Extensions of the Standard Model

Part 2 – Prof. Jorgen D'Hondt

Content:

- Short reminder of the ElectroWeak theory & the Higgs mechanism
- The ElectroWeak fit as constraint on the Higgs boson mass
- Theoretical constraints on the Higgs boson
- Phenomenology of the Standard Model Higgs boson
- Searching for the Standard Model Higgs boson
- Two Higgs Doublet Models (2HDM)
- Problems with the Standard Model
- Quick introduction to Supersymmetry
- The Higgs sector in Supersymmetric Models (MSSM)
- Constraints on the MSSM & its Higgs sector

http://w3.iihe.ac.be/~jdhondt/Website/BeyondTheStandardModel.html

Extensions of the Standard Model

Material:

- Slides will be available via the website of the course
  http://w3.iihe.ac.be/~jdhondt/Website/BeyondTheStandardModel.html
- Lecture notes will be handed out
- Some of them will be available via the course website

Important note: whenever we note "Higgs boson" (or mechanism), we mean the well-known Brout-Englert-Higgs boson or mechanism.

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Short reminder of EW physics & Higgs mechanism

Aim:

- Get everyone on the same footing.
- Not a full ElectroWeak course! Just a reminder.
- Not intended to be complete!

References:

- Divers books on Standard Model physics
- You will get enough info in the written lecture notes

Spontaneously broken QED theory

Let us illustrate the "Higgs" mechanism with a massive U(1) theory before going to the symmetry group $SU(2)_L$ x $U(1)_Y$. The Lagrangian of QED is:

$$\mathcal{L}_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{\psi}(i\gamma^\mu D_\mu - m)\psi$$

This is invariant under the U(1) gauge transformation

$$\psi \rightarrow e^{-i\alpha(x)}\psi$$

$$A_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu \alpha(x)$$

Now we wish to give the photon a mass by adding the term

$$\mathcal{L}_{mass} = \frac{m_A^2}{2}A_\mu A^\mu$$

Which breaks the initial U(1) gauge symmetry. Hence need to invoke a mechanism which introduces a mass without breaking the symmetry.

Spontaneously broken QED theory

Introduce a complex scalar field Φ as

$$\mathcal{L} = \mathcal{L}_{QED} + (D_\mu \Phi)^* (D^\mu \Phi) - V(\Phi)$$

with the potential V defined as $V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$ which is symmetric under the transformation $\Phi \rightarrow -\Phi$

We can choose a parametrization as

$$\Phi = \frac{1}{\sqrt{2}} \phi(x) e^{i\xi(x)}$$

where both fields ϕ and ξ are real fields.

The potential becomes

$$V(\Phi) = \frac{\mu^2}{2} \phi^2 + \frac{\lambda}{4} \phi^4$$

where the Higgs self-coupling term should be positive (λ>0) to get a potential bound from below. When $\mu^2 < 0$ a non-zero vacuum expectation value is obtained.

$$< 0|\phi^2|0 >= \phi_0^2 = \frac{\mu^2}{\lambda} = v^2$$

Spontaneously broken QED theory

Therefore we can normalize the field $\xi(x)$ as $\dfrac{\xi(x)}{\phi_0}$.

We can choose the unitary gauge transformation

$$\alpha(x) = -\frac{\xi(x)}{\phi_0}$$

and then Φ becomes real-valued everywhere. The kinetic term in the Lagrangian becomes

$$(D_\mu\Phi)^*(D^\mu\Phi) \to \frac{1}{2}\partial_\mu\psi\partial^\mu\psi + \frac{e^2}{2}A_\mu A^\mu\psi^2$$

The Lagrangian can be expanded around its minimum ϕ_0 by introducing a degree of freedom h (a new field). The potential becomes

$$V(\phi \to \phi_0 + h) = -\frac{m_h^2}{2}h^2 - \frac{\mu'}{3!}h^3 - \frac{\eta}{4!}h^4$$

with $m_h^2 = 2\lambda\phi_0^2$ and $\mu' = \dfrac{3m_h^2}{\phi_0}$ and $\eta = 6\lambda = 3\dfrac{m_h^2}{\phi_0^2}$

Spontaneously broken QED theory

The kinetic term becomes

$$\frac{1}{2}\partial_\mu(\phi_0 + h)\partial^\mu(\phi_0 + h) + \frac{e^2}{2}A_\mu A^\mu(\phi_0 + h)^2$$

and with $\partial_\mu \phi_0 = 0$ this becomes

$$\frac{e^2}{2}A_\mu A^\mu \phi_0^2 + e^2 A_\mu A^\mu \phi_0 h + \frac{e^2}{2}A_\mu A^\mu h^2 + \frac{1}{2}(\partial_\mu h)(\partial^\mu h)$$

where the first term provides a mass to the photon $m_A^2 = e^2\phi_0^2$, the second term gives the interaction strength of the coupling A-A-h, the third term the interaction strength of the coupling A-A-h-h

In the new potential term $V(\phi_0 + h)$ also cubic terms appear which break the reflexion symmetry $\phi \rightarrow -\phi$.

This U(1) example is the most trivial example of a spontaneous broken symmetry.

Spontaneously broken SU(2)xU(1) theory

The bosonic part of the Lagrangian is

$$\mathcal{L}_{bosonic} = |D_\mu \Phi|^2 - \mu^2 |\Phi|^2 - \lambda |\Phi|^4 - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu}$$

with Φ a doublet field consisting out of two complex scalar fields or components

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix}$$

We need at least 3 massive gauge bosons, hence need at least 2 complex fields (cfr. Goldstone theorem).

$$\begin{aligned} D_\mu \Phi &= \left(\partial_\mu + ig\tfrac{\tau^a}{2} W^a_\mu + ig' \tfrac{Y}{2} B_\mu\right) \Phi \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \\ W^a_{\mu\nu} &= \partial_\nu W^a_\nu - \partial_\nu W^a_\mu - g f^{abc} W^b_\mu W^c_\nu \end{aligned}$$

with τ^a the Pauli matrices and f^{abc} the structure constants of the SU(2)$_L$ group.

Spontaneously broken SU(2)xU(1) theory

The B_μ field corresponds to the generator Y of the $U(1)_Y$ group and the three W_μ^a fields to the generators T^a of the $SU(2)_L$ group.

$$T^a = \frac{1}{2}\tau^a$$
$$\left[T^a, T^b\right] = if^{abc}T^c$$
$$Tr\left[T^aT^b\right] = \frac{\delta_{ab}}{2}$$

When μ^2<0 the vacuum expectation value of Φ is non-zero.

$$< 0|\Phi|0 >= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad with \qquad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

The VEV will carry the hypercharge and the weak charge into the vacuum, but the electric charge remains unbroken, hence $Q = T^3 + \frac{Y}{2}$ and we break $SU(2)_L$x$U(1)_Y$ to $U(1)_Q$ with only one generator. Expending the terms in the Lagrangian around the minimum of the potential gives

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

Spontaneously broken SU(2)xU(1) theory

We obtain

$$|D_\mu\Phi|^2 \to \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{8}g^2(v+h)^2|W_\mu^{(1)} + iW_\mu^{(2)}|^2 + \frac{1}{8}(v+h)^2|gW_\mu^{(3)} - g'B_\mu|^2$$

and define the following fields

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}}\left(W_\mu^{(1)} \mp iW_\mu^{(2)}\right) \\ Z_\mu &= \frac{gW_\mu^{(3)} - g'B_\mu}{\sqrt{g^2+g'^2}} \\ A_\mu &= \frac{gW_\mu^{(3)} + g'B_\mu}{\sqrt{g^2+g'^2}} \end{aligned}$$

which we can transform into expressions for $B_\mu \quad and \quad W_\mu^{(i)}$
and put this in the above equation for $\left|D_\mu\Phi\right|^2$ **and isolate the Higgs boson interaction terms**

$$\mathcal{L}_{Higgs\ int} = \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{m_Z^2}{2} Z_\mu Z^\mu\right)\left(1+\frac{h}{v}\right)^2 - \frac{m_h^2}{2} - \frac{\xi}{3!}h^3 - \frac{\eta}{4!}h^4$$

Spontaneously broken SU(2)xU(1) theory

…

$$\mathcal{L}_{Higgs\ int} = \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{m_Z^2}{2} Z_\mu Z^\mu\right)\left(1+\frac{h}{v}\right)^2 - \frac{m_h^2}{2} - \frac{\xi}{3!}h^3 - \frac{\eta}{4!}h^4$$

with

$$\begin{aligned} m_W^2 &= \tfrac{1}{4} g^2 v^2 \\ m_Z^2 &= \tfrac{1}{4}(g^2 + g'^2)v^2 \\ m_h^2 &= 2\lambda v^2 \\ \xi &= 3\frac{m_h^2}{v} \\ \eta &= 6\lambda = 3\frac{m_h^2}{v^2} \end{aligned}$$

where it is convenient to define the Weinberg mixing angle θ_W

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

and therefore

$$\frac{m_W^2}{m_Z^2} = 1 - sin^2\theta_W$$

Spontaneously broken SU(2)xU(1) theory

From experiment we know

$$\begin{aligned} m_W &\simeq 80GeV \\ m_Z &\simeq 91GeV \\ g &\simeq 0.65 \\ g' &\simeq 0.35 \end{aligned}$$

Hence we obtain $v \simeq 246\ GeV$

And for the couplings between V=W/Z bosons and the Higgs boson

$$\begin{aligned} g_{hVV} &= 2\frac{m_V^2}{v} \\ g_{hhVV} &= 2\frac{m_V^2}{v^2} \\ g_{hhh} &= 3\frac{m_h^2}{v} \\ g_{hhhh} &= 3\frac{m_h^2}{v^2} \end{aligned}$$

We observe that the Higgs sector in the Standard Model is completely determined from the mass of the Higgs boson.

The ElectroWeak fit

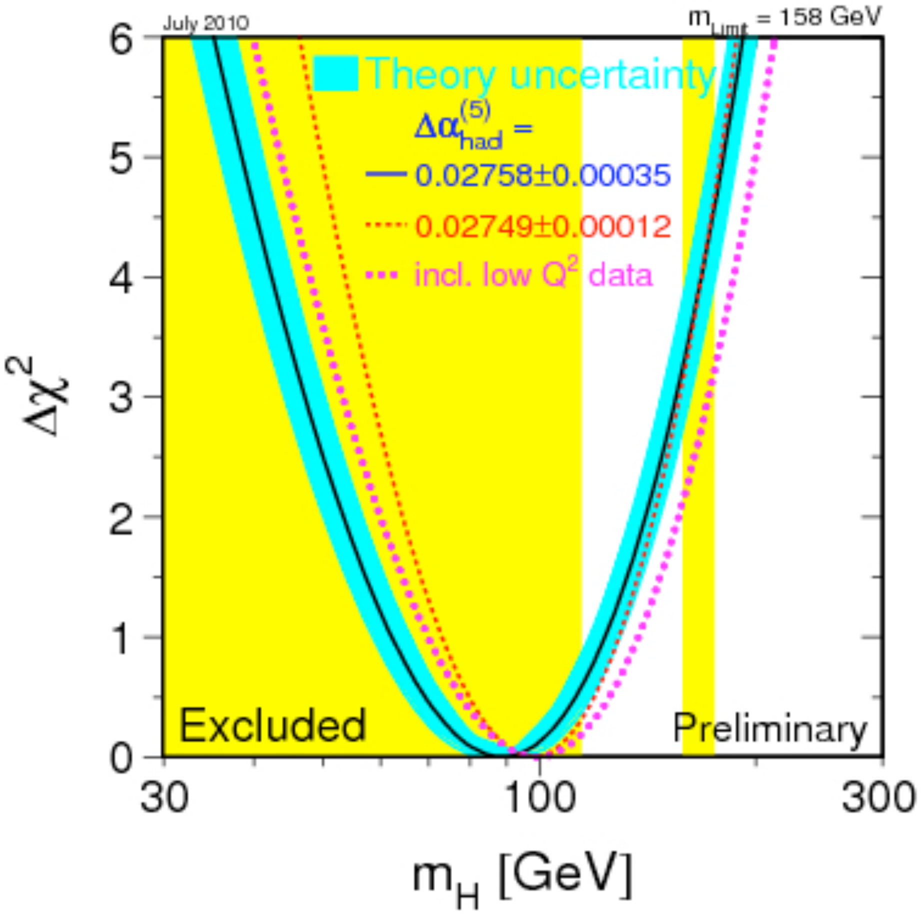
Aim:

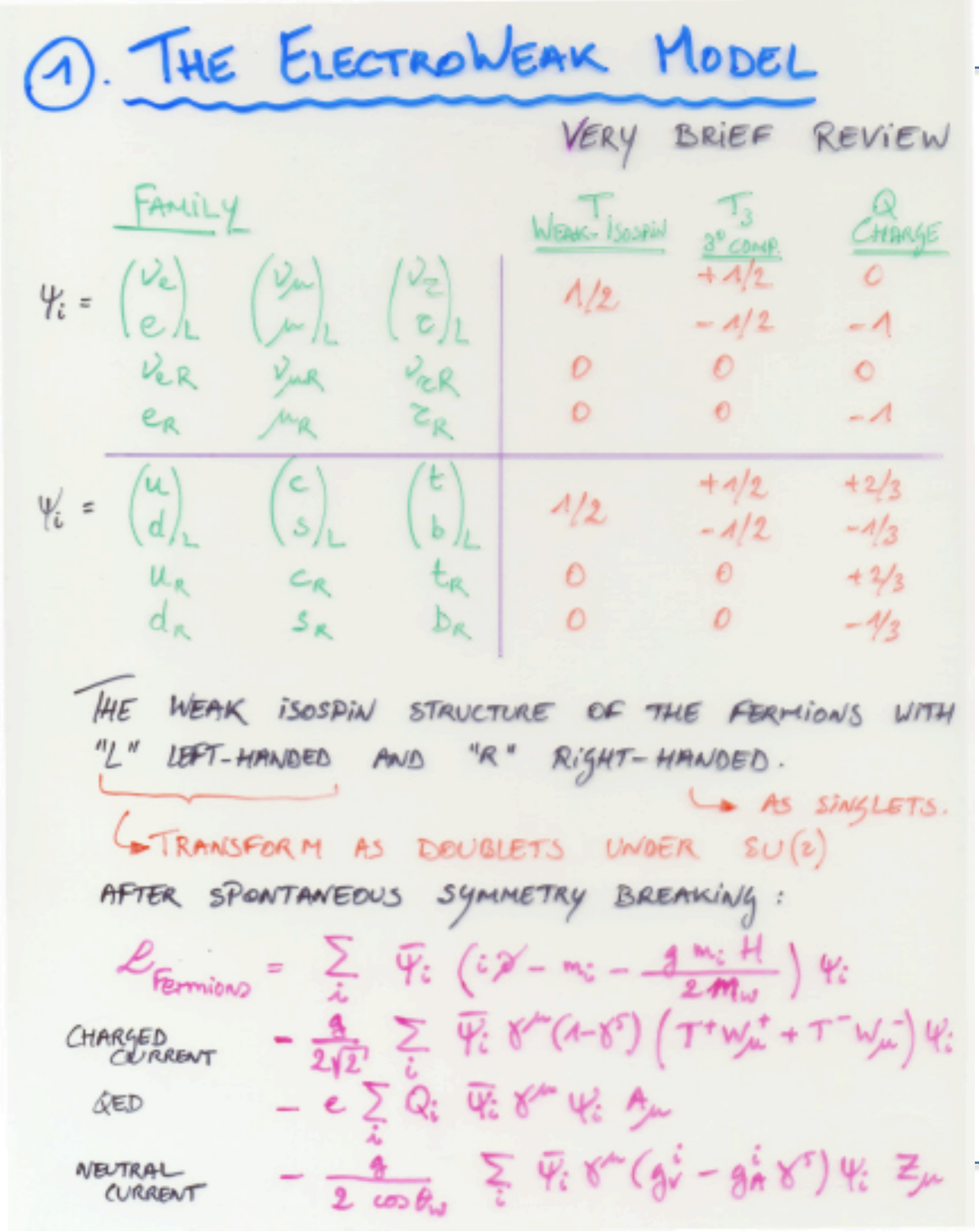
- What do we know experimentally on the Higgs boson mass.
- Know how one can make a theoretical interpretation via radiative corrections on experimental quantities.

