Hunting a CP-odd non-standard Higgs boson @ a (Super) B factory*

**Based on hep-ph/0702190, hep-ph/0610046*
hep-ph/020156, hep-ph/0307313

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Light neutral Higgs scenarios

$$\hat{H}_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad \hat{H}_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}, \quad \hat{S}$$

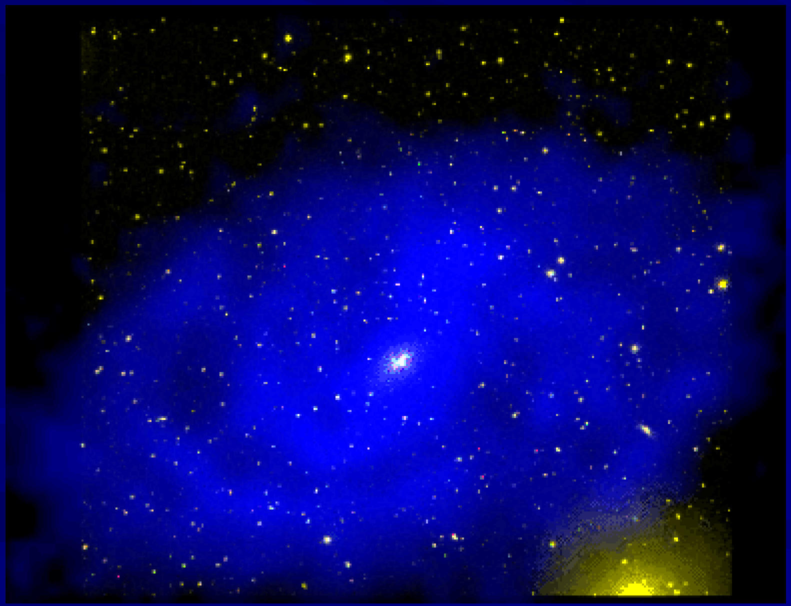
Higgs sector in the NMSSM: (seven)

2 neutral CP-odd Higgs bosons ($A_{1,2}$)
3 neutral CP-even Higgs bosons ($H_{1,2,3}$)
2 charged Higgs bosons ($H^{\pm}$)

L & H
Light and heavy Higgs bosons can live together

PQ symmetry or $U(1)_R$ slightly broken → **a light pseudoscalar Higgs A_1** → A^0

$$A_1 = \cos\theta_A \, A_{MSSM} + \sin\theta_A \, A_s$$

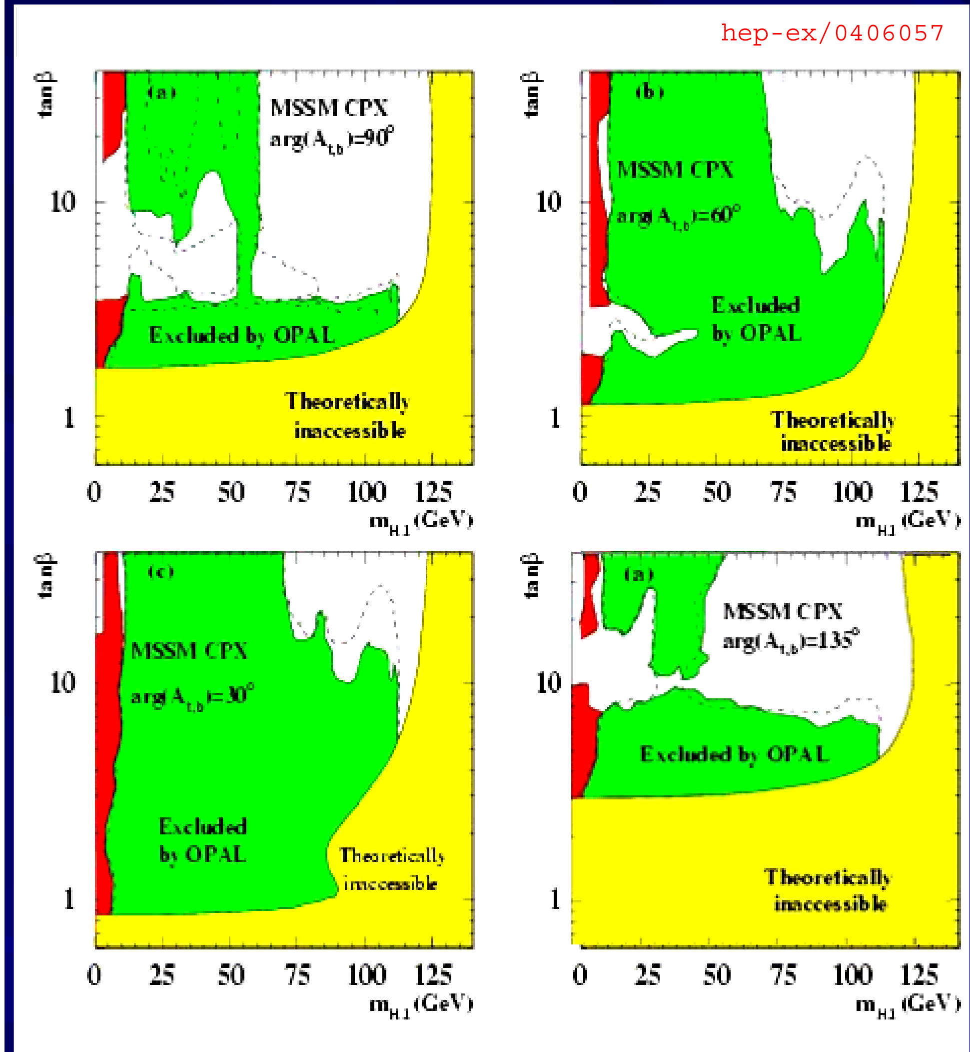


Coupling of A_1 to down type fermions $\propto \cos\theta_A \tan\beta$

Light dark matter?

