Search for LFV and a light Higgs boson in $\Upsilon(nS)$ decays at Belle

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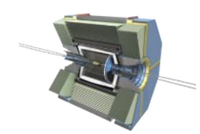
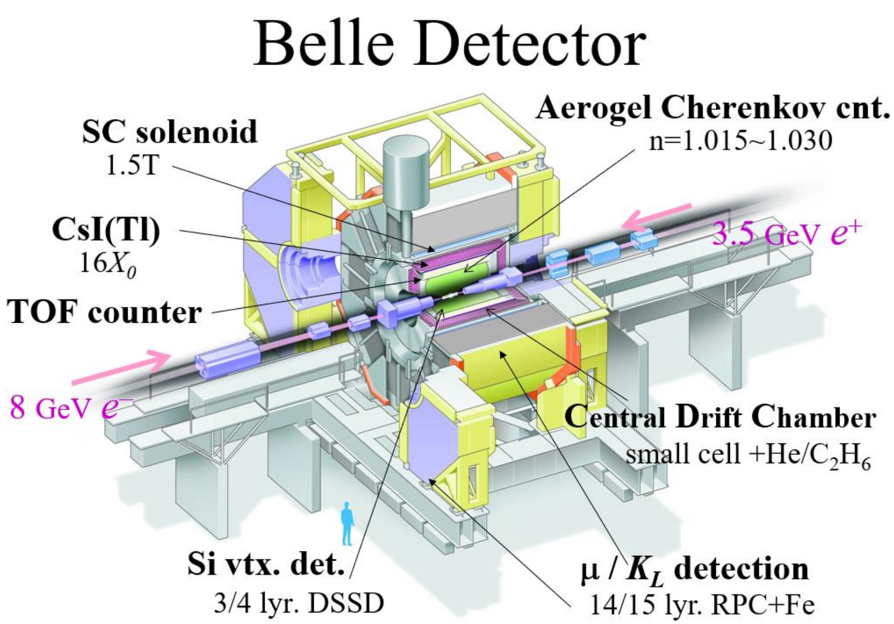
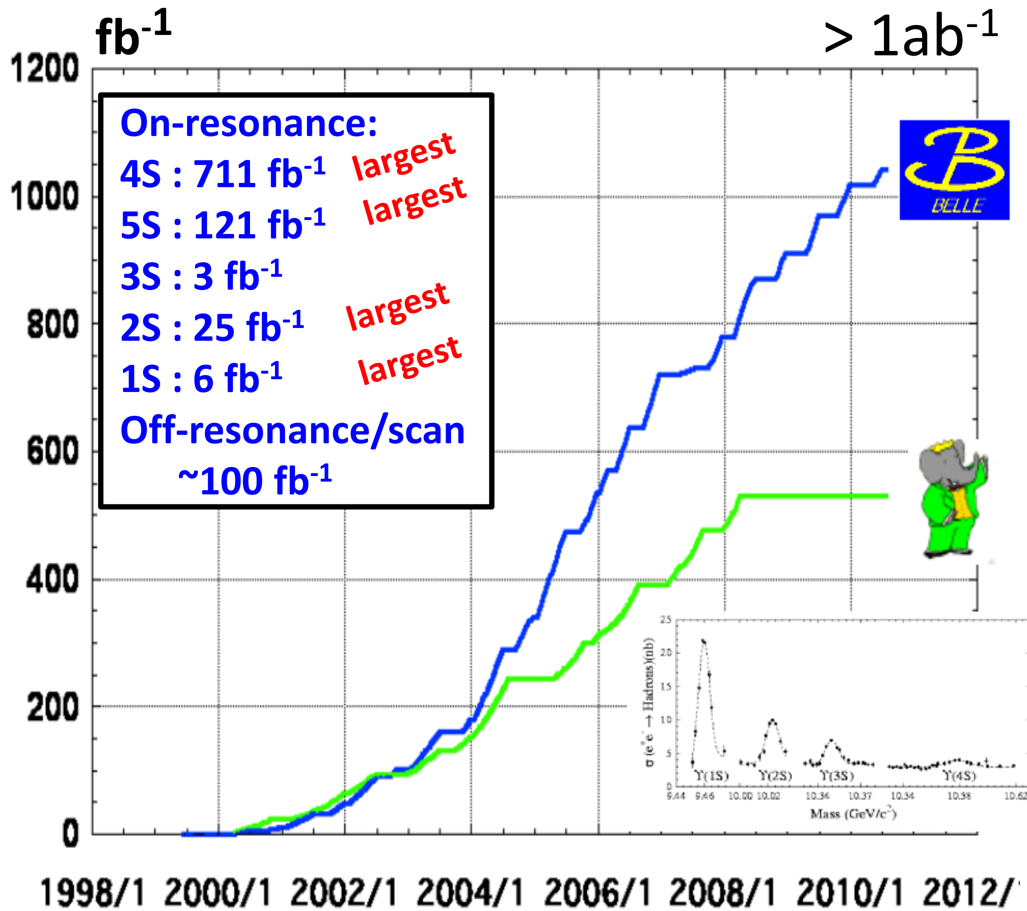
(on the behalf of Belle collaboration)

IISER Mohali



Belle detector





Belle (1 ab^{-1})

General purpose detector, built to test Standard Model mechanism for *CP* violation in B decays to charmonium ($B^0 \to c\bar{c}K_S^0$).

Belle, PRL 108, 171802 (2012)

Lepton Flavor Violation

- Lepton Flavor Conservation: number of leptons belonging to each generations is conserved in any interaction (accidental lepton family symmetry).
- 1998, the Super-Kamiokande experiment announced the evidence for neutrino oscillation (neutrino mass and neutrino oscillation). Super-Kamiokande PRL **81**, 1562 (1998)
- Suggest the accidental lepton family symmetry in SM is broken → family lepton number can be violated.

- Considering the neutrino oscillations into account, Charged LFV decays can occur through oscillations in loops but are suppressed by $(\Delta m_{ij}/M_W)^4$
  - $B.R.(\mu^{\pm} \rightarrow e^{\pm}\gamma) \sim 10^{-54}$ Raidal *et al* EPJC **57**, 13 (2008)
  - $B.R.(\tau^{\pm} \rightarrow \mu^{\pm}\gamma) \sim 10^{-40}$ Cvetič *et al* PRD **66**, 034008 (2002)

Abada *et al* PRD **91**, 113013 (2016)

- Several NP physics models inspired by the grand unified theory predict the enhancement of the CLFV interactions.
- No known symmetry principle protects lepton flavour conservation in the presence of lepton non-universality. Glashow *et al* PRL **114**, 091801 (2015)
- Further, it has also been suggested that New physics models which describe the LFU violations, can also be studied using the CLFV measurements.