References:

- “A combination of preliminary Electroweak Measurements and Constraints on the Standard Model”, hep-ex/0612034 (and recent updates)
- “Precision Electroweak measurements on the Z boson resonance”, hep-ex/0509008

A general aim is to understand how one obtains the so-called Higgs Blueband plot which is a driving force for many activities in particle physics.





①. THE ELECTROWEAK MODEL

VERY BRIEF REVIEW

	FAMILY			T WEAK-ISOSPIN	T_3 3° COMP.	Q CHARGE
$\psi_i =$	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	1/2	+1/2 -1/2	0 -1
	ν_{eR}	$\nu_{\mu R}$	$\nu_{\tau R}$	0	0	0
	e_R	μ_R	τ_R	0	0	-1
$\psi_i =$	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	1/2	+1/2 -1/2	+2/3 -1/3
	u_R	c_R	t_R	0	0	+2/3
	d_R	s_R	b_R	0	0	-1/3

THE WEAK ISOSPIN STRUCTURE OF THE FERMIONS WITH "L" LEFT-HANDED AND "R" RIGHT-HANDED.

$\underbrace{\text{"L" LEFT-HANDED}}$ ↳ TRANSFORM AS DOUBLETS UNDER SU(2)

"R" RIGHT-HANDED ↳ AS SINGLETS.

AFTER SPONTANEOUS SYMMETRY BREAKING :

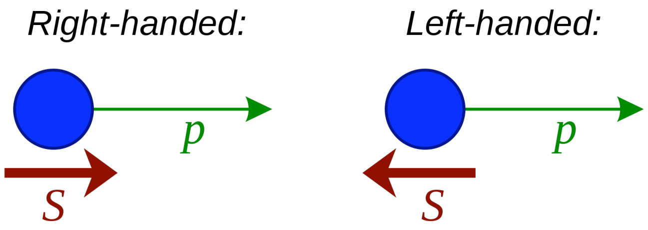
$$\mathcal{L}_{\text{Fermions}} = \sum_i \bar{\psi}_i \left(i\not{\partial} - m_i - \frac{g\, m_i H}{2 M_W} \right) \psi_i$$

CHARGED CURRENT $$- \frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu (1-\gamma^5) \left(T^+ W_\mu^+ + T^- W_\mu^- \right) \psi_i$$

QED $$- e \sum_i Q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu$$

NEUTRAL CURRENT $$- \frac{g}{2 \cos\theta_W} \sum_i \bar{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi_i Z_\mu$$

Helicity of the particle



Projecting operator for a field

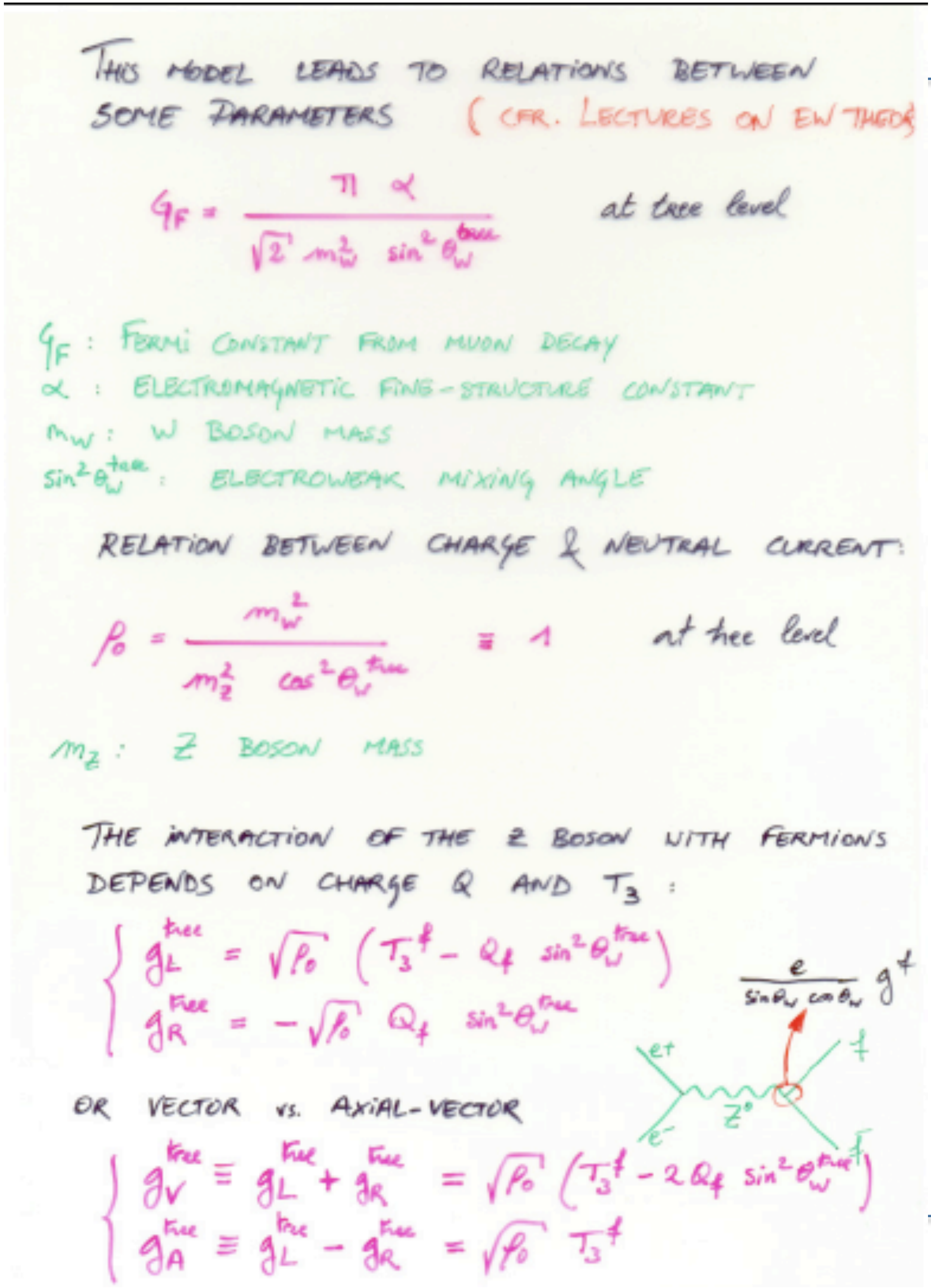
$$\frac{1-\gamma^5}{2}$$ left-handed component

$$\frac{1+\gamma^5}{2}$$ right-handed component

Hence introducing parity violation in the weak interaction according to observation.

Vector: $P(\psi) = -\psi$

Axial-vector: $P(\psi) = \psi$



THIS MODEL LEADS TO RELATIONS BETWEEN SOME PARAMETERS (CFR. LECTURES ON EW THEOR

$$G_F = \frac{\pi\ \alpha}{\sqrt{2}\ m_W^2\ \sin^2\theta_W^{tree}}$$ at tree level

G_F : FERMI CONSTANT FROM MUON DECAY
α : ELECTROMAGNETIC FINE-STRUCTURE CONSTANT
m_W : W BOSON MASS
$\sin^2\theta_W^{tree}$: ELECTROWEAK MIXING ANGLE

RELATION BETWEEN CHARGE & NEUTRAL CURRENT:

$$\rho_0 = \frac{m_W^2}{m_Z^2\ \cos^2\theta_W^{tree}} \equiv 1$$ at tree level

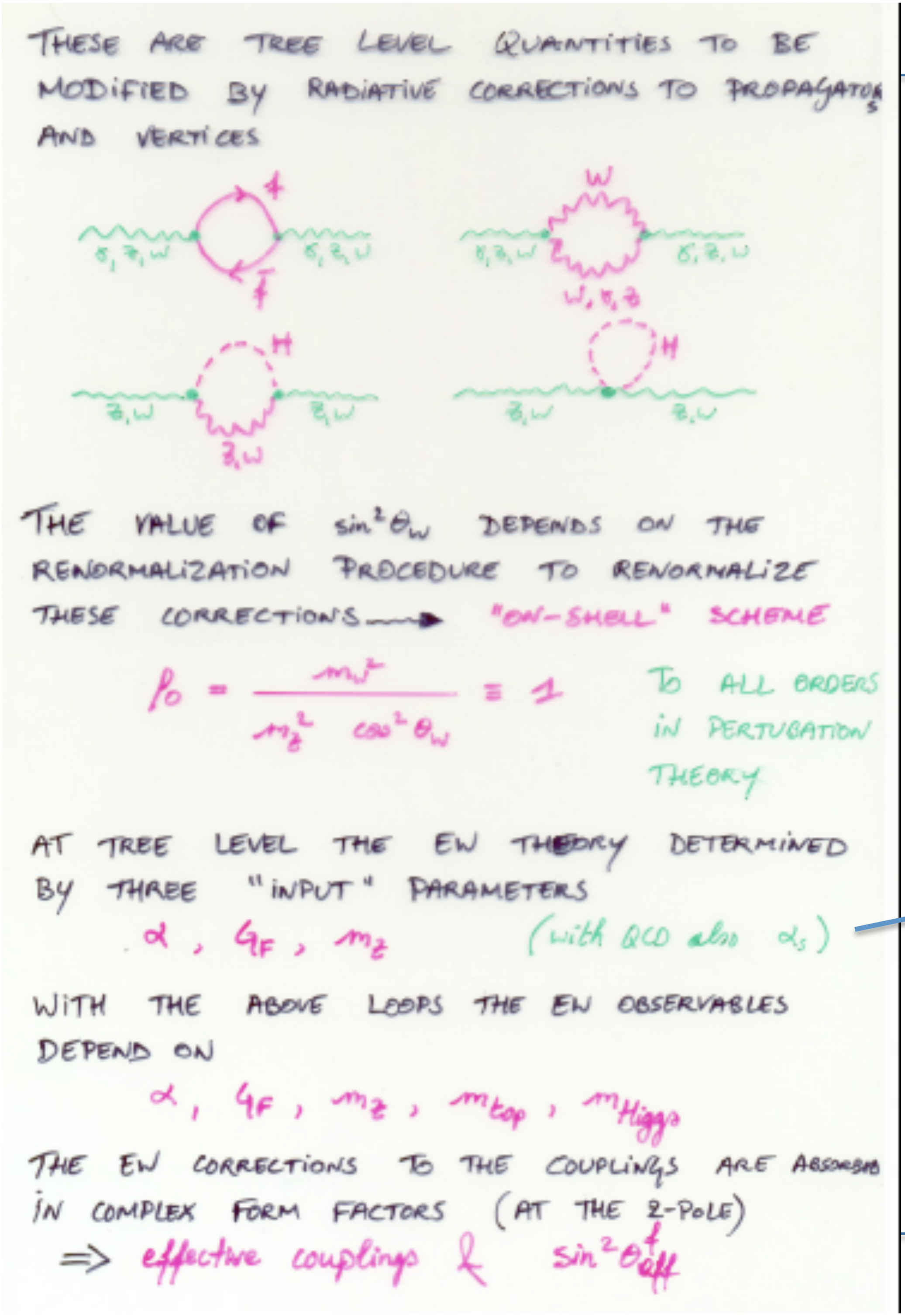
m_Z : Z BOSON MASS

THE INTERACTION OF THE Z BOSON WITH FERMIONS DEPENDS ON CHARGE Q AND T_3 :

$$\begin{cases} g_L^{tree} = \sqrt{\rho_0}\ \left(T_3^f - Q_f\ \sin^2\theta_W^{tree}\right) \\ g_R^{tree} = -\sqrt{\rho_0}\ Q_f\ \sin^2\theta_W^{tree} \end{cases}$$

OR VECTOR vs. AXIAL-VECTOR

$$\begin{cases} g_V^{tree} \equiv g_L^{tree} + g_R^{tree} = \sqrt{\rho_0}\ \left(T_3^f - 2Q_f\ \sin^2\theta_W^{tree}\right) \\ g_A^{tree} \equiv g_L^{tree} - g_R^{tree} = \sqrt{\rho_0}\ T_3^f \end{cases}$$



THESE ARE TREE LEVEL QUANTITIES TO BE MODIFIED BY RADIATIVE CORRECTIONS TO PROPAGATORS AND VERTICES

THE VALUE OF $\sin^2\theta_W$ DEPENDS ON THE RENORMALIZATION PROCEDURE TO RENORMALIZE THESE CORRECTIONS ⟶ "ON-SHELL" SCHEME

$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \equiv 1$$

TO ALL ORDERS IN PERTURBATION THEORY

AT TREE LEVEL THE EW THEORY DETERMINED BY THREE "INPUT" PARAMETERS

α , G_F , m_Z (with QCD also α_s)