NMSSM candidate compatible with present bounds:
Light neutralino with a singlet component
[hep-ph:0509024]

Light Higgs windows at LEP (CPV MSSM)



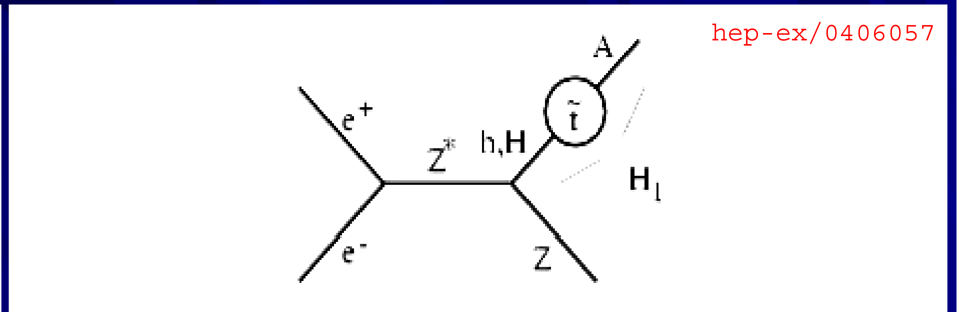
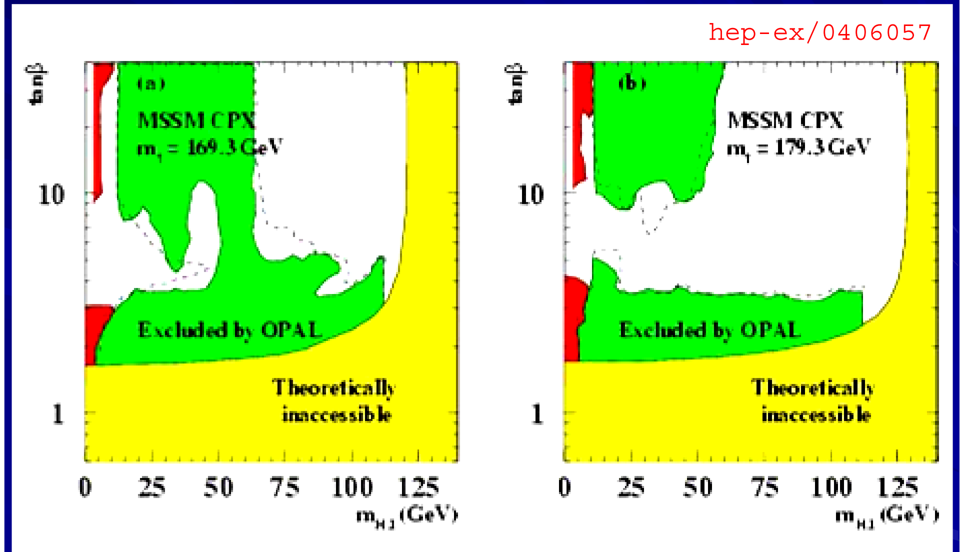


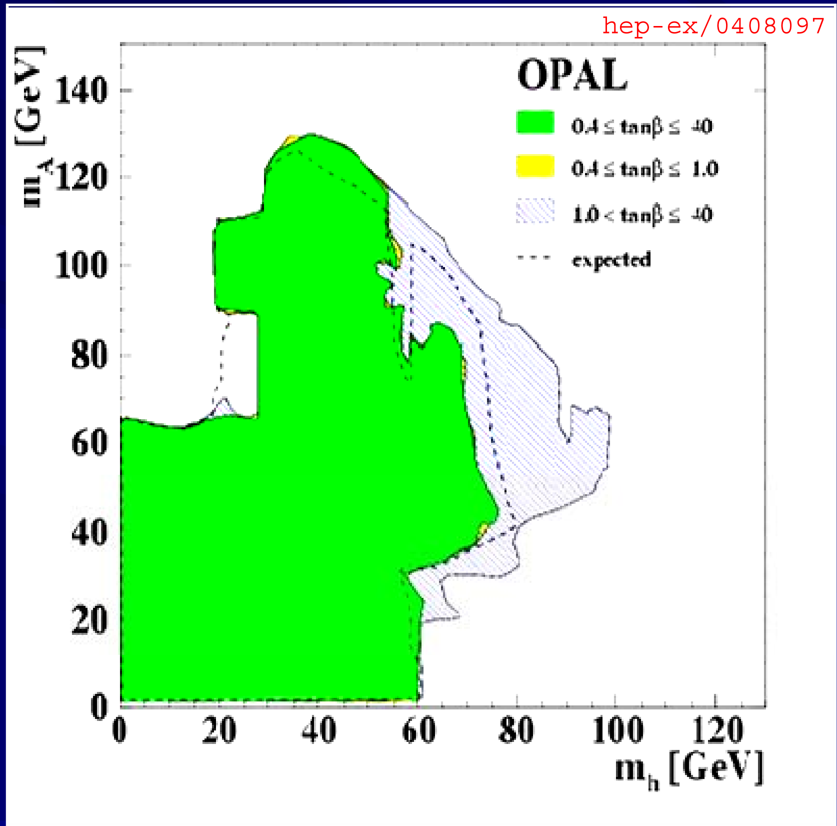
Diagram illustrating the effective coupling of a Higgs mass eigenstate H1 to the Z. Only the CP-even admixture h and H couple to Z while the CP-odd A does not: hence the coupling of the H_1 is reduced wrt a CPC scenario.

