Searching for a light Higgs boson in Upsilon radiative decays

Subtitle: *It's now or never*

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Two-Higgs Doublet Model (II)

MSSM

Higgs sector

$$\hat{H}_{SM} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \rightarrow \hat{H}_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix},\ \hat{H}_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}$$

Physical Higgs bosons: (five)

1 neutral CP-odd Higgs bosons (A^0)

2 neutral CP-even Higgs bosons (h^0 H^0)

2 charged Higgs bosons ($H^{\pm}$)

Coupling of fermions and the CP-odd Higgs A^0

In a 2HDM of type II

Enhancement

$$L_{\rm int}^{f\bar{f}} = \tan\beta \frac{m_f}{v} A^0\, \bar{d}\,(i\gamma_5)\,d\ ,\ d = d,\ s,\ b,\ e,\ \mu,\ \tau$$

Suppresion

$$L_{\rm int}^{f\bar{f}} = \cot\beta \frac{m_f}{v} A^0\, \bar{u}\,(i\gamma_5)\,u\ ,\ u = u,\ c,\ t,\ \nu_e,\ \nu_\mu,\ \nu_\tau$$

if $\tan\beta > 1$

tanβ stands for the 2 Higgs VEVs ratio $< H_u >/< H_d >$

A **large value of tanβ** implies a **large A^0 coupling to the bottom quark** but a **small coupling** (i.e. small cot β) to the **charm quark**. Therefore, in the quest for NP effects we **will focus on bottomonium** decays and spectroscopy but **not on charmonium:**

$$B(\psi' \rightarrow ee) = (7.41 \pm 0.28)\times 10^{-3} \approx B(\psi' \rightarrow \mu\mu) = (7.3 \pm 0.8)\times 10^{-3} < B(\psi' \rightarrow \tau\tau) = (2.8 \pm 0.7)\times 10^{-3}$$

Next-to-Minimal-Supersymmetric Standard Model (NMSSM)

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

← New gauge-singlet superfield

Physical Higgs bosons: (seven)

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

Higgs sector

Six "free" parameters vs three in the MSSM :

$\kappa \quad \lambda \quad A_\kappa \quad A_\lambda \quad \mu_{eff} \quad \tan\beta$

PQ symmetry or $U(1)_R$ slightly broken

↓

light pseudoscalar Higgs

Non-singlet component   Singlet component

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

$\tan\beta = v_u / v_d$

↓

A_1 coupling to down type fermions $\propto X_d = \cos\theta_A \tan\beta$

Light dark matter?

NMSSM candidate compatible with present bounds:
Light neutralino with a singlet component
Gunion, Hooper, McElrath [hep-ph:0509024]
McElrath [hep-ph/0506151], [arXiv:0712.0016]

Light neutral Higgs scenarios

Susy scale ~ O(100) GeV–O(1) TeV
sets the expected Higgs mass

↓

Protective symmetry?

↓

Light Higgs !

Well-known example:

The photon is massless while W^+, W^- & Z^0
are quite heavy!

Gauge symmetry explains such a mass difference

L & H

Light and heavy Higgs
bosons can live together

A possible (and promising) scenario in the NMSSM

$$m_{A_1} < m_{H_1} < m_{A_2} \approx m_{H_1} \approx m_{H_2} \approx m_{H^+} = m_{H^-}$$

~10 GeV

~100 GeV
SM-like

~300 GeV almost degenerate

Peccei-Quinn & R-symmetries

$$W_{Higgs} = \lambda \hat{S} (\hat{H}_u \hat{H}_d) + \frac{\kappa}{3} \hat{S}^3 \quad \Rightarrow \quad V_{soft} = \lambda A_\lambda S (H_u \circ H_d) + \frac{\kappa}{3} A_\kappa S^3 + h.c.$$

Solves the "μ−problem"

where $\mu_{eff} = \lambda s, \quad s = \langle S \rangle = \mu_{eff} / \lambda$

If $\kappa = 0$ → U(1) Peccei-Quinn symmetry

Spontaneous breaking → NGB (massless), an "axion" (+QCD anomaly): ruled out experimentally

If the **PQ symmetry** is not exact but explicitly broken → provides a mass to the (pseudo) NGB

leading to a **light CP-odd scalar** for small κ

If A_λ and $A_\kappa = 0$ → **$U(1)_R$ symmetry**; but if $U(1)_R$ is slightly broken

→ **light pseudoscalar Higgs too**

CPV MSSM

At one-loop level, MSSM with complex parameters is <u>not CP conserving</u>

The three Higgs neutral bosons mix together and the resulting three physical mass eigenstates:

H_1, H_2 and H_3 ($M_{H1} < M_{H2} < M_{H3}$)

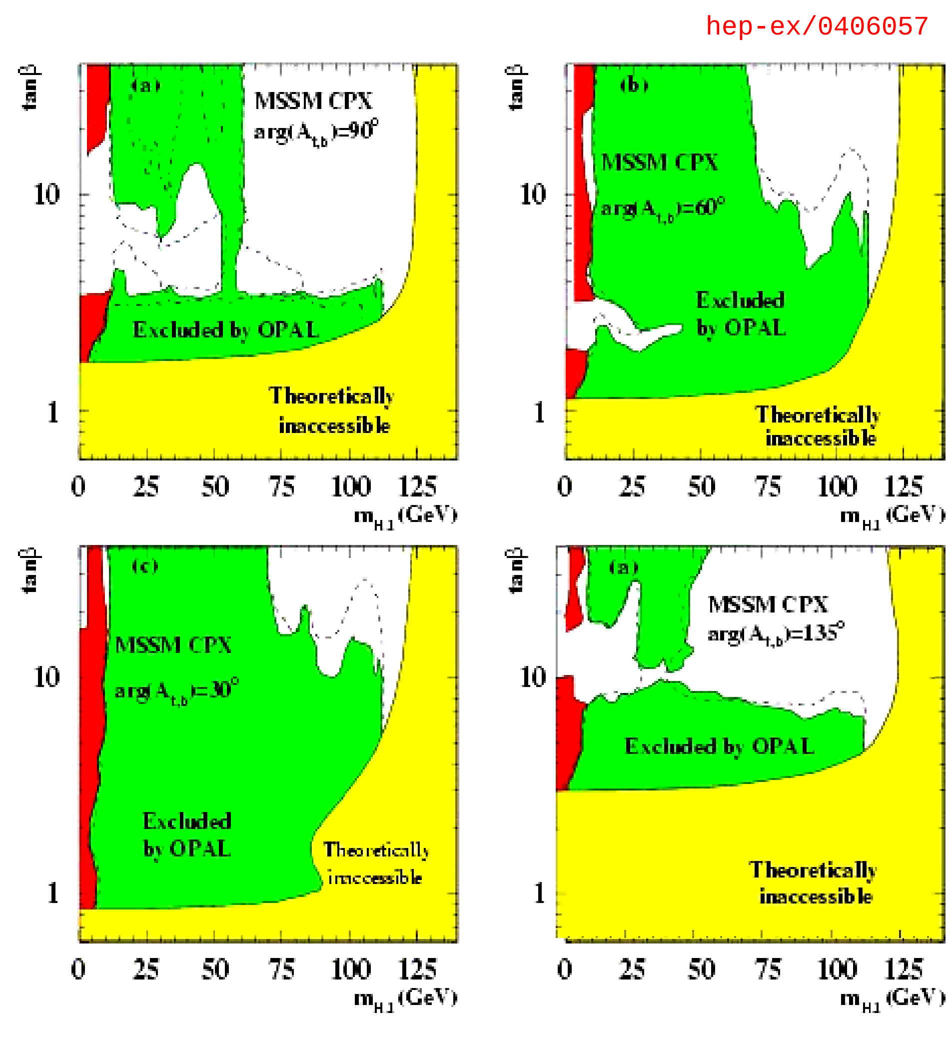
have mixed parities

Higgs couplings to the Z boson would vary:

The H_1ZZ coupling can be significantly suppressed raising the possibility of

a relatively light H_1 boson having evaded detection at LEP [hep-ph/0211467]

Light Higgs windows at LEP (CPV MSSM)



