

# Elementary Particles II

## Higgs Short Notes

Higgs Field, Vacuum Nightmares, End of the World

Production, Decays

Strategies, Detectors

Observation

# 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

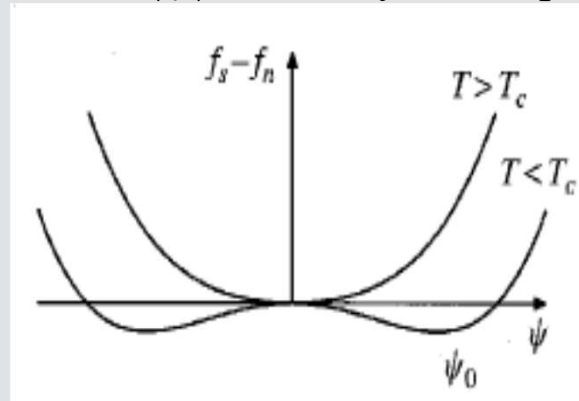
# About the Higgs Field - II

Better analogy: Superconductor

Energy difference between normal and s.c. state at two different temperatures

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

$\psi$  is the Cooper pair 'wave function'  $\rightarrow |\psi|^2 \sim$  density of Cooper pairs



Below  $T_c$ , the minimum energy state ('vacuum') occurs for  $\psi = \psi_0 \neq 0$ , phase undefined

$\rightarrow U(1)$  QED gauge invariance spontaneously broken

$\rightarrow$  Photon becomes 'massive'  $\rightarrow \mathbf{B} = 0$  inside

# About the Higgs Field - III

$\psi$  'Higgs field' of superconductivity:  $\langle \psi \rangle \neq 0 \leftrightarrow$  Permanent supercurrents

Superconductive state:

'Higgs field' = 'Wave function' of Cooper pairs

→ Not a fundamental field

→ 'Composite' field of fundamental 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*  $V(\phi)$

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

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

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

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

$$\rho_{\text{Higgs}} \sim 1.210^8 \text{ GeV}^4$$

By assuming  $\rho$  to be a cosmological term, compare:

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

$\rightarrow \rho_{\text{Higgs}}$  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

→ Must be quantized

→ Will be used perturbatively

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

Similar to vacuum polarization corrections to Coulomb potential in QED

(Uehling potential & Lamb shift)

Standard effect: Running constants, including  $\lambda$

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

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

→  $m_H$  modified by radiative corrections

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

→  $\lambda$  evolution depending on  $\beta$ -functions



# About the Higgs Field - VIII

Running couplings and  $\beta$ -functions:

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

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

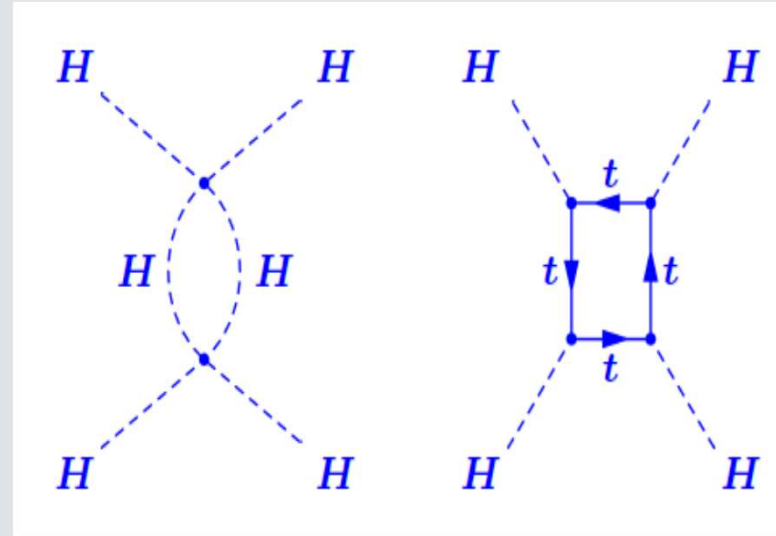
For the EW interaction:

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

Higgs couplings:

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

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



# About the Higgs Field - IX

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

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

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

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

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

$$\rightarrow \text{New physics required at scale } \Lambda < Q_{LP} \rightarrow \ln \frac{\Lambda}{\nu} < \left(\frac{2\sqrt{2}\pi^2}{3G_F m_H^2}\right) \rightarrow m_H < \left(\frac{2\sqrt{2}\pi^2}{3G_F \ln \frac{\Lambda}{\nu}}\right)^{1/2} \sim \begin{matrix} O(140 \text{ GeV}), \Lambda \sim m_{\text{Planck}} \approx 1.210^{19} \text{ GeV} \\ O(650 \text{ GeV}), \Lambda \sim 1 \text{ TeV} \end{matrix}$$

# About the Higgs Field - X

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

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

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

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

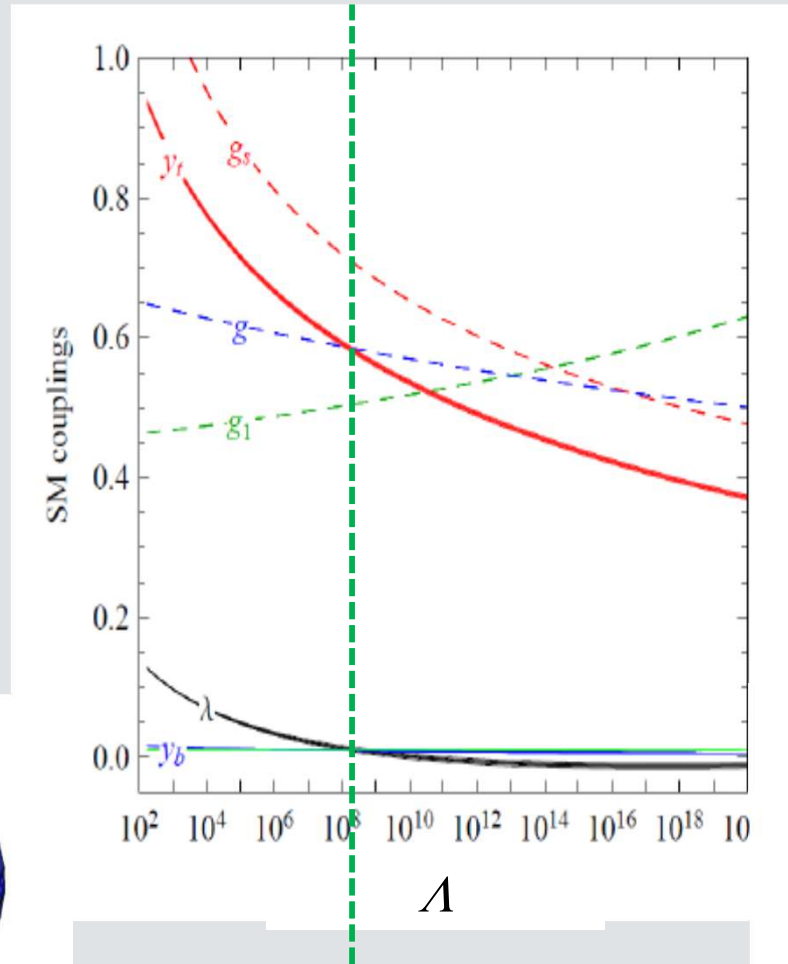
Don't like a too quick End of the World

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

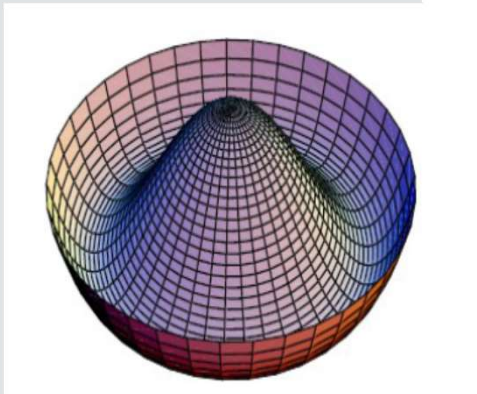
$$\rightarrow m_H > \left( \frac{3h_t^4}{\sqrt{2}\pi^2 G_F} \ln \frac{\Lambda}{\nu} \right)^{1/2}$$

# About the Higgs Field - XI

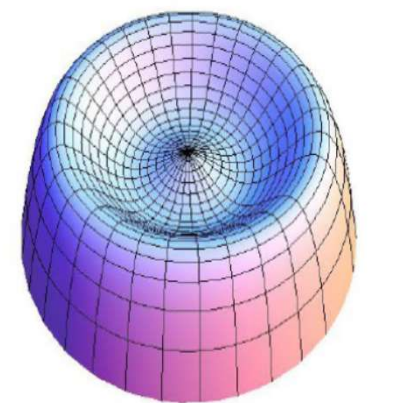
Running couplings:



Sombrero:  $\lambda > 0$   
Relax



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

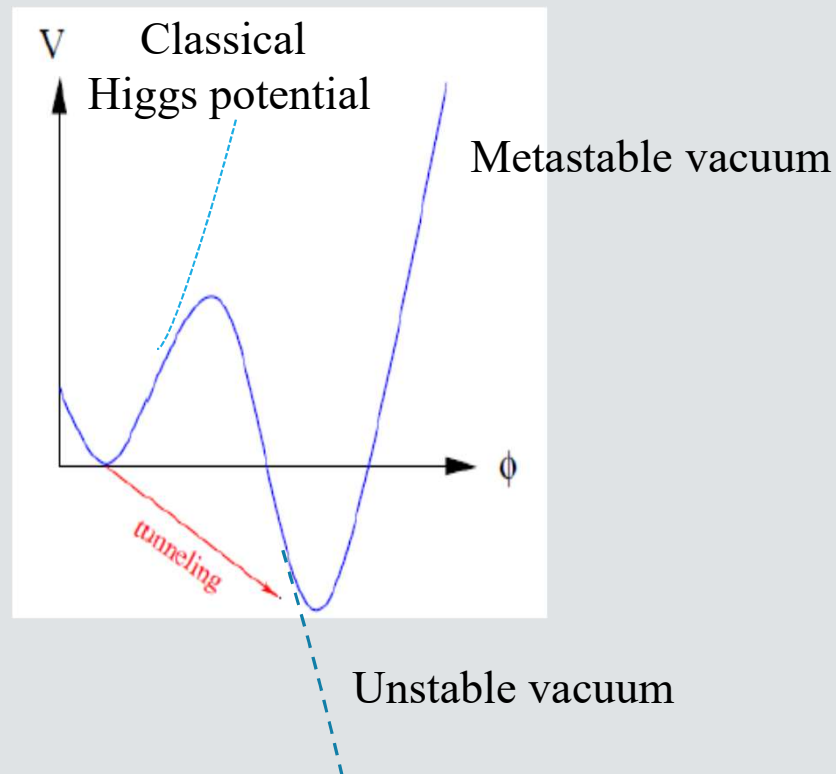


# About the Higgs Field - XII

Radiative corrections leading to major changes in the effective Higgs potential at large  $\phi$  values:

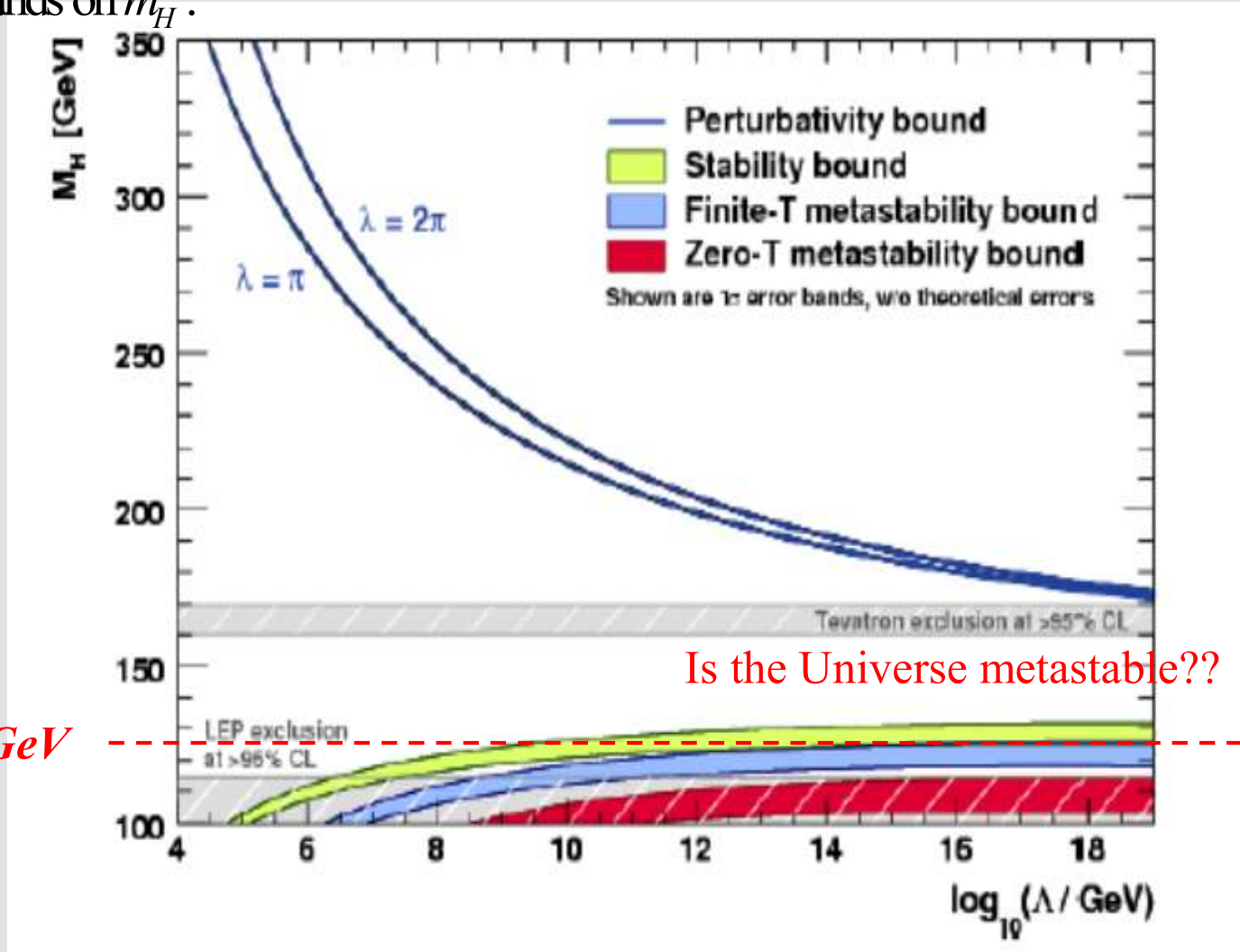
Details tied to  $m_H, m_t$

Might induce vacuum instability/metastability through fast/slow tunneling



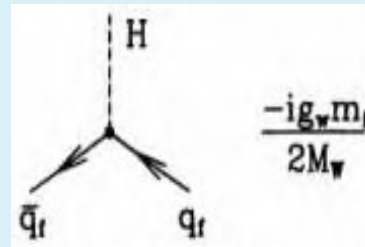
# About the Higgs Field - XIII

Upper & lower bounds on  $m_H$  :

