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BSM Physics with Bottomonium: Light Higgs searches from χ_{b0} decay

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1. Introduction

SuperKEKB/ Belle-II offers a new era in high-statistics studies of Scalar bottomonium via radiative Υ decays $\Upsilon \to \gamma\chi_{b0}$

- $250\ \text{fb}^{-1}$ on $\Upsilon(3S) \to 5.9 \times 10^7 \chi_{b0}(2P) + 2.7 \times 10^6 \chi_{b0}(1P)$
- $250\ \text{fb}^{-1}$ on $\Upsilon(2S) \to 6.2 \times 10^7 \chi_{b0}(1P)$

χ_{b0} has the same spin and CP quantum #'s as the Higgs.
Can its decays be used to probe (BSM) Higgs Physics?

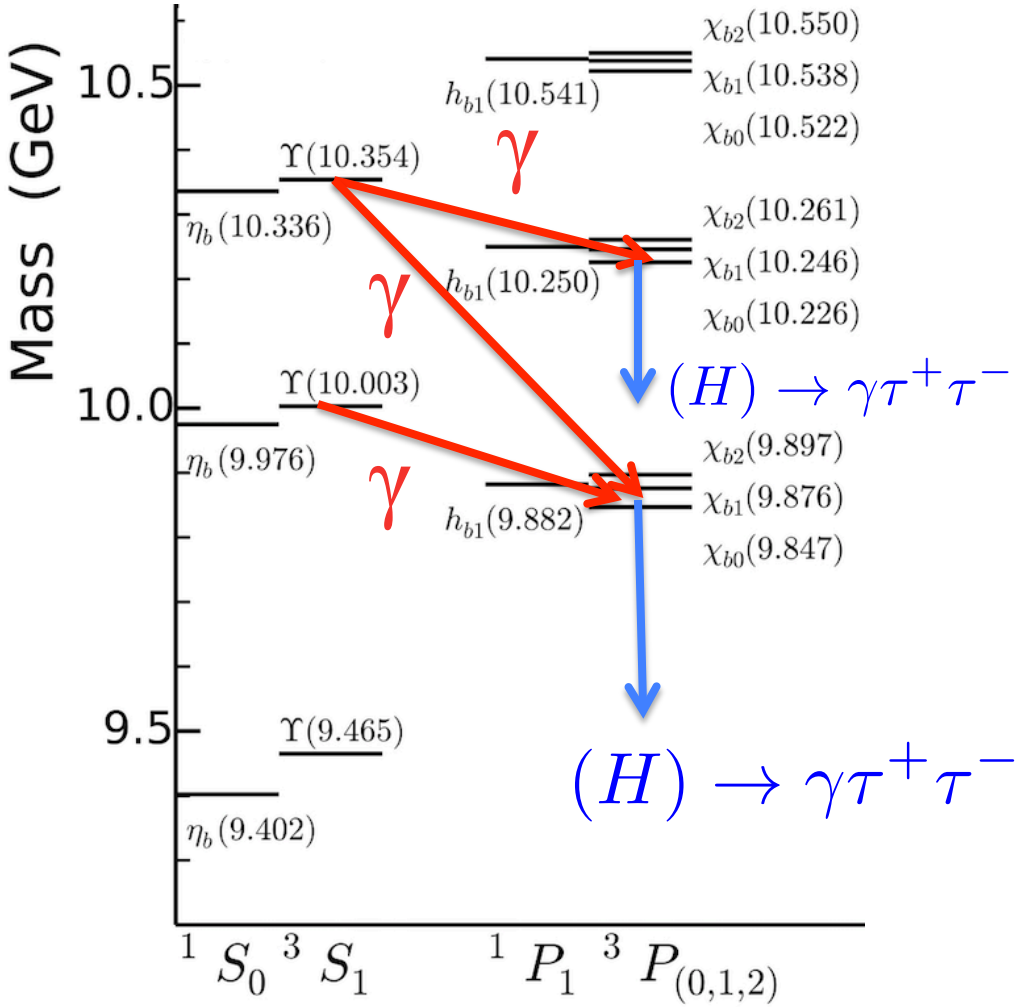
Precedents:

- $B^+ \to \tau^+\nu$ sensitive to s-channel charged Higgs [Hou PRD48 2342 (1993)]
- $\eta_b \to \tau^+\tau^-$ sensitive to s-channel CP-odd Higgs [Rashed et al PRD82 054031 (2010)]

$\Rightarrow \chi_{b0} \to \tau^+\tau^-$ should be sensitive to s-channel CP-even Higgs [Haber Kane & Sterling NPB161 483 (1979)]

Light Higgs searches from χ_{b0} decay

$$\Upsilon \to \gamma\chi_{b0} \to \gamma\tau^+\tau^-$$



Estimate sensitivity of BR of $\chi_{b0} \to \tau^+\tau^-$ to s-channel Higgs from $\Upsilon \to \gamma\chi_{b0} \to \gamma\tau^+\tau^-$

Will find can constrain parameter space of Type II 2HDM in which the scalar couplings to $b\bar{b}$ and $\tau^+\tau^-$ can be enhanced

Need:

- Estimate of χ_{b0} decay constant
- Calculate branching ratios
- Any competing SM processes:
    - $\chi_{b0} \to \tau^+\tau^-$ via 2-photon intermediate state
- Irreducible backgrounds
    - $e^+e^- \to \gamma\tau^+\tau^-$

χ_{b0} decay constant

The matrix element $\chi_{b0} \to \tau^+\tau^-$ is given by:

$$\mathcal{M}^H = \langle \ell^+\ell^- | \frac{m_\ell}{v}\bar{\ell}\ell|0\rangle \frac{i}{M_H^2}\langle 0|\frac{m_q}{v}\bar{q}q|\chi_0\rangle = -\left(\frac{m_q m_\ell}{v^2 M_H^2}\right) f_{\chi_0}\bar{u}(p_{\ell^-})v(p_{\ell^+}),$$

where $\langle 0|\bar{q}q \mid M(\vec{K})\rangle = i f_{\chi_0}$

So need f_{χ_0} which was calculated the *mock meson* approach which in the non-relativistic limit is:

$$f_{\chi_{b0}} = -\frac{3\sqrt{3M_{\chi_{b0}}}}{\sqrt{\pi}\tilde{m}_b}R'(0) = \begin{cases} -4.17\ \text{GeV}^2 & \text{for } \chi_{b0}(1P) \\ -4.31\ \text{GeV}^2 & \text{for } \chi_{b0}(2P) \end{cases}$$

Partial widths and BR's for SM

For the standard model (with Higgs exchange):

$$\Gamma^H(\chi_0 \to \ell^+\ell^-) = \frac{M_{\chi_0}}{8\pi}\left[1-\frac{4m_\ell^2}{M_{\chi_0}^2}\right]^{3/2}\left(\frac{m_q m_\ell}{v^2 M_H^2}\right)^2 f_{\chi_0}^2$$

$$= \begin{cases} 4.3\times10^{-16}\ \text{GeV} & \text{for } \chi_{b0}(1P) \\ 4.8\times10^{-16}\ \text{GeV} & \text{for } \chi_{b0}(2P) \end{cases}$$

To estimate BR's need total widths which which we estimate using measured BR's for radiative transitions with theory estimates of partial widths

$$\Gamma^{tot}_{\chi_{b0}(1P)} = 1.35\ \text{MeV}, \qquad \Gamma^{Tot}_{\chi_{b0}(2P)} = (247\pm93)\ \text{keV}$$

Putting together we obtain:

$$\text{BR}^H(\chi_{b0}(1P)\to\tau^+\tau^-) = 3.1\times10^{-13}$$

$$\text{BR}^H(\chi_{b0}(2P)\to\tau^+\tau^-) = (1.9\pm0.5)\times10^{-12}$$

With $O(10^7)$ events in 250 fb^{-1} SM BR too small

Partial widths and BR's for 2 HDM

Can *s*-channel Higgs contribution be enhanced?

