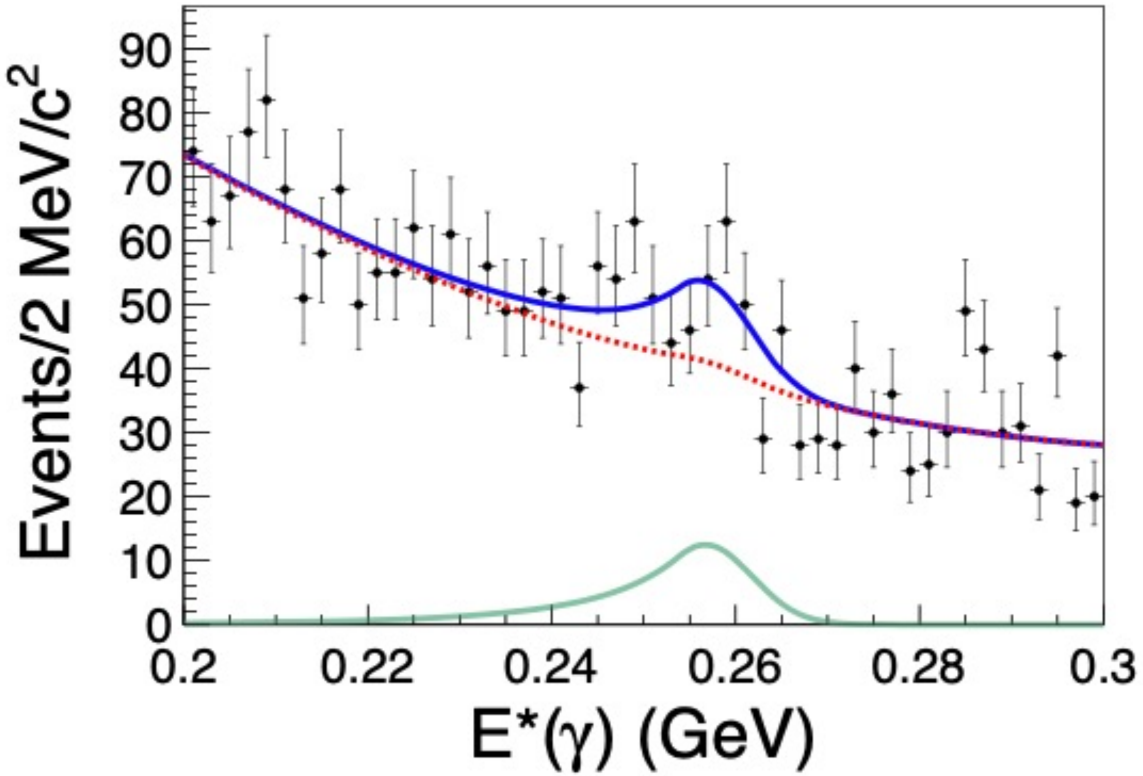
Cover at least $\pm 10\sigma$ region to reduce the background fluctuation

