Motto: “waiting for Higgs”

Higgs Physics at Future Colliders

UW - acad. year 2003/2004 (summer sem.: Friday, 14-16,room 118 IPJ)
in collaboration with IPJ, UJ/IFJ-Kraków, UŚ-Katowice, UŁ-Łódź !

- Standard Model
- 2 Higgs Doublet Model and Minimal Supersymmetric Standard Model
- Direct searches
- Precision measurements or indirect searches

- High energy colliders: LEP, TEVATRON, HERA, ...LHC, LC, PLC
- Low energy experiments: g-2...

Motto: “Looking for Higgs -16.10.2004”

Higgs Mechanism in Standard Model and beyond

Maria Krawczyk

- Standard Model
- 2 Higgs Doublet Model and Minimal Supersymmetric Standard Model
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- Precision measurements or indirect searches

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Standard Models

SM = 1HDM ⇒ one Higgs SU(2) doublet

One scalar (spin zero) doublet ϕ

Basic parameter v - vacuum expecation value of scalar field

one Higgs boson

one unknown parameter describing whole sector:

mass or selfcoupling

interaction with gauge bosons: $M_V \sim gv$ (v $\sim$ 246 GeV),

coupling $\sim M_V$

Yukawa interaction with fermions: $m_f \sim g_f$

Direct searches: $M_{H_{SM}}$ larger than 114.4 GeV.

2HDM $\Rightarrow$ two Higgs SU(2) doublets

Two scalar (spin zero) doublets ϕ_1 and ϕ_2
with vacuum exp. values v_1 and v_2

(with $v^2 = v_1^2 + v_2^2$, often we use $\tan\beta = v_2/v_1$)

Counting degrees of freedom: 8 fields - 3 (for long.components of W/Z) = 5

$\Rightarrow$ five physical Higgs bosons, spin 0, 3 -el. neutral, two charged !!

Other charecteristics: quantum numbers - C,P..., however how can we use this property if weak inter. does not respect such symmetries..? Nevertheless we can postulate that in Higgs sector CP symmetry holds.

Number of paramaters? Depends on the form of potential, between 8 to 14 (minus 1 for v-constraint, minus 1 for rephasing)

CP or not CP concervation in Higgs sector

• CP conservation: Higgs sector: h,H,A, $H^{\pm}$; $\tan\beta = v_2/v_1$
parameters: masses $M_h, M_H, M_A, M_{H^{\pm}}$, mixing between (h,H) α + ...
h,H - CP-even, A - CP-odd

• CP violation: mixing between h_1, h_2, h_3, more mixing angles
CP parity of Higgs bosons - not defined

more on 2HDM

Interaction with gauge bosons and fermions- Higgs bosons share obligations

$$(g_W^h)^2 + (g_W^H)^2 + (g_W^A)^2 = (g_W^{H_{SM}})^2$$

Various models of Yukawa interaction with fermions:
eg Model II where one scalar doublet couples to up-type quarks, other to down-type quarks and charged leptons
The potential problems:
•Flavour Changing Neutral Current may be large (in nature FCNC small)

•CP-violation may be large (in nature - small effects)

C transf.: $\phi \to exp(i\theta)\phi^*$ (θ arbitrary, put zero)
complex fields and parameters - may signal violation of C (CP)

(for spin 0 particles C conservation is equiavalent to CP conserv., when fermions are included P parity matters)

MSSM=2HDM(II) in Higgs sector

Higgs sector of MS-SM has structure of 2HDM (II)!
in addition there are supersymmetric relations between parameters, eg λ and g
In MSSM: CP conservation, number of independent parameters at tree level:2
In more general case all couplings treated as effective ones like in 2HDM(II) ...

2HDM models without and with CP violation

I. Ginzburg, M. Krawczyk, P. Osland

2HDM Potential: quartic and quadratic terms separated:

$$V = \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 \\ + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\ + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] \\ + \left\{\left[\lambda_6(\phi_1^\dagger\phi_1) + \lambda_7(\phi_2^\dagger\phi_2)\right](\phi_1^\dagger\phi_2) + \text{h.c.}\right\} \\ - \frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}$$

soft violation of Z_2 symmetry

No (ϕ_1, ϕ_2) mixing if Z_2 symmetry satisfied:
$\phi_1 \to -\phi_1$, $\phi_2 \to \phi_2$ (or vice versa) $\Rightarrow \lambda_6 = \lambda_7 = m_{12}^2 = 0$

14 parameters: $\lambda_1, \lambda_2, \lambda_3, \lambda_4$, $\lambda_5, \lambda_6, \lambda_7$, m_{11}^2, m_{22}^2, Re m_{12}^2,Im m_{12}^2

Hard violation of Z_2 symmetry: quartic terms with λ_6, λ_7 (below =0)

Lee, Diaz-Cruz, Mendez, Haber, Pomarol, Barroso, Santos, Hollik, Djouadi, Illana, Branco,Gunion, Akeroyd, Arhrib,...

Minimum (vacuum) at:

$$\phi_1 = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}} v_1 \end{bmatrix} \phi_2 = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}} v_2 \, e^{i\xi} \end{bmatrix}$$

Note, that

$$m_{12}^2 = [\mu^2/v^2 + i\,\mathrm{Im}(\lambda_5 e^{2i\xi})] v_1 v_2 e^{-i\xi},$$

so

$$\mu = \mathrm{Re}\,(m_{12}) v_1 v_2 / v^2$$

$$\boxed{\mathrm{Im}(m_{12}^2 e^{i\xi}) = \mathrm{Im}(\lambda_5 e^{2i\xi}) v_1 v_2}$$

Naive conclusion: phase ξ violates CP (“complex” fermion masses)

However (eg. Branco), phase ξ can be removed by suitable redefinitions of phases of Higgs fields $\phi_{1,2}$, λ_5 and m_{12}^2:

$$\phi_{1,2} \to \phi_{1,2}\, e^{-i\rho_{1,2}},$$
$$\lambda_5 \to \lambda_5\, e^{2i(\rho_2 - \rho_1)}$$
$$m_{12}^2 \to m_{12}^2\, e^{i(\rho_2 - \rho_1)}$$

and the same for fermion fields. So, the ξ disappears ...

Mass terms (CP consv.$\rightarrow$ Im $\lambda_5 = 0$)

For CP-even, CP-odd and charged Higgs sectors: $\rightarrow$ 2 x 2 mass matrices
Masses of pseudoscalar and charged Higgs bosons:

$$M^2_{A^0} = \mu^2 - \lambda_5 v^2, \qquad M^2_{H^\pm} = \mu^2 - \frac{1}{2}(\lambda_4 + \lambda_5)v^2$$

To get large masses we need:

large μ (leading to decoupling) Haber,..

or

large $\lambda_{4,5}$ (non-decoupling)

μ-parameter crucial !

