Physics after the discovery of the Higgs boson

J. J. van der Bij
Institut für Physik
Albert-Ludwigs Universität Freiburg

DESY Zeuthen,
3 März, 2016

Triangle meeting Utrecht-Paris-Rome (Utrecht 1979)

Already then it was clear that the standard model is basically right, but people were dissatisfied.

- Naturalness, G. 't Hooft
- Simplicity, M. Veltman
- Fixed point, J. Iliopoulos

Old physics

- No BSM particles at the LHC
- No new plavour physics at the LHC
- The Higgs field has been found
- General agreement with precision data

New physics

- Dark matter
- Sterile neutrino
- $(g-2)_\mu$

Therefore if there is new physics at all, it must be hidden. There is no new flavour physics and the precision tests agree largely with the standard model.
Extensions must be minimalistic, so they do not effect the fundamental structure of the standard model. This leaves few possibilities. Examples are inert scalar multiplets, that do not couple to fermions. Also non-chiral fermions. These are both good candidates for dark matter.
But the simplest "safe" extensions are of course singlets.
It is reasonable to expect singlet fields to be present in the scalar sector, after all they exist in the fermion and in the gauge sector.
Moreover they are the extensions of the standard model with the smallest number of parameters.
Since singlets do not change the basic gauge structure of the standard model it is a matter of taste whether such extensions still belong to the standard model. One could call it the non-minimal standard model (NMSM).
I will discuss two examples for which there is indirect evidence.

What do we know?

- Vectorbosons exist $\rightarrow$ a Higgs field exists.
- QFT is right $\rightarrow$ The Higgs field has a Källén-Lehmann spectral density.
- EW precision data $\rightarrow$ the field is light.
- LHC data $\rightarrow$ most of the spectral density is around 126 GeV.

This does not mean the full Higgs field
consists of a single particle peak only.

Since the Higgs field is in some way different from other fields,
a non-trivial density is quite natural.

The scientific goal regarding EW symmetry breaking is therefore to measure the Källén-Lehmann spectral density of the Higgs propagator.

In praxis this means measuring the Higgs lineshape (width) and looking for further peaks with a smaller than standard model signal strength.

A renormalization group analysis of the Hill model and its HEIDI extension

J. J. van der Bij
Institut für Physik
Albert-Ludwigs Universität Freiburg

DESY Zeuthen,
3 März, 2016

L. Basso, O. Fischer and J. J. van der Bij;
Physics Letters B, **730** (2014) 326.

Is the standard model Higgs insufficient?

Instability of the Higgs potential before the Planck scale.
The large top mass destabilizes the Higgs potential, so the Higgs must be heavy to compensate.
Recent analysis (De Grassi et all. JHEP08(2012)098) :

$$m_{higgs} > 129.4 \pm 1.8 GeV$$

.

m_{higgs} around 126 GeV is close to a scale invariance near the Planck scale: $\lambda = 0$; $\beta_\lambda = 0$.
A possible instability of the vacuum can be easily corrected through the presence of extra singlet fields.

Extended standard model (with A. Hill)†.
Now officially Hill model.

Higgs Sector

$$\mathcal{L} = -\frac{1}{2}(D_\mu\Phi)^\dagger(D_\mu\Phi) - \lambda_1/8(\Phi^\dagger\Phi - f_1^2)^2 - \frac{1}{2}(\partial_\mu H)^2 - \frac{\lambda_2}{8}(2f_2 H - \Phi^\dagger\Phi)^2$$

