The Standard Model Higgs

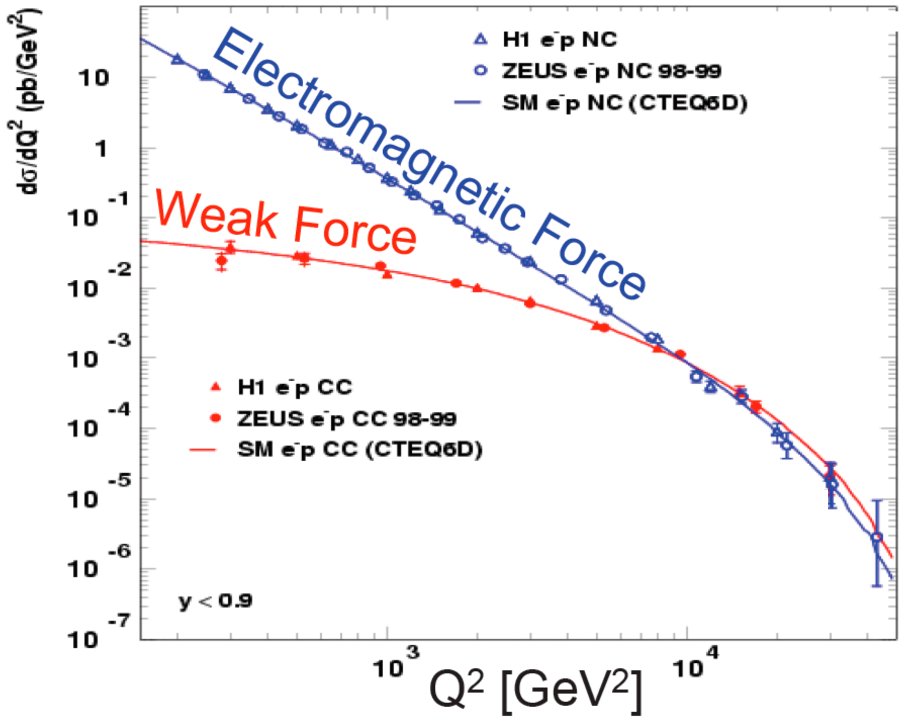
C. Anastasiou, CTEQ-MCnet summer school 2008,
http://conference.ippp.dur.ac.uk/conferenceOtherViews.py?view=ippp&confId=156
S. Dawson, Introduction to Electroweak Symmetry Breaking, http://arxiv.org/abs/0812.2190

The Standard Model

- Gauge Group:
  $SU(3) \times SU(2) \times U(1)$
  QCD Electroweak

- Gauge Bosons:
  - SU(3): G_μ^i, i=1,...,8
  - SU(2): W_μ^i, i=1,2,3
  - U(1): B_μ

EW unification beautifully demonstrated



Massless fermions and bosons

$\Downarrow$

Need for a mechanism to provide masses:

The SM Higgs mechanism

Since an explicit mass term in the Lagrangian would violate local gauge invariance, which is the guiding principles of SM, a complex Higgs SU(2) doublet:

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

is included in the SM, with a SU(2)xU(1) invariant scalar potential $V = \mu^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2$

Higgs Lagrangian

Lagrange equation: $$\partial_\mu \frac{\partial L}{\partial(\partial_\mu \Phi)} - \frac{\partial L}{\partial \Phi} = 0$$

where:
ϕ = wave or field amplitude ($\equiv \phi_{RE}$)
$\partial_\mu = \dfrac{\partial}{\partial x_\mu}$ = 4-vector space-time derivative

For free <u>scalar</u> particles of mass μ:

$$L = T - V = \tfrac{1}{2}(\partial_\mu \Phi)^2 - \tfrac{1}{2}\mu^2\Phi^2$$

$\Rightarrow \partial_\mu{}^2\Phi - \mu^2\Phi = 0$ (Klein-Gordon eq.)

Higgs $\Rightarrow$ scalar particles that interact with each other:

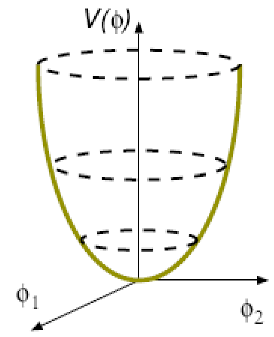
the most general, non-trivial, renormalizable potential is:

$$V = \tfrac{1}{2}\mu^2\Phi^2 + \tfrac{1}{4}\lambda\Phi^4$$

(λ = positive dimensionless constant $\equiv$ coupling of the four-boson vertex)

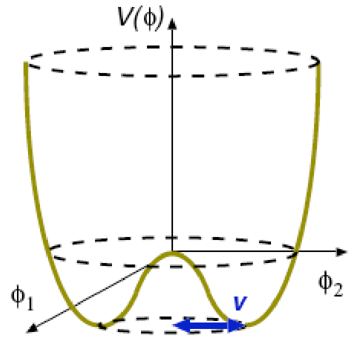
Let us inspect the vacuum of this field:

Higgs potential

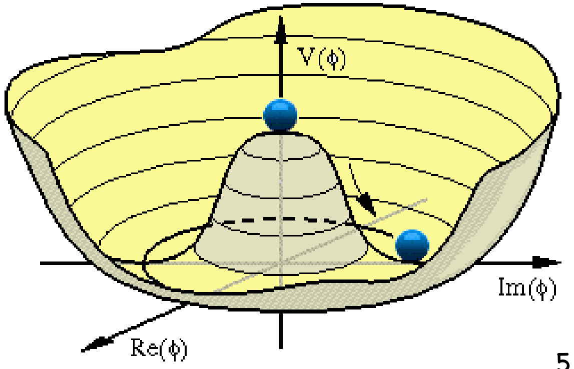


Vacuum $\Rightarrow$ minimum of V: $\Phi(\mu^2 + \lambda\Phi^2) = 0$

If $\mu^2 > 0$ (massive particle) $\Rightarrow \Phi_{min} = 0$
(nothing special happens...)



If $\mu^2 < 0 \Rightarrow \Phi_{min} = \pm v = \pm(-\mu^2/\lambda)^{½}$
These two minima in one dimension correspond to a continuum of minimum values in SU(2).
The point $\Phi = 0$ is now instable.
Choosing the minimum (e.g. at +v) gives the vacuum a preferred direction in isospin space
$\Rightarrow$ spontaneous symmetry breaking.



Perform perturbation around the minimum:

The Higgs boson

Expansion of $L = \frac{1}{2}(\partial_\mu \Phi)^2 - \frac{1}{2}\mu^2\Phi^2 - \frac{1}{4}\lambda\Phi^4$ around the minimum, $\Phi = v + \sigma(x)$, gives:

$$L = \frac{1}{2}(\partial_\mu \sigma)^2 - \lambda v^2\sigma^2 - \lambda(v\sigma^3 + \frac{1}{4}\sigma^4)$$

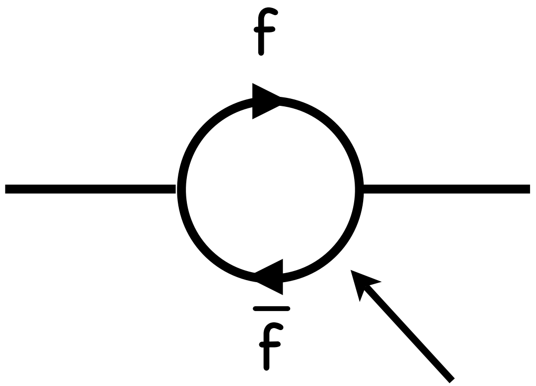
mass term   self interaction

Therefore, we obtain a massive scalar, self-interacting

⬇

the Higgs Boson

Vacuum in quantum theory



Very busy place!
virtual particle-antiparticle pairs
produced out of nothing,
according to $\Delta E \cdot \Delta t < \hbar$

virtual particles:
same quantum numbers & properties
as the real one, except for $E^2 - p^2 \neq m^2$

the Higgs mechanism

The masses do not emerge alone from the SM.

According to the Standard Model,

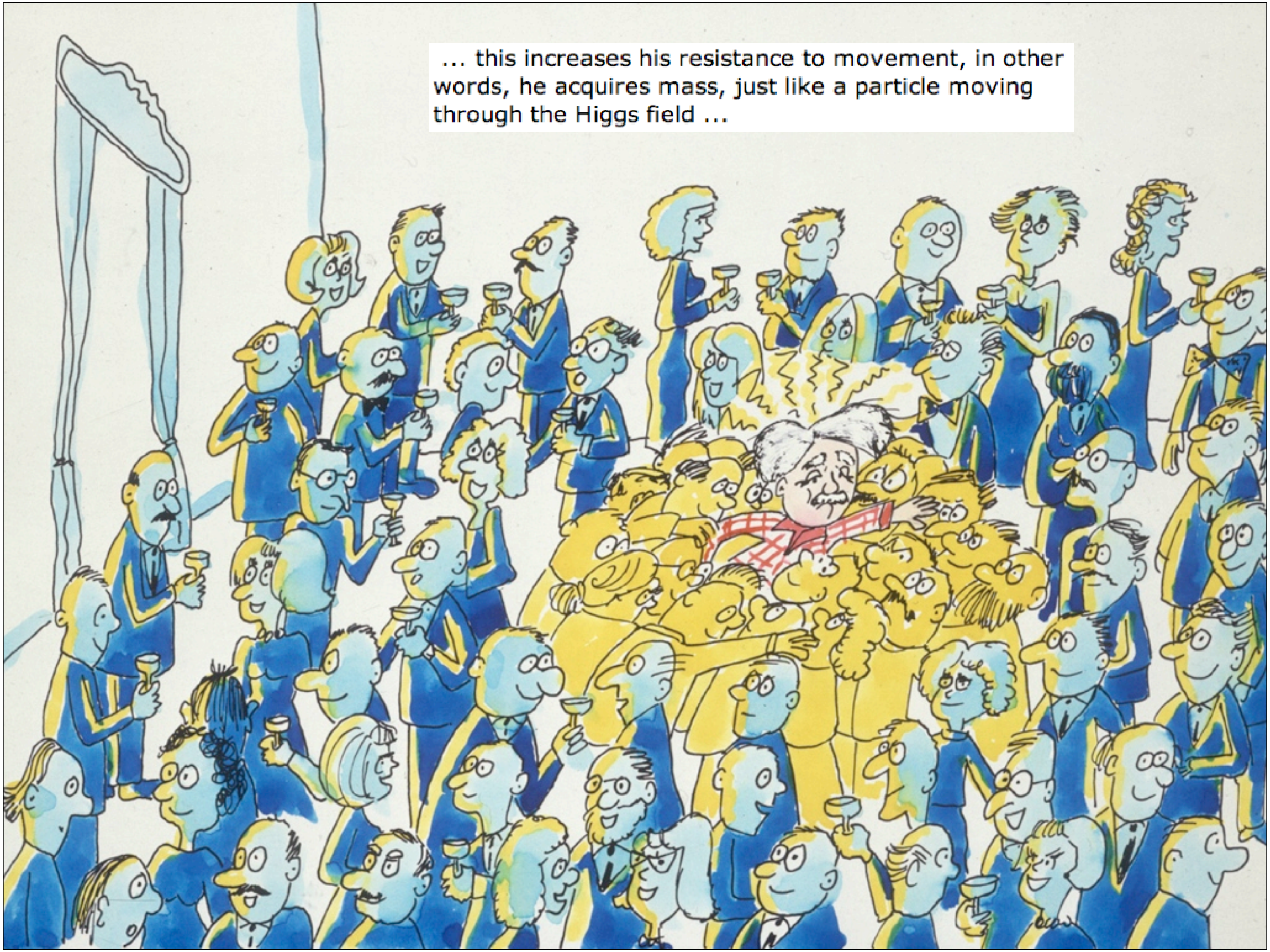
the vacuum is filled with a condensate of Higgs particles: quarks, leptons, W and Z bosons continuously collide with these Higgs particles as they travel through the "vacuum". The Higgs condensate acts like molasses and slows down anything that interacts with it. The stronger the interactions between the particles and the Higgs condensate are, the heavier the particles become.

In other words:

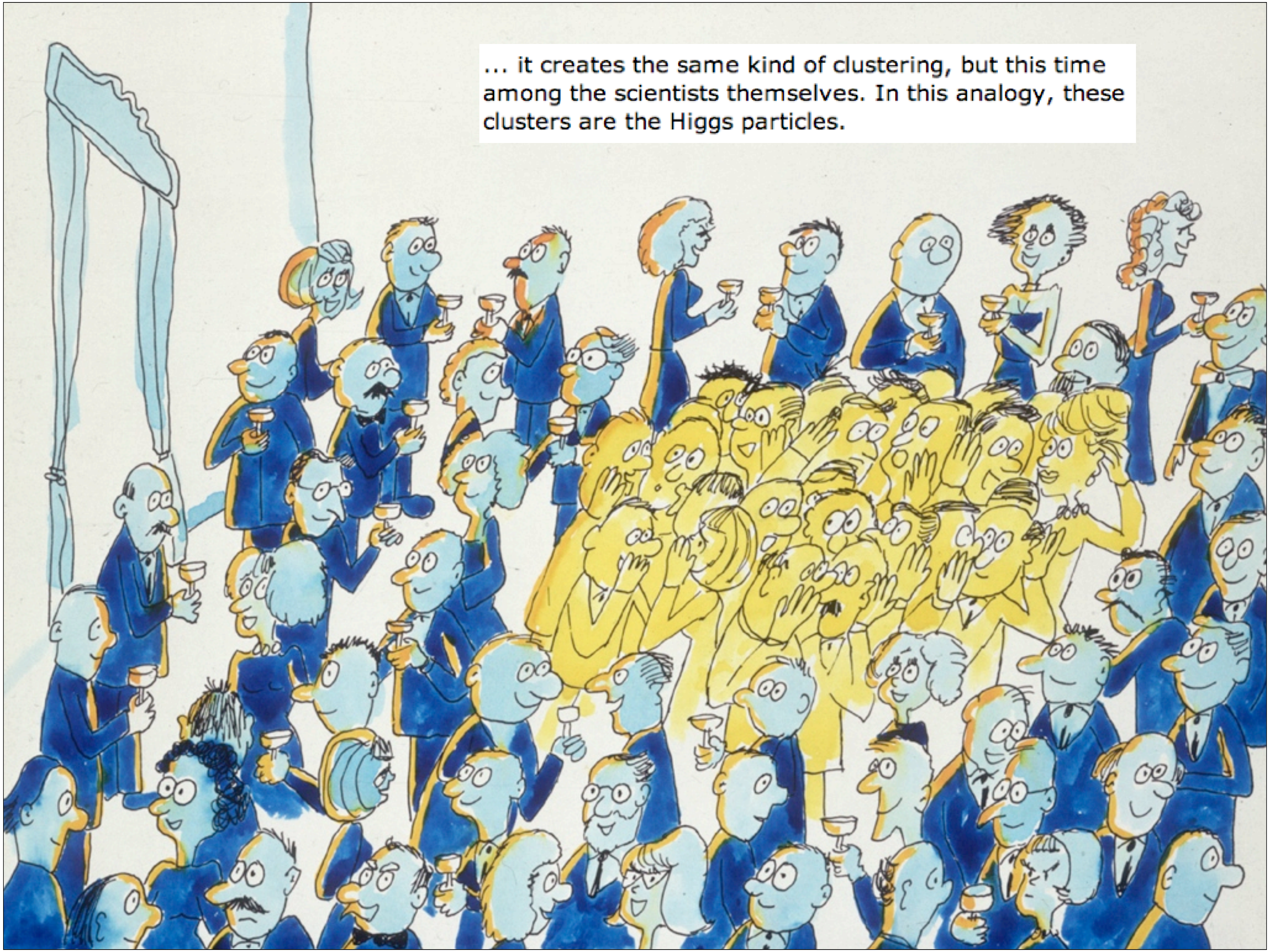
the coupling to the Higgs boson is proportional to the mass.


To understand the Higgs mechanism, imagine that a room full of physicists quietly chattering is like space filled only with the Higgs field....


... a well known scientist walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step ...


... this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field ...


... if a rumour crosses the room ...


... it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.

Higgs sector parameters

The Higgs mass and the vacuum expectation value of the Higgs field can be written in terms of the two free parameters of the Higgs potential $V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$:

$$v^2 = \frac{\mu^2}{2\lambda} \qquad\qquad M_H^2 = 2v^2\lambda$$

Also, since $$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}$$

the well measured value of G_F gives: $v = (\sqrt{2}G_F)^{-1/2} = 246\ \text{GeV}$

⇒ typical scale of EW symmetry breaking!

After choosing the vacuum: $M_{W\pm} = gv/2$ and $M_Z = \frac{1}{2}v(g'^2+g^2)^{1/2}$

$$\Rightarrow \qquad \frac{M_W}{M_Z} = \frac{g'}{(g^2+g'^2)^{1/2}} = \cos\theta_W$$ (prediction!!)

SM Higgs couplings

Higgs couples to fermion masses:

$L \ni \sum_f m_f \, f \bar{f} \cdot (1 + H/v)^2$ ⇒ largest coupling is to heaviest fermion

- no Higgs coupling to neutrinos
- huge top mass somehow special?

Higgs couples to gauge boson masses:

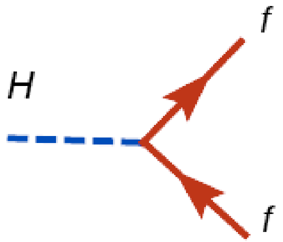
$L \ni M_W^2 \cdot W^{+\mu} W^-_\mu \cdot (1+H/v)^2 + ½\, M_Z^2 \cdot Z^\mu Z_\mu \cdot (1+H/v)^2$

Note that the only unknown parameter is the Higgs mass.

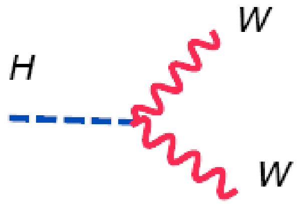
The theory is fully testable since everything else is calculable.

Feynman Rules

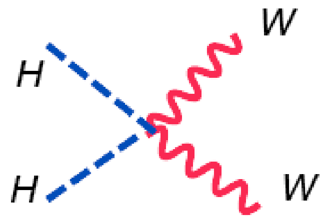
They are independent of the details of the Higgs potential except the vev



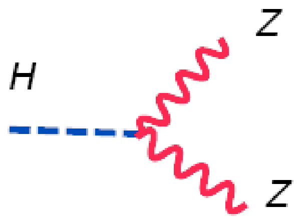
$$i\frac{m_f}{v}\delta_{ij}$$



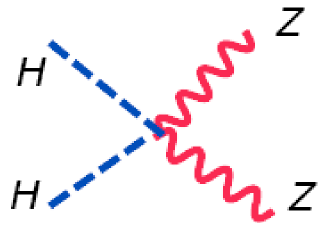
$$2i\frac{M_W^2}{v}g_{\mu\nu}$$



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



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



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

Higgs coupling proportional to m_f, M_W^2, M_Z^2

from C. Anastasiou, CTEQ-MCnet summer school 2008

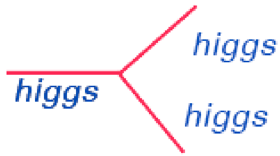
In summary:

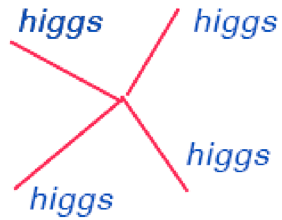
- The Higgs mechanism is introduced in the SM to generate mass:
  - introduce single Higgs doublet Φ and self interaction term Φ^4 in the Lagrangian (simplest case)
  - before spontaneous symmetry breaking: massless W_i, B and complex Φ
  - Higgs v.e.v. $\neq 0$ breaks the SU(2) x U(1) local gauge symmetry
  - after spontaneous symmetry breaking: massive $W^{\pm}$ and Z, massless γ, physical Higgs boson H
- Only two parameters: the Higgs mass (M_H) and the v.e.v. (v)
- The coupling is proportional to masses (by construction)
- This mechanisms is one of the many possibilities, but it is simple, "natural" in the theory, and fully testable:

$\Rightarrow$ MUST FIND THE HIGGS BOSON !!!