Lepton Flavor Violation searches

LFV searches in many sector and many experiments

$$\mu \to e\gamma, \mu^- \to e^+e^-e^-, \mu N \to eN$$
$$\tau \to \mu\mu\mu, \tau \to \mu V\ V \in \{\rho, \Omega, \phi, K^{*0}\}$$
$$H \to \ell\ell'$$
$$B \to K\tau\ell, B_{(s)} \to \tau\ell$$
$$V \to \ell_1\ell_2, \ell_1\ell_2 \in \{\Upsilon(nS), Z, J/\psi, \ldots\}$$

$\Upsilon(nS), n = 1,2,3$ following results are available

Search for decay	Experiment	Upper Bound , $\times 10^{-6}$	
$\Upsilon(1S) \to \mu\tau$	CLEO	< 6.0 (95% CL)	PRL **101**, 201601 (2008)
$\Upsilon(2S) \to \mu\tau$	CLEO	<14.4 (95%CL)	PRL **101**, 201601 (2008)
$\Upsilon(2S) \to \mu\tau$	BaBar	<3.3 (90% CL)	PRL **104**, 151802 (2010)
$\Upsilon(2S) \to e\tau$	BaBar	<3.2 (90% CL)	PRL **104**, 151802 (2010)
$\Upsilon(3S) \to \mu\tau$	CLEO	<26.3 (95% CL)	PRL **101**, 201601 (2008)
$\Upsilon(2S) \to \mu\tau$	BaBar	<3.1 (90% CL)	PRL **104**, 151802 (2010)
$\Upsilon(2S) \to e\tau$	BaBar	< 4.2 (90% CL)	PRL **104**, 151802 (2010)
$\Upsilon(3S) \to e\mu$	BaBar	<0.36 (90% CL)	PRL **128**, 091804 (2022)

No signal observed yet.
It would be a clear signal of New Physics.

$\ell(\ell'): e, \mu, \tau$

$\Upsilon(1S) \to \ell\ell'(\gamma)$

$\Upsilon(1S) \to \ell^{\pm}\ell'^{\mp}$

Two body vector meson CLFV process

Probing the vector and tensor operators of the effective Lagrangian for NP.

$\Upsilon(1S) \to \ell^{\pm}\ell'^{\mp}\gamma$ Hazard, Petrov PRD **94**, 074023 (2016)

Non-resonant three-body radiative decays of vector states could be used to constrain the scalar operators, which are not accessible in two-body decays of vector.

First study of three-body radiative CLFV (RLFV) → provides complementary access to NP.

$\Upsilon(2S) \to \Upsilon(1S)\pi\pi$ events preferred over $\Upsilon(1S)$

Pros

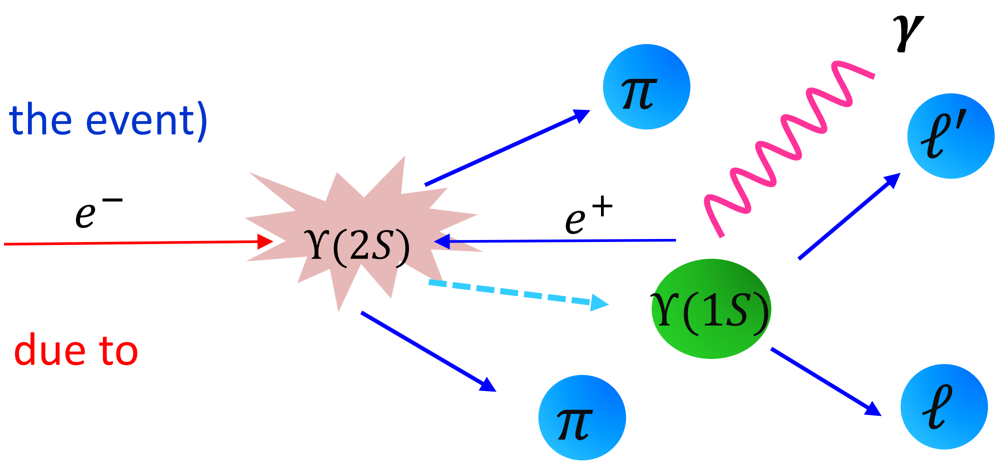
Higher trigger efficiency (two more tracks in the event)

Easier QED background suppression

Cons

Smaller statistics (28 Million vs 102 Millions) due to

$\mathcal{B}\left(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)\right) \sim 18\%$



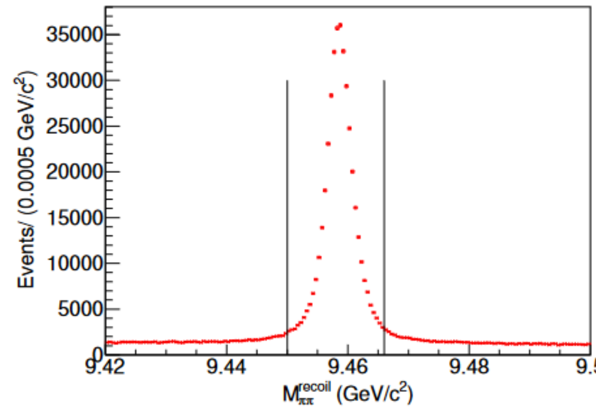
Background is studied on off-resonance data at 10.52 GeV/c^2.

$\Upsilon(1S) \to \ell\ell'(\gamma)$: The Analysis Belle JHEP (**2022**) 95

To suppress events coming from $\Upsilon(2S)$ other than $\Upsilon(2S) \to \Upsilon(1S)\pi\pi$

$$M_{\pi\pi}^{recoil} = \sqrt{(E_{e^+e^-} - E_{\pi\pi})^2 - |\vec{p}_{\pi\pi}|^2}$$

$$M_{\pi\pi}^{recoil} \epsilon (9.45, 9.466) \mathrm{GeV/c^2}$$



Modes under study

$\Upsilon(1S) \to e^\pm\mu^\mp$, $\Upsilon(1S) \to e^\pm\tau^\mp$ $\Upsilon(1S) \to \mu^\pm\tau^\mp$

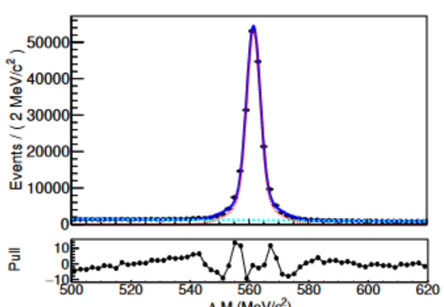
$\Upsilon(1S) \to e^\pm\mu^\mp\gamma$, $\Upsilon(1S) \to e^\pm\tau^\mp\gamma$ $\Upsilon(1S) \to \mu^\pm\tau^\mp\gamma$