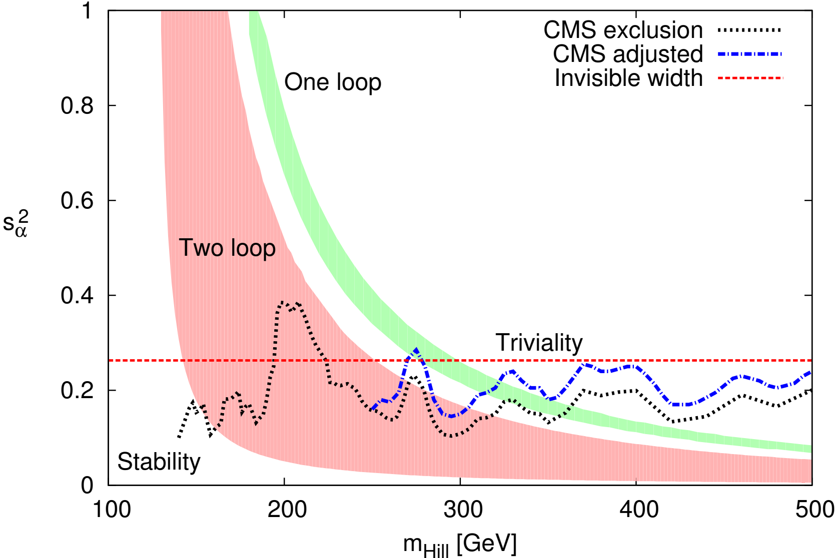
N.B. no H^4 coupling: pure mixing model.
Renormalizable !!

Two Higgses with reduced couplings

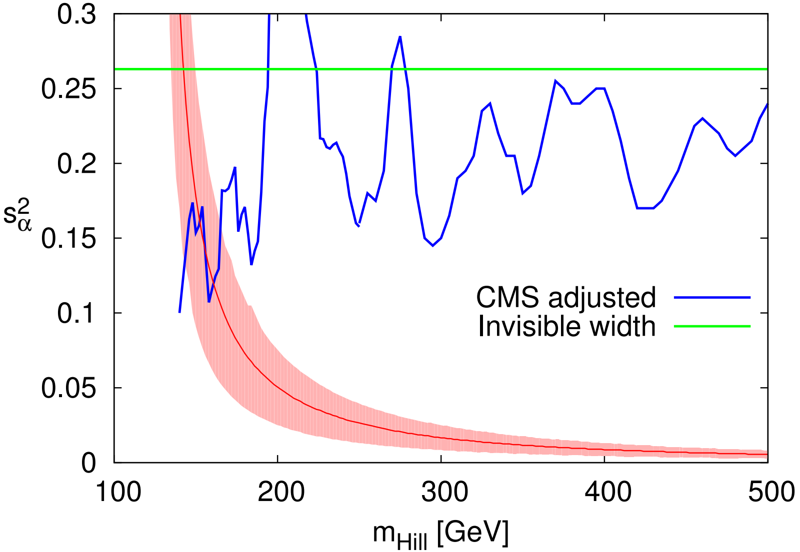
$$D_{HH}(k^2) = \frac{sin^2\alpha}{k^2 + m_+^2} + \frac{cos^2\alpha}{k^2 + m_-^2}$$

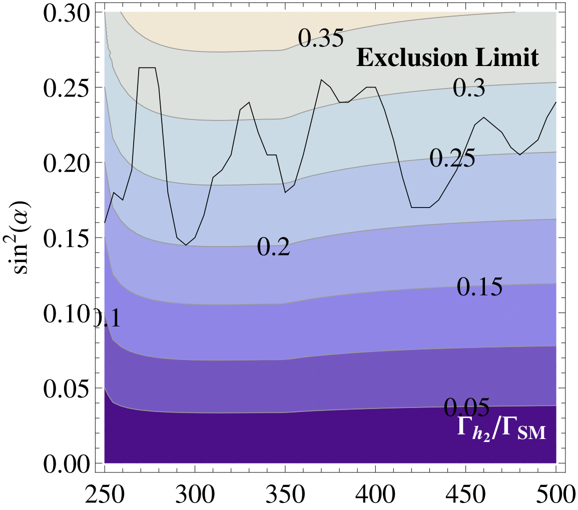
This is sufficient to study Higgs signals (interaction basis).