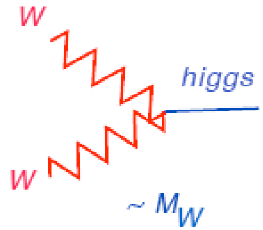
What is the Higgs boson?

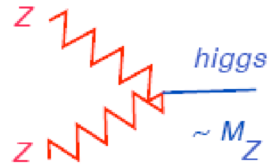
- A neutral elementary scalar field which can interact with himself:

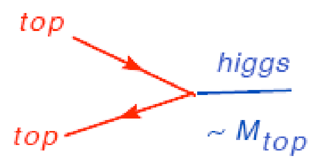




- It interacts stronger with short-lived very-massive particles





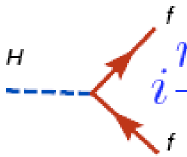


- Hard to find it since his interaction with the particles we collide (e, u, d) is very weak, therefore at colliders Higgs bosons must be radiated off heavy states, like W, Z, top

$$\Downarrow$$

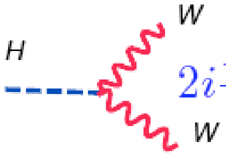
must pay big energy price !

The end of a Higgs boson



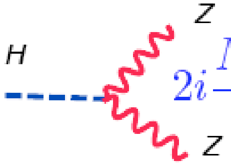
$$i\frac{m_f}{v}\delta_{ij}$$

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



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

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



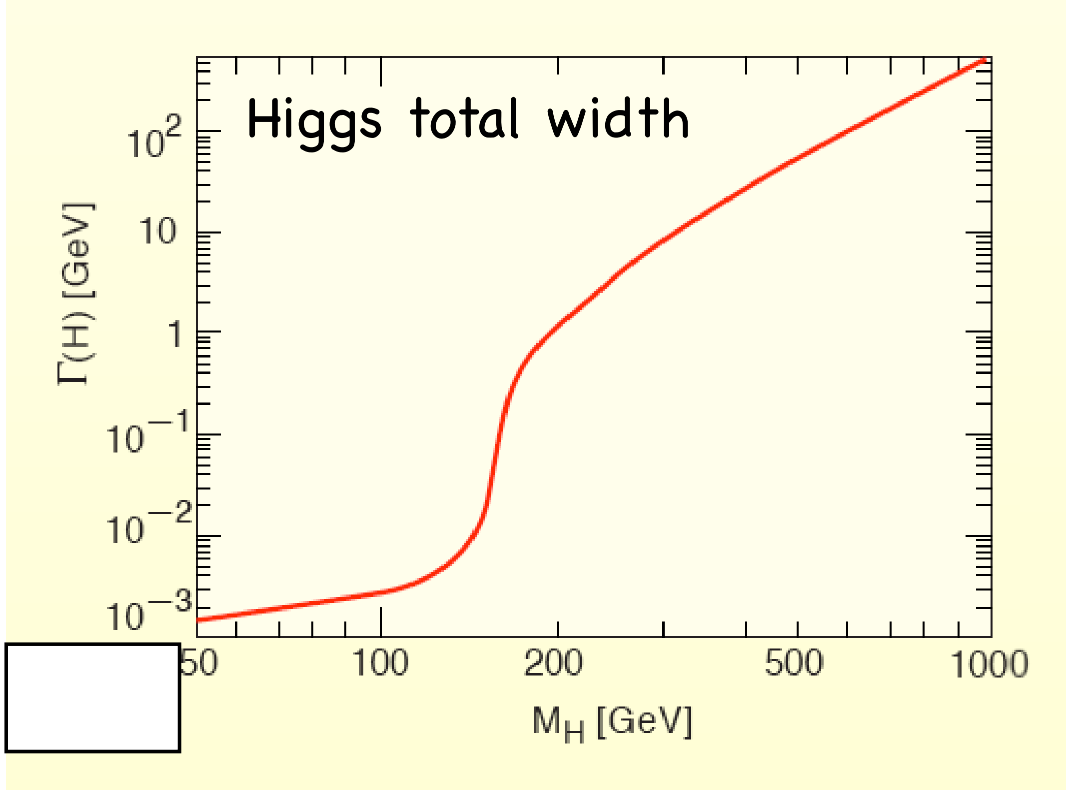
$$2i\frac{M_Z^2}{2v}g_{\mu\nu}$$

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

from C. Anastasiou, CTEQ-MCnet summer school 2008

Higgs boson width

SM prediction:



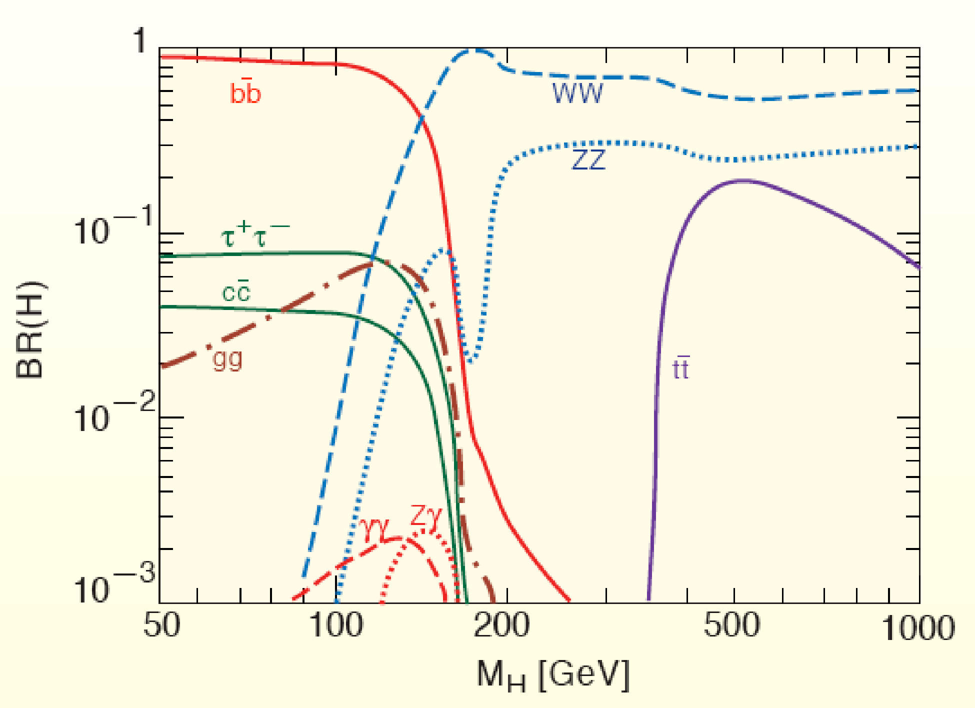
Narrow resonance (below detector resolution) for m_H < 170 GeV.
no clear resonance for large masses

Higgs lifetime:
for example,
if $m_H \approx 140$ GeV,
$\Gamma_H \approx$ few MeV,
$\tau_H \approx 10^{-22}$ s
Higgs boson decays very quickly

New physics can change significantly this prediction

Higgs decay branching ratios

The Higgs boson decays into the heaviest massive particle that is allowed by phase space.



The Higgs couplings to:
- fermions grow with their mass
- W_L, Z_L grows as m^2.

Heaviest available fermion (b quark) always dominate, until WW, ZZ thresholds open

At low m_H:
b->jets dominate, but large backgrounds and b-jet resolution
-> must use the clean but rare decays into two photons (BR ≈ 0.2%)

150 < m_H < 180 GeV:
"tough window" where only WW->2l + MET channel is available (Tevatron at work...)

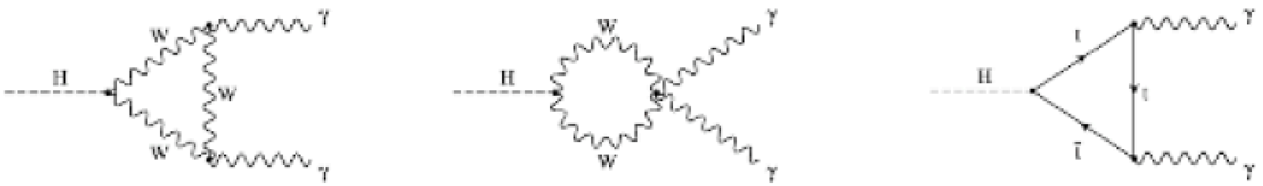
Heavy Higgs:
can be "easily" seen in ZZ -> 4 leptons

Higgs Decays to Photons

- Dominant contribution is W loops
- Contribution from top is small

$$\boxed{\Gamma(H \to \gamma\gamma) \approx \frac{\alpha^3}{256\pi^2 s_\theta^2} \frac{M_H^3}{M_W^2} \left| 7 - \frac{16}{9} + \ldots \right|^2}$$

W top

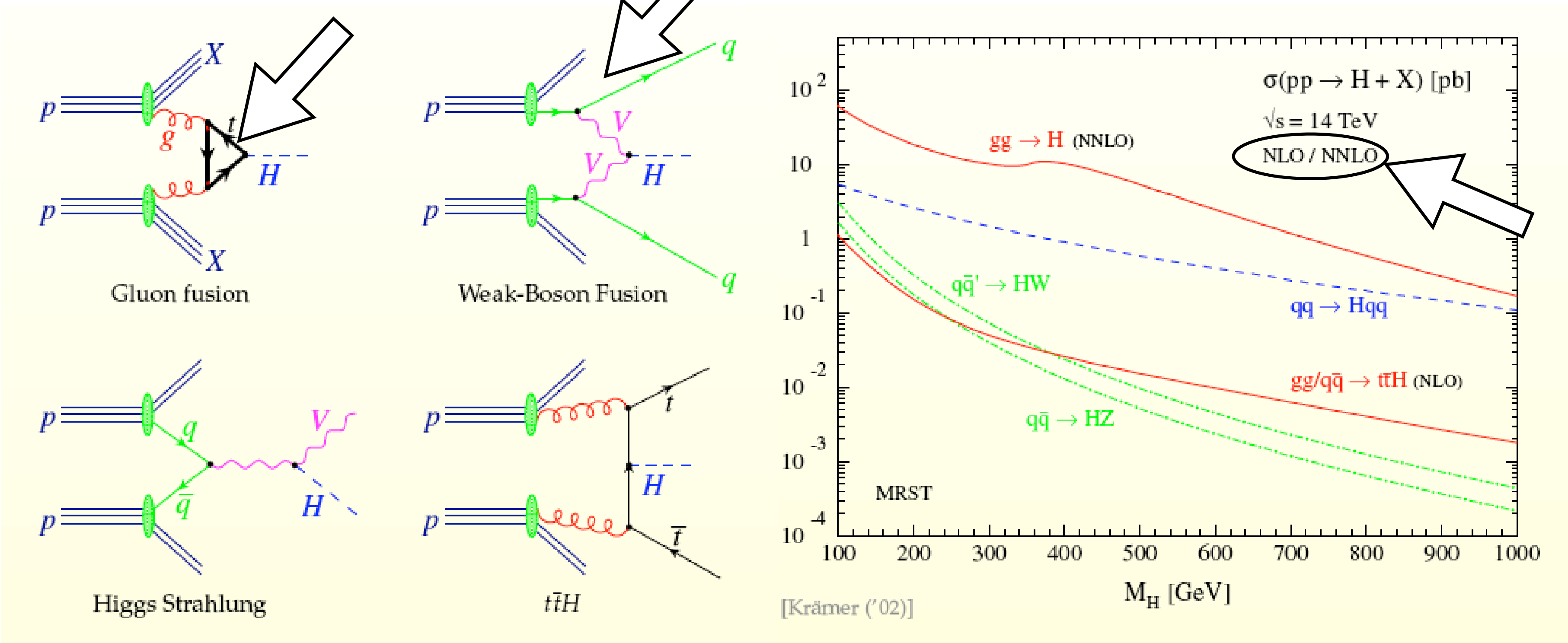


from S. Dawson

Higgs production at the LHC

Dominant production
gg→H (!)

Large production
and clear signature



$\sigma_{gg\to H} \approx 30$ pb at $m_H \approx 130$ GeV

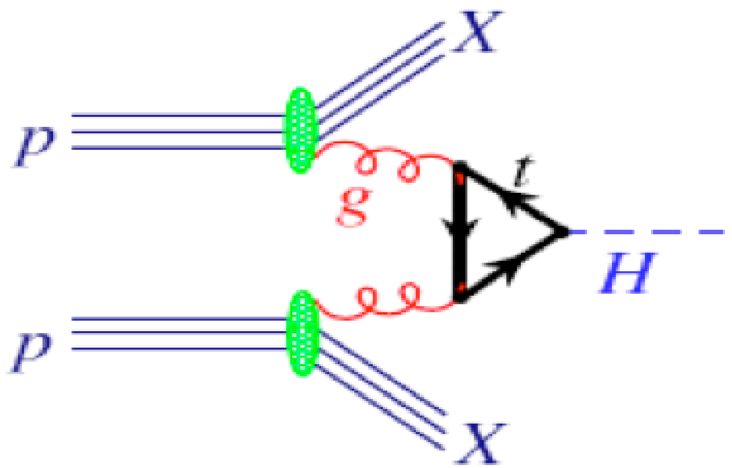
$\Rightarrow N_{evt} = L/\sigma \approx 30$k events for Lumi = 1 fb^{-1} !!

Can we see them ?

The gluon-gluon fusion

- Higgs boson does not couple to (massless) gluons directly, but through virtual loops

- Although any quark could circulate in the loop, the largest contribution is due to the top quark since, again, Higgs coupling is proportional to fermion mass



Very hard to compute to higher QCD orders, since we start already with a loop.

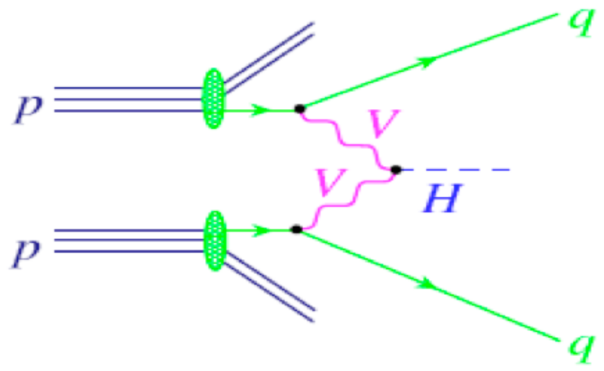
Trick used: assume effective H-gg coupling in the limit $m_t \rightarrow \infty$ (shown to be valid for $m_H < m_t$)

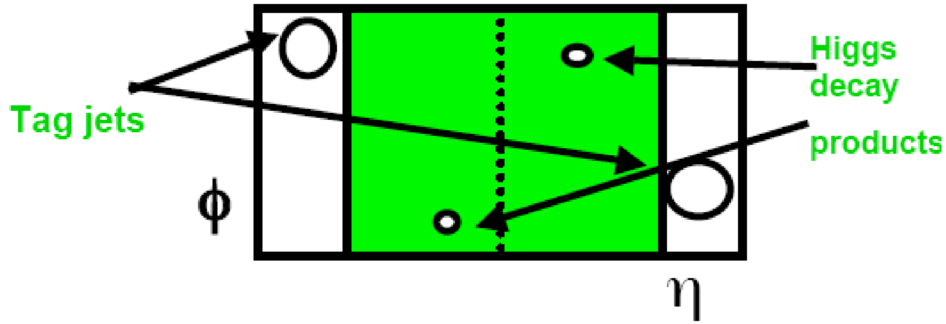
NNLO reached using this approach

- it probes the structure of the vacuum; therefore it would be sensitive to the presence of new heavy particles BSM

Vector Boson Fusion

- EW process ⇒ lower cross section than gg fusion
- very clear signature:
  - quarks get little kick when radiating W or Z boson -> two low-E_T and forward jets
  - no color flow -> rapidity gap





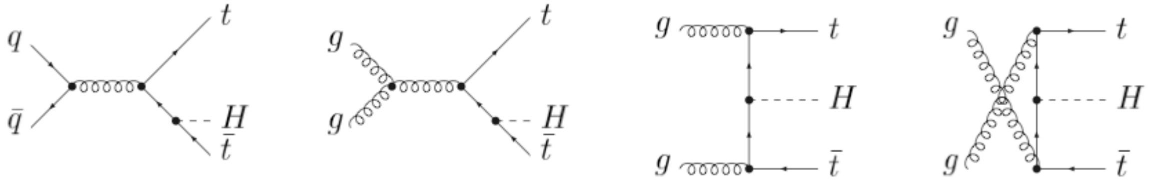
But: remember the troubles with MB+UE in the jet reconstruction in the forward regions !