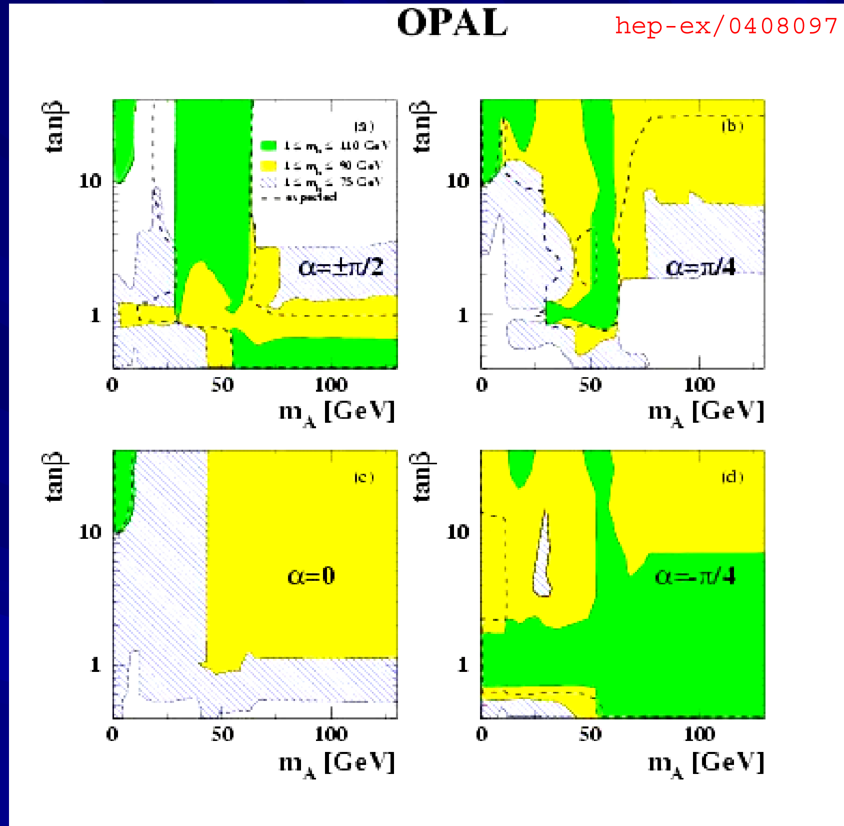


CPX MSSM 95% exclusion areas using scans with different values of arg ($A_{t,b}$). The region excluded by Yukawa searches, Z-width constraints or decay independent searches is shown in red

CPX MSSM 95% exclusion areas using scans with different values of the top mass

Light Higgs windows at LEP (2HDM-II)



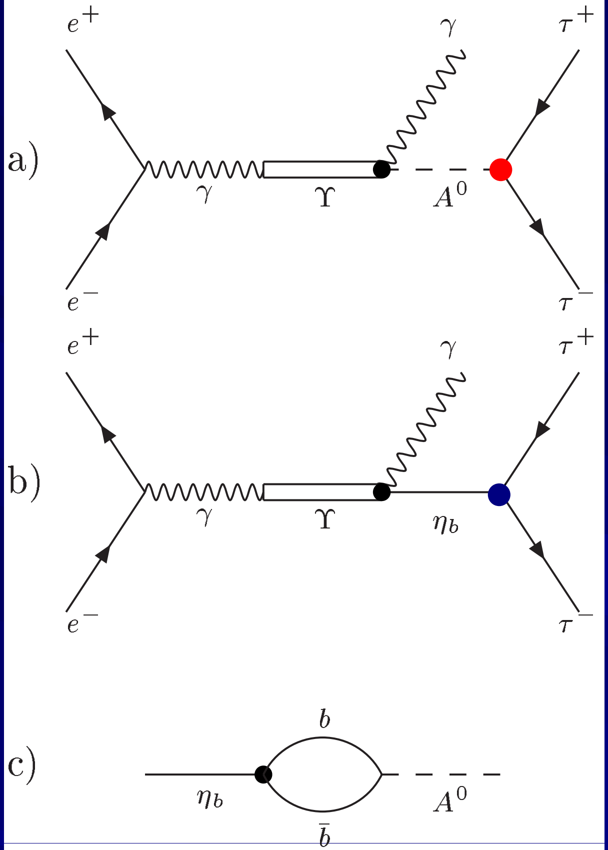


Excluded (m_A,m_h) region independent of the CP even Higgs mixing angle α from flavor-independent and b-tagging searches at LEP interpreted according to a 2HDM(II)

Excluded regions in the (m_A,tanβ) plane for different choices of α. In the MSSM $-\pi/2 \leq \alpha \leq 0$; in a general 2HDM(II) $-\pi/2 \leq \alpha \leq \pi/2$

Mixing of a pseudoscalar Higgs A^0 and a η_b resonance

$e^+ e^- \to \Upsilon \to \gamma\, \tau^+ \tau^-$



$$\delta m^2 \approx \left(\frac{3 m_{\eta_b}^3}{4\pi v^2}\right)^{1/2} |R_{\eta_b}(0)| \times X_d$$

$X_d = \cos\theta_A \tan\beta$

$$\mathbf{M}^2 = \begin{pmatrix} m_{A_0}^2 - i m_{A_0}\Gamma_{A_0} & \delta m^2 \\ \delta m^2 & m_{\eta_{b0}}^2 - i m_{\eta_{b0}}\Gamma_{\eta_{b0}} \end{pmatrix}$$

$\sin 2\alpha \approx \delta m^2$

A_0^0 , η_{b0} unmixed states

$$A^0 = \cos\alpha\, A_0^0 + \sin\alpha\, \eta_{bo}$$
$$\eta_b = \cos\alpha\, \eta_{b0} - \sin\alpha\, A_0^0$$