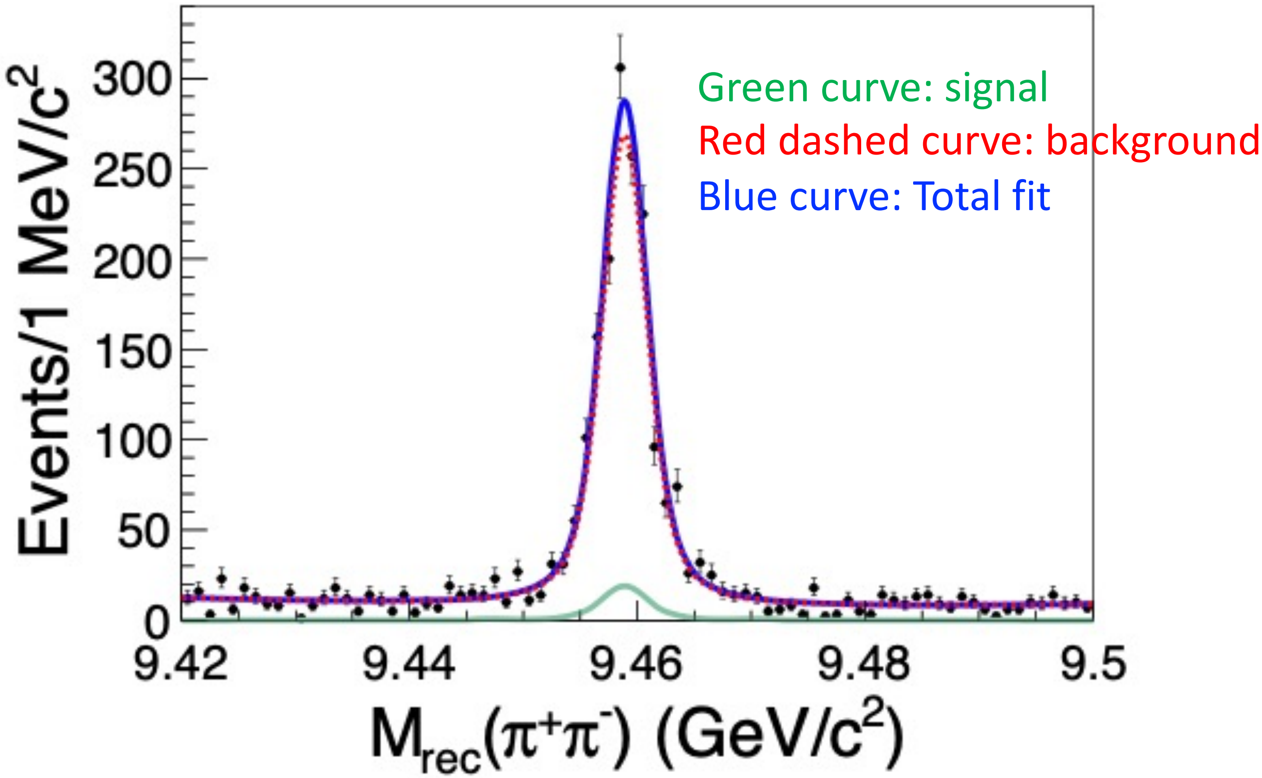
$E^*(\gamma)$ and $M(\mu^+\mu^-)$ resolutions: 55 → 5 MeV/c^2 from $\tau^+\tau^-$ mass threshold to 9.2 GeV/c^2; 1.4 → 10 MeV/c^2 from $\mu^+\mu^-$ threshold to 9.2 GeV

Efficiency: 2.1% → 0.7% for $A^0 \to \tau^+\tau^-$ and 4.7% → 0.6% for $A^0 \to \mu^+\mu^-$ with the increased A^0 mass

Fitted results for $A^0 \to \tau^+\tau^-$

The fitted result corresponding to the maximum local significance:

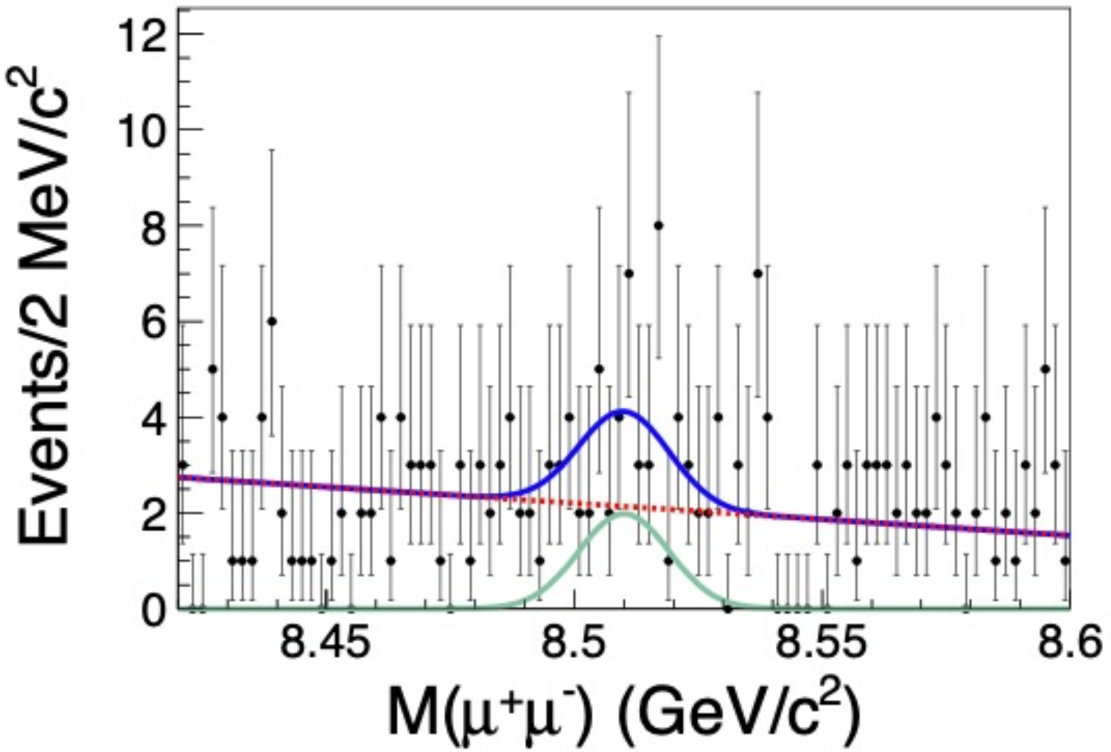


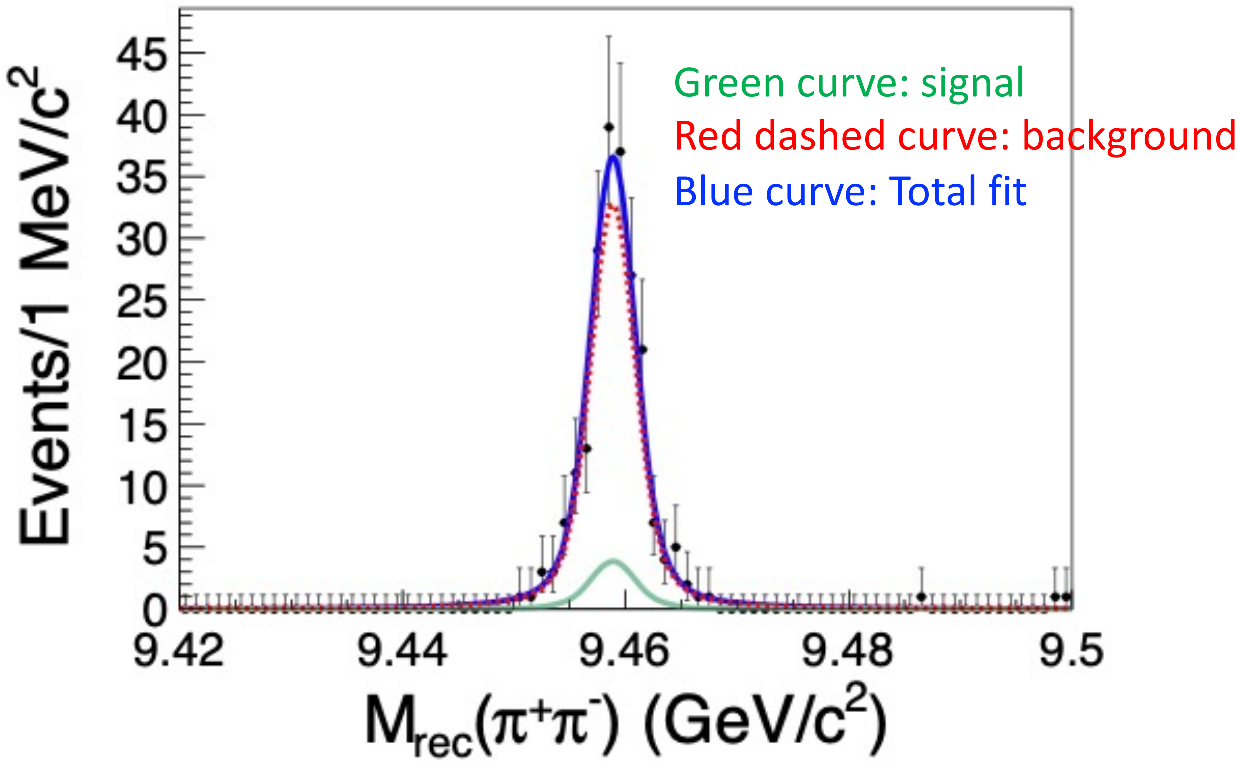


- The signal yield is 116 ± 33 with a statistical significance of 3.5σ when $m(A^0) = 9.2\ \text{GeV}/c^2$.
- The global significance is obtained to be 2.2σ with look-elsewhere-effect included within $0.15 < E^*(\gamma) < 0.4$ GeV.

Fitted results for $A^0 \rightarrow \mu^+\mu^-$

The fitted result corresponding to the maximum local significance:





- The signal yield is 23 ± 8 with a statistical significance of 3.0σ when $m(A^0)$ = 8.51 GeV/c^2.
- The global significance is obtained to be 2.0σ with look-elsewhere-effect included within $8.3 < M(\mu^+\mu^-) < 8.7$ GeV/c^2.

Results

