Higgs physics at the Large Hadron Collider

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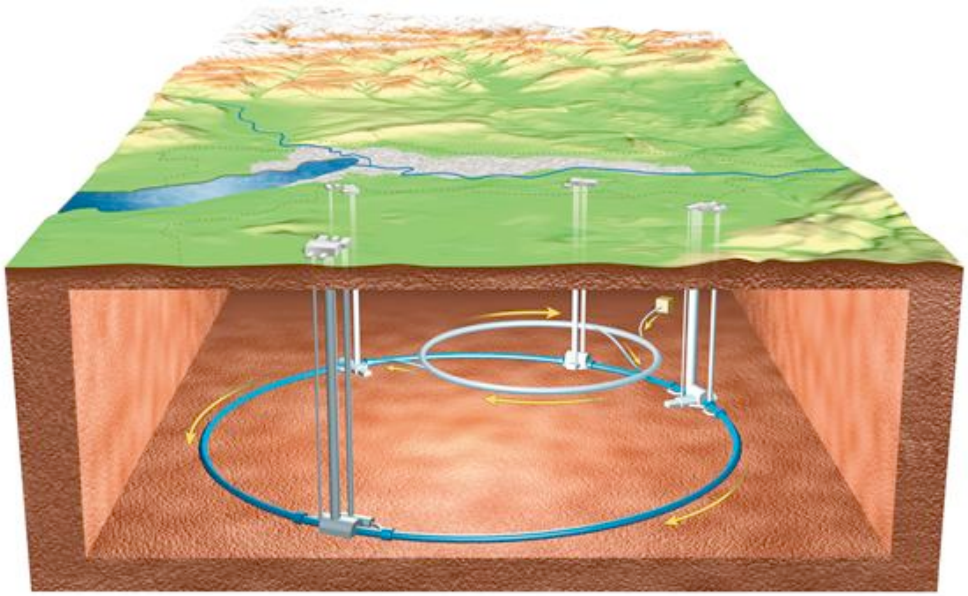
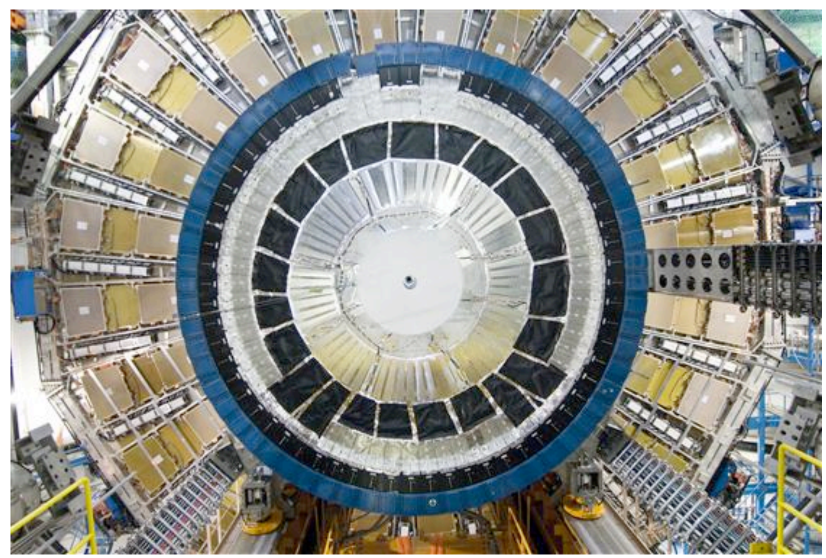
Debrecen, August 2008



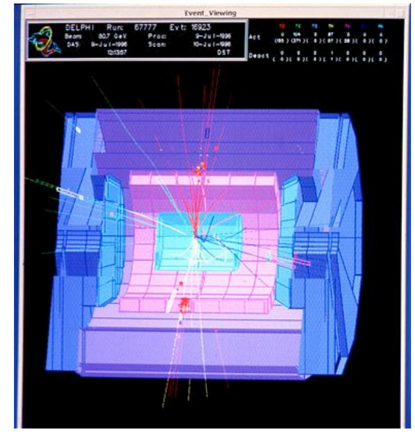
- Excitement
- Hope for discoveries
- Lucky to do research in particle physics at this time

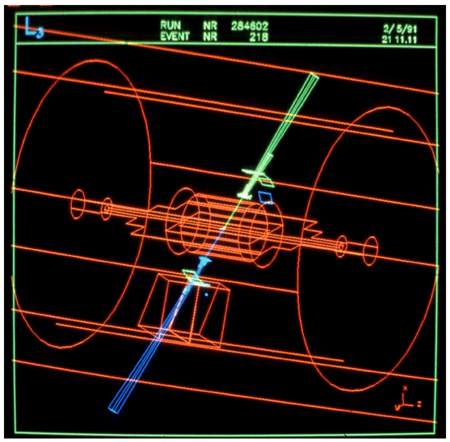


What do we know already?

$M_Z = 91.1876 \pm 0.0021\ GeV$?

$M_\gamma = 0\ GeV$

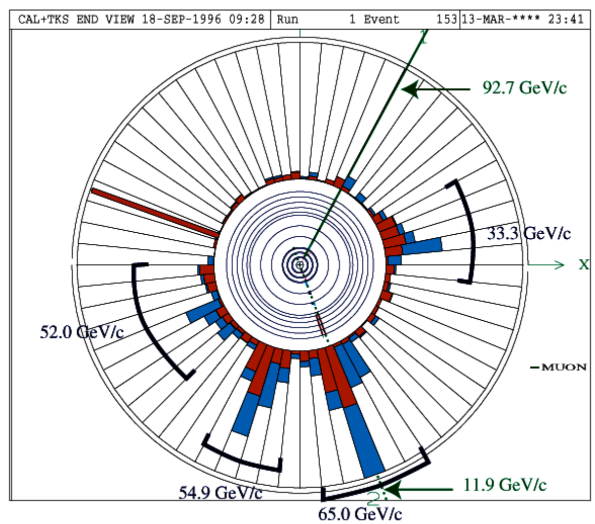


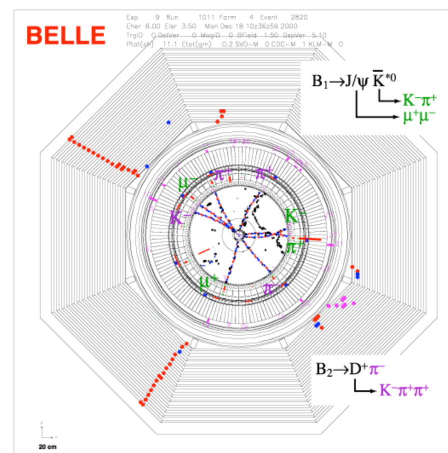


$M_W = 80.403 \pm 0.029\ GeV$?

Exhaustive studies of the electro-weak force

D-Zero Detector at Fermi National Accelerator Laboratory



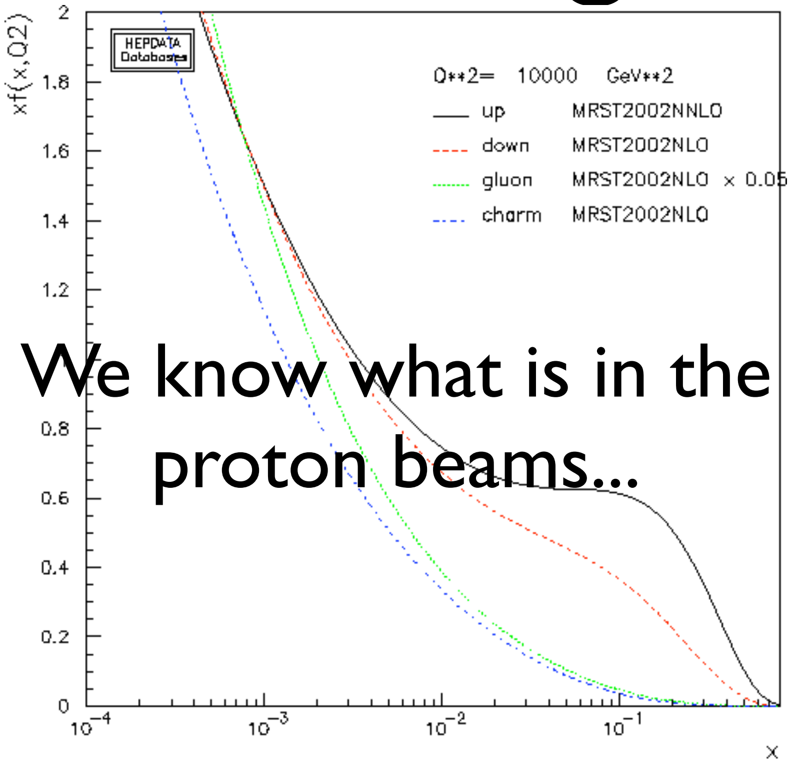


A third generation of quarks and leptons

$M_{top} = 172.5 \pm 1.3 \pm 1.9\ GeV$?

