Electroweak Interactions and the discovery of the Higgs Boson

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Spring workshop on nuclear and particle physics.

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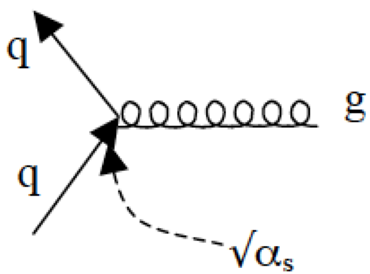
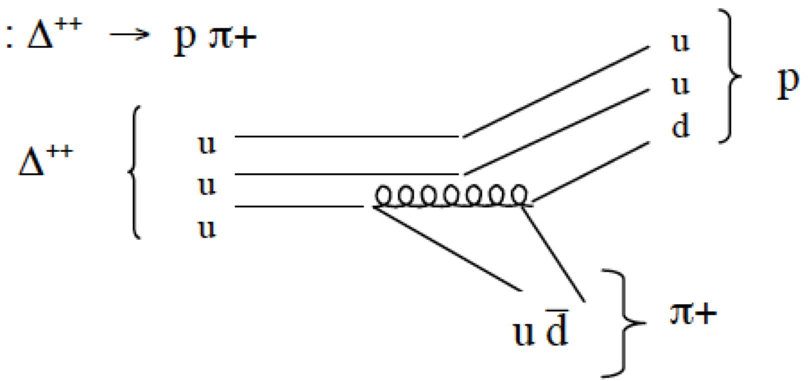
Foundamental Interactions

- Strong interactions



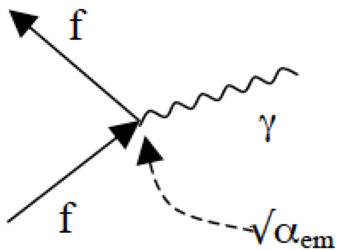
quark

Ex: : $\Delta^{++} \rightarrow p\,\pi^+$

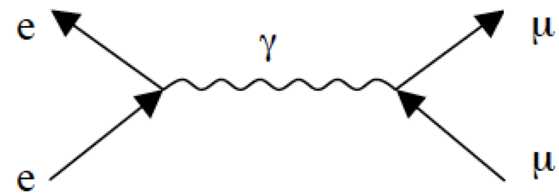


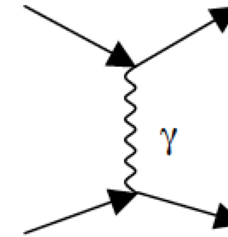
Range ~ $1/m_\pi$ ~ 1 F
$\tau = 10^{-23}$ s
σ ~ 10 mb
α_s ~ 1

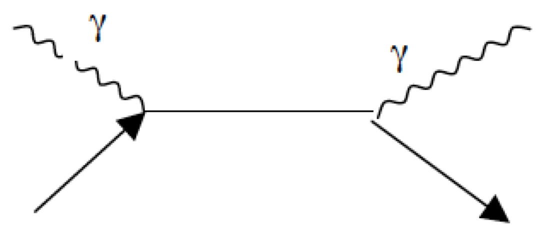
• Electromagnetic interactions



Ex:







Charged fermions

Range $\sim 1/m_\gamma \sim$ infinit
$\tau = 10^{-16}$ - 10^{-20} s
$\sigma \sim 10^{-3}$ mb
$\alpha_{em} \sim 1/137$

- # Weak interactions

$$\Sigma^+ \to n\,\pi^+ \quad \& \quad \Delta^+ \to n\,\pi^+$$

Have the same phase space since masses are similar, but $\tau(\Sigma^+) \sim 10^{13}\,\tau(\Delta^+)$

It is a new interaction with a new coupling constant α_w

$$\tau(\Delta^+ \to n\,\pi^+) / \tau(\Sigma^+ \to n\,\pi^+) \sim 10^{-23} / 10^{-10} \sim (\alpha_s/\alpha_w)^2$$

$$\to \quad \alpha_w \sim 10^{-6}$$

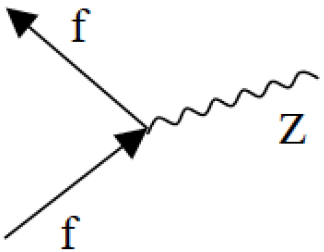
There is flavour changing and it is a charged current
If we make the hypothesis that it is similar to the EM current
but with a massive mediator (Glashow idea), we can then estimate:

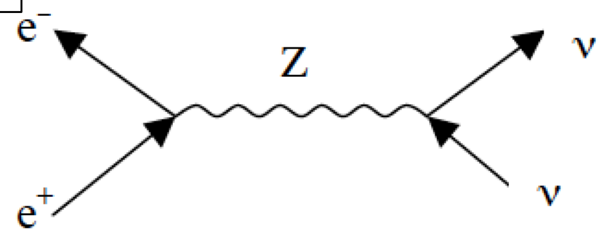
$$\alpha_w = \alpha_{em} / M^2 \quad \to \quad M \sim 100\ \text{GeV}.$$

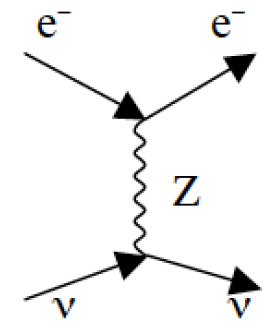
Range $\sim 1/M \sim 10^{-16}$
$\tau = 10^{-16}$ s
$\alpha_{em} \sim 10^{-6}$

Leptons

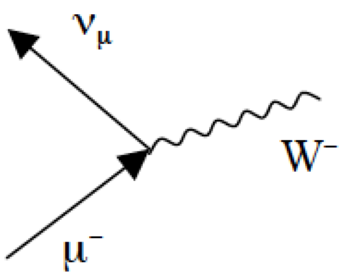
Neutral Currents



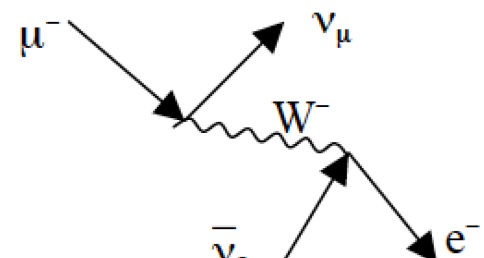




Charged Currents

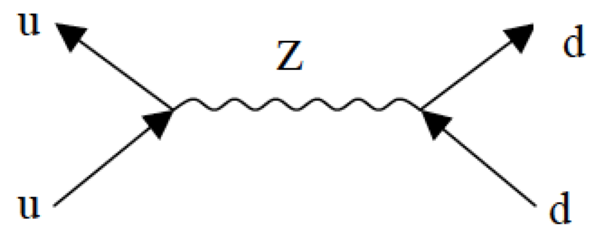


Ex: $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

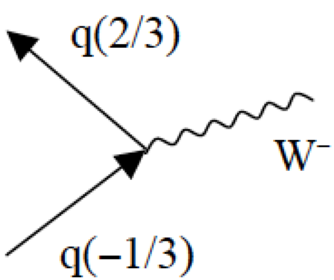


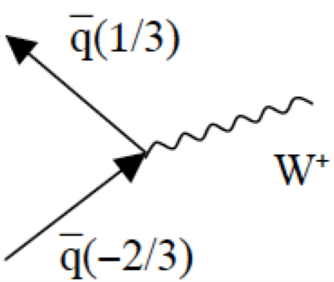
Quark:

Neutral Currents

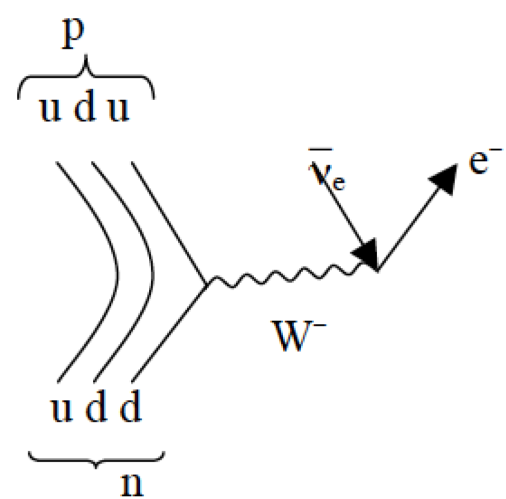


Charged Currents





Ex: $n \rightarrow p\, e\, \bar{\nu}$



For the weak interactions the quark doublets are not the same of the strong interactions (Cabibbo 1963):

Strong

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Weak

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} Vud & Vus & Vub \\ Vcd & Vcs & Vcb \\ Vtd & Vts & Vtb \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The CKM matrix

For 2 doublets:

$$d' = d \cos\theta_C + s \sin\theta_C$$
$$s' = -d \sin\theta_C + s \cos\theta_C$$

$Vud \sim \cos\theta_C$ & $Vus \sim \sin\theta_C$

The Cabibbo angle

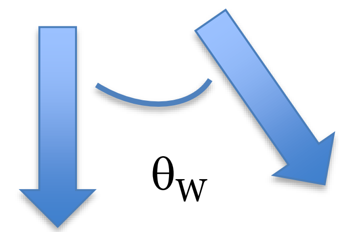
Features of weak interactions

- The Range is very short (the propagator is massive ~ 100 GeV)
- If m_f=0, fermions exist only Left Handed (anti-fermions Right Handed) → violation of the charge conjugation symmetry.
- Cabibbo first unification: the gauge bosons couple only with fermions with an intensity proportional to the weak charge. The weak coupling is the same for all the particles: (u,d') has the same coupling as (ν, e) and (ν,μ)
- Only charged current can change flavour with the rule: $\Delta s = \Delta Q$ thus FCNC do not exist.
- Lepton number is conserved L_e, L_μ, L_τ
- Weak interaction do not conserve Parity, Charge conjugation, nor CP

The Standard Model

Interaction	Strong	Electroweak		
Local simmetry	$SU(3)_C$	$SU(2)_I$	$U(1)_Y$	
Coupl Const	α_s	g	g'	
Gauge field	gluons	$W_1W_2W_3$	B	

Spontaneous symmetry Breaking	Higgs



W=Weinberg

Gauge field		W+,W-	Z	γ (Q=I3+Y/2)
Coupl const		g	$g/\cos\theta_W$	$e=g\sin\theta_W=g'\cos\theta_W$
Matter field	quark	f_L	$f_L + f_R$	$f_{L,R}(Q>0)$
Conserved quantity	barionic number color charge isospin	Leptonic number, Q		

Structure of the theory

- Isospin doublets Left Handed

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad \begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

- Isospin Singlet Right Handed (m>0)

$$e_R \quad \mu_R \quad \tau_R \quad u_R \quad d_R \quad c_R \quad s_R \quad t_R \quad b_R$$

Why not add ν_{iR} ?

		Leptoni						Quark		
	I	I_3	Q	Y			I	I_3	Q	Y
ν_L	1/2	1/2	0	−1		u_L	1/2	1/2	2/3	1/3
e_L	1/2	−1/2	−1	−1		d_L	1/2	−1/2	−1/3	1/3
e_R	0	0	−1	−2		u_R	0	0	2/3	4/3
						d_R	0	0	−1/3	−1/3

$$Q = I_3 + Y/2$$

The gauge bosons

- Before the breaking : W1,W2,W3, B

- The physical fields are:

$$\begin{cases} W_\mu^+ = \frac{1}{2}\,(W_\mu^1 - iW_\mu^2) \\ W_\mu^- = \frac{1}{2}\,(W_\mu^1 + iW_\mu^2) \end{cases}$$

$$\begin{cases} A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W \\ Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W \end{cases}$$

Weinberg angle

Neutral Current

$$\begin{cases} W_\mu^3 = Z_\mu \cos\theta_W + A_\mu \sin\theta_W \\ B_\mu = -Z_\mu \sin\theta_W + A_\mu \cos\theta_W \end{cases}$$

Thus the neutral electro-weak interaction is:

$$-igJ^{3\mu}W_\mu^3 - i\frac{g'}{2}J^{Y\mu}B_\mu =$$

$$-ig\sin\theta_W J^{3\mu}A_\mu - ig\cos\theta_W J^{3\mu}Z_\mu + i\frac{g'}{2}\sin\theta_W J^{Y\mu}Z_\mu - i\frac{g'}{2}\cos\theta_W J^{Y\mu}A_\mu =$$

$$-i(g\sin\theta_W J^{3\mu} + g'\cos\theta_W \frac{J^{Y\mu}}{2})A_\mu - i(g\cos\theta_W J^{3\mu} - g'\sin\theta_W \frac{J^{Y\mu}}{2})Z_\mu$$

Since we know that the EM interaction is: $-ieJ_\mu^{em}A^\mu$ and $J_\mu^{em} = J_\mu^3 + \frac{J_\mu^Y}{2}$.

We have: $g\sin\theta_W J_\mu^3 + g'\cos\theta_W \frac{J_\mu^Y}{2} \Rightarrow J_\mu^{em}$

Thus: $$e = g \sin \theta_W = g' \cos \theta_W$$

And $$\tan \theta_W = \frac{g'}{g}$$

The Weinberg angle is the ratio of the coupling constants of the groups $SU(2)_L$ and $U(1)_Y$

There are 2 independent parameters: **g, g'** or **e, sinθ$_W$**

From the equation before we can write:

$$- ieJ_\mu^{em} A^\mu - i \frac{g}{\cos \theta_W} (J_\mu^3 - \sin^2 \theta_W J_\mu^{em}) Z^\mu$$

Thus the fondamental Electroweak Neutral Interaction is:

$$- i\, e\, J_\mu^{em} A^\mu - i\, g / \cos\theta_W\, J_\mu^{NC}\, Z_\mu$$

The current associated to the Z boson is $J_\mu^{NC} = J_\mu^3 - \sin^2\theta_W J_\mu^{em}$

- Thus the current associated to the Z boson is the sum of the third weak current and of the Electromagnetic current → thus the Z bosons couples with both L and R fermions.

- The W bosons instead couple only with L fermions.

- $\sin\theta_W$ and e must be determined experimentally.

- In the SM these coupling are the same for all the fermions: must be verified experimentally.

FCNC

- For the quarks: $J_\mu^{NC} = J_\mu^3 - \sin^2\theta_W J_\mu^{em}$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

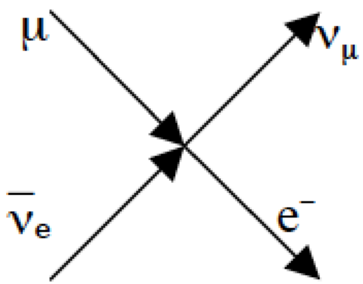
$$d' = d\cos\theta_C + s\sin\theta_C$$
$$s' = -d\sin\theta_C + s\cos\theta_C$$

If we solve the equation, we get that the mixed terms ($d\, s \sin\theta_C \cos\theta_C$) cancel, and that the Z couples only to uu, dd, ss, cc ....

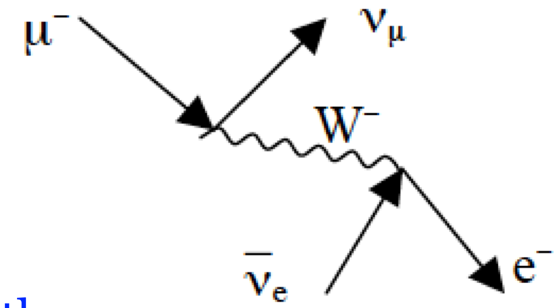
i.e. FCNC do not exists

$$\Delta s = \Delta Q = 0$$

CC: Fermi Theory & SM Theory



$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



The two matrix elements must be the same

$$4\frac{G_F}{\sqrt{2}} = \frac{g^2}{2M_W^2}$$

$$G_F = \frac{10^{-5}}{m_p^2} GeV^{-2} \quad \& \quad g^2 = \frac{e^2}{\sin^2\theta_W}$$

$$M_W = \left(\frac{\sqrt{2}g^2}{8G_F}\right)^{1/2} = \left(\frac{\sqrt{2}e^2}{8G_F \sin^2\theta_W}\right)^{1/2} = \frac{37.3}{\sin\theta_W} GeV$$

NC: Fermi Theory & SM Theory

$$\nu q \rightarrow \nu q$$

$$4\frac{G_N}{\sqrt{2}}2 = \frac{g^2}{M_Z^2 \cos^2\theta_W}$$ and if $G_N = \rho G_F$

$$4\frac{G_F\rho}{\sqrt{2}} = \frac{g^2}{2M_Z^2 \cos^2\theta_W}$$

$$M_Z = \frac{74.6}{\sin 2\theta_W}$$

$$\boldsymbol{\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W}}$$

ρ is the ratio of the CC and NC couplings. It is **1**.

ρ=1 if the Higgs field is a « simple » doublet of complex scalar fields.

Universality

- GF is universal for CC, NC, leptons, quarks, semileptonic, hadronic decays… but always considering the Cabibbo angle, i.e. the EW quark doublets

$$G_F \cdot \cos\theta_C \quad \text{for} \quad \Delta s = 0$$
$$G_F \cdot \sin\theta_C \quad \text{for} \quad \Delta s = 1$$

$n \rightarrow p\, e\bar{\nu}_e$ $\qquad G_F(n) = 1.136 \pm 0.003 \times 10^{-5}\ \mathrm{GeV}^{-2}$

$\mu \rightarrow \nu_\mu\, e\bar{\nu}_e$ $\qquad G_F(\mu) = 1.16632 \pm 0.00002 \times 10^{-5}\ \mathrm{GeV}^{-2}$

$$G_F(n) = G_F(\mu) \cdot \cos\theta_C \qquad (\sin\theta_C = 0.2229 \pm 0.0022)$$

The discovery of the neutral currents

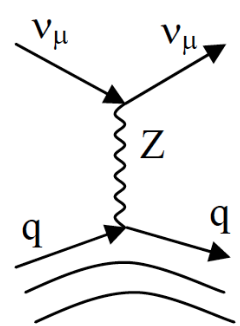
- In 1973 the Gargamelle experiment at the PS (Proton Syncrotron) at Cern discovers the weak neutral current interaction.
- In the '70 at CERN neutrino beams were available.

Neutrinos and anti-neutrinos beams on a bubble chamber filled with heavy liquid. (Freon, of density 1.5×10^3 kg/m^3)

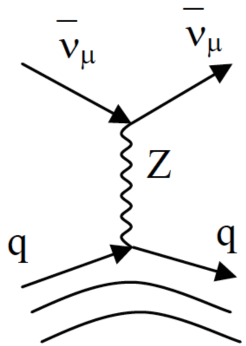
NC

$$\nu_\mu / \bar{\nu}_\mu + N \rightarrow \nu_\mu / \bar{\nu}_\mu + had$$

Absence of $\mu^\pm$ in the final state



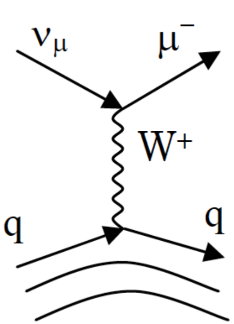
e



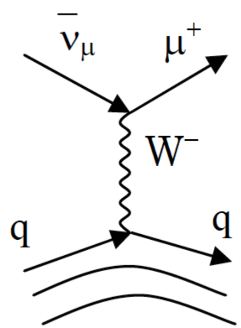
CC

$$\nu_\mu / \bar{\nu}_\mu + N \rightarrow \mu^- / \mu^+ + had$$

Presence of $\mu^\pm$ in the final state



e



Neutral current of anti-neutrinos

$\bar{\nu}_\mu \rightarrow$

Figure 1.6 First example of weak neutral-current process $\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$ observed in heavy-liquid bubble chamber Gargamelle at CERN irradiated with a $\bar{\nu}_\mu$ beam (Hasert *et al.*, 1973). A single electron of energy 400 MeV is projected at a small angle ($1.5 \pm 1.5°$) to the beam, and is identified by bremsstrahlung and pair production along the track (see Chapter 2). About 10^9 $\bar{\nu}_\mu$'s traverse the chamber in each pulse and three such events were observed in 1.4 million pictures. (Courtesy CERN.)

