Higgs and Higgses

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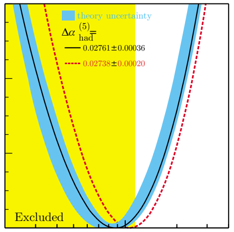
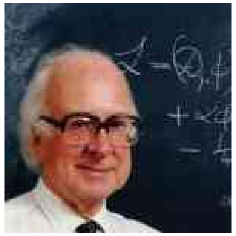
Karlsruhe - Fall 2001

- No pretense for accuracy or depth
- A simple reminder of a few things
- Next week seminar of M. Narain





Higgs and sociology

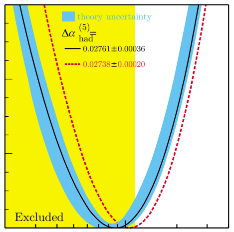
SSC was justified for its potential for Higgs discovery

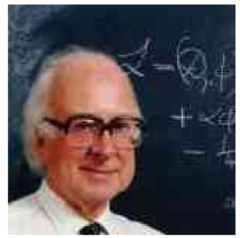
TeV-I is today devoted to Higgs: CDF and DØ.

Major portion of US (and world) resources devoted to Higgs search

LHC under construction is commonly justified for Higgs discovery and study.

ATLAS and CMS, 2 detectors and 2 collaborations
>3000 physicists

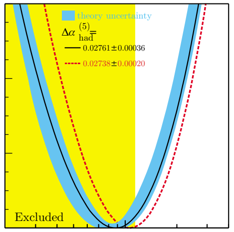


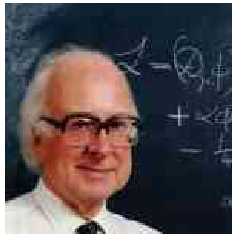


Why?

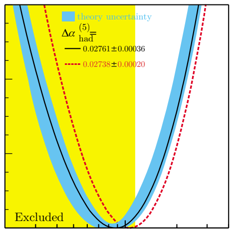
For example

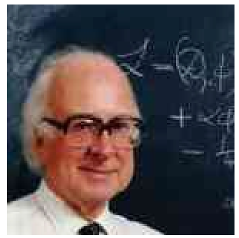
- SM is still fine, it just survived the muon anomaly attack.
- Is the Higgs fundamental or can it be substituted by something else?
- If the Higgs is heavy then there something nearby (see MEP)
- Experiments are big and expensive.
- Other reasons?





Look-up Michael E Peskin home page





Weak interaction, history

S-wave unitarity:

$$\sigma_\ell = \frac{4\pi}{k^2}(2\ell+1)|a_\ell|^2 \le \frac{4\pi(2\ell+1)}{k^2}$$

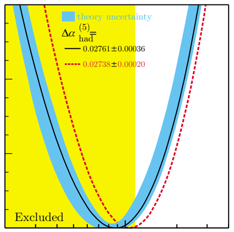
$$\sigma_{\ell=0} \sim \frac{1}{s} \qquad \sigma_{\mathrm{F}} = G^2 s$$

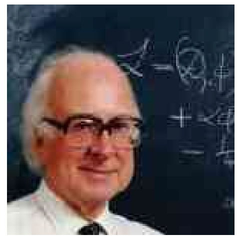
Unitarity bound is violated for:

$$\sigma_{\mathrm{F}} \ge \sigma_{\ell=0} \qquad s \ge \frac{1}{G}$$

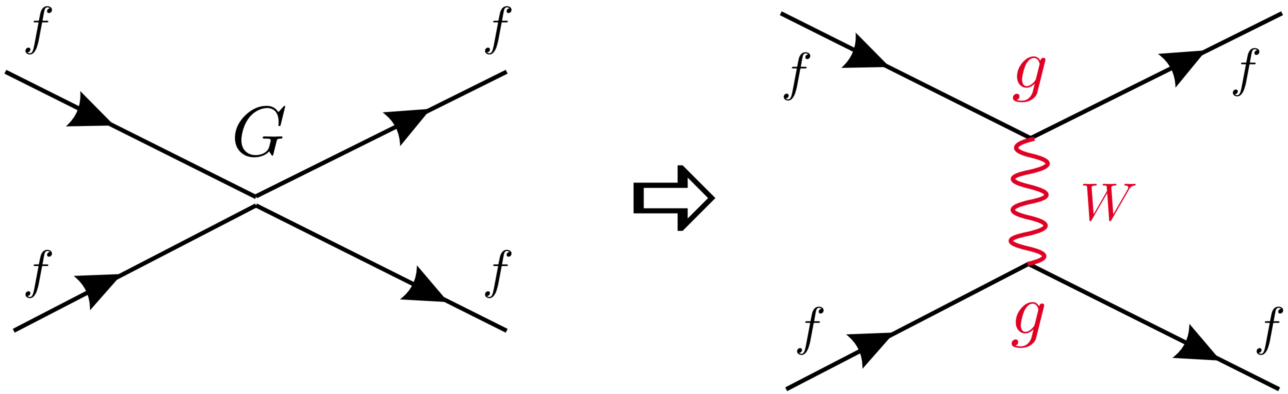
$$E \ge \sqrt{1/G} \sim 300\ \mathrm{GeV}$$

π=2=1 above.





But suppose that:



then

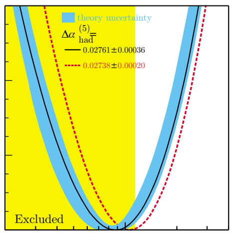
$$\frac{d\sigma}{d|t|} \propto \frac{g^4}{(M_W^2 - t)^2}$$

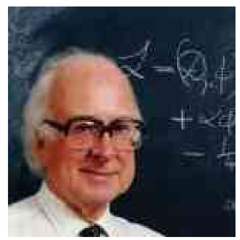
instead of $d\sigma/d|t| \propto G^2$. Low energy phenomenology ($|t|, s \ll M_W^2$) requires $g^2 \approx G \times M_W^2$.

Late 50's, M_W few GeV.

Today: $g^2 \sim 10^{-5}\ \text{GeV}^{-2} \times 80^2\ \text{GeV}^2 \sim 0.064 \sim \alpha$.

$(\pi,\ 2,\ \surd,\ \theta)$





This suggest unifying weak and electromagnetic interactions with the help of vector bosons.

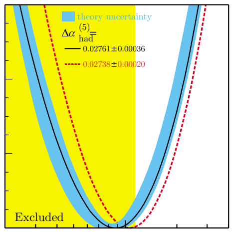
EM: $J_\mu A^\mu$. Current J_μ is a Lorentz vector and is "neutral"

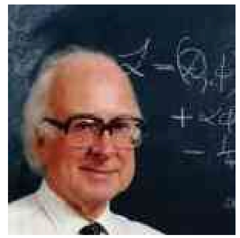
WI $(V-A)_\mu W^\mu$. Current $(V-A)_\mu$ is a Lorentz vector and axial vector, violates parity, is "charged".

Can one do it all from a local gauge invariance principle?

QED follows form an abelian local U(1) invariance. All of QED follows from $\not\partial_\mu \to \not\partial + ieA_\mu$. The current couples to a massless gauge field $H = J_\mu A^\mu$.

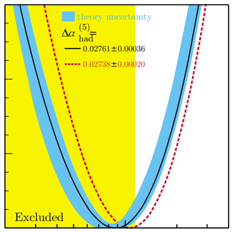
WI are more complex, because of $\Delta Q = \pm 1$. Minimal group is SU(2) but then you get three gauge fields, W^+, W^- and W^0!

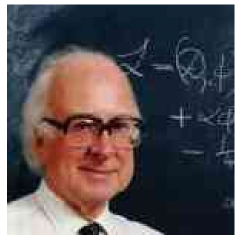




Neutral currents appear in experiments in the late 60's. There is another problem with local gauge theories. Gauge bosons ought to be massless. After a real tour de force – Nambu-Goldston-Higgs – spontaneous symmetry breaking is understood and the gauge bosons are allowed to have a mass. But. . . is the E-W interaction renormalizable?

It turns out it is – t'Hooft-Lee-Veltman – and the E-W interaction the – Glashow-Salam-Weinberg – theory of the so-called Standard Model is finally respectable. It is a local non-abelian gauge theory. The gauge group is $SU(2) \times U(1)$. There are two couplings which are related to α and G_F.

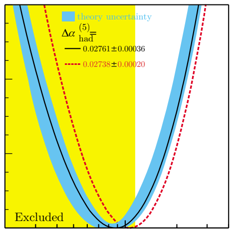


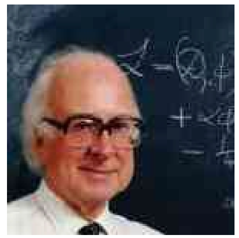


$SU(2)_{\text{w-ispin}} \times U(1)_Y$: 4 generators $\Rightarrow$ 4 gauge fields: W^+, W^0, W^- and B^0.

There is also a mixing angle which gets from W^0_μ–B^0_μ to Z^0_μ–A_μ, with A_μ a mass-less field, the photon.

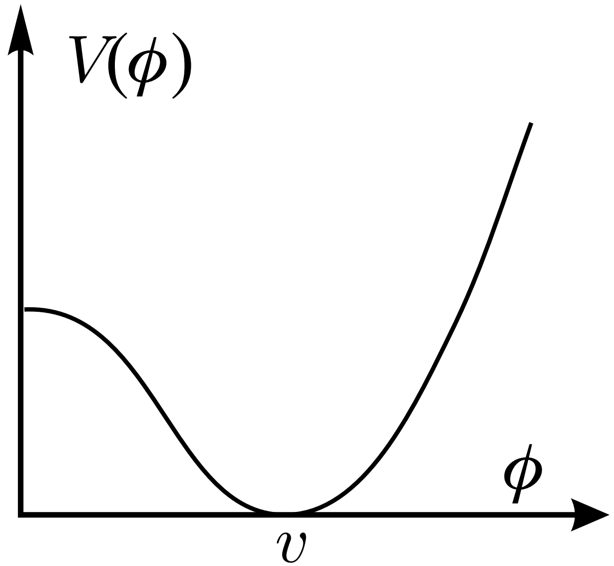
Specifically a complex scalar doublet is introduced in the Lagrangian. The manifest initial symmetry is spontaneously broken. The vacuum acquires non zero energy. Or rather the "true" vacuum, the lowest energy state, corresponds to a non zero value of the scalar field ϕ.



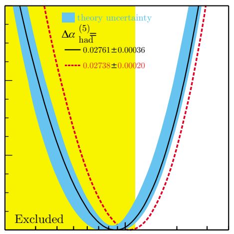


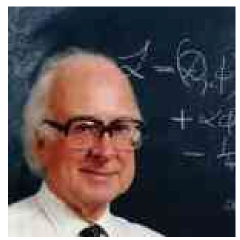
One number is well defined,

$$v = \langle \phi \rangle = \sqrt{\frac{1}{\sqrt{2}\,G}} = 246 \text{ GeV}$$



But because the gauge symmetry is local, three of the degrees of freedom of the Higgs field, $\phi^+, \phi^0, \bar{\phi}^0$ and ϕ^- become the zero helicity states of the gauge bosons which thus acquire mass.





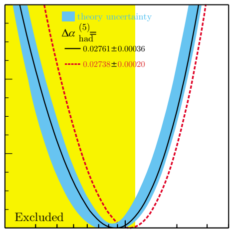
The vector boson masses are

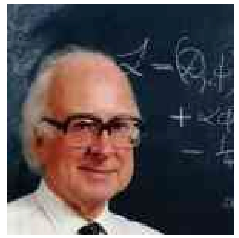
$$M_W = \frac{1}{\sin\theta}\left(\frac{\pi\alpha}{\sqrt{2}G}\right)^{1/2} = \frac{37.3}{\sin\theta}\ \text{GeV}$$

$$M_Z = \frac{M_W}{\cos\theta}$$

One scalar boson survives as an observable elementary particle, it is called the Higgs boson.

So all is left to be done is to find the Higgs.



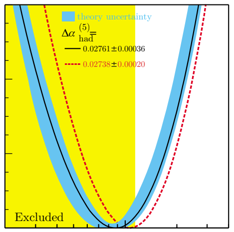


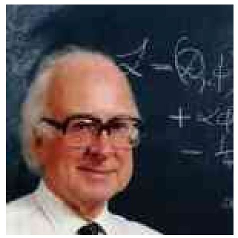
Searching for Higgs

It would help to know how and where, *i.e.*

1. Mass - at least some guess
2. Production and decays or couplings to the world
3. Anything else

It is typical of the SM that it can relate many things but it has not much predictive power about the many parameters that enter into it. The Higgs mass is certainly one such example.



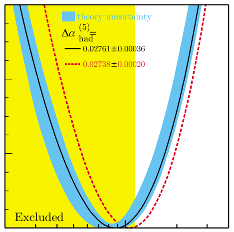


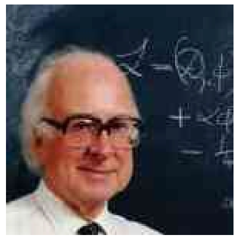
Mass

There is no a priori knowledge about the Higgs mass as well as many other things. But...

