Higgs, Symmetry Breaking and the New Physics

Fawzi BOUDJEMA

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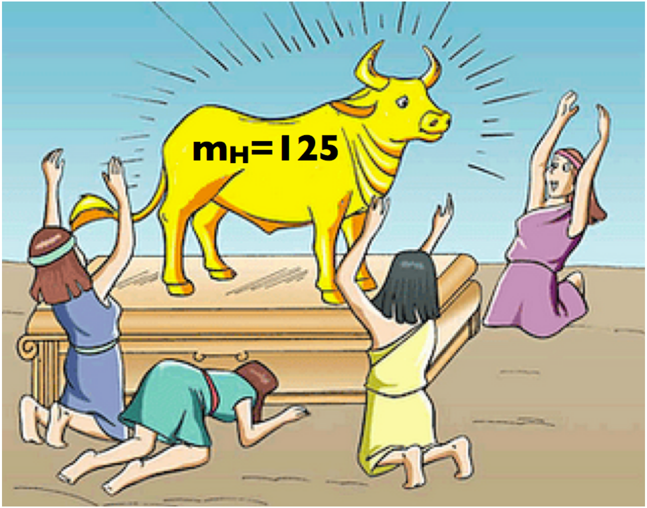
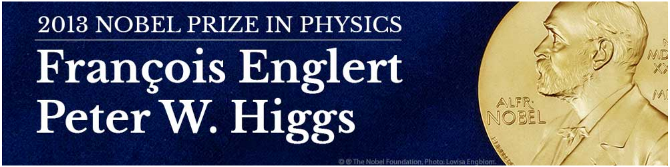
4th of July 2012, Discovery of a resonance at 125-126GeV

Hare Higgsna, Hare Hare...



from Adam Martin, from? why not just praise the Lord and the SM

The holy cow has got 4 legs: 3 Goldstones and one scalar



Press Release

8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Be

and

Peter W. Higgs
University of Edinburgh, UK

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Mechanism...Spontaneous Symmetry Breaking

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The Nobel Prize in Physics 2008

Photo: University of Chicago
Yoichiro Nambu

© The Nobel Foundation
Photo: U. Montan
Makoto Kobayashi

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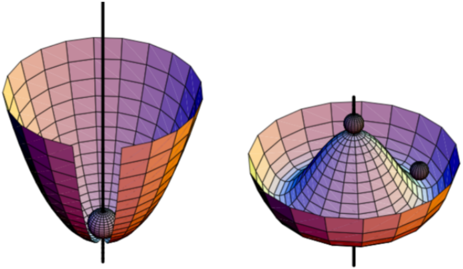
Photo: U. Montan
Toshihide Maskawa

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

Higgs in the SM model



$V = \lambda(|\Phi|^2 - v^2/2)^2$

$(\lambda > 0)$

$\langle 0|\phi|0\rangle = v/\sqrt{2}$

$Q_{em}|0\rangle = |0\rangle$

$y_\Phi = Y_\Phi = \frac{1}{2}$

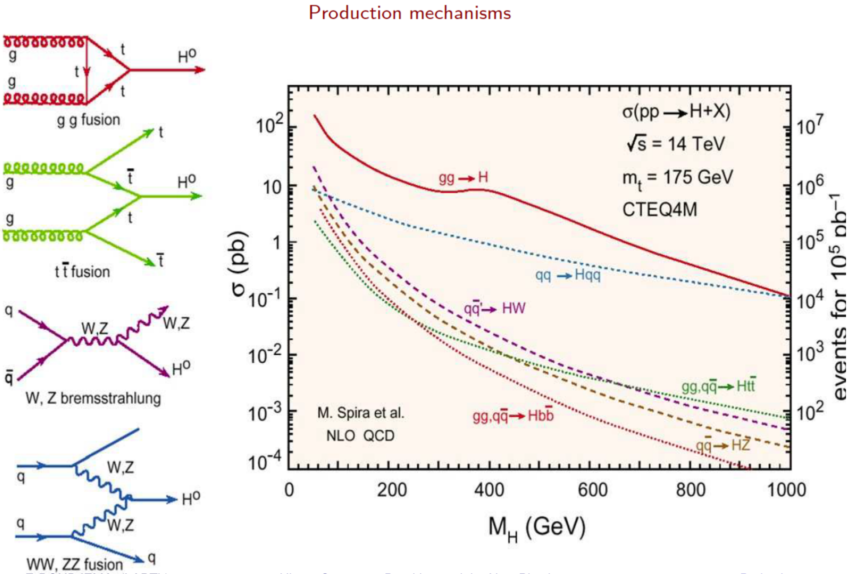
$$\Phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+H) \end{pmatrix} e^{i\frac{\omega^j\tau^j}{2v}}$$

$$\mathcal{L}_{\text{Higgs}} = (D^\mu\Phi)^\dagger(D_\mu\Phi) - V(\Phi^\dagger\Phi), \quad V(\Phi^\dagger\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$

$$\mathcal{L}_{m_f} = -\left(y_u\bar{u}_R\tilde{\Phi}^\dagger Q_L + {}^{y}_{d}\,\bar{d}_r\Phi^\dagger Q_L\right) + h.c, \quad \tilde{\Phi} = i\tau_2\Phi^* \quad m_{d,u} = y_{d,u}\frac{v}{\sqrt{2}}$$

Production at LHC:

Important contribution from the theory side to get precise HiggsXsections, novel techniques,...