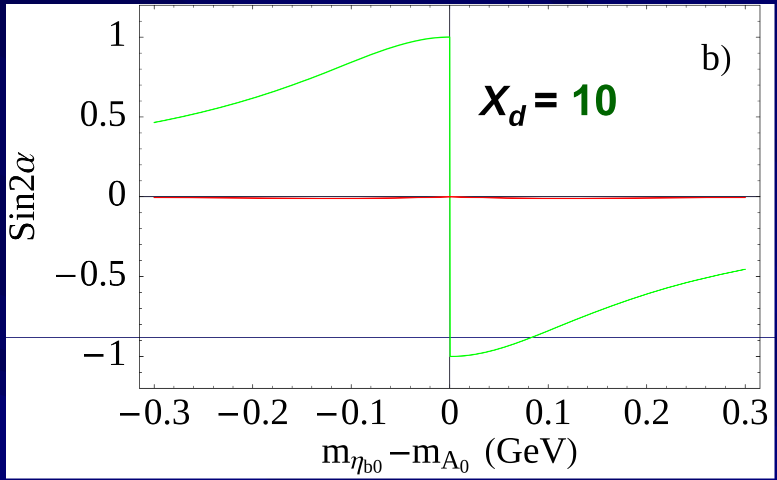
A^0 , η_b mixed (physical) states

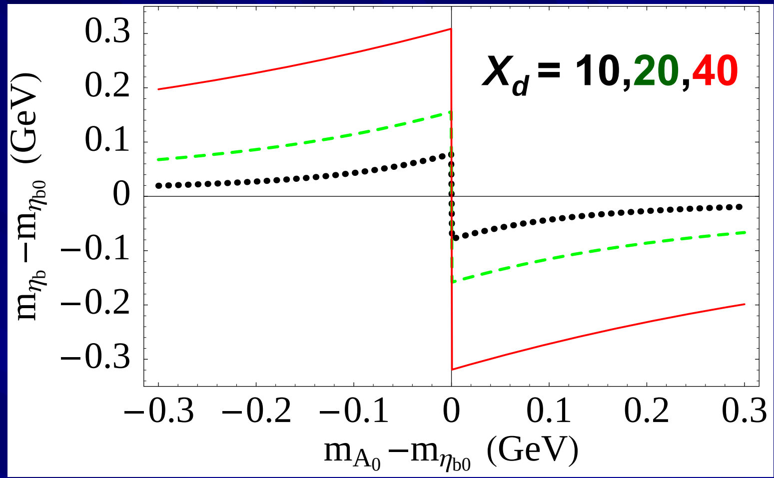
$$g_{A^0\tau\tau} = \cos\alpha\, g_{A_0^0\tau\tau} + \sin\alpha\, \underbrace{g_{\eta_{bo}\tau\tau}}_{0}$$
$$g_{\eta_b\tau\tau} = \cos\alpha\, \underbrace{g_{\eta_{b0}\tau\tau}}_{0} - \sin\alpha\, g_{A_0^0\tau\tau}$$

$$\Gamma_{A^0} = |\cos\alpha|^2\, \Gamma_{A_0^0} + |\sin\alpha|^2\, \Gamma_{\eta_{bo}}$$
$$\Gamma_{\eta_b} = |\cos\alpha|^2\, \Gamma_{\eta_{b0}} + |\sin\alpha|^2\, \Gamma_{A_0^0}$$

A^0 / η_b mixing

$X_d = \cos\theta_A \tan\beta$





Spectroscopic consequences

broader η_b

η_b mass shift

New physics contribution

$\Gamma_{\eta_b} > \Gamma[\eta_b \to 2g]$

Hyperfine splitting m_{Υ}-m_{η_b} unexpectedly large/or small

Searches for η_b states over more than 20 years

No signal found so far!

Entangled both theoretically and experimentally?

Mixing

η_b resonance / A^0 Higgs boson

Petit bourgeois

Enfant terrible

Spectroscopic consequences: quite larger or smaller hyperfine splitting
An unlikely but not impossible situation:

Υ(ns) and η_b(nS) mass levels might be reversed!

Test of lepton universality in Υ leptonic decays

$$R_{\tau/\ell} = \frac{\Gamma_{\Upsilon(nS)\to\gamma\,\tau\tau}}{\Gamma_{\ell\ell}^{(em)}} = \frac{B_{\tau\tau} - B_{\ell\ell}}{B_{\ell\ell}} = \frac{B_{\tau\tau}}{B_{\ell\ell}} - 1$$

Wilczek formula

- Non-resonant decay

Mixing effect

$$R_{\tau/l} = \frac{m_\Upsilon^2 X_d^2}{8\pi\alpha v^2}\left(1 - \frac{m_{A^0}^2}{m_\Upsilon^2}\right) \times \frac{|\cos\alpha|^2\ \Gamma[A^0 \to \tau^+\tau^-]}{|\cos\alpha|^2\ \Gamma_{A_0^0} + |\sin\alpha|^2\ \Gamma_{\eta_{b0}}}$$