- sensitive to the nature of coupling to vector bosons

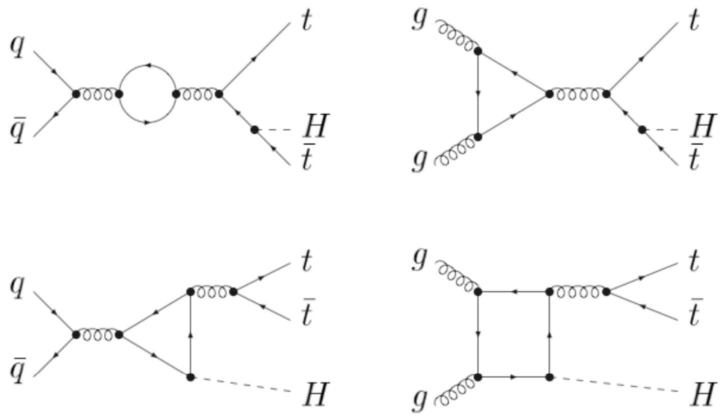
Diagrams, diagrams …

case for ttH production:

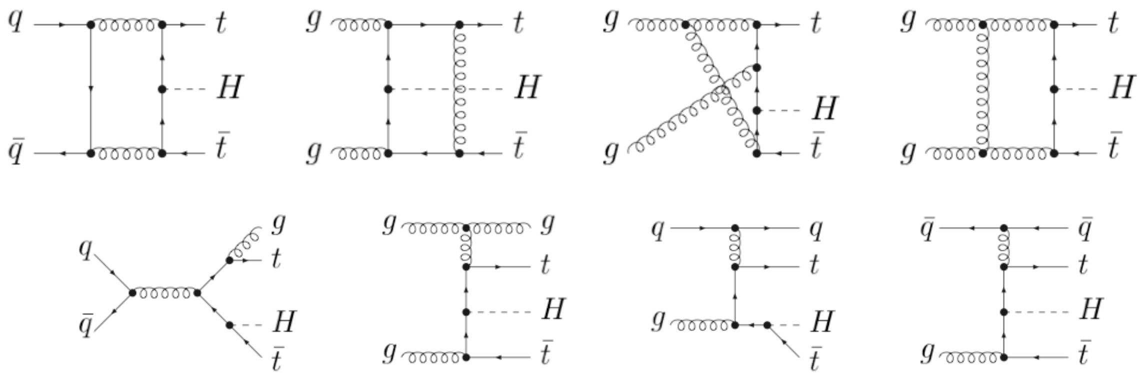
LO:



NLO:



Nucl.Phys.B653:151-203,2003
e-Print: **hep-ph/0211352**



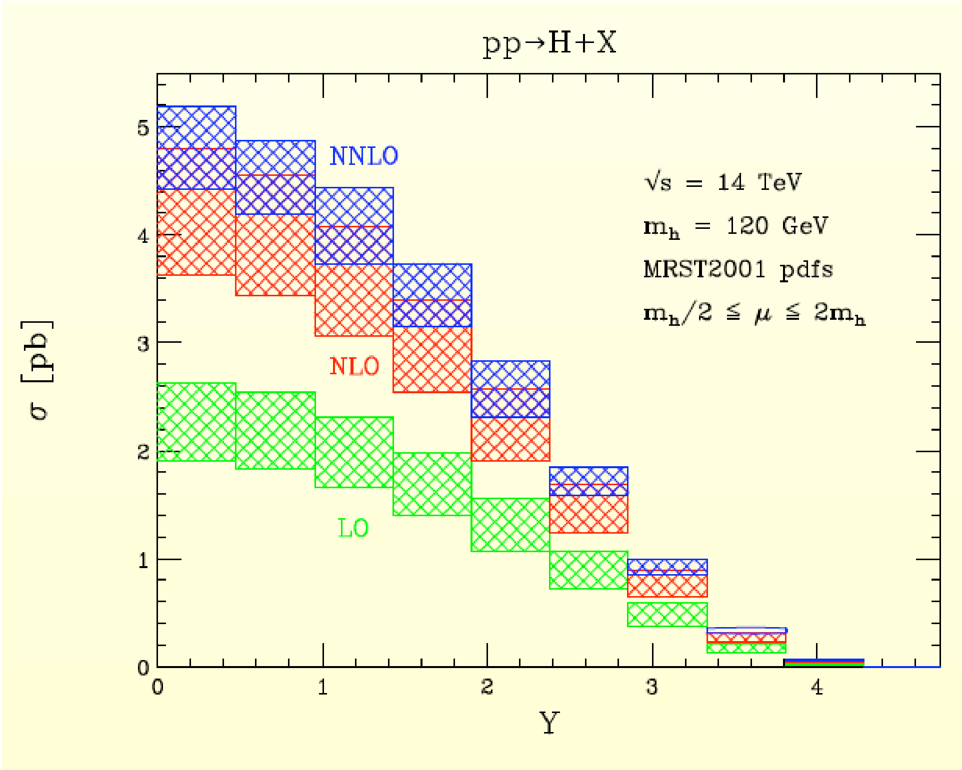
NLO and NNLO corrections to gg→H

Singularly large NLO corrections:

$K_{NLO} \approx 1.7$

$K_{NLO+NNLO} \approx 2$

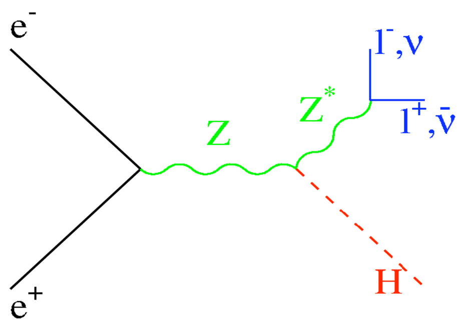
origin of these large corrections: virtual and soft gluons

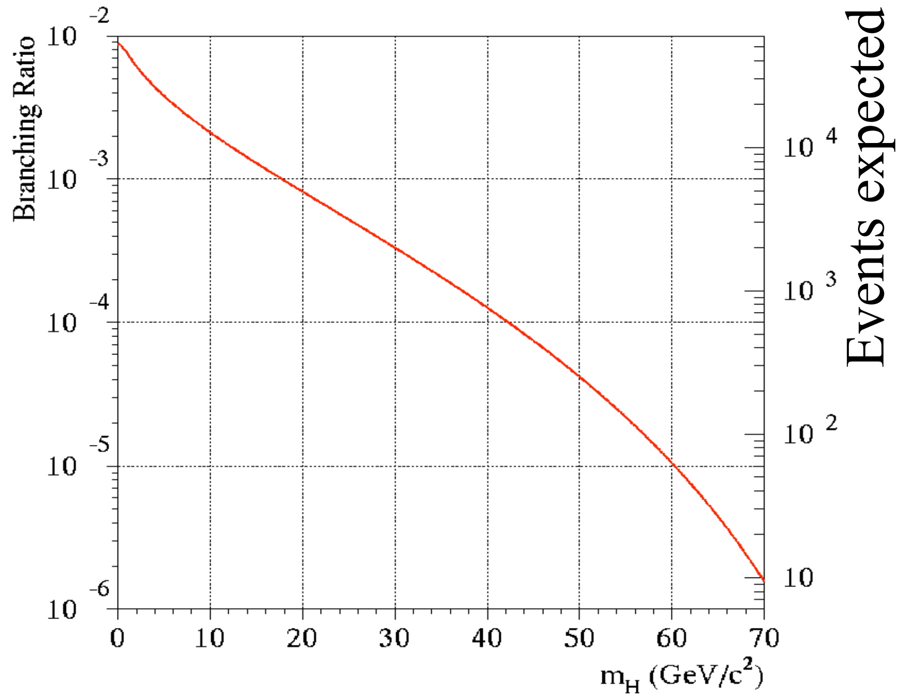


Experimental searches

Direct Searches at LEP 1

$e^+e^- \to Z \to Z^*H$

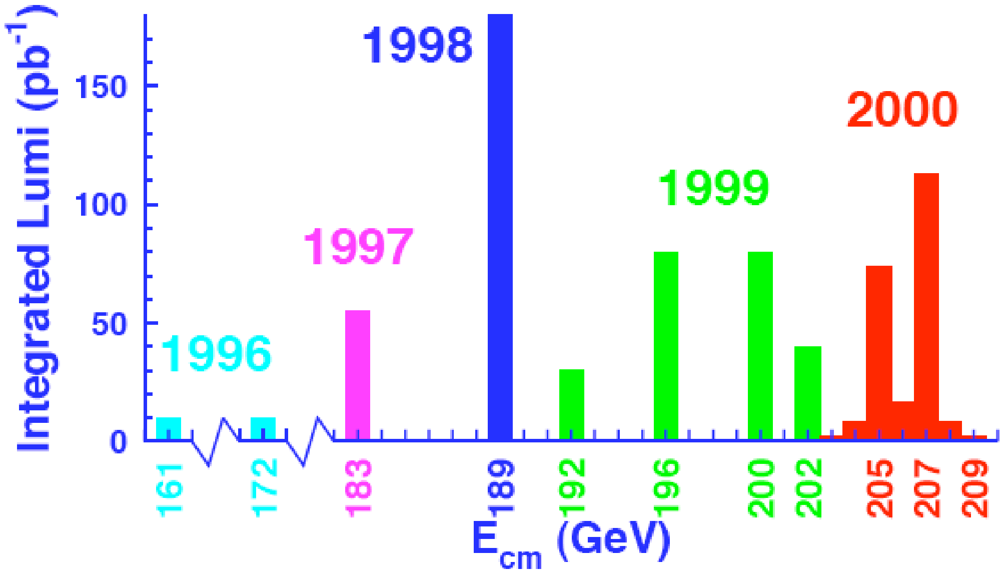




$0.0 < m_H < 65$ GeV/c^2 excluded at 95% C.L.

Direct searches at LEPII

LEPII luminosity

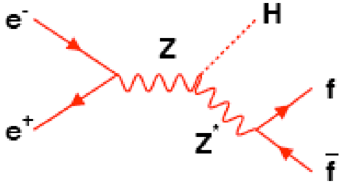


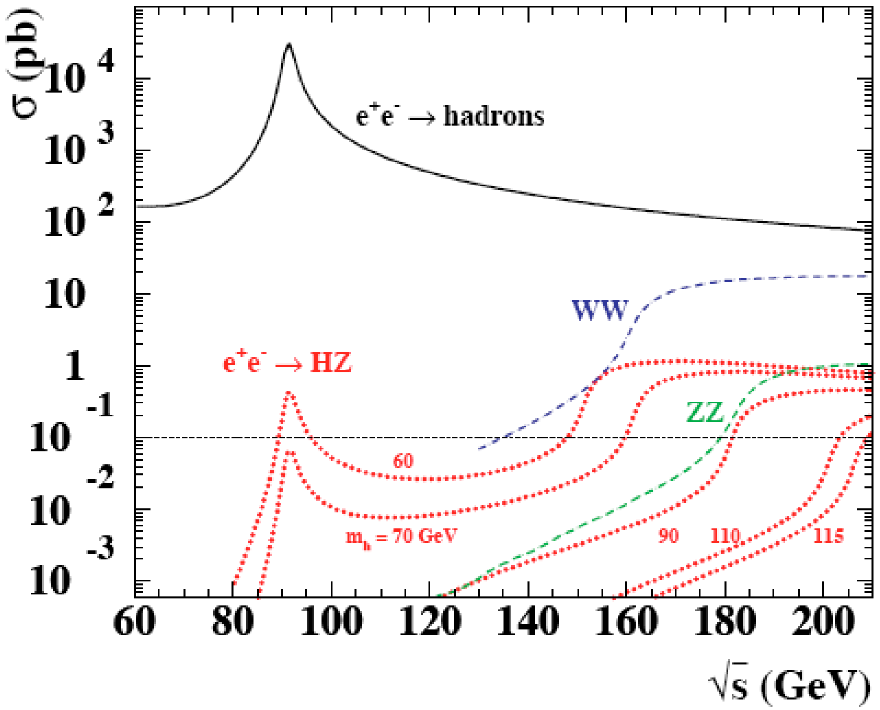
c.m. energy raised in steps from M_Z to 208 GeV.

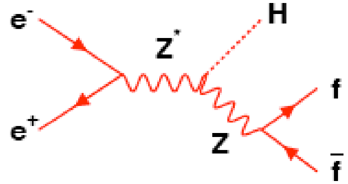
Impressive machine performance:

- increase beam energy, RF system pushed beyond design
- delivered high lumi ($\approx$ 0.5 fb^{-1})

Higgs production cross-section







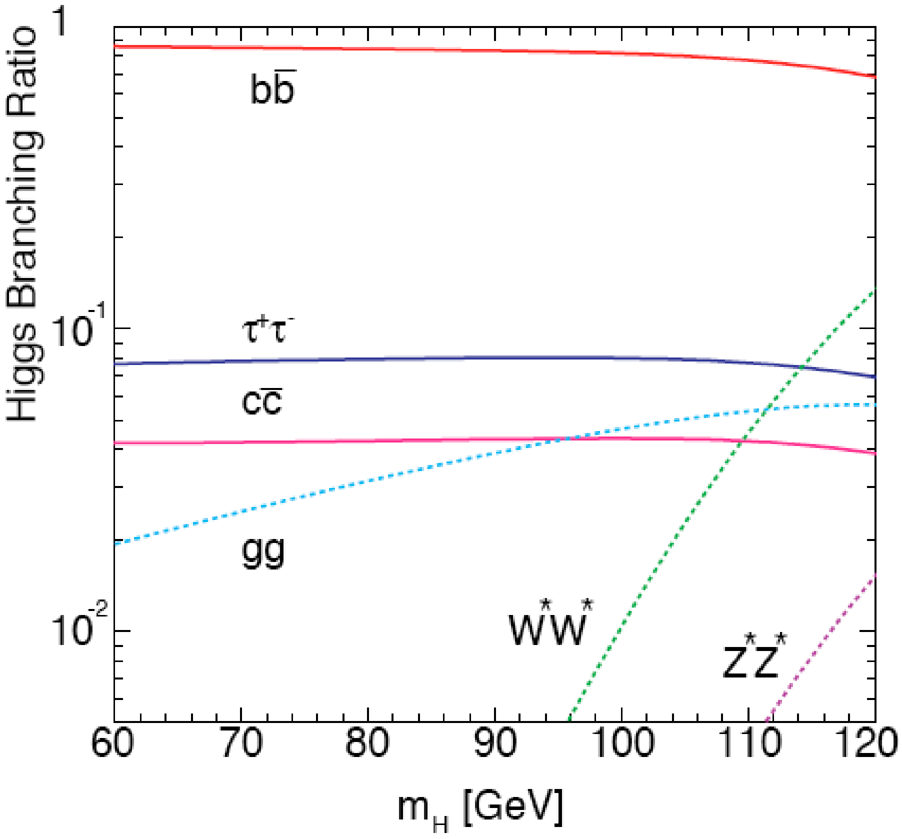
With a luminosity of about 100pb^{-1} and reasonable detection efficiency, sensitive to a cross section of $O(0.1)$ pb.

Need LEP2 to produce $m_H \gtrsim 65$ GeV. Reach $m_H \lesssim \sqrt{s} - M_Z$

Must take into account many background processes

Higgs decay branching ratios

"Higgs couples to mass"



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	

Clearly, favoured channel is $H \rightarrow bb$ and $Z \rightarrow qq$

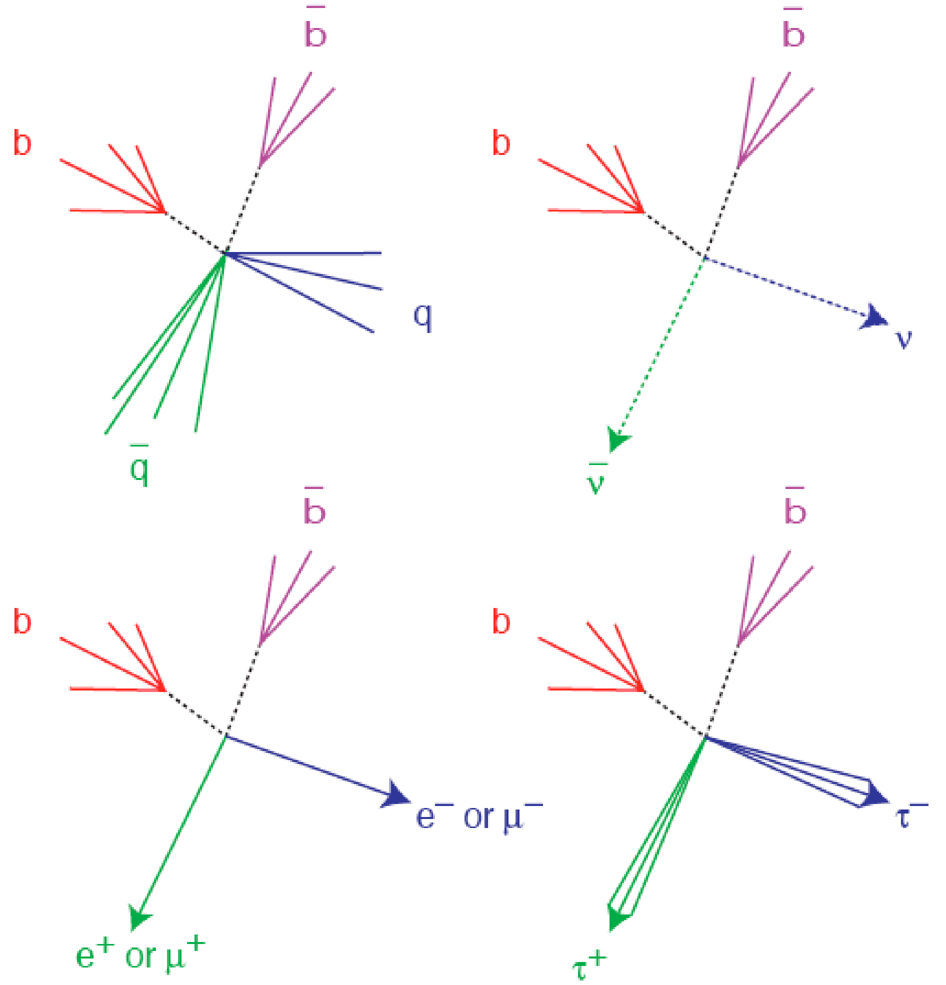
HZ decays

Four jets, 60%

$H \rightarrow b\bar{b}$, $Z \rightarrow q\bar{q}$

Missing energy, 18%

$H \rightarrow b\bar{b}$, $Z \rightarrow \nu\bar{\nu}$



Leptonic, 6%

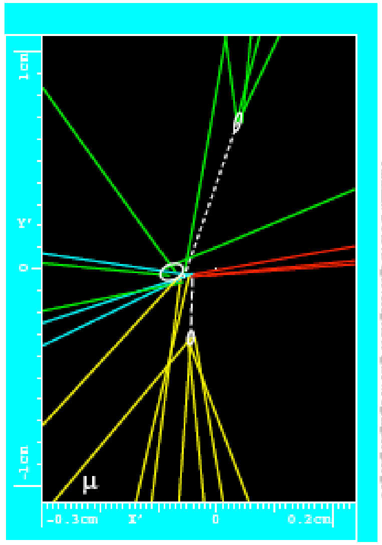
$H \rightarrow b\bar{b}$, $Z \rightarrow \ell^+\ell^-$