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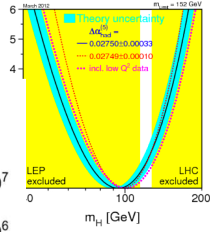
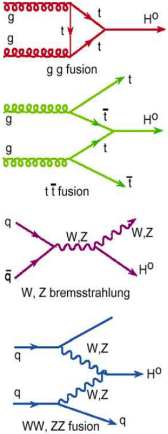
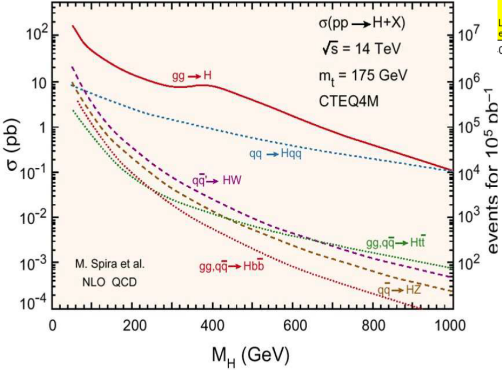
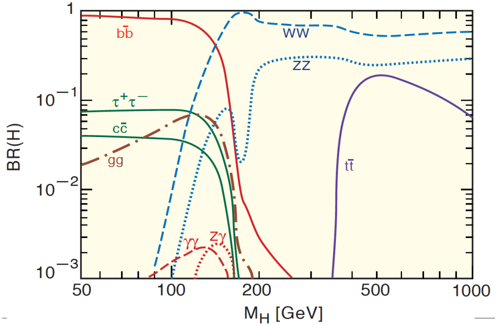


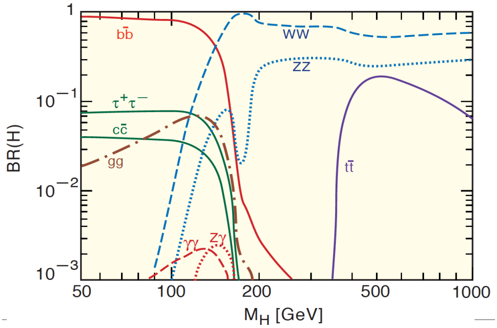
Production mechanisms



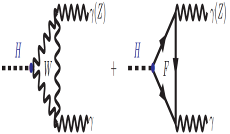




$M_H = 125$GeV a very lucky strike, many channels open/accessible/useful. Allows more tests.



Indirect effects again, for a crucial channel, top, W loops

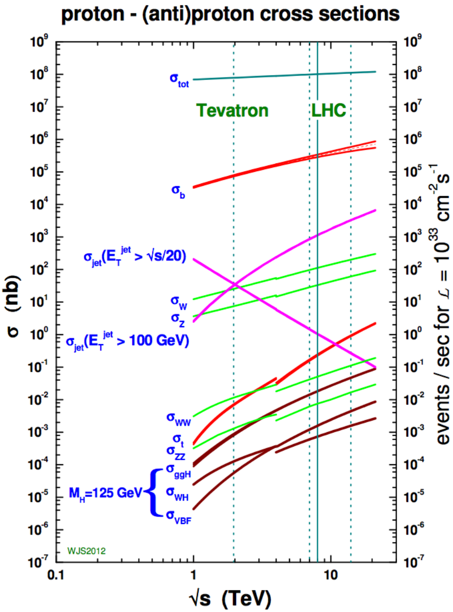


$$\mathcal{L}_{H\gamma\gamma} = c\frac{\alpha}{4\pi}F_{\mu\nu}F^{\mu\nu}\frac{H}{v}$$

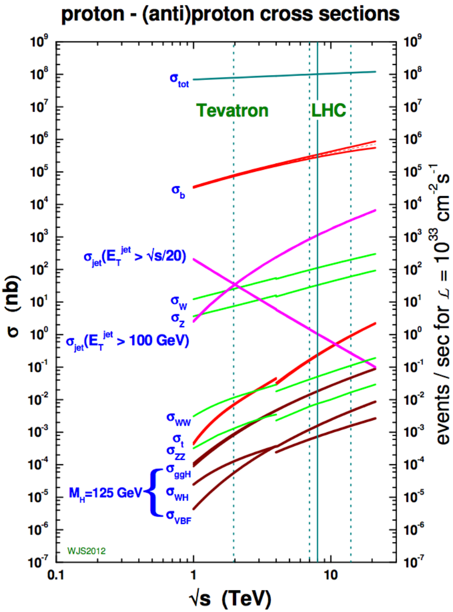
$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu M_H^3}{\sqrt{2}}\frac{\alpha^2}{128\pi^3}\sum_i |Q_i^2 N_{C,i} F_i|^2, \qquad F_i = \begin{cases} +7 \; (W^\pm) \\ -\frac{4}{3} \text{ fermion} \\ -\frac{1}{3} \text{ scalar} \end{cases}$$

Related to the β function.
4th generation reduces the rate by 15%.

in ATLAS

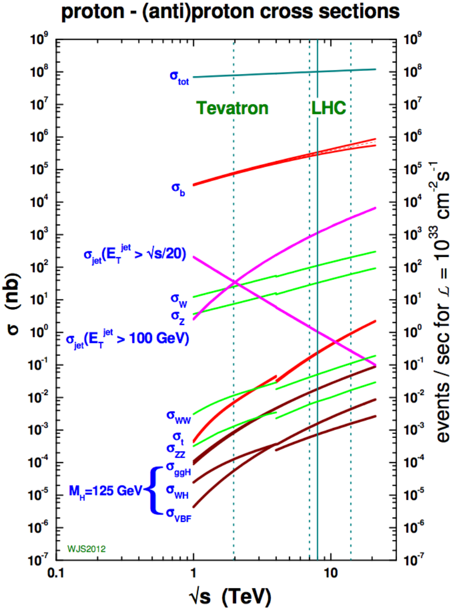


proton - (anti)proton cross sections
Tevatron
LHC
σ_{tot}
σ_b
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100$ GeV)
σ_{WW}
σ_t
σ_{ZZ}
M_H=125 GeV
σ_{ggH}
σ_{WH}
σ_{VBF}
WJS2012
σ (nb)
events / sec for $\mathcal{L} = 10^{33}$ $cm^{-2}s^{-1}$
√s (TeV)
0.1
1
10



in ATLAS

- 1 Higgs in 2×10^9 pp coll.