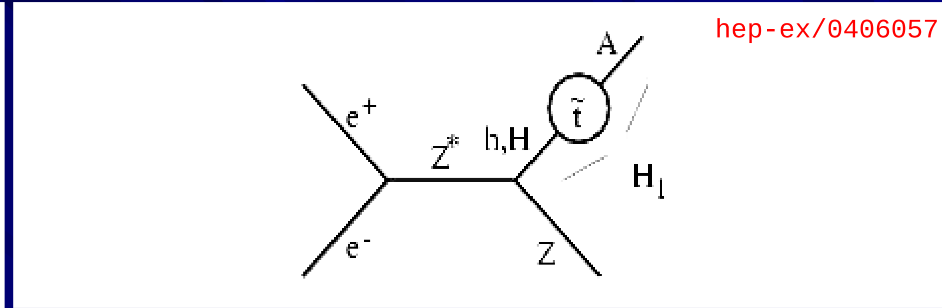
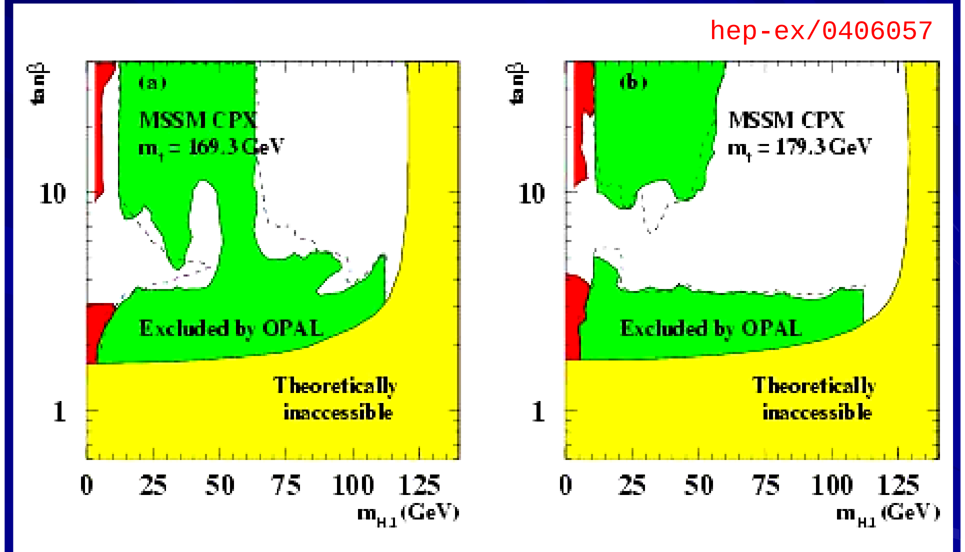


Diagram illustrating the effective coupling of a Higgs mass eigenstate H1 to the Z. Only the CP-even admixture h and H couple to Z while the CP-odd A does not: hence the H_1ZZ coupling is reduced wrt a CPC scenario.



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

What about the NMSSM?

Less constrained by LEP data
and B-physics observables than the **MSSM**
(depending on the singlet component fraction)

↓

Higgs mass values allowed down to several GeV

Dermisek & Gunion, hep-ph/0510322 (LEP limits and low-fine-tuning)

Hiller, hep-ph/0404220
Domingo & Ellwanger, arXiv:0710.3714 } B physics

Similarly for Little Higgs models with an extended structure of global U(1) symmetries broken both spontaneously and explicitly, possibly leading to light pseudoscalar particles in the Higgs spectrum

Kraml et al. hep-ph/0608079

Evading LEP limits from Z h^0 final-state events (where the h^0 decays into b's)

- Interpretation:

SM Higgs with < 114 GeV decaying primarily to b's ruled out

$e^+ e^- \to Z\, h^0$

$\to A_1^0 A_1^0$ (BF ~ 90 %)

$\to \tau^+ \tau^-$

$\to \tau^+ \tau^-$

$\to b\, \bar{b}$

Can be dominant if $2m_\tau < m_{A1} < 2m_b$

Mass of a SM-like Higgs H_1 (h^0) lower than 114 GeV is allowed provided that $m_{A1} < 2m_b$

- Explains the Higgs-like event excess found at $m_{h0} \sim 100$ GeV

Low-fine-tuning required, Dermisek & Gunion arXiv:0705.4387

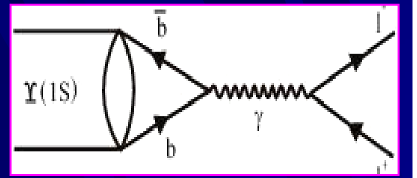
Our Proposal *

Test of Lepton Universality in $\Upsilon(1S,2S,3S)$ decays
to (below) the few percent level
@ a (Super) B factory

Lepton universality in the SM:
Gauge bosons couple to all lepton species
with equal strength

*M.A.S.L. hep-ph/0610042

Leptonic width of Υ resonances



Lowest Feynman diagram

- Γ_{ll} (as presented in the PDG tables) is an *inclusive* quantity:

  $\Upsilon \to l^+ l^-$ is accompanied by an infinite number of soft photons

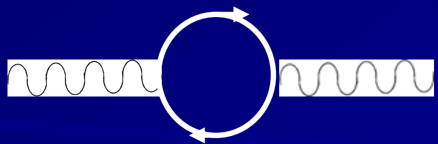
The test of lepton universality can be seen as complementary to searches for a (monochromatic) photon in the $\Upsilon \to \gamma\, \tau\tau$ channel

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

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

7.6%

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



Warning!

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

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

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

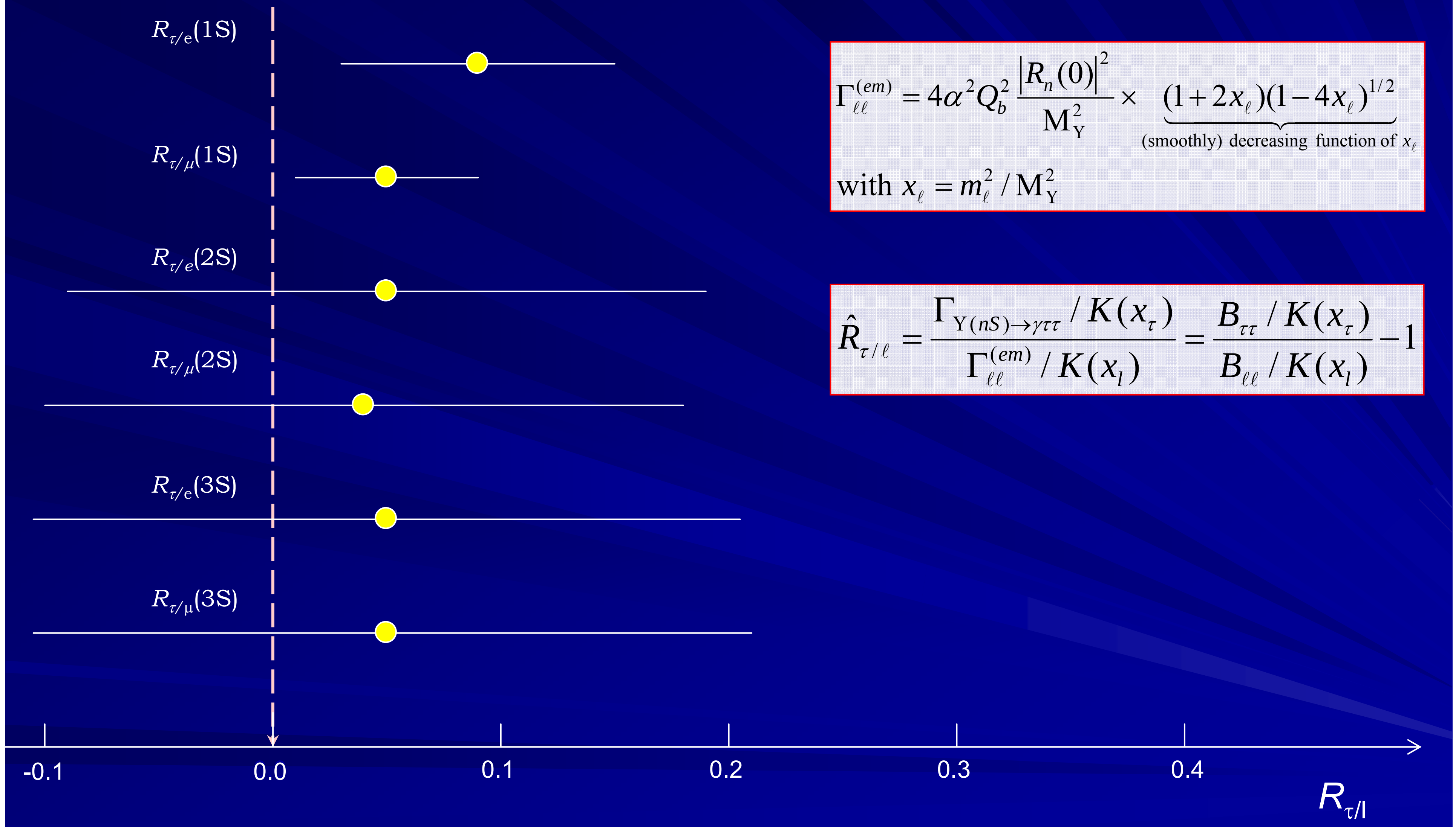
Channel: *	BF[e^+e^-]	BF[$\mu^+\mu^-$]	BF[$\tau^+\tau^-$]	$R_{\tau/l}$
Υ(1S)	2.38 ± 0.11 %		2.60 ± 0.10 %	0.09 ± 0.06
Υ(1S)		2.48 ± 0.05 %	2.60 ± 0.10 %	0.05 ± 0.04
Υ(2S)	1.91 ± 0.16 %		2.00 ± 0.21 %	0.05 ± 0.14
Υ(2S)		1.93 ± 0.17 %	2.00 ± 0.21 %	0.04 ± 0.14
Υ(3S)	2.18 ± 0.20 %		2.29 ± 0.30 %	0.05 ± 0.16
Υ(3S)		2.18 ± 0.21 %	2.29 ± 0.30 %	0.05 ± 0.16