- Resonant decay

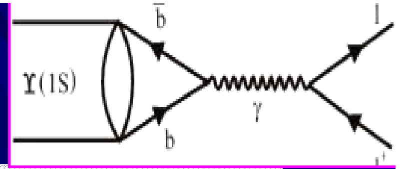
Mixing effect

$$R_{\tau/l} = \frac{B[\Upsilon \to \gamma\eta_b]}{B[\Upsilon \to l^+l^-]} \times \frac{|\sin\alpha|^2\ \Gamma[A^0 \to \tau^+\tau^-]}{|\sin\alpha|^2\ \Gamma_{A_0^0} + |\cos\alpha|^2\ \Gamma_{\eta_{b0}}}$$

$$B(\Upsilon \to \gamma_s \eta_b) = \frac{\Gamma^{M1}_{\Upsilon\to\gamma\eta_b}}{\Gamma_\Upsilon} \cong \frac{1}{\Gamma_\Upsilon} \times \frac{4\alpha I^2 Q_b^{\,2} k^3}{3m_b^2}$$

M1 transition probability

Lepton universality in the SM



$$\mathrm{BF}(\Upsilon \to e^+e^-) = \mathrm{BF}(\Upsilon \to \mu^+\mu^-) = \mathrm{BF}(\Upsilon \to \tau^+\tau^-) \quad \Leftrightarrow \quad \Gamma_{ee} = \Gamma_{\mu\mu} = \Gamma_{\tau\tau}$$

Neglecting phase space and helicity flip effects
Higher-order SM effects are negligible

- Γ_{ll} is an *inclusive* quantity: $\Upsilon \to l^+ l^-$ is accompanied by an infinite number of soft photons

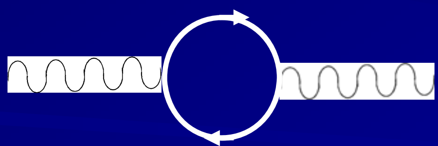
- To order α^3: $\Gamma_{ll} = \Gamma_{ll}^{\,0}\,[1+\delta_{vac}+\delta_{vertex}] \sim \Gamma_{ll}^{\,0}\,[1+\delta_{vac}]$

$3\alpha/4\pi \sim 0.17\%$

Warning!

7.6%

$\delta_{vac} = \delta_{ee} + \delta_{\mu\mu} + \delta_{\tau\tau} + \delta_{quarks}$



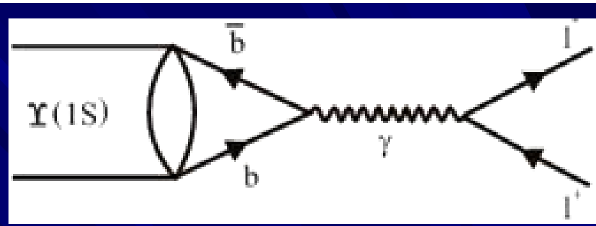
Contribution potentially dangerous for testing lepton universality **if final-state radiation is not properly taken into account in the MC to obtain the detection efficiency** in the analysis of experimental data
Albert et al. Nucl. Phys. B 166 (1980) 460

- Divergencies/singularities free at any order: Bloch and Nordsieck theorem & Kinoshita-Sirlin-Lee-Nauenberg theorem

Testing Lepton Universality

$$\mathrm{BF}(\Upsilon \to e^+e^-) = \mathrm{BF}(\Upsilon \to \mu^+\mu^-) = \mathrm{BF}(\Upsilon \to \tau^+\tau^-)$$

$$\Gamma_{ee} = \Gamma_{\mu\mu} = \Gamma_{\tau\tau}$$



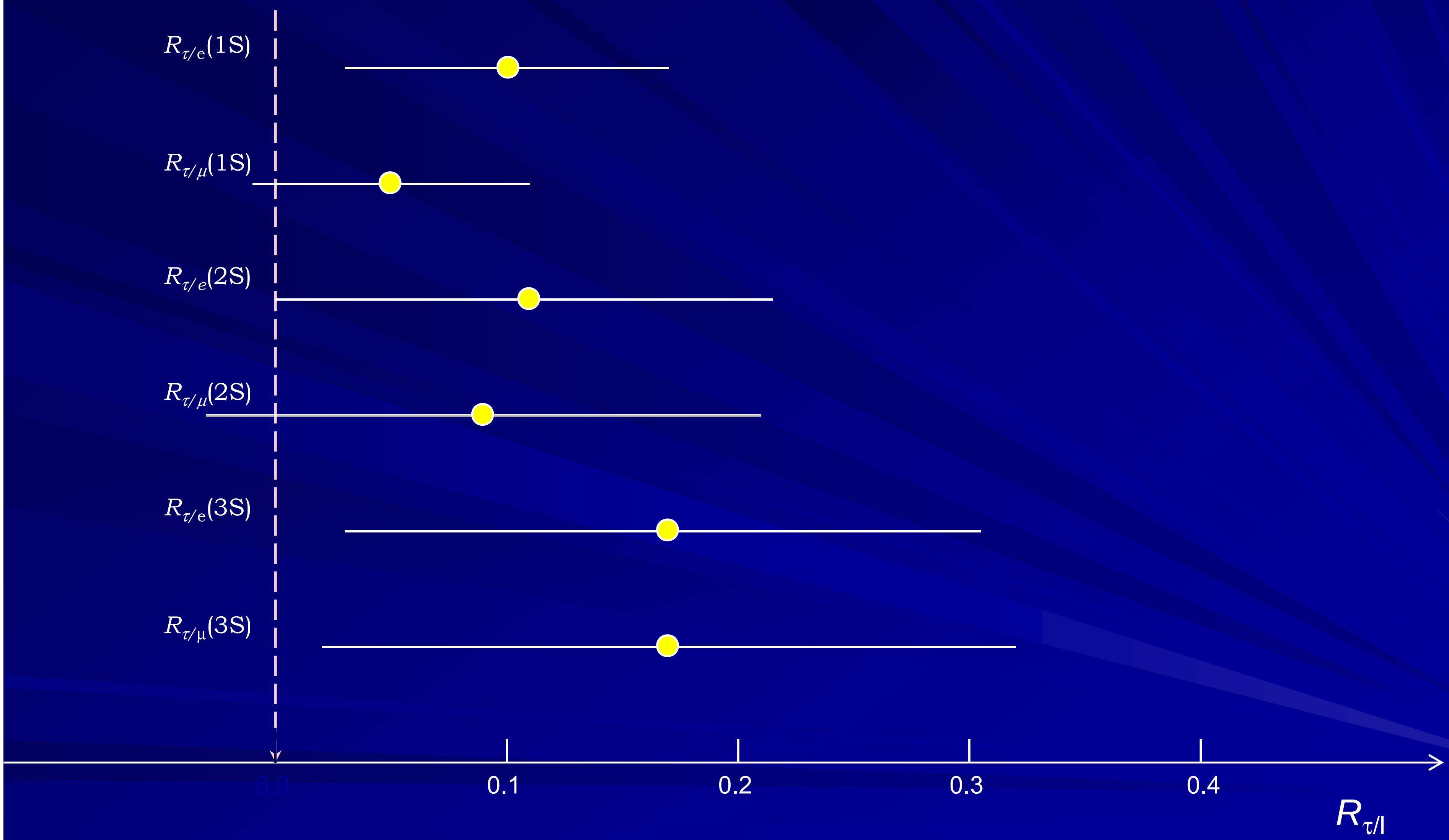
Channel: *	BF[e⁺e⁻]	BF[μ⁺ μ⁻]	BF[τ⁺τ⁻]	$R_{\tau/l}$
ϒ(1S)	2.38 ± 0.11 %		2.61 ± 0.13 %	0.10 ± 0.07
ϒ(1S)		2.48 ± 0.06 %	2.61 ± 0.13 %	0.05 ± 0.06
ϒ(2S)	1.91 ± 0.16 %		2.11 ± 0.15 %	0.11 ± 0.11
ϒ(2S)		1.93 ± 0.17 %	2.11 ± 0.15 %	0.09 ± 0.12
ϒ(3S)	2.18 ± 0.20 %		2.55 ± 0.24 %	0.17 ± 0.14
ϒ(3S)		2.18 ± 0.21 %	2.55 ± 0.24 %	0.17 ± 0.15