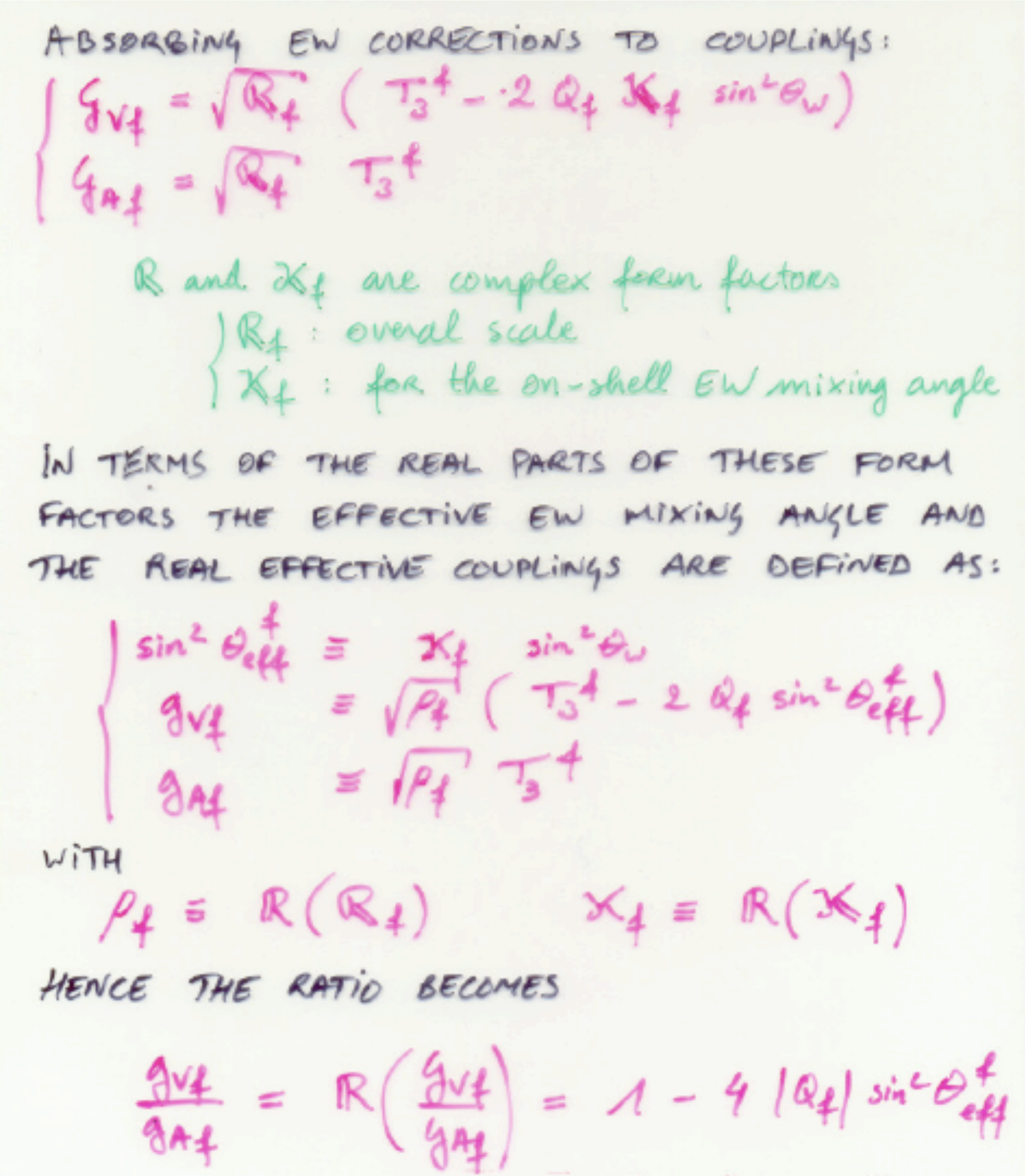
5 parameters & 2 equations, hence 3 free parameters

WITH THE ABOVE LOOPS THE EW OBSERVABLES DEPEND ON

α , G_F , m_Z , m_{top} , m_{Higgs}

THE EW CORRECTIONS TO THE COUPLINGS ARE ABSORBED IN COMPLEX FORM FACTORS (AT THE Z-POLE)

⇒ effective couplings & $\sin^2\theta^f_{eff}$



ABSORBING EW CORRECTIONS TO COUPLINGS:

$$\begin{cases} g_{Vf} = \sqrt{\mathbb{R}_f}\,\left(T_3^f - 2\,Q_f\,\mathcal{K}_f\,\sin^2\theta_W\right) \\ g_{Af} = \sqrt{\mathbb{R}_f}\;T_3^f \end{cases}$$

$\mathbb{R}$ and $\mathcal{K}_f$ are complex form factors

$\mathbb{R}_f$: overall scale
$\mathcal{K}_f$: for the on-shell EW mixing angle

IN TERMS OF THE REAL PARTS OF THESE FORM FACTORS THE EFFECTIVE EW MIXING ANGLE AND THE REAL EFFECTIVE COUPLINGS ARE DEFINED AS:

$$\begin{cases} \sin^2\theta_{eff}^f \equiv \kappa_f\,\sin^2\theta_W \\ g_{Vf} \equiv \sqrt{\rho_f}\,\left(T_3^f - 2\,Q_f\,\sin^2\theta_{eff}^f\right) \\ g_{Af} \equiv \sqrt{\rho_f}\;T_3^f \end{cases}$$

WITH

$$\rho_f \equiv \mathbb{R}(\mathbb{R}_f) \qquad \kappa_f \equiv \mathbb{R}(\mathcal{K}_f)$$

HENCE THE RATIO BECOMES

$$\frac{g_{Vf}}{g_{Af}} = \mathbb{R}\left(\frac{g_{Vf}}{g_{Af}}\right) = 1 - 4\,|Q_f|\,\sin^2\theta_{eff}^f$$

THE CORRECTIONS ARE IN THE DEFINITION OF ρ_f AND κ_f :

$$\begin{cases} \rho_f = 1 + \Delta\rho_{se} + \Delta\rho_f \\ \kappa_f = 1 + \Delta\kappa_{se} + \Delta\kappa_f \end{cases}$$

↳ flavour specific vertex corrections

↳ universal corrections from the propagator self-energies

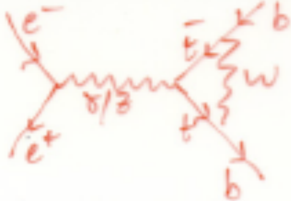
IN LEADING ORDER : for $m_H \gg m_W$

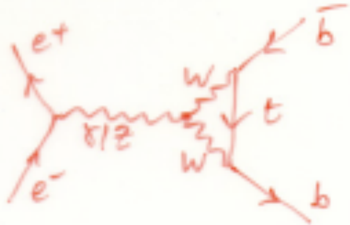
$$\Delta\rho_{se} = \frac{3 G_F m_W^2}{8\sqrt{2}\,\pi^2}\left[\frac{m_t^2}{m_W^2} - \frac{\sin^2\theta_W}{\cos^2\theta_W}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \dots\right]$$

$$\Delta\kappa_{se} = \frac{3 G_F m_W^2}{8\sqrt{2}\,\pi^2}\left[\frac{m_t^2}{m_W^2}\,\frac{\cos^2\theta_W}{\sin^2\theta_W} - \frac{10}{9}\cdot\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \dots\right]$$

THE RADIATIVE CORRECTIONS HAVE A QUADRATIC DEPENDENCE ON m_t AND A WEAKER LOG DEPENDENCE ON m_H.

THE FLAVOUR DEPENDENCE IS VERY SMALL EXCEPT FOR THE b- QUARK .





AS $|V_{tb}| \approx 1$ THE TOP QUARK HAS A SIGNIFICANT CONTRIBUTION

$$\Delta\kappa_b = \frac{G_F\, m_t^2}{4\sqrt{2}\,\pi^2} + \dots$$

$$\Delta\rho_b = -2\,\Delta\kappa_b + \dots$$

also

THE PARAMETER ρ IS MODIFIED BY LOOPS:

$$\rho = 1 + \Delta\rho$$

FROM THE PREVIOUS RELATIONS WE GET

$$\cos^2\theta_W \sin^2\theta_W = \frac{\pi\,\alpha(0)}{\sqrt{2}\, m_Z^2\, G_F}\cdot\frac{1}{1-\Delta R}$$

low mom. transfer

$$\cos^2\theta_{eff}^f \sin^2\theta_{eff}^f = \frac{\pi\,\alpha(0)}{\sqrt{2}\, m_Z^2\, G_F}\cdot\frac{1}{1-\Delta R^f}$$

at the Z-pole

WITH

$$\begin{cases}\Delta R = \Delta\alpha + \Delta R_W \\ \Delta R^f = \Delta\alpha + \Delta R_W^f\end{cases}$$

THE $\Delta\alpha$ TERM ARISES FROM THE RUNNING OF THE ELECTROMAGNETIC COUPLING DUE TO FERMION LOOPS IN THE PHOTON PROPAGATOR, USUALLY DIVIDED AS:

$$\Delta\alpha(s) = \underbrace{\Delta\alpha_{e\mu\tau}(s) + \Delta\alpha_{top}(s)}_{\text{precise calculations}} + \underset{\downarrow}{\Delta\alpha^{(5)}_{had}(s)}$$

FROM THE ANALYSIS OF LOW ENERGY e^+e^- DATA USING A DISPERSION RELATION

THE EFFECTS ARE ABSORBED AS

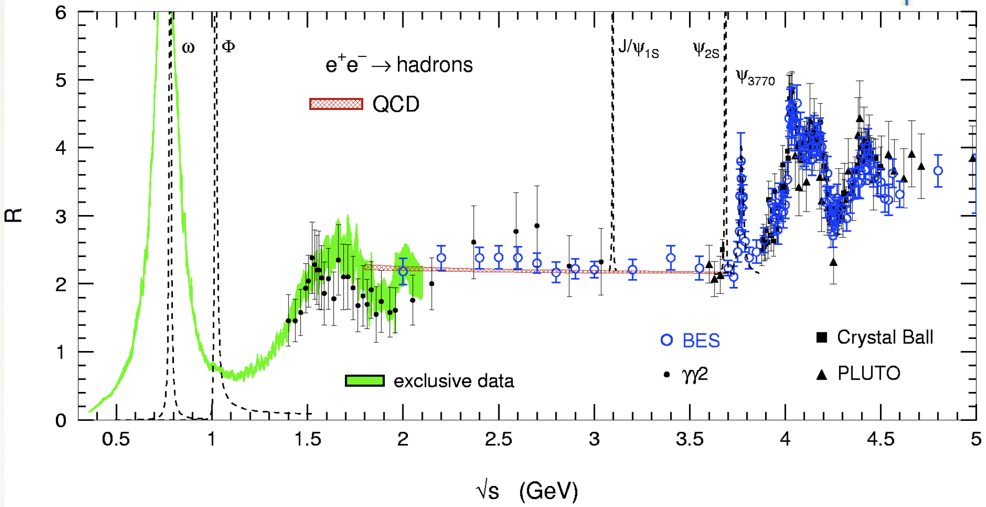
$$\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)}$$

$$\alpha(0) = 1/137.036 \;\rightarrow\; \alpha(m_Z) = 1/128.945$$

Dispersion relation

$$\Delta\alpha^{(5)}_{hadr}(s) = -\frac{\alpha s}{3\pi} Re \int_{4m_\pi^2}^{E^2_{cut}} ds' \frac{R^{DATA}(s')}{s'(s'-s) - i\epsilon}$$

$$R = \frac{\sigma(e^+e^- \rightarrow \gamma \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-)}$$



USUALLY G_F AND m_Z ARE BETTER MEASURED COMPARED TO m_W, HENCE ONE USUALLY CALCULATES m_W VIA G_F AND m_Z:

$$m_W^2 = \frac{m_Z^2}{2}\left(1 + 1 - 4\frac{\pi\alpha}{\sqrt{2}\,G_F\,m_Z^2}\cdot\frac{1}{1-\Delta R}\right)+\cdots$$

=> THIS GIVES YOU A DEPENDENCY BETWEEN m_W, m_t, m_H ... AND PREVIOUS EQUATIONS BETWEEN $\sin^2\theta_W$, m_t, m_H, ...

ALL THE ABOVE IS IN LEADING ORDER TO ILLUSTRATE THE MAIN ELECTROWEAK RELATIONS THE FULL CALCULATIONS AND SO-CALLED EW-FIT ARE PERFORMED TO HIGHER ORDER (programs as TOPAZ0 and ZFITTER)

ALL TOGETHER:

- MEASURING COUPLINGS → SENSITIVE TO $\sin^2\theta_W$
- MEASURE m_W

=> THESE PARAMETERS ARE AT THE HEART OF THE ELECTROWEAK THEORY & SENSITIVE TO m_t & m_H VIA LOOP CORRECTIONS

THE ABOVE EQUATIONS PROVIDE THE BASIS FOR THE INTERPRETATIONS

HENCE APART FROM OTHER FERMION MASSES AND MIXINGS, THE STANDARD MODEL HAS 3 FREE PARAMETERS: α, G_F, m_Z (+ m_H, m_t VIA LOOPS)

- (i) MEASURE eg. COUPLINGS PRECISELY $\Rightarrow \sin^2\theta_W$
- (ii) MEASURE THE "FREE" PARAMETERS PRECISELY (PREDICT eg. $\sin^2\theta_W$ & m_W)

  ↳ POSSIBLE SINCE THE PRECISE m_Z MEASUREMENT
- TEST CONSISTENCY BETWEEN eg. $\sin^2\theta_W$ BETWEEN (i) & (ii)
- CONSTRAIN UNMEASURED QUANTITY m_H
- FIND THE HIGGS BOSON ...

$\alpha = 1 / 137.03599911\ (46)$ (eg. magnetic moment $e^\pm$)

(defined at very low energy scales)

$\Downarrow$

run up to higher scales $\alpha = \alpha(M_Z)$

$G_F = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2}$ (muon life time)

$m_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}$ (lineshape)

$\Rightarrow$ GET EXPERIMENTS WHICH CAN MEASURE OBSERVABLES SENSITIVE TO $\sin^2\theta_W$ & m_W WHICH IS ON HIS TURN SENSITIVE TO m_H AND m_t

②. THE EXPERIMENTS FOR $\sin^2\theta_W$

THE PROCESS UNDER STUDY IS $e^+e^- \to f\bar{f}$

TWO ACCELERATORS DESIGNED DURING THE 1980s TO ESTIMATE THE Z-POLE PARAMETERS WITH HIGH PRECISION: LEP & SLC

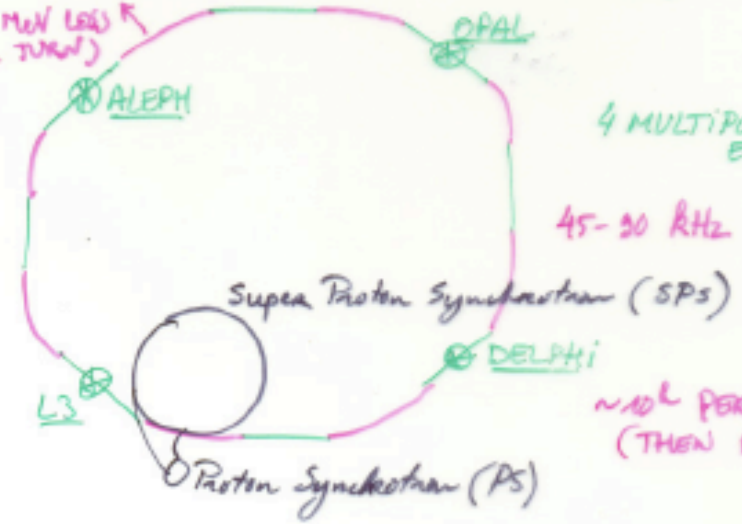
I. LEP: LARGE ELECTRON-POSITRON COLLIDER

(1989 – 2000)

THE LARGEST PARTICLE ACCELERATOR IN THE WORLD WITH 27 km CIRCUMFERENCE.