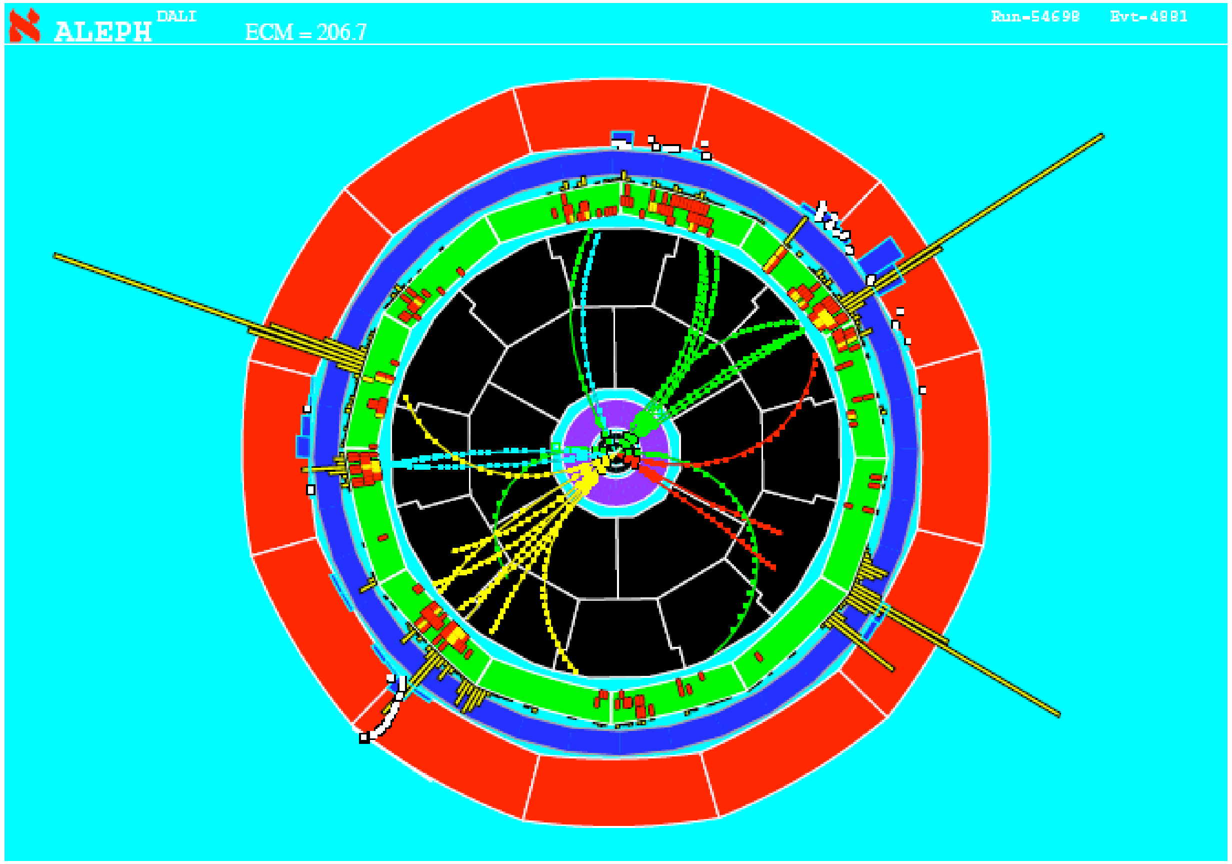
Tau channels, 9%

$H \rightarrow b\bar{b}(\tau^+\tau^-)$, $Z \rightarrow \tau^+\tau^-(q\bar{q})$

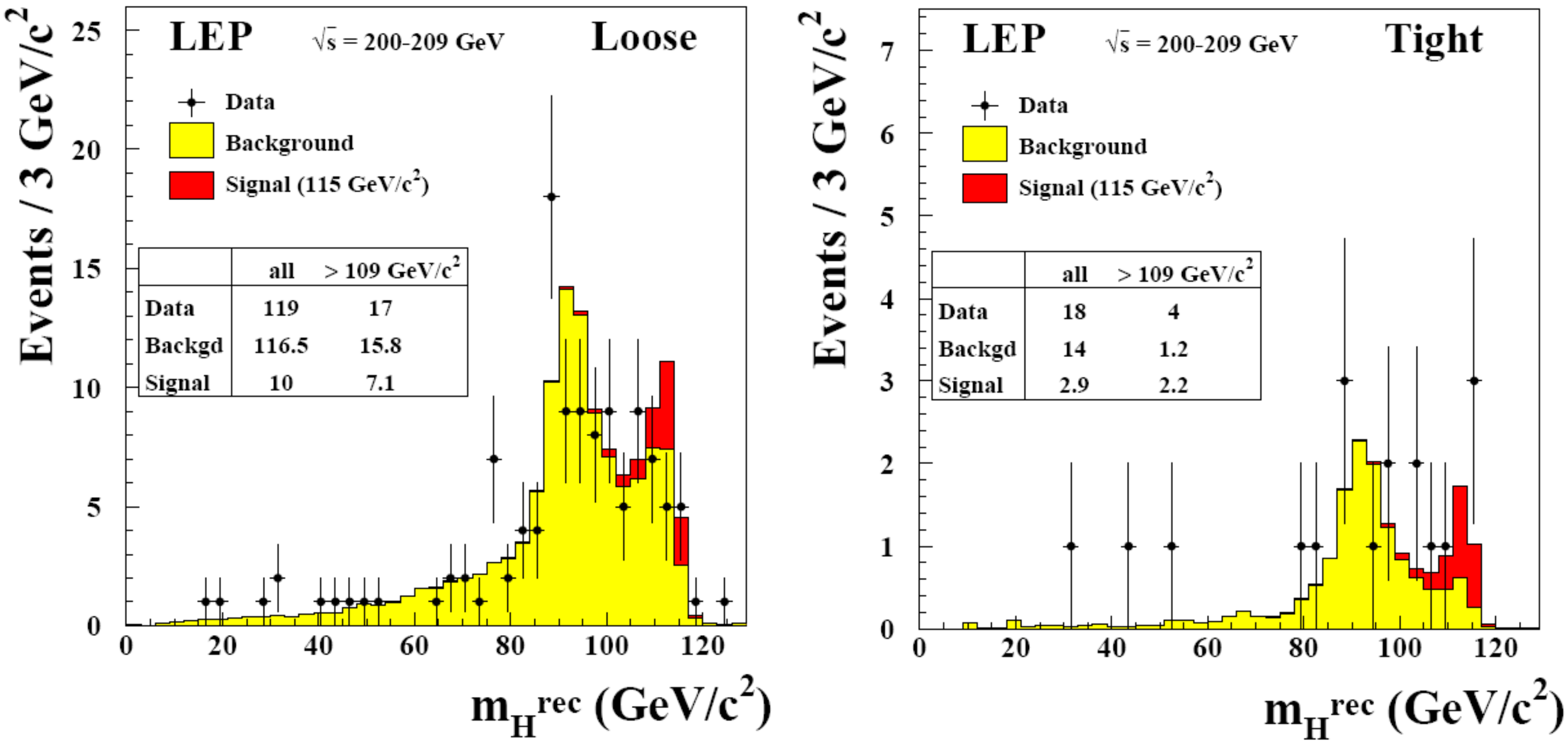
ALEPH Events - four jets with b tags

Zoom right inside the beam pipe:





Higgs candidates mass



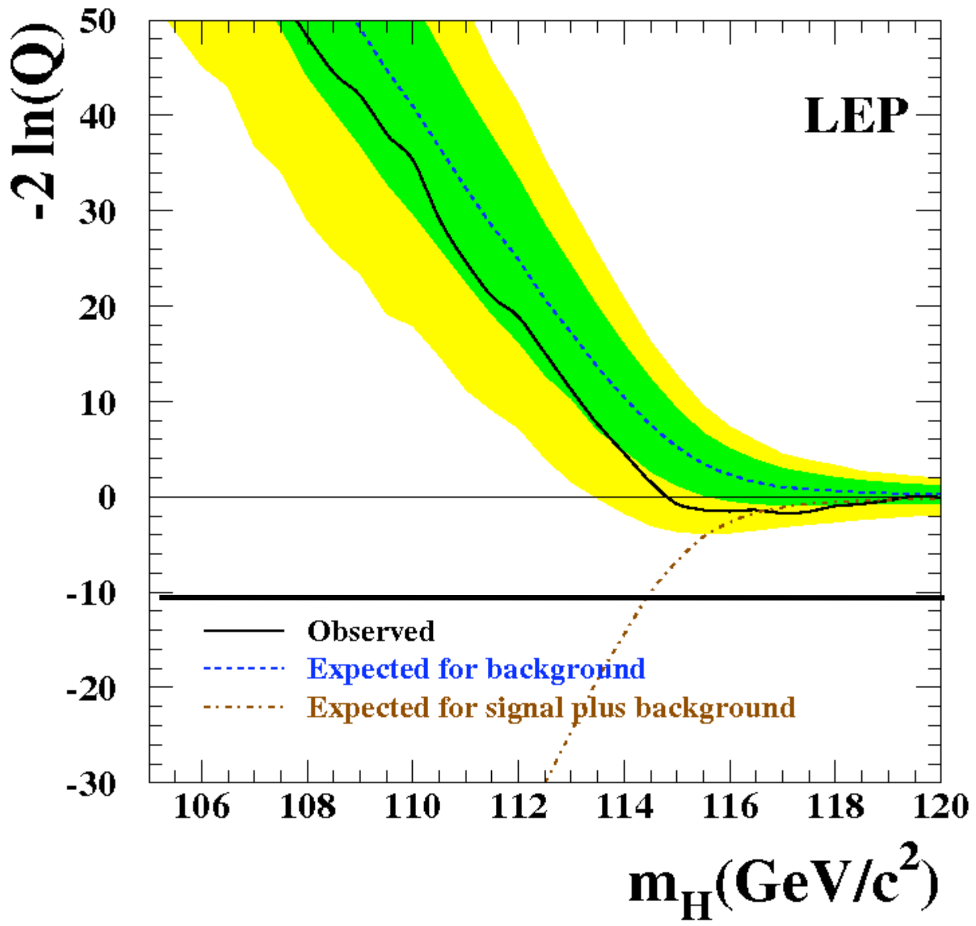
Final LEPII result

M_H > 114.4 GeV

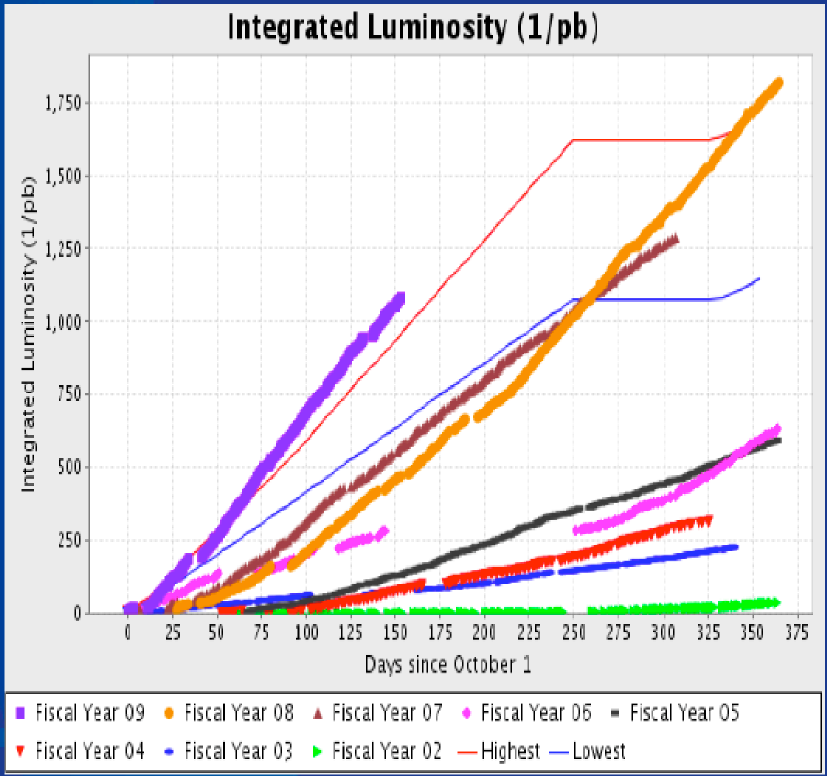
at 95%CL

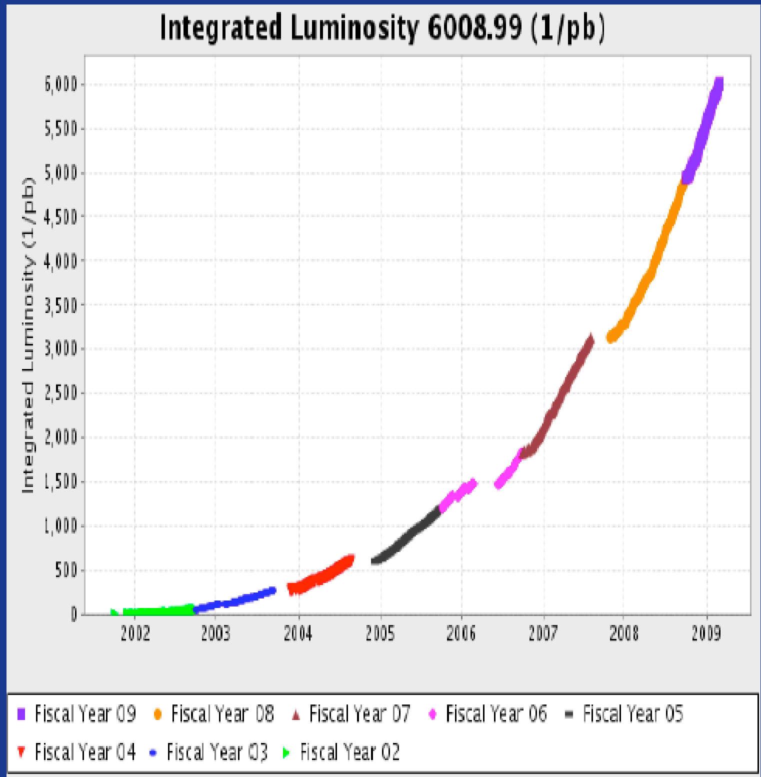
Excess at 115 GeV would happen in 9% cases without signal

But signal remains the best fit

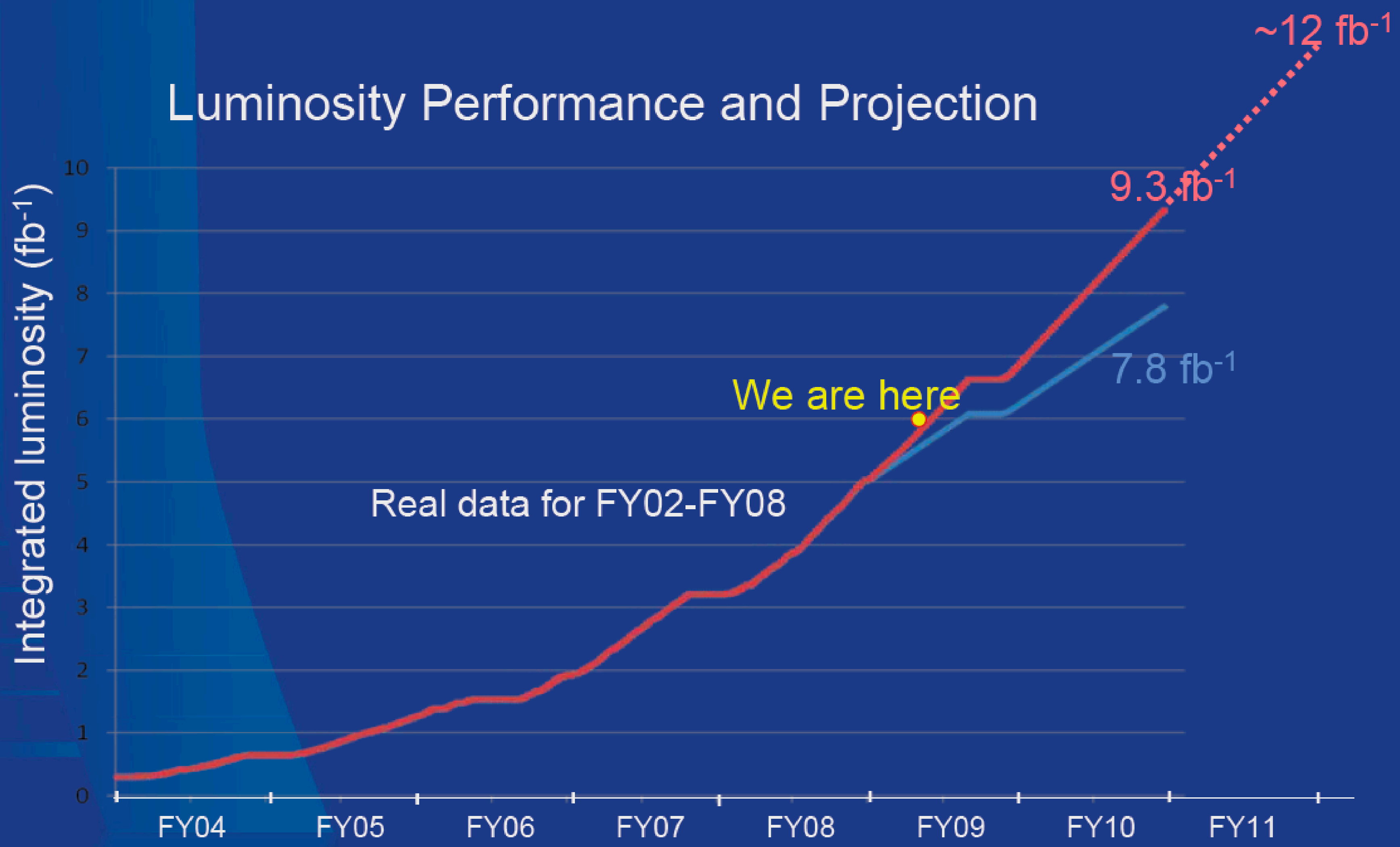


The Energy Frontier: Tevatron

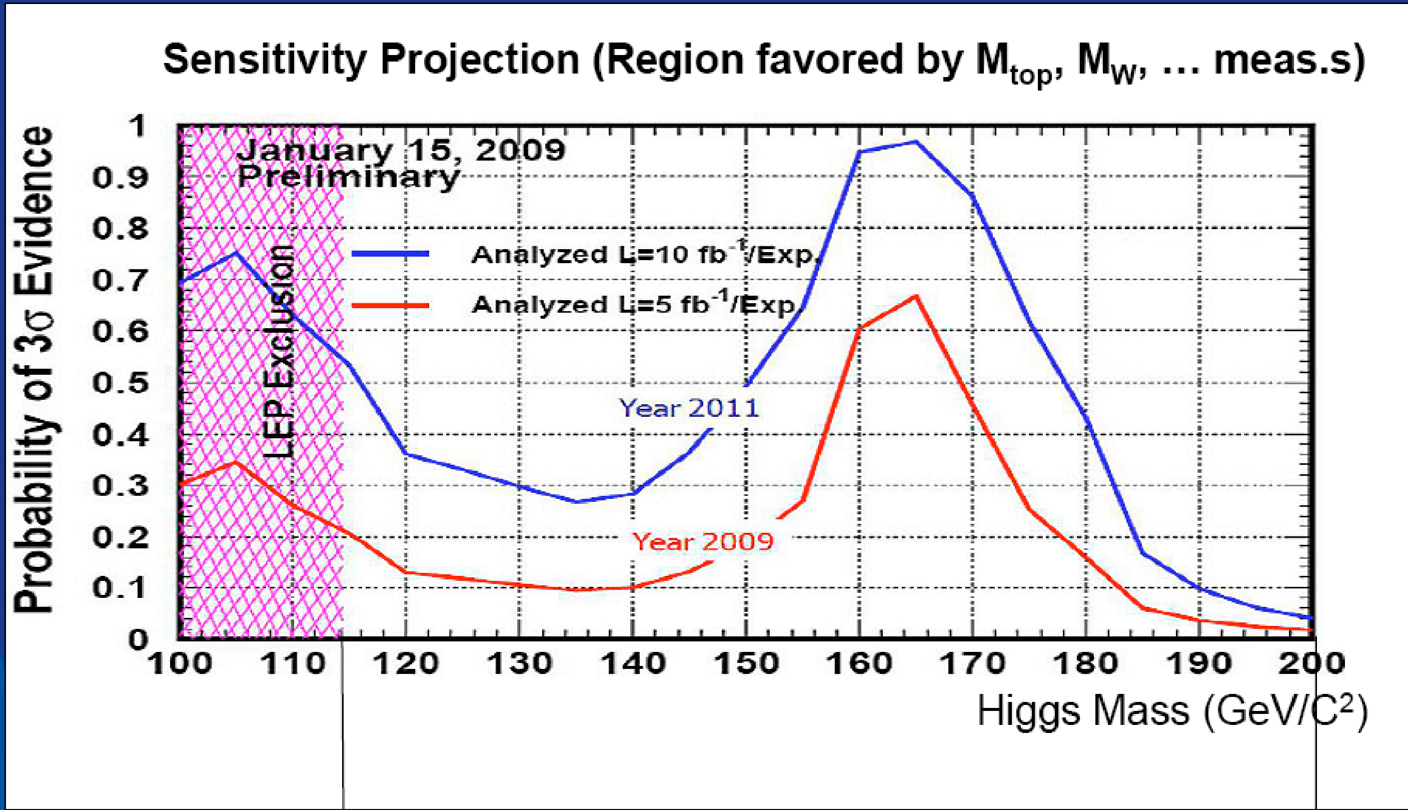


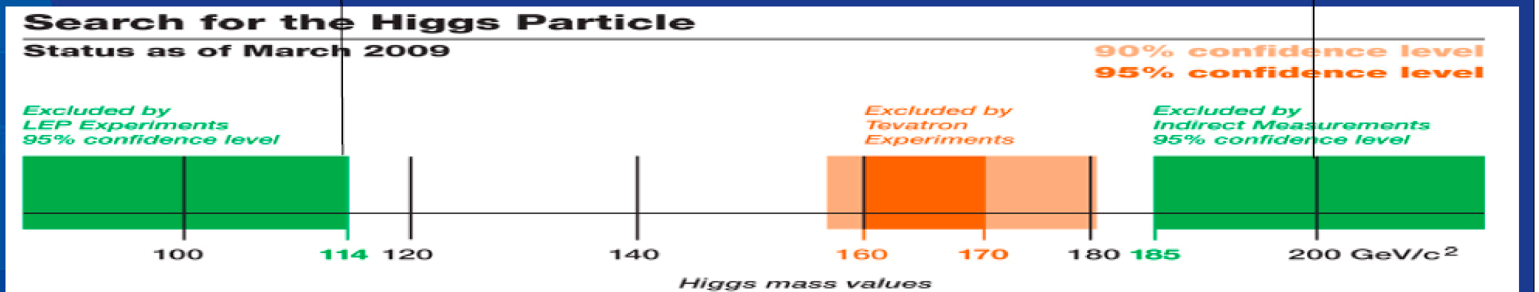


The Energy Frontier: Tevatron



The Energy Frontier: Tevatron Higgs





Fermilab

Higgs searches at Tevatron

- Multiple direct searches at $\sqrt{s}$ = 1.96 GeV
- Luminosity: 2.0-3.6 (CDF) 0.9-4.2(D0) fb^{-1}
- Production: $gg \rightarrow H$, $q\bar{q} \rightarrow VH$, $q\bar{q} \rightarrow q'\bar{q}'H$
- Higgs decay modes: bbar, W^+W^-, $\tau^+\tau^-$, $\gamma\gamma$
- 75 mutually excluding final states (23 for CDF, 52 for D0)