Statistical and systematic errors are summed in quadrature

Lepton Universality
in Upsilon decays implies
$\langle R_{\tau/l} \rangle = 0$

$$R_{\tau/\ell} = \frac{\Gamma_{\Upsilon(nS)\to\gamma_s\tau\tau}}{\Gamma_{\ell\ell}^{(em)}} = \frac{B_{\tau\tau} - B_{\ell\ell}}{B_{\ell\ell}} = \frac{B_{\tau\tau}}{B_{\ell\ell}} - 1$$

Lepton Universality Breaking?



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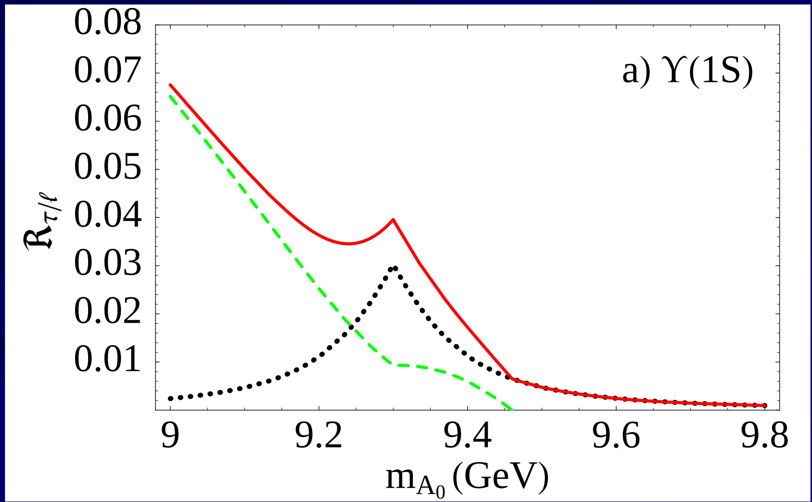
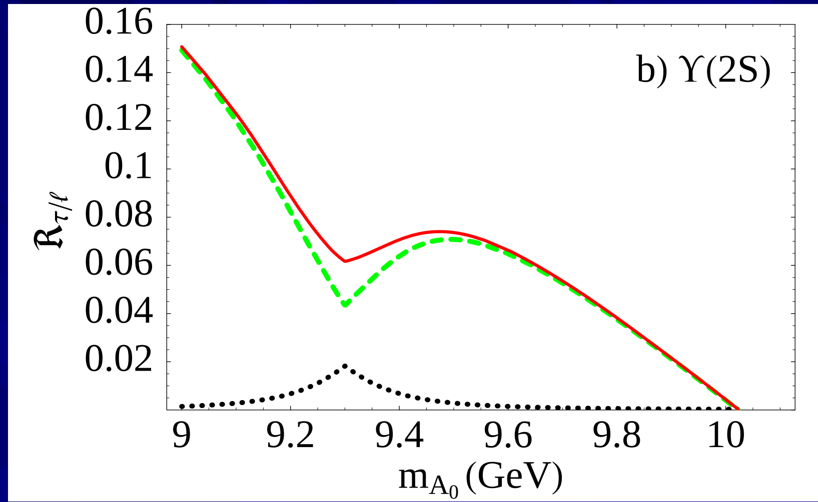
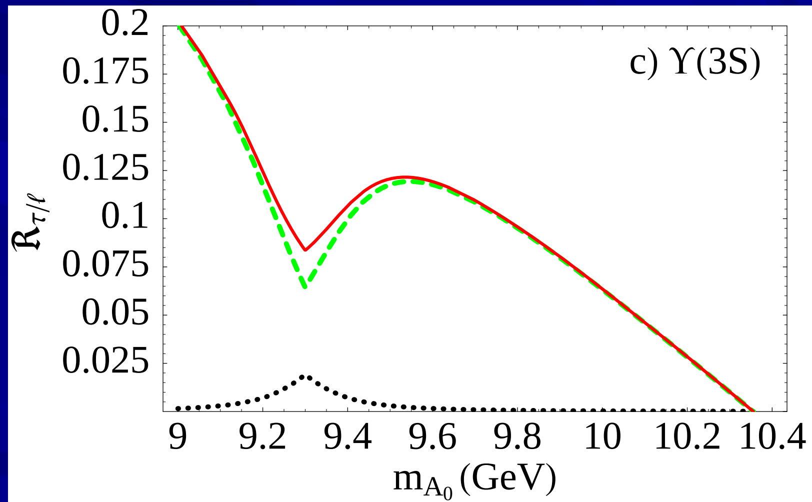
Expected LU breaking