* From PDG '07

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

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

Lepton Universality Breaking?



$$\Gamma_{\ell\ell}^{(em)} = 4\alpha^2 Q_b^2 \frac{|R_n(0)|^2}{M_\Upsilon^2} \times \underbrace{(1+2x_\ell)(1-4x_\ell)^{1/2}}_{\text{(smoothly) decreasing function of } x_\ell}$$

with $x_\ell = m_\ell^2 / M_\Upsilon^2$

$$\hat{R}_{\tau/\ell} = \frac{\Gamma_{\Upsilon(nS)\to\gamma\tau\tau} / K(x_\tau)}{\Gamma_{\ell\ell}^{(em)} / K(x_l)} = \frac{B_{\tau\tau} / K(x_\tau)}{B_{\ell\ell} / K(x_l)} - 1$$

Our conjecture to interpret an *apparent* Lepton Universality breakdown:

photon unseen*

$\Upsilon(nS) \to \gamma\; A^0(\to l^+ l^-)$ n, n' = 1,2,3

$\Upsilon(nS) \to \gamma\; \eta_b^{(*)}(n'S)\; [\to A^{0*} \to l^+ \; l^-]$

$$\Gamma_{\ell\ell}^{(em)} = 4\alpha^2 Q_b^2 \frac{|R_n(0)|^2}{M_\Upsilon^2} \times \underbrace{(1+2x_\ell)(1-4x_\ell)^{1/2}}_{\text{(smoothly) decreasing function of } x_\ell}$$

with $x_\ell = m_\ell^2 / M_\Upsilon^2$

Key ideas:

Experimental

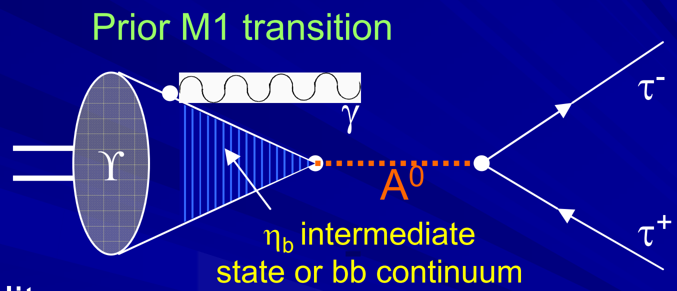
- Such NP contribution would be **unwittingly** ascribed to the leptonic branching fraction (photon undetected*). Actually only for the tauonic decay mode.

Theoretical

- A leptonic mass dependence of the decay width from the A^0 coupling to fermions would break lepton universality. Contributions from SM processes (like Z0 – exchange) should be negligible.

*the photon can be looked for but might be not monochromatic if the intermediate state is broad

Tree-level NP process theoretically very simple!



Prejudice against a light Higgs?

Notice that a light non-standard Higgs boson has **not** been excluded by LEP direct searches for a broad range of model parameters in different scenarios

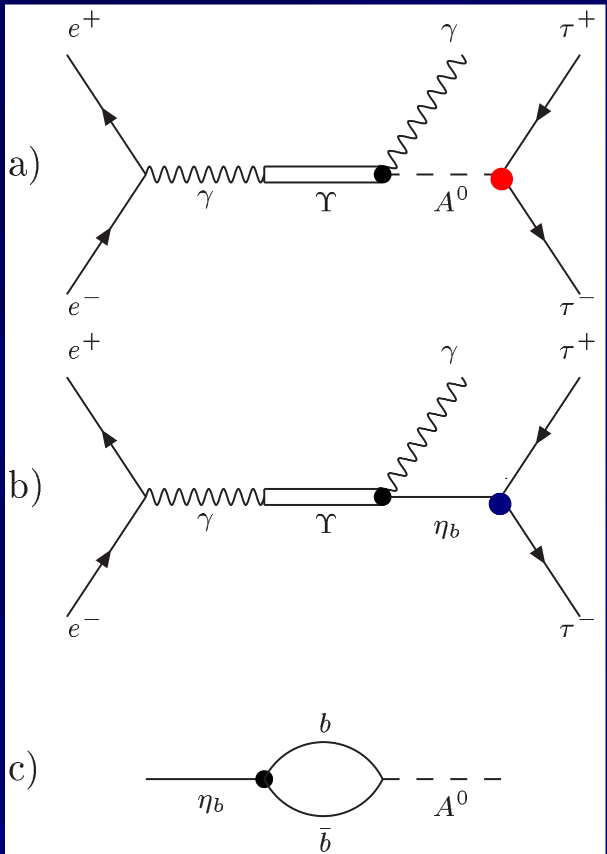
Υ radiative decays into leptons

Mixing formalism*

* Drees and Hikasa, Franzini and Gilman, Fullana and M.A.S.L. [hep-ph/0702190]

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

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



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

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

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

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

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

0 ($g_{\eta_{bo}\tau\tau}$, $g_{\eta_{b0}\tau\tau}$)

The η_b decays to leptons because of its mixing with the CP-odd Higgs

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

$X_d = \cos\theta_A \tan\beta$ ←

Smaller coupling strength than in the MSSM but still can be larger than in the SM If $X_d > 1$

Resonant and non-resonant decays

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

QCD+binding energy effects small for a pseudoscalar A^0

Polchinski, Sharpe and Barnes
Pantaleone, Peskin and Tye
Nason

Leading-order 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

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

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

M1 transition probability

In the limit of small mixing, one recovers the leading-order perturbative expression

Small mixing-angle limit

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

small

$$\Gamma(\eta_b \to \ell^+\ell^-) = \frac{3m_b^4 m_\ell^2 (1-4x_\ell)^{1/2} |R_n(0)|^2 \tan^4\beta}{2\pi^2 (M_{\eta_b}^2 - M_{A^0}^2)^2 v^4}$$

← Perturbative calculation

M.A.S.L. hep-ph/0307313

$$B(\Upsilon \to \gamma_s \ell^+\ell^-) \cong B(\Upsilon \to \gamma_s \eta_b) \times B(\eta_b \to \ell^+\ell^-)$$

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

↓ dividing by B_{ll}

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

→

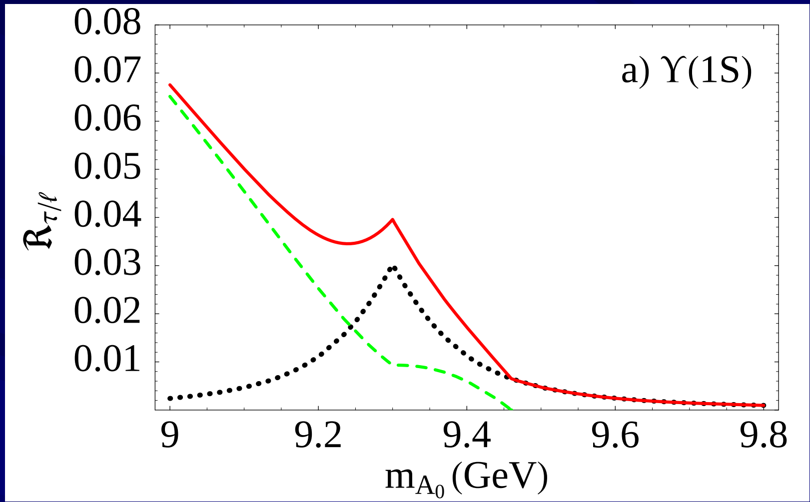
$$R_{\tau/\ell} \approx \frac{m_b^2 \tan^4\beta\, k^3}{8\pi^2 \alpha (1+2x_\tau) \Gamma_{\eta_b} v^4} \times \frac{m_\tau^2}{\Delta M^2}$$

