Elementary Particles II

3 – The Higgs Particle at the LHC

Predictions, Strategies, Machines, Detectors, Data, Measurements, Tests of SM

E.Menichetti - Universita' di Torino

SSB - I

Field theory: Real scalar field

$$L = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - V(\varphi)$$

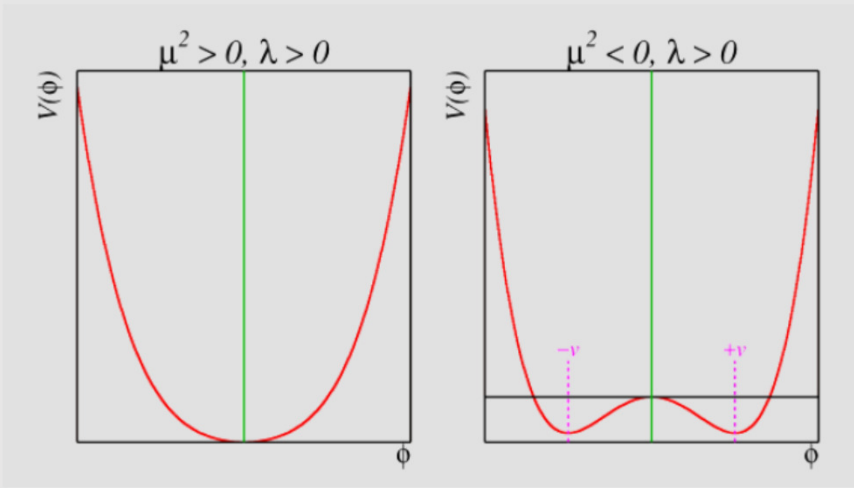
$$V(\varphi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda^2\phi^4, \lambda > 0$$

Reflection symmetric: $V(\varphi) = V(-\varphi)$

V Minima:

$\mu^2 > 0 : \phi = 0$

$\mu^2 < 0 : \phi = v = \pm\sqrt{-\frac{\mu^2}{\lambda}}$



V Minima: Defining *vacuum* state $\left(\leftarrow \text{Cannot have less energy}\right)$

$\mu^2 > 0$: Vacuum (non degenerate) $\equiv$ Zero field

$\mu^2 < 0$: Vacuum (degenerate!) = $v \neq$ Zero field !!

v = Vacuum Expectation Value (VEV) of ϕ

SSB - II

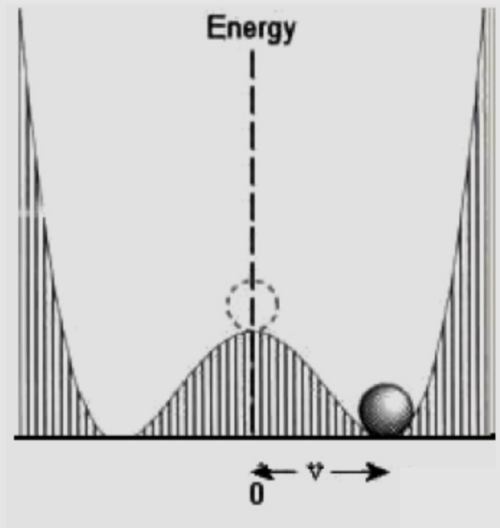
Choose vacuum state:

$\langle \phi(x) \rangle_0 = v$ Spontaneous Symmetry Breaking

Define: $\phi(x) = v + \eta(x)$

$$\rightarrow L = \frac{1}{2}(\partial_\mu \eta)^2 - \lambda\left(v^2\eta^2 - v\eta^3 - \frac{1}{4}\eta^4\right) = \left[\frac{1}{2}(\partial_\mu \eta)^2 - \lambda v^2 \eta^2\right] - \lambda v \eta^3 - \frac{1}{4}\lambda\eta^4$$

$$L = \frac{1}{2}(\partial_\mu \eta)^2 - \lambda v^2 \eta^2 \; \text{+higher powers of } \eta$$



$\rightarrow$ Free Klein-Gordon equation

$\rightarrow$ Scalar quantum field

$m^2 = 2\lambda v^2 \rightarrow m = \sqrt{-2\mu^2} > 0$

$\left[\text{Observe:} \mu^2 < 0 \rightarrow \text{Imaginary mass in original } L!\right]$

KO: $L(\eta) \neq L(-\eta)$

Reflection symmetry *spontaneously broken*

SSB - III

Field theory: Complex scalar field

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2), \phi^* = \frac{1}{\sqrt{2}}(\phi_1 - i\phi_2)$$

$$L = (\partial_\mu \phi)(\partial^\mu \phi)^* - V(\phi)$$

$$V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2, \lambda > 0, \mu^2 < 0$$

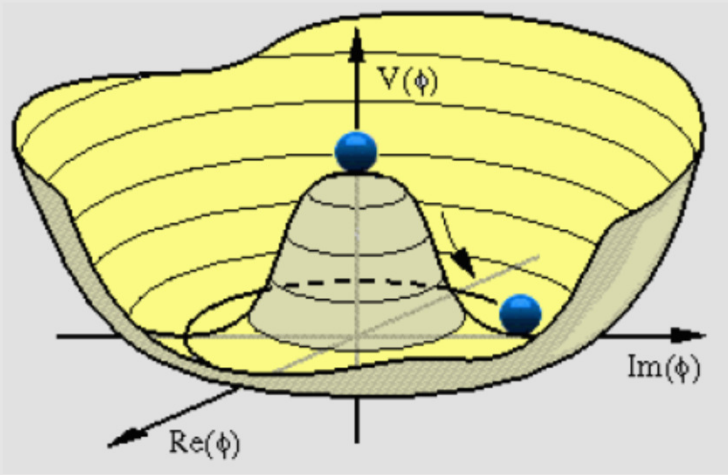
$U(1)$ symmetric: $\phi \to \phi' = e^{i\alpha}\phi$

Observe: $U(1)$ *continuous* symmetry

V Minima:

$$\mu^2 < 0 : \phi_1^2 + \phi_2^2 = -\frac{\mu^2}{\lambda}$$

$\rightarrow$ Vacuum *infinitely* degenerate



Choose vacuum = $(v, 0)$

$\rightarrow U(1)$ symmetry *spontaneously broken*

SSB - IV

Define:

$$\phi(x) = \frac{1}{\sqrt{2}}\left[v + \xi(x) + i\eta(x)\right]$$

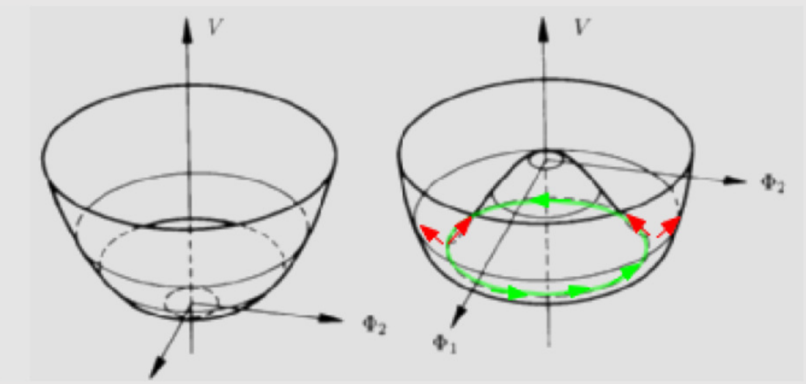
$$L = \frac{1}{2}\left[\left(\partial_\mu \xi\right)^2 + \left(\partial_\mu \eta\right)^2\right] + \mu^2\eta^2 \; \cancel{+\text{higher powers of } \eta}$$

Free Klein-Gordon equations for (ξ, η)

But: "Kinetic energy" terms for both ξ, η; Mass term only for η

$\rightarrow$ η field excitations: *massive* scalar particles

ξ field excitations: *massless* scalar particles, aka *Goldstone Bosons*



SSB - V

SSB of a continuous, global $(\leftarrow$ non local$)$ symmetry

$\rightarrow \infty$ degenerate vacuum states

Symmetry generators transform any vacuum state into another one

Indeed, for a non-degenerate vacuum:

$\langle\phi\rangle_0$ Invariant under G:

$\rightarrow e^{i\alpha G}\langle\phi\rangle_0 \simeq (1+i\alpha G)\langle\phi\rangle_0 = \langle\phi\rangle_0 \leftrightarrow G\langle\phi\rangle_0 = 0$

$\rightarrow G$ does annihilate a non-degenerate vacuum

For a degenerate vacuum:

$\langle\phi\rangle_0$ Non-invariant under G:

$\rightarrow$ Goldstone Theorem:

n generators not annihilating the vacuum $\rightarrow$ Appearance of n massless scalars

Also called *Goldstone bosons*

SSB - VI

Example from condensed matter physics: Ferromagnet

Interaction rotationally invariant

But, below Curie temperature

→ Spontaneous magnetization in a random orientation

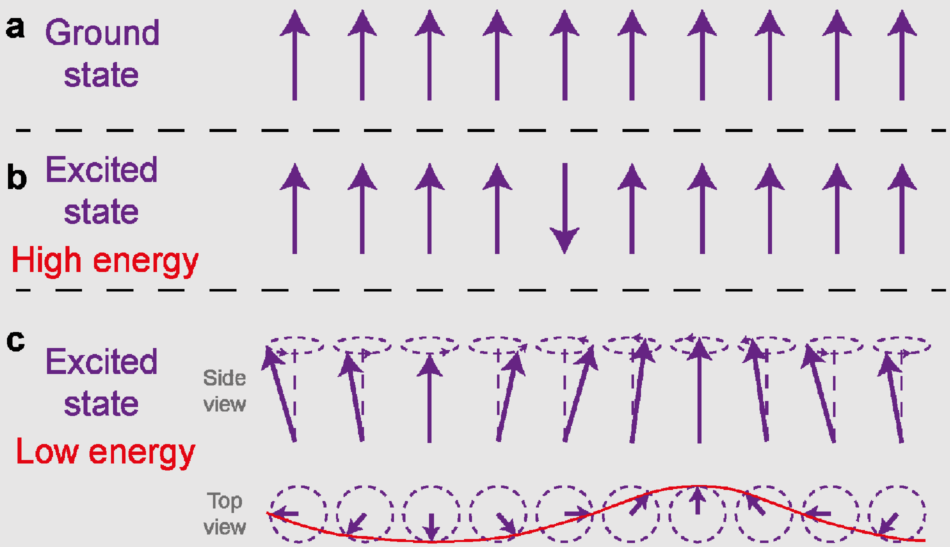
→ Rotational symmetry lost

→ Degenerate vacuum

→ Goldstones

Non-relativistic version of *massless*

Spin waves ≡ Zero energy-gap *quasi - particles* (i.e. lattice excitation)



Higgs Mechanism - I

Goldstone theorem would seem to definitely destroy
our hint of a Standard Model:

$3+1$ massless gauge bosons, only one observed
4 massless scalar bosons, none observed

Local gauge invariance + SSB:
Higgs mechanism
evading Goldstone's theorem

Simple, yet subtle way of giving mass to gauge bosons
without spoiling gauge invariance (and renormalizability)

Higgs Mechanism - II

Example by Higgs :

$U(1)$ gauge group, require *local* symmetry:

Gauge vector boson A_μ to be introduced, coupling to some current as usual

Now: Add "sombrero" potential for a complex, scalar field $\phi = \phi_1 + i\phi_2$

$$L = \underbrace{\left[\left(\partial_\mu - ieA_\mu\right)\phi^*\right]\left[\left(\partial^\mu + ieA^\mu\right)\phi\right]}_{EM \text{ interaction of (charged) } \phi} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \mu^2\phi^*\phi - \lambda\left(\phi^*\phi\right)^2 + \underbrace{\ldots\ldots}_{\substack{\text{Current-field} \\ \text{interaction etc}}}$$

As found before:

Degenerate vacuum state $\rightarrow$ SSB picks as vacuum state $(v, 0)$

Higgs Mechanism - III

$\rightarrow \phi = v + \eta_1 + i\eta_2$

L written in terms of η_1, η_2 :

Upon quantization, 2 scalar particles $\rightarrow m_1 = \sqrt{2\lambda v^2}, m_2 = 0$

Plugging $\phi = v + \eta_1 + i\eta_2$ into L:

$$L = \frac{1}{2}(\partial_\mu \eta_1)(\partial^\mu \eta_1) - \frac{1}{2}\overbrace{2\lambda v^2}^{m_1^2}\eta_1^2 + \frac{1}{2}(\partial_\mu \eta_2)(\partial^\mu \eta_2)$$

$$+\underbrace{\frac{1}{2}\overbrace{(ev)^2}^{m_V^2} A^\mu A_\mu}_{Massive\ vector!} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \underbrace{evA^\mu \partial_\mu \eta_2}_{??} + \ldots$$

Attempting to understand L:

Massive vector field A^μ + Massive scalar field η_1 + Massless scalar field η_2

Troubling term coupling A^μ and η_2

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Higgs Mechanism - IV

Use gauge invariance:

$$\begin{cases} \phi \to \phi' = e^{-ie\theta(x)}\phi \\ A^\mu \to A'^\mu = A^\mu + \partial_\mu \theta \end{cases}$$

Choose θ to make ϕ real: Then $\eta_2 \equiv 0$ $\left(\leftarrow \text{Unitary gauge}\right)$

$$\to L = \frac{1}{2}\left(\partial_\mu \eta_1\right)\left(\partial^\mu \eta_1\right) - \frac{1}{2}2\lambda v^2 \eta_1^2 + \underbrace{\frac{1}{2}\overbrace{(ev)^2}^{M_V^2} A^\mu A_\mu}_{Massive\ vector!} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \dots$$

Massive vector field A^μ + Massive scalar field η_1

Counting degrees of freedom:

$\underbrace{2}_{A_\mu} + \underbrace{1+1}_{\phi} = \underbrace{3}_{A_\mu} + \underbrace{1}_{\eta_1}$ OK

Standard picture:

By effect of a smart gauge transformation,

the massless vector field A_μ has eaten the Goldstone boson η_2

to become massive

Higgs Mechanism - V

Attempting to dissipate some misunderstandings likely to sneak in:

Mostly related to our naive perception of what is really a 'particle'

1) Where is the mass?

To identify mass terms in *L*: Not necessarily a trivial task

Key point: Particle content *only meaningful in perturbative expansion*

Example: $L = \left(\partial_\mu \phi\right)\left(\partial^\mu \phi\right)^* - \left(-\mu^2 \phi^* \phi\right) - \lambda\left(\phi^* \phi\right)^2, \lambda > 0, \mu^2 > 0$

$-\mu^2 \rightarrow$ Imaginary mass $\rightarrow$ Nonsense $\rightarrow$???

But: To use this form of L to extract Feynman rules, should expand around $|\phi| = 0$

Unstable extremum $\rightarrow$ Can't make it

Rewrite by expanding around $\eta = 0 : L = \frac{1}{2}\left(\partial_\mu \eta\right)^2 - \lambda \nu^2 \eta^2 + \cdots$

Stable extremum $\rightarrow$ OK

$\rightarrow$ Particle content should be identified in this form

Higgs Mechanism - VI

2)What's so special in unitary gauge?
Nothing: L invariant under local gauge transformations,
including the one to unitary gauge:
$\rightarrow$ L describe the same physics before and after the gauge transofrmation
But: Particle content much easier to extract in the unitary gauge

3) Disappearing Goldstones !?
Indeed: And re-appearing as extra degrees of freedom for massive gauge bosons
See comment above on the tricky business of defining what is a particle...

4)What decides which vacuum is selected among the many?
Not really relevant: Any choice yields identical results

5) Could we make it with the SM without SSB and all that complicated swapping of degrees of freedom?
Actually no: SSB is an *intrinsic* feature of certain quantum systems
(with an infinite number of degrees of freedom)

SM Reminder - I

Extend Abelian Higgs model to non-Abelian gauge symmetry:

Gauge group = $SU(2)_L \otimes U(1)_Y$

To add SSB to the Standard Model:

Add a doublet of complex, scalar fields:

$$\phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix}$$

Assuming $y = 1 \rightarrow \begin{cases} Q\left[\phi^+(x)\right] = +1 \\ Q\left[\phi^0(x)\right] = 0 \end{cases}$

SM Reminder - II

$SU(2)_L \otimes U(1)_Y$ Gauge transformation of doublet:

$$\phi \rightarrow \phi' = \exp\left\{-i\left[\frac{g}{2}\boldsymbol{\alpha}(x)\cdot\boldsymbol{\tau} + \frac{g'}{2}y\theta(x)I\right]\right\}\phi$$

$SU(2)_L \otimes U(1)_Y$ Covariant derivative:

$$D^\mu = \partial^\mu + i\left[\frac{g}{2}\boldsymbol{\tau}\cdot\mathbf{W}^\mu + \frac{g'}{2}yB^\mu\right]$$

$\rightarrow$ Additional term to EW lagrangian:

$$L_H = D_\mu\phi^\dagger D^\mu\phi - \mu^2\phi^\dagger\phi - \lambda\left(\phi^\dagger\phi\right)^2$$

Take $\mu^2 < 0, \quad \lambda > 0$:

$$|\phi|^2_{\min} = -\frac{\mu^2}{2\lambda} = \frac{v^2}{2} \rightarrow v = \sqrt{-\frac{\mu^2}{\lambda}}$$

Pick ground state (= vacuum) as

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \rightarrow \text{SSB of Electroweak gauge symmetry}$$

$v = 246\ GeV$

SM Reminder - III

Introduce field deviation from vacuum:

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \sigma_1 + i\sigma_2 \\ v + \eta_1 + i\eta_2 \end{pmatrix} \rightarrow V = -\frac{\mu^4}{4\lambda} + \lambda v^2 \eta_1^2 + \lambda v \eta_1 \left(\sigma_1^2 + \sigma_2^2 + \eta_1^2 + \eta_2^2\right) + \frac{\lambda}{4}\left(\sigma_1^2 + \sigma_2^2 + \eta_1^2 + \eta_2^2\right)^2$$

After properly 'rotating' to Unitary Gauge:

1 massive scalar: $\eta_1, m_{\eta_1} \equiv m_H = \sqrt{2\lambda v^2} \leftarrow$ The Higgs

2 massive, charged vectors: $W^{\pm}, m_W = \frac{g}{2}\sqrt{-\frac{\mu^2}{\lambda}}$

1 massive, neutral vector: $Z^0, m_Z = \frac{\sqrt{\left(g^2 + g'^2\right)}}{2}\sqrt{-\frac{\mu^2}{\lambda}}$

$\rightarrow$ Relating model parameters to independently measured constants $e, G_F, \sin\theta_W$:

$$M_W = \sqrt{\frac{\sqrt{2}g^2}{8G_F}} = \sqrt{\frac{\sqrt{2}e^2}{8G_F \sin^2\theta_W}} \simeq 77.5\ \ GeV, \quad M_Z = \frac{M_W}{\cos\theta_W} \simeq 88.4\ \ GeV$$

$$M_H = \frac{\sqrt{2}\lambda}{G_F} = ???$$

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SM Reminder - IV

Gauge terms of L in the unitary gauge, in terms of the physical fields:

$$L_B + L_H$$

$$= -\frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) \qquad \text{Photon}$$

$$-\frac{1}{2} F^{W}{}_{\mu\nu}(x) F^{W\dagger\mu\nu}(x) + \frac{1}{2} m_W^2 W_\mu^\dagger W^\mu \qquad W^\pm \text{ boson}$$

$$-\frac{1}{4} Z_{\mu\nu}(x) Z^{\mu\nu}(x) + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \qquad Z^0 \text{ boson}$$

$$+\left(\partial_\mu \sigma\right)\left(\partial^\mu \sigma\right) - \frac{1}{2} m_H^2 \sigma^2 \qquad H \text{ Higgs boson}$$

$$+L^I_{BB} + L^I_{HH} + L^I_{HB} \qquad \text{Gauge-Higgs, Higgs self-, Gauge self-interactions}$$

SM Reminder - V

Fermion masses: Yukawa (scalar) coupling

Describing interaction between Dirac and scalar fields:

Example: Single lepton family

$$L_{HL} = -g_l\left[\overline{\Psi}_l^L \Phi \psi_l^R + \overline{\psi}_l^R \Phi^\dagger \Psi_l^L\right] - \underbrace{g_{\nu_l}}_{=0 \text{ for massless neutrino}} \left[\overline{\Psi}_l^L \tilde{\Phi} \psi_{\nu_l}^R + \overline{\psi}_{\nu_l}^R \tilde{\Phi}^\dagger \Psi_l^L\right], \quad \tilde{\Phi} = \begin{pmatrix} \phi_b^* \\ -\phi_a^* \end{pmatrix}$$

In the unitary gauge:

$$L_{HL} = -\frac{1}{v} m_l \overline{\psi}_l \psi_l \sigma - \frac{1}{v} m_{\nu_l} \overline{\psi}_{\nu_l} \psi_{\nu_l} \sigma$$

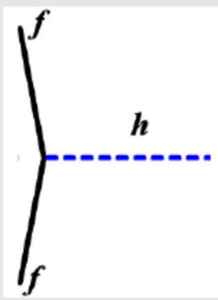
Lepton masses in terms of model parameters:

$$m_l = \frac{v g_l}{\sqrt{2}}, \quad m_{\nu_l} = \frac{v g_{\nu_l}}{\sqrt{2}} (= 0 \text{ in the Minimal Standard Model})$$

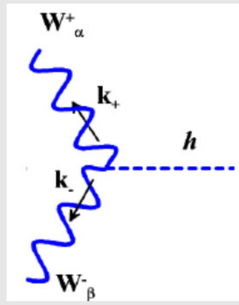
g_l individual constant

SM Reminder - VI

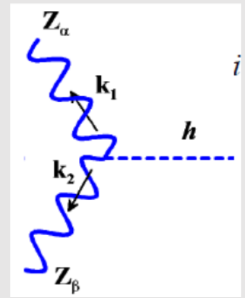
Higgs vertexes:



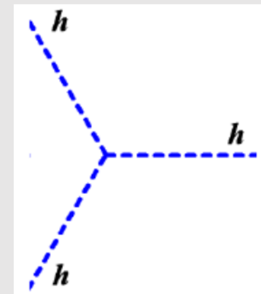
$$-im_f\sqrt{\sqrt{2}G_F}\,\bar{f}\,f$$



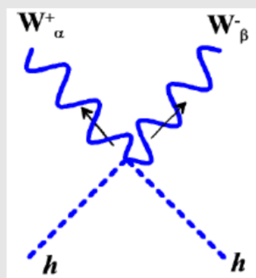
$$2iM_W^2\sqrt{\sqrt{2}G_F}\,g^{\alpha\beta}W_\alpha^{+\dagger}W_\beta^{-\dagger}h$$



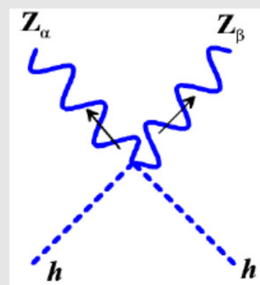
$$2iM_Z^2\sqrt{\sqrt{2}G_F}\,g^{\alpha\beta}Z_\alpha^\dagger Z_\beta^\dagger h$$



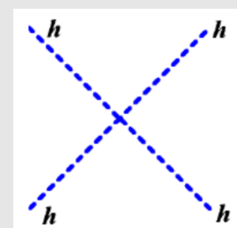
$$-3im_h^2\sqrt{\sqrt{2}G_F}\,hhh$$



$$2iM_W^2\sqrt{2}G_F\,g^{\alpha\beta}hhW_\alpha^{+\dagger}W_\beta^{-\dagger}$$



$$2iM_Z^2\sqrt{2}G_F\,g^{\alpha\beta}hhZ_\alpha^\dagger Z_\beta^\dagger$$



$$-3im_h^2\sqrt{2}G_F\,hhhh$$

Observe: Amplitude ~ mass(fermions), mass^2(bosons)

About the Higgs Field - I

Universal, constant field

Lorentz scalar $\to$ Same value in any frame, rotation invariant

Non-standard feature:

Vacuum expectation value $v \neq 0$

Usual analogy: Spontaneously magnetized ferromagnet:

$\mathbf{M} \neq 0$ below Curie temperature

$\to$ Pick up a direction

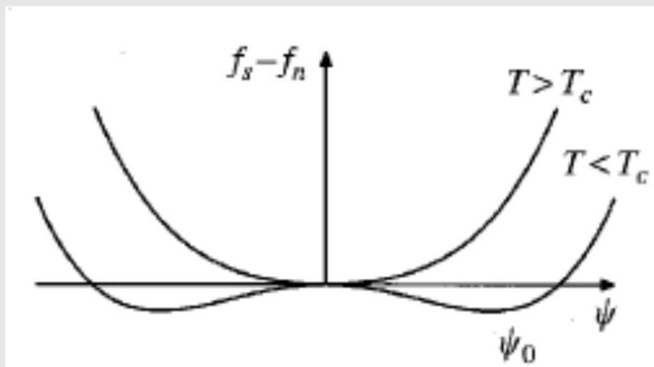
Ground state rotationally not symmetric, in spite of H being symmetric

About the Higgs Field - II

Better analogy: Superconductor
Energy difference between normal and s.c. state at two different temperatures

$$\Delta E = a(T)|\psi|^2 + \frac{1}{2}b(T)|\psi|^4 + ...$$ Landau theory of phase transitions

ψ is the Cooper pair 'wave function' → $|\psi|^2$ ~ density of Cooper pairs



Below T_c, the minimum energy state ('vacuum') occurs for $\psi = \psi_0 \neq 0$, phase undefined
→*U(1) QED* gauge invariance spontaneously broken

→ Photon becomes 'massive' → $\boldsymbol{B} = 0$ inside

About the Higgs Field - III

ψ 'Higgs field' of superconductivity: $<\psi>\neq 0$ ↔ Permanent supercurrents

Superconductive state:
'Higgs field' = 'Wave function' of Cooper pairs

→Not a fundamental field
→'Composite' field of fundamentals fermions (electrons)

Why there is the composite?

e-e effective interaction: Attractive (!) due to *e* – lattice interaction

Is the 'real' Higgs field a genuine, fundamental field or a composite?

Good question..No answer (yet):
Take it as a fundamental field

About the Higgs Field - IV

A couple of questions:

1) What about the nonzero VEV of the Higgs field?

Higgs: Unique field whose VEV $\neq 0$

Similar to magnetization $\mathbf{M} \neq 0$ in a ferromagnet

But:

In a vacuum $\rightarrow$ Not related to many body effects

Lorentz scalar $\rightarrow$ No preferred direction, reference frame

2) Does it involve a new force? 'Giving mass to $\approx$ all the fundamental constituents' ??

- Part of the standard EW interaction, often as a negligible contribution:
  Higgs *particle* exchange diagrams between Fermion lines normally strongly suppressed by m_f / m_W factors as compared to $\gamma, Z^0, W^\pm$ exchange (Not true for t quark!)
  $3-$ & $4-$boson diagrams with and without H similar
- Crucial role as 'Background' interaction:
  For most particles Higgs *field* coupling translates into *inertial mass* !

