New physics in bottomonium decay

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Based on S. Godfrey and H.E. Logan, 1510.04659 (PRD 2016)

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

- 250 fb^{-1} on $\Upsilon(2S) \to 6.2 \times 10^7$ $\chi_{b0}(1P)$

χ_{b0} has the same spin and CP quantum numbers 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 1993
- $\eta_b \to \tau\tau$ sensitive to s-channel CP-odd Higgs Rashed et al 2010

$\to$ $\chi_{b0} \to \tau\tau$ should be sensitive to s-channel CP-even Higgs

Haber, Kane & Sterling, NPB 1979

$\chi_{b0} \to \tau\tau$: s-channel Higgs

Matrix element (SM Higgs exchange):

$$\mathcal{M}^H = \langle \ell^+ \ell^- | \frac{i m_\ell}{v} \bar{\ell}\ell | 0 \rangle \; \frac{i}{M_{\chi_{b0}}^2 - M_H^2} \; \langle 0 | \frac{i m_b}{v} \bar{b}b | \chi_{b0} \rangle$$

First we need the χ_{b0} decay constant,

$$\langle 0 | \bar{b}b | \chi_{b0} \rangle = i f_{\chi_{b0}}$$

- No Lattice calculation yet
- A few QCD sum-rules results, but we couldn't tell what normalization they used

$\rightarrow$ Computed $f_{\chi_{b0}}$ using quark model "mock meson" approach

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

($\tilde{m}_b$ = constituent quark mass)

$\chi_{b0} \to \tau\tau$: s-channel Higgs

Partial width (SM Higgs exchange):

$$\Gamma^H(\chi_{b0} \to \tau\tau) = \frac{M_{\chi_{b0}}}{8\pi}\left[1 - \frac{4m_\tau^2}{M_{\chi_{b0}}^2}\right]^{3/2}\left(\frac{m_b m_\tau}{v^2 M_H^2}\right)^2 f_{\chi_{b0}}^2$$
$$= \begin{cases} 4.3 \times 10^{-16}\ \text{GeV} & \text{for } \chi_{b0}(1P) \\ 4.8 \times 10^{-16}\ \text{GeV} & \text{for } \chi_{b0}(2P) \end{cases}$$

neglecting $M_{\chi_{b0}}^2$ relative to M_H^2 in the propagator

Total widths not measured: combine measured $\chi_{b0} \to \gamma\Upsilon(1S)$ BRs with predictions for that decay's partial width (quark model):

$$\Gamma^{\text{tot}}_{\chi_{b0}(1P)} = 1.35\ \text{MeV}, \qquad \Gamma^{\text{tot}}_{\chi_{b0}(2P)} = (247 \pm 93)\ \text{keV}$$

$$\text{BR}^H(\chi_{b0}(1P) \to \tau\tau) = 3.1 \times 10^{-13}$$
$$\text{BR}^H(\chi_{b0}(2P) \to \tau\tau) = (1.9 \pm 0.5) \times 10^{-12}$$

Compare $\mathcal{O}(10^7)$ events in 250 fb^{-1}: BR way too small in SM!

Can s-channel Higgs contribution be enhanced?

Matrix element (SM Higgs exchange):

$$\mathcal{M}^H = \langle \ell^+ \ell^- | \frac{i m_\ell}{v} \bar{\ell} \ell | 0 \rangle \; \frac{i}{M_{\chi_{b0}}^2 - M_H^2} \; \langle 0 | \frac{i m_b}{v} \bar{b} b | \chi_{b0} \rangle$$

Tiny BR is due to (1) small b and τ Yukawa couplings and (2) Higgs mass suppression in propagator.