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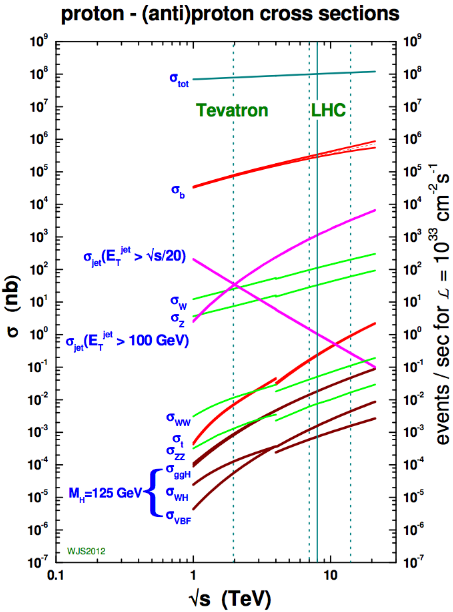
- 1 $H \to \gamma\gamma$ in 4×10^{12} collisions (like looking for one person among the population of 500 Earths!)



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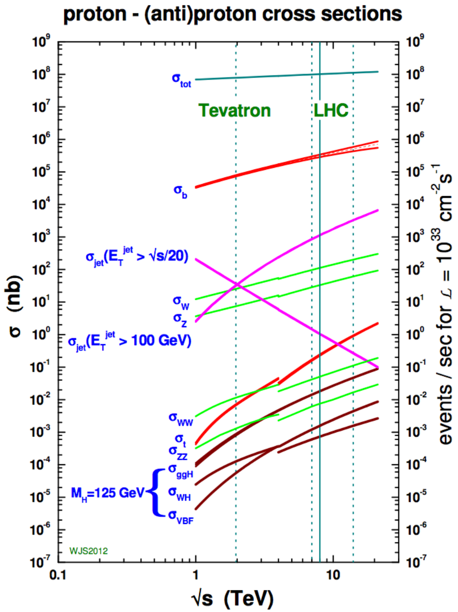

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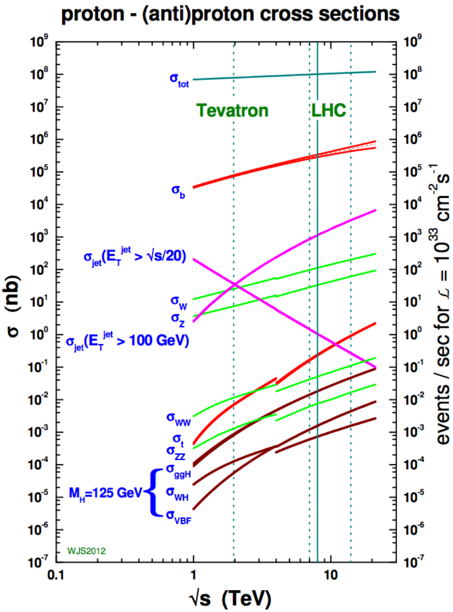

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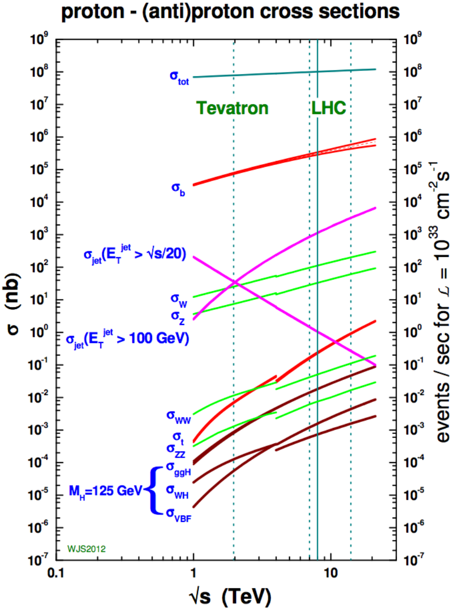

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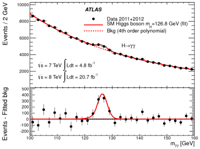
  - 

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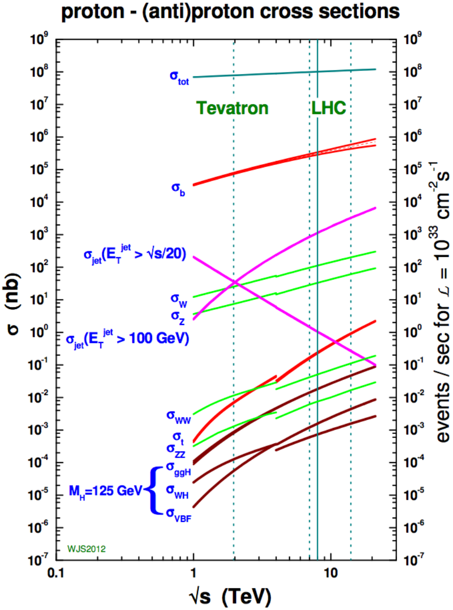
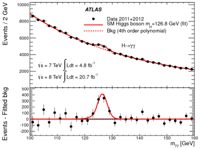
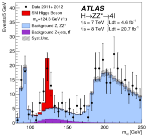
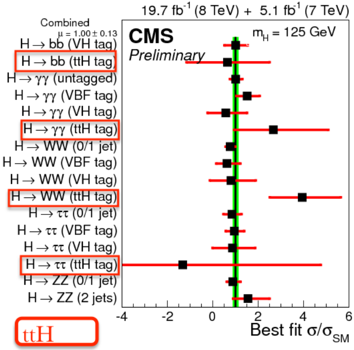
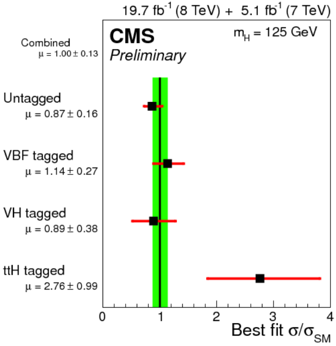


- 

- 

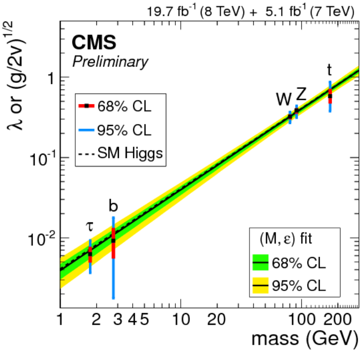
Higgs looks fairly standard





$$\mu_{\rm combined} = 1.00 \pm 0.13$$

Coupling proportional to mass



in the SM, Higgs and Mass are "ONE"

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- Origin of the potential:????
- Spin: Spin can only be 0 in this picture. A particle with a v.e.v can only by of spin-0 (angular momentum....)