Yes! In Type II 2HDM the scalar couplings to b-quarks and τ leptons are enhanced for large values of tanβ which is the ratio of vev's of the two Higgs doublets

Two Higgs doublets: Φ_1 and Φ_2

Both contribute to electroweak symmetry breaking with

$$v_1^2 + v_2^2 = v_{SM}^2 \qquad v_2/v_1 = \tan\beta$$

- U-type quark mass from Φ_2 coupling strength m_u/v_2
- D-type quark, lepton masses from Φ_1 coupling strength $m_{d,l}/v_1$

Partial widths and BR's for 2 HDM

The model has

- 2 CP-even neutral Higgs
- 1 CP-odd neutral Higgs
- Pair of charged Higgs

- Identify with the 125 GeV object and the 2nd can be heavier or lighter

In this limit where the 125 GeV object is exactly SM-like

$$H_{new}\bar{u}u = -i\frac{m_u}{v}[1 \mp \cot\beta] \qquad H_{new}\bar{d}d(\bar{\ell}\ell) = -i\frac{m_{d(\ell)}}{v}[\mp \tan\beta]$$

Large tanβ -> large enhancement of $H_{new}bb$ and $H_{new}\tau\tau$ couplings

Partial widths and BR's for 2 HDM

The Higgs exchange matrix element gets modified by:

$$\left(\frac{m_b m_\tau}{v^2 M_H^2}\right)^2 \rightarrow \left(\frac{m_b m_\tau}{v^2 M_H^2}\right)^2 \left[1 + \frac{M_H^2}{M_{new}^2 - M_{\chi_{b0}}^2} \tan^2\beta\right]^2$$

So the partial width is modified by:

$$\Gamma(\chi_{b0} \rightarrow \tau^+\tau^-) = \Gamma^{SM}(\chi_{b0} \rightarrow \tau^+\tau^-) \times \left[1 + \frac{M_H^2}{M_{new}^2 - M_{\chi_{b0}}^2} \tan^2\beta\right]^2$$

An enhancement of $(M_H/M_{H_{new}})\tan\beta \sim 30$

gives ~ 100 signal events in $\Upsilon \rightarrow \gamma\chi_{b0}(2P) \rightarrow \gamma\tau^+\tau^-$