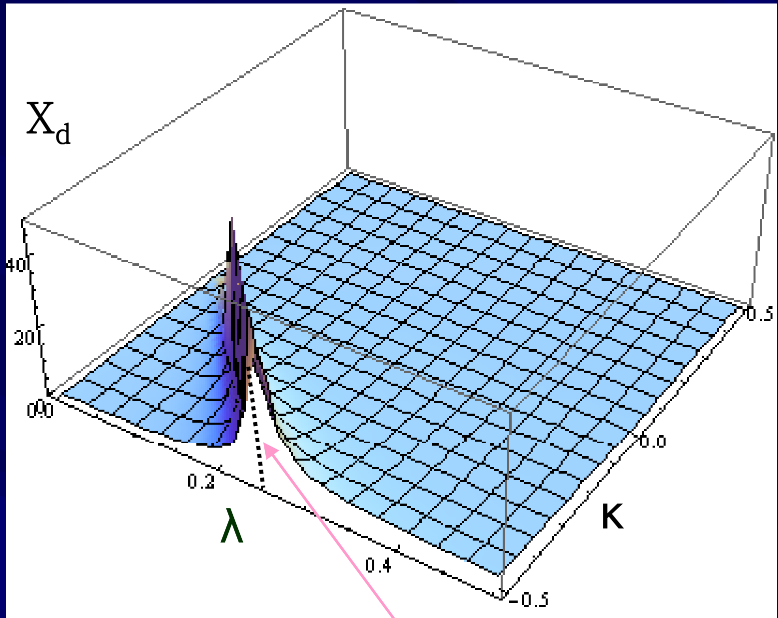


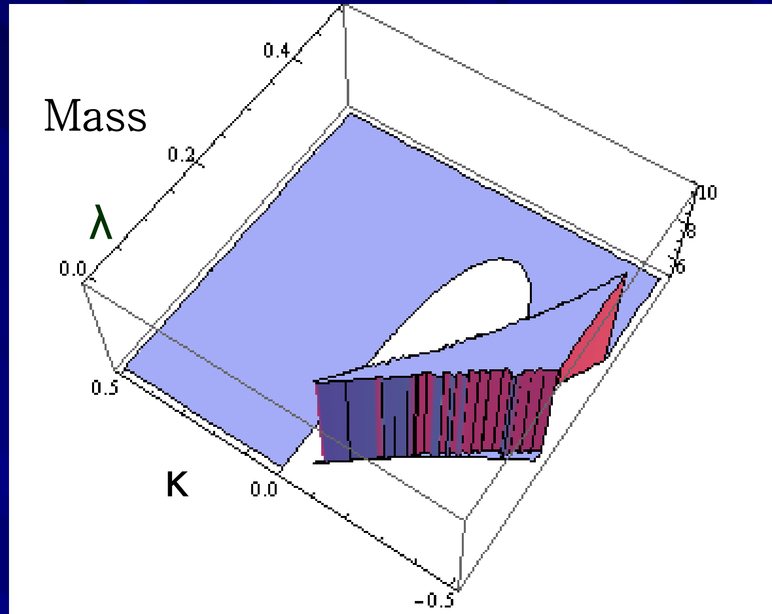


Green line: non-resonant decay
Black line: resonant decay
Red line: sum

X_d=10, $\Gamma_{\eta_{b0}}$ = 5 MeV







A_λ = 200 GeV
μ = 100 GeV
A_κ = -10 GeV
tanβ= 40

$A_\lambda \sim -K\,\mu / \lambda$

$K / \lambda \sim -2$

$0.1 \leq \cos\theta_A \leq 1$

$$\cos\theta_A \cong -\frac{\lambda v(A_\lambda - 2\kappa s)\sin 2\beta}{2\lambda s(A_\lambda + \kappa s) + 3\kappa A_\kappa s \sin 2\beta}$$

$$m_{A_1}{}^2 \cong 3s\left(\frac{3\lambda A_\lambda \cos^2\theta_A}{3\sin 2\beta} - 2\kappa A_\kappa \sin^2\theta_A\right)$$

Proposal of testing lepton universality (to the percent level) @ a (Super) B factory

hep-ph/0610046

- With the machine sitting on the $\Upsilon(3S)$

Final state & BF

$\Upsilon(3S) \to \pi^+\pi^- \Upsilon(1S,2S) \to \mu^+ \mu^-$
BF ~ 2-4 x 10^{-2} BF ~ 2 x 10^{-2}