RF COPPER CAVITIES
(125 MeV LOSS PER TURN)

8 STRAIGHT SECTIONS



4 MULTIPURPOSE EXPERIMENTS

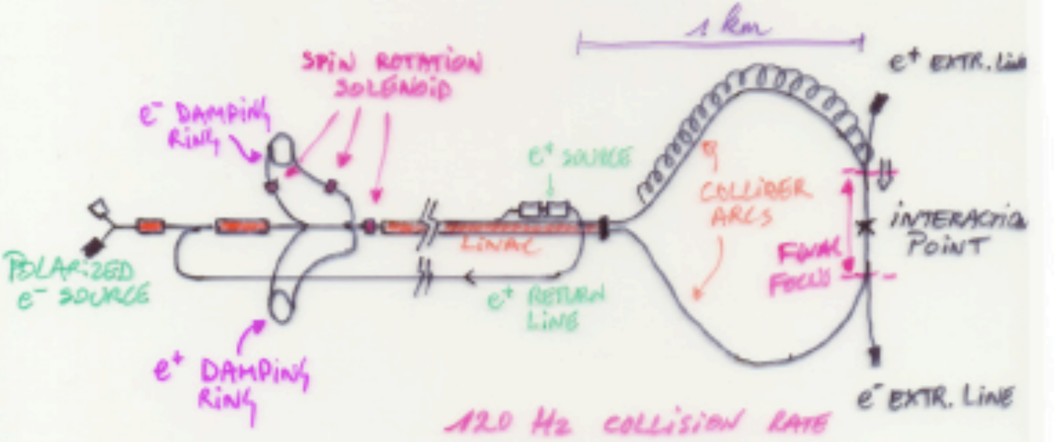
45 – 90 kHz COLLISION RATE

~10h PER FILL
(THEN BEAM DUMP)

AT PEAK LUMINOSITY $(2 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1})$ EACH EXPERIMENT COLLECTED ABOUT 1000 Z BOSONS EVERY HOUR.

II. STANFORD LINEAR COLLIDER @ SLAC

THE FIRST e^+e^- LINEAR COLLIDER OF 3.2 km LENGTH



120 Hz COLLISION RATE

DAMPING RINGS REDUCE THE SIZE & ENERGY SPREAD OF THE ELECTRON & POSITRON BUNCHES

- STARTS WITH 2 CLOSELY SPACED ELECTRON BUNCHES (1 LONGITUDINALLY POLARISED)
- STORED IN DAMPING RING AT 1.2 GeV
- BACK IN LINAC AT 30 GeV TO A TARGET FOR POSITRON CREATIO (THEY GO BACK TO START AT 200 MeV AND GO TO DAMPING RING)
- SYNCHRONIZATION WITH SECOND 2-ELECTRON BUNCH START
- FINAL ENERGY OF 46.5 GeV (1 GeV LOST IN ARCS)
- ELECTRONS MANIPULATED TO GET LONGITUDINAL POLARISATION AT INTERACTION POINT

MAIN ADVANTAGE COMPARED TO LEP IS THE POLARIZATION (LOTS OF WORK TO KEEP POLARIZATION FROM SOURCE TO COLLISION)

CRUCIAL : MEASURE THE POLARIZATION

(PRECISION OF 0.5% ACHIEVED WHILE DESIGNED WAS 1%)

HEAD-ON COMPTON SCATTERING OF A POLARIZED HIGH-POWER LASER BEAM WITH THE ELECTRON BEAM

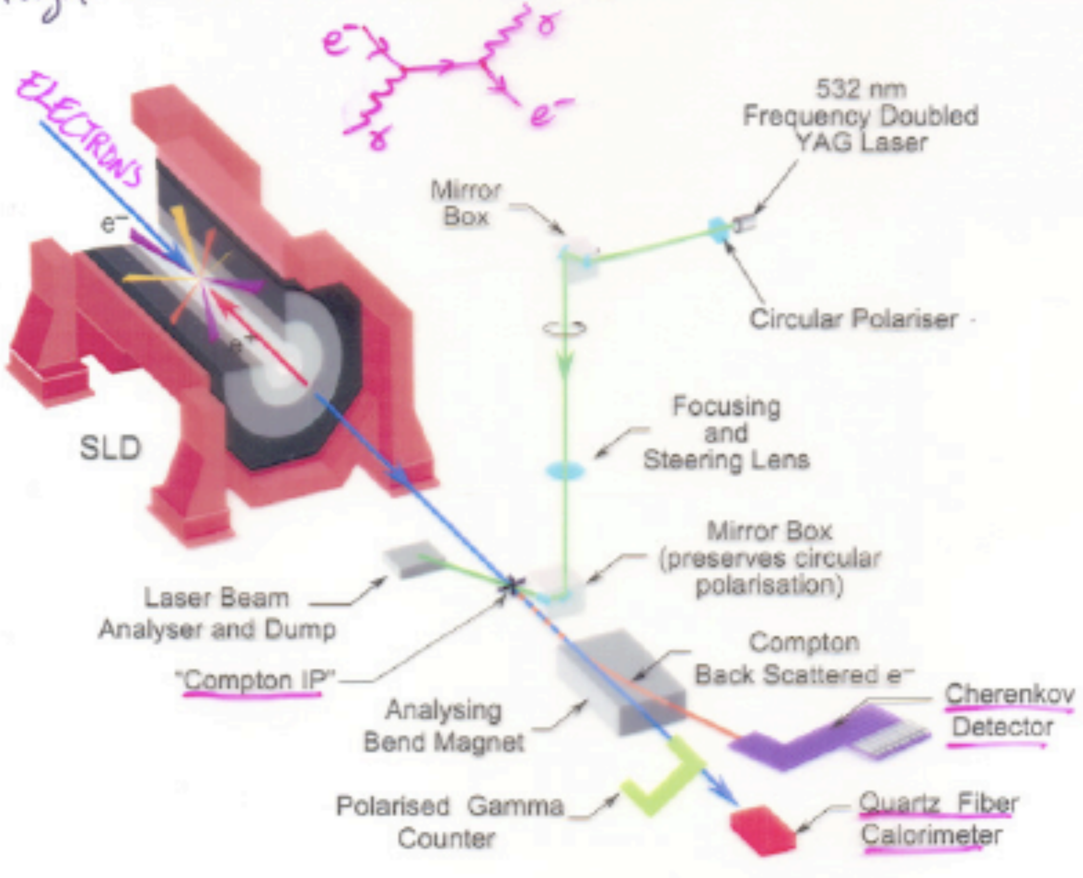


Figure 3.1: A conceptual diagram of the SLD Compton Polarimeter. The laser beam, consisting of 532 nm wavelength 8 ns pulses produced at 17 Hz and a peak power of typically 25 MW, were circularly polarised and transported into collision with the electron beam at a crossing angle of 10 mrad approximately 30 meters from the IP. Following the laser/electron-beam collision, the electrons and Compton-scattered photons, which are strongly boosted along the electron beam direction, continue downstream until analysing bend magnets deflect the Compton-scattered electrons into a transversely-segmented Cherenkov detector. The photons continue undeflected and are detected by a gamma counter (PGC) and a calorimeter (QFC) which are used to cross-check the polarimeter calibration.

HADRONIC CROSS SECTION VERSUS $\sqrt{s}$

LEP : 1989 → 2000 $\sqrt{s} = m_Z \pm 3$ GeV → 17M Z^0

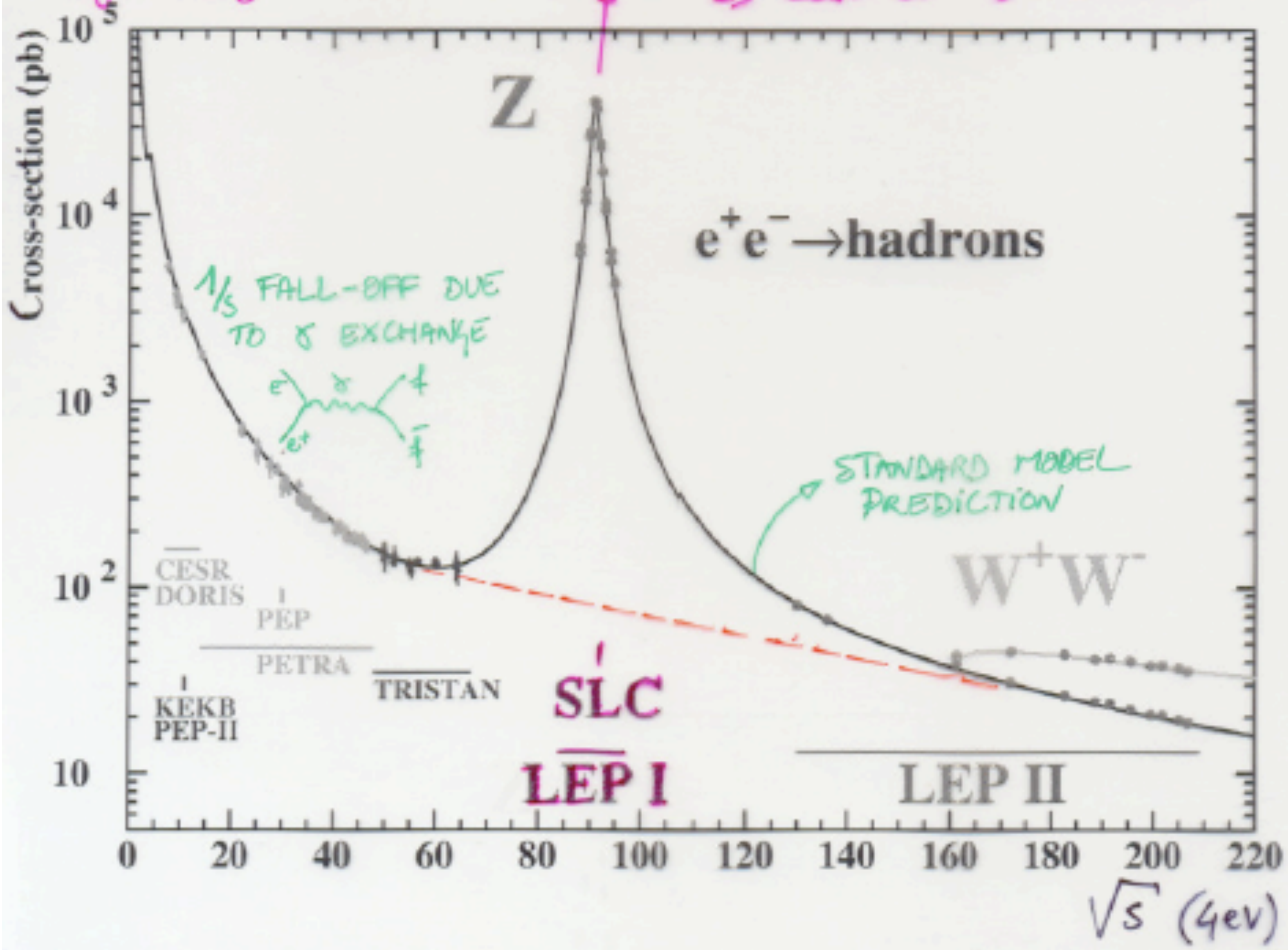
SLC : 1989 → 1998   → 0.6M Z^0

(with longitudinal polarization)

OPTIMAL ENERGY REGION TO STUDY THE $e^+e^- \to f\bar{f}$ PROCESSES

VERY HIGH CROSS SECTION ⇒ LOTS OF Z BOSONS

LOG-SCALE !



$1/s$ FALL-OFF DUE TO γ EXCHANGE

STANDARD MODEL PREDICTION

EXAMPLE OF THE ACHIEVEMENTS OF LEP & SLC

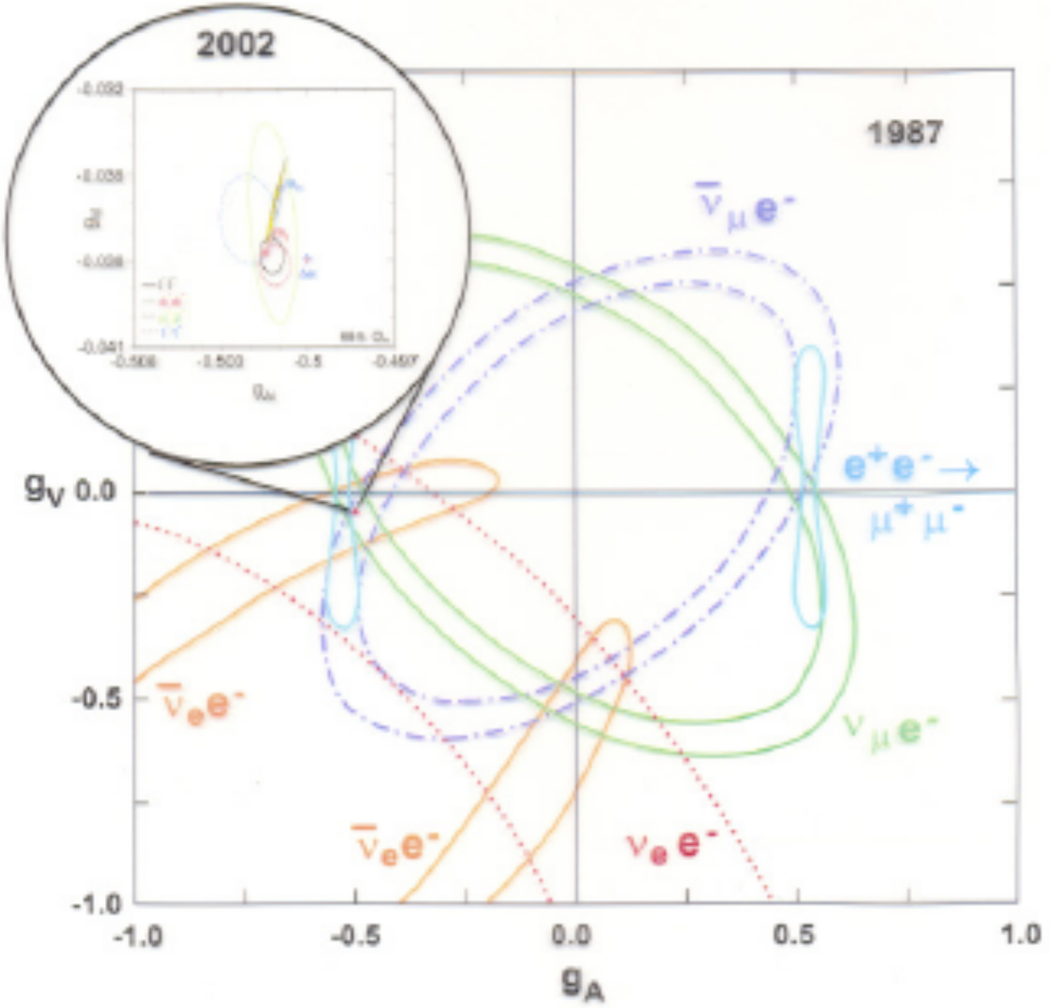


Figure 1.15: The neutrino scattering and e^+e^- annihilation data available in 1987 constrained the values of $g_{V\ell}$ and $g_{A\ell}$ to lie within broad bands, whose intersections helped establish the validity of the SM and were consistent with the hypothesis of lepton universality. The inset shows the results of the LEP/SLD measurements at a scale expanded by a factor of 65 (see Figure 7.3). The flavour-specific measurements demonstrate the universal nature of the lepton couplings unambiguously on a scale of approximately 0.001.

③. BASIC MEASUREMENTS

THE DETAILED DETECTORS AROUND THE COLLISION POINTS ARE ABLE TO MEASURE PRECISELY THE $e^+e^- \to \gamma/Z \to f\bar{f}$ PROCESS. ALSO THE FLAVOURS OF LEPTONS AND SOME QUARKS CAN BE DISTINGUISHED.

