
HAVE YOU HEARD? THEY DISCOVERED THE GOD PARTI...
IT'S CALLED THE HIGGS BOSON!

BSM Higgs Lecture

Sven Heinemeyer, IFT (CSIC, Madrid)

Daejeon, 09-10/2025

1. The SM Higgs & Motivation for BSM Higgs
2. BSM Higgs sectors: RxSM, 2HDM, N2HDM, MSSM, . . .
3. BSM Higgs sectors: collider phenomenology & more
4. Anomalies and possible explanations

BSM Higgs Lecture

The SM Higgs & Motivatin for BSM Higgs

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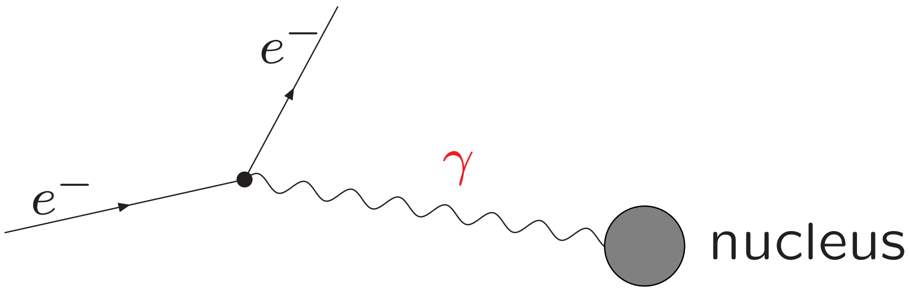
1. Why Higgs?
2. The Higgs in the SM
3. Higgs mass predictions before the LHC
4. Electroweak Precision Observables (EWPO)
5. The (SM) Higgs at the LHC
6. Motivation for BSM Higgs

1. Why Higgs?

Construction principle of the SM: gauge invariance

Example: Quantum electro-dynamics (QED)

field quanta: photon A_μ



Lagrangian:

$$\mathcal{L}_{\mathrm{QED}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi \ .$$

ψ is the electron spinor, A_μ is the photon (vector) field
with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

D_μ denotes the covariant derivative

$$D_\mu = \partial_\mu + i\, e\, A_\mu \ .$$

Construction principle of the SM: gauge invariance

The QED Lagrangian is invariant under the local $U(1)$ gauge symmetry,

$$\psi \to e^{-i\alpha(x)}\psi \ , \qquad (1)$$

$$A_\mu \to A_\mu + \frac{1}{e}\partial_\mu \alpha(x) \ . \qquad (2)$$

Introducing a mass term for the photon,

$$\mathcal{L}_{\text{photon mass}} = \frac{1}{2} m_A^2 A_\mu A^\mu \ ,$$

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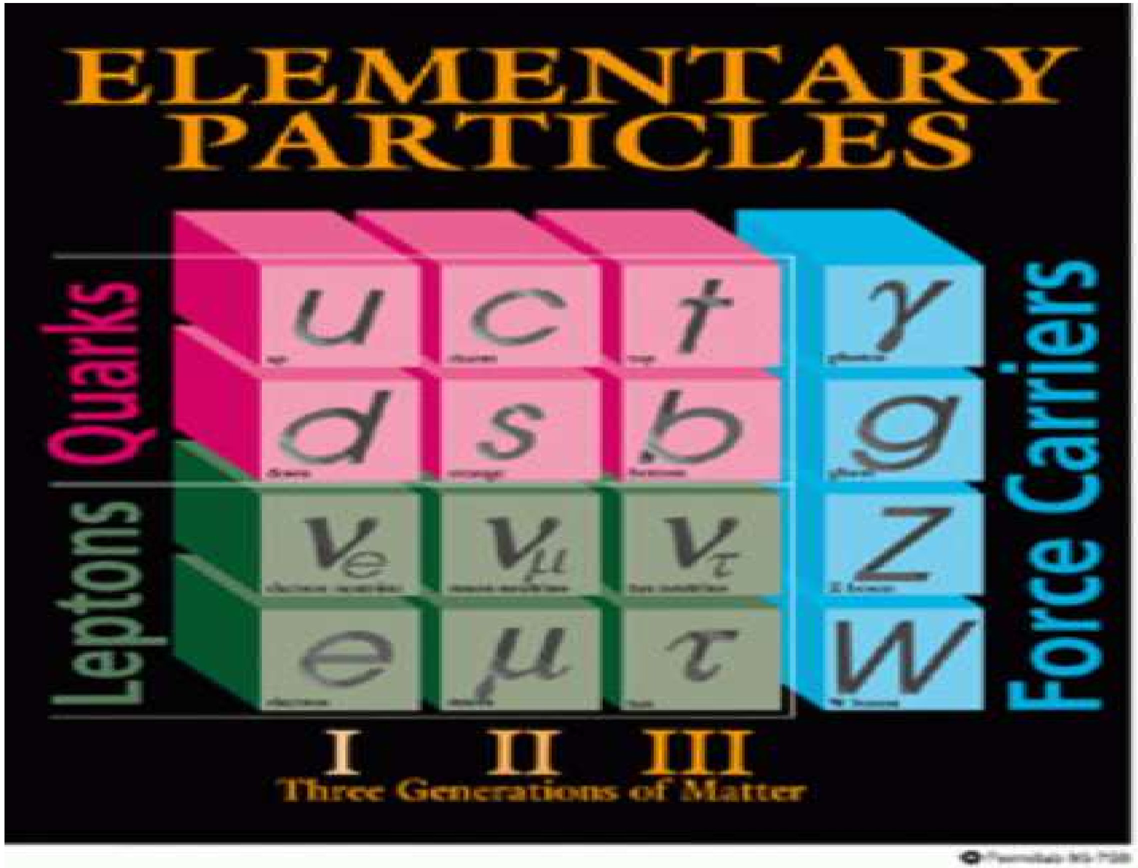
however, is not gauge-invariant. Applying eq. (2) yields

$$\frac{1}{2} m_A^2 A_\mu A^\mu \to \frac{1}{2} m_A^2 \left[A_\mu A^\mu + \frac{2}{e} A^\mu \partial_\mu \alpha + \frac{1}{e^2} \partial_\mu \alpha \, \partial^\mu \alpha \right] \ .$$

$\Rightarrow$ the gauge bosons must bw massless!

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen (as of 2011)

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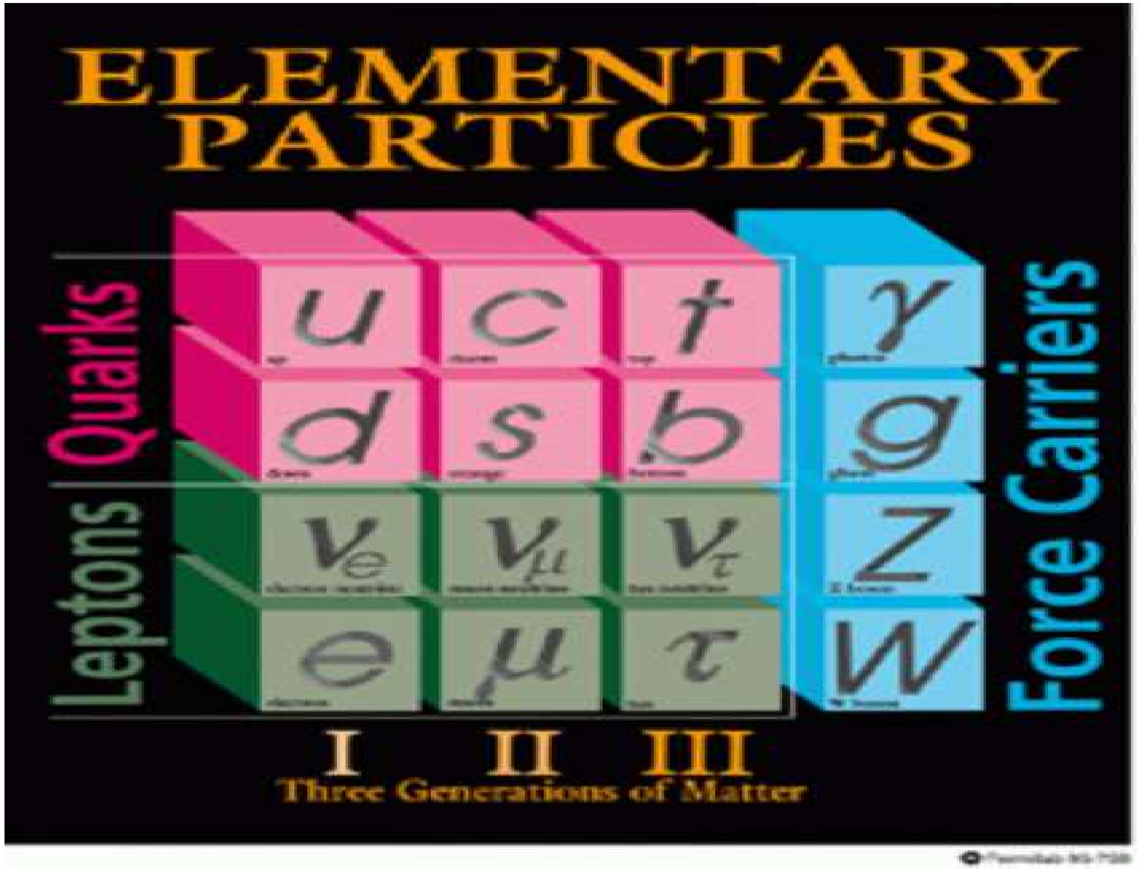

⇒ all particles experimentally seen (as of 2011)

⇒ but it predicts massless gauge bosons . . .

Solution: The Higgs mechanism

The simplest implementation uses one elementary complex scalar Higgs field Φ that has a vacuum expectation value v (vev) that is constant in space and time. The Lagrangian of the new Higgs field reads

$$\mathcal{L}_{\Phi} = \mathcal{L}_{\Phi,\mathrm{kin}} + \mathcal{L}_{\Phi,\mathrm{pot}} \tag{3}$$

with

$$\mathcal{L}_{\Phi,\mathrm{kin}} = (D_\mu \Phi)^* (D^\mu \Phi) \;, \tag{4}$$

$$-\mathcal{L}_{\Phi,\mathrm{pot}} = V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 \;. \tag{5}$$

Choices for λ and μ?

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Choices for λ and μ?

– λ has to be chosen positive to have a potential bounded from below.

– μ^2 can be either positive or negative (to be chosen "by hand")
  $\mu^2 < 0$ yields the desired vev

The complex scalar field Φ can be parametrized by two real scalar fields ϕ and η,

$$\Phi(x) = \frac{1}{\sqrt{2}}\phi(x)e^{i\eta(x)} \ , \tag{6}$$

yielding

$$V(\phi) = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 \ . \tag{7}$$

Minimizing the potential one finds . . .

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Minimizing the potential one finds . . .

$$\left.\frac{\mathrm{d}V}{\mathrm{d}\phi}\right|_{\phi=\phi_0} = \mu^2\phi_0 + \lambda\phi_0^3 \stackrel{!}{=} 0 \ .$$

Only for $\mu^2 < 0$ this yields the desired non-trivial solution

$$\phi_0 = \sqrt{\frac{-\mu^2}{\lambda}} (= \langle\phi\rangle =: v) \ . \tag{8}$$

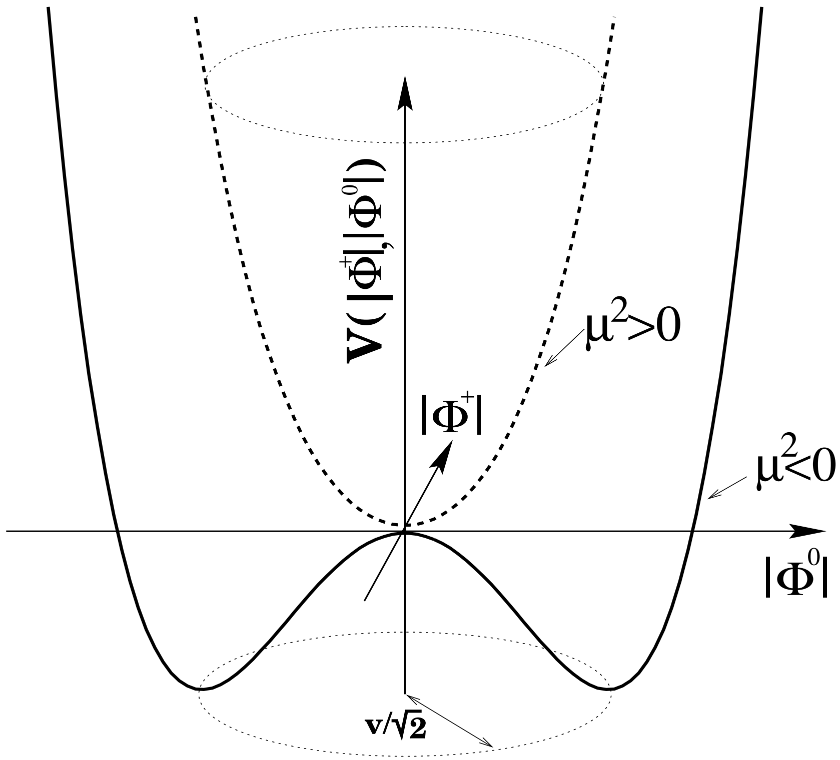
Higgs sector in the Standard Model:

Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking



minimum of potential at $|\langle\Phi_0\rangle| = \sqrt{\frac{-\mu^2}{2\,\lambda}} \equiv \frac{v}{\sqrt{2}}$

$1/\sqrt{2}$ is convention . . .

Unitary gauge: $\alpha(x) = -\eta(x)/v$

The kinetic term now reads

$$(D_\mu \Phi)^* (D^\mu \Phi) \to \frac{1}{2}(\partial_\mu \phi)^2 + \frac{1}{2} e^2 q^2 \phi^2 A_\mu A^\mu \ , \tag{9}$$

where q is the charge of the Higgs field.

Expand the Higgs field around its vev,

$$\phi(x) = v + H(x) \ . \tag{10}$$

The remaining degree of freedom, $H(x)$, is a real scalar boson, the Higgs boson.

The Higgs boson mass and self-interactions are obtained by inserting eq. (10) into the Lagrangian (neglecting a constant term),

$$-\mathcal{L}_{\text{Higgs}} = \frac{1}{2} m_H^2 H^2 + \frac{\kappa}{3!} H^3 + \frac{\xi}{4!} H^4 \ , \tag{11}$$

with

$$m_H^2 = 2\lambda v^2, \quad \kappa = 3\frac{m_H^2}{v}, \quad \xi = 3\frac{m_H^2}{v^2} \ . \tag{12}$$

Inserting eq. (10) into eq. (9)
(neglecting the kinetic term for ϕ),

$$\mathcal{L}_{\text{Higgs-photon}} = \frac{1}{2} m_A^2 A_\mu A^\mu + e^2 q^2 v H A_\mu A^\mu + \frac{1}{2} e^2 q^2 H^2 A_\mu A^\mu \tag{13}$$

– first term: the photon mass,

$$m_A^2 = e^2 q^2 v^2 \ . \tag{14}$$

– second term: Higgs-photon-photon interaction

– third term: Higgs-Higgs-photon-photon interaction

Another important feature can be observed:
the coupling of the photon to the Higgs is proportional
to its own mass squared!
⇒ characteristic prediction of the Higgs mechanism!

Masses for the fermions:

Similarly a gauge invariant Lagrangian can be defined to give mass to the chiral fermion $\psi = (\psi_L, \psi_R)^T$,

$$\mathcal{L}_{\text{fermion mass}} = y_\psi \psi_L^\dagger \Phi \psi_R + \text{c.c.} \, , \qquad (15)$$

where y_ψ denotes the dimensionless Yukawa coupling.

Inserting $\Phi(x) = (v + H(x))/\sqrt{2}$ one finds . . .

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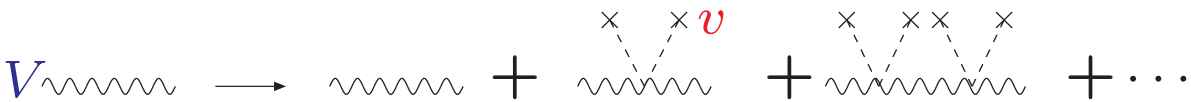
$$\mathcal{L}_{\text{fermion mass}} = m_\psi \psi_L^\dagger \psi_R + \frac{m_\psi}{v} H \, \psi_L^\dagger \psi_R + \text{c.c.} \; , \tag{16}$$

$$\text{with} \quad m_\psi = y_\psi \frac{v}{\sqrt{2}} \; . \tag{17}$$

Again the important feature can be observed:
By construction the coupling of the fermion to the Higgs boson is proportional to its own mass m_ψ.

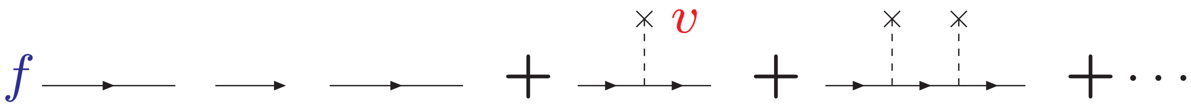
Alternative view: masses arise from the interaction with the vev:

1.) $VV\Phi\Phi$ coupling:



$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \; : \; M^2 = g^2\frac{v^2}{2} \quad \Rightarrow M \propto g$$

2.) fermion mass terms: Yukawa couplings:



$$\frac{1}{\not q} \to \frac{1}{\not q} + \sum_j \frac{1}{\not q}\left[\frac{g_f v}{\sqrt{2}}\frac{1}{\not q}\right]^j = \frac{1}{\not q - m_f} \; : \; m_f = g_f\frac{v}{\sqrt{2}} \quad \Rightarrow m_f \propto g_f$$

2. The Higgs in the SM

The electroweak sector of the SM is described by the gauge symmetry $SU(2)_L \times U(1)_Y$. The bosonic part of the Lagrangian is given by

$$\mathcal{L}_{\text{bos}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu} + |D_\mu \Phi|^2 - V(\Phi), \quad (18)$$

$$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 \; . \quad (19)$$

Φ is a complex scalar doublet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} , \quad (20)$$

Covariant derivative:

$$D_\mu = \partial_\mu + ig \frac{\tau^a}{2} W_{\mu\,a} + ig' \frac{Y}{2} B_\mu \; , \quad (21)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \; , \quad (22)$$

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g f^{abc} W_{\mu\,b} W_{\nu\,c} \; . \quad (23)$$

g and g' are the $SU(2)_L$ and $U(1)_Y$ gauge couplings
τ^a are the Pauli matrices
f^{abc} are the $SU(2)$ structure constants

Choosing $\mu^2 < 0$ the minimum of the Higgs potential is found at

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{with} \quad v := \sqrt{\frac{-\mu^2}{\lambda}} \ . \tag{24}$$

$\Phi(x)$ can now be expressed through the vev, the Higgs boson and three Goldstone bosons $\phi_{1,2,3}$, (**Q: why three?**)

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1(x) + i\phi_2(x) \\ v + H(x) + i\phi_3(x) \end{pmatrix} \ . \tag{25}$$

Diagonalizing the mass matrices of the gauge bosons, one finds that the three massless Goldstone bosons are absorbed as longitudinal components of the three massive gauge bosons, $W_\mu^\pm, Z_\mu$, while the photon A_μ remains massless,

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp iW_\mu^2\right) \ , \tag{26}$$

$$Z_\mu = c_W W_\mu^3 - s_W B_\mu \ , \tag{27}$$

$$A_\mu = s_W W_\mu^3 + c_W B_\mu \ . \tag{28}$$

Weak mixing angle: $\theta_W = \arctan(g'/g)$, and $s_W := \sin\theta_W$, $c_W := \cos\theta_W$

The Higgs-gauge boson interaction Lagrangian reads,

$$\mathcal{L}_{\text{Higgs-gauge}} = \left[M_W^2 W_\mu^+ W^{-\,\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right] \left(1 + \frac{H}{v}\right)^2$$
$$- \frac{1}{2} M_H^2 H^2 - \frac{\kappa}{3!} H^3 - \frac{\xi}{4!} H^4 \ , \qquad (29)$$

with

$$M_W = \frac{1}{2} g v, \quad M_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v, \qquad (30)$$

$$(M_H^{\text{SM}} :=)\ M_H = \sqrt{2\lambda}\, v, \quad \kappa = 3\frac{M_H^2}{v}, \quad \xi = 3\frac{M_H^2}{v^2}\ . \qquad (31)$$

From the measurement of the gauge boson masses and couplings one finds $v \approx 246$ GeV.