$\Rightarrow$ Consider Type-II two-Higgs-doublet model with (1) enhanced b and τ Yukawas and (2) relatively light non-SM CP-even Higgs boson in propagator

Type-II two-Higgs-doublet model

Two Higgs doublets: Φ_1 and Φ_2

Both contribute to electroweak symmetry breaking:
vacuum expectation values $v_1^2 + v_2^2 = v_{\rm SM}^2$, $v_2/v_1 \equiv \tan\beta$

Type-II model: specifies pattern of fermion mass generation
- Up-type quark masses from Φ_2: coupling strength m_u/v_2
- Down-type quark, lepton masses from Φ_1: coupling strength $m_{d,\ell}/v_1$

Physical Higgs states:
- 2 CP-even neutral Higgs bosons, h^0 (lighter) and H^0 (heavier)
- 1 CP-odd neutral Higgs boson, A^0
- Pair of charged Higgs bosons, $H^\pm$

We will consider the scenario in which:
- The 125 GeV Higgs is very SM-like: call it H_{125}
- The 2nd Higgs boson could be heavier or lighter: call it $H_{\rm new}$

Type-II two-Higgs-doublet model: couplings to fermions

$$h^0 V_\mu V^\mu : \quad 2i\frac{M_V^2}{v}\sin(\beta-\alpha)$$
$$h^0 \bar{u}u : \quad -i\frac{m_u}{v}\left[\sin(\beta-\alpha)+\cot\beta\cos(\beta-\alpha)\right]$$
$$h^0 \bar{d}d : \quad -i\frac{m_d}{v}\left[\sin(\beta-\alpha)-\tan\beta\cos(\beta-\alpha)\right]$$

$$H^0 V_\mu V^\mu : \quad 2i\frac{M_V^2}{v}\cos(\beta-\alpha)$$
$$H^0 \bar{u}u : \quad -i\frac{m_u}{v}\left[-\cot\beta\sin(\beta-\alpha)+\cos(\beta-\alpha)\right]$$
$$H^0 \bar{d}d : \quad -i\frac{m_d}{v}\left[\tan\beta\sin(\beta-\alpha)+\cos(\beta-\alpha)\right]$$

(leptons same as down-type quarks with $m_d \to m_\ell$)

For simplicity (and accordance with LHC data), assume H_{125} couplings are exactly SM-like: "alignment limit".
For $H_{125} = h^0(H^0)$,

$$H_{\rm new}\bar{u}u : -i\frac{m_u}{v}[\mp\cot\beta] \qquad H_{\rm new}\bar{d}d : -i\frac{m_d}{v}[\pm\tan\beta]$$

Large $\tan\beta \to$ large enhancement of $H_{\rm new}\bar{b}b$, $H_{\rm new}\bar{\tau}\tau$ couplings.

$\chi_{b0} \to \tau\tau$: s-channel H_{125} and $H_{\rm new}$

Matrix element (alignment limit for H_{125}):

$$\mathcal{M}^H = \langle \ell^+\ell^- | \frac{i m_\ell}{v} \bar{\ell}\ell | 0 \rangle \frac{i}{M^2_{\chi_{b0}} - M^2_{H_{125}}} \langle 0 | \frac{i m_b}{v} \bar{b} b | \chi_{b0} \rangle + \langle \ell^+\ell^- | \frac{i m_\ell \tan\beta}{v} \bar{\ell}\ell | 0 \rangle \frac{i}{M^2_{\chi_{b0}} - M^2_{H_{\rm new}}} \langle 0 | \frac{i m_b \tan\beta}{v} \bar{b} b | \chi_{b0} \rangle$$

Including $H_{\rm new}$ exchange the partial width becomes:

$$\Gamma^H(\chi_{b0} \to \tau\tau) = \frac{M_{\chi_{b0}}}{8\pi} \left[1 - \frac{4 m_\tau^2}{M^2_{\chi_{b0}}} \right]^{3/2} \left(\frac{m_b m_\tau}{v^2 M^2_{H_{125}}} \right)^2 f^2_{\chi_{b0}} \times \left[1 + \frac{M^2_{H_{125}} \tan^2\beta}{M^2_{\rm new} - M^2_{\chi_{b0}}} \right]^2$$