(NOT THE MAIN TOPIC OF THIS LECTURE)

- TOTAL CROSS-SECTIONS

$$\sigma = \frac{N_{sel} - N_{bck}}{\varepsilon_{sel} \cdot \mathcal{L}}$$

N_{bck} & ε_{sel} FROM SIMULATION

- CROSS-SECTION VERSUS $\sqrt{s}$

  NEEDED FOR Z BOSON MASS AND WIDTH

- RATIO OF CROSS-SECTIONS OF DIFFERENT DECAYS

  FOR PARTIAL WIDTHS & RELATIVE STRENGTH OF Z COUPLINGS

- ASYMMETRIES OF ANGULAR DISTRIBUTIONS

  MIXTURE OF VECTOR & AXIAL-VECTOR COUPLINGS

  → HERE THE POLARIZATION OF THE COLLIDING e^- AND e^+ CAN HELP

⊛ $$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$ forward-backward asymmetry

(NEEDS 4π ACCEPTANCE, HENCE A_{FB} USUALLY FROM FITS ON ANGULAR DISTRIBATIONS)

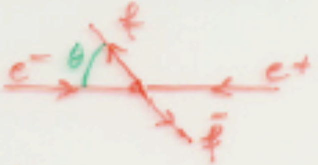
⊛ $$A_{LR} = \frac{N_L - N_R}{N_L + N_R} \cdot \frac{1}{\langle P_e \rangle}$$ left-right asymmetry

DOES NOT NEED ACCEPTANCE

(N_L: #Z FOR LH e^- BUNCHES) ($\langle P_e \rangle$: MAGN. OF POLARISATION)

④. THE PROCESS $e^+e^- \to f\bar{f}$

DIFFERENTIAL CROSS-SECTION AROUND Z-POLE USING THE COMPLEX-VALUED EFFECTIVE COUPLING CONSTANTS



$$\frac{2s}{\pi}\,\frac{1}{N_c^f}\,\frac{d\sigma_{EW}}{d\cos\theta}(e^+e^-\to f\bar{f}) =$$

$$\begin{aligned}
\sigma^{\gamma}\qquad & |\alpha(s)\,Q_f|^2\,(1+\cos^2\theta)\\
\gamma\text{-}Z\ \text{interference}\qquad & -8\,\mathbb{R}\Big\{\alpha^*(s)\,Q_f\,\chi(s)\Big[g_{Ve}\,g_{Vf}\,(1+\cos^2\theta)+2\,g_{Ae}\,g_{Af}\cos\theta\Big]\Big\}\\
\sigma^{Z}\qquad & +16\,|\chi(s)|^2\Big[\big(|g_{Ve}|^2+|g_{Ae}|^2\big)\cdot\big(|g_{Vf}|^2+|g_{Af}|^2\big)\cdot(1+\cos^2\theta)\\
& \qquad +8\,\mathbb{R}\{g_{Ve}\,g_{Ae}^*\}\,\mathbb{R}\{g_{Vf}\,g_{Af}^*\}\cos\theta\Big]
\end{aligned}$$

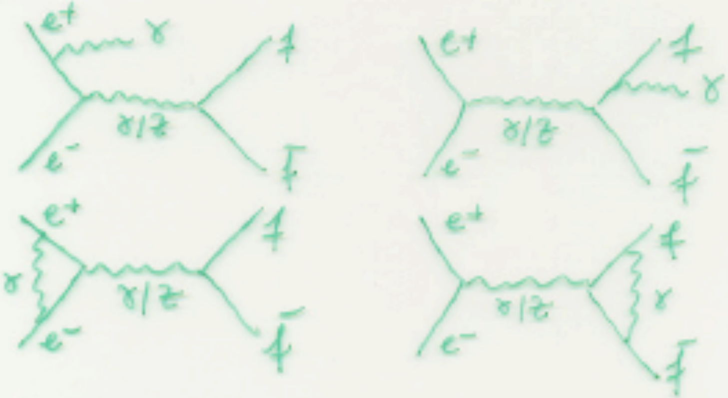
WITH $\chi(s) = \frac{G_F\, m_Z^2}{8\pi\sqrt{2}}\cdot\frac{s}{s-m_Z^2+is\frac{\Gamma_Z}{m_Z}}$ propagator term

N_c^f : one for leptons & three for quarks

RATHER MODEL-INDEPENDENT IF COUPLINGS ARE FREE ONLY ASSUMPTION IS THAT THE Z PROCESSES VECTOR & AXIAL-VECTOR COUPLINGS TO FERMIONS, HAS SPIN 1 AND INTERFERES WITH THE PHOTON.

[FOR ELECTRONS $e^+e^- \to e^+e^-$ ALSO THE BHABHA TERM)

PHOTON RADIATION FROM INITIAL & FINAL STATES LIKE



AND THEIR INTERFERENCE ARE TREATED BY CONVOLUTING THE EW KERNEL CROSS-SECTION $\sigma_{ew}(s)$ WITH A QED RADIATOR

$$\sigma(s) = \int_{4m_f^2/s}^{1} dz \; H_{QED}^{tot}(z,s) \; \sigma_{ew}(zs)$$

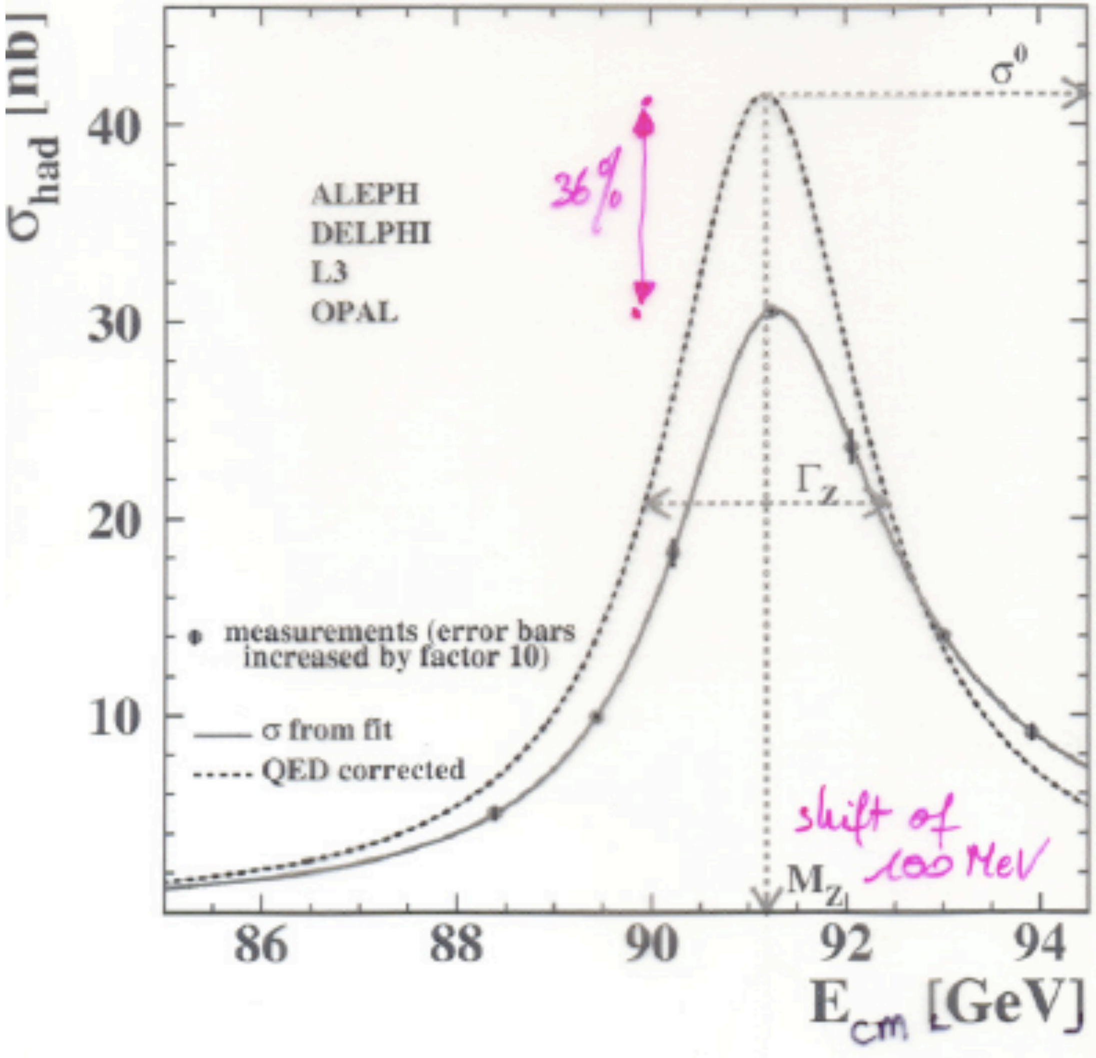
THE SAME PROCEDURE IS USED FOR THE FORWARD-BACKWARD ASYMMETRIES $\sigma_F - \sigma_B$ WITH H_{QED}^{FB}.
[calculated to 3° ORDER]

THESE CORRECTIONS ARE IMPORTANT AND ESSENTIALLY INDEPENDENT OF THE EW CORRECTIONS DISCUSSED PREVIOUSLY.

⇒ HENCE THE PARAMETERS IN EQUATION $d\sigma_{EW}/d\cos\theta$ CAN BE EXTRACTED FROM DATA IN A MODEL-INDEPENDENT WAY

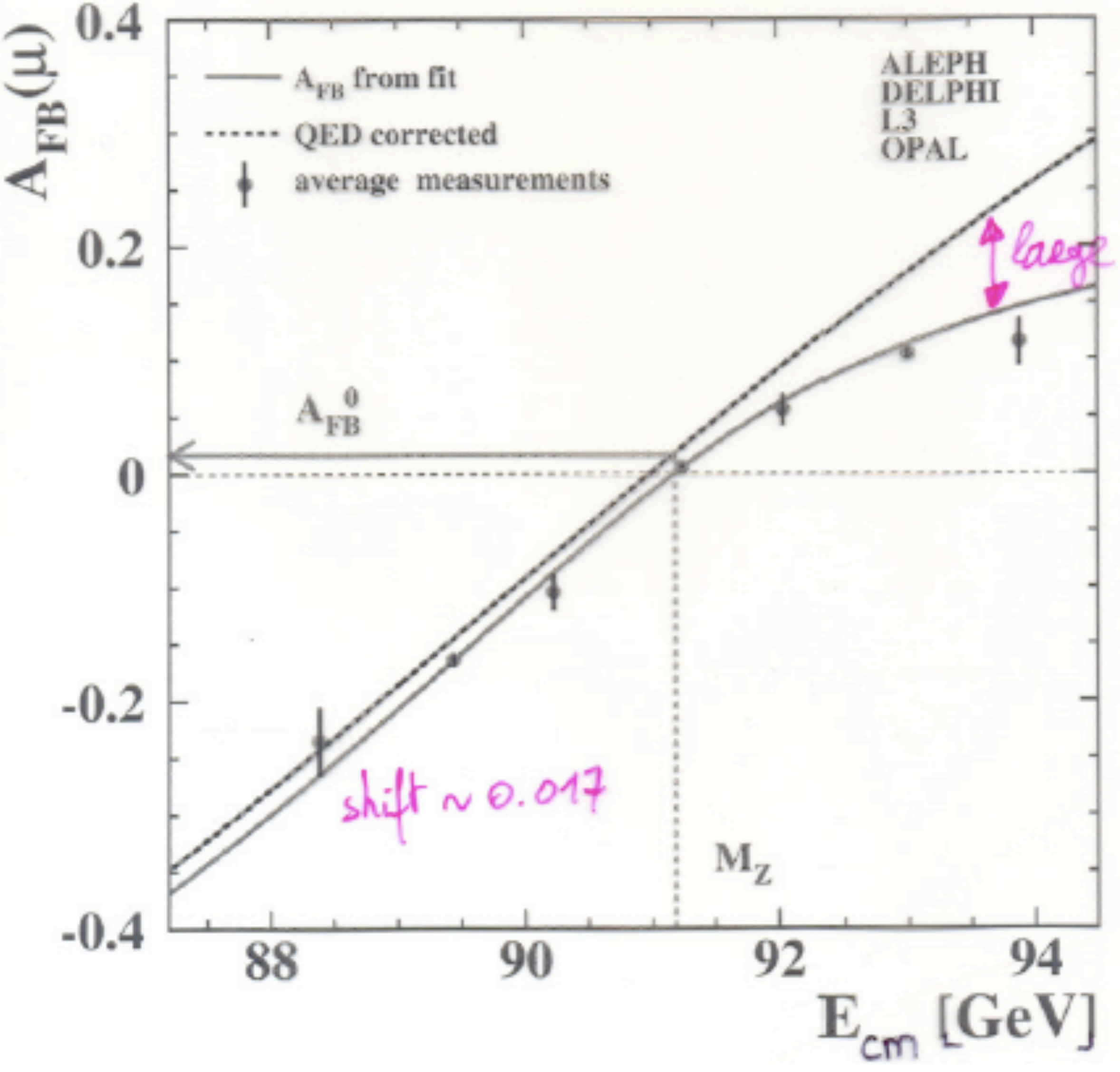
EFFECT OF QED RADIATIVE CORRECTIONS ON THE LINESHAPE OF THE Z

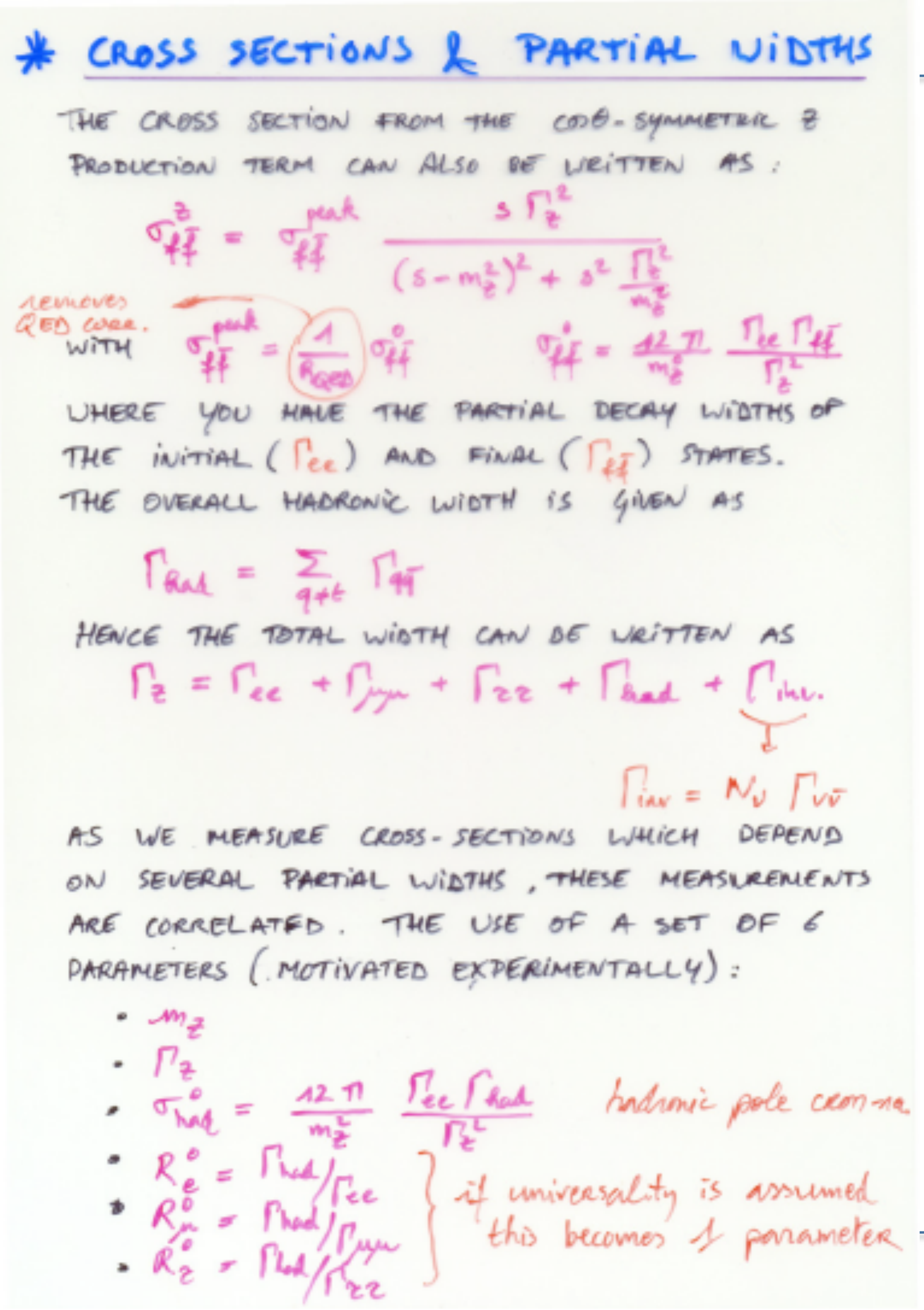
(hadronic cross section)



EFFECT OF QED RADIATIVE CORRECTIONS ON THE FORWARD-BACKWARD ASYMMETRIES.