Stability up to the Planck mass

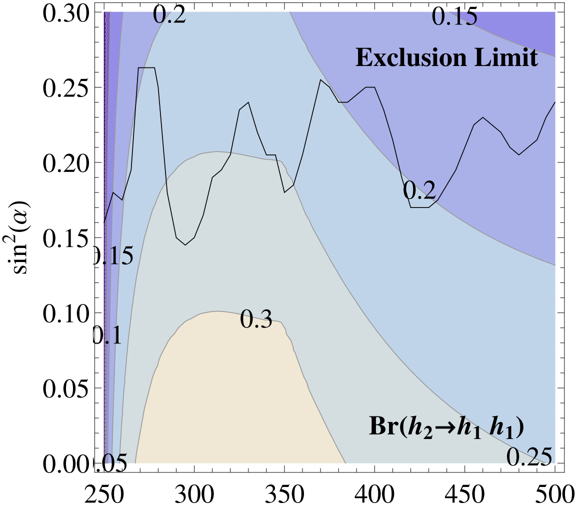


λ=0 at the Planck scale

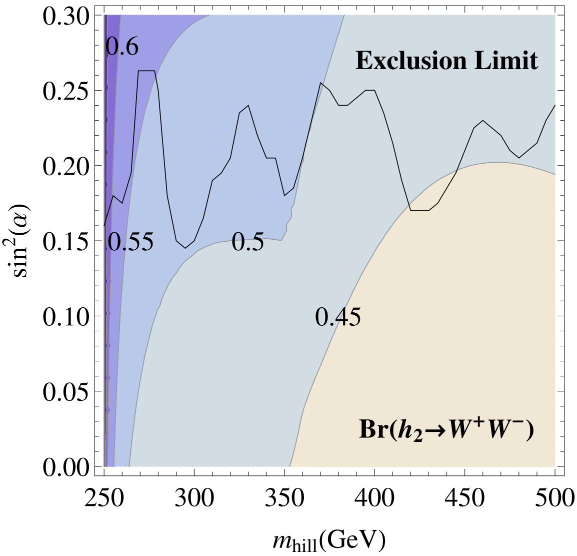




0.35
Exclusion Limit
0.3
0.25
0.2
0.15
0.1
0.05
Γ_{h_2}/Γ_{SM}
$\sin^2(\alpha)$
0.30
0.25
0.20
0.15
0.10
0.05
0.00
250
300
350
400
450
500



0.30
0.25
0.20
0.15
0.10
0.05
0.00
250
300
350
400
450
500
sin$^2(\alpha)$
0.2
0.15
Exclusion Limit
0.2
0.15
0.3
0.1
0.05
Br($h_2 \to h_1 h_1$)
0.25


Exclusion Limit
$\mathrm{Br}(h_2 \to W^+W^-)$
0.6
0.55
0.5
0.45
0.30
0.25
0.20
0.15
0.10
0.05
0.00
250
300
350
400
450
500
$\sin^2(\alpha)$
m_{hill}(GeV)

The generalization to more fields is straightforward.

n Higgses H_i with couplings g_i.

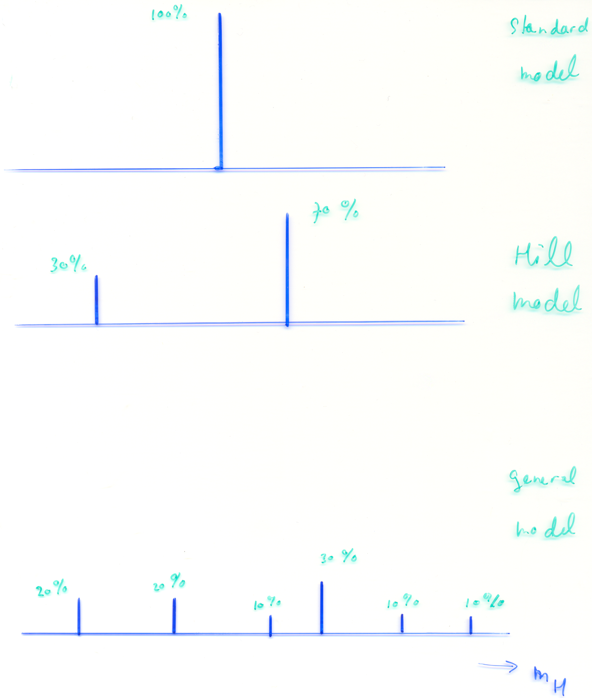
Sum rule:

$$\Sigma g_i^2 = g_{Standard\ model}^2$$

This can be generalized to a continuum.

$$\int \rho(s) ds = 1$$

Källén-Lehmann density.