The Higgs-mediated BRs are also multiplied by this factor:

$$\left.\begin{array}{l} {\rm BR}^H(\chi_{b0}(1P) \to \tau\tau) = 3.1 \times 10^{-13} \\ {\rm BR}^H(\chi_{b0}(2P) \to \tau\tau) = (1.9 \pm 0.5) \times 10^{-12} \end{array}\right\} \times \left[1 + \frac{M^2_{H_{125}} \tan^2\beta}{M^2_{\rm new} - M^2_{\chi_{b0}}} \right]^2$$

Will only need $(M_{H_{125}}/M_{H_{\rm new}}) \tan\beta \sim 30$ for $\mathcal{O}(100)$ signal events in $\Upsilon(3S) \to \gamma \chi_{b0}(2P) \to \gamma\tau\tau$

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

- Tagging photon energies E_γ in the Υ center-of-mass frame

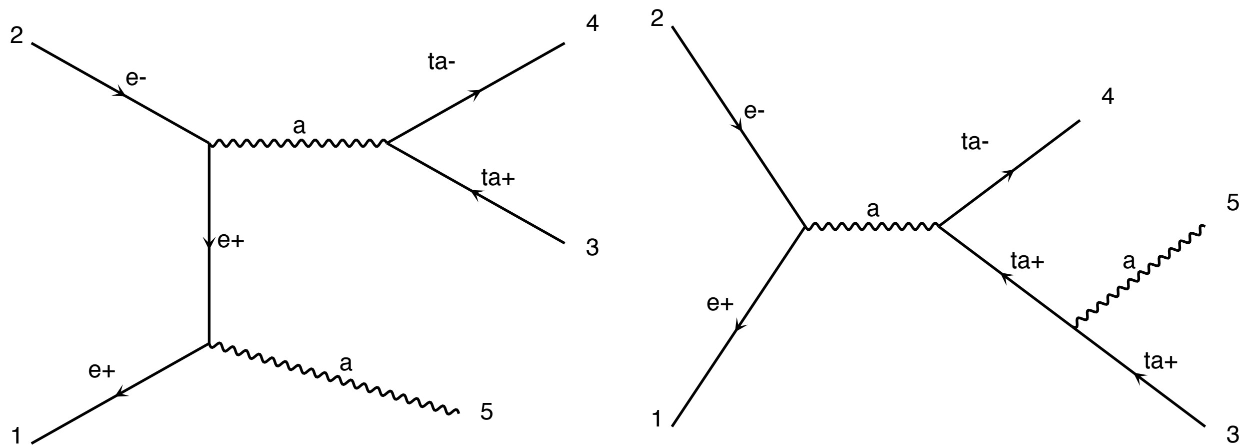
- Linewidth δE_γ of the photon peak is determined by χ_{b0} width

- Continuum $e^+e^- \to \gamma\tau^+\tau^-$ background: differential cross section $d\sigma_B/dE_\gamma$ at E_γ computed using MadGraph (next slide)

- Ignoring reducible background $\Upsilon \to \gamma\chi_{b0}$, $\chi_{b0} \to$ not $\tau\tau$

- Number N_B of continuum background events in a window of width $2\delta E_\gamma$ centered at the photon peak in 250 fb^{-1} of e^+e^- luminosity at Υ resonance