About the Higgs Field - V

Apparently contributing to vacuum energy density:

Beware: Take *potential energy* $V(\phi)$

$$
\begin{aligned}
V_{\min} = V(v) &= \frac{1}{2}\mu^2 v^2 + \frac{1}{4}\lambda v^4 \quad \text{use } \mu^2 = -\lambda v^2 \\
&= -\frac{1}{4}\lambda v^4 \qquad\qquad \text{use } m_h^2 = 2\lambda v^2 \\
&= -\frac{1}{8} m_h^2 v^2
\end{aligned}
$$

Constant term: Usually not considered

Does not enter field equations, where only energy *differences* count

But: Taken into account by gravity

→ Cosmological term ?

Cosmological constant : Possibly additional term in Einstein's field equations

May yield long range attraction/repulsion, according to sign

Invented by Einstein in order to guarantee static universes

Rejected by Einstein at the time of discovery of expansion of the Universe

Recently resurrected following the discovery of accelerated expansion

About the Higgs Field - VI

Zero point energy = $-\frac{1}{8}m_h^2 v^2 \sim \rho_{Higgs}$

Indeed: $\left[-\frac{1}{8}m_h^2 v^2\right] = \underbrace{E^4}_{GeV^4} = E\left(E^{-1}\right)^{-3} \rightarrow \frac{E}{L^3}$ Energy density

$\rho_{Higgs} \sim 1.2 10^8 \; GeV^4$

By assuming ρ to be a cosmological term, compare:

$\rho_{observed} \sim 10^{-47} \; GeV^4$!

$\rightarrow \rho_{Higgs}$ 55 orders of magnitude too big

(and with the wrong sign...)

Quick fix: $V(v)$ can be set = 0 by adding a constant to $V(\phi)$

Constant apparently unrelated to m_h, v...

...to be chosen to an accuracy of 1 part out of 10^{55} !

Fine tuning problem, still essentially unsolved

Something missing?

About the Higgs Field - VII

Higgs boson: Quantum excitation of the field, mass m_H *not* given by the field

Further issue:

$V(\phi)$ appearing in L: *Classical* potential

$\rightarrow$ Must be quantized

$\rightarrow$ Will be used perturbatively

$\rightarrow$ Radiative corrections will modify the classical $V(\phi)$

Similar to vacuum polarization corrections to Coulomb potential in QED

(Uheling potential & Lamb shift)

Standard effect:

Running constants, including λ

$$L_H = D_\mu \phi^\dagger D^\mu \phi - \mu^2 \phi^\dagger \phi - \lambda \left(\phi^\dagger \phi \right)^2$$

$$\lambda = \lambda\left(q^2\right)$$

$\rightarrow m_H$ modified by radiative corrections

Upon taking $\mu^2 < 0, \quad \lambda(0) > 0$

$\rightarrow \lambda$ evolution depending on $\beta -$ *functions*

About the Higgs Field - VIII

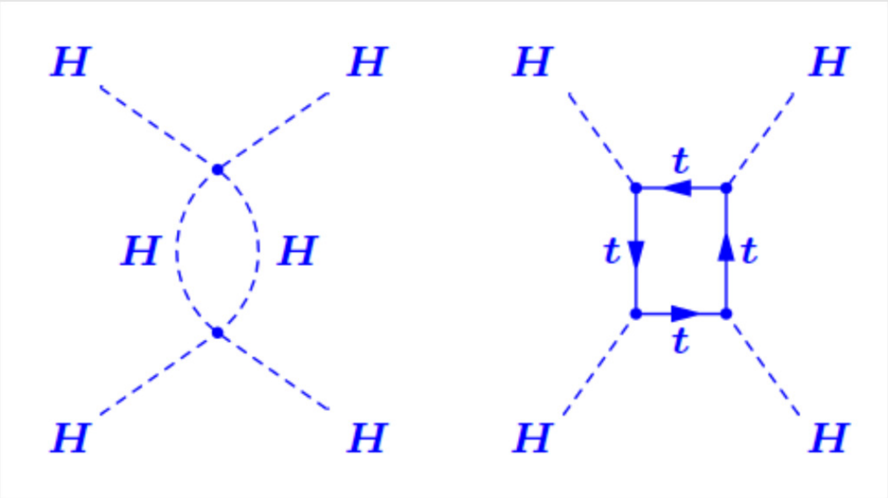
Running couplings and $\beta-$functions:

$$\frac{dg^2}{d\ln Q^2} \equiv 4\pi\beta\left(g^2\right) = \underbrace{bg^4}_{\text{1 loop}} + \underbrace{O\left(g^6\right)}_{\text{2 loop}} + \cdots$$

$$\rightarrow \frac{dg_i^2}{d\ln Q^2} = 4\pi\beta_i\left(g_i^2\right) \simeq b_i g_i^4$$

For the EW interaction:

$$b_g = -\frac{19}{6\cdot 16\pi^2}, \qquad b_{g'} = +\frac{41}{6\cdot 16\pi^2}$$



Higgs couplings:

$$\frac{d\lambda}{d\ln Q^2} = \frac{1}{32\pi^2}\left[24\left(\lambda^2 + h_t^2 - h_t^4\right) - 3\lambda\left(3g^2 + g'^2\right) + \frac{3}{8}\left(2g^4 + \left(g^2 + g'^2\right)^2\right)\right] \text{ Self}$$

$$\frac{dh_t}{d\ln Q^2} = \frac{1}{32\pi^2}\left[9h_t^3 - h_t\left(8g_s^2 + \frac{9}{4}g^2 + \frac{17}{12}g'^2\right)\right] \text{ Top (Yukawa)}$$

$$\rightarrow m_H < \left(\frac{2\sqrt{2}\pi^2}{3G_F \ln\frac{\Lambda}{\nu}}\right)^{1/2} \sim \begin{array}{c} O\left(140\ GeV\right),\ \Lambda \sim m_{Planck} \approx 1.2 10^{19}\ GeV \\ O\left(650\ GeV\right),\ \Lambda \sim 1\ TeV \end{array}$$

About the Higgs Field - IX

$$\frac{d\lambda}{d\ln Q^2} \sim \frac{3\lambda^2}{4\pi^2}$$ Neglect smaller contributions at large λ

$$\frac{d\lambda}{\lambda^2} \sim \frac{3}{4\pi^2} d\ln Q^2 \to -\frac{1}{\lambda(Q^2)} + \frac{1}{\lambda(\nu^2)} \sim \frac{3}{4\pi^2}\ln\frac{Q^2}{\nu^2}$$

$$\to \frac{1}{\lambda(Q^2)} \sim \frac{1}{\lambda(\nu^2)} - \frac{3}{4\pi^2}\ln\frac{Q^2}{\nu^2}$$

$$\lambda(\nu^2) = \frac{G_F m_H^2}{\sqrt{2}}$$

$$\to \lambda(Q^2) \sim \frac{\lambda(\nu^2)}{1 - \frac{3}{4\pi^2}\lambda(\nu^2)\ln\frac{Q^2}{\nu^2}}$$

$\lambda \to \infty$ as $\frac{3}{4\pi^2}\lambda(\nu^2)\ln\frac{Q^2}{\nu^2} \to 1$ Diverging at 'Landau pole' $Q_{LP} = v\exp\left(\frac{2\pi^2}{3\lambda(\nu^2)}\right) = v\exp\left(\frac{2\sqrt{2}\pi^2}{3G_F m_H^2}\right)$

$\to$ New physics required at scale $\Lambda < Q_{LP} \to \ln\frac{\Lambda}{v} < \left(\frac{2\sqrt{2}\pi^2}{3G_F m_H^2}\right) \to m_H < \left(\frac{2\sqrt{2}\pi^2}{3G_F \ln\frac{\Lambda}{\nu}}\right)^{1/2}$

About the Higgs Field - X

$$\frac{d\lambda}{d\ln Q^2} \sim -\frac{3h_t^4}{4\pi^2}$$ Neglect smaller contributions at small λ

$$\to d\lambda \sim -\frac{3h_t^4}{4\pi^2} d\ln Q^2$$

$$\to \lambda\left(Q^2\right) \sim \lambda\left(\nu^2\right) - \frac{3h_t^4}{4\pi^2} \ln\frac{Q^2}{\nu^2}$$

λ must stay $+ve$ in order to keep vacuum stable (!):

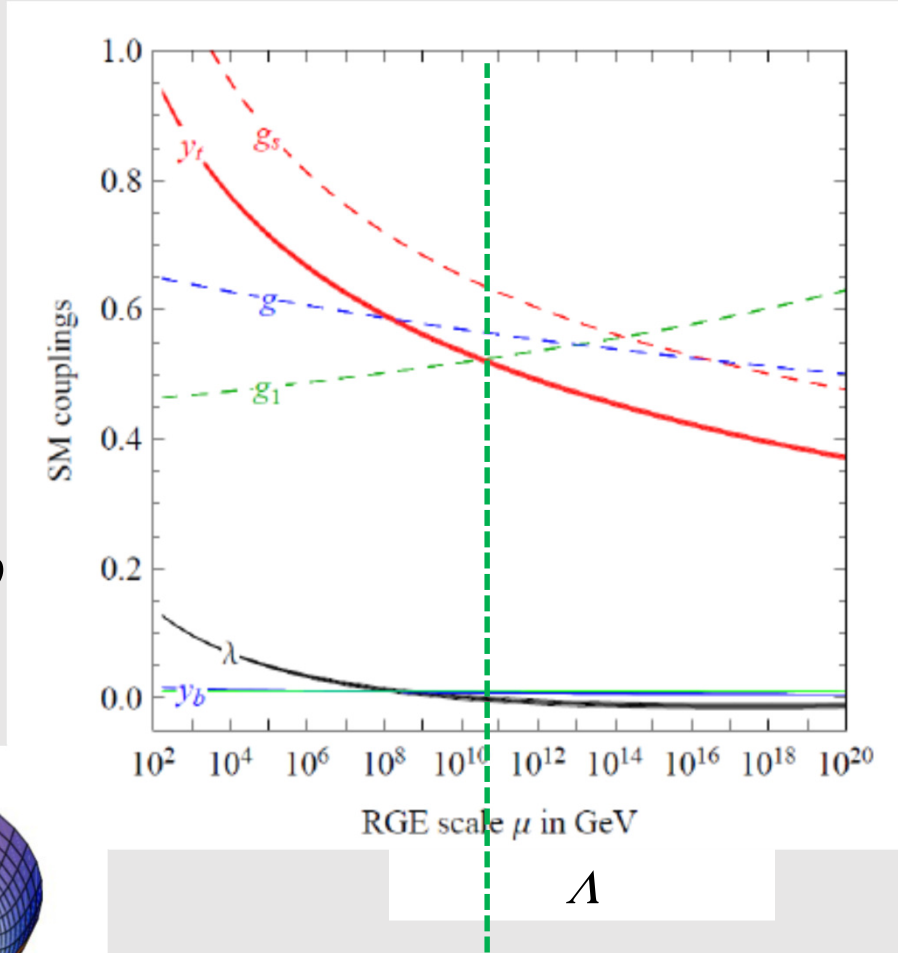
Don't like a too quick End of the World

$$\to \lambda\left(\nu^2\right) > \frac{3h_t^4}{4\pi^2} \ln\frac{Q^2}{\nu^2} \to \frac{G_F m_H^2}{\sqrt{2}} > \frac{3h_t^4}{4\pi^2} \ln\frac{Q^2}{\nu^2}$$ for some $Q \sim \Lambda$

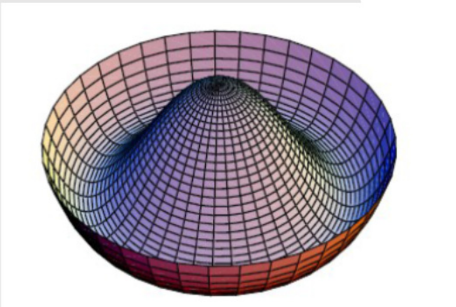
$$\to m_H > \left(\frac{3h_t^4}{\sqrt{2}\pi^2 G_F} \ln\frac{\Lambda}{\nu}\right)^{1/2}$$

About the Higgs Field - XI

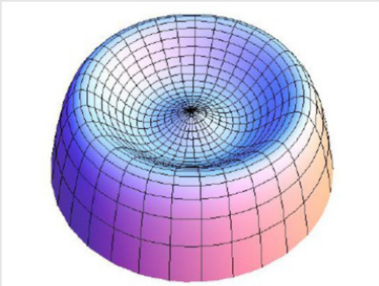
Running couplings:



Sombrero: $\lambda>0$
Relax



Dog Bowl: $\lambda<0$
End of the World
(sometime)

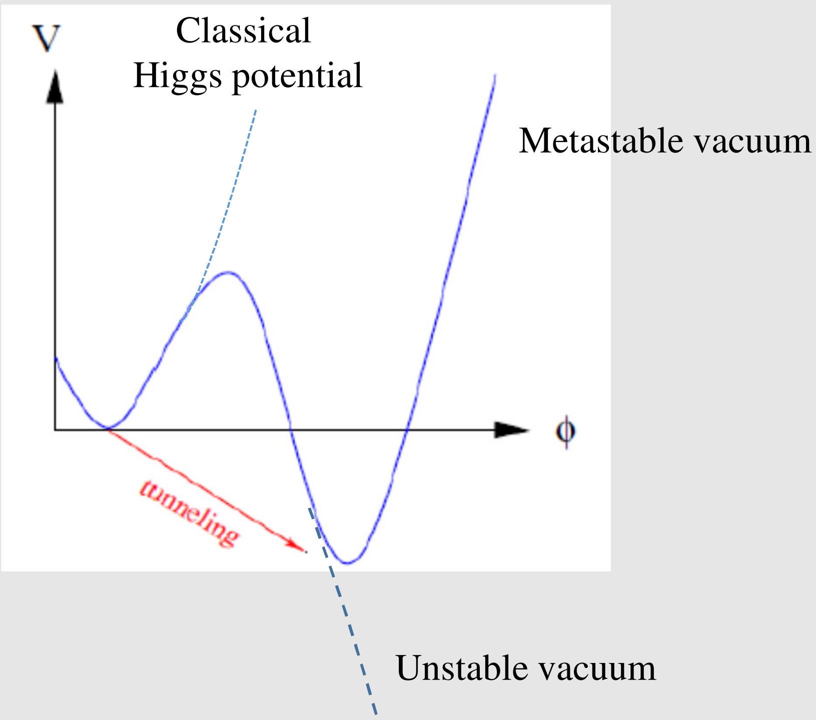


About the Higgs Field - XI

Radiative corrections leading to major changes in the effective Higgs potential at large ϕ values:

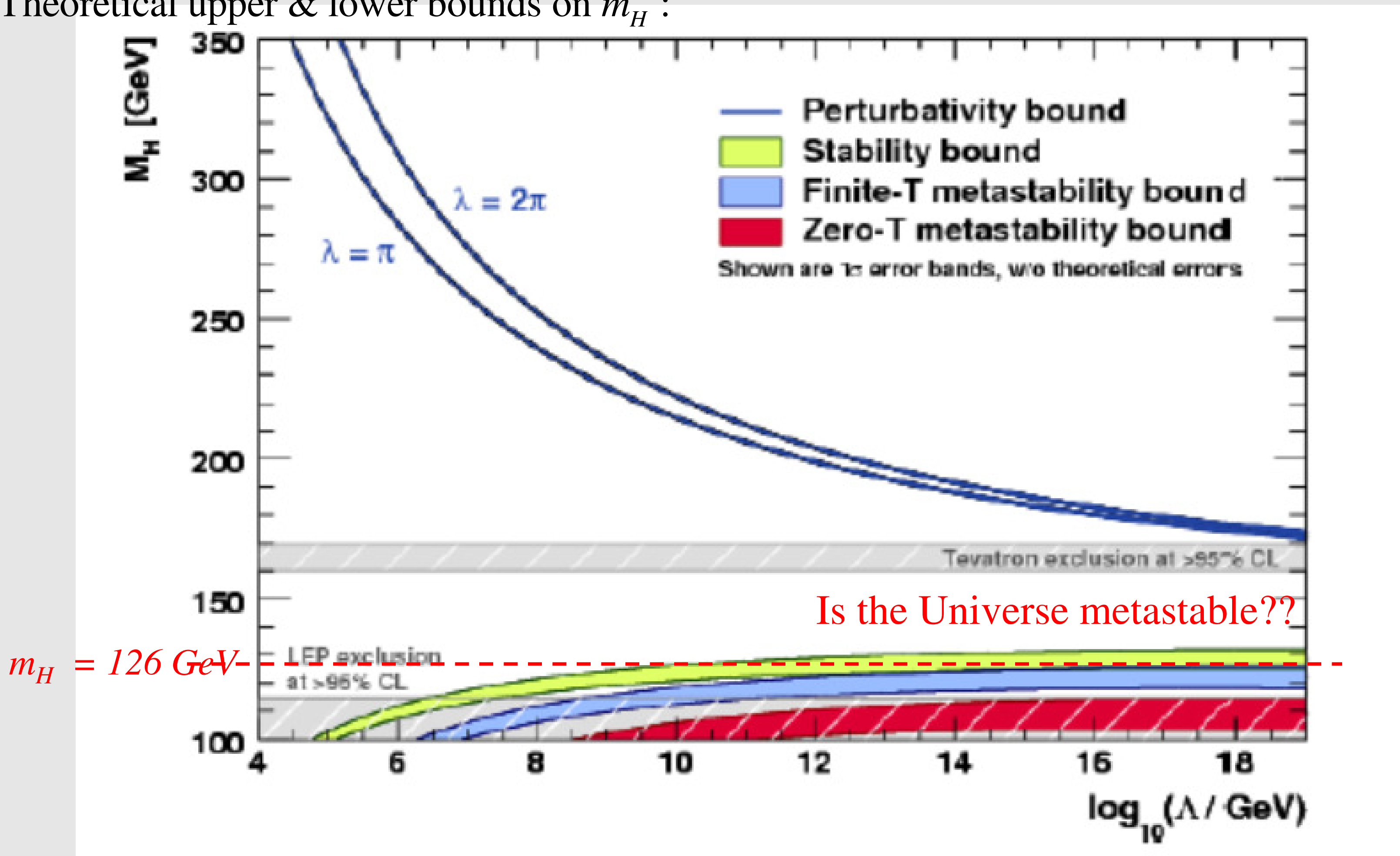
Details tied to m_H, m_t

Might induce vacuum instability/metastability through fast/slow tunneling



About the Higgs Field - XII

Theoretical upper & lower bounds on m_H :



Hunting the Higgs

Try to sketch some guidelines:

(i) Production modes $\longrightarrow$ Machines

(ii) Decay modes $\longrightarrow$ Detectors

Both related to couplings

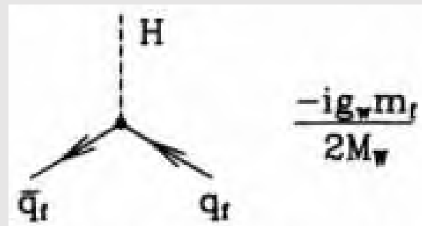
Compare rates, backgrounds

$\longrightarrow$ Sensitivity

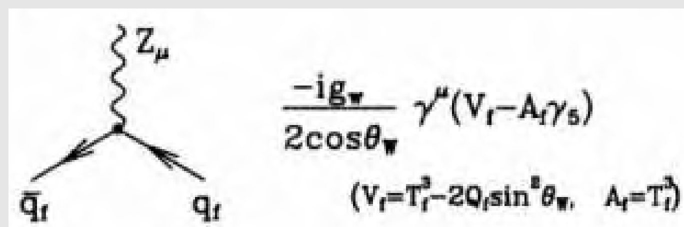
$\longrightarrow$ Further observables (Spin/Parity, Width, Branching Ratios,..)

Higgs Production - I

Start from H coupling to Fermions:



Compare to coupling to Z^0 :

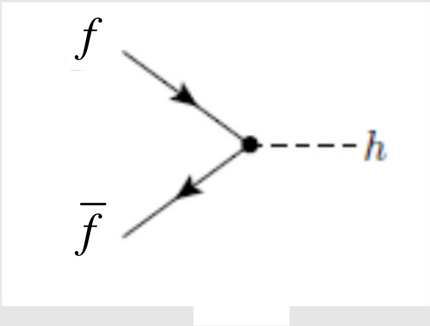


$\rightarrow H$ coupling down by a factor $\sim \frac{m_f}{m_W}$ as compared to Z^0

Higgs Production - II

First mode:

s-channel formation:



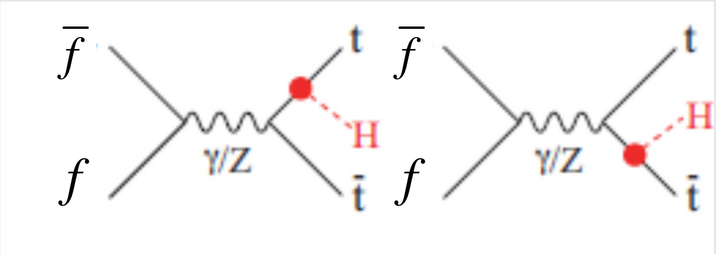
Ideal for lineshape scan, provided cross-section is big enough

Lepton colliders:

Tough requirements on luminosity, energy resolution

Higgs Production - III

Second mode:
H radiation from quarks, sizeable contribution from Top:



$t\bar{t}$ signature might be useful to tag

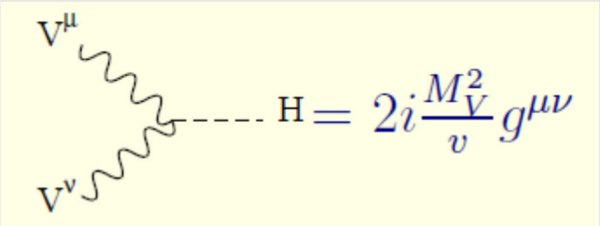
Higgs Production - IV

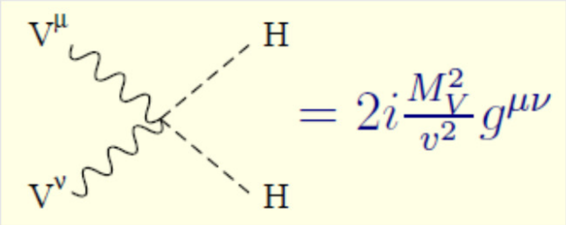
Shift to gauge bosons:

Exclude massless photon, gluon *at tree level*

[Photon, gluon *loop* contribution to be taken into account: See later]

More promising: W, Z mass very large

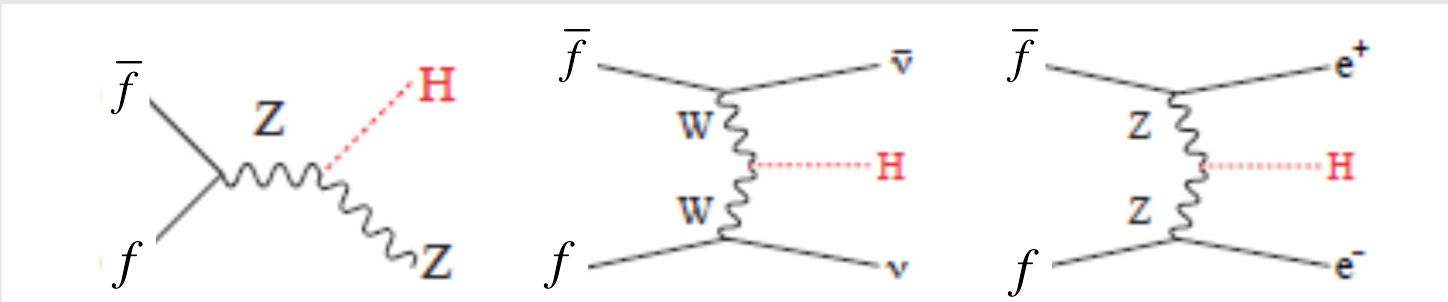




Higgs Production - V

Best modes:

'Higgsstrahlung', 'Gauge boson fusion'

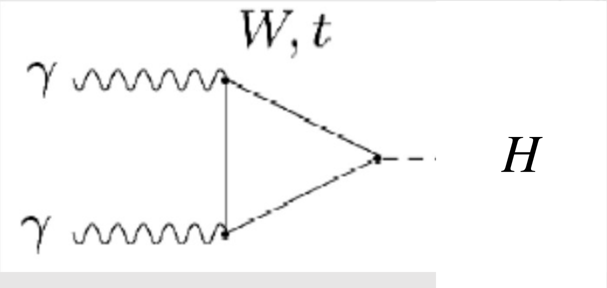


Higgs Production - VI

Beyond tree level: Very Important Loops

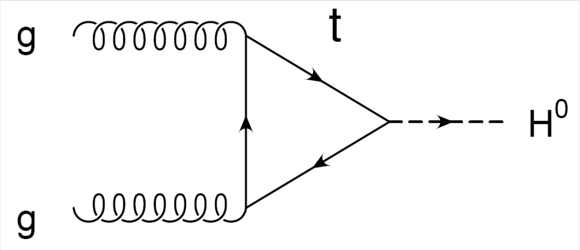
Lepton machines:

Interesting diagrams, also quite relevant to detection

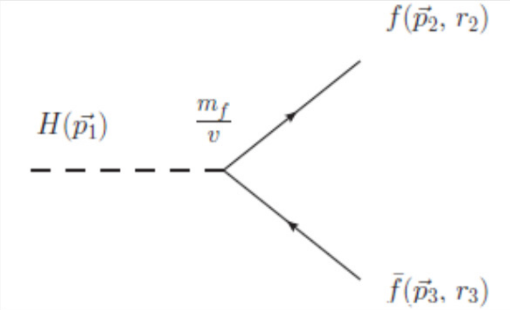


Parton machines:

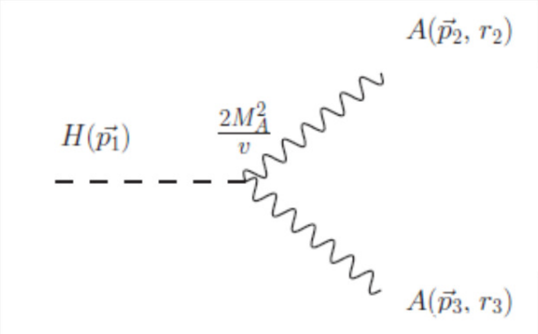
Dominant diagram at LHC



Higgs Decays - I



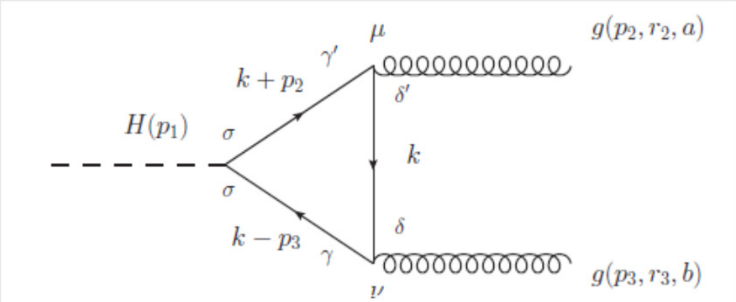
$$\Gamma(H \to f\bar{f}) = N_C \frac{1}{8\pi}\frac{m_f^2}{v^2} M_H (1 - \frac{4m_f^2}{M_H^2})^{3/2}$$