100%
Standard model
70%
30%
Hill model
general model
30%
20%
20%
10%
10%
10%
m_H

HEIDI Models (with S. Dilcher and B. Puliçe)

Higher dimensional singlet ⇒ Few Parameters !

In terms of the modes H_i the Lagrangian is the following:

$$\begin{aligned} L &= -\frac{1}{2}D_\mu\Phi^\dagger D_\mu\Phi - \frac{M_0^2}{4}\Phi^\dagger\Phi - \frac{\lambda}{8}(\Phi^\dagger\Phi)^2 \\ &- \frac{1}{2}\sum(\partial_\mu H_k)^2 - \sum\frac{m_k^2}{2}H_k^2 \\ &- \frac{g}{2}\Phi^\dagger\Phi\sum H_k - \frac{\zeta}{2}\sum H_i H_j \end{aligned}$$

$m_k^2 = m^2 + m_\gamma^2\,\vec{k}^2$, where $\vec{k}$ is a γ-dimensional vector, $m_\gamma = 2\pi/L$ and m a d-dimensional mass term for the field H.

$$S = \int d^{4+\gamma}x \prod_{i=1}^{\gamma}\delta(x_{4+i})\left(g_B H(x)\Phi^\dagger\Phi - \zeta_B H(x)H(x)\right)$$

Propagator

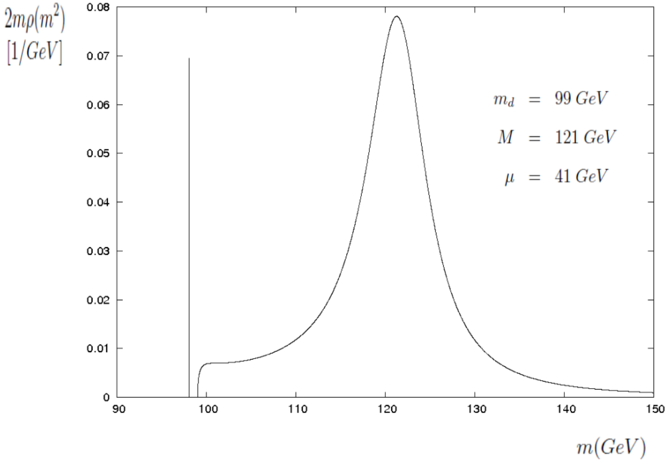
$$D_{HH}(q^2) = \left(q^2 + M^2 - \frac{\mu^{8-d}}{(q^2+m^2)^{\frac{6-d}{2}} \pm \nu^{6-d}} \right)^{-1}$$

