The Higgs Boson and New Physics: the Why's and the How's

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- *The phenomenology related to its discovery*
- *A broad hint: the very existence of the Higgs $\Rightarrow$ physics beyond the standard model (BSM)*
- *BSM possibilities and ways of pinning them down*

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  (a) Parity-violating fermion-gauge interaction.
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- *Aspirations : good high-energy behaviour and renormalizability.*

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- *The solution should*

  (a) retain renormalizability, and
  (b) respect unitarity (cross-sections should go down with rising $\sqrt{s}$).

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- **In fact, the minimum lies at**
  $\langle \Phi \rangle = (0, v/\sqrt{2})$, **with**
  $v^2 = -\mu^2 / 2\lambda$

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- **Unphysical dof's become longitudinal components of** $W^{\pm}, W^0$**.**

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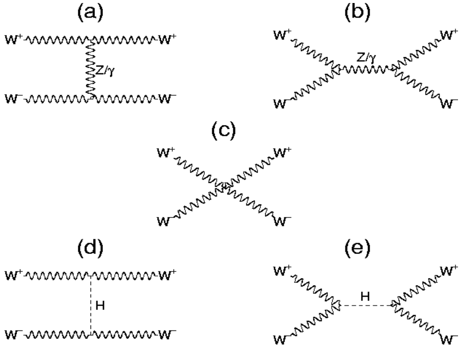
- **The photon is spared since is does not couple to the neutral component of** Φ
- **Renormalisability demonstrated ('t Hooft + Veltman)**



The H-mediated diagrams cause the cross-section to fall with increasing $\sqrt{s} \Rightarrow$ Unitarity restored

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- *There is no HXY coupling*
- *For any particle X (other than γ, g),*
  $\mathcal{L}_{\mathcal{H}\mathcal{X}\mathcal{X}} \sim m_X$

  Crucial in studying Higgs production and decays at colliders

How did we guess that a TeV collider was likely to uncover the Higgs?

- $m_H^2 \sim \lambda$
  Higher $m_H \Rightarrow$ *higher* λ

The unitarity limit.....

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The unitarity limit.....

- $m_H^2 \sim \lambda$
  Higher $m_H \Rightarrow$ higher λ
- For some m_H,
  $HH \longrightarrow HH$ becomes nonperturbative
- If we believe in perturbativity, then
  $m_H \leq TeV$

A more rigorous limit.....

For any $2 \longrightarrow 2$ *scattering,* $\frac{d\sigma}{d\Omega}|_{cm} = \frac{|A|^2}{64\pi^2 s}$
$A = 16\pi\Sigma(2l+1)P_l(\cos\theta)a_\ell$
$\theta =$ *scattering angle,*
$a_\ell = \ell$*th partial wave amplitude*

$\sigma = \frac{16\pi}{s}\Sigma(2\ell+1)|a_\ell|^2$

Unitarity of the scattering matrix
$\Rightarrow$ *The 'optical theorem':* $\sigma = \frac{1}{s}[\mathcal{A}(\theta = 0)]$

$\sigma = \frac{1}{s}Im[A(\theta = 0)]$
$\Rightarrow$ $|Re(a_\ell)| < 1/2$ *for every* ℓ

Now consider the Higgs self-coupling λ.........

For any amplitude that grows with λ,

$\Rightarrow \ |Re(a_\ell)| < 1/2$

$\Rightarrow$ *An upper limit on* λ

$\Rightarrow$ *An upper limit on* m_H

Example: $W_L W_L \longrightarrow W_L W_L$

At high energy, this is equivalent to the scattering of charged Goldstone bosons (unphysical components of the Higgs doublet)

$V_L V_L$ *scattering* $\Rightarrow$ *Higgs self-scattering yields* $m_H \leq 870\ GeV$

Thus a TeV collider $\Rightarrow$ *Higgs or new physics*

Precision electroweak data.........