$$\mathcal{B}^{\mathrm{UL}}[\Upsilon(1S) \to \gamma A^0]\mathcal{B}(A^0 \to \tau^+\tau^-/\mu^+\mu^-) = \frac{N^{\mathrm{UL}}}{N^{\mathrm{total}}_{\Upsilon(2S)} \times \varepsilon}$$

$$\frac{\mathcal{B}[\Upsilon(1S) \to \gamma A^0]}{\mathcal{B}[\Upsilon(1S) \to \ell^+\ell^-]} = \frac{f^2_{\Upsilon(1S)}}{\sqrt{2}\pi\alpha}\left(1 - \frac{m^2_{A^0}}{m^2_{\Upsilon(1S)}}\right)$$

- $f_{\Upsilon(1S)}$ is the Yukawa coupling [PRL 39, 1304 (1977), PLB 175, 223 (1986), Mod. Phys. Lett. A 22, 1373 (2007).
- $B_1 = \mathcal{B}(\Upsilon(1S) \to \gamma A^0)$, $B_2 = \mathcal{B}(A^0 \to \tau^+\tau^-)$, and $B_3 = \mathcal{B}(A^0 \to \mu^+\mu^-)$

Results

Blue curve: our results at Belle
Red line: BaBar results [PRD 88, 071102 (2013), PRD 87, 031102 (2013)]