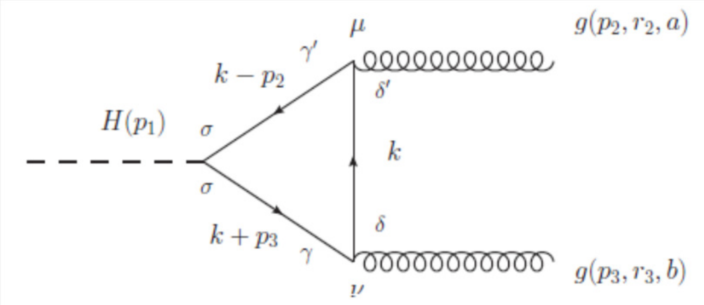
$$\Gamma(H \to WW) = \frac{1}{4\pi}\frac{M_W^4}{M_H v^2}\left(1 - \frac{4M_W^2}{M_H^2}\right)^{1/2}\left(3 + \frac{1}{4}\frac{M_H^4}{M_W^4} - \frac{M_H^2}{M_W^2}\right)$$

$$\Gamma(H \to ZZ) = \frac{1}{8\pi}\frac{M_Z^4}{M_H v^2}\left(1 - \frac{4M_Z^2}{M_H^2}\right)^{1/2}\left(3 + \frac{1}{4}\frac{M_H^4}{M_Z^4} - \frac{M_H^2}{M_Z^2}\right)$$

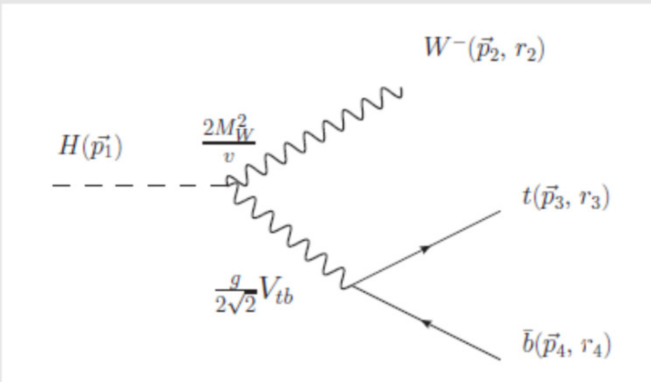
Higgs Decays - II



$$\Gamma(H \to gg) = \frac{M_H^3}{8\pi\, v^2} \left(\frac{\alpha_s}{\pi}\right)^2 n^2\, |D(n)|^2$$

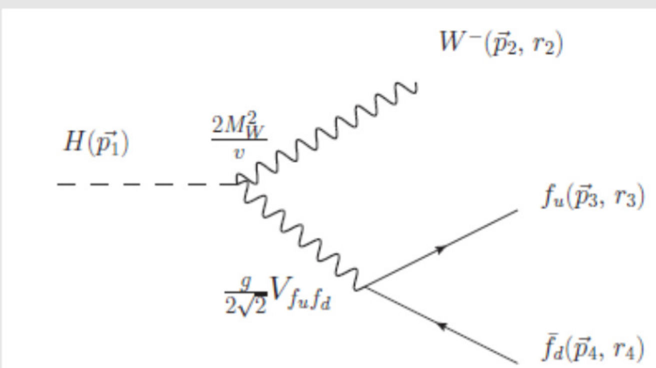


Higgs Decays - III



$$\Gamma(H \to W tb) = N_C \frac{g^2}{2v^2}\frac{M_W^4}{M_H}|V_{tb}|^2 \int dQ_3 \frac{G^{\beta\nu}T_{\beta\nu}}{[s_{34} - M_W^2]^2}$$

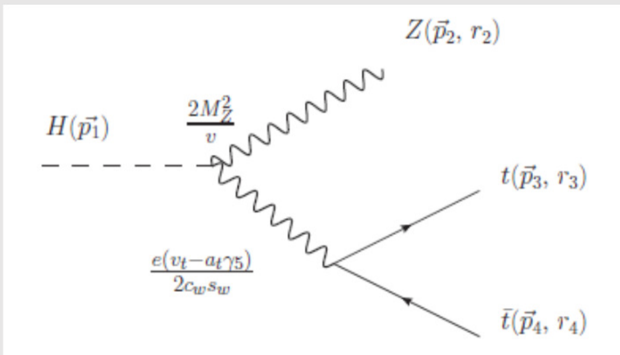
3-body phase space factor



$$\Gamma(H \to W f_u\, f_d) = \frac{g^2}{v^2}\frac{3M_W^2}{256\pi^3} M_H\, S(x)$$

3-body phase space factor

Higgs Decays - IV

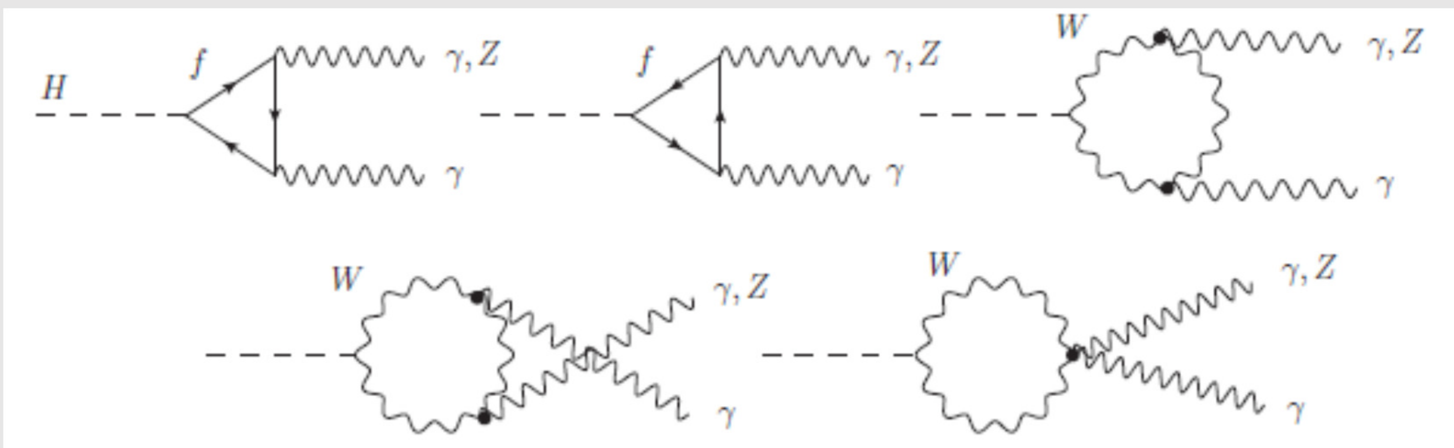


$$\Gamma(H \to Z f \bar{f}) = \frac{g^2}{v^2}\frac{3M_Z^2}{256\,\pi^3} M_H\, S(x)\frac{R(\theta_w)}{\cos^2\theta_w}$$

$$\left(\frac{7}{12} - \frac{10}{9}\sin^2\theta_w + \frac{40}{27}\sin^4\theta_w\right)$$

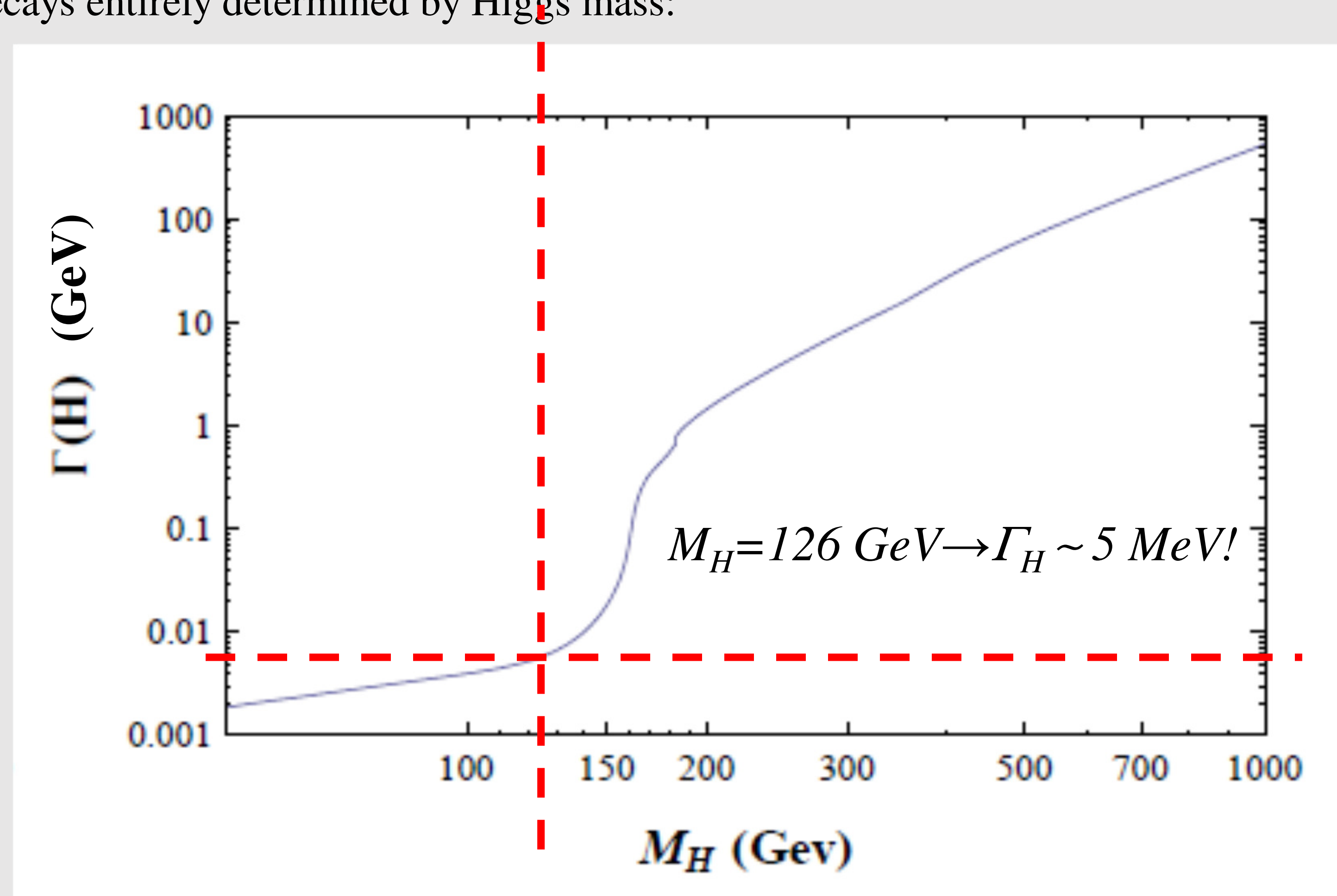
3-body phase space factor

$$\Gamma\left(H \to Z/\gamma, \gamma\right)$$



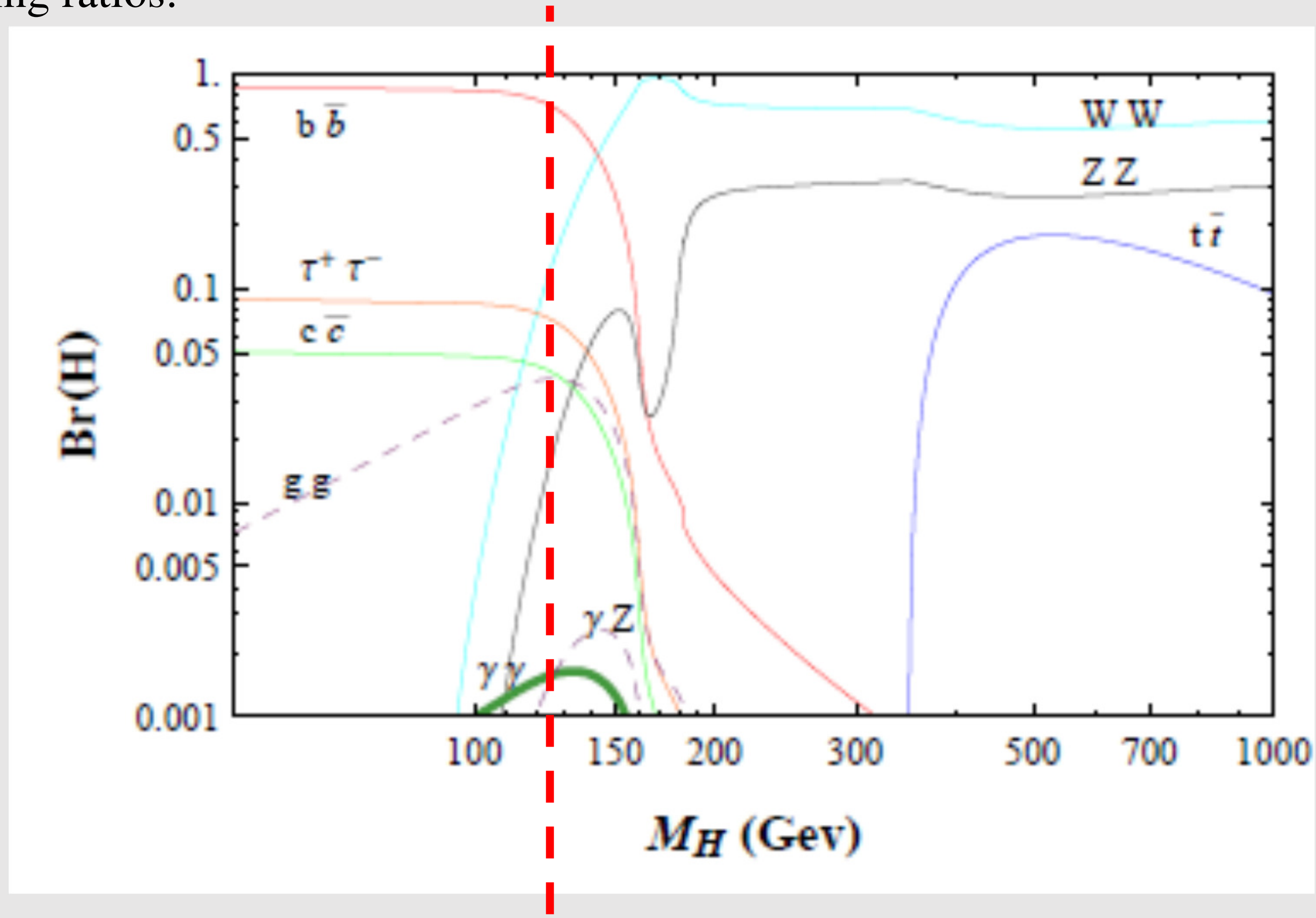
Higgs Decays - V

H decays entirely determined by Higgs mass:

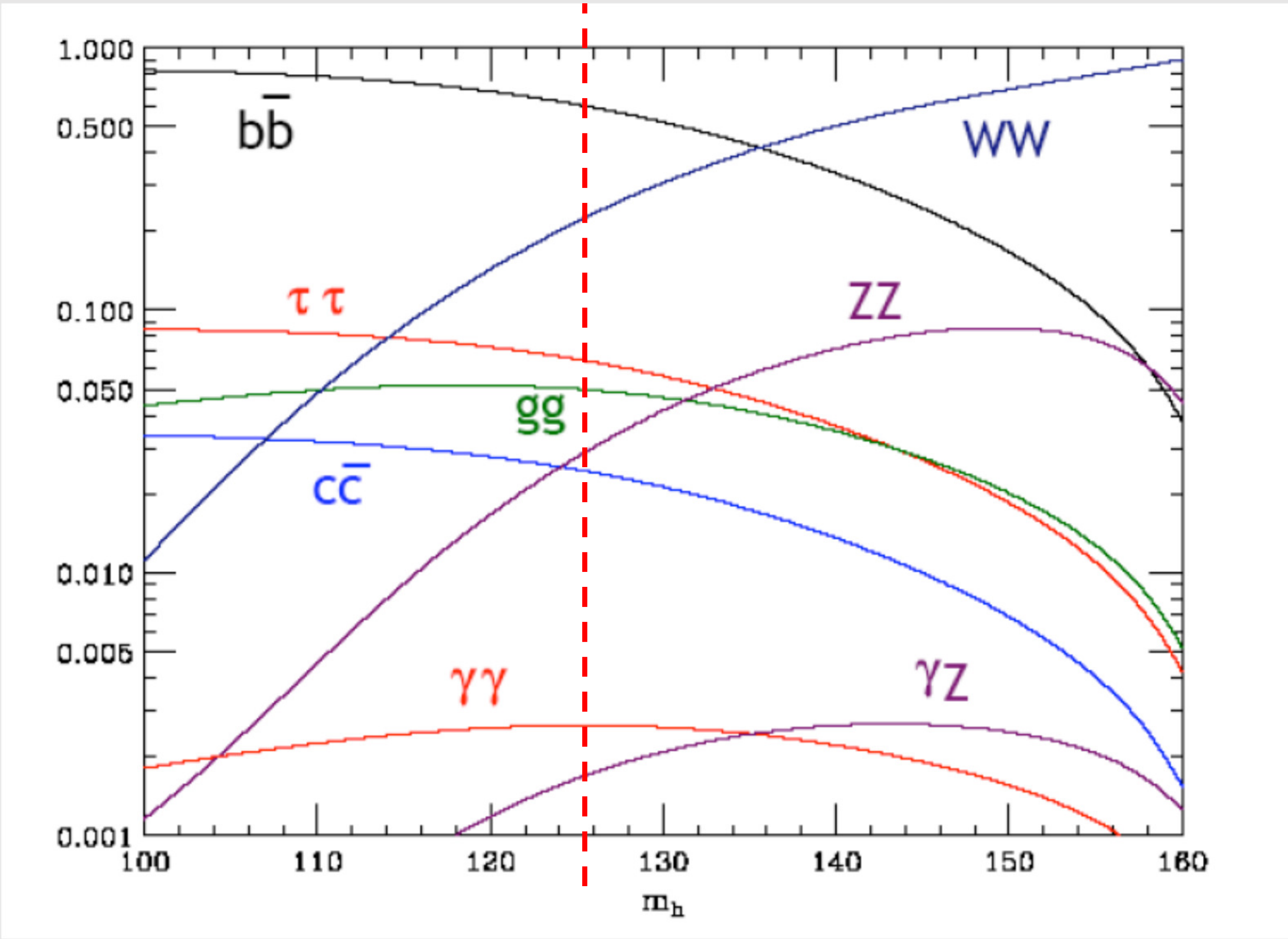


Higgs Decays - VI

H branching ratios:



Higgs Decays - VII



Lepton Collider - I

Leptons: Easier to handle

Taking lifetime into account: Restrict to electron, muon $(?)$

Linear vs. Circular

$s-$channel formation:

Not feasible at $e^- e^+$ colliders:

Factor $\frac{m_e^2}{M_W^2} \sim 4\ 10^{-11} \rightarrow$ Tiny cross section

Better chance for a $\mu^- \mu^+$ collider

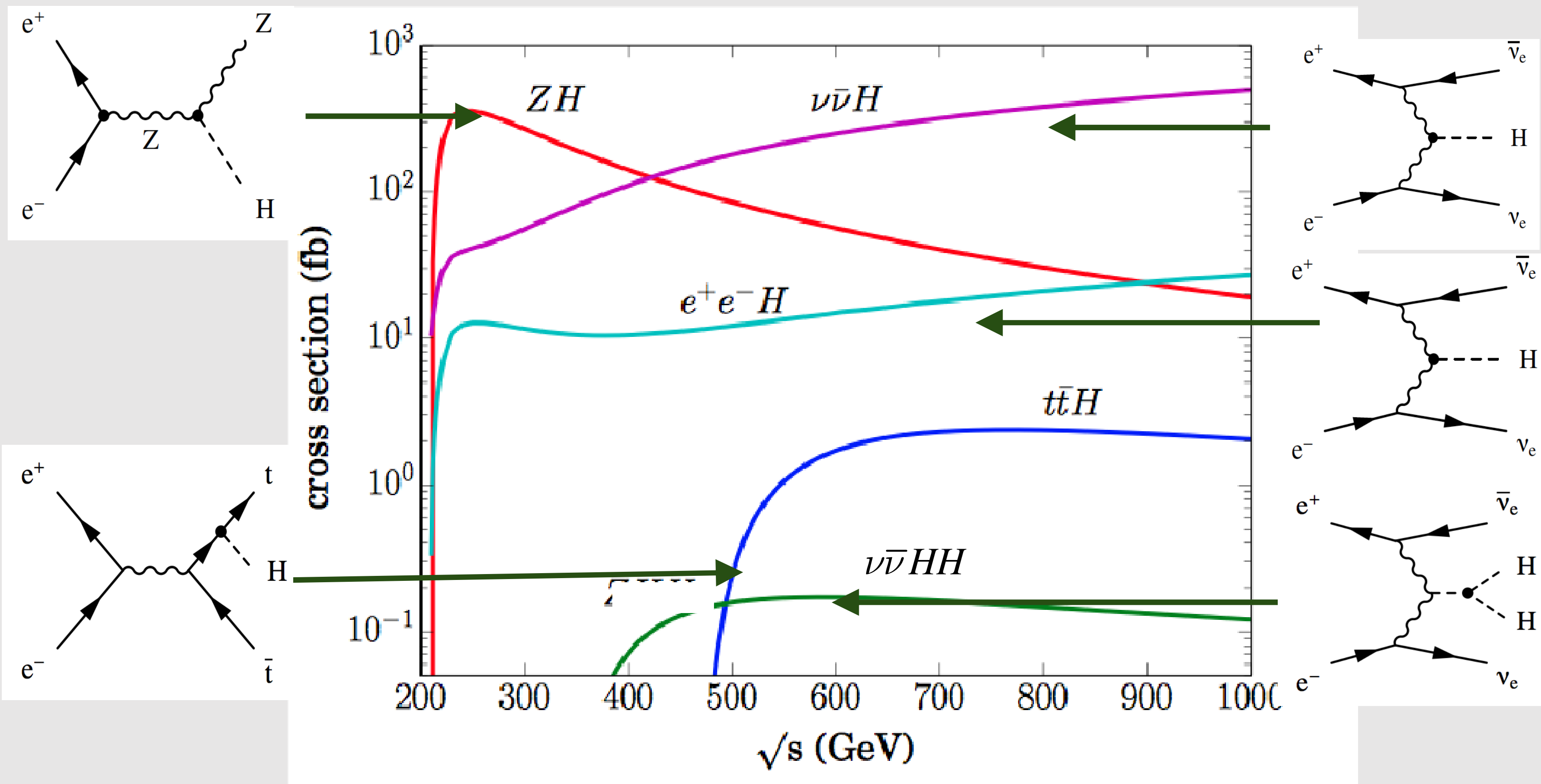
$$\frac{m_\mu^2}{M_W^2} \sim 1.6\ 10^{-6}$$