Mass and the Higgs, mass without a Higgs

$$\hat{H} \neq H + v$$

- Dynamical mass from strong dynamics
- naive prototype: technicolour (3GB and no Higgs)
- Technicolour revamped, larger symmetries (modern parlance Composite Higgs)
- More implementations, X as pseudo-scalars and other dynamics
  - $SO(5)/SO(4) \to 4\text{PGB} : \omega^{\pm}, \omega^3, H$ Agashe,Contino,Pomarol
  - 5PGB + H,A, Gripaiois, Pomarol,Riva, Serra '09
  - ...
  - more dynamics? updated walking technicolour (X+dilaton, resonances, 60(!) PGB): Bando, Kamawaki, Ken Lane and friends,...

Masses in a Gauge Invariant Way without Higgs

The W, Z, γ kinetic pure gauge term still of the same origin but

mass and longitudinals through a system of Goldstones without the Higgs (still gauge invariant): Non-Linear realisation of SB

$$\Sigma = exp(\frac{i\omega^i\tau^i}{v}) \quad (v = 246\ GeV \text{ is the vev}) \quad \text{and} \quad \mathcal{D}_\mu\Sigma = \partial_\mu\Sigma + \frac{i}{2}\left(g\boldsymbol{W}_\mu\Sigma - g'B_\mu\Sigma\tau_3\right)$$

$$\mathcal{L}_M = \frac{v^2}{4}\mathrm{Tr}(\mathcal{D}^\mu\Sigma^\dagger\mathcal{D}_\mu\Sigma) \equiv -\frac{v^2}{4}\mathrm{Tr}\left(\mathcal{V}_\mu\mathcal{V}^\mu\right) \quad \text{with} \quad \mathcal{V}_\mu = \left(\mathcal{D}_\mu\Sigma\right)\Sigma^\dagger$$

Replaces all of the Higgs sector, potential and all.

Not renormalisable? and so what...!

Higgsless

$$\mathcal{L}_{\rm GB} = \frac{1}{2}\left(\partial_\mu \omega^i\right)^2 - \frac{1}{6v^2}\left(\left(\omega^i \partial_\mu \omega^i\right)^2 - \left(\omega^i\right)^2\left(\partial_\mu \omega^i\right)^2\right) + \cdots$$

$$\omega^i \omega^j \to \omega^k \omega^l \Longrightarrow \mathcal{A}^{ijkl}(s,t,u) = \text{Sym } \tilde{A}(s,t,u)\delta^{ij}\delta^{kl}$$

$$\tilde{A}(s,t,u) = \frac{s}{v^2} \qquad \text{Weinberg LET}$$

breaks for energies beyond $4\pi v$

This calls for New Physics, the Higgs and the SM Higgs alone ?

The "chirally coupled" Higgs, composite Higgs

Chivukula and Koulovassilopoulos ('93,94)

FB+Chopin, '95

Grojean et al.

Coupling the Higgs X, to the chiral Lagrangian

$$
\begin{aligned}
\Sigma &= exp(\frac{i\omega^i\tau^i}{v}) \\
\mathcal{L}_{M,X} &= \frac{1}{2}(\partial_\mu X)^2 - \frac{1}{2}M_X^2 X^2 \\
&+ \frac{v^2}{4}\mathrm{Tr}(\mathcal{D}^\mu\Sigma^\dagger\mathcal{D}_\mu\Sigma)\left(1+2a\frac{X}{v}+b\frac{X^2}{v^2}+\cdots\right) - Y_{ij}\overline{\psi}^i_L\Sigma\psi^j_R\left(1+c_{ij}\frac{X}{v}+\cdots\right) \\
&- \frac{1}{2}M_X^2 X^2\frac{X}{v}\left(h_3+h_4\frac{X}{4v}\right)+\cdots \\
\text{for} \quad X &= H, \qquad a=b=c=1, \qquad h_3=h_4=1 \\
\text{Composite } X & \qquad \text{better have } c_{ij}=c \text{ else FCNC}
\end{aligned}
$$

The Chiral Higgs

$$W^+W^- \to W^+W^- \Longrightarrow \mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - M_X^2}\right) \to a = \pm 1$$

The Chiral Higgs

$$W^+W^- \to t\bar{t} \Longrightarrow ac = 1$$

The Chiral Higgs

$$W^+W^- \to XX \Longrightarrow b = a^2$$

The Chiral Higgs

Couplings to W, and more so perhaps to top need to be measured quite precisely

The potential: Stability up to which scale?

the Higgs boson self-coupling $\lambda = M_H^2/2v^2$

$\lambda = M_H^2/2v^2 = 0.118(M_H = 125GeV) \quad \lambda^2/4\pi \sim 1/900 \ll \alpha_{\rm em}$

$\lambda = M_H^2/2v^2 = 4.9(M_H = 800GeV).$

$\lambda > 0.$

Behaviour of $\lambda(Q^2)$?