In the Lagrangian we find a quartic coupling $\lambda\phi^4$, where λ is an arbitrary dimensionless coupling constant. The Higgs mass is given by $M_H = v\sqrt{\lambda/2}$. What is λ?.

From effective HH coupling, $M_H > \alpha v$
$M_H >$ 7.3 GeV. If $<$, the vacuum becomes unstable...!
This limit can be somewhat softened.





There is an exception: if m_t~80 GeV the lower bound disappears:

$M_H > 0$ if m_t=80 GeV

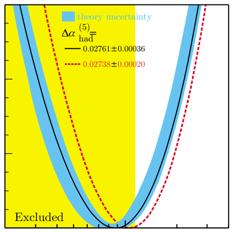
This is just of historical interest.

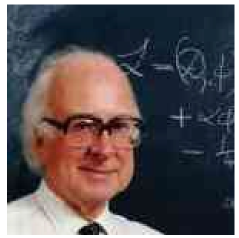
Upper limits.

If $M_H > 1$ TeV than WW scattering exceeds unitarity.

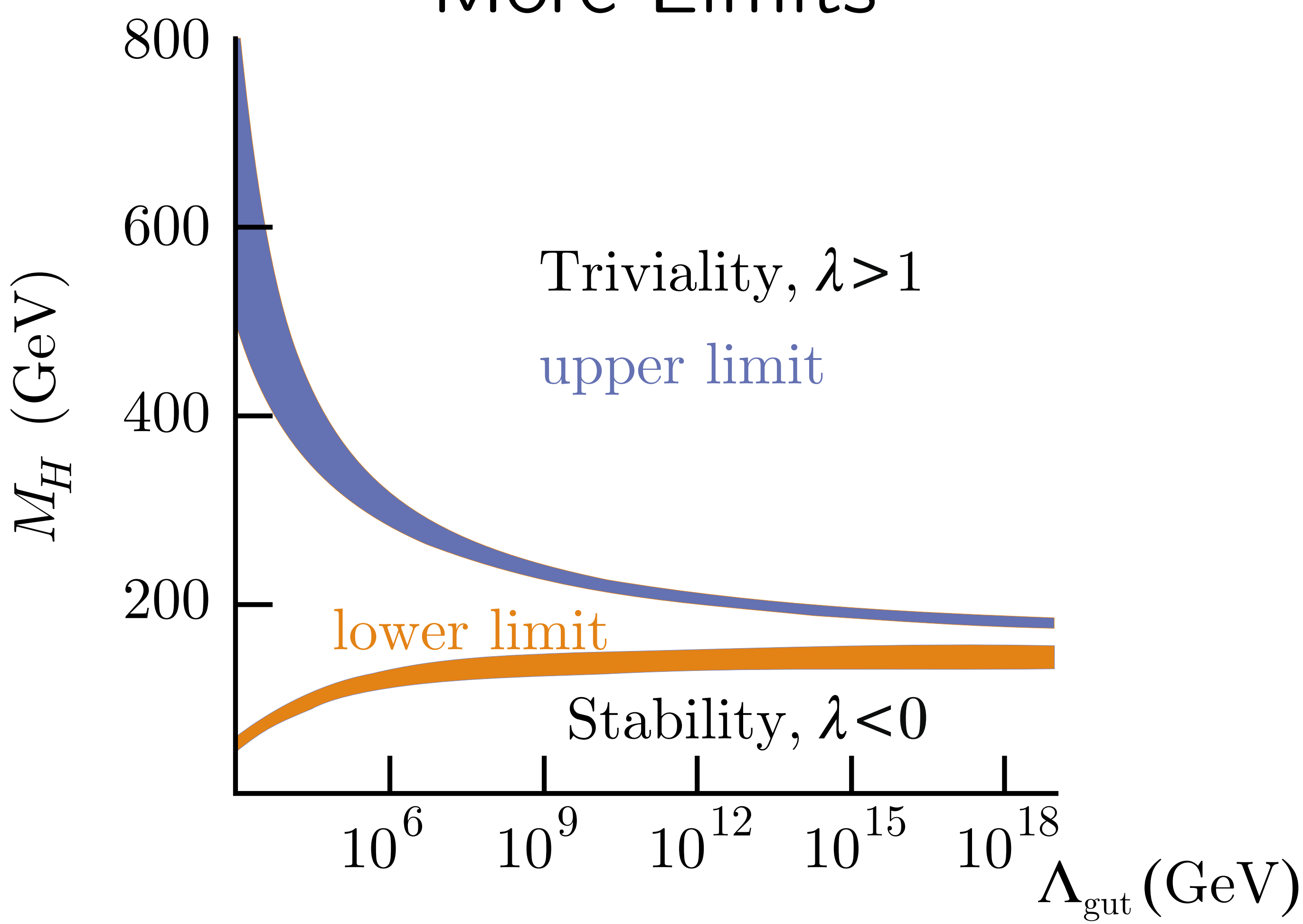
What, again?

Also for M_H~1 TeV, Γ_H~1 TeV...

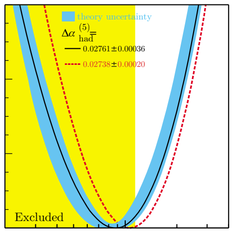


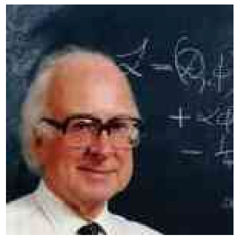


More Limits



Higgs mass limit vs new physics scale Λ. Upper unitarity, lower stability.





Radiative Corrections

Example:

$$M_W = \frac{(\pi\alpha/\sqrt{2}G)^{1/2}}{\sin\theta(1-\Delta r)}$$

where Δr are the $SU(2) \times U(1)$ radiative corrections.

$\Delta r = \Delta r_0 - \rho_t / \tan^2\theta + \mathcal{O}(\log M_H/\Lambda)$

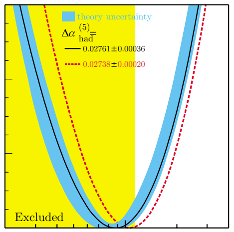
$\Delta R_0 = 1 - \alpha/\alpha(M_Z) = 0.0664$

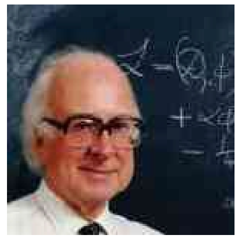
$\rho_t = \ldots G m_t^2 \ldots = 0.00925 \times (m_t/174.3\ \text{GeV})^2 + \text{logs}$

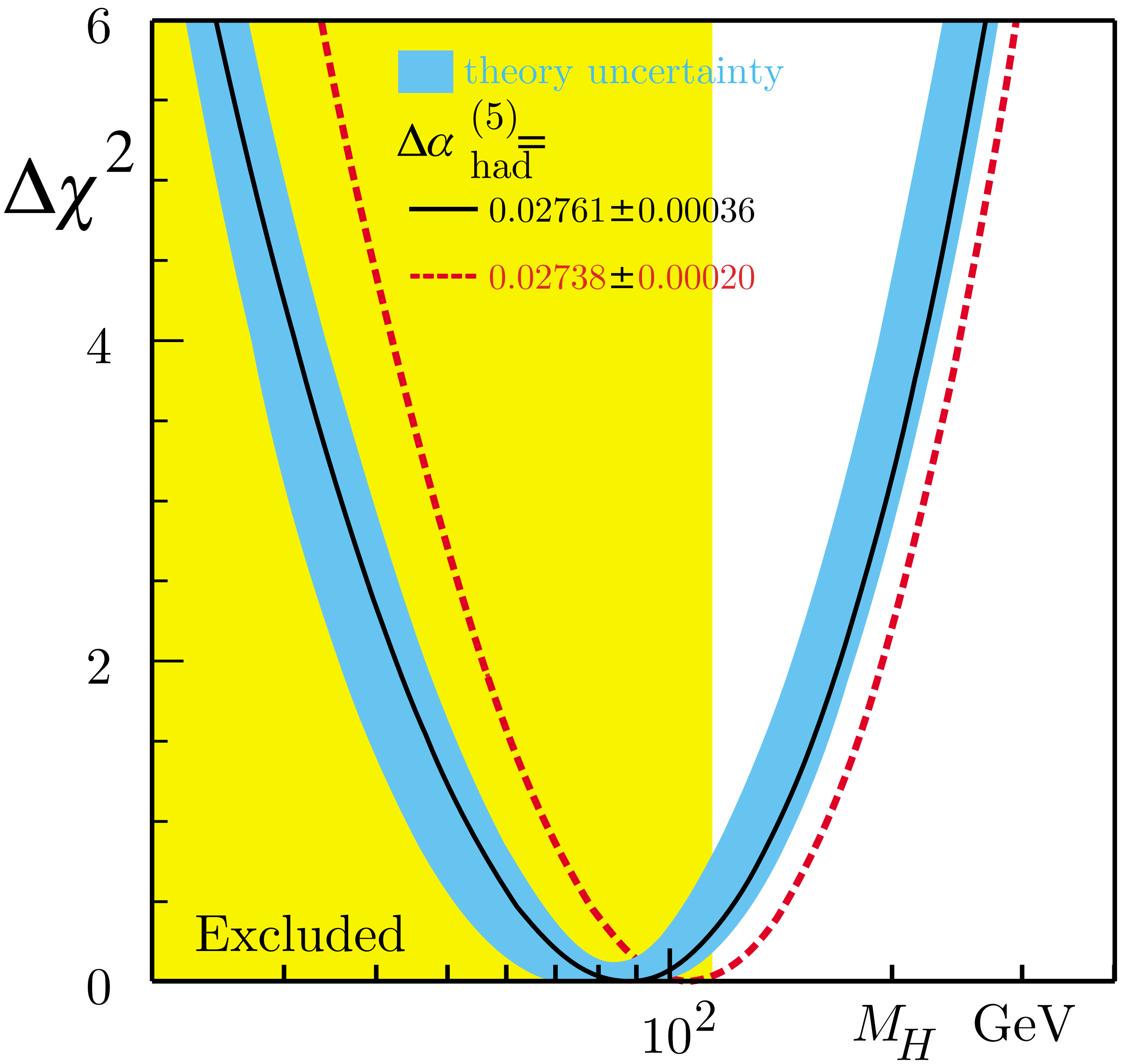
predicts m_t, partly cancels QED

$\Delta r = 0.0350 \pm 0.0019 \pm 0.0002.$ Last error from $\alpha(M_Z)$

From M_Z, M_W, m_t, etc., find M_H.