$(e^+e^- \rightarrow \mu^+\mu^-)$





* CROSS SECTIONS & PARTIAL WIDTHS

THE CROSS SECTION FROM THE $\cos\theta$-SYMMETRIC Z PRODUCTION TERM CAN ALSO BE WRITTEN AS:

$$\sigma^{Z}_{f\bar{f}} = \sigma^{peak}_{f\bar{f}} \frac{s\,\Gamma_Z^2}{(s-m_Z^2)^2 + s^2 \frac{\Gamma_Z^2}{m_Z^2}}$$

removes QED corr.

WITH $\sigma^{peak}_{f\bar{f}} = \boxed{\frac{1}{R_{QED}}} \sigma^0_{f\bar{f}}$ $\qquad \sigma^0_{f\bar{f}} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$

WHERE YOU HAVE THE PARTIAL DECAY WIDTHS OF THE INITIAL (Γ_{ee}) AND FINAL ($\Gamma_{f\bar{f}}$) STATES.

THE OVERALL HADRONIC WIDTH IS GIVEN AS

$$\Gamma_{had} = \sum_{q \neq t} \Gamma_{q\bar{q}}$$

HENCE THE TOTAL WIDTH CAN BE WRITTEN AS

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \underbrace{\Gamma_{inv.}}_{\Gamma_{inv} = N_\nu \Gamma_{\nu\bar{\nu}}}$$

AS WE MEASURE CROSS-SECTIONS WHICH DEPEND ON SEVERAL PARTIAL WIDTHS, THESE MEASUREMENTS ARE CORRELATED. THE USE OF A SET OF 6 PARAMETERS (MOTIVATED EXPERIMENTALLY):

- m_Z
- Γ_Z
- $\sigma^0_{had} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$ hadronic pole cross-se
- $R^0_e = \Gamma_{had}/\Gamma_{ee}$
- $R^0_\mu = \Gamma_{had}/\Gamma_{\mu\mu}$
- $R^0_\tau = \Gamma_{had}/\Gamma_{\tau\tau}$

} if universality is assumed this becomes 1 parameter

TRADITIONALLY THE BRANCHING RATIOS TO HEAVY QUARKS ARE TREATED INDEPENDENTLY

$$R_b^0 = \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}}$$

$$R_c^0 = \frac{\Gamma_{c\bar{c}}}{\Gamma_{had}}$$

THIS IS POSSIBLE WITH THE PRECISE TRACKING DETECTORS IN THE LEP & SLC DETECTORS.

SLD slightly better in heavy quark identification.

* INVISIBLE WIDTH & # NEUTRINOS

ASSUMING LEPTON UNIVERSALITY AND $R^0_{inv} = \Gamma_{inv}/\Gamma_{\ell\ell}$ WE OBTAIN

$$R^0_{inv} = \sqrt{\frac{12\pi R^0_\ell}{\sigma^0_{had}\, m_Z^2}} - R^0_\ell - (3 + \delta_Z)$$

↓ effect of Z mass

$\delta_Z \simeq -0.23\%$

HENCE ASSUMING ONLY INVISIBLE DECAYS TO NEUTRINOS AND THE SM PREDICTION FOR $\Gamma_{\nu\bar{\nu}}/\Gamma_{\ell\ell}$ WE CAN ESTIMATE THE NUMBER OF NEUTRINOS

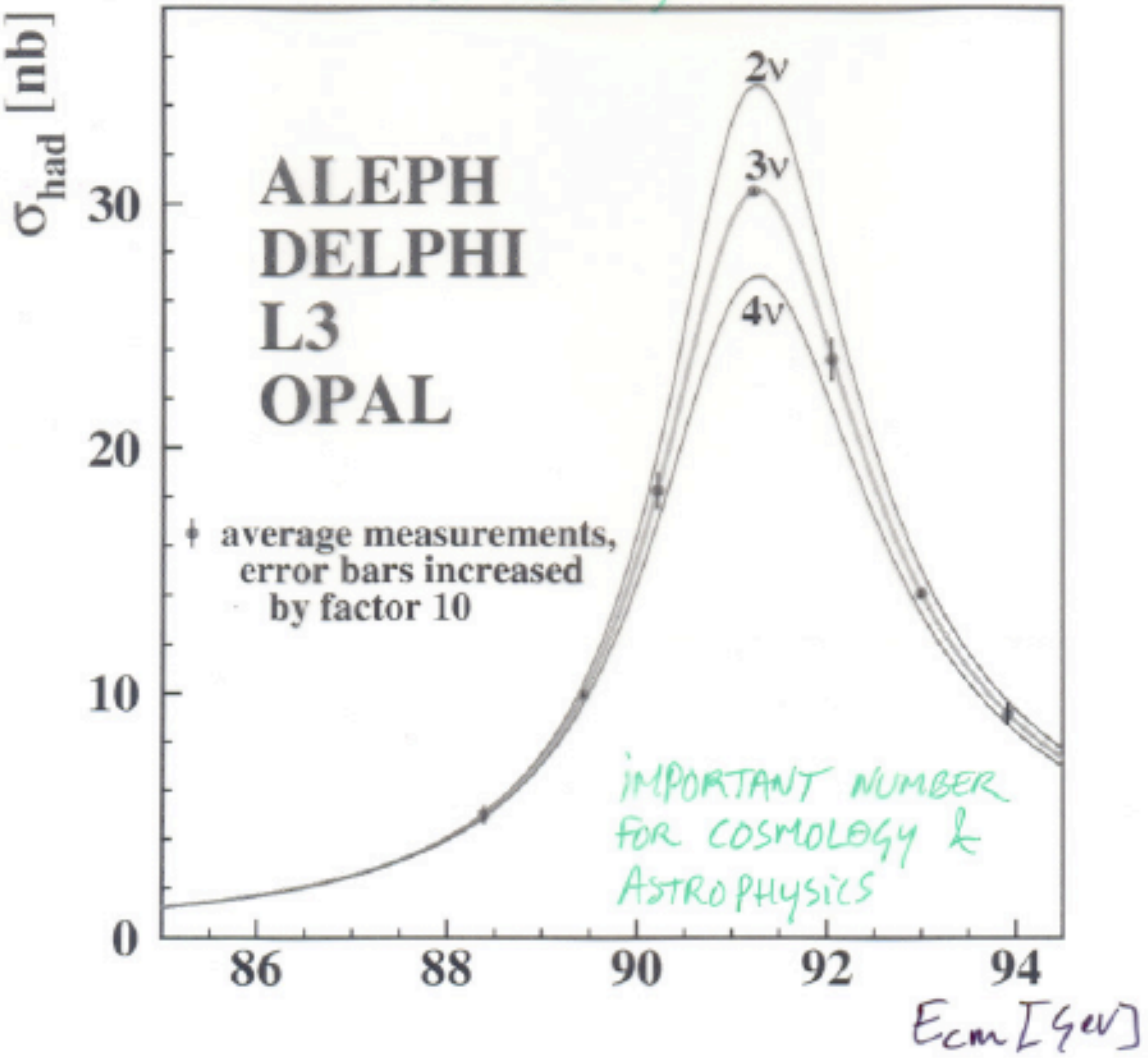
$$R^0_{inv} = N_\nu \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\ell\ell}}\right)_{SM}$$

DEPENDS ON HADRONIC CROSS SECTION (→ cfr. plot)

DEPENDENCY OF HADRONIC CROSS SECTION ON THE NUMBER OF NEUTRINO SPECIES.

$N_\nu = 2.9840 \pm 0.0082$

(2σ below 3)



IMPORTANT NUMBER FOR COSMOLOGY & ASTROPHYSICS

* ASYMMETRIES & POLARISATION

ADDITIONAL OBSERVABLES ARE INTRODUCED TO DESCRIBE THE $\cos\theta$ DEPENDENCY in $d\sigma_{f\bar{f}}/d\cos\theta$. THEY QUANTIFY THE AMOUNT OF PARITY VIOLATION OF THE NEUTRAL CURRENT, HENCE THE VECTOR & AXIAL-VECTOR COUPLINGS TO THE Z BOSON.

$\Rightarrow$ MEASURE OF $\sin^2\theta^f_{eff}$

(i). EVEN IF THE INITIAL ELECTRONS & POSITRONS ARE NOT POLARISED, THE Z BOSON CAN HAVE A LONGITUDINAL POLARIZATION IN ITS DECAY. THIS BECAUSE THE LEFT-RIGHT-HANDED COUPLING TO FERMIONS ARE UNEQUAL. HENCE THE ANGULAR DISTRIBUTION WILL BE FORWARD-BACKWARD ASYMMETRIC.

THE Z EXCHANGE CROSS SECTION CAN BE WRITTEN AS

$$\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{3}{8}\sigma^{tot}_{f\bar{f}}\left[(1-P_e A_e)(1+\cos^2\theta) + 2(A_e - P_e)A_f\cos\theta\right]$$

electron beam polarisation
(assuming no positron polarisation)

WITH

$$A_f = \frac{g^2_{Lf} - g^2_{Rf}}{g^2_{Lf} + g^2_{Rf}} = \frac{2\,g_{Vf}\,g_{Af}}{g^2_{Vf} + g^2_{Af}} = 2\,\frac{g_{Vf}/g_{Af}}{1 + \left(g_{Vf}/g_{Af}\right)^2}$$

WHERE THE LAST TERM CLEARLY SHOWS THE DEPENDENCY ON $\sin^2\theta_W$

WHEN INTEGRATING THE CROSS SECTIONS OVER THE FORWARD OR BACKWARD HEMISPERE WE OBTAIN

σ_F : forward
σ_B : backward

IDENTICAL FOR RIGHT & LEFT ELECTRON HELICITIES.

THREE BASIC ASYMMETRIES CAN BE MEASURED

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

⇝ picks out the coefficient $A_e A_f$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \cdot \frac{1}{\langle P_e \rangle}$$

⇝ picks out the coefficient A_e

$$A_{LRFB} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} \cdot \frac{1}{\langle P_e \rangle}$$

⇝ picks out the coefficient A_f

(ii) POLARISATION OF A FINAL-STATE FERMION IS THE DIFFERENCE BETWEEN THE CROSS SECTIONS FOR RIGHT- AND LEFT-HANDED FINAL STATE HELICITIES DIVIDED BY THEIR SUM

$$P_f = \frac{d(\sigma_R - \sigma_L)/d\cos\theta}{d(\sigma_R + \sigma_L)/d\cos\theta}$$

AGAIN WE CAN INTEGRATE OVER FORWARD AND BACKWARD HEMISPHERES :

$$\langle P_f \rangle = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \quad \rightsquigarrow \text{ picks out } A_f$$

$$A_{FB}^{pol} = \frac{(\sigma_R - \sigma_L)_F - (\sigma_R - \sigma_L)_B}{(\sigma_R + \sigma_L)_F + (\sigma_R + \sigma_L)_B} \quad \rightsquigarrow \text{ picks out } A_e$$

THESE VARIABLES CAN BE OBTAINED FROM A MEASUREMENT OF

$$P_f(\cos\theta) = -\frac{A_f(1+\cos^2\theta) + 2A_e\cos\theta}{(1+\cos^2\theta) + 2A_f A_e \cos\theta}$$