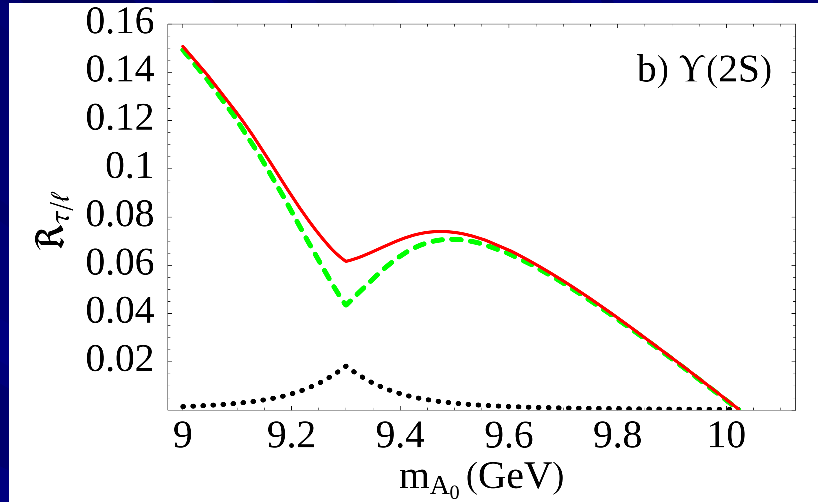
Mixing calculation

Agreement! as it should

$$\Delta M = |M_{A^0} - M_{\eta_b}|$$

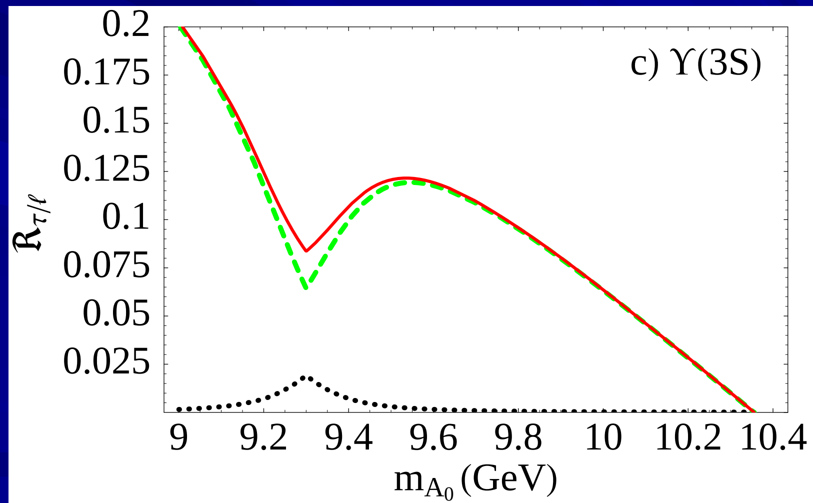
Expected LU breaking





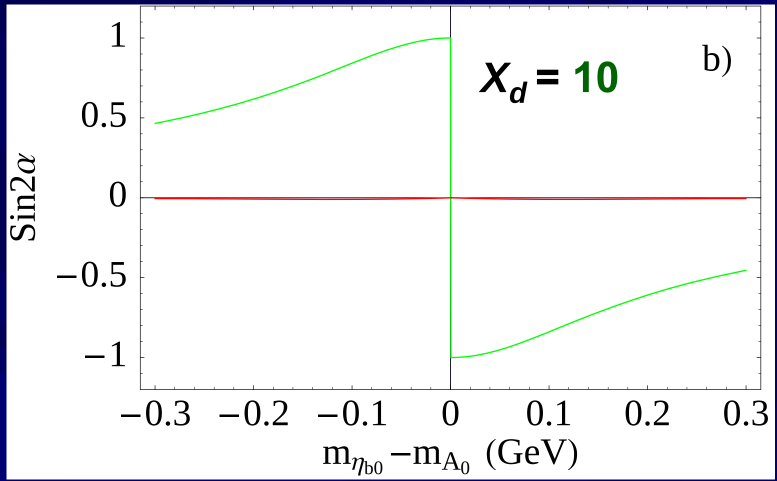
Green line: non-resonant decay
Black line: resonant decay
Red line: sum

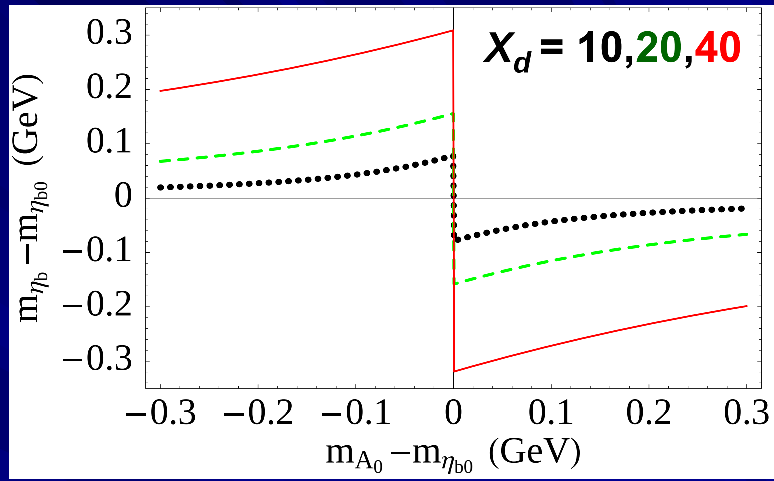
X_d=10, $\Gamma_{\eta_{b0}}$ = 5 MeV



Possible spectroscopic consequences

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





η_b / A^0 mixing

broader η_b ?

η_b mass shift ?

due to the new physics contribution

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

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

Searches of η_b states for over more than 30 years

No signal found so far!

"Is there any point to which you would wish to draw my attention?"
"To the curious incident of the dog in the night-time"
"The dog did nothing in the night-time"
"That was the curious incident", remarked Sherlock Holmes
from "Silver Blaze" by Sir A.C.D.