Charged current: ν+n → μ+p

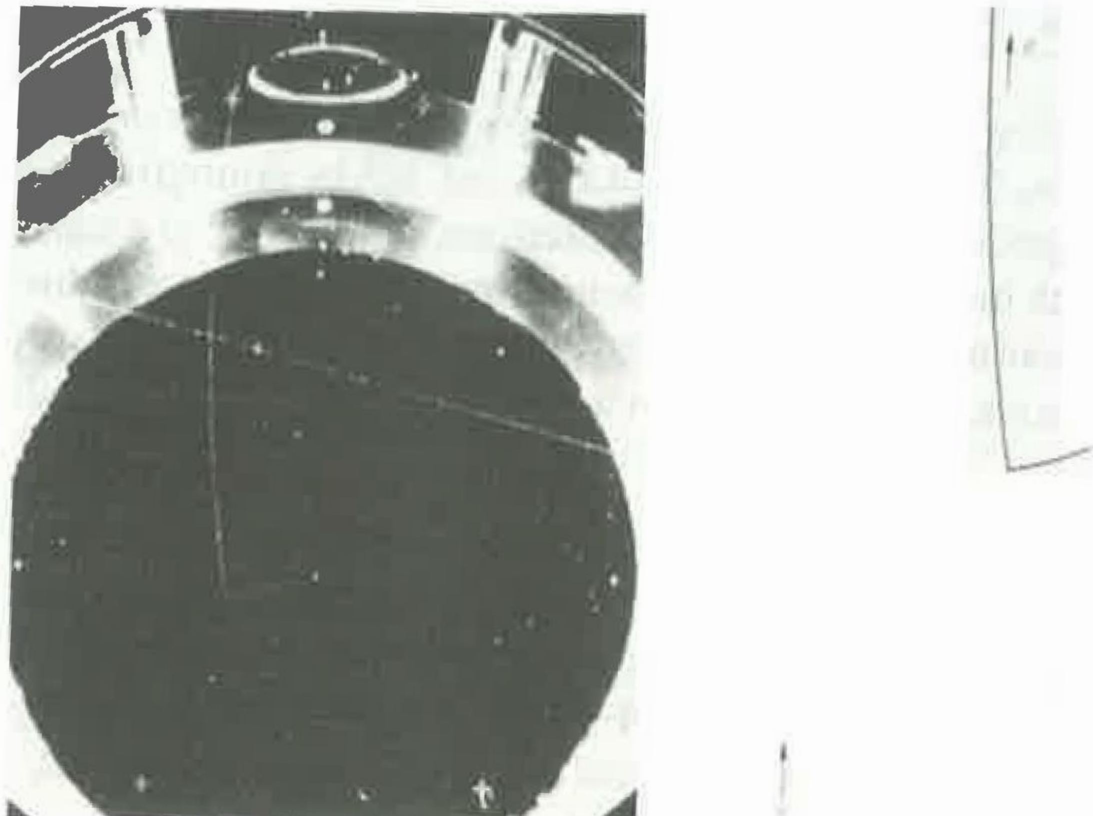
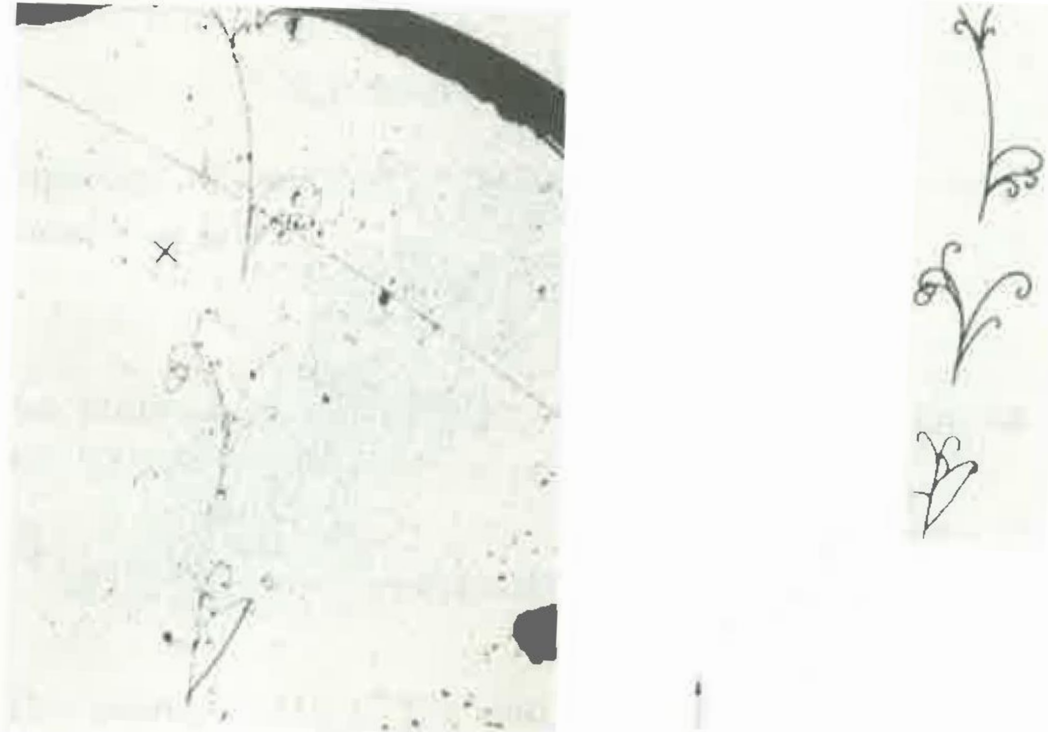


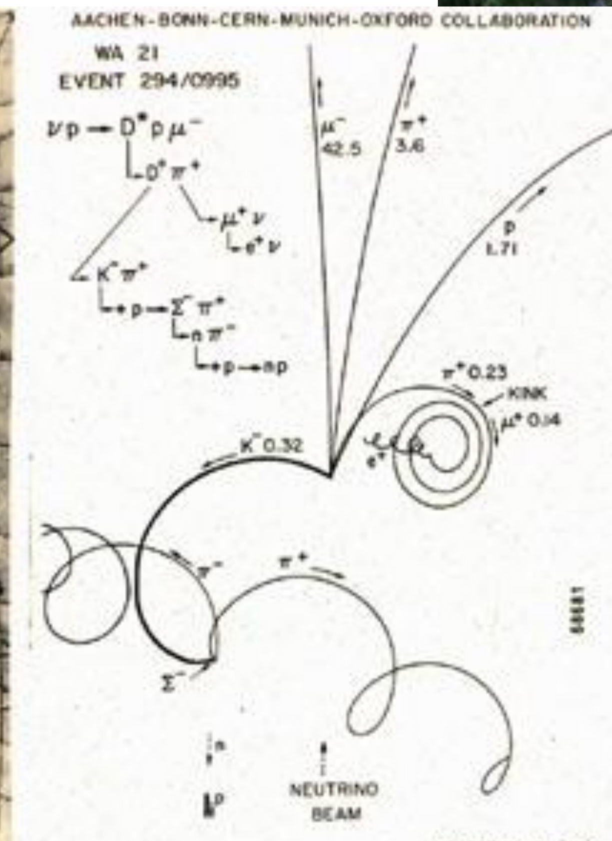
Figure 7.13 Early examples of "elastic" neutrino interactions observed in a heavy-liquid bubble chamber at CERN in 1963. (a) shows an event attributed to the reaction $\nu_\mu + n \rightarrow p + \mu^-$. The noninteracting muon passes out of the chamber, and the recoil proton comes to rest inside the



(b)

(b) Event produced by interaction of an electron-neutrino ν_e: $\nu_e + n \rightarrow p + e^-$. The incident beam consists mostly of muon-neutrinos ν_μ, with a very small admixture of ν_e $(\sim\frac{1}{2}\%)$ from the three-body decays in flight, $K^+ \rightarrow \pi^0 + e^+ + \nu_e$. The high-energy electron secondary is recognized by the characteristic shower it produces by the processes of bremsstrahlung and pair production. (Courtesy CERN.)

Gargamelle


AACHEN-BONN-CERN-MUNICH-OXFORD COLLABORATION
WA 21
EVENT 294/0995
νp → D*pμ⁻
D⁰π⁺
μ⁺ν
e⁺ν
K⁻π⁺
p → Σ⁻π⁺
nπ⁻
p → np
μ⁻
42.5
π⁺
3.6
p
1.71
π⁺ 0.23
KINK
μ⁺ 0.14
K⁻ 0.32
e⁺
π⁻
π⁺
Σ⁻
n
p
NEUTRINO
BEAM
MOMENTUM IN GeV/c

The weak neutral current discovery, 1973

The quantities to be measured are:

$$R = \frac{NC}{CC} = \frac{\nu_\mu N \rightarrow \nu_\mu X}{\nu_\mu N \rightarrow \mu X}$$

$$R = \frac{NC_\nu}{NC_{\bar{\nu}}} = \frac{\nu_\mu N \rightarrow \nu_\mu X}{\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X}$$

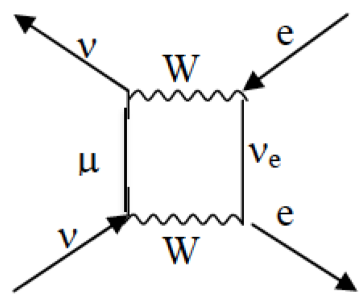
$$R\left(\frac{NC}{CC}\right)_\nu = \frac{1}{2} - \sin^2\theta_W + \frac{20}{27}\sin^4\theta_W$$

$$R\left(\frac{NC}{CC}\right)_{\bar{\nu}} = \frac{1}{2} - \sin^2\theta_W + \frac{20}{9}\sin^4\theta_W$$

$$R = \frac{NC_\nu}{CC_\nu} = \frac{102}{428}\,evt \sim \sin^2\vartheta_W \qquad R = 0.24 \pm 0.03$$

$$R = \frac{NC_{\bar{\nu}}}{CC_{\bar{\nu}}} = \frac{64}{148}\,evt \sim \sin^2\vartheta_W \qquad R = 0.42 \pm 0.03$$

The NC is a process of the same order of the CC, thus what Gargamelle observes is not a second order CC process



$\sin^2\theta_W \sim 0.23$

The W and Z discovery 1983

- The measurement of $\sin^2\theta_W$ by Gargamelle allowed an estimate of the W and Z boson mass:
  for $\sin^2\theta_W \sim 0.23$ → $m_W = 80$ GeV/c², $m_Z = 92$ GeV/c²

- Rubbia proposed the Sp$\bar{p}$S and in 1983 discovers the W and soon after the Z

  → **MW =80.5 ± 0.5 GeV/c²** **MZ = 93 ± 2.9 GeV/c²**

- First test of the standard model:

$$M_W^2 = M_Z^2 \cos^2\theta_W \quad \Rightarrow \quad \sin^2\theta_W = 0.220 \pm 0.009$$

in agreement with neutrino-experiments.

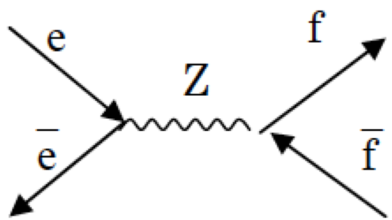
$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1.000 \pm 0.036$$

compatible with the Standard Model of Glashow Salam and Weinberg

LEP and the triumph of the SM

LEP: e^+e^- collider , E_{cm}~M_Z , 2M_W … 209 GeV

t-channel



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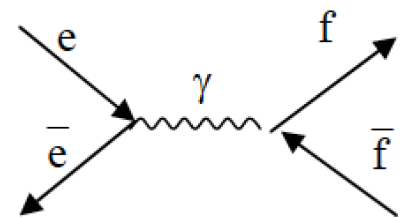
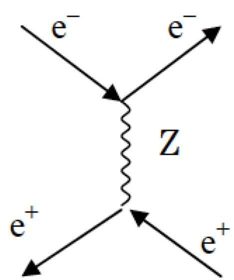


s-channel



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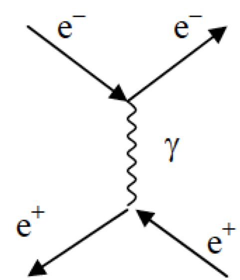


Cross sections

$$\sigma_\gamma = \frac{\hbar c g_e^2}{48\pi}\frac{Q_f^2}{E^2}$$

For photon exchange

$$\sigma_Z = \frac{(c g_Z^2 E)^2}{48\pi}\frac{a}{[(2E)^2 - M_Z^2]^2 + (M_Z \Gamma_Z)^2}$$

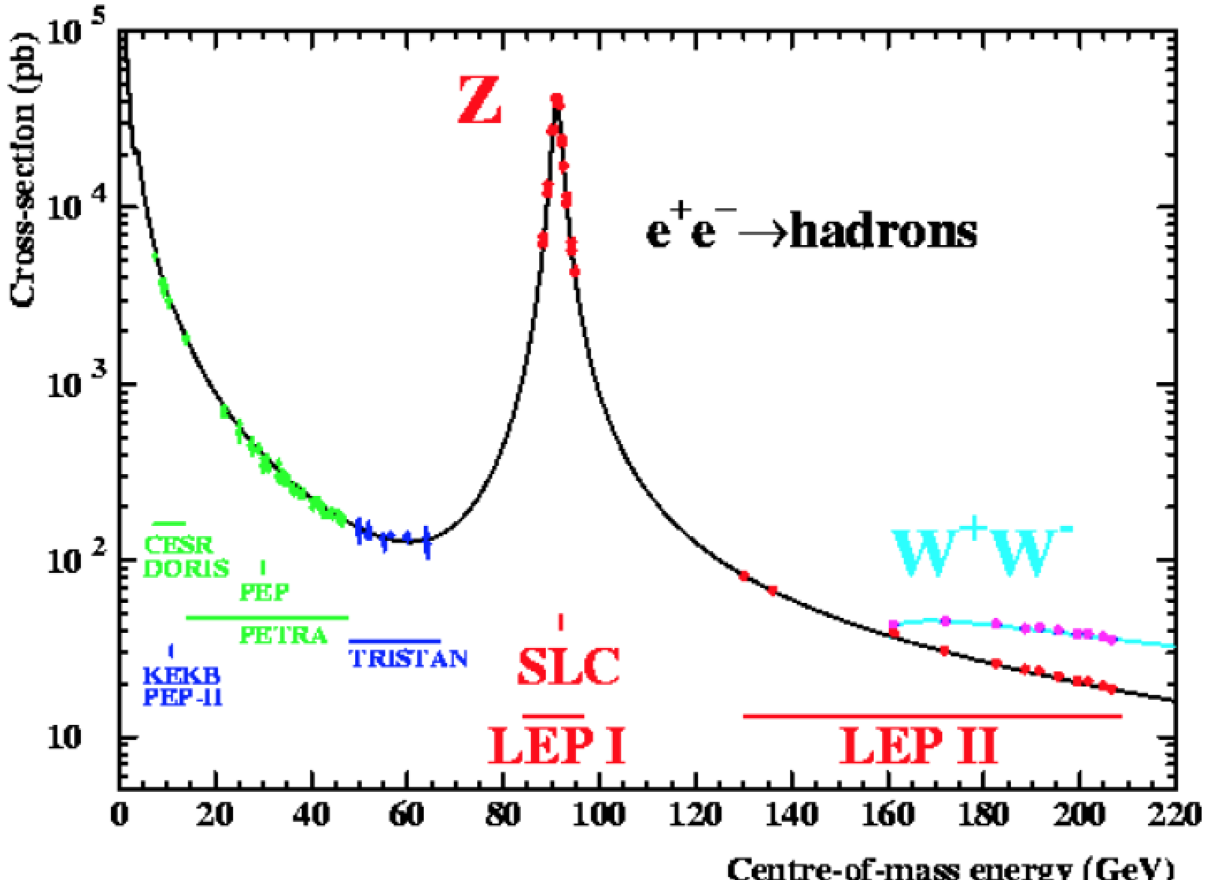
For Z exchange

For $(2E) << M_Z c^2 \Rightarrow \frac{\sigma_Z}{\sigma_\gamma} \approx 2 \cdot (\frac{E}{M_Z c^2})^4$ Photon is dominant

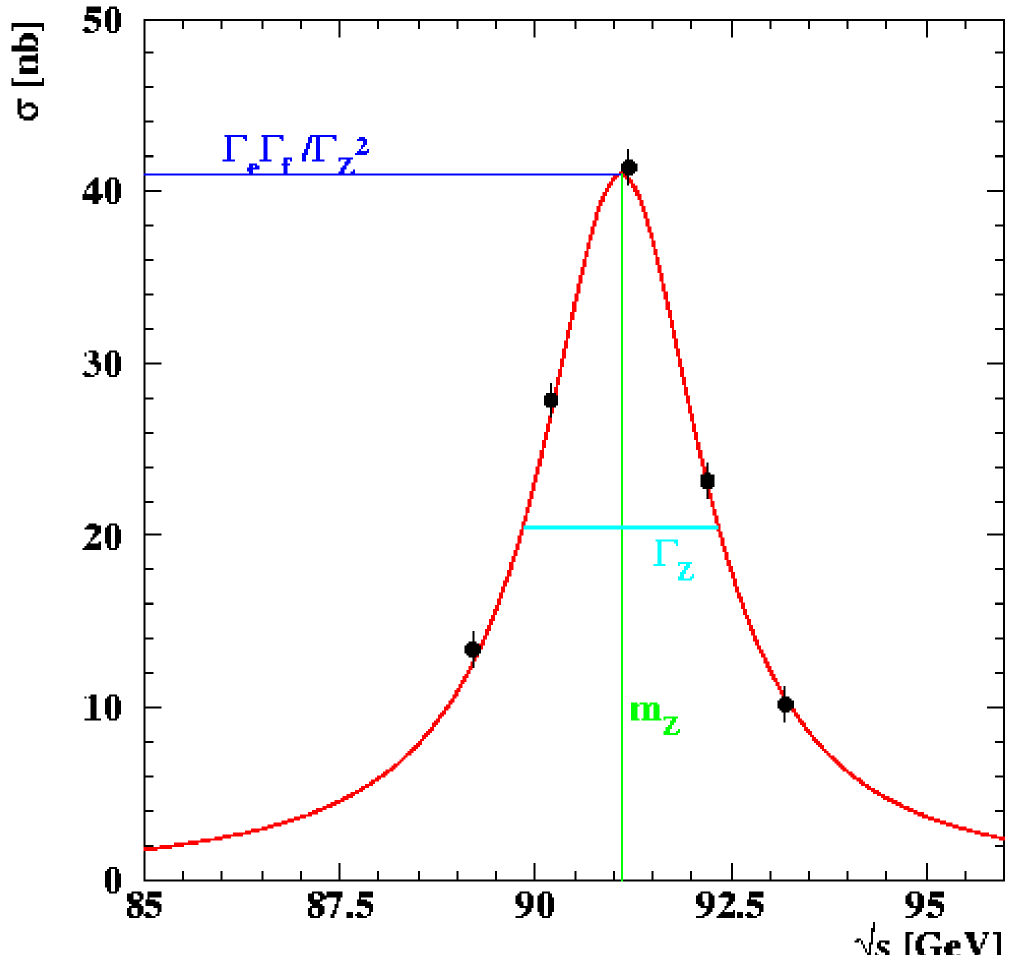
At E_{cm}= 40 GeV, $\sigma_Z \sim 1\%$ of σ_γ