The two massive gauge boson masses are related via

$$\frac{M_W}{M_Z} = \frac{g}{\sqrt{g^2 + g'^2}} = c_W\ . \qquad (32)$$

Fermion masses in the SM:

$$\mathcal{L}_{\text{Higgs-fermion}} = y_b Q_L^\dagger \, \Phi \, b_R \; + \; y_t Q_L^\dagger \, \Phi_c \, t_R + \text{ h.c.} \tag{33}$$

$Q_L = (t_L, b_L)^T$ is the left-handed $SU(2)_L$ doublet.
Going to the "unitary gauge" the Higgs field can be expressed as

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} , \tag{34}$$

and it is obvious that this doublet can give masses only to the bottom(-type) fermion(s). A way out is the definition of

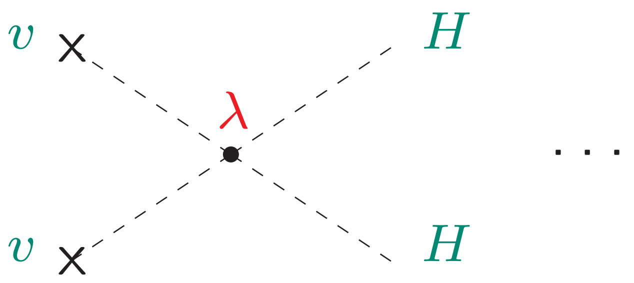
$$\Phi_c = i\sigma^2 \Phi^* = \frac{1}{\sqrt{2}} \begin{pmatrix} v + H(x) \\ 0 \end{pmatrix} , \tag{35}$$

which is employed to generate the top(-type) mass(es) in eq. (33). Inserting eqs. (34), (35) into eq. (33) yields

$$\mathcal{L}_{\text{Higgs-fermion}} = m_b \bar{b} b \left(1 + \frac{H}{v}\right) + m_t \bar{t} t \left(1 + \frac{H}{v}\right) \tag{36}$$

where we have used $\bar{\psi}\psi = \psi_L^\dagger \psi_R + \psi_R^\dagger \psi_L$ and $m_b = y_b v/\sqrt{2}$, $m_t = y_t v/\sqrt{2}$.

3.) mass of the Higgs boson: self coupling



$$\lambda = M_H^2 / v^2$$

$M_H = v\sqrt{\lambda}$ free parameter

$\to$ last unknown (now measured) parameter of the SM

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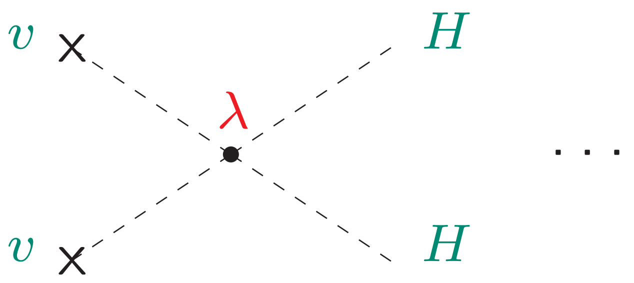


$\lambda = M_H^2/v^2$

$M_H = v\sqrt{\lambda}$ free parameter

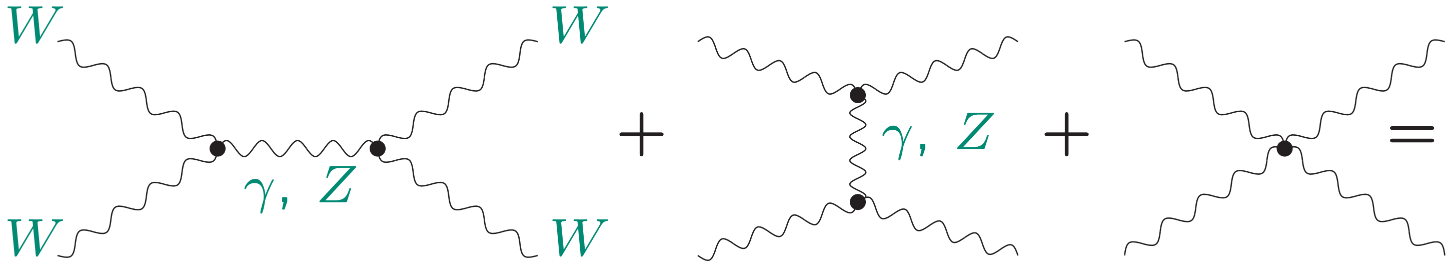
$\rightarrow$ last unknown (now measured) parameter of the SM

$\Rightarrow$ establish Higgs mechanism $\equiv$ find the Higgs $\oplus$ measure its couplings

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \to W_L W_L$

$\mathcal{M}_V =$



$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$

for $E \to \infty$

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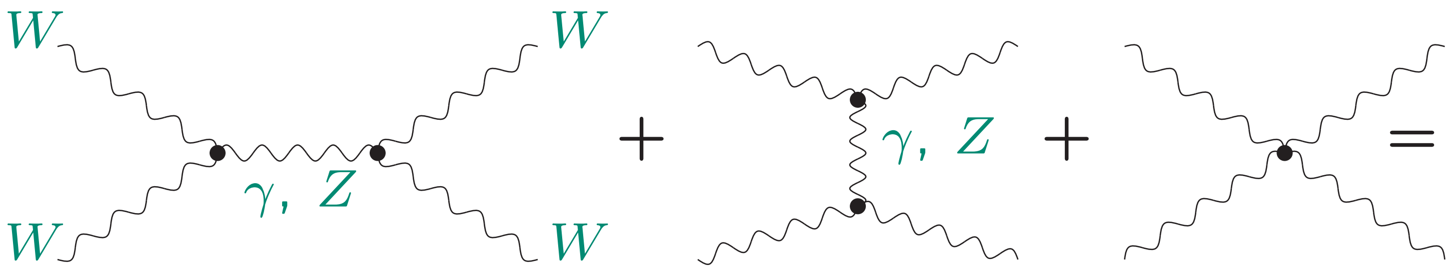

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Q: Why is this dangerous?

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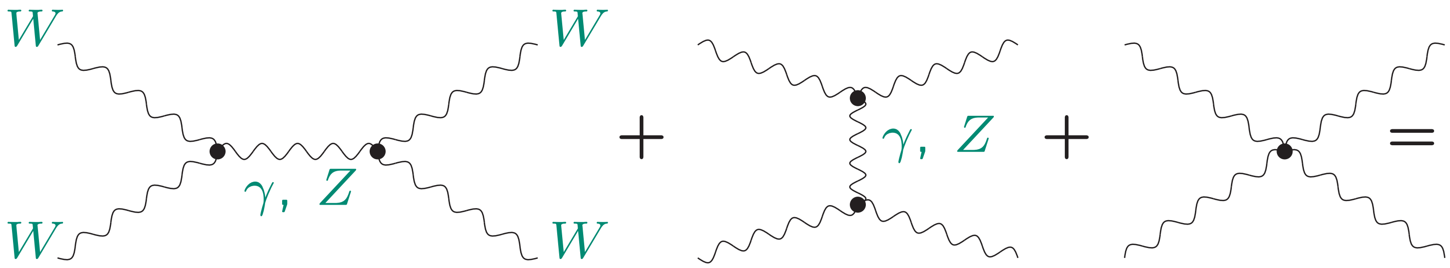
$\mathcal{M}_V =$

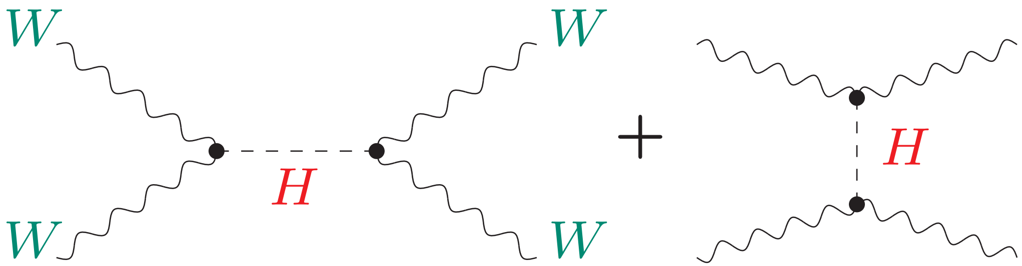


$$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1) \quad \text{for } E \to \infty$$

$\Rightarrow$ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$\mathcal{M}_S =$



$$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1) \quad \text{for } E \to \infty$$

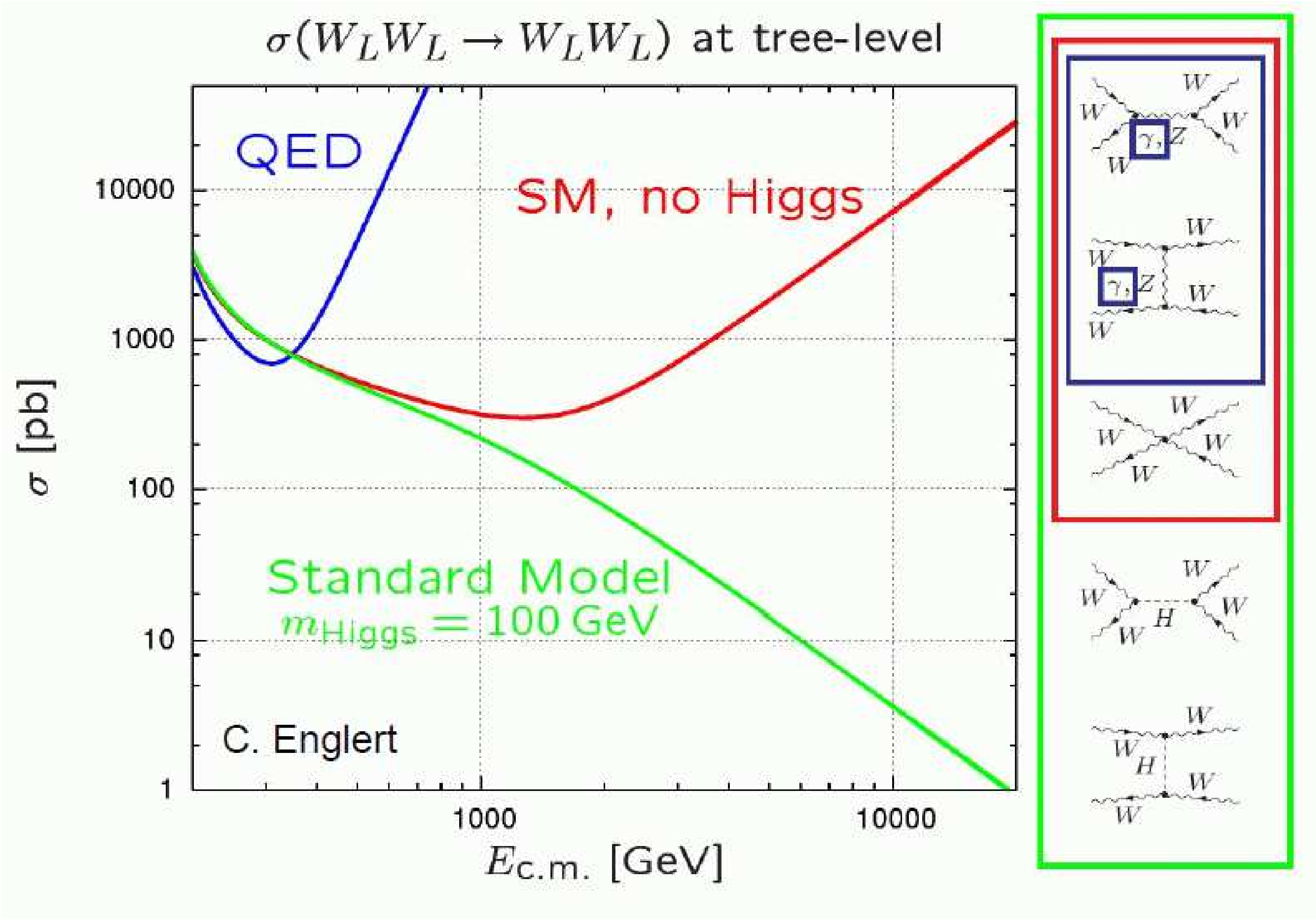
$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4}\left(g_{WWH}^2 - g^2\, M_W^2\right) + \ldots$$

$\Rightarrow$ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g\, M_W$$

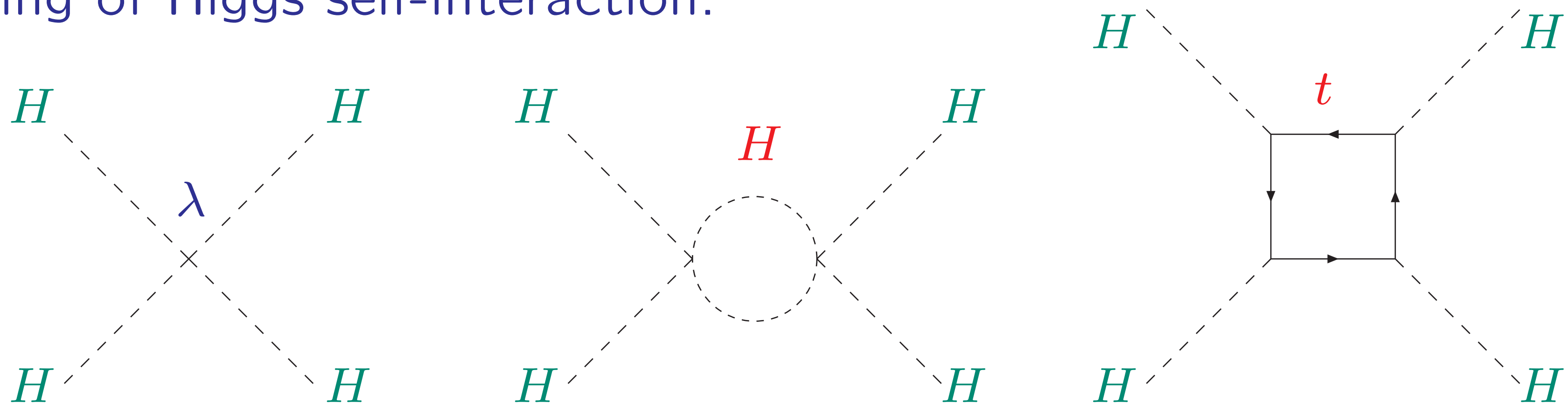
Cross section with/without the Higgs:

[*taken from M. Schumacher '12 / C. Englert*]



3. Higgs mass predictions before the LHC

Running of Higgs self-interaction:



Renormalization group equation:

$$\frac{d\,\lambda}{d\,t} = \frac{3}{8\,\pi^2}\left[\lambda^2 + \lambda g_t^2 - g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right] \;, \qquad t = \log\left(\frac{Q^2}{v^2}\right)$$

Two conditions:

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

2.) avoid vacuum instability (for small/negative λ)

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left[\lambda^2\right]$$

$$\Rightarrow \qquad \lambda(Q^2) = \frac{\lambda(v^2)}{1 - \frac{3\lambda(v^2)}{8\pi^2}\log\left(\frac{Q^2}{v^2}\right)}$$

$$\lambda(\Lambda) < \infty \Rightarrow M_H^2 \leq \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)} \quad : \text{upper bound on } M_H$$

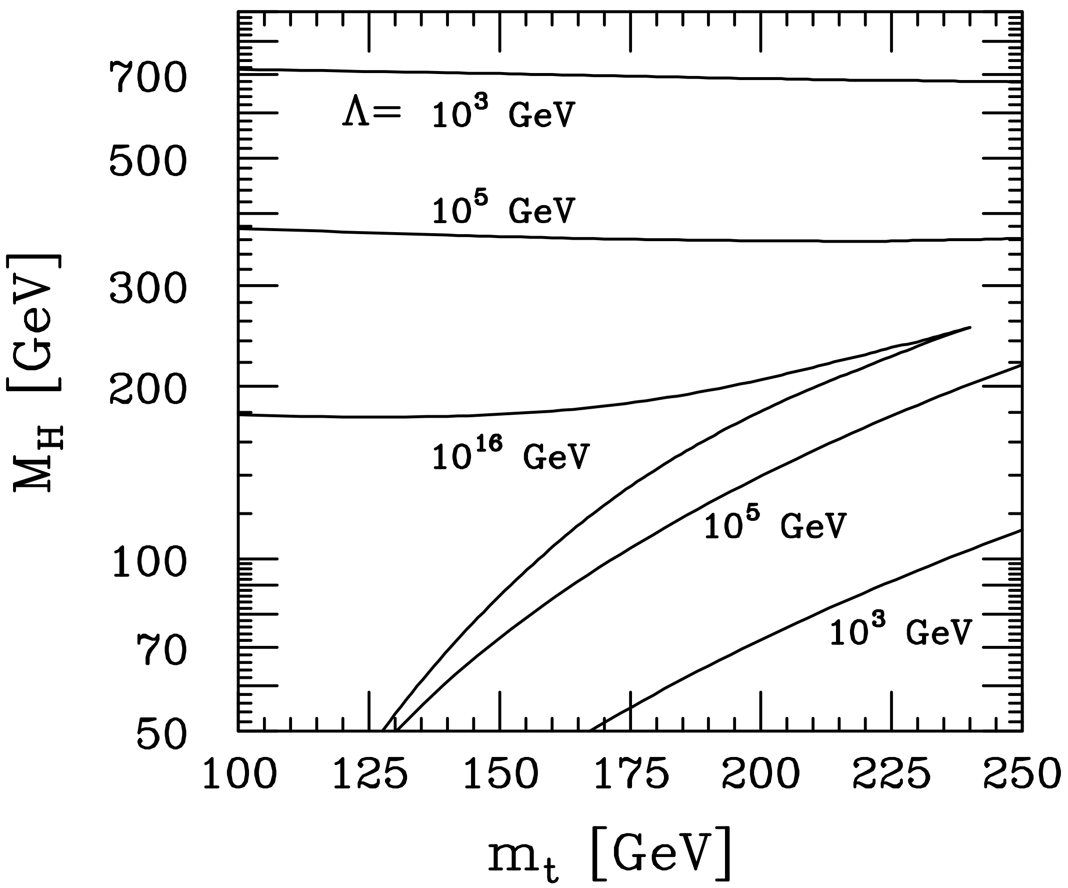
2.) avoid vacuum instability (for small/negative λ): $V(v) < V(0) \Rightarrow \lambda(\Lambda) > 0$