Verification of force strengths in the Standard Model.

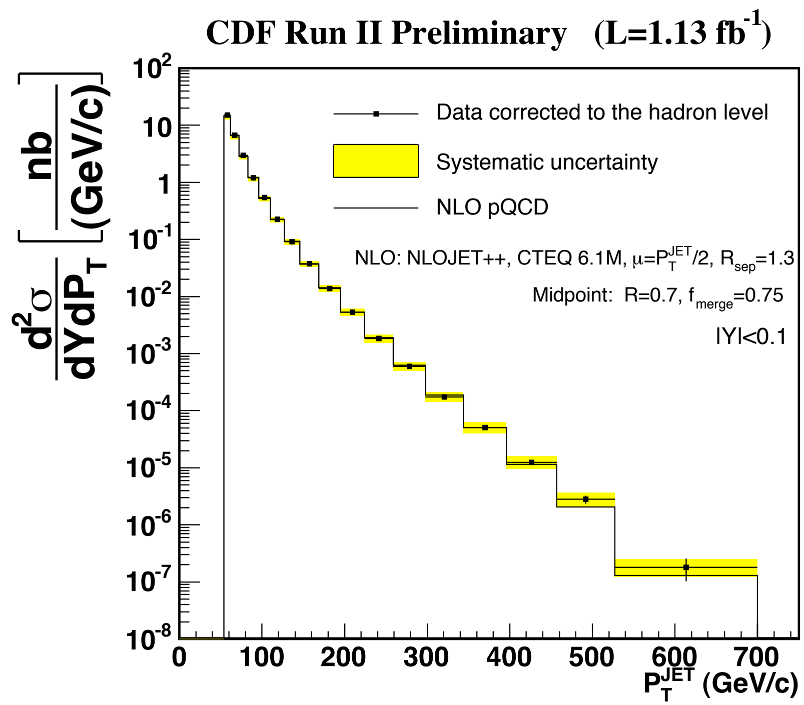
Amazing control on QCD



We know what is in the proton beams...

A strongly coupled theory at low energies

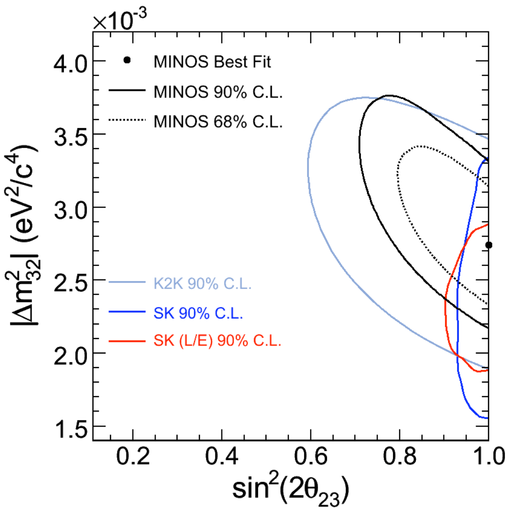
weak and perturbative at high energies



We know with 10-50% precision how quarks and gluons interact

What do we not understand with the SM?

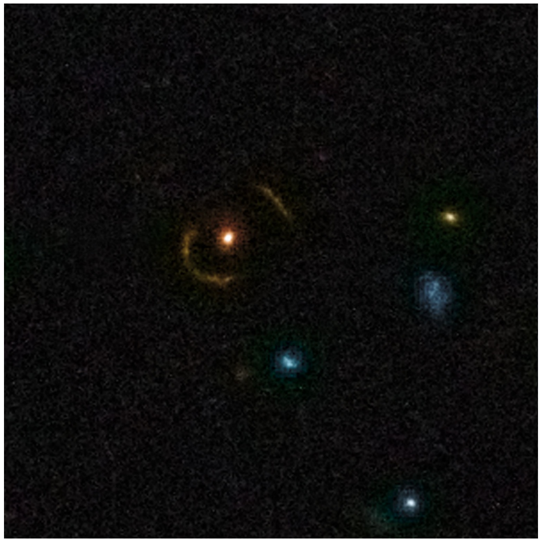
Neutrinos have mass



Gravity?

$$F = G\frac{m_1 m_2}{r^2}$$

Dark matter in the universe



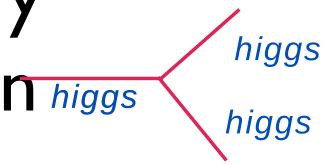
The Standard Model explanation for

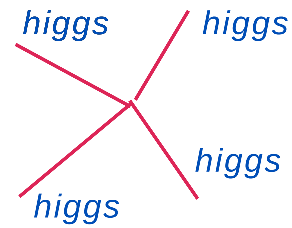
$$M_W, M_Z, M_{top}, \ldots \neq M_\gamma$$

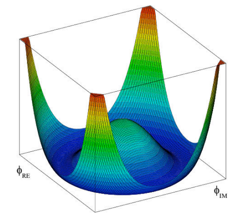
...an untested hypothesis!

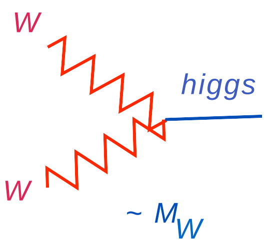
What is the Higgs boson?

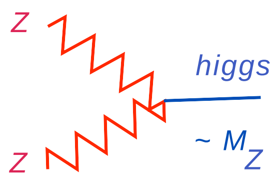
A neutral elementary scalar field which can interact with itself:

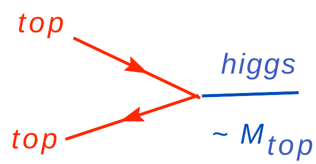












It interacts stronger with short-lived very massive particles

Hard to find since it does not interact with particles that we know how to collide, i.e. electrons, up and down quarks

The discovery of the Higgs boson is the main reason for constructing the LHC. *Anything more is a present of nature that we have not paid the bill for.*

A scalar sector $\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

$$\mathcal{L} \ni (D_\mu \phi)^\dagger (D^\mu \phi) - V\left(\phi^\dagger \phi\right)$$

It varies due to gauge bosons

$$D_\mu = \partial_\mu - i\frac{g_2}{2} W_\mu^a \tau^a - i\frac{g_1}{2} B_\mu$$

Required to fills all space

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \neq 0$$

Higgs boson physical state with zero vev

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

The covariant derivative does it "all"...

$$D_\mu = \begin{pmatrix} \partial_\mu - \frac{i}{2}\left[g_1 B_\mu + g_2 W_3\right] & -i\frac{g_2}{2}\left(W_\mu^1 - iW_\mu^2\right) \\ -i\frac{g_2}{2}\left(W^1 + iW^2\right) & \partial_\mu - \frac{i}{2}\left[g_1 B_\mu - g_2 W_\mu^3\right] \end{pmatrix}$$

...introducing physical gauge bosons: $W_\mu^\pm = \dfrac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}$

$$Z_\mu = \frac{1}{\sqrt{g_1^2 + g_2^2}}\left[g_1 B_\mu - g_2 W_\mu^3\right] \qquad A_\mu = \frac{1}{\sqrt{g_1^2 + g_2^2}}\left[g_1 B_\mu + g_2 W_\mu^3\right]$$

$$D_\mu = \begin{pmatrix} \partial_\mu - \frac{i}{2}\sqrt{g_1^2 + g_2^2} A_\mu & -ig_2\frac{\sqrt{2}}{2} W_\mu^+ \\ -ig_2\frac{\sqrt{2}}{2} W_\mu^- & \partial_\mu - \frac{i}{2}\sqrt{g_1^2 + g_2^2} Z_\mu \end{pmatrix}$$

Masses and couplings!