$y_t = \sqrt{2}m_t/v \simeq 1$

Running of couplings in the SM

$$\frac{d\lambda}{dt} = \frac{1}{16\pi^2}\Bigg\{ \quad +24\lambda^2 - \lambda\left(\frac{9}{5}g_1^2 + 9g_2^2 + 12y_t^2\right)$$
$$-6y_t^4$$
$$+\frac{9}{8}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2 g_2^2 + g_2^4\right)\Bigg\}$$

Again importance of top, Higgs (self-coupling), gauge bosons

Running of the quartic coupling (one-loop)

$\lambda = M_H^2/2v^2 = 0.118(M_H = 125GeV); 4.9(M_H = 800GeV).$

$$\frac{d\lambda}{dt} = \frac{1}{16\pi^2}\left\{ +24\lambda^2 - \lambda\left(\frac{9}{5}g_1^2 + 9g_2^2 + 12y_t^2\right) - 6y_t^4 + \frac{9}{8}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2 g_2^2 + g_2^4\right)\right\}$$

$+ \Rightarrow$ Coupling will increase until very large values and will no longer be perturbative.

$+ \Rightarrow$ like with em coupling, breaks at the Landau pole, Q_{LP}

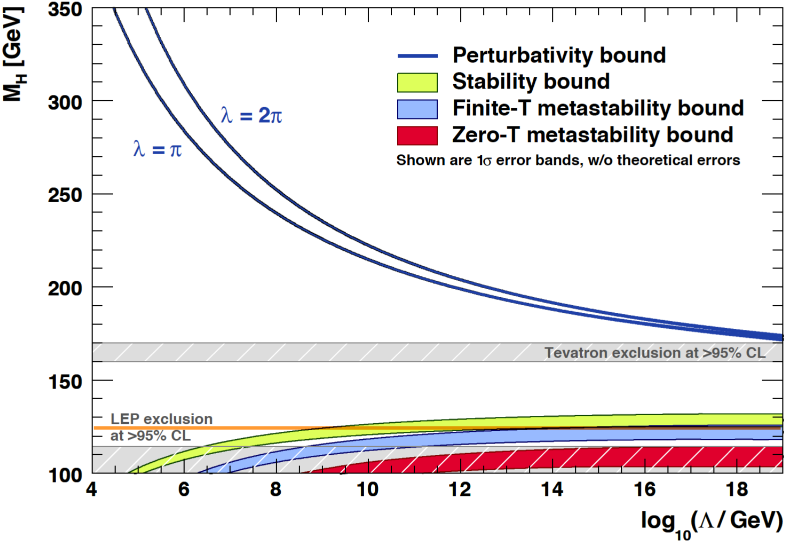
Running of the quartic coupling (one-loop)

$$\frac{d\lambda}{dt} = \frac{1}{16\pi^2}\left\{ +24\lambda^2 - \lambda\left(\frac{9}{5}g_1^2 + 9g_2^2 + 12y_t^2\right) -6y_t^4 + \frac{9}{8}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2 g_2^2 + g_2^4\right)\right\}$$

– ⇒ Coupling will decrease and may turn negative!

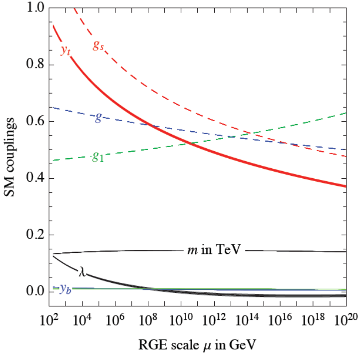
– ⇒ the Higgs potential will be unbounded from below: vacuum is no longer stable

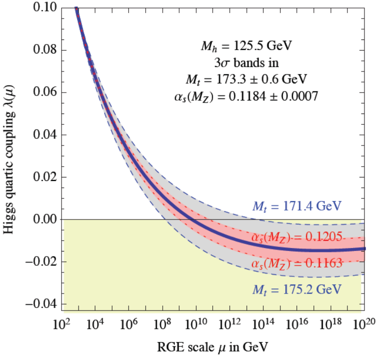
Stability and Perturbativity



J. Ellis, Espinosa, Giudice, Hoecker and Riotto '09

Stability: The Miracle (Degrassi et al '12,)





Also Bezrukov, Shaposhnikov,..., Buttazzo,...

λ turns negative but "not too much" it levels out ... β_λ vanishes over a wide range, starting from $\mu > 10^8$GeV.

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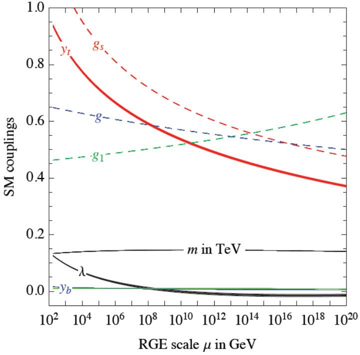

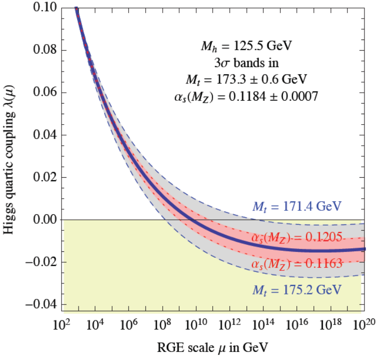

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some new physics contribution could easily move us to a stable region and perhaps give gauge coupling unification

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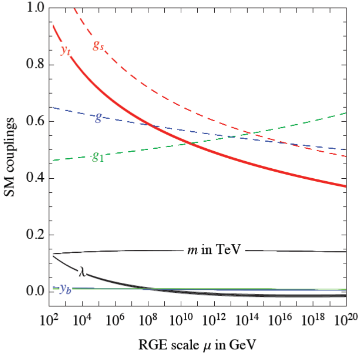

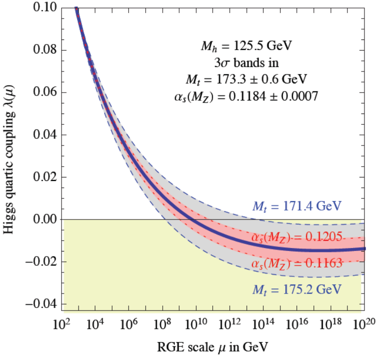

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Is there any meaning in this? M_h *vs* Planck Scale. Higgs as inflaton?