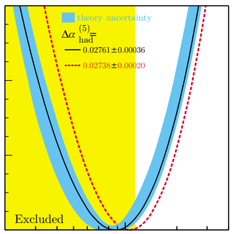


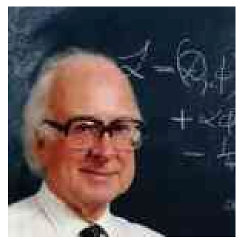




$M_H = 88^{+53}_{-35}$ GeV

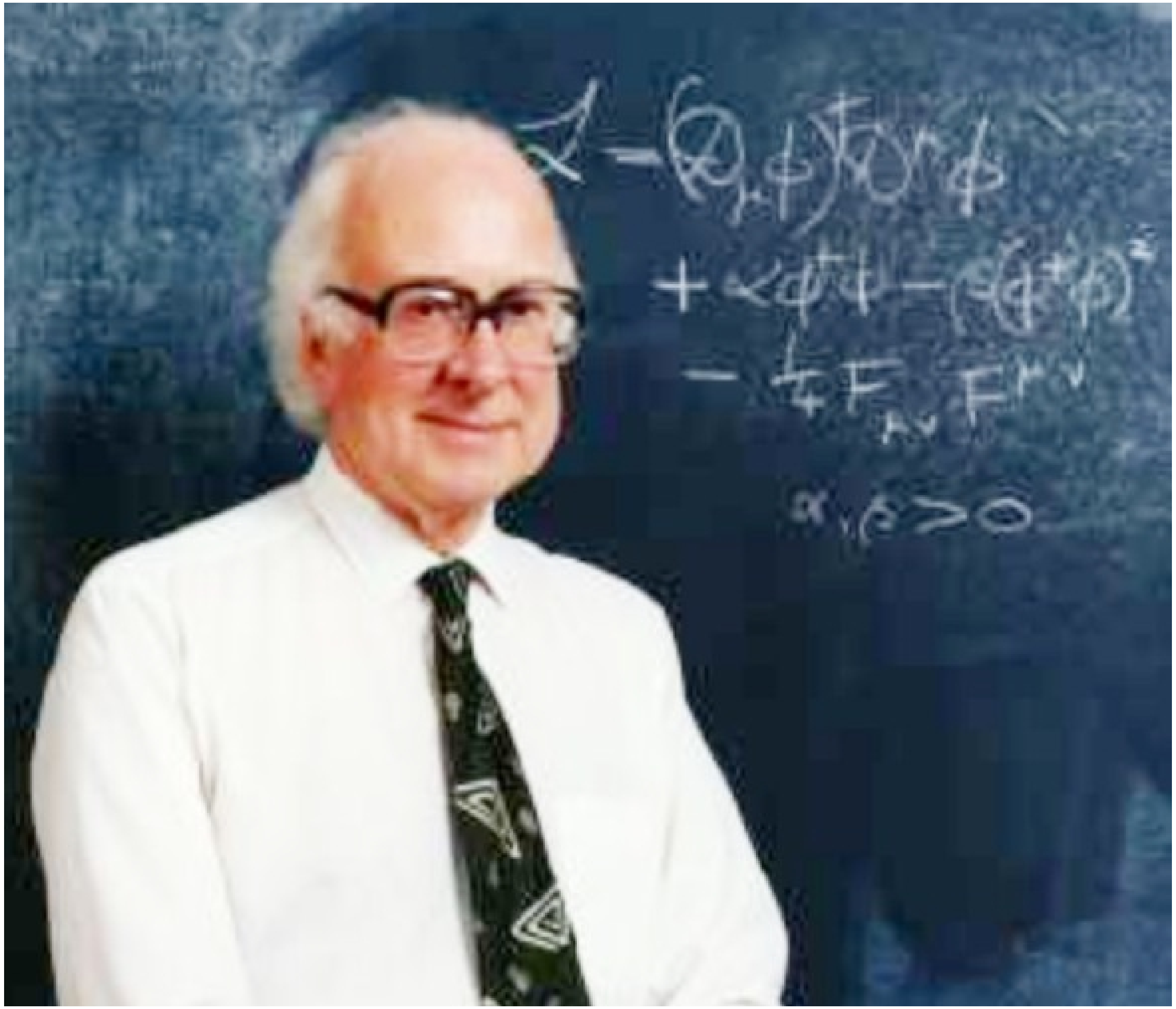
$M_H < 196$ GeV (95% CL)

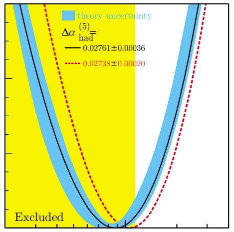


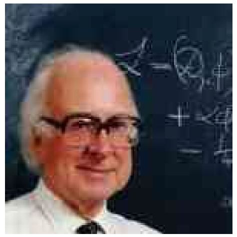


Breaking Symmetry

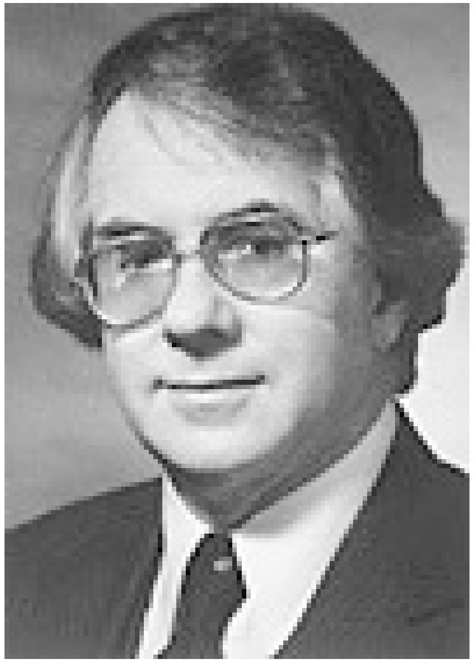
Peter
Higgs





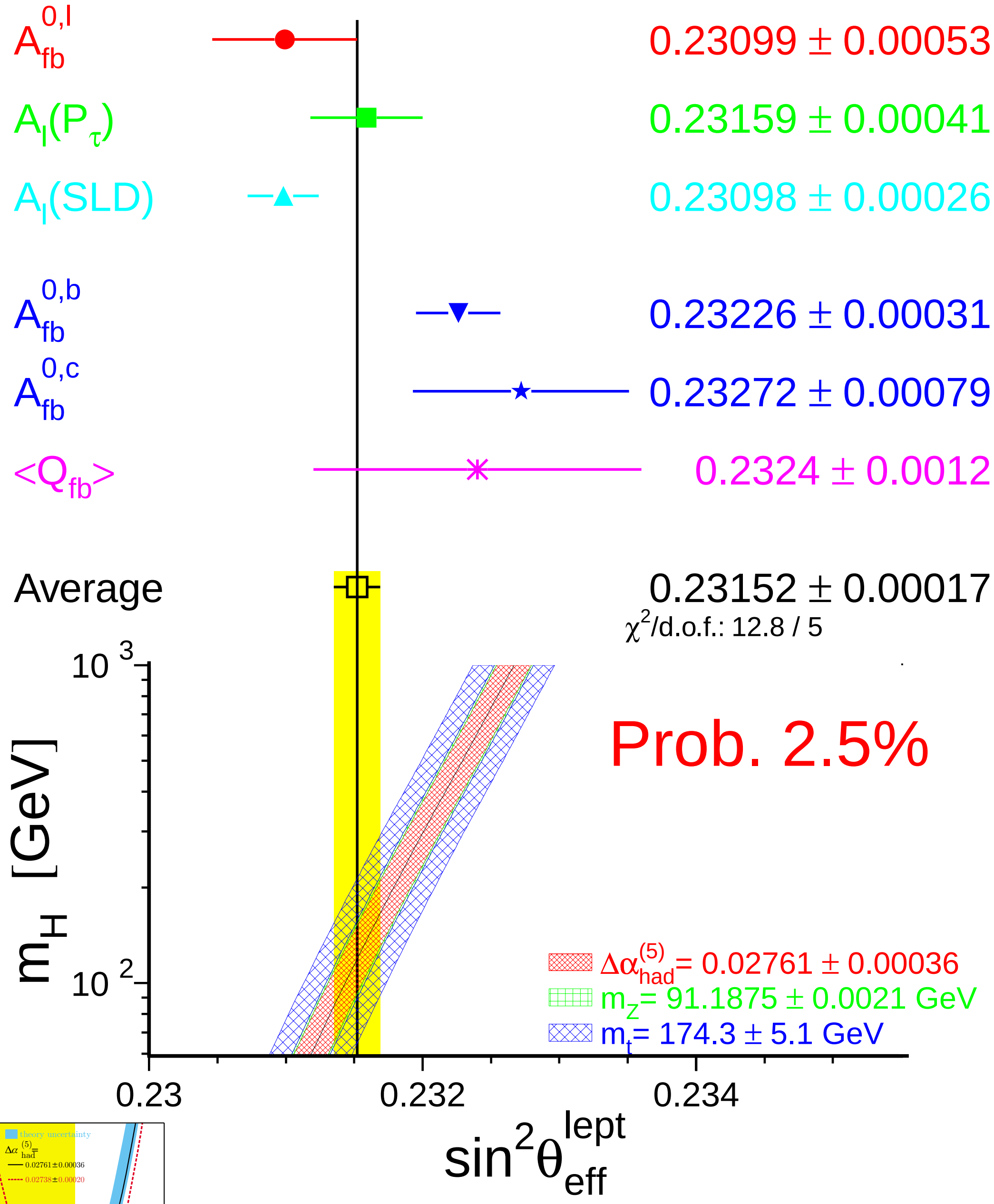


Restoring Symmetry



Glashow Salam Weinberg

However. . .



$\sin^2\theta_{eff}^{lept}$ from only

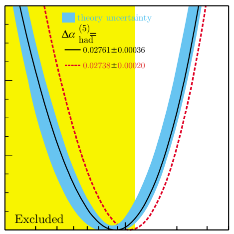
leptons	.23113 ± .00021
hadrons	.23230 ± .00029

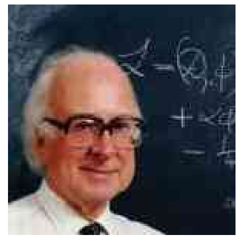
Either:

- Statistical fluctuation,
- unknown sources of systematic errors,
- or evidence for new physics.

Note:

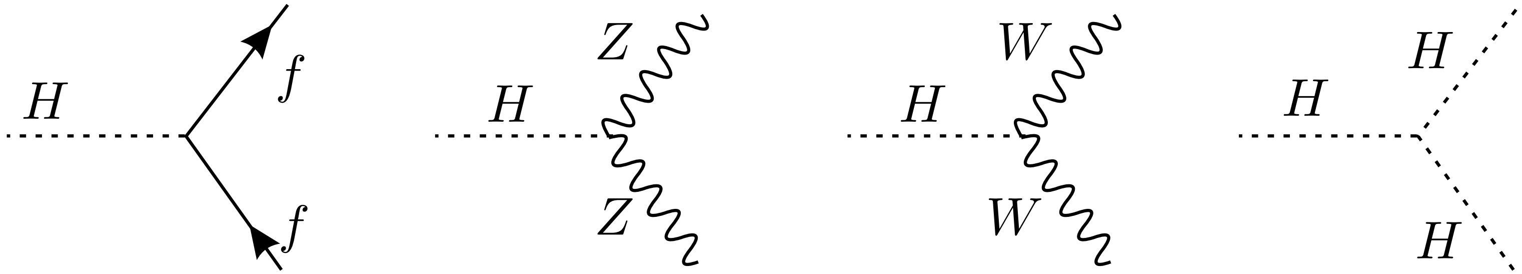
Only average $\sin^2\theta_{eff}$ consistent with m_H O(100 GeV) .





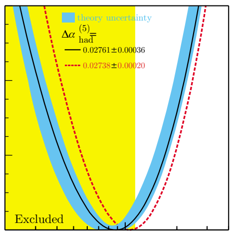
Production and decay

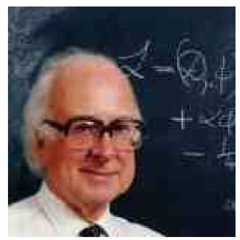
The Higgs couples universally to fermion and vector bosons



and therefore also to photons and gluons

Couplings $\propto$(mass). We can chose the best way to detect it!



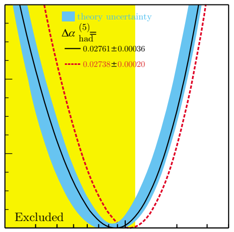


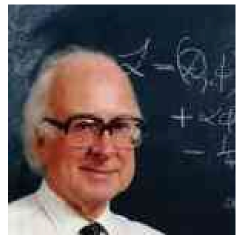
$$\Gamma(H \to gg) = \left(\frac{\alpha M_H}{8\sin^2\theta}\right) \frac{M_H^2}{M_W^2} \frac{\alpha_s^2}{9\pi^2} \left|\sum_q I(M_H^2/m_q^2)\right|^2$$

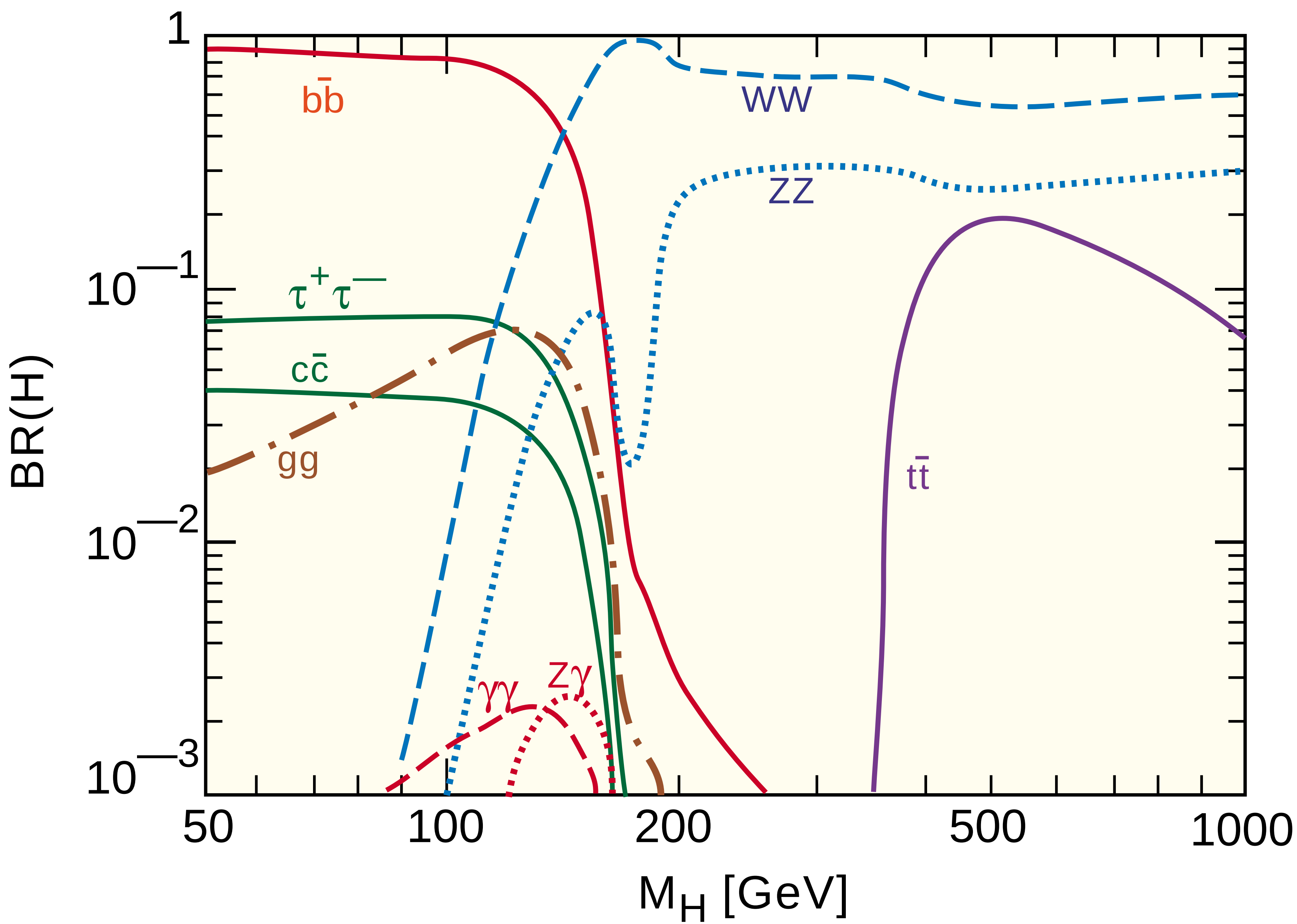
$$I(0) = 1, I(\infty) = 0$$

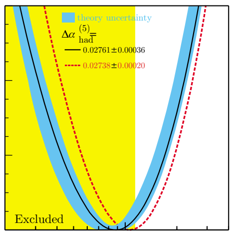
$\Gamma(H \to \gamma\gamma \ldots)$etc.