After choosing the vacuum:

$$D_\mu \phi = \begin{pmatrix} -i\frac{g_2}{2} W_\mu^+ (v+H) \\ \frac{1}{\sqrt{2}}\partial_\mu H - \frac{i}{2}\sqrt{\frac{g_1^2+g_2^2}{2}} Z_\mu (v+H) \end{pmatrix}$$

$$\mathcal{L} \ni \frac{1}{2}(\partial_\mu H)^2 - V\left(\phi^\dagger \phi\right)$$
$$+ \left[\frac{1}{4} g_2^2 v^2\right] W_\mu^+ W^{-\mu} \left(1 + \frac{H}{v}\right)^2$$
$$+ \frac{1}{2}\left[\frac{(g_1^2+g_2^2)v^2}{4}\right] Z_\mu Z^\mu \left(1 + \frac{H}{v}\right)^2$$

$$M_W = \frac{g_2 v}{2}, \qquad M_Z = \frac{\sqrt{g_1^2+g_2^2}\, v}{2}$$

Mass-coupling relations

PREDICTION:

$$\frac{M_w}{M_z} = \frac{g_2}{\sqrt{g_1^2+g_2^2}} = \cos\theta_W$$

Masses and Higgs-Gauge interactions

Gauge-boson masses

↕

WWH, WWHH, ZZH, ZZHH interactions

$$\mathcal{L} \ni \frac{1}{2}(\partial_\mu H)^2 - V\left(\phi^\dagger\phi\right)$$
$$+M_W^2 W_\mu^+ W^{-\mu}\left(1+\frac{H}{v}\right)^2$$
$$+\frac{1}{2}M_Z^2 Z_\mu Z^\mu\left(1+\frac{H}{v}\right)^2$$

Strengths proportional to (mass)^2

Yukawa interactions

$$\mathcal{L} \ni \sum_{i,j=1}^{3} f_{ij}\,(N_L^i, E_L^i)\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} E_R^j$$

$$+f_{ij}\,(U_L^i, D_L^i)\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} D_R^j + g_{ij}\,(U_L^i, D_L^i)\begin{pmatrix}\phi^0\\ -\phi^-\end{pmatrix} U_R^j$$

$$+\text{hermitian conjugate}$$

$$f_{ij}, g_{ij}, h_{ij}$$

Arbitrary parameters...
we would prefer a better
explanation for their values!

Fermion masses and Higgs interaction

After symmetry breaking:

$$\mathcal{L} \ni \frac{1}{\sqrt{2}}(v+H)\sum_{i,j=1}^{3} f_{ij}\left(E_L^i E_R^j + E_R^i E_L^j\right)$$
$$+g_{ij}\left(D_L^i D_R^j + D_R^i D_L^j\right) + h_{ij}\left(U_L^i U_R^j + U_R^i U_L^j\right)$$

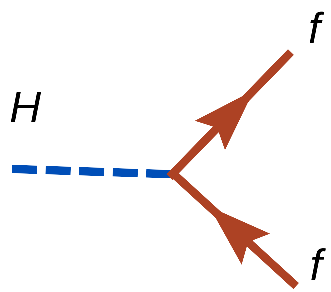
Diagonalizing: $$\mathcal{L} \ni -\left(1+\frac{H}{v}\right)\sum_f m_f \bar{f} f$$

Fermion mass ➡ ffH interactions

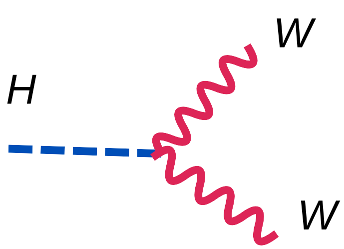
Strengths proportional to (mass)

Feynman Rules

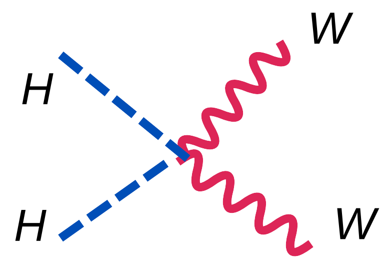
They are independent of the details of the Higgs potential except the vev



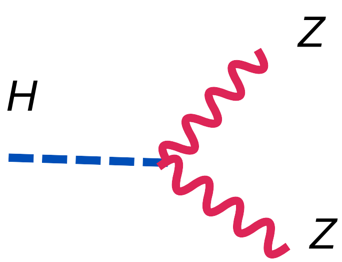
$$i\frac{m_f}{v}\delta_{ij}$$



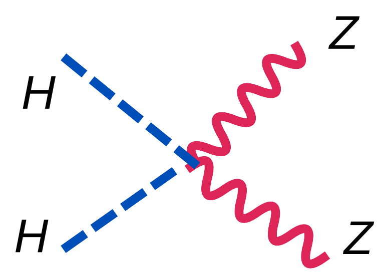
$$2i\frac{M_W^2}{v}g_{\mu\nu}$$



$$2i\frac{M_W^2}{2v}g_{\mu\nu}$$



$$2i\frac{M_Z^2}{2v}g_{\mu\nu}$$



$$2i\frac{M_Z^2}{4v}g_{\mu\nu}$$

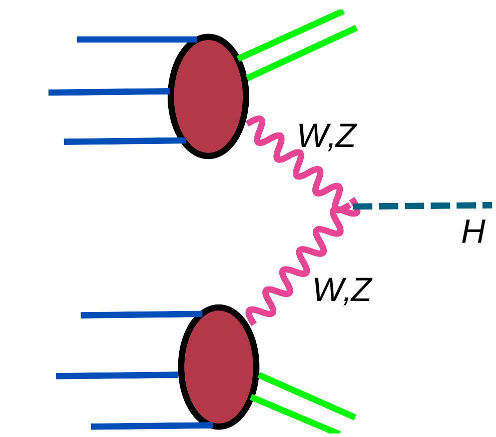
Higgs boson at colliders

Higgs bosons must be radiated off heavy states: W, Z, top → Big energy price

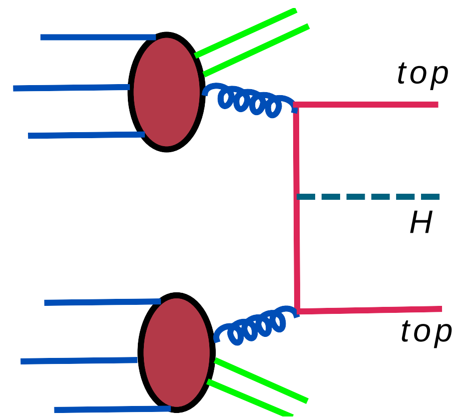
LEP looked for it, excluding Mh < 114 GeV

Tevatron is hunting the Higgs boson. If the SM is correct and the Higgs boson is light it has already produced about 5000 of them. Ironically, we might never be able to tell them apart from other stuff...