For $(2E) = M_Z c^2 \Rightarrow \frac{\sigma_Z}{\sigma_\gamma} \approx \frac{1}{8} \cdot (\frac{M_Z c^2}{\hbar \Gamma_Z}) \sim 200$ Z is dominant

Photon and Z exchange

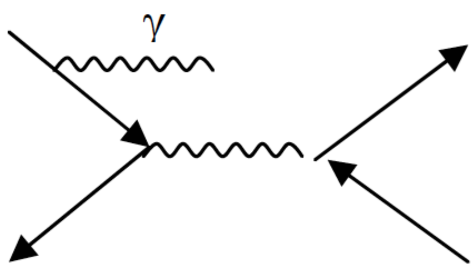


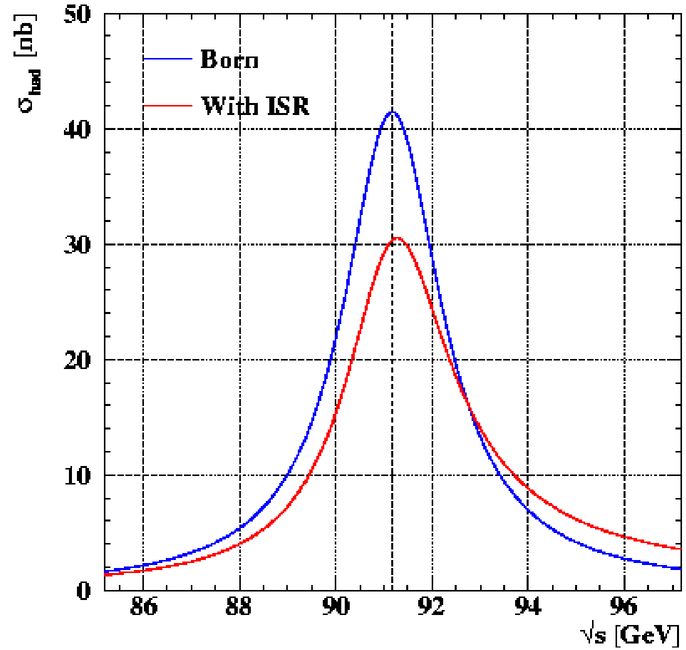
Z line shape



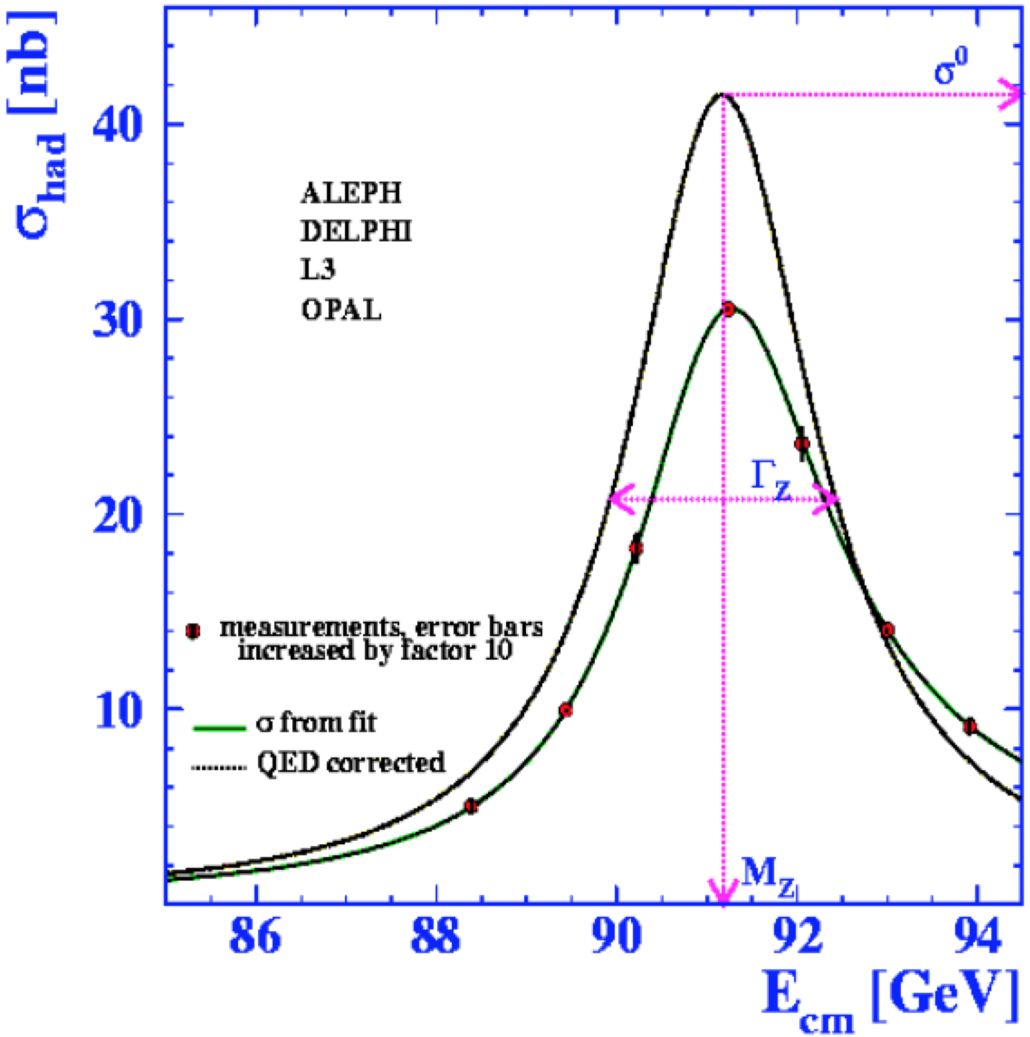
σ [nb]
50
40
30
20
10
0
85
87.5
90
92.5
95
√s [GeV]
$\Gamma_e \Gamma_f / \Gamma_Z^2$
Γ_Z
m_Z

Radiative Correction - QED



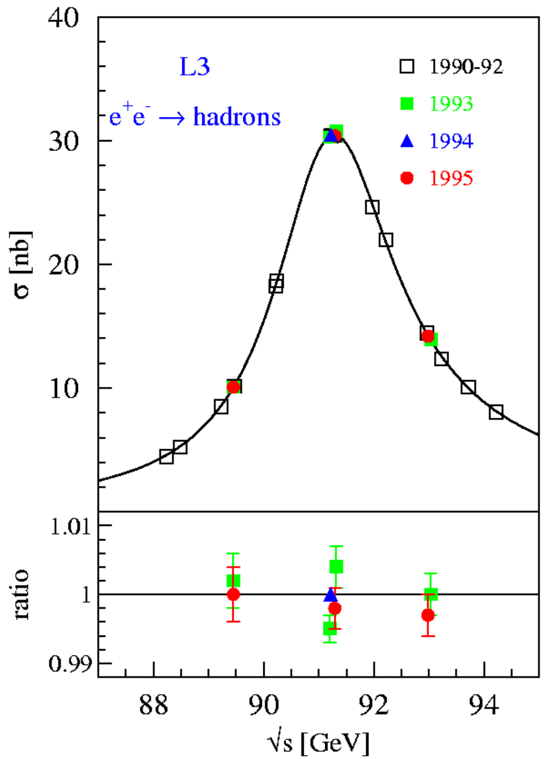


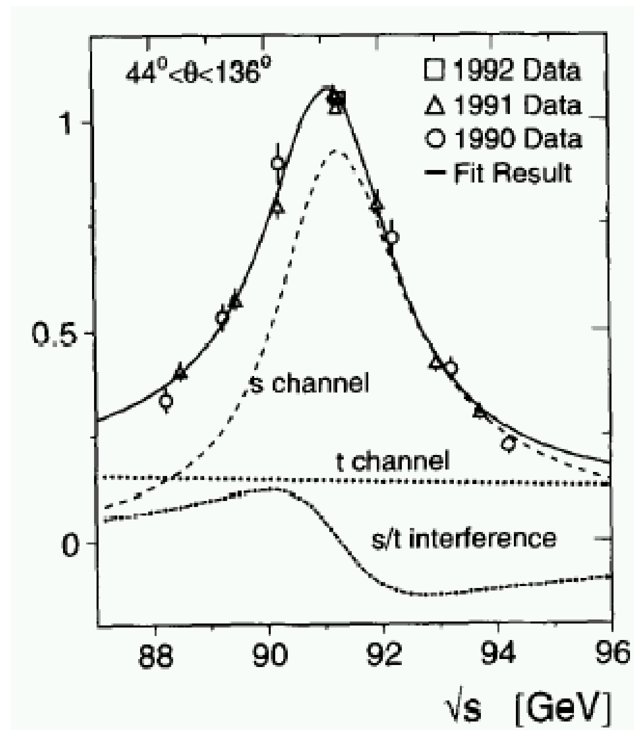
The Z "Breit e Wigner" is modified by the QED corrections: the blue line is the Born cross section (symmetric wrt M_Z). The red line is what we expect experimentally, that is after QED radiative corrections.



σ_{had} [nb]
σ^0
40
30
20
10
ALEPH
DELPHI
L3
OPAL
Γ_Z
measurements, error bars increased by factor 10
σ from fit
QED corrected
M_Z
86
88
90
92
94
E_{cm} [GeV]

Z line shape for ee→Z→qq,ee



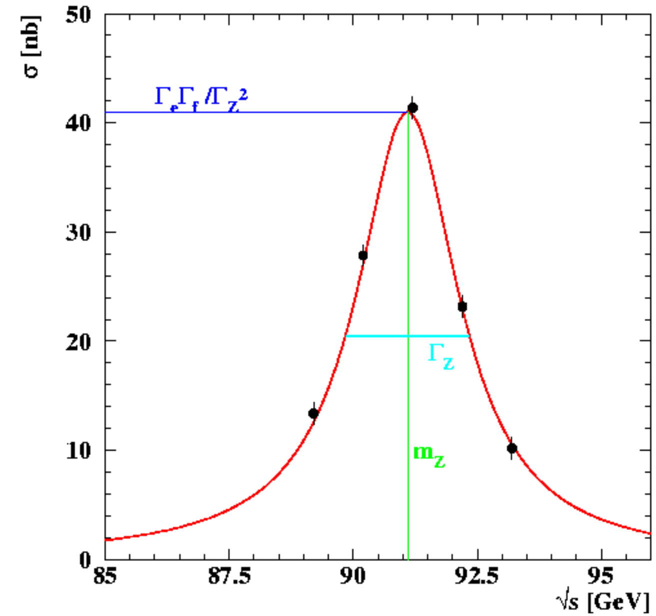


The line-shape

- To measure the Z boson "line-shape" we measure cross-sections as a function of the center of mass energy for the selected final state.

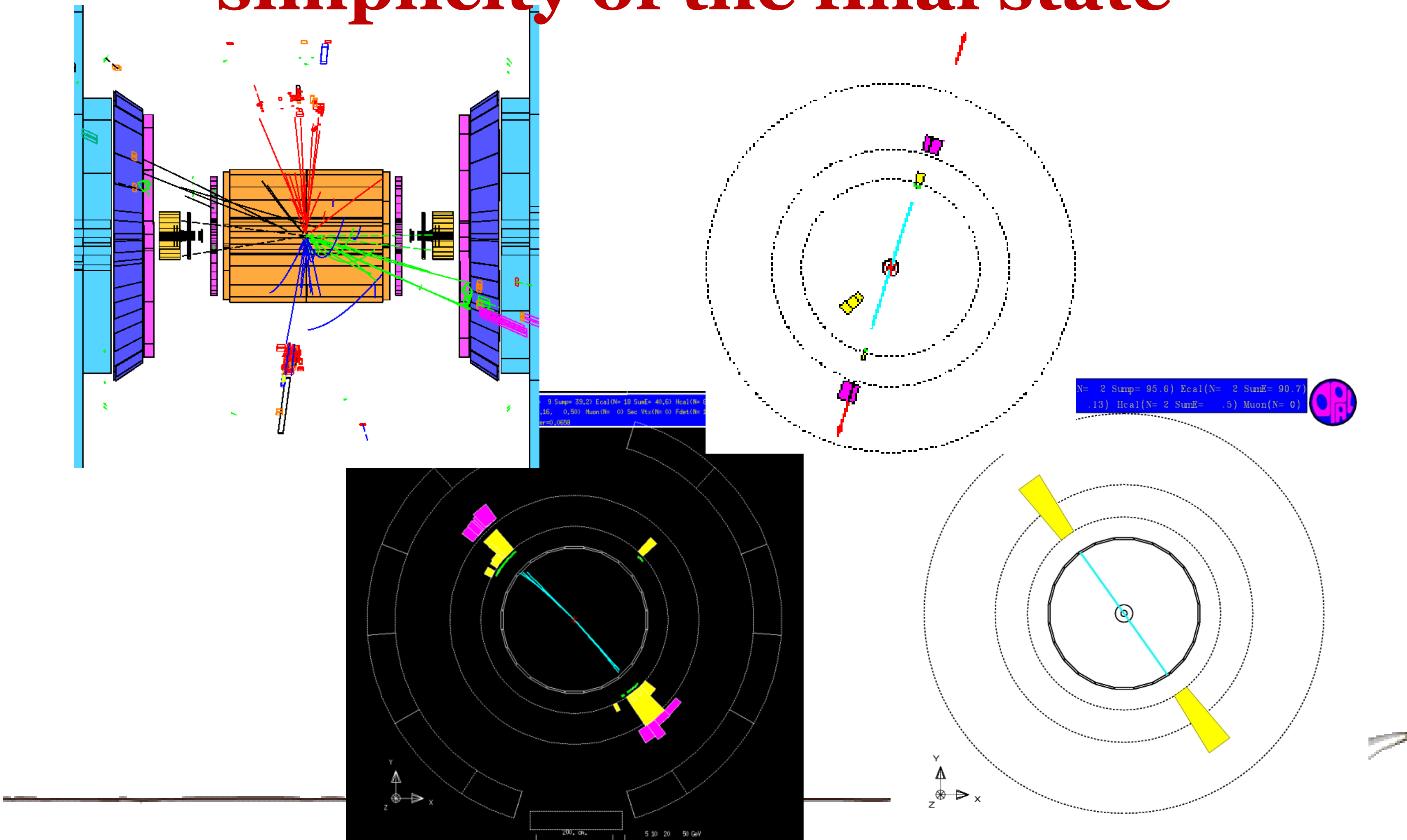
  σ = (Ndata – Nbckg) / ε × Luminosity   vs   **Ecm**

- Experimentally:
  - Count the events (Ndata)
  - Determine the efficiency ε of the detector
  - determine the background events (Nbckg)
  - Measure the Luminosity
  - Measure the beam energy

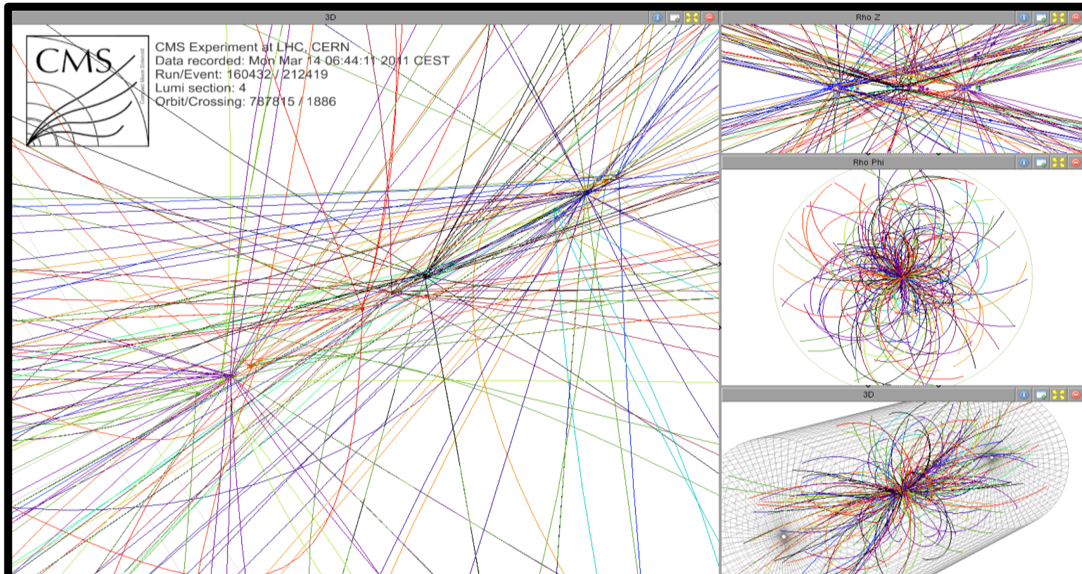


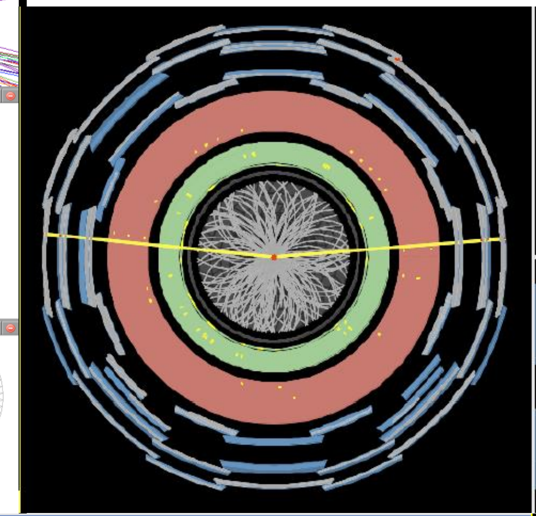
- To reach **a precision of fractions of per mille** on the Z boson parameters, we need to reach these precisions on the initial state e^+e^- (Ecm and Luminosity) and on the final state f^+f^-.