This is renormalizable up to 6 dimensions, while

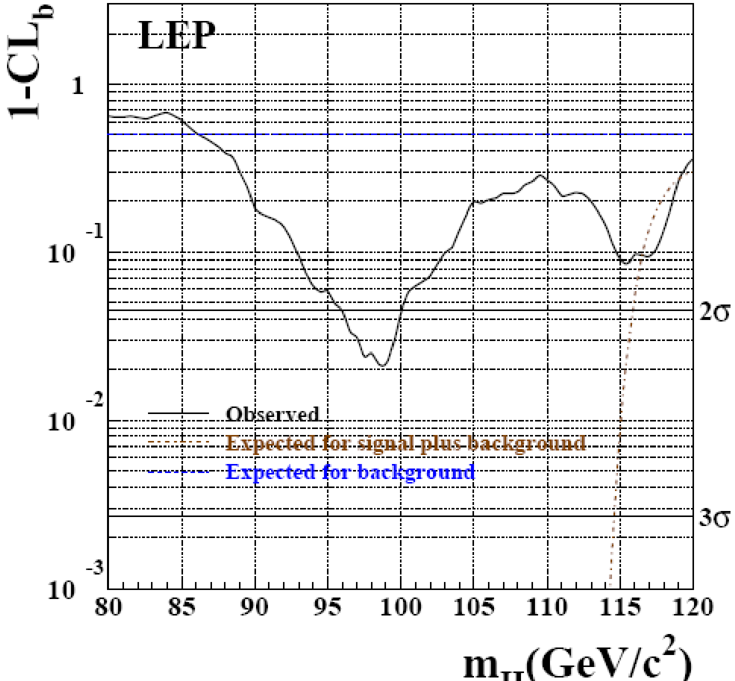
$$H\Phi^\dagger\Phi$$

is superrenormalizable in four dimensions

Corresponding Källén-Lehmann spectral density:
zero, one or two peaks plus continuum

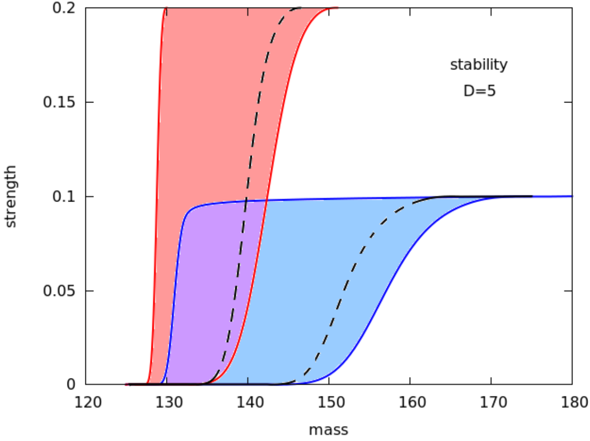


$2m\rho(m^2)$
$[1/GeV]$
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
90
100
110
120
130
140
150
$m(GeV)$
$m_d = 99\,GeV$
$M = 121\,GeV$
$\mu = 41\,GeV$

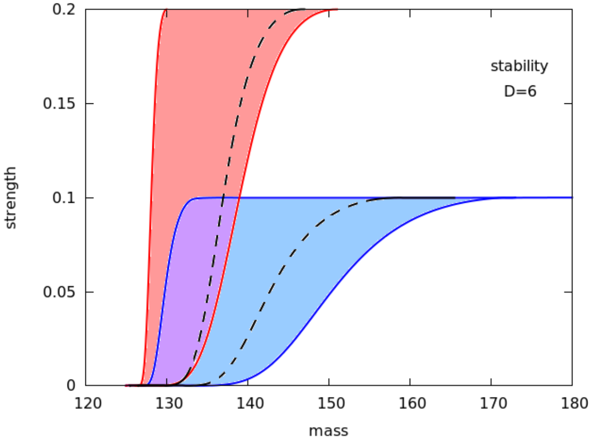


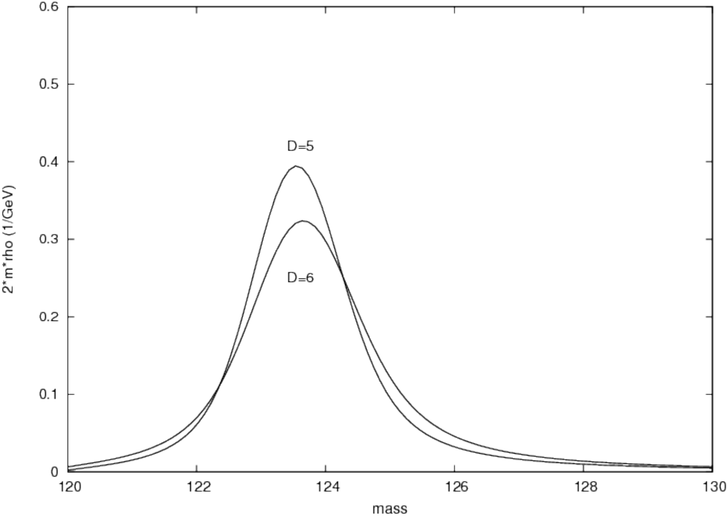
LEP
1-CL_b
1
10^-1
10^-2
10^-3
2σ
3σ
Observed
Expected for signal plus background
Expected for background
80
85
90
95
100
105
110
115
120
m_H(GeV/c^2)