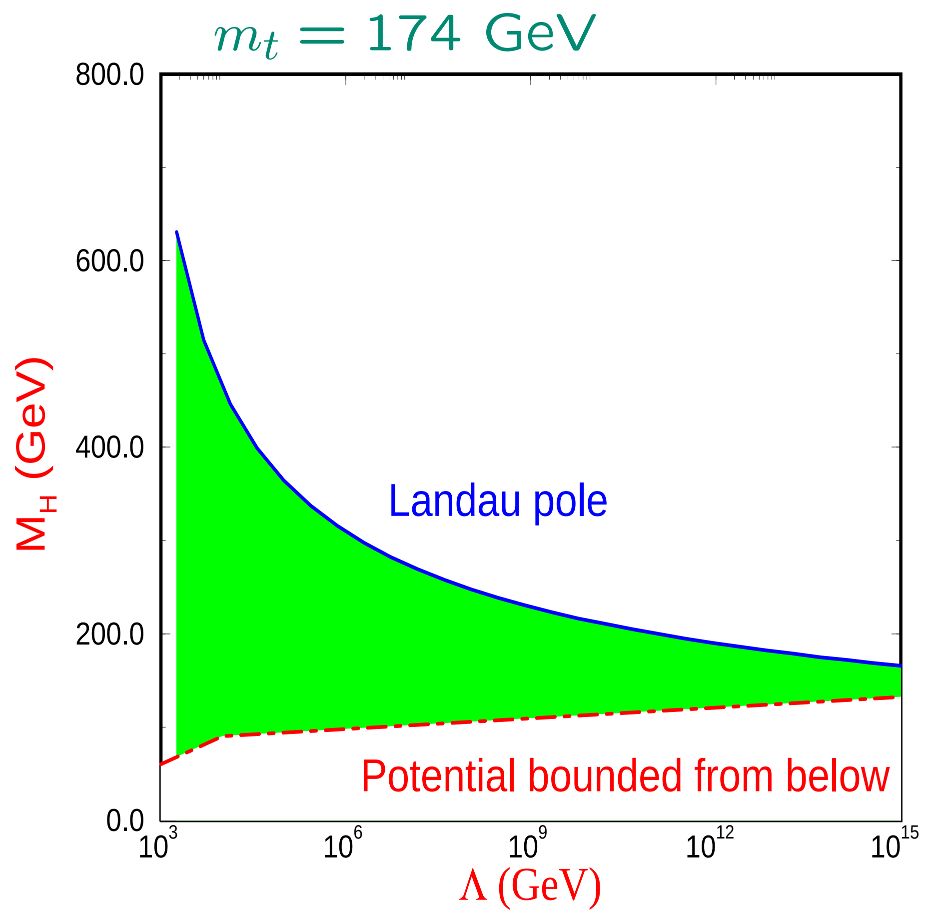
$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

$$\Rightarrow \qquad \lambda(Q^2) = \lambda(v^2)\frac{3}{8\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\left(\frac{Q^2}{v^2}\right)$$

$$\lambda(\Lambda) > 0 \Rightarrow M_H^2 > \frac{v^2}{4\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\left(\frac{\Lambda^2}{v^2}\right) \ : \text{lower bound}$$

Both limits combined:



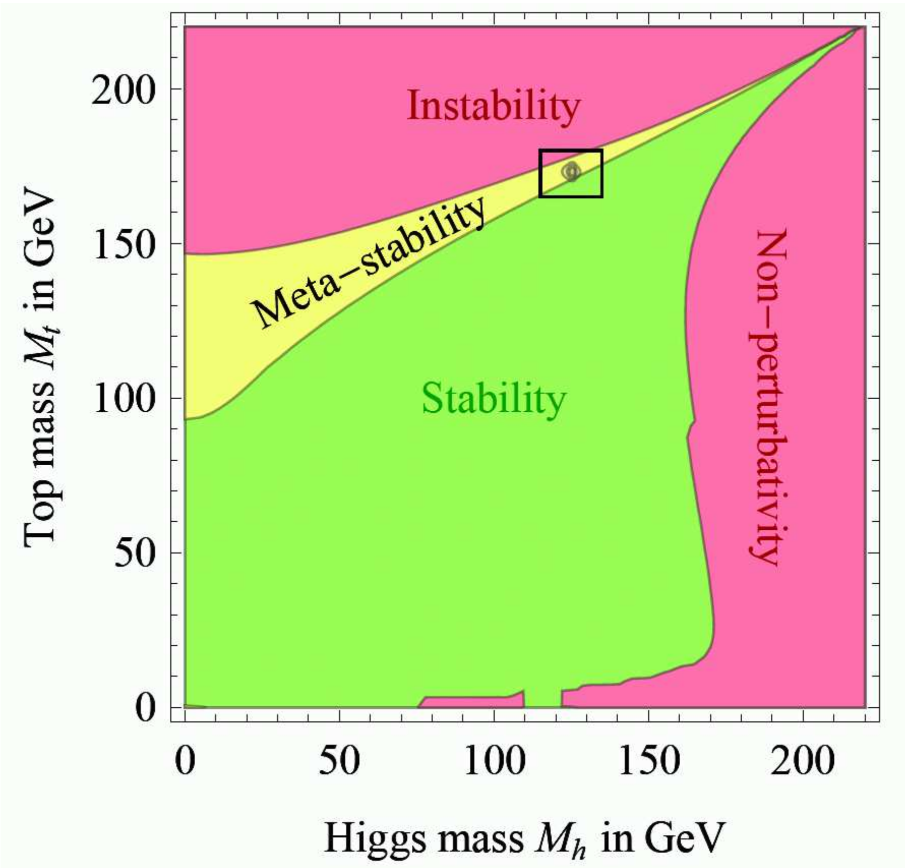


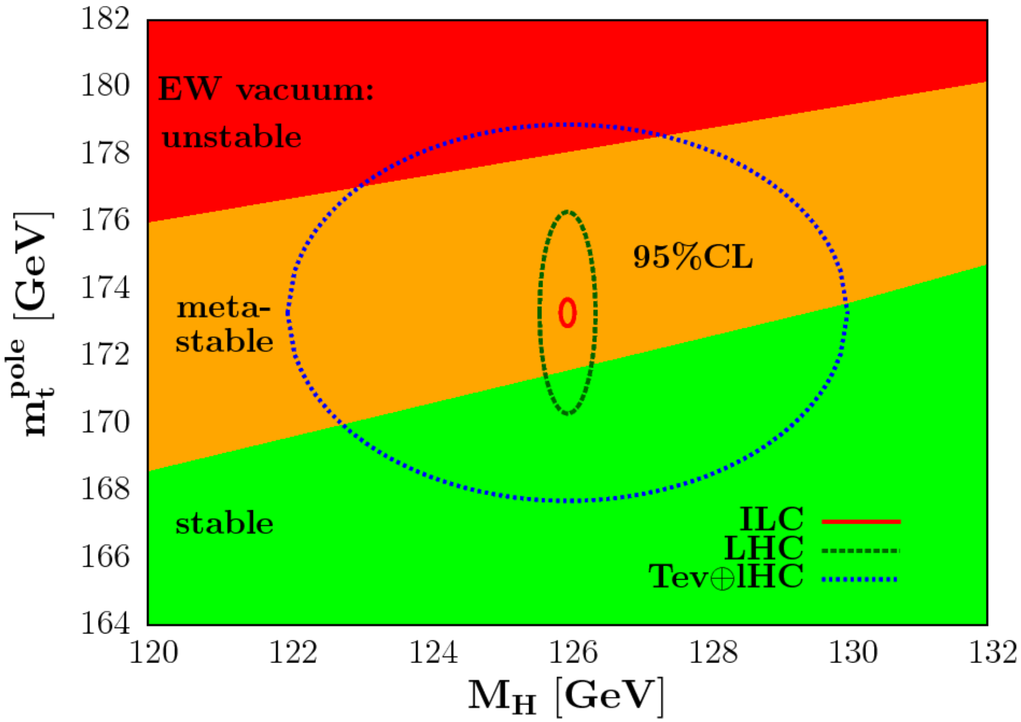
Λ: scale up to which the SM is valid

$\Lambda = M_{\text{GUT}} \Rightarrow 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$

$M_H = 125$ GeV $\Rightarrow$ we live in a meta-stable vacuum!

[*Degrassi et al. '12*] [*Alehkin et al. '12*]





...if there is nothing else than the SM up to the Planck scale!

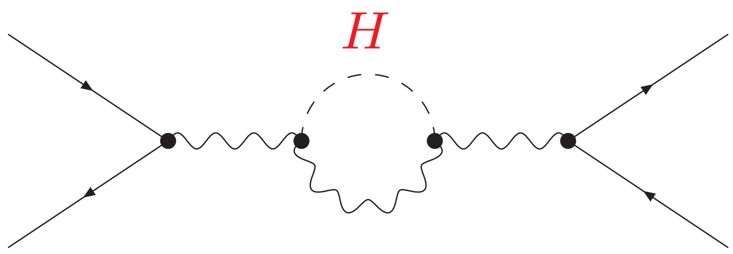
Electroweak Precision Observables (EWPO):

Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$M_W, \sin^2\theta_{\mathrm{eff}}, a_\mu$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. H



$\Downarrow$

SM: limits on M_H

Very high accuracy of measurements and theoretical predictions needed

Precision observables in the SM (and BSM)

M_W, $\sin^2\theta_{\rm eff}$, M_h, $(g-2)_\mu$, b physics, ...

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

$\Updownarrow$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[*A. Sirlin '80*] , [*W. Marciano, A. Sirlin '80*]

$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

$$\sim \log\frac{M_Z}{m_f} \qquad \sim m_t^2 \qquad \log(M_H/M_W)$$

$$\sim 6\% \qquad \sim 3.3\% \qquad \sim 1\%$$

Precision observables in the SM (and BSM)

M_W, $\sin^2\theta_{\rm eff}$, M_h, $(g-2)_\mu$, b physics, . . .

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}\,(1+\Delta r)$$

$\Updownarrow$

loop corrections

B) Effective mixing angle:

$$\sin^2\theta_{\rm eff}=\frac{1}{4\,|Q_f|}\left(1-\mathrm{Re}\,\frac{g_V^f}{g_A^f}\right)$$

Higher order contributions:

$$g_V^f \to g_V^f+\Delta g_V^f, \quad g_A^f \to g_A^f+\Delta g_A^f$$

Comparison of SM prediction of M_W with direct measurements:

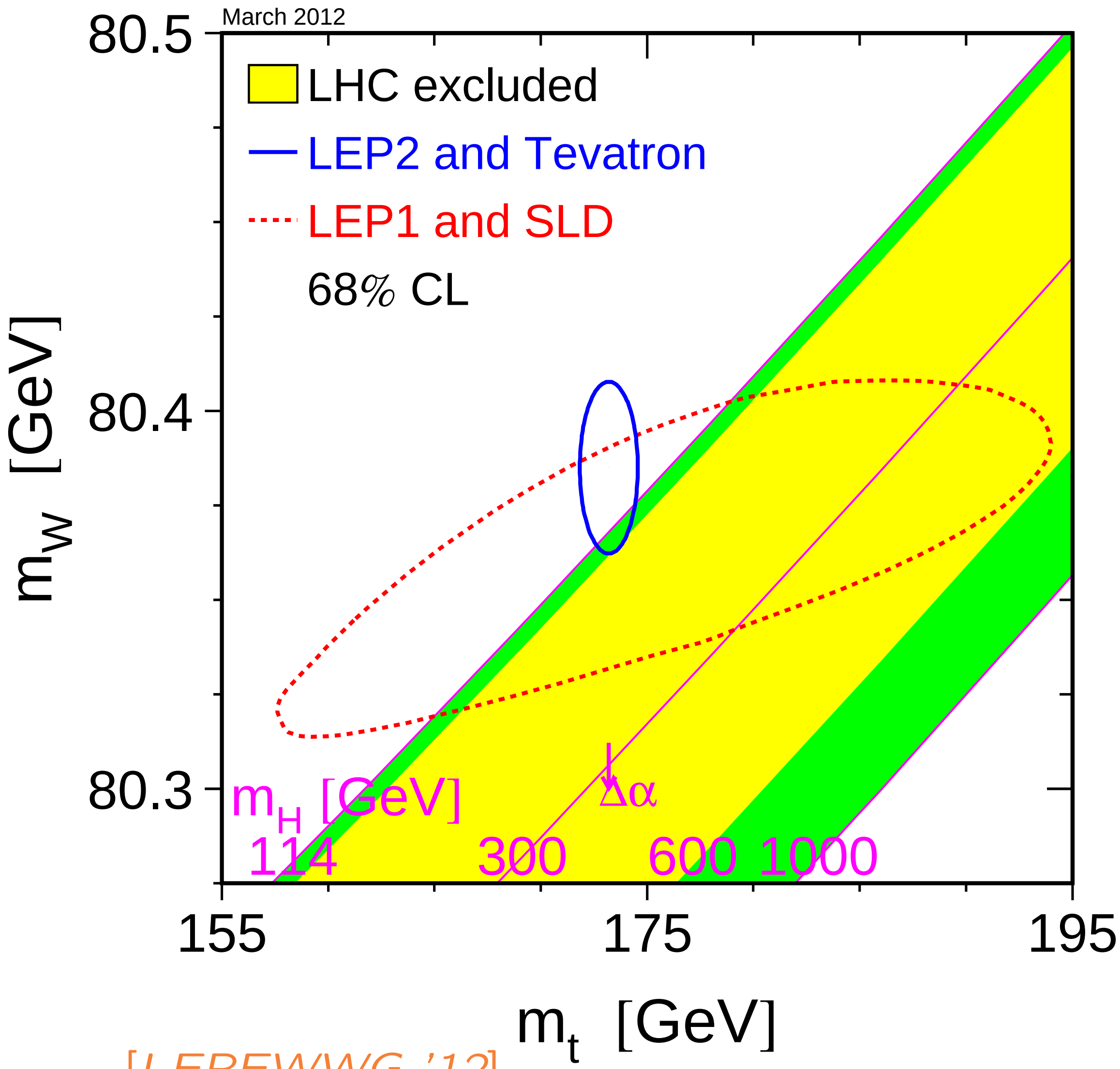
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2} \frac{s_W^2}{c_W^2} \log\left(\frac{M_H}{M_W}\right)$$

general for EWPO:

$$\Delta \sim g_2^2 \left[\log\left(\frac{M_H}{M_W}\right) + g_2^2 \frac{M_H^2}{M_W^2} \right]$$

leading term: $\log(M_H)$

first term $\sim M_H^2$ with g_2^4

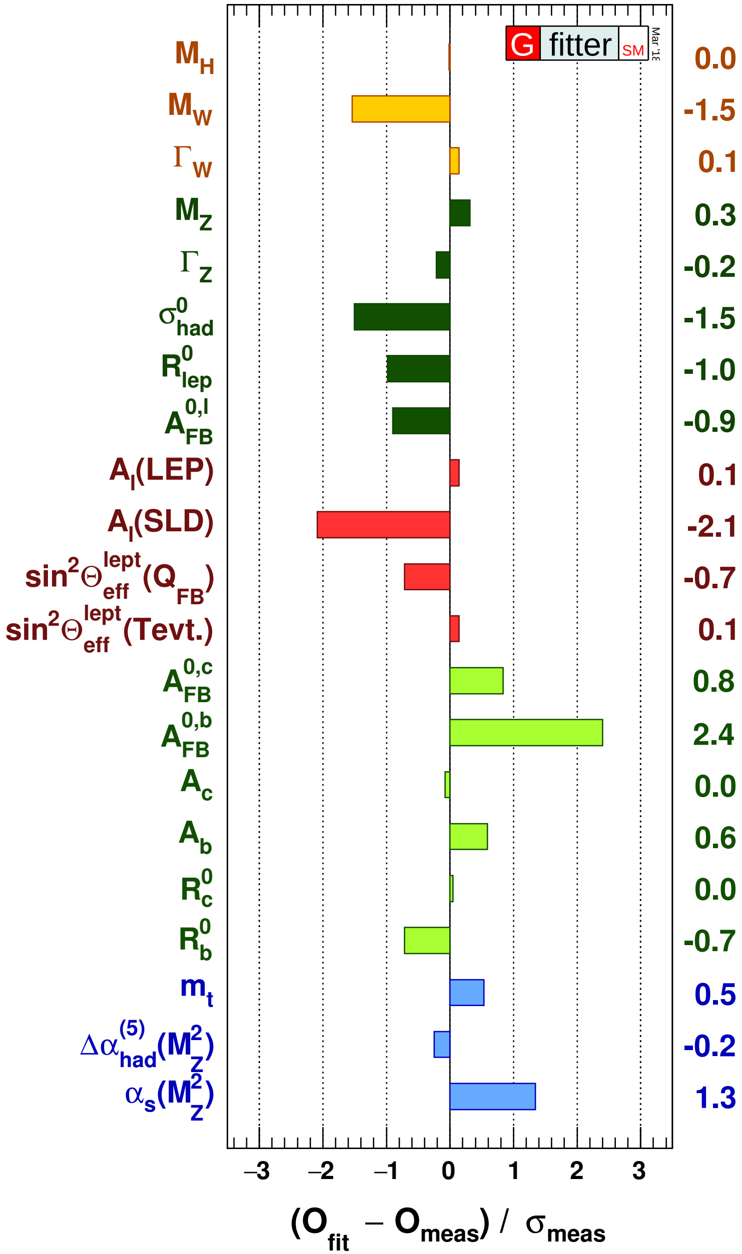


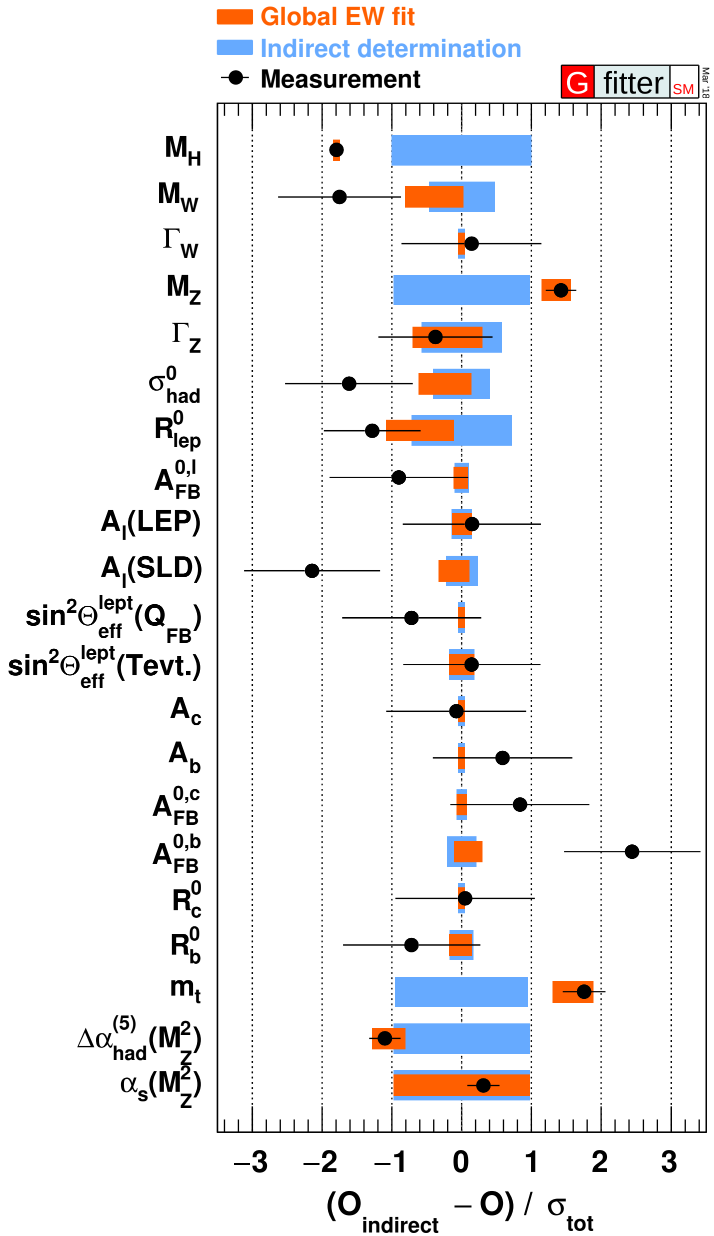
[LEPEWWG '12]