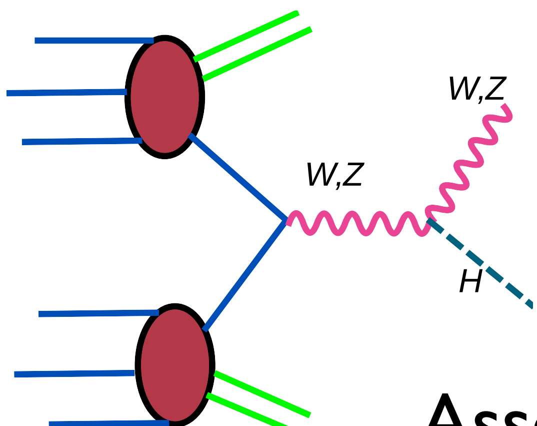
Higgs hadroproduction



Weak
boson
fusion



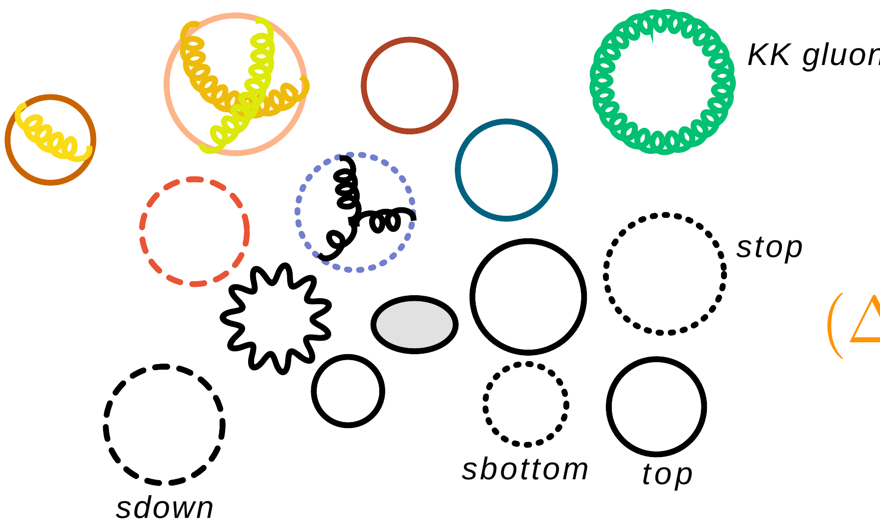
Associated Top
pair



Associated
Drell-Yan

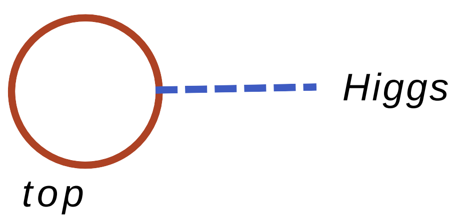
A vacuum full of energy

particles



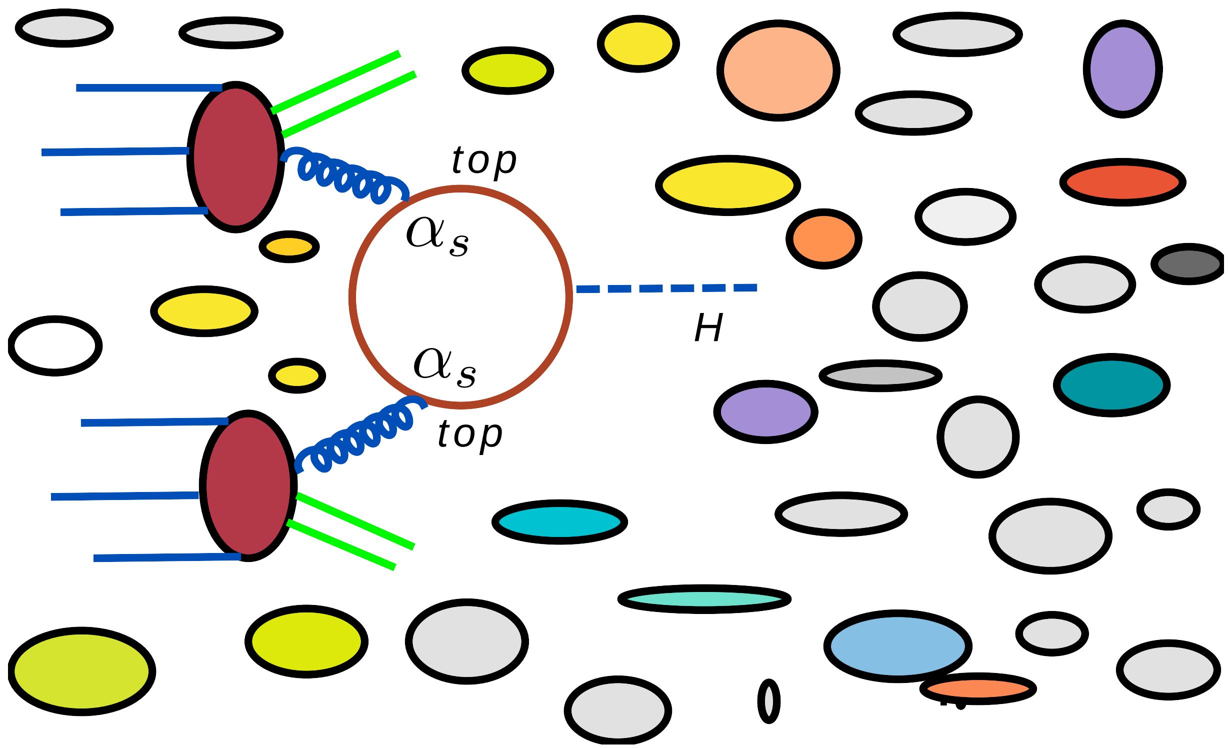
$$(\Delta E)\,(\Delta t) \simeq \hbar$$

We cannot radiate Higgs bosons out of the vacuum:



(violates momentum conservation)

Tickling the vacuum!

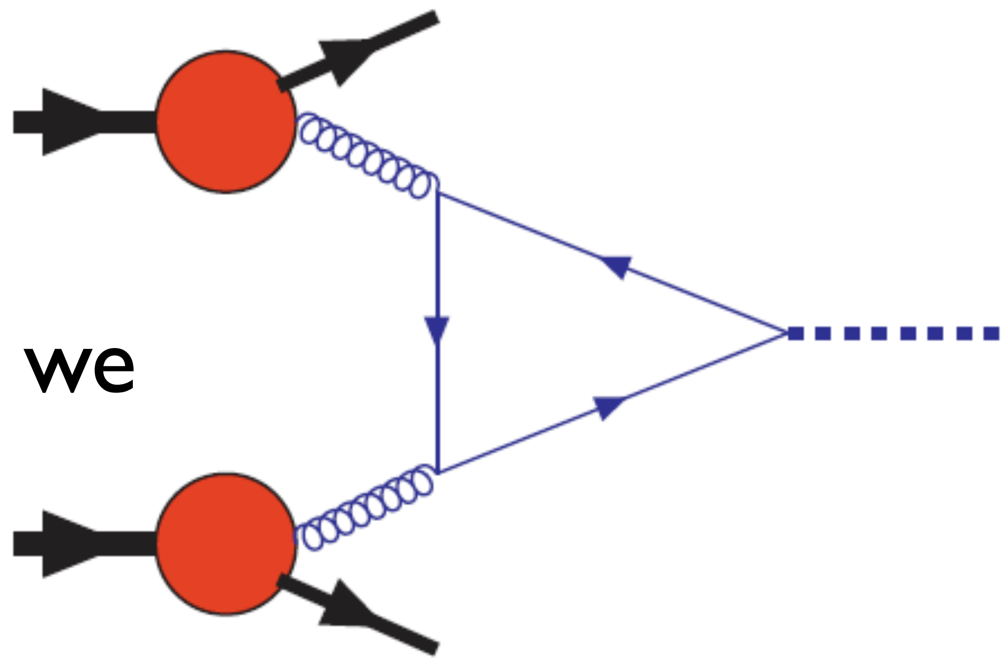


PRICE: Energy = Higgs mass

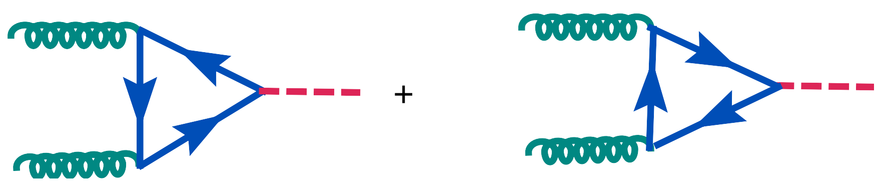
Two powers of the strong coupling α_s

The gluon-fusion process

- It probes the structure of the vacuum
- Sensitive to particles which we may not know about



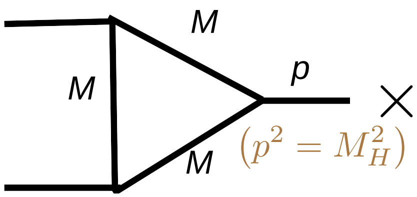
Non-decoupling of heavy states



$$\sim \frac{\delta^{ab}}{v}\left[p_1 \cdot p_2 \epsilon_1 \cdot \epsilon_2 - \epsilon_1 \cdot p_2 \epsilon_2 \cdot p_1\right] \alpha_s \times \left[1 + \mathcal{O}\left(\frac{m_H^2}{4M_f^2}\right)\right]$$

The Yukawa coupling compensates for the loop suppression! It costs no more to "tickle" very heavy states since they couple stronger to the Higgs boson