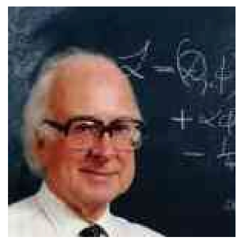
Graph!






1
10^{-1}
10^{-2}
10^{-3}
BR(H)
$b\bar{b}$
WW
ZZ
$\tau^+\tau^-$
$c\bar{c}$
gg
$t\bar{t}$
γγ
Zγ
50
100
200
500
1000
M_H [GeV]

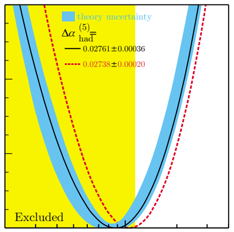


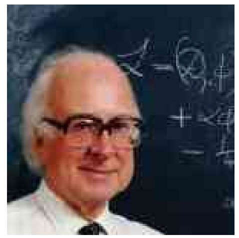


Yield vs background

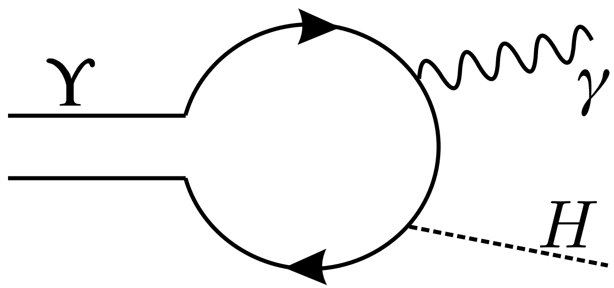
As long as $\Gamma(H) < 1$ GeV, a rare final state can be better than a a copious one.

- e^+e^- $\mu^+\mu^-$ can be measured to few %.
- $\gamma\gamma$ could have best resolution for low M_H, BR lowest.
- $\tau\tau$ is characteristic but has no mass resolution.
- Jet-jet has poor mass resolution but b-tag might help
- Missing energy, always an interesting signal, but. . .

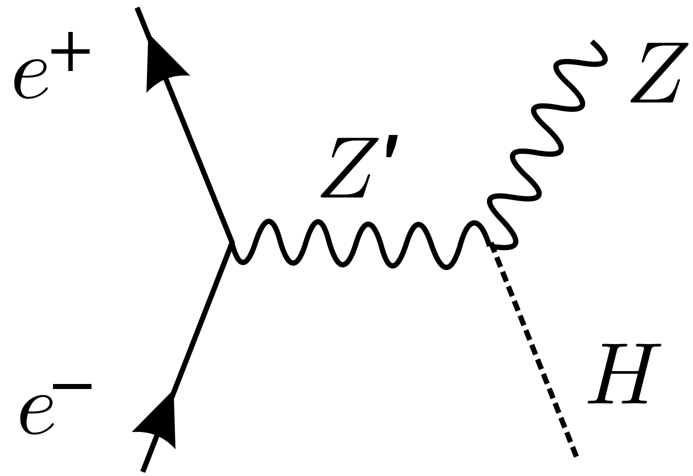


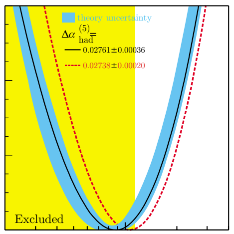


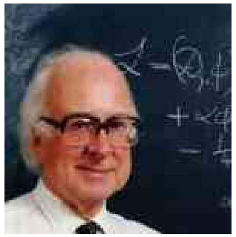
Very light Higgs and axions. Heavy quarks couple more to Higgs. Can search for light Higgs in $\Upsilon \to \gamma + H$. CUSB excluded Higgs with $M_H <$ 3-4 GeV



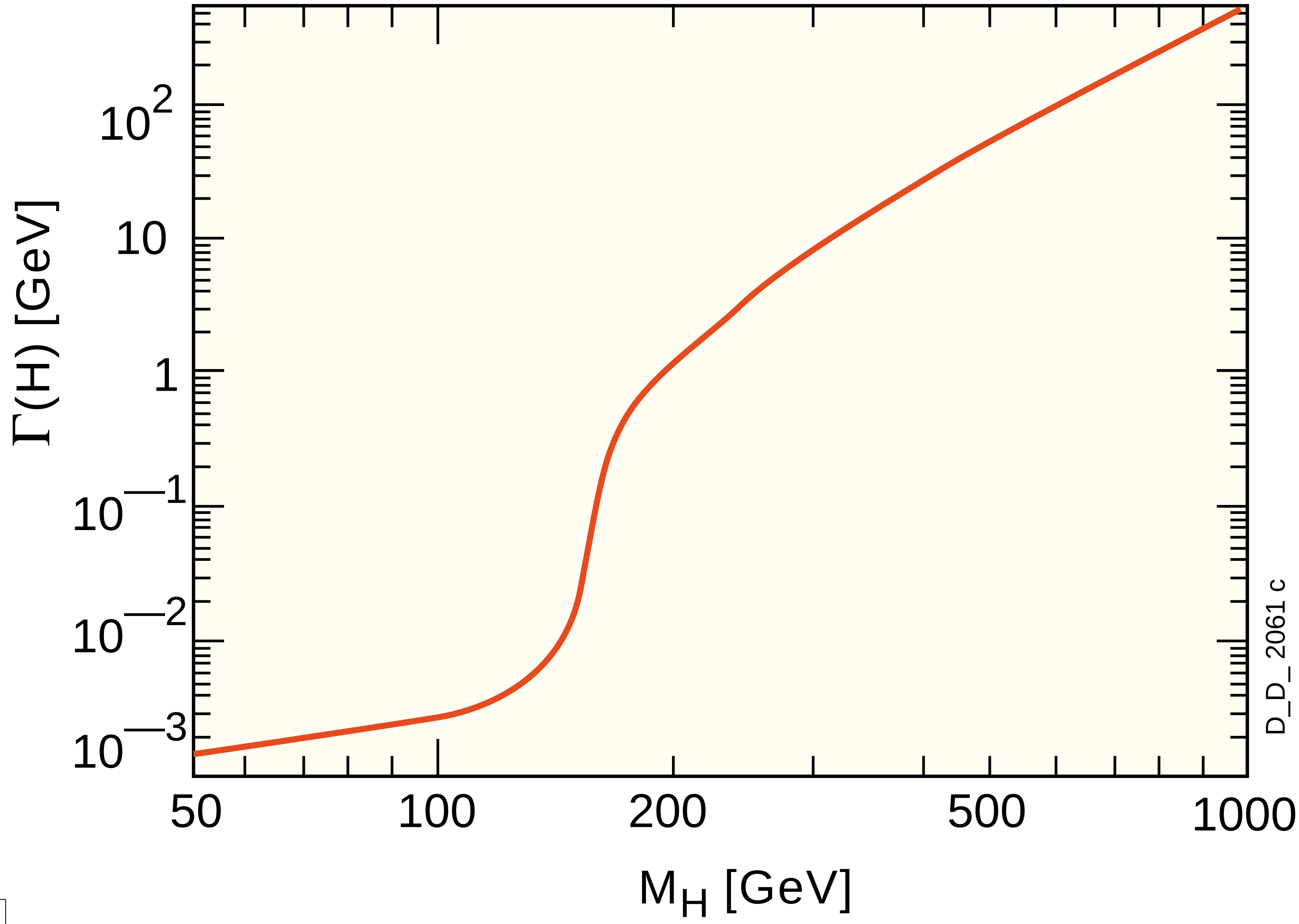
Generic Higgs production at e^+e^- colliders