Other channels more promising

Lepton Collider - II

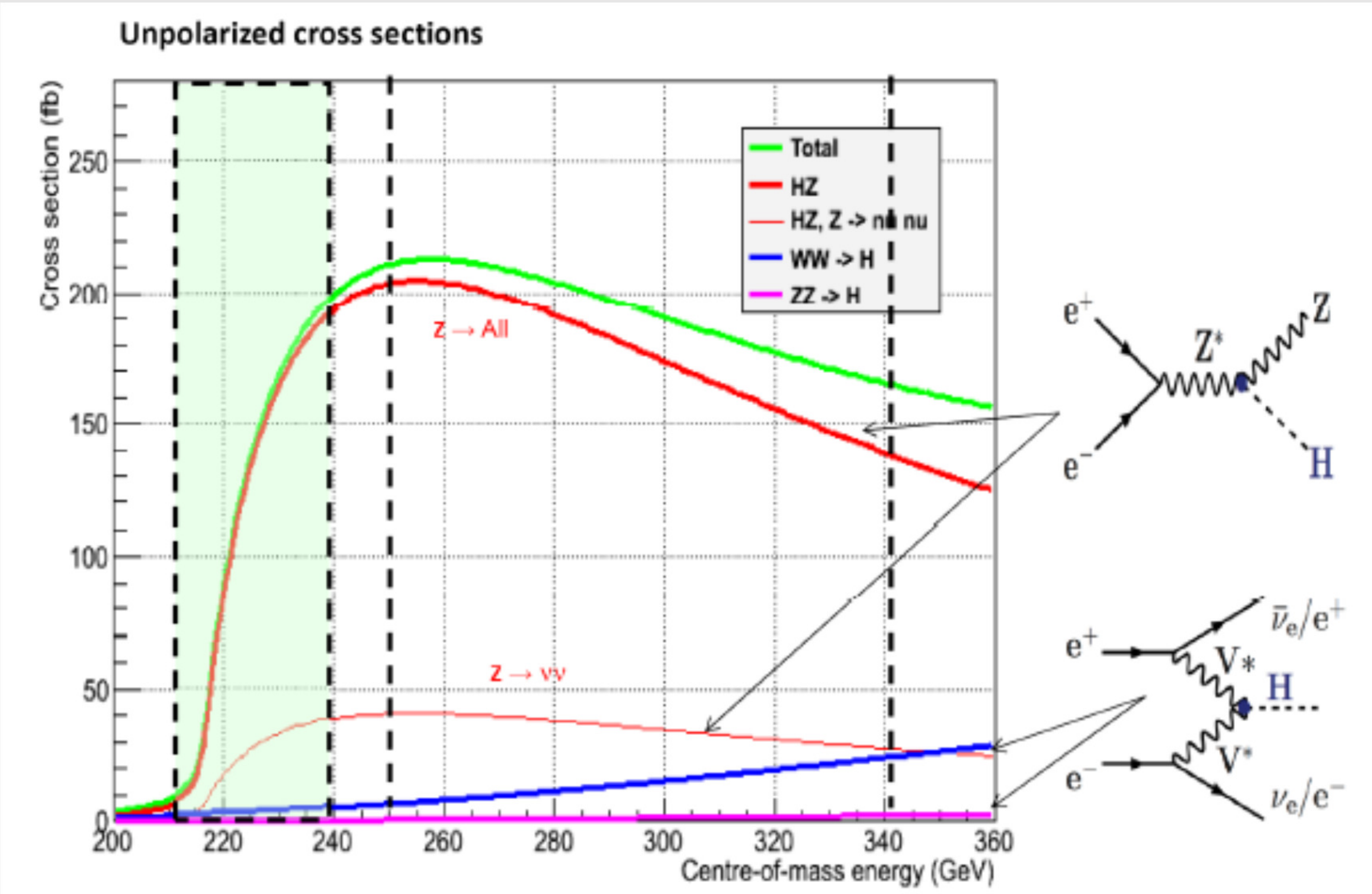
Higgs width

Electron collider: Tree level contributing diagrams



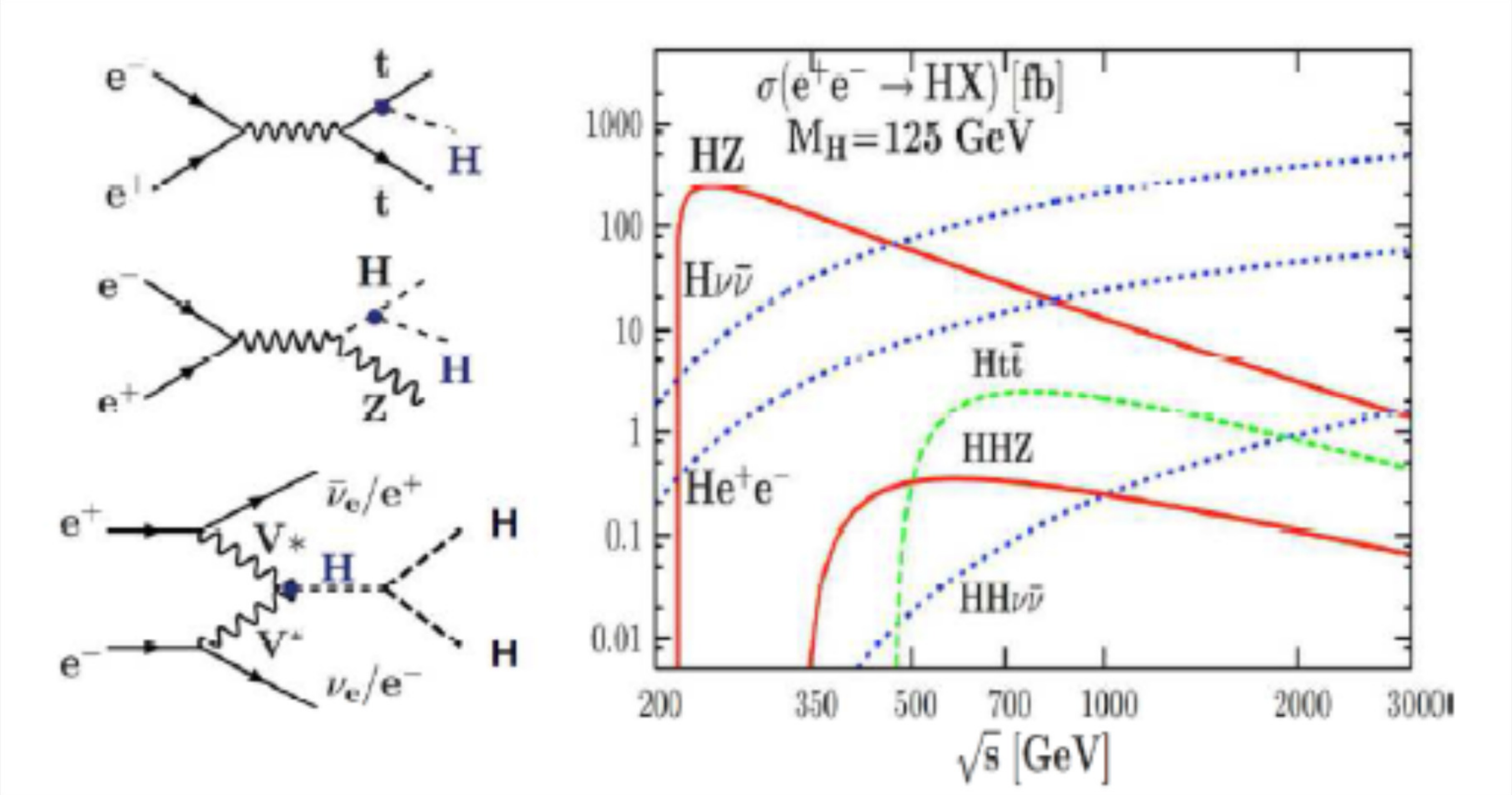
Lepton Collider - III

Electron collider: 'Low energy' option



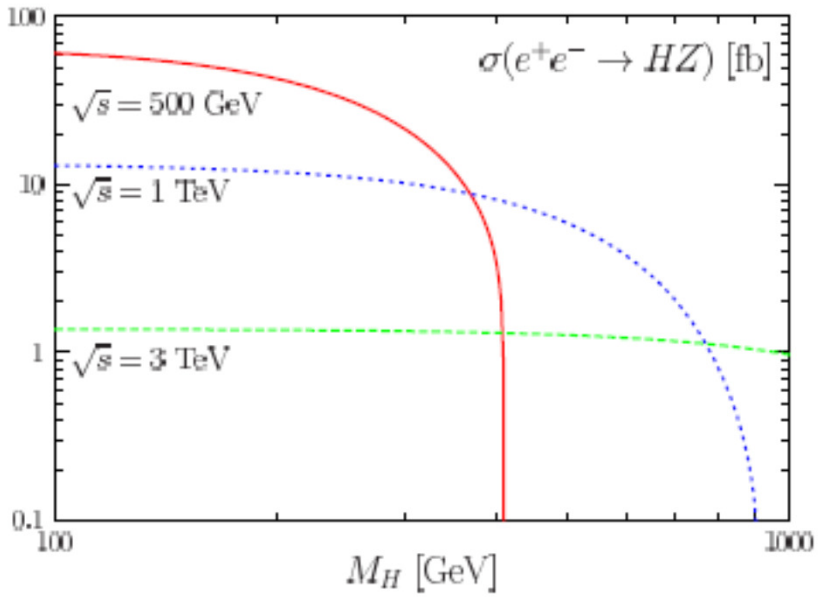
Lepton Collider - IV

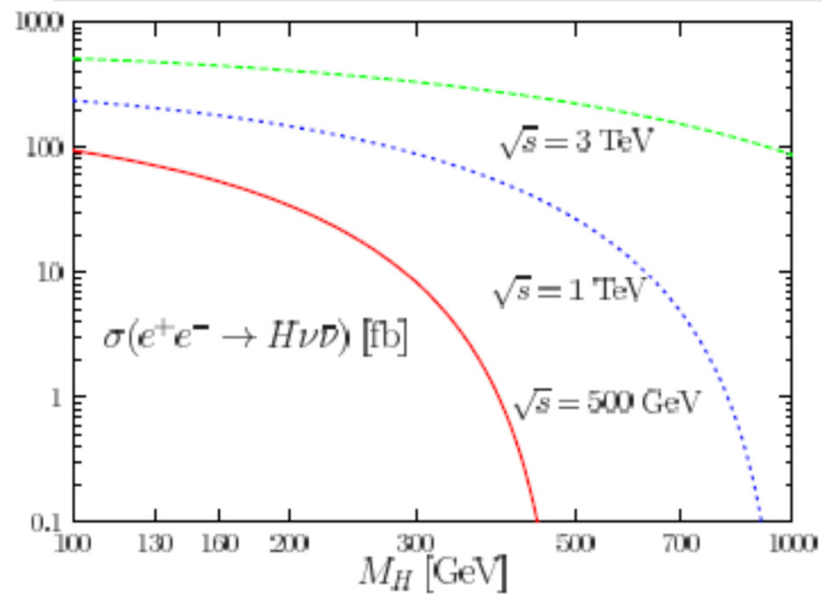
Electron collider: 'High energy' option



Lepton Collider - V

m_H dependence:





Lepton Collider - VI

√s (GeV)	<L >(ab-1/year)*	Rate (Hz) ee—>hadrons	Years	Statistics
90	5.6	$2\ 10^4$	1	$2\ 10^{11}$ Z decays
160	1.6	25	1-2	$2\ 10^7$ W pairs
240	0.5	3	5	$5\ 10^5$ HZ events
350	0.13	1	5	$2\ 10^5$ ttbar

* each interaction point

- Precise measurement (0.1% to 1%) of the Higgs Couplings
- Improve precision (statistics x 10^5) on the measurements of the Z parameters [M_Z, Γ_Z , R_ℓ, R_b, R_c, Asymmetries & weak mixing angle]. Z rare decays.
- Scan W threshold (aiming at 0.5 MeV precision). W rear decays
- Scan ttbar threshold (aiming at 10 MeV)

Fall 2017

E.Menichetti - Universita' di Torino

Lepton Collider - VII

Circular collider: Two main issues, among many

Bending field: Must keep the beam on orbit

Orbit radius: $R = \dfrac{3.3p}{B} \quad m, GeV, T$

First look:

Either low B, large R or high B, small R

RF power: Must provide energy to beam up to max. energy

(also compensating for synchrotron radiation loss)

Ex: LEP I

$$B = \frac{3.3\ 45}{4300} \approx 0.034\ T$$

$$\left.\begin{array}{l}\text{128 2 m cavities}\\ \text{Typical cavity max field: } 1.5\ MV/m\\ \text{Typical beam current: } 6{+}6\ mA\end{array}\right\}$$

$\rightarrow$ Max. energy gain $\sim 128*3 \sim 375 MeV/turn$; RF max power $\sim 125\ kW/cavity$

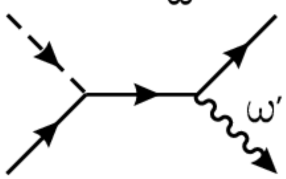
Lepton Collider - VIII

Another crucial point: Minimize *synchrotron radiation* loss

Process related to EM interaction of ultrarelativistic charged particles moving in a **B** field:

Similar to Bremsstrahlung

External
B field $d\sigma \sim \frac{1}{\omega'}$



Critical energy:

$\epsilon_c = 3hc\gamma^3 \;/(2R)$

$\epsilon_c(\mathrm{keV}) = 2.218\ \mathrm{E}^3(\mathrm{GeV})\ /\mathrm{R(m)}$

Ex: LEP II

$E = 104\ GeV \rightarrow \varepsilon_c \sim 580\ keV$

Energy loss per particle, per turn:

$$\Delta E(KeV) = \frac{e^2\gamma^4}{3\varepsilon_0 R} = \begin{cases} 88.5\dfrac{E(GeV)^4}{R(m)} & \text{Electrons} \\ 6.03\dfrac{E(TeV)^4}{R(m)} & \text{Protons} \end{cases}$$

Power loss by a beam current I_b, to be restored by RF:

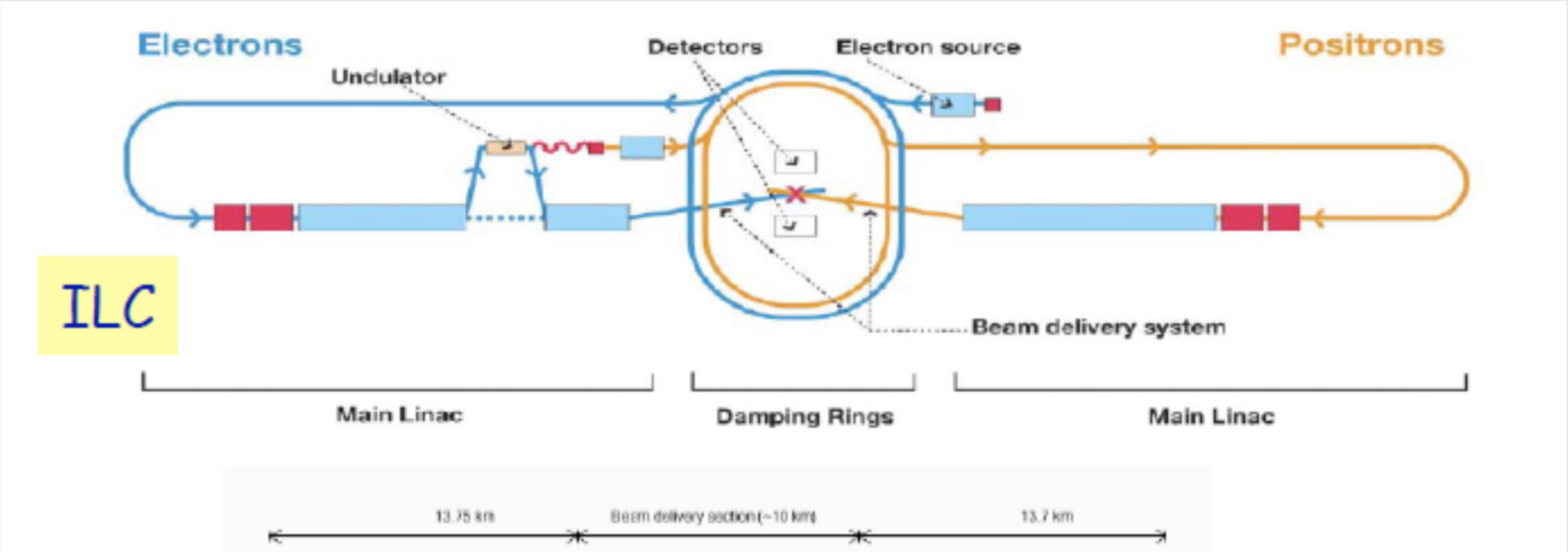
$$P(kW) = \frac{e\gamma^4}{3\varepsilon_0 R} I_b = \begin{cases} 88.5\dfrac{E(GeV)^4}{R(m)} I_b(A) & \text{Electrons} \\ 6.03\dfrac{E(TeV)^4}{R(m)} I_b(A) & \text{Protons} \end{cases}$$

$\rightarrow$ Pointing to large $R \rightarrow$ low B

Lepton Collider - IX

Electron collider: Linear

International **L**inear **C**ollider (Japan?)

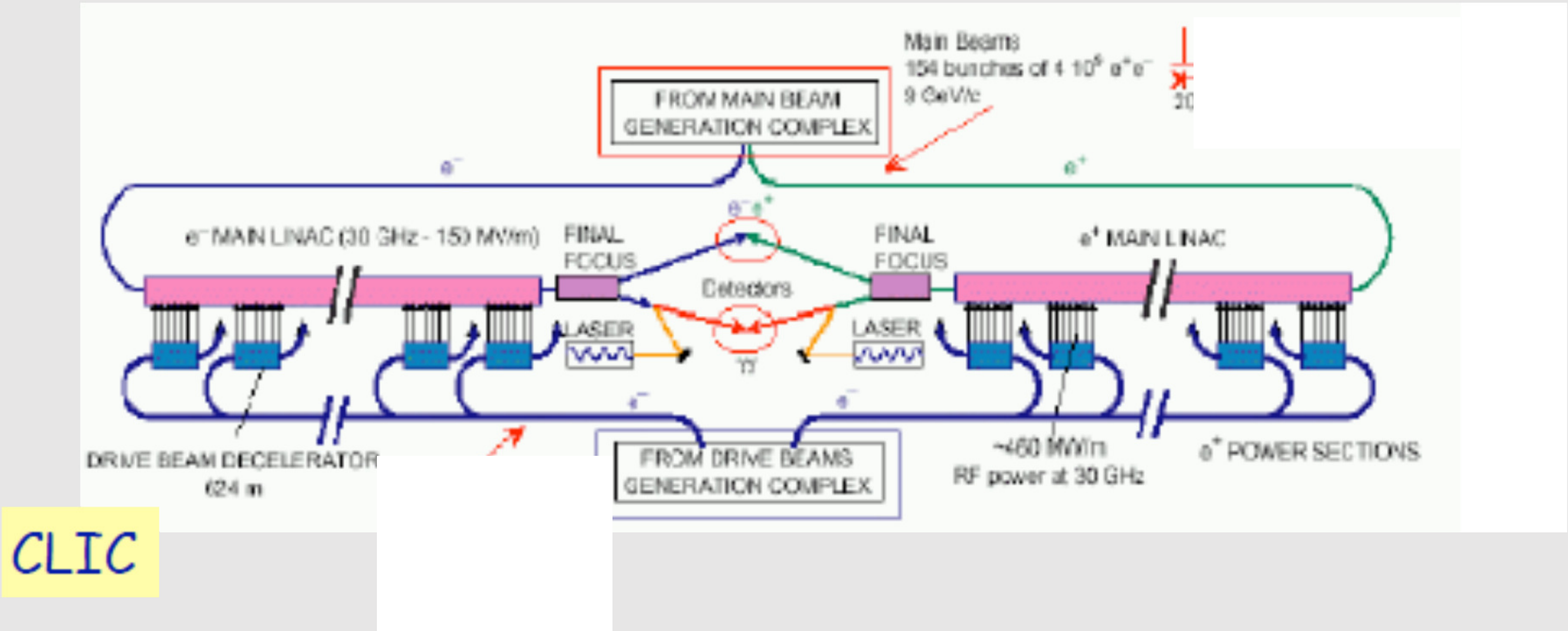


- Superconducting RF cavities
- Gradient 32 MV/m
- $\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
- L ~ 2 10^{34} $cm^{-2}s^{-1}$
- Focus on ≤ 500 GeV, physics studies also for 1 TeV
- Length ~ 31 km (500 GeV)

Lepton Collider - X

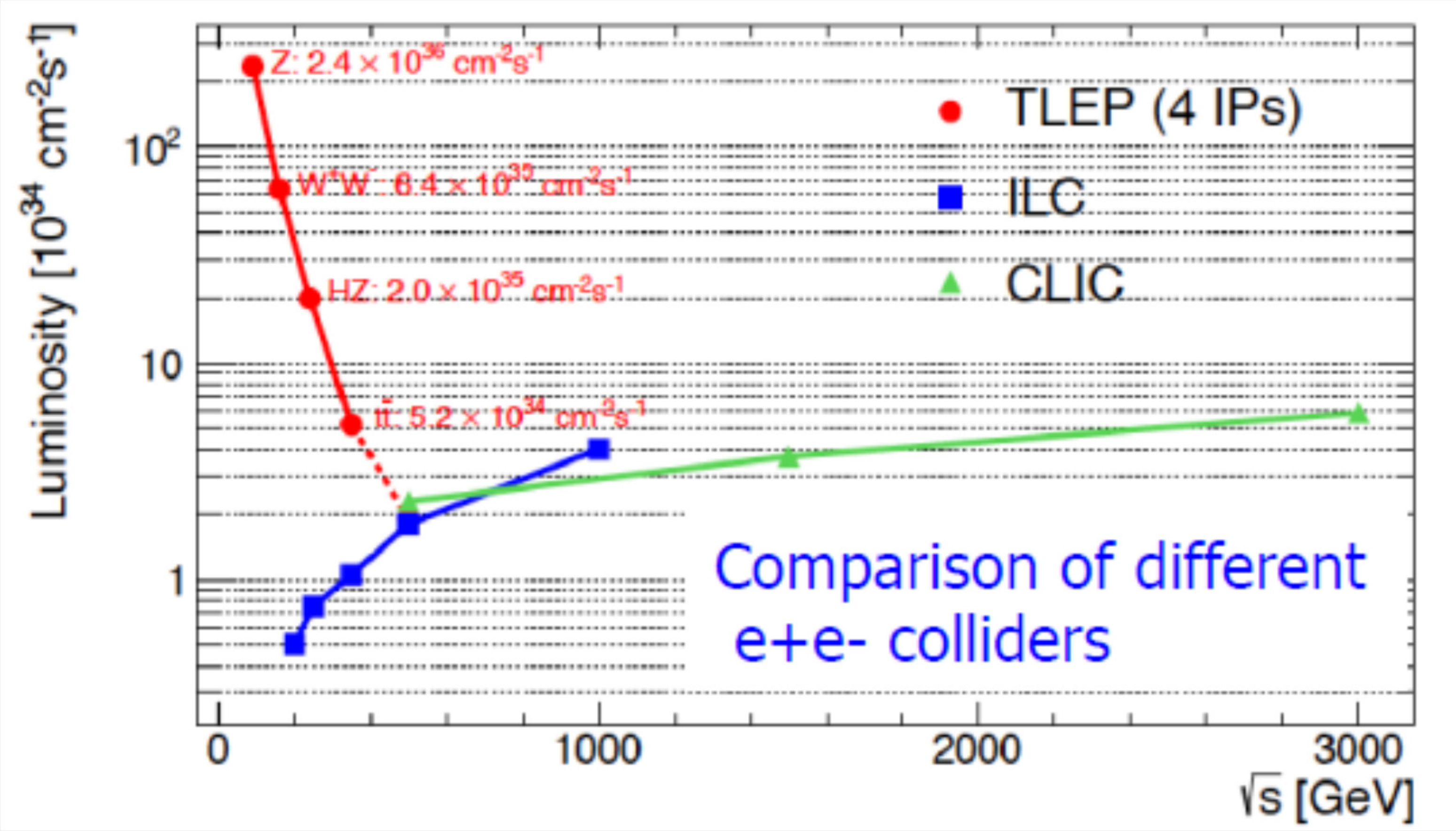
Electron collider: Linear

Compact **LI**near **C**ollider (CERN?)



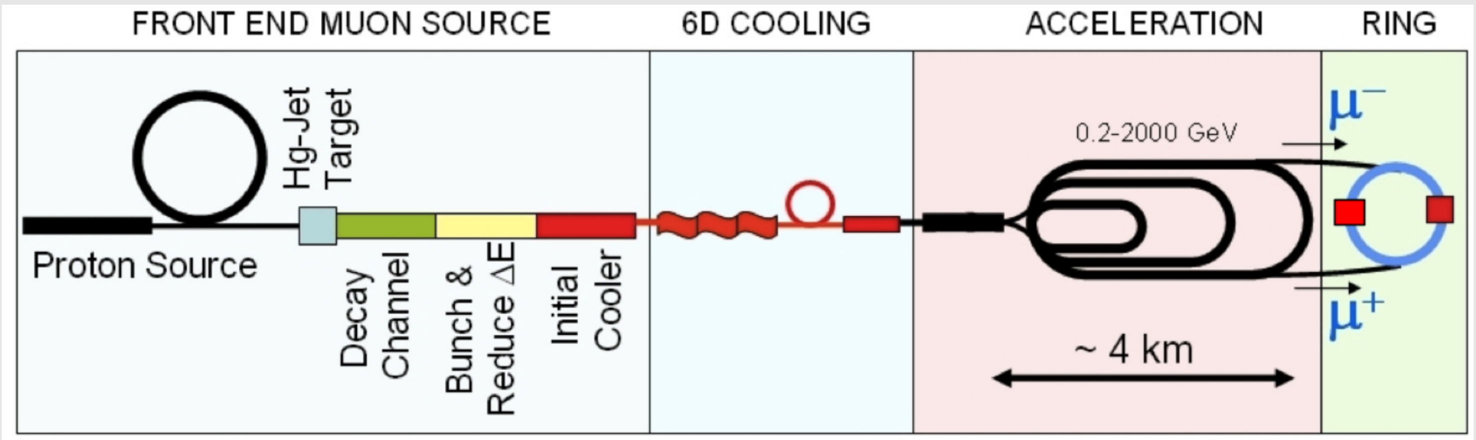
- Copper RF cavities
- Gradient 150 MV/m (!)
- $\sqrt{s}$ = 3 TeV
- L ~ 6 10^{34} $cm^{-2}s^{-1}$
- Length ~ 41 km (500 GeV)

Lepton Collider - XI



Lepton Collider - XII

Muon collider: Overall layout



Critical points:

– Proton LINAC+Booster (4 MW)

$16\ GeV \times 1.5\ 10^{15}\ pps = 16\ GeV \times\ 250\mu A = 4MW$!