Masses of neutral Higgs bosons

$$M^2_{h,H} = \frac{1}{2}\left[\mathcal{M}_{11} + \mathcal{M}_{22} \mp \sqrt{(\mathcal{M}_{11} - \mathcal{M}_{22})^2 + 4\mathcal{M}^2_{12}}\right]$$
$$\equiv \frac{1}{2}\left[\mathcal{M}_{11} + \mathcal{M}_{22} \mp R\right]$$

Diagonalization gives:

$$\sin 2\alpha = \frac{2\mathcal{M}_{12}}{R}, \qquad \cos 2\alpha = \frac{\mathcal{M}_{11} - \mathcal{M}_{22}}{R}, \mathcal{M}_{11} - \mathcal{M}_{22} = R\cos 2\alpha$$

$$M^2_H + M^2_h = \mathcal{M}_{11} + \mathcal{M}_{22} = \frac{1}{2}\mu^2 + \lambda_1 v_1^2 + \lambda_2 v_2^2 \qquad (1)$$
$$M^2_H - M^2_h = R = \frac{2\mathcal{M}_{12}}{\sin 2\alpha} = \frac{\sin 2\beta}{\sin 2\alpha}(\lambda_{345} v^2 - \mu^2)$$
$$\mathcal{M}_{11} - \mathcal{M}_{22} = R\cos 2\alpha$$

λ_i in terms of masses, μ^2 etc.

Solving:

$$\lambda_1 v^2 = \frac{1}{\cos^2\beta}\{M_H^2 \cos^2\alpha + M_h^2 \sin^2\alpha\} - \mu^2 \tan^2\beta$$
$$\lambda_2 v^2 = \frac{1}{\sin^2\beta}\{M_H^2 \sin^2\alpha + M_h^2 \cos^2\alpha\} - \mu^2 \cot^2\beta$$

Remaining λ_i:

$$\lambda_5 = \frac{1}{v^2}[-M_{A^0}^2 + \mu^2]$$
$$\lambda_4 = \frac{1}{v^2}[M_{A^0}^2 - 2M_{H^\pm}^2 + \mu^2]$$
$$\lambda_3 = \frac{1}{v^2}\left[2M_{H^\pm}^2 + \frac{\sin 2\alpha}{\sin 2\beta}(M_H^2 - M_h^2) - \mu^2\right]$$

CP violation: Im $\lambda_5 \neq 0$

All three neutral Higgs states mix

$$M = v^2 \begin{pmatrix} \lambda_1 c_\beta^2 + \nu s_\beta^2 & (\lambda_{345} - \nu) c_\beta s_\beta & -\frac{1}{2}\mathrm{Im}\,\lambda_5\, s_\beta \\ (\lambda_{345} - \nu) c_\beta s_\beta & \lambda_2 s_\beta^2 + \nu c_\beta^2 & -\frac{1}{2}\mathrm{Im}\,\lambda_5\, c_\beta \\ -\frac{1}{2}\mathrm{Im}\,\lambda_5\, s_\beta & -\frac{1}{2}\mathrm{Im}\,\lambda_5\, c_\beta & -\,\mathrm{Re}\,\lambda_5 + \nu \end{pmatrix}$$

$$\nu = \mu^2/(2v^2)$$

When Im $\lambda_5 = 0$, block-diagonal structure
Using $\delta \equiv -\frac{1}{2} v$ Im $\lambda_5 \neq 0$

$$m_1^2 = M_h^2 - \delta^2 v^2 \frac{\cos^2(\beta+\alpha)}{M_A^2 - M_h^2},$$

$$m_2^2 = M_H^2 - \delta^2 v^2 \frac{\sin^2(\beta+\alpha)}{M_A^2 - M_H^2},$$

$$m_3^2 = M_A^2 + \delta^2 v^2 \frac{M_A^2 - \cos^2(\beta+\alpha) M_H^2 - \sin^2(\beta+\alpha) M_h^2}{(M_A^2 - M_H^2)(M_A^2 - M_h^2)}$$

The CP-violating terms $\propto$ Im λ_5 only appear in off-diagonal elements, so the sum is preserved:

$$m_1^2 + m_2^2 + m_3^2 = M_h^2 + M_H^2 + M_A^2$$

CP conservation: Higgs masses and couplings

Physical content of potential

- Higgs masses (quadratic couplings)
- Higgs trilinear couplings
- Higgs quartic couplings

Note, if selfcouplings are expressed in terms of masses, also μ enters!

$$
\begin{aligned}
g_{hhh} &= -3v\Big[-\cos\beta\sin^3\alpha\,\lambda_1 + \sin\beta\cos^3\alpha\,\lambda_2 - \tfrac{1}{2}\sin 2\alpha\cos(\beta+\alpha)\lambda_{345}\Big], \\
&= \frac{-3g}{\sin 2\beta\, M_W}\Big[(\cos\beta\cos^3\alpha - \sin\beta\sin^3\alpha)M_h^2 - \cos^2(\beta-\alpha)\cos(\beta+\alpha)\mu^2\Big],
\end{aligned}
$$

Basic couplings to gauge bosons $V = W/Z$ and fermions u, d-types

Independent of potential are:

- couplings to gauge bosons: hWW, HWW, $AWW = AZZ = 0$
  for eg. Z: $g_h^2 + g_H^2 = g_{H_{SM}}^2$
- couplings to fermions (Yukawa)
  e.g. Model **II**:

It is useful to express all couplings in terms of the relative "basic couplings":

$$\chi_i^\phi = \frac{g_i^\phi}{g_i^{\text{SM}}}, \qquad \phi = h, H$$

with $i = V, u, d$

DIRECT COUPLINGS in 2HDM

$$\chi_V^h = \sin(\beta - \alpha)$$
$$\chi_u^h = \sin(\beta - \alpha) + \cot\beta\cos(\beta - \alpha)$$
$$\chi_d^h = \sin(\beta - \alpha) - \tan\beta\cos(\beta - \alpha)$$

$$\chi_V^H = \cos(\beta - \alpha)$$
$$\chi_u^H = \cos(\beta - \alpha) - \cot\beta\sin(\beta - \alpha)$$
$$\chi_d^H = \cos(\beta - \alpha) + \tan\beta\sin(\beta - \alpha)$$

$\tan\beta$ – the ratio of the vacuum expectation values of the two basic Higgs doublets [$(0, \pi/2)$]

α –parameterizes mixing among the two neutral CP-even Higgs fields [eq. $(-\pi, 0)$]

Pattern relation

We found that for both h and H:

$$(\chi_u - \chi_V)(\chi_V - \chi_d) + \chi_V^2 = 1$$

or

$$(\chi_u + \chi_d)\chi_V = 1 + \chi_u \chi_d.$$

Also,

$$\tan^2 \beta = \frac{\chi_V - \chi_d}{\chi_u - \chi_V} = \frac{1 - \chi_d^2}{\chi_u^2 - 1}$$

The pattern relation was obtained here in the tree approximation. Radiative corrections will modify it at the level of *few percents*.