Two-peak + continuum model



Two-peak + continuum model





Center point of the fits

Conclusion

- The Higgs field has been found at the LHC and possibly at LEP-200.
- Its properties are consistent with the electroweak precision data.
  Maybe not quite, see the following.
- A dark matter candidate can be included.
- The spectrum is not completely fixed.

Caveats

Significance roughly 2.3 sigma for the LEP data.

Questions for the LHC

- Constrain the height of the peak
- Get an upper (better a lower) limit on the width
- Go down to 90 GeV
- Check the branching ratios
- Improve the upper limit for further peaks

Beyond the LHC: A Higgs factory

The question is : of what kind?

Obviously a lepton collider is needed, but how well can one do?

$$e^+e^- \to Z \quad H.$$

Measurement of line-shape and invisible decay BR's.

- Energy about 250-300 GeV
- High precision (SM width 4 MeV!)
- Theory: benchmark models
- Beam Strahlung: machine
- Resolution: detector
- Unfolding: analysis

ILC

A muon collider: Science fiction ?

A large circular collider: VLLC or TLEP!

Conclusion:
Higher dimensions may be hidden in the Higgs lineshape!

Where is Heidi hiding ?

Heidi is hidden

in the high-D Higgs Hill !

Precision tests of unitarity in leptonic mixing

J. J. van der Bij
Institut für Physik
Albert-Ludwigs Universität Freiburg

DESY Zeuthen,
3 März, 2016

L. Basso, O. Fischer and J. J. van der Bij;
Europhysics letters: EPL, **105** (2014) 11001;
doi: 10.1209/0295-5075/105/11001.

Importance of the LHC results

- The **standard model Higgs** boson has been discovered.
- No new physics, carrying standard model charges at the weak scale, appears to be present.
- Therefore only limited extensions of the standard model are possible.

Theory predictions:

- Precision predictions are sensitive to radiative corrections dependent on m_H.
- Higgs mass before the LHC: 110 GeV $\leq m_H \leq$ 160 GeV.
- The knowledge of m_H fixes the radiative corrections.
- The quantitative comparison of precision data with predictions is now possible at a much higher level than ever before !

Sterile neutrinos

The model:

- n neutral (sterile) fermions (Dirac or Majorana)
- Mixing with left-handed neutrinos of the standard model
- *PMNS* matrix is a part of the general mixing matrix (Pontecorvo-Maki-Nakagawa-Sakata)

Motivation:

- Provide dark matter candidates
- Baryogenesis via leptogenesis
- Essentially invisible at the LHC
- Right-handed neutrinos and *PMNS* matrix exist

The *PMNS* matrix

- Mass eigenstates and flavour basis ($\alpha = e, \mu, \tau$): $\{\nu_i = \nu_{L_\alpha},\, N_n\}$ expressed via a unitary $(3+n) \times (3+n)$ matrix:

$$\begin{pmatrix} \nu_1 \\ \vdots \\ \nu_{3+n} \end{pmatrix} = \begin{pmatrix} PMNS & \mathcal{W} \\ \mathcal{W}^\dagger & \mathcal{V} \end{pmatrix} \begin{pmatrix} \nu_{L_e} \\ \vdots \\ N_n \end{pmatrix} .$$

- Unitarity of *PMNS* as submatrix not generally true
- Definition of the ϵ parameters:

$$\epsilon_\alpha = \sum_{i>3} |\mathcal{U}_{\alpha i}|^2 = 1 - \sum_\beta |\mathcal{U}_{\alpha\beta}|^2 .$$