⇒ light Higgs boson preferred

Overview about all EWPO:

[GFitter '18]

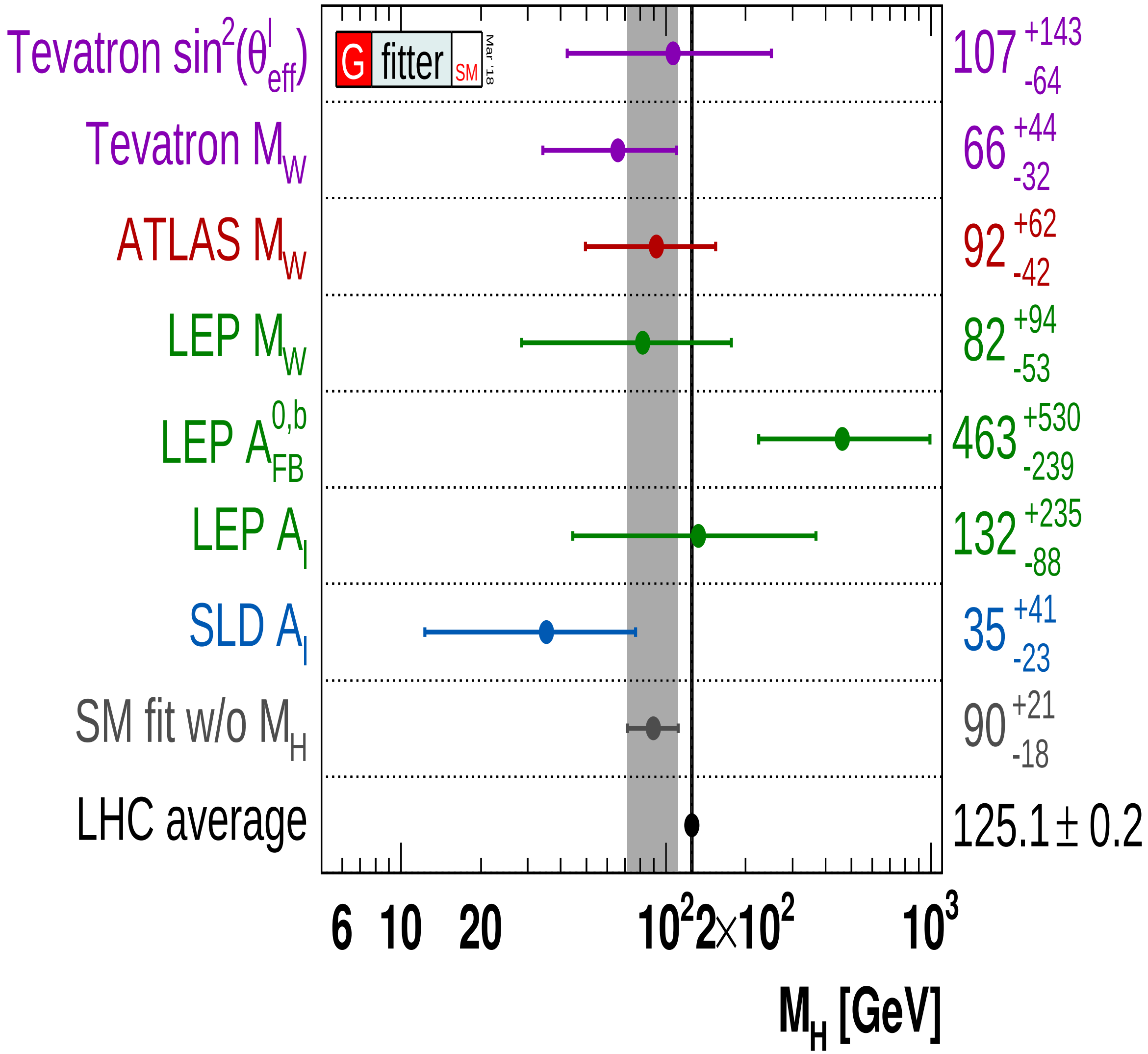




Results for M_H from other EWPO:

light Higgs preferred by:
M_W, $A^l_{\rm LR}$ (SLD)

heavier Higgs preferred by:
$A^b_{\rm FB}$ (LEP)
⇒ keeps SM alive



⇒ light Higgs boson preferred

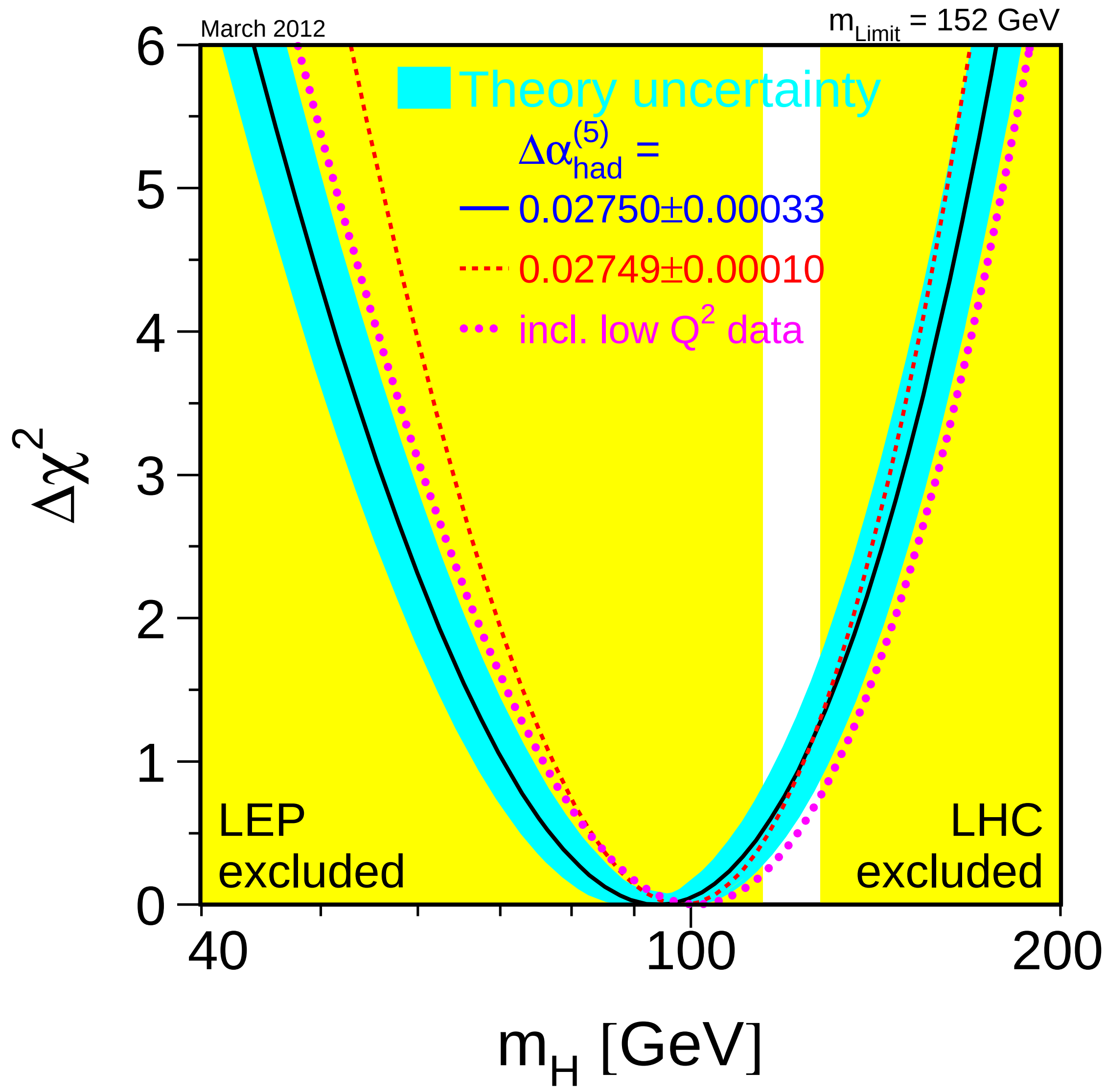
[GFitter '18]

Global fit to all SM data:

[*LEPEWWG '12*]

$\Rightarrow M_H = 94^{+29}_{-24}$ GeV

$M_H < 152$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

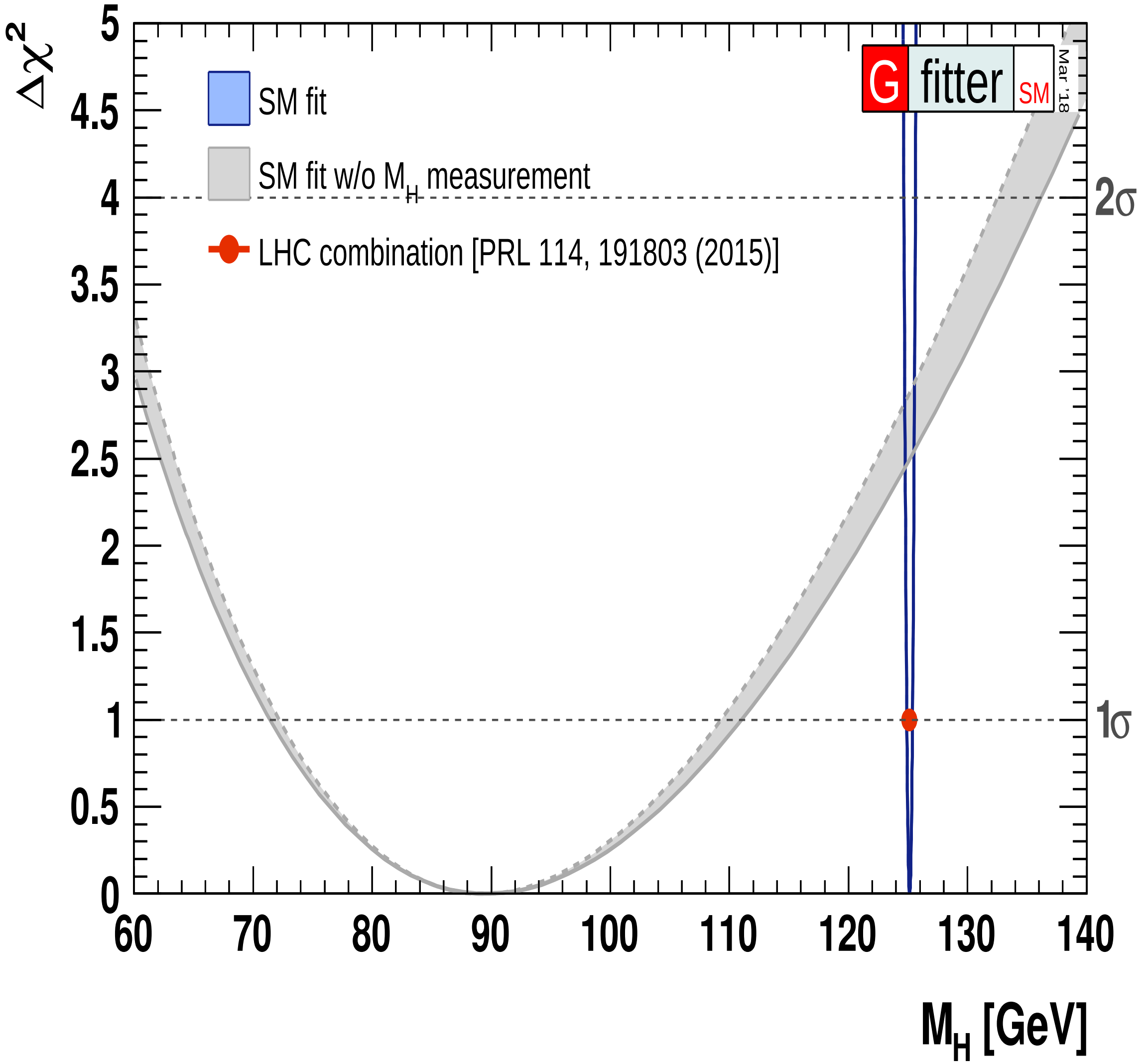
$\Rightarrow$ Prediction before discovery: in the SM: $M_H \lesssim 160$ GeV

Latest global fit to all SM data:

[*GFitter '18*]

$\Rightarrow$ $M_H = 90^{+21}_{-18}$ GeV

"agreement" at $1.8\,\sigma$



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ slightly rising "tension" over the last years . . .

Experimental errors of the precision observables:

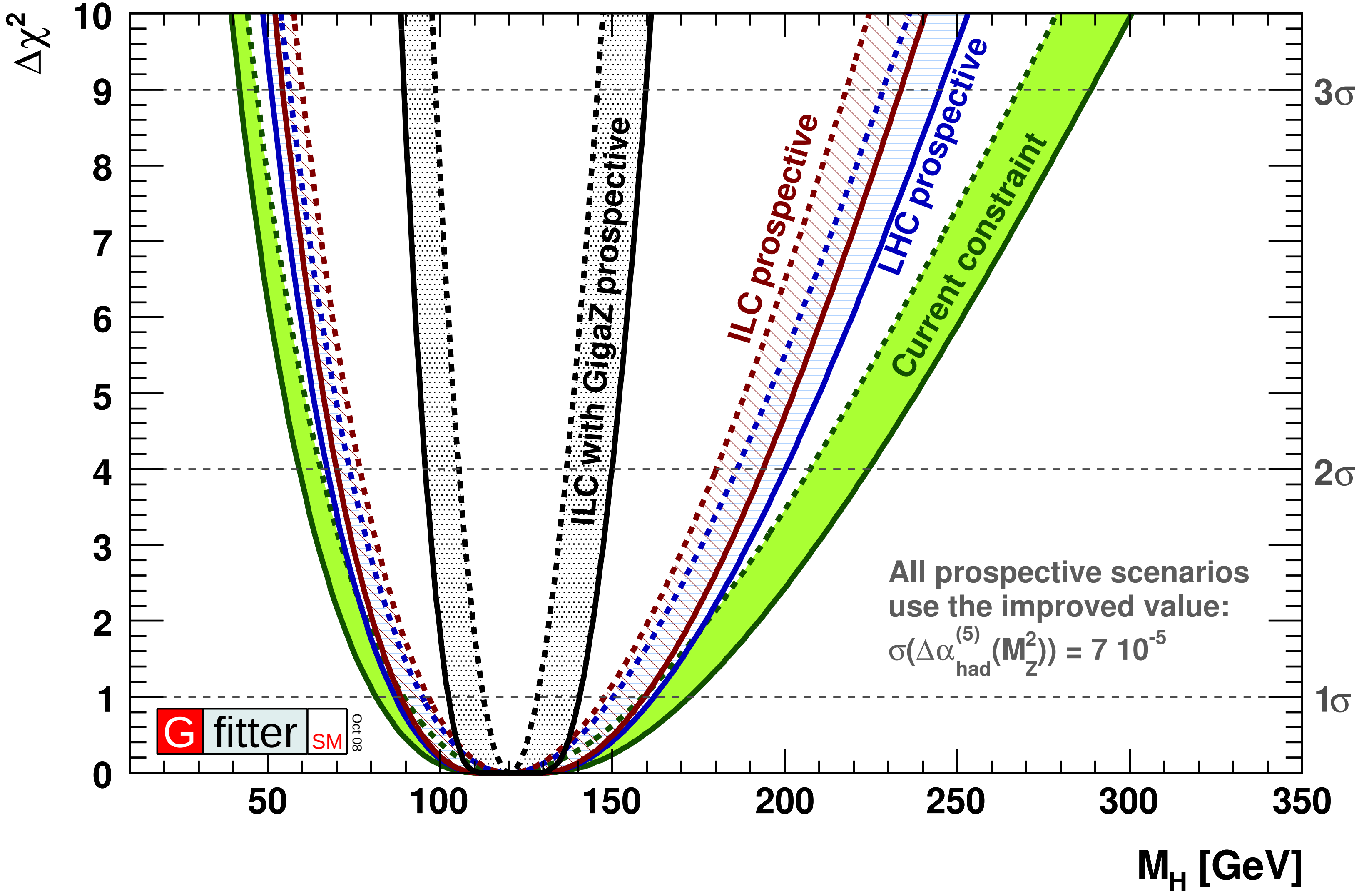
	today	Tev./LHC	LC	GigaZ
$\delta \sin^2\theta_{\rm eff}(\times 10^5)$	15	$\leq$15	–	1.3
δM_W [MeV]	12	$\leq$12	2-3	2-3
δm_t [GeV]	0.7	$\leq$0.5	0.1	0.1

Relevant SM parametric errors: $\delta(\Delta\alpha_{\rm had}) = 5 \times 10^{-5}$, $\delta M_Z = 2.1$ MeV

	$\delta m_t = 2$	$\delta m_t = 1$	$\delta m_t = 0.1$	$\delta(\Delta\alpha_{\rm had})$	δM_Z
$\delta \sin^2\theta_{\rm eff}$ [10^{-5}]	6	3	0.3	1.8	1.4
ΔM_W [MeV]	12	6	1	1	2.5

Improvement in the Blue Band plot:

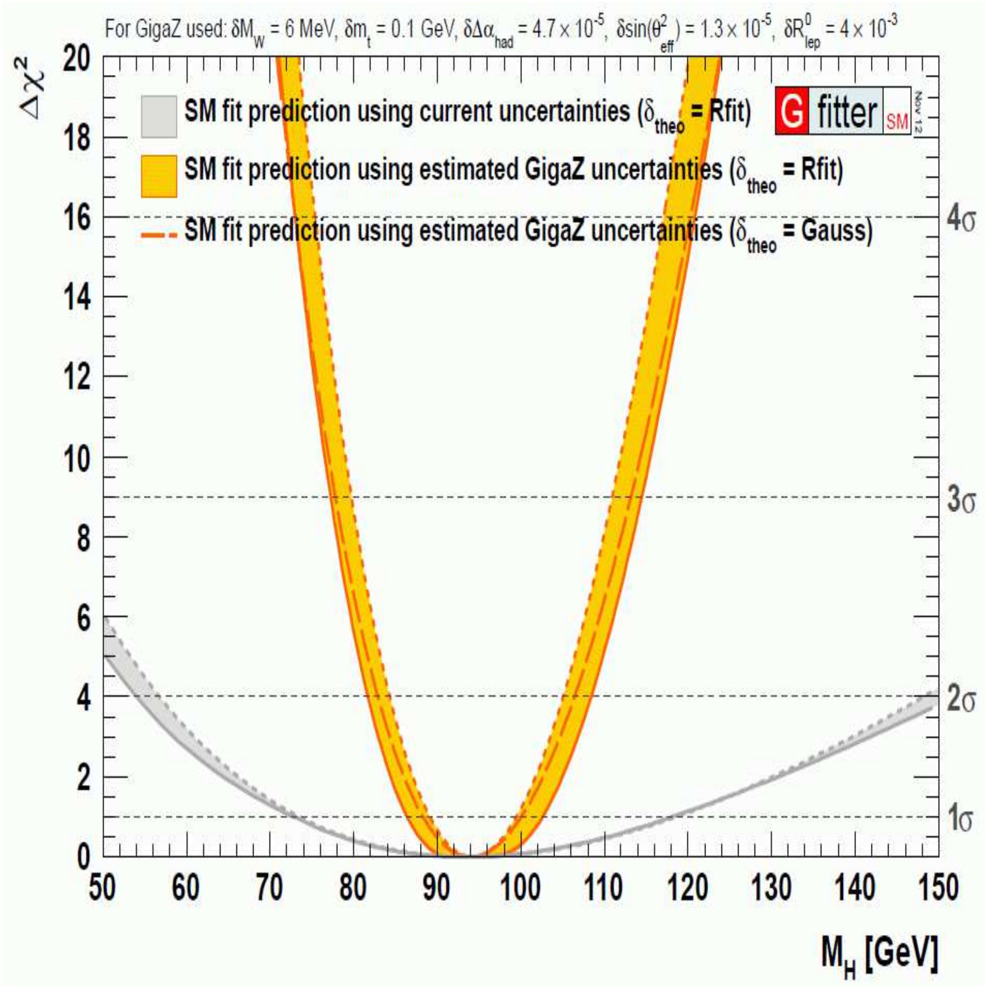
[GFitter '09]

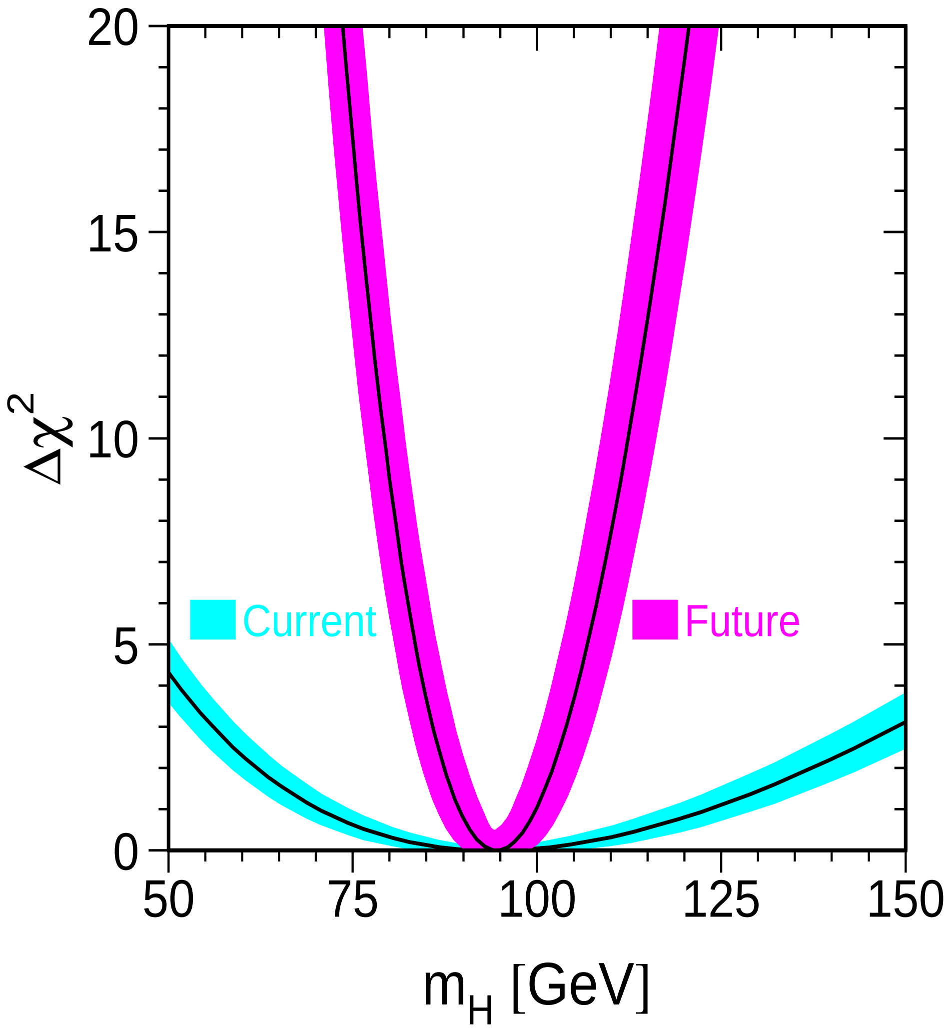


(note: artificially $M_H^{\rm SM} = 120$ GeV)

Most precise M_H test with the ILC:

[GFitter '13] [LEPEWWG '13]





⇒ $\delta M_H^{\rm ind} \lesssim \pm 6$ GeV

⇒ extremely sensitive test of SM (and BSM) possible

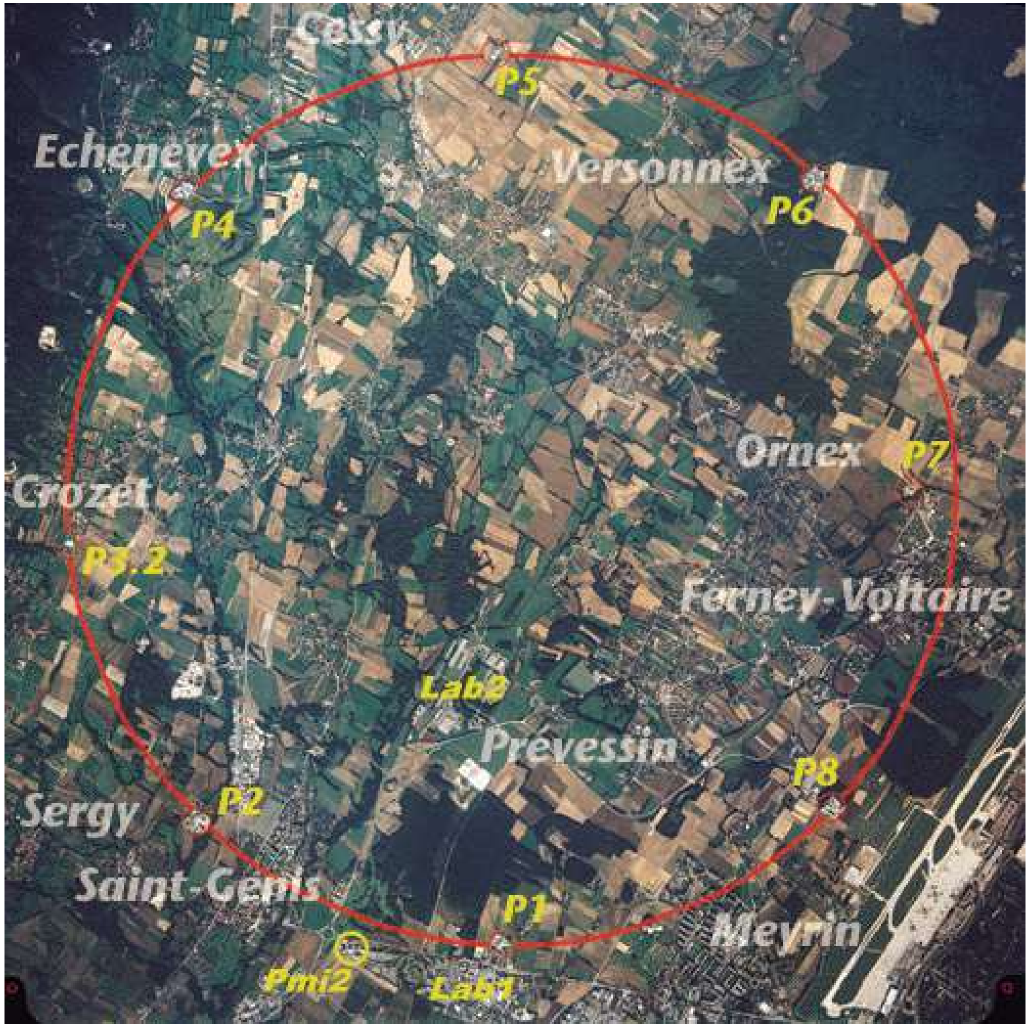
4. The (SM) Higgs boson at the LHC

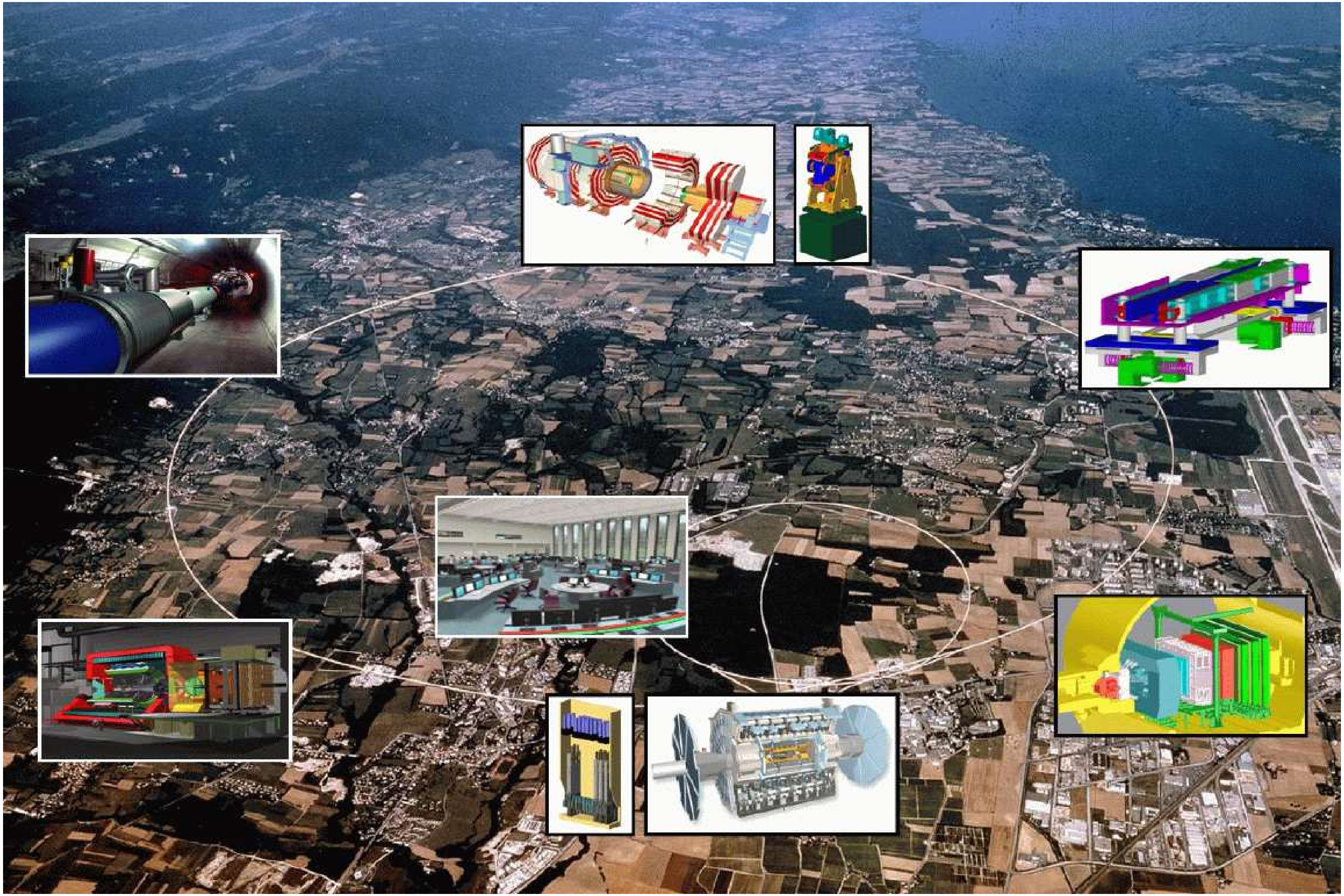
The LHC

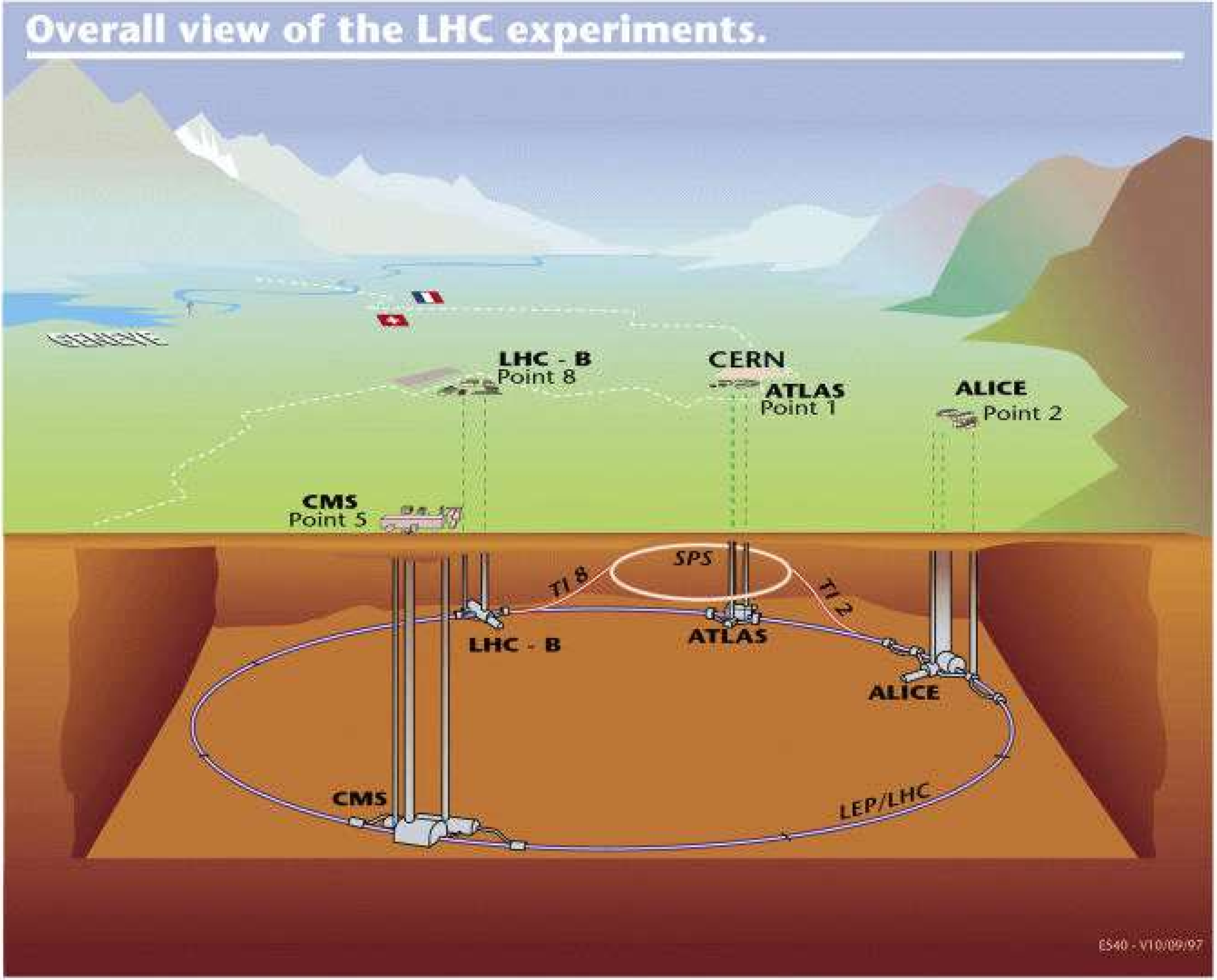
LHC:

$p\,p$ collisions at $\sqrt{s} \lesssim 14$ TeV

– 27 km circumference
– two general purpose detectors: ATLAS and CMS
– one B physics detector: LHCb
– one heavy ion detector: Alice






Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

The (un)official (optimistic?) LHC time line:

03/2010: first collisions at record breaking energy

2010: $\lesssim 0.05\,\text{fb}^{-1}$ (at $\sqrt{s} = 7$ TeV)

2011: $\sim 5\,\text{fb}^{-1}$ (at $\sqrt{s} = 7$ TeV) $\Rightarrow$ first physics results!

2012: $\sim 20\,\text{fb}^{-1}$ (at $\sqrt{s} = 8$ TeV) $\Rightarrow$ **Higgs discovery!**

2013 – 2014 shutdown, further splice checks, repairs, . . .

2015 – 2018: $\sim 40\,\text{fb}^{-1}$ per year $\Rightarrow$ physics results at $\sqrt{s} = 13$ TeV

2019 – 2021: shutdown, preparation for "higher luminosity"

2022 – 2026: $\gtrsim 50\,\text{fb}^{-1}$ per year $\Rightarrow$ physics results with "high" luminosity

2026 – 2028: upgrade to HL-LHC

2029 + X (X > 0): HL-LHC

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YOU live in an exciting time!!!

LHC Results: Executive Summary (take home message)

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Standard Model has been rediscovered!

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Groundbreaking discovery in the Higgs searches!

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Standard Model has been rediscovered!

Groundbreaking discovery in the Higgs searches!