Selfcouplings in terms of observables

Using relative couplings
$g_{hhh} = \frac{-3g}{2M_W}\Big[(\cos^2\alpha\,\chi_u^h + \sin^2\alpha\,\chi_d^h)(M_h^2 - \frac{1}{2}\mu^2) + \chi_V^h\mu^2\Big]$

One can introduce a relative coupling for $\phi H^+ H^-$, $\phi = h, H$:

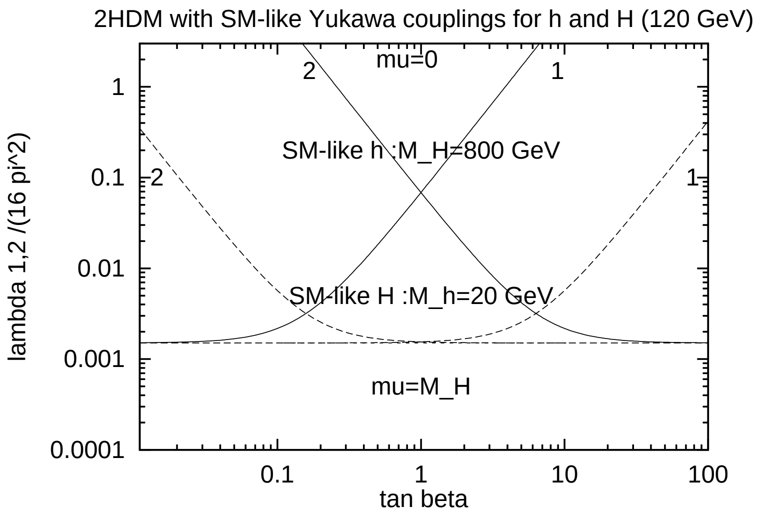
$$\chi_{H^\pm}^\phi \equiv -\frac{v g_{\phi H^+ H^-}}{2iM_{H^\pm}^2} = \left(1 - \frac{M_\phi^2}{2M_{H^\pm}^2}\right)\chi_V^\phi + \frac{M_\phi^2 - \mu^2}{2M_{H^\pm}^2}(\chi_u^\phi + \chi_d^\phi)$$

"Finite" for "large" $M_{H^\pm}^2$ (non-decoupling for small μ)
important for $\gamma\gamma\phi$ loop-coupling.

Perturbativity: λ_i in terms of masses and basic couplings

$$\lambda_1 v^2 = (1+\tan\beta^2)M_H^2 - \chi_d^2[M_H^2 - M_h^2] - \frac{1}{2}\mu^2\tan^2\beta$$
$$\lambda_2 v^2 = (1+\cot\beta^2)M_H^2 - \chi_u^2[M_H^2 - M_h^2] - \frac{1}{2}\mu^2\cot^2\beta$$

Take $\chi_d = \chi_u = 1$ for Higgs boson with mass 120 GeV



SM-like Higgs:

- h (M_H=800GeV)
- H (M_h=20GeV)

Existing constraints for 2HDM (II)

CP conserv. 2HDM(II) with soft violation of Z_2 symmetry (μ^2 term):

$\Rightarrow$ five Higgs bosons: h,H,A,$H^\pm$

$\Rightarrow$ 7 parameters :$M_h, M_H, M_A, M_{H^\pm}$, α, β, and μ^2

MODEL II (as in MSSM)

Couplings (relative to SM):	h	A
to W/Z:	$\chi_V = \sin(\beta - \alpha)$	0
to down quarks/leptons:	$\chi_d = \chi_V - \sqrt{1-\chi_V^2}\tan\beta$	$-i\gamma_5 \tan\beta$
to up quarks:	$\chi_u = \chi_V + \sqrt{1-\chi_V^2}/\tan\beta$	$-i\gamma_5/\tan\beta$

For H couplings like for h with:

$\sin(\beta-\alpha) \leftrightarrow \cos(\beta-\alpha)$ and $\tan\beta \to -\tan\beta$.

Pattern relation holds: $(\chi_u + \chi_d)\chi_V = 1 + \chi_u \chi_d$

I. Ginzburg, MK, P. Osland, hep-ph/0101208

DATA

LEP • direct:(h) Bjorken process $Z \to Zh$,
(hA) pair prod. $e^+e^- \to hA$,
(h/A) Yukawa pro. $e^+e^- \to bbh/A$
($H^\pm$) $e^+e^- \to H^+H^-$
via loop:(h/A, and $H^\pm$) $Z \to h/A\gamma$

Others exp.• via loop:(h/A) Wilczek process $\Upsilon \to h/A\gamma$
loop: ($H^\pm$) $b \to s\gamma$ $M_{H^\pm} > 350$GeV

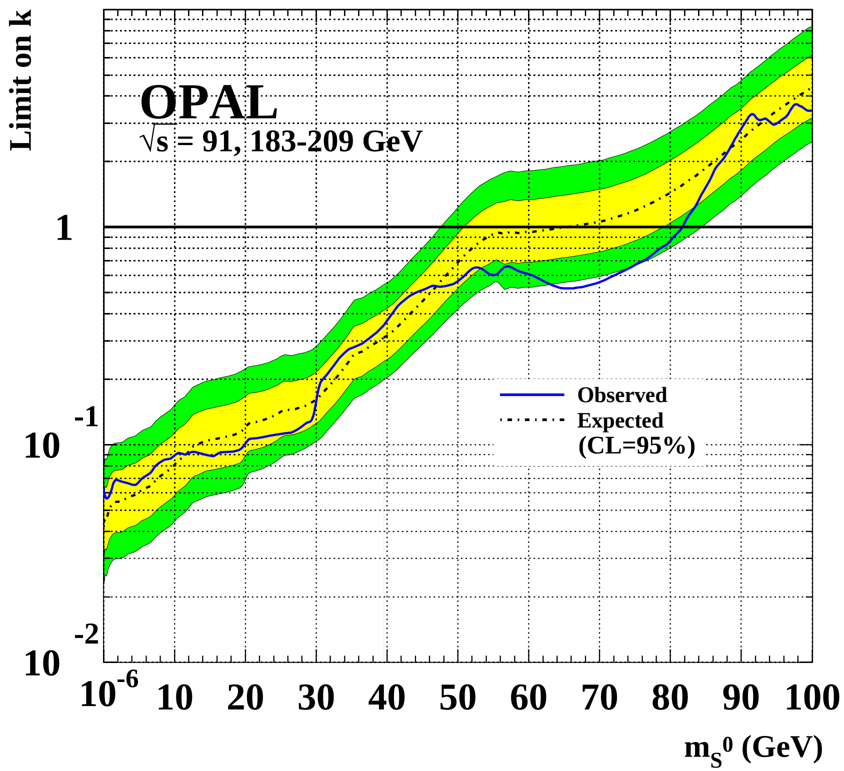
Global fit •(all Higgses)
Chankowski at al., EPJC 11,661,1999, also PL B496,195,2000
Cheung and Kong - hep-ph/0302111