– Cooling (fast, large)

Ionization: $dE\,/\,dx$ reducing both $p_{\parallel}$ and $p_{\perp}$

RF restoring $p_{\parallel} \rightarrow \frac{p_{\perp}}{p_{\parallel}}$ reduced

Lepton Collider - XIII

Muon collider

Pros:

Large H cross section in the s-channel $\left(\sigma_{\mu\mu} \approx 4\ 10^4 \sigma_{ee}\right) E$

Best energy resolution $\left('Beamstrahlung'\right.$ strongly suppressed$\left.\right)$

$\rightarrow$ Unique feature: Can perform full scan of lineshape

Main requirements:

$$\text{Energy resolution:} \begin{cases} E = \dfrac{m_H}{2} \simeq 63\ GeV \\ \sigma_E \leq \Gamma_H = 4.2\ MeV \end{cases} \rightarrow R = \frac{\sigma_E}{E} \leq 5 10^{-5}$$

Feasible, but $L \sim 10^{31} cm^{-2} s^{-1}$

$\rightarrow 1\ y$ data taking $\sim 10^{38} cm^2 = 100\,pb^{-1}$

$\rightarrow N_H \sim 2000\,y^{-1}$

$\rightarrow \sigma_M \sim 100 keV, \sigma_\Gamma \sim 200 keV, \sigma_{\mu\ \text{coupling}}$ to 3% in 1 year

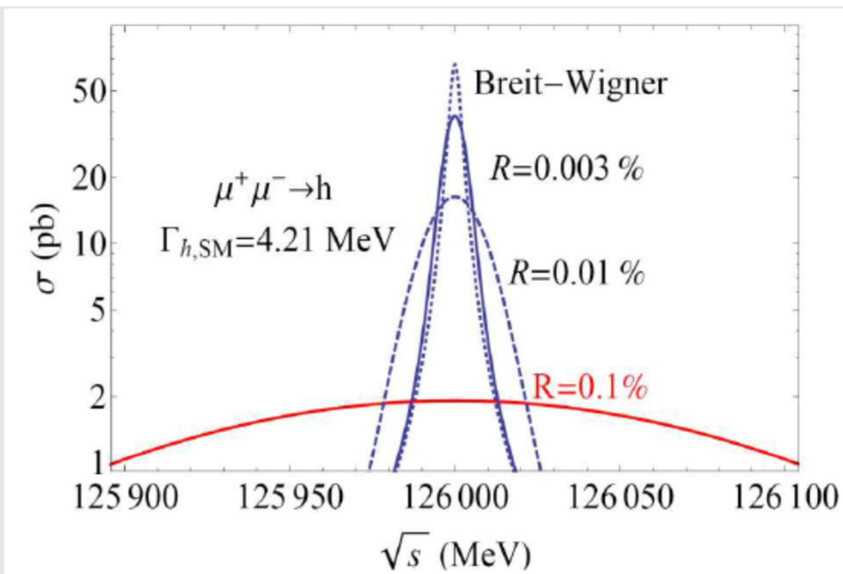
Lepton Collider - XIV

Breit-Wigner/Gaussian convolution:

$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h \to \mu^+\mu^-)\mathrm{Br}(h \to X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$

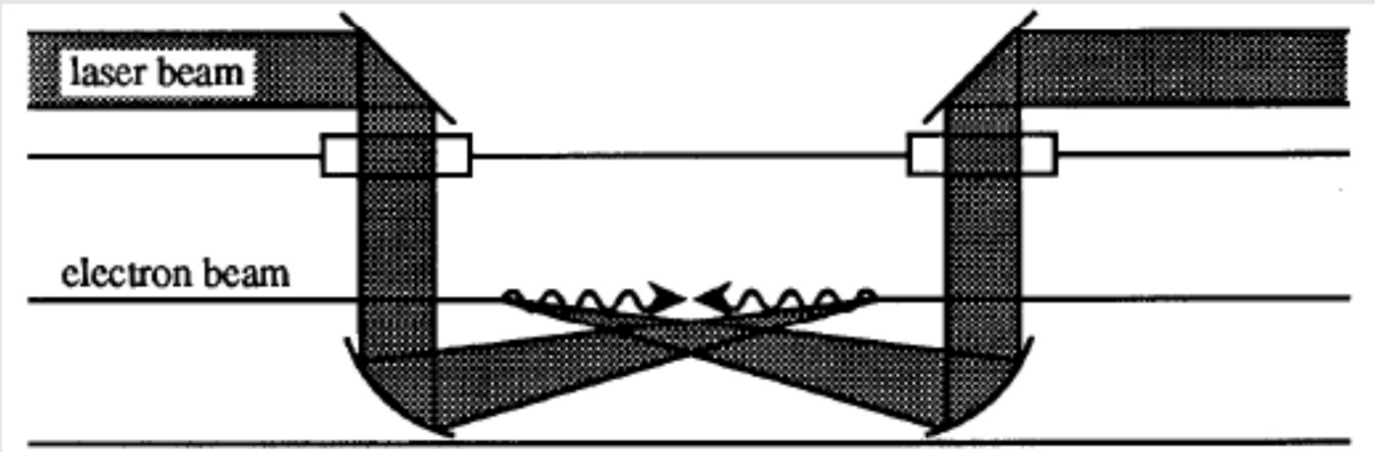
$$\sigma_{\text{eff}}(s) = \int d\sqrt{\hat{s}}\, \frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}} \sigma(\mu^+\mu^- \to h \to X)$$

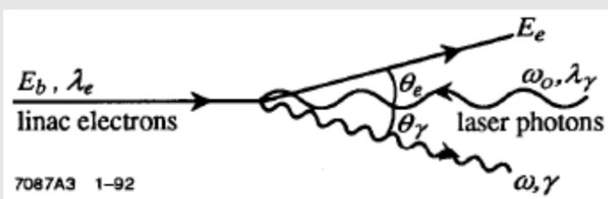
$$\propto \begin{cases} \Gamma_h^2 B/[(s - m_h^2)^2 + \Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B \exp[\frac{-(m_h - \sqrt{\hat{s}})^2}{2\Delta^2}](\frac{\Gamma_h}{\Delta})/m_h^2 & (\Delta \gg \Gamma_h). \end{cases}$$



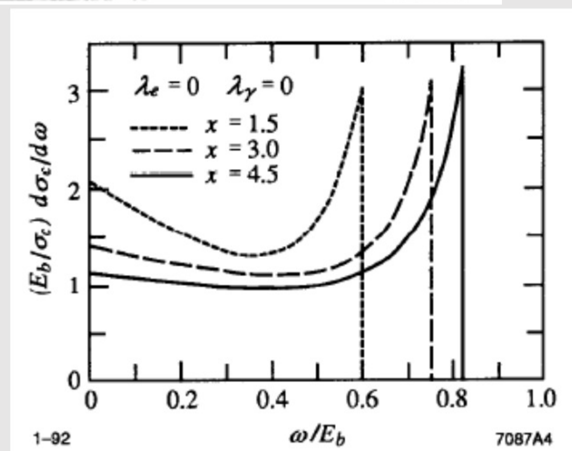
Photon Collider - I

General idea: Compton back-scattering of intense laser beam by the e beam



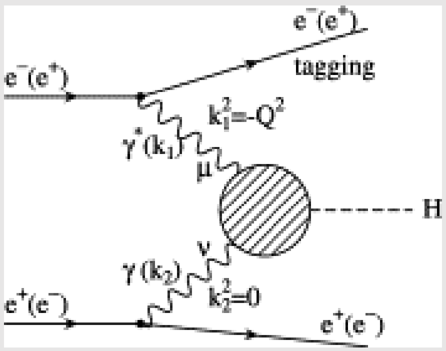


$$x \equiv (4E_b\omega_o/m_e^2)\cos^2(\alpha/2) \approx 15.3\left(\frac{E_b}{\text{TeV}}\right)\left(\frac{\omega_o}{\text{eV}}\right)$$

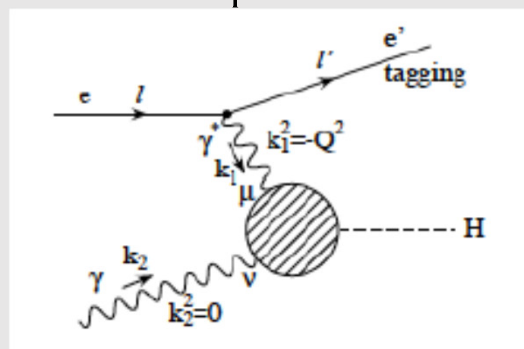


Photon Collider - II

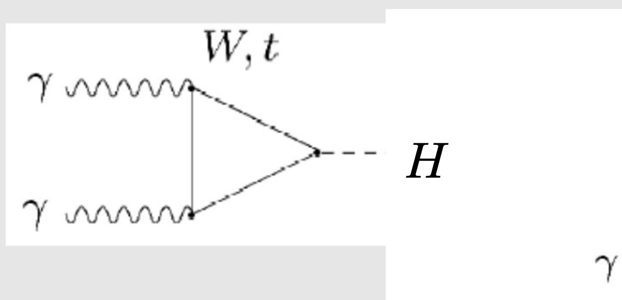
Virtual+Virtual photons

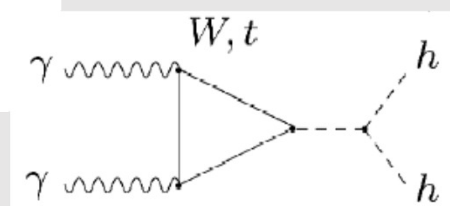


Virtual+Real photons



Most important loop diagrams for the 'blob': Dominated by largest mass fermions, gauge bosons





Making for a particularly clean study of H self-coupling

Photon Collider - III

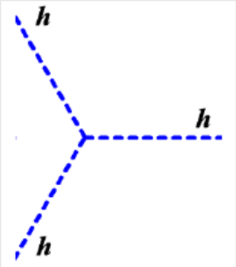
Higgs self-couplings: Very important for $\begin{cases} \text{radiative corrections to } m_h \\ \text{signs of new physics} \end{cases}$

Origin of 3- and 4-linear self-couplings:

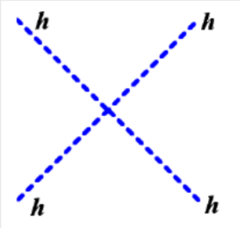
Re-writing L upon introducing shifted field, 1D example

$$\text{Kinetic term:} \quad \mathcal{L}_{\text{kin}}(\eta) = \frac{1}{2}(\partial_\mu(\eta+v)\partial^\mu(\eta+v)) = \frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta)$$

$$\text{Potential term:} \quad V(\eta) = +\frac{1}{2}\mu^2(\eta+v)^2 + \frac{1}{4}\lambda(\eta+v)^4 = \lambda v^2\eta^2 + \lambda v\eta^3 + \frac{1}{4}\lambda\eta^4 + \frac{1}{4}\lambda v^4$$



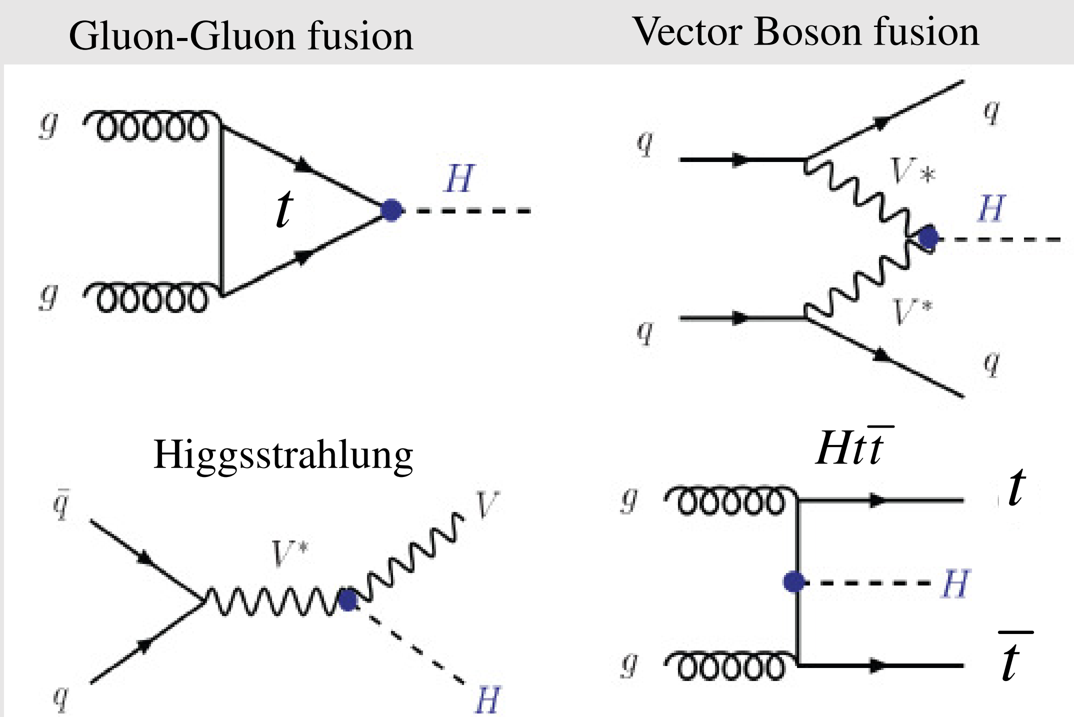
$$-3im_h^2\sqrt{\sqrt{2}G_F}\,hhh$$



$$-3im_h^2\sqrt{2}G_F\,hhhh$$

Parton Collider - I

Dominant diagrams for H production:



Parton Collider - II

Basic ingredient: PDFs

Quarks: Look for heavy ones

Tree diagrams: Best bet is with b

Factor $\frac{m_b^2}{M_W^2} \sim 3\ 10^{-3}$ encouraging

But: No b-quark beams, must rely on $b\bar{b}$ sea inside the nucleon

b-quark partonic density small...

Taking H production at small rapidity $y \sim 0,$ with a 7 TeV beam $x \sim 10^{-2}$

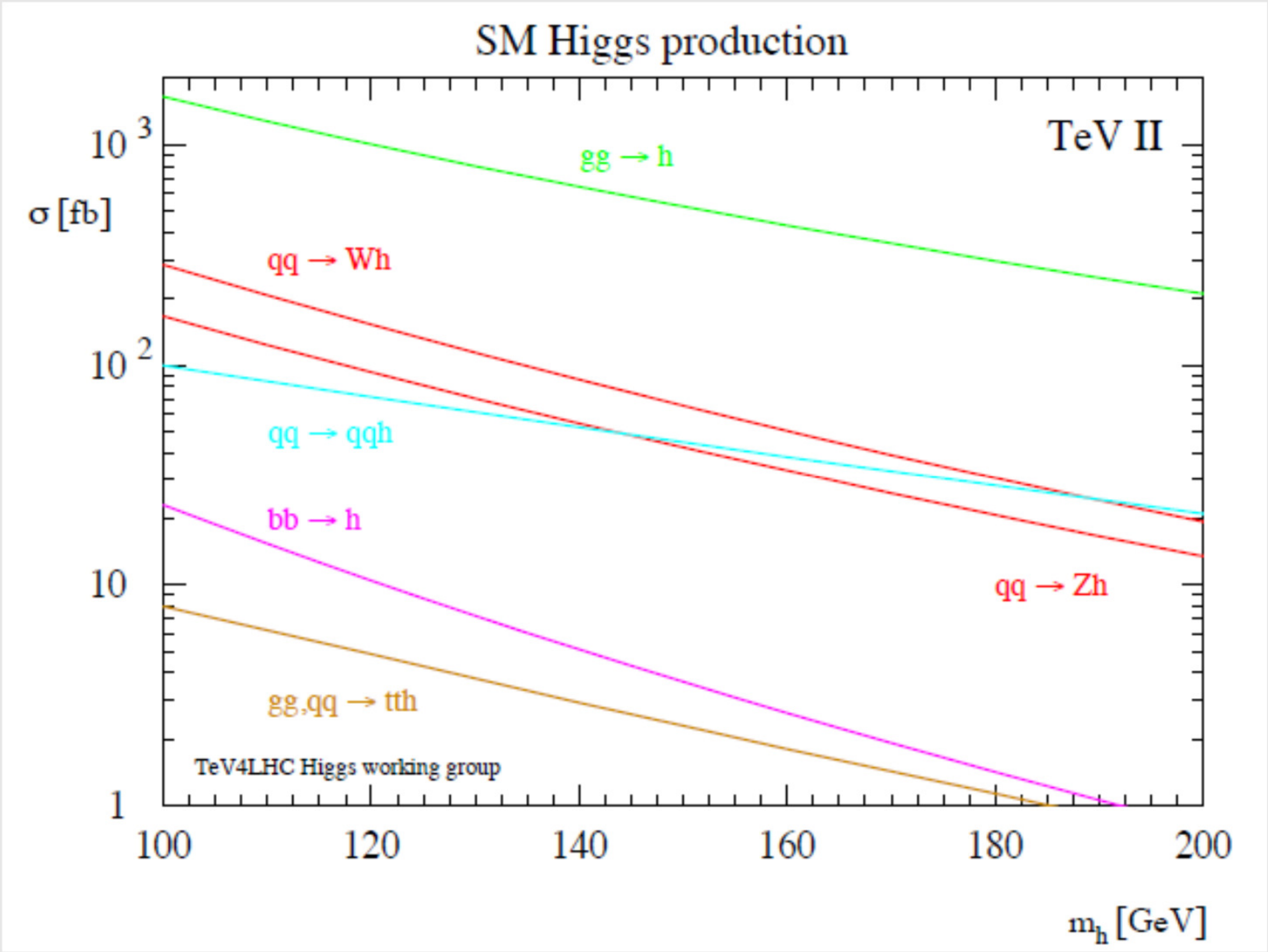
$\rightarrow$ Incident flux of sea b-quarks very small

Gluons: Main contribution

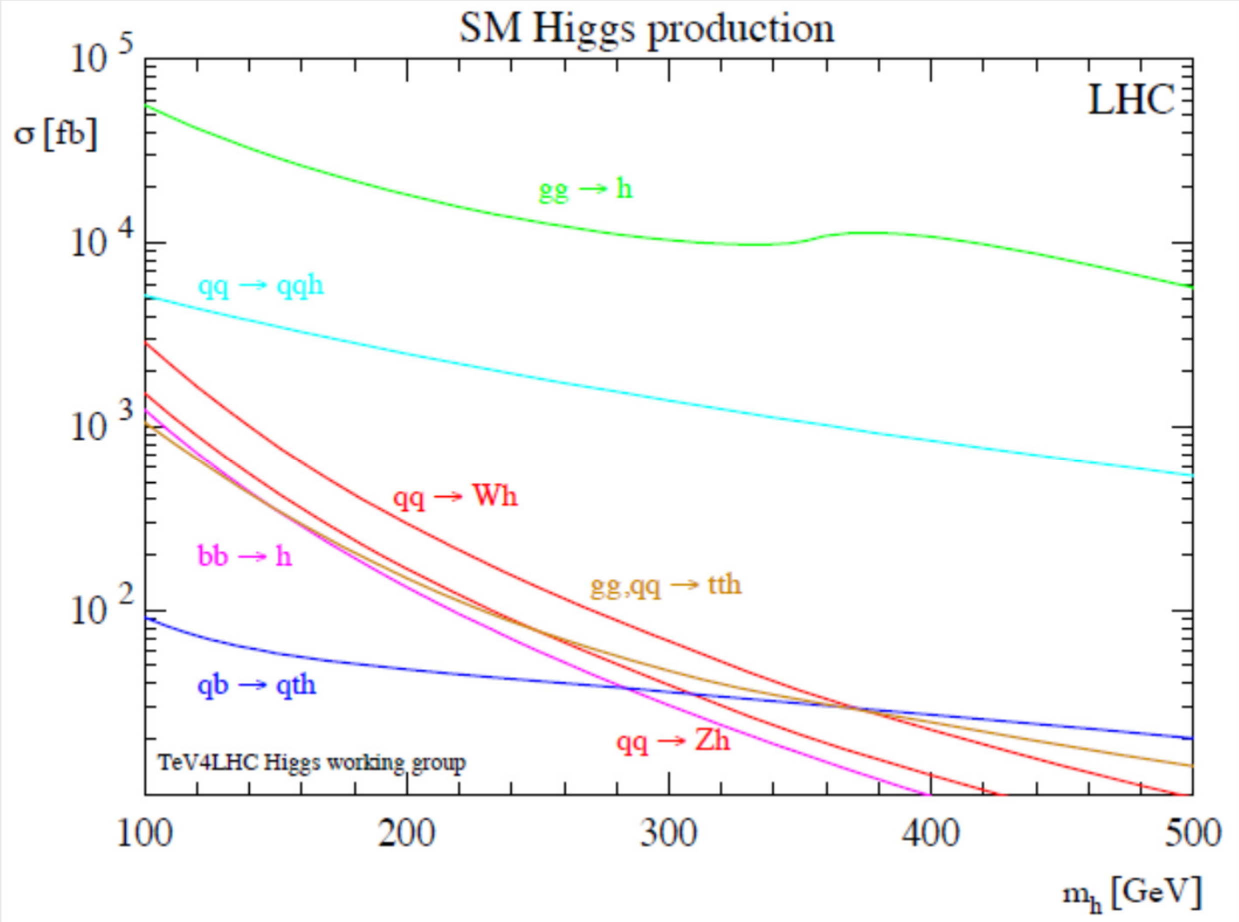
Loop diagrams, dominated by t quark

PDF somewhat dependent on Q^2

Parton Collider- III

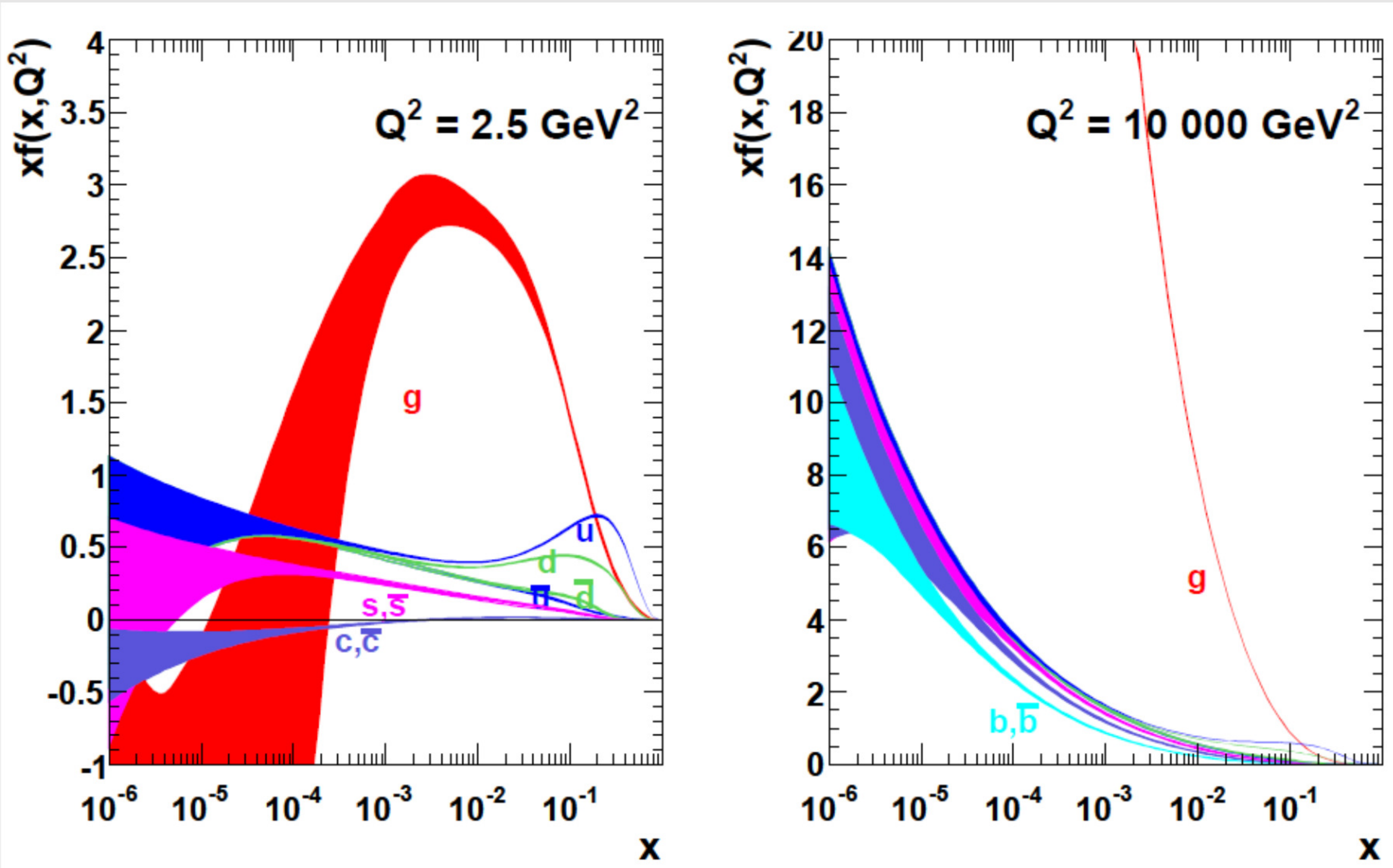


Parton Collider- IV

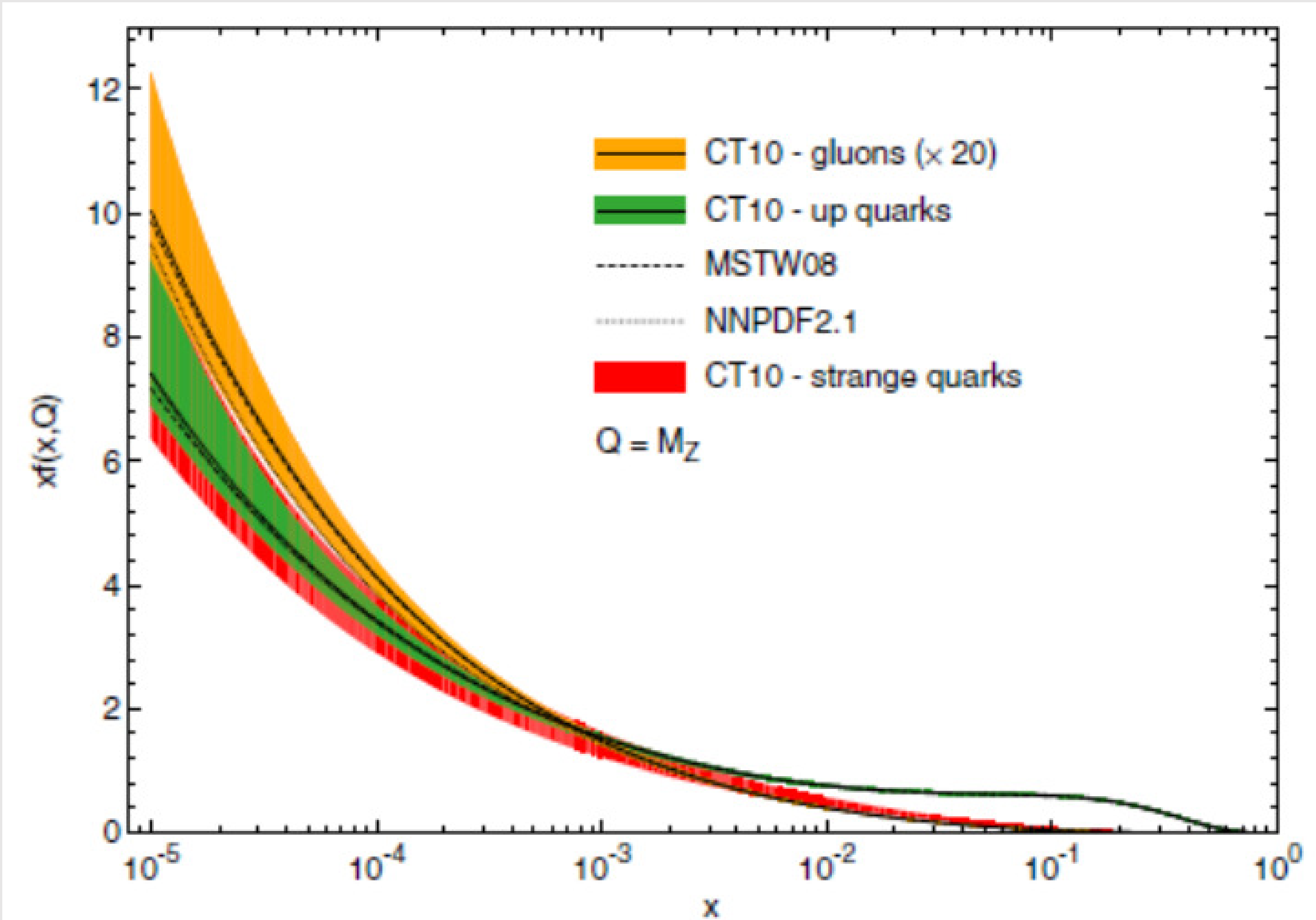


Parton Collider - V

Parton densities:

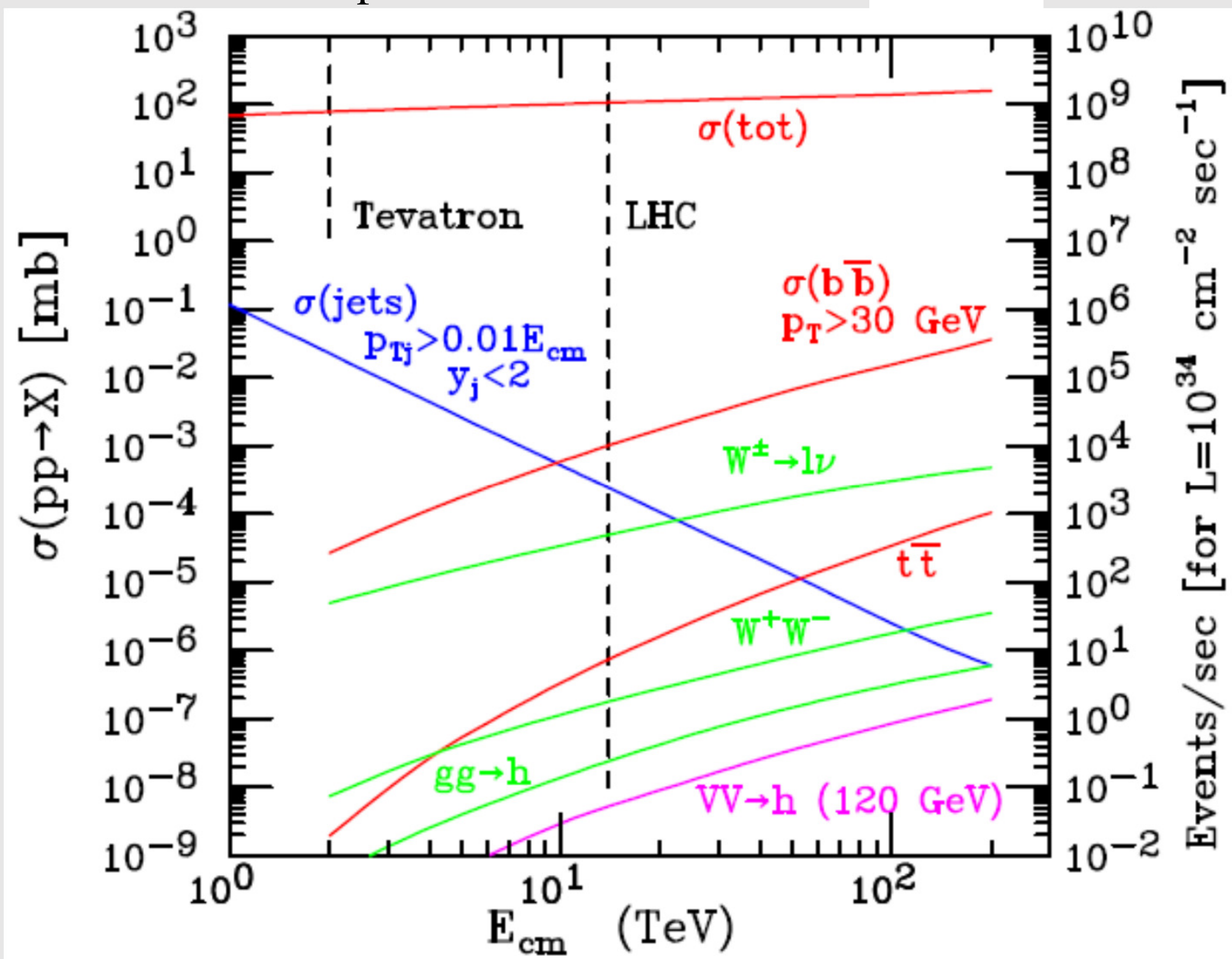


Parton Collider - VI



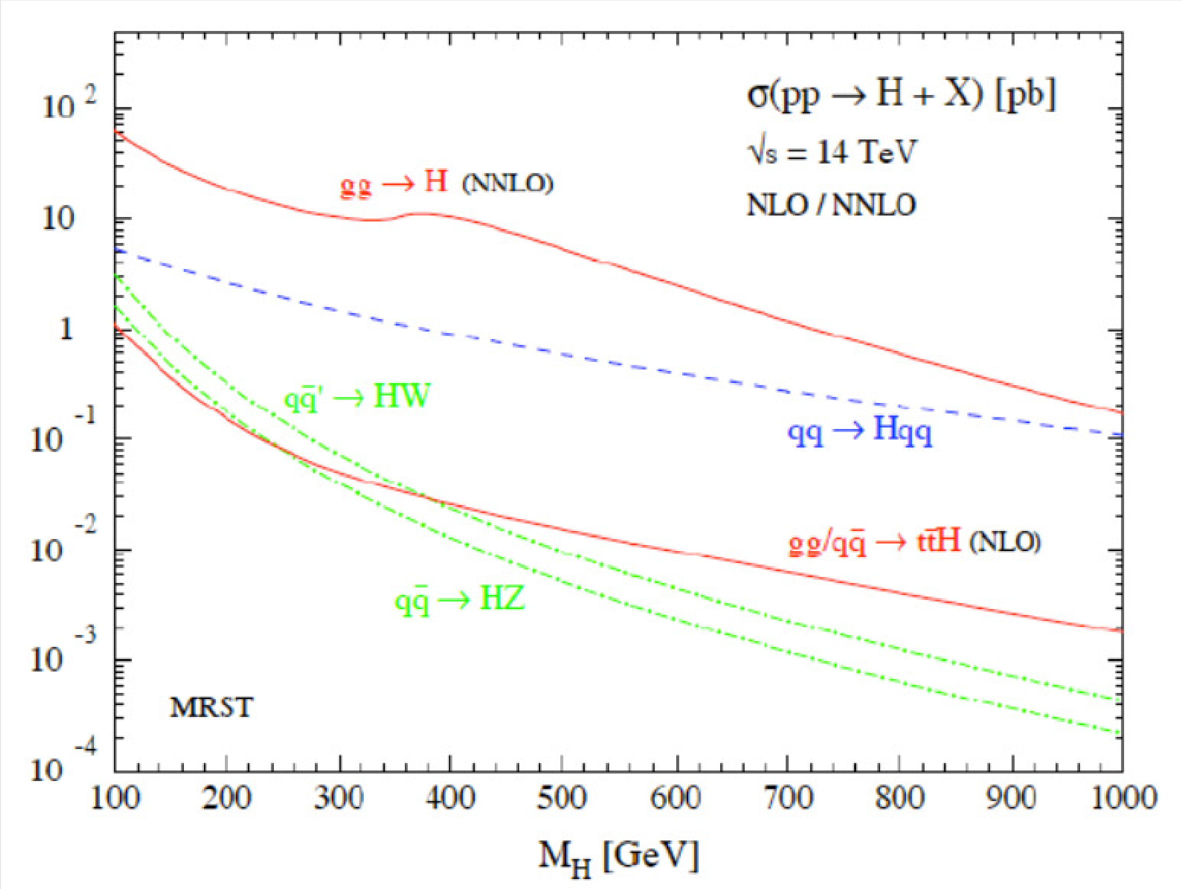
Parton Collider - VII

Expected cross sections for parton colliders:



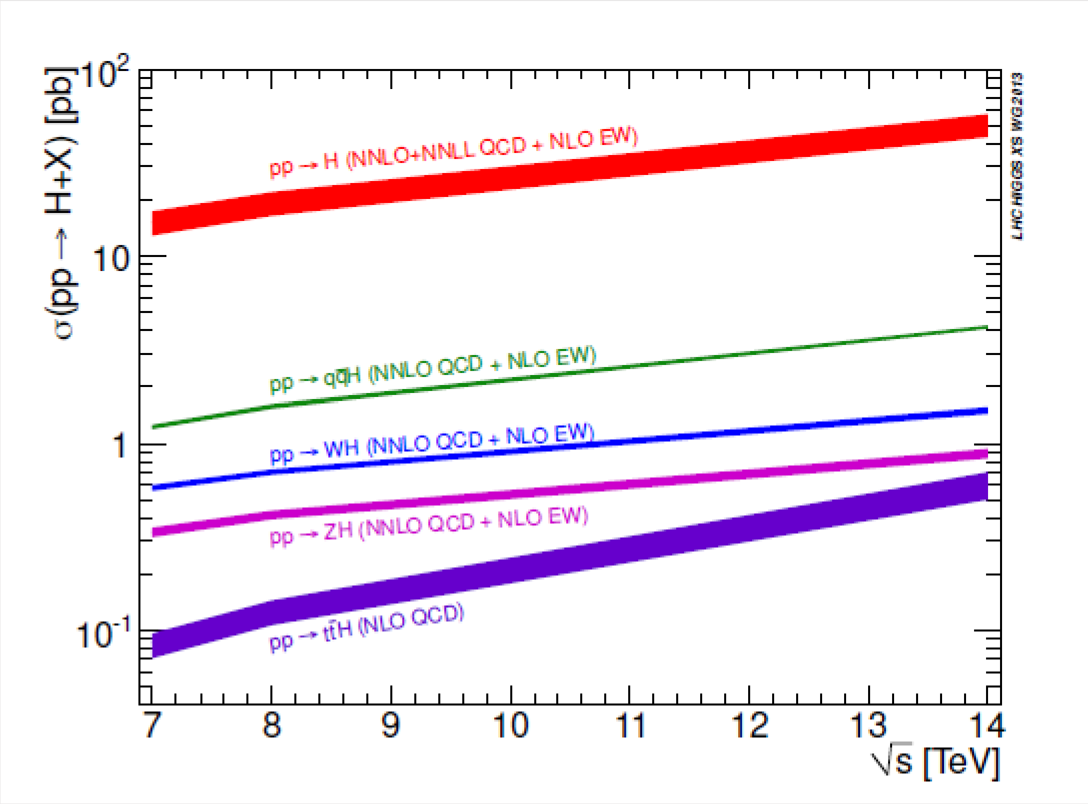
Parton Collider - VIII

Results for LHC cross sections



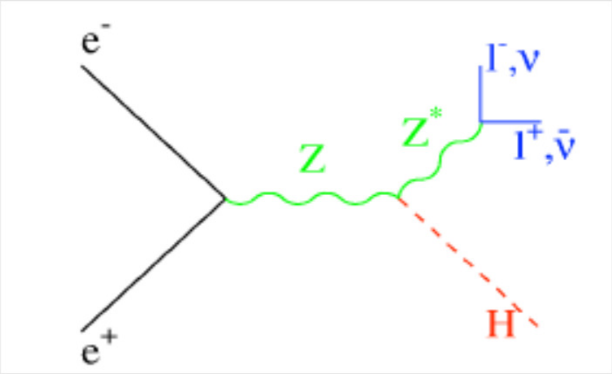
Parton Collider - IX

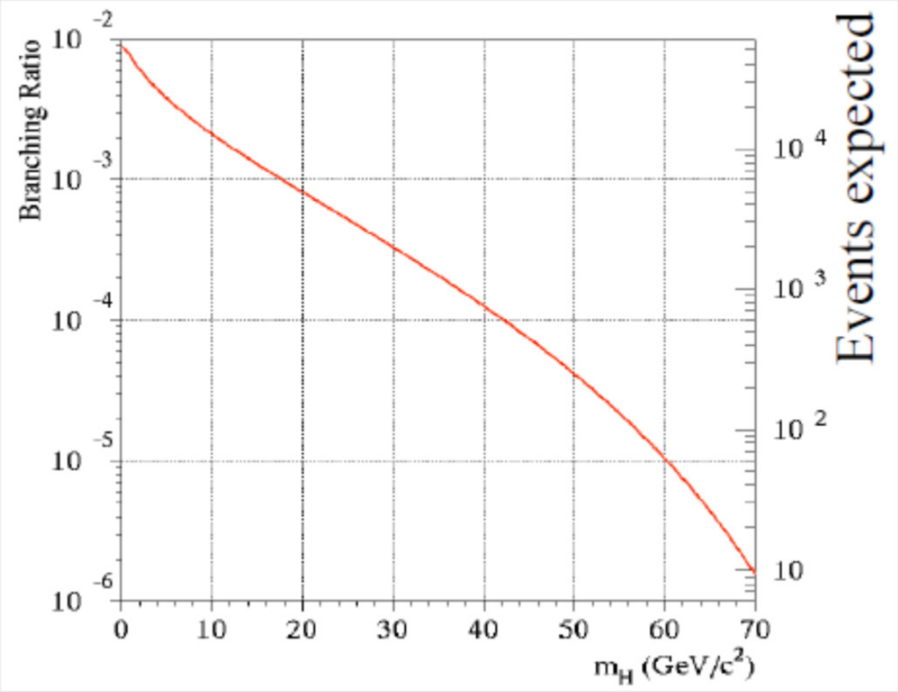
Cross-sections for a 126 GeV Higgs



H Searches - I

Direct searches at LEP I:
Higgsstrahlung
Z off-shell detected by lepton decay



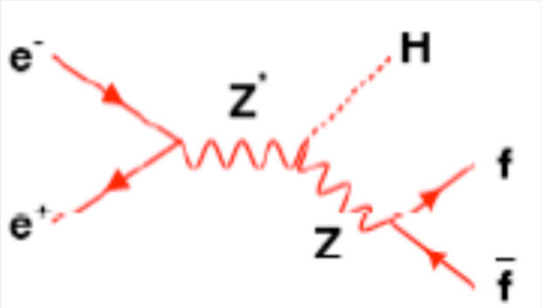


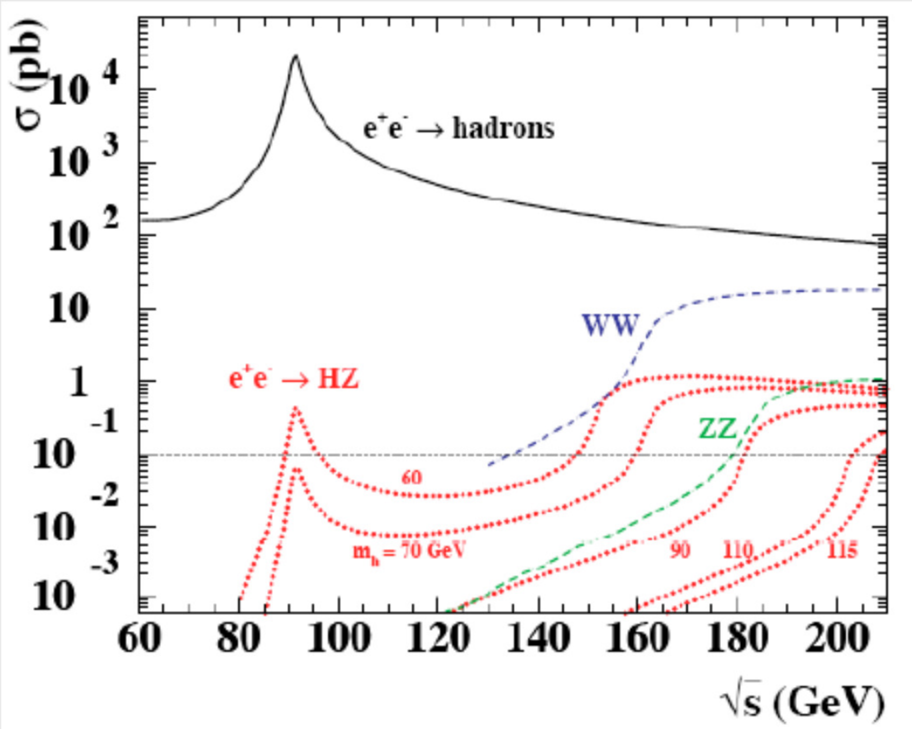
Final LEP I result:

$m_H < 65\ GeV$ excluded at 95% CL

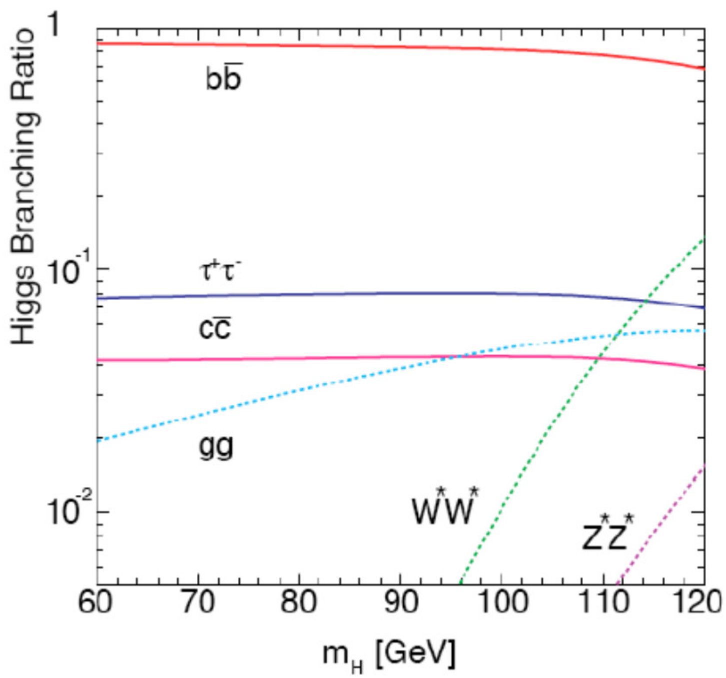
H Searches - II

Direct searches at LEP II:
Higgsstrahlung
Z on-shell detected by lepton decay





H Searches - III



BR(%)	Higgs 115 GeV	Z boson
$q\bar{q}$		70
$b\bar{b}$	74	15
$c\bar{c}$	4	12
gg	6	0
$\ell^+\ell^-$		10
$\tau^+\tau^-$	7	3
$\nu\bar{\nu}$		20
W^*W^*	8	
Z^*Z^*	1	

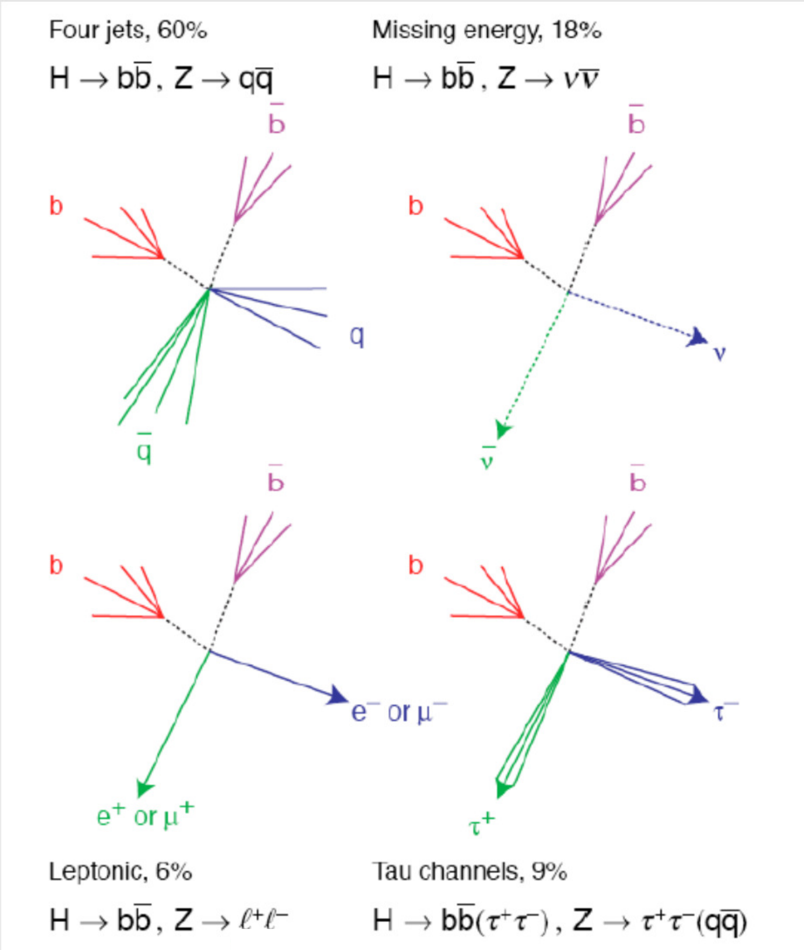
Best channel:

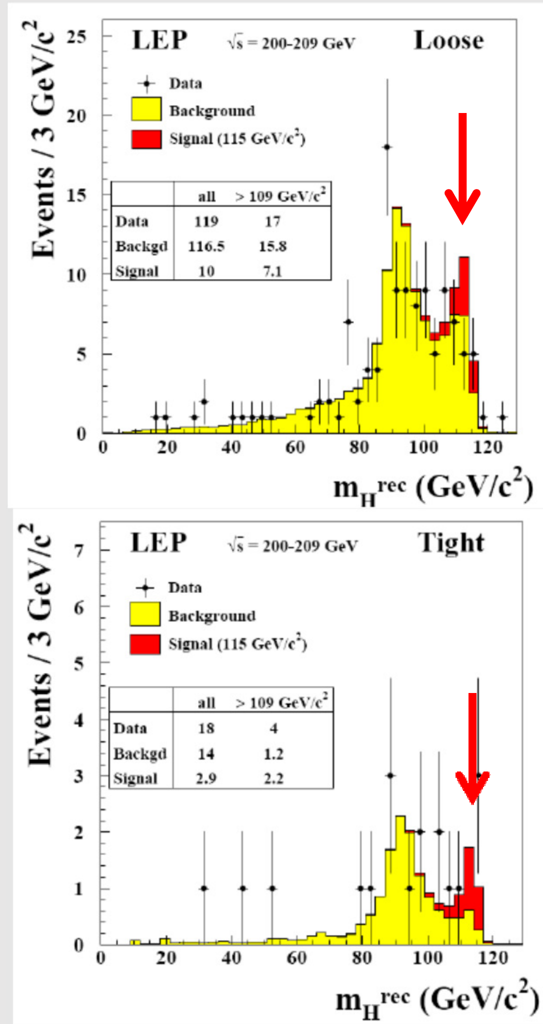
$H \to b\bar{b}$

$Z \to q\bar{q}$

H Searches - IV

HZ event topologies:





Loose	all	> 109 GeV/c²
Data	119	17
Backgd	116.5	15.8
Signal	10	7.1

Tight	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

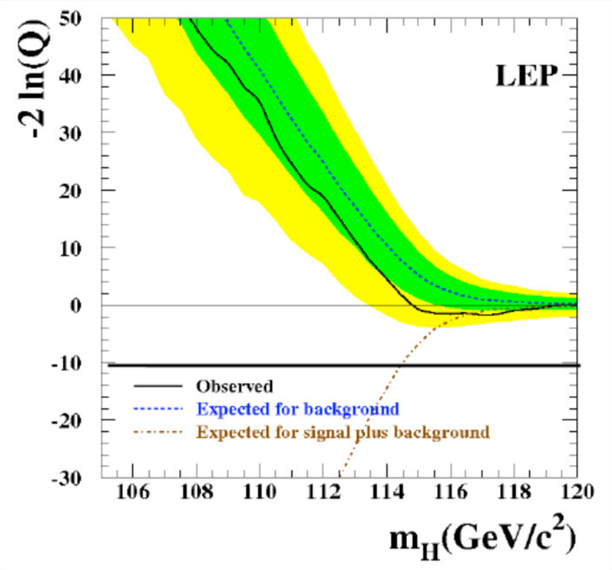
H Searches - V

Likelihood ratio test

$$Q = \frac{L_{sign+bckg}}{L_{bckg}} \rightarrow -2\ln Q \approx \Delta\chi^2$$

Final LEP II result:

$m_H > 114.4\ \ GeV$ at 95% CL



A false alarm:

'Signal' = Best fit

But: Excess at 115 GeV expected in 9% of cases from pure background

H Searches - VI

Tevatron direct searches:

Two large experiments, CDF & D0
Among tens of channels investigated, main results from:

$q\overline{q} \rightarrow WH \rightarrow l\nu b\overline{b}$
$gg \rightarrow H \rightarrow WW \rightarrow l\nu l\nu$

Rather complex topologies, heavy use of *neural networks*
Sophisticated, parallel logic networks capable of handling
many parameters in order to select candidate events

Can be 'trained' by tuning selection criteria across Montecarlo samples
of signal and background

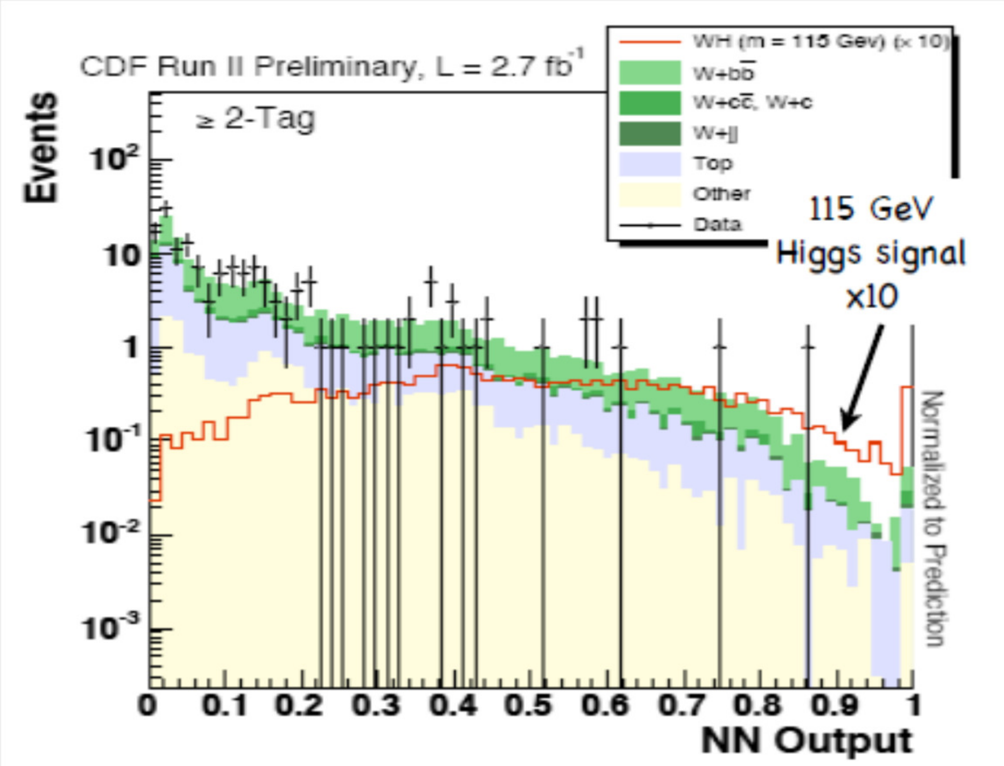
H Searches - VII

CDF :

$q\bar{q} \to WH \to l\nu b\bar{b}$

Neural Network tagging

LEP 'indication' at 115 GeV: Expect 4.8 events, observe 5.6



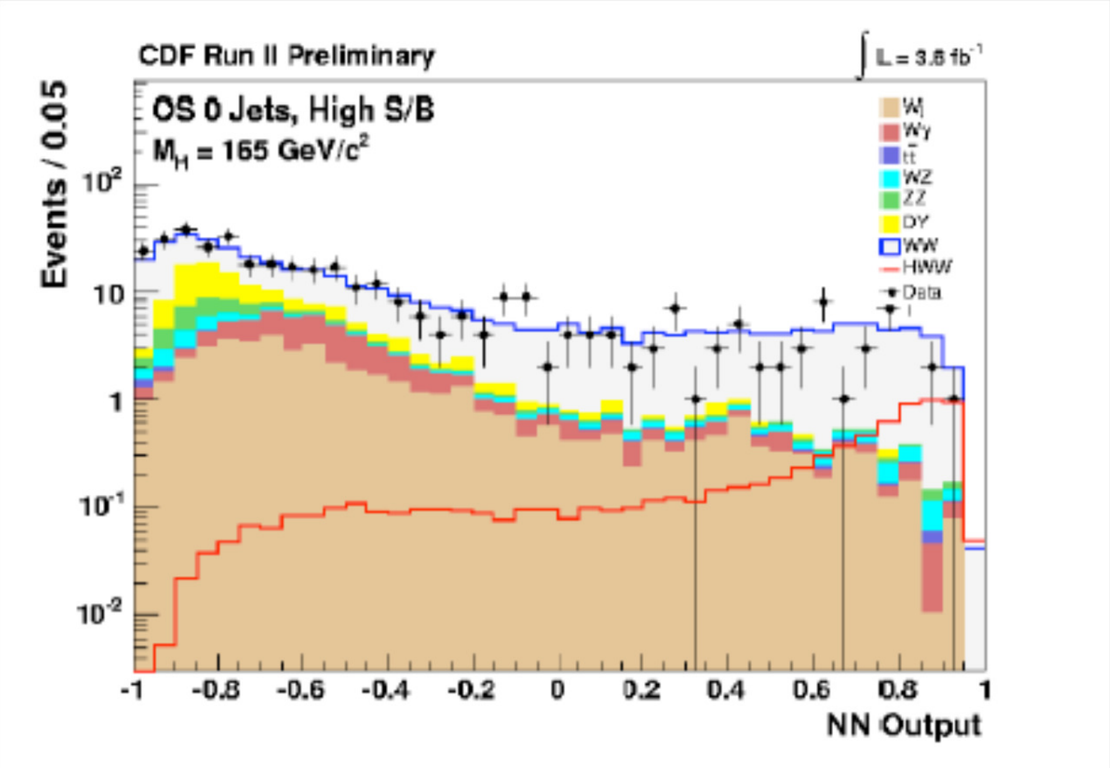
H Searches - VIII

CDF :