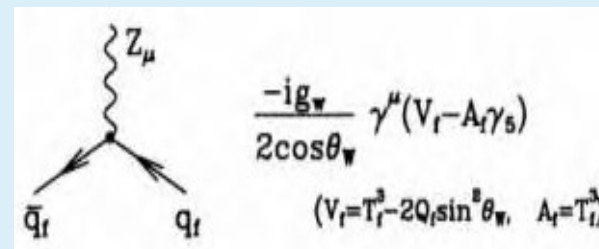


# Higgs Production - I

Start from  $H$  coupling to Fermions:



Compare to coupling to  $Z^0$ :

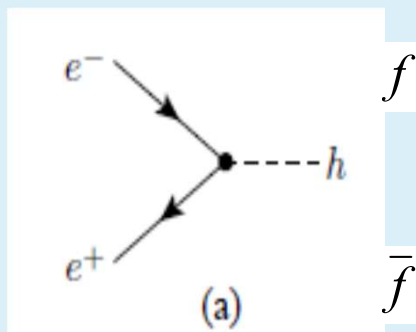


→  $H$  coupling down by a factor  $\sim \frac{m_f}{m_W}$  as compared to  $Z^0$

# Higgs Production - II

First mode:

$s$ -channel formation:



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

Lepton colliders:

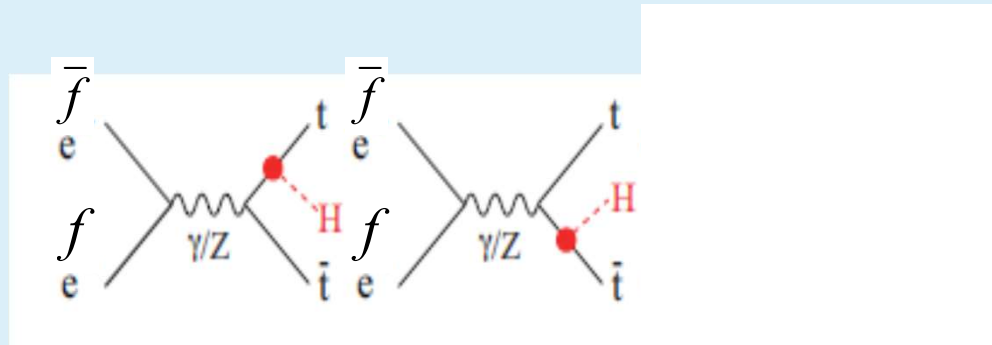
Tough requirements on luminosity, energy resolution



# Higgs Production - III

Second mode:

$H$  radiation from quarks, sizeable contribution from Top:



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

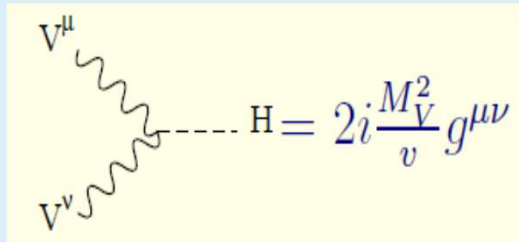
# Higgs Production - IV

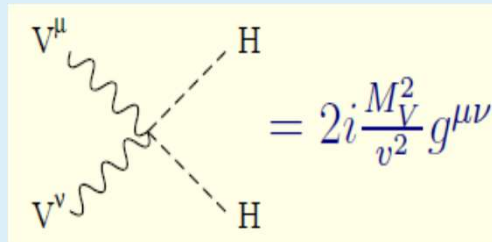
Shift to gauge bosons:

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

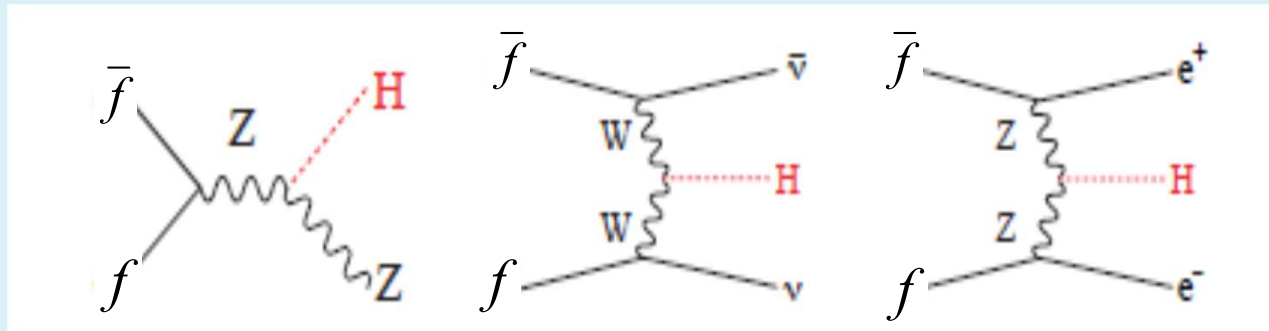

$$V^\mu \quad V^\nu \quad \text{---} H = 2i \frac{M_V^2}{v} g^{\mu\nu}$$


$$V^\mu \quad V^\nu \quad \text{---} H = 2i \frac{M_V^2}{v^2} g^{\mu\nu}$$

# Higgs Production - V

Best modes:

'Higgsstrahlung', 'Gauge boson fusion'

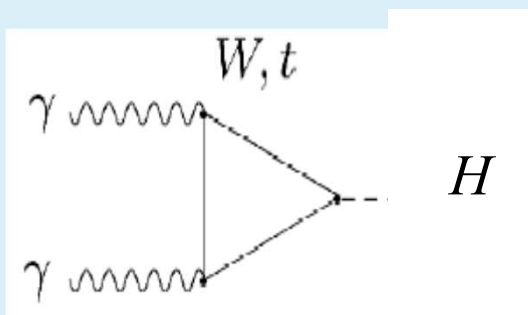


# Higgs Production - VI

Beyond tree level: Very Important Loops

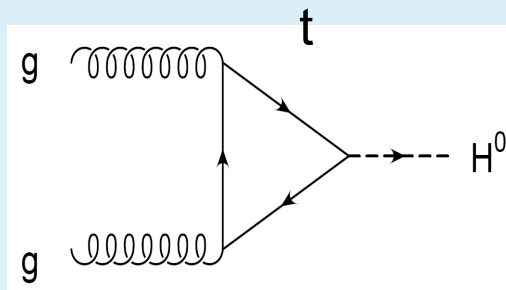
Lepton machines:

Interesting diagrams, also quite relevant to detection

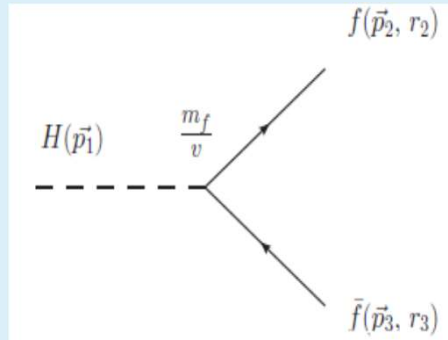


Parton machines:

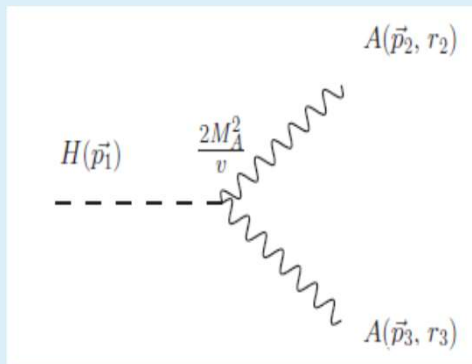
Dominant diagram at LHC



# Higgs Decays - I



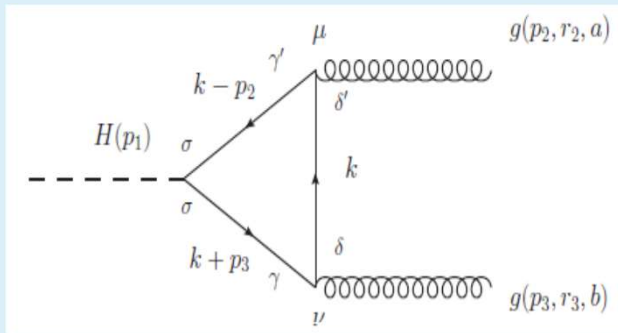
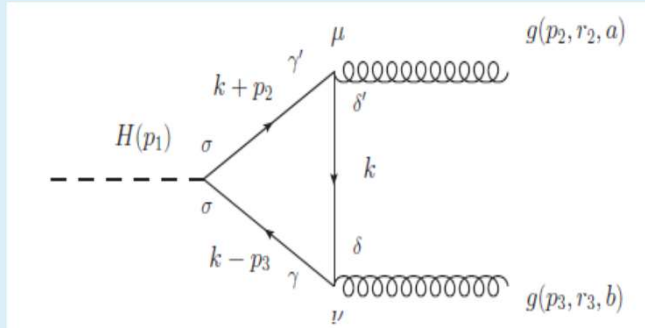
$$\Gamma(H \rightarrow f\bar{f}) = N_C \frac{1}{8\pi} \frac{m_f^2}{v^2} M_H \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$



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

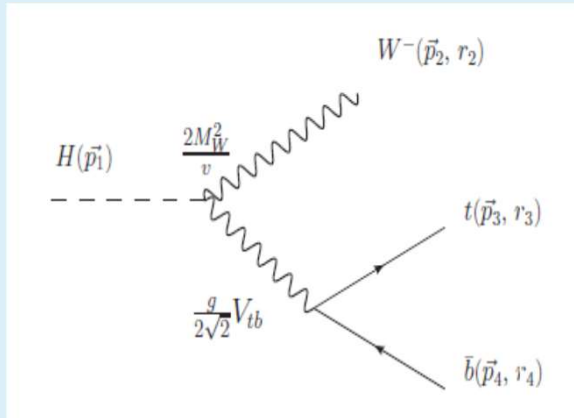
$$\Gamma(H \rightarrow ZZ) = \frac{1}{8\pi} \frac{M_Z^4}{M_H v^2} \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{1/2} \left(3 + \frac{1}{4} \frac{M_H^4}{M_Z^4} - \frac{M_H^2}{M_Z^2}\right)$$

# Higgs Decays - II



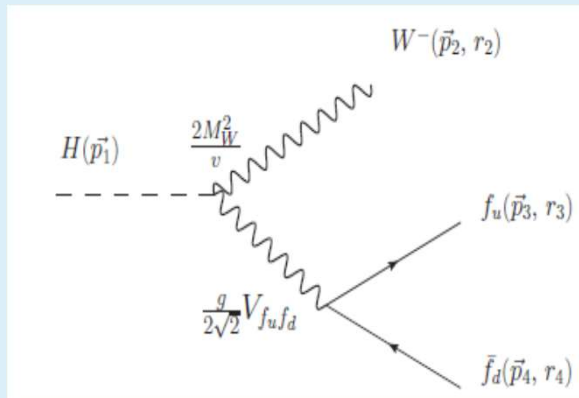
$$\Gamma(H \rightarrow gg) = \frac{M_H^3}{8\pi v^2} \left(\frac{\alpha_s}{\pi}\right)^2 n^2 |D(n)|^2$$

