Elementary Particles II

3 – The Higgs Particle at the LHC

Predictions, Strategies, Machines, Detectors, Data

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:

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

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

Reminder - II

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

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

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

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

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

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

Pick ground state (= vacuum) as

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

$v = 246\ GeV$

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 $e, G_F, \sin\theta_W$:

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

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

Reminder - IV

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

$$L_B + L_H$$

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

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

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

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

$$+L_{BB}^I + L_{HH}^I + L_{HB}^I$$ Gauge-Higgs, Higgs self-, Gauge self-interactions

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:

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

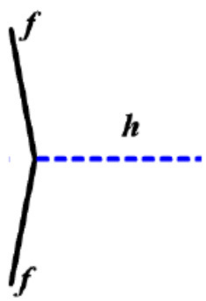
Lepton masses in terms of model parameters:

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

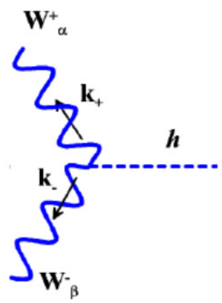
g_l individual constant

Reminder - VI

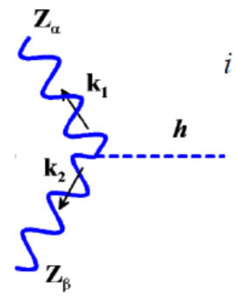
Higgs vertexes:



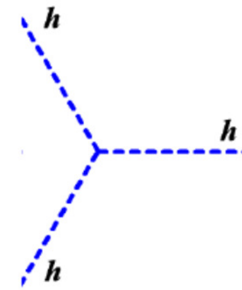
$-im_f\sqrt{\sqrt{2}G_F}\,\bar{f}\,f$



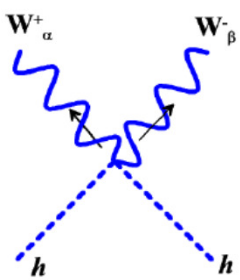
$2iM_W^2\sqrt{\sqrt{2}G_F}\,g^{\alpha\beta}W_\alpha^{+\dagger}W_\beta^{-\dagger}h$



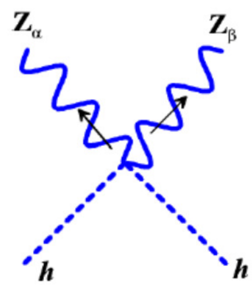
$2iM_Z^2\sqrt{\sqrt{2}G_F}\,g^{\alpha\beta}Z_\alpha^\dagger Z_\beta^\dagger h$



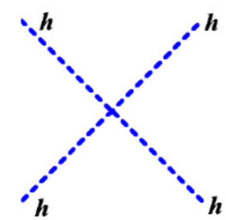
$-3im_h^2\sqrt{\sqrt{2}G_F}\,hhh$



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



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



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

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

About the Higgs Field - I

Universal, constant field

Lorentz scalar $\rightarrow$ 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

$\rightarrow$ Pick up a direction

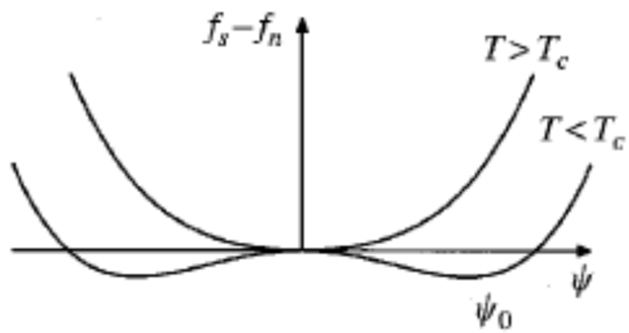
Ground state rotationally not symmetric, in spite of H being symmetric

About the Higgs Field - II

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

$$\Delta E = a(T)|\psi|^2 + \frac{1}{2}b(T)|\psi|^4 + \ldots$$ 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 very natural question:

What about the nonzero VEV of the Higgs field?

What does it mean?

Should we expect some contribution to vacuum energy, or what?

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

'Giving mass to $\approx$ all the fundamental constituents'

Does not involve a new force

Background interaction for most particles equivalent to 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

$\rightarrow$ 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

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

By assuming ρ to be a cosmological term, compare:

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

$\rightarrow \rho_{Higgs}$ 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

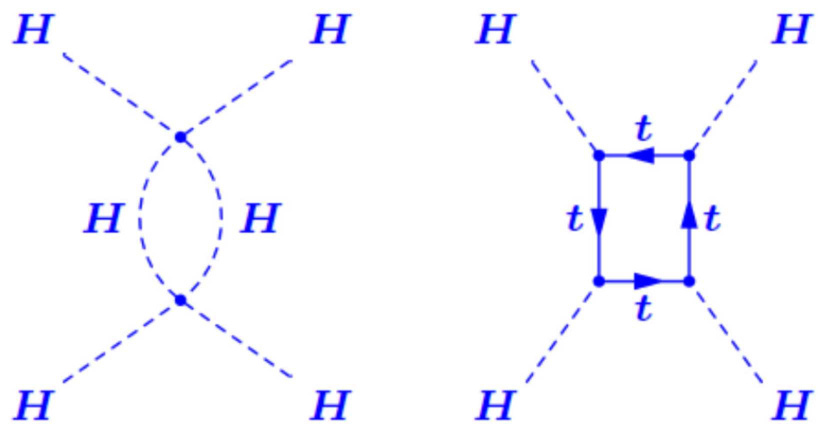
Running couplings and $\beta -$functions:

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

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

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Don't like a too quick End of the World

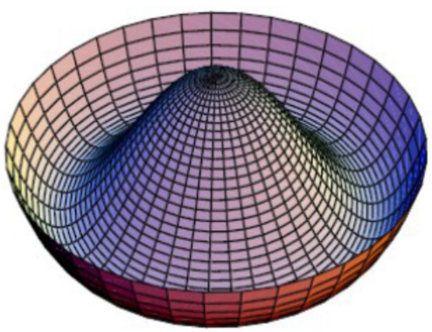
$$\rightarrow \lambda\left(\nu^2\right) > \frac{3h_t^4}{4\pi^2} \ln\frac{Q^2}{\nu^2} \rightarrow \frac{G_F m_H^2}{\sqrt{2}} > \frac{3h_t^4}{4\pi^2} \ln\frac{Q^2}{\nu^2}$$ for some $Q \sim \Lambda$

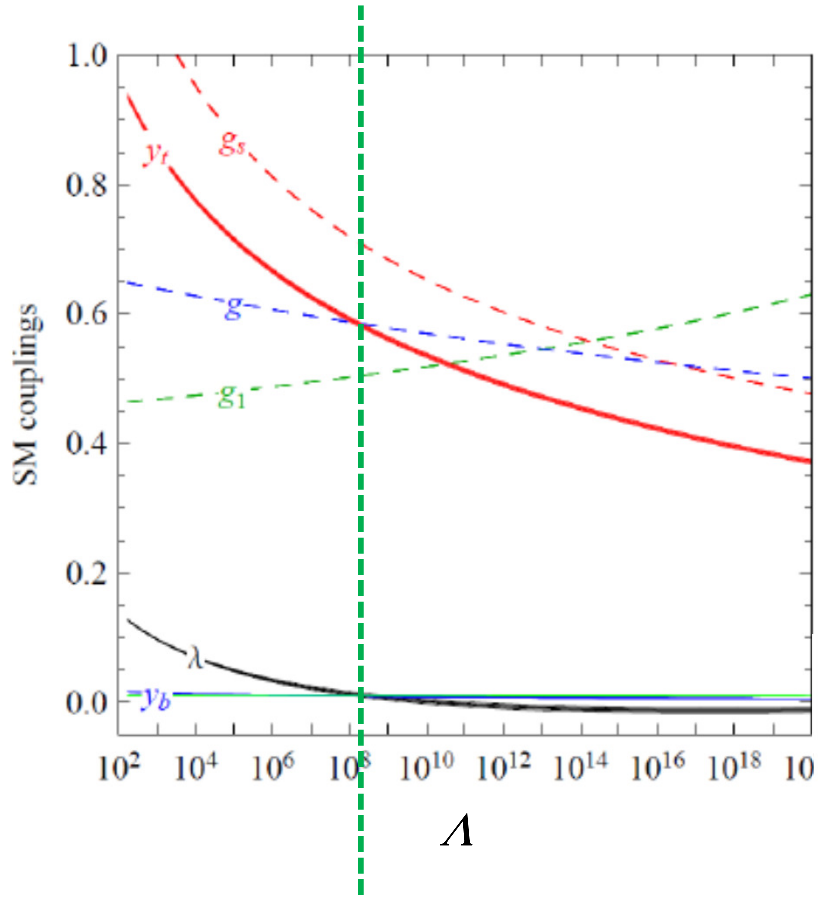
$$\rightarrow m_H > \left(\frac{3h_t^4}{\sqrt{2}\pi^2 G_F} \ln\frac{\Lambda}{\nu}\right)^{1/2}$$

About the Higgs Field - XI

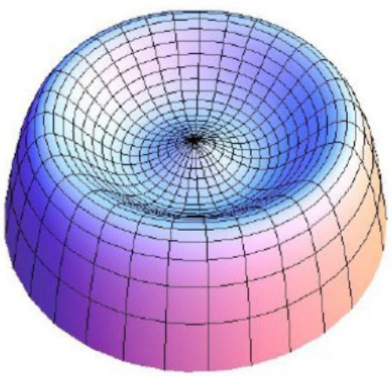
Running couplings:

Sombrero: $\lambda>0$
Relax





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

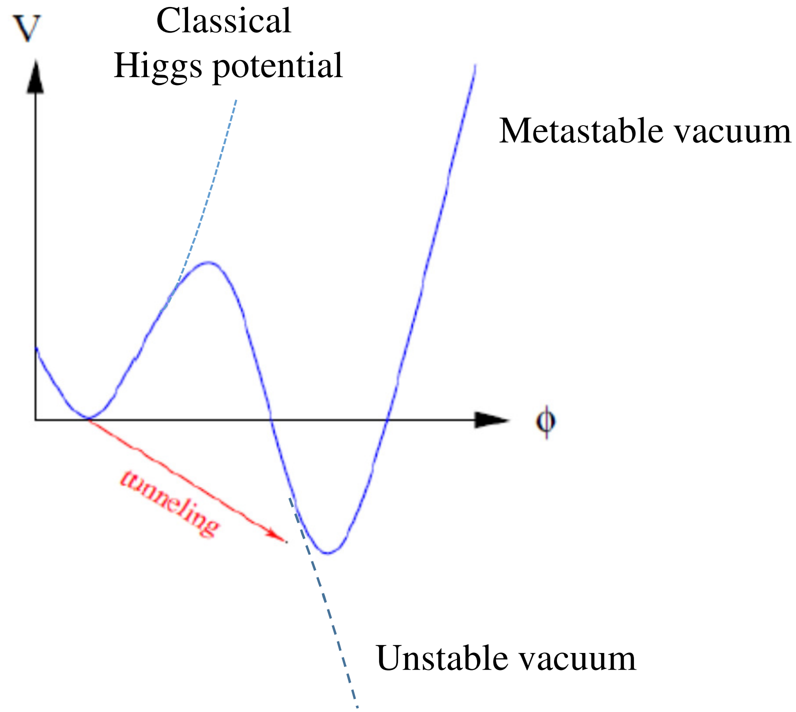


About the Higgs Field - XI

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

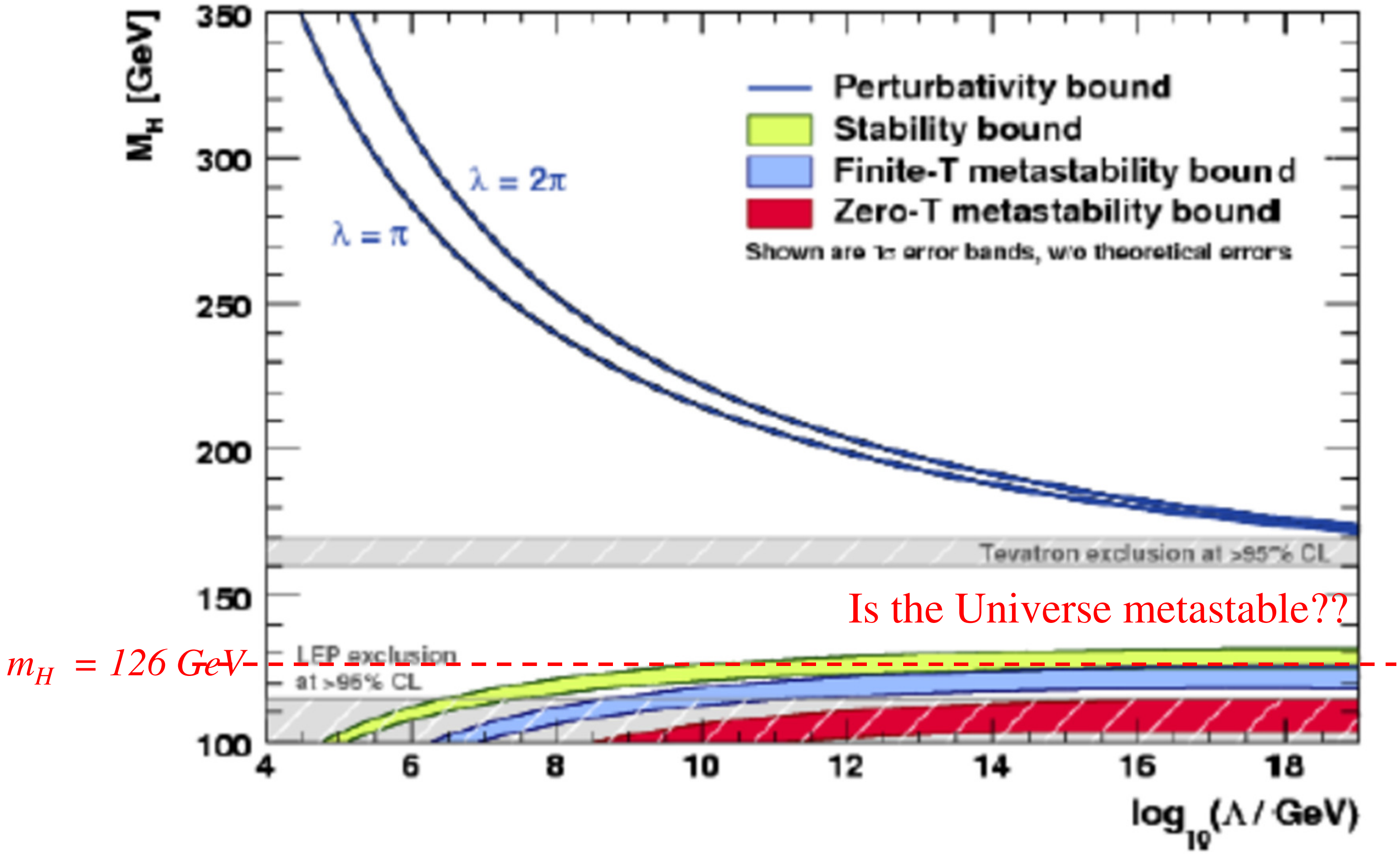
Details tied to m_H, m_t

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

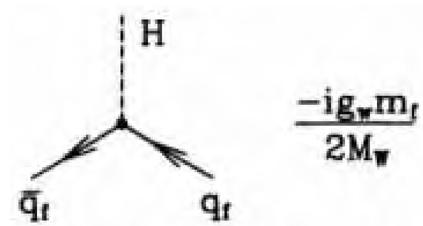
Compare rates, backgrounds

$\longrightarrow$ Sensitivity

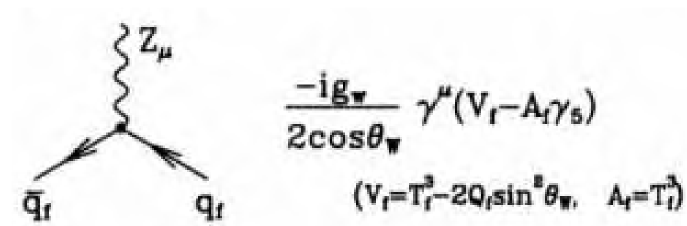
$\longrightarrow$ Further observables (Spin/Parity, Width, Branching Ratios,..)

Higgs Production - I

Start from H coupling to Fermions:



Compare to coupling to Z^0 :

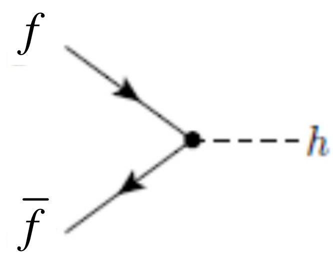


$\rightarrow H$ coupling down by a factor $\sim \frac{m_f}{m_W}$ as compared to Z^0

Higgs Production - II

First mode:

s-channel formation:



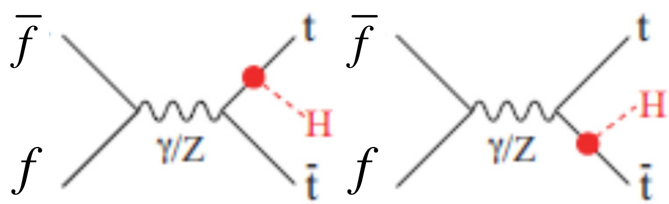
Ideal for lineshape scan, provided cross-section is big enough

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

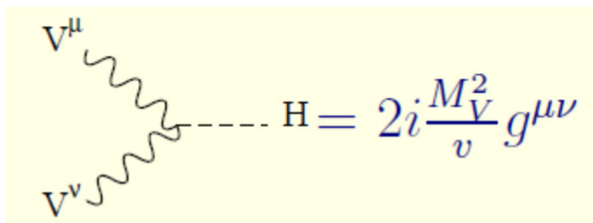
Higgs Production - IV

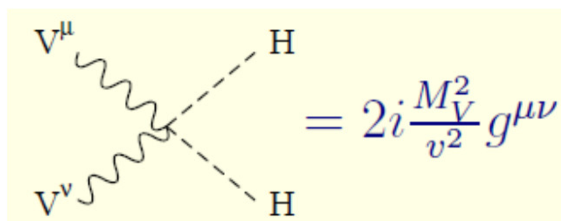
Shift to gauge bosons:

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

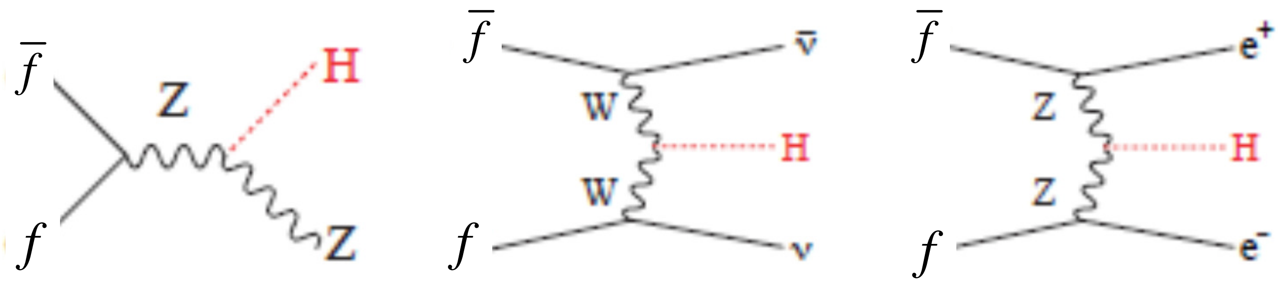




Higgs Production - V

Best modes:

'Higgsstrahlung', 'Gauge boson fusion'

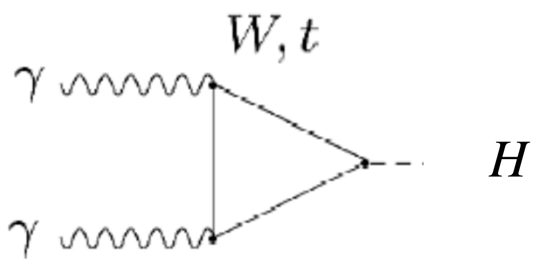


Higgs Production - VI

Beyond tree level: Very Important Loops

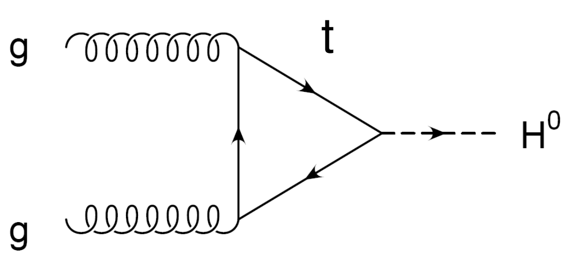
Lepton machines:

Interesting diagrams, also quite relevant to detection

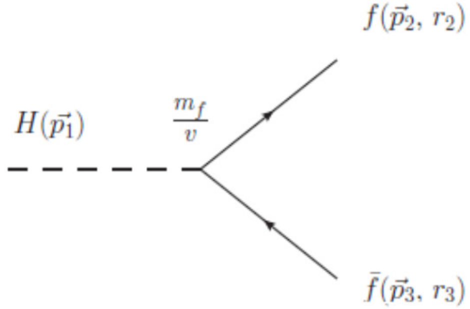


Parton machines:

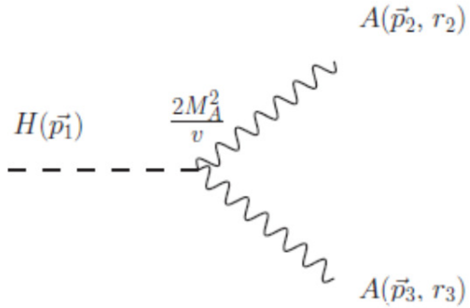
Dominant diagram at LHC



Higgs Decays - I



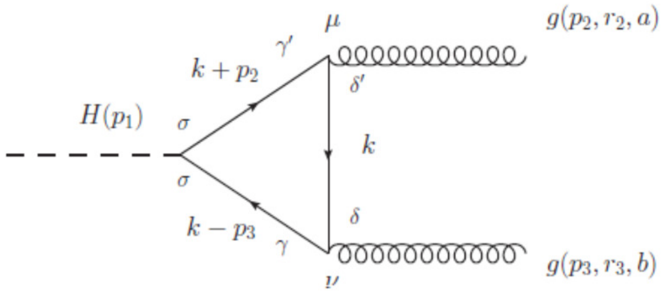
$$\Gamma(H \to f\bar{f}) = N_C \frac{1}{8\pi}\frac{m_f^2}{v^2} M_H (1 - \frac{4m_f^2}{M_H^2})^{3/2}$$

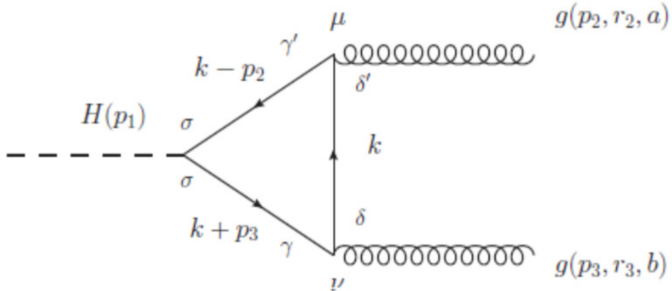


$$\Gamma(H \to WW) = \frac{1}{4\pi}\frac{M_W^4}{M_H v^2}\left(1 - \frac{4M_W^2}{M_H^2}\right)^{1/2}\left(3 + \frac{1}{4}\frac{M_H^4}{M_W^4} - \frac{M_H^2}{M_W^2}\right)$$

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

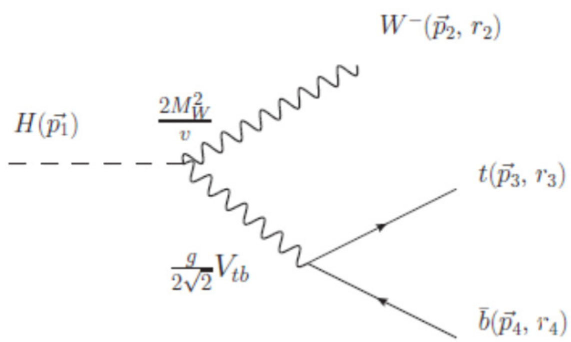
Higgs Decays - II





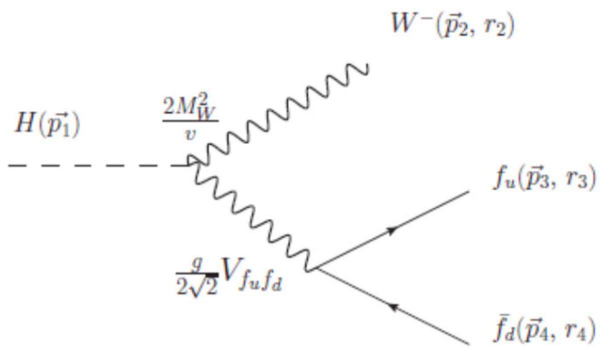
$$\Gamma(H \to gg) = \frac{M_H^3}{8\pi\, v^2}\left(\frac{\alpha_s}{\pi}\right)^2 n^2\, |D(n)|^2$$

Higgs Decays - III



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

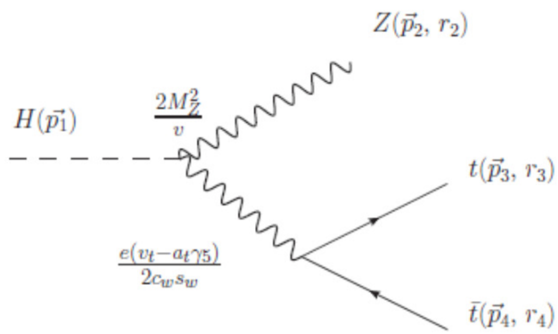
3-body phase space factor



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

3-body phase space factor

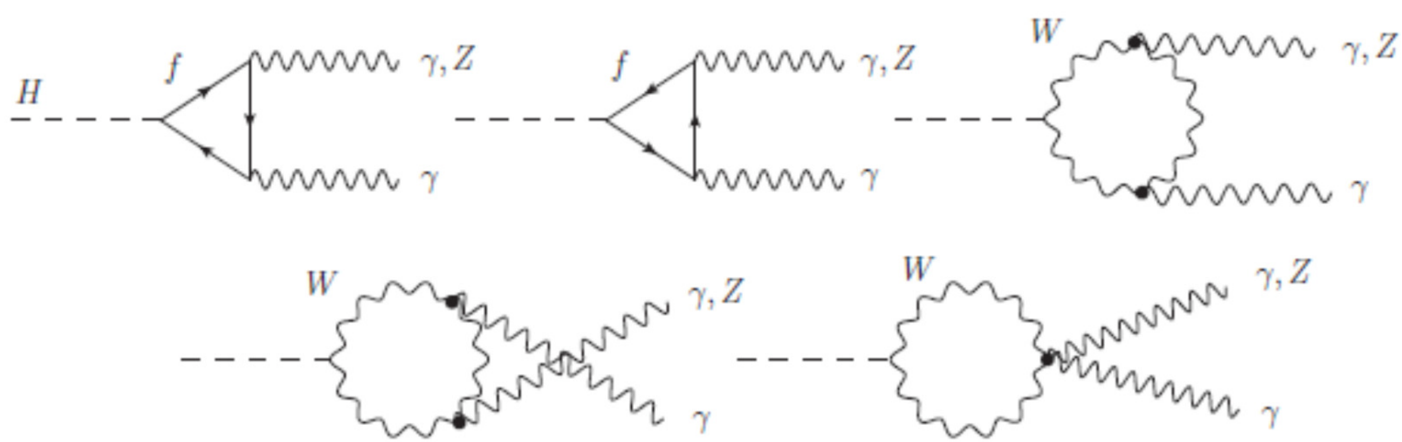
Higgs Decays - IV



$$\Gamma(H \to Z f \bar{f}) = \frac{g^2}{v^2} \frac{3M_Z^2}{256\,\pi^3} M_H \, S(x) \frac{R(\theta_w)}{\cos^2\theta_w}$$
$$\left(\frac{7}{12} - \frac{10}{9}\sin^2\theta_w + \frac{40}{27}\sin^4\theta_w\right)$$

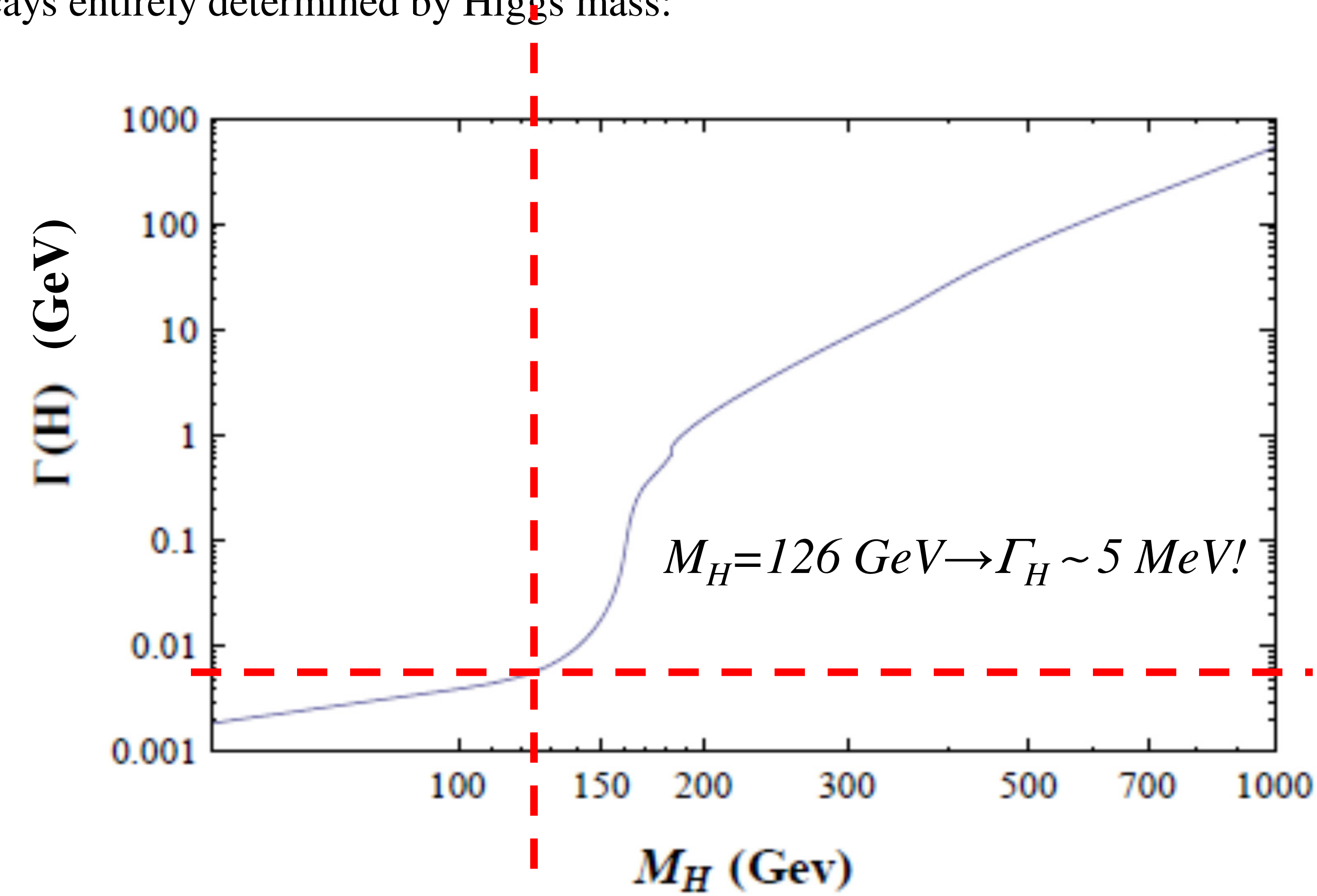
3-body phase space factor

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



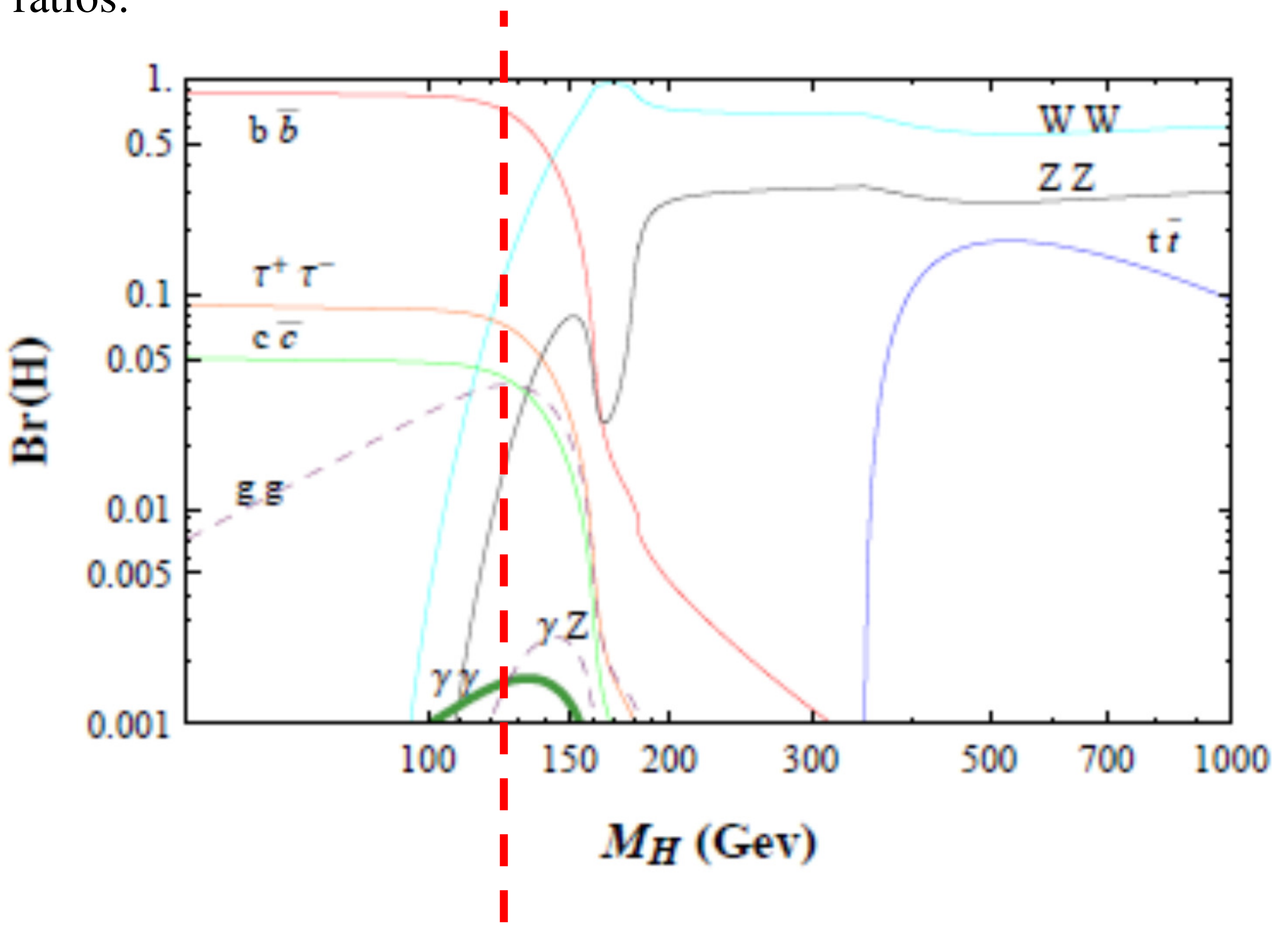
Higgs Decays - V

H decays entirely determined by Higgs mass:

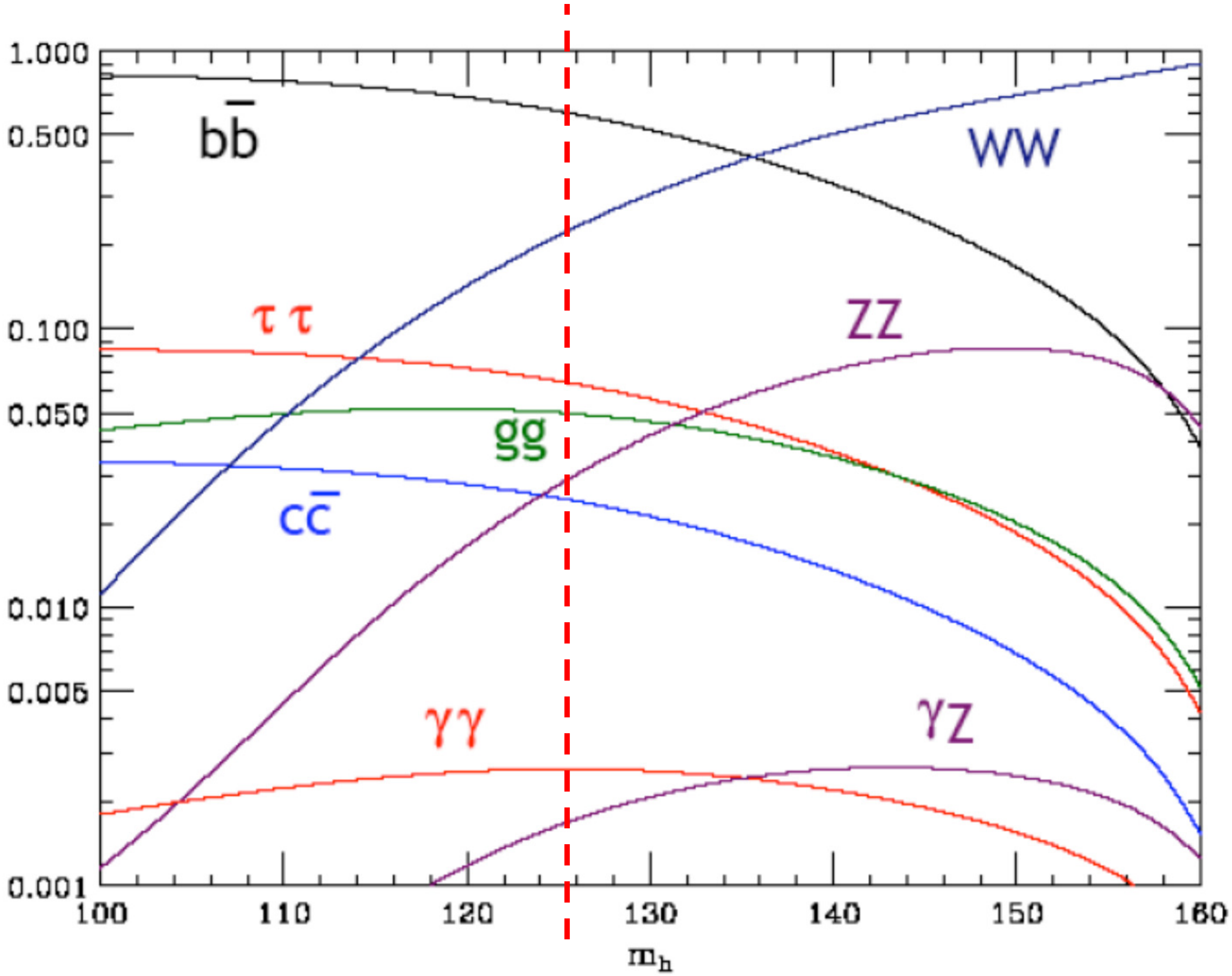


Higgs Decays - VI

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

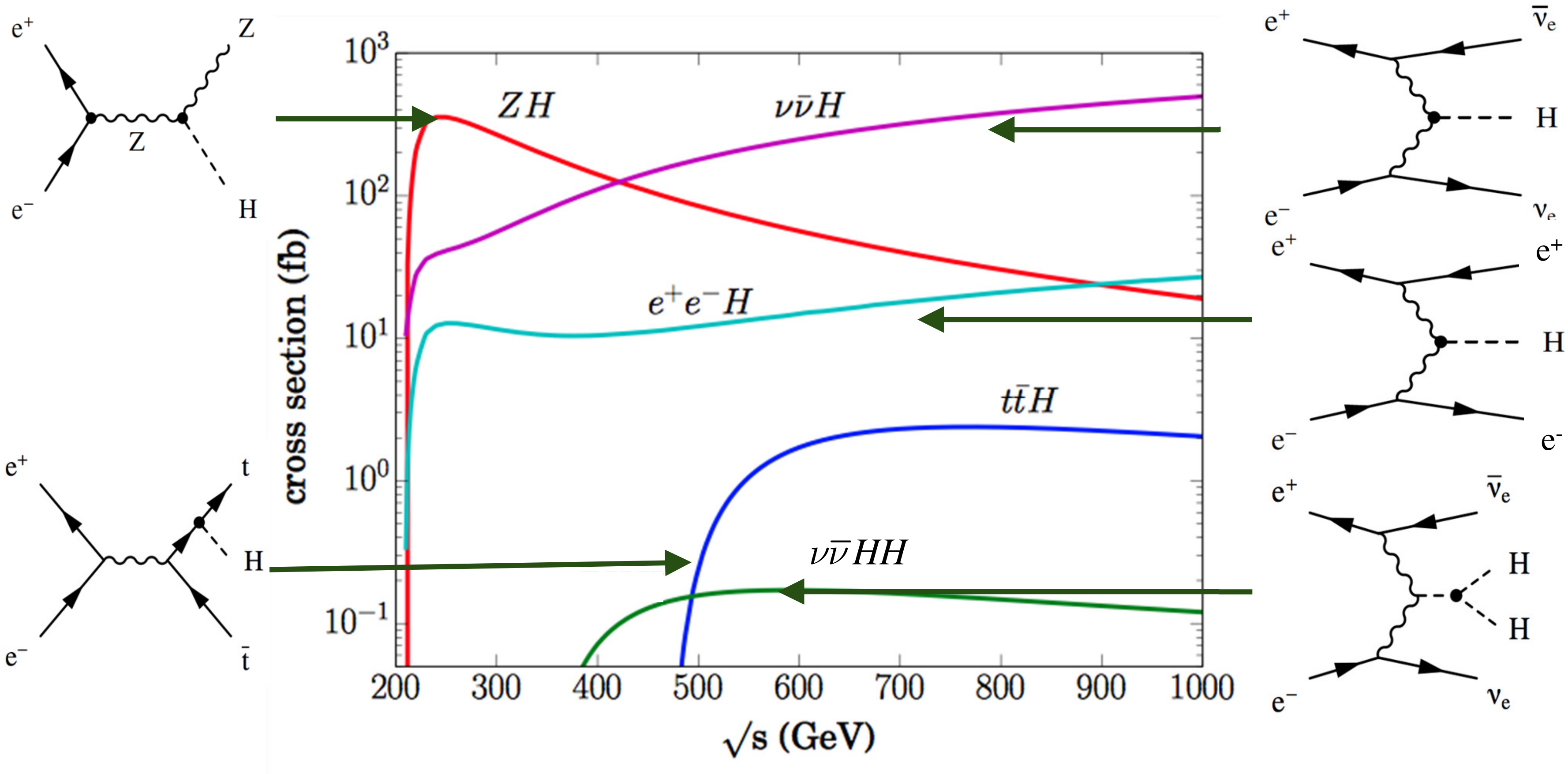
Better chance for a $\mu^- \mu^+$ collider