$H \to WW \to l\nu l\nu$

Neural Network tagging

Consistent with $t\bar{t}$ background



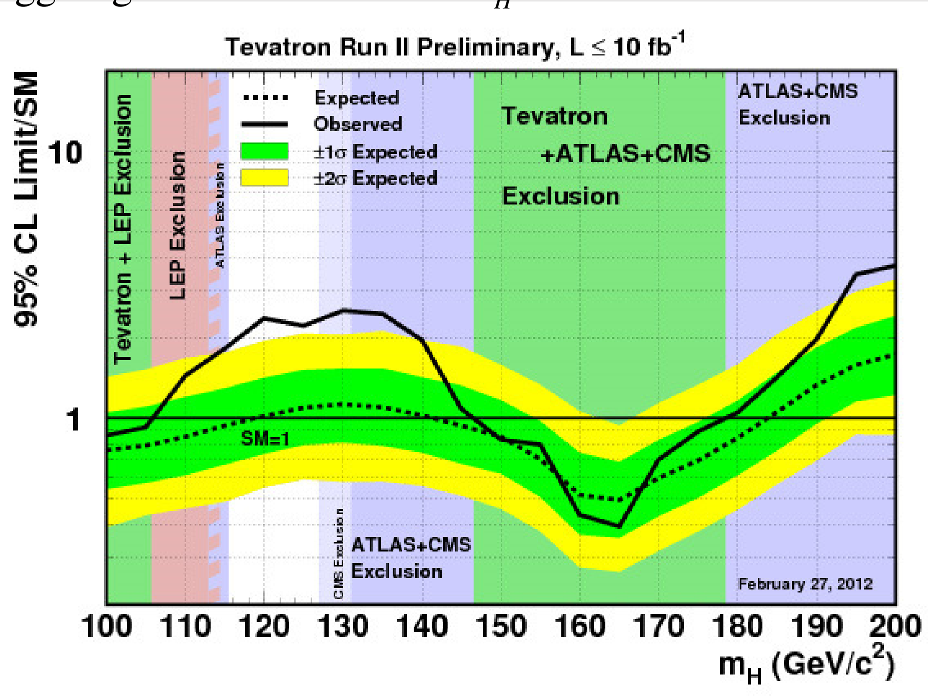
H Searches - IX

Main Tevatron result : "Brazilian Flag" plot

Continuous line : Upper limit of (Higgs+SM Background) observed
Dashed line: SM Background ($\underbrace{\pm 1\sigma}_{Green\ band}$, $\underbrace{\pm 2\sigma}_{Yellow\ band}$) expected

(both lines $vs.\ m_H$)

Unit: Expected SM Higgs signal as a function of m_H

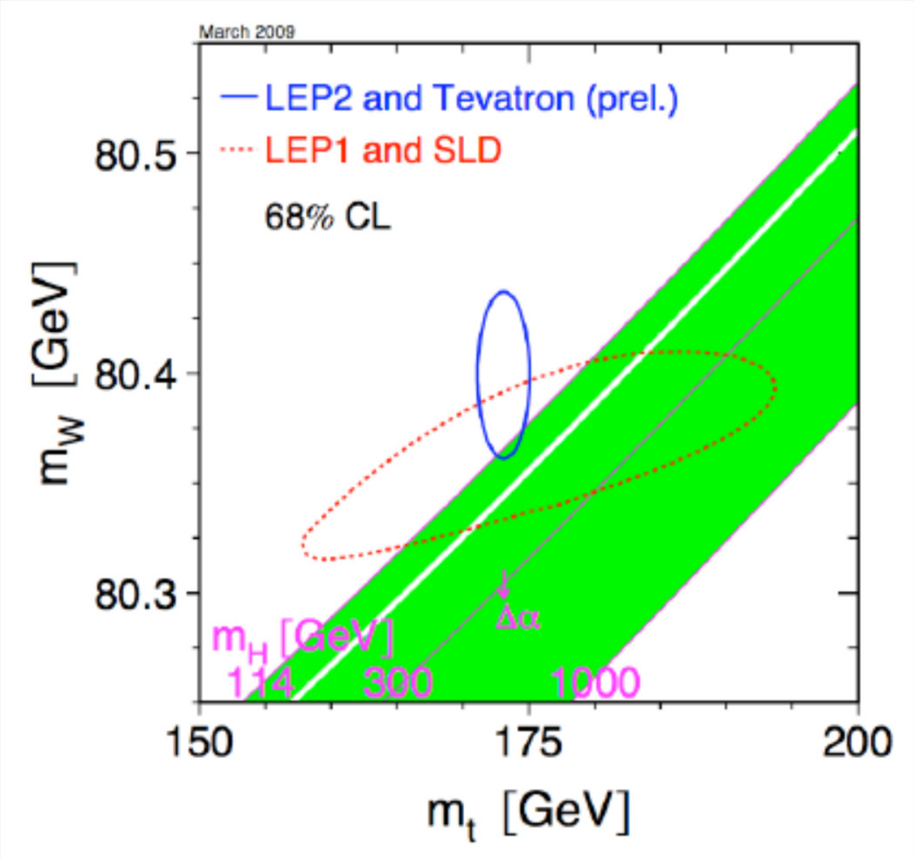


H Searches - X

Indirect searches:

Radiative corrections to many EW observables receiving contributions $\propto \ln m_H, m_t^2$

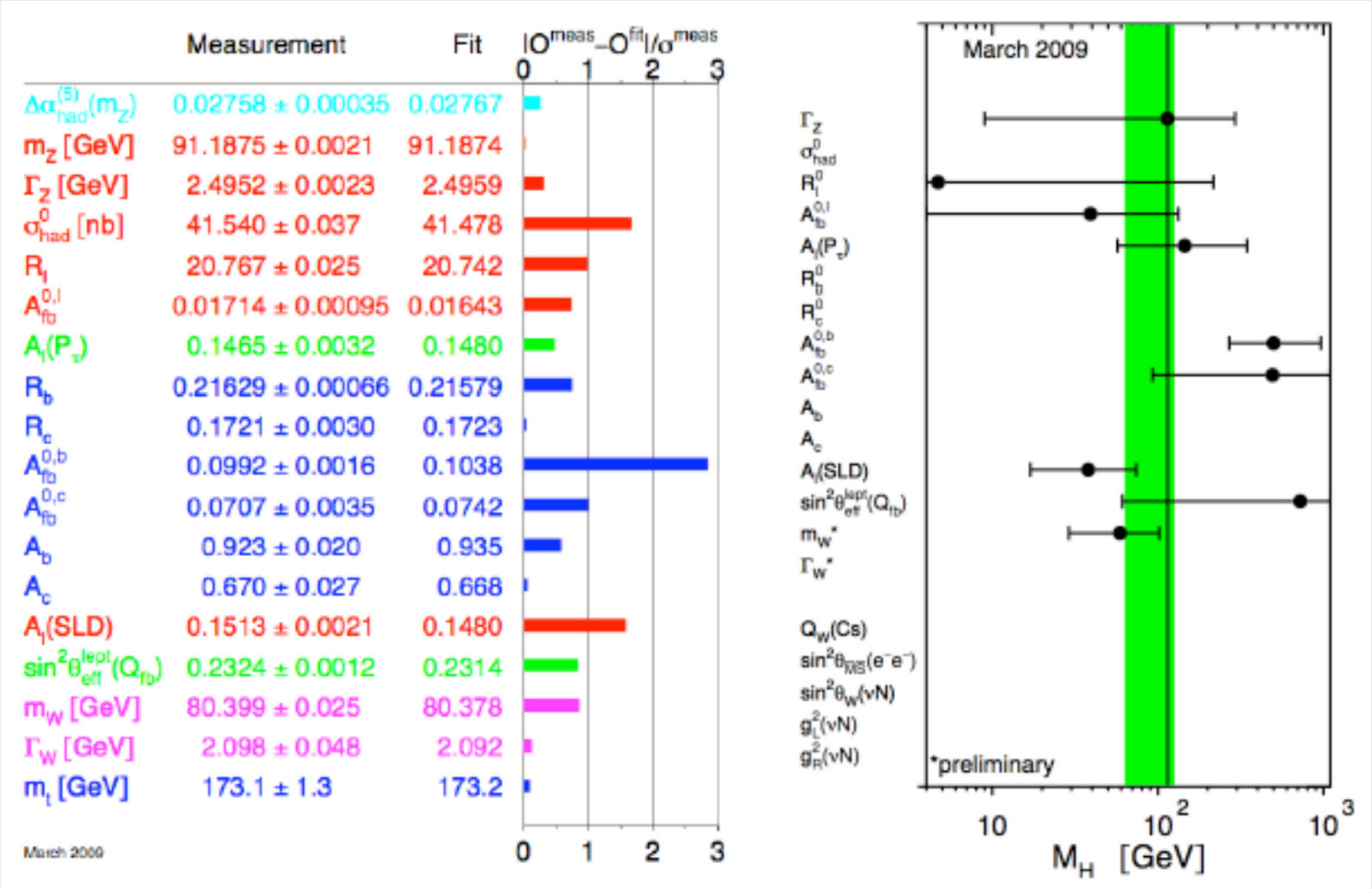
Ex: m_W



H Searches - XI

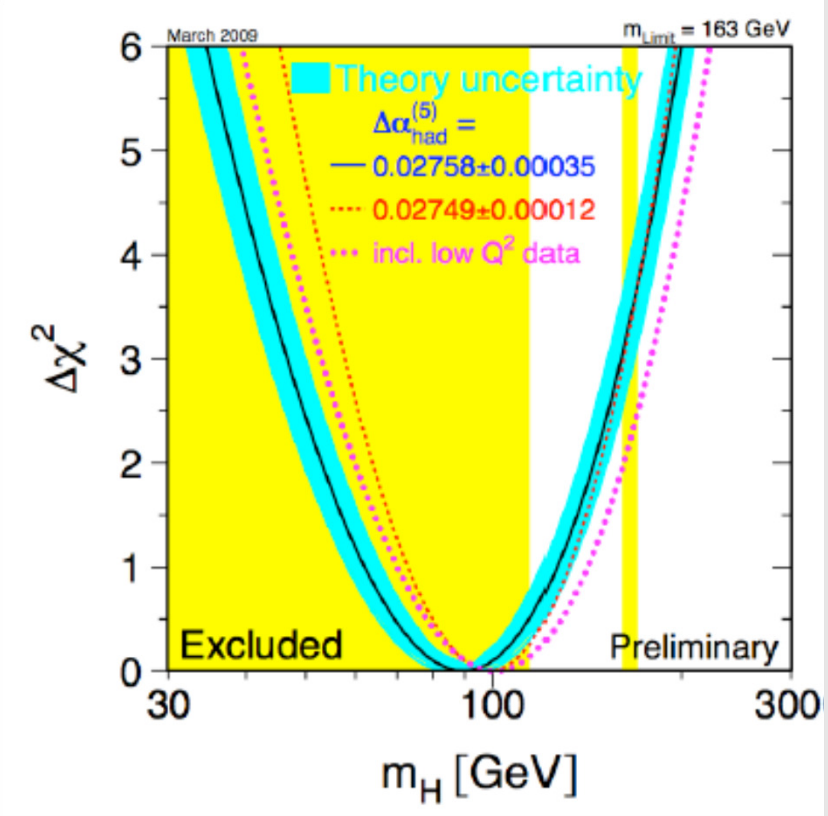
Global fit to $\sim$ 20 EW observables:

Best indirect estimate of m_H



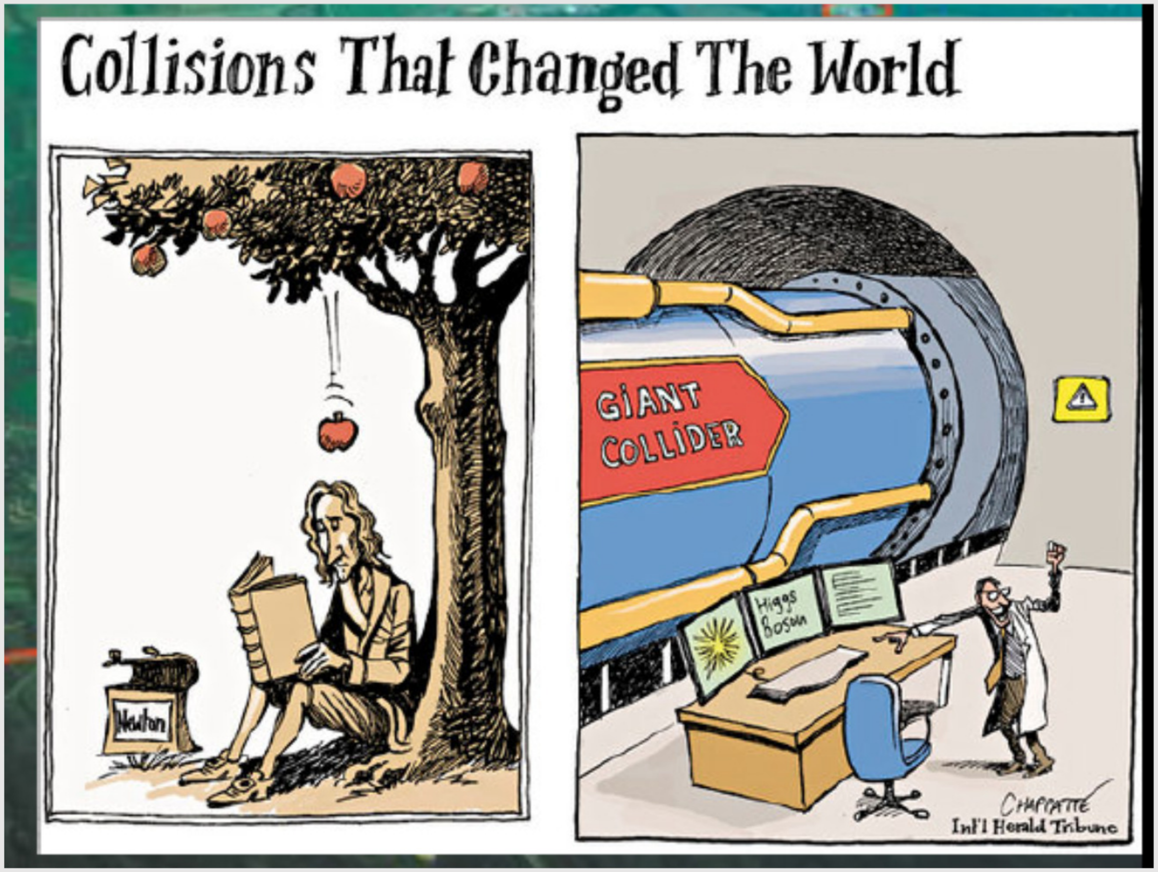
H Searches - XII

χ^2 minimization:



$$m_H = 90^{+36}_{-27} \ \ GeV, \ \ 68\% \text{ CL}$$

LHC: Machine - I



LHC: Machine - II

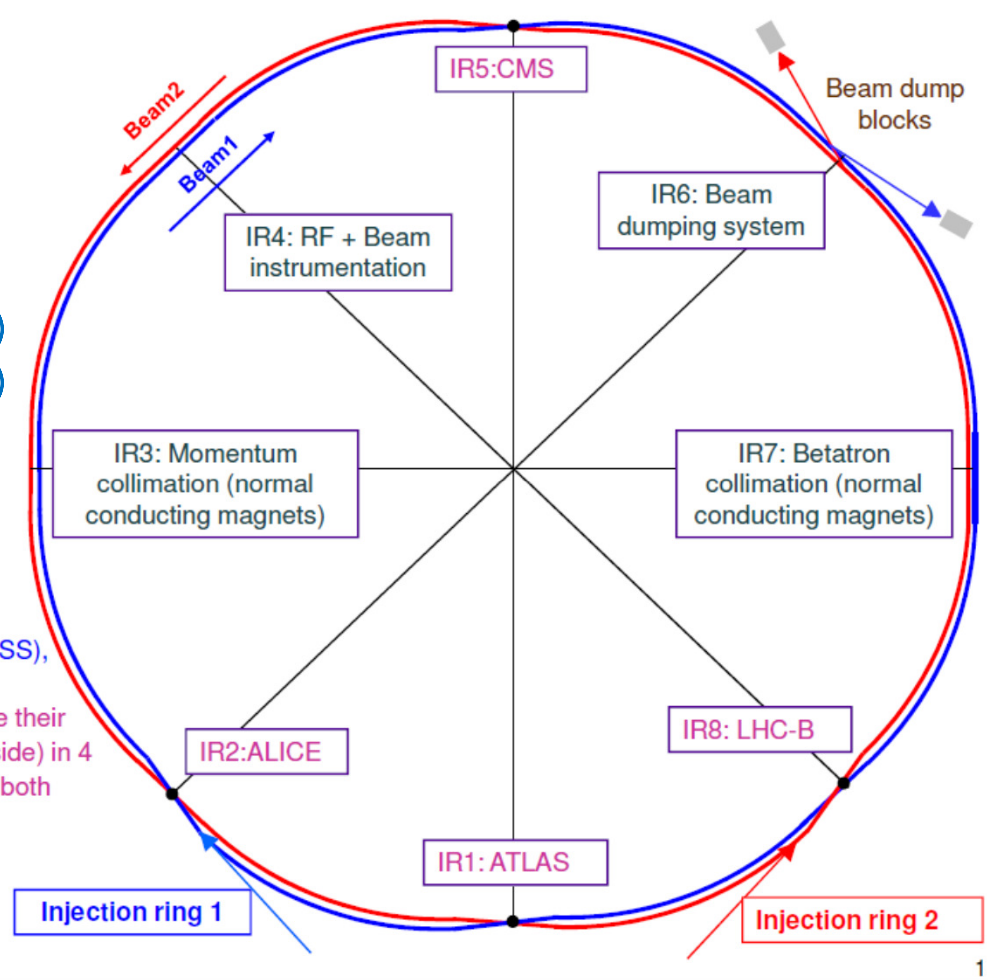
LHC dipole field 8.3 T

(HERA/Tevatron ~4 T)

LHC pp ~ 10^{34} cm^{-2} s^{-1}

(Tevatron pp 3×10^{32} cm^{-2} s^{-1})

(SppbarS pp 6×10^{30} cm^{-2} s^{-1})



LHC Layout

- 8 arcs.
- 8 straight sections (LSS), ~ 700 m long.
- The beams exchange their positions (inside/outside) in 4 points to ensure that both rings have the same circumference !

LHC: Machine - III

$R = L\sigma$ Rate, Luminosity,Cross-Section

$$L = \frac{kN^2 f}{4\pi\sigma^*_x\sigma^*_y}$$

k = number of bunches = 2808

N = no. protons per bunch = 1.15×10^{11}

f = revolution frequency = 11.25 kHz

σ^*_x,σ^*_y = beam sizes at collision point (hor./vert.) = 16 mm

High L:

Many bunches (k)

Many protons per bunch (N)

A small beam size $\sigma^*_u = (\beta^*\varepsilon)^{1/2}$

} High beam "brilliance" N/ε (particles per phase space volume) → Injector chain performance. Small envelope → Strong focusing

β^*: Beam envelope (optics) } Optics property

ε: Phase space volume occupied by the beam (constant along the ring) } Beam property

LHC: Machine - IV

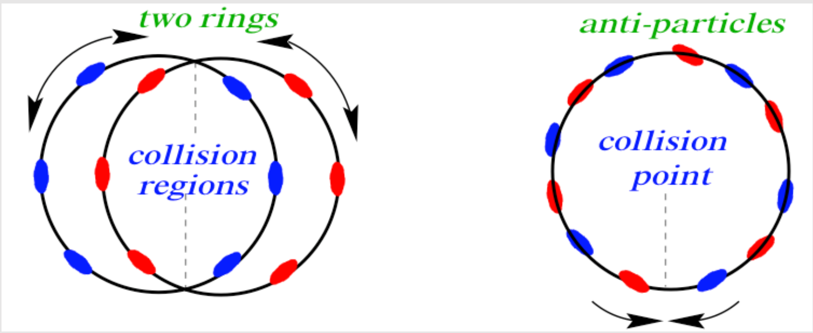
$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

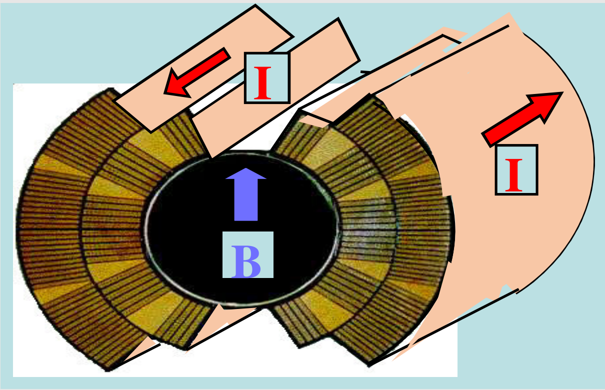
LHC: ρ = 2.8 km given by LEP tunnel

To reach p = 7 TeV/c given a bending radius of ρ = 2805 m:

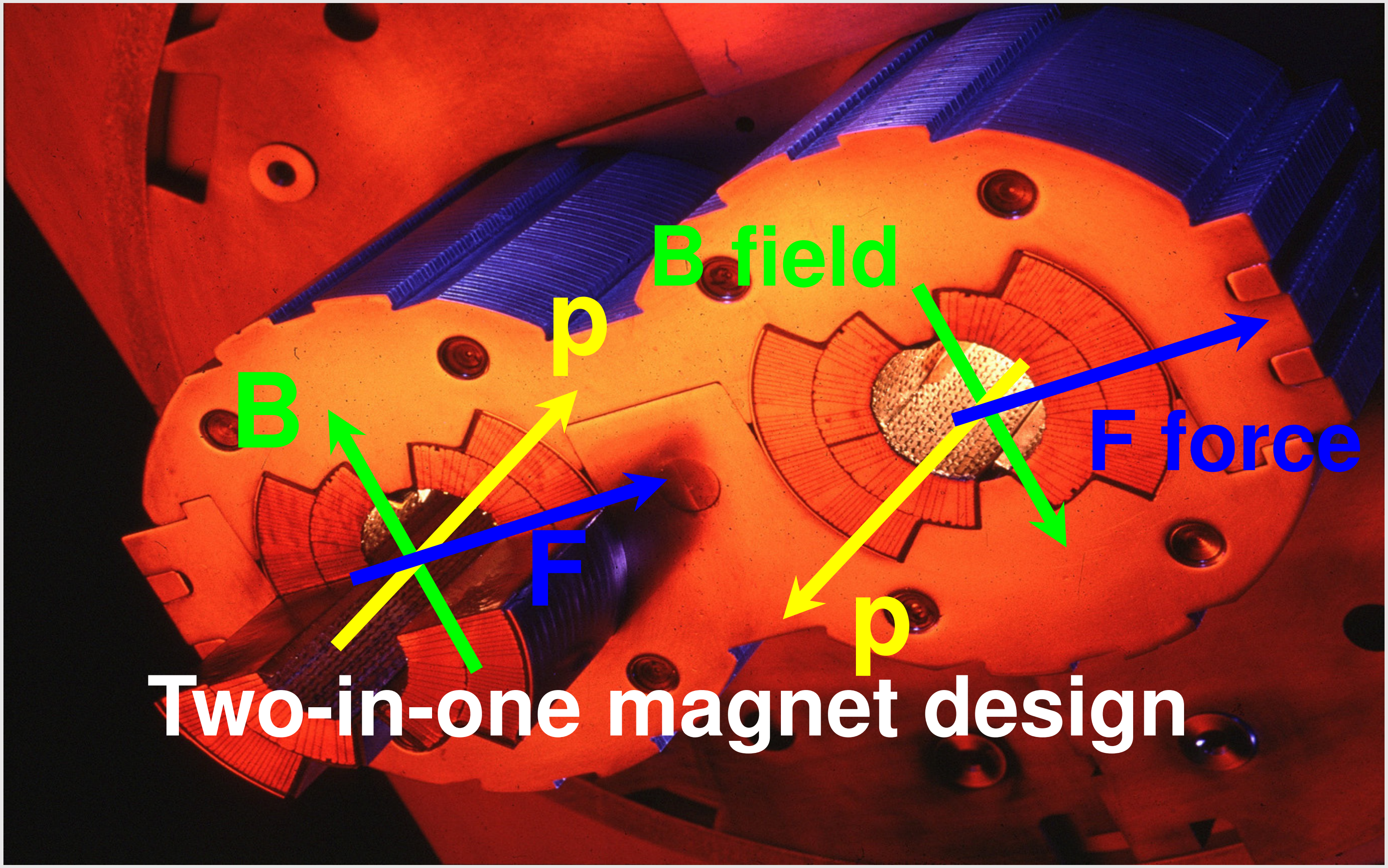
Bending field : B = 8.33 T

→Superconducting magnets



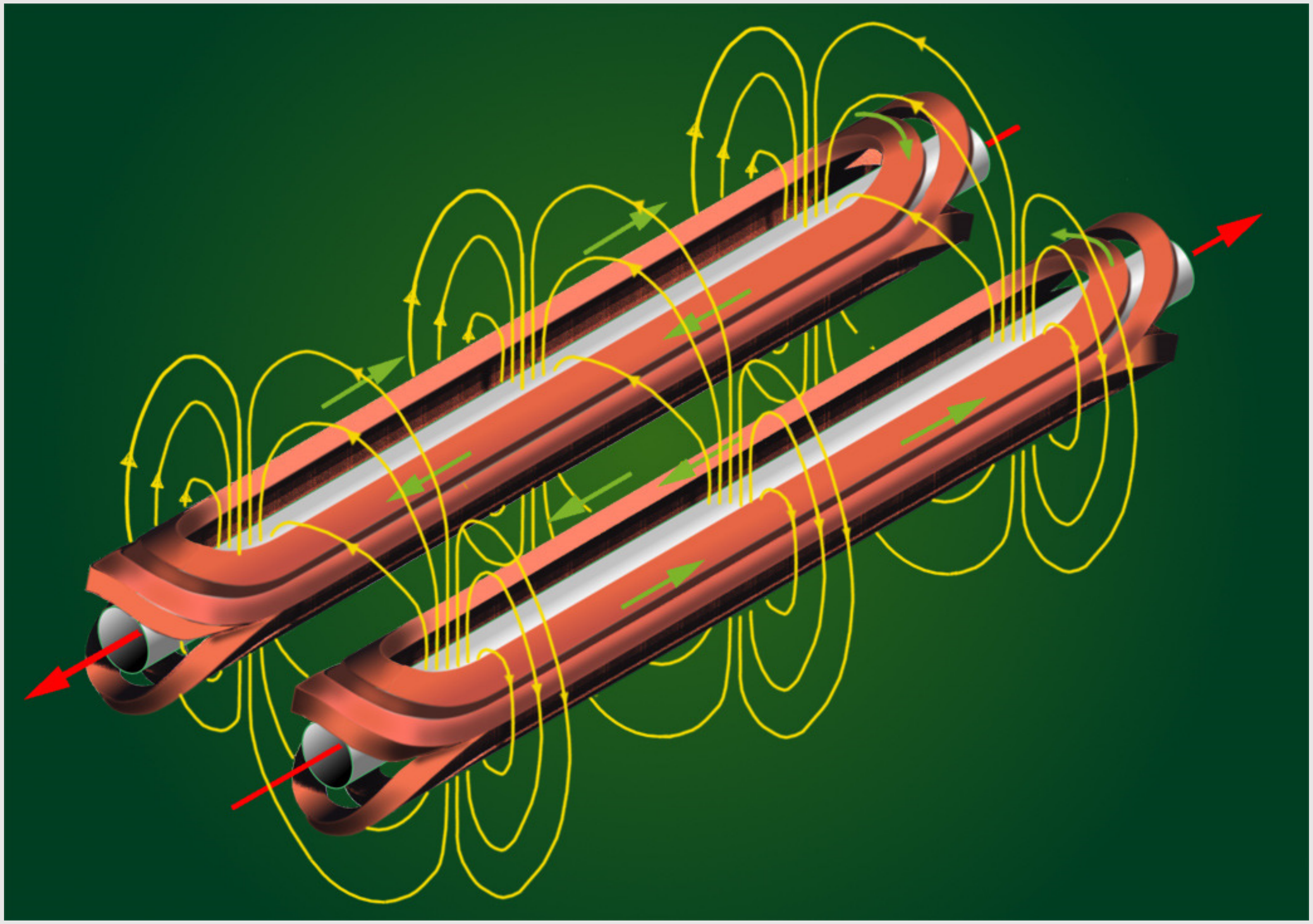


LHC: Machine - V



LHC: Machine - VI

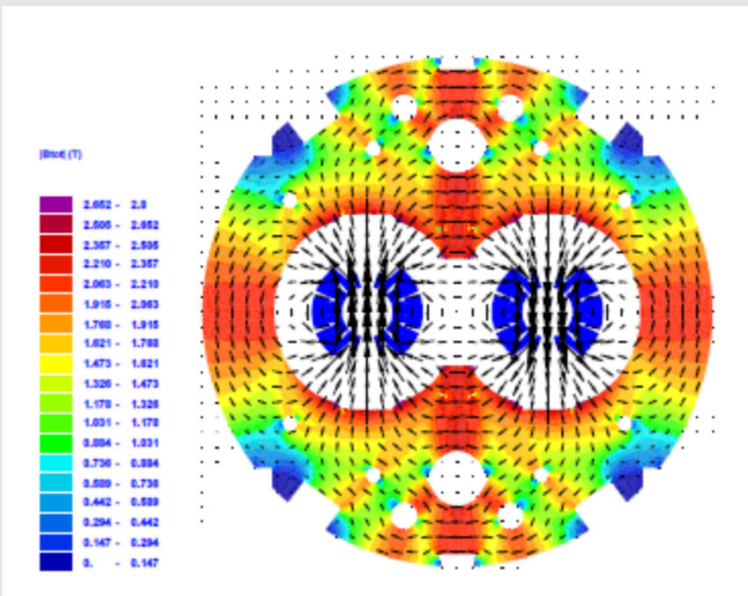
Superconducting coils:

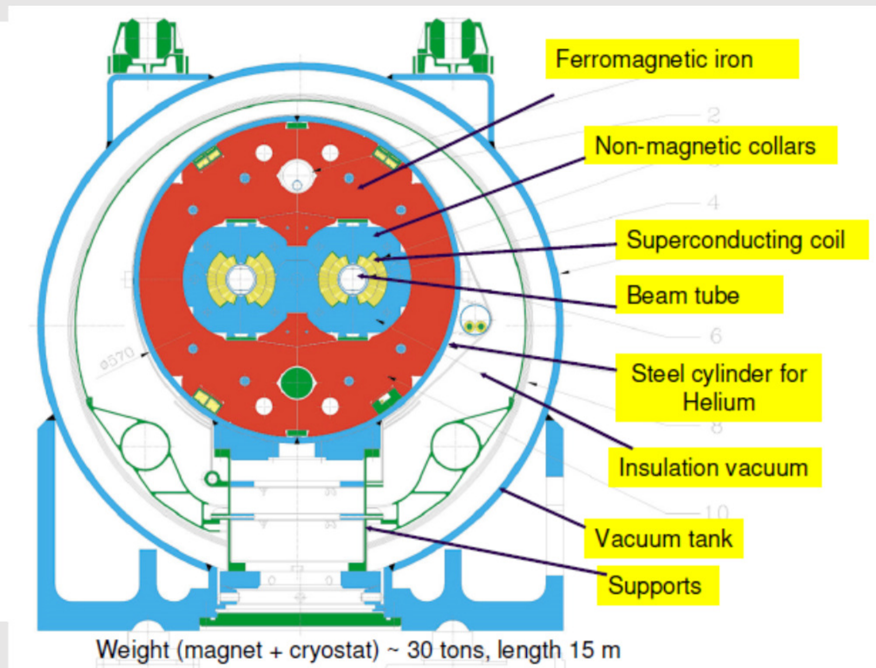


LHC: Machine - VII

LHC main dipole:

Two magnets in a single module





LHC: Machine - VIII

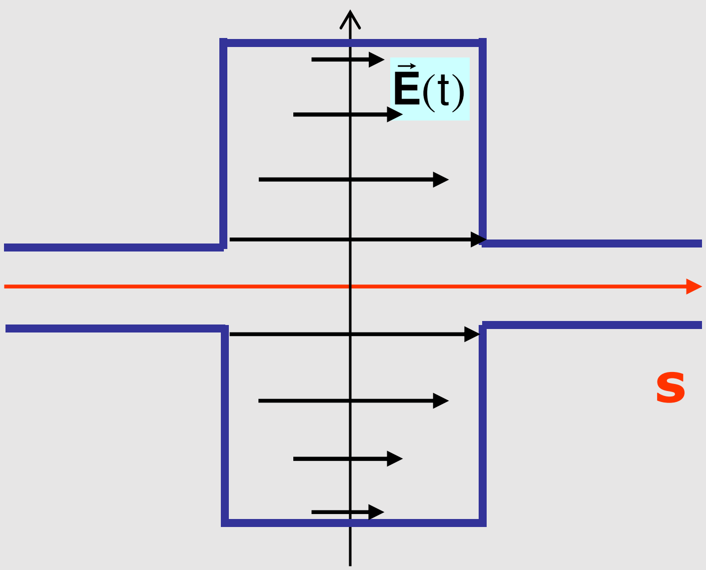
RF system:

4 + 4 Superconducting RF cavities

400 MHz

$\sim$ 0.5 MeV/turn

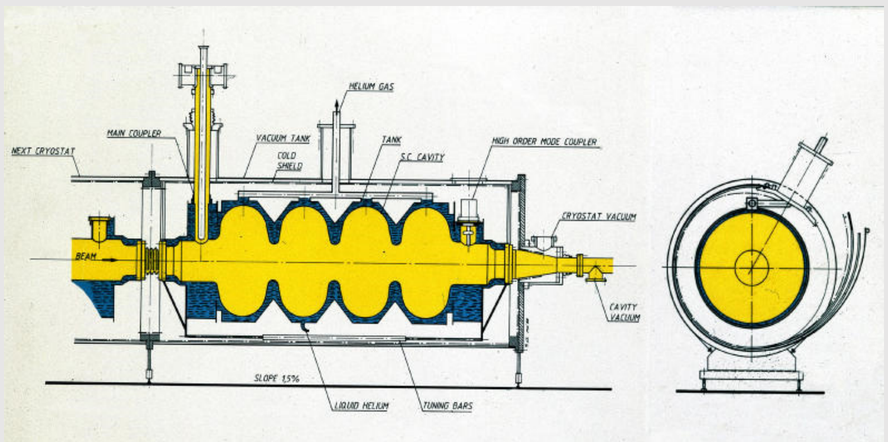
20 minutes for 450 GeV $\rightarrow$ 7 TeV



	Synchrotron radiation loss
LHC @ 3.5 TeV	0.42 keV/turn
LHC @ 7 TeV	6.7 keV /turn
LEP @ 104 GeV	~3 GeV /turn

LHC: Machine - IX

Superconducting cavity



SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT

H - I

Selecting best decay channels for detection:

Strongly dependent on (unknown) M_H

By taking $M_H < 2M_W$

$b\bar{b}$: Large $BR > 50\ \%$, good signature (secondary vertexes), *lots* of QCD background

$\tau^+\tau^-$: Large $BR \sim 7\ \%$, somewhat harder than $b\bar{b}$ (neutrinos)

$\gamma\gamma$: Tiny $BR \sim 2\ 10^{-3}$, small background, experimentally challenging

gg : Large $BR \sim 5\ \%$, 2 jets, *lots* of QCD background

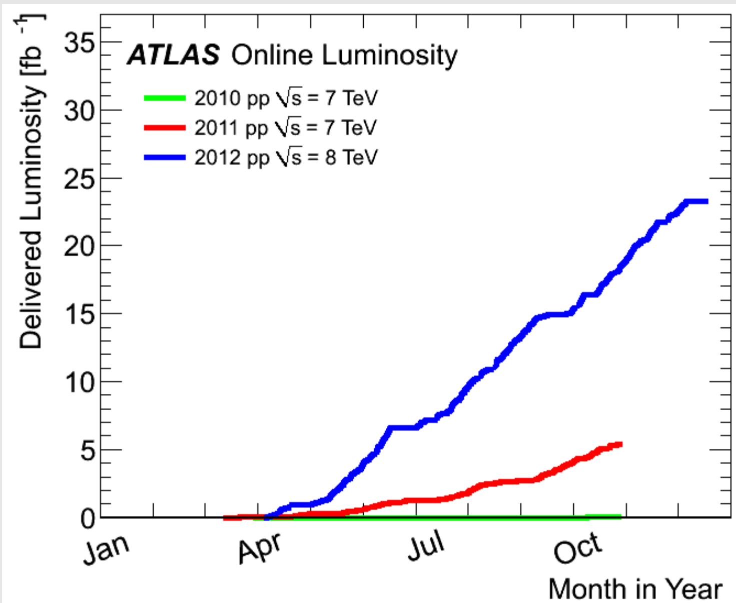
ZZ^*: Small $BR \sim 3\ \%$, small background in the 4 leptons mode

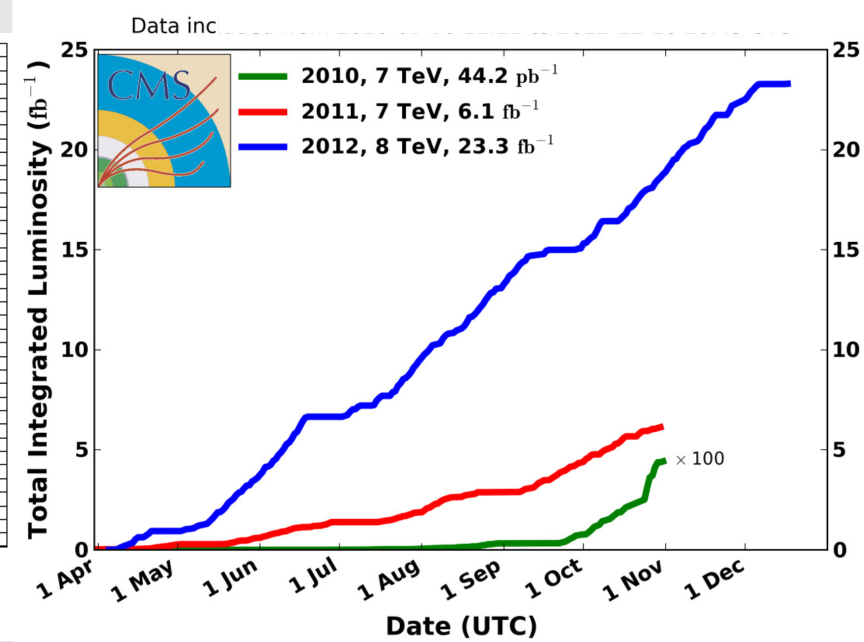
WW^* : Large $BR \sim 20\ \%$, sizeable QCD background in the 4 jets mode, harder than ZZ^* in leptonic modes (neutrinos)

H - II

Total integrated luminosity:

$\sim 30\, fb^{-1}$ / experiment



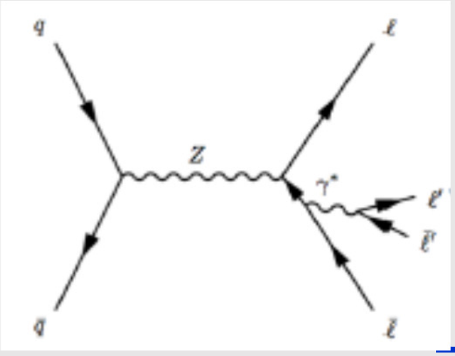


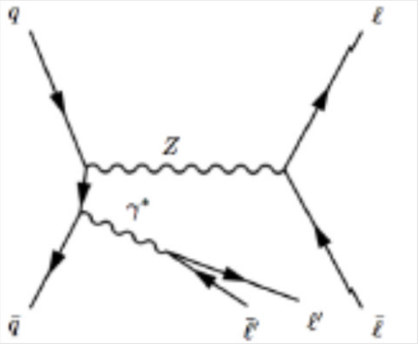
Phenomenal performance:

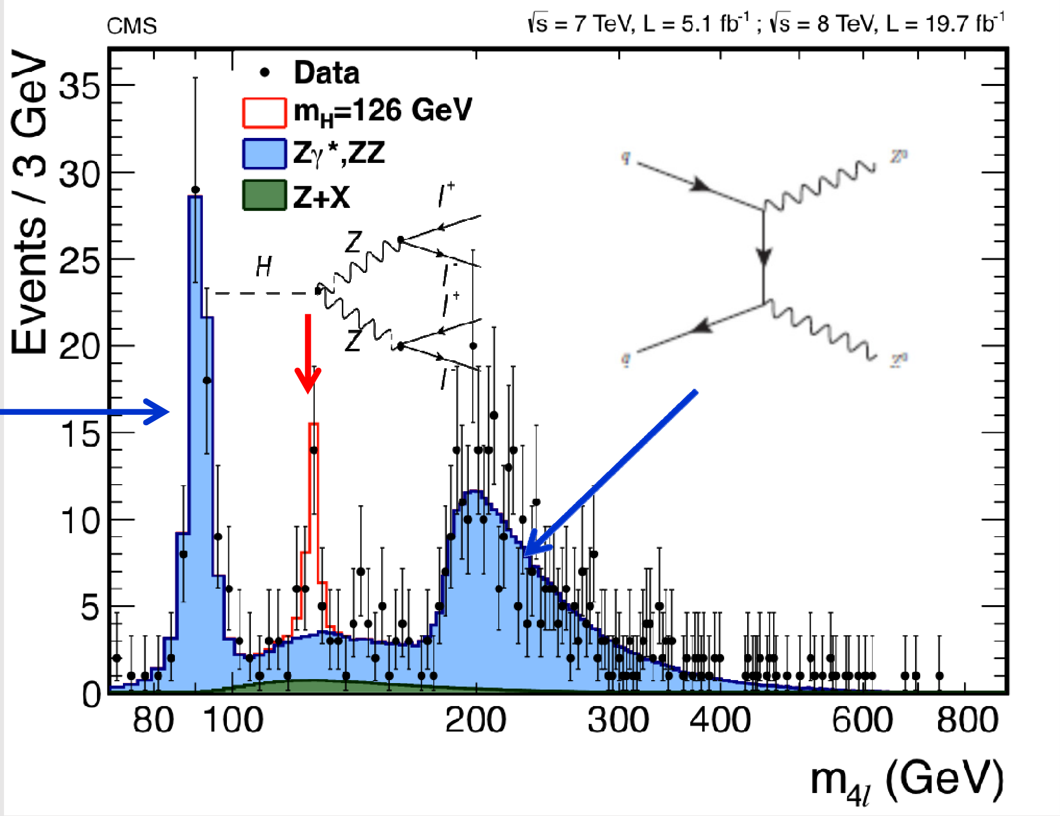
- Record luminosity (> 5 x 10^{33}) obtained soon after startup in 2012
- Sustained data collection rate of > 1.0 fb^{-1} /wk
- Delivered/recorded @ 8 TeV = [23.3 / 21.3 (ATLAS) , 21.8 (CMS)] fb^{-1}

H - III

4 leptons:
~7σ observation

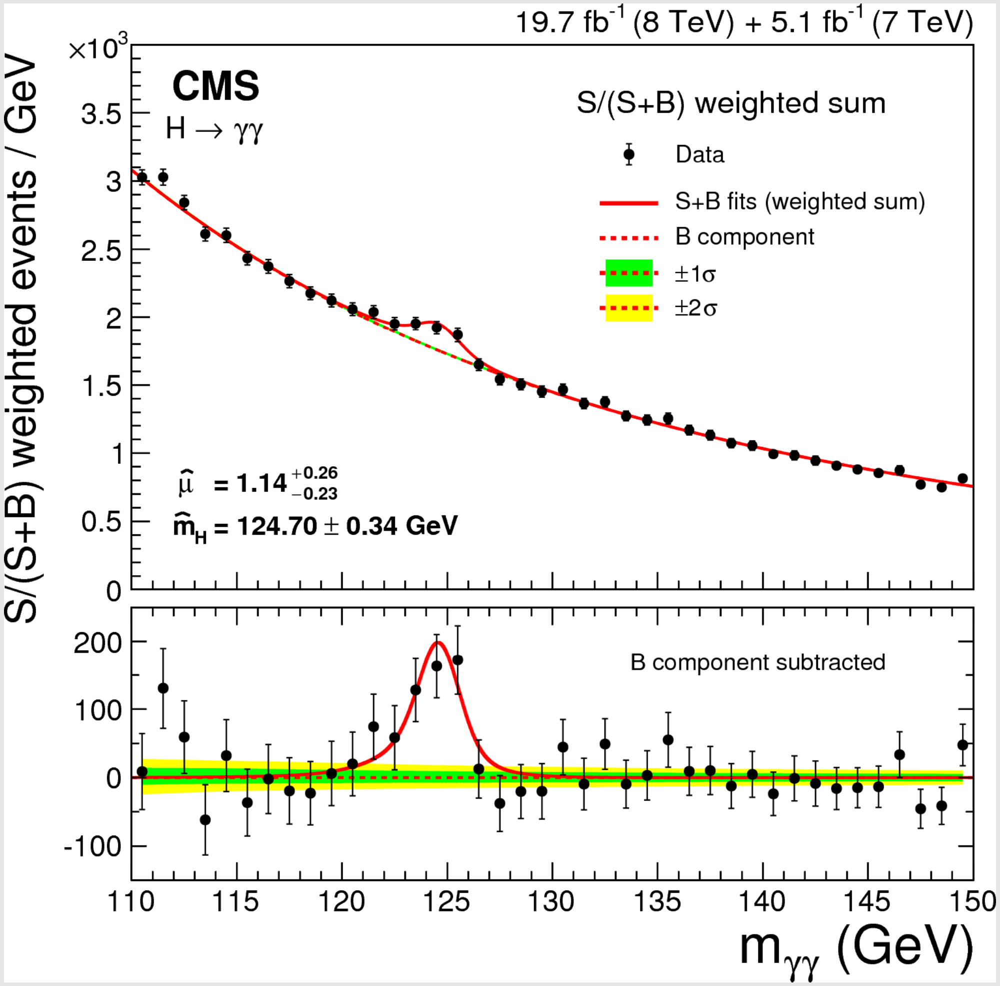






H - IV

2 γ's:
~6 σ observation



H - V

Signal strength:

	ATLAS (expected)	**ATLAS (observed)**	**CMS (expected)**	**CMS (observed)**
$h \to \gamma\gamma$	4.1	7.4	5.2	5.7
$h \to ZZ$	4.4	6.6	6.7	6.8
$h \to WW$	3.7	3.8	5.8	4.3
$h \to \tau\tau$	3.2	4.1	3.6	3.4
$h \to bb$	1.6	~0	2.1	2.1

H - VI

Combined mass: All modes

$$m_H\left(\text{ATLAS}\right) = 125.36\ \pm 0.37\ (\text{stat}) \pm 0.18\ (\text{syst})$$

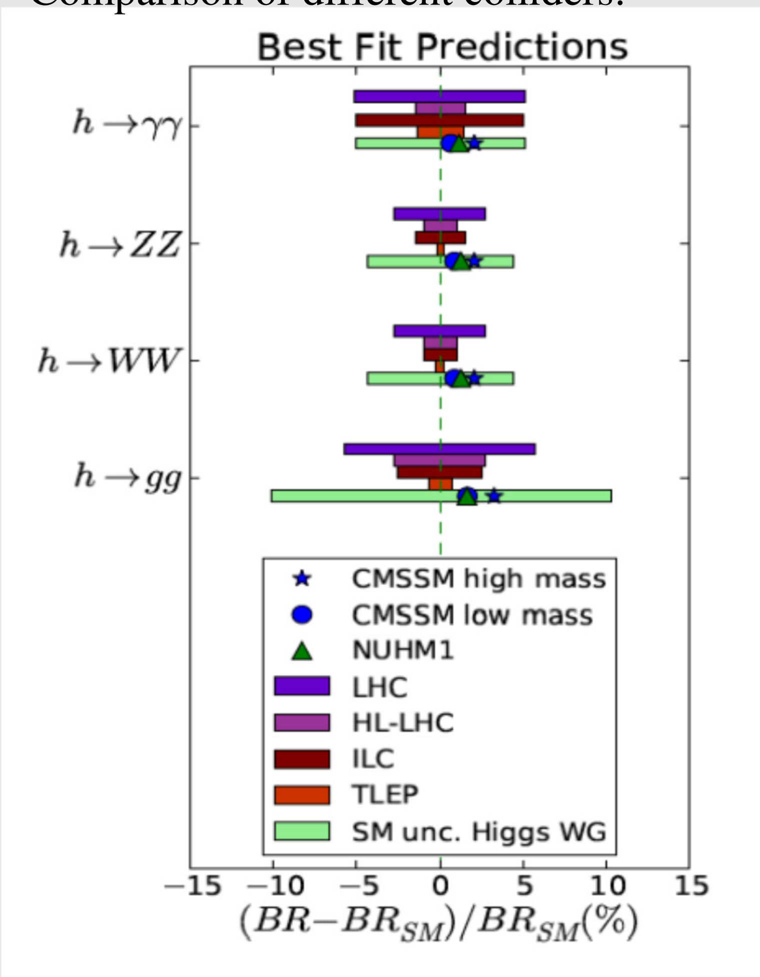
$$m_H\,(\text{CMS}) = 125.03^{+0.26}_{-0.27}(\text{stat})^{+0.13}_{-0.15}(\text{syst})$$

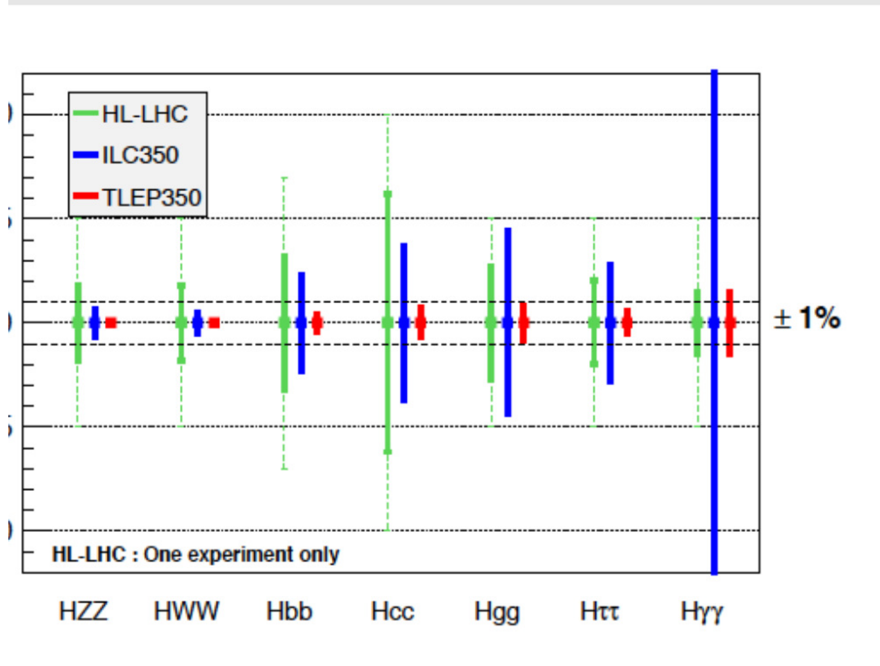
Many more results on spin/parity, couplings, width...

....Next time!

Future Collider Comparison - I

Comparison of different colliders:





Future Collider Comparison - II

Accelerator → Physical Quantity ↓	**LHC** 300 fb^{-1} /expt	**HL-LHC** 3000 fb^{-1} /expt	**ILC** 250 GeV 250 fb^{-1} 5 yrs	**Full ILC** 250+350+ 1000 GeV 5yrs each	**CLIC** 350 GeV (500 fb^{-1}) 1.4 TeV (1.5 ab^{-1}) 5 yrs each	**LEP3, 4 IP** 240 GeV 2 ab^{-1} (*) 5 yrs	**TLEP, 4 IP** 240 GeV 10 ab^{-1} 5 yrs (*) 350 GeV 1.4 ab^{-1} 5 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν	7.5×10^4 ZH 4.7×10^5 Hνν	4×10^5 ZH	2×10^6 ZH 3.5×10^4 Hνν
m_H (MeV)	100	50	35	35	100	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	ongoing	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	ongoing	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	ongoing	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	$<$ 3%	2.2%	0.7%
$\Delta g_{Hww} / g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	~1%	1.5%	0.25%
$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	~1%	0.65%	0.2%
$\Delta g_{HHH} / g_{HHH}$	--	$<$ 30% (2 expts)	--	~30%	~22% (~11% at 3 TeV)	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	$<$ 30%	$<$ 10%	--	--	10%	14%	7%
$\Delta g_{H\tau\tau} / g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	≤ 3%	1.5%	0.4%
$\Delta g_{Hcc} / g_{Hcc}$	--	--	3.7%	2%	2%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	1%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	5%	3%	--	30%