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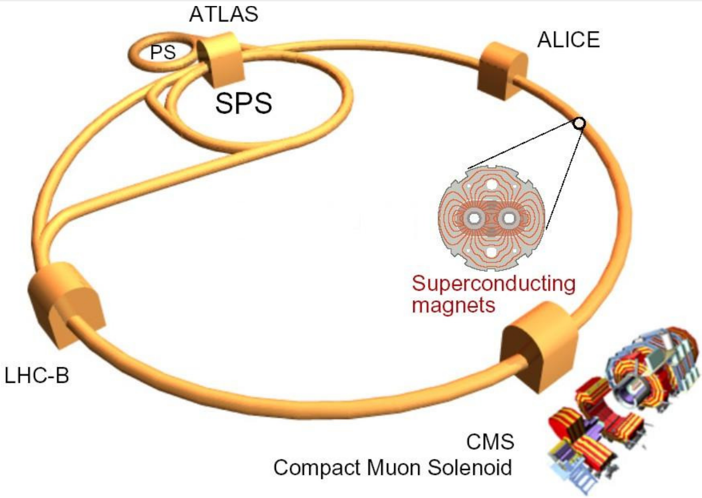
- *Lesson: the low-end (above 114.5 GeV) should be closely scanned*

But this makes the search trickier.........

The Higgs is seen through its decay products
For $m_H > 2m_z$,
$H \longrightarrow ZZ$ *makes the peak conspicuous*
For $2m_Z > m_H > 2m_W$,
$H \longrightarrow WW$ *has good statistics*
(Even for moderate virtuality of one W)
For low-lying m_H*, the* $b\bar{b}$ *channel has large branching ratio: backgrounds tend to wash out signals*

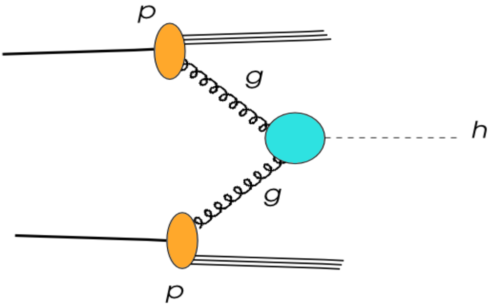
One needed to explore $WW^*, ZZ^*, \tau^+\tau^-, \gamma\gamma$
The $\gamma\gamma$ *decay channel is loop-suppressed: rare but spectacular*

The Large Hadron Collider (LHC).........



$p \Rightarrow \Leftarrow p$
$7/8/14$ TeV

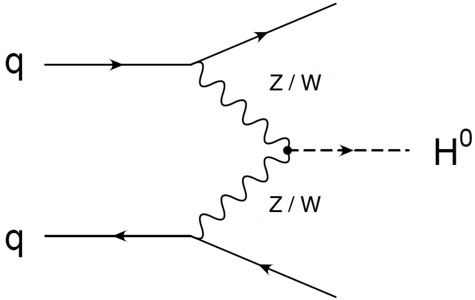
The main Higgs production channel........



Main driver: top quark intermediate states

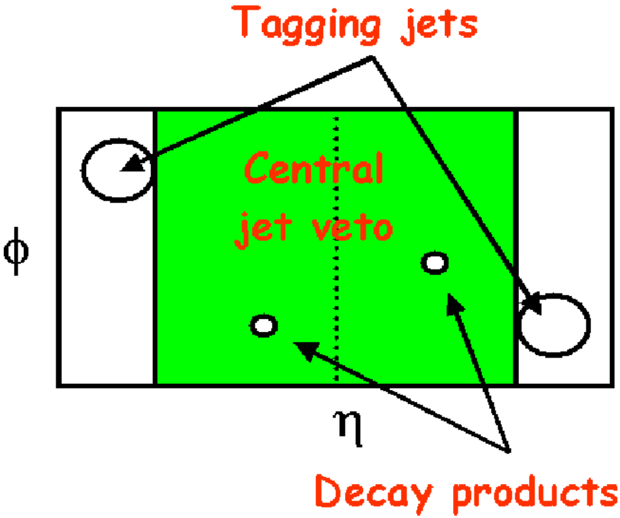
Enhanced gluon pdf $\Rightarrow$ substantial rates
But no useful tag available

Another channel: VBF



H + **forward jets with reduced activity in between**

The VBF channel......