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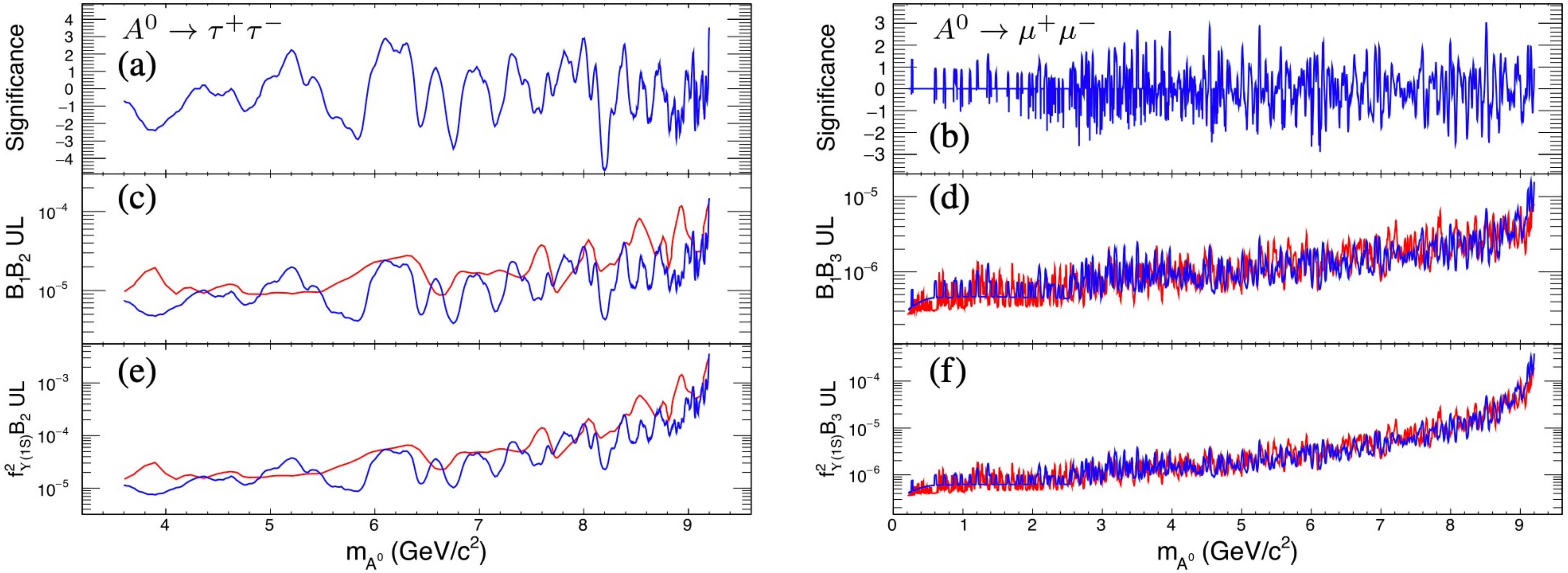

- For $\Upsilon(1S) \to \gamma A^0 (\to \tau^+\tau^-)$: an approximately twofold improvement on the current world best upper limits.
- For $A^0 \to \mu^+\mu^-$: at the same level as the world average limits.

The mixing angle ($\sin\theta_{A^0}$)

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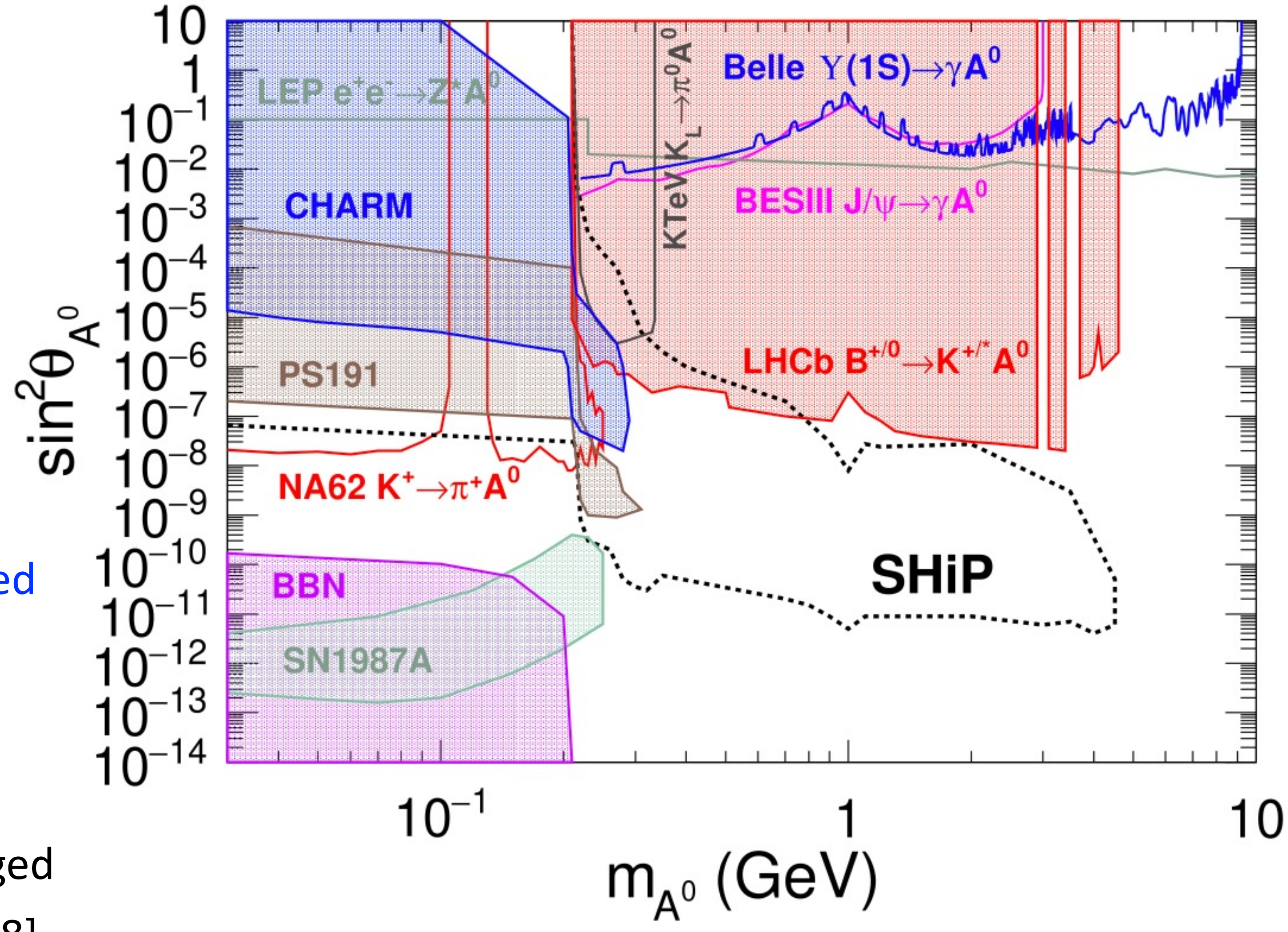
$$\frac{\mathcal{B}[\Upsilon(1S)\to\gamma A^0]\mathcal{B}(A^0\to \text{hadrons})}{\mathcal{B}[\Upsilon(1S)\to\ell^+\ell^-]}$$