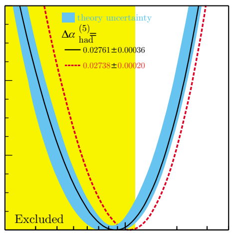


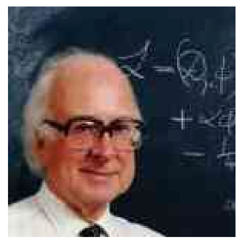




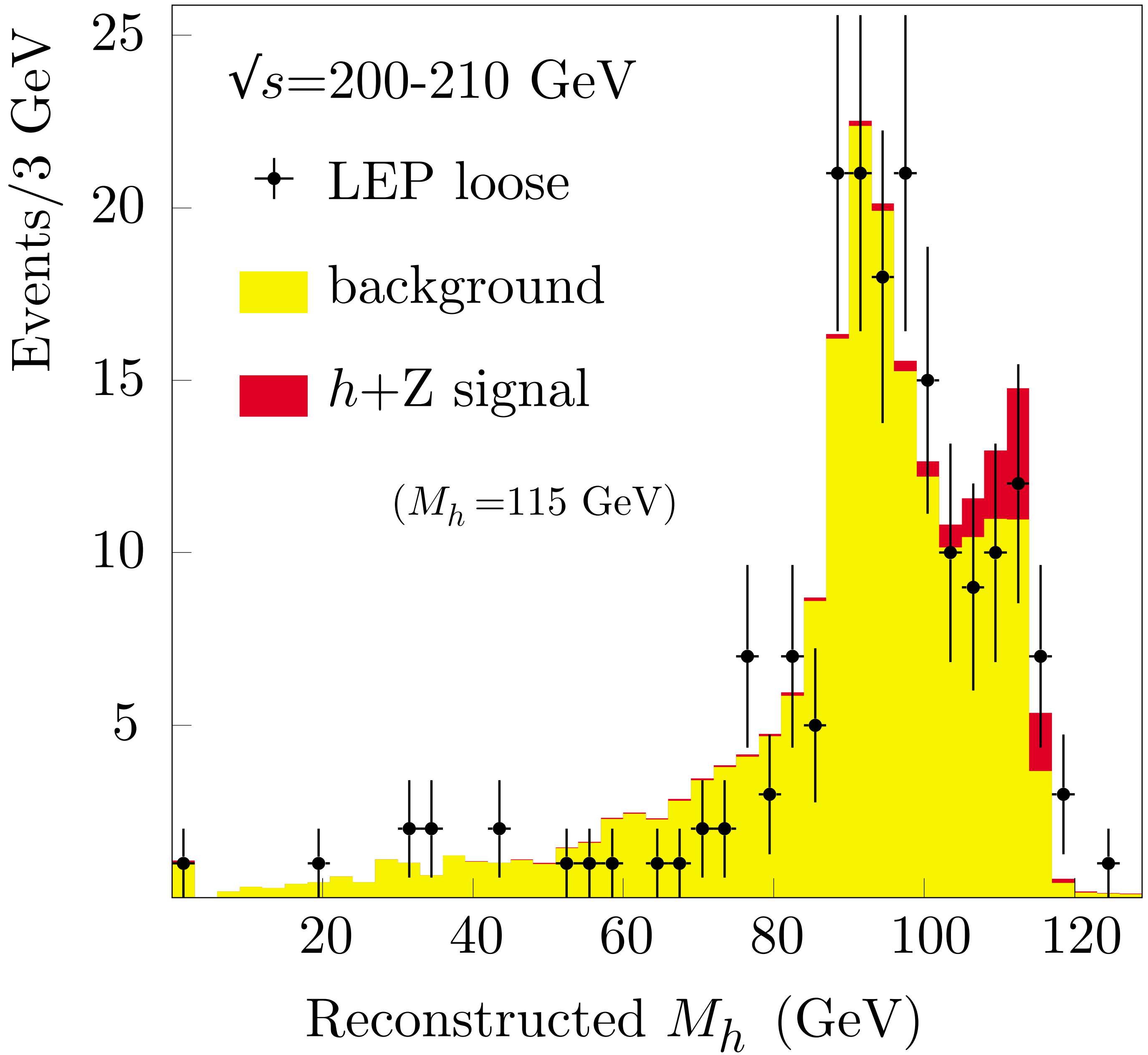
Higgs width



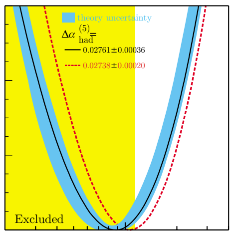




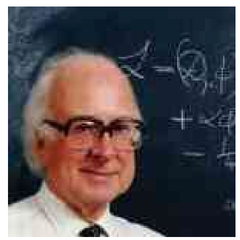
LEP



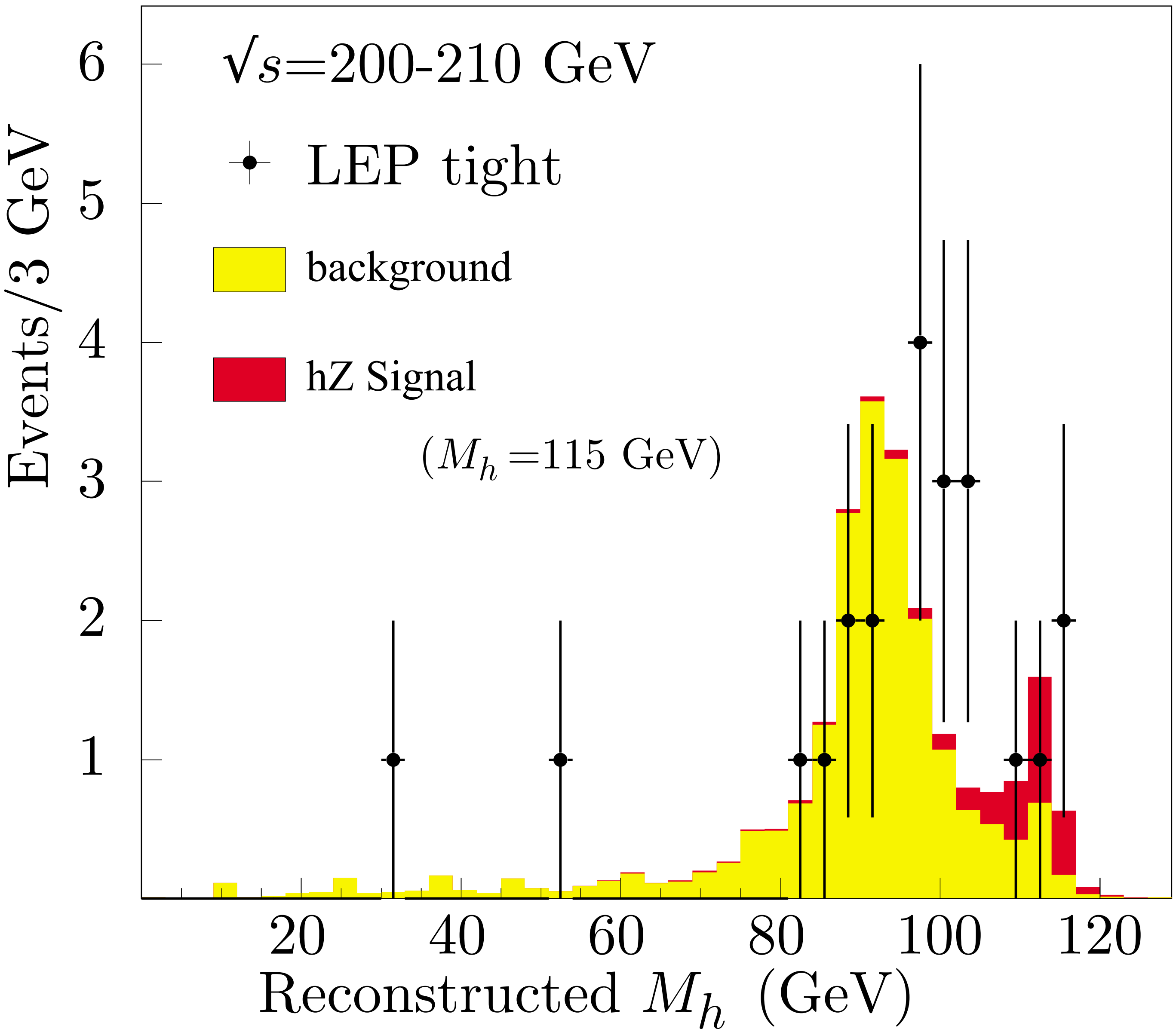
√s=200-210 GeV
LEP loose
background
h+Z signal
(M_h =115 GeV)
Events/3 GeV
25
20
15
10
5
20
40
60
80
100
120
Reconstructed M_h (GeV)



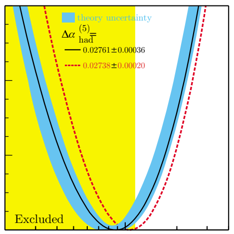
Excluded



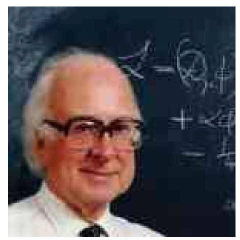
LEP



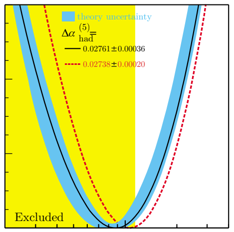
√s=200-210 GeV
LEP tight
background
hZ Signal
(M_h =115 GeV)
Events/3 GeV
Reconstructed M_h (GeV)
1
2
3
4
5
6
20
40
60
80
100
120

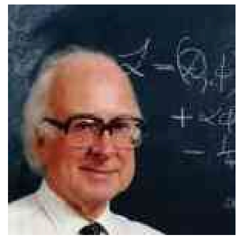


Excluded



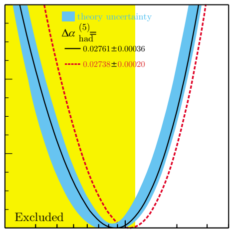
	Expt	E_{cm}	Decay	M_H (GeV)	ln$(1 + s/b)$ @115 GeV
1	Aleph	206.7	4-jet	114.3	1.73
2	Aleph	206.7	4-jet	112.9	1.21
3	Aleph	206.5	4-jet	110.0	0.64
4	L3	206.4	E-miss	115.0	0.53
5	Opal	206.6	4-jet	110.7	0.53
6	Delphi	206.7	4-jet	114.3	0.49
7	Aleph	205.0	Lept	118.1	0.47
8	Aleph	208.1	Tau	115.4	0.41
9	Aleph	206.5	4-jet	114.5	0.40
10	Opal	205.4	4-jet	112.6	0.40
11	Delphi	206.7	4-jet	97.2	0.36
12	L3	206.4	4-jet	108.3	0.31
13	Aleph	206.5	4-jet	114.4	0.27
14	Aleph	207.6	4-jet	103.0	0.26
15	Opal	205.4	E-miss	104.0	0.25
16	Aleph	206.5	4-jet	110.2	0.22
17	L3	206.4	E-miss	110.1	0.21
18	Opal	206.4	E-miss	112.1	0.20
19	Delphi	206.7	4-jet	110.1	0.20
20	L3	206.4	E-miss	110.1	0.18

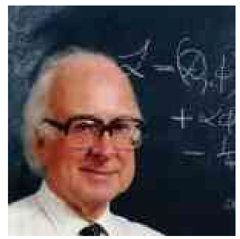




LEP Limitation

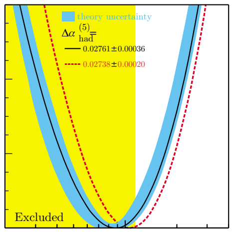
If 2σ signal at M_H=115 GeV, it would have taken $\geq 6\times$ more integrated luminosity to reach a 5σ proof of the Higgs existence.

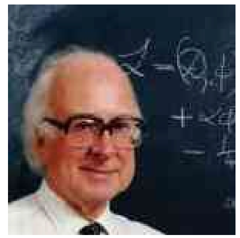




The Future

The next place where to continue the Higgs hunt is FNAL at the Tevatron operated as collider at $W=\sqrt{s}$=2 TeV.





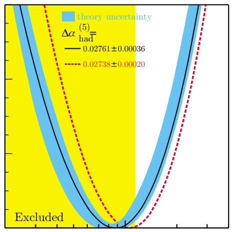
Lots more to do

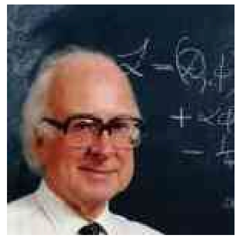
Even if a Higgs is found, lots more needs doing: BR's, $h, H, A, H^{\pm}$, ratio of vev's – see later

That is in any case a job for LHC, W=14 TeV.

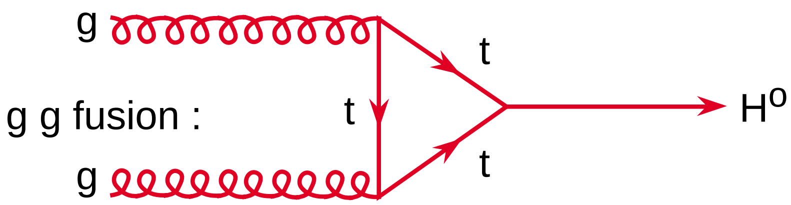
When:

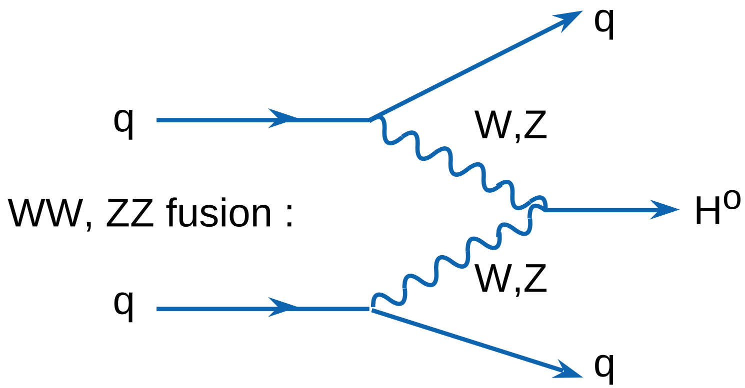
1. CDF (with Karlsruhe) and DØ. OK for low mass. 2002??
2. LHC. Atlas and CMS (with Karlsruhe), but it will be a few years before there is an LHC.