Other useful channels......

$$p(q)p(\bar{q}') \longrightarrow W^* \longrightarrow WH$$
$$p(q)p(\bar{q}) \longrightarrow Z^* \longrightarrow ZH$$
$$p(g)p(g) \longrightarrow t\bar{t}H$$

With the available tags, the $b\bar{b}$ mode can be spotted!

Total event rate/Higgs-driven event rate $\simeq 10^{12}$!!

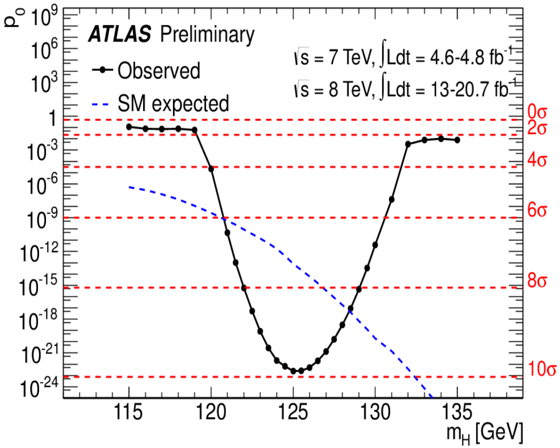
The main challenge: filtering out the signal

To develop event selection criteria which suppress backgrounds

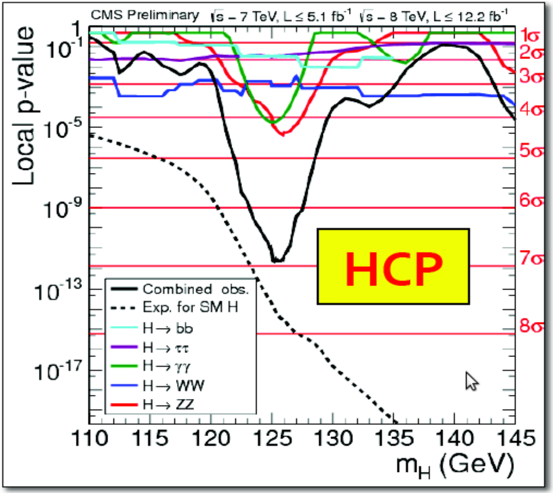
Examples:

- **Look for an M_{inv} peak in $ZZ^*, \gamma\gamma$**
- **Demand $p_{e\mu} < 50$ GeV in** $pp \longrightarrow H \longrightarrow WW^* \longrightarrow e\nu_e\mu\nu_\mu$
- **For VBF, demand the tagging jet pair to have $\Delta\eta > 2.8$, $m_{inv} > 500$ GeV**

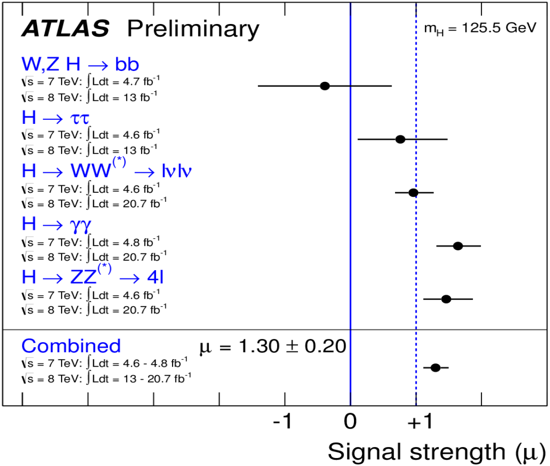
ATLAS results: p-values......



CMS results: p-values......