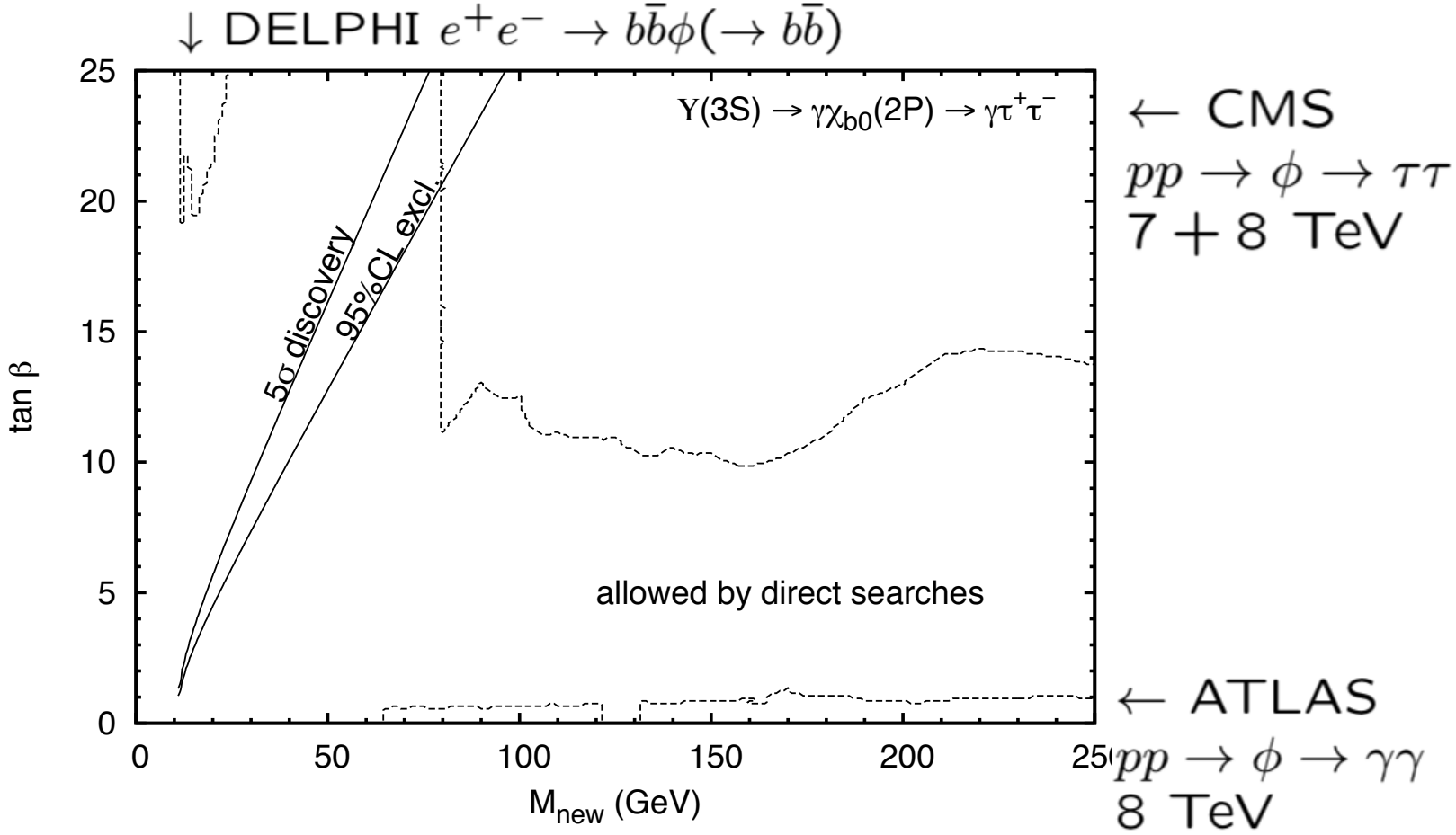
Experimental Strategy

Parent	Daughter	E_γ	δE_γ	$d\sigma_B/dE_\gamma$	N_B
$\Upsilon(3S)$	$\chi_{b0}(2P)$	122 MeV	0.24 MeV	36 fb/MeV	4320
$\Upsilon(3S)$	$\chi_{b0}(1P)$	484 MeV	1.3 MeV	8.8 fb/MeV	5720
$\Upsilon(2S)$	$\chi_{b0}(1P)$	163 MeV	1.3 MeV	30 fb/MeV	19500