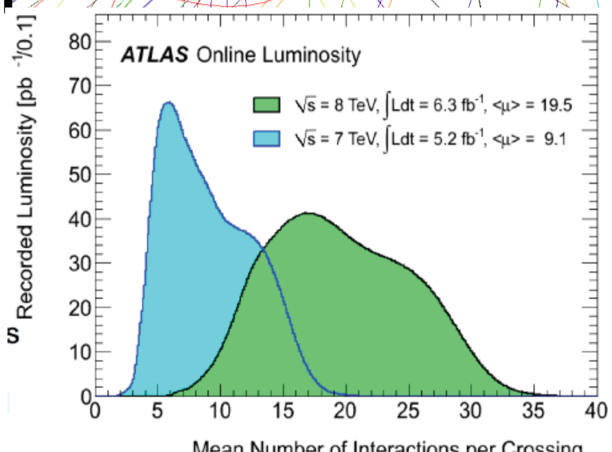
Simplicity of the initial state → simplicity of the final state

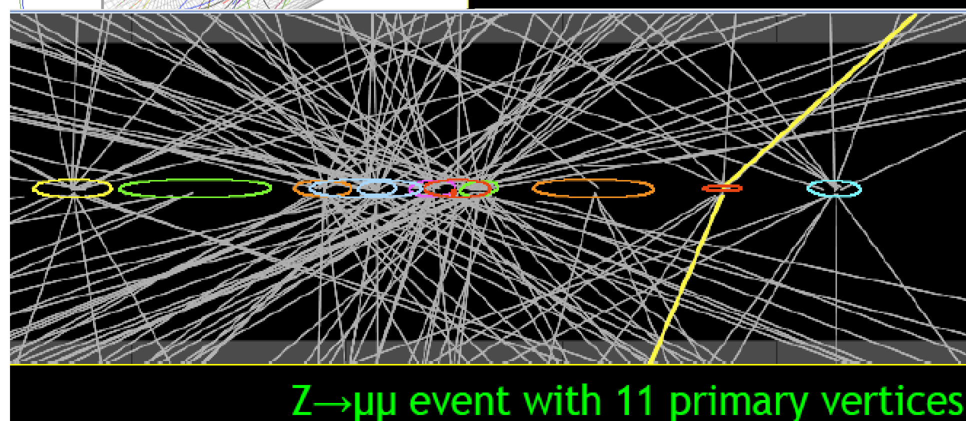


Z → μμ at LHC

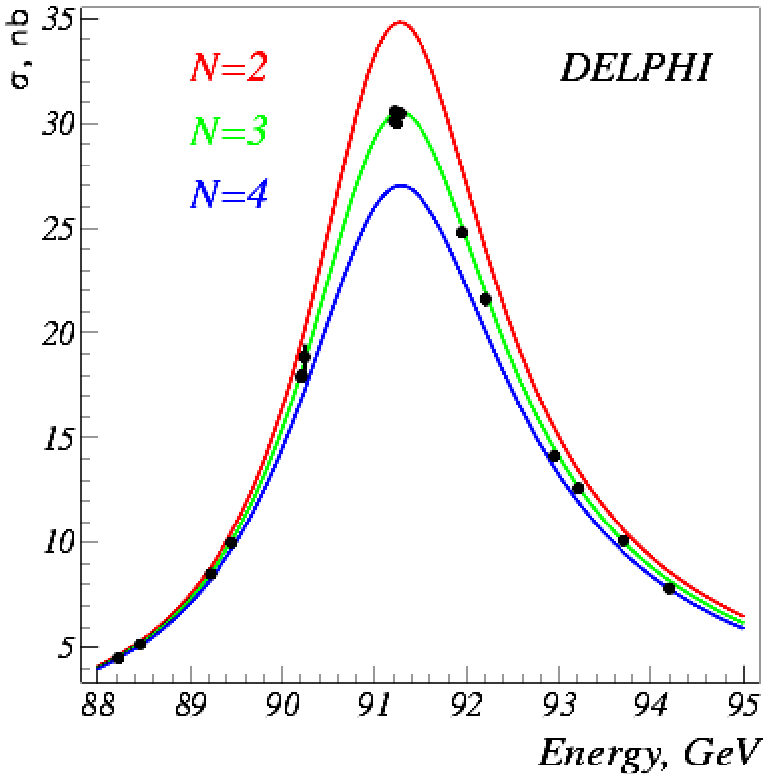

CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Mar 14 06:44:11 2011 CEST
Run/Event: 160432 / 212419
Lumi section: 4
Orbit/Crossing: 787815 / 1886
3D
Rho Z
Rho Phi
3D




ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 6.3 fb⁻¹, <μ> = 19.5
√s = 7 TeV, ∫Ldt = 5.2 fb⁻¹, <μ> = 9.1
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
35
40


Z→μμ event with 11 primary vertices

Why so precise?



$R_{inv} = \Gamma_{inv}/\Gamma_{ll} = (\Gamma_Z - \Gamma_{had} - 3\,\Gamma_{ll})/\Gamma_{ee}$

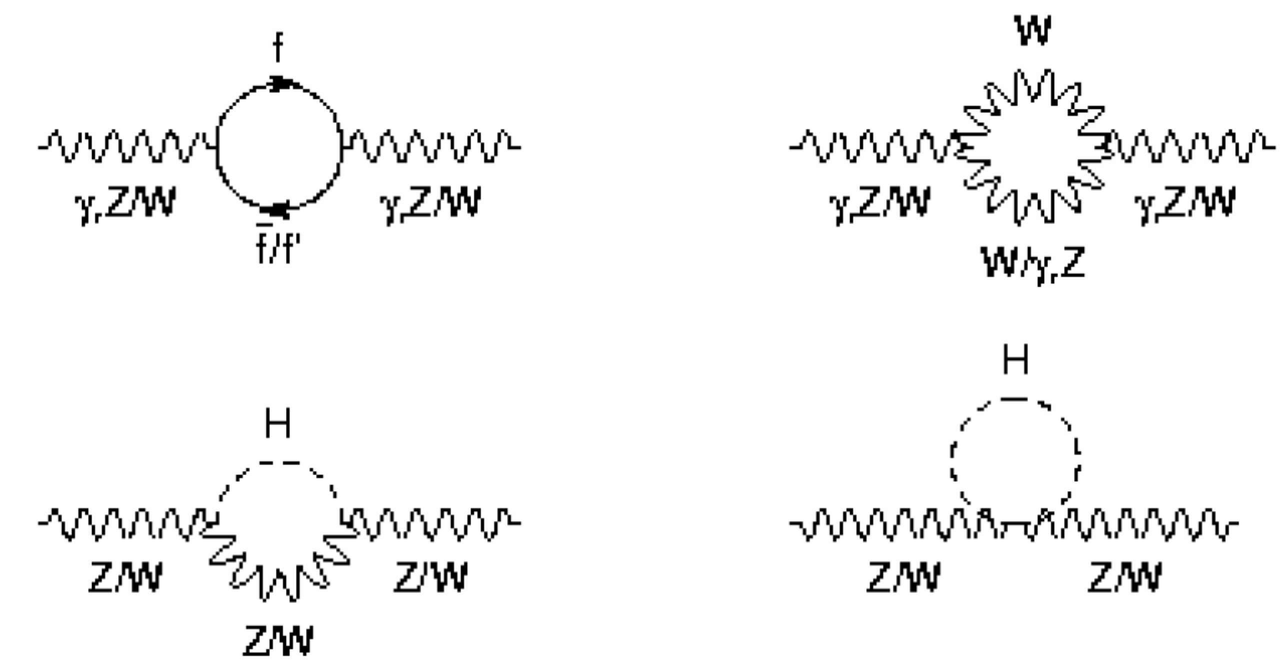
$R_{inv} = N(\nu) * [\Gamma_{\nu\nu}/\Gamma_{ll}]_{SM}$

$N(\nu) = 2.9841 \pm 0.0083$

The number of neutrinos is 3
→ the number of lepton families is 3

If there would have been only 2 or 4 neutrinos, the total width of the Z would have been narrower or larger.
Before LEP the experimental result was N(ν) = 3.0 ±0.9, 2 orders of magnitude less precise.
This was leaving many hyphotesys open.
(The tau-neutrino - ν_τ has been directly detected in the DONUT experiment at Fermilab only in 2000)

ElectroWeak Radiative Correction



The lowest order Feynman diagrams are accompanied at second order, by diagrams where the propagator (gamma, Z or W) is modified by the EW Rad. Corr., i.e. by bosonic and fermionic loops.

First calculations from G. Passarino and M. Veltman.

Radiative Corrections

- Because of the EW Rad Corr , the foundamental expressions between SM variables change:

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} \qquad \bar{\rho} = 1 + \Delta\rho \qquad \Delta\rho = f(\sin^2 \theta_W, G_F, m_t^2, \log m_H)$$

- The Rad. Corr. Depends from the top-quark-mass squared and from the log of the Higgs-mass.

  Thus strong dependence from top-mass, weak dependence from the Higgs-mass.

- **When comparing the experimental measurements of the precision variables with the Standard Model prediction the top-mass can be determined in an indirect way, and limits on the Higgs-mass can be set.**

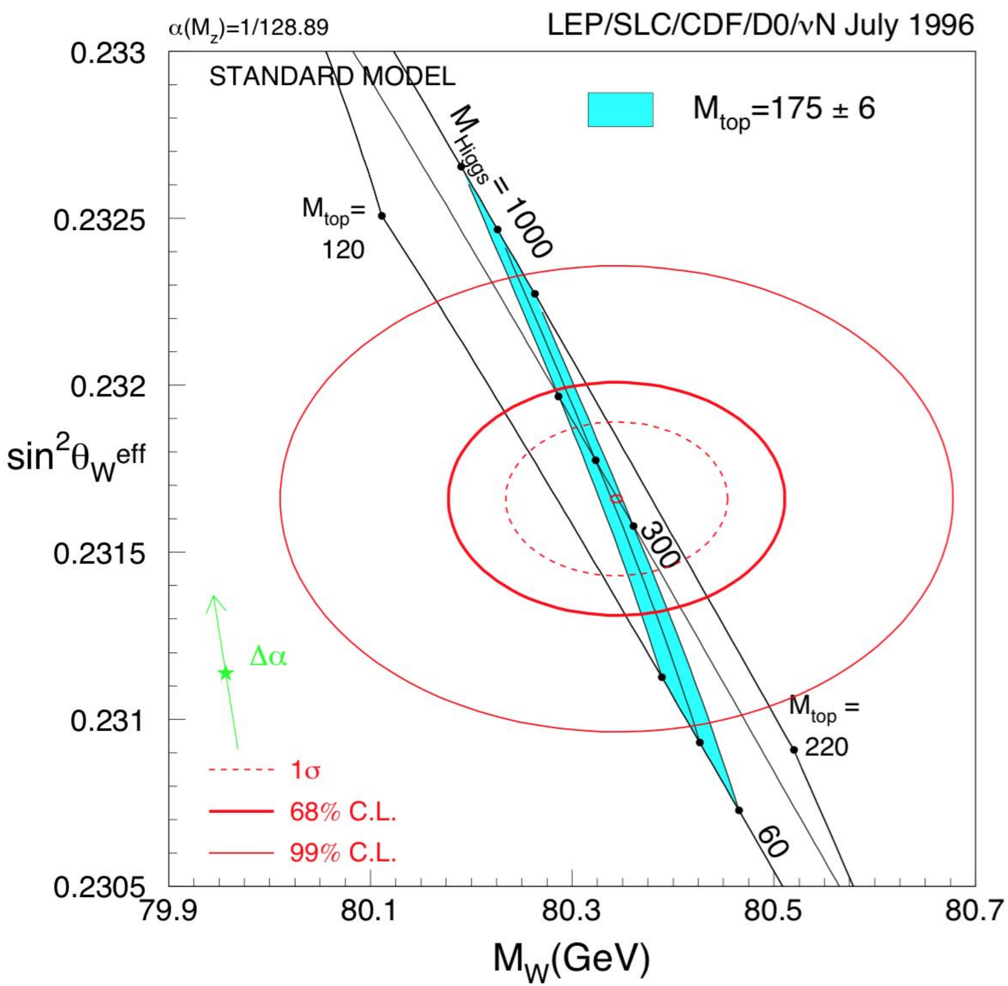
Some new physics in the loop?

- The Rad. Corr. are very important to get precision measurements, but also to get information on what is not directly produced at LEP.

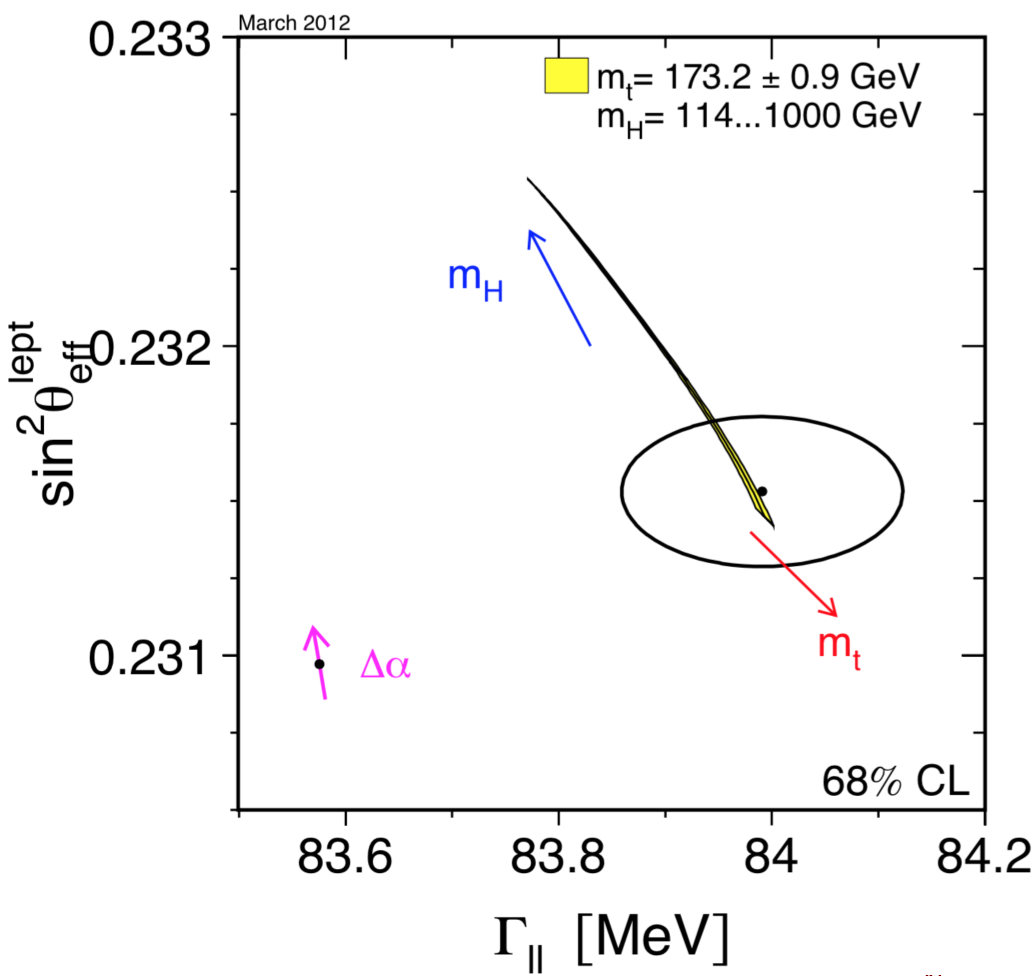
$$\overline{\rho}_{lept} = 1.0050 \pm 0.0010$$

5σ away from 1, but in perfect agreement with the SM prediction with Rad.Corr

Top and Higgs in 1996



The end of LEP



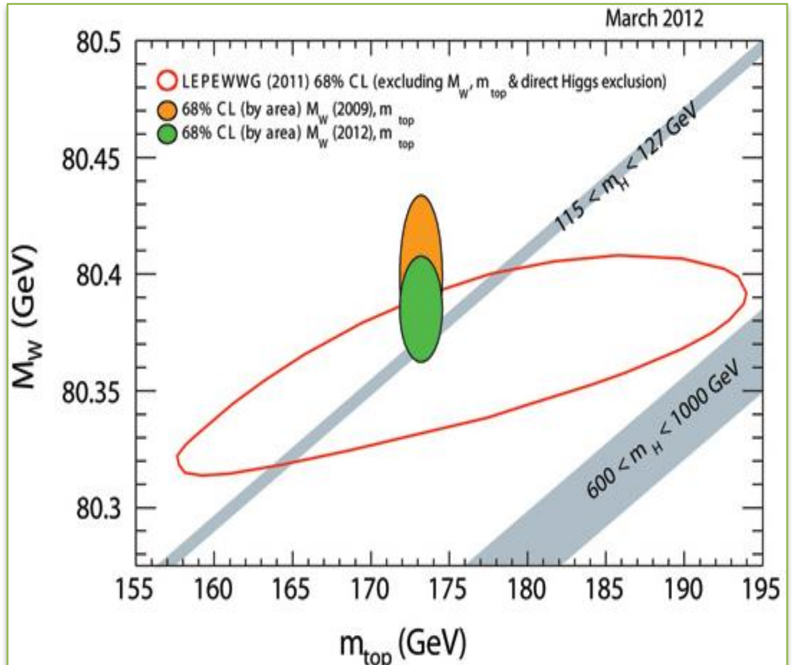
The central value is at the center of the circle, the circle represents 68% of the confidence level. The experimental result can be compared with the predictions of the Standard Model. In the figure the predictions of the Standard Model are shown with vectors. The vector on the left (in magenta) represents the value of the SM in the absence of radiative electroweak corrections, and the extension of the arrow represents how much this value could change when the electromagnetic coupling constant α_{em} changes. The other 3 vectors (blue, red and yellow) are the predictions of the SM when taking into account the radiative electroweak corrections, and varying the little known or unknown quantities, such as the mass of the top (m_{top} = 174+- 5.1 GeV), the strong coupling constant (α_s = 0.118+- 0.002) and the Higgs mass (m_H = 300 +- 700-186 GeV)

Where we stood before 4-July

M_{top} vs M_W

Tevatron M_W *Tour de Force!!*

$m_W = 80385 \pm 15$ MeV
(World Ave – Mar 2012)

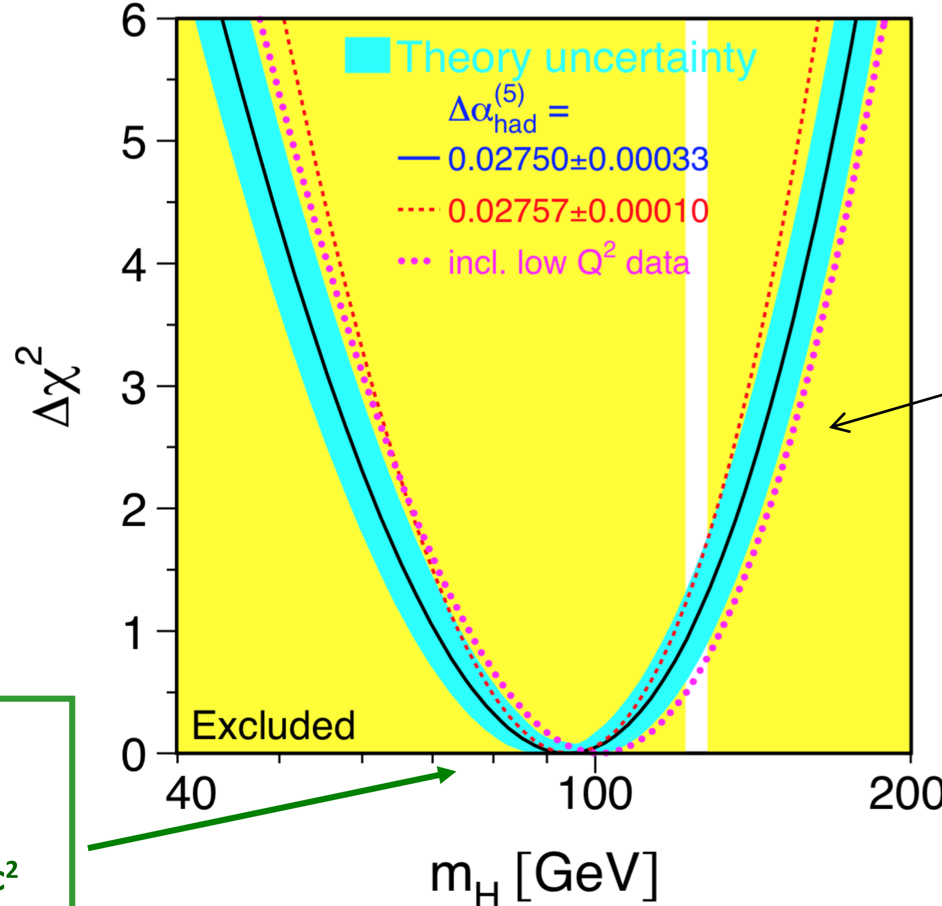


LHC Excluded a wide range of Higgs masses in 2011

Beginning of 2012

LEP Expected to exclude: mH<115.3

Excluded: mH< 114.4 GeV



m(H)≤ 152 GeV/c^2 at 95% CL

EW precision measurements

m(H)= 94 $^{+29}_{-24}$ GeV/c^2

The Higgs mechanism

- The Higgs mechanism has been invented to give mass to the elementary particles. (Brout, Englert, Higgs - 1964)

- The idea is the following:
  - The photons are massless and they travel at the speed of light in the vacuum.
  - In relativity: $v=c \rightarrow m=0$
  - In the matter, $v < c$: the electromagnetic field interacts with the matter and the wave is slowed down.
  - This is equivalent to the photon acquiring an *effective mass*

- The vacuum if filled by the Higgs field (10^{-10} s after the big bang) and the elementary particles interact with it and acquire their mass.