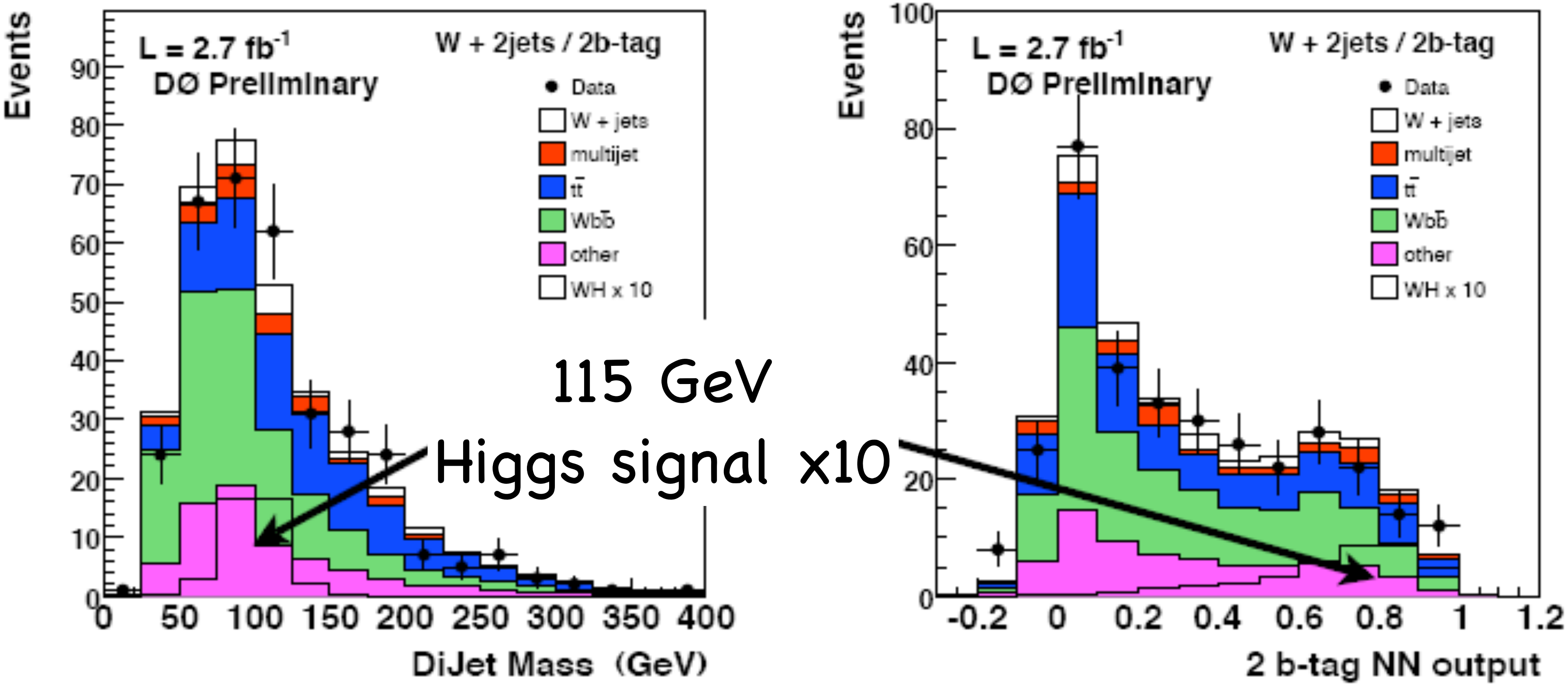
Two fronts:

$M_H \approx$ 115 GeV best channel $WH \rightarrow l\upsilon bb$

$M_H \approx$ 165 GeV best channel $gg \rightarrow H \rightarrow WW \rightarrow l\upsilon l\upsilon$

Well understood detectors, b-tagging, etc.

D0: WH → lνbb



2.7 fb^{-1} : expected 6.4, observed 6.7 s/b = 1/20

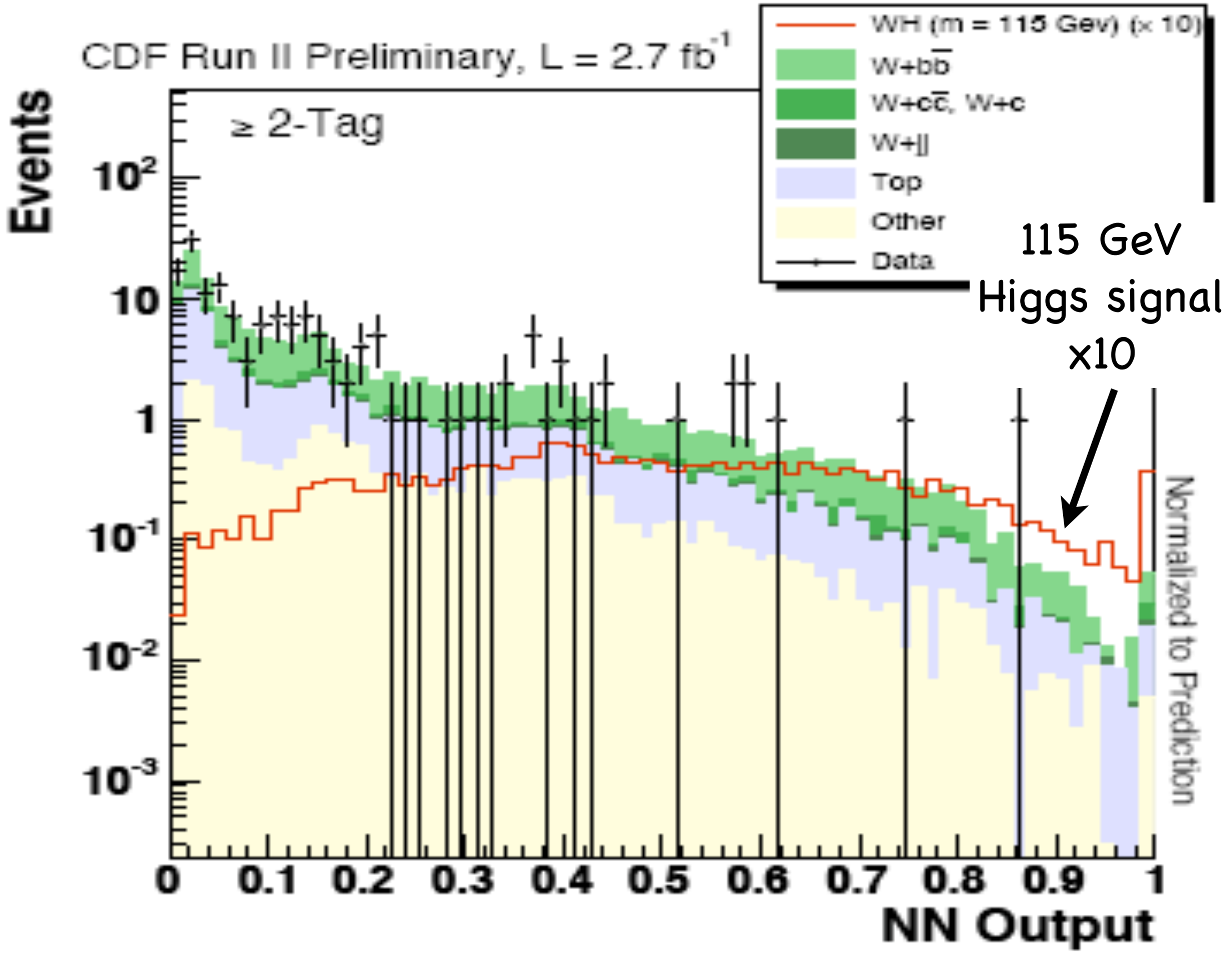
CDF: WH → lνbb

2.7 fb^{-1}

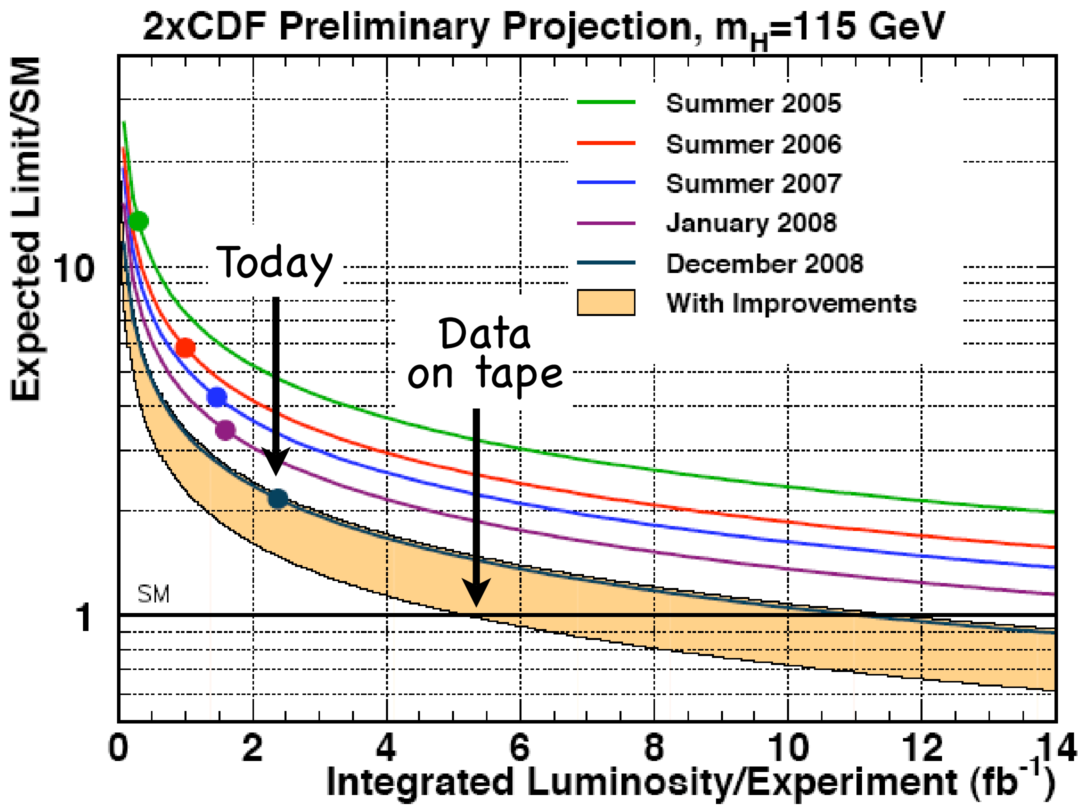
Expected 4.8

Observed 5.6

s/b 1/10

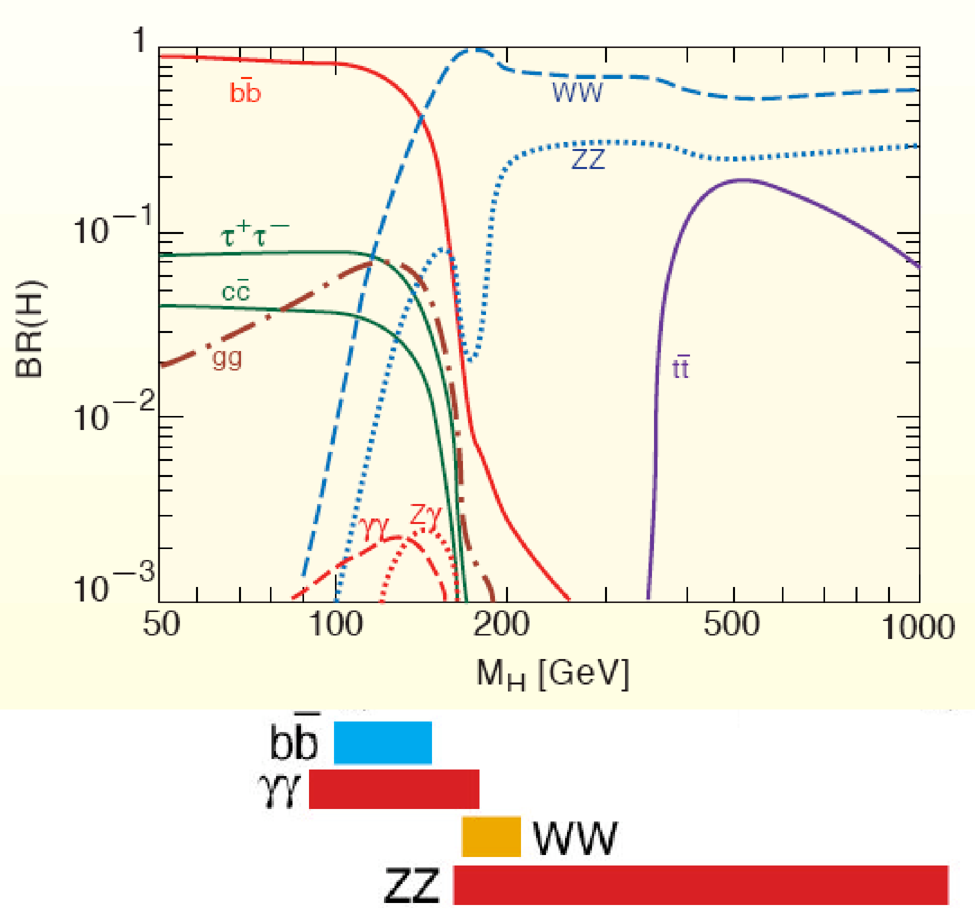


Tevatron: future prospects



In the near future, the two experiment combined should be able to exclude m_H = 115 GeV with ≈ 6 fb^{-1} each

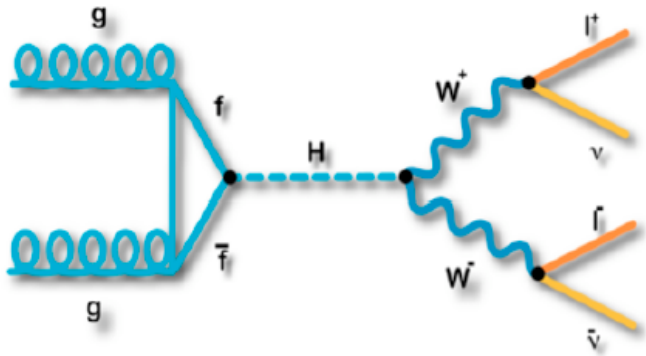
Intermediate masses:



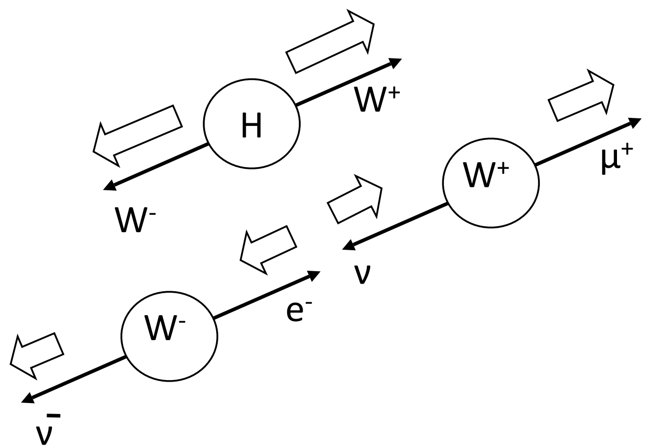
The H→WW is the best channel for m_H < 200 GeV in which the Tevatron could have something to say

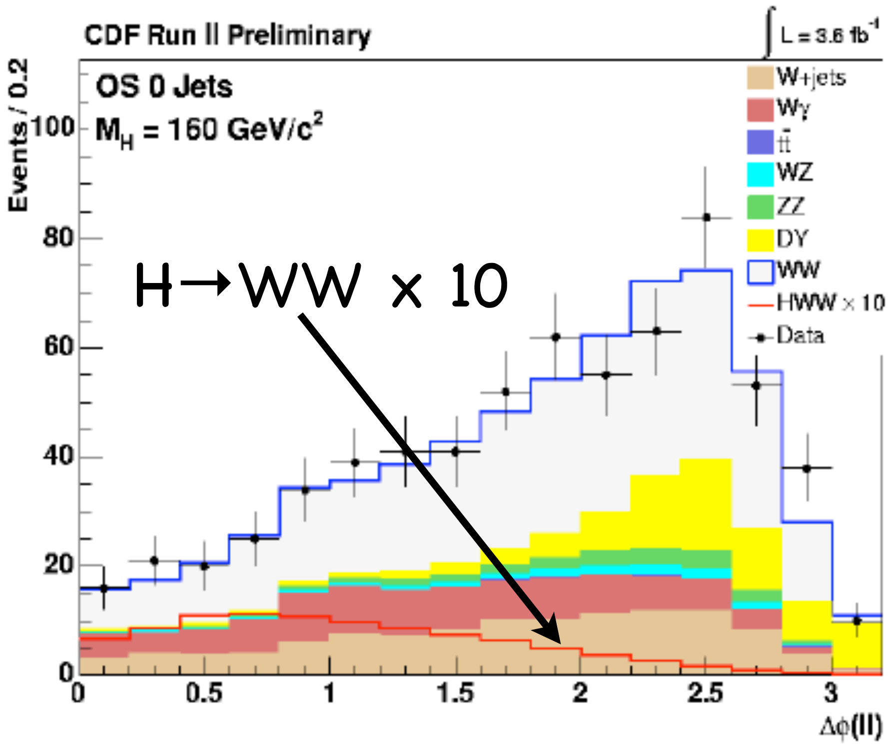
SM Higgs: H→WW→lνlν

signature:
two high-p_T leptons and E_T^{miss}
background:
WW and top in di-lepton decay