Channelwise signal strength: ATLAS......



$$\mu = \sigma / \sigma_{SM}$$

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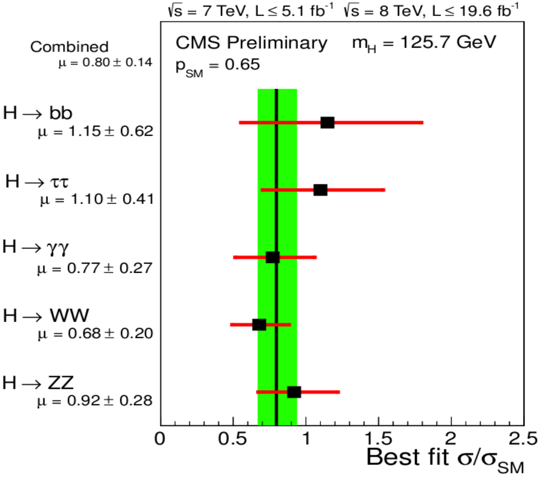

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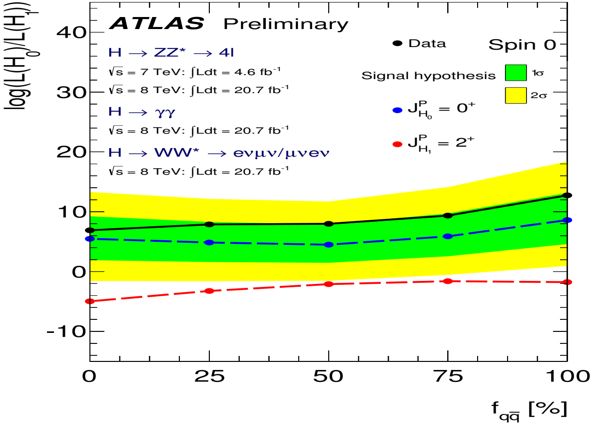
Spin/parity information (spin-0 vs spin-2)......



Ruled out: $J^P = 0^-$ at 97.8% C.L., 2^+ at 99.9% C.L.

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- *Possible odd-parity admixture constrained, but more statistics required for confirmation.*
- *Data available on various interactions $\Rightarrow$ It is almost certainly 'a Higgs boson' , but may still not be 'the Higgs boson' .*
- **A crucial observation: The very existence of the Higgs boson suggests physics beyond the standard model.**

Triviality.....

An established result of quantum field theory:

The strength of Higgs self-interaction is dependent on the energy scale (Q) at which interaction is taking place

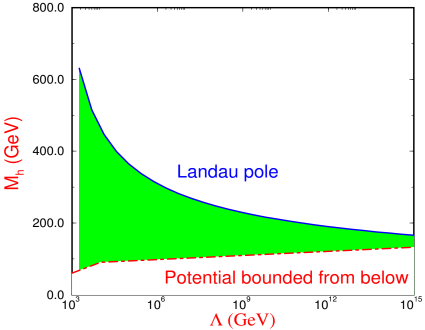
$$\lambda(Q) = \frac{\lambda(v)}{1 - \frac{3}{4\pi^3}\log\frac{Q^2}{v^2}\lambda(v)}$$

A pole hit unless $\lambda(v) = 0$: *Landau Pole*

A similar fate for large λ *even if the running includes all interactions*

Triviality.....

A solution: A cut-off Λ such that the pole lies above $\Lambda \Rightarrow$ An upper limit on Higgs mass



Consequence: an upper limit on the standard model

Vacuum stability.....

- *The Higgs potential is*
  $V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$
  $\mu^2 < 0$

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- *For large* λ *(large* m_H*), the first term dominates, and* λ *increases at higher energy scales*

  For small λ *(small* m_H*), the term* $\sim y_t^2$ *is all-important*

  $\Rightarrow \lambda(Q) < 0$ *for some* Q

$\Rightarrow$ *Some new physics scale* Λ,
and such a $\lambda(m_Z)$ *as to ensure* $\lambda(\Lambda) > 0$

$\Rightarrow$ *The existence of* $m_H^{min}(\Lambda)$

"The vacuum stability bound"

Beyond Λ, $\lambda^{effective} < 0$
Since
$V^{effective}(\Phi) = \lambda^{effective}(\Phi^\dagger\Phi)^2$,