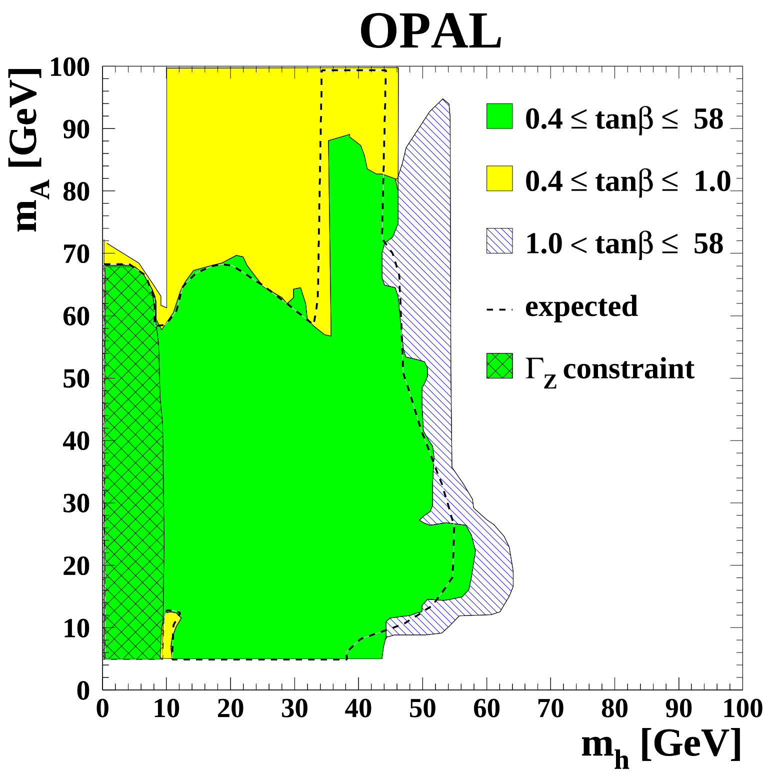
Coupling to gauge boson, and mass plot

Light h OR light A in agreement with current data

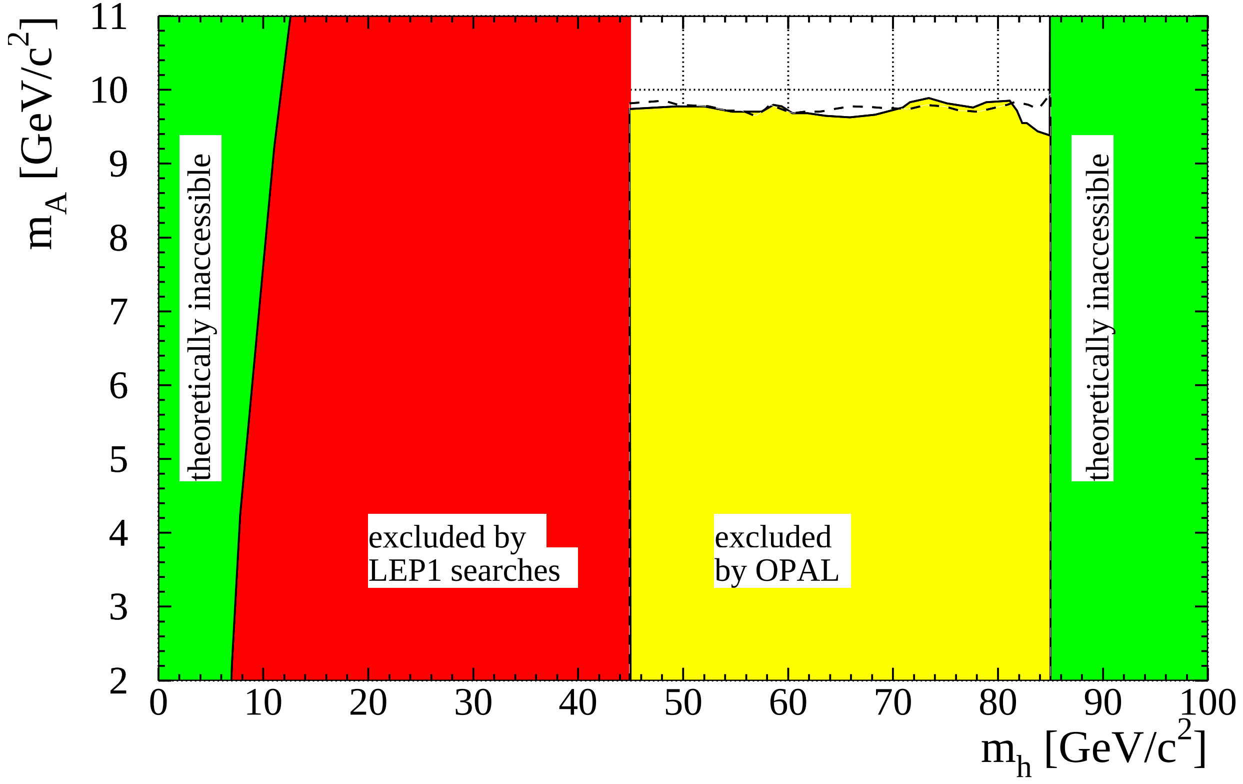
hZZ: $sin(\beta-\alpha)$ and hAZ: $cos(\beta-\alpha)$