Mixing

η_b *resonance* / A^0 Higgs boson

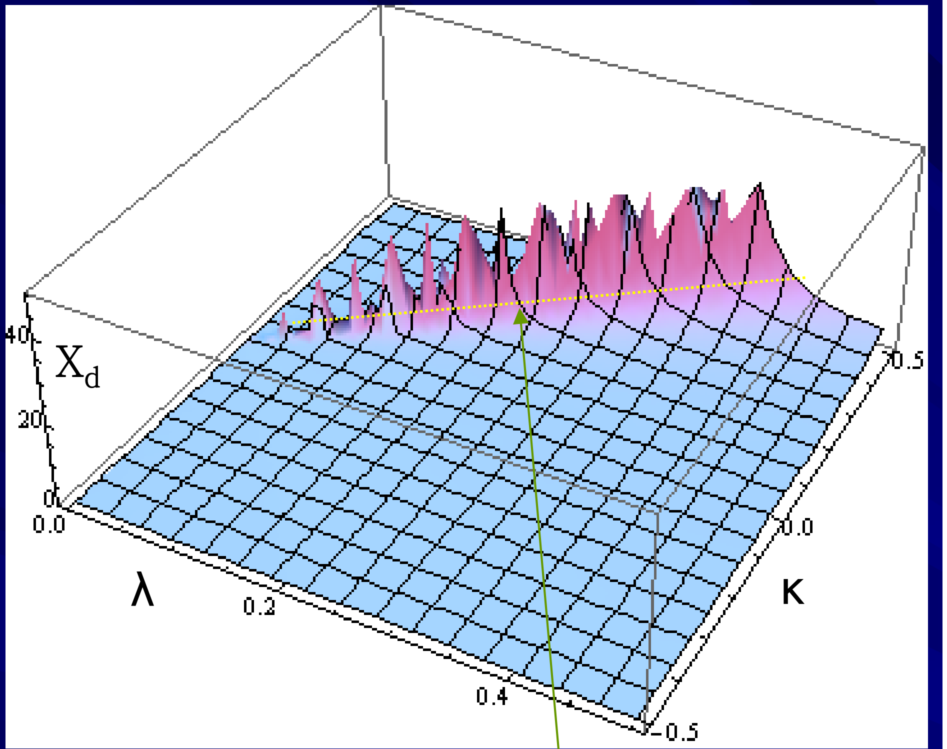
Petit bourgeois

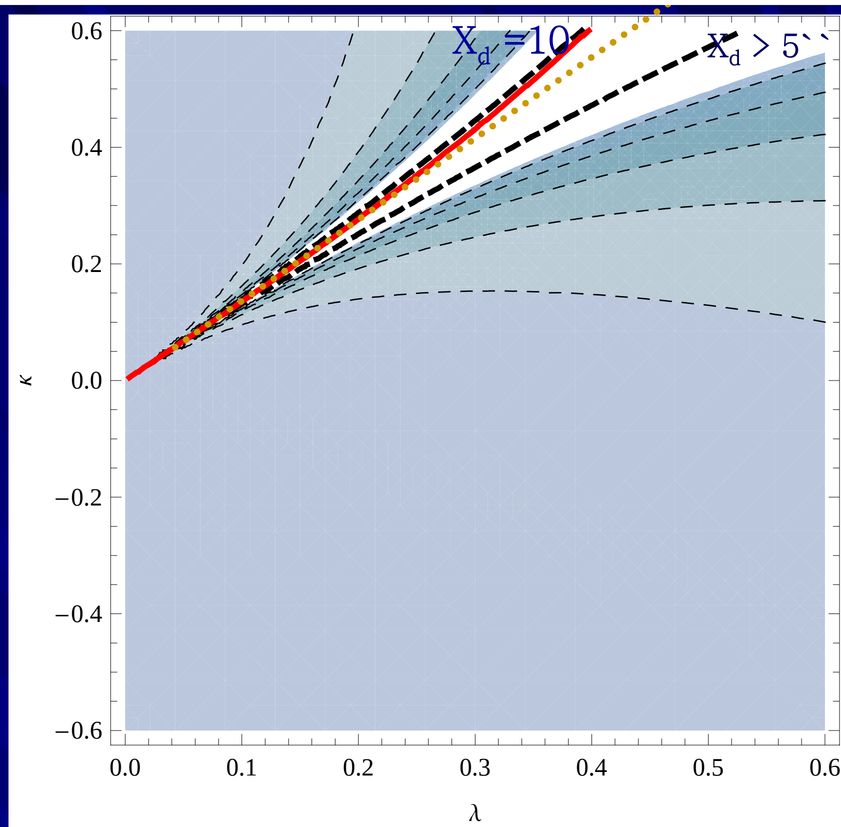
Enfant terrible

A close look at a region of NMSSM parameter space

focusing on

allowed light Higgs bosons with
non-negligible couplings to down-type fermions
but evading all experimental bounds





A_λ = -200 GeV
A_κ = -15 GeV
μ = 150 GeV
tan β= 40

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

$K - (4/3)\,\lambda = 0$

$0.1 \leq |\cos\theta_A| \leq 0.5$

tanβ ~ 1/ [A_λ+ K μ / λ]
Ananthanarayan & Pandita, hep-ph/9601372

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

$$\cos\theta_A = \frac{c_0}{1+\varepsilon\tan\beta}, \quad c_0 = -\lambda\frac{v}{A_\kappa}, \quad \varepsilon = \frac{2\lambda(A_\lambda + \kappa s)}{3\kappa A_\kappa}$$

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

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

M_{A_2}= 300 GeV

X_d = 10

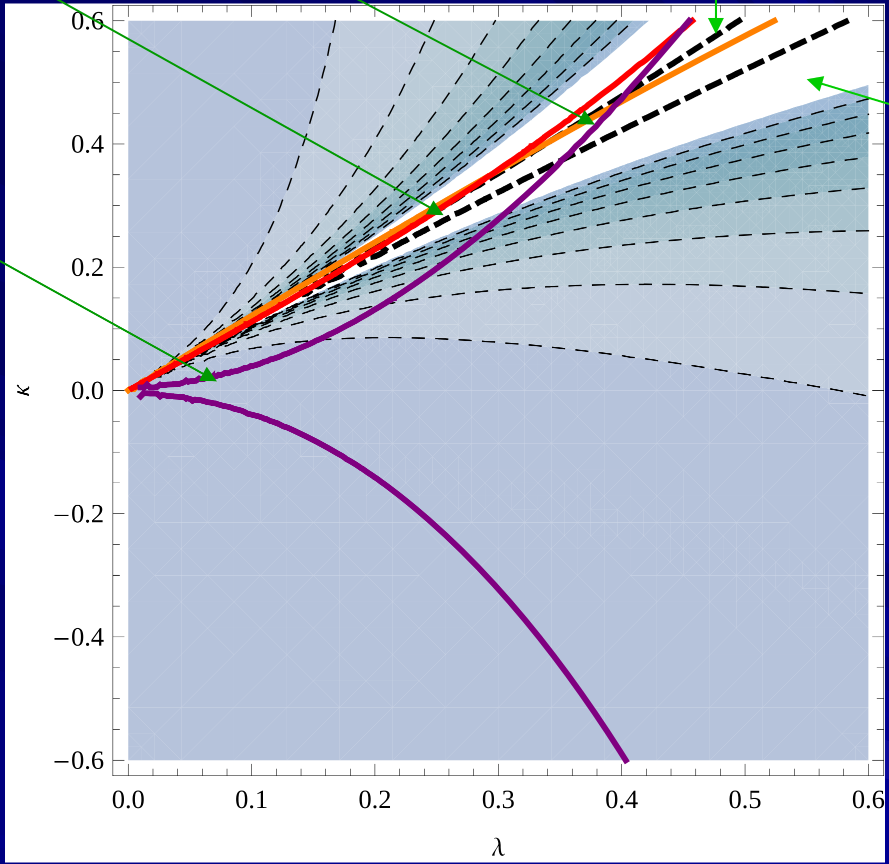
A_λ = -220 GeV
A_κ = -25 GeV
μ = 200 GeV
tan β = 20

M_{A_1}= 9 GeV

M_{H_1} =98 GeV

X_d > 5

X_d = cosθ$_A$ tanβ



No Lep/B-physics constraints imposed

"Avvocato del diavolo"
Devil's Advocate

If there exists such a light Higgs boson…

why it has not been observed yet?

Present experimental bounds for a light
(~ 10 GeV) non-standard Higgs boson*
coming from