Massive internal particles



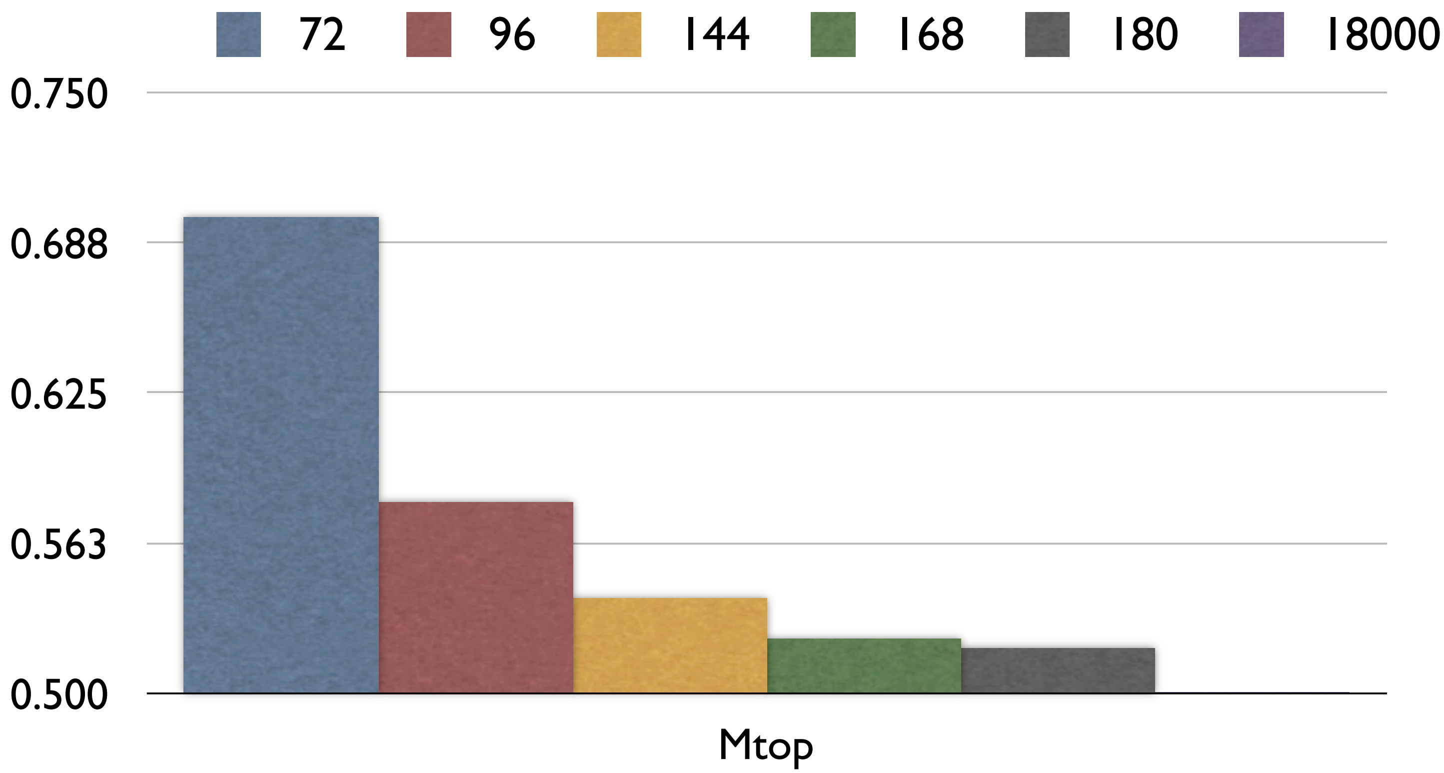
$$\times M^2 = \int \frac{d^4k}{i\pi^2} \frac{M^2}{(k^2 - M^2)\left[(k+p_1)^2 - M^2\right]\left[(k+p_1+p_2)^2 - M^2\right]}$$

$$= \int_0^1 dx dy \frac{(1-x)M^2}{M^2 - yx(1-x)M_H^2} = \frac{1}{2}\frac{M^2}{M_H^2} \log\left[\frac{1+\sqrt{1-\frac{4M^2}{M_H^2}}}{1-\sqrt{1-\frac{4M^2}{M_H^2}}}\right]$$

$$\xrightarrow{(M \to \infty)} \quad \frac{1}{2}$$

What is infinite?

$M_{higgs} = 120\text{GeV}$

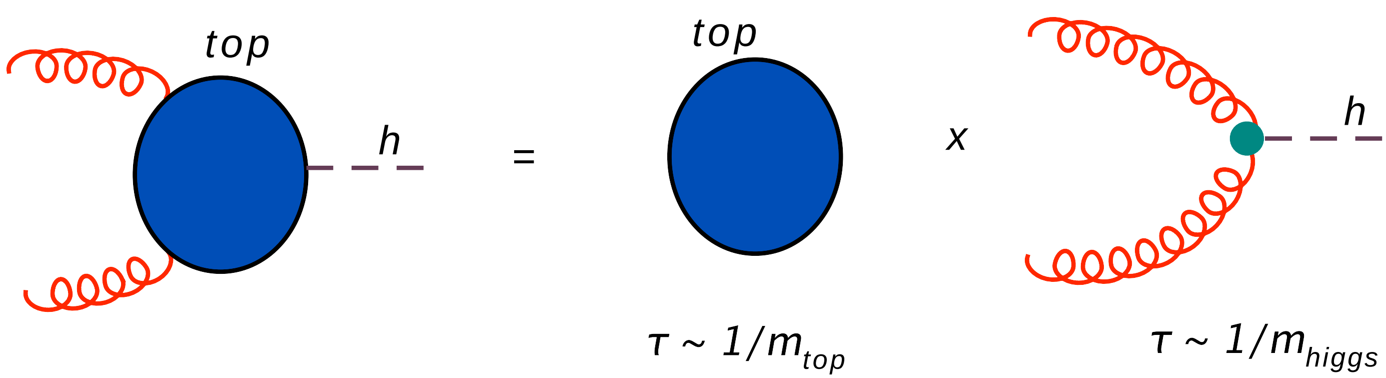


A fantastic approximation

Nothing to do with gluon densities and soft gluon re-summation

Characteristic times

Infinitely heavy internal particles approximation is the limit of zero external to external momenta or slow varying external fields.



Factorization of phenomena at different time-scales

Effective theory

$$\mathcal{L}_{hgg} = \; C(m_t)\,\frac{h}{v}\left[-\frac{Z}{4}G^a_{\mu\nu}G^{\mu\nu;a}\right]$$