$\lambda^{effective}(\Lambda) < 0 \Rightarrow V^{effective}(\Lambda) < 0$

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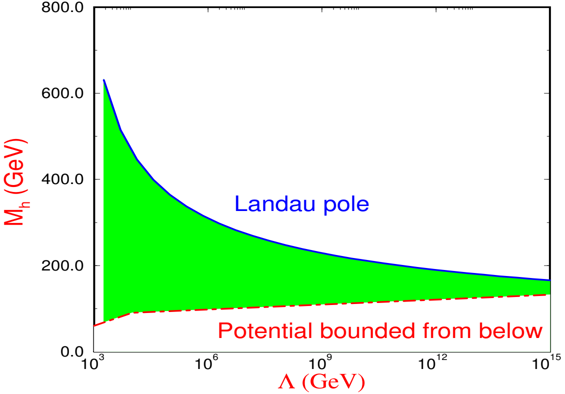


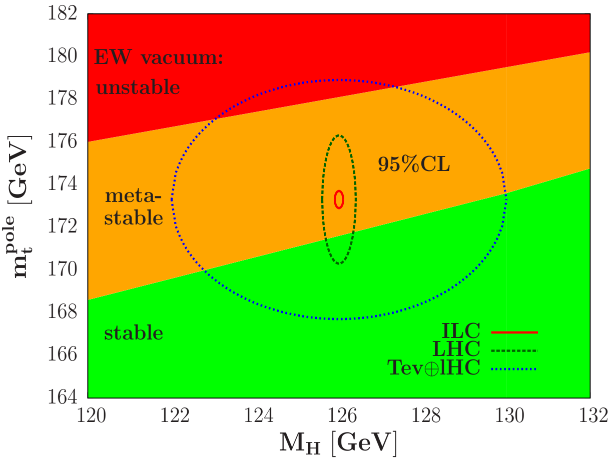
Vacuum stability.....

$m_H \simeq 125\ GeV \Rightarrow \lambda \simeq 0.129$

If $y_t(m_t)$ is on the higher side of the present uncertainty band, $V^{effective}(\Phi)$ can turn negative below the Planck mass

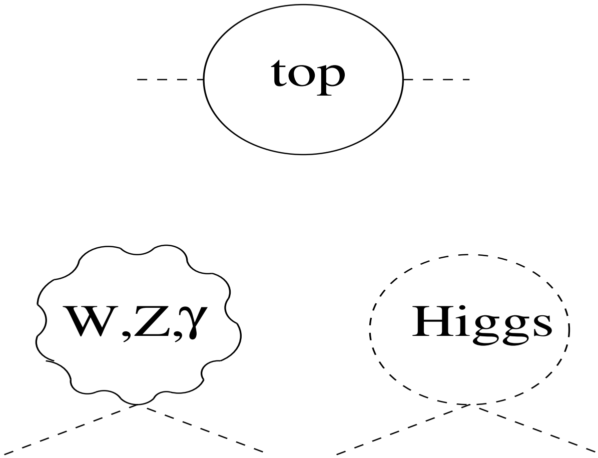
For $m_t \simeq 171\ GeV$, $\Lambda > M_{Planck}$
For $m_t \simeq 173\ GeV$, $\Lambda \simeq 10^{8-10}\ GeV$
The present vacuum may be unstable or metastable

Vacuum stability.....



From S. Alekhin, A. Djouadi, S. Moch, arXiv:1207.0980 [hep-ph]

The Higgs mass is not protected from higher-order corrections



Corrections to the Higgs mass.....

$$|\delta m_H^2| = |\frac{3G_F}{4\sqrt{2}\pi^2}(2m_W^2 + m_Z^2 - m_H^2 - 4m_t^2)\Lambda_{SM}^2|$$
$$= (200\, GeV\, \Lambda_{SM}/0.7\, TeV)^2$$

where

Λ_{SM} = *upper limit of validity of the standard model*

Thus the Higgs tends to become superheavy unless one has either fine-tuning or $\Lambda_{SM} \simeq TeV$

$\Rightarrow$ *BSM effects likely to be seen at the LHC!*

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- *Global fits show how much departure from SM is still possible*

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- *There can be higher-dimensional operators such as $\frac{f}{\Lambda^2}\Phi^\dagger\Phi W_{\mu\nu}W^{\mu\nu}$, with $\frac{f}{\Lambda^2} \leq 5$ TeV^{-2}*

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- *Wait for a higher energy hadron collider.....*