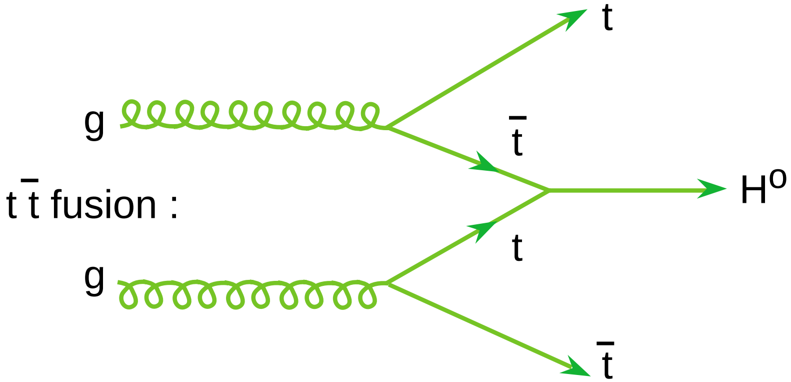


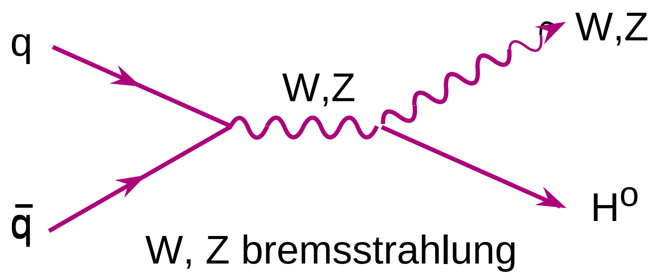


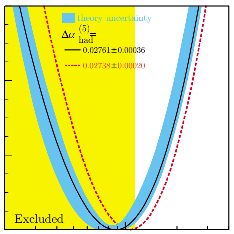
Higgs production in hadron collisions

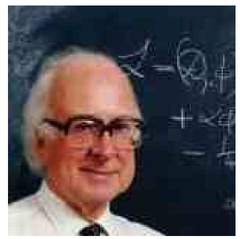




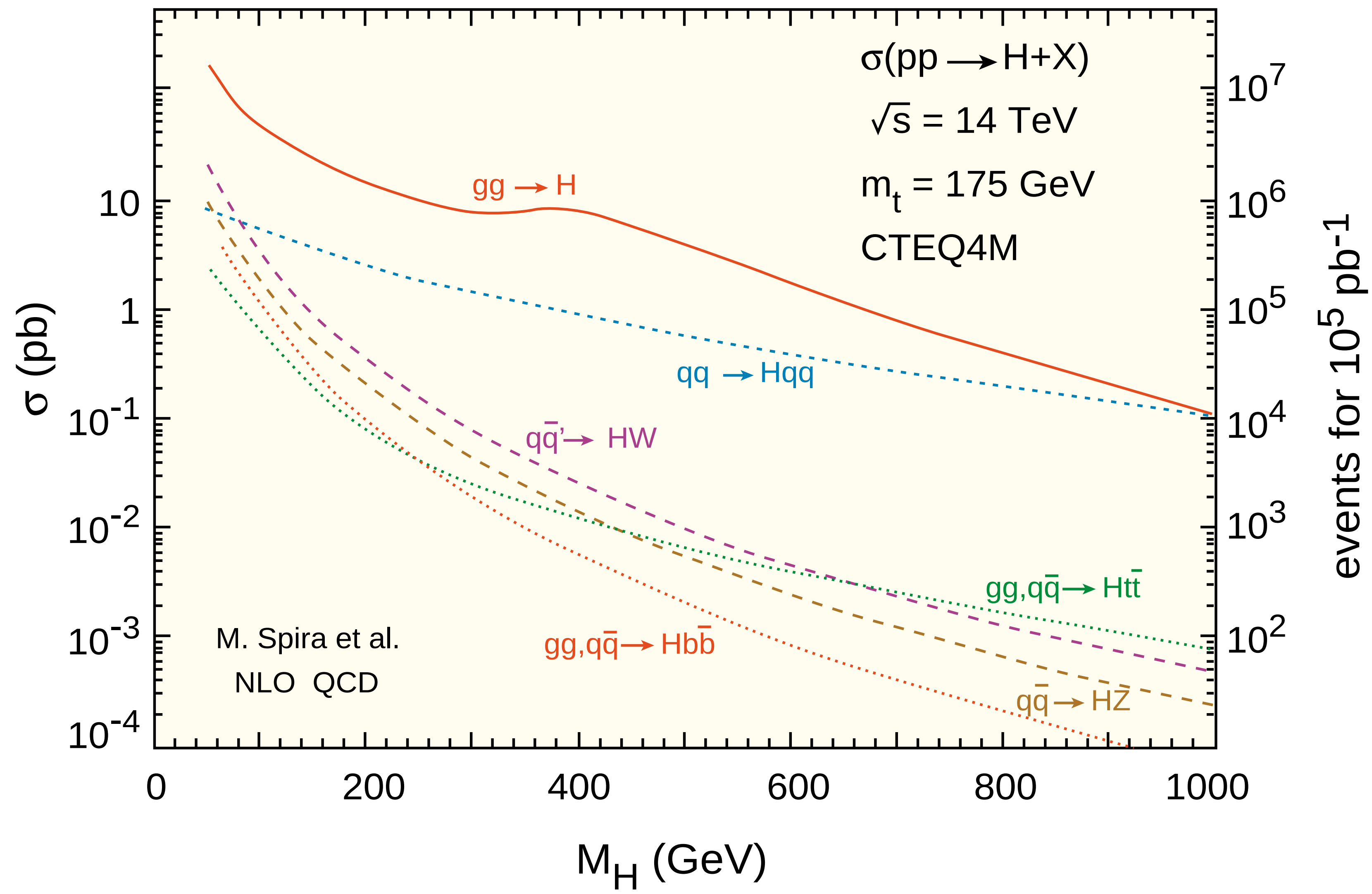


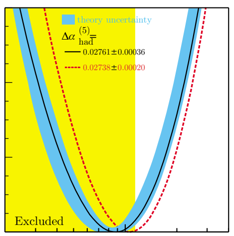


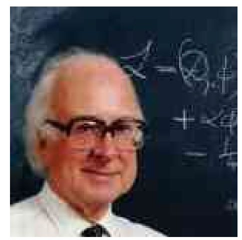




Higgs production in hadron collisions

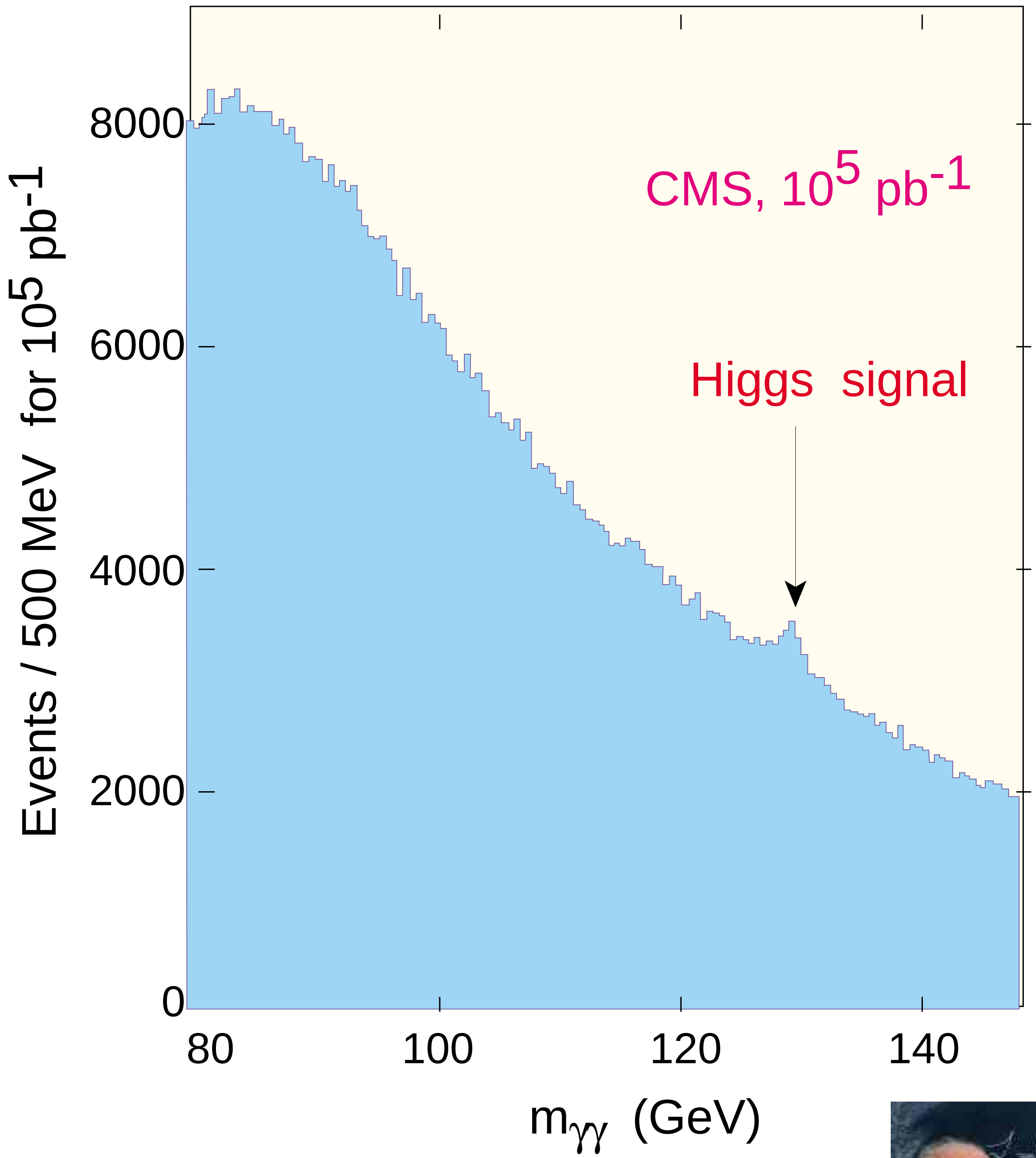




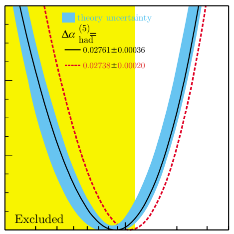


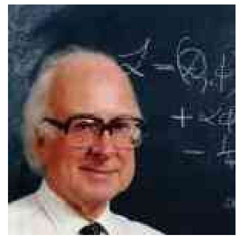
$H_{SM} \rightarrow \gamma\gamma$

Simulated 2γ mass plot
for 10^5 pb^{-1} m_H =130 GeV
in the lead tungstate calorimeter



This is an advertising





Many Higgs-bosons

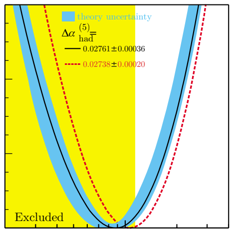
Supersymmetry adds more Higgs. In MSSM just one more complex doublet. No new Higgs is necessary for giving mass to additional gauge boson and we now have 5 physical particles:

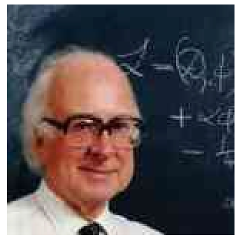
1. Two neutral scalars, h^0, H^0
2. One neutral pseudoscalar, A^0
3. Two charged scalars, H^+, H^-

At tree level:

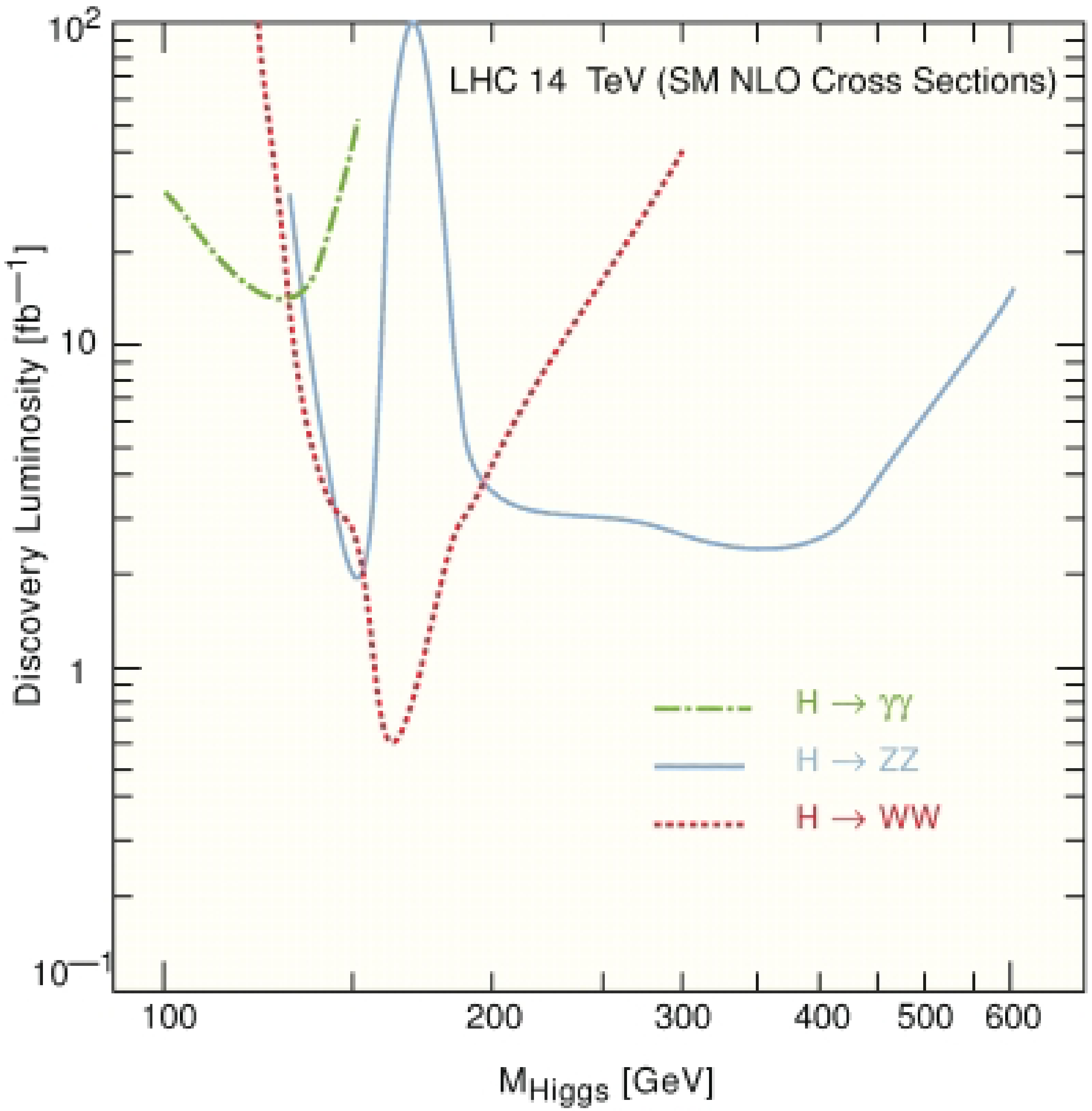
$$M_h \leq M_Z \leq M_H \qquad M_A \leq M_H \qquad M_{H^\pm} \leq M_{W^\pm}$$

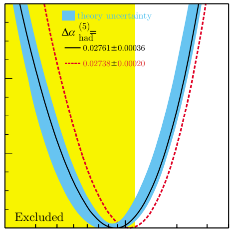
After radiative corrections $M_h \leq 135$ GeV.