# Higgs Decays - III



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

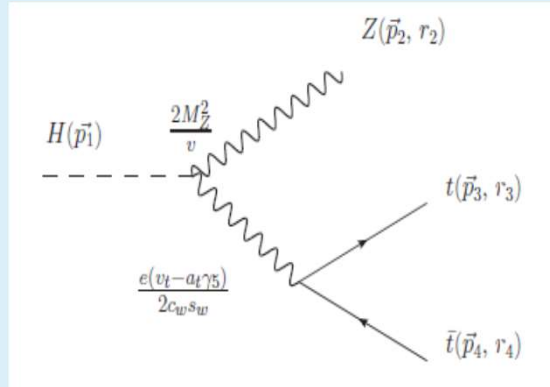
3-body phase space factor



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

3-body phase space factor

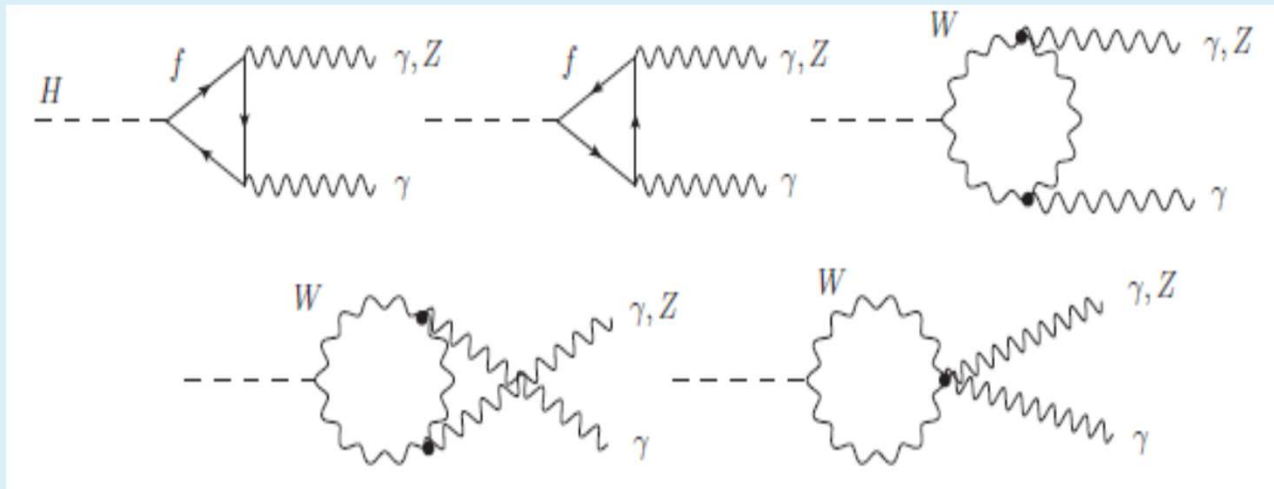
# Higgs Decays - IV



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

3-body phase space factor

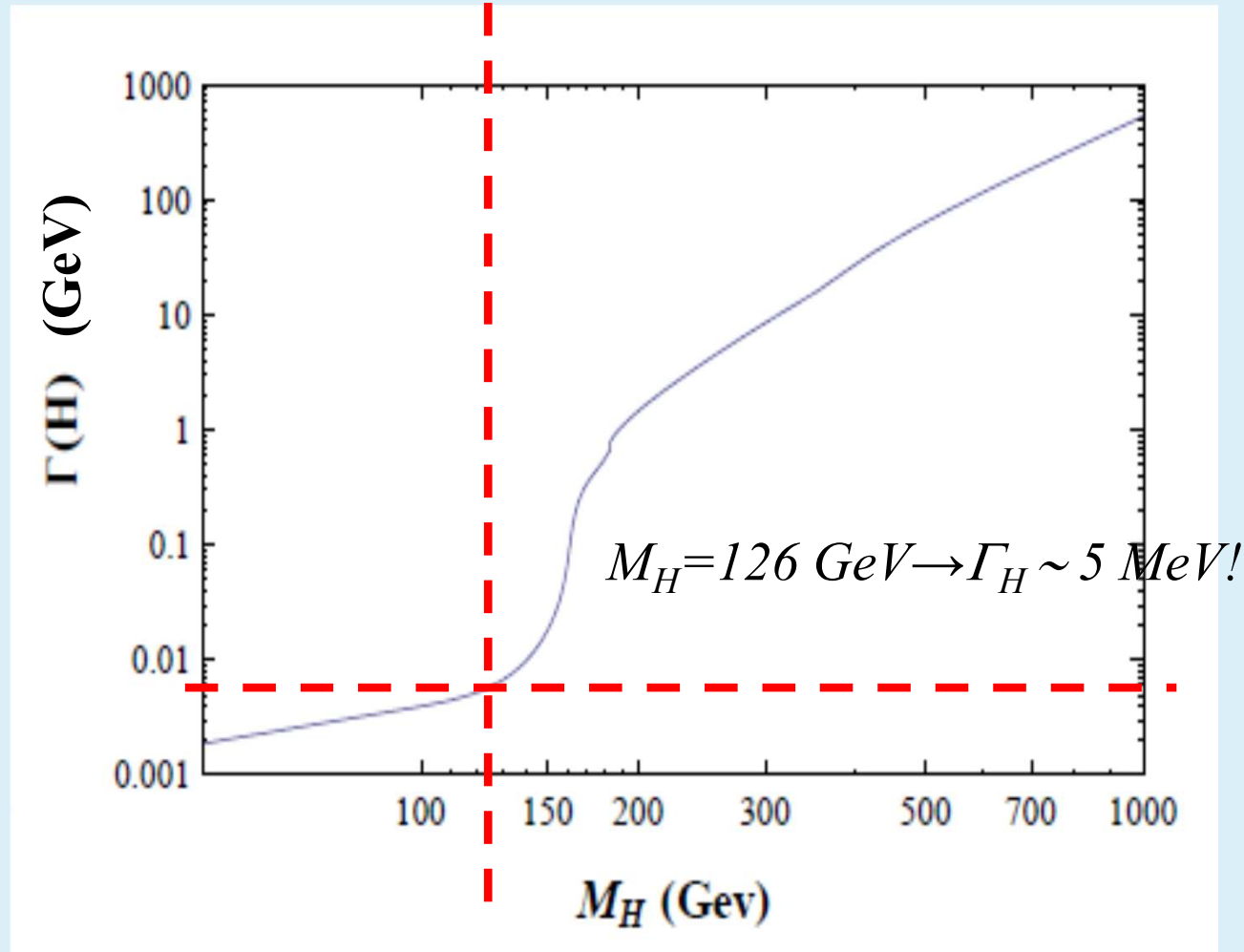
$$\Gamma(H \rightarrow Z/\gamma, \gamma)$$





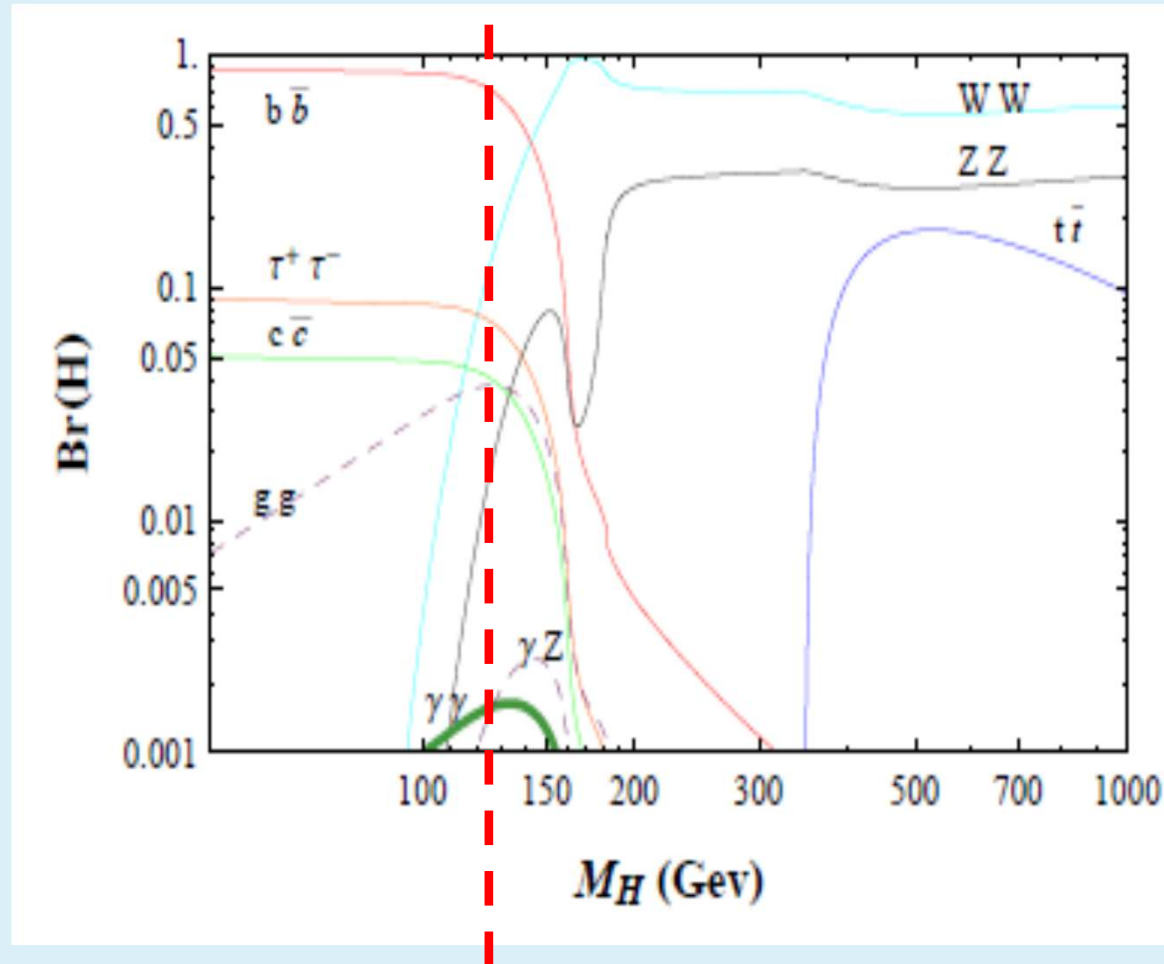
# Higgs Decays - V

$H$  decays entirely determined by Higgs mass:

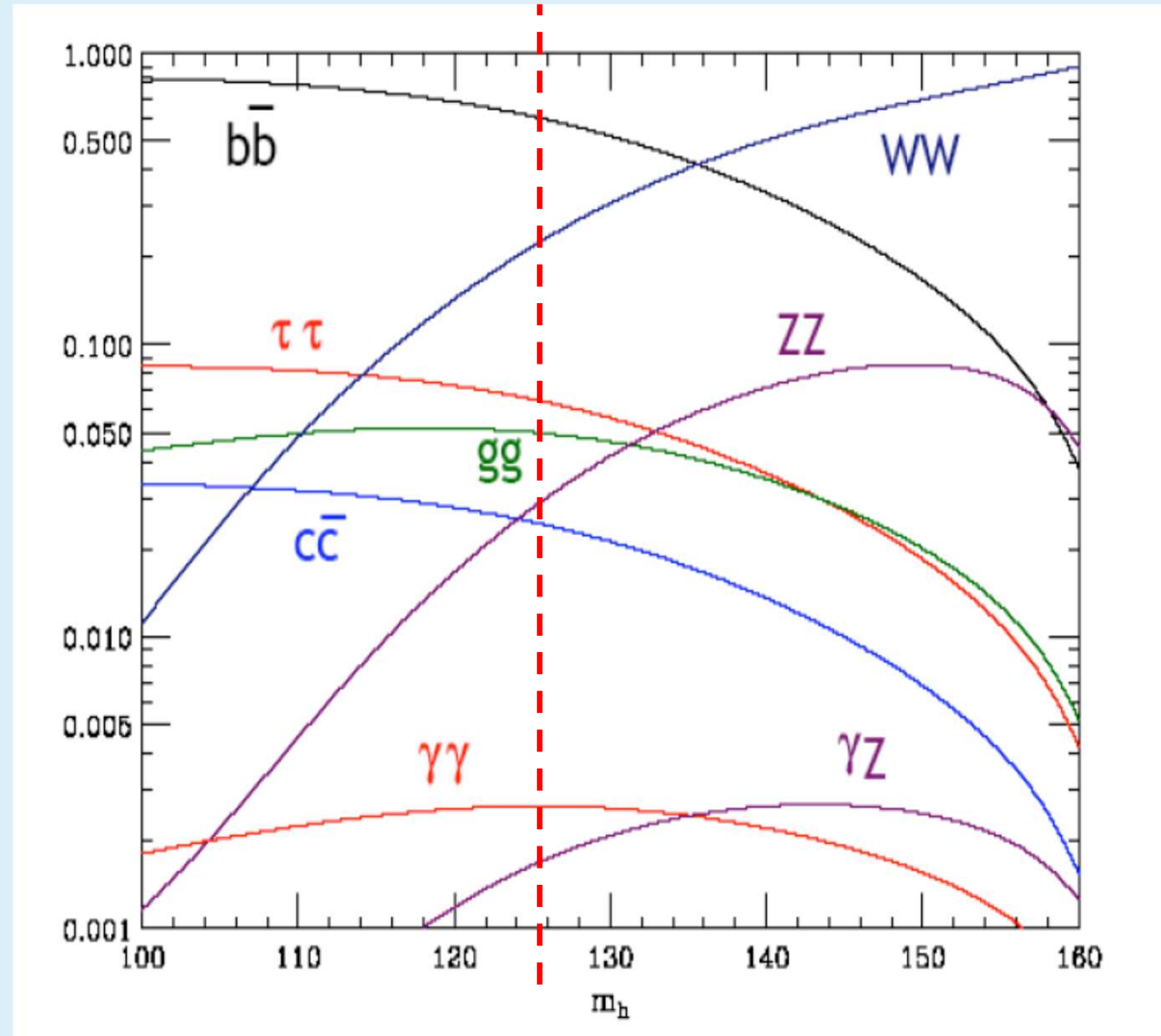


# Higgs Decays - VI

$H$  branching ratios:



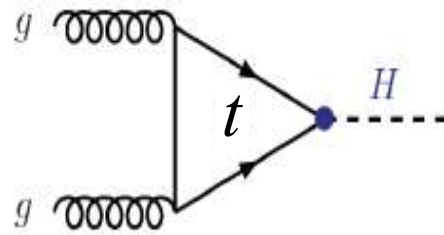
# Higgs Decays - VII



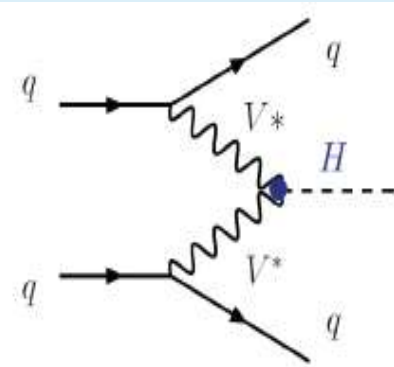
# Parton Collider - I

Dominant diagrams for  $H$  production:

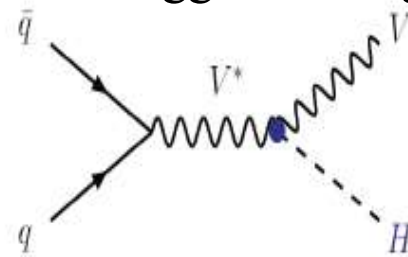
Gluon-Gluon fusion



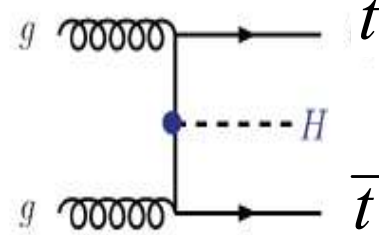
Vector Boson fusion



Higgsstrahlung



$Ht\bar{t}$



# Parton Collider - II

Basic ingredient: PDFs

Quarks: Look for heavy ones

Tree diagrams: Best bet is with  $b$

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

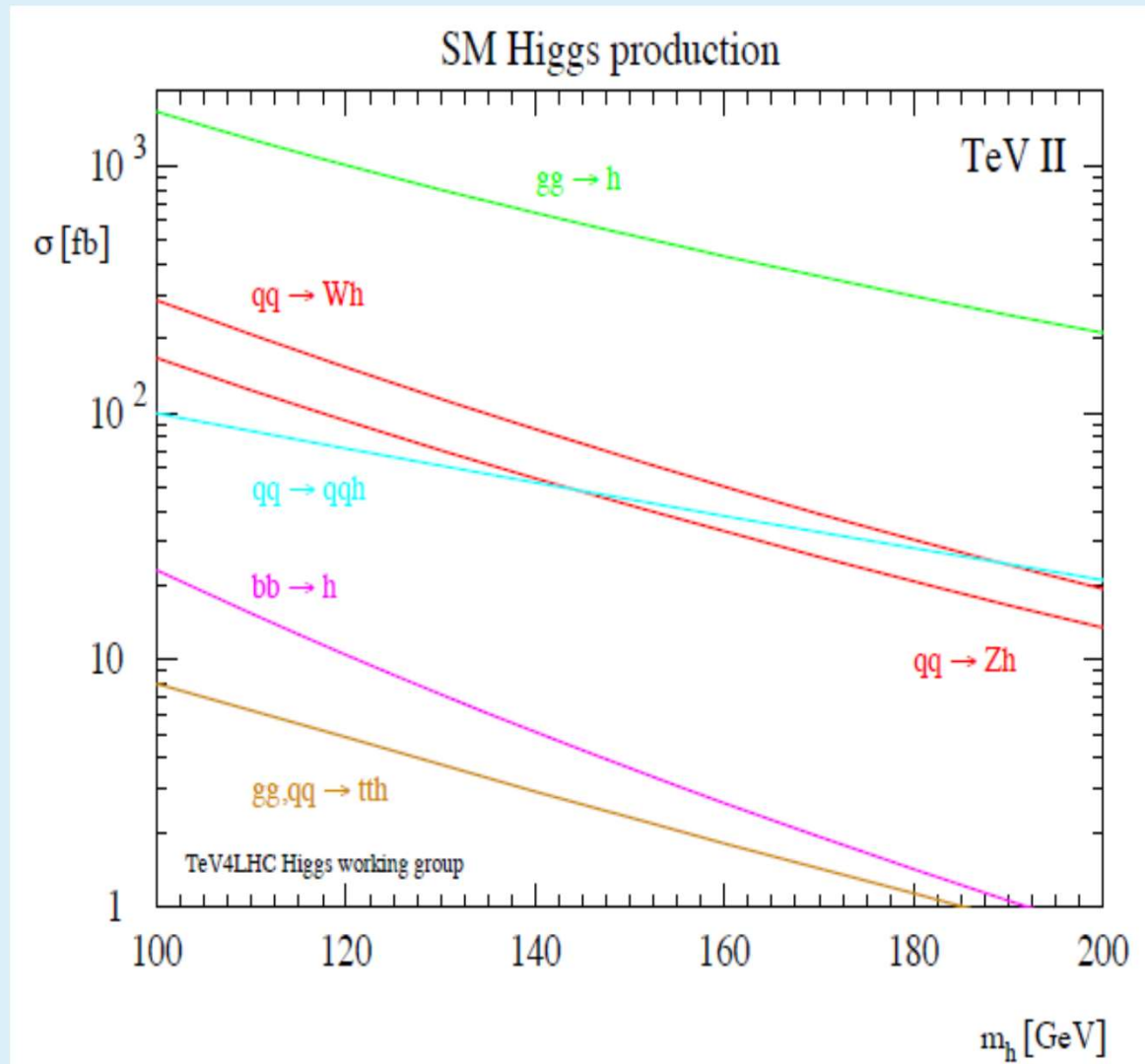
→ Incident flux of sea  $b$ -quarks very small