- **In relativistic quantum mechanic we expect a particle associated to the Higgs field: the Higgs Boson**

- This field must be a scalar (no direction preferred, no change with the reference system), and the value at the minimum of energy must be =/ 0

The Higgs mechanism

The SM Lagrangian must be symmetric, gauge invariant and conserve all the properties.
But particles have mass.
Mass terms like are of the kind "$\Psi_L^+ \Psi_R$" and violate gauge invariance
(Ψ_L, Ψ_R having different quantum numbers).
The Higgs mechanism is able to add masses without breaking the symmetry of the L.
It add a complex scalar fields doublet
(i.e. the minimal representation of $SU(2)_I$)

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

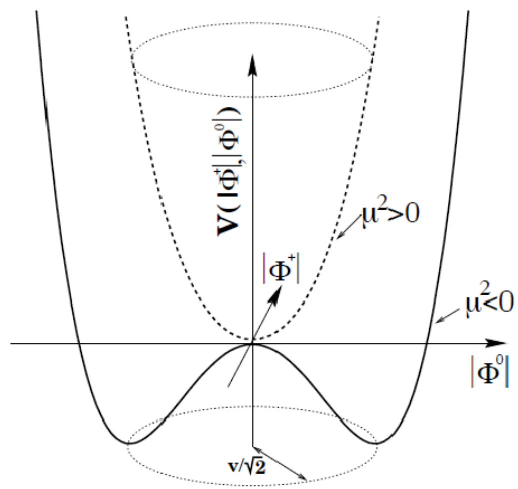
With a potential

$$V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$$

With $\mu^2 < 0$

The vacuum

$$\phi_0(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v + h(x)\end{pmatrix}$$



The scalar field must have specific quantum numbers:
$\phi^0 \rightarrow I=1/2$, $I3 = -1/2$, $Q = 0$ and $Y=1$,
this is necessary to have $M\gamma=0$ (the vacuum is invariant for $U(1)_{EM}$)
It must be a scalar, $J=0$, since it must be a Lorentz invariant.

Gauge boson masses

$M_\gamma = 0$ by construction - it forces ϕ^0 to have Y=1

$M_W = 1/2\ vg$

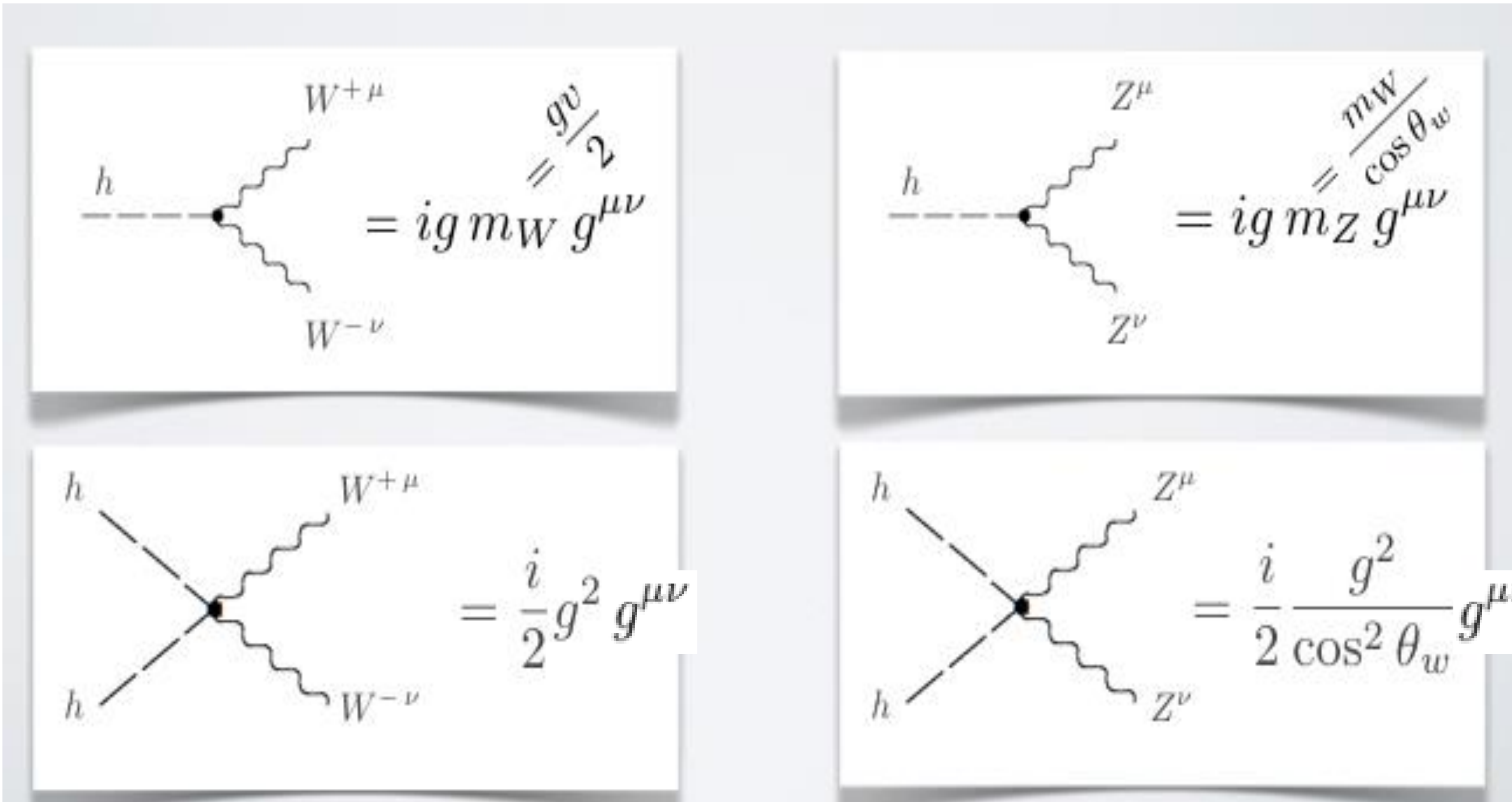
$M_Z = ½\ v\sqrt{(g^2+g'^2)}$ $= 1/2\ vg/\cos\theta_W$ ($M_Z \neq M_W$, Z is a mix of B and W_3)

→ $M_W/M_Z = \cos\theta_W$

$\rho = M^2_W/M^2_Z \cos^2\theta_W = 1$

And since $G_F/\sqrt{2} = g^2/8M^2_W = 1/(2v^2)$ → **v=246 GeV**

Feynman rules



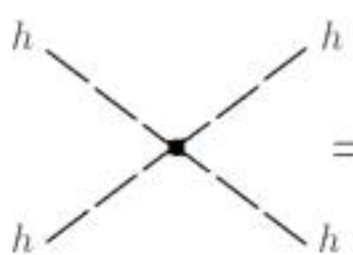
The Higgs potential

mass

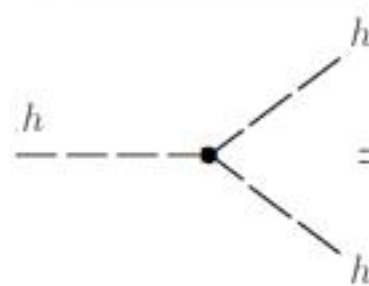
$$V(\Phi^\dagger\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 = \frac{1}{2}m_h^2h^2 + \sqrt{\frac{\lambda}{2}}m_hh^3 + \frac{\lambda}{4}h^4$$

Self coupling

$$m_H^2 = 2\lambda v^2$$



$$= -i\frac{3}{4}\frac{g^2\,m_h^2}{m_W^2}$$



$$= -i\frac{3}{2}\frac{g\,m_h^2}{m_W}$$

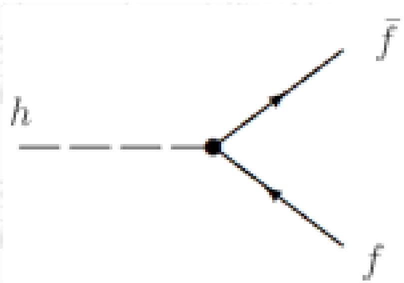
Fermion masses

- The same Higgs doublet that gives mass to W,Z can give mass to the fermions

$$L_3 = -\frac{G_e v}{\sqrt{2}}(\bar{e}_L e_R + \bar{e}_R e_L) - \frac{G_e}{\sqrt{2}}(\bar{e}_L e_R + \bar{e}_R e_L)h$$

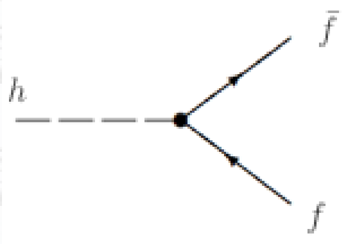
mass term

interaction term with the Higgs field

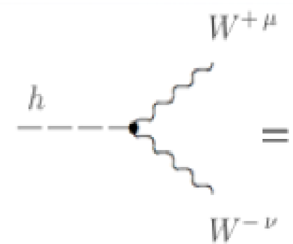


$$= i\frac{m_f}{v}$$

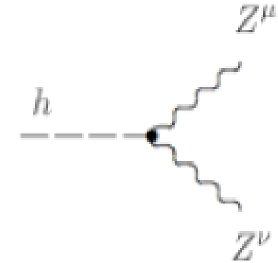
Higgs properties



$= i\frac{m_f}{v}$



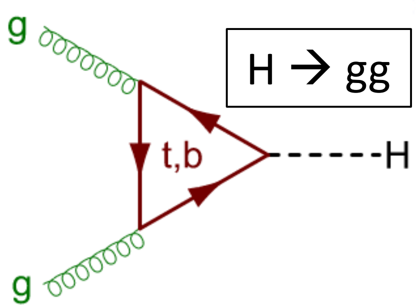
$= i g m_W g^{\mu\nu}$ ($m_W = gv/2$)



$= i g m_Z g^{\mu\nu}$ ($m_Z = \frac{m_W}{\cos\theta_w}$)

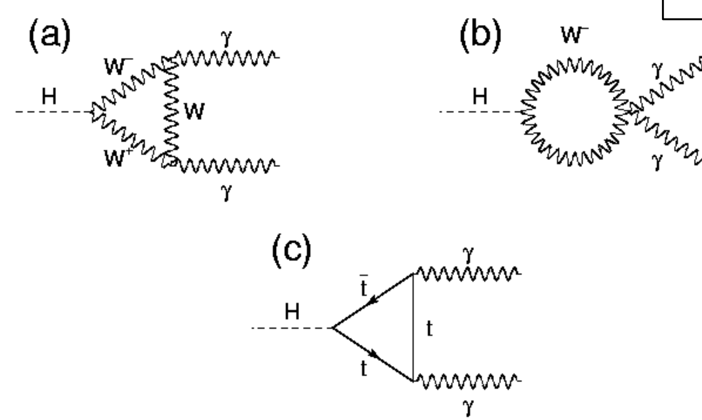
No direct decay to neutral particles

H → gg



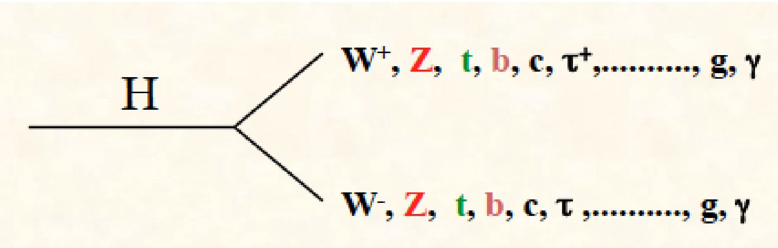
Top is dominating

H → γγ



destructive interference between W and top

Given a H mass, decay properties are fixed



$$\Gamma(H \to f\bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2(M_H^2) M_H$$

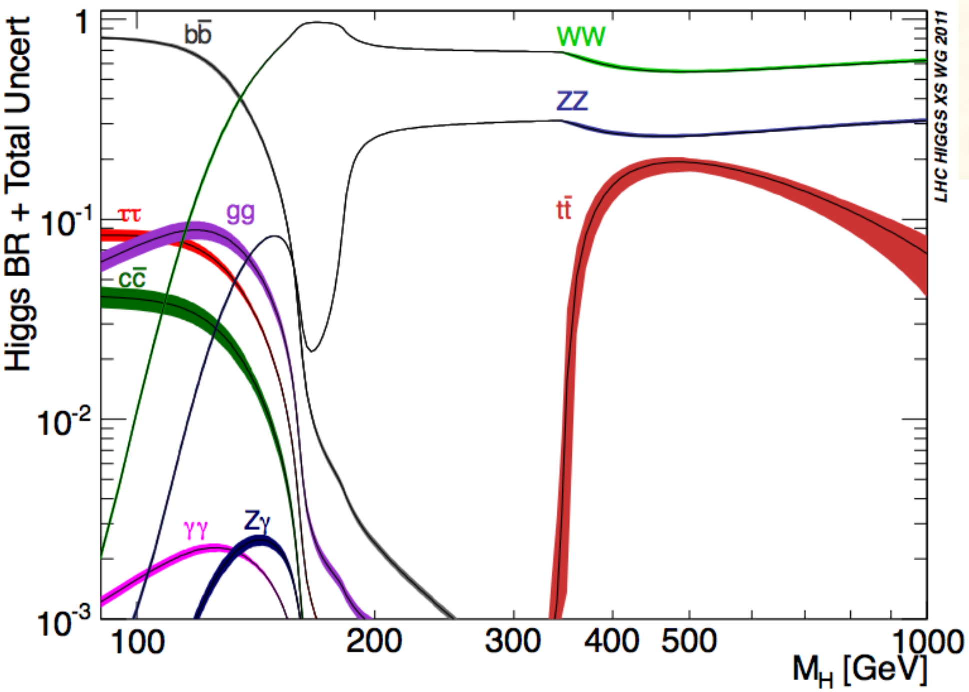
$$\Gamma(H \to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 (1 - 4x + 12x^2)\beta_V$$

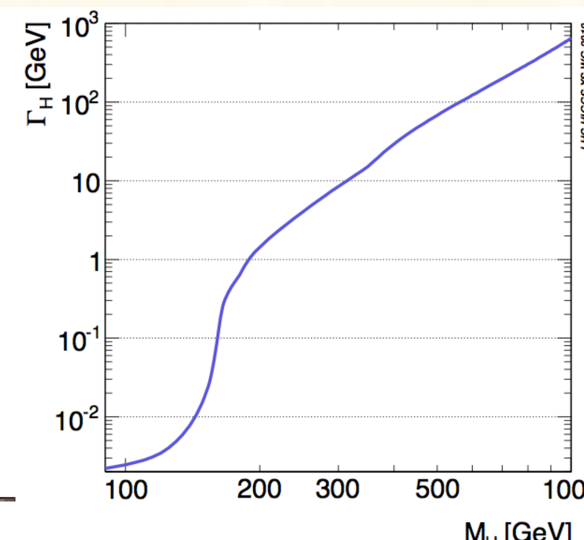
where: $\delta_Z = 1,\ \delta_W = 2,\ x = M_V^2 / M_H^2,\quad \beta = \text{velocity}$

(+ W-loop contributions)

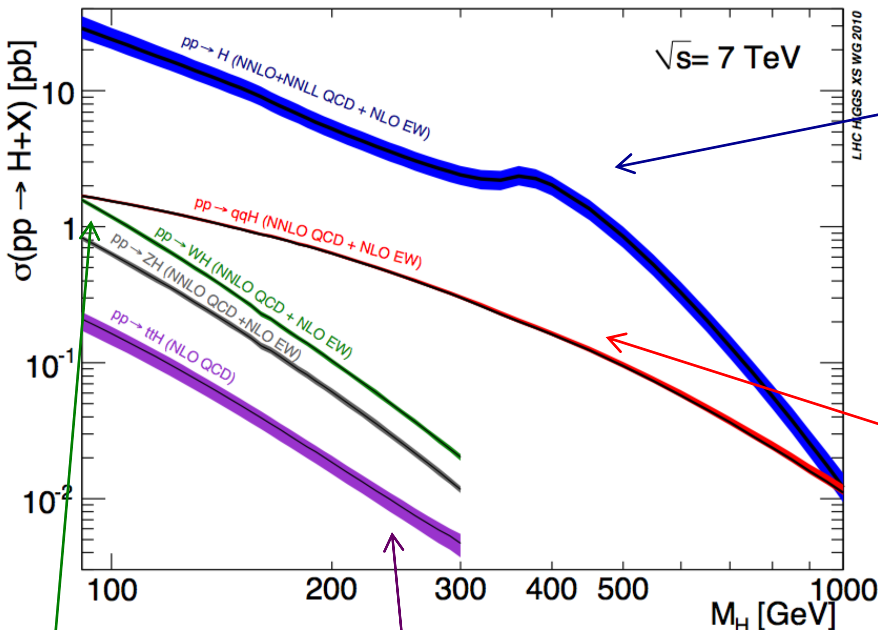
$$\Gamma(H \to gg) = \frac{G_F \alpha_a^2(M_H^2)}{36\sqrt{2}\pi^3} M_H^3 \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right)\frac{\alpha_a}{\pi}\right]$$

$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha_a^2}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