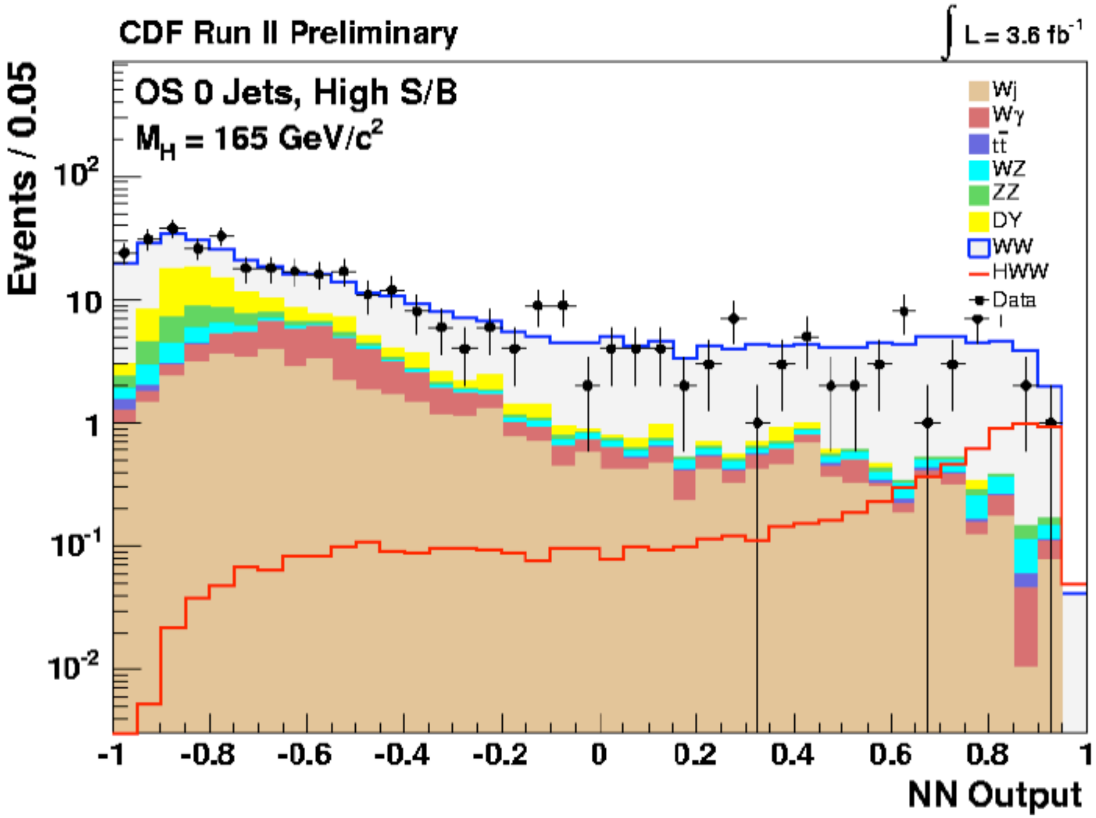


Help from spin correlation:
the two charged leptons
go in the same direction





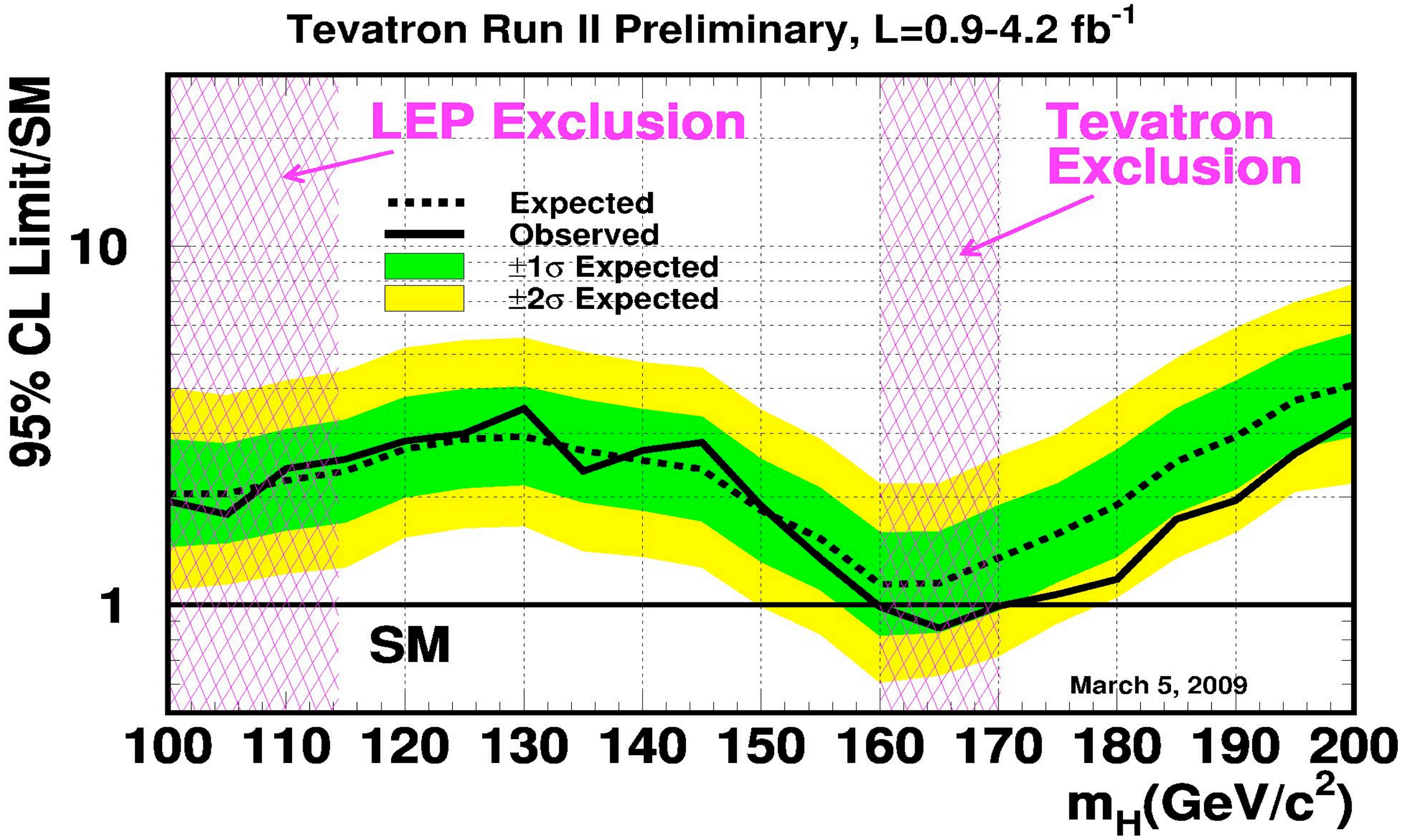
SM Higgs: H→WW



CDF Run II Preliminary
∫ L = 3.6 fb⁻¹
OS 0 Jets, High S/B
M_H = 165 GeV/c²
Events / 0.05
NN Output
Wj
Wγ
tt̄
WZ
ZZ
DY
WW
HWW
Data

Tevatron Higgs Combination

75 mutually excluding channels !!!

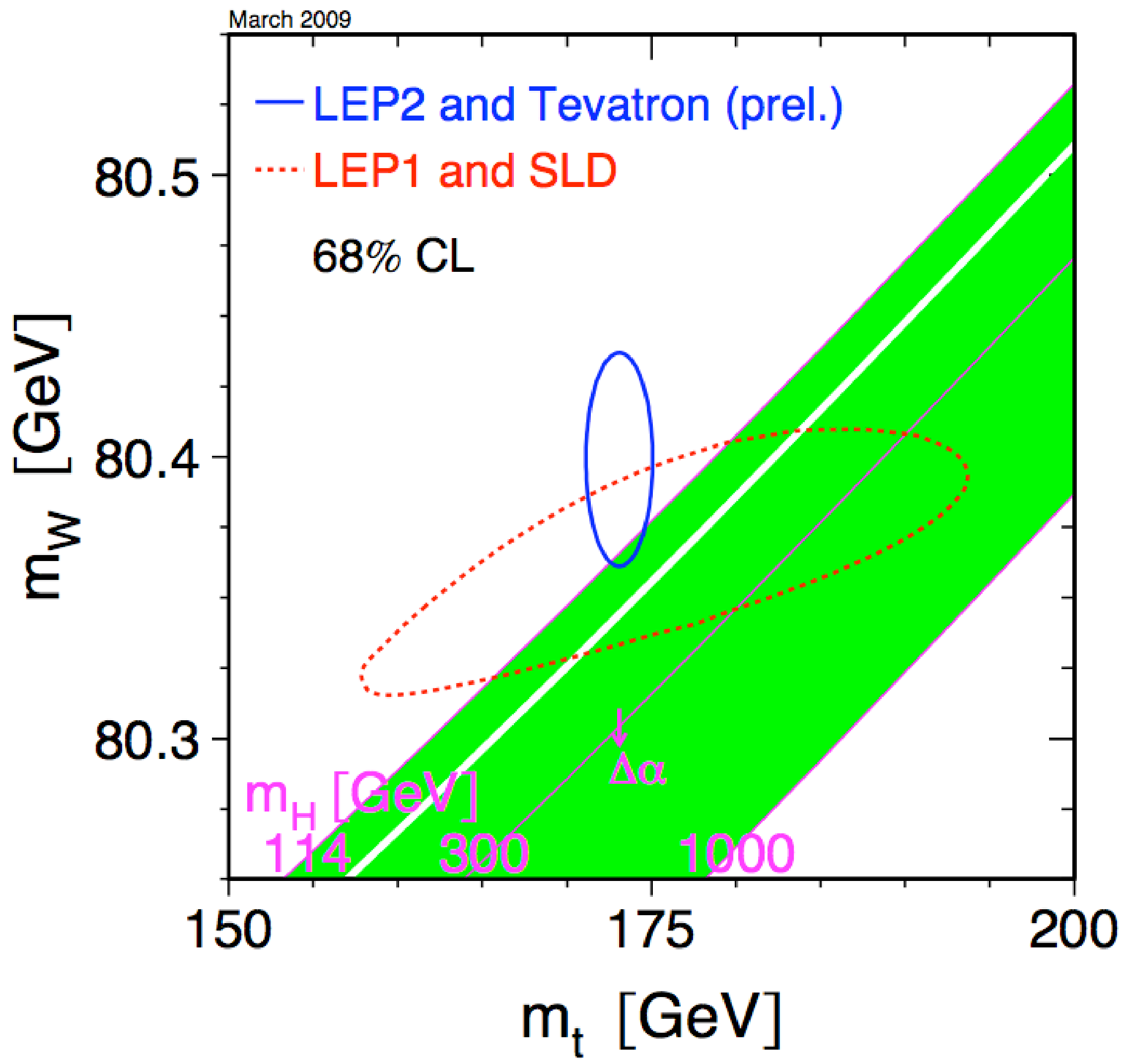


Note the fluctuation at 160-170 GeV

Indirect limits

- The consistency of the data can be used to test the use of EW correction
- It also constrains the Higgs mass

The Electroweak fit:

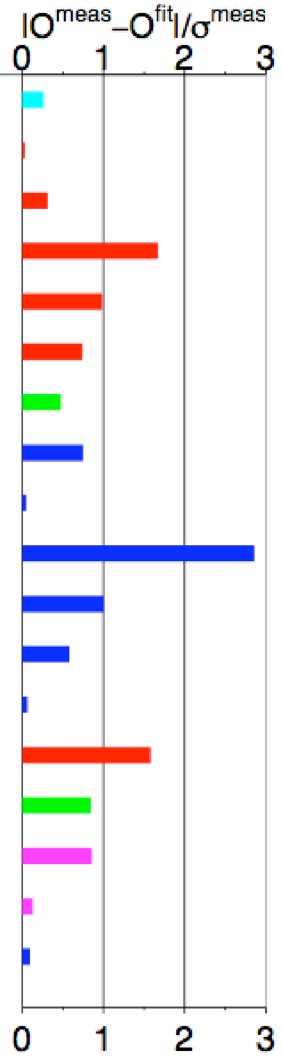


Indirect searches: EW variables depend on $(m_t)^2$ and $\ln(m_H)$ through radiative corrections

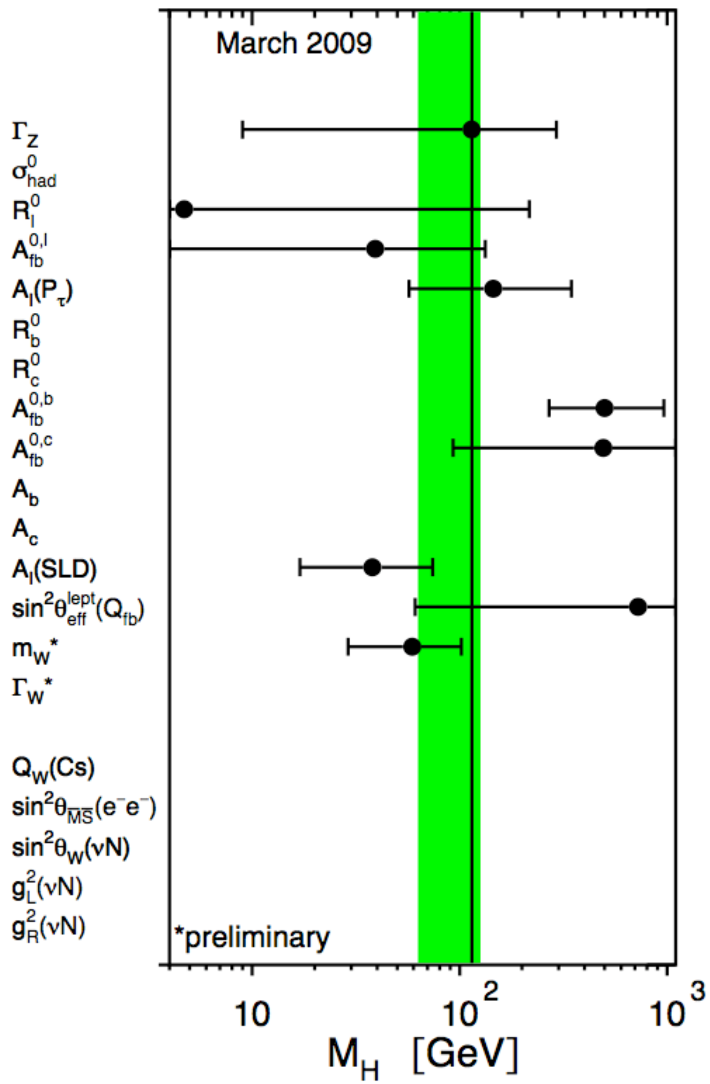
Direct and indirect searches agree:

$M_H \approx 100$ GeV

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.378
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2



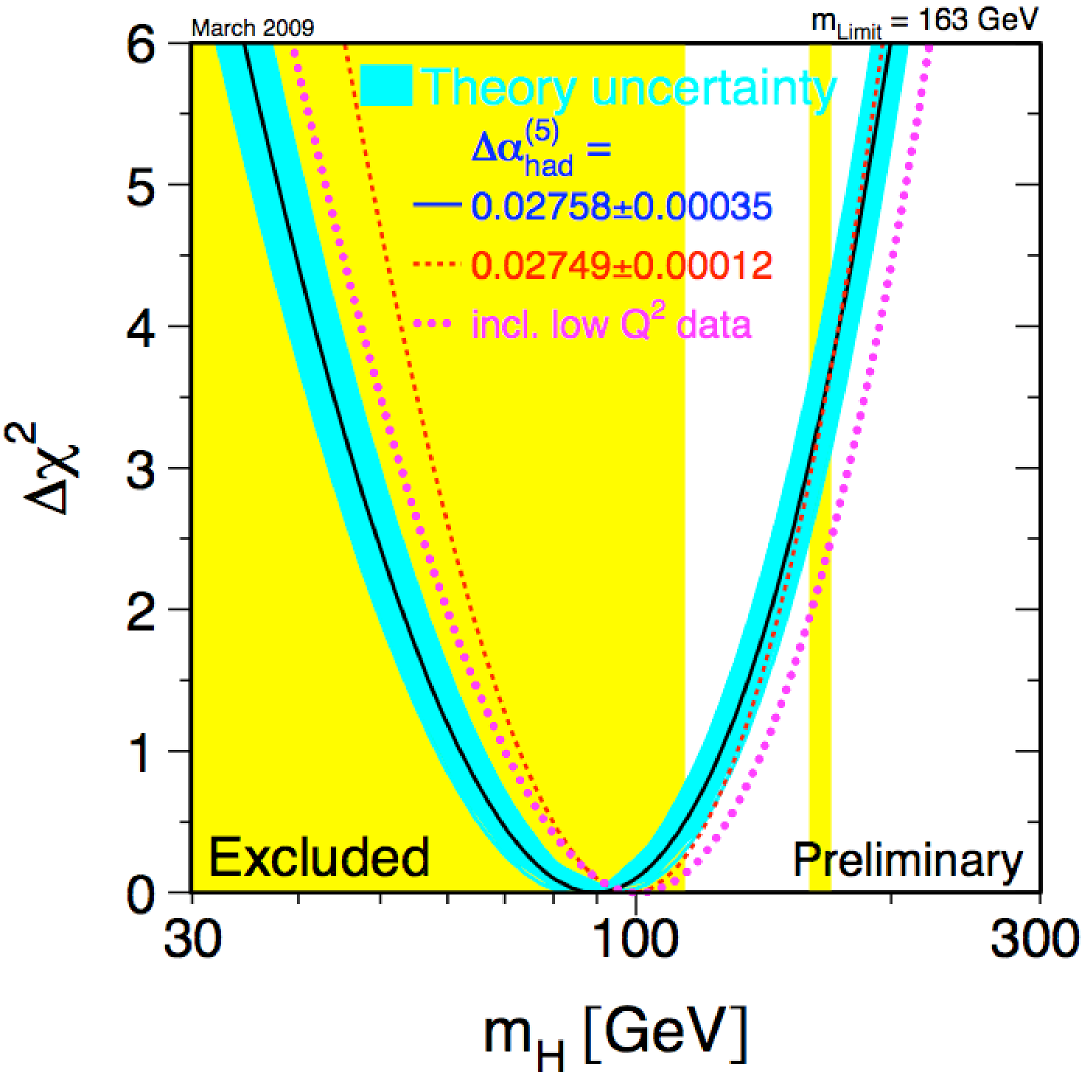
March 2009



Limits on Higgs mass

$\Delta\chi^2$ from precision EW high Q^2 measurements from LEP, SLD, CDF, D0 vs. m_H, assuming the SM to be the correct theory of nature.
The preferred value is $m_H = 90^{+36}_{-27}$ GeV at 68% CL

Upper limits:
$m_H < 163$ GeV (one sided 95% CL)
$m_H < 191$ GeV (when including LEPII exclusion)



Theoretical arguments on m_H limits

If the Higgs mass value is too large, the amplitude for

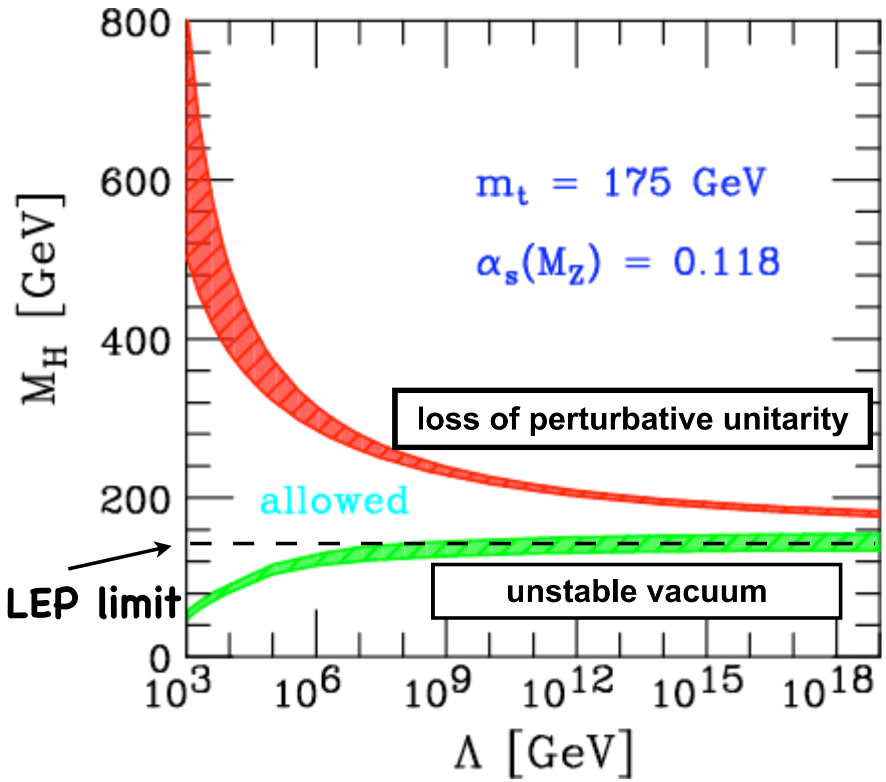
$$WW \rightarrow H \rightarrow ZZ$$

exceeds the unitarity bound in perturbative theory.
As a consequence, either m_H is below ≈ 700 GeV or there should be new physics at the TeV scale

Note that this is a rigorous argument !!