Low energy parameters

The theory prediction for meson decays is dependent on the ratio:

$$\frac{g_\alpha}{g_\beta} = 1 - \frac{\epsilon_\alpha - \epsilon_\beta}{2}. \tag{1}$$

The epsilon parameters modify the Fermi constant via the following relation:

$$G_\mu^2 = G_F^2 (1 - \epsilon_e)(1 - \epsilon_\mu)\,, \tag{2}$$

with G_μ the Fermi constant measured in muon decay, and G_F the theoretical Fermi parameter.
They also affect the unitarity of the Cabibbo-Kobayashi-Maskawa matrix:

$$CKM = 1 + \epsilon_\mu\,, \tag{3}$$

High energy parameters

$$
\begin{aligned}
\frac{M_W}{[M_W]_{\mathrm{SM}}} &= 1 + 0.11\,(\epsilon_e + \epsilon_\mu) \\
&\quad +0.0056\,T \qquad (4) \\
\frac{\Gamma_{\mathrm{inv}}/\Gamma_{\mathrm{lept}}}{\left[\Gamma_{\mathrm{inv}}/\Gamma_{\mathrm{lept}}\right]_{\mathrm{SM}}} &= 1 - 0.76\,(\epsilon_e + \epsilon_\mu) - 0.67\,\epsilon_\tau \\
&\quad -0.0015\,T \qquad (5) \\
\frac{\Gamma_{\mathrm{lept}}}{\left[\Gamma_{\mathrm{lept}}\right]_{\mathrm{SM}}} &= 1 + 0.60\,(\epsilon_e + \epsilon_\mu) \\
&\quad +0.0093\,T \qquad (6) \\
\frac{\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}}{\left[\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}\right]_{\mathrm{SM}}} &= 1 - 0.72\,(\epsilon_e + \epsilon_\mu) \\
&\quad -0.011\,T. \qquad (7)
\end{aligned}
$$

Observable	Experiment	standard model
$(g_\mu/g_e)_\tau$	1.0020(16)	1.0
$(g_\tau/g_e)_\tau$	1.0029(21)	1.0
$(g_\mu/g_e)_\pi$	1.0021(16)	1.0
$(g_\tau/g_\mu)_\pi$	0.9965(33)	1.0
CKM	0.9999(6)	1.0
M_W (GeV)	80.385(15)	80.359(11)
$\Gamma_{\rm inv}/\Gamma_{\rm lept}$	5.942(16)	5.9721(2)
$\Gamma_{\rm lept}$ (MeV)	83.984(86)	84.005(15)
$s_{\rm eff}^{2,\rm lept}$	0.23113(21)	0.23150(1)
$s_{\rm eff}^{2,\rm hadr}$	0.23222(27)	0.23150(1)

Table: Experimental results and standard model prediction for lepton universality and electroweak observables.

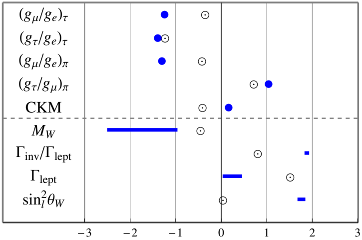
Observable	χ^2_{SM}	χ^2_{T}	χ^2_{ϵ}	$\chi^2_{\epsilon+T}$
$(g_\mu/g_e)_\tau$	19.8	18.8	17.5	17.4
$(g_\tau/g_e)_\tau$	20.3	19.3	14.0	13.5
$(g_\mu/g_e)_\pi$	19.7	18.6	17.4	17.2
$(g_\tau/g_\mu)_\pi$	20.0	19.0	17.3	17.3
CKM	21.3	20.3	15.9	15.2
M_W (GeV)	19.4	19.4	16.9	11.6
$\Gamma_{\rm inv}/\Gamma_{\rm lept}$	17.8	16.9	15.8	15.4
$\Gamma_{\rm lept}$ (MeV)	21.4	20.2	17.6	17.5
$s^{2,\text{lept}}_{\text{eff}}$	18.2	18.1	16.2	16.0
$s^{2,\text{hadr}}_{\text{eff}}$	14.2	10.5	5.3	5.3
Total χ^2	21.3	20.3	18.0	18.0

Table: The χ^2 for the standard model (χ^2_{SM}), the minimum with unitarity violation (χ^2_ϵ), with unitarity violation and the T parameter ($\chi^2_{\epsilon+T}$), and the T parameter only, are evaluated *excluding* the entry on each line. The total χ^2 (considering all entries) is given for reference.