Continuum (irreducible) background: $e^+e^- \to \tau^+\tau^-\gamma$

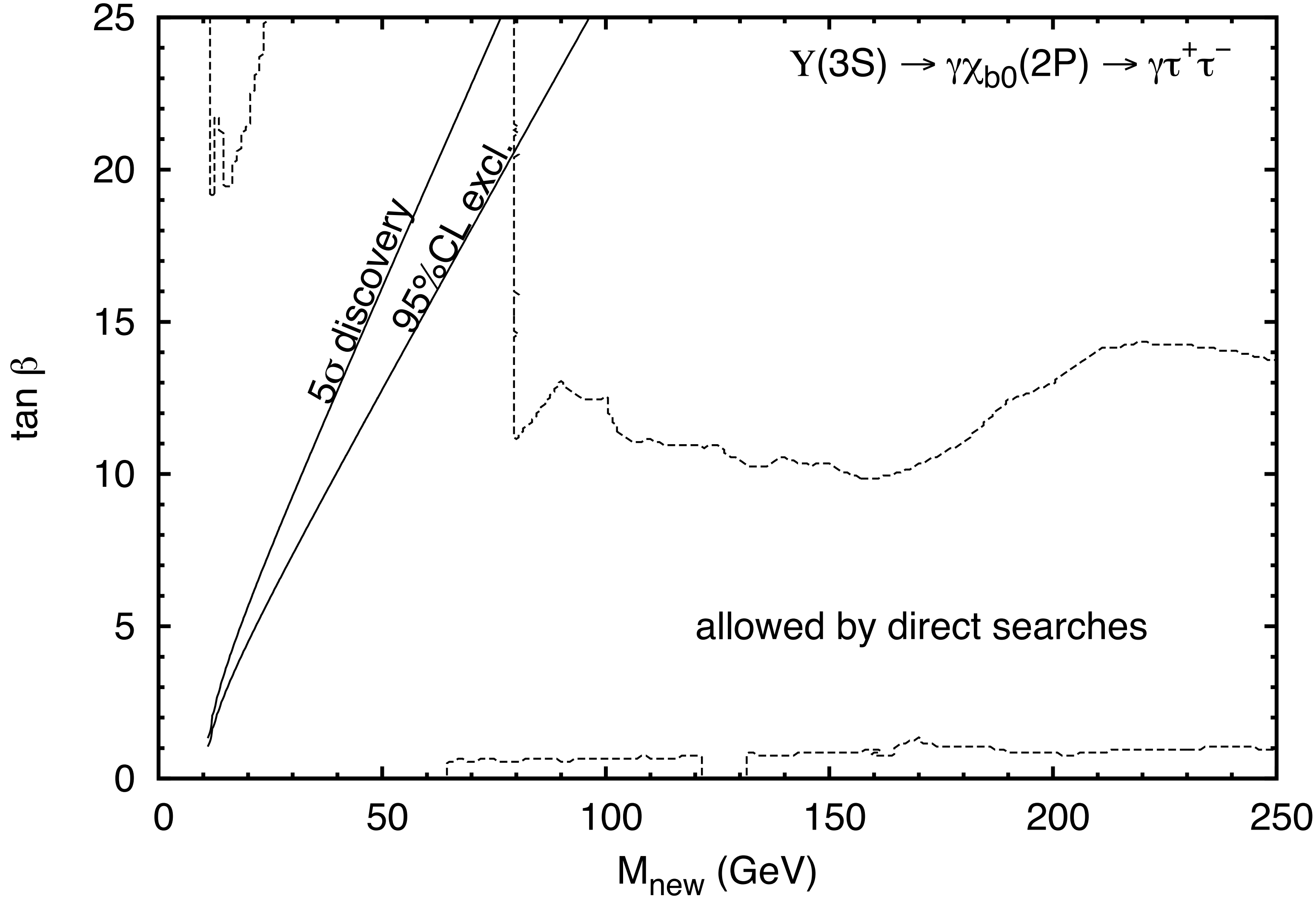


Used MadGraph5 to compute $d\sigma_B/dE_\gamma$ at photon energy E_γ in CM frame

Cuts: we required only $|\eta_\gamma| < 5$ in CM frame

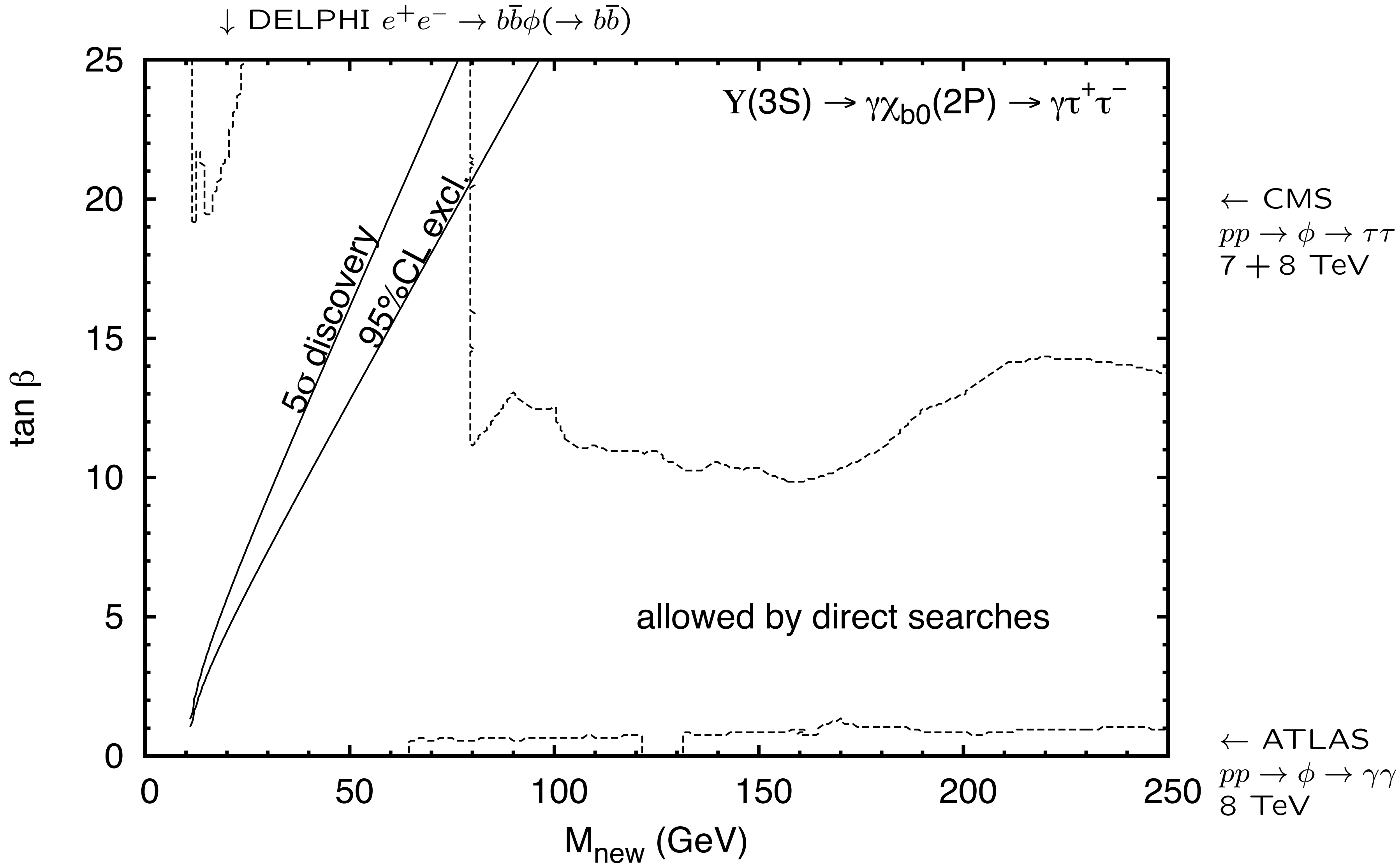
Room for improvement:
- Signal and background have different τ angular distributions with respect to beam line
- Photon distribution relative to beam line and to $\tau^\pm$ directions also different
- τ polarization distributions also different

Results: $\Upsilon(3S)$



Direct search exclusions: HiggsBounds 4.2.0 S. Godfrey and H.E. Logan, 1510.04659