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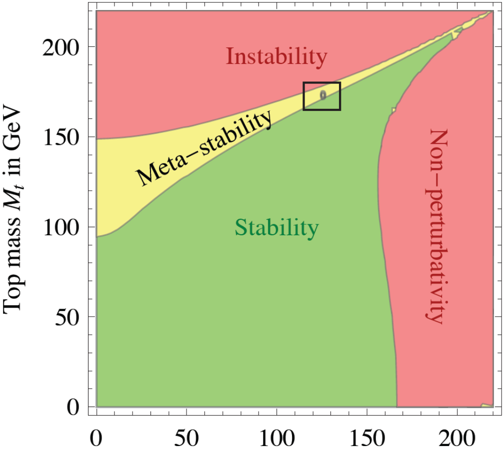

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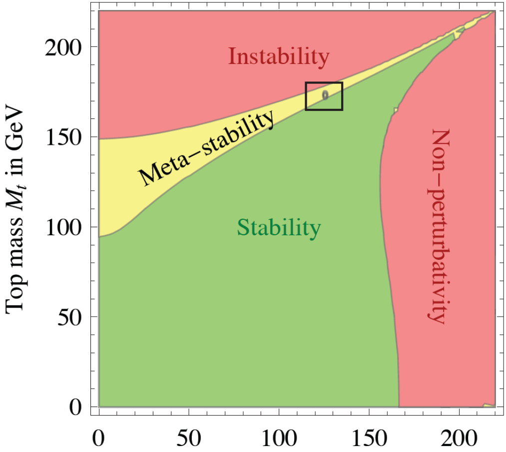


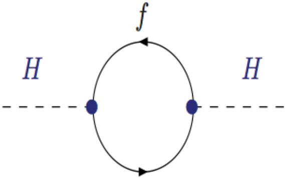
some new physics contribution could easily move us to a stable region

m_t essential (which m_t?)

The trouble with the SM Higgs: $\Lambda\phi^2$

why is then $M_H \ll \Lambda$

Unnaturalness and fine-tuning



Take a fermion f with Yukawa coupling $\lambda_f = \sqrt{2} m_f / v$. (Assume for simplicity that the fermion is very heavy so that one can neglect the external Higgs momentum)

$$\Delta M_H^2 = \frac{\lambda_f^2}{8\pi^2}\left[-\Lambda^2 + 6m_f^2 \log\frac{\Lambda}{m_f} - 2m_f^2\right] + \mathcal{O}(1/\Lambda^2)$$

$$\Delta M_H^2 \propto \Lambda^2$$

if $\Lambda = \Lambda_P$ tuning of contributions at the level of 30 digits

Calls for BSM

What is problematic about the Higgs in the SM:

A pathological description: why $M_H < 1 TeV$??

at one-loop:

Spin-1, Local gauge symmetry (Current is conserved, locally)

$$\mathbf{M}^2_\gamma = M^2_{\gamma,0} = 0$$

Spin-1/2, Chiral symtrie (global)

$$\mathbf{m_e} = \mathbf{m_e^0} \left(1 + \frac{3}{2}\frac{\alpha}{\pi}\log(\mathbf{\Lambda^2}/\mathbf{m_e^2})\right) \quad \mathbf{\Lambda} = \mathbf{\Lambda_P} \Longrightarrow \delta_\mathbf{m} \sim \mathbf{30\%}$$

Spin-0, a lone spin-0 has no symmetry

$$\mathbf{M^2_H} - \mathbf{M^2_{H,0}} \sim \frac{\alpha}{\pi}\mathbf{\Lambda^2}$$

Fine-tuning, hierarchy problem

Ways beyond the SM Higgs, naturalness argument as guiding principle?

The New Physics must explain why:

$$\mathbf{M_H} \;, \quad \ll \quad \mathbf{\Lambda}_{\mathrm{Planck}}$$

3 Solutions

- Higgsless models (equality has no sense, a term M_H is missing
- $\Lambda \sim 1, 10, , , 100$TeV: Extra-Dimensions: Λ large or G_{Newton} small because gravity is diluted in a much larger space! , ,..
- $\ll$: symmetry=supersymmetry is one implementation

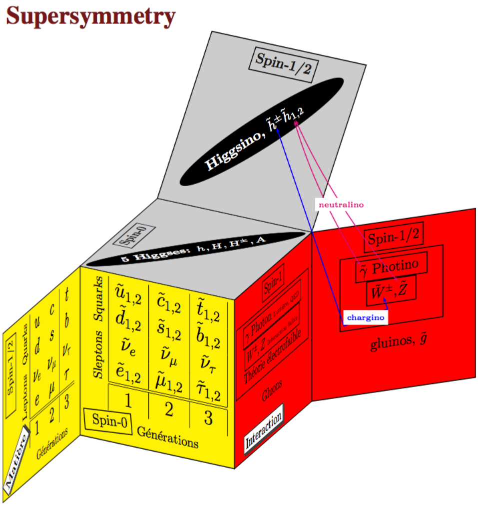
This argument certainly implies New Physics with New Particles

One of these particles: neutral and stable is a Dark Matter candidate: Higgs as a Portal

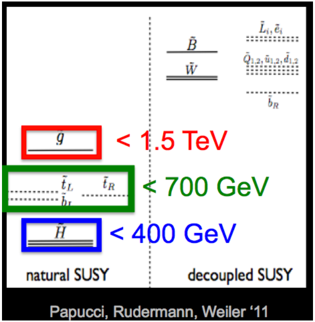
(new philopsophy: reject the fine-tuning argument, anthropic principle, ex: Tides)