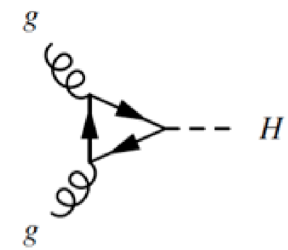




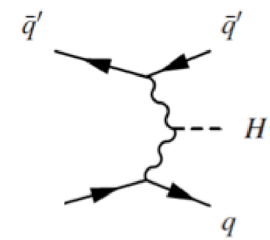
Higgs production at LHC



ggF: NNLO+NNLL QCD + NLO EW

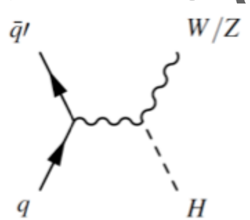


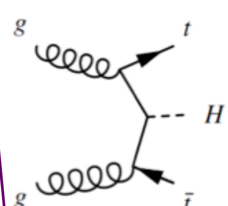
qqH: NNLO QCD + NLO EW



WH: NNLO QCD + NLO EW

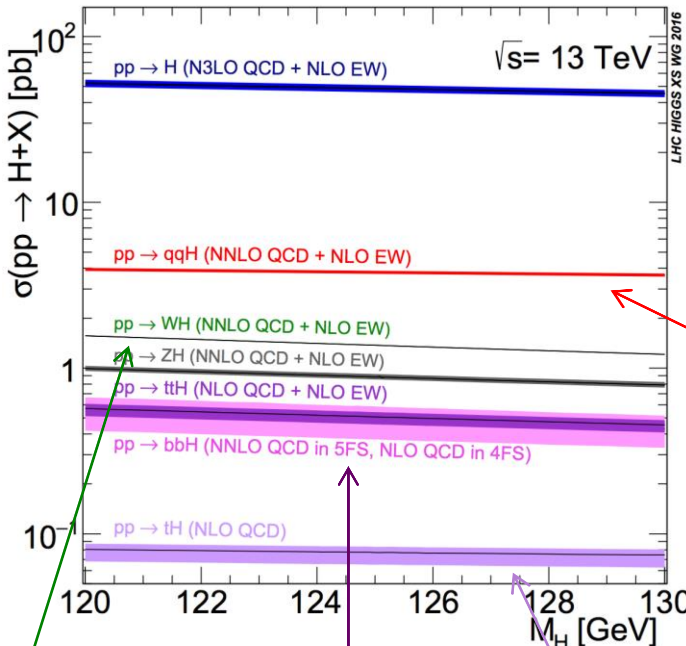
ZH: NNLO QCD + NLO EW





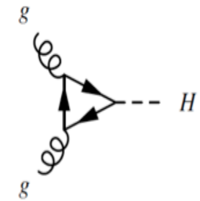
ttH: NLO QCD

Higgs production at LHC - 2016

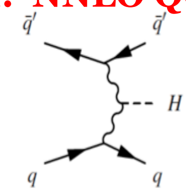


The LHC Higgs Cross Section WG
YR1, YR2, YR3, YR4

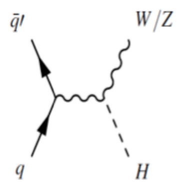
ggF: N3LO + NLO EW

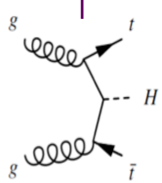


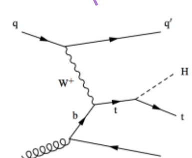
qqH: NNLO QCD + NLO EW



WH: NNLO QCD + NLO EW
ZH: NNLO QCD + NLO EW







ttH: NNLO QCD **tH: NLO QCD**
bbH: NNLO QCD

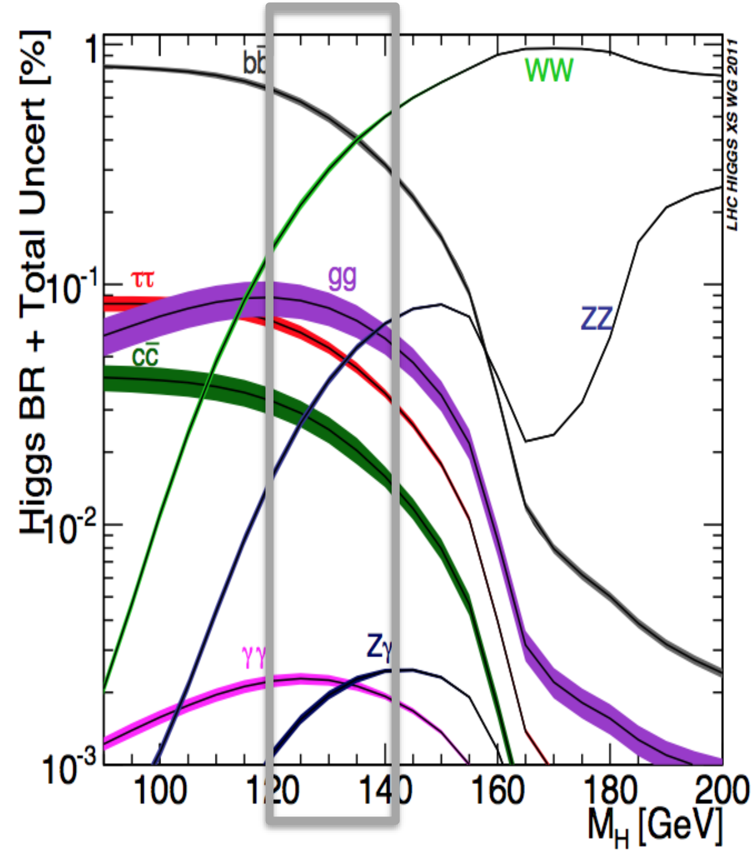
	Scale	PDF	Total error
ggF	4%	1.9%	~7-10%
VBF	0.4%	2.1%	2.5%
WH/ZH	0.5 - 3%	1.5%	4-5%
ttH	+6% -9%	±3%	~13%

The channels at LHC

5 decay modes exploited

	Exp Sig (CMS) @125.7	σ_M/M
• bb	2.6σ	10%
• ττ	3.9σ	10-20%
• WW	5.4σ	16%
• ZZ	6.3σ	1-2%
• γγ	5.3σ	1-2%

- and searches in Zγ, μμ

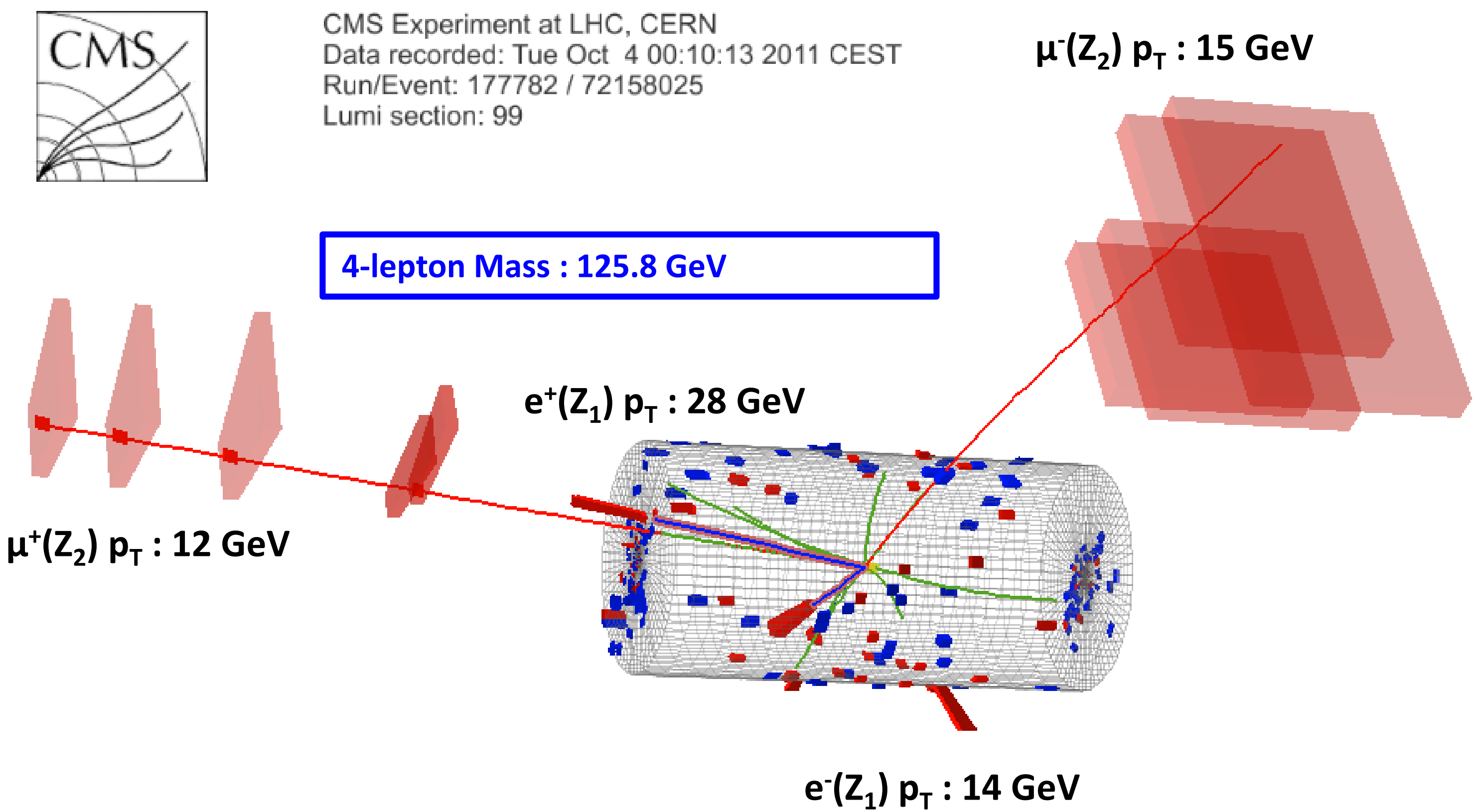


Improved treatment of the uncertainties on the BR, news from LHCHXSWG

H →ZZ→4l (l=e,μ)

- The probability that the H → ZZ→4l is very small
  The Higgs boson decays in 4l only in 10% of the cases.

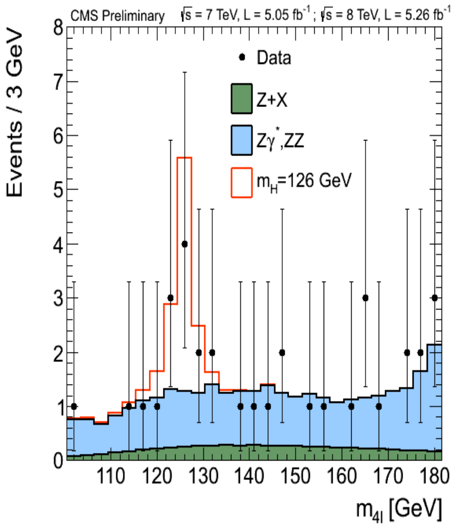
- The events are very "CLEAN"
  4 leptons (electrons or muons)
  - with very high identification and reconstruction efficiency
  - coming from the primary vertex (Higgs lifetime is 10^{-22} s)
  - and with very high transverse momentum (p_T~15 - 45 GeV)
  - isolated (i.e. not inside jets)



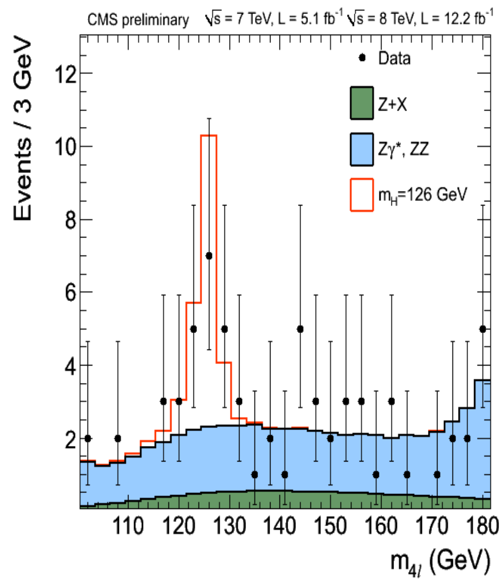
The experimental resolution is excellent, we measure with high precision muons and electrons.

A beautiful peak

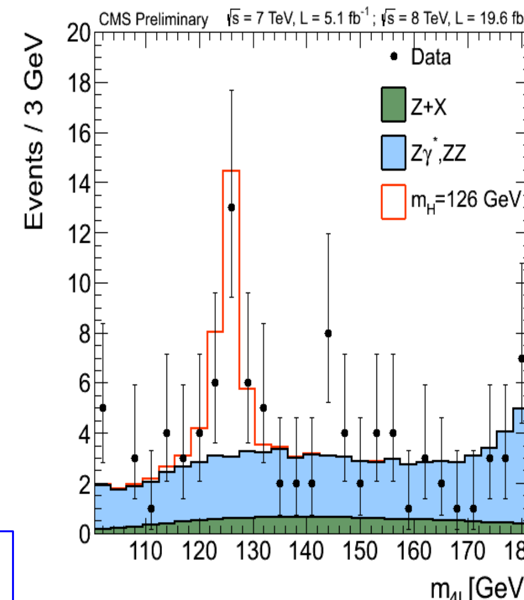
4 July



Nov 2012

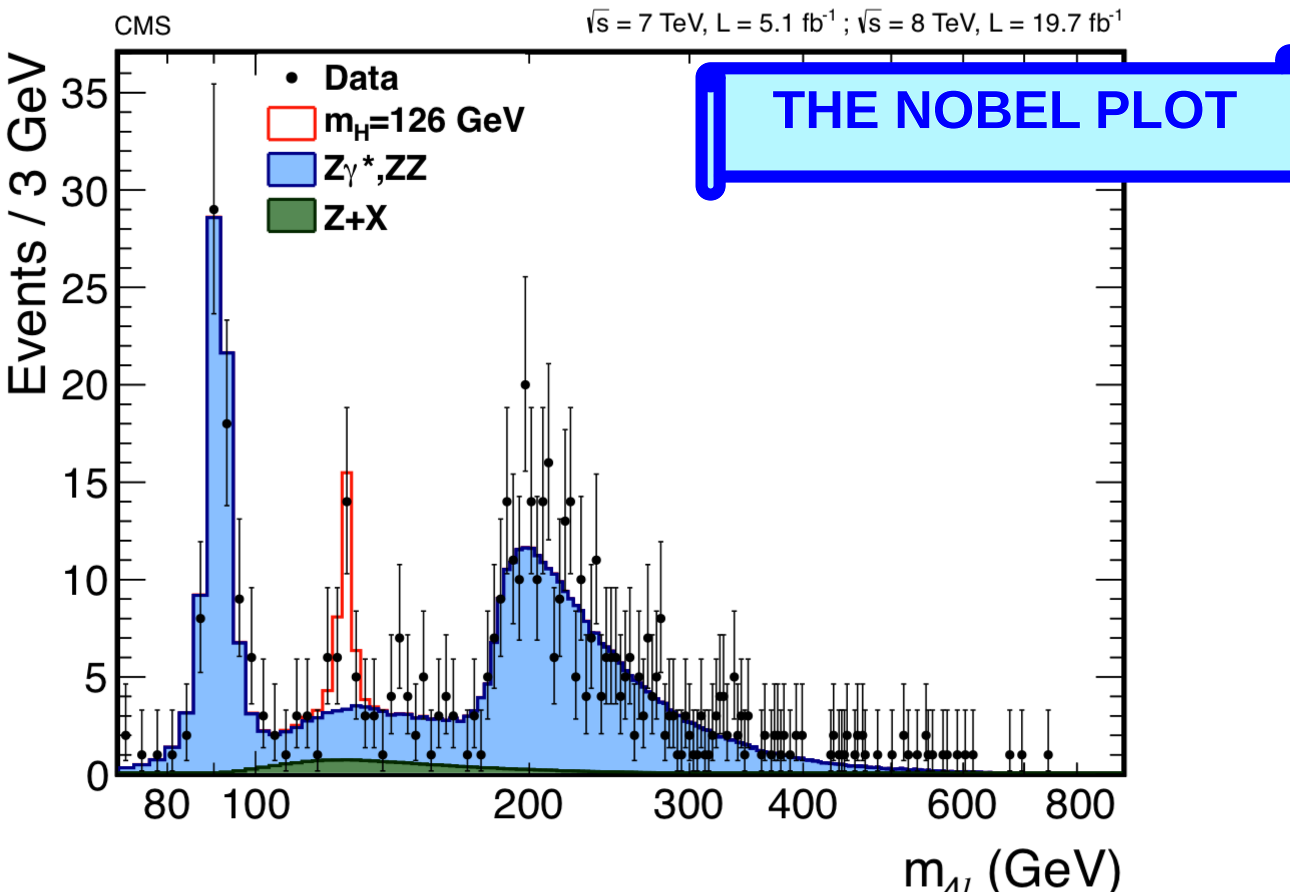


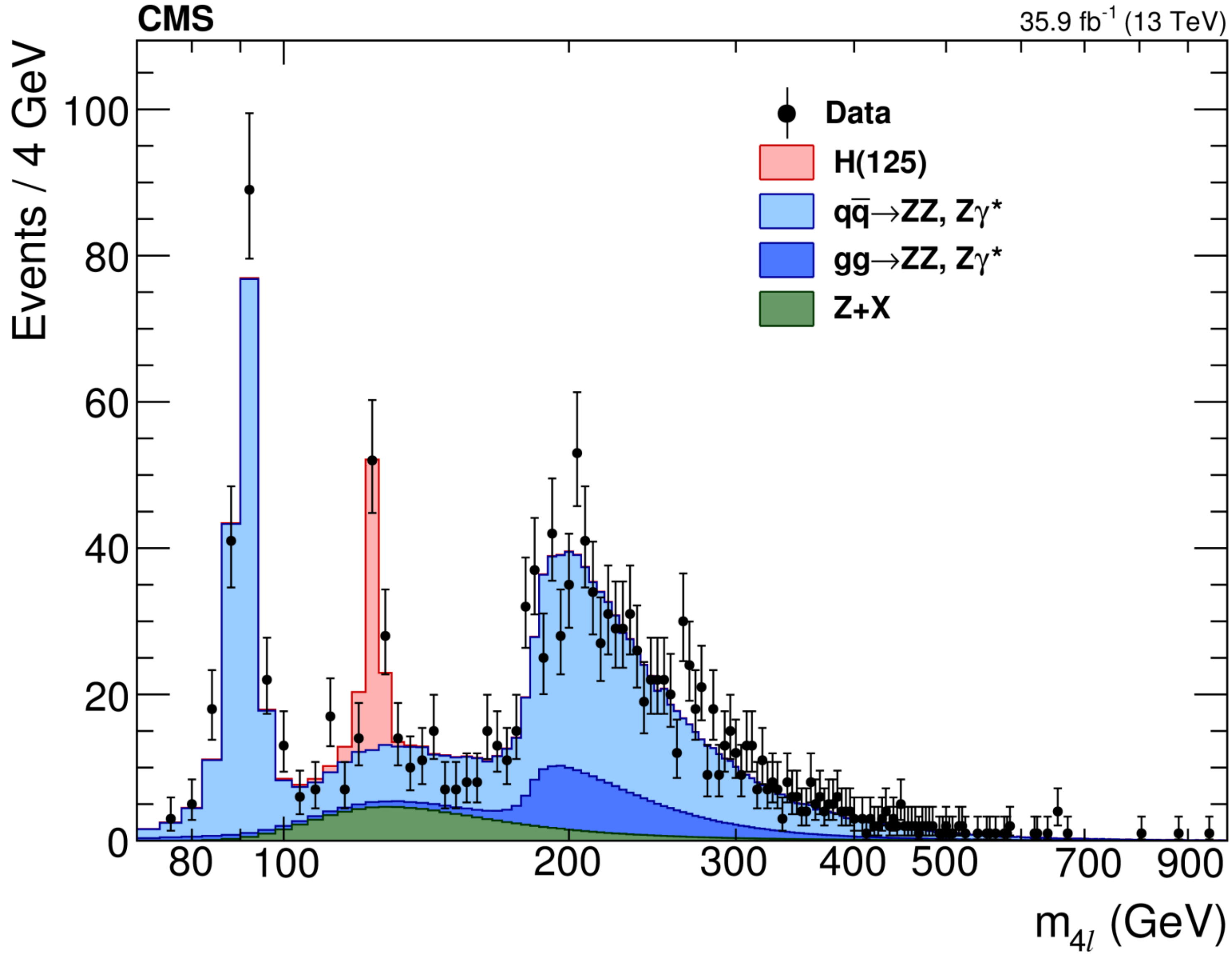
Dic 2012



The beauty of an equation is more important than its correctness, in the sense that if an equation is beautiful, sooner or later it will be demonstrated to be correct. Paul Dirac

The 4l mass spectra

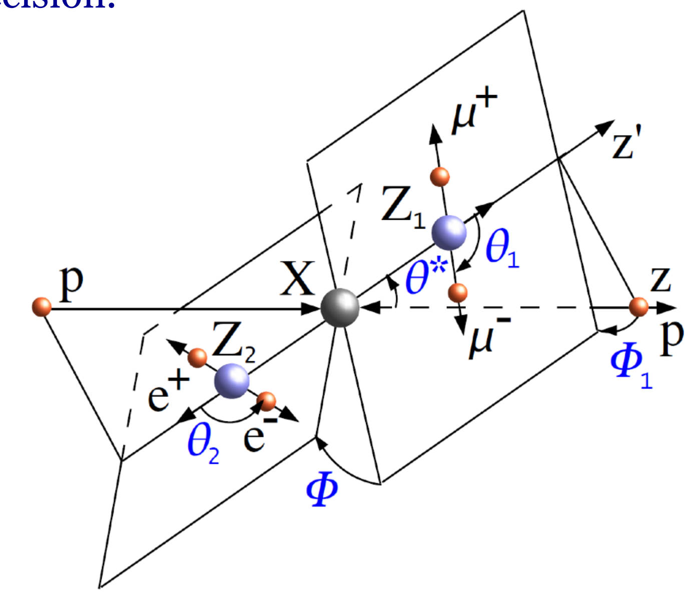




CMS
35.9 fb-1 (13 TeV)
Events / 4 GeV
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
0
20
40
60
80
100
80
100
200
300
400
500
700
900
m4l (GeV)

The properties

- The 4l channel allows to measure the properties (Spin, Parity, mass) of the Higgs with high precision.