Wilson coefficient C(M)
encapsulates the (heavy)
particle content of the vacuum

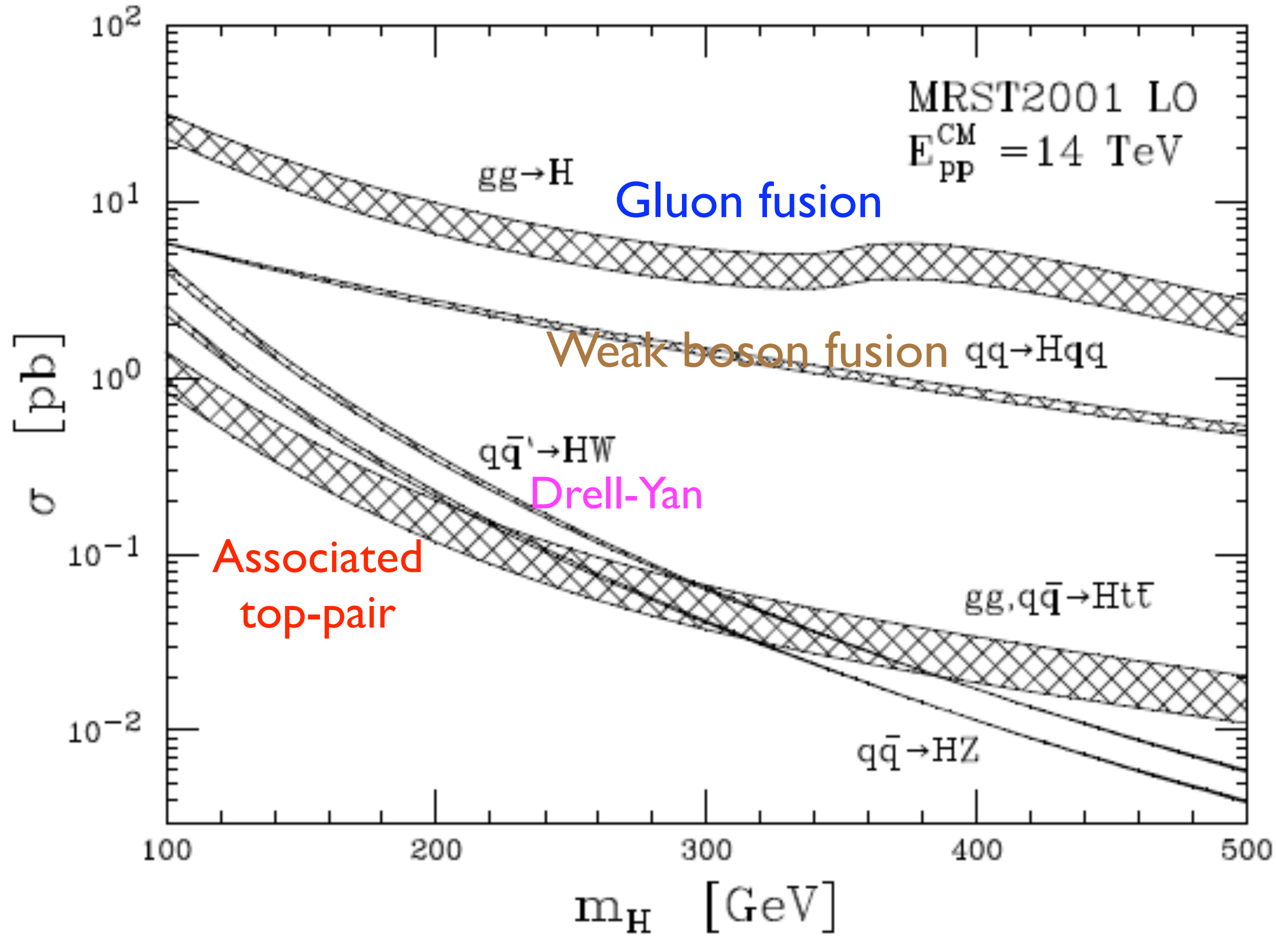
Higgs-gluon
operator describes

QCD effects

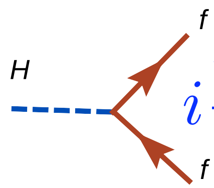
A neat separation of QCD from
the details of the electroweak symmetry
breaking model

Higgs cross-sections

The LHC will produce 50,000 - 500,000 light Higgs bosons every year.
Can we see these events and prove that we have seen them?

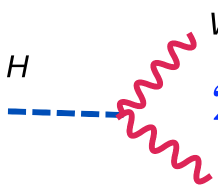


The end of a Higgs boson



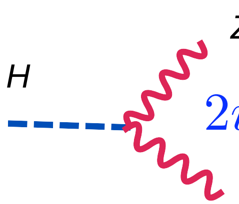
$$i\frac{m_f}{v}\delta_{ij}$$

$$\Gamma\left(H \to f\bar{f}\right) = \frac{M_H}{8\pi}\left(\frac{M_f}{v}\right)^2 N_c\left(1-\frac{4M_f^2}{M_H^2}\right)^{\frac{3}{2}}$$



$$2i\frac{M_W^2}{v}g_{\mu\nu}$$

$$\Gamma\left(H \to WW\right) = \frac{M_H}{16\pi}\left(\frac{M_H}{v}\right)^2\left(1-\frac{4M_W^2}{M_H^2}\right)^{\frac{1}{2}}$$
$$\times\left[1-4\left(\frac{M_W^2}{M_H^2}\right)+12\left(\frac{M_W^2}{M_H^2}\right)^2\right]$$



$$2i\frac{M_Z^2}{2v}g_{\mu\nu}$$

$$\Gamma\left(H \to ZZ\right) = \frac{M_H}{32\pi}\left(\frac{M_H}{v}\right)^2\left(1-\frac{4M_Z^2}{M_H^2}\right)^{\frac{1}{2}}$$
$$\times\left[1-4\left(\frac{M_Z^2}{M_H^2}\right)+12\left(\frac{M_Z^2}{M_H^2}\right)^2\right]$$

A quick death...

The Higgs boson likes to decay to the heaviest massive particle that is allowed from phase-space. Is there time to detect it before this happens?

$$\Gamma_{total} > \Gamma\left(H \to b\bar{b}\right) = \left(3.5 \times 10^{-5}\right) M_H$$

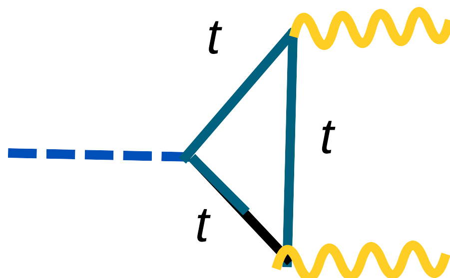
$$> 4\mathrm{MeV}$$

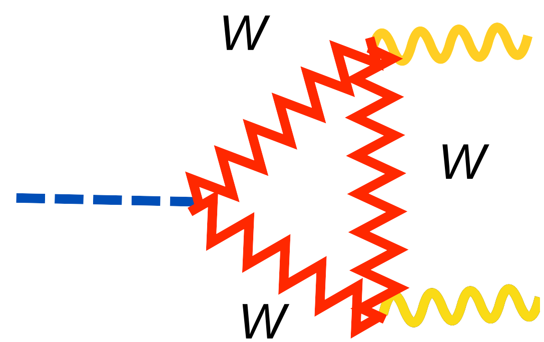
The Higgs boson lifetime is very short:

$$\tau\left(H\right) < 1.6 \times 10^{-22} s$$

Two photon decay

Small decay width



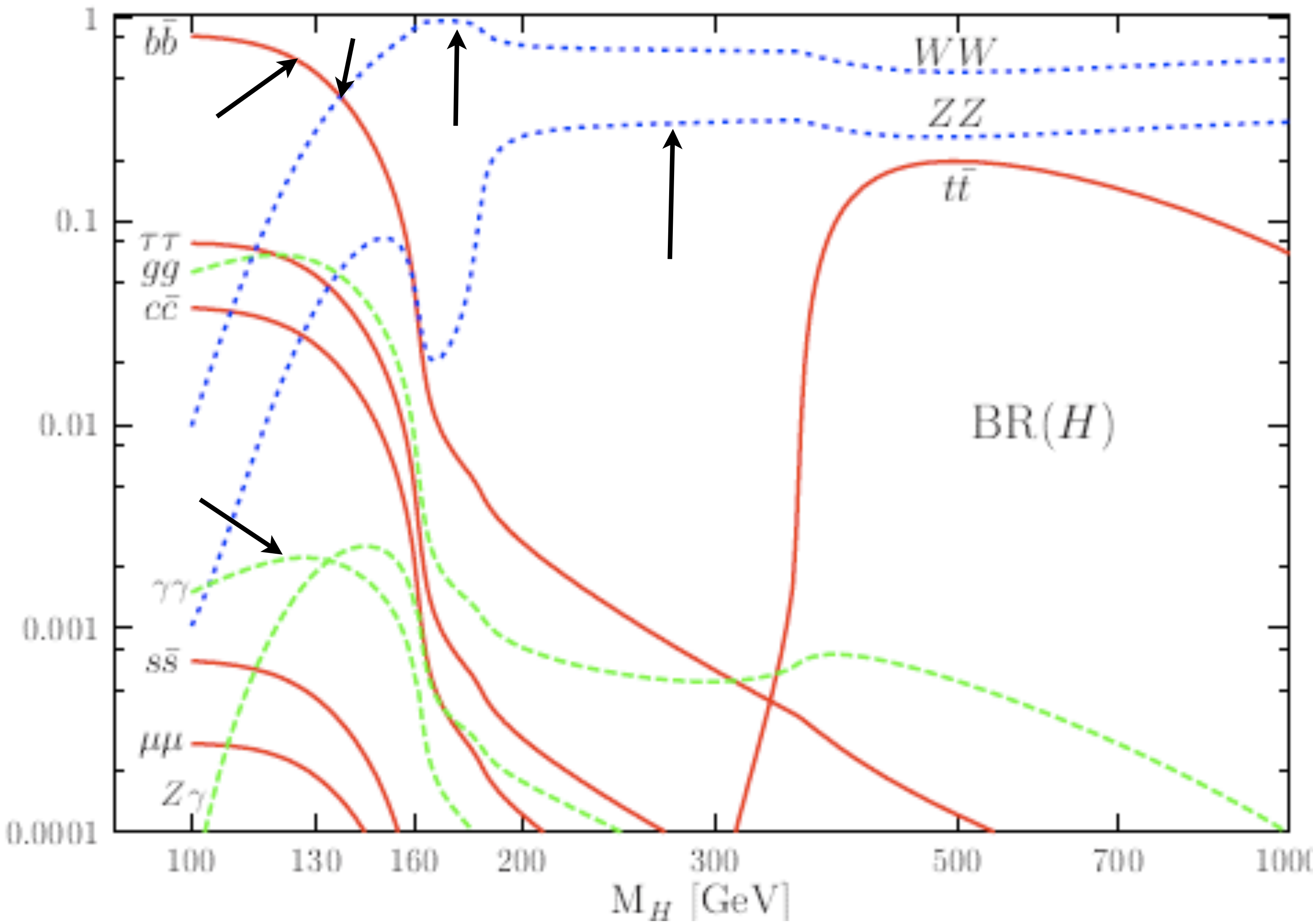


(Light Higgs)