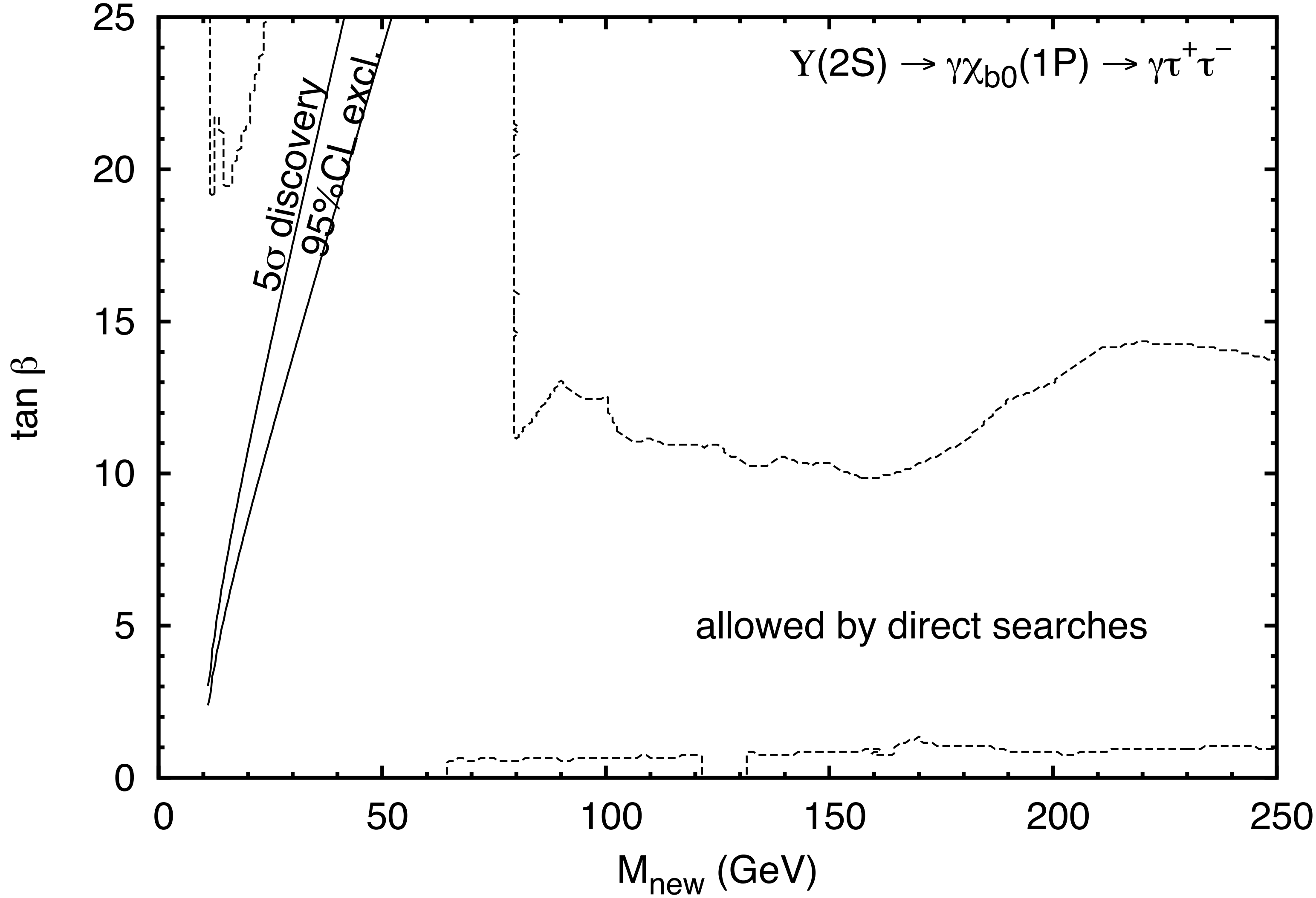
Results: $\Upsilon(3S)$



Direct search exclusions: HiggsBounds 4.2.0 S. Godfrey and H.E. Logan, 1510.04659

Results: $\Upsilon(2S)$

worse sensitivity mainly due to larger $\chi_{b0}(1P)$ total width



Direct search exclusions: HiggsBounds 4.2.0

S. Godfrey and H.E. Logan, 1510.04659

Summary

SuperKEKB/Belle-II offers high statistics sample of bottomonia

χ_{b0} is a CP-even neutral scalar: $\chi_{b0} \to \tau\tau$ sensitive to light CP-even neutral Higgs with enhanced $b\bar{b}$, $\tau\tau$ couplings