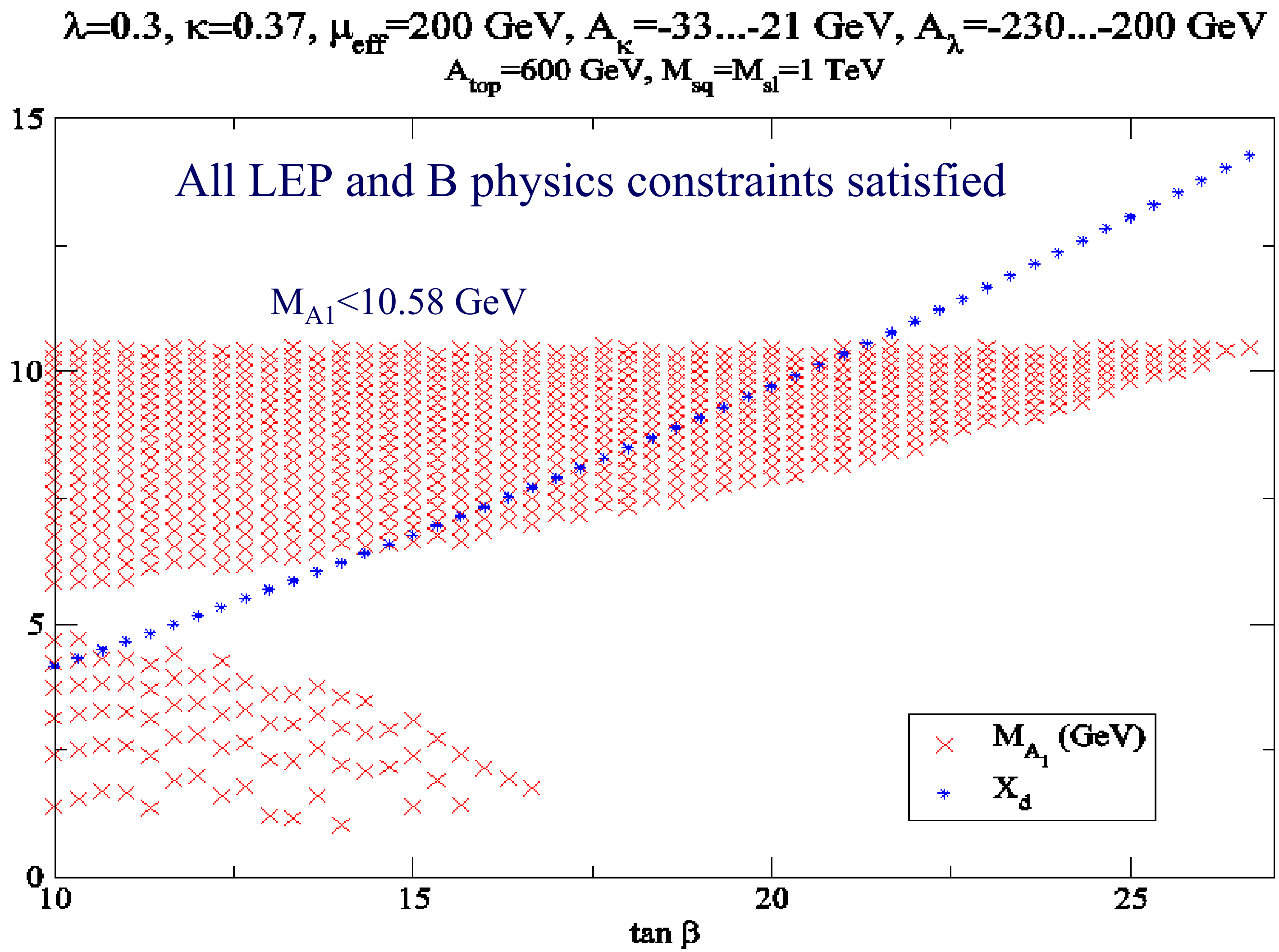
LEP (e.g. final state Z^0 + 4b)

B physics (e.g. $B_s \to \mu^+ \mu^-$)

Cosmology (e.g. dark matter relic abundance)

*Quite common prejudice: light Higgses were ruled out by LEP
(only true in the CPC MSSM)

Plot of M_{A1} & X_d versus tanβ using NMHDECAY scan*



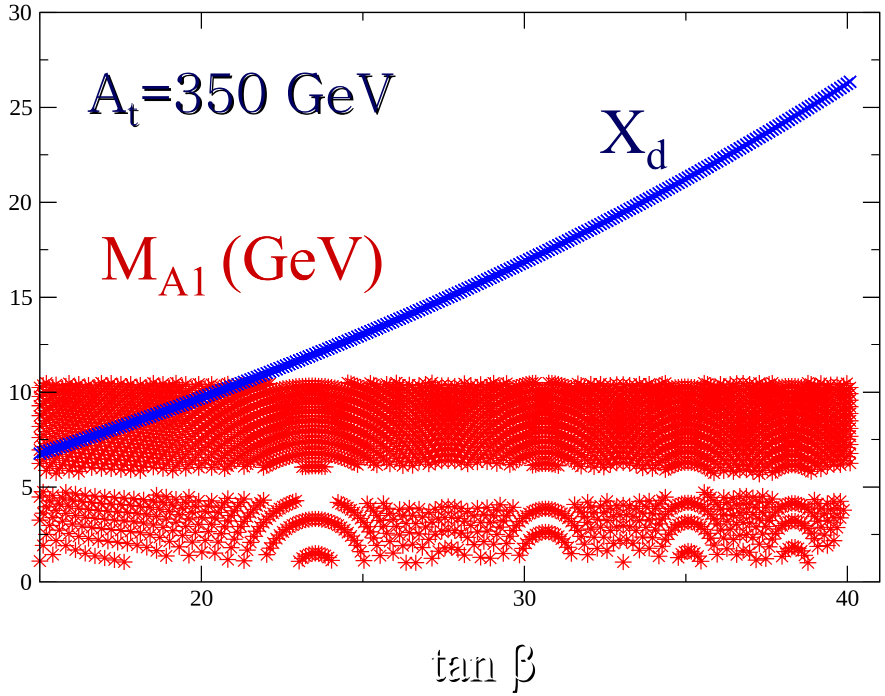
*Special thanks to U.Ellwanger

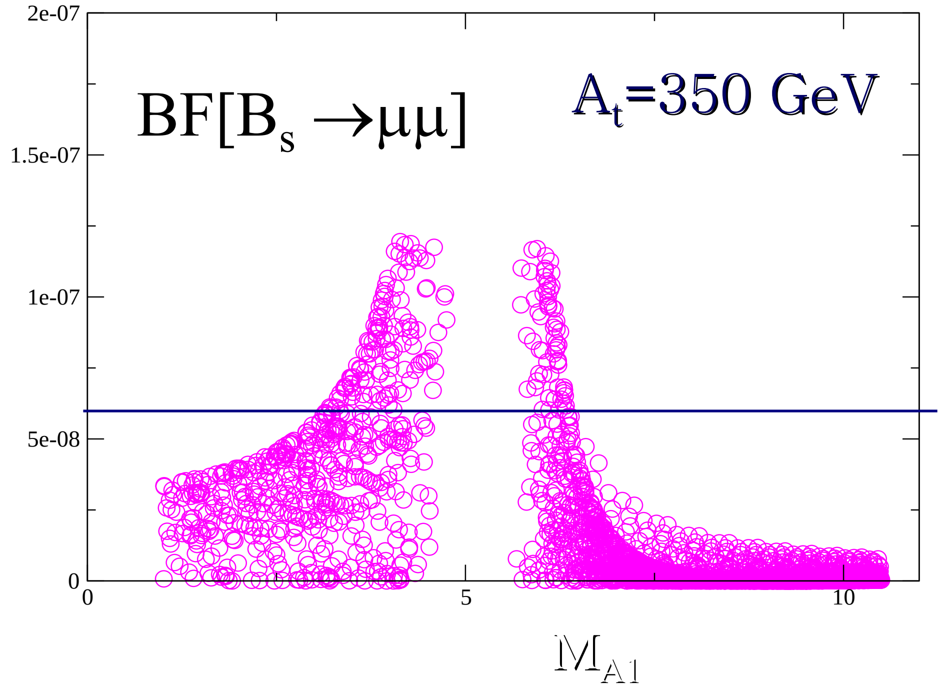
$B_s \to \mu^+ \mu^-$

- Current limit BF $[B_s \to \mu^+ \mu^-] < 5.8\ 10^{-8}$

$\cos^2 \Theta_A$ in the NMSSM

- BF $[B_s \to \mu^+ \mu^-] \sim (\mu A_t/\tilde{m}_t)^2$ $\tan^6\beta / M_A^4$





In several NMSSM parameter regions (mainly at moderate λA_λ and small κA_κ) it may happen at the same time:

- Large $\tan\beta$ (for $A_\lambda + \kappa s \approx 0$)
- $0.1 \leq |\cos\theta_A| \leq 0.5$ (A^0 mainly singlet but not completely)
- $|X_d| = 5 - 25$ for $\tan\beta = 10\text{-}40$
- Low mass (e.g. 10 GeV) of the lightest CP-odd Higgs boson A_1
- $M_A \sim 300$ GeV (not too large mass of the next CP-odd Higgs A_2)
- Low fine-tunning in order to get a SM-like Higgs of mass about 100 GeV decaying into two pseudoscalars, thereby explaining the Z+b-jets event excess at LEP (Dermisek & Gunion, hep-ph/0510322)

Fine tuning or suggestive coincidences !