$\tau^- \to e^-\bar{\upsilon}_e\upsilon_\tau$ $\tau^- \to \pi^-\pi^+\pi^-\upsilon_\tau$

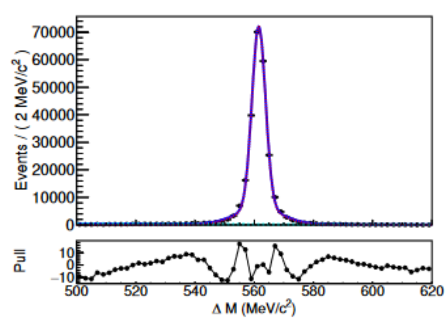
For $e^\pm\tau^\mp$ ($\mu^\pm\tau^\mp$)final state, τ decaying into $e^-\bar{\upsilon}_e\upsilon_\tau$ ($\mu^-\bar{\upsilon}_\mu\upsilon_\tau$) not used to avoid fake combinations.

$\Upsilon(1S) \to e^\pm e^\mp$, $\Upsilon(1S) \to \mu^\pm\mu^\mp$ used as calibration modes

$$\Delta M = M_{\pi\pi\ell\ell} - M_{\ell\ell}$$



$\Upsilon(1S) \to e^\pm e^\mp$



$\Upsilon(1S) \to \mu^\pm\mu^\mp$

	Branching fraction, $\times 10^{-2}$	
	Study	World Average
$\Upsilon(1S) \to e^\pm e^\mp$	$2.40 \pm 0.01 \pm 0.12$	2.38 ± 0.11
$\Upsilon(1S) \to \mu^\pm\mu^\mp$	$2.46 \pm 0.01 \pm 0.11$	2.48 ± 0.05

$\Upsilon(1S) \to \ell\ell'(\gamma)$: The Analysis

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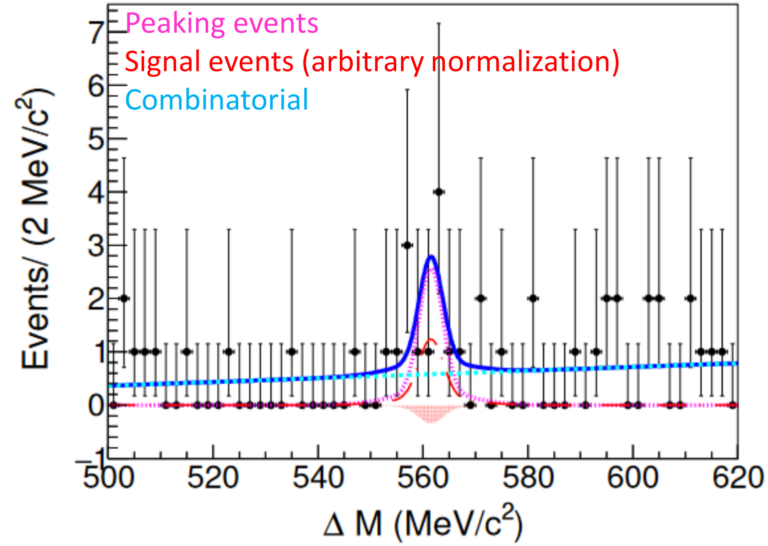
$$\Upsilon(1S) \to e^{\pm}\mu^{\mp}, \quad \Upsilon(1S) \to e^{\pm}\mu^{\mp}\gamma$$

$$\Delta M = M_{\pi\pi(\gamma)\ell\ell'} - M_{(\gamma)\ell\ell'}$$

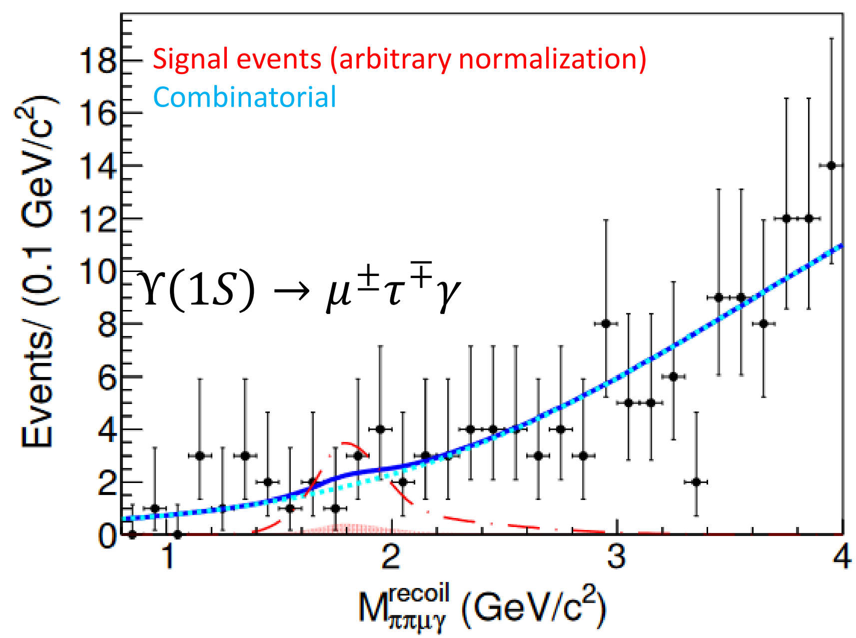
Expected ~ 9 peaking background from $\Upsilon(1S) \to \mu\mu$
$\mu \leftrightarrow e$ mis-identification evaluated using dimuon events



$$\Upsilon(1S) \to e^{\pm}\tau^{\mp}, \quad \Upsilon(1S) \to \mu^{\pm}\tau^{\mp}, \Upsilon(1S) \to e^{\pm}\tau^{\mp}\gamma \quad \Upsilon(1S) \to \mu^{\pm}\tau^{\mp}\gamma$$

The τ cannot be fully reconstructed.
The 4-momentum of the τ is inferred from initial e^+e^- and $\pi\pi\ell\ell(\gamma)$ system

$$M^{recoil}_{\pi\pi\ell\ell(\gamma)} \sim m_{\tau}$$



Dominant background comes from $\Upsilon(1S) \to \tau\tau$

$\Upsilon(1S) \to \ell\ell'(\gamma)$: The Result

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In absence of signal in any of the LFV decays, upper limit are estimated:

$$\mathcal{B}[\Upsilon(1S) \to \ell^{\pm}\ell'^{\mp}(\gamma)] < \frac{N_{sig}^{UL}}{N_{\Upsilon(2S)} \times \mathcal{B}[\Upsilon(2S) \to \Upsilon(2S)\pi^{\pm}\pi^{\mp}] \times \epsilon}$$