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

Other channels more promising

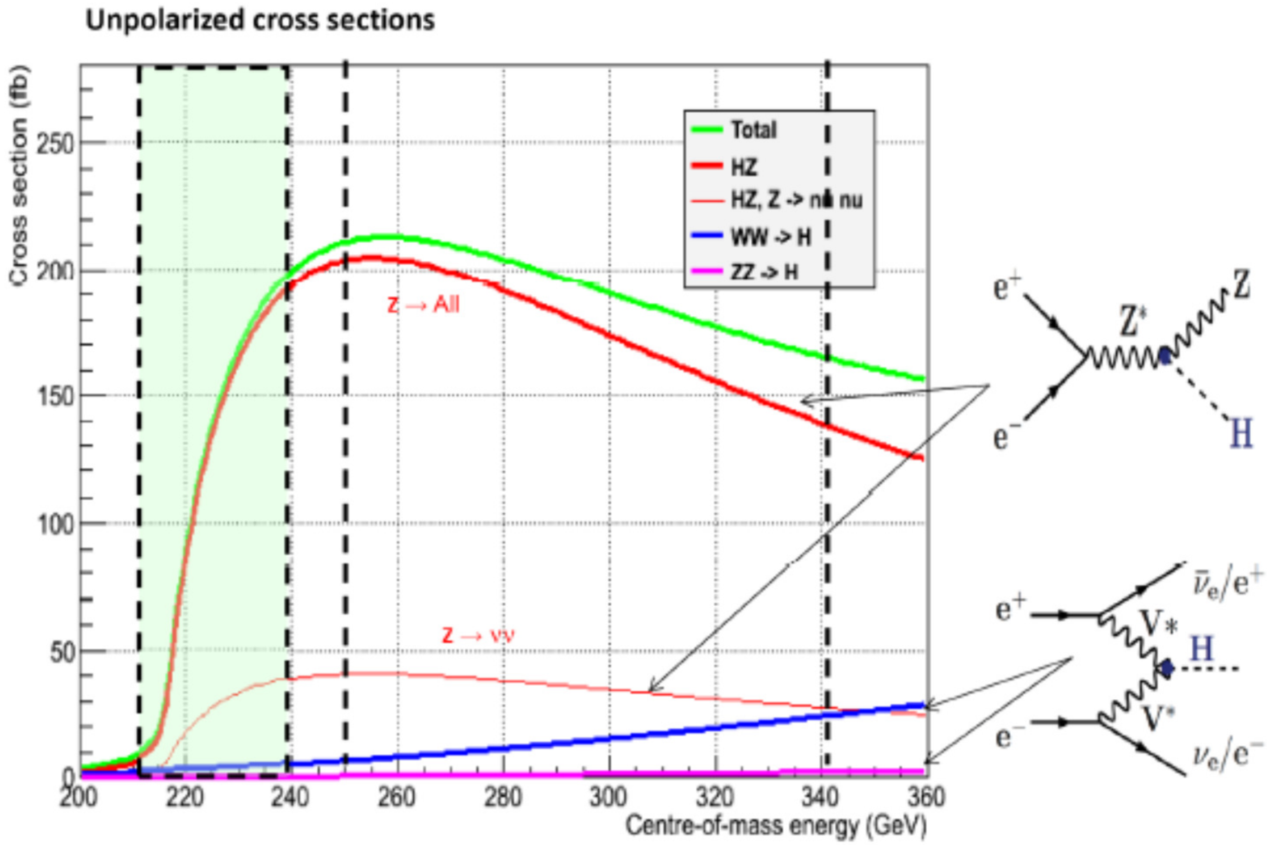
Lepton Collider - II

Electron collider: Tree level contributing diagrams



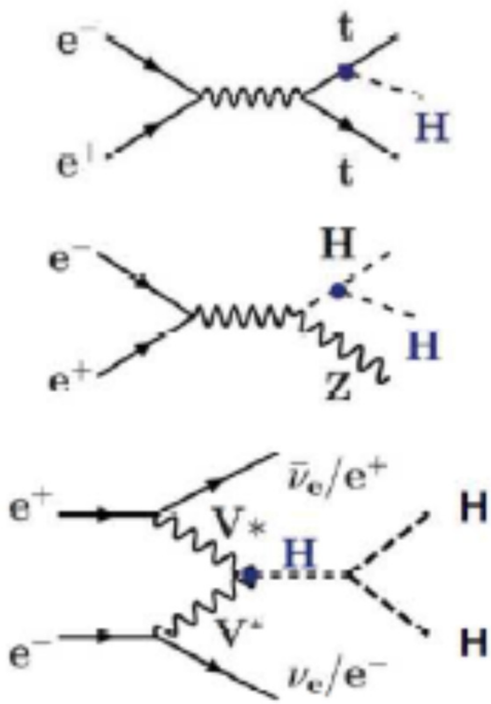
Lepton Collider - III

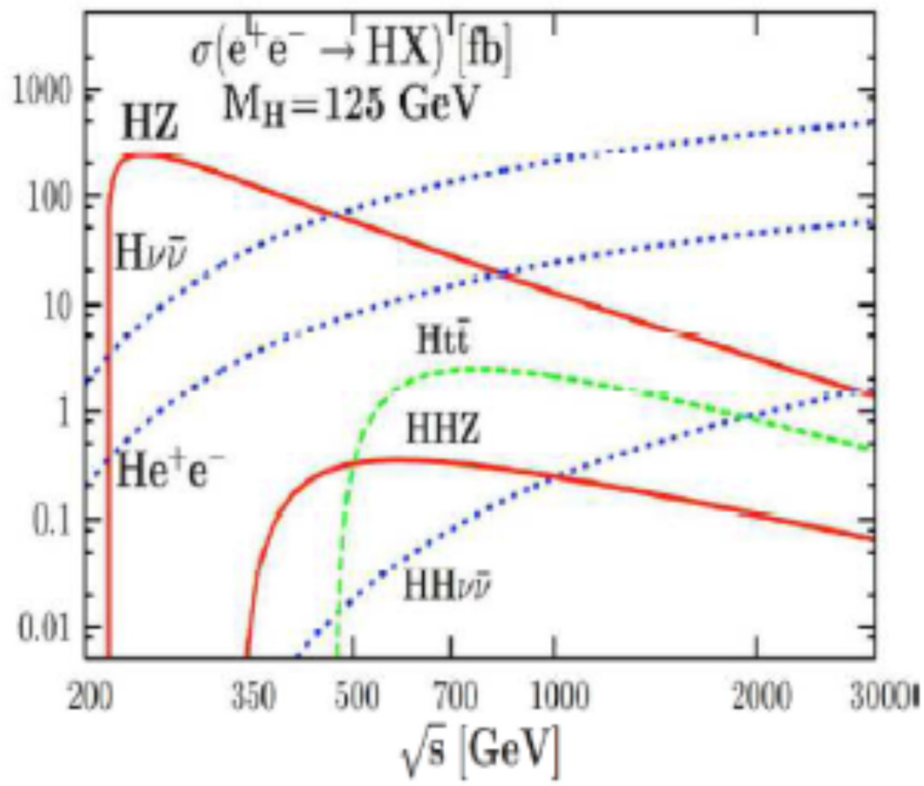
Electron collider: 'Low energy' option



Lepton Collider - IV

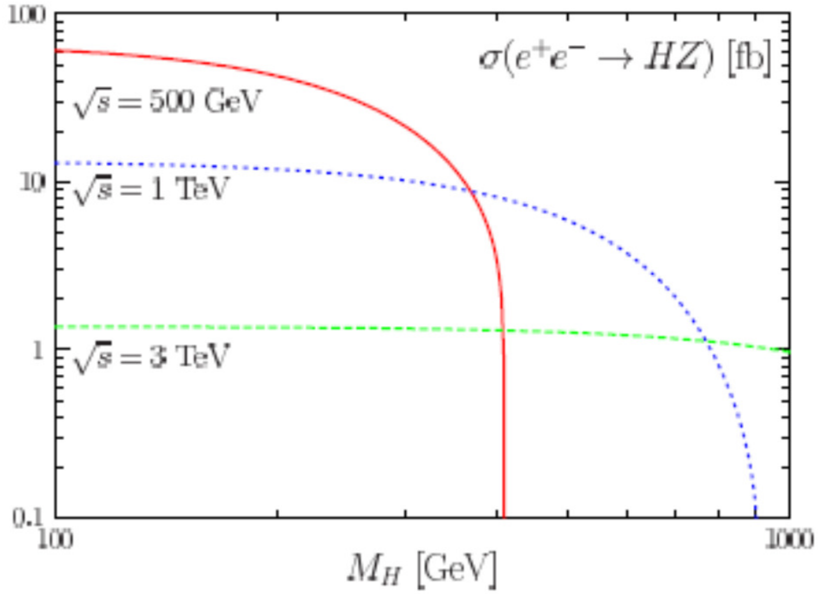
Electron collider: 'High energy' option

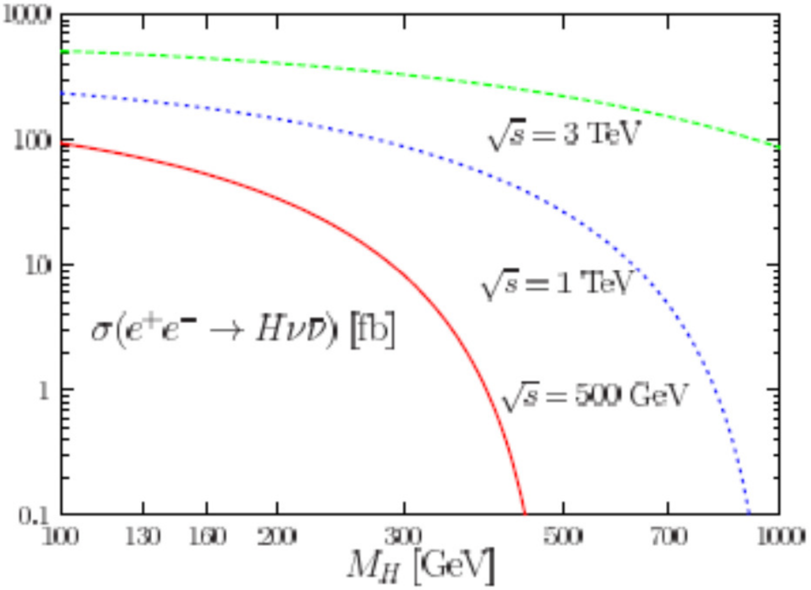




Lepton Collider - V

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)

Lepton Collider - VII

Circular collider: Two main issues, among many

Bending field: Must keep the beam on orbit

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

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

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

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

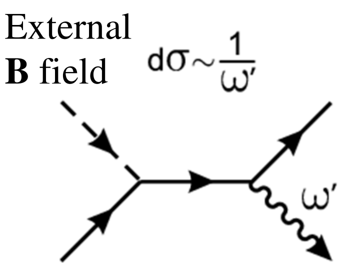
$\rightarrow$ Max. energy gain $\sim 128*3 \sim 375 MeV/turn$; RF max power $\sim 125\ kW/cavity$

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



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:

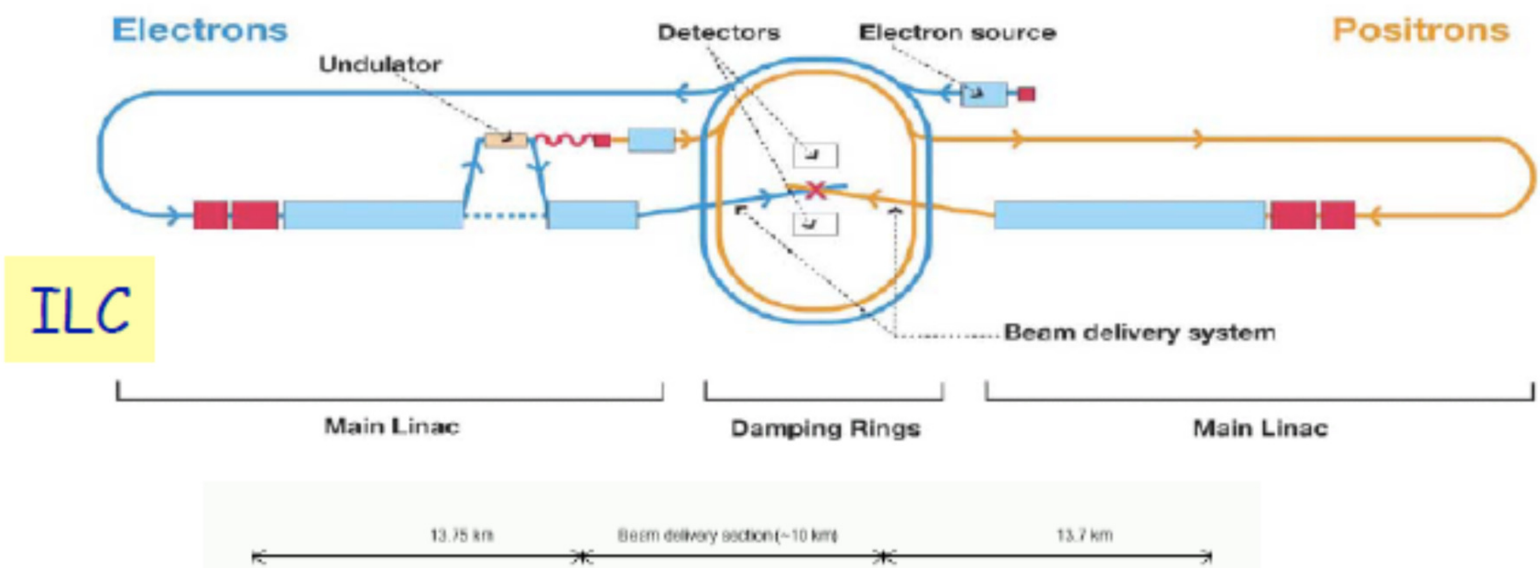
$$P(kW) = \frac{e\gamma^4}{3\varepsilon_0 R} I_b = \begin{cases} 88.5 \dfrac{E(GeV)^4}{R(m)} I_b(A) & \text{Electrons} \\ 6.03 \dfrac{E(TeV)^4}{R(m)} I_b(A) & \text{Protons} \end{cases}$$

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

Lepton Collider - IX

Electron collider: Linear

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

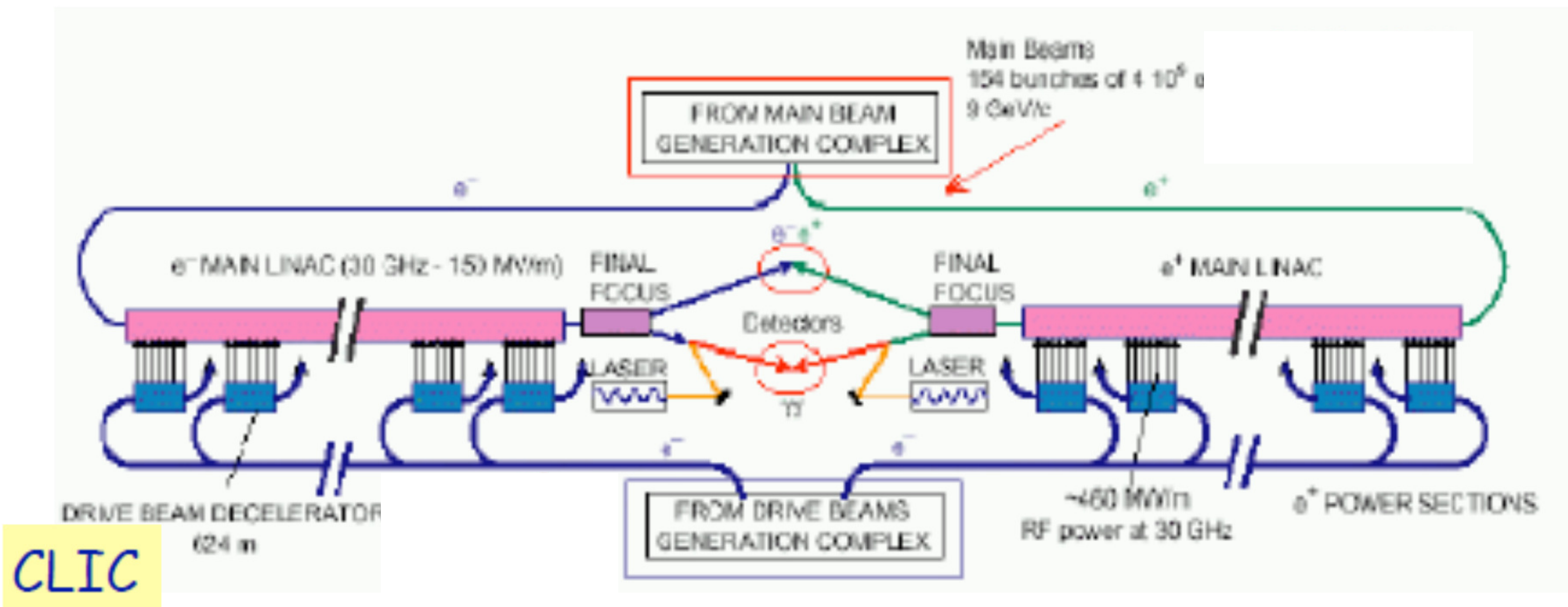


- Superconducting RF cavities
- Gradient 32 MV/m
- $\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
- L ~ 2 10^{34} $cm^{-2}s^{-1}$
- Focus on ≤ 500 GeV, physics studies also for 1 TeV
- Length ~ 31 km (500 GeV)