WHICH IS ONLY MEASURED FOR τ-LEPTONS IN THE FINAL STATE OF WHICH WE CAN OBTAIN THE POLARISATION

HENCE ALL TOGETHER WHEN WE MEASURE THE ASYMMETRIES (FORWARD-BACKWARD AND/OR LEFT-RIGHT) WE CAN RELATE THEM TO THE PARAMETERS A_f :

$$A_{FB}^{0,f} = \frac{3}{4} A_e A_f$$

$$A_{LR}^{0} = A_e \longrightarrow$$

using this LEP can also measure A_f

$$A_{LRFB}^{0} = \frac{3}{4} A_f$$

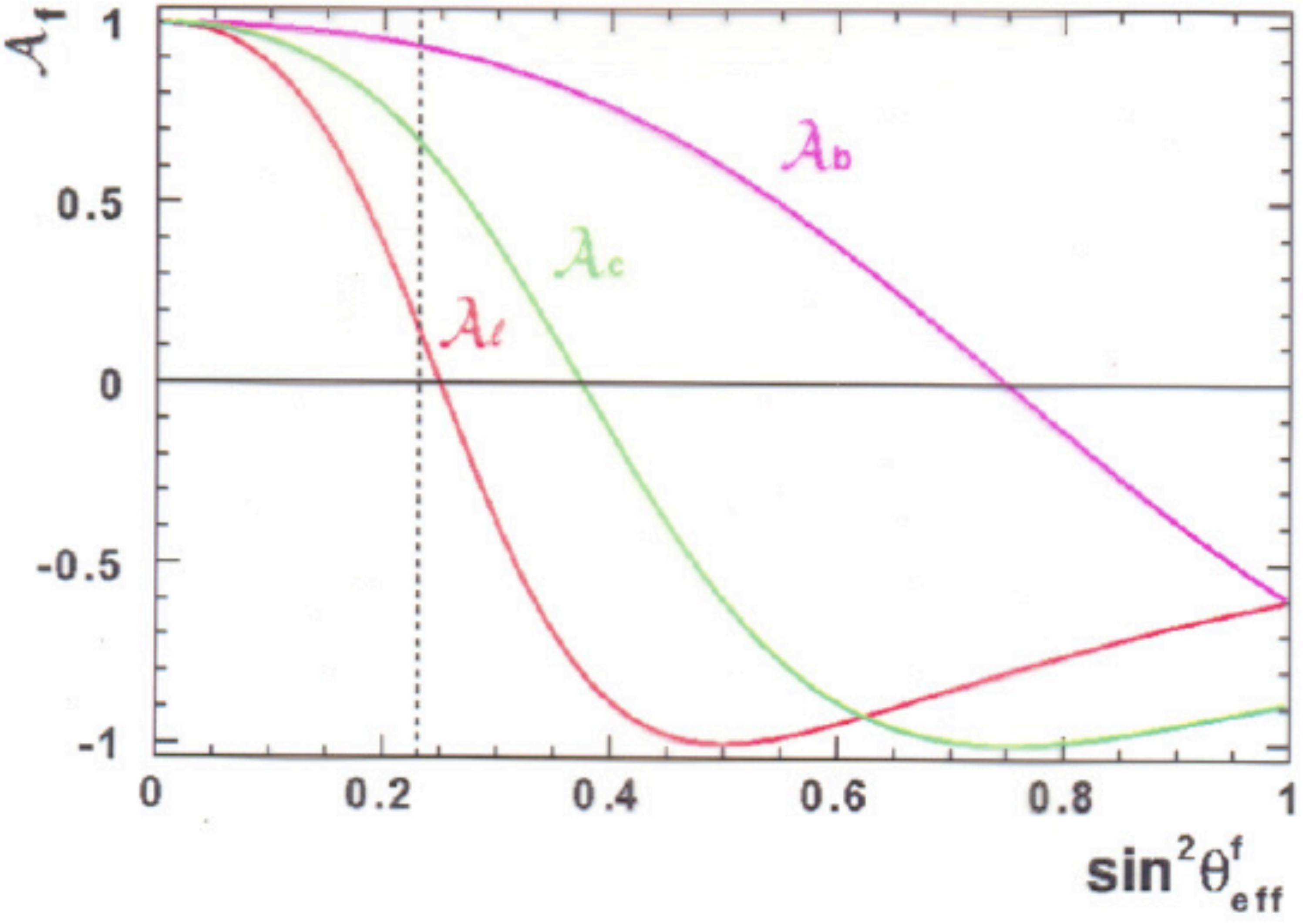
$$\langle P_\tau^0 \rangle = -A_\tau$$

$$A_{FB}^{pol,0} = -\frac{3}{4} A_e$$

LEP: A_{FB}^{0} for all final states & P_τ

SLD: A_{LR}^{0} , A_{LRFB}^{0} for all final states

SENSITIVITY OF $\mathcal{A}_f$ TO $\sin^2\theta^f_{eff}$



FROM THEORY TO EXPERIMENT

THE ABOVE PARAMETERS ARE NOT "REALISTIC OBS" BUT WHICH HAVE SIGNIFICANT THEORY CORRECTIONS

→ PSEUDO – OBSERVABLES

(denoted by superscript o)

eg. σ_{had} is the measured hadronic cross section
σ^{o}_{had} is the pole cross-section derived from σ_{had}

R_b is the measurement of b-quark cross section divided by the hadronic one $\sigma_{b\bar{b}}/\sigma_{had}$
R^{o}_{b} is $\Gamma_{b\bar{b}}/\Gamma_{had}$ derived from this

THE EXPERIMENTAL CROSS SECTIONS & ASYMMETRIES ARE MEASURED IN THE ACCEPTANCE OF THE DETECTOR

→ CORRECT THEM BY EXTRAPOLATING TO PERFECT (= FULL) ACCEPTANCE

NINE PSEUDO-OBSERVABLES DESCRIBE THE Z RESONANCE IN A MODEL INDEPENDENT WAY.
("THEORY" & "EXPERIMENT" REMAIN DISTINCT)

m_Z , Γ_Z , σ^{o}_{had} , R^{o}_{ℓ} , $A^{o,\ell}_{FB}$

A^{o}_{LR} , A^{o}_{LRFB} , $\langle P^{o}_{\tau} \rangle$, $A^{pol,o}_{FB}$

need a fit to take into account the correlations between them, only then an interpretation is possible

LEP RESULTS IN THE LEPTON SECTOR

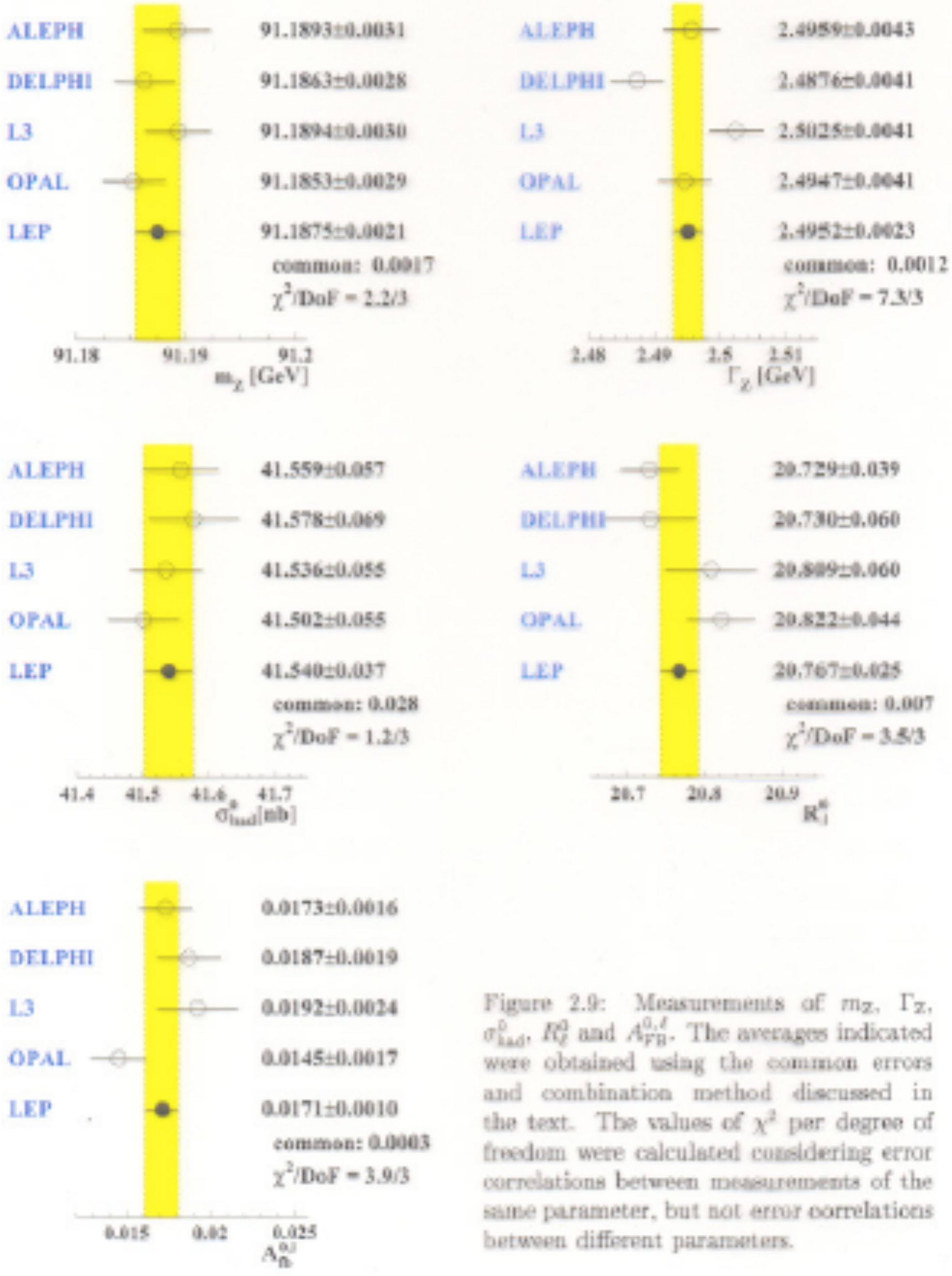


Figure 2.9: Measurements of m_Z, Γ_Z, σ^0_{had}, R^0_ℓ and $A^{0,\ell}_{FB}$. The averages indicated were obtained using the common errors and combination method discussed in the text. The values of χ^2 per degree of freedom were calculated considering error correlations between measurements of the same parameter, but not error correlations between different parameters.

GOOD COMPARISON BETWEEN LEPTON FLAVOURS

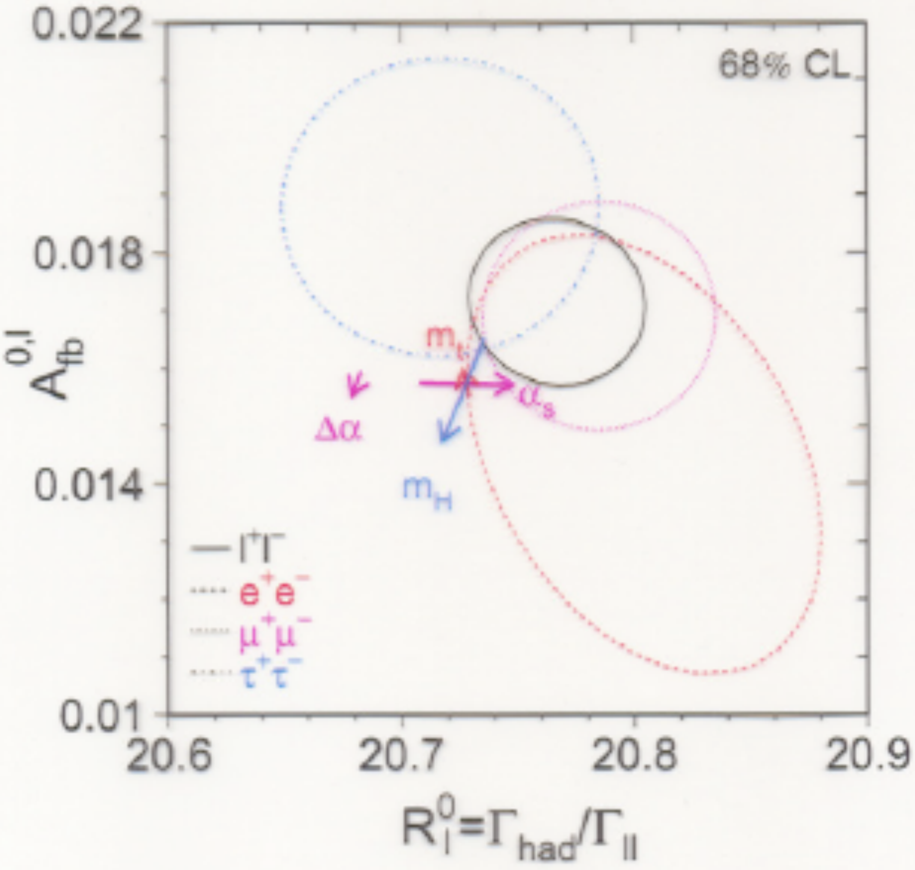


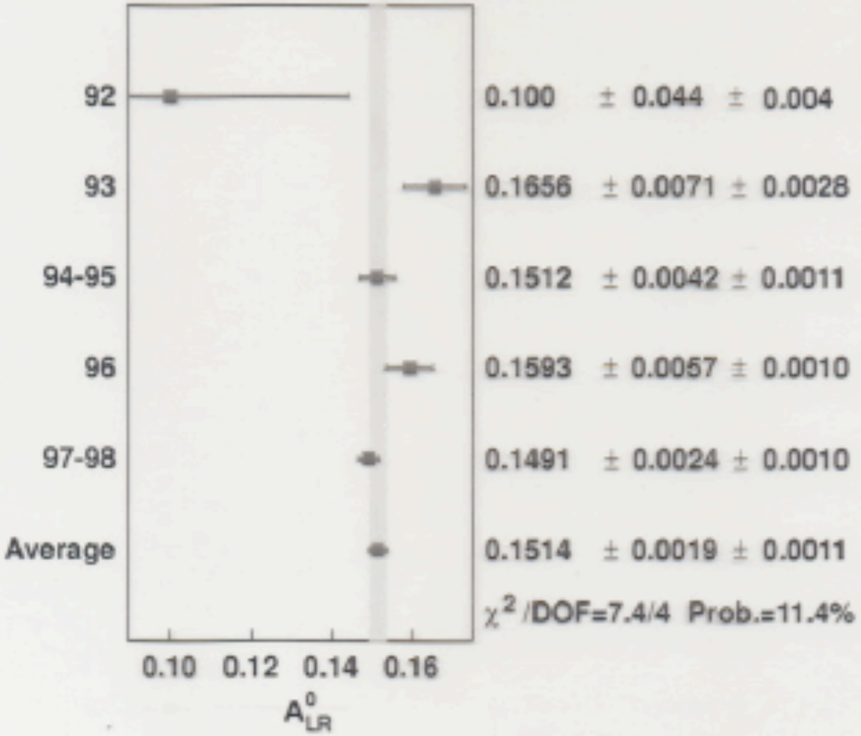
Figure 2.11: Contour lines (68 % CL) in the R^0_ℓ–$A^{0,\ell}_{\rm FB}$ plane for e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states and for all leptons combined. For better comparison the results for the τ lepton are corrected to correspond to the massless case. The SM prediction for $m_Z = 91.1875$ GeV, $m_t = 178.0$ GeV, $m_H = 300$ GeV, and $\alpha_S(m_Z^2) = 0.118$ is also shown as the intersection of the lines with arrows, which correspond to the variation of the SM prediction when m_t, m_H and $\alpha_S(m_Z^2)$ are varied in the intervals $m_t = 178.0 \pm 4.3$ GeV, $m_H = 300^{+700}_{-186}$ GeV, and $\alpha_S(m_Z^2) = 0.118 \pm 0.003$, respectively. The arrow showing the small dependence on the hadronic vacuum polarisation $\Delta\alpha^{(5)}_{\rm had}(m_Z^2) = 0.02758 \pm 0.00035$ is displaced for clarity. The arrows point in the direction of increasing values of these parameters.