$k = sin^2(\beta-\alpha)$





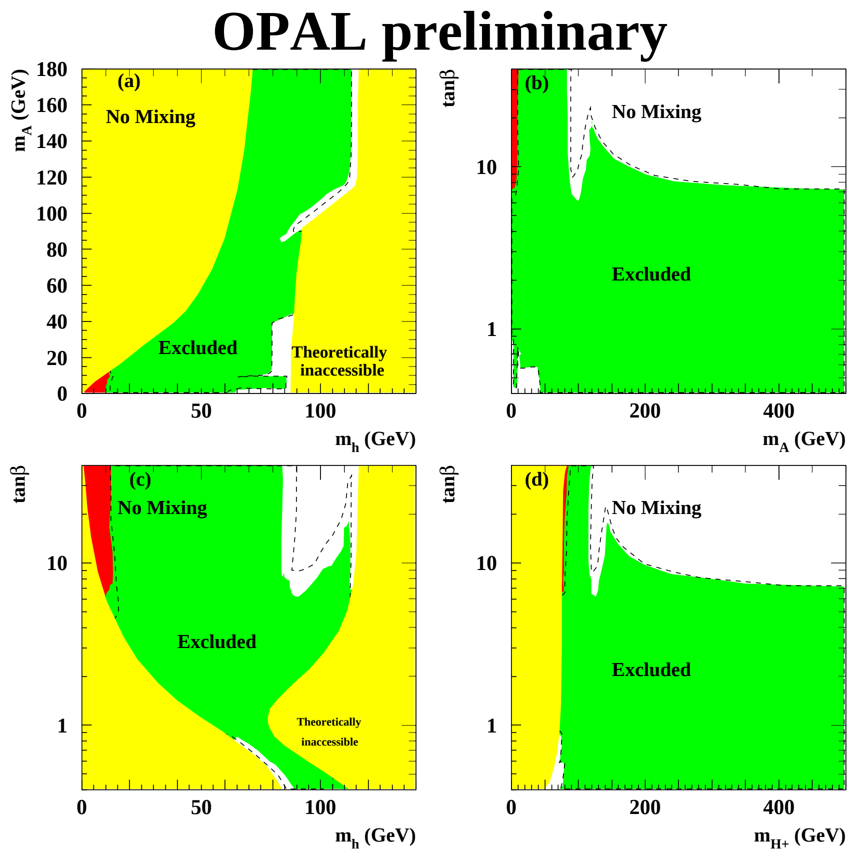
Light A

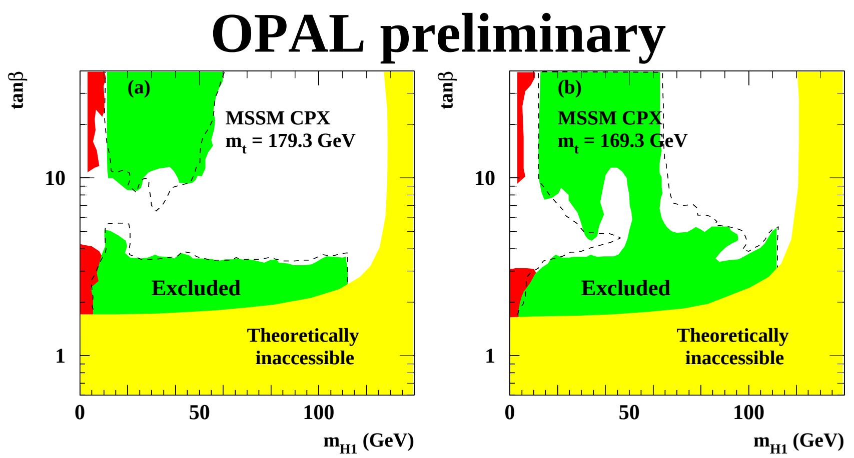


m_A [GeV/c^2]
11
10
9
8
7
6
5
4
3
2
0
10
20
30
40
50
60
70
80
90
100
m_h [GeV/c^2]
theoretically inaccessible
excluded by
LEP1 searches
excluded
by OPAL
theoretically inaccessible

CP viol. MSSM

Light h_1 allowed in CP viol. MSSM

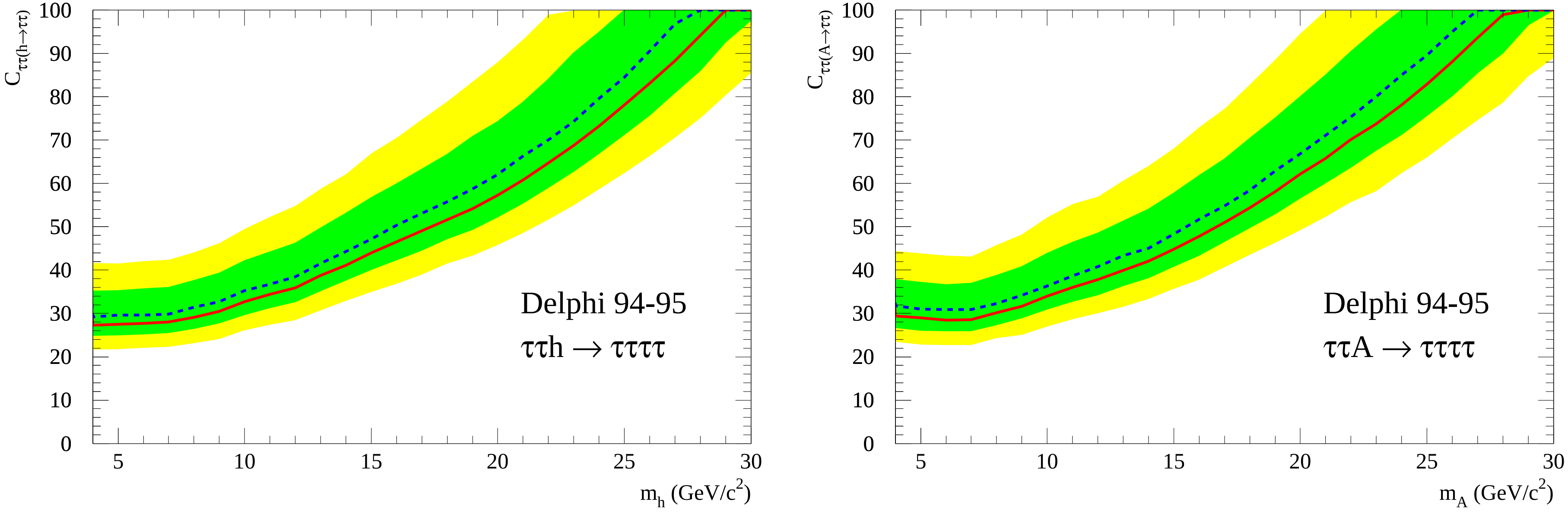


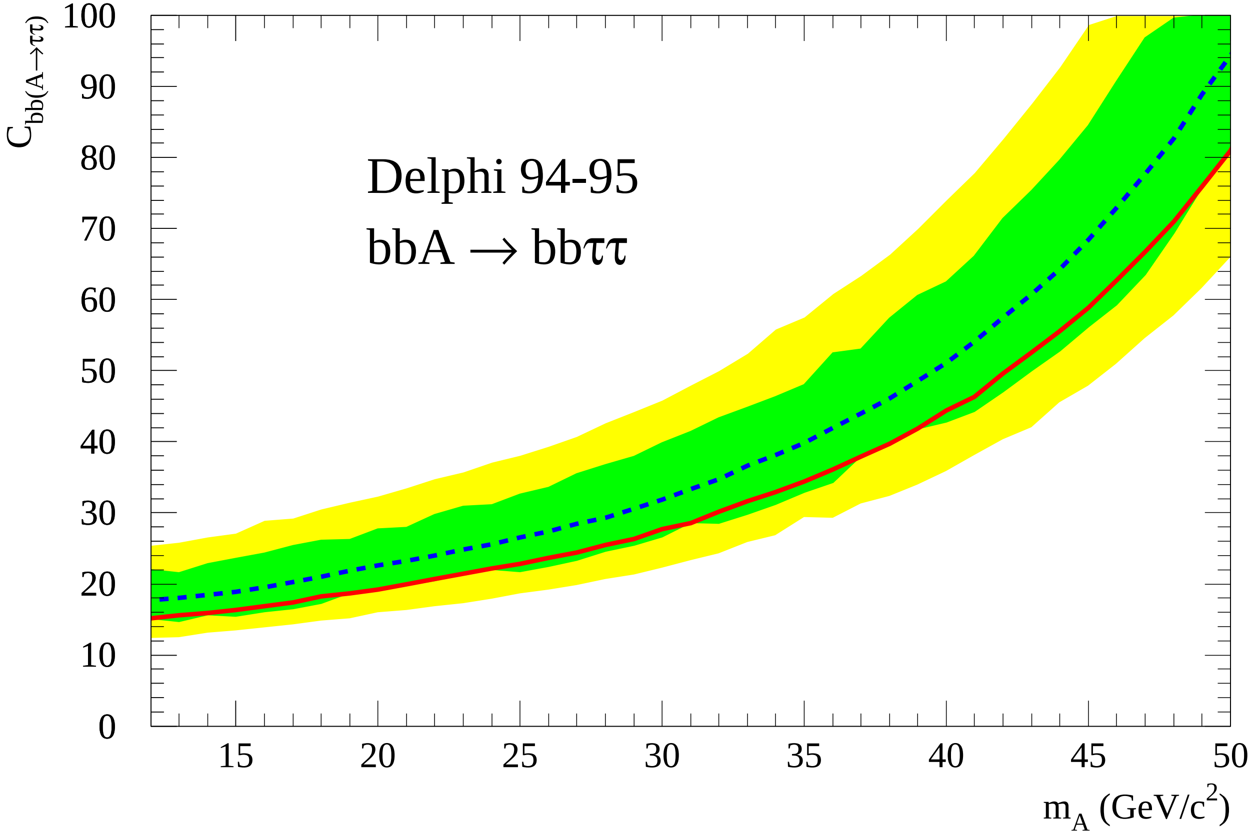


CP conserv.