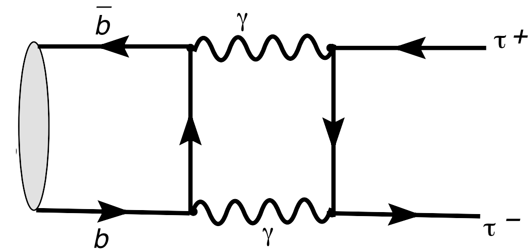
250 fb^{-1} on the $\Upsilon(3S)$ can exclude $M_h \equiv M_{\text{new}} < 80$ GeV for $\tan\beta \geq 20$ [best signal is from $\chi_{b0}(2P)$]

250 fb^{-1} on the $\Upsilon(2S)$ can exclude $M_h \equiv M_{\text{new}} < 40$ GeV for $\tan\beta \geq 20$ [forced to use $\chi_{b0}(1P)$: larger total width means smaller BR($\tau\tau$), more continuum background]

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

BACKUP

$\chi_{b0} \to \tau\tau$: 2-photon process



Rashed, Duraisamy & Datta, 1004.5419

Estimate using optical theorem:

$$\Gamma^{2\gamma}(\chi_{b0} \to \tau\tau) \simeq \frac{\alpha_{\rm em}^2}{2\beta_\tau} \left[\frac{m_\tau}{M_{\chi_{b0}}} \ln \frac{(1+\beta_\tau)}{(1-\beta_\tau)} \right]^2 \Gamma(\chi_{b0} \to \gamma\gamma)$$

where

$$\Gamma(\chi_{b0} \to \gamma\gamma) = \frac{4\pi\alpha_{\rm em}^2}{81 M_{\chi_{b0}}^3} f_{\chi_{b0}}^2 \qquad \beta_\tau = \sqrt{1 - \frac{4m_\tau^2}{M_{\chi_{b0}}^2}}$$

which gives

$$\mathrm{BR}^{2\gamma}(\chi_{b0}(1P) \to \tau\tau) \simeq 1 \times 10^{-9}$$
$$\mathrm{BR}^{2\gamma}(\chi_{b0}(2P) \to \tau\tau) \simeq 6 \times 10^{-9}$$

- 3000 $\times$ bigger than SM Higgs exchange
- Still < 1 event in 250 fb^{-1}

Nonresonant signal $\Upsilon \to \gamma H^*_{\rm new} \to \gamma\tau\tau$?

- Photon is not mono-energetic
- For $M_{H_{\rm new}} \gg M_{\chi_{b0}}$, event rate is at most a few percent of our main resonant $\Upsilon \to \gamma\chi_{b0} \to \gamma\tau\tau$ signal

How to calculate, neglecting SM Higgs contribution:

$$\Gamma(\Upsilon \to \gamma H^*_{\rm new} \to \gamma\tau\tau) = \frac{1}{\pi}\int_{4m_\tau^2}^{M_\Upsilon^2} \frac{dQ^2\, Q\, \Gamma(\Upsilon \to \gamma H^*_{\rm new})\, \Gamma(H^*_{\rm new} \to \tau\tau)}{(Q^2 - M^2_{\rm new})^2 + M^2_{\rm new}\Gamma^2_{\rm new}}$$

where

$$\Gamma(\Upsilon \to \gamma H^*_{\rm new}) = \frac{(m_b \tan\beta)^2}{2\pi\alpha_{\rm em} v^2}\left[1 - \frac{Q^2}{M_\Upsilon^2}\right]\Gamma(\Upsilon \to \mu^+\mu^-)$$

$$\Gamma(H^*_{\rm new} \to \tau\tau) = \frac{(m_\tau \tan\beta)^2 Q}{8\pi v^2}\left[1 - \frac{4m_\tau^2}{Q^2}\right]^{3/2}$$

Integrate numerically over offshell $H_{\rm new}$ invariant mass Q.

- For $M_{H_{\rm new}} \sim M_{\chi_{b0}}$, mixing will become important; we have not considered this
- $M_{H_{\rm new}} < M_\Upsilon$ is excluded by on-shell $\Upsilon \to \gamma H_{\rm new}$