Gluons: Main contribution

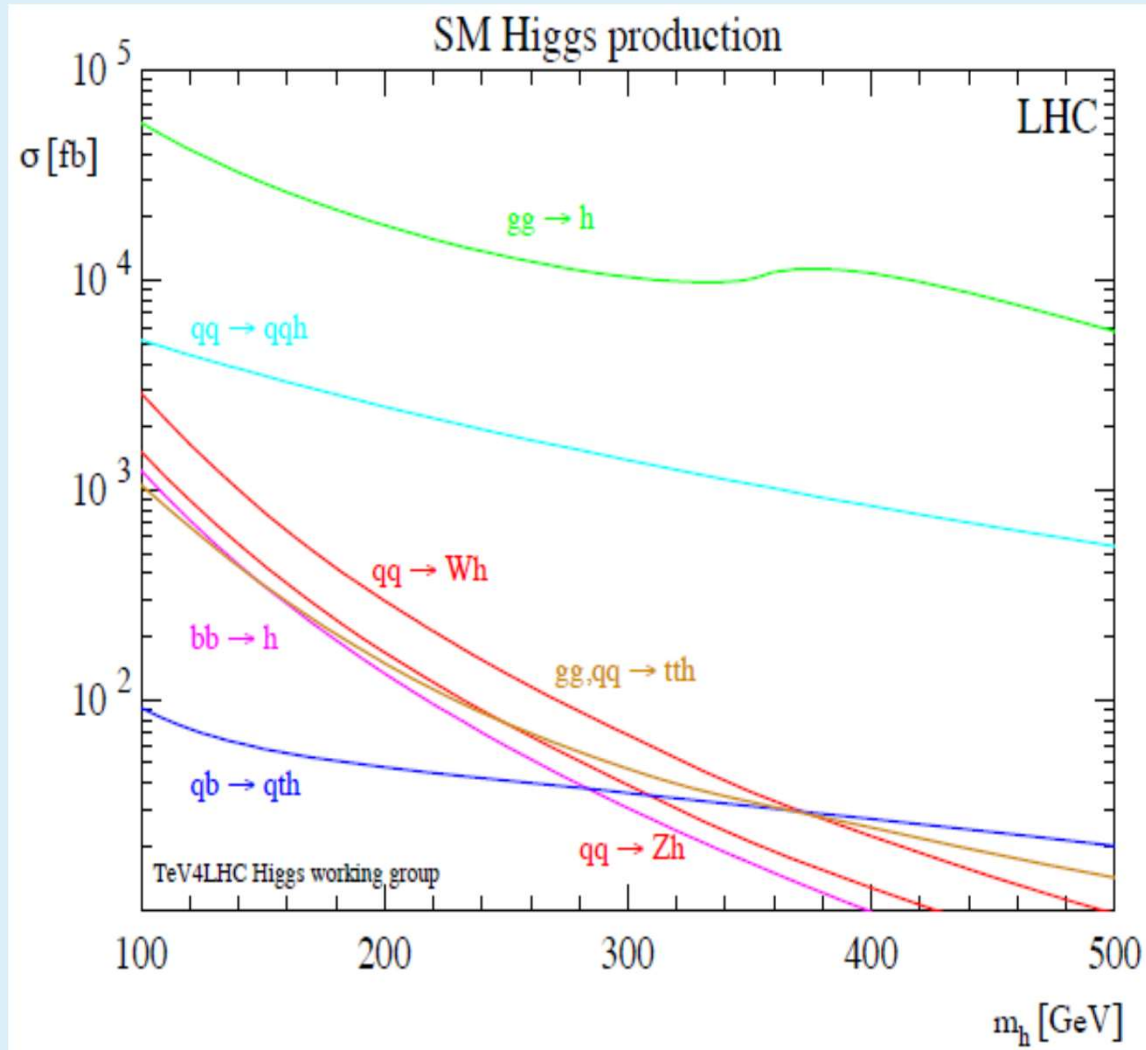
Loop diagrams, dominated by  $t$  quark

PDF somewhat dependent on  $Q^2$

# Parton Collider- III

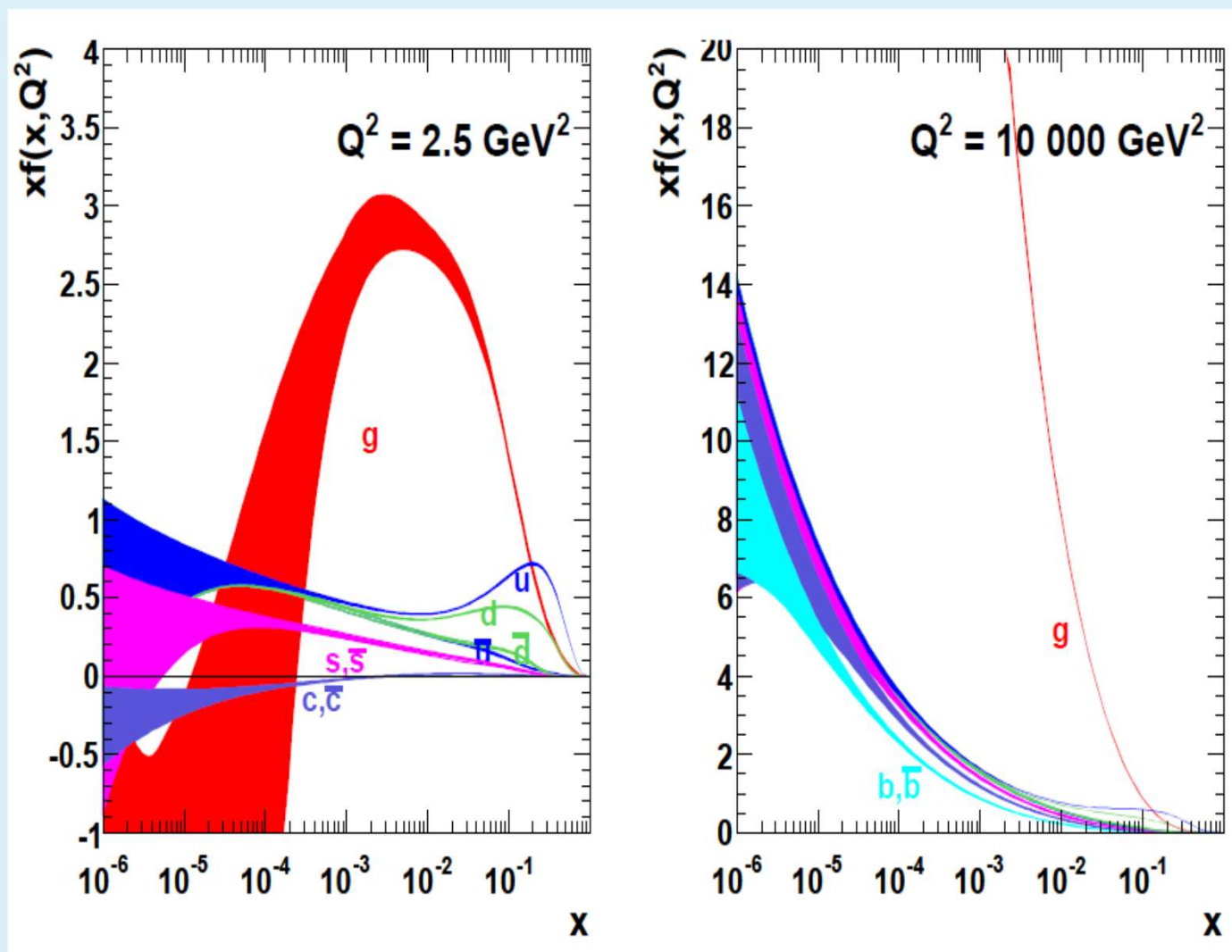


# Parton Collider- IV



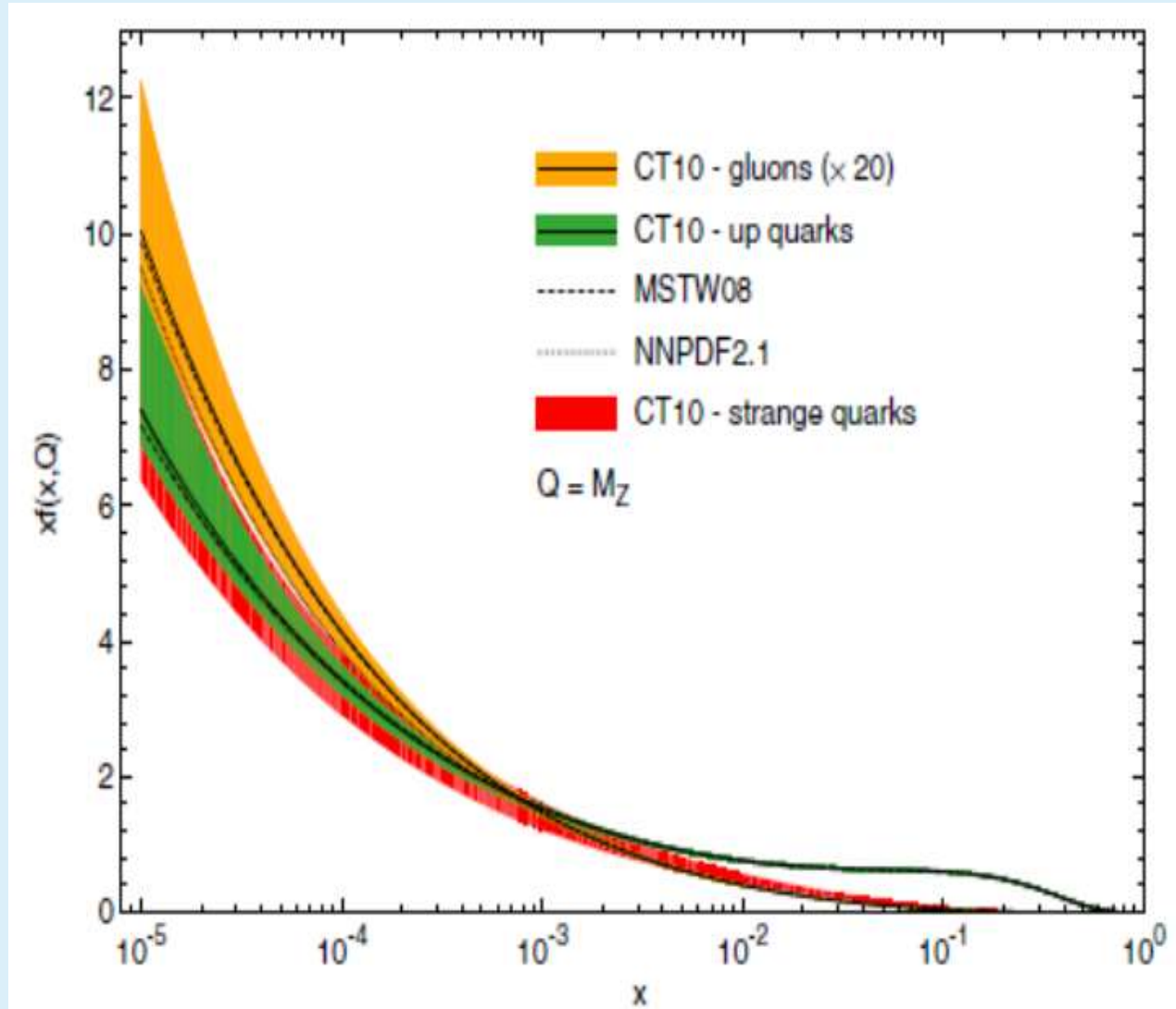
# Parton Collider - V

Parton densities:



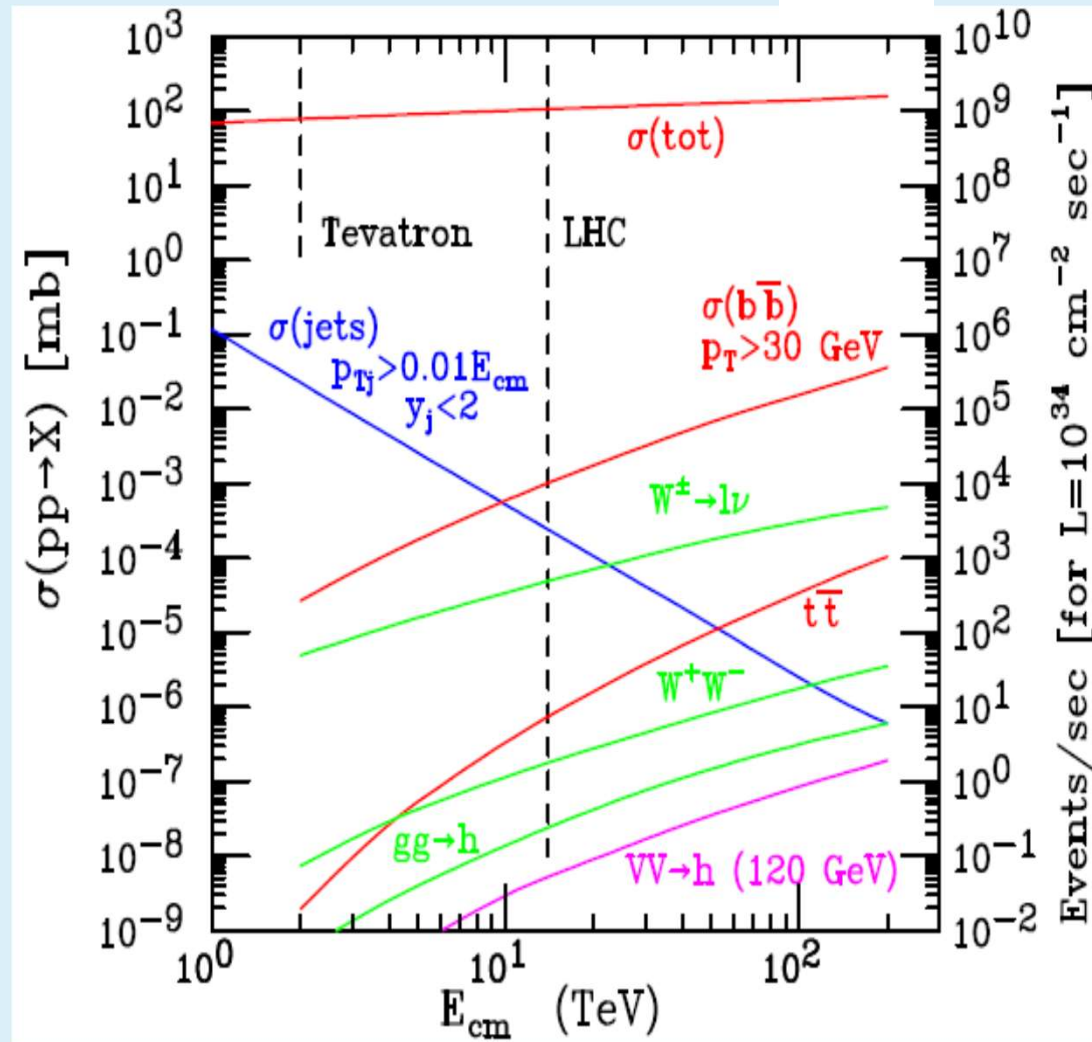


# Parton Collider - VI



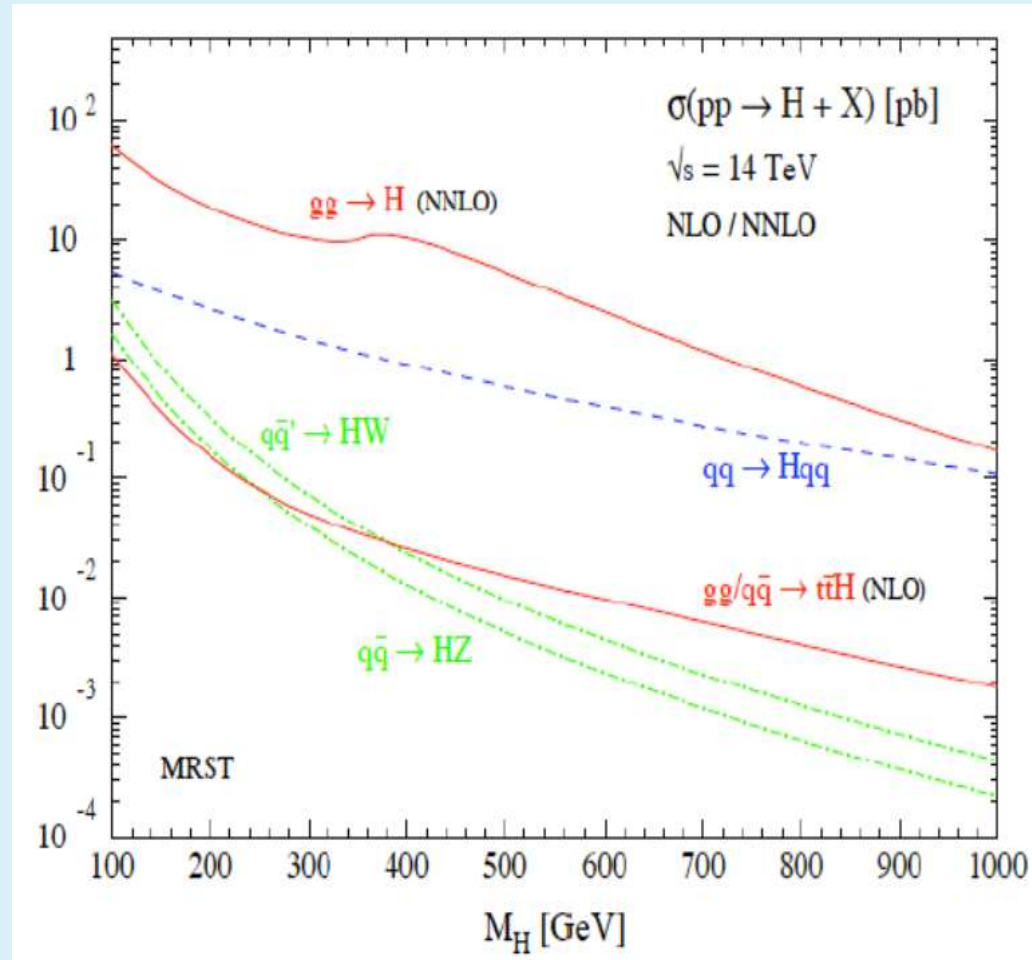
# Parton Collider - VII

Expected cross sections for parton colliders:



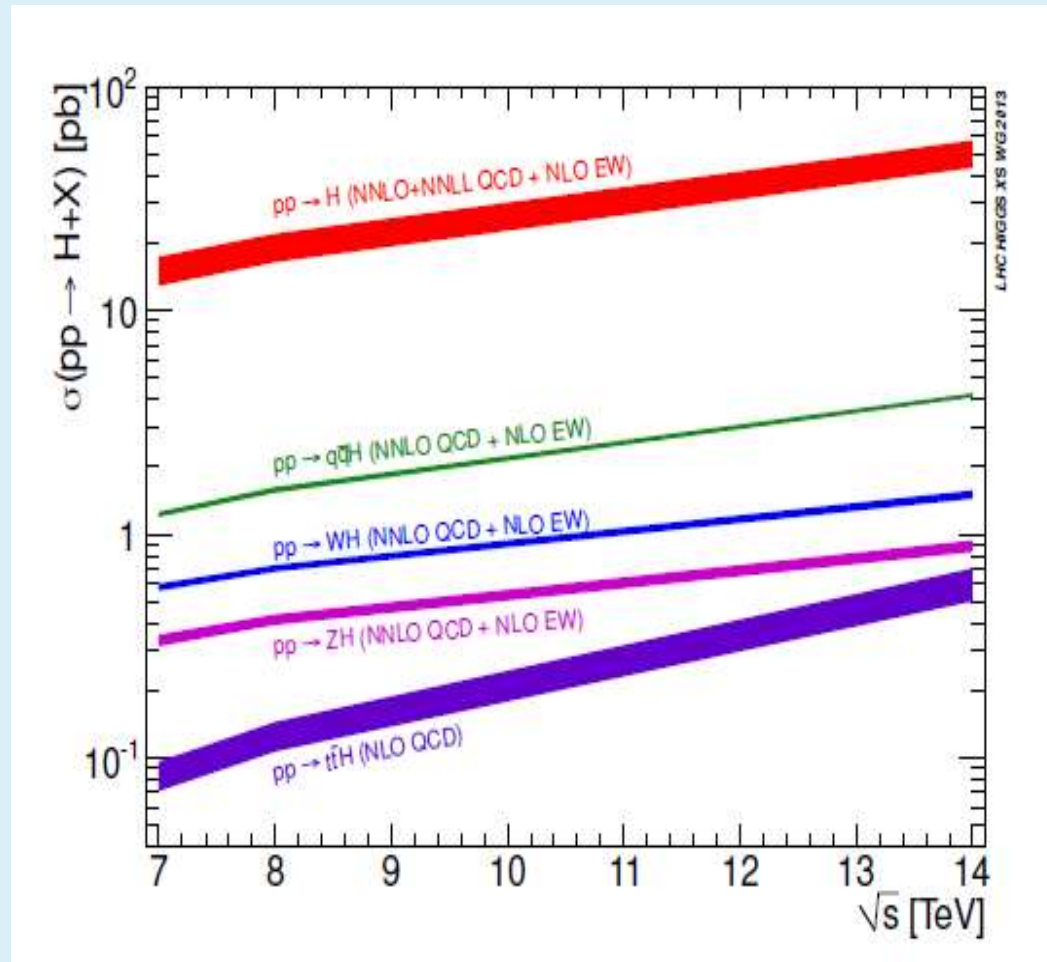
# Parton Collider - VIII

## Results for LHC cross sections

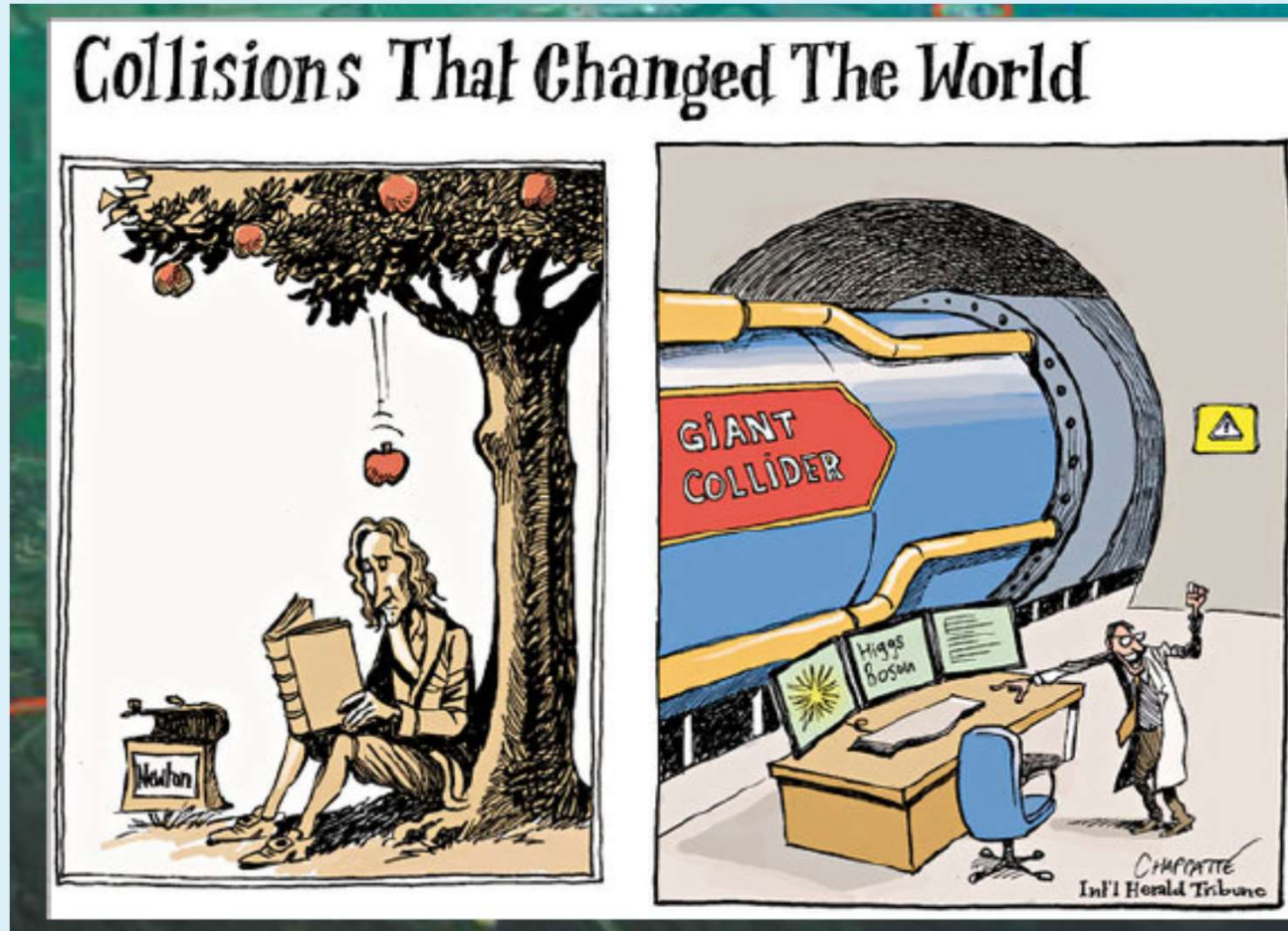


# Parton Collider - IX

Cross-sections for a 126 GeV Higgs



# LHC: Machine - I





# LHC: Machine - II

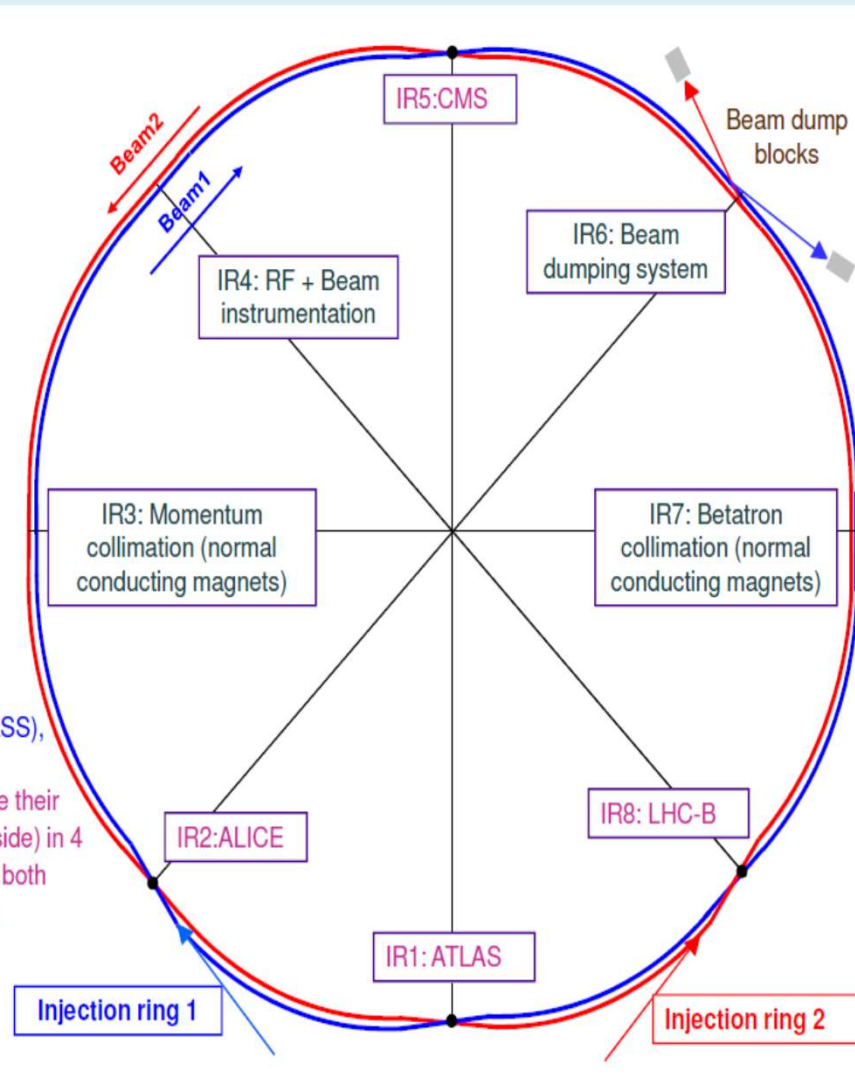
LHC dipole field 8.3 T  
(HERA/Tevatron ~4 T)

LHC pp  $\sim 10^{34}$   
 $\text{cm}^{-2} \text{s}^{-1}$

(Tevatron pp  $3 \times 10^{32}$   
 $\text{cm}^{-2} \text{s}^{-1}$ ) (SppbarS pp  
 $6 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$ )

## 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

$$L = \frac{kN^2f}{4\pi\sigma_x^*\sigma_y^*}$$

$k$  = number of bunches = 2808

$N$  = no. protons per bunch =  $1.15 \times 10^{11}$

$f$  = revolution frequency = 11.25 kHz

$\sigma_x^*, \sigma_y^*$  = beam sizes at collision point (hor./vert.) = 16 mm

High L:

Many bunches ( $k$ )

Many protons per bunch ( $N$ )

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

$\beta^*$  : Beam envelope (optics)

$\varepsilon$  : Phase space volume occupied  
by the beam (constant along the  
ring)

} High beam “brilliance”  $N/\varepsilon$   
(particles per phase space volume)  
→ Injector chain performance

} Small envelope  
→ Strong focusing  
Optics

} property  
Beam  
property

# LHC: Machine - IV

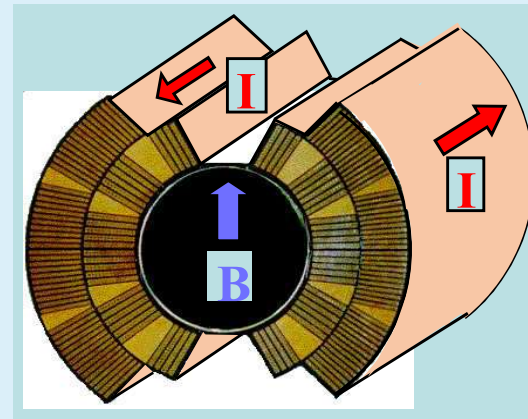
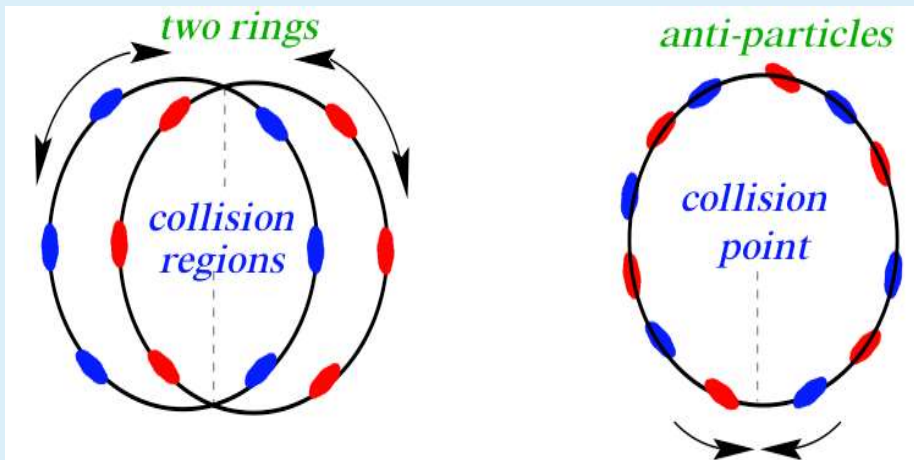
$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