Decay	$\epsilon(\%)$	N_{sig}^{fit}	N_{sig}^{UL}	$\mathcal{B}^{UL}, \times 10^{-6}$
$\Upsilon(1S) \to e^{\pm}\mu^{\mp}$	32.5	-1.3 ± 3.7	3.6	0.39
$\Upsilon(1S) \to \mu^{\pm}\tau^{\mp}$	8.8	-1.5 ± 4.3	6.8	2.7
$\Upsilon(1S) \to e^{\pm}\tau^{\mp}$	7.1	-3.5 ± 2.7	5.3	2.7
$\Upsilon(1S) \to \gamma e^{\pm}\mu^{\mp}$	24.6	$+0.8 \pm 1.5$	2.9	0.42
$\Upsilon(1S) \to \gamma\mu^{\pm}\tau^{\mp}$	5.8	$+2.1 \pm 5.9$	10.0	6.1
$\Upsilon(1S) \to \gamma e^{\pm}\tau^{\mp}$	5.0	-9.5 ± 6.3	9.1	6.5

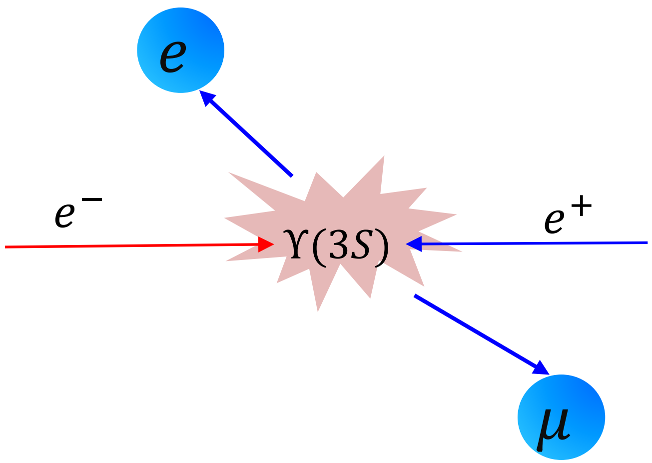
6.0×10^{-6}, CLEO

- All UL are dominated by statistical uncertainty.
- Largest source of systematic uncertainty comes from $N_{\Upsilon(2S)}$
- 2 times more stringent result for $\Upsilon(1S) \to \mu\tau$ than previous CLEO's result.
- All other modes searched for the first time.

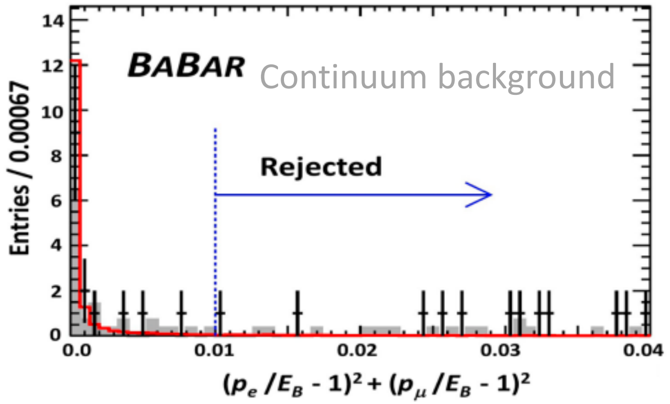
$\Upsilon(3S) \to \mu e$

BaBar, PRL **128**, 091804(2022)

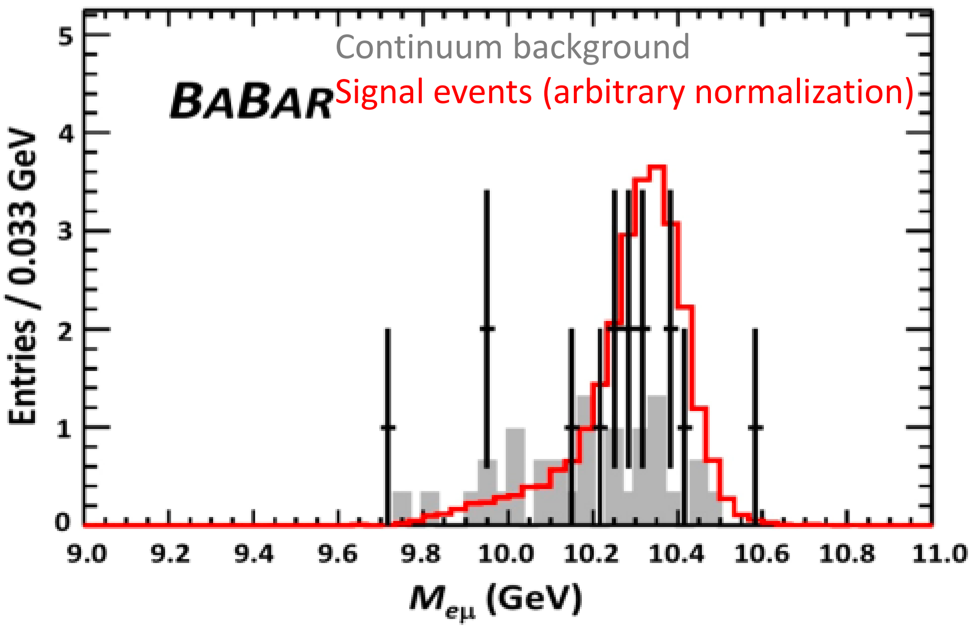
118 x 10^6 $\Upsilon(3S)$ decays



- Angle between e and μ tracks in the c.m. is required to be more than 179°.
- Primary muon candidates is required to deposit at least 50 MeV in EMC.



Continuum background estimated to be 12.2 ± 2.1 events.



In absence of any significant signal.