CP violation

Yukawa couplings 2HDM (II) with CP conservation

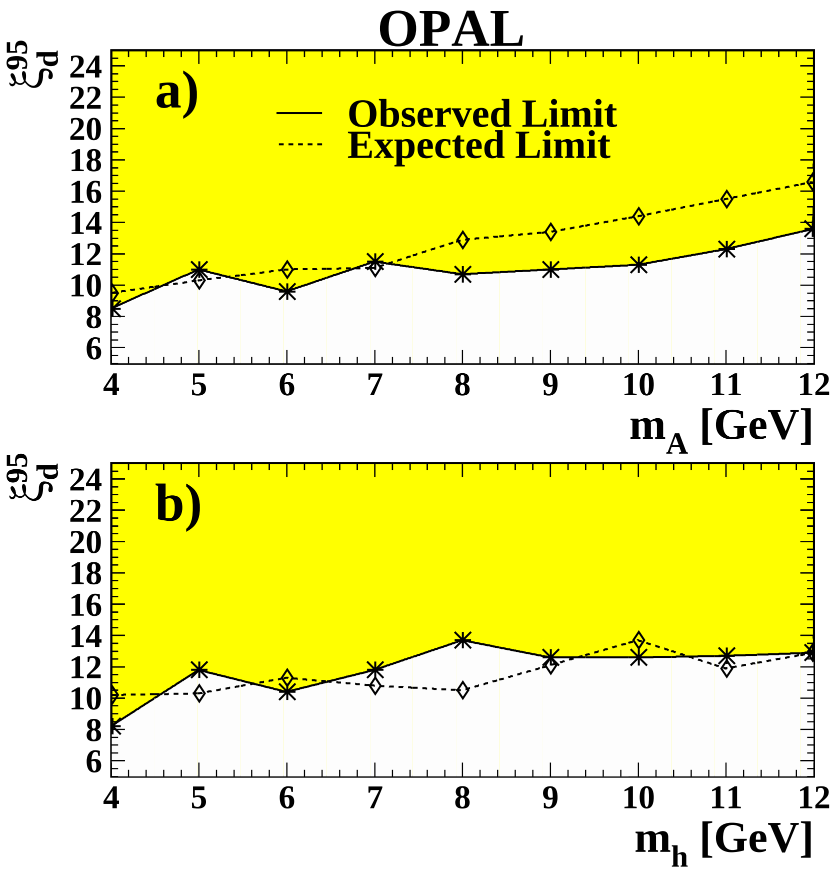




Large Yukawa coupling ($\tan\beta$) allowed (95%)!

Yukawa coupling contd.

Maximal allowed at 95% CL coupling to down-type quarks/leptons for h and A



Precision results for (g-2) for muon

and

the lightest Higgs boson in 2HDM(II)

hep-ph/0103223v3
hep-ph/0112112 Snowmass proc
Acta Phys. Pol. B 33 (2002) 2621
(hep-ph/020807)

DATA and SM prediction for $g-2$ for muon $a_\mu \equiv \frac{(g-2)_\mu}{2}$

$a_\mu^{exp} = 11659203(8) \cdot 10^{-10}$

E821, Phys. Rev. Lett. **89** (2002) 101804 [Erratum-ibid. **89** (2002) 129903] [arXiv:hep-ex/0208001]

$a_\mu^{SM} = a_{QED} + a_\mu^{EW} + a_\mu^{had}$

had=vac.pol.1+vac.pol.2+ lbl

$\longrightarrow$

A significant revision due to change in sign of the light by light hadronic contribution to a_μ light-by-light (lbl):

previous av: -8.5(2.5)10^{-10}

recent:

Knecht,Nyffeler +8.3(1.2)

Hayakawa,Kinoshita +8.9(1.5)

Bijnens,et al +8.3(3.2)

Blokland,et al. +5.6

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$$

SM contributions

Hadronic contribution	[in 10^{-11}]	
ho (Krause)	– 100	(6)
lbl (Nyffeler)	80	(40)
vp1 (Jeg02)	6889	(58)
had [FJ02]	6869	(71)

SM and data

SM contribution		[in 10^{-11}]
QED	116 584 705.7	(2.9)
had[FJ02]	6 869.0	(70.7)
EW	152.0	(4.0)
tot	116 591 726.7	(70.9)
$\Delta a_\mu(\sigma)$		303.3 (106.9)
lim(95%)		$93.8 \leq \delta a_\mu \leq 512.8$

[HMNT (ex)]: $\Delta a_\mu(\sigma) = 297.0\,(107.2)$ $87.2 \leq \delta a_\mu \leq 507.4$,

[HMNT(in)] : $\Delta a_\mu(\sigma) = 357.2\,(106.4)$ $148.7 \leq \delta a_\mu \leq 565.7$

[DEHZ (e+e-)]: $\Delta a_\mu(\sigma) = 339.0\,(112)$

Jegerlehner, Talk at Marseille, March 2002
Hagiwara et al (hep-ph/0209187v2)
Davier et al (hep-ph/0208177)
19.09.03 $\Delta a_\mu(\sigma) = 234\,(119)$ $0.076 \leq \delta a_\mu \leq 467$
BNL 10.01.2004 $\Delta a_\mu(\sigma) = 301\,(104.1)$ $96.96 \leq \delta a_\mu \leq 505$

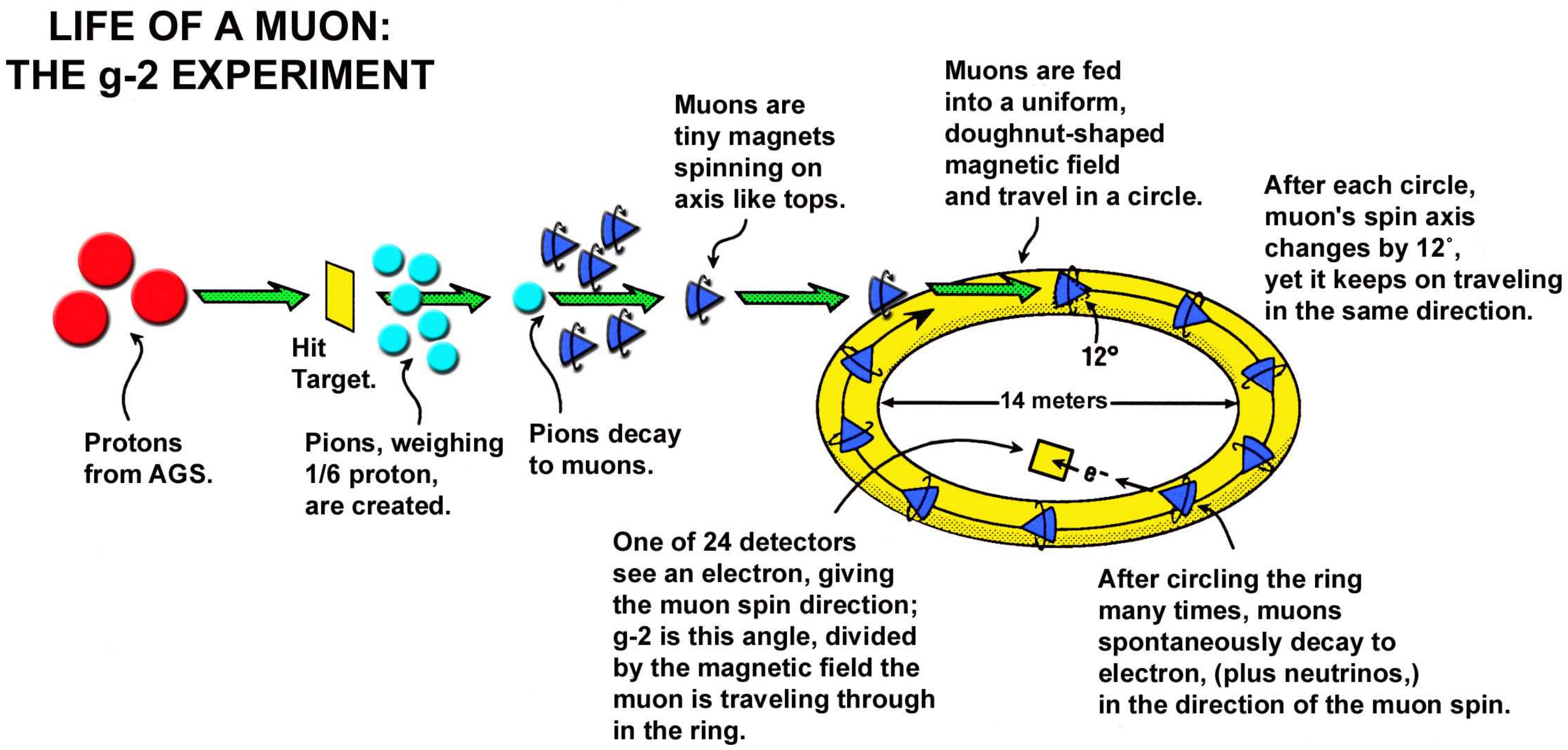
δa_μ region can be used to constrain parameters of new models