Theoretical arguments on m_H limits

Assuming SM with a single Higgs doublet (i.e. no SUSY Higgs extensions):



Λ = energy scale for new physics (above it SM no longer valid)

Upper limit → "triviality":
$\lambda \cdot \ln(\Lambda/m_T) > 1 \Rightarrow$ no pert. unitarity
($\lambda = \frac{1}{2}(m_H/v)^2$ = Higgs self coupling)

Lower limit → "vacuum instability":
i.e. requirement that spontaneous symmetry breaking occurs:
$V(v) < V(0)$ (or $\lambda < 0$).

It carries a terrible message: $m_H \lesssim 180$GeV could mean "the desert"!!!
This argument is a bit less rigorous than WW unitarity.

Search for the Higgs boson at the LHC

LHC challenges

Immense rates, PetaBytes data volume

Very large number of SM processes

Quantitative and accurate description is the key to control backgrounds and disentangle Higgs (and new physics)

Our friend pQCD can describe hard processes. However, W, Z, multijets and Higgs production require NLO and NNLO accuracy

MC programs for data analysis

As well, they should be as accurate as possible: need non-pert. modelling + as much pQCD as possible (MC@NLO)

Process	σ(nb)	Rates (Hz) $L=10^{34}$ $cm^{-2}s^{-1}$
Inelastic	10^8	10^9
bb	5×10^5	5×10^6
$W\to l\nu$	15	100
$Z\to ll$	2	20
tt	1	10
H (100 GeV)	0.05	0.1
H (500 GeV)	10^{-3}	10^{-2}

An experimenter's wishlist

Run II Monte Carlo Workshop

Single Boson	Diboson	Triboson	Heavy Flavour
$W+\le 5j$	$WW+\le 5j$	$WWW+\le 3j$	$t\bar{t}+\le 3j$
$W+b\bar{b}\le 3j$	$W+b\bar{b}+\le 3j$	$WWW+b\bar{b}+\le 3j$	$t\bar{t}+\gamma+\le 2j$
$W+c\bar{c}\le 3j$	$W+c\bar{c}+\le 3j$	$WWW+\gamma\gamma+\le 3j$	$t\bar{t}+W+\le 2j$
$Z+\le 5j$	$ZZ+\le 5j$	$Z\gamma\gamma+\le 3j$	$t\bar{t}+Z+\le 2j$
$Z+b\bar{b}+\le 3j$	$Z+b\bar{b}+\le 3j$	$ZZZ+\le 3j$	$t\bar{t}+H+\le 2j$
$Z+c\bar{c}+\le 3j$	$ZZ+c\bar{c}+\le 3j$	$WZZ+\le 3j$	$t\bar{b}\le 2j$
$\gamma+\le 5j$	$\gamma\gamma+\le 5j$	$ZZZ+\le 3j$	$b\bar{b}+\le 3j$
$\gamma+b\bar{b}\le 3j$	$\gamma\gamma+b\bar{b}\le 3j$		single top
$\gamma+c\bar{c}\le 3j$	$\gamma\gamma+c\bar{c}\le 3j$		
	$WZ+\le 5j$		
	$WZ+b\bar{b}\le 3j$		
	$WZ+c\bar{c}\le 3j$		
	$W\gamma+\le 3j$		
	$Z\gamma+\le 3j$		

Higgs golden channels

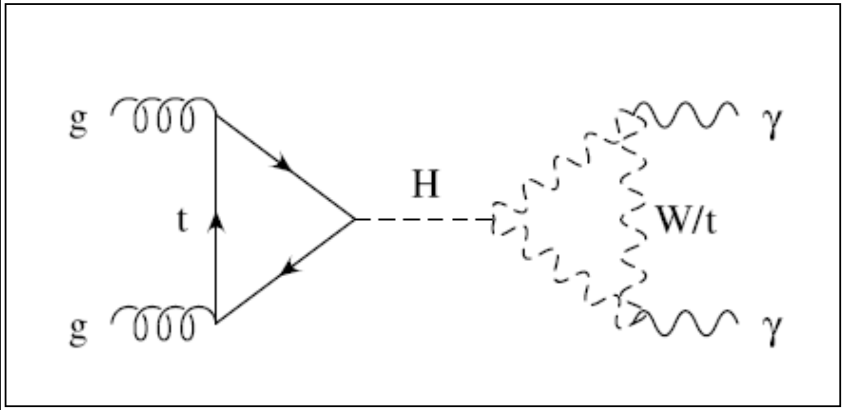
	Tevatron	LHC
$m_H \approx 115$ GeV	$WH \to l\nu bb$	too large backgrounds
	$ZH \to \nu\nu bb$, $llbb$	too large backgrounds
	cross section too small	$H \to \gamma\gamma$
	cross section too small	$qqH \to qq\tau\tau$
	cross section too small	$ttH \to l\nu bbX$
$m_H \approx 165$ GeV	$H \to WW \to l\nu l\nu$	$H \to WW \to l\nu l\nu$
	cross section too small	$H \to ZZ^* \to 4l$
	cross section too small	$qqH \to qqWW$
	cross section too small	$qqH \to qqWW \to qql\nu l\nu$

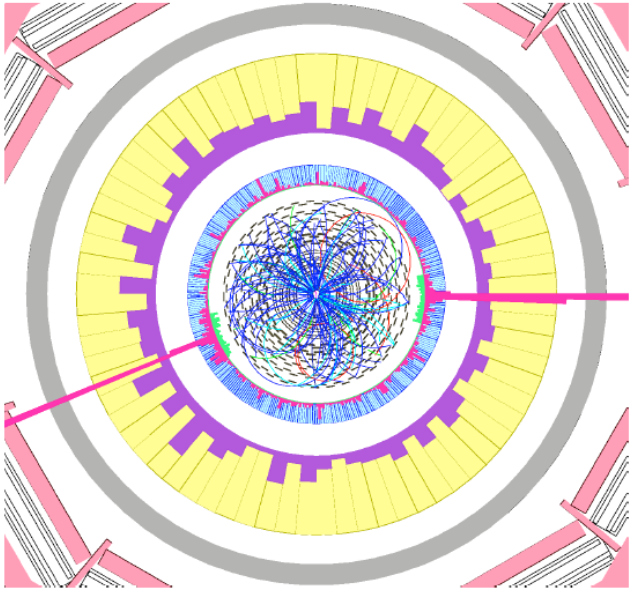
large m_H

For $m_H < 200$ GeV, $\sigma_{LHC}/\sigma_{Tevatron} \approx$ 70 ($gg \to H$), $\approx$ 60 (VBF)

$\approx$ 100 ($gg \to ttH$), $\approx$ 10 ($qq \to VH$)

Low Mass (M_H<140 GeV): H $\rightarrow\gamma\gamma$

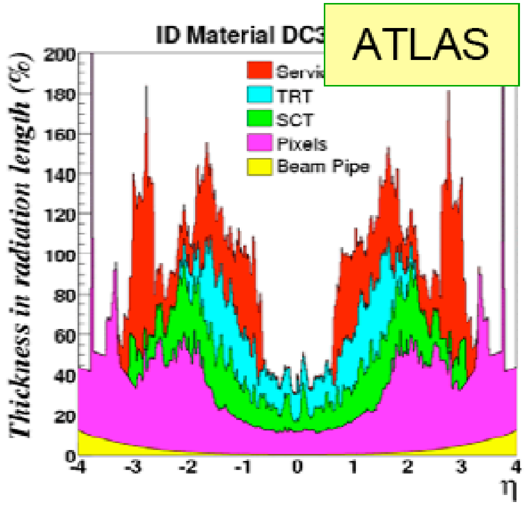


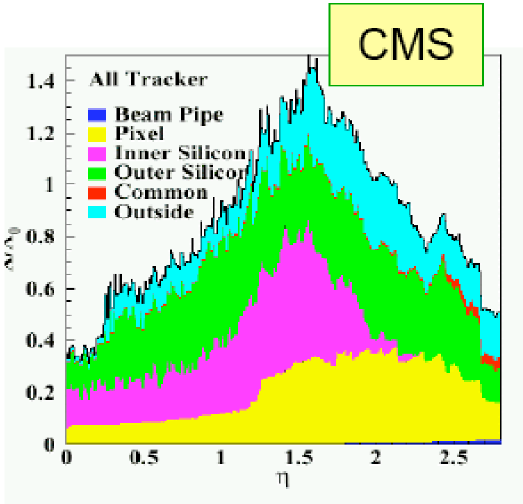


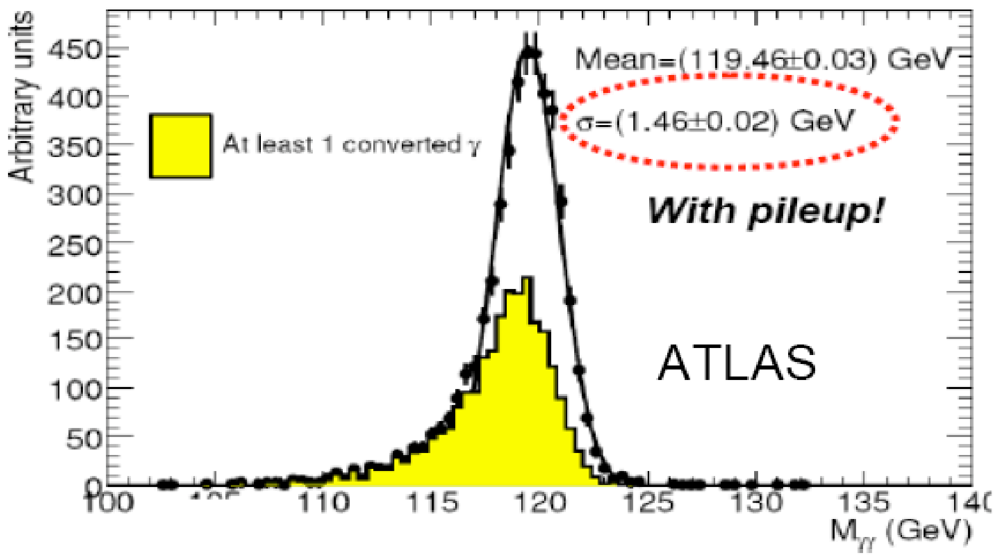
CMS Physics TDR, 2006

- Small branching ratio (≈0.2%), but two clean em clusters (for unconverted γ)
- Clear mass peak due to excellent em CAL energy resolutions (motivation for LAr and $PbWO_4$ choice in ATLAS and CMS)
- Tools:
  - longitudinal and surface segmentation
  - isolation
- CMS: $\sigma_E \approx 1$ GeV for $m_H = 100$ GeV
- Expected s/b ≈ 1/20

γ conversions

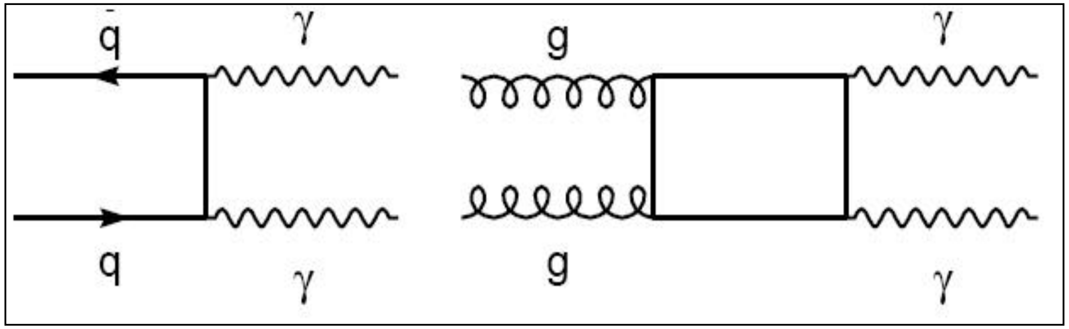






Although ≈ 50% of conversions in the material, the Higgs-mass resolution is still expected ≈ GeV

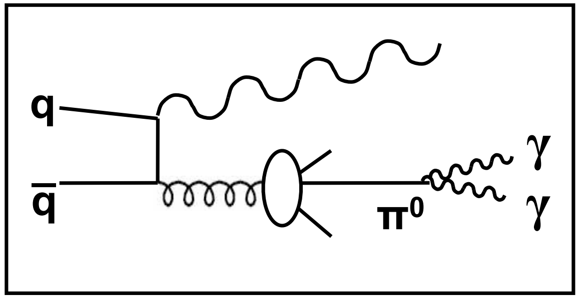
H → γγ – Backgrounds

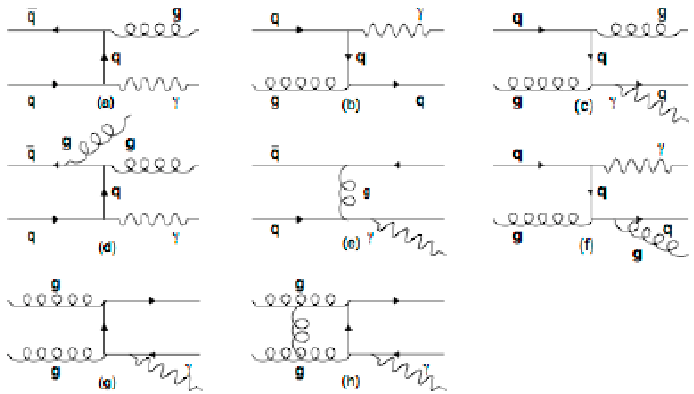


Irreducible:
direct γγ QCD production

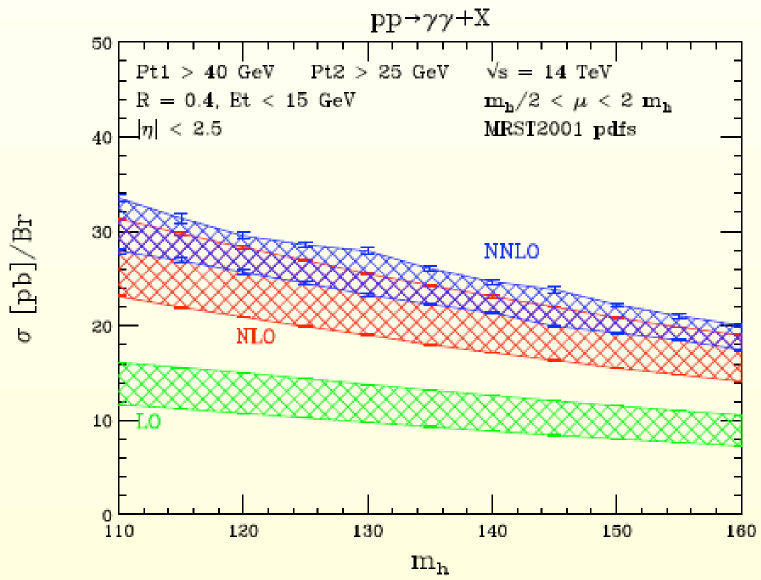
Reducible:
2 jets, 1 jet + direct γ

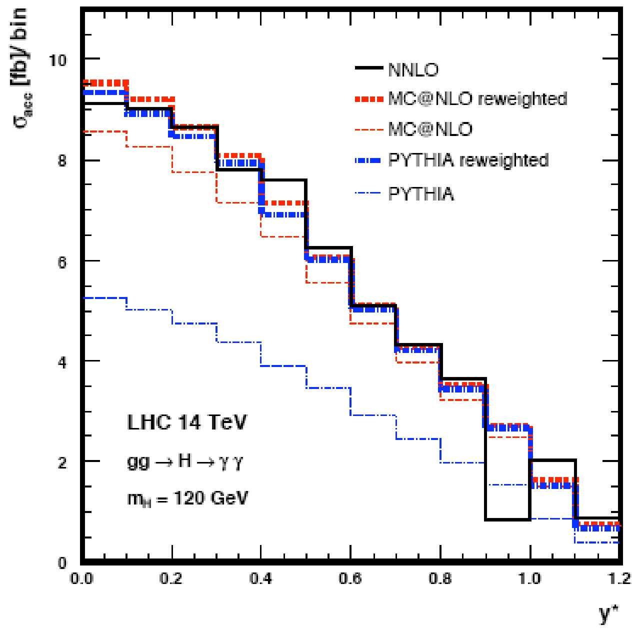
(e.g., by highly segmented em calorimeter),
but many processes contribute ⇒ large background





Precision results for $H\gamma\gamma$ signal





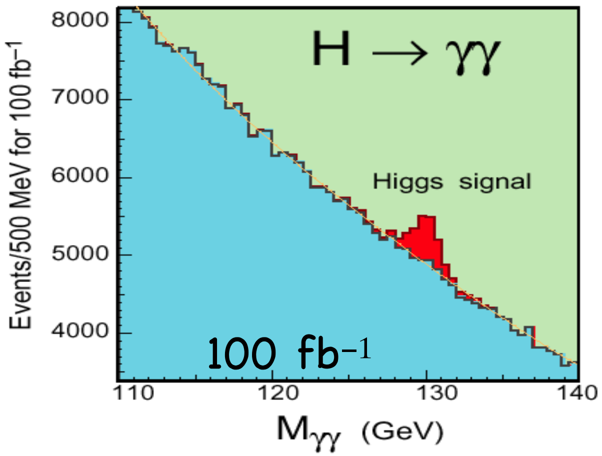
The cross-section at NNLO is two times of the LO result.