- The experiments have measured the compatibility of the data with many different hypotheses.
- With very high confidence level (more than 99%) the quantum numbers are the one of the Higgs boson as predicted by the SM.

(S=0, P=+)

Spin and parity

Most known particles have a property which physicists call "spin": in some experiments they behave as they were macroscopical objects rotating about some axis. Electrons, protons, photons and even neutrinos have a spin.

The Higgs boson is not allowed to have a spin: it must be what physicists call a **"scalar"** particle, a particle with zero spin. Why?
The reason is somewhat technical.

The first idea to understand is that particles (all particles) are interpreted as excitations of some underlying field, something like a long string with its two endpoints fixed: if you tickle the string at one endpoint, a deformation of the original string is created, and propagates along the string until it reaches the opposite endpoint, where it is absorbed. Photons, for example, are excitations of electric and magnetic fields. Needless to say, when the string is left untouched (when there are no electric or magnetic fields around), there is no propagating deformation (no photons): fields are zero in the lowest-energy state. This is true for all fields, except the one associated with the Higgs boson: the mechanism by which particles acquire masses is precisely the fact that the Higgs field is different from zero (it takes some constant value) even when there are no Higgs bosons around.

Spin and parity

The numerical value of this constant field is long known, and it is a fundamental constant of Nature, much like the proton charge or the Planck constant.

The second important idea is what we call "relativistic invariance", a difficult name for a very simple thing: the fundamental laws of physics must look the same for all observers, even if they choose different reference frames. We call a "scalar" any physical quantity which has just the same value for all observers. The mass of an object, for example, is a scalar quantity. A vector, such as for example an electric or magnetic field, or the spin vector, does not share the same property: vectors look different to different observers.

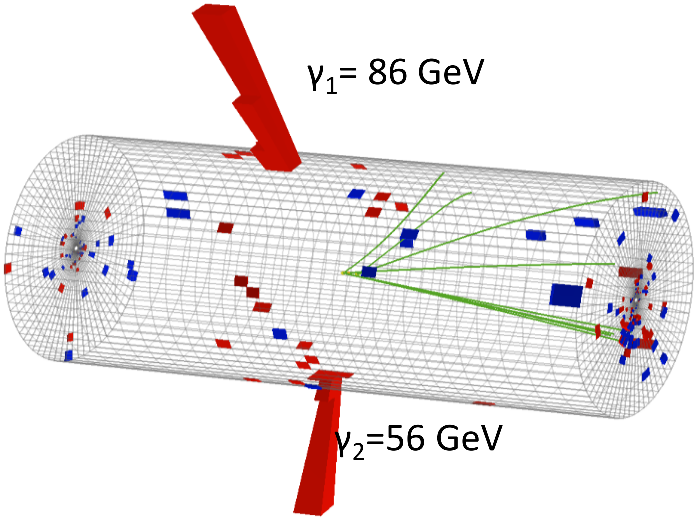
This is why the Higgs field must be a scalar field: because it takes a constant non-zero value in the lowest-energy state, this constant must take the same value in all reference frame. This is only possible if the Higgs boson carries no spin.

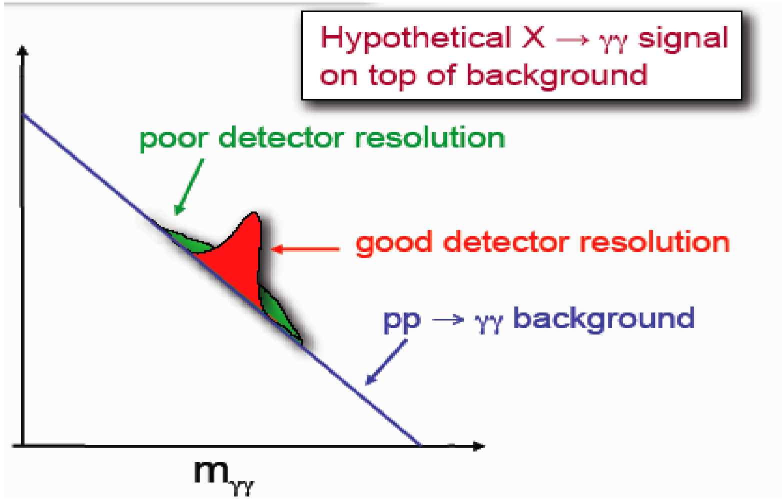
from Prof Giovanni Ridolfi (Genova)

Spin and parity

The particle's parity, a property which characterizes how differently the Higgs behaves when observed in a mirror. With the Higgs, there should be no difference; otherwise, the interaction of other particles with it, and so the mass they acquire, would depend on the speed and direction with which they travel through the Higgs field.

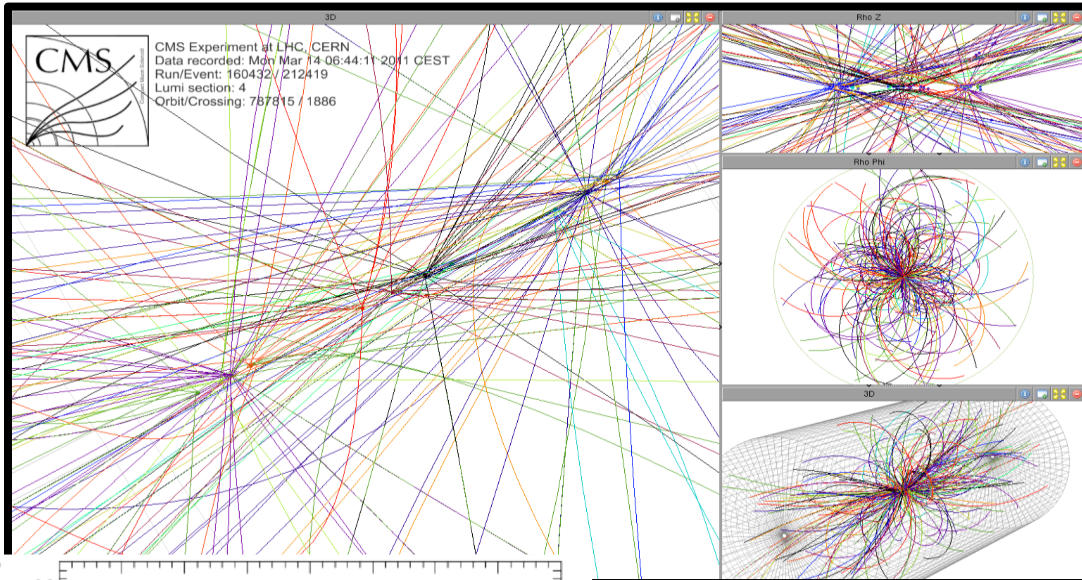
$H \rightarrow \gamma\gamma$



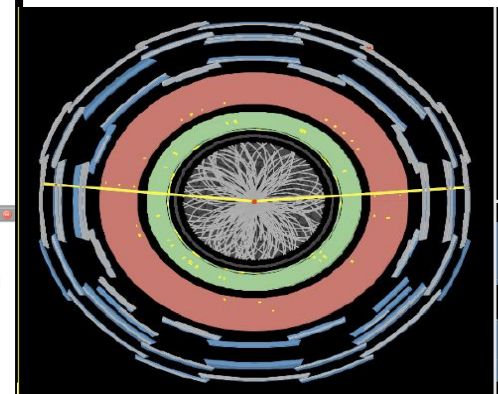


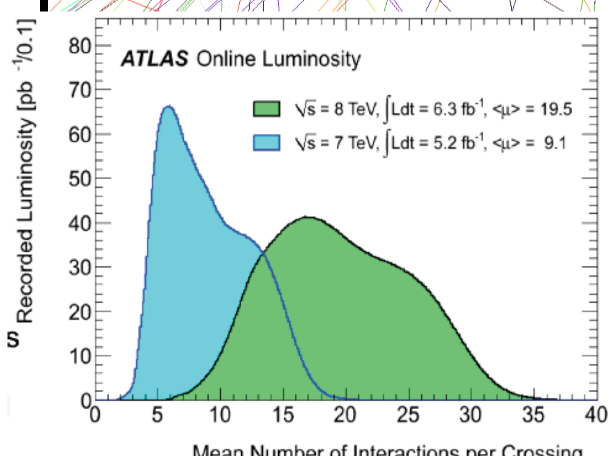
- In the $\gamma\gamma$ final state the background is dominating (2 photons produced by quark interactions)
- The 2 photons do not leave a track in the tracking detector, only an electromagnetic shower in the calorimeter. Thus their primary vertex is not know with precision.
- This can be an additional problem when working with high pile-up, high instantaneous luminosity.

Pile-up

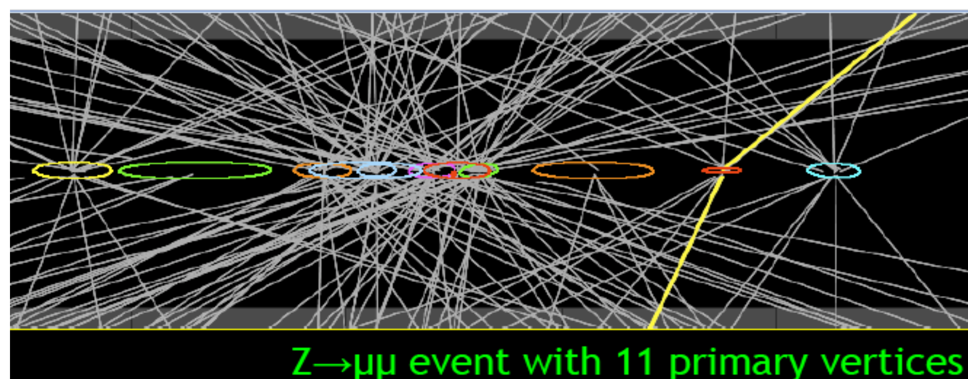


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Mar 14 06:44:11 2011 CEST
Run/Event: 160432 / 212419
Lumi section: 4
Orbit/Crossing: 787815 / 1886
3D
Rho Z
Rho Phi



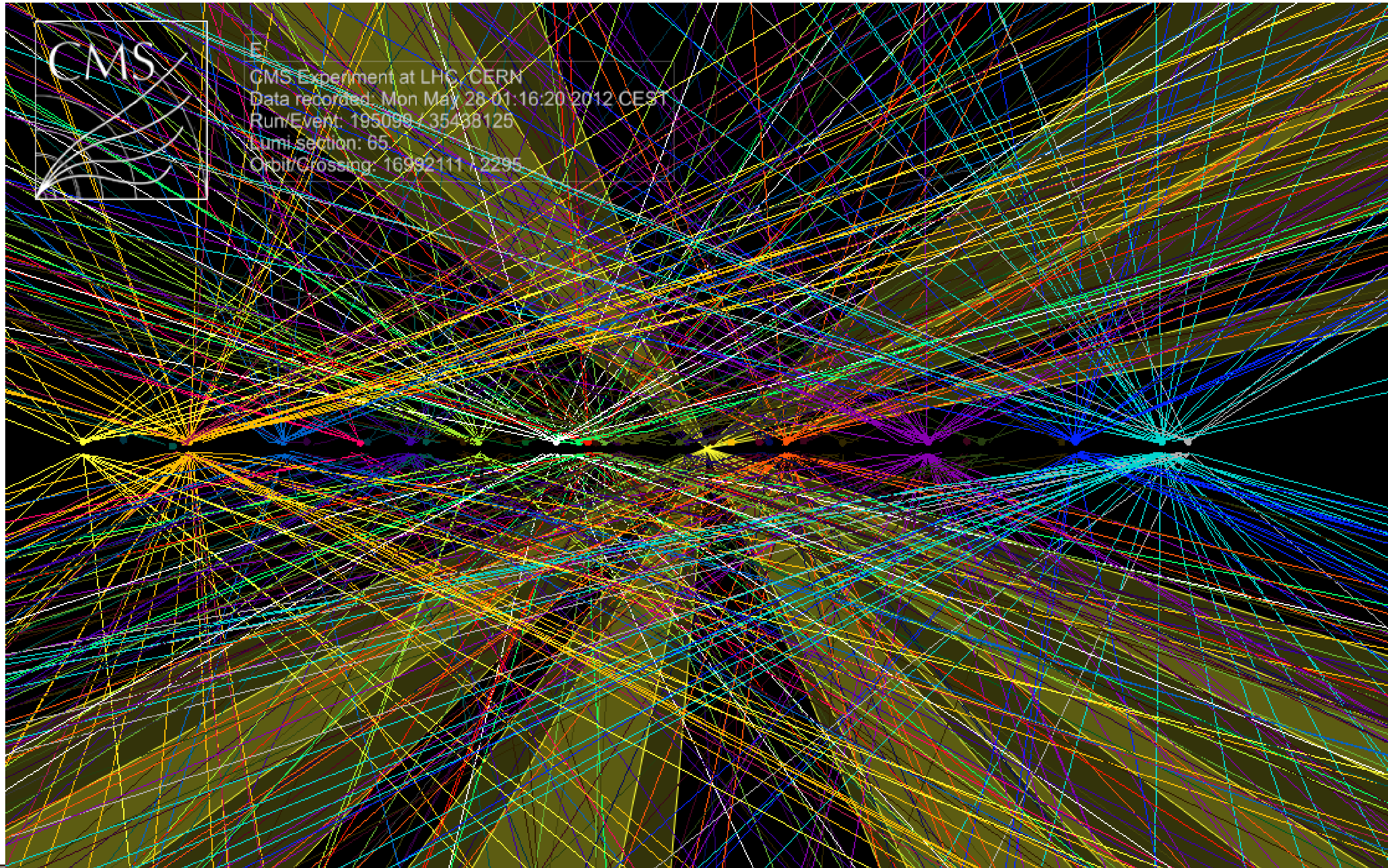


ATLAS Online Luminosity
$\sqrt{s}$ = 8 TeV, $\int$Ldt = 6.3 fb^{-1}, <μ> = 19.5
$\sqrt{s}$ = 7 TeV, $\int$Ldt = 5.2 fb^{-1}, <μ> = 9.1
Recorded Luminosity [pb^{-1}/0.1]
Mean Number of Interactions per Crossing