Supersymmetry and the Higgs

Particles that play a rôle

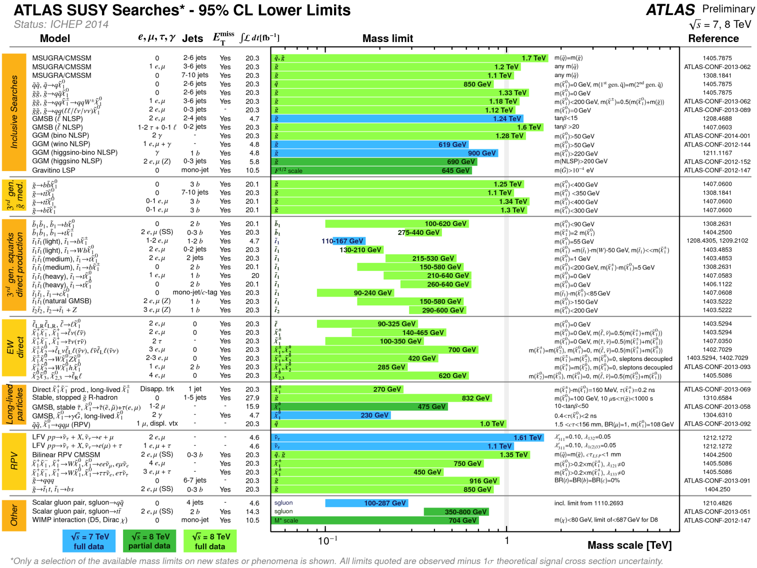


Supersymmetry and the Higgs

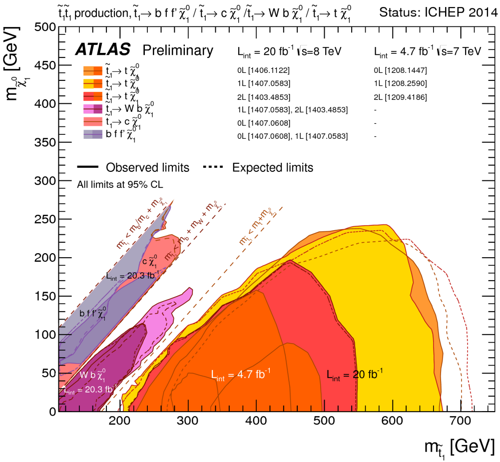


Some already tested, not much is seen

Why haven't we seen anything



Conspirancies: Compressed spectra, stealth models, (R_p violation



weak production for some, more energy and more luminosity

Or shall we give up on naturalness ? ?

the landscape/multiverse ?

anthropic principle ?

Humm ?

At the same time, New Physics must exist but perhaps not at the LHC..

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  Does the Higgs provide a link in the sense of a portal? the stability of the potential can be affected

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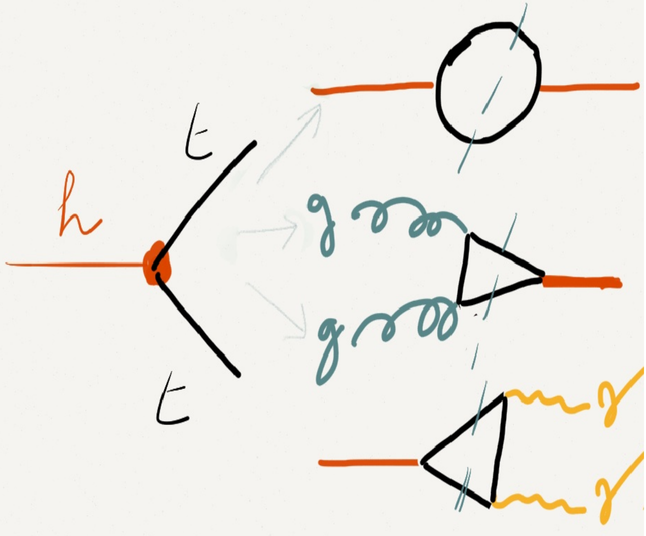
- the view from ... the top

The Higgs and the Top FB, Godbole, Guadagnoli, Mohan/ yesterday on arXiv, also Ellis et al.,



What do we know about the $t\bar{t}h$ vertex ?

$t\bar{t}H$ vertex and " parity"

$$\mathcal{L}_{tth} \;=\; -g_{tth}\,\bar{t}\,(\mathbf{a_t}\,+\,i\mathbf{b_t}\,\gamma_5)\,H\,t\;,$$

where $g_{tth} = m_t/v$ normalizes the coupling to the SM strength.

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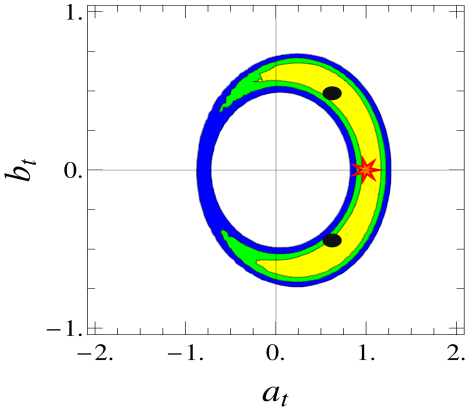
one can also check

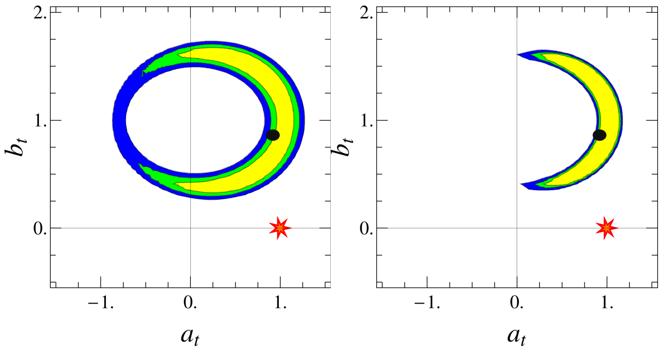
$$\mathcal{L}_{hVV} = \frac{g}{2}\kappa_V m_W h \left(W^\mu W_\mu + \frac{1}{\cos\theta_W^2} Z^\mu Z_\mu \right) .$$



The ● indicates the best-fit value $(a_t, b_t) = (0.93, 1.17)$.