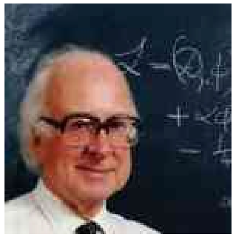




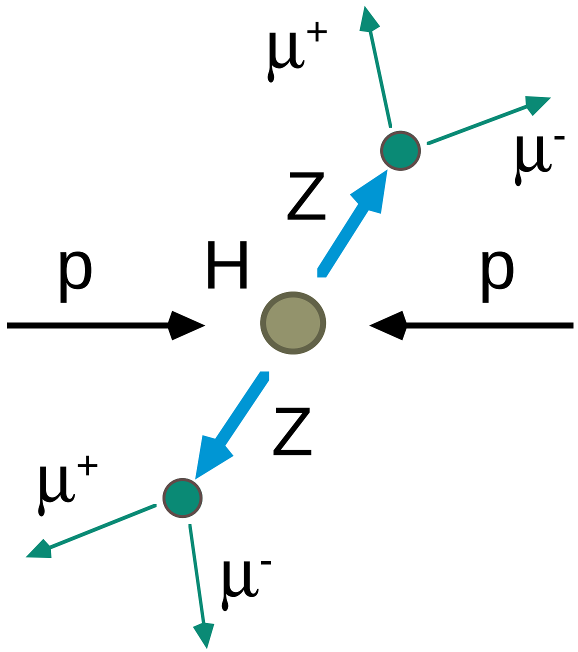
Energy and Luminosity





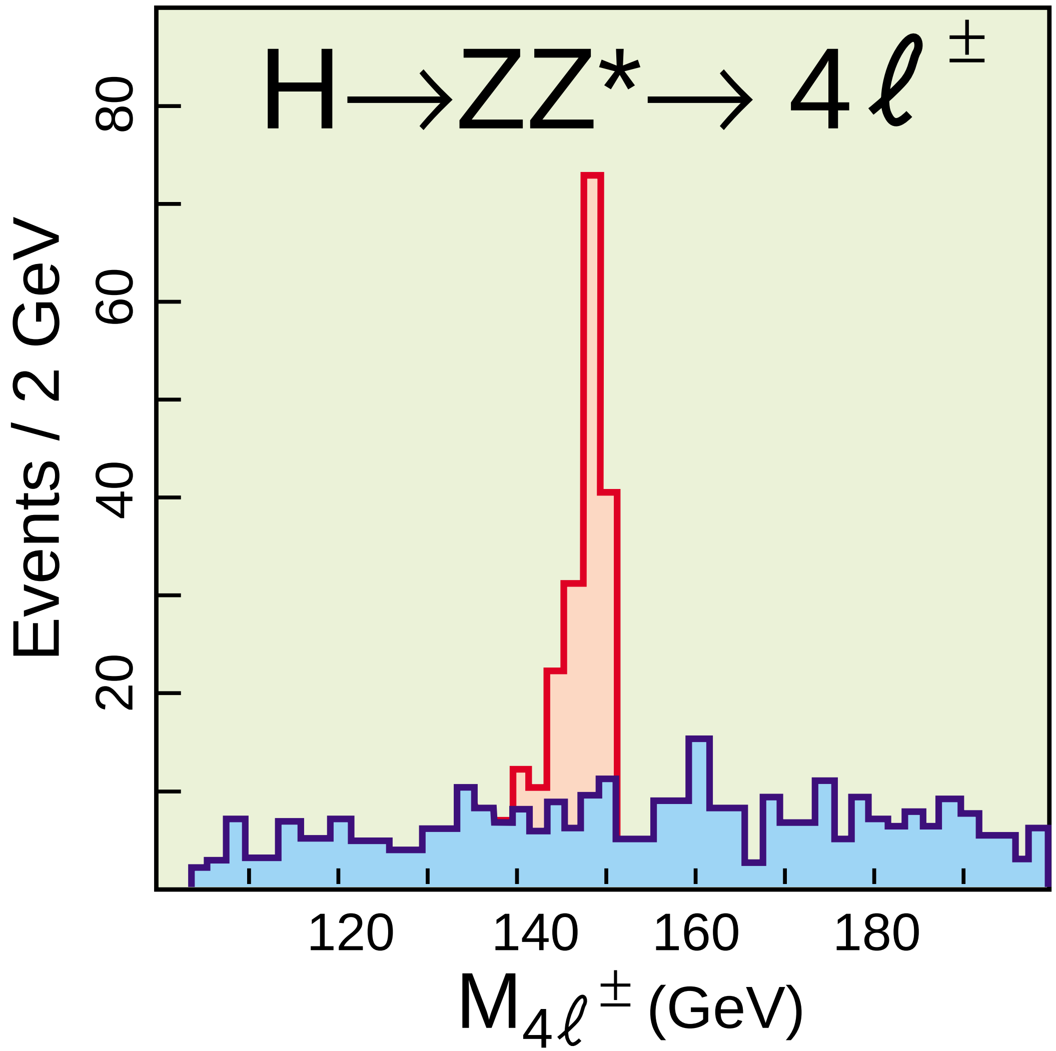


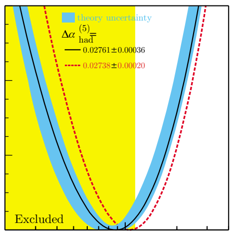
Clean signals

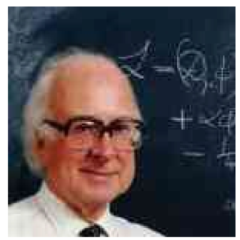


$\mathrm{BR}(H \to 4\mu) 4 \times 10^{-4}$

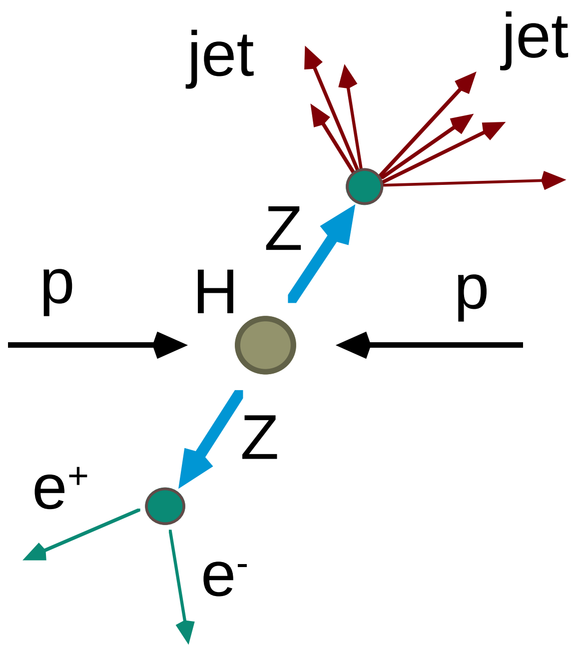
$\mathrm{BR}(H \to 4\ell) 1.2 \times 10^{-3}$