$\pi^+\pi^-\mu^+\mu^-$
BF ~ 4 - 8 x 10^{-4}

$\Upsilon(3S) \to \pi^+\pi^- \Upsilon(1S,2S) \to \tau^+\tau^-$
BF ~ 10^{-1} $\tau^+\tau^- \to l^+ l^- X$, $l = e, \mu$

$\pi^+\pi^- l^+ l^-$
BF ~ 5 - 10 x 10^{-5}

Compare rates

- $\Upsilon(3S) \to \mu^+\mu^-$
BF ~ 2 x 10^{-2}

$\mu^+\mu^-$
BF ~ 2 x 10^{-2}

$\Upsilon(3S) \to \tau^+\tau^-$
$\to l^+ l^- X$, $l = e, \mu$

$l^+ l^- X$
BF ~ 2 x 10^{-3}

Compare rates

Statistical error ≈ 0.07 / $\sqrt{\# \text{fb}^{-1}}$

Systematic error ≤ 0.037

- With the machine sitting on the $\Upsilon(4S)$

$\Upsilon(4S) \to \pi^+\pi^- \Upsilon(1S,2S) \to \mu^+ \mu^-$
BF ~ 10^{-4} BF ~ 2 x 10^{-2}

$\pi^+\pi^-\mu^+\mu^-$
BF ~ 2 x 10^{-6}

$\Upsilon(4S) \to \pi^+\pi^- \Upsilon(1S,2S) \to \tau^+\tau^-$
BF ~ 10^{-1} $\tau^+\tau^- \to l^+ l^- X$, $l = e, \mu$

$\pi^+\pi^- l^+ l^- X$
BF ~ 2 x 10^{-7}

Compare rates

Summary

What if...

there exists a light Higgs-like particle about 10 GeV?

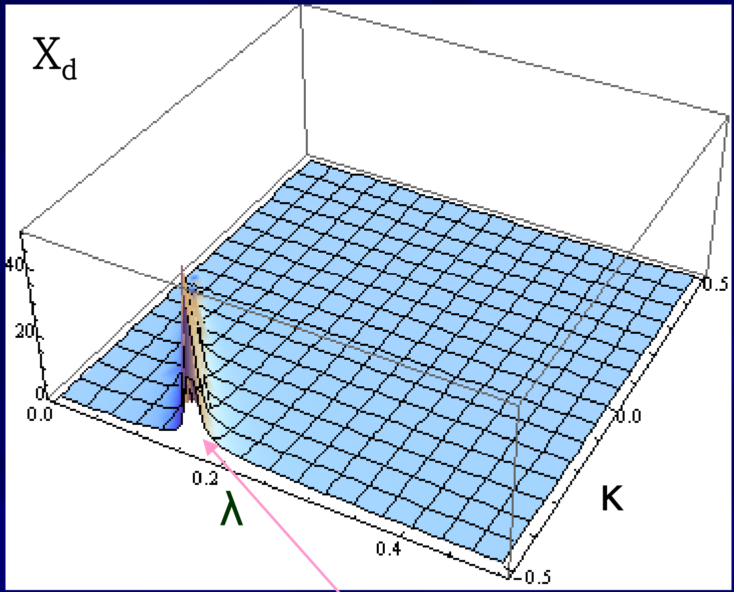
Man (Person) who waits that a roast duck flies directly to his (her) mouth has to wait for a very long time ... (Confucius)

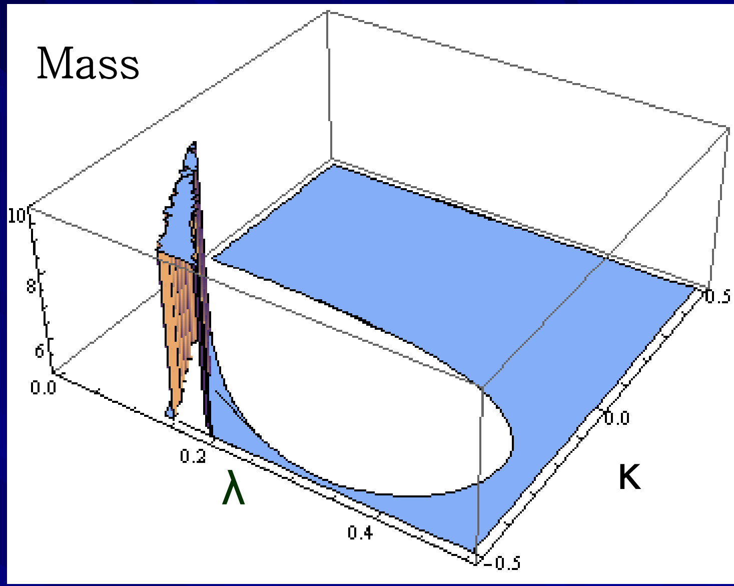
- A high luminosity B factory is the ideal place to discover/study it

  decay into $\tau^+ \tau^-$ (γ): Lepton universality test, direct searches, distortion of bottomonium spectroscopy/decays …

- Complementary/Implications to LHC/ILC searches!
  - Related topics: muon g-2 anomaly, dark matter searches

Back up





A_λ = 450 GeV
μ = 150 GeV
A_κ = -10 GeV
tanβ= 40

$A_\lambda \sim - K\,\mu / \lambda$

$K / \lambda \sim -3$

$\cos\theta_A \geq 0.1$

$$\cos\theta_A \cong -\frac{\lambda v (A_\lambda - 2\kappa s)\sin 2\beta}{2\lambda s(A_\lambda + \kappa s) + 3\kappa A_\kappa s \sin 2\beta}$$

$$m_{A_1}{}^2 \cong 3s\left(\frac{3\lambda A_\lambda \cos^2\theta_A}{3\sin 2\beta} - 2\kappa A_\kappa \sin^2\theta_A\right)$$