Lepton Collider - X

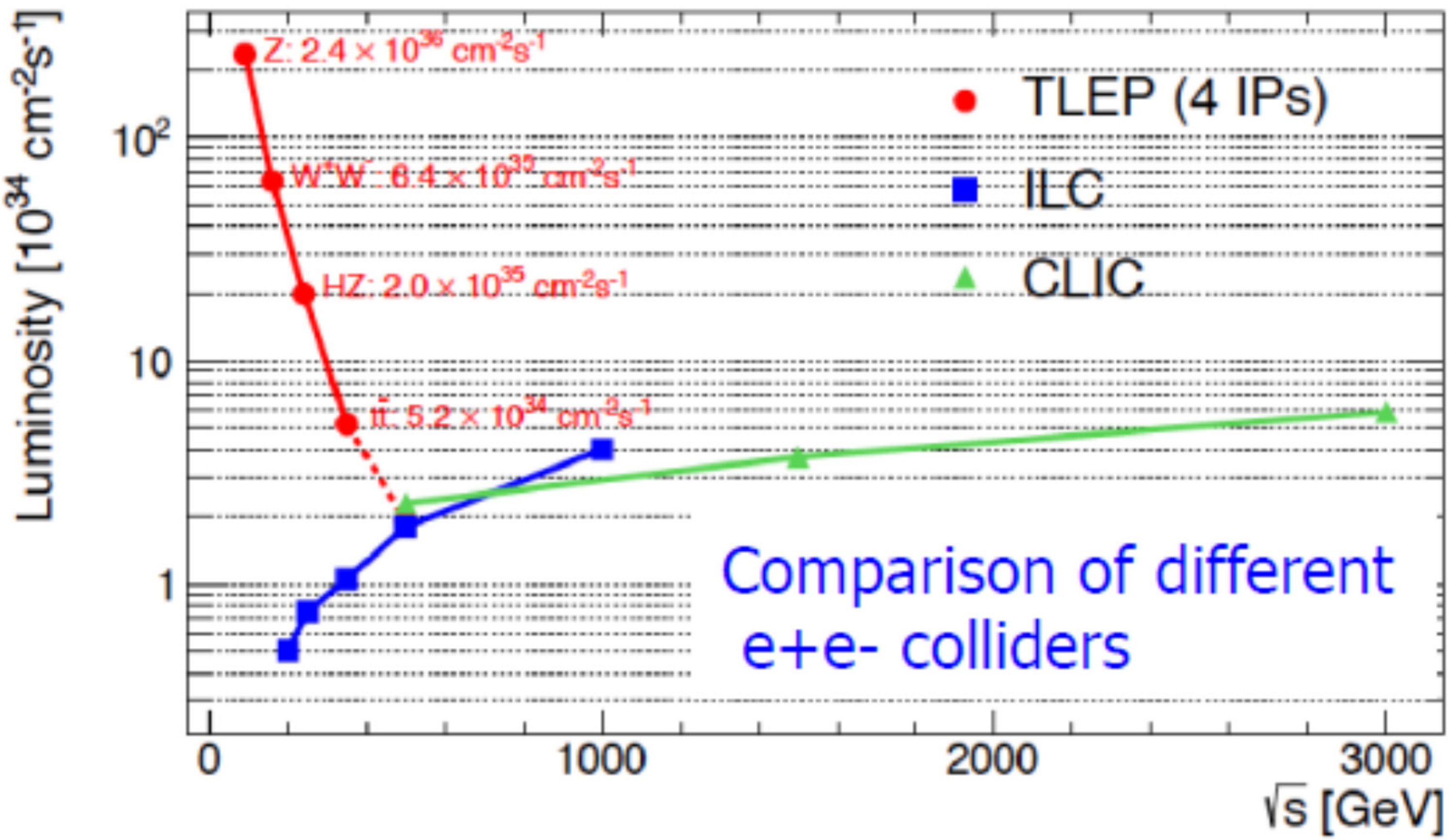
Electron collider: Linear

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



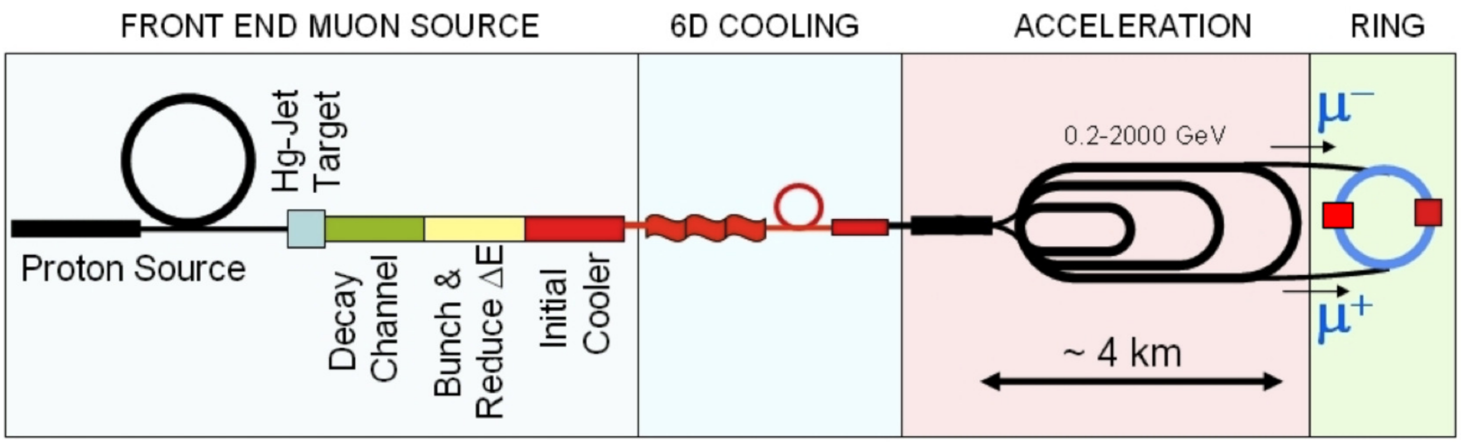
- Copper RF cavities
- Gradient 150 MV/m (!)
- $\sqrt{s}$ = 3 TeV
- L ~ 6 10^{34} $cm^{-2}s^{-1}$
- Length ~ 41 km (500 GeV)

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 ('*Beamstrahlung*' strongly suppressed)

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

Main requirements:

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

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

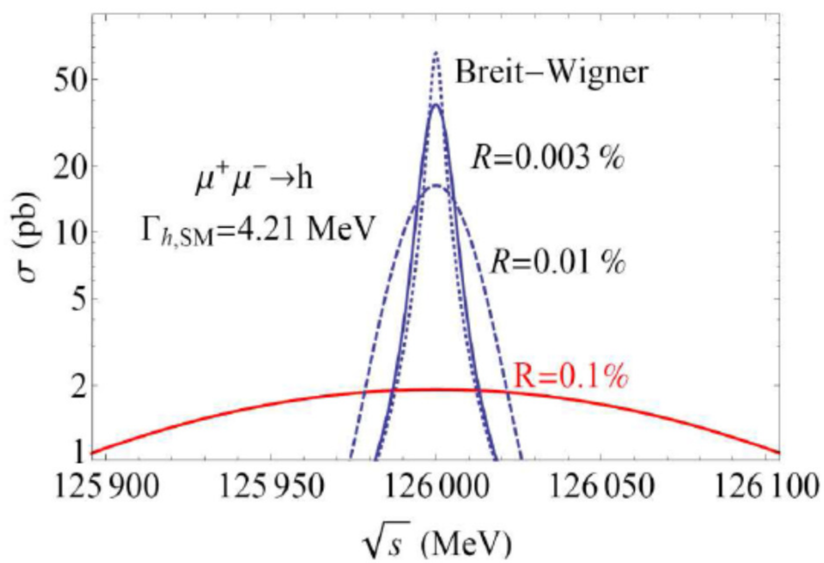
Lepton Collider - XIV

Breit-Wigner/Gaussian convolution:

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

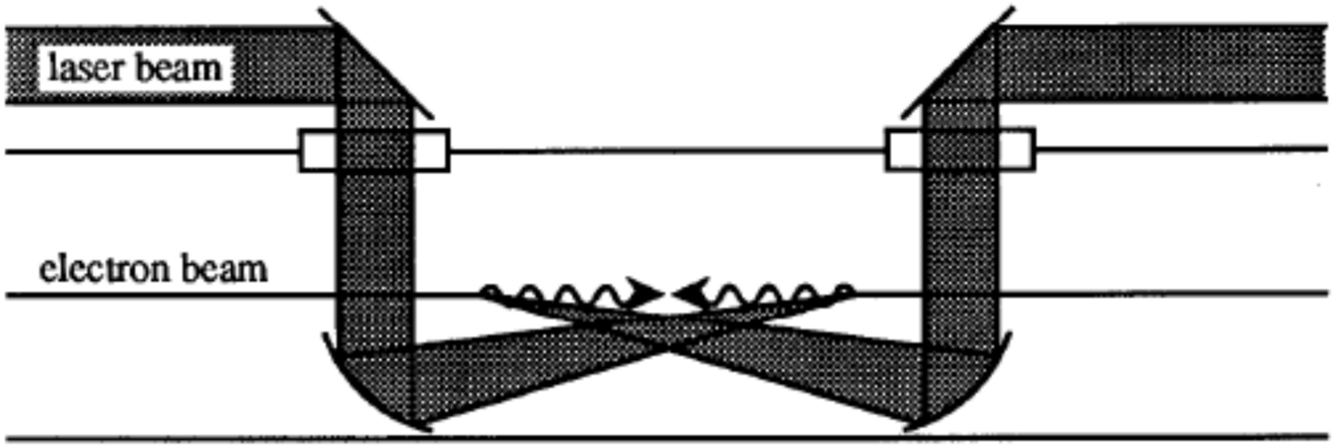
$$\sigma_{\rm eff}(s) = \int d\sqrt{\hat{s}}\,\frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}}\sigma(\mu^+\mu^- \to h \to X)$$

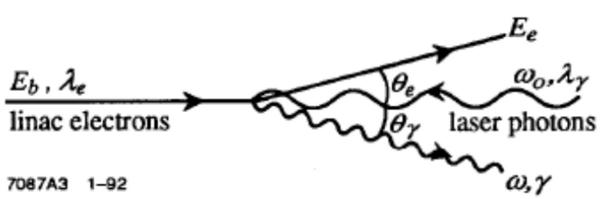
$$\propto \begin{cases} \Gamma_h^2 B/[(s-m_h^2)^2+\Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B\exp[\frac{-(m_h-\sqrt{s})^2}{2\Delta^2}](\frac{\Gamma_h}{\Delta})/m_h^2 & (\Delta \gg \Gamma_h). \end{cases}$$



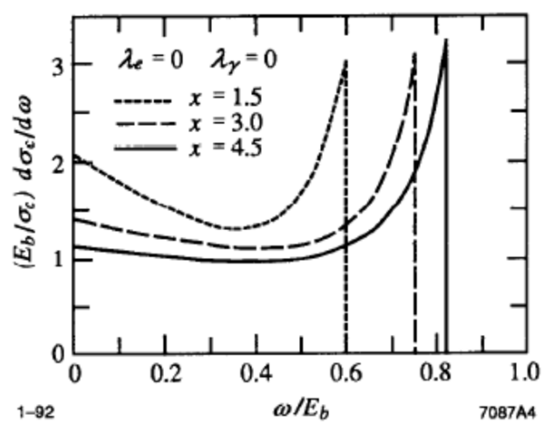
Photon Collider - I

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



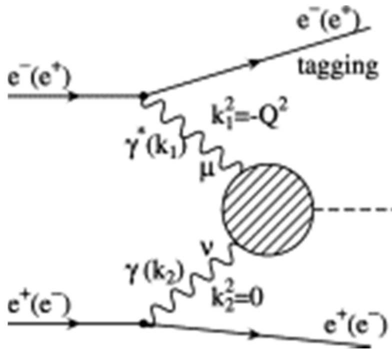


$$x \equiv (4E_b\omega_o/m_e^2)\cos^2(\alpha/2) \simeq 15.3\left(\frac{E_b}{\text{TeV}}\right)\left(\frac{\omega_o}{\text{eV}}\right)$$

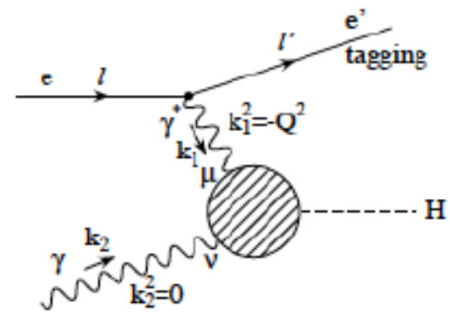


Photon Collider - II

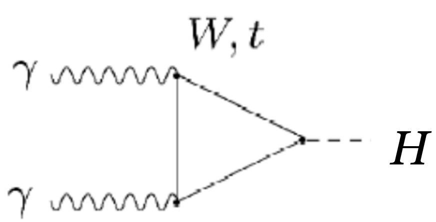
Virtual+Virtual photons



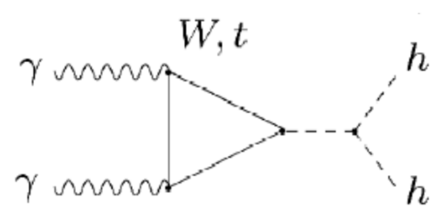
Virtual+Real photons



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

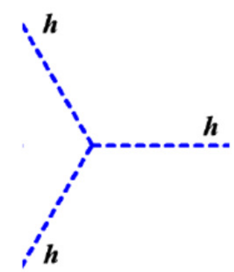
Higgs self-couplings: Very important for { radiative corrections to m_h; signs of new physics }

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

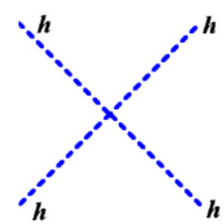
Re-writing L upon introducing shifted field, 1D example

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

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



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

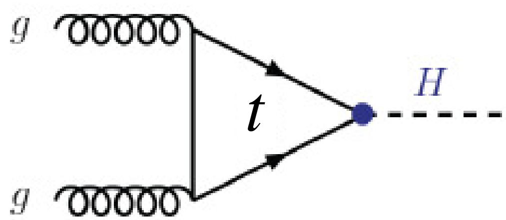


$-3im_h^2\sqrt{2}G_F\,hhhh$

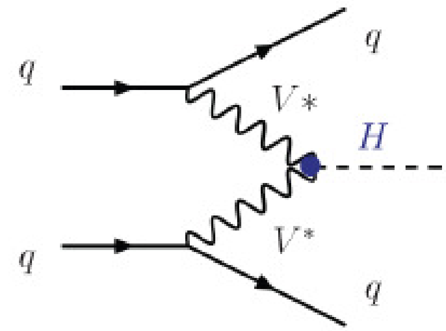
Parton Collider - I

Dominant diagrams for H production:

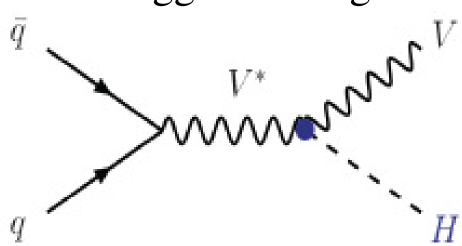
Gluon-Gluon fusion



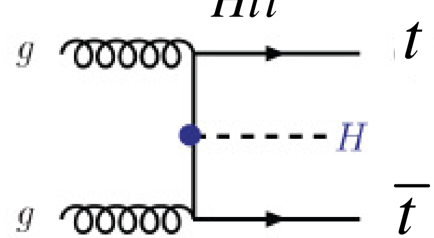
Vector Boson fusion



Higgsstrahlung



$Ht\bar{t}$



Parton Collider - II

Basic ingredient: PDFs

Quarks: Look for heavy ones

Tree diagrams: Best bet is with b

Factor $\dfrac{m_b^2}{M_W^2} \sim 3\ 10^{-3}$ 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 $x \sim 10^{-2}$

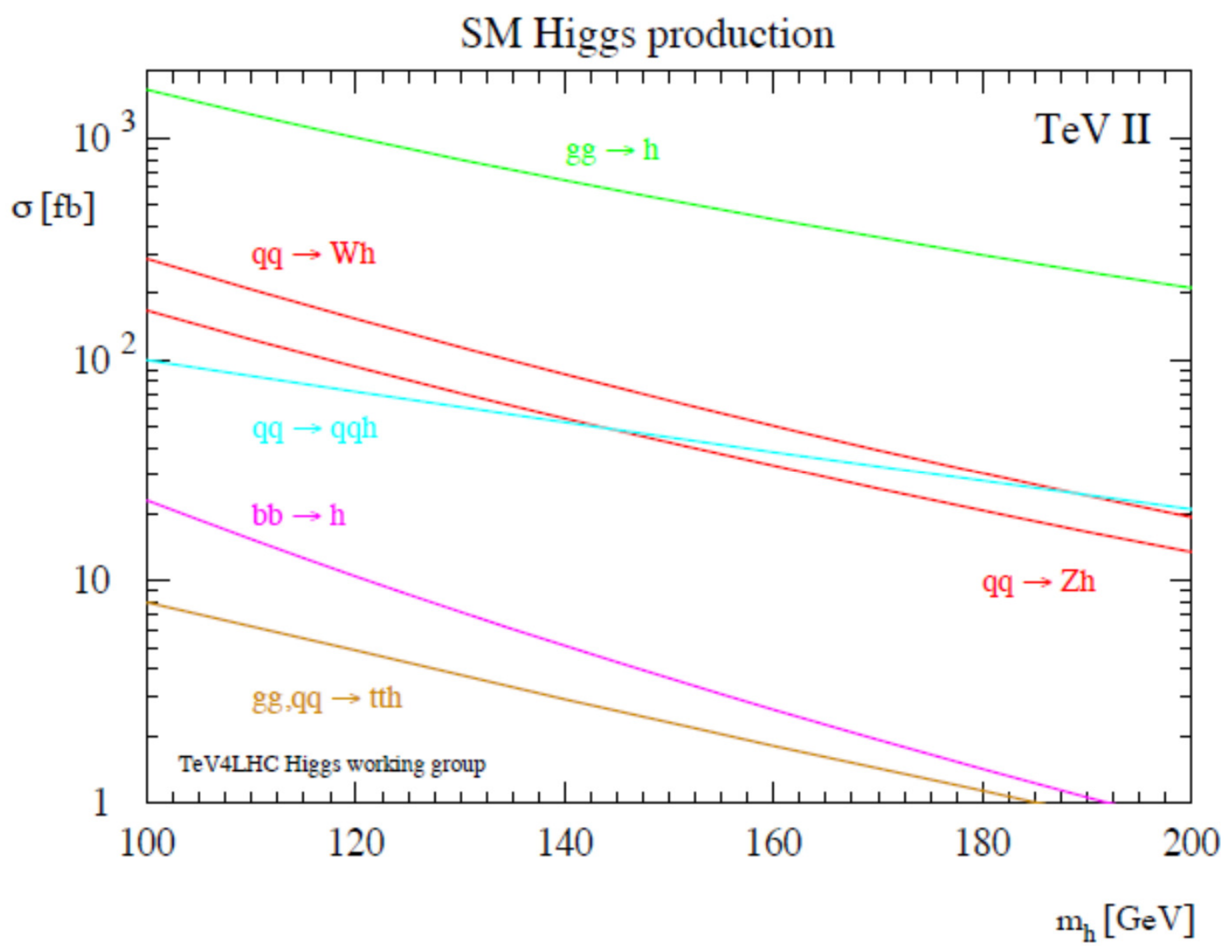
$\rightarrow$ Incident flux of sea b-quarks very small