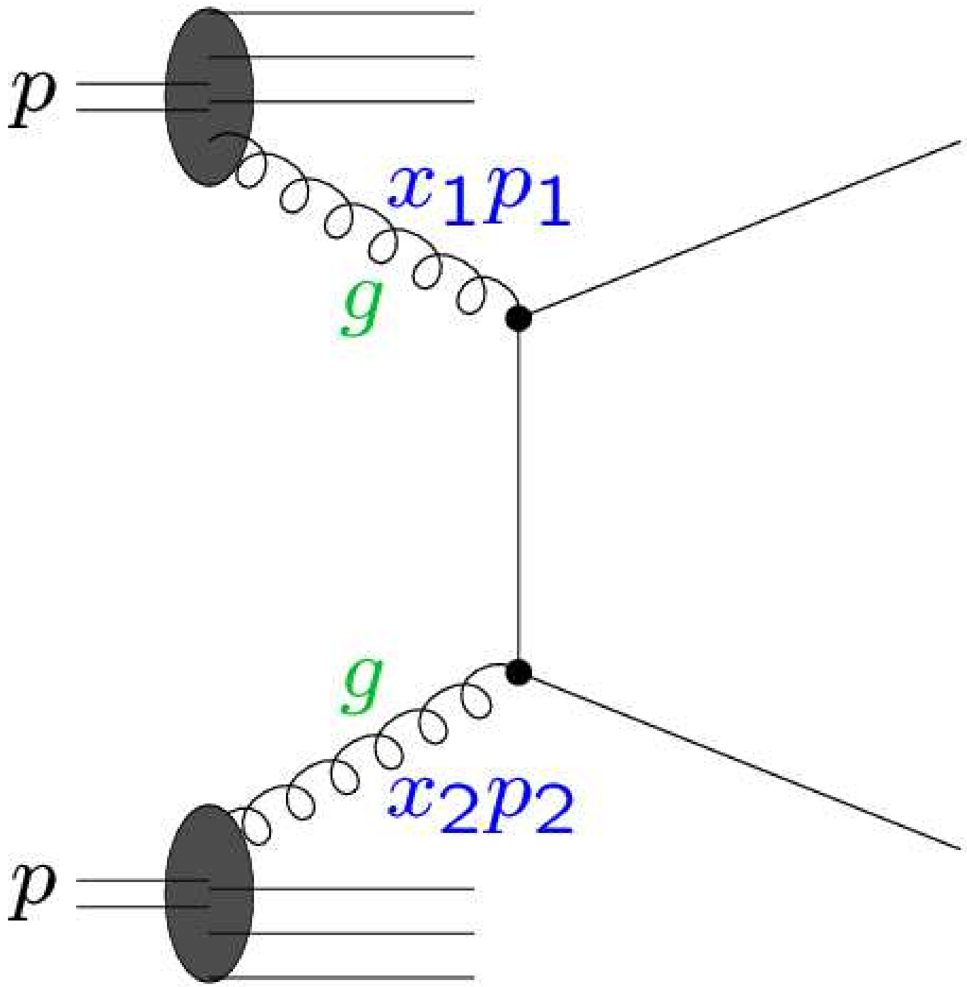
No clear evidence for BSM physics - yet! But . . . :-)

Physics at the LHC: basics

$p\,p$ scattering at $\sqrt{s} = 14$ TeV

Scattering process of proton constituents (q, $\bar{q}$, g) with energy up to several TeV, strongly interacting

⇒ huge QCD backgrounds, low signal–to–background ratios

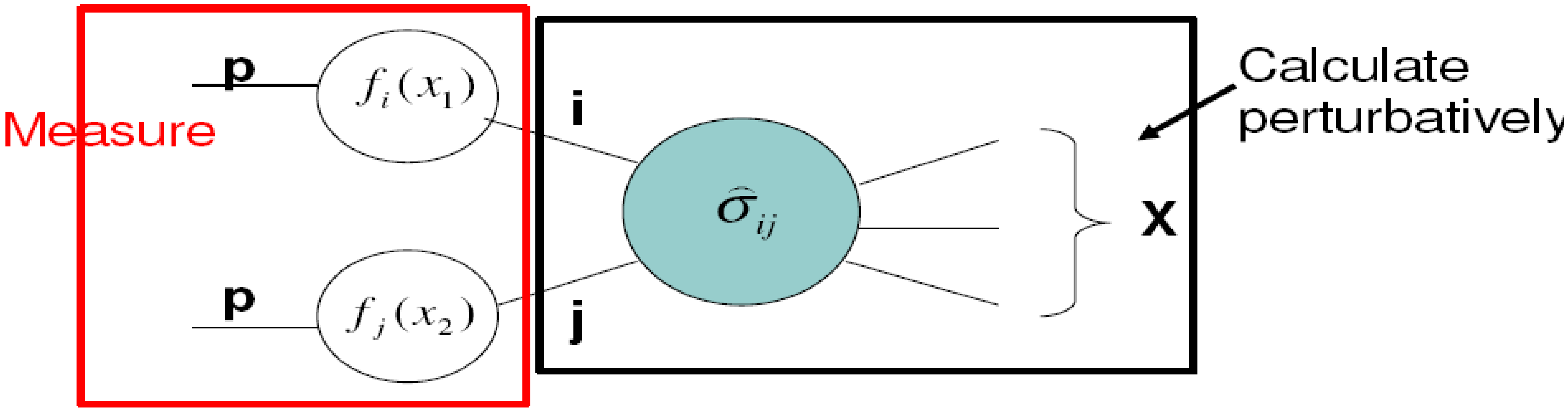


interaction rate of 10^9 events/s

⇒ can trigger on only 1 event in 10^7

The Master formula for all LHC cross section calculations:

$$\sigma(pp \to X) = \sum_{ij} \int dx_1 dx_2\, f_i(x_1, \mu_f)\, f_j(x_2, \mu_f)\, \hat{\sigma}(ij \to X)$$



$f(x, \mu_f)$: parton density functions (PDFs)
$x_{1,2}$: momentum fraction carried by the incoming quarks, gluons
$\hat{\sigma}$: partonic cross section, calculated perturbatively

Parton Density Functions (PDFs):

- PDFs cannot be calculated perturbatively
  $\Rightarrow$ they have to be measured experimentally (at a certain scale)

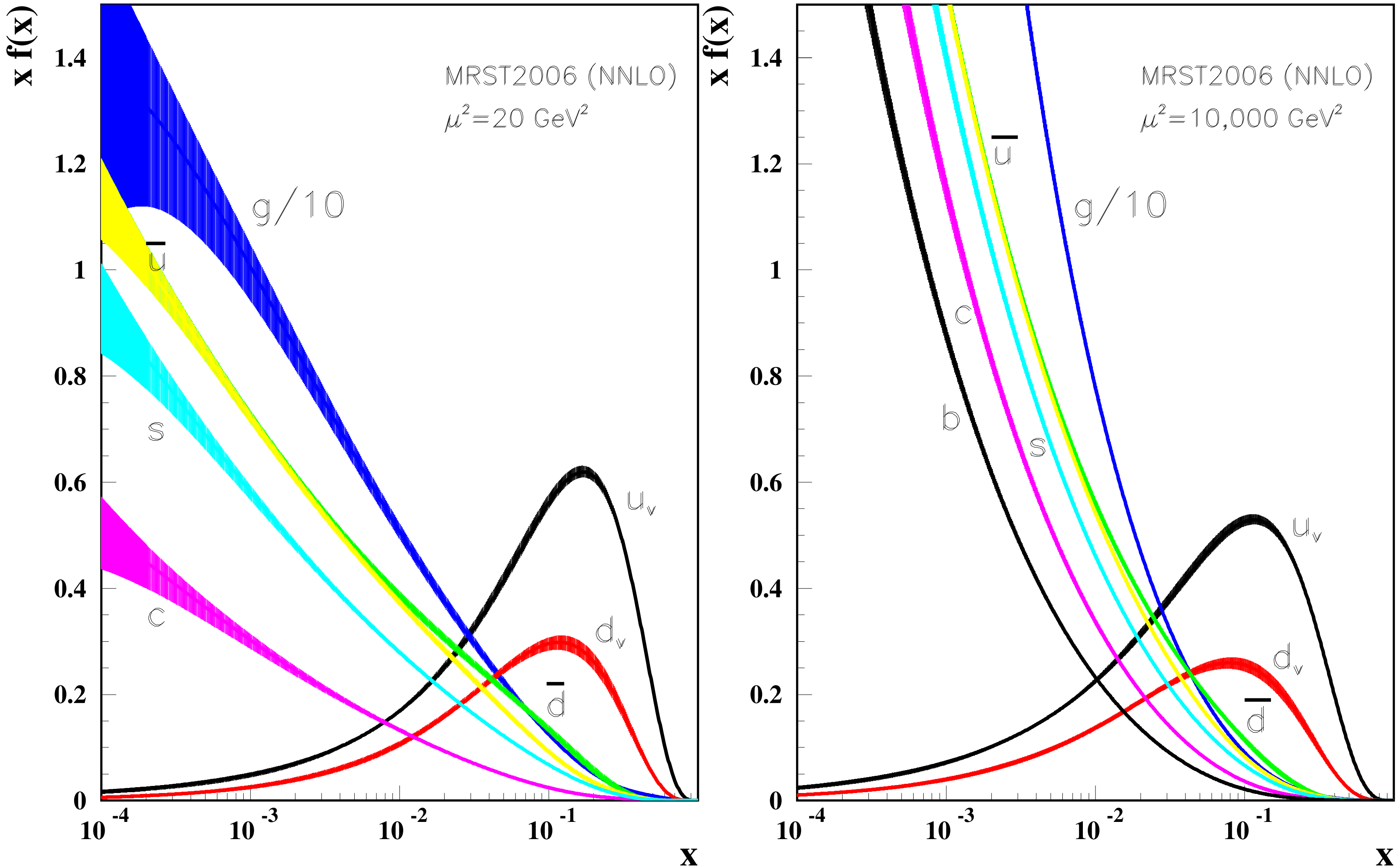
- QCD predicts the evolution of the PDFs via the
  Altarelli-Parisi/DGLAP equations,
  i.e. once we know the PDFs for a certain scale, QCD predicts them for all other scales

- PDFs are universal, e.g. PDFs determined at HERA can directly be used for LHC calculations

- PDFs are different for valence and sea quarks

- PDFs come in the form of Fortran codes, mainly by several groups:
  MRST/MSTW, CTEQ/CT, NNPDF, HERAPDF, ... collaborations

Example for PDFs of the proton:



⇒ The LHC is (mainly) a gluon gluon collider

Properties of the SM Higgs boson

1.) Decay to fermions:

coupling:

$$g_{f\bar{f}H} = \left[\sqrt{2}\,G_\mu\right]^{1/2} m_f$$

decay width:

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_\mu\, M_H}{4\sqrt{2}\,\pi} m_f^2(M_H^2) \left(1 - 4\frac{m_f^2}{M_H^2}\right)^{3/2}$$

with N_c = number of colors

Bulk of QCD corrections for decays to quarks are mapped into

$$m_q^2(\text{pole}) \to m_q^2(M_H^2)$$

Q: What is the strongest/most important decay?

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Dominant decay process: $H \to b\bar{b}$

2.) Decay to heavy gauge bosons ($V = W, Z$):

coupling:

$$g_{VVH} = 2 \left[\sqrt{2}\, G_\mu\right]^{1/2} M_V^2$$

on-shell decay width ($M_H > 2M_V$):

$$\Gamma(H \to VV) = \delta_V \frac{G_\mu M_H^3}{16\,\sqrt{2}\,\pi} \left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right) \left(1 - 4\frac{M_V^2}{M_H^2}\right)^{1/2}$$

with $\delta_{W,Z} = 2, 1$

off-shell decay width ($M_H < 2M_V$):

$$\Gamma(H \to VV^*) = \delta'_V \frac{3G_\mu^2 M_H}{16\,\pi^3} M_V^4 \times \text{Integral}$$

3.) Decay to massless gauge bosons (gg, $\gamma\gamma$):

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Q: How is this possible?
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Q: What are the most important loops?

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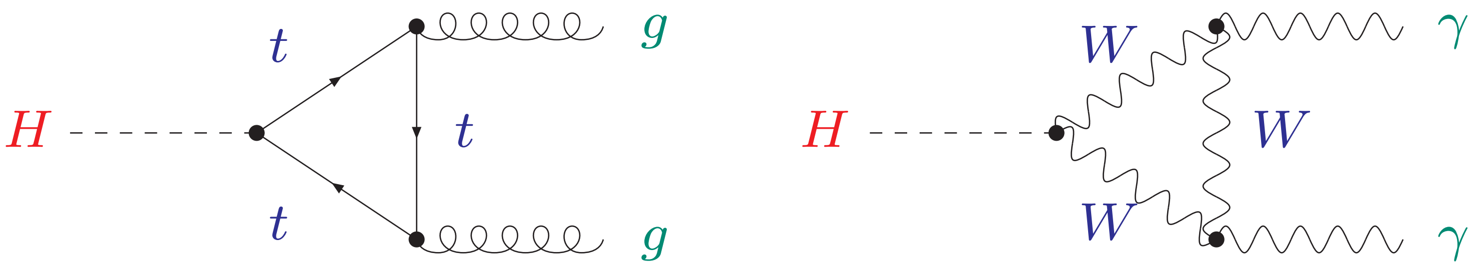


$$\Gamma(H \to gg) = \frac{G_\mu \, \alpha_s^2(M_H^2) \, M_H^3}{36\sqrt{2}\,\pi^3} \left[1 + C \frac{\alpha_s(\mu)}{\pi} \right]$$

via the top quark loop with

$$C = \frac{215}{12} - \frac{23}{6} \log\left(\frac{\mu^2}{M_H^2}\right) + \mathcal{O}(\alpha_s)$$

⇒ huge QCD corrections

$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu \, \alpha^2 \, M_H^3}{128\sqrt{2}\,\pi^3} \left| \frac{4}{3} e_t^2 - 7 \right|^2$$

via the top quark and W boson loop

Total width:

sum over all decay widths

$$\Gamma_{H,\text{tot}} := \sum_{\text{dd}'} \Gamma(H \to \text{dd}')$$

$$= \Gamma(H \to t\bar{t}) + \Gamma(H \to b\bar{b}) + \Gamma(H \to c\bar{c}) + \ldots$$

$$+ \Gamma(H \to \tau^+\tau^-) + \Gamma(H \to \mu^+\mu^-) + \ldots$$

$$+ \Gamma(H \to WW^{(*)}) + \Gamma(H \to ZZ^{(*)}) + \Gamma(H \to \gamma\gamma) + \ldots$$

$$+ \ldots$$

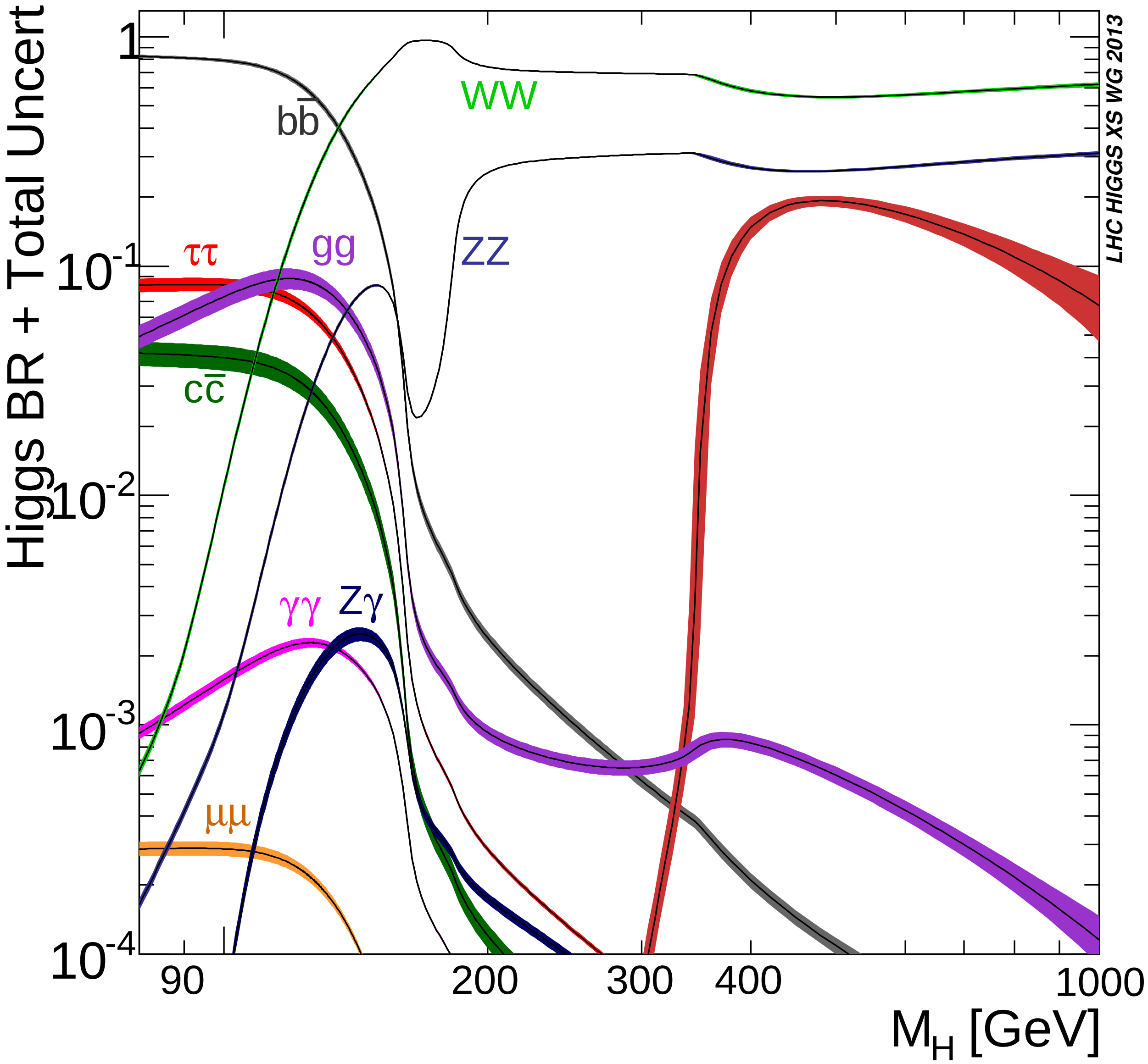
Branching ratio:

probability that a particle decays to a certain final state

$$\text{BR}(H \to \text{dd}') := \frac{\Gamma(H \to \text{dd}')}{\Gamma_{H,\text{tot}}}$$

Theory predictions for the SM Higgs: branching ratios

[*LHC Higgs XS WG '13*]