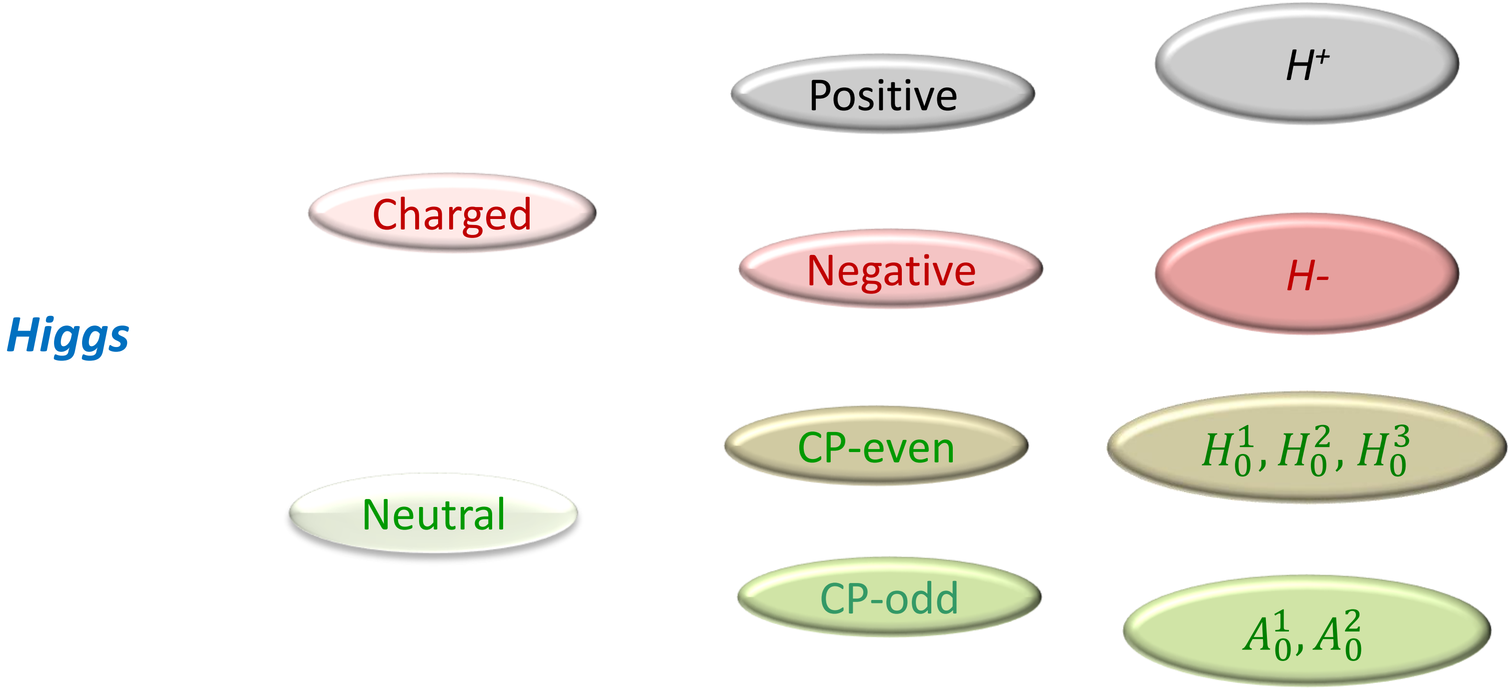
$$\mathcal{B}[\Upsilon(3S) \to \mu^+\mu^-] < 3.6 \times 10^{-7}$$

@ 90% CL

Using this, they also give 90% C.L. upper limit of $\Lambda_{NP}/g_{NP}^2 > 80$ TeV.

Next-to-Minimal Supersymmetric Standard Model (nMSSM)

- ***SUSY*** is an elegant solution for the limitation of the SM.
- The supersymmetric extension of SM also runs into two problems:
  - "***μ −problem***" and "***little hierarchy problem***".
- For which, nMSSM is suggested to be prescription.
- Besides the massive Higgs boson, three CP-even, two CP-odd and two charged Higgs bosons are predicted by the nMSSM



Light Higgs Boson search at $\Upsilon(1S)$

If the CP-odd Higgs (A^0) is light enough

- It can be produced via bottomonium decays: $\Upsilon \to \gamma A^0$

If the mass is smaller than twice the mass of the b quark

- Accessible via radiative $\Upsilon(nS) \to \gamma A^0 (n = 1,2,\text{ and } 3)$ decays.

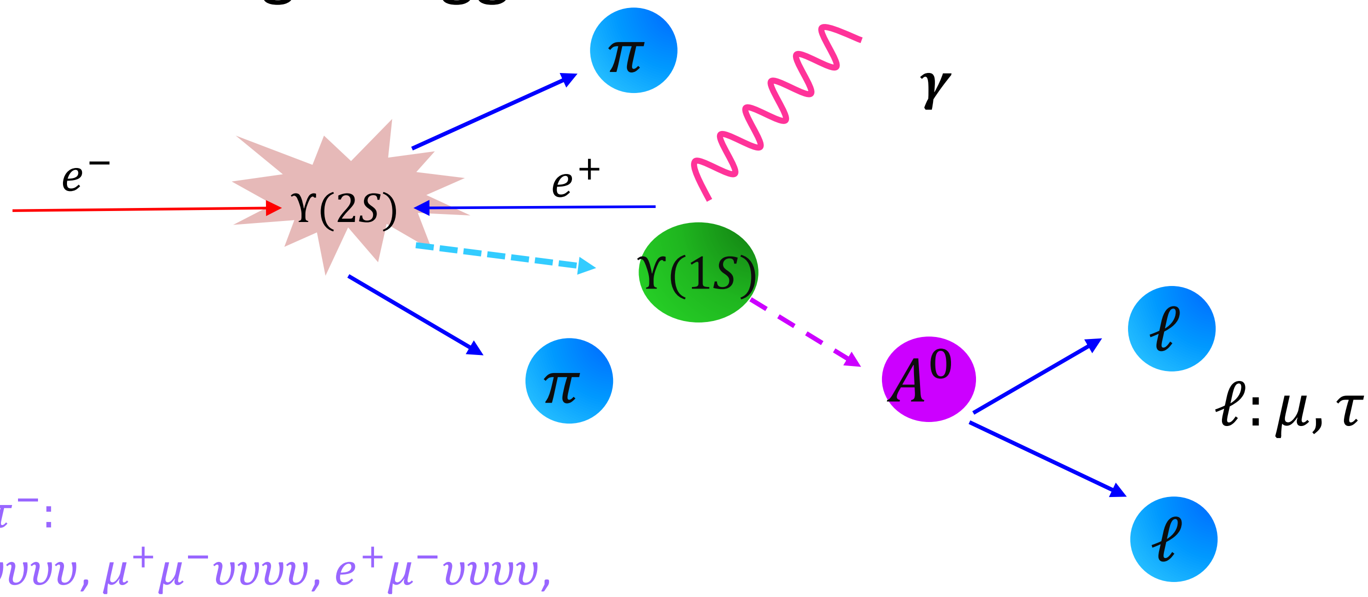
Region $m_{A^0} < 2m_b$ is easily accessible to the *B*-factories.