LHC:  $\rho = 2.8$  km given by LEP tunnel

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

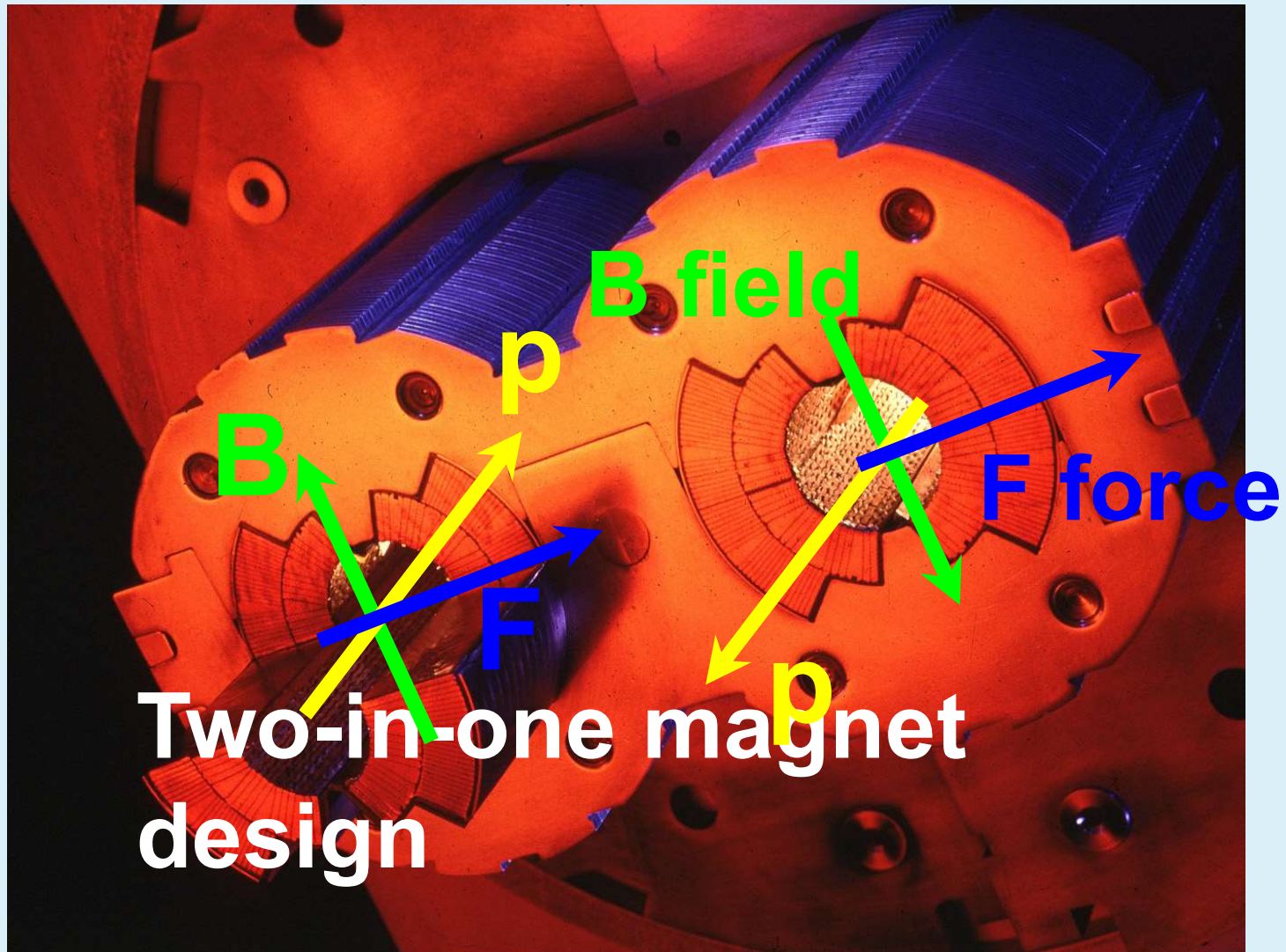
Bending field :  $B = 8.33$  T

→ Superconducting magnets



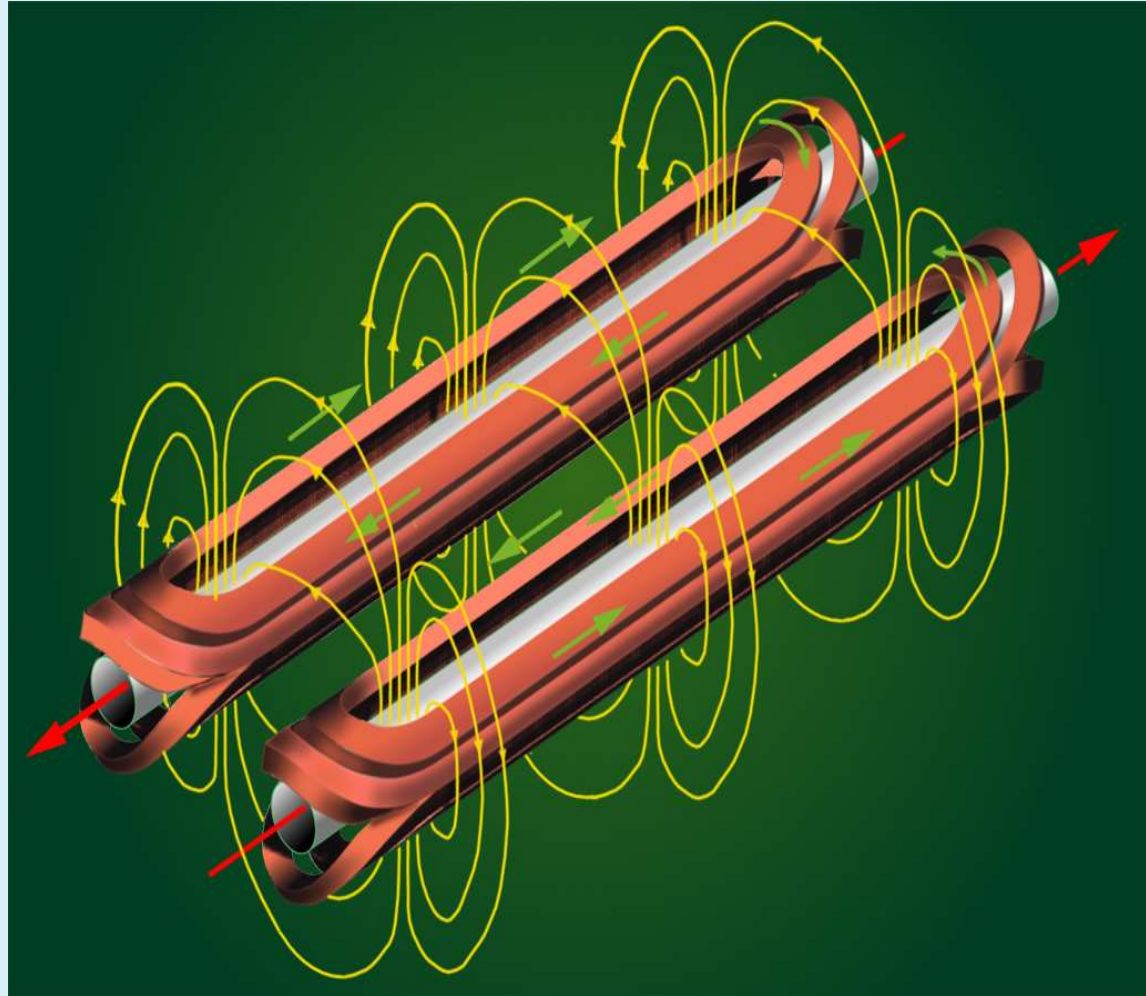


# LHC: Machine - V



# LHC: Machine - VI

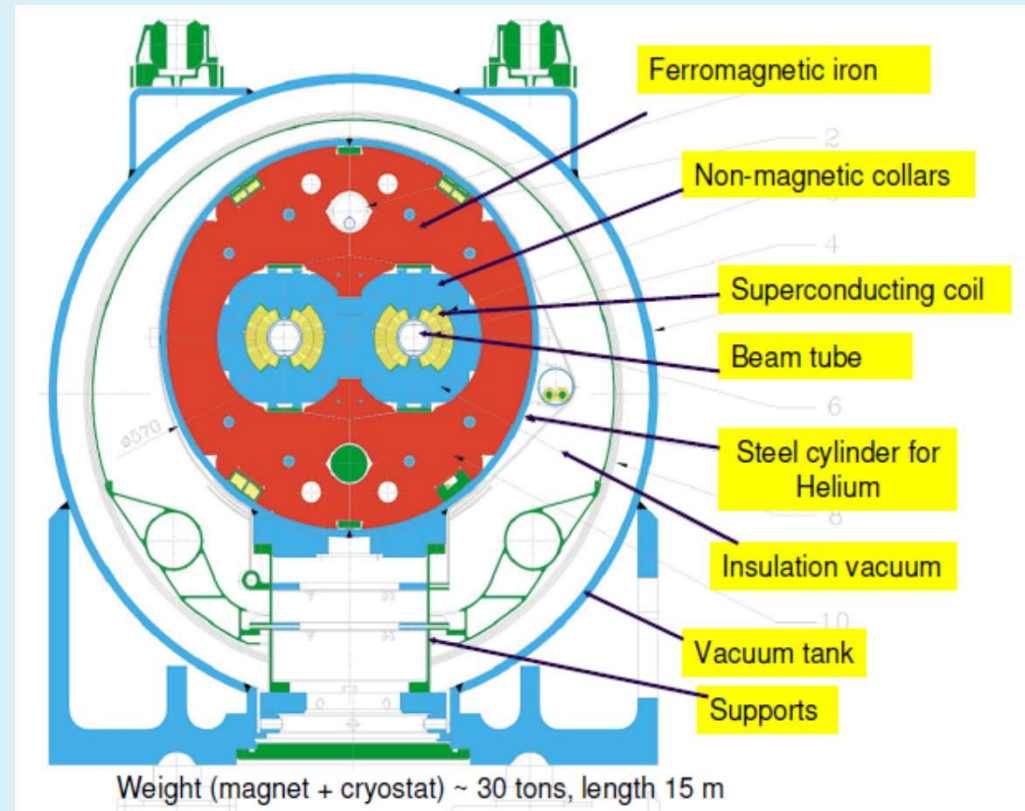
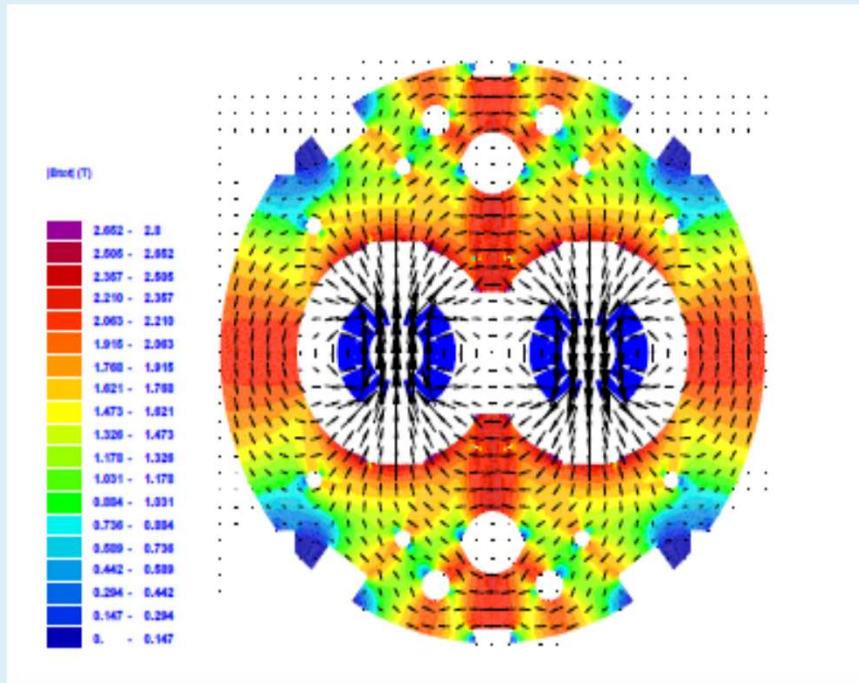
Superconducting coils:



# LHC: Machine - VII

LHC main dipole:

Two magnets in a single module



# LHC: Machine - VIII

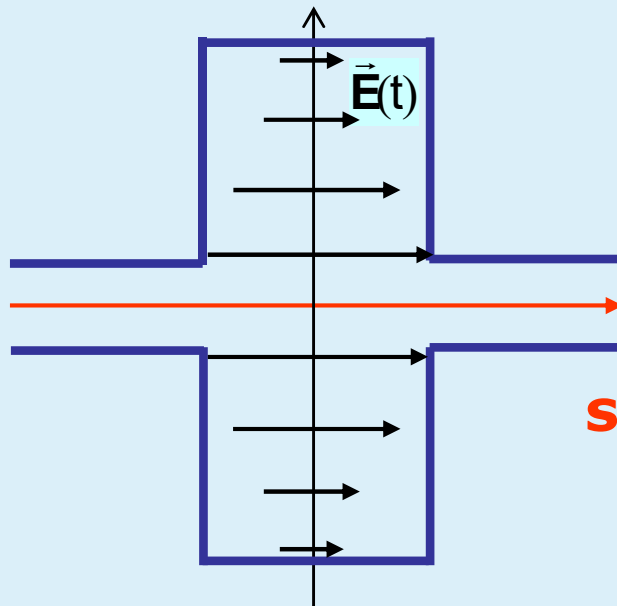
RF system:

4 + 4 Superconducting RF cavities

400 MHz

$\sim 0.5$  MeV/turn

20' for 450 GeV  $\rightarrow$  7 TeV

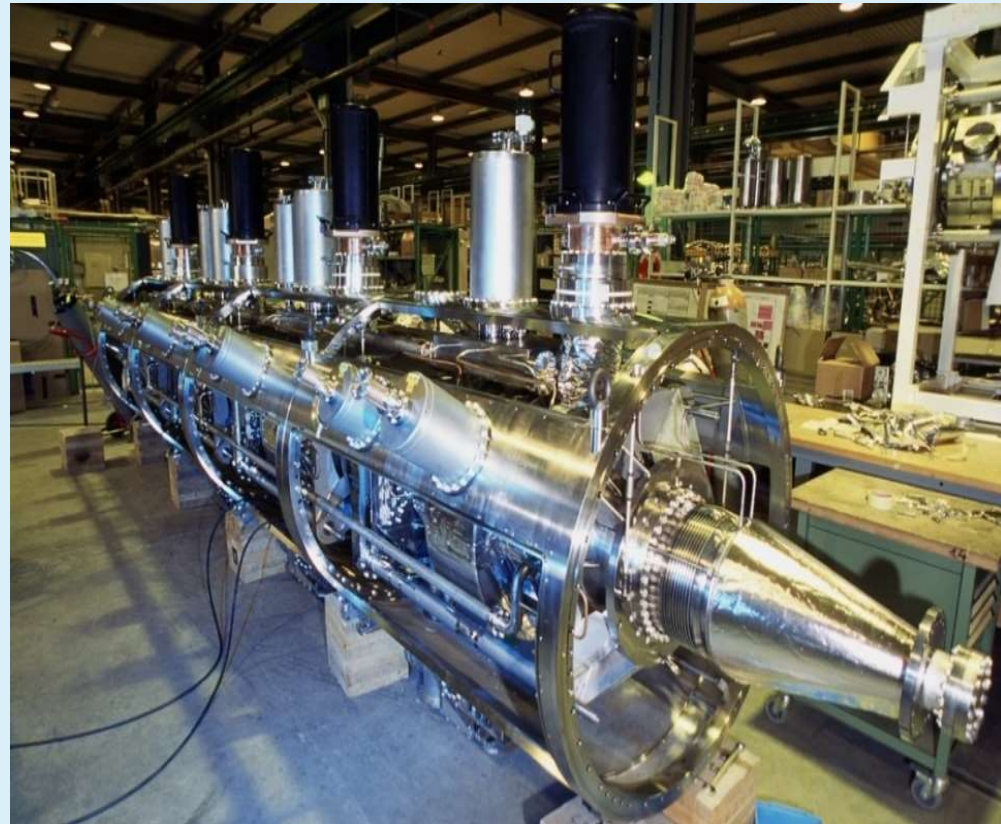
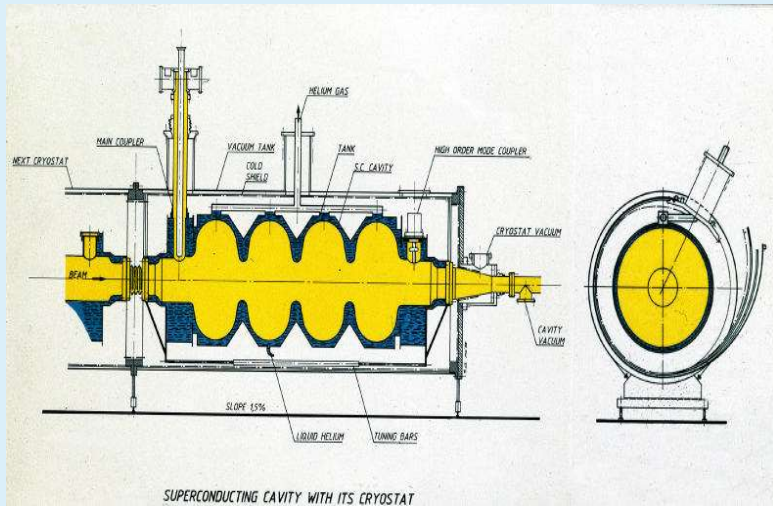