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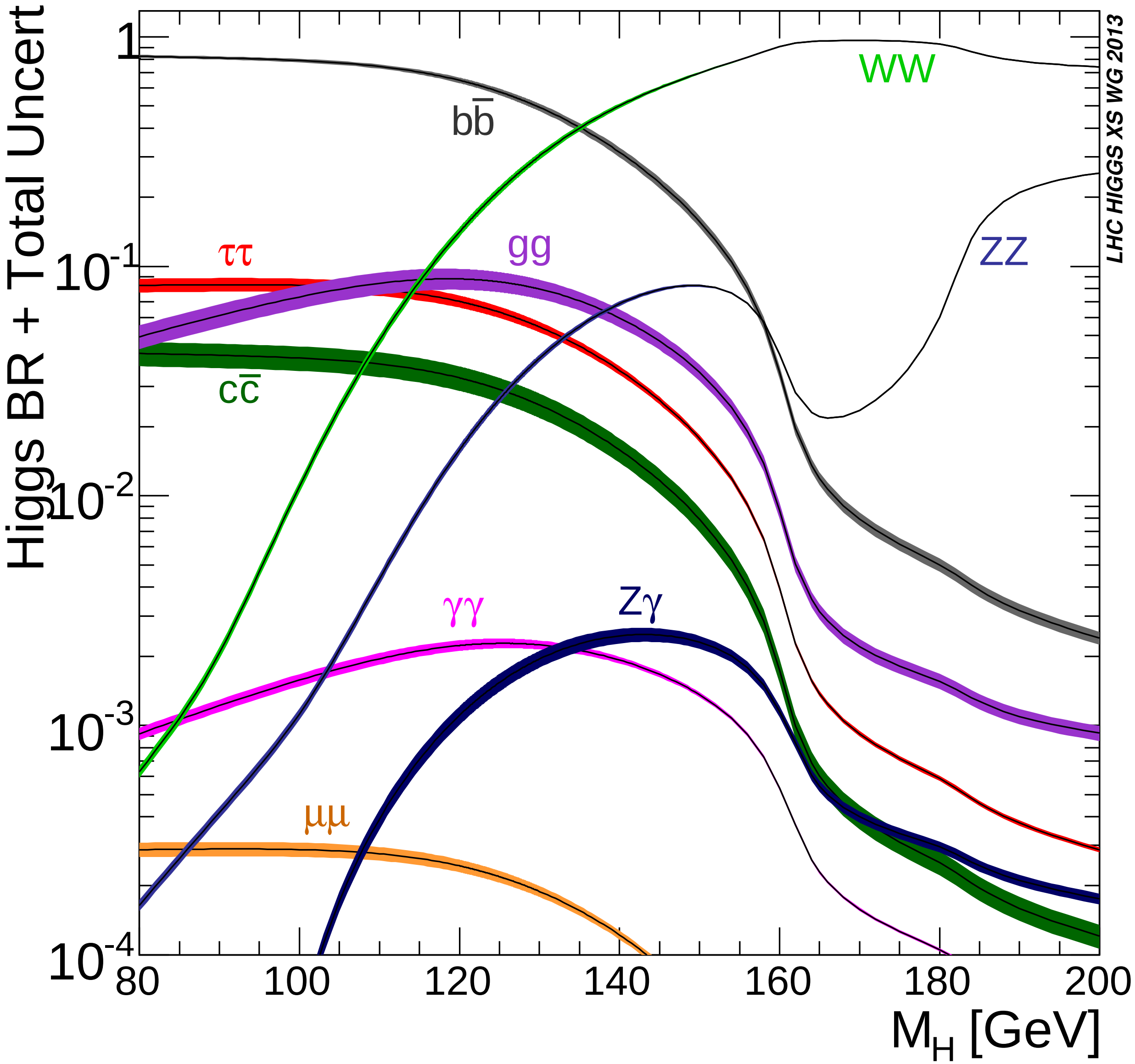
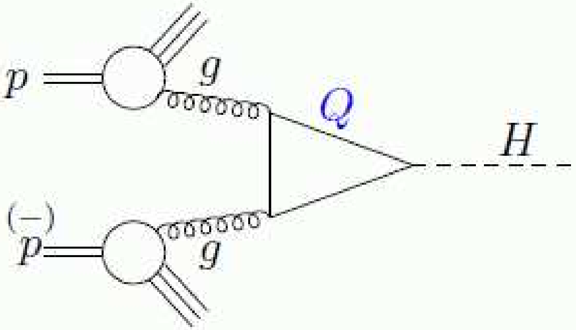


Higgs production modes at the LHC:

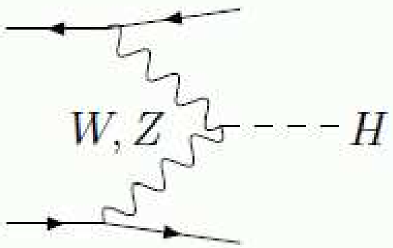
- **Gluon Gluon Fusion**

  $pp \to gg \to H$



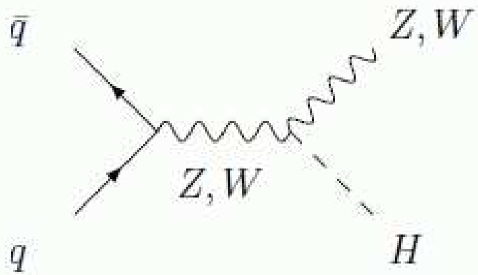
- **W/Z Fusion**

  $pp \to qq \to qq + WW/ZZ \to qq + H$



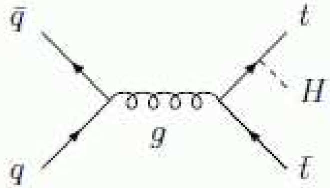
- **Higgs-strahlung**

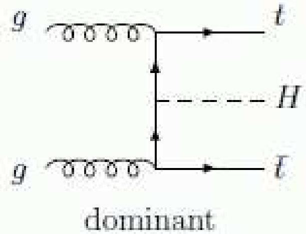
  $pp \to W^*/Z^* \to W/Z + H$



- **Associated production with $t\bar{t}$**

  $pp \to t\bar{t} + H$

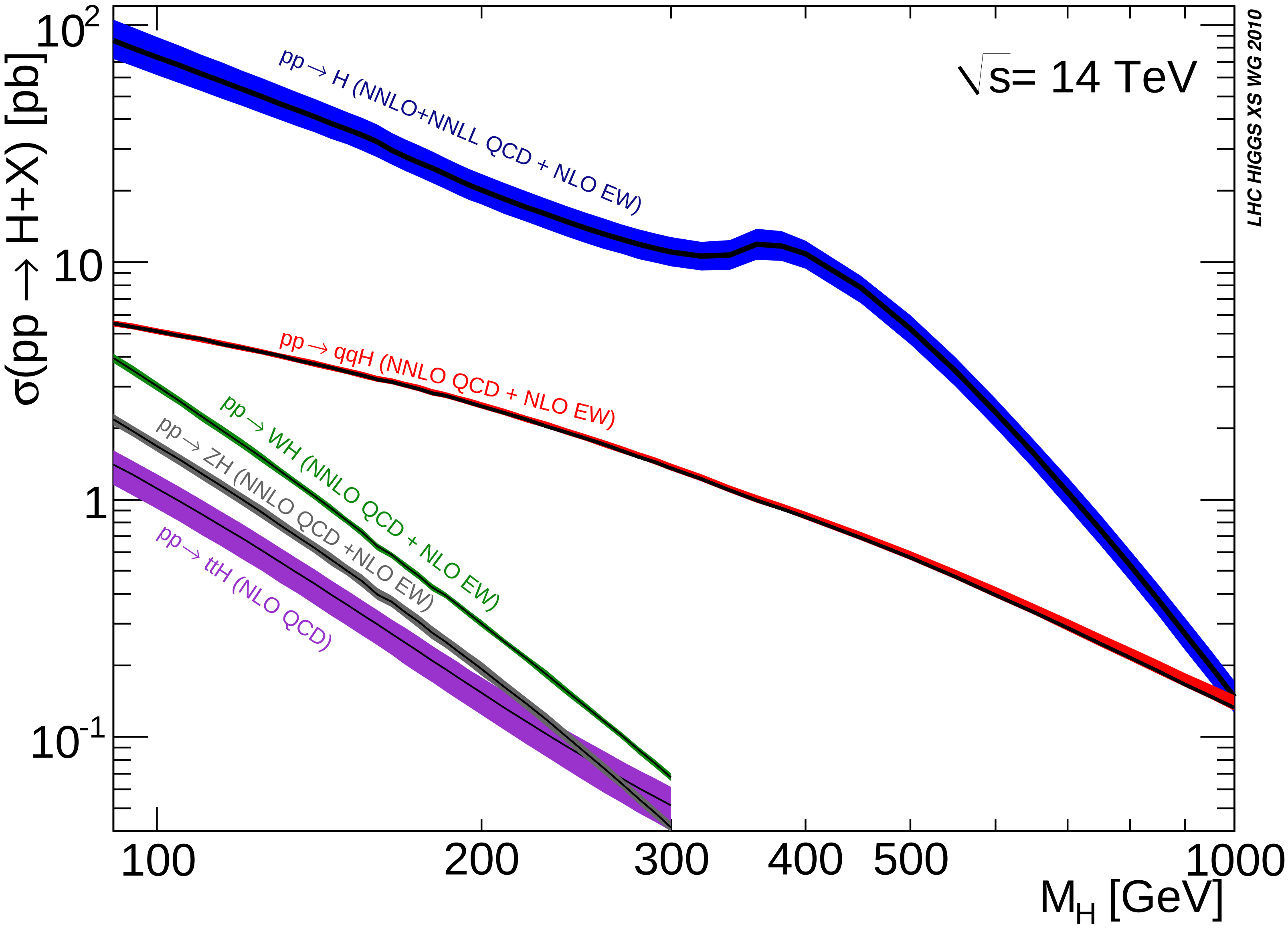




[*taken from M. Mühlleitner*]

Theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '10*]



Various possible (LHC) “observables” for the Higgs discovery:

→ normally given as a function of M_H

- Local p_0 value:

  probability that the observed signal/number of events is caused by “background only” (i.e. the SM without a Higgs)

- $\sigma_{\text{excl.}}/\sigma_{\text{SM}}$:

  excluded cross section divided by SM cross section:
  if for a certain M_H a cross section smaller than the SM cross section excluded, this M_H value is excluded, as it would have led to more events than observed.

- signal strength μ:

$$\mu := \frac{\sigma(pp \to H) \times \text{BR}(H \to dd')_{\text{observed}}}{\sigma(pp \to H) \times \text{BR}(H \to dd')_{\text{SM}}}$$

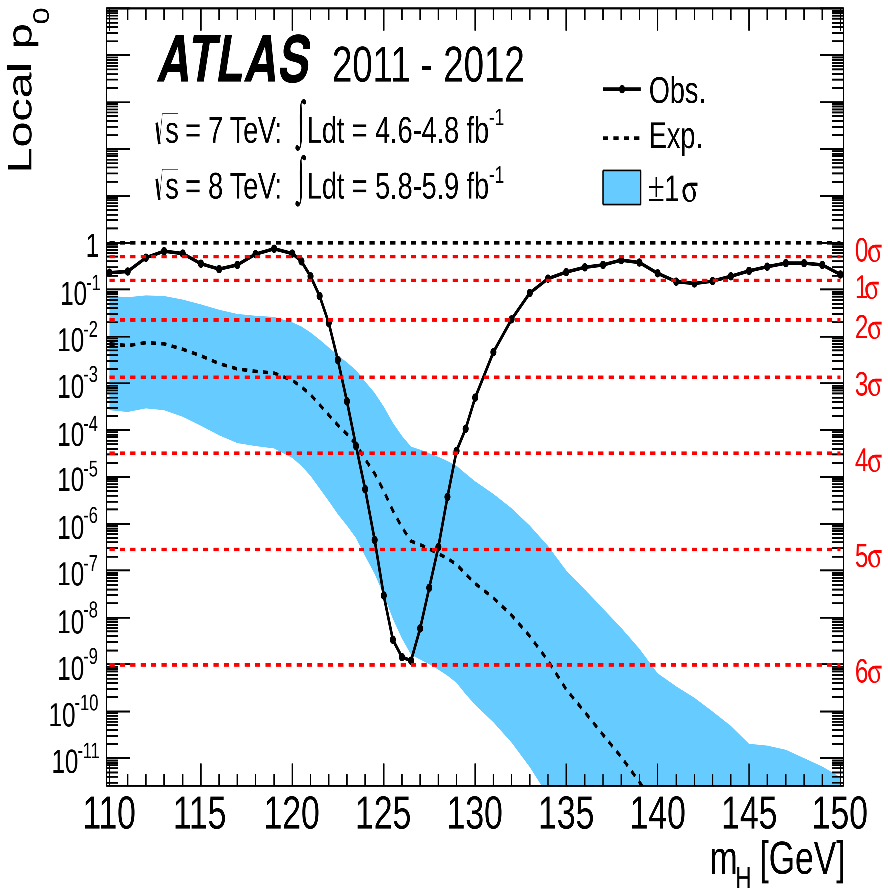
  should be “around 1” to find agreement with SM

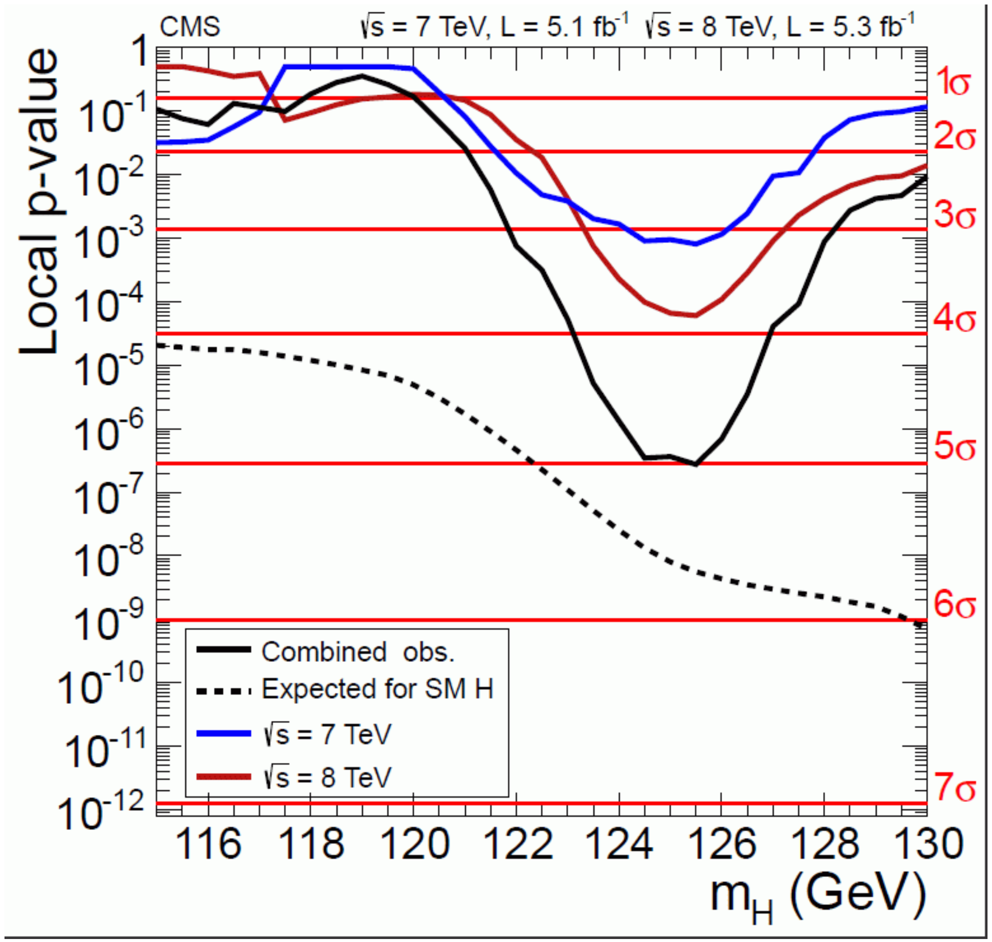
Why July 4th is celebrated (not only in the US): Q: Why?

5. Motivation for BSM Higgs

Fact I: The physics world changed on 04.07.2012:

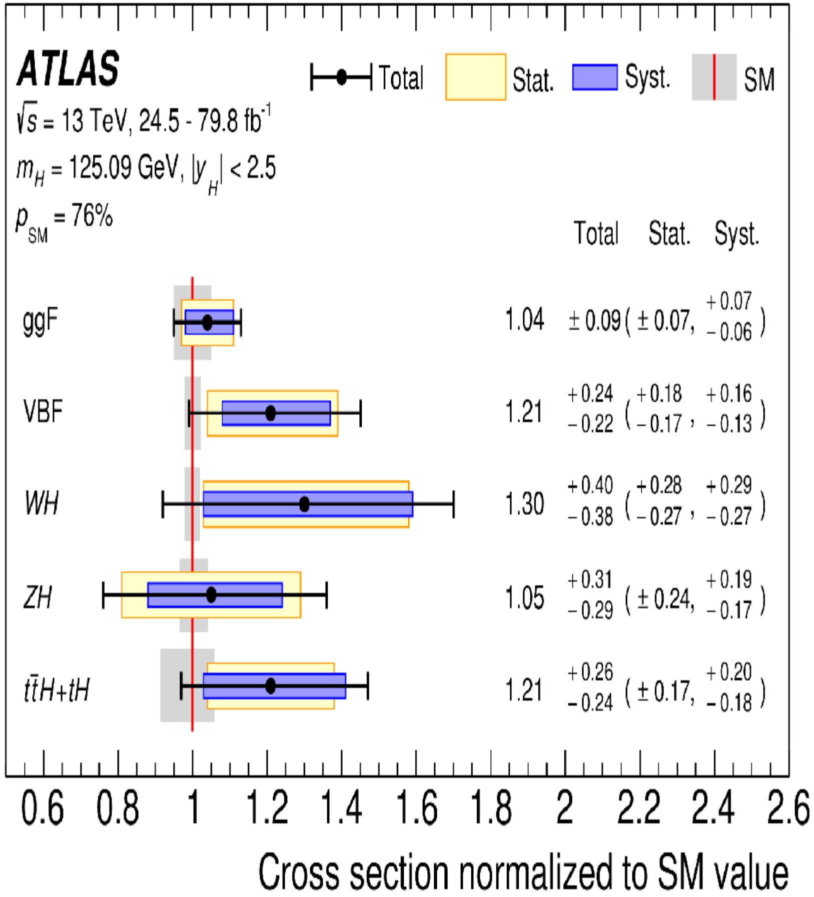
We have a discovery!

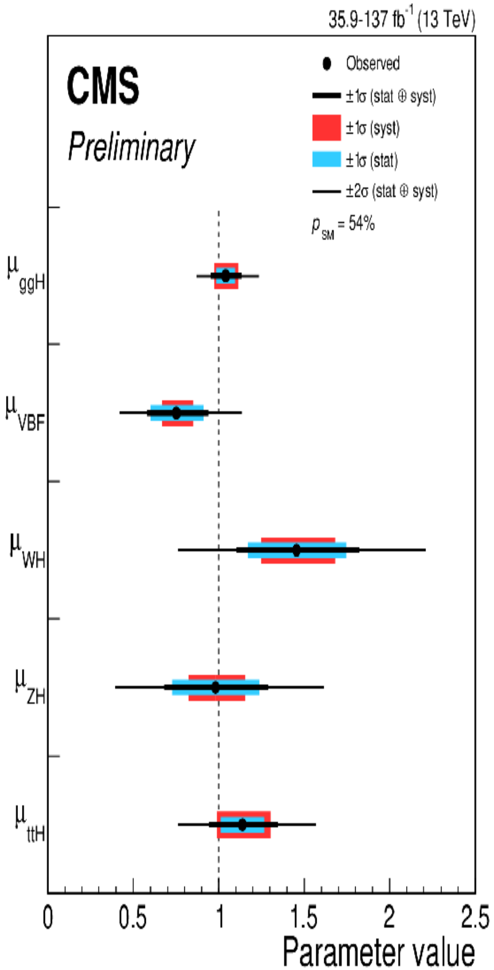


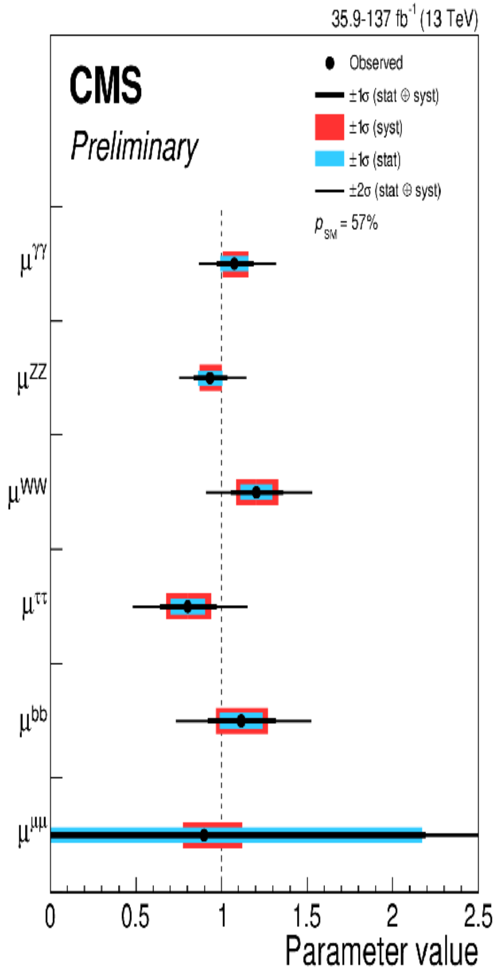


Fact I: The physics world changed on 04.07.2012:

We have an SM-like discovery!