The branching fraction of $\Upsilon(nS) \to \gamma A^0$ could be as large as 10^{-4} , depending on the values of the A^0 mass, $\tan\beta$, and $\cos\theta_A$.

- $2m_\tau < m_{A^0} < 2m_b$, the decay of $A^0 \to \tau^+\tau^-$ is expected to dominate.
- $m_{A^0} < 2m_\tau$, the $A^0 \to \mu^+\mu^-$ events can be copiously produced

	Data sample	Channel	A^0 mass (GeV/c^2)	$\mathcal{B}^{\rm UL}(\Upsilon(1S) \to \gamma A^0)\times$ $\mathcal{B}(A^0 \to \tau^+\tau^-/\mu^+\mu^-)$
CLEO, PRL **101**, 151802 (2008)	21.5×10^6 $\Upsilon(1S)$	$\Upsilon(1S) \to \gamma A^0(\to \tau^+\tau^-)$	$2m_\tau < M(\tau^+\tau^-) < 7.5$	$(1-5)\times 10^{-5}$
	21.5×10^6 $\Upsilon(1S)$	$\Upsilon(1S) \to \gamma A^0(\to \mu^+\mu^-)$	$0.212 < M(\mu^+\mu^-) < 3.554$	$(1-9)\times 10^{-6}$
BaBar, PRD **88**, 071102 (2013)	92.8×10^6 $\Upsilon(2S)$	$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ $\Upsilon(1S) \to \gamma A^0(\to \tau^+\tau^-)$	$2m_\tau < M(\tau^+\tau^-) < 9.2$	$(0.9-13)\times 10^{-5}$
BaBar, PRD **87**, 031102 (2013)	92.8×10^6 $\Upsilon(2S)$ 116.8×10^6 $\Upsilon(3S)$	$\Upsilon(2S, 3S) \to \pi^+\pi^-\Upsilon(1S)$ $\Upsilon(1S) \to \gamma A^0(\to \mu^+\mu^-)$	$0.212 < M(\mu^+\mu^-) < 9.2$	$(0.28-9.7)\times 10^{-6}$

Light Higgs Boson search at Belle



$A^0 \to \tau^+\tau^-$:

$e^+e^-\upsilon\upsilon\upsilon\upsilon, \mu^+\mu^-\upsilon\upsilon\upsilon\upsilon, e^+\mu^-\upsilon\upsilon\upsilon\upsilon,$

$\mu^+\pi^-\upsilon\upsilon,\ \mu^+\pi^-\pi^0\upsilon\upsilon,\ \mu^+\pi^-\pi^0\pi^0\upsilon\upsilon,\ e^+\pi^-\upsilon\upsilon,\ e^+\pi^-\pi^0\upsilon\upsilon,\ e^+\pi^-\pi^0\pi^0\upsilon\upsilon,$

Events in which both τ leptons decays hadronically suffer from larger and poorly modelled background, and are therefore excluded.

Multiple A^0 masses are generated: 3.6 (0.22) GeV/c² to 9.2 GeV/c² in steps of 0.5 GeV/c² or less for $A^0 \to \tau^+\tau^-(\mu^+\mu^-)$

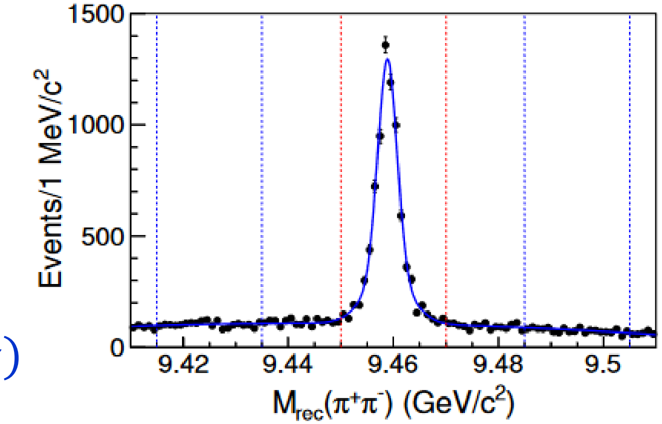
- π^0 veto applied to clean the γ
- $\cos\theta(\gamma\pi^\pm) < 0.4$: Reject π^0 background from $\rho^+ \to \pi^+\pi^0$
- $\cos\theta(\gamma e) < 0.95$ & $\cos\theta(\gamma\mu) < 0.8$: suppress FSR and $\Upsilon(1S) \to e^\pm e^\mp(\gamma)$ & $\Upsilon(1S) \to \mu^\pm\mu^\mp(\gamma)$

Four-constraint kinematic fit constraining the four momenta of the final-state particles to the initial e^+e^- collisions system is performed to suppress background with multiple photons and improve resolution.

Light Higgs search: The Analysis

Belle PRL **128** 081804 (2022)

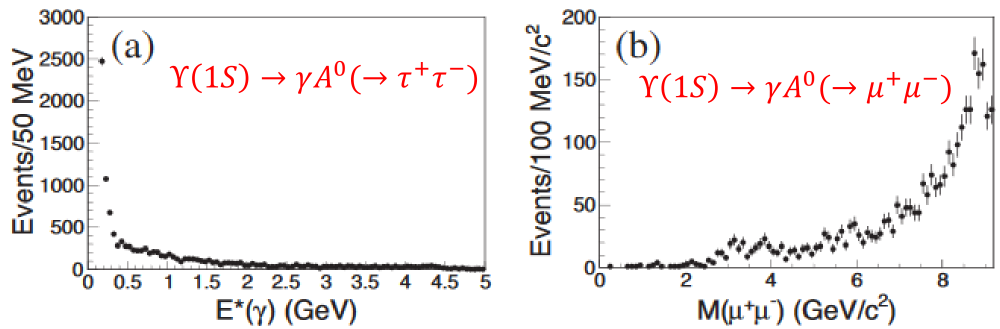
$$M_{\pi\pi}^{recoil} = \sqrt{(E_{e^+e^-} - E_{\pi\pi})^2 - |\vec{p}_{\pi\pi}|^2}$$



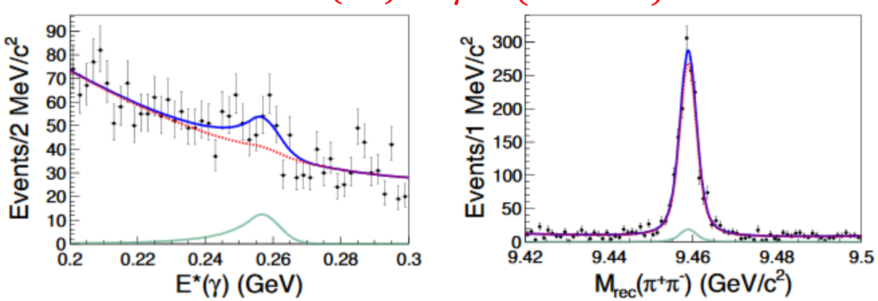
Considering τ decays with undetected neutrinos