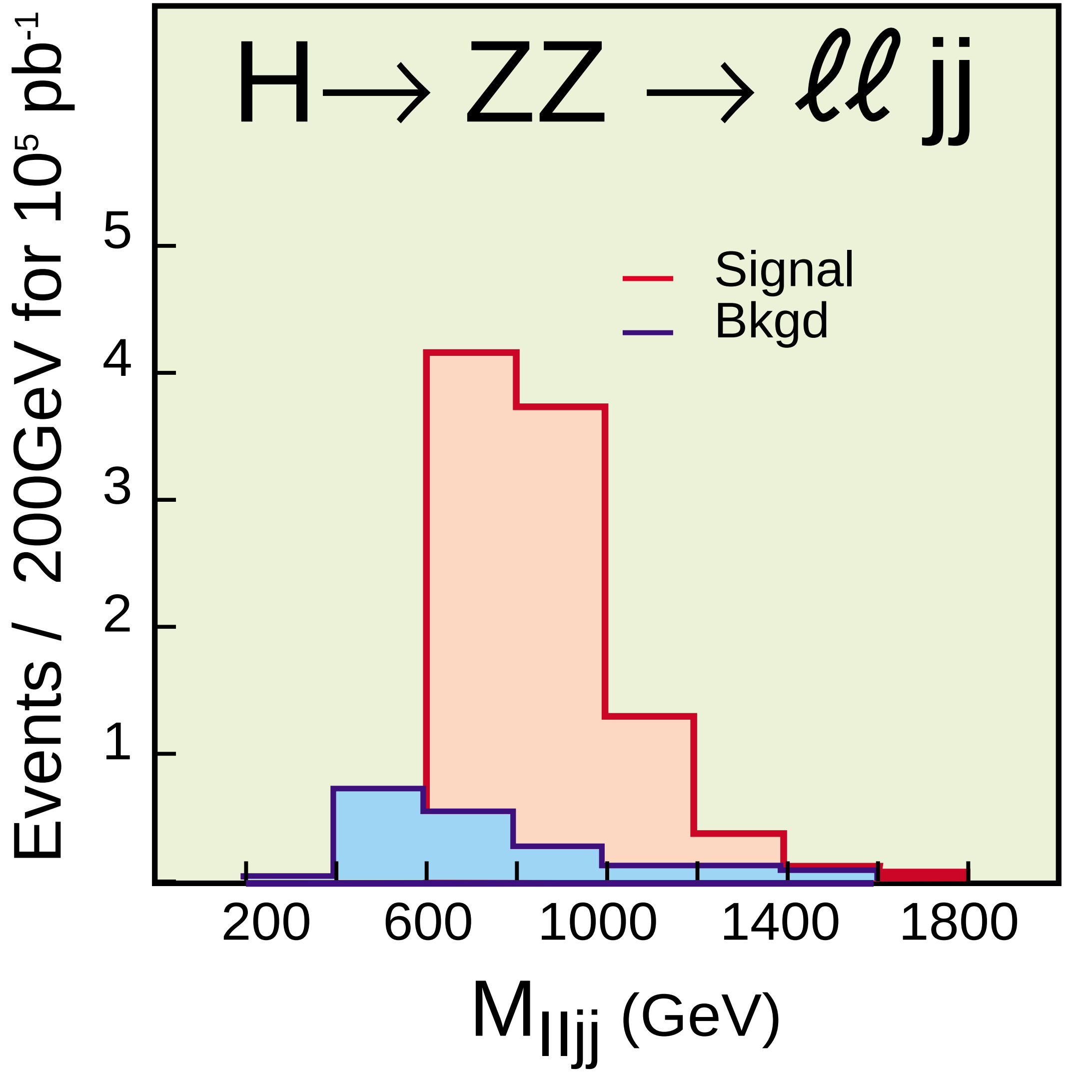


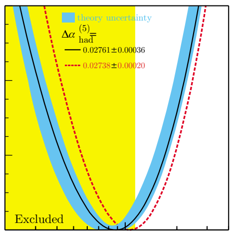


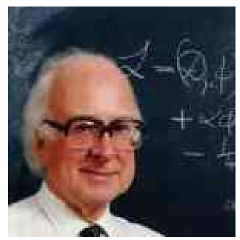


High mass Higgs

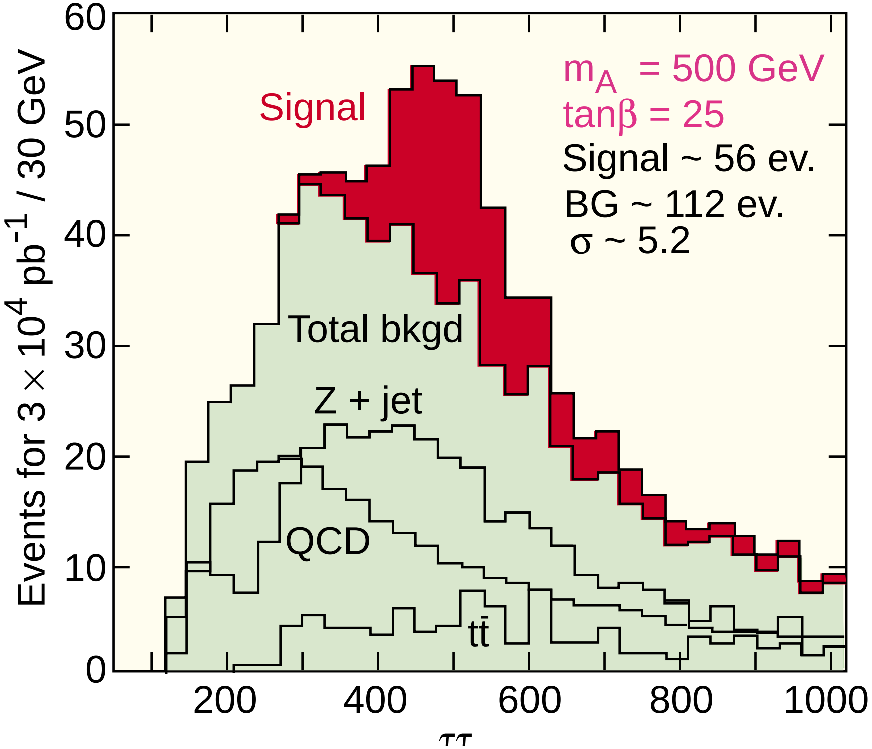




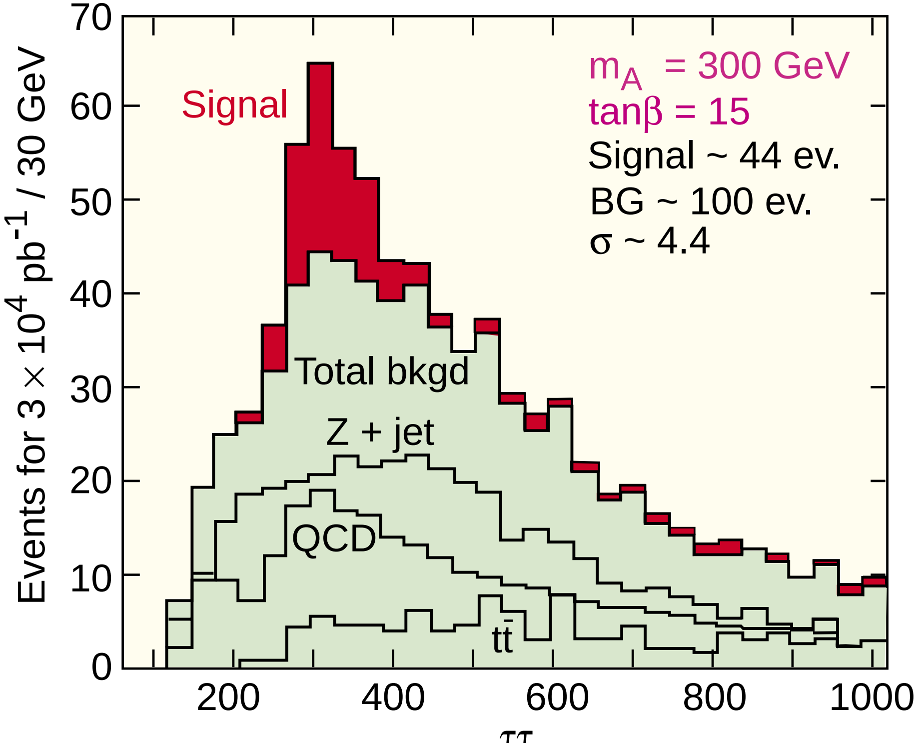




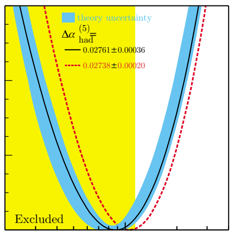
Search for A



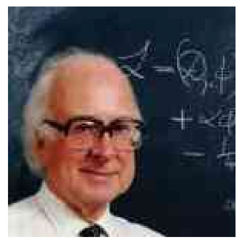
Signal
m_A = 500 GeV
tanβ = 25
Signal ~ 56 ev.
BG ~ 112 ev.
σ ~ 5.2
Total bkgd
Z + jet
QCD
$t\bar{t}$
Events for 3×10^4 pb^{-1} / 30 GeV
0
10
20
30
40
50
60
200
400
600
800
1000



Signal
m_A = 300 GeV
tanβ = 15
Signal ~ 44 ev.
BG ~ 100 ev.
σ ~ 4.4
Total bkgd
Z + jet
QCD
$t\bar{t}$
Events for 3×10^4 pb^{-1} / 30 GeV
0
10
20
30
40
50
60
70
200
400
600
800
1000



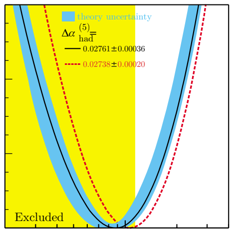
Excluded

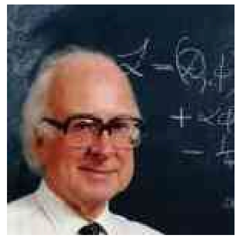


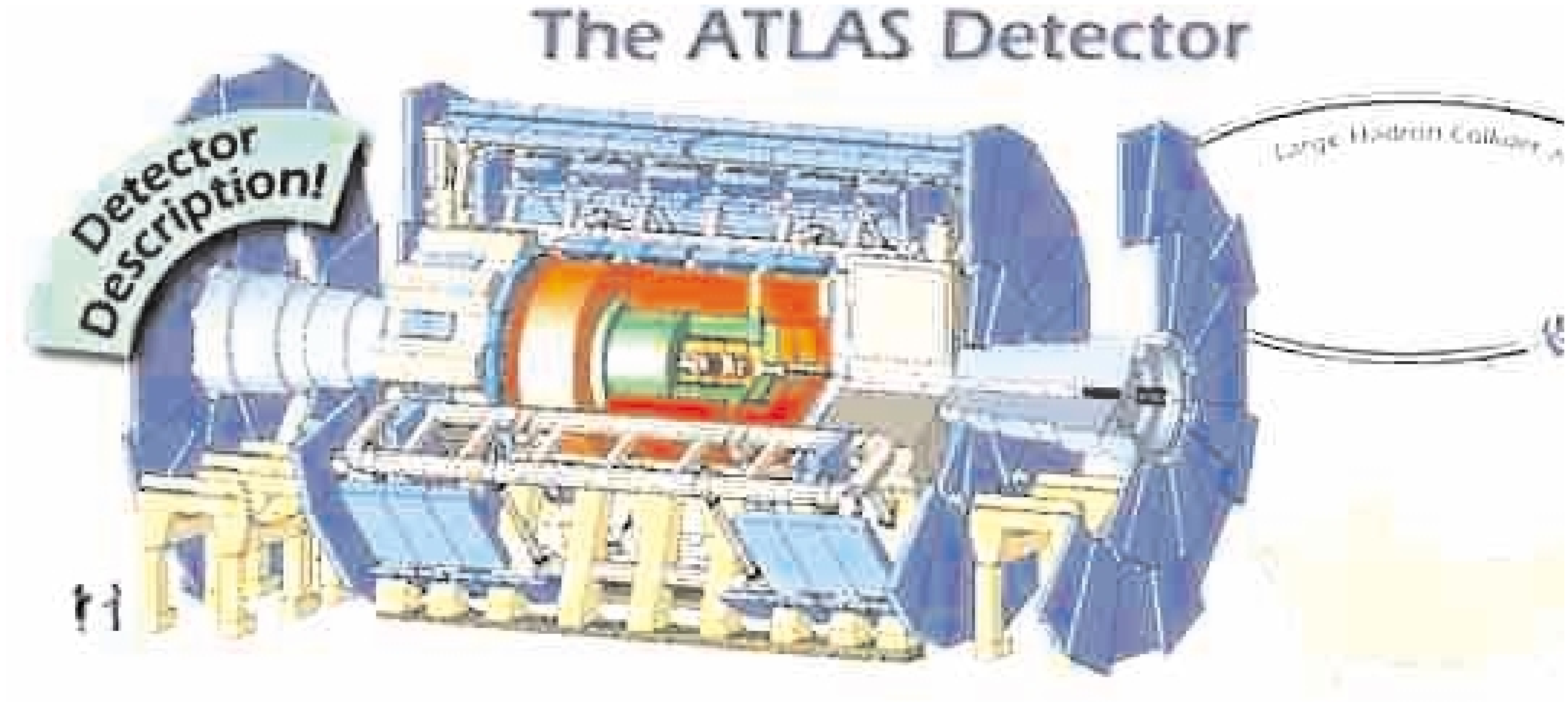
Can the Higgs mass exceed the value from the standard model fit? It has been proved that there are several ways to generate an apparent downward shift of the Higgs mass in the SM fit shown.

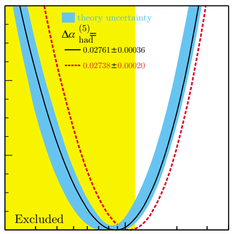
In some models, new fermions and boson with electroweak charge are assumed, in others new vector boson are introduced. It is even possible to reach the same result without new particles. In this case there are unique predictions in the way the SM parameters should change, within the present constraint.

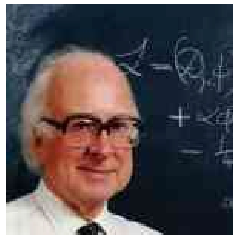
The first possibility is verifiable LHC. The latter could be verified by new precise measurements at a linear collider.

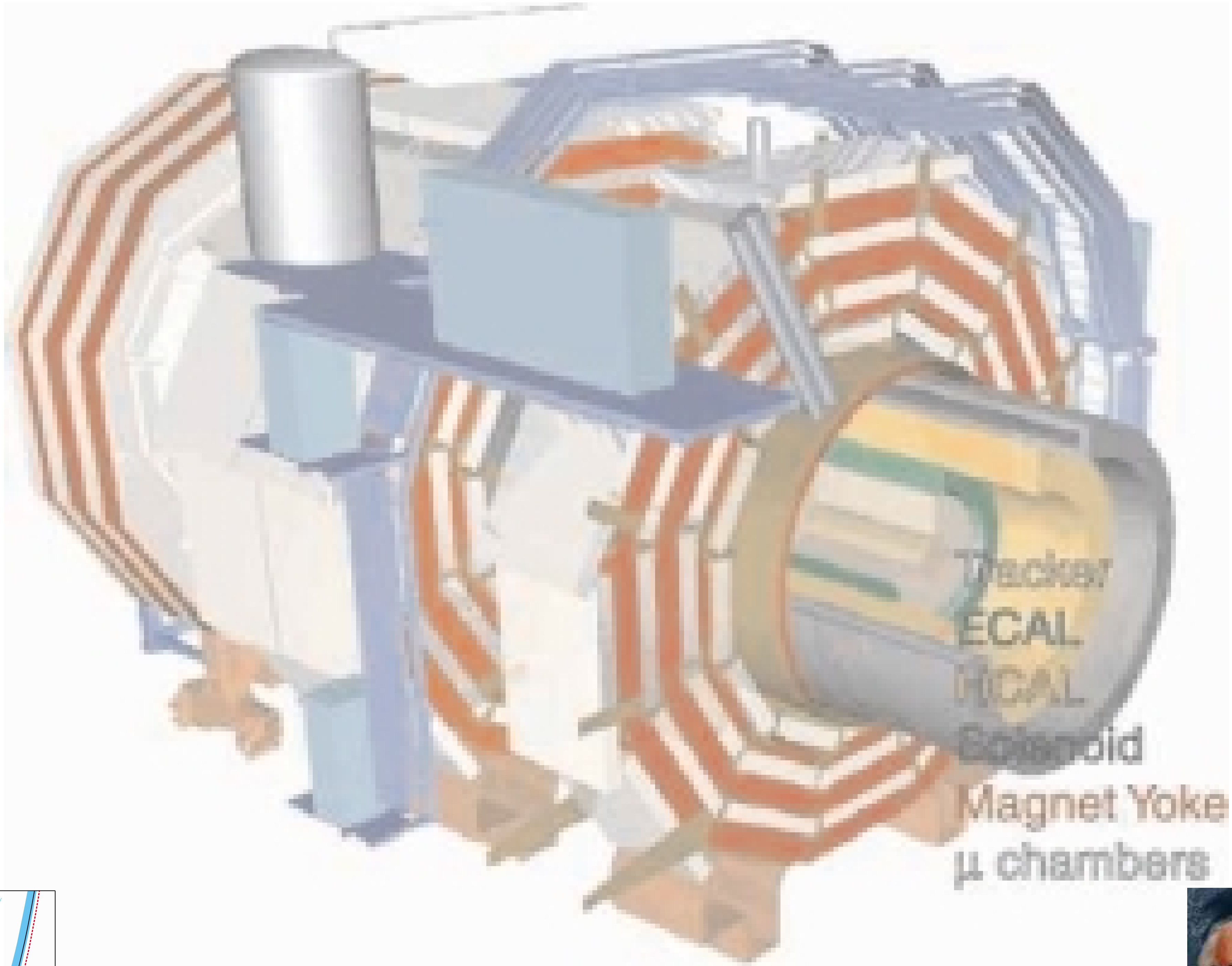


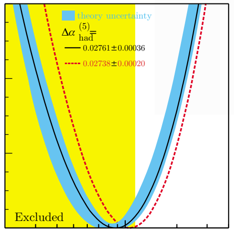



The ATLAS Detector
Detector Description!
Large Hadron Collider


Excluded




Tracker
ECAL
HCAL
Solenoid
Magnet Yoke
μ chambers


theory uncertainty
0.02761±0.00036
0.02738±0.00020
Excluded