Fact II:

The SM cannot be the ultimate theory!

Some sub-facts:

1. gravity is not included

2. the hierarchy problem

3. no unification of the three forces

4. Dark Matter is not included

5. Baryon Asymmetry of the Universe cannot be explained

6. neutrino masses are not included

7. Some interesting experimental anomalies . . .

Fact I & II:

We have discovered an SM-like Higgs!

The SM cannot be the ultimate theory!

Conclusion: The discovered Higgs cannot be "the SM Higgs"!

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Q: Does the BSM physics have any (relevant) impact on the Higgs?
$\Rightarrow$ any hints from LHC results (as guideline/toy example)?

Q': Which model?

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Q: Does the BSM physics have any (relevant) impact on the Higgs?
⇒ any hints from LHC results (as guideline/toy example)?
Q': Which model?

A1: check changed properties of the h_{125}

A2: check for additional Higgs bosons
check for additional Higgs bosons above and below 125 GeV
⇒ any evidence yet? :-)

Back to fact II:

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4. Dark Matter is not included $\Rightarrow$ BSM Higgs
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7. Some interesting experimental anomalies . . . $\Rightarrow$ BSM Higgs

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Some sub-facts:

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2. the hierarchy problem $\Leftarrow$ and here?
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5. Baryon Asymmetry of the Universe cannot be explained $\Rightarrow$ BSM Higgs
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Back to fact II:

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Some sub-facts:

1. gravity is not included $\Rightarrow$ SUSY
2. the hierarchy problem $\Rightarrow$ SUSY
3. no unification of the three forces $\Rightarrow$ SUSY
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5. Baryon Asymmetry of the Universe cannot be explained $\Rightarrow$ SUSY
6. neutrino masses are not included $\Rightarrow$ SUSY
7. Some interesting experimental anomalies . . . $\Rightarrow$ SUSY

My favorite motivation

My favorite motivation

My favorite motivation

⇒ Why is there more matter than antimatter? ⇒ (EW) baryogenesis

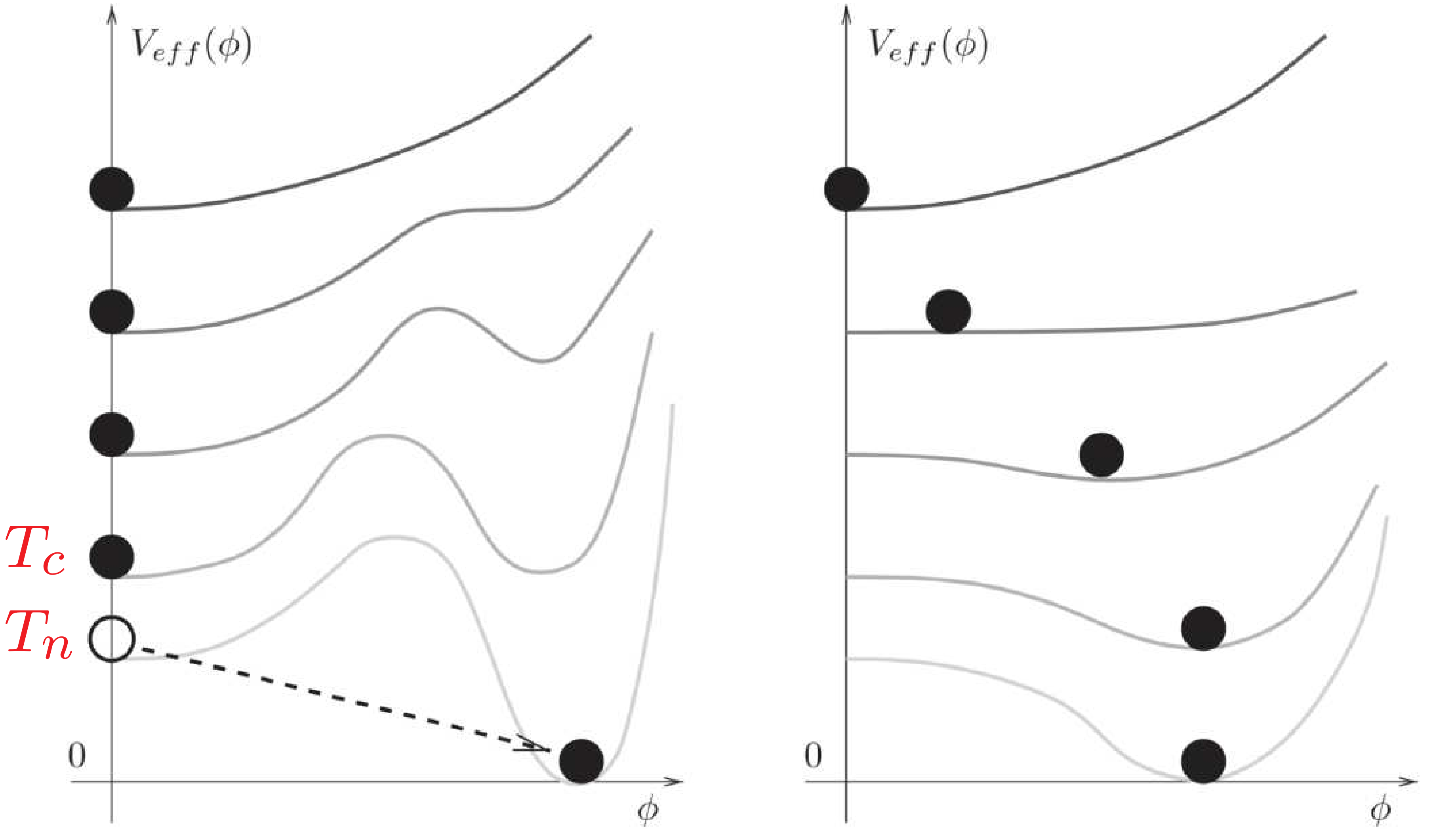
⇒ requires First Order EW Phase Transition (FOEWPT)

FOEWPT not possible in the SM ⇒ BSM Higgs sector required

FOEWPT can cause Gravitational Waves (GW), detectable with LISA, . . .

Phase transition: BSM vs. SM

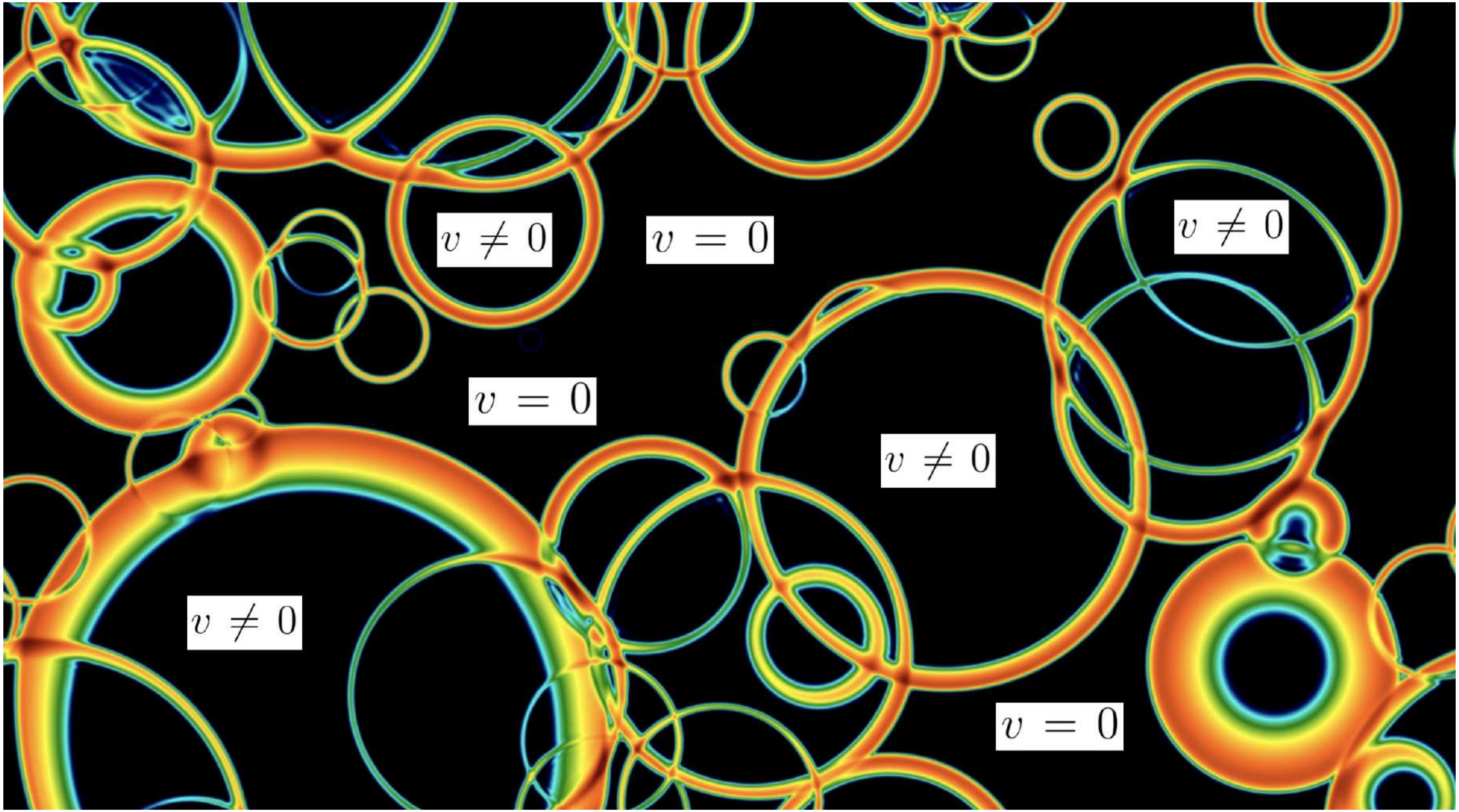
[*taken from V. A. Rubakov and D. S. Gorbunov*]



⇒ BSM Higgs sector required to realized FOEWPT

Bubble formation can lead to Gravitational Waves

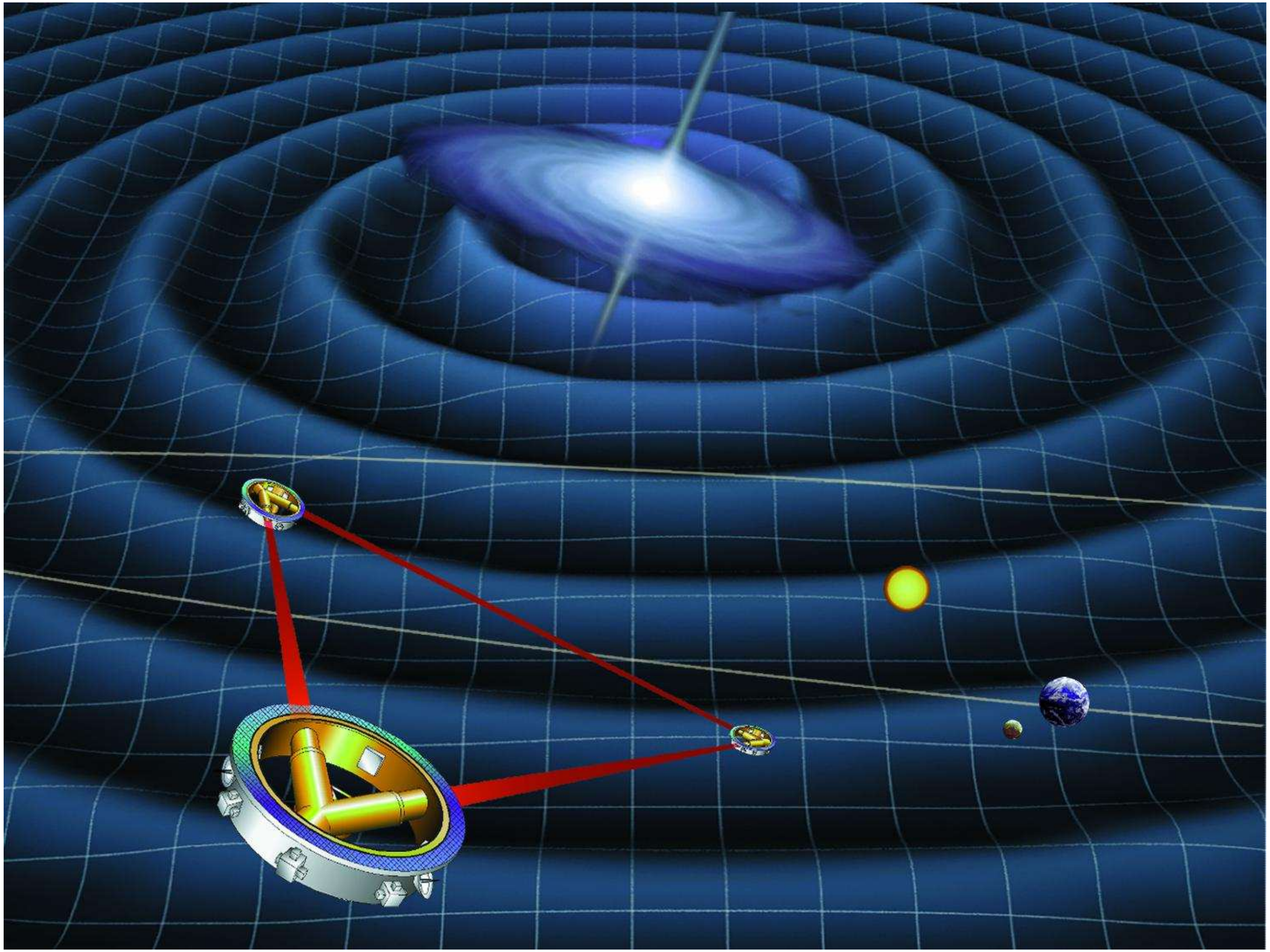
[*taken from D. Weir*]



$\Rightarrow$ Interesting interplay of Higgs physics and Gravitational Waves!

GW observatory: LISA

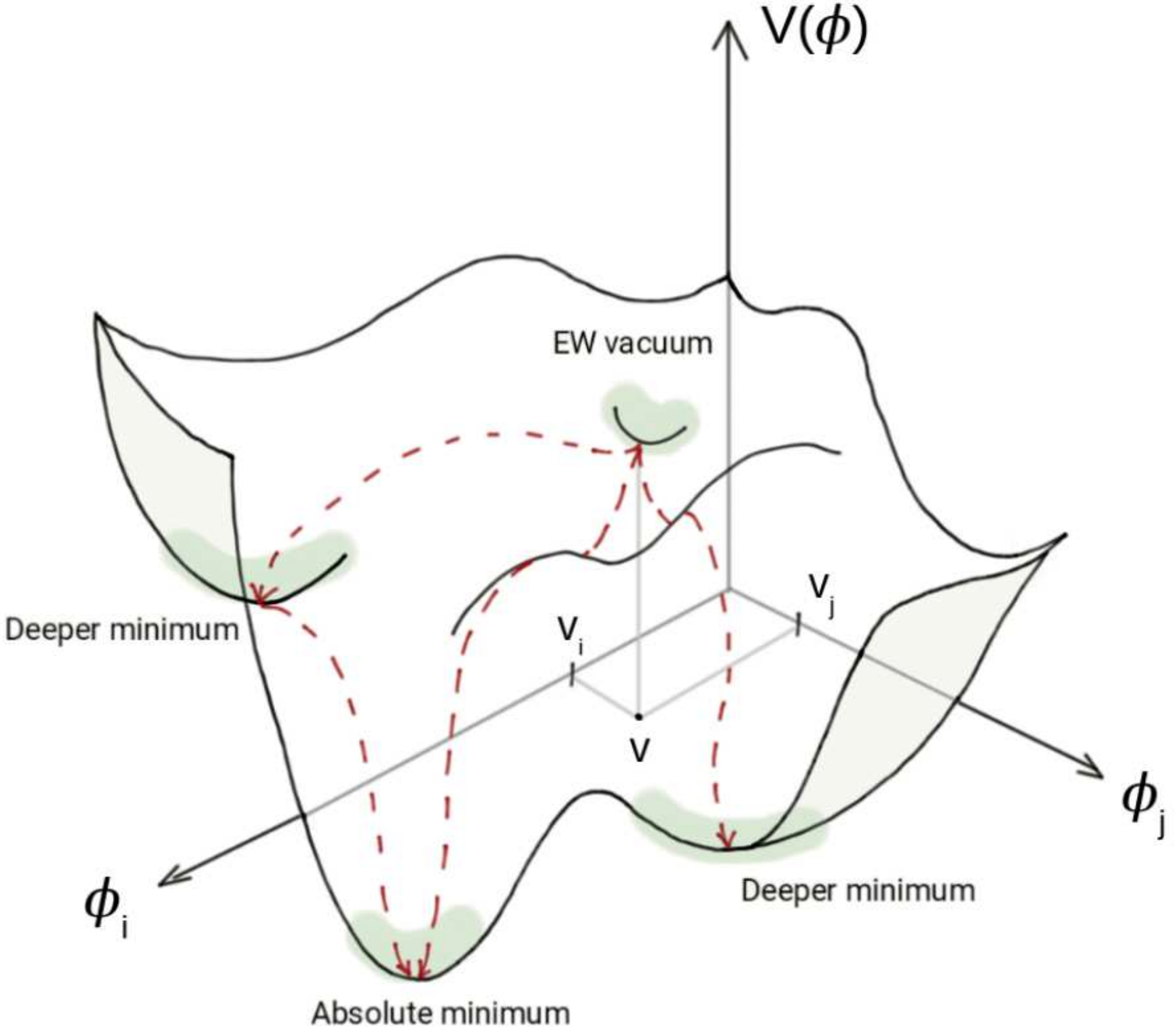
[*NASA*]



Approved launch date: ~ 2035

BSM Higgs sectors can (should) behave very different from SM Higgs

[*K. Radchenko '24*]



⇒ much more complicated structure, very^2 little known . . .