- Identify A^0 signal using the photon energy in the $\Upsilon(1S)$ rest frame [$E^*(\gamma)$]
- Easily converted to $M(\tau^+\tau^-) = m^2_{\Upsilon(1S)} - 2m_{\Upsilon(1S)}E^*(\gamma)$

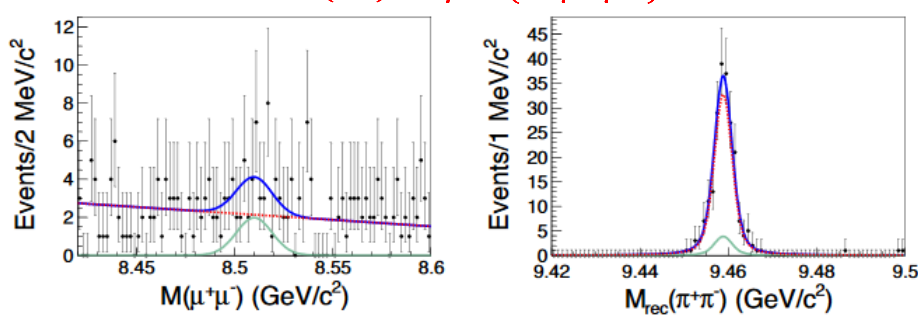
$m_{\Upsilon(1S)}$: nominal mass of $\Upsilon(1S)$



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



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

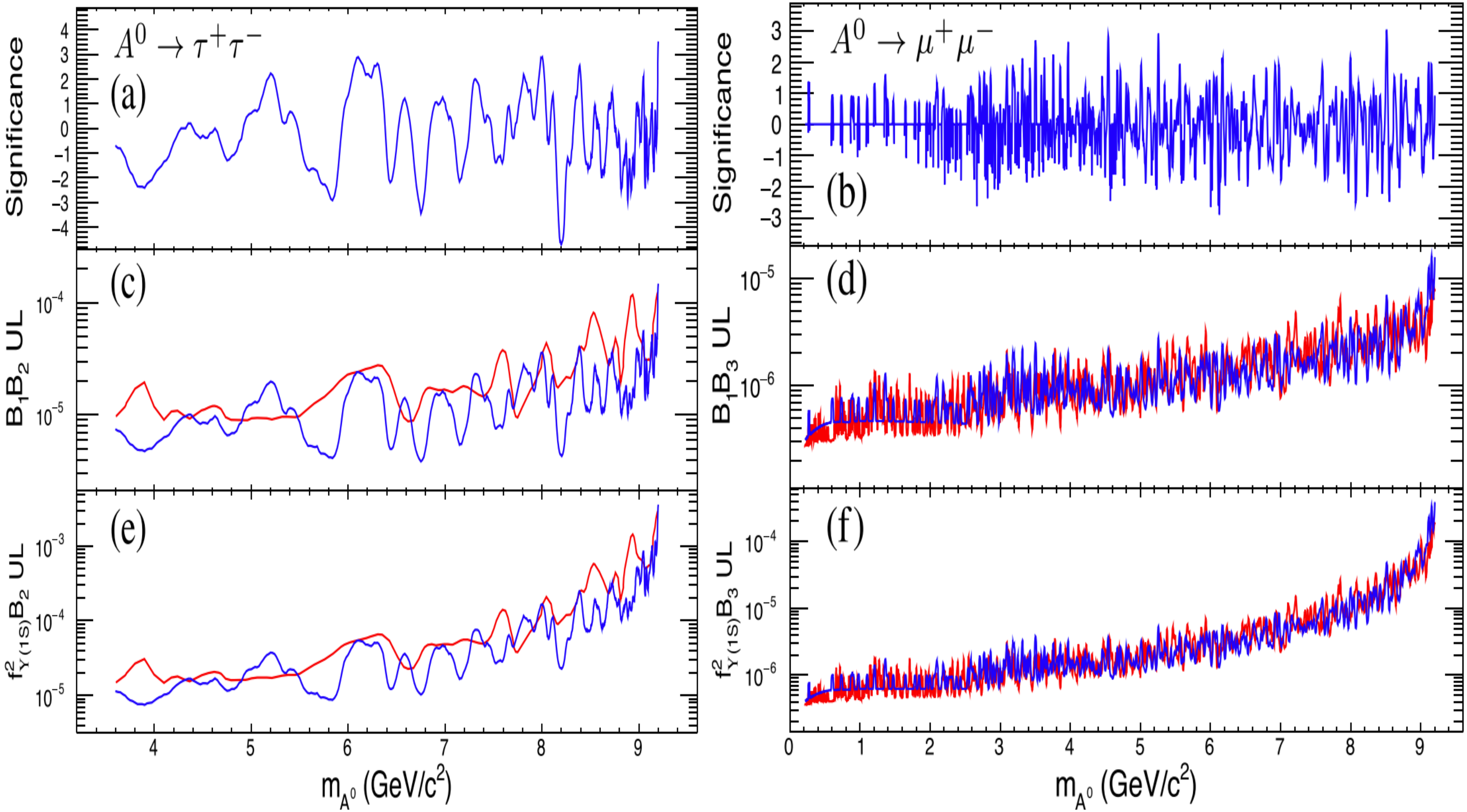


A^0 mass fixed at 9.2 GeV/c²
Maximum Local significance of 3.5σ

A^0 mass fixed at 8.51 GeV/c²
Maximum Local significance of 3.0σ

Light Higgs search: The Result

Belle PRL **128** 081804 (2022)