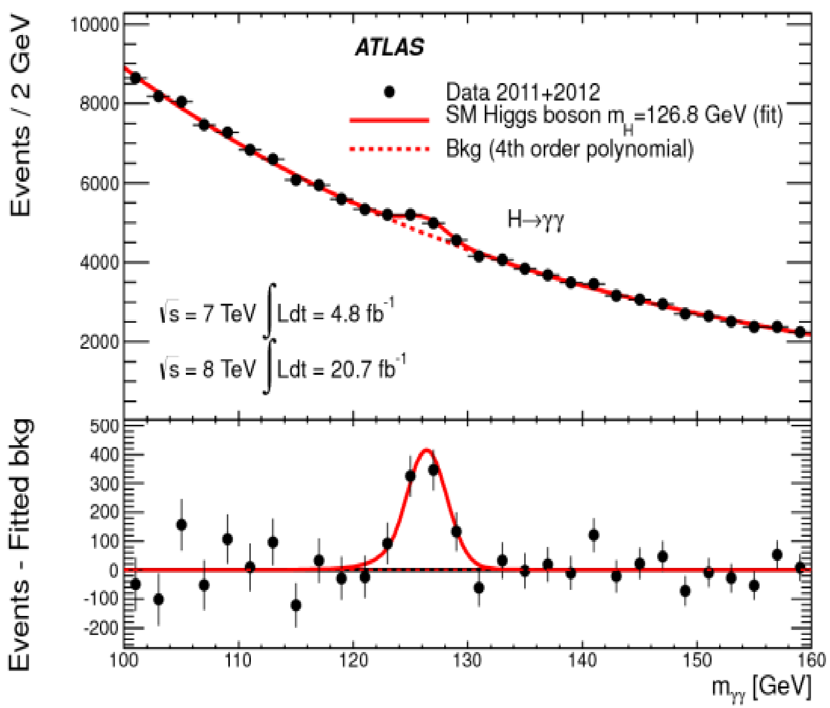
Z→μμ event with 11 primary vertices

Pile-up

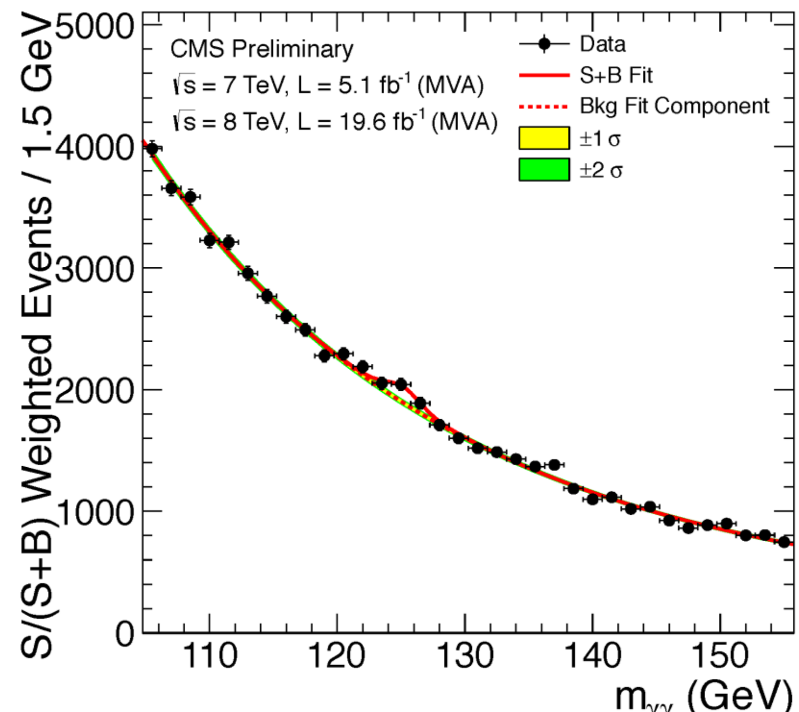

CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295

H → γγ

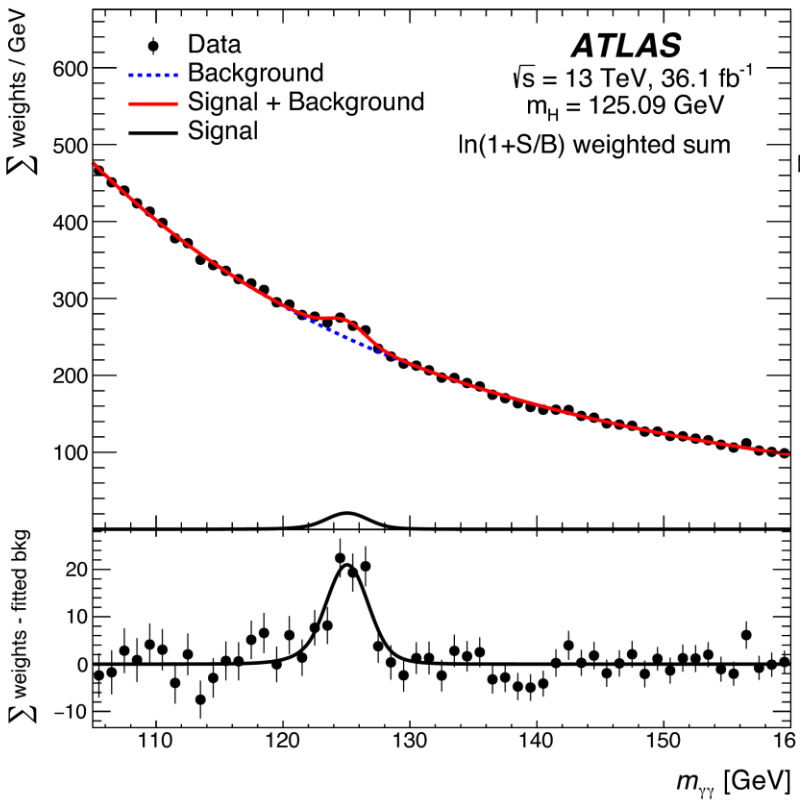
ATLAS



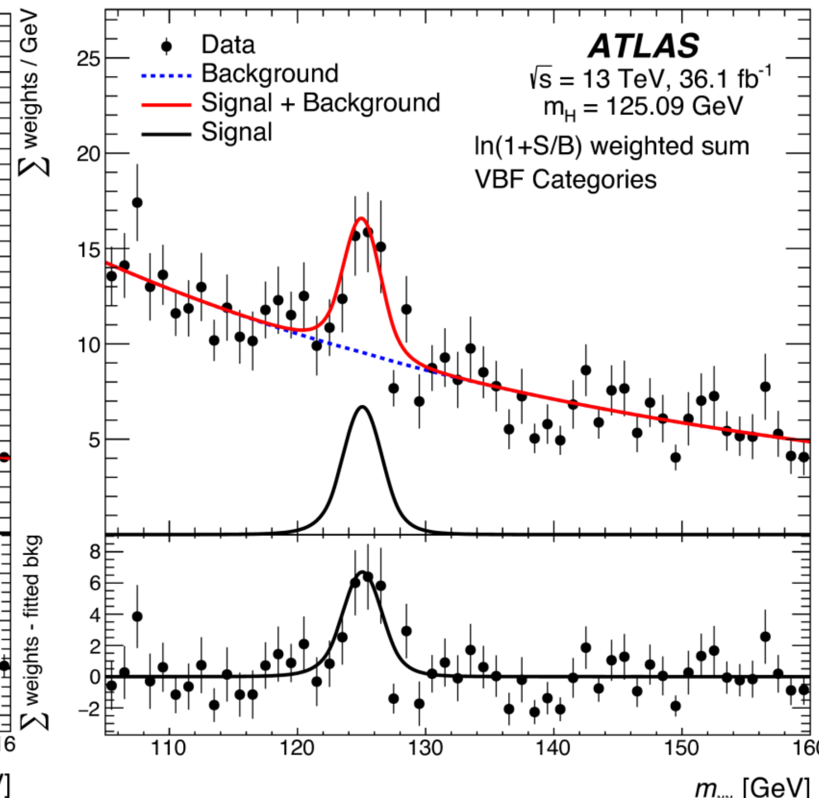
CMS



H → γγ at 13 TeV



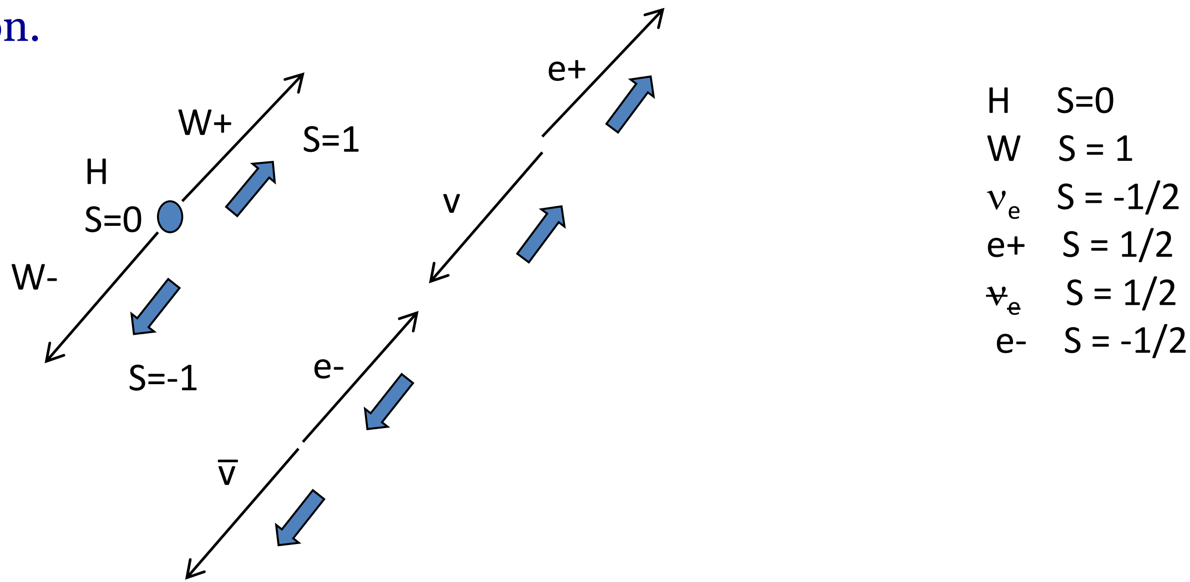
Data
Background
Signal + Background
Signal
ATLAS
√s = 13 TeV, 36.1 fb-1
mH = 125.09 GeV
ln(1+S/B) weighted sum
∑ weights / GeV
∑ weights - fitted bkg
mγγ [GeV]



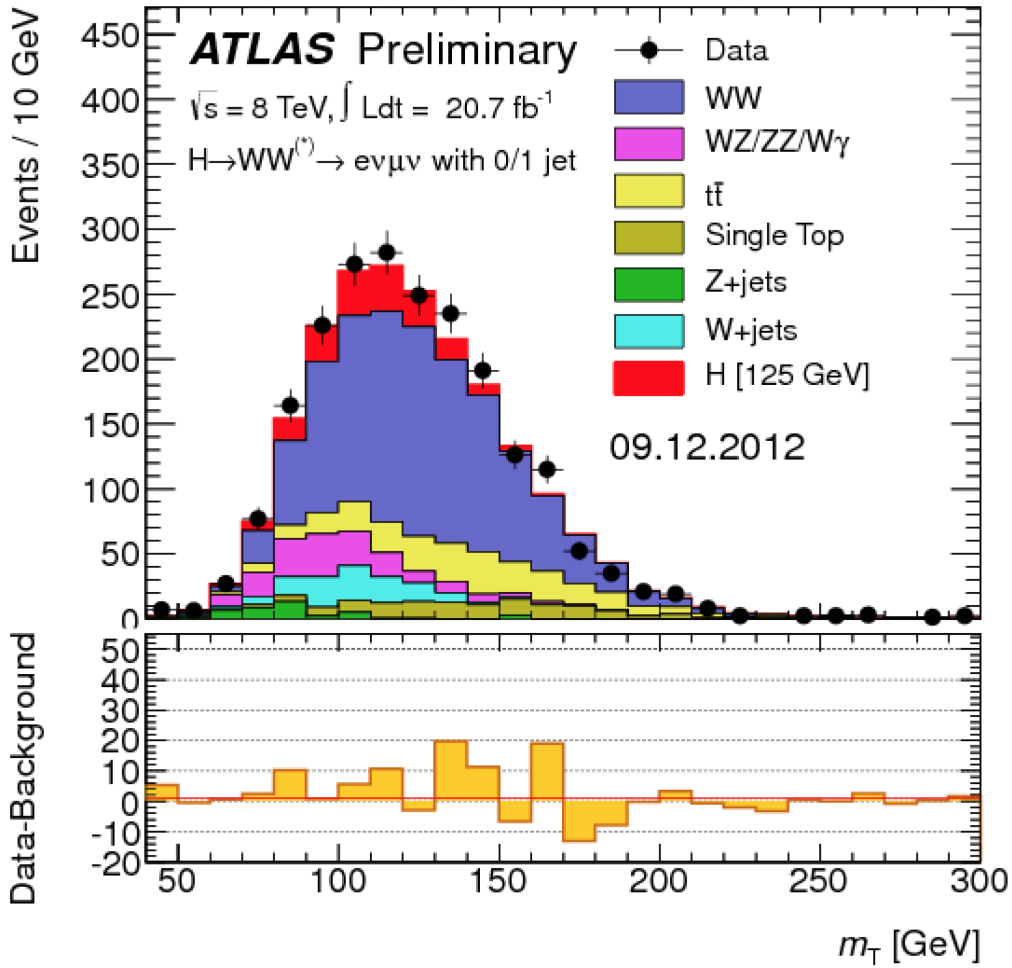
Data
Background
Signal + Background
Signal
ATLAS
√s = 13 TeV, 36.1 fb-1
mH = 125.09 GeV
ln(1+S/B) weighted sum
VBF Categories
∑ weights / GeV
∑ weights - fitted bkg
mγγ [GeV]

H → WW→ lνlν

- This channel is more complex, since there is the presence of 2 neutrinos, thus "large missing energy".
- The background is dominating.
- The neutrinos having m~0 are Left-Handed , thus their spin is opposite to the momentum directions. Thus we expect to have the 2 leptons going in the direction.

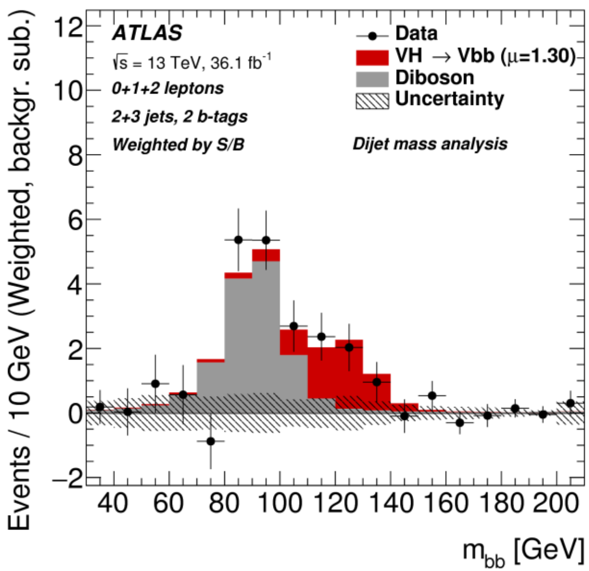


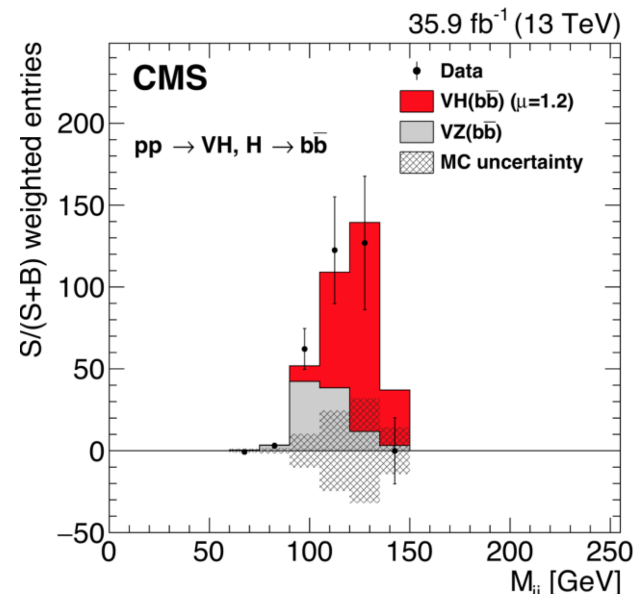
H →WW→lνlν


ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 20.7 fb-1
H→WW(*)→ eνμν with 0/1 jet
Data
WW
WZ/ZZ/Wγ
tt̄
Single Top
Z+jets
W+jets
H [125 GeV]
09.12.2012
Events / 10 GeV
Data-Background
mT [GeV]

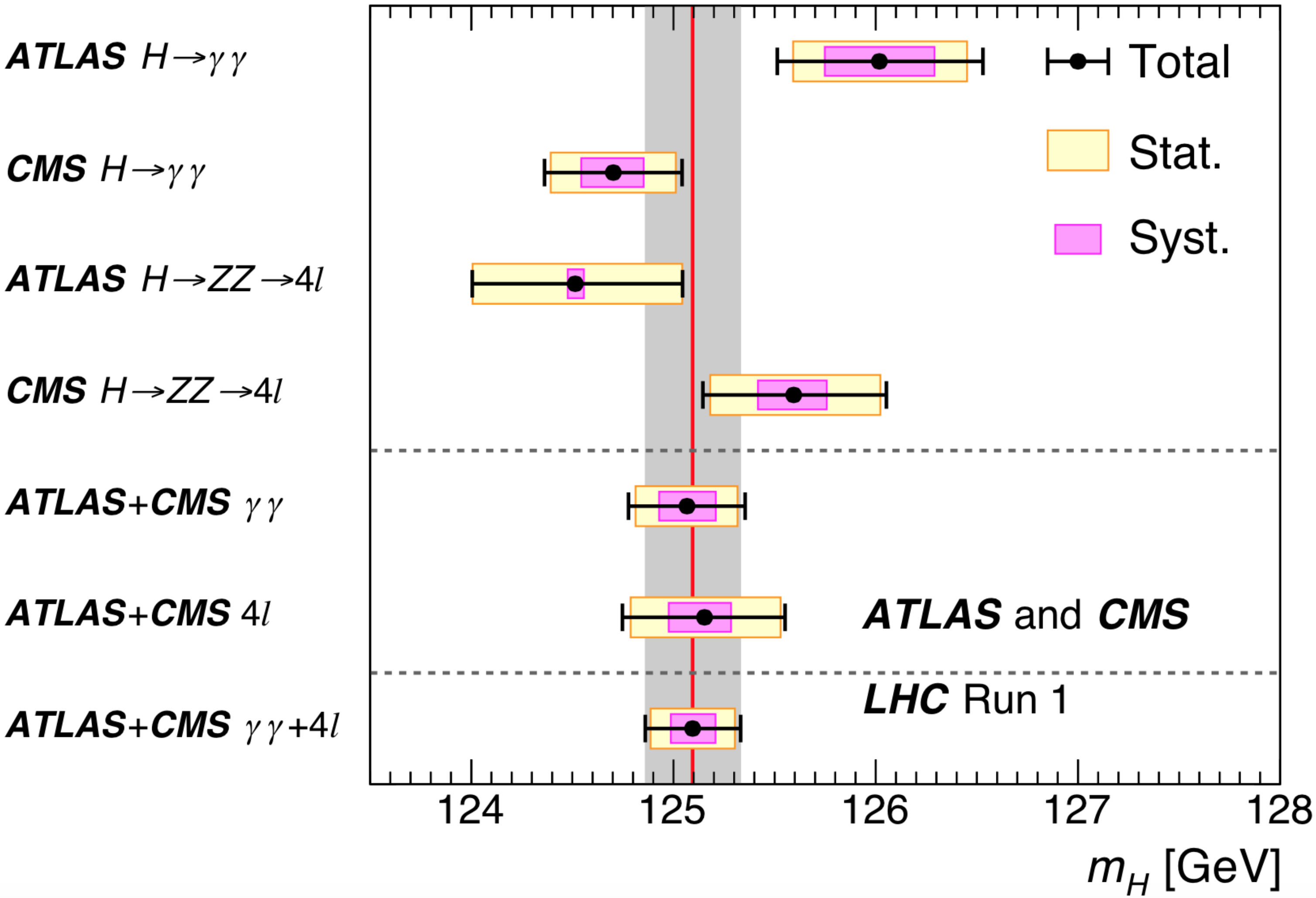
H → bb

- Higgs decay into bb quarks.
- The b quark is identified via its decay (it has a long lifetime) , but the ID has not high efficiency and purity. Background is dominant.
- $\sigma(bb) \sim 10^7\ \sigma(H \to bb)$





$$m_H = 125.09 \pm 0.24\ (\pm 0.21\ \text{stat} \pm 0.11\ \text{syst})\ \text{GeV}$$



The SM: a long journey

- 54 Yang & Mills define the gauge theory for massless particles (interaction between particles and gauge fields). The theory is renormalisable.
- 61 Glashow the EM and Weak interactions are of the same kind, but the propagators are different: one has M=0 the other M~100 GeV
- 64 Brout, Englert, Higgs et al: the Higgs mechanism
- 67-68 Weinberg and Salam: Spontaneously broken gauge theory: Yang e Mills + Higgs → SM th of EW interaction
- 70 't Hooft: : the SM th of EW interaction is renormalizable
- 73 Gargamelle : discovery of the week neutral current
- 83: Ua1 & UA2: W and Z discovery
- 89-2000: LEP and HERA: the triumph of the SM
- 95: Tevatron: top quark discovery
- 2012: LHC: discovery of a Higgs like boson

...and the LHC, Atlas and CMS long journey