Hot News: BNL hep-ex/0401008

Measurement of the Negative Muon Anomalous Magnetic Moment to 0.7 ppm

The measurement - on muon spin precession in a magnetic storage ring with electrostatic focusing. The same experimental technique as in a_{μ^+}, and a similar precision of 0.7 ppm was achieved.

Overview of the experiment



The anomalous magnetic moments of the muon and the electron $\Rightarrow$ an important role in the development of the SM. Compared to the electron, the muon anomaly has a relative sensitivity to heavier mass scales proportional to $(m_\mu/m_e)^2$.

The negative muon anomalous magnetic moment from data collected in early 2001.

$$a_{\mu^-} = 11\,659\,214(8)(3) \times 10^{-10} (0.7\, ppm)$$

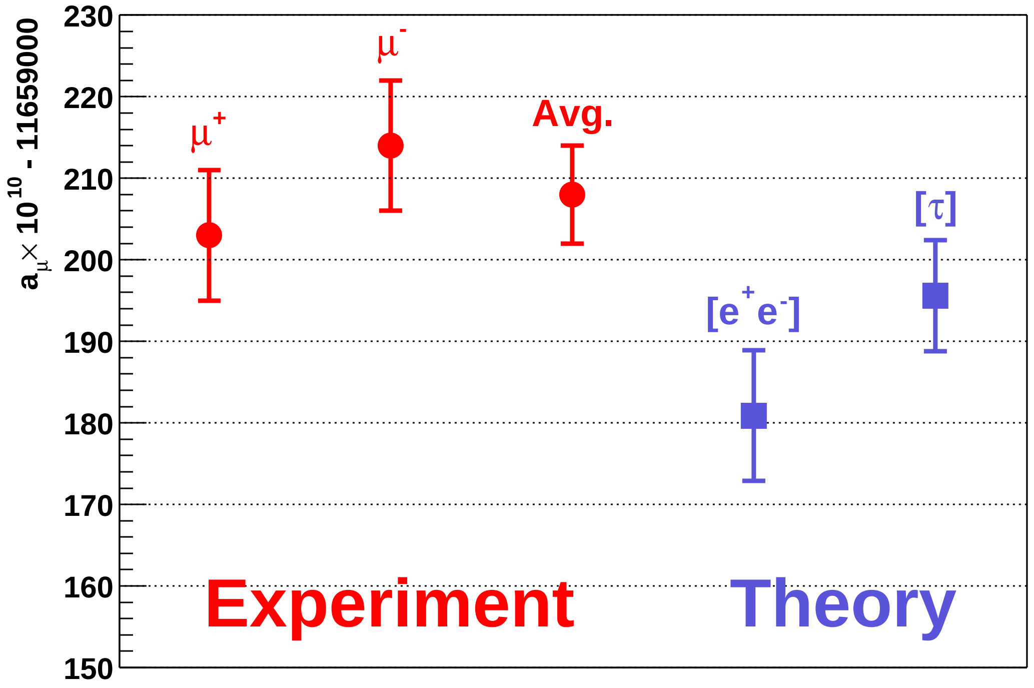
(statistical + systematic)

consistent with previous measurements of the anomaly for the positive and negative muon $a_\mu(\text{exp}) = 11\,659\,203(8) \times 10^{-10}$.

The average for the muon anomaly is

$$a_\mu(\text{exp}) = 11\,659\,208(6) \times 10^{-10} (0.5\, ppm)$$

(correlated systematic errors between the data sets)



Two data sets do not give consistent results for the pion form factor. e^+e^- annihilation gives $a_\mu(\text{SM}) = 11\,659\,181(8) \times 10^{-10}$ (0.6 ppm)

τ decay gives result 15×10^{-10} larger.

So, The difference of a_μ^{exp} and the SM the e^+e^- or τ data for the calculation of the hadronic vacuum polarization is 2.7 σ and 1.4 σ

95 CL new physics contribution in 10^{-11}

(MK - 10.01.2004):

$$96.96 - 505 (e^+ e^-)$$

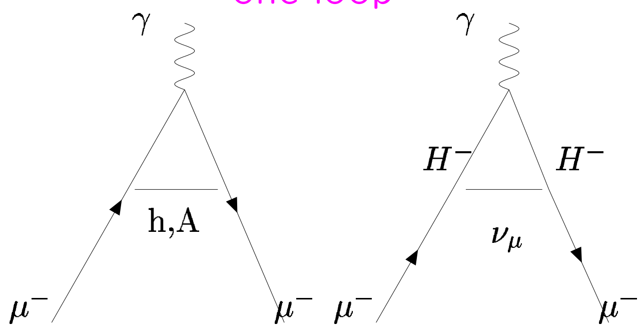
$$-47.5 - 315.5 (\tau)$$

2HDM contribution to a_μ: $a_\mu^{\text{2HDM}} = a_\mu^h + a_\mu^A + a_\mu^H + a_\mu^{H^\pm}$

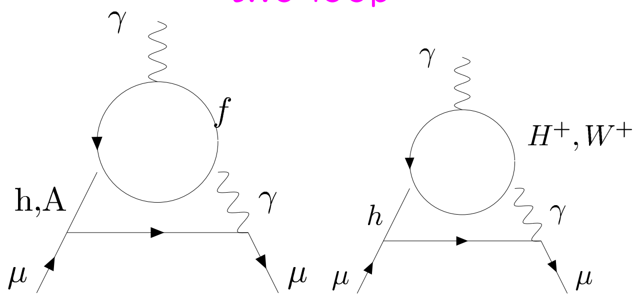
•light h scenario : $a_\mu^{\text{2HDM}} \approx a_\mu^h$