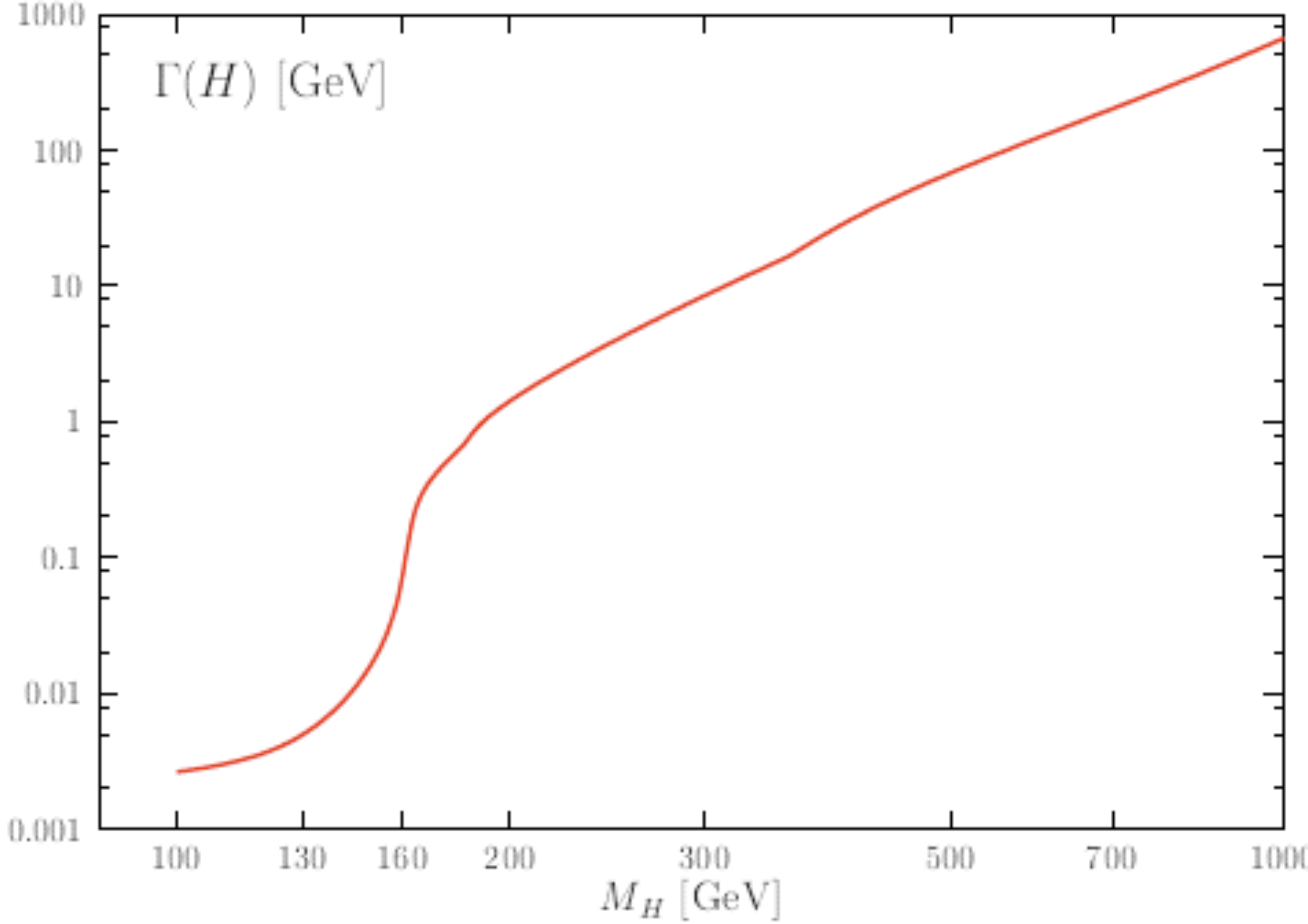
$N_c Q_t^2 (4/3)$ (-7)

Probes the electroweak content of the vacuum. Sensitive to new heavy gauge bosons.

Higgs branching ratios



Higgs Total Width



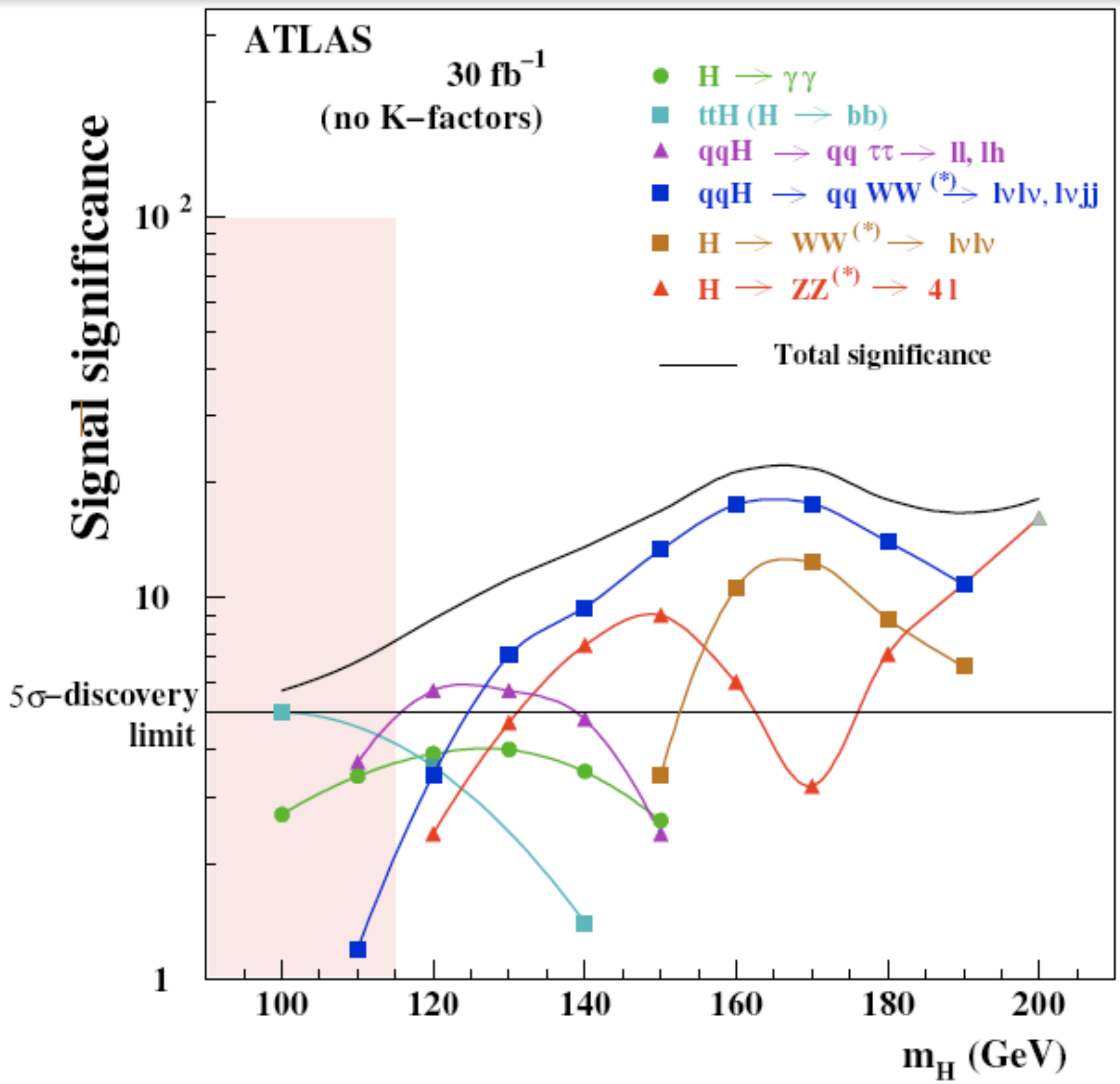
Remarks on BRs

- Below the WW threshold the Higgs boson decays to bottom quarks...unfortunately large backgrounds. We can look at clean but rare decays to two photons.
- A heavy Higgs can be easily seen in the ZZ channel (decaying into leptons)
- A "tough window" 160-180 GeV where only the WW channel is available (missing energy from W decays)
- A window 125-150 GeV where we can see the Higgs boson in more than one channels; this helps to extract couplings for Higgs interactions.