Conclusions I

What if…

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

- A high luminosity B factory would be the ideal place to discover/study it, e.g. looking at

  - decay into $\tau^+ \tau^- (\gamma)$: Lepton universality test (M.A.S.L., arXiv:0709.3747)

  - direct searches for monochromatic photons

    Dermisek, Gunion and McElrath, hep-ph/0612031

    (also *Mangano and Nason* in $\Upsilon \rightarrow \gamma \mu\mu$ decays, arXiv:0704:1719)

- Closely related topics: B_s decay, muon g-2 anomaly, light dark matter …

Conclusions II

- Perspectives for a Super Flavour Factory

On the physics case

"Pushing the high-energy frontier, i.e. increasing the centre-of-mass energy in order to produce and observe new particles, is not the only way to look for NP. New particles can reveal themeselves through their virtual effects … the name of the game is rather high precision" arXiv:0710.3799

Browder, Ciuchini, Gershon, Hazumi, Hurth, Okada and Stocchi

- However, there could still exist Higgs-like particles whose mass is low enough to be produced (not only virtually) **a**t a Super Flavour Factory

- The seek of these states is complementary/prior to other searches to be performed at LHC/ILC

Back up

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*

$\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S,2S) \rightarrow \mu^+\mu^-$

BF ~ 2-4 x 10^{-2} BF ~ 2 x 10^{-2}

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

$\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S,2S) \rightarrow \tau^+\tau^-$

BF ~ 10^{-1} $\tau^+\tau^- \rightarrow l^+ l^- X$, $l = e, \mu$

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

Compare rates

- $\Upsilon(3S) \rightarrow \mu^+\mu^-$

BF ~ 2 x 10^{-2}

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

$\Upsilon(3S) \rightarrow \tau^+\tau^-$

$\rightarrow l^+ l^- X$, $l = e, \mu$

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

Compare rates

Statistical error ≈ 0.07 / √ # fb^{-1}

Systematic error ≤ 0.037

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

$\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(1S,2S) \rightarrow \mu^+\mu^-$

BF ~ 10^{-4} BF ~ 2 x 10^{-2}

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

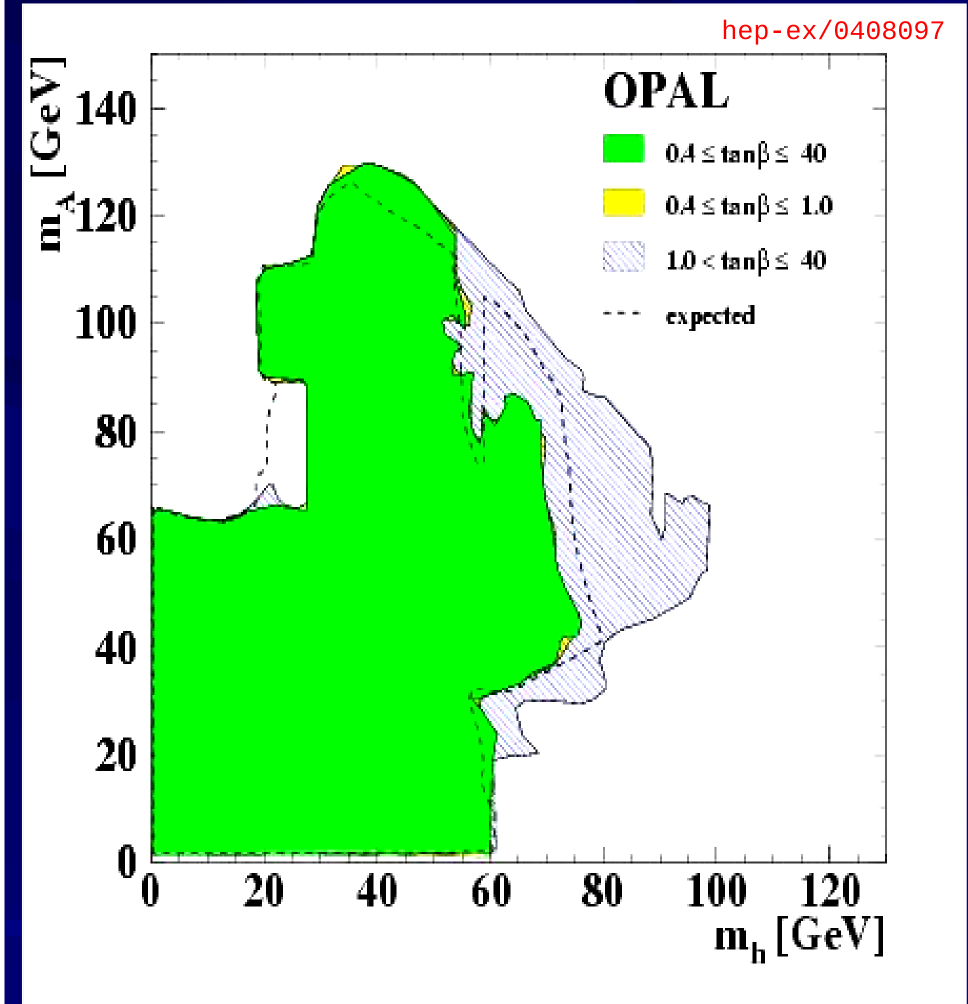
$\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(1S,2S) \rightarrow \tau^+\tau^-$

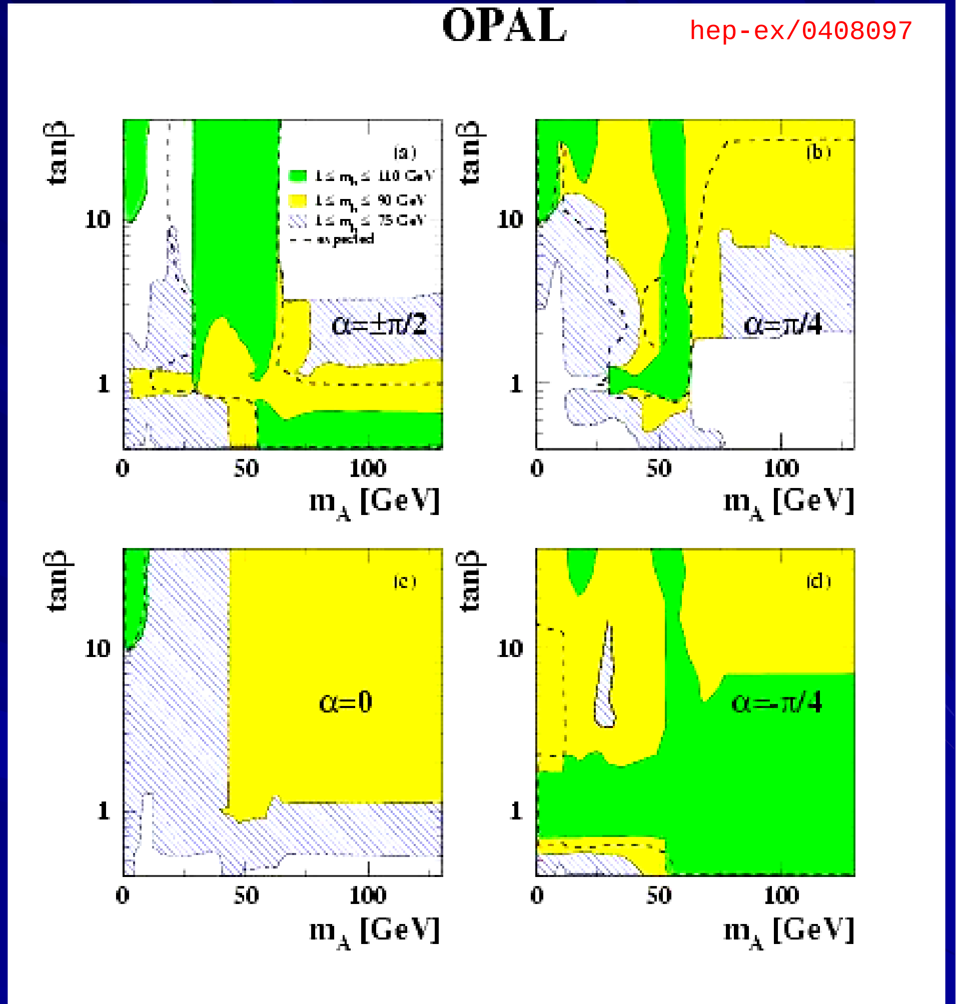
BF ~ 10^{-1} $\tau^+\tau^- \rightarrow l^+ l^- X$, $l = e, \mu$

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

Compare rates

Light Higgs windows at LEP (2HDM(II))



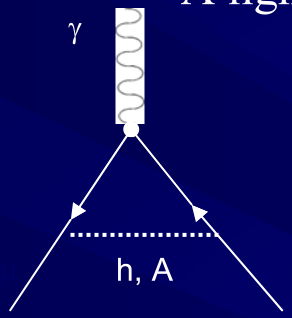


Excluded (m_A,m_h) region independent of the CP even Higgs mixing angle α from flavor-independent and b-tagging searches at LEP interpreted according to a 2HDM(II)