•light A scenario : $a_\mu^{\text{2HDM}} \approx a_\mu^A$

one loop



two loop

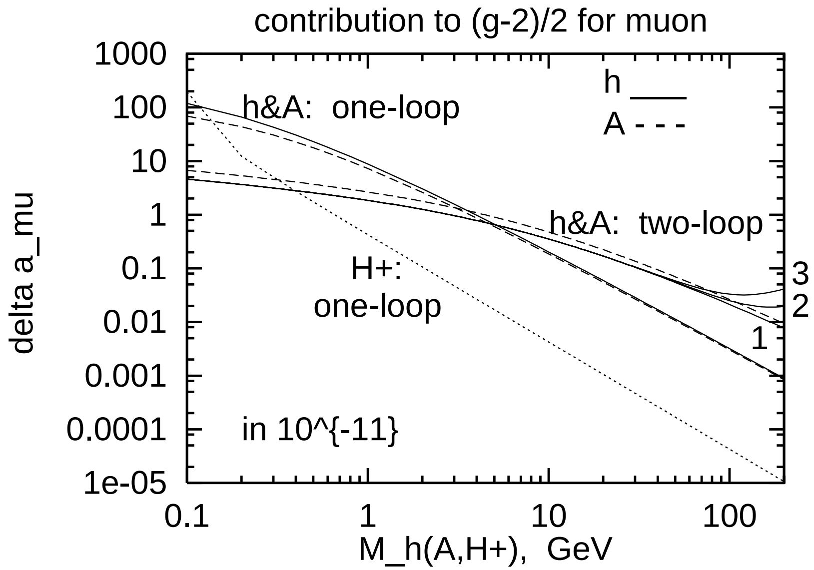


Zochowski,MK'96,MK'01;Dedes,Haber'01 Chang at al.,Cheung at al, Wu,Zhou, MK'01,'02..

Two loop contributions larger than one-loop for mass $\sim$ few GeV!

Various contributions for couplings = 1

2HDM(II):



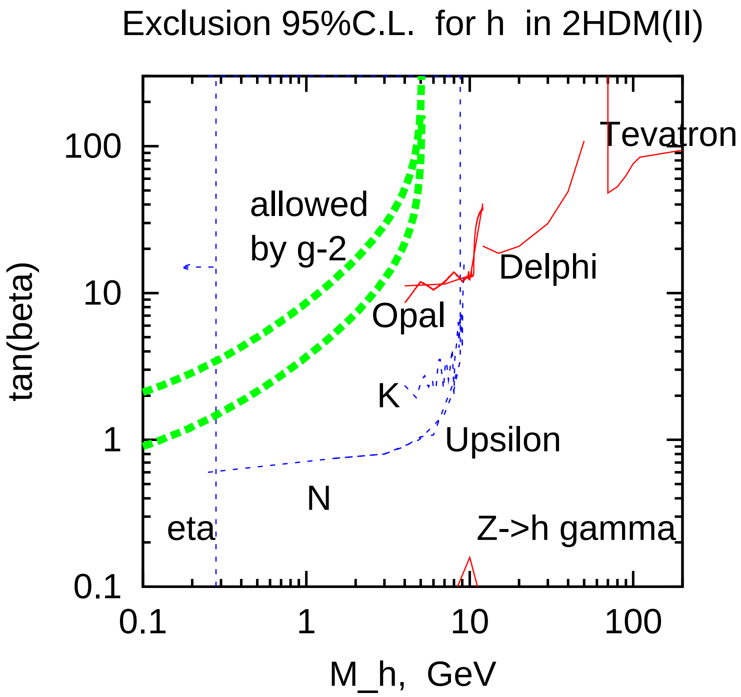
1–
no H^+
2–
$M_{H^\pm}$=800GeV
3–
$M_{H^\pm}$=400GeV

light A
contr. positive
for mass above 5 GeV

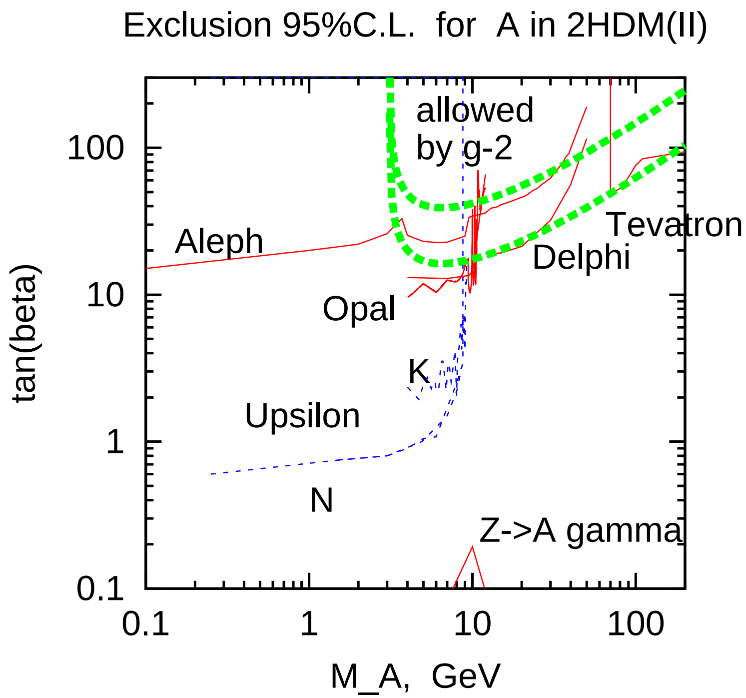
light h
contr. positive
for mass below 3 GeV
$\beta - \alpha = 0$, $\mu^2 = 0$

Combined 95% CL constraints for h and A in 2HDM(II) '2004

scalar h for $\beta - \alpha = 0, \mu^2 = 0$



pseudoscalar A



thick lines : upper & lower limits from g-2

plus LEP data, etc

New estimations ⇒ allowed regions for A only if all existing data are taken into account

A with mass 25-70 GeV and $25 < \tan\beta < 115$ in agreement with all data

Conclusions

- In 2HDM - various potentials possible
- Large masses of Higgs particle can be obtained in two different ways:

  $\rightarrow$ by large μ parameter related to the soft term in the potential

  $\rightarrow$ by large (but not too large) couplings λ_i
- The selfcoupling of Higgs particles, like $g_{hH^+H^-}$, if expressed in terms of masses, depends on μ
- The $H \rightarrow \gamma\gamma$ process, due to loop with H^+, is sensitive to this coupling. It can be used to distinguish between SM and SM-like 2HDM(II)
- Light h ot A even with mass $\sim$ 10 GeV in agreement with data

What that means: SM in agreement with data?

2HDM (II) - in agreement with data even in such extreme cases:

with the lightest Higgs boson

- very light, with mass eg. few GeV,
  and with very weak (or no) coupling to Z/W

- SM-like, with mass eg. 115 GeV, couplings as for H_{SM}
  (relative couplings $\chi_V, \chi_u, \chi_d = 1$)

Challenge $\rightarrow$ SM-like scenarios in the extensions of the SM

Light or Little Higgs?