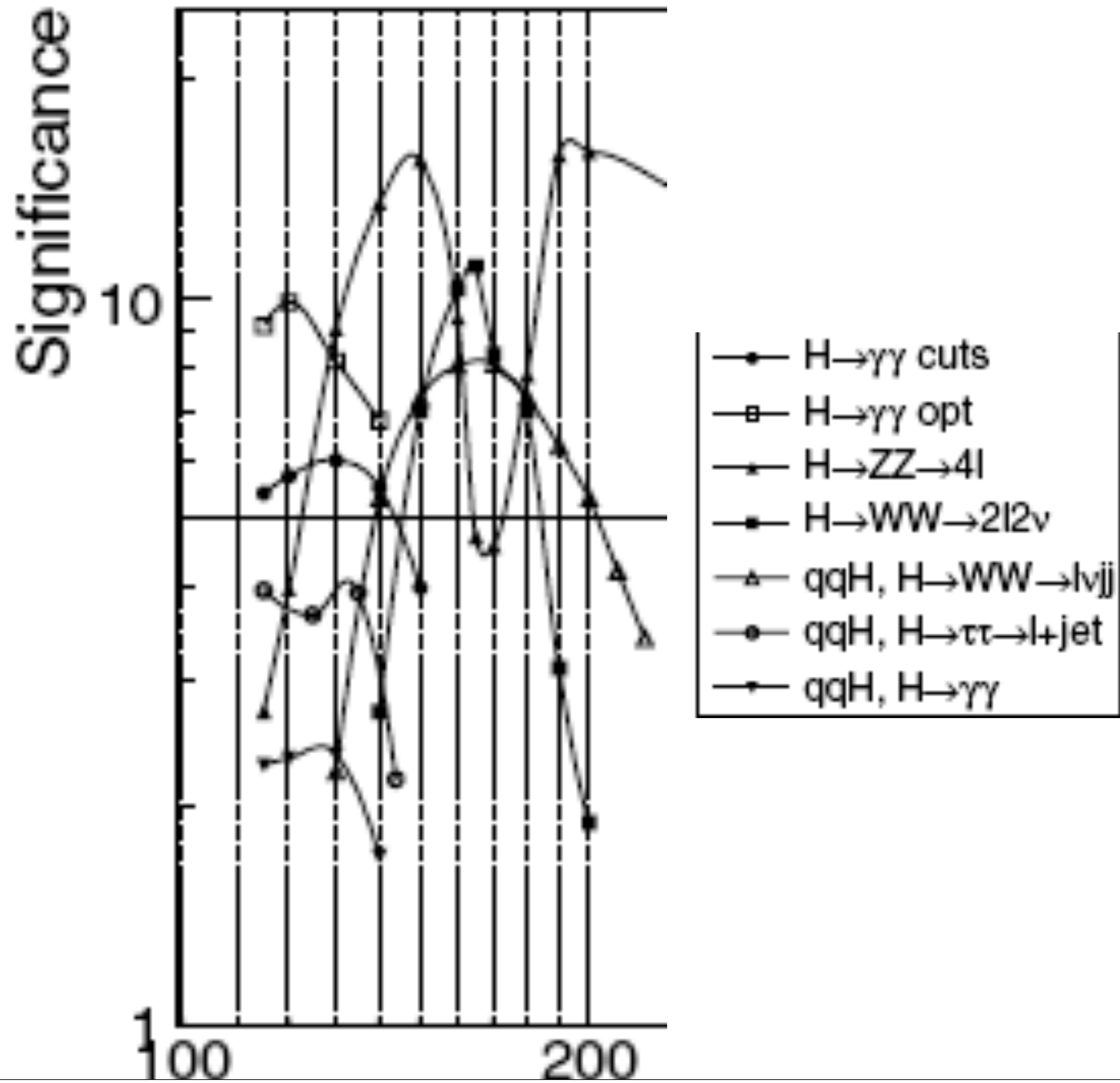
How do we find the Higgs boson?

- Consider all possibilities for (production) x (decay)
  Typical production cross-sections ~1-50pb
  Typical BR ~0.05 - 0.001
- Other cross-sections with the same final state are always (much) larger. Devise cuts suppressing the backgrounds

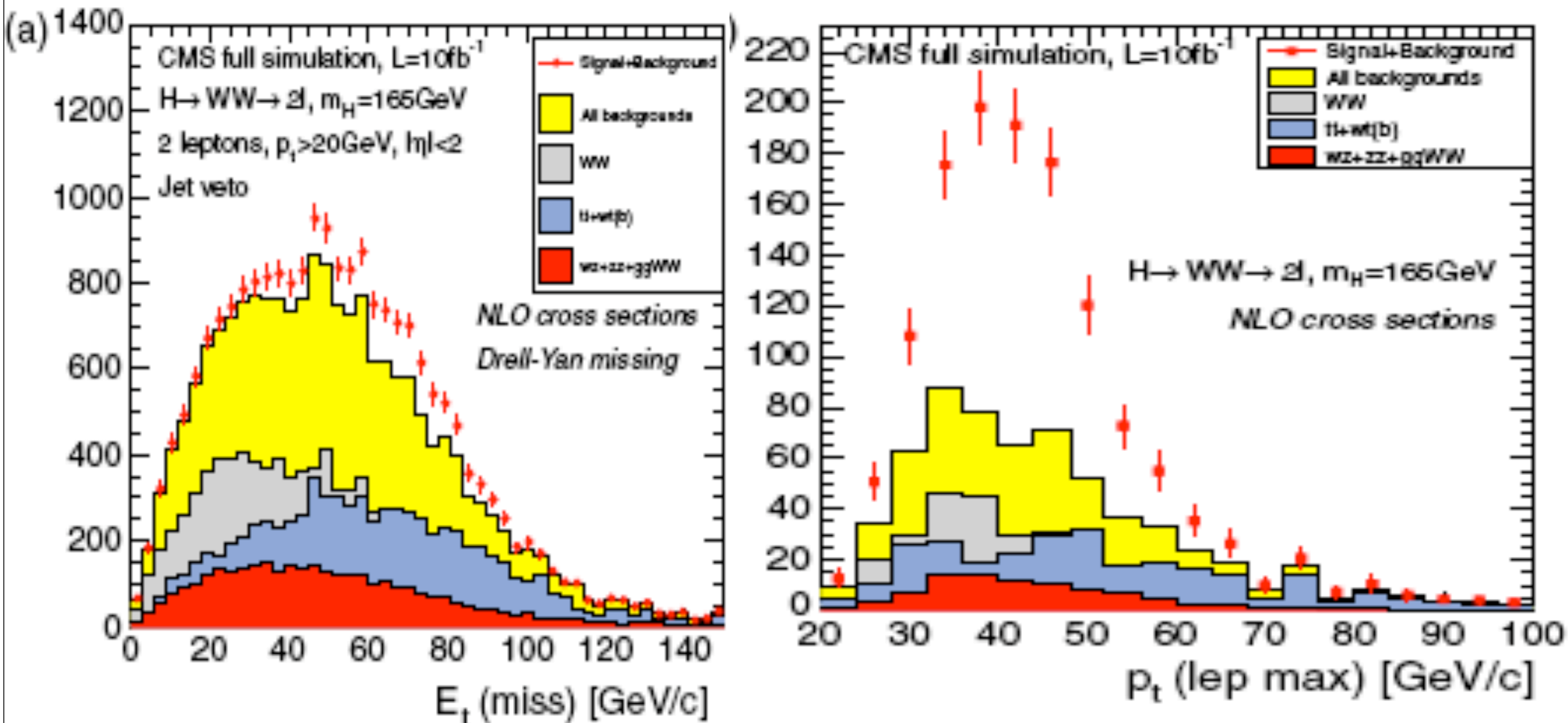
ATLAS discovery reach



CMS discovery reach



We are after rare processes



Summary of part I

- There is a vev! There must be something like a Higgs boson.
- Elusive particle. Hard to create! Hard to detect! But LHC can do it.
- Higgs cross-sections will provide a new test for the SM and all its viable extensions
- NEXT: What can change the cross-sections?