Hypothesis testing: Non-unitary lepton mixing

Analysis with ϵ parameters:

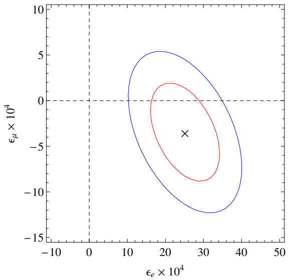
- Total fit: $\chi^2/\text{dof} = 18.0/7$
- Corresponding likelihood: 1.5%
- Best fit for $\{s^{2,\text{hadr}}_{\text{eff}}\}$ removed
- $\chi^2/\text{dof} = 5.3/5$

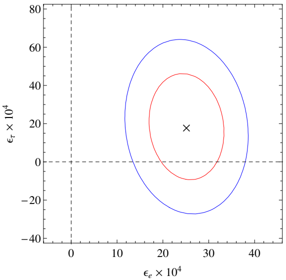


$\Rightarrow$ Likelihood that data without $\{s^{2,\text{hadr}}_{\text{eff}}\}$ is described by the Standard Model plus non-unitary lepton mixing is 50%.

$\Rightarrow$ Inclusion of oblique parameters barely improves the fit.

The unitarity violation parameters



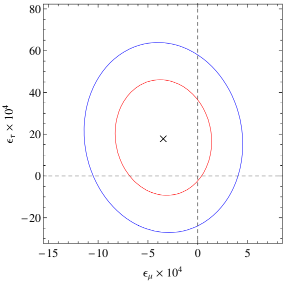


Quantify mixing and universality:

ϵ_e non zero at $\sim 3\sigma$

ϵ_μ small, compatible with zero

ϵ_τ not well constrained



Experimental constraints on sterile neutrinos

Probing the model further:

- $\epsilon_e + \epsilon_\mu + \epsilon_\tau \neq \left(UU^\dagger\right)_{e\mu} + \left(UU^\dagger\right)_{e\tau} + \left(UU^\dagger\right)_{\mu\tau}$
- Rare decays like $\mu \to e\,\gamma$ cannot be assessed
- New constraint on models with lepton unitarity violation
- Direct neutrino mixing experiments still too imprecise

Neutrinoless double beta decay:

- No constraints if Dirac fermions
- Masses $\mathcal{O}$(100 TeV) and/or *PMNS* cancellations if Majorana

See-saw models:

- Mixing $\sim \epsilon_e$ *too large* for type-I see-saw
- Strong cancellations in the *PMNS* matrix required

Summary and Conclusions

- Measurement of the Higgs boson mass makes precision tests meaningful.
- Standard Model cannot explain discrepancies in precision data.
- Removing $s^{2,\mathrm{hadr}}_{\mathrm{eff}}$ improves consistency between data and theory.
- 3.0σ evidence for lepton unitarity violation of $\mathcal{O}(10^{-3})$.
- Indication for mixing of left-handed neutrinos with sterile neutrinos.
- Additional oblique corrections are unnecessary.

Outlook

- Clarification of the discrepancy between $s_{\mathrm{eff}}^{2,\mathrm{hadr}}$ and $s_{\mathrm{eff}}^{2,\mathrm{lept}}$, Mainz, JLab;
- Tau-factories: improved precision of τ–decays, Peking;
- LHC: improved measurement of M_W;
- Higher order theoretical calculations;
- new beamdump experiment at CERN, SHIP (search for heavy invisible particles).

$\Rightarrow$ More than 5σ for ϵ_e possible.

$\Rightarrow$ Sterile neutrino model becomes *predictive*.

Precision = Discovery !!