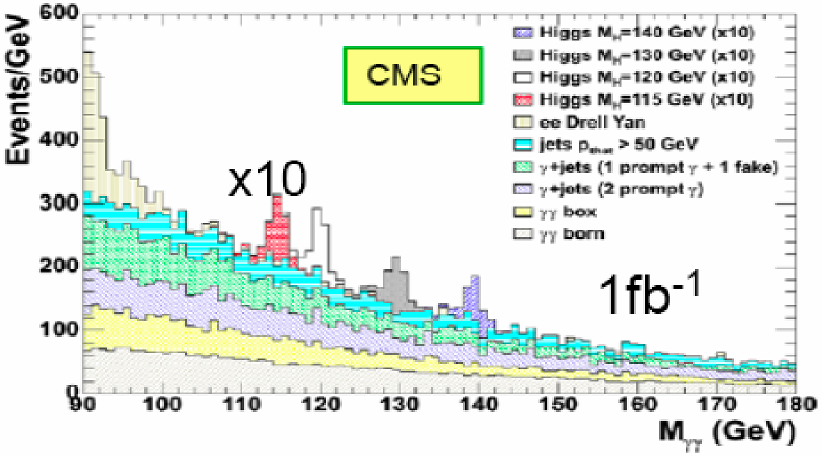
pseudo rapidity difference distributions for di-photon events

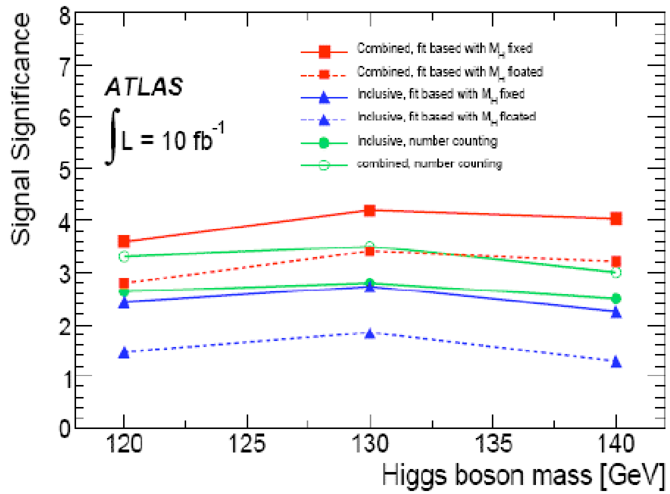
H→γγ signals and significance

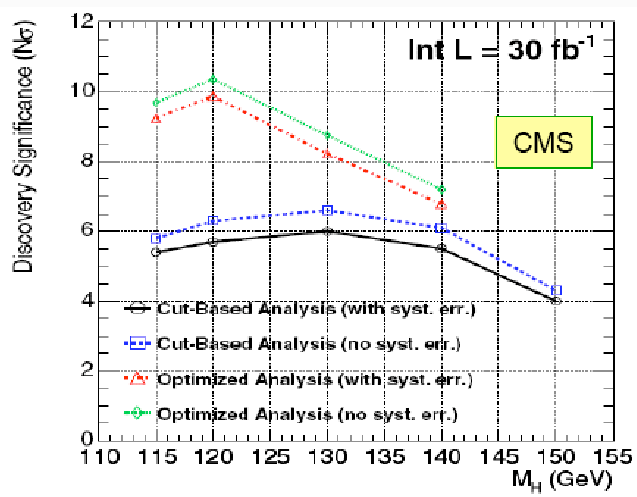
Isolation cuts: $\Delta R = \sqrt{\Delta\eta^2 + \Delta\Phi^2} < 0.4, E_{\mathrm{T,hadr}} < 15\mathrm{GeV}$

Kinematical cuts: $p_\perp^{(1)} \geq 25\mathrm{GeV}\ p_\perp^{(2)} \geq 40\mathrm{GeV}\ |\eta_{1,2}| \leq 2.5$

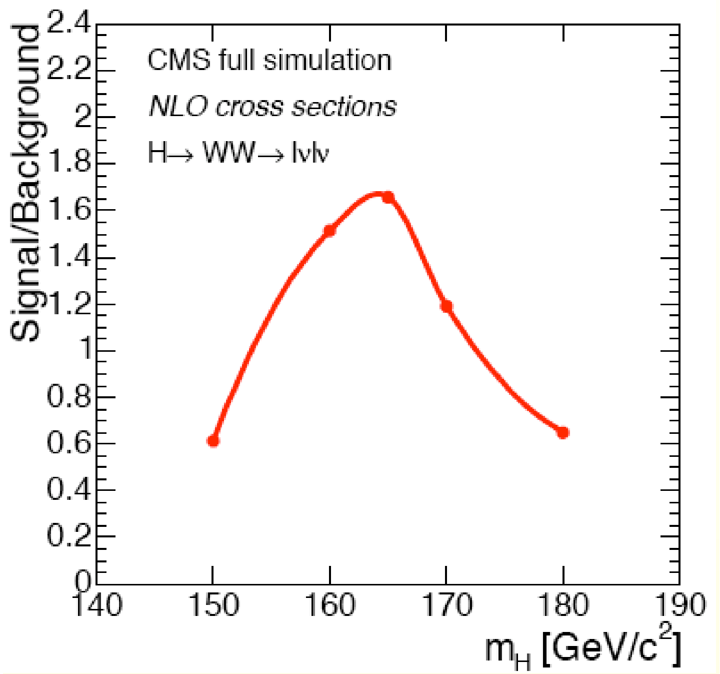


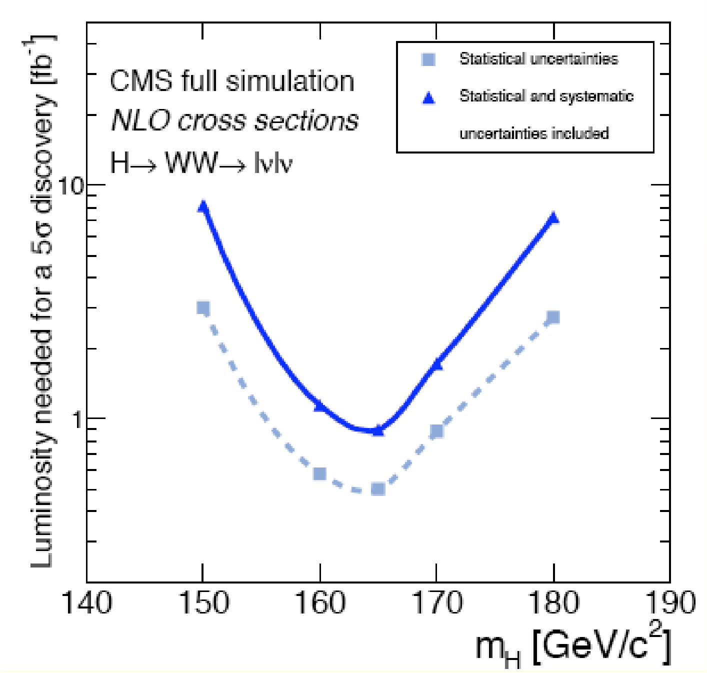






$H \rightarrow WW^* \rightarrow l\nu l\nu$





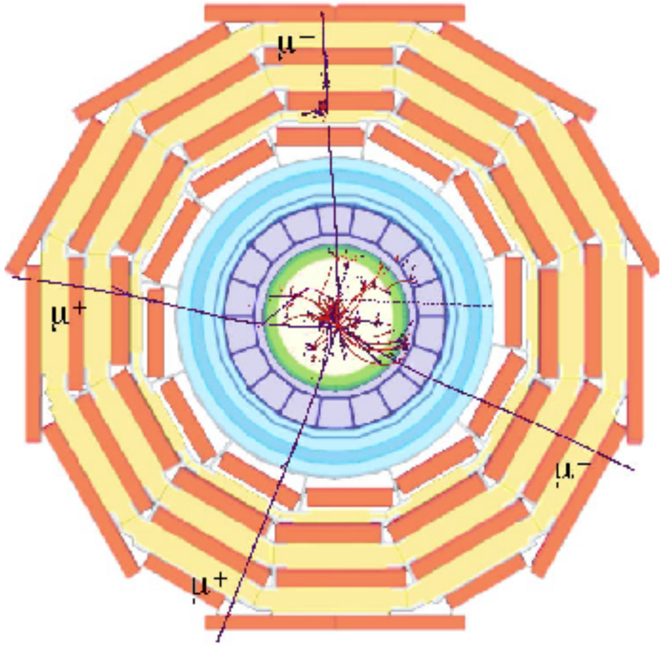
1 fb^{-1} needed for 5σ claim

(Tevatron just excluded 160 < m_H < 170 GeV at 95% CL)

The golden channel: $H \rightarrow 4l$

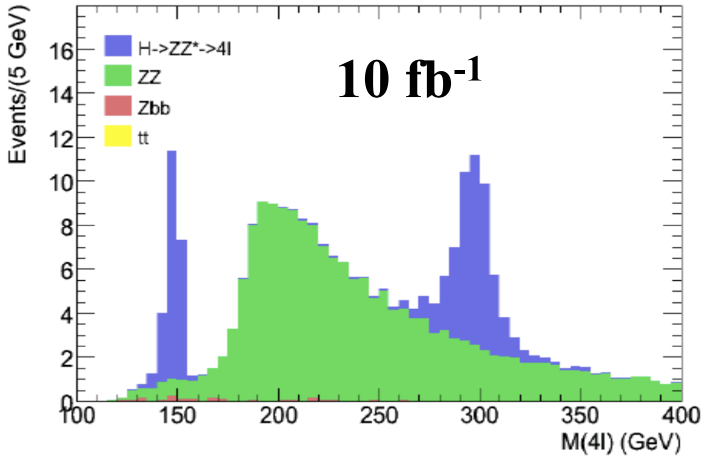
$$H \rightarrow ZZ^* \rightarrow l^+l^- \ l^+l^- \quad (l = e, \mu)$$

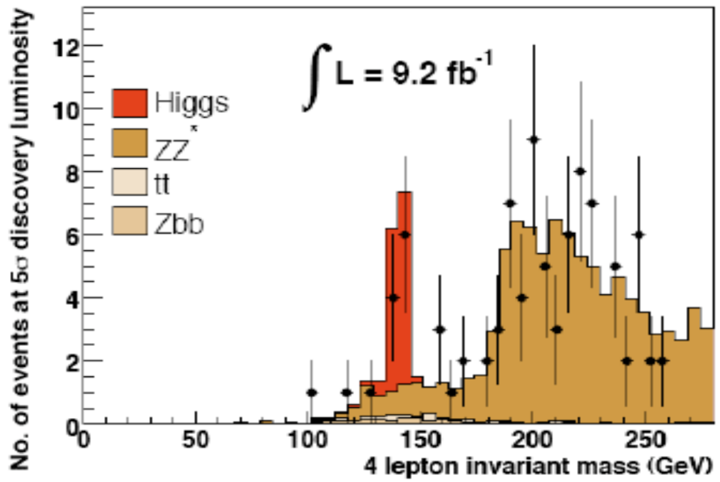
Very little background (ZZ, Zbb, tt)

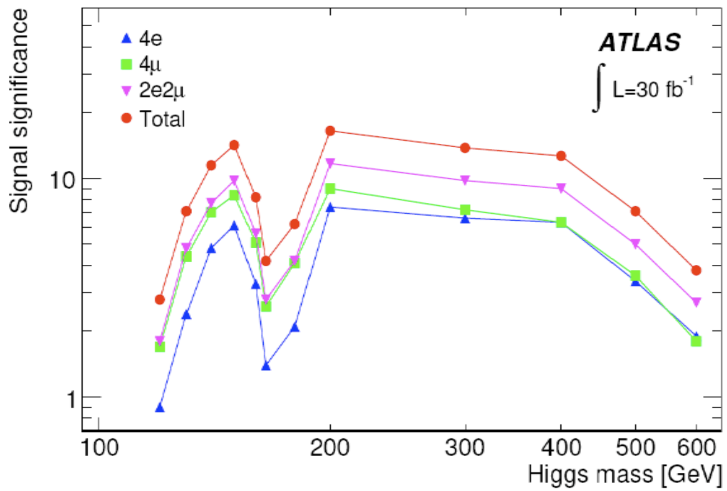


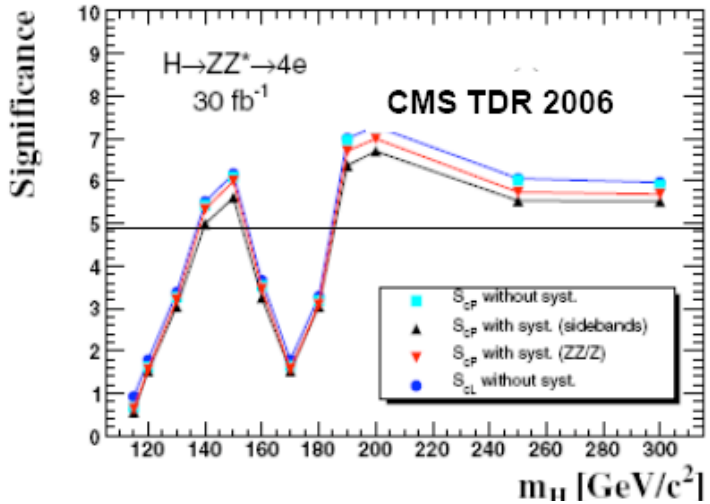
Expected mass resolution better than 1 GeV at 100 GeV

$H \to ZZ^{(*)} \to 4l$





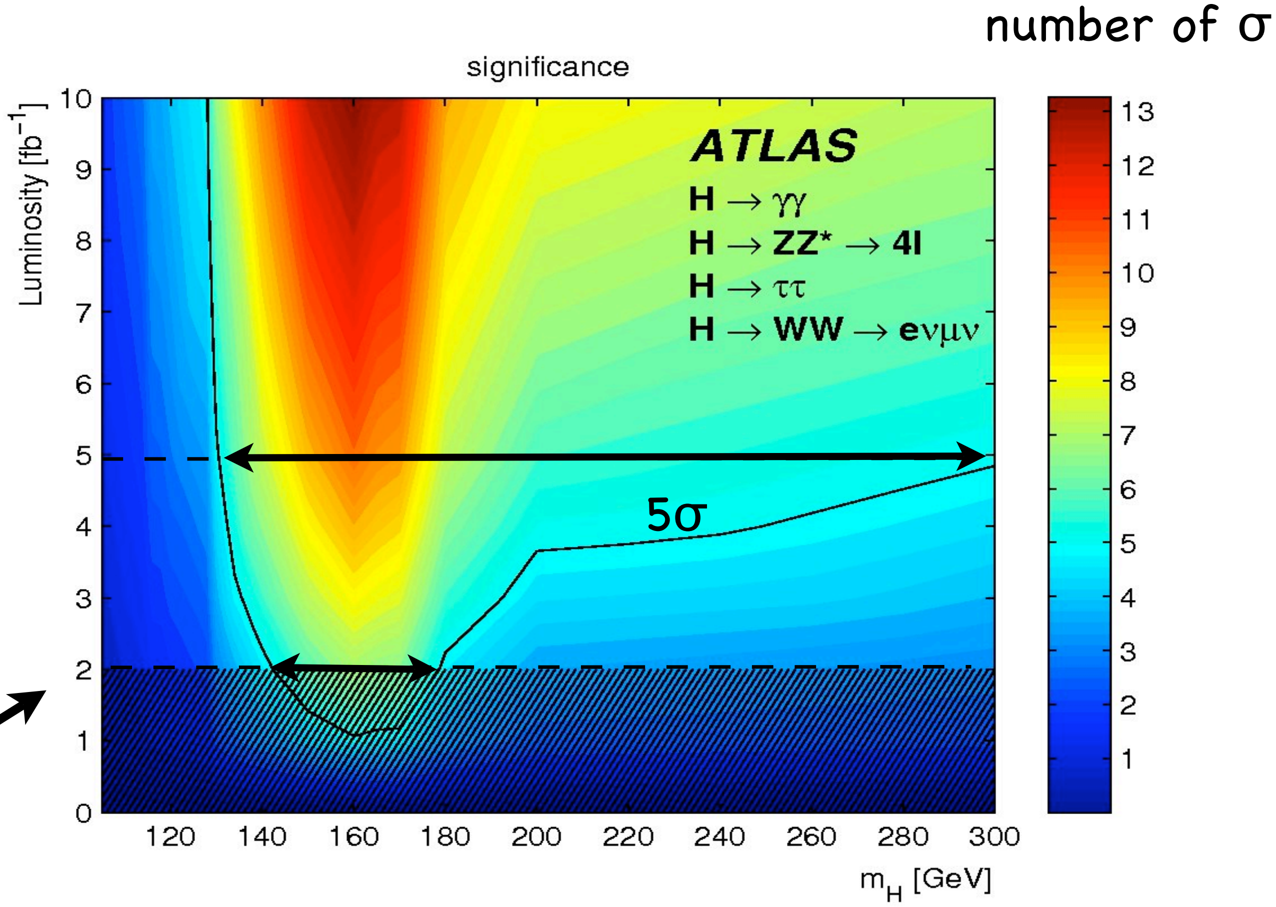




5σ discovery with 5 fb^{-1}

for $m_H \approx 150$ GeV or $200 \lesssim m_H \lesssim 400$ GeV

Combined signal significance:



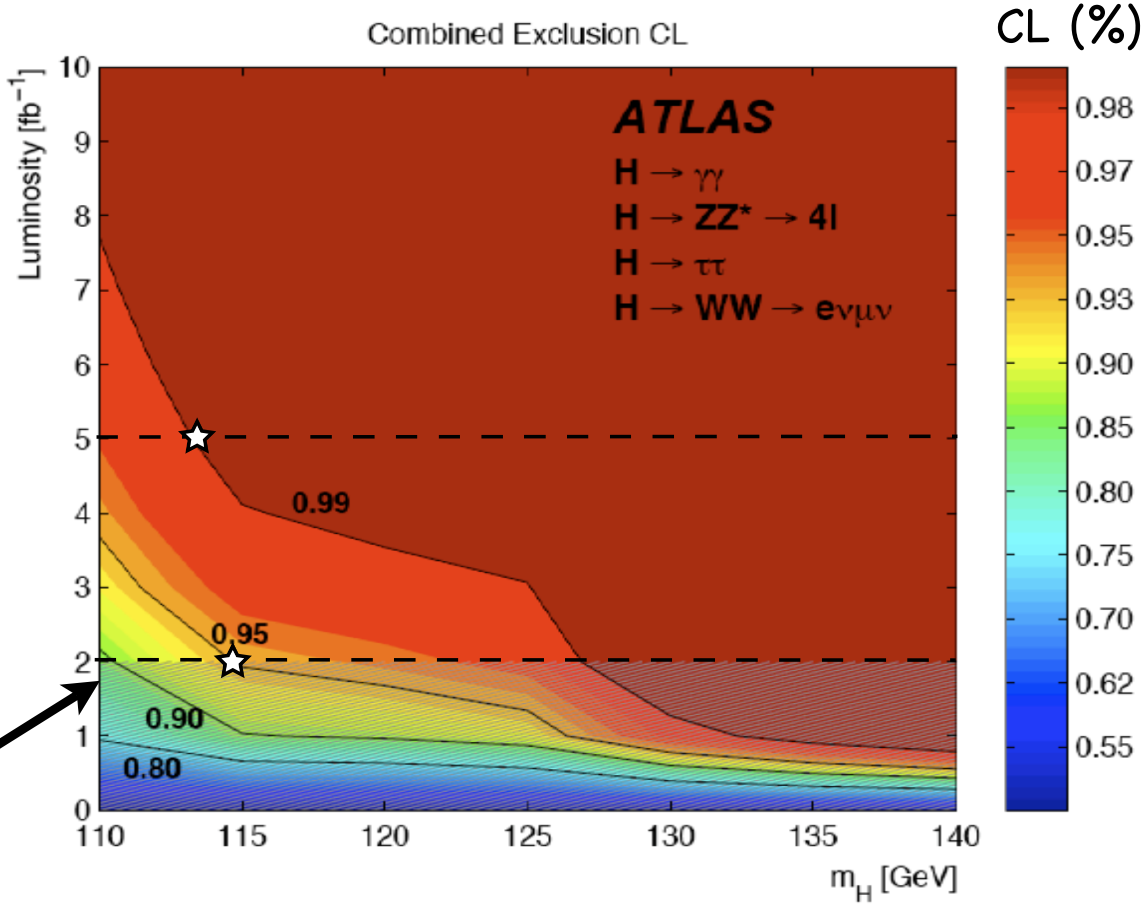
Approximations in combination not always accurate for $L < 2\ fb^{-1}$ but in most cases conservative

5σ significance:

$2\ fb^{-1} \Rightarrow 144 \lesssim m_H \lesssim 180$ GeV

$5\ fb^{-1} \Rightarrow 130 \lesssim m_H \lesssim 300$ GeV

Combined exclusion CL



Approximations in combination not always accurate for L < 2 fb^{-1} but in most cases conservative

2 fb^{-1} exclude $m_H \gtrsim 114$ GeV at 95% CL

5 fb^{-1} exclude $m_H \gtrsim 114$ GeV at 99% CL

In summary

If the SM remains valid, a few fb^{-1} (i.e. a few years) should be enough to dig the weak Higgs signals out of the huge LHC QCD background.