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

$f_{\Upsilon(1S)}$ Yukawa coupling

α fine structure constant

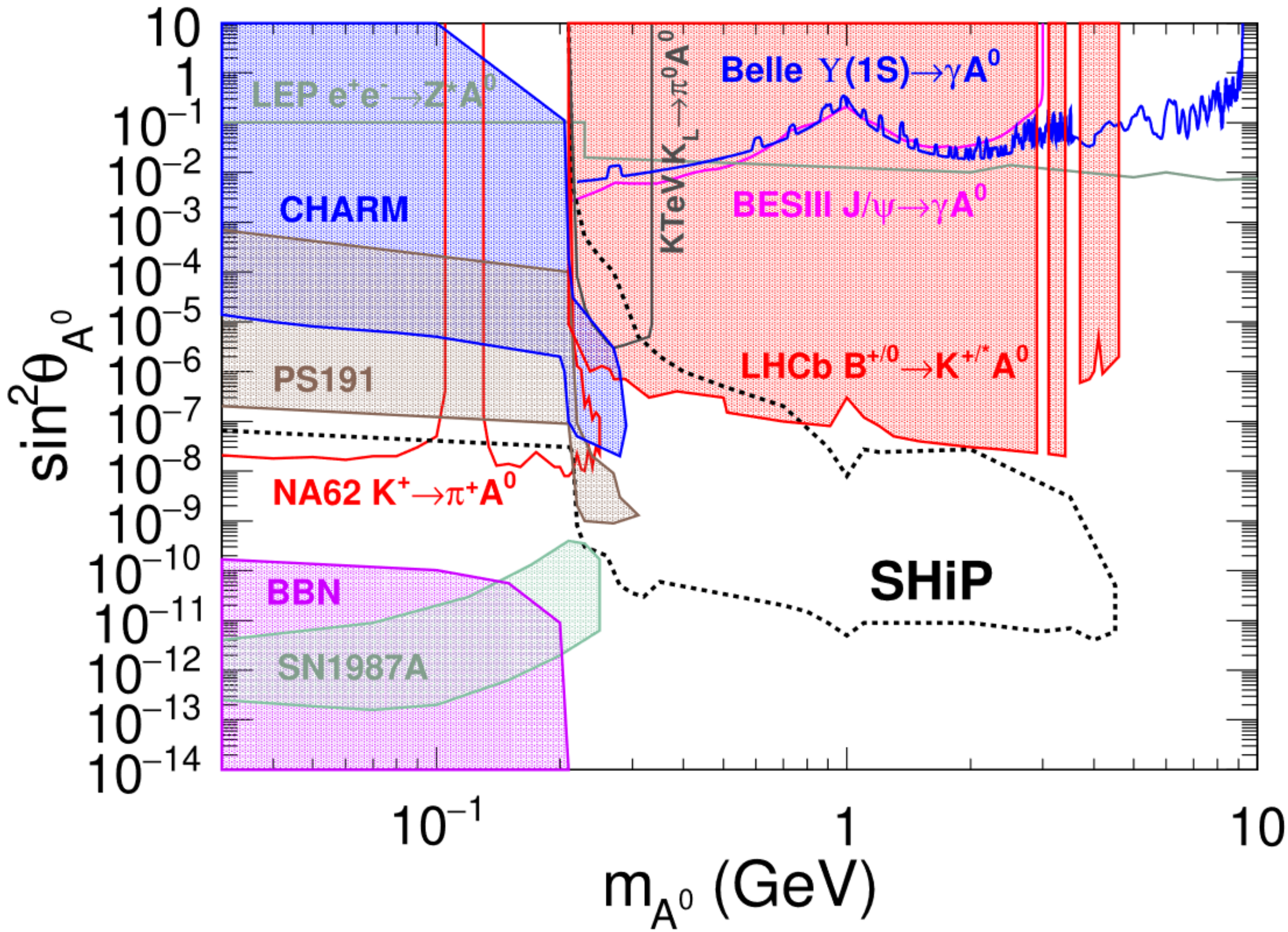
$$\frac{\mathcal{B}[\Upsilon(1S) \to \gamma A^0]}{\mathcal{B}[\Upsilon(1S) \to \ell^+\ell^-]} = \frac{f^2_{\Upsilon(1S)}}{\sqrt{2}\pi\alpha}\left(1 - \frac{m^2_{A^0}}{m^2_{\Upsilon(1S)}}\right)$$

$\sin^2\theta_{A^0}$: mixing angle
G_F : fermi constant
m_b : mass of b quark

Belle PRL **128** 081804 (2022)

Light Higgs search: The Constraints

$$\frac{\mathcal{B}[\Upsilon(1S) \to \gamma A^0]\mathcal{B}(A^0 \to \text{hadrons})}{\mathcal{B}[\Upsilon(1S) \to \ell^+\ell^-]} = \sin^2\theta_{A^0} \frac{G_F m_b^2}{\sqrt{2}\pi\alpha} \sqrt{\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(1S)}^2}\right)},$$



Summary

Unique $\Upsilon(2S)$ data set allow one to search for charged LFV decays and light Higgs.

Charged LFV decays:

- More stringent result for $\Upsilon(1S) \to \mu\tau$ than previous result
- All other modes searched for the first time.
- First experimental constraints for RLFV decays.

Belle JHEP **(2022)** 095

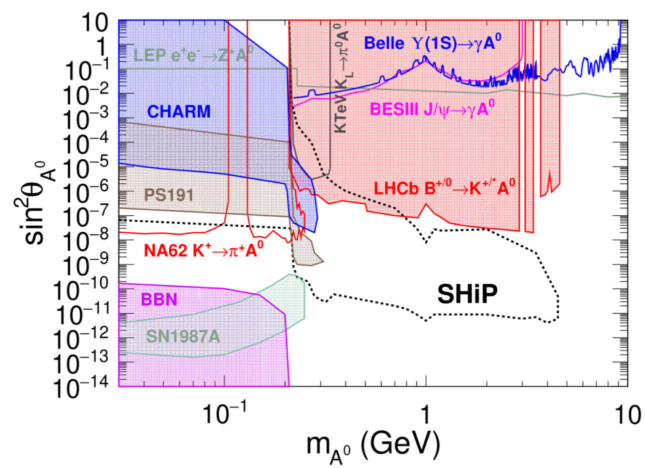
$\ell_1\ell_2$	$\mu\tau$	$e\tau$	$e\mu$
$\Upsilon(1S) \to \ell_1\ell_2$	$< 2.7 \times 10^{-6}$	$< 2.7 \times 10^{-6}$	$< 3.9 \times 10^{-7}$
$\ell_1\ell_2\gamma$	$\mu\tau\gamma$	$e\tau\gamma$	$e\mu\gamma$
$\Upsilon(1S) \to \ell_1\ell_2\gamma$	$< 6.1 \times 10^{-6}$	$< 6.5 \times 10^{-6}$	$< 4.2 \times 10^{-7}$

Precise
First time

Belle PRL **128** 081804 (2022)

Search for Light Higgs :

- Along with other measurements, the Belle result can further constrain parameter space in nMSSM model for $\Upsilon \to \gamma A^0(\to \tau\tau)$ and have same restrictions for $\Upsilon \to \gamma A^0(\to \mu\mu)$.
- Belle limits are applicable to any light scalar or pseudoscalar boson and dark matter, which arises in various extensions of SM.



Thank you