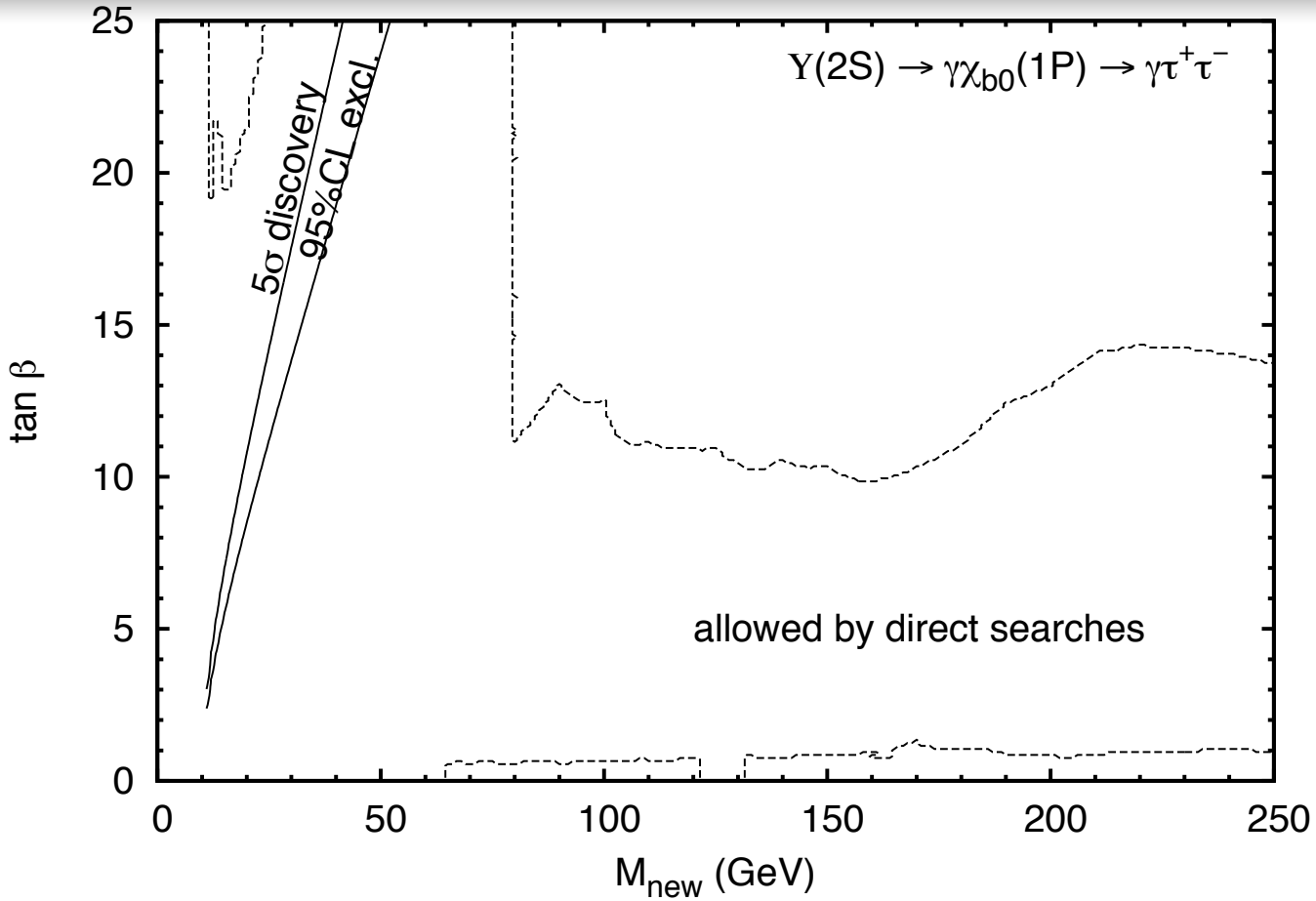
- Tag photon energies E_γ in Υ center-of-mass frame
- Linewidth δE_γ of the photon peak determined by χ_{b0} width
- continuum $e^+e^- \to \gamma\tau^+\tau^-$ background: $d\sigma_B/dE_\gamma$ computed at E_γ using Madgraph
- Ignore reducible background for $\Upsilon \to \gamma\chi_{b0}$, $\chi_{b0} \to$ not $\tau\tau$
- Number, N_B of continuum background events in window $2\delta E_\gamma$ centered at photon peak with 250 fb^{-1} luminosity at Υ peak

Results

The number of signal events grows with tan β
5 σ limits and 95% CL exclusion (based on irreducible background):



Results



H_{new} below 10 GeV generally excluded by $\Upsilon \rightarrow \gamma H_{new}$

Summary

- SuperKEKB /Belle-II offers high statistics sample of bottomonia

- χ_{b0} is a CP-even neutral scalar so $\chi_{b0} \to \tau\tau$ is sensitive to light CP-even neutral Higgs with enhanced bb, $\tau\tau$ couplings
- Propose to to put constraints on 2HDM using radiative decays of $\Upsilon(3S)$ to $\chi_{b0} \to \tau^+ \tau^-$

- 250 fb^{-1} on the $\Upsilon(3S)$ can exclude $M_{new}<80$ GeV for $\tan\beta>20$
- 250 fb^{-1} on the $\Upsilon(2S)$ can exclude $M_{new}<40$ GeV for $\tan\beta>20$

- Prospects for improvement with smarter kinematic selection to suppress $e^+e^- \to \tau\tau\gamma$ background

- Future work is to look at $\mu^+\mu^-$ final states