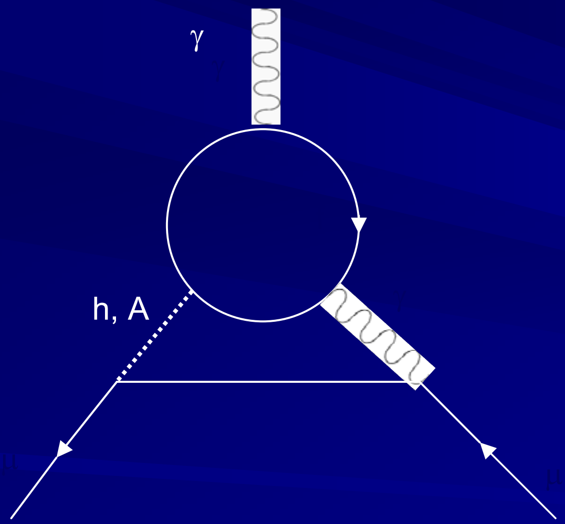
Excluded regions in the $(m_A,\tan\beta)$ plane for different choices of α. In the MSSM $-\pi/2 \le \alpha \le 0$; in a general 2HDM(II) $-\pi/2 \le \alpha \le \pi/2$

g-2 muon anomaly in a 2HDM(II)

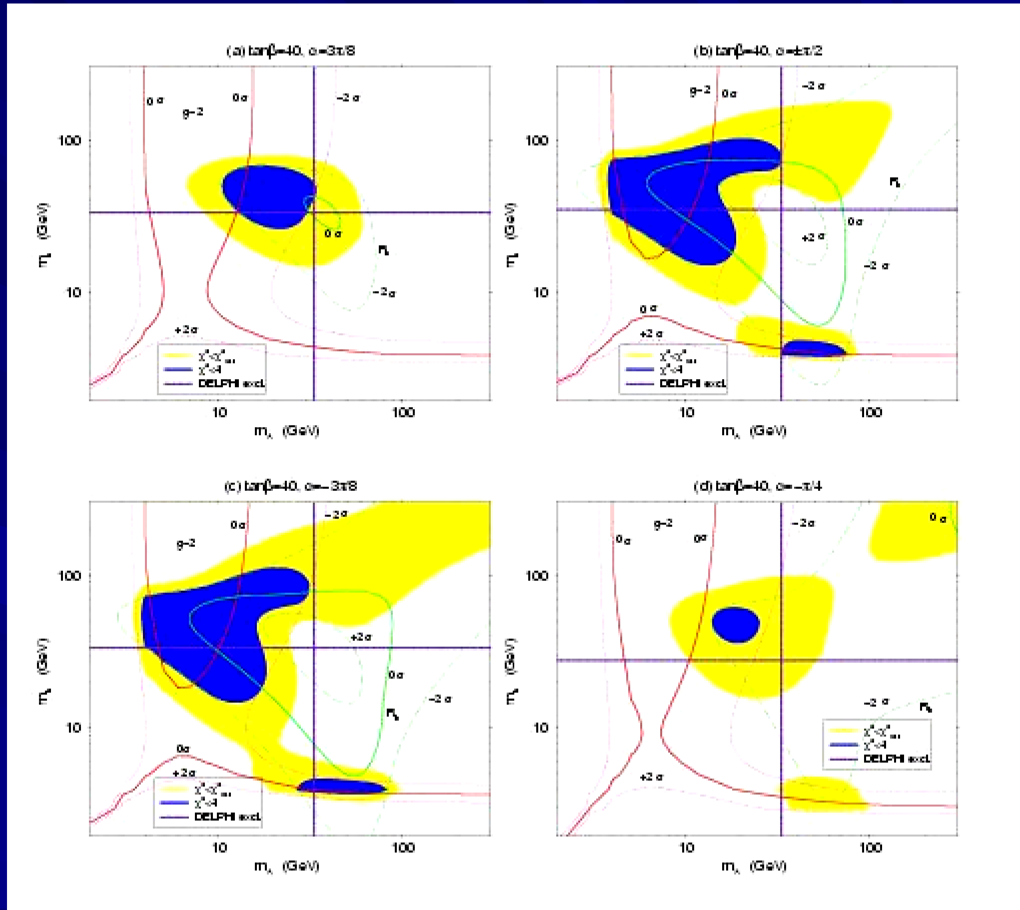
A light pseudoscalar Higgs might be necessary to explain the g-2 anomaly



One.loop vertex correction



Cheung & Kong hep-ph/0302111



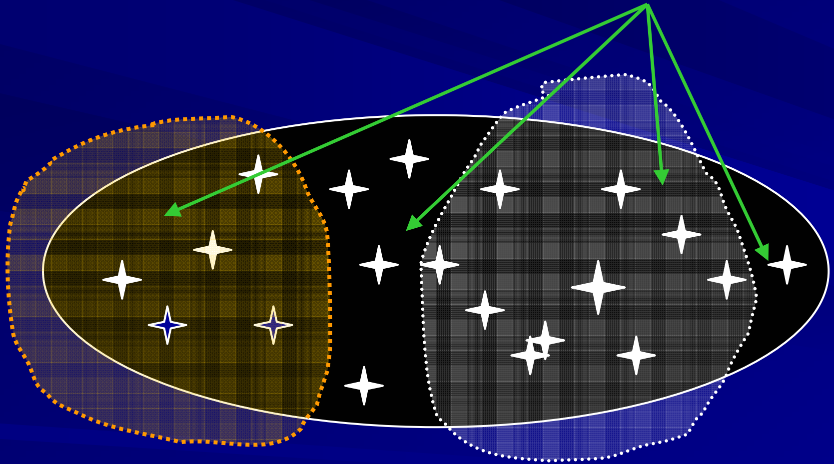
The 2σ allowed regions in the (m_A, m_h) plane due to the constraints of a_μ and R_b for tanβ=40. The blue region is where the total χ^2 is less than 4 while the yellow region is where the total χ^2 is less than the χ^2 (SM)

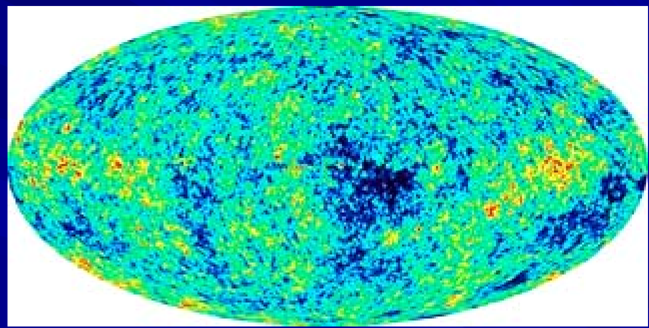
Domain walls

- NMSSM has a Z_3 symmetry implying 3 separate but degenerate vacua

↓

Causally disconnected regions of space could choose different vacuum → Large anisotropies in the cosmic microwave background in contradiction with WMAP





- Non-renormalizable operators breaking Z_3 would lead to a preference for one particular vacuum

Light dark matter relic abundance

- Light dark matter candidate from the NMSSM:

  the lightest neutralino χ^0

- Current abundance of dark matter has to be explained through the annihilation into SM particles.

$$\chi^0\,\chi^0 \rightarrow A^0 \rightarrow f\ f$$

- The annihilation cross section has to be large enough to predict the current neutralino relic density

- Recent limits from CLEO and Belle on invisible decay of quarkonium do not apply to a (pseudo)scalar mediator

$\Upsilon \rightarrow \chi^0\,\chi^0$ requires a vector mediator!

The Higgs sector in the SM

One doublet of two complex fields (four real fields)

$$\hat{H}_{SM} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

Four degrees of freedom

SM Higgs

W^+ W^- Z^0

become massive while

γ remains massless

Spontaneous Symmetry Breaking + Higgs mechanism

$$L_{\text{int}}^{f\bar{f}} = -\frac{m_f}{\text{v}} H^0 \bar{f} f$$

SM Higgs coupling to fermions

$< H^0 > = \text{v} / \sqrt{2}$

v=246 GeV

Conclusions (epilog)

- The search for a light non-standard Higgs and the study of its associated phenomenology is possible at BaBaR with the machine running off the $\Upsilon(4S)$
- Test of lepton universality (at the few percent level) could provide a first glimpse of such new physics
- About 10 fb^{-1} at $\Upsilon(3S)$ would be required to carry out the search for the radiative decays of Υ resonances to leptons mediated by a light A^0
- A Super Flavour Factory would be the ideal place where following uo this investigation with an unprecedented precision

Thanks!