MEASUREMENT OF THE LEFT-RIGHT ASYMMETRY BY SLC

NEEDED FOR A PRECISE DETERMINATION OF $\mathcal{A}_e$

COUNT THE NUMBER OF Z BOSONS PRODUCED BY LEFT AND RIGHT LONGITUDINALLY POLARISED ELECTRONS

$$A_{LR} = \frac{N_L - N_R}{N_L + N_R} \frac{1}{\langle P_e \rangle}$$



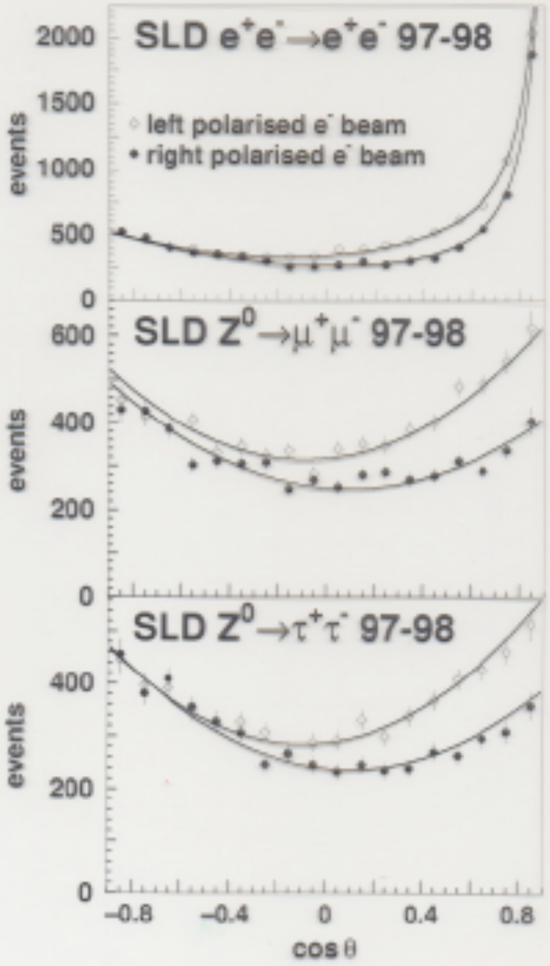
$$A^0_{LR} = \frac{2\left(1-4\sin^2\theta^{lept}_{eff}\right)}{1+\left(1-4\sin^2\theta^{lept}_{eff}\right)^2}$$

$$\Rightarrow \quad \sin^2\theta^{lept}_{eff} = 0.23097 \pm 0.00027$$

LEPTON ASYMMETRY MEASUREMENTS

VIA MEASUREMENTS OF $A^{0,\ell}_{LRFB} = \frac{3}{4}|P_e|A_\ell$

OBTAINED FROM A FIT ON $d\sigma/d\cos\theta$



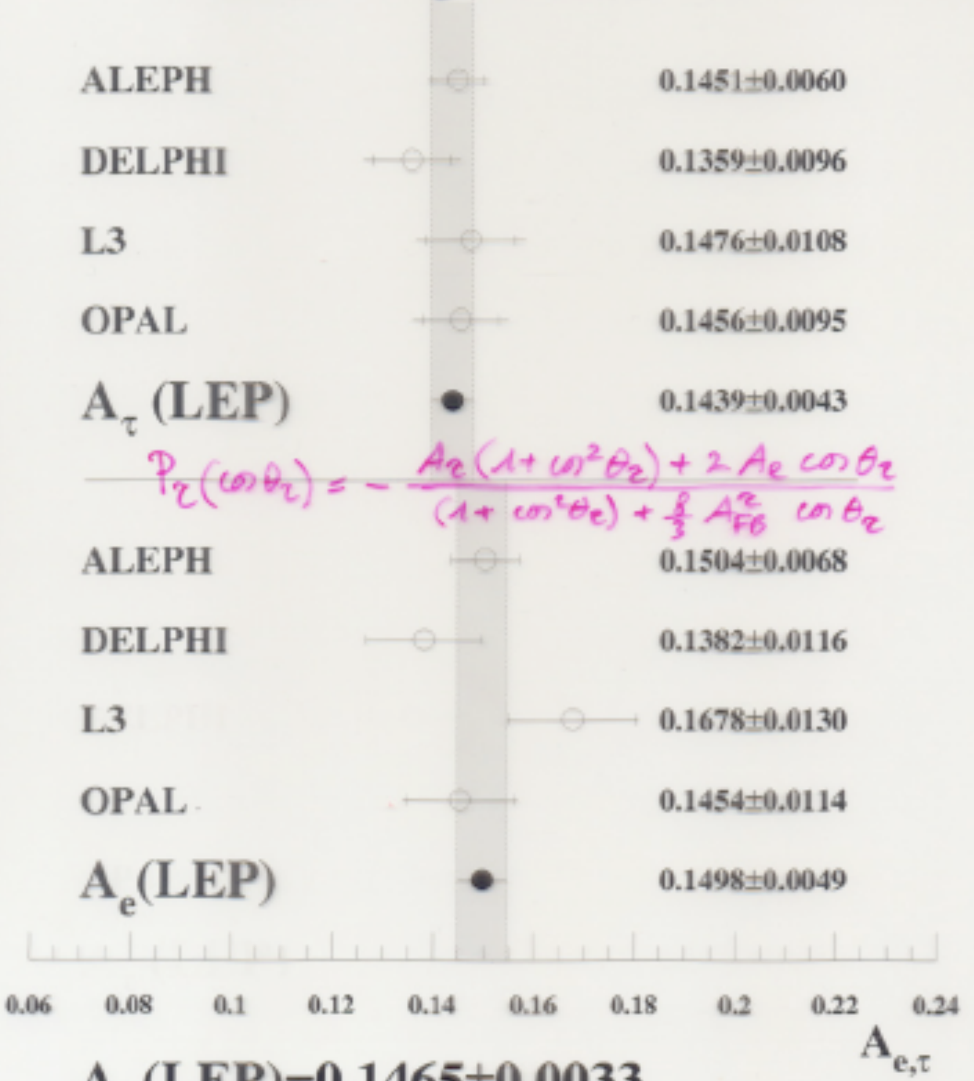
$A_\ell = 0.1513 \pm 0.001$

$\Rightarrow \sin^2\theta^{lept}_{eff} = 0.23098 \pm 0.00026$

THE τ POLARISATION MEASUREMENTS

DEPENDS ON THE DEPENDENCE OF KINEMATIC DISTRIBUTIONS OF THE OBSERVED τ DECAY ON THE HELICITY OF THE PARENT τ LEPTON.

⇒ EXTRACT P_τ AS A FUNCTION OF $\cos\theta_\tau$



$$P_\tau(\cos\theta_\tau) = -\frac{A_\tau(1+\cos^2\theta_\tau)+2A_e\cos\theta_\tau}{(1+\cos^2\theta_\tau)+\frac{8}{3}A_{FB}^{\tau}\cos\theta_\tau}$$

A_l (LEP)=0.1465±0.0033

χ^2/DoF=4.7/7

$\Rightarrow \sin^2\theta_{eff}^{lept} = 0.23159 \pm 0.00041$

HEAVY FLAVOUR PARTIAL WIDTH (using b- and c-tagging)

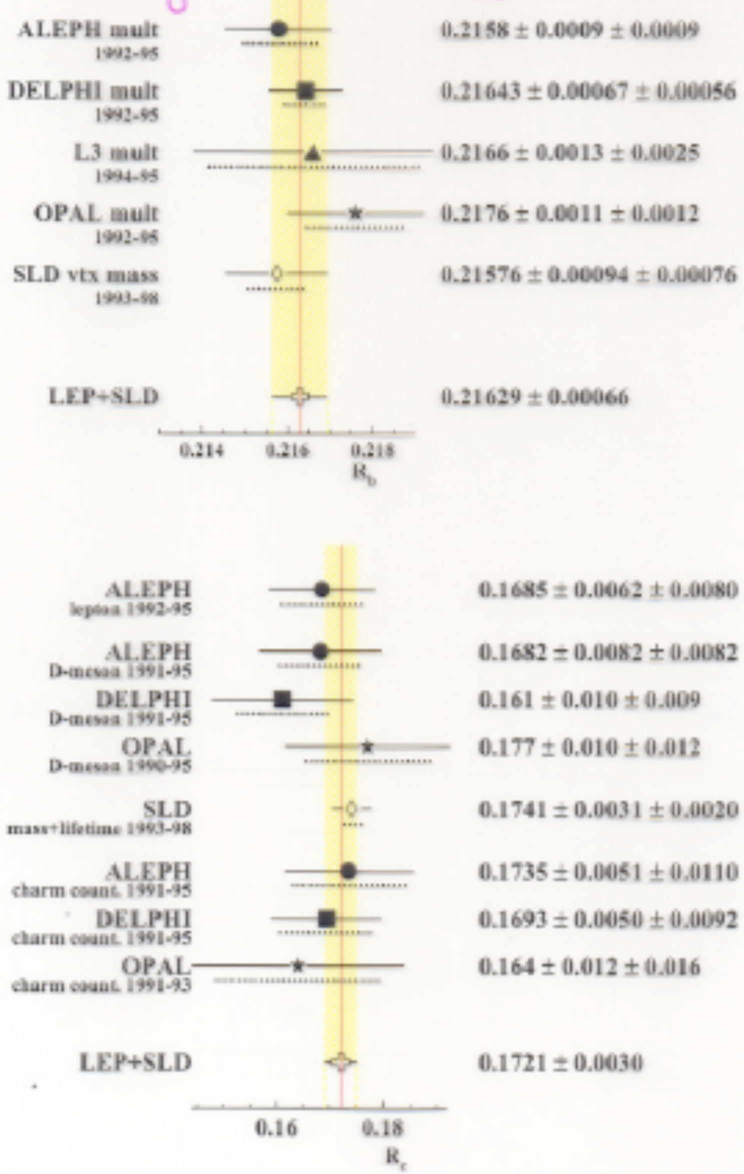


Figure 5.13: R_b^0 and R_c^0 measurements used in the heavy flavour combination, corrected for their dependence on parameters evaluated in the multi-parameter fit described in the text. The dotted lines indicate the size of the systematic error.

HEAVY FLAVOUR ASYMMETRIES

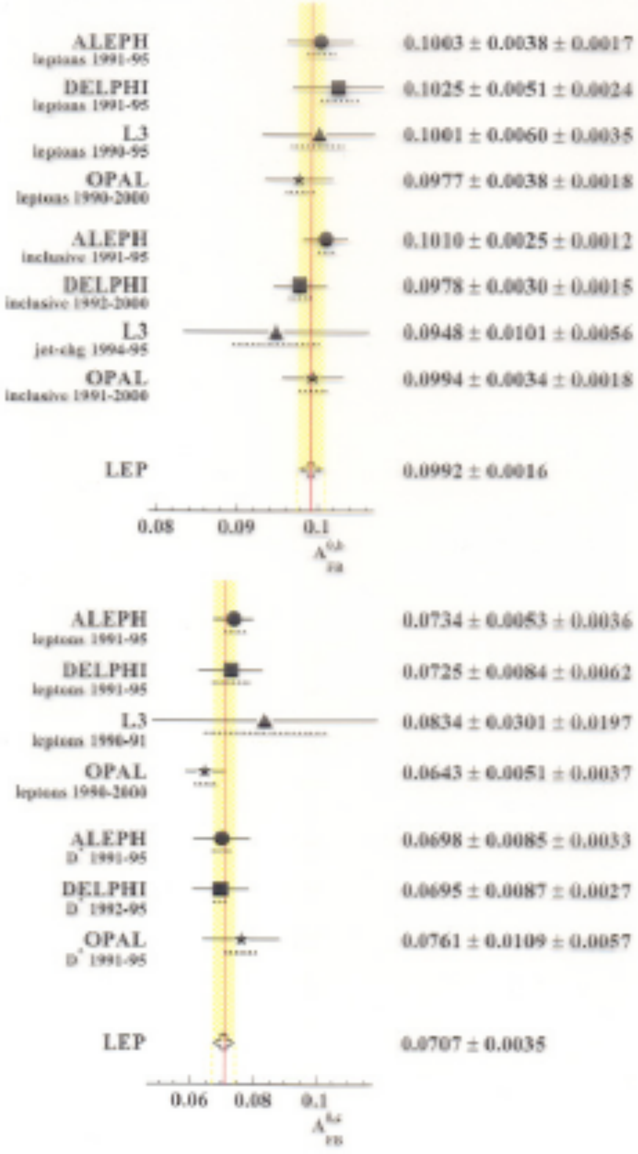


Figure 5.14: $A_{FB}^{0,b}$ and $A_{FB}^{0,c}$ measurements used in the heavy flavour combination, corrected for their dependence on parameters evaluated in the multi-parameter fit described in the text. The $A_{FB}^{0,b}$ measurements with D-mesons do not contribute significantly to the average and are not shown in the plots. The experimental results are derived from the ones shown in Tables C.3 to C.8 combining the different centre of mass energies. The dotted lines indicate the size of the systematic error.

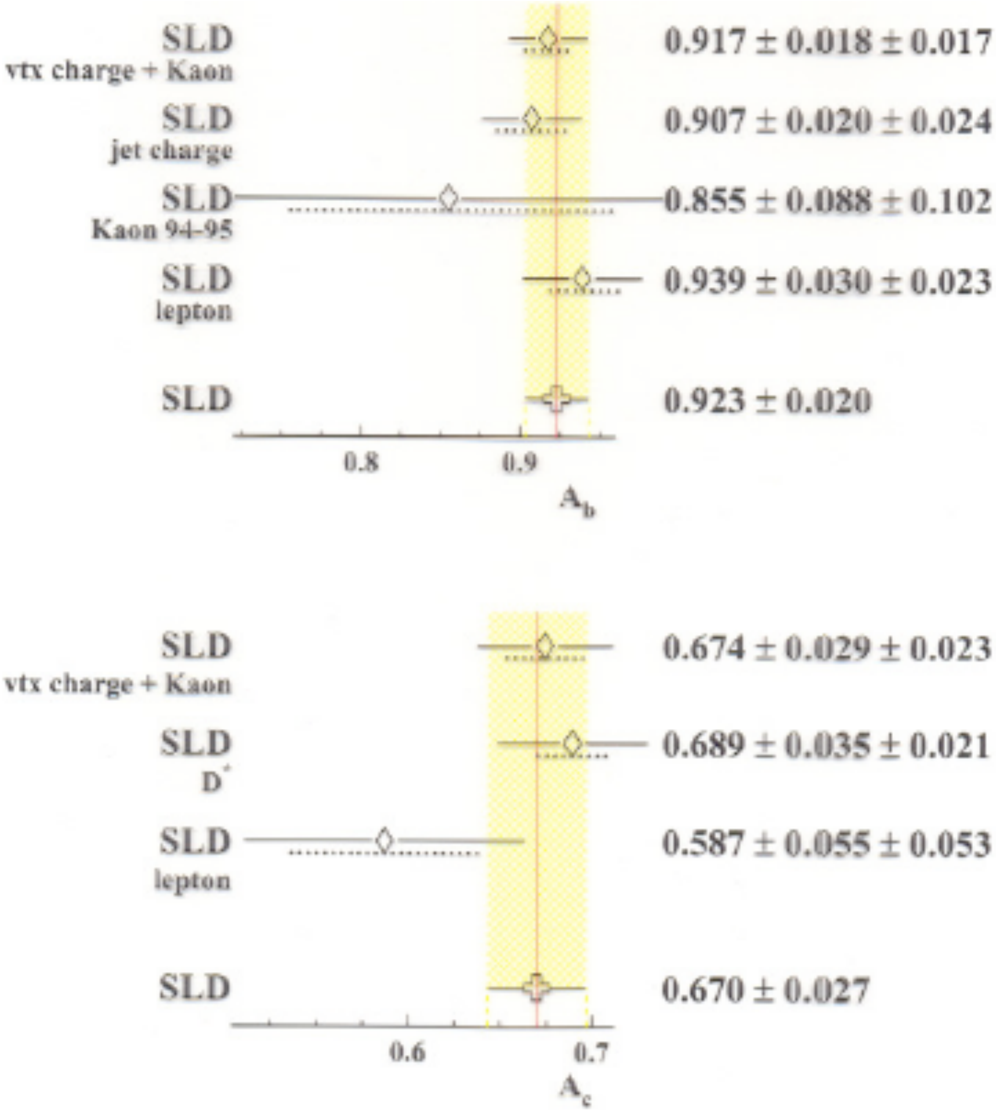