	Synchrotron radiation loss
LHC @ 3.5 TeV	0.42 keV/turn
LHC @ 7 TeV	6.7 keV /turn
LEP @ 104 GeV	$\sim 3$ GeV /turn



# LHC: Machine - IX

## Superconducting cavity



# H - I

Selecting best decay channels for detection:

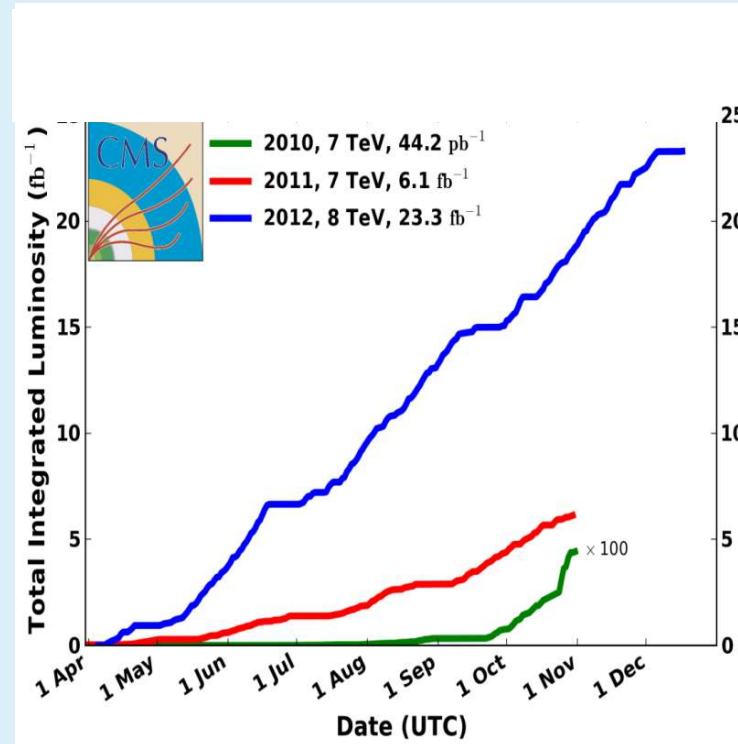
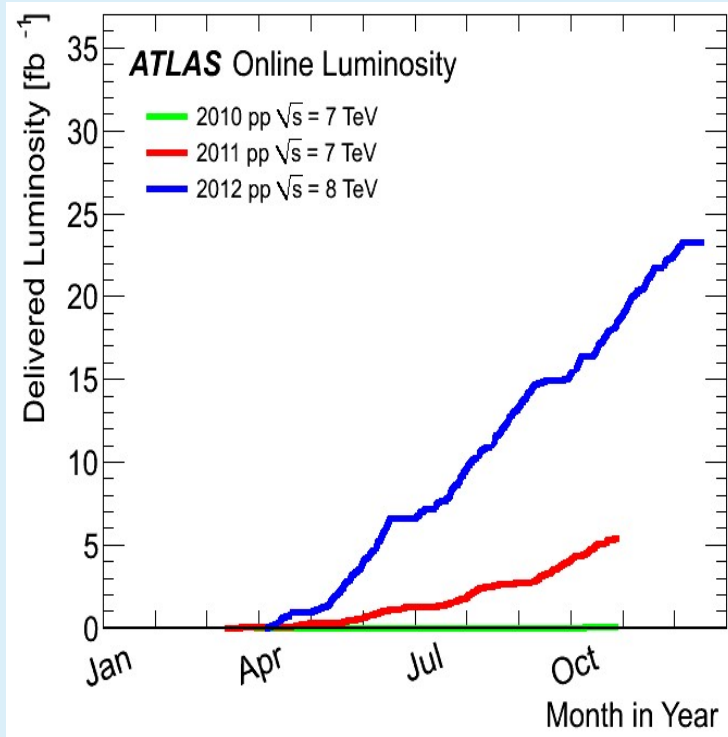
Strongly dependent on (unknown)  $M_H$

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  $BR \sim 2 \cdot 10^{-3}$ , 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:  $\sim 30 \text{ fb}^{-1}$  / experiment



Phenomenal performance:

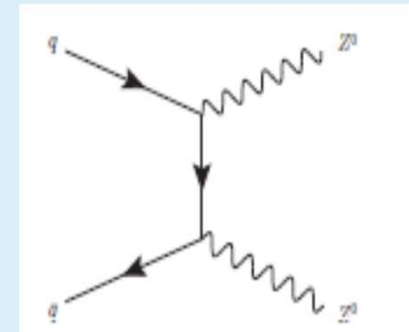
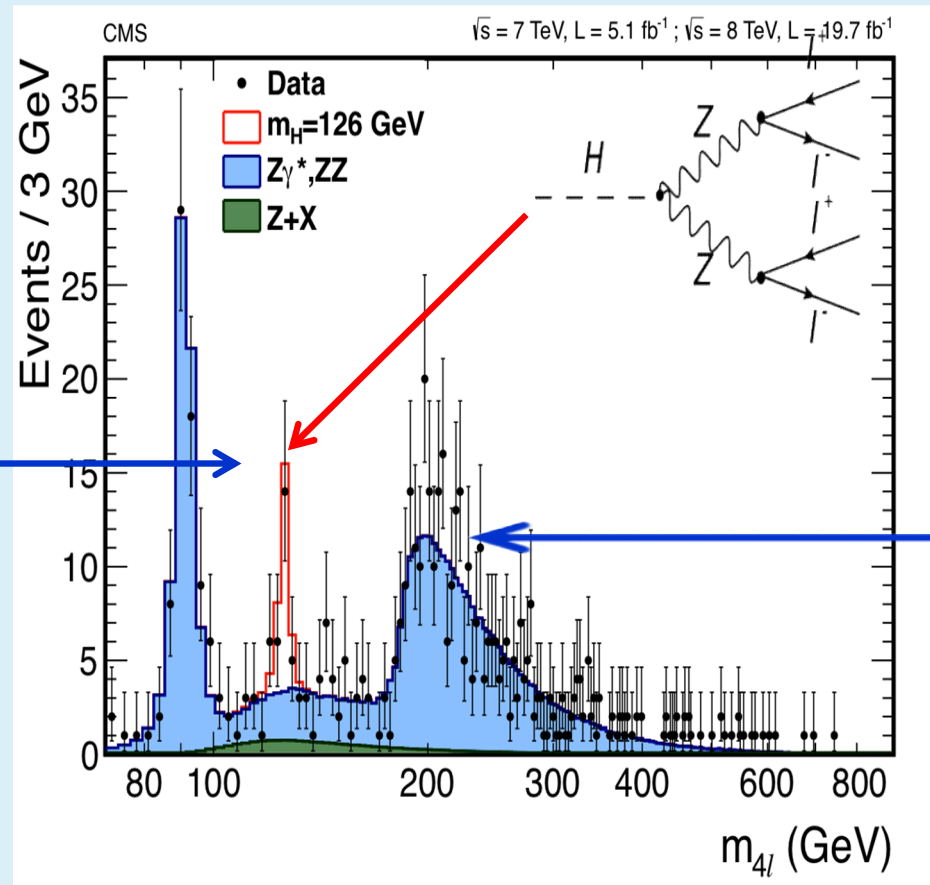
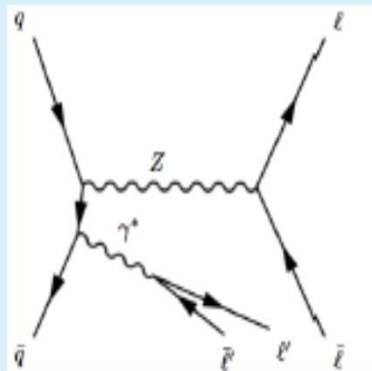
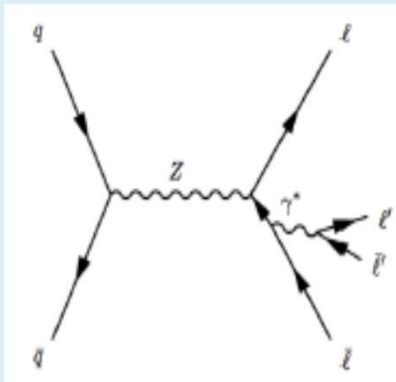
Record luminosity ( $> 5 \times 10^{33}$ ) obtained soon after startup in 2012

Sustained data collection rate of  $> 1.0 \text{ fb}^{-1} / \text{wk}$

Delivered/recorded @ 8 TeV = [ 23.3 / 21.3 (ATLAS) , 21.8 (CMS) ]  $\text{fb}^{-1}$

# H - III

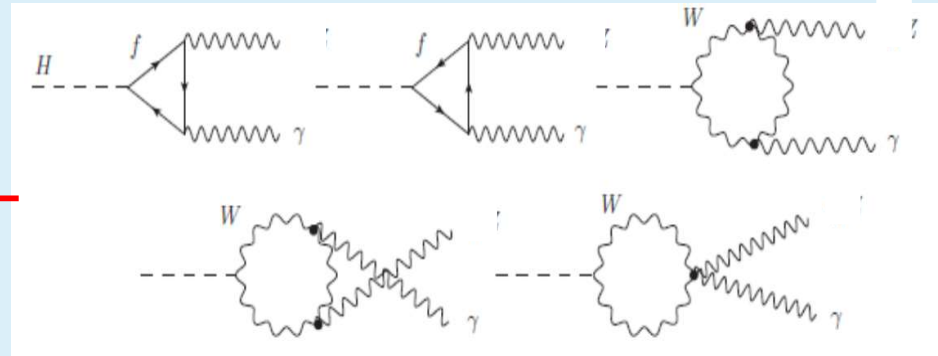
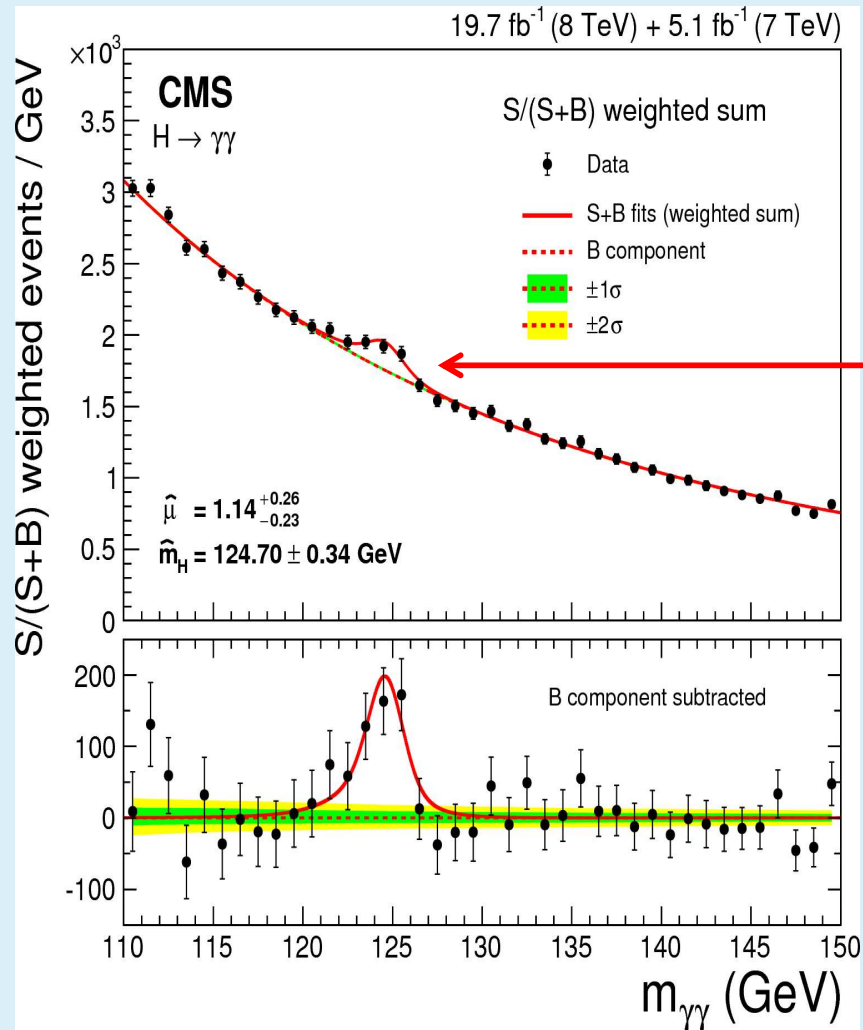
4 leptons:  $\sim 7\sigma$  observation





# H - IV

2  $\gamma$ 's:  $\sim 6 \sigma$  observation



# H - V

Signal strength:

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

# H - VI

Combined mass: All modes

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

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

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

...Next time!