68% , 95%, 99.7% CL

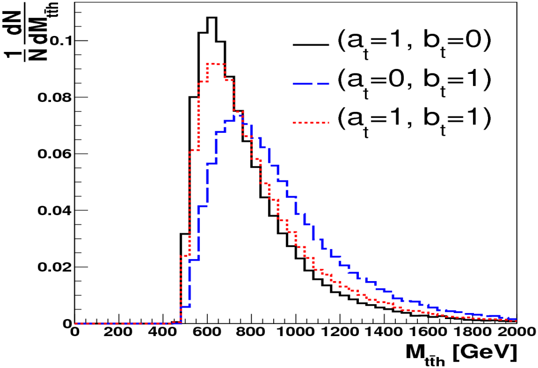
⋆ SM



Fits to a_t vs. b_t in a scenario with $\tilde{\kappa}_{gg} = \tilde{\kappa}_{\gamma\gamma} = -1$ and $\kappa_{gg} = \kappa_{\gamma\gamma} = 0$. Black dots indicate the best-fit values. The yellow , green and blue areas represent the 68%, 95% and 99.7% confidence-level regions, respectively. The red star shows the SM point $(a_t, b_t) = (1, 0)$. The plot to the right shows the same fit as the plot to the left, but with pseudo-data, with namely all the signal strengths set to the SM values and the uncertainties reduced by half.

Total cross sections

$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} \sim a_t^2 + 0.42 b_t^2$ $\qquad$ $\sigma(p_T^h > 100 GeV)/\sigma^{SM}(p_T^h > 100 GeV) = a_t^2 + 0.60\ b_t^2$



More rapid increase with energy ($\hat{s}$) in the case of the scalar

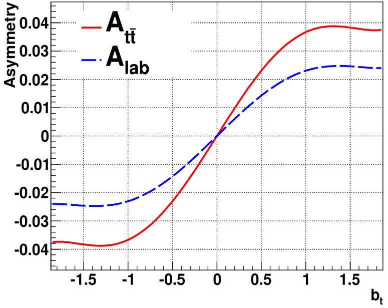
Asymmetries

$\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-)$ and $\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+)$ it is useful to define CP asymmetries as follows:

$$A_{t\bar{t}} = \frac{\sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) > 0) - \sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) < 0)}{\sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) > 0) + \sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) < 0)}$$

and

$$A_{\rm lab} = \frac{\sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) > 0) - \sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) < 0)}{\sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) > 0) + \sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) < 0)}.$$



C’était l’histoire d’un Higgs

LE MONDE DIPLOMATIQUE – SEPTEMBRE 1991

Supplément

Quelle recherche pour l’Europe ?

Des programmes en quête d’un nouveau souffle

Le troisième programme-cadre communautaire (1990-1994) de recherche et développement technologique, adopté après bien des difficultés, est le reflet des contradictions qui traversent la Commission et les Douze. Bien que significativement doté (5,7 milliards d’écus pour cinq ans, soit 4 % du total des budgets de recherche des Etats membres), il ne satisfait pleinement ni les néolibéraux – qui récusent un volontarisme technologique réputé perturber les « lois » du marché – ni les tenants d’une véritable politique industrielle européenne, qui, eux, déplorent les tergiversations dans les prises de décision politiques et la lourdeur des procédures administratives de Bruxelles.

Mais, au-delà des acquis indiscutables de ses programmes, en particulier la montée en puissance d’une véritable « identité européenne » chez les scientifiques et les ingénieurs, n’est-il pas grand temps, pour la Communauté, de cesser d’assigner à la recherche l’unique objectif de renforcer la compétitivité industrielle de l’Europe ? C’est, en effet, la notion même de compétitivité qui, si on l’étend à l’échelle d’une planète caractérisée par sa finitude (voir, page 32, l’article de Riccardo Petrella), mérite pour le moins examen. D’où la nécessité, pour une Europe qui ne limiterait pas son ambition à la conquête de marchés, de mettre également la recherche au service de nouvelles formes de solidarité mondiale centrées sur les besoins de l’homme. Et d’en faire un très grand projet, comme ceux dans lesquels elle est déjà engagée aux côtés des Etats-Unis et du Japon.

HALL EXPERIMENTAL DU CERN

Une présence affirmée dans les grands projets

Par HERVÉ LE TELLIER*

Favoriser l’émergence d’une industrie commune

Par CHRISTIAN DAMBRINE *

Chasser le boson

Décrypter le génome

Fusionner les tokamaks

Les Éditions de l’INED

INSTITUT NATIONAL D’ÉTUDES DÉMOGRAPHIQUES

La collection des Congrès et Colloques

(Lire la suite page 28.)

C'était l'histoire d'un Higgs

… (à 50 % financé par le Japon), et de 120 millions de francs en 1991.

En physique fondamentale, l'Europe peut néanmoins redresser la tête : *« Nous avons mis trente ans pour rattraper les Américains, pour former une équipe de physiciens*, explique M. Pierre Darriulat, directeur des programmes du CERN (1), *et il n'est plus question de refaire de la physique aux Etats-Unis. »* Les bosons intermédiaires W+, W-, Zo, qui ont valu aux Européens deux prix Nobel, ont en effet été découverts dans le tunnel de 27 kilomètres de circonférence du LEP (2), au CERN, en 1983. Le collisionneur de la prochaine génération, le Large Hadron Collider (LHC), devrait être construit sur le même site et mis en service

en 1995. Pour 2 milliards de francs suisses, l'Europe devrait pouvoir « chasser » le boson 2x.

Face à cette reconquête, le projet américain de collisionneur proton-proton SSC doit faire