$$=\sin^2\theta_{A^0}\frac{G_F m_b^2}{\sqrt{2}\pi\alpha}\sqrt{\left(1-\frac{m_{A^0}^2}{m_{\Upsilon(1S)}^2}\right)}$$

- When the mass of A^0 is smaller than $\tau^+\tau^-$ threshold, upper limits from $A^0\to\mu^+\mu^-$ are used to calculate the $\sin\theta_{A^0}$; on the contrary, upper limits from $A^0\to\tau^+\tau^-$ are used.
- The ratios of $\mathcal{B}(A^0\to\mu^+\mu^-)/\mathcal{B}(A^0\to\text{hadrons})$ and $\mathcal{B}(A^0\to\tau^+\tau^-)/\mathcal{B}(A^0\to\text{hadrons})$ are changed from 0.08 to 0.28 and 0.7 to 1.0 [PRD 99, 015018].



Summary

- We have searched for the light CP-odd Higgs boson in $\Upsilon(1S) \to \gamma A^0(\to \tau^+\tau^-/\mu^+\mu^-)$ with $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ tagging method using the largest data sample of Υ(2S) at Belle.
- We set the upper limits at 90% C.L. on the product branching fractions for $\Upsilon(1S) \to \gamma A^0$ and $A^0 \to \tau^+\tau^-$ varying from 3.8×10^{-6} to 1.5×10^{-4}. Our results represent an approximately twofold improvement on current world best upper limits for the $\Upsilon(1S) \to \gamma A^0(\to \tau^+\tau^-)$ production.
- For $A^0 \to \mu^+\mu^-$, the upper limits on the product branching fractions for $\Upsilon(1S) \to \gamma A^0$ and $A^0 \to \mu^+\mu^-$ are basically at the same level as the world average limits, and vary from 3.1×10^{-7} to 1.6×10^{-5}.
- The upper limits at 90% C.L. on the Yukawa coupling $f_{\Upsilon(1S)}$ and mixing angle $\sin\theta_{A^0}$ are also given. For the latter, various processes from different experiments are compared to it.

Thanks for your attention!