Gluons: Main contribution

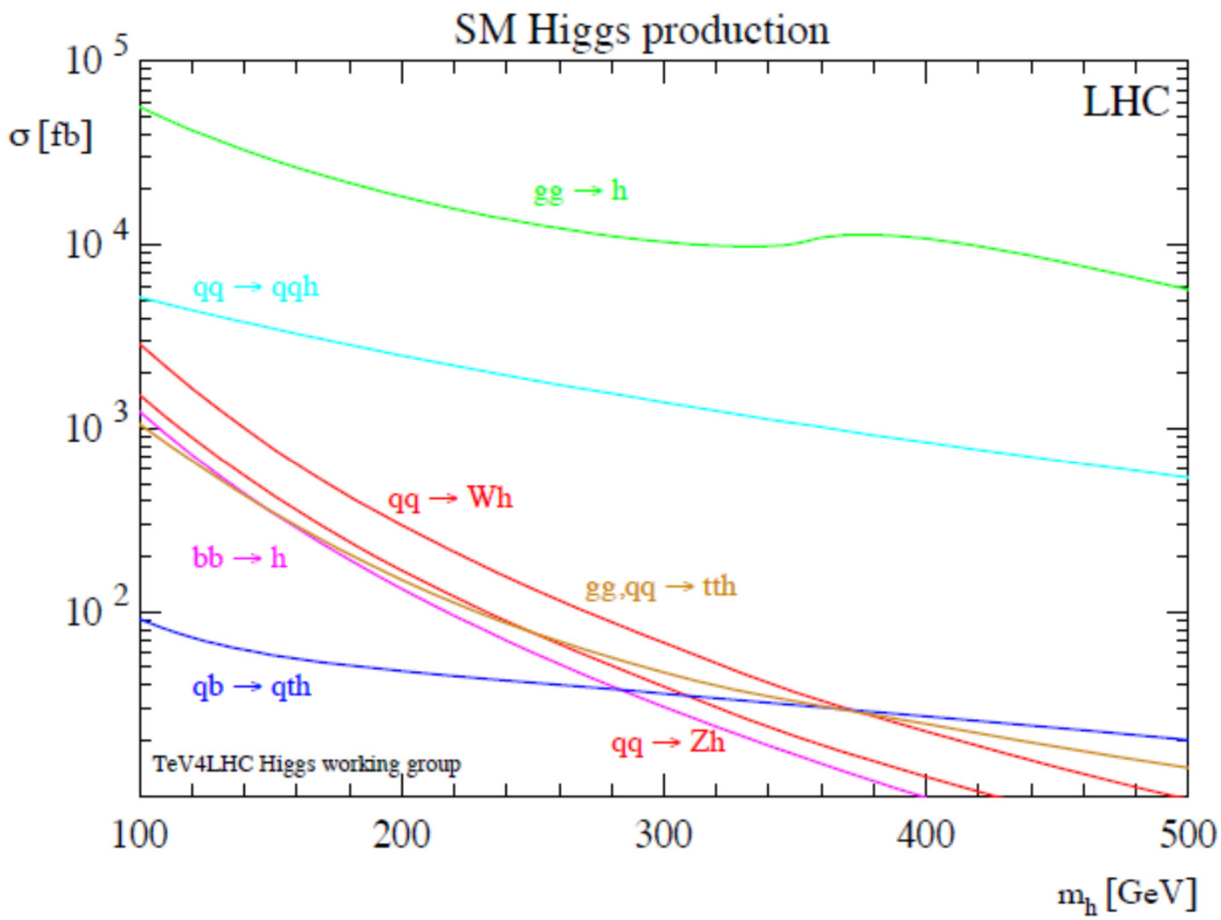
Loop diagrams, dominated by t quark

PDF somewhat dependent on Q^2

Parton Collider- III

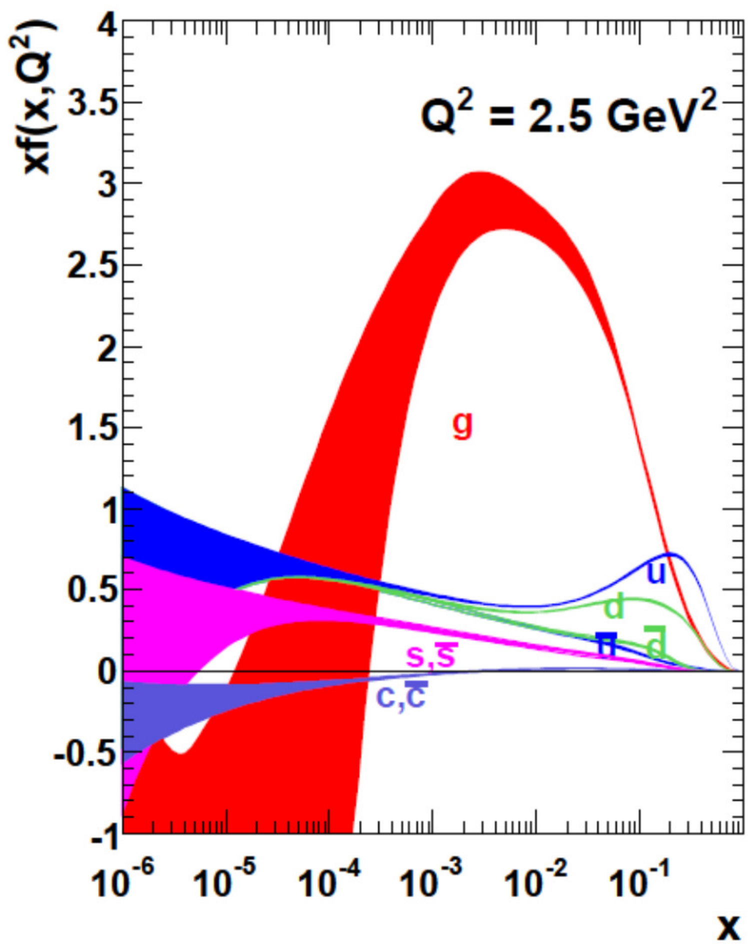


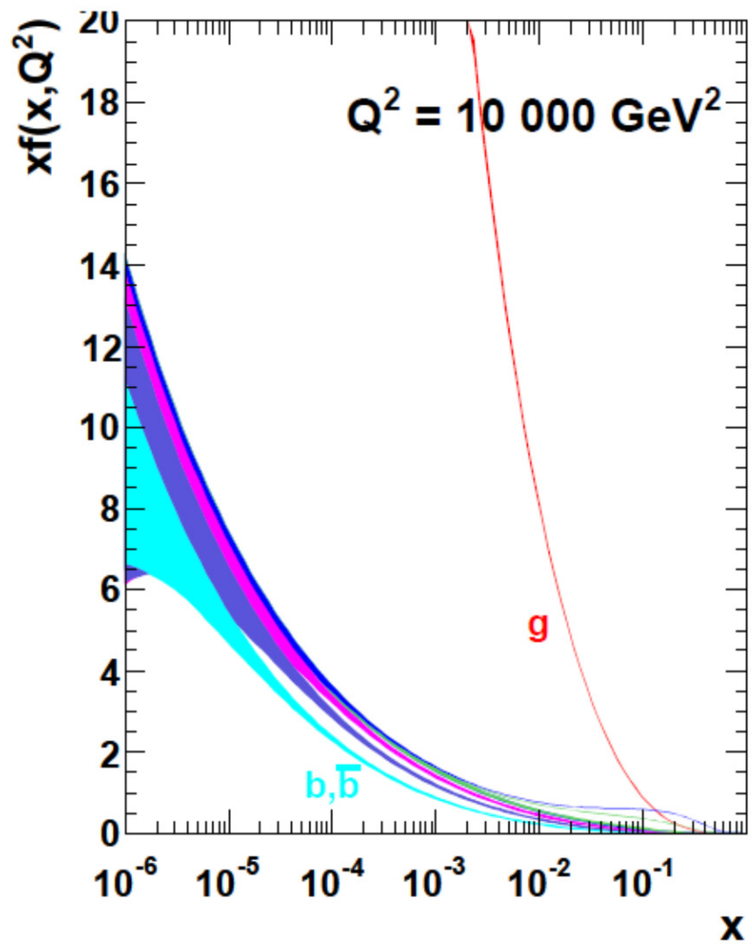
Parton Collider- IV



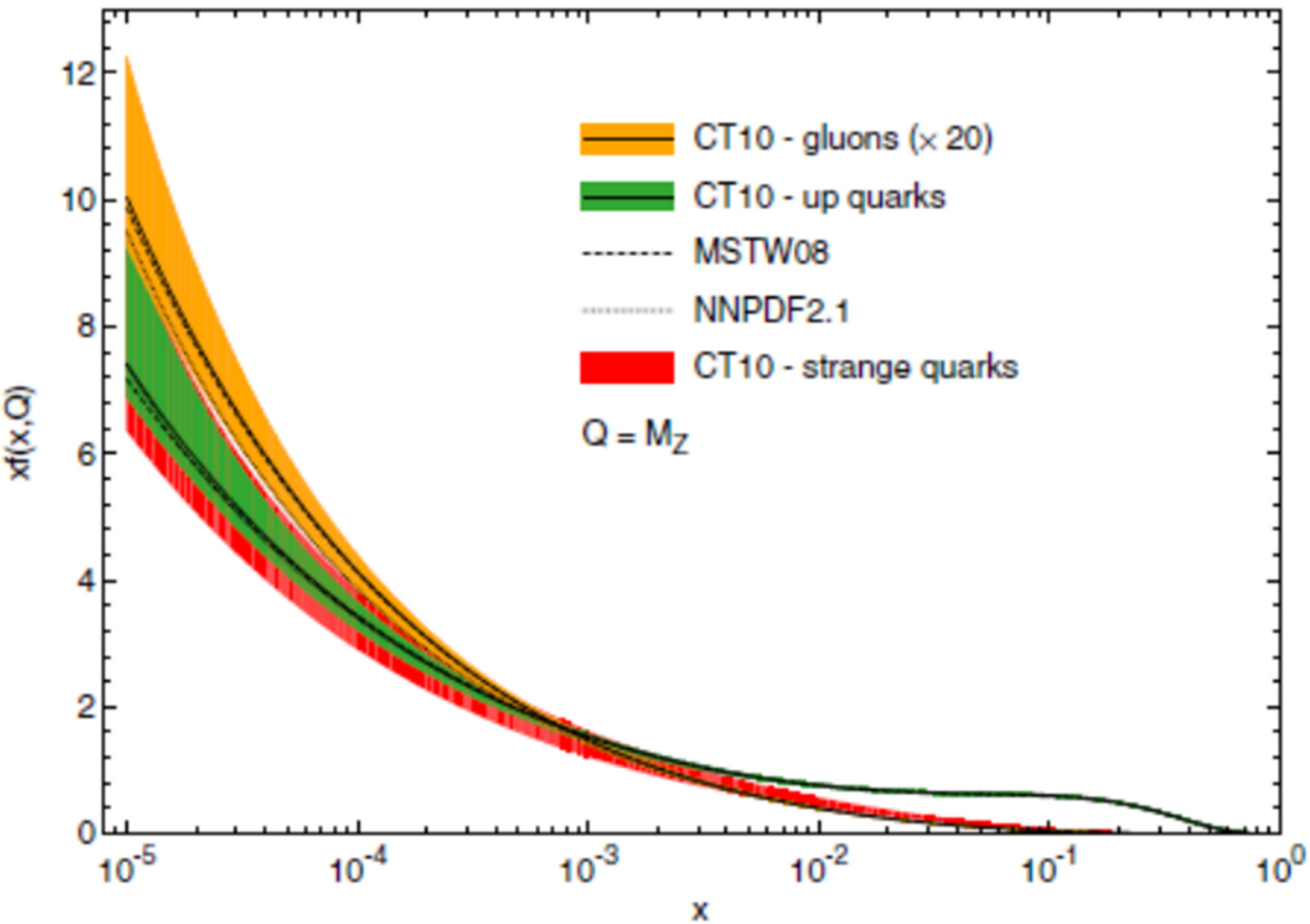
Parton Collider - V

Parton densities:



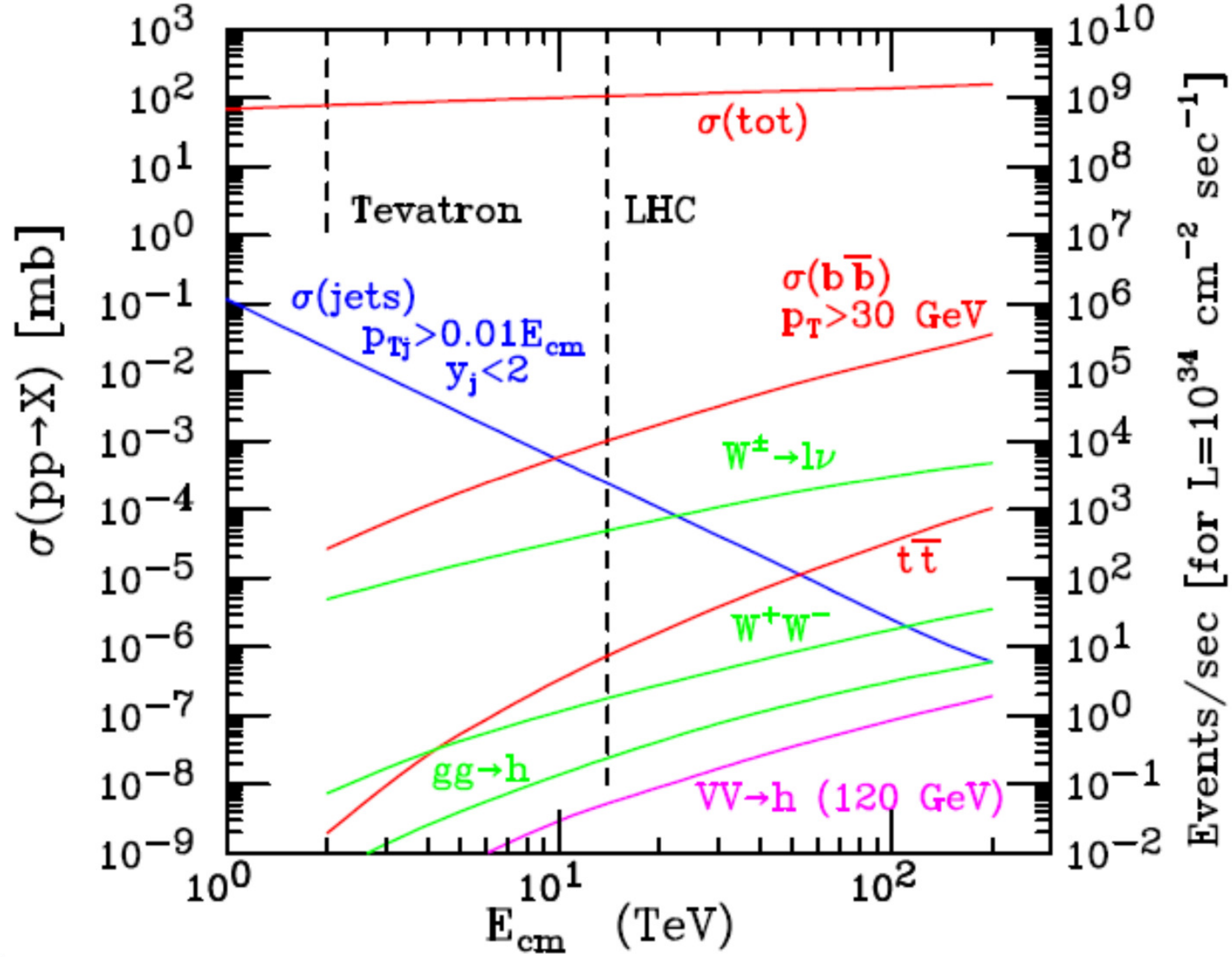


Parton Collider - VI



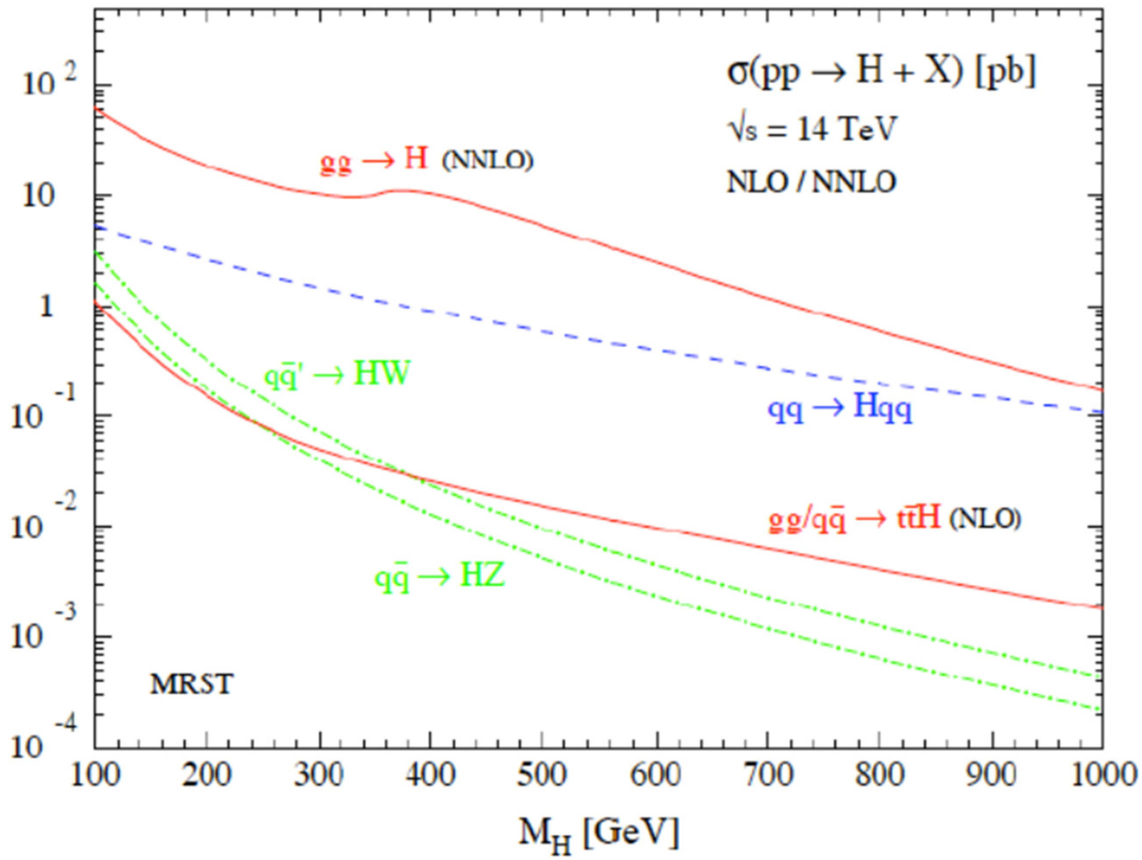
Parton Collider - VII

Expected cross sections for parton colliders:



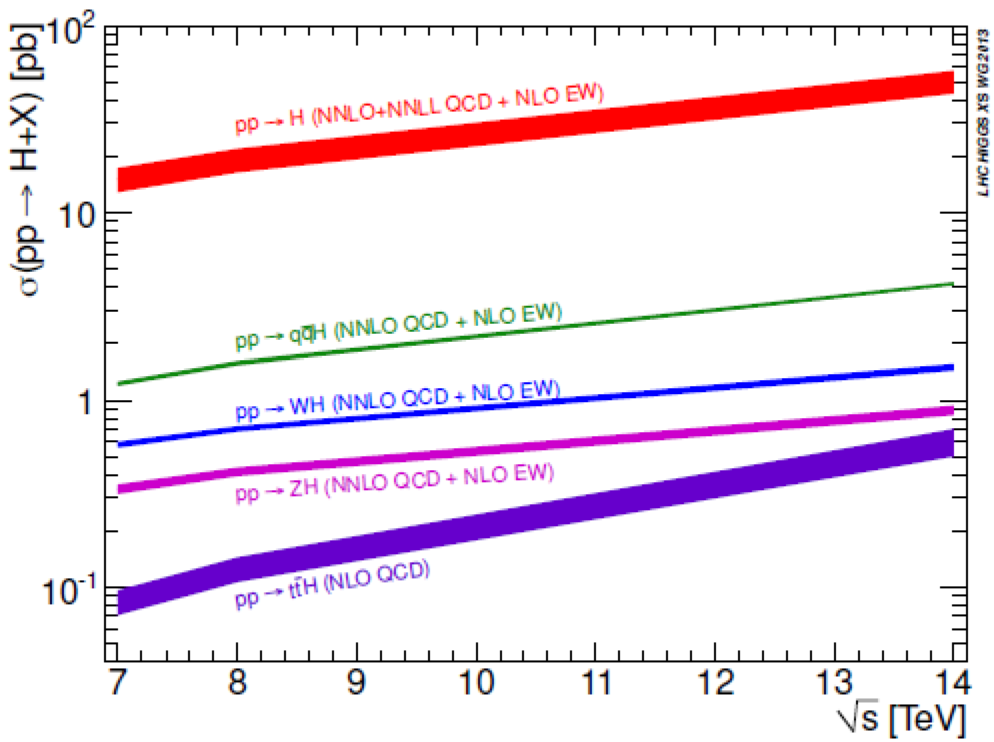
Parton Collider - VIII

Results for LHC cross sections



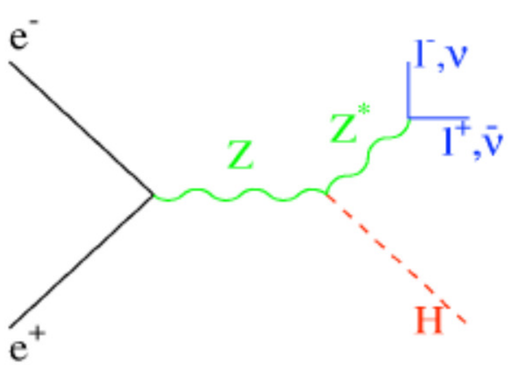
Parton Collider - IX

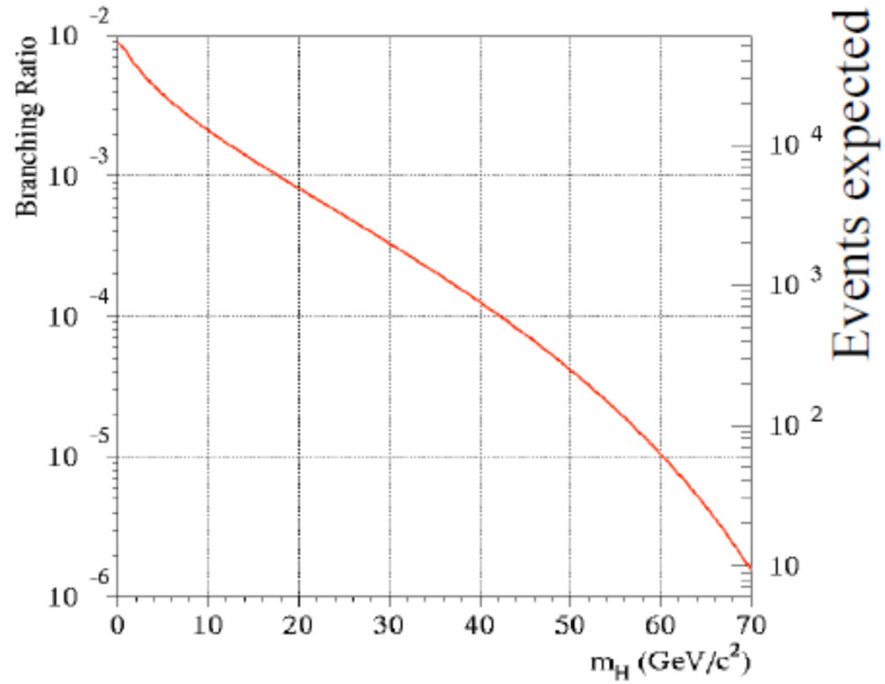
Cross-sections for a 126 GeV Higgs



H Searches - I

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



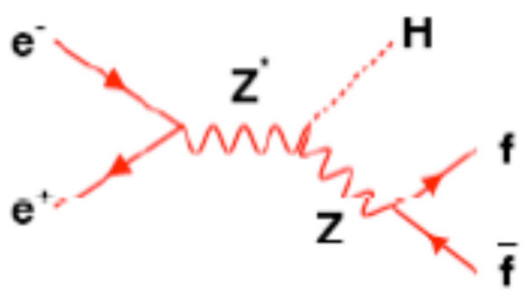


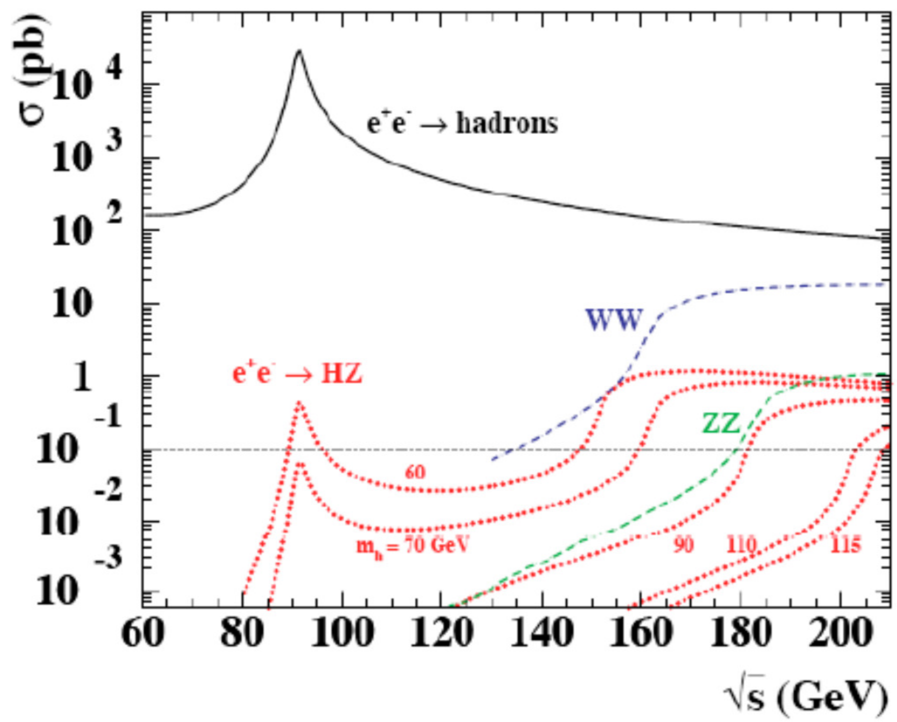
Final LEP I result:

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

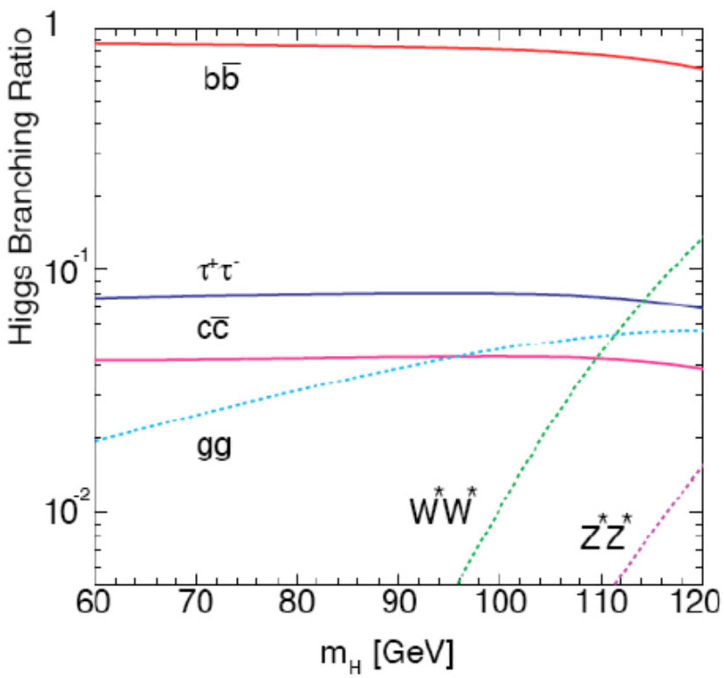
H Searches - II

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	

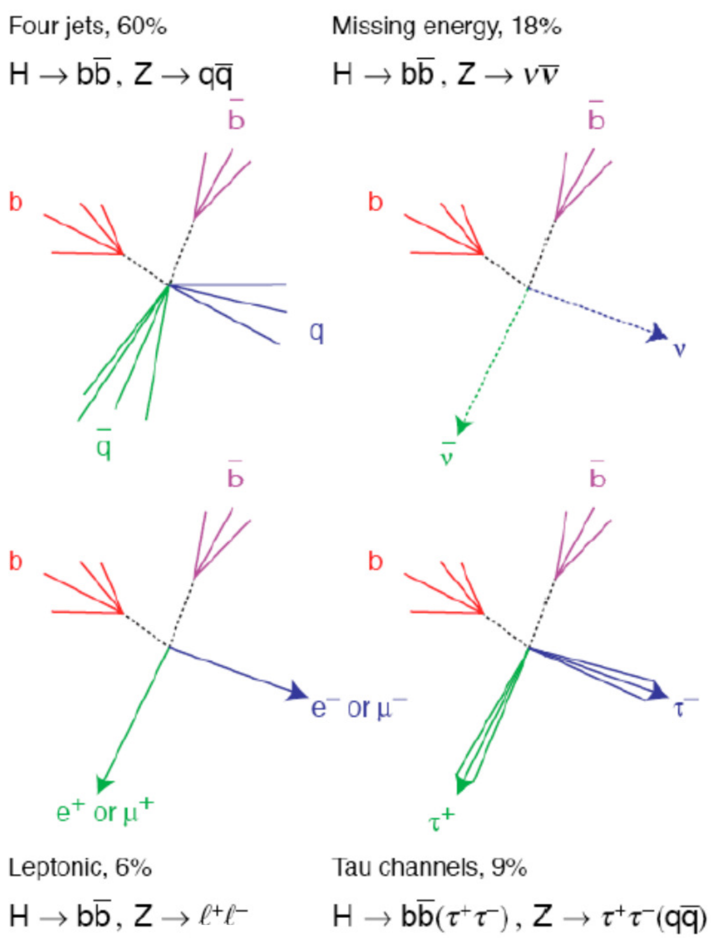
Best channel:

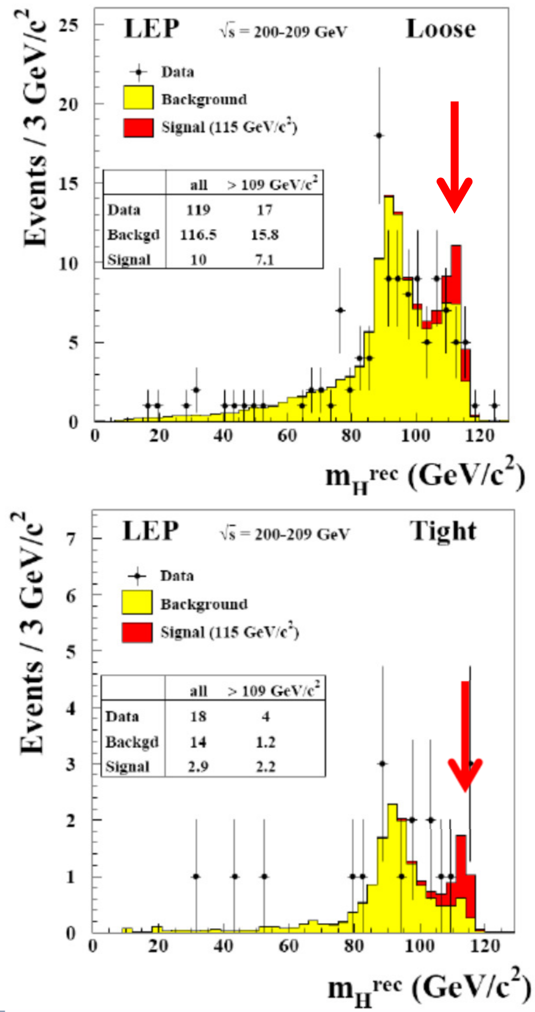
$H \to b\bar{b}$

$Z \to q\bar{q}$

H Searches - IV

HZ event topologies:





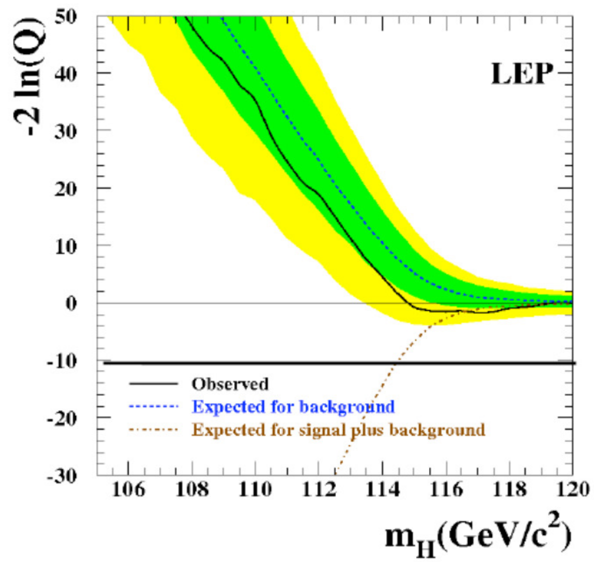
H Searches - V

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:

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

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

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

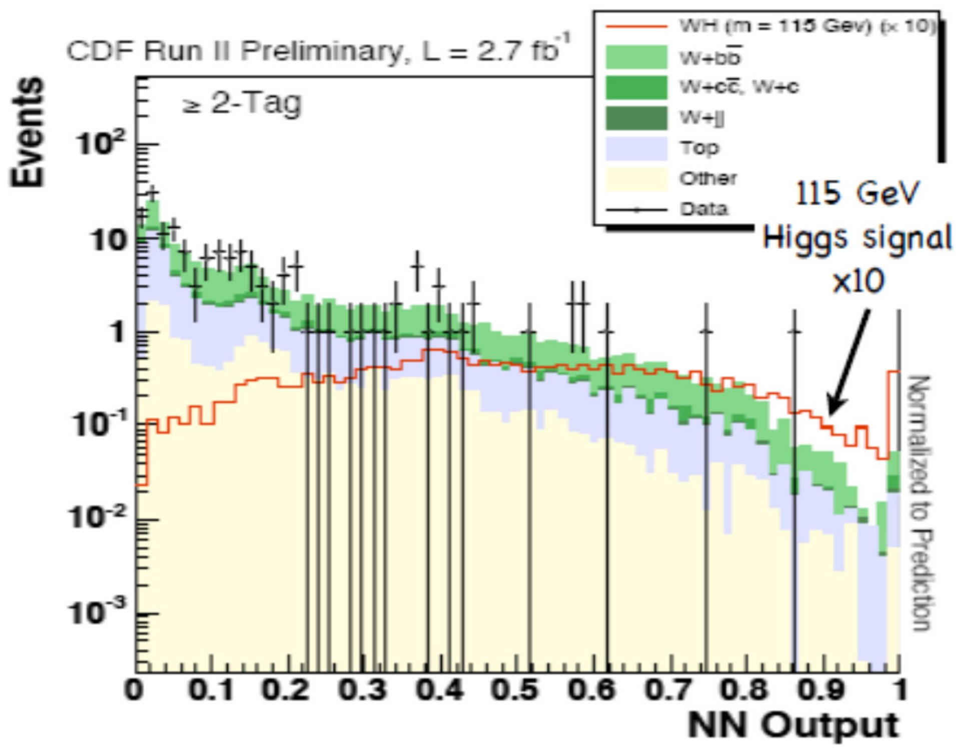
H Searches - VII

CDF :

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

Neural Network tagging

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



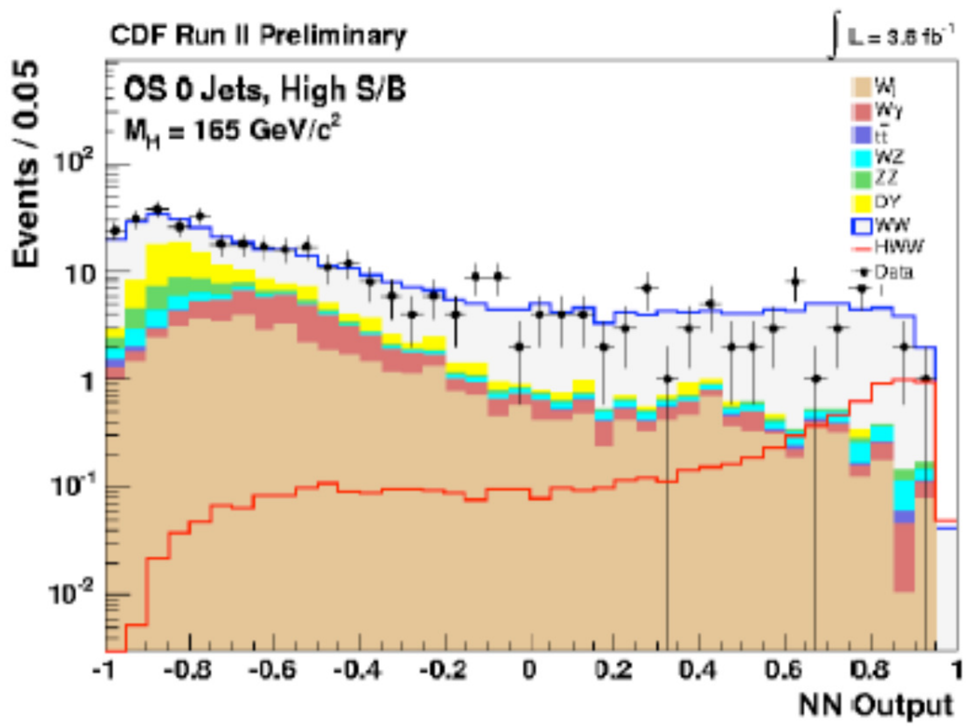
H Searches - VIII

CDF :

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

Neural Network tagging

Consistent with $t\bar{t}$ background

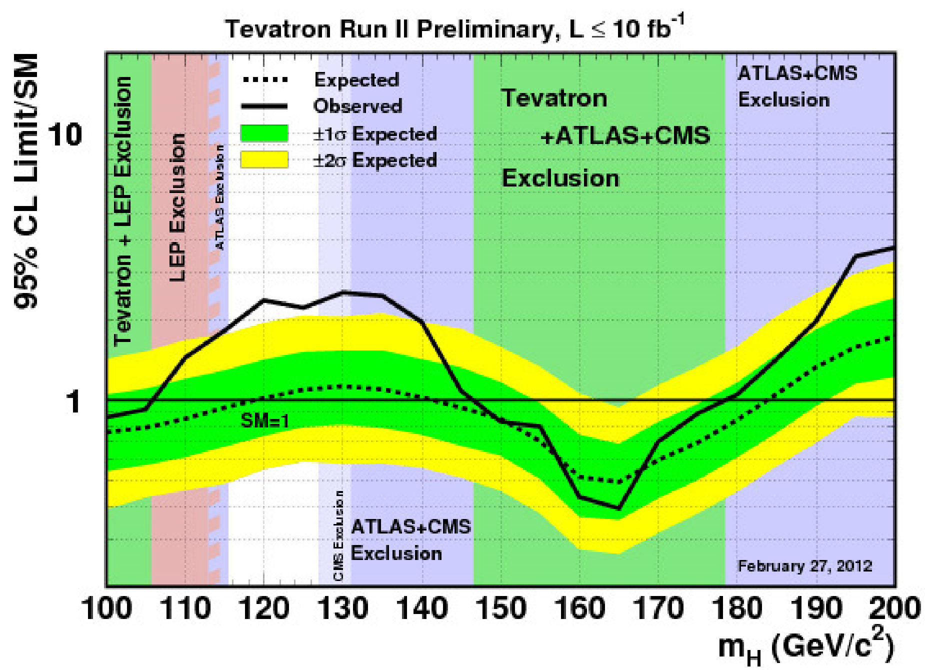


H Searches - IX

Main Tevatron result : "Brazilian Flag" plot

$$\left.\begin{array}{l}\text{Continuous line: Upper limit of } \left(\text{Higgs+SM Background}\right) \text{ observed} \\ \text{Dashed line: SM Background (} \underbrace{\pm 1\sigma}_{Green\ band} \text{ , } \underbrace{\pm 2\sigma}_{Yellow\ band} \text{) expected}\end{array}\right\} vs.\ m_H$$

Unit: Expected SM Higgs signal as a function of m_H

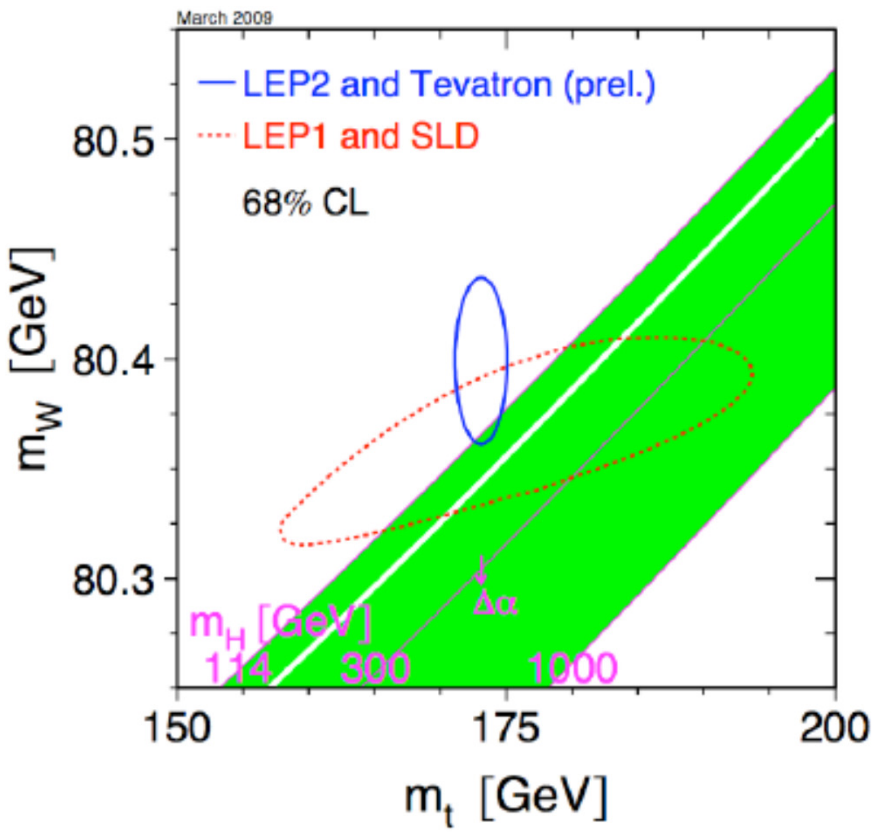


H Searches - X

Indirect searches:

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

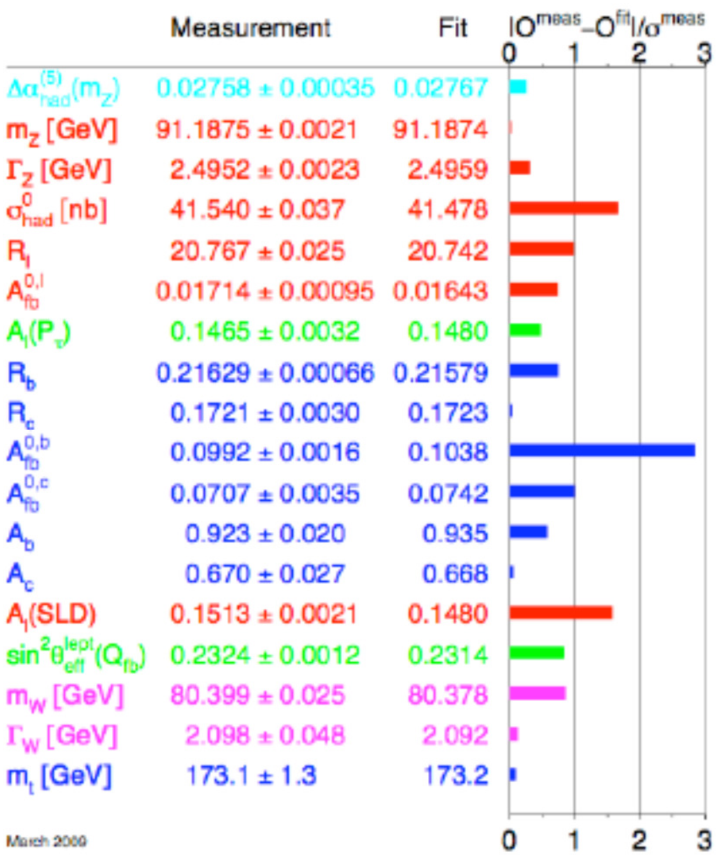
Ex: m_W

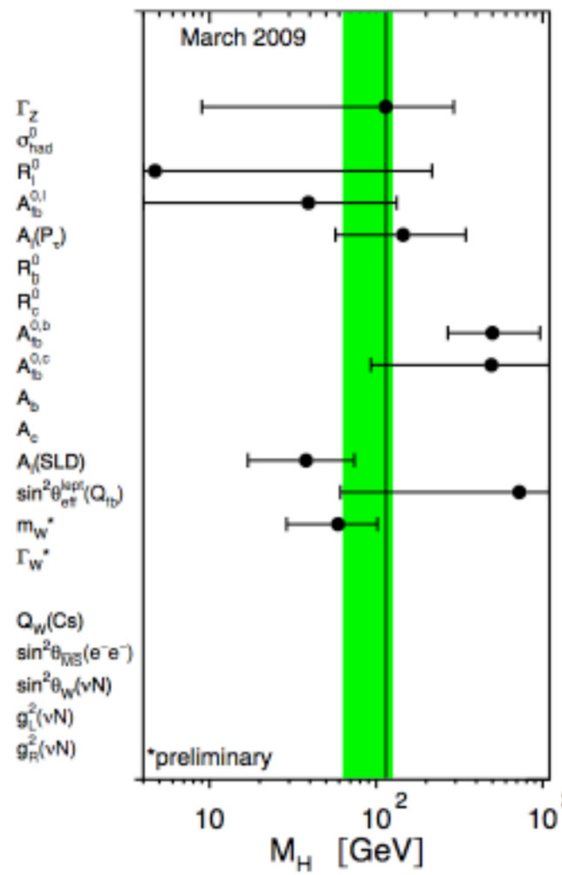


H Searches - XI

Global fit to $\sim$ 20 EW observables:

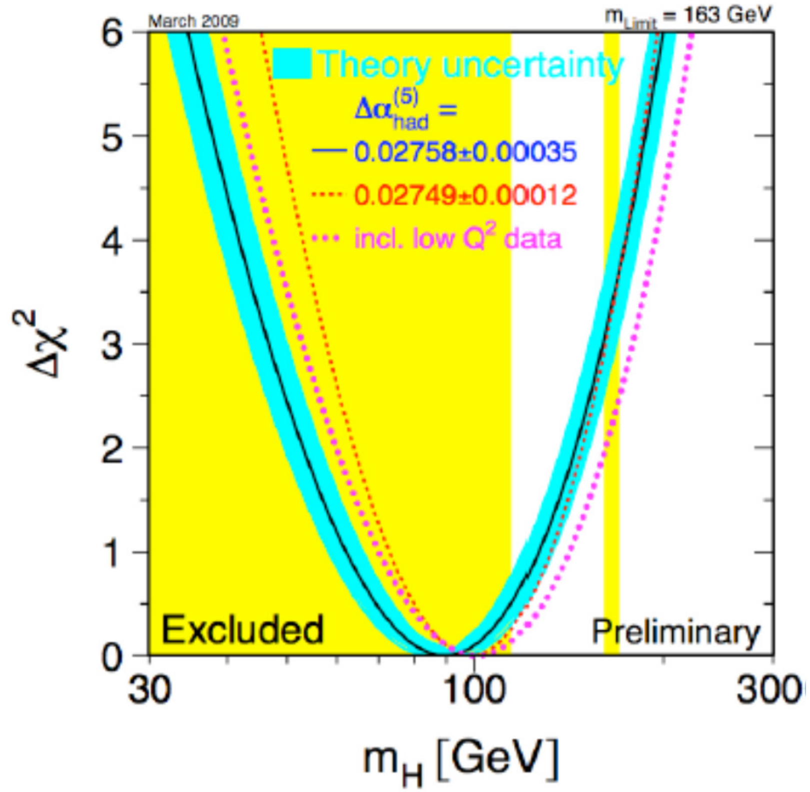
Best indirect estimate of m_H





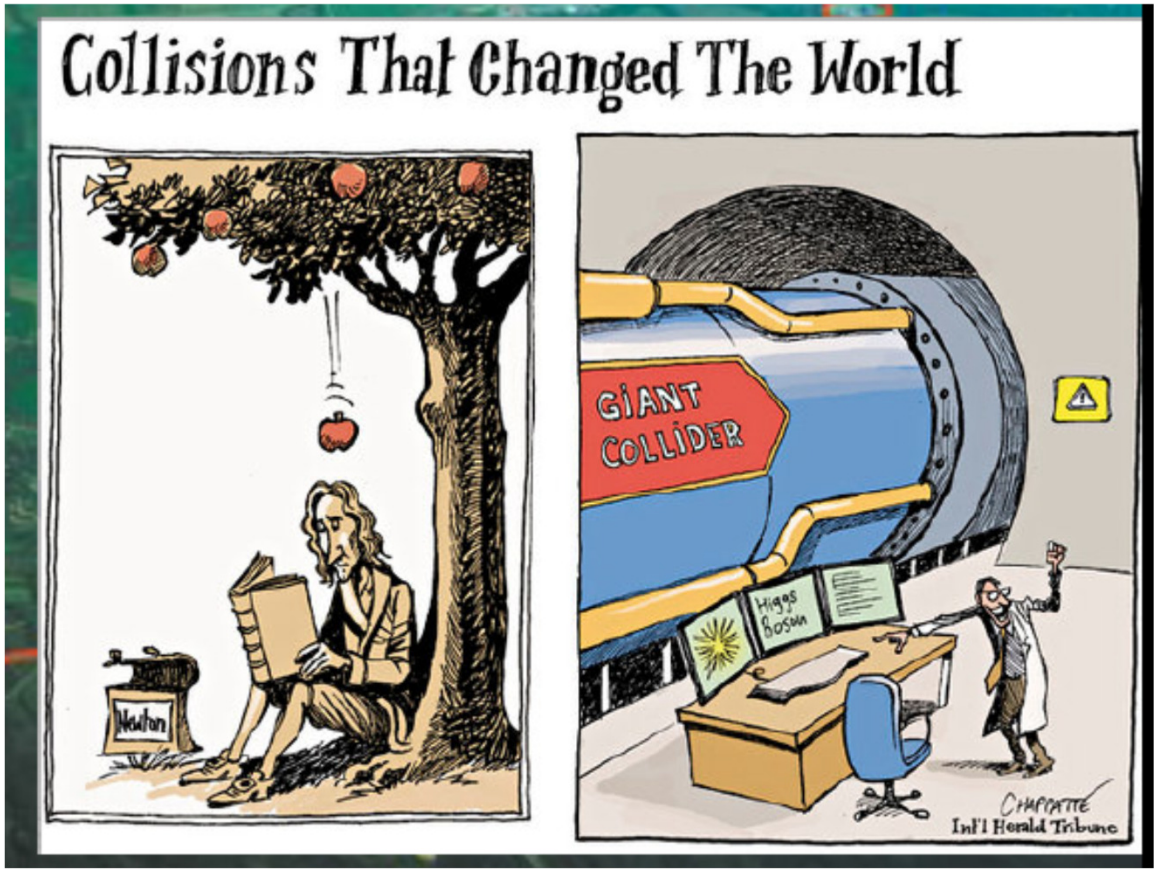
H Searches - XII

χ^2 minimization:



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

LHC: Machine - I



LHC: Machine - II

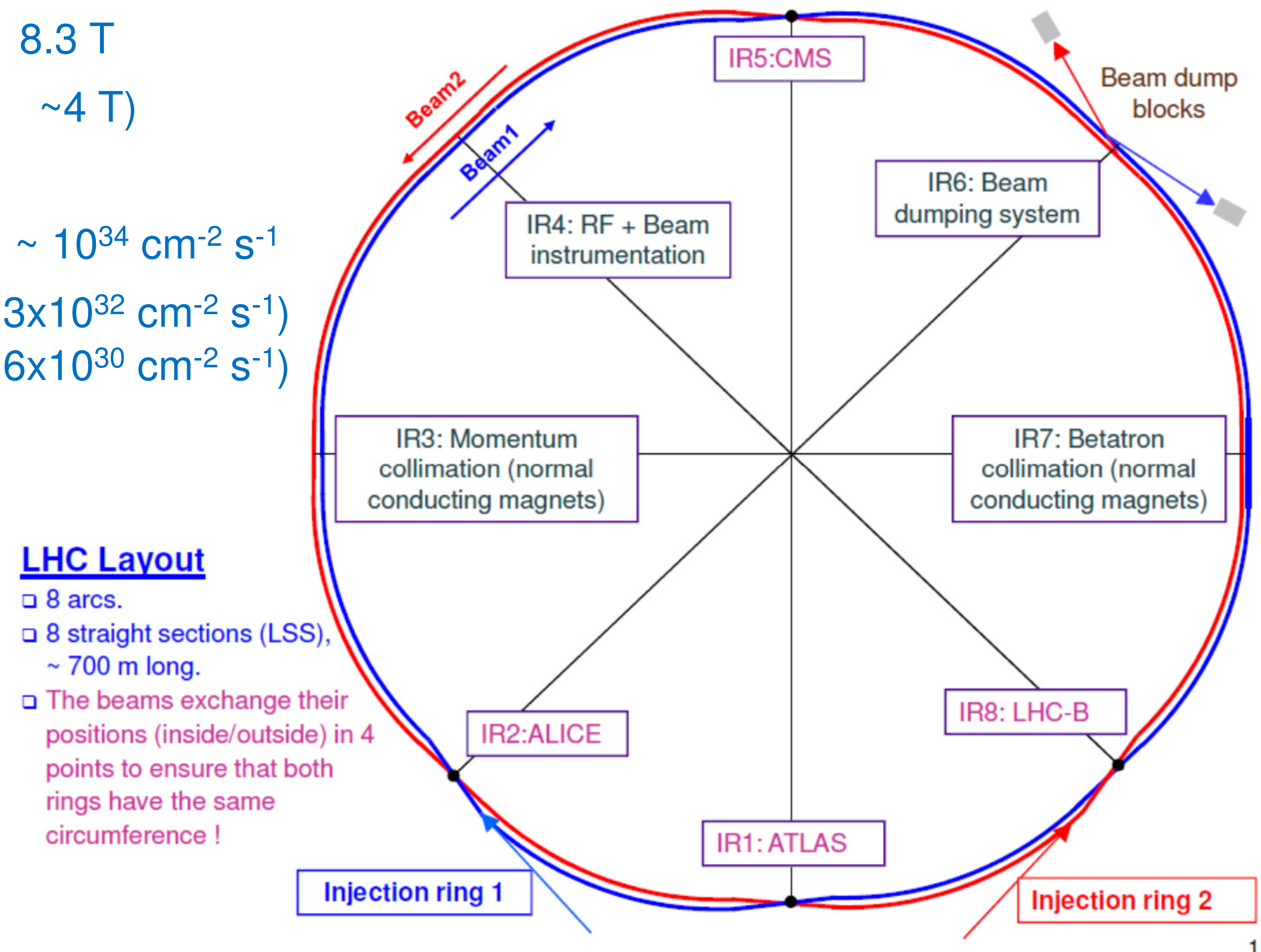
LHC dipole field 8.3 T

(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: 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

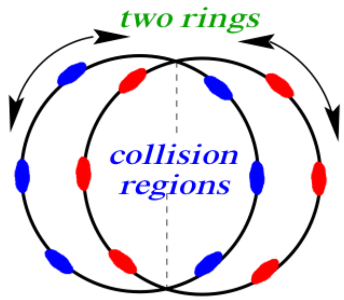
$$B\rho = \frac{mv}{\mathrm{e}} = \frac{p}{\mathrm{e}}$$

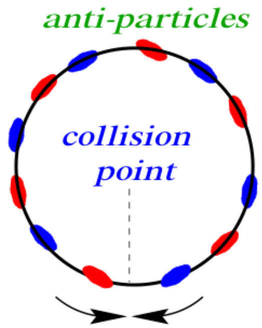
LHC: ρ = 2.8 km given by LEP tunnel

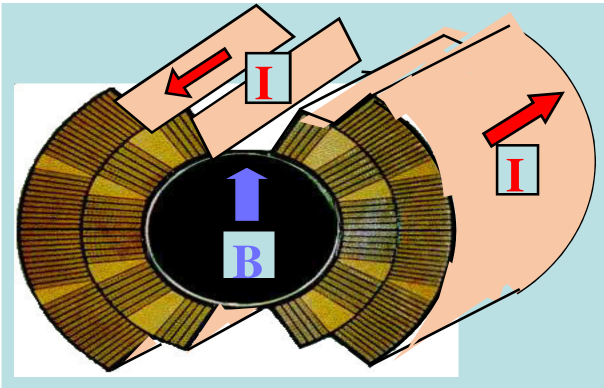
To reach p = 7 TeV/c given a bending radius of ρ = 2805 m:

Bending field : B = 8.33 T

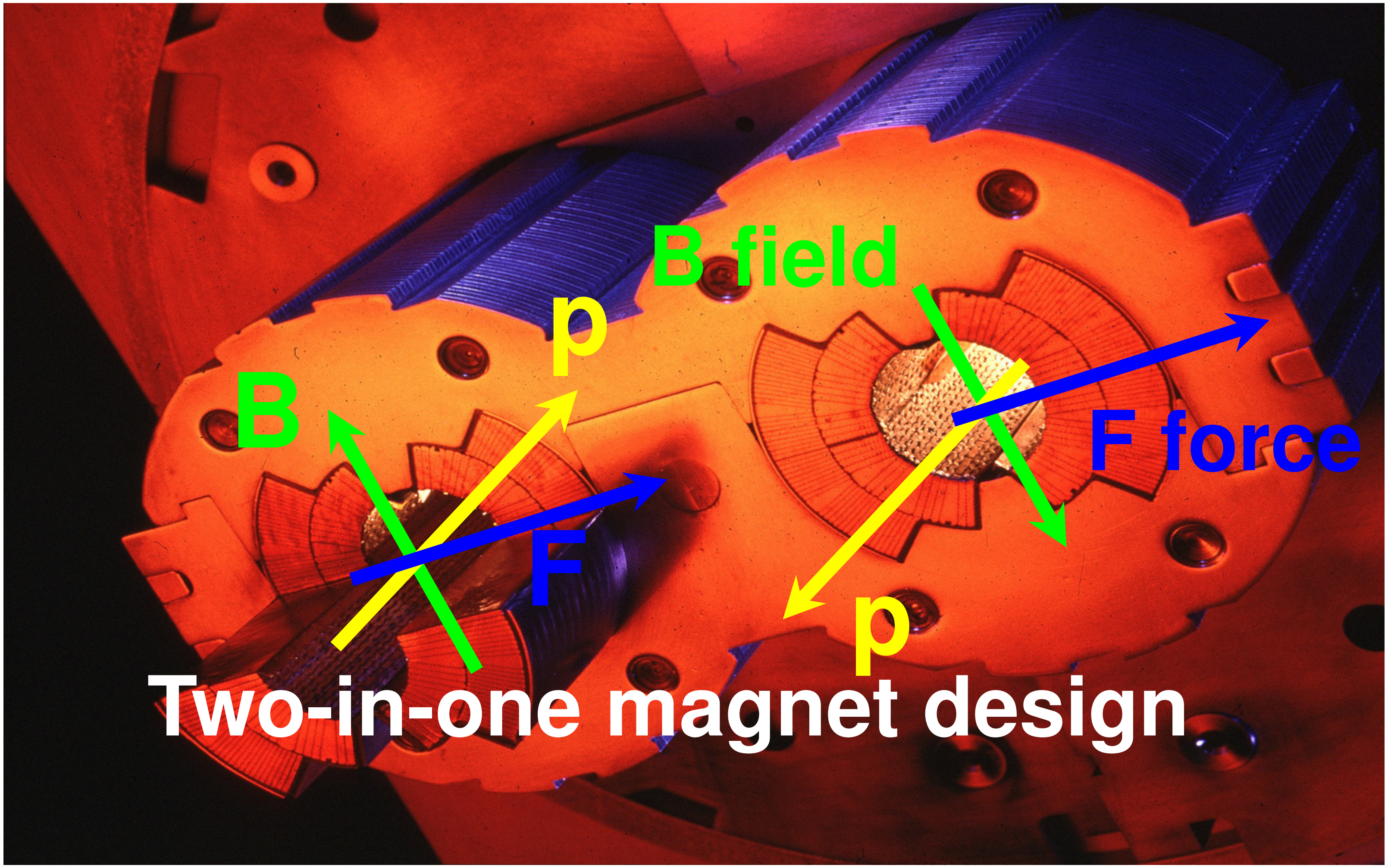
→Superconducting magnets





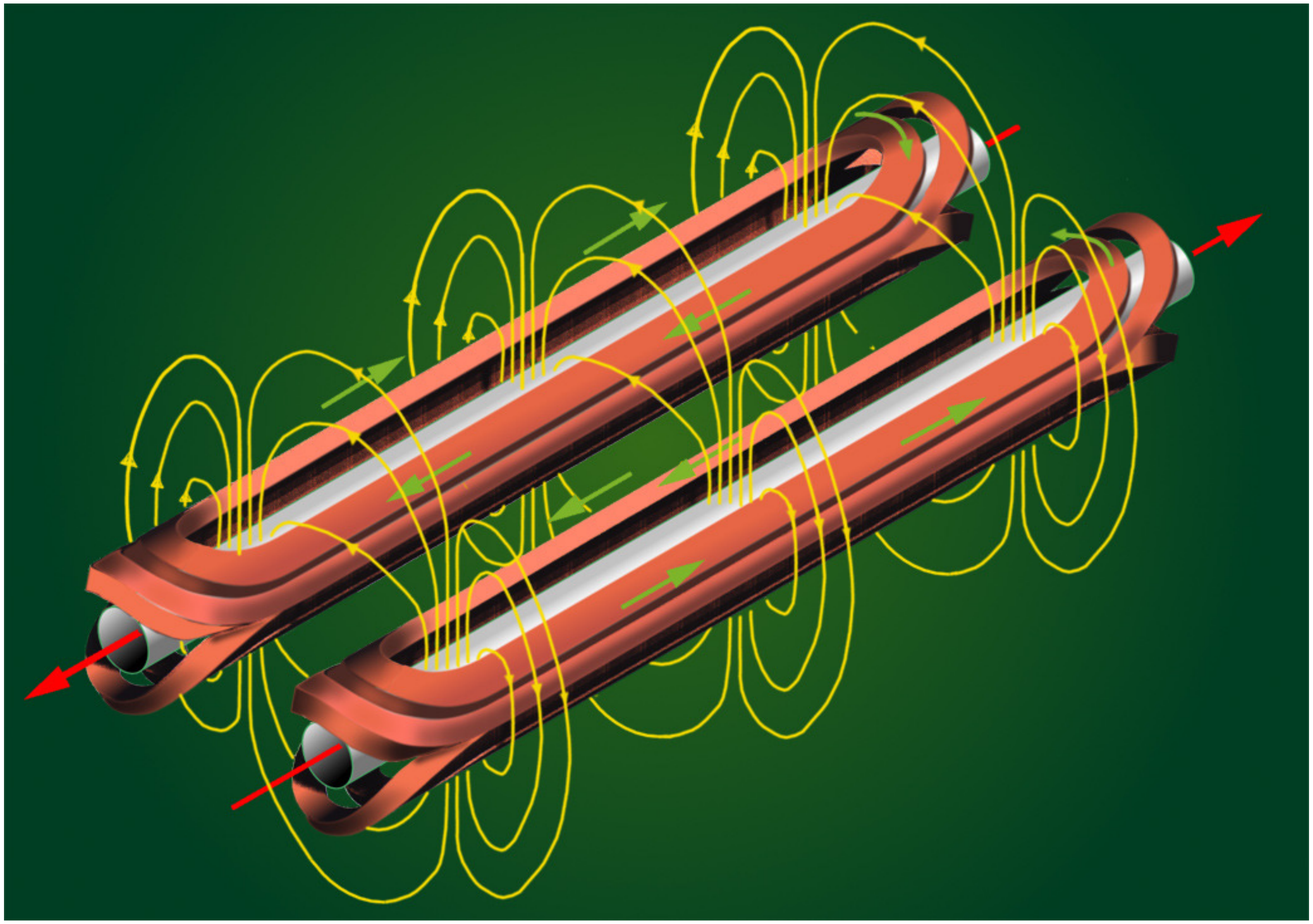


LHC: Machine - V



LHC: Machine - VI

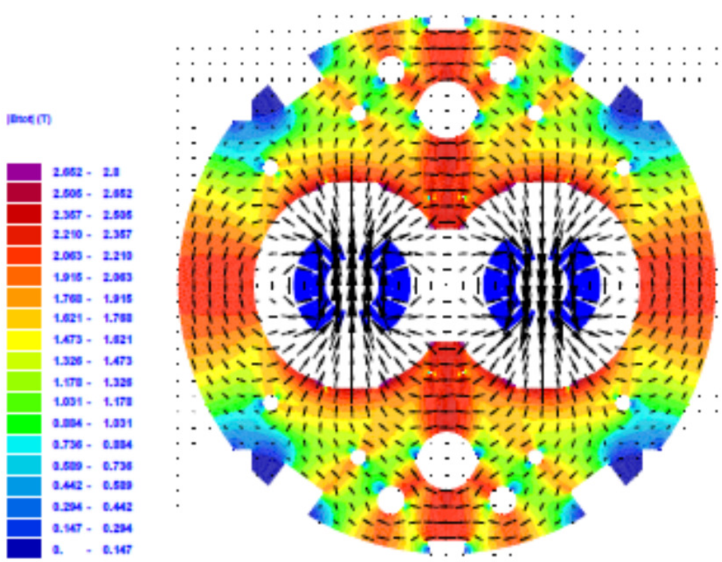
Superconducting coils:

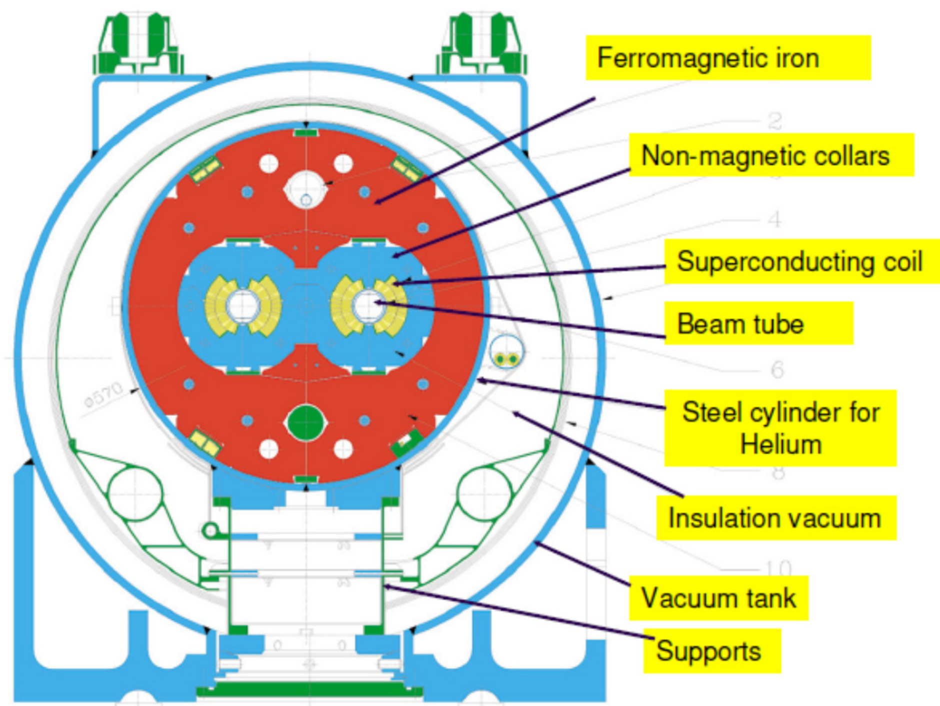


LHC: Machine - VII

LHC main dipole:

Two magnets in a single module





Weight (magnet + cryostat) ~ 30 tons, length 15 m

LHC: Machine - VIII

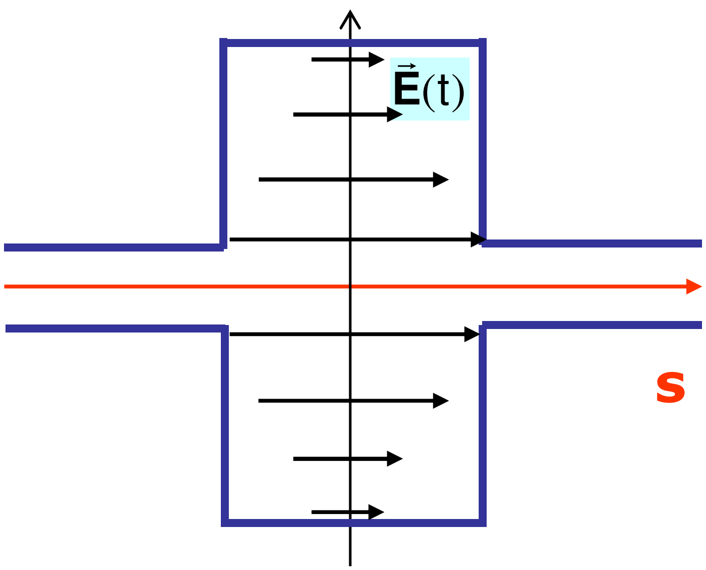
RF system:

4 + 4 Superconducting RF cavities

400 MHz

$\sim$ 0.5 MeV/turn

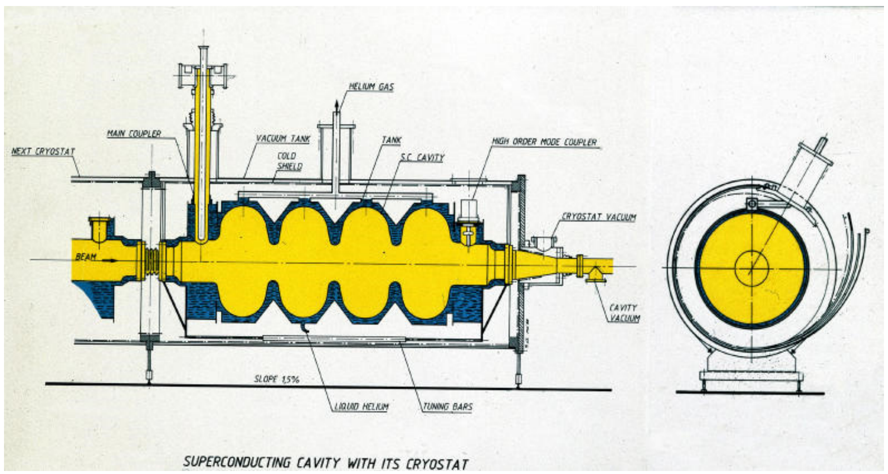
20 minutes for 450 GeV $\rightarrow$ 7 TeV



	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



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

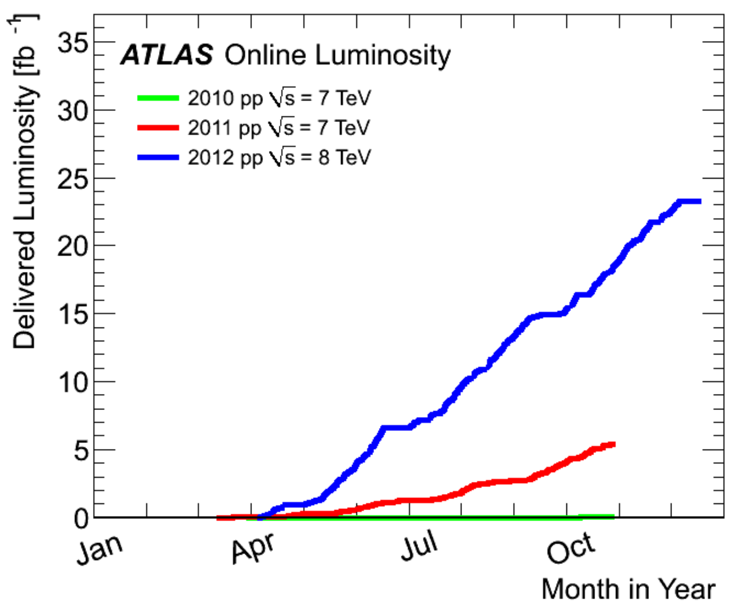
ZZ^*: Small $BR \sim 3\ \%$, small background in the 4 leptons mode

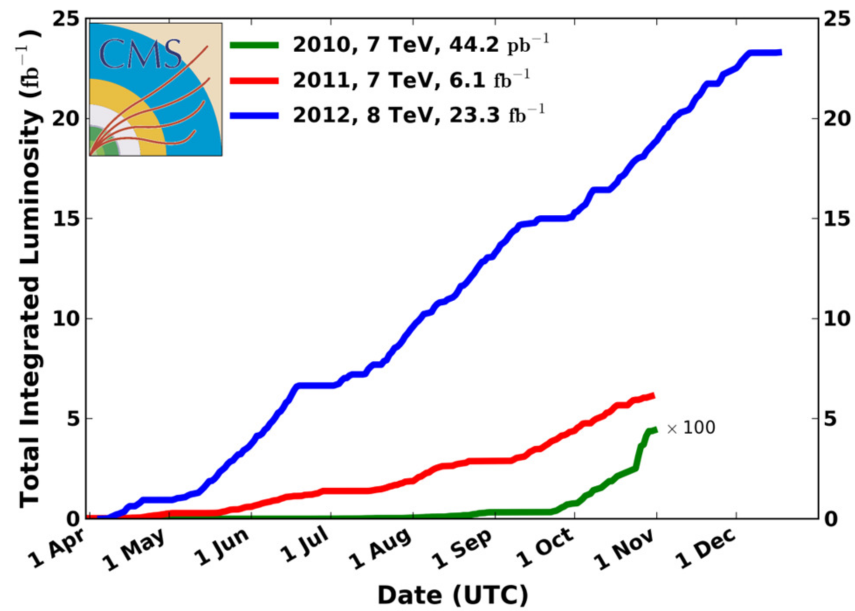
WW^* : Large $BR \sim 20\ \%$, sizeable QCD background in the 4 jets mode, harder than ZZ^* in leptonic modes (neutrinos)

H - II

Total integrated luminosity:

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



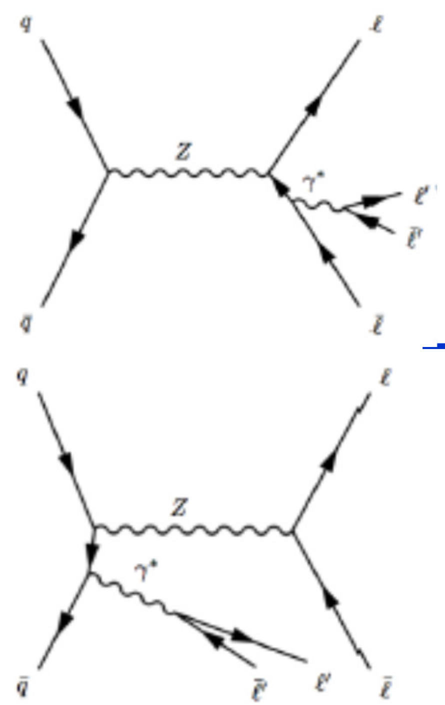


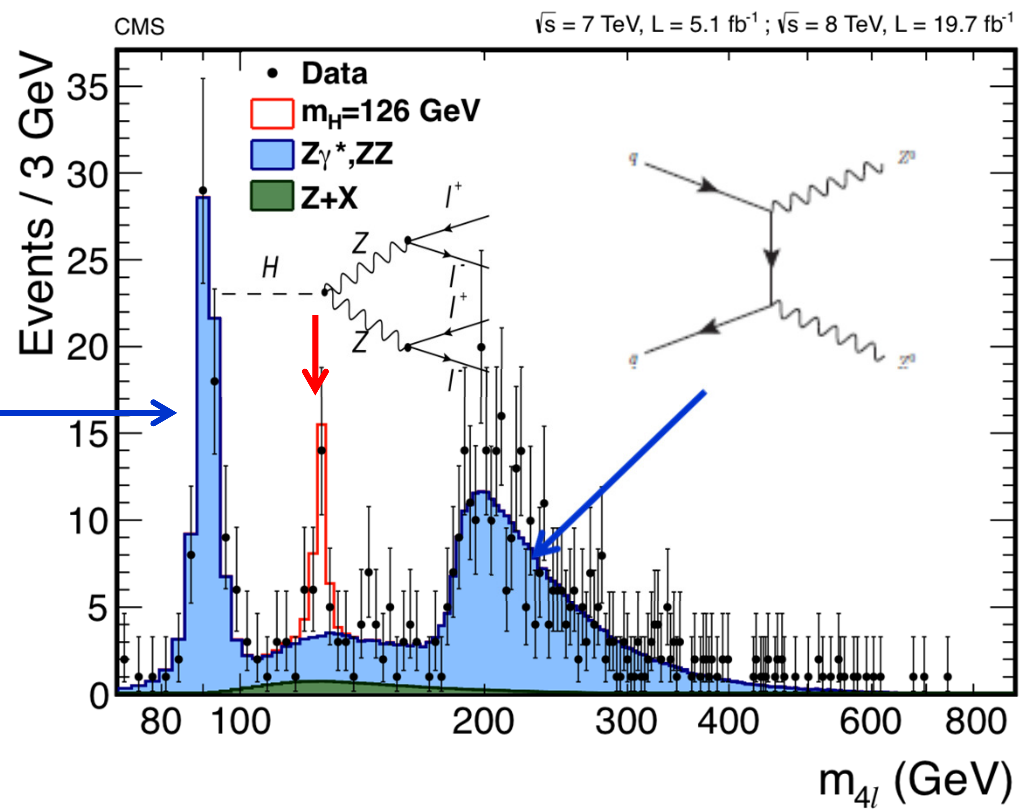
Phenomenal performance:

- 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

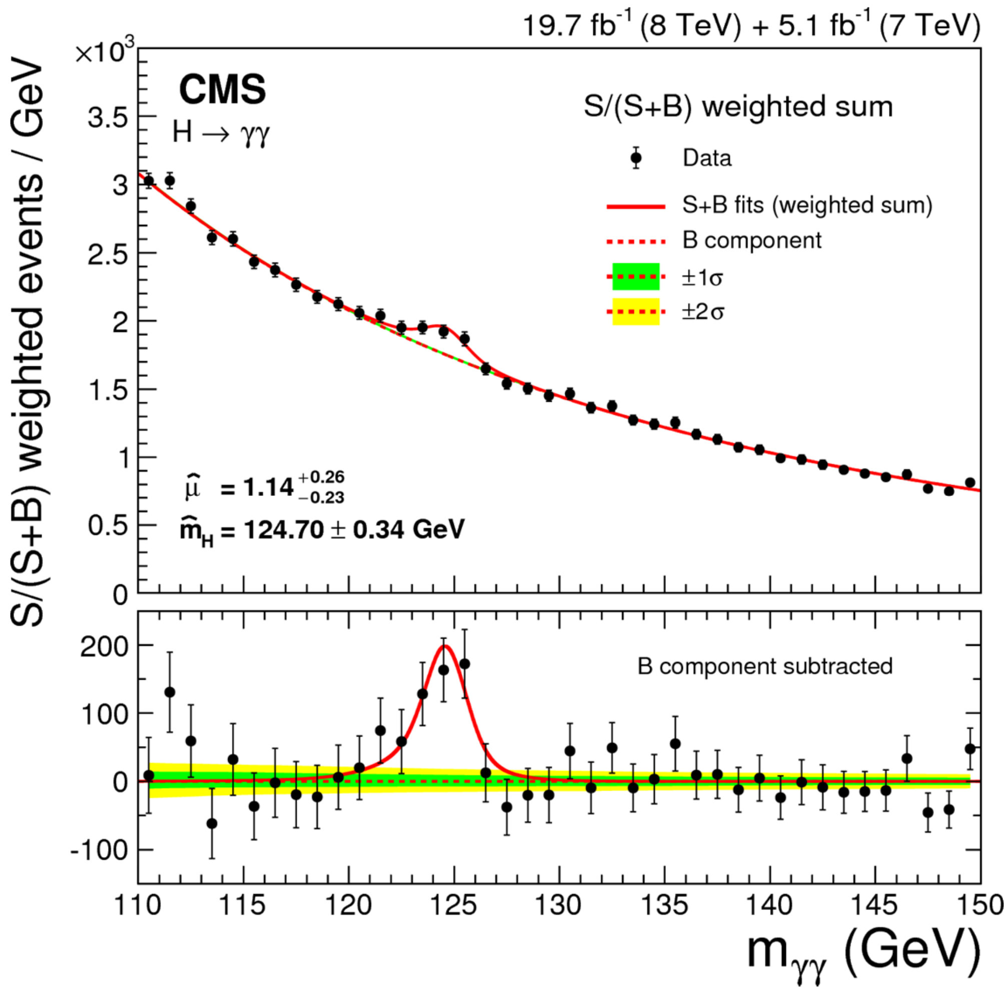
4 leptons:
~7σ observation





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

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

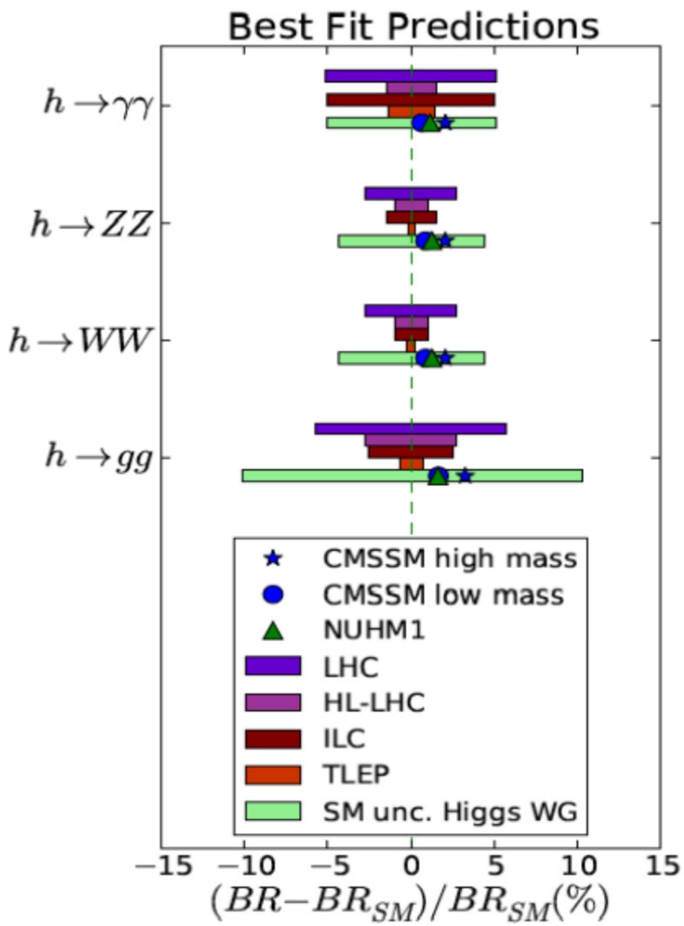
$$m_H\,(\text{CMS}) = 125.03^{+0.26}_{-0.27}(\text{stat})^{+0.13}_{-0.15}(\text{syst})$$

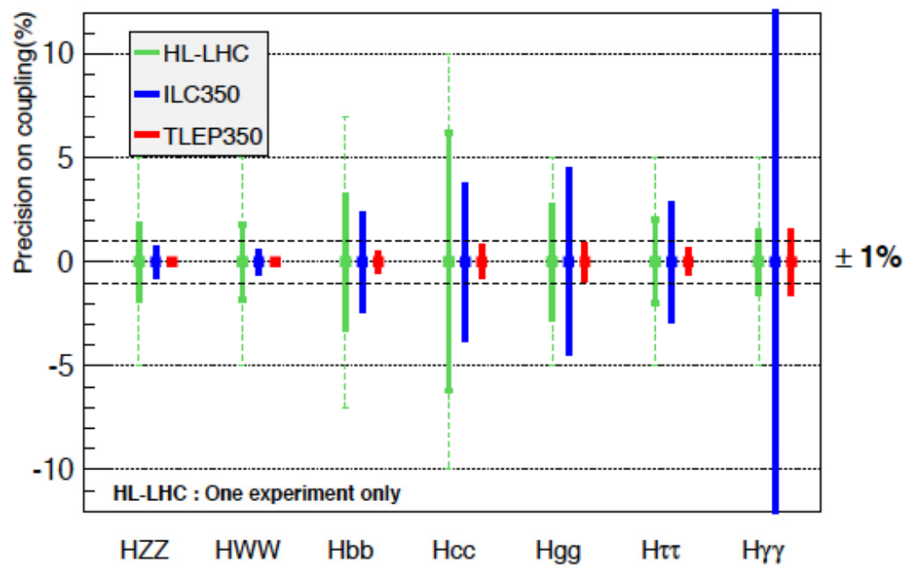
Many more results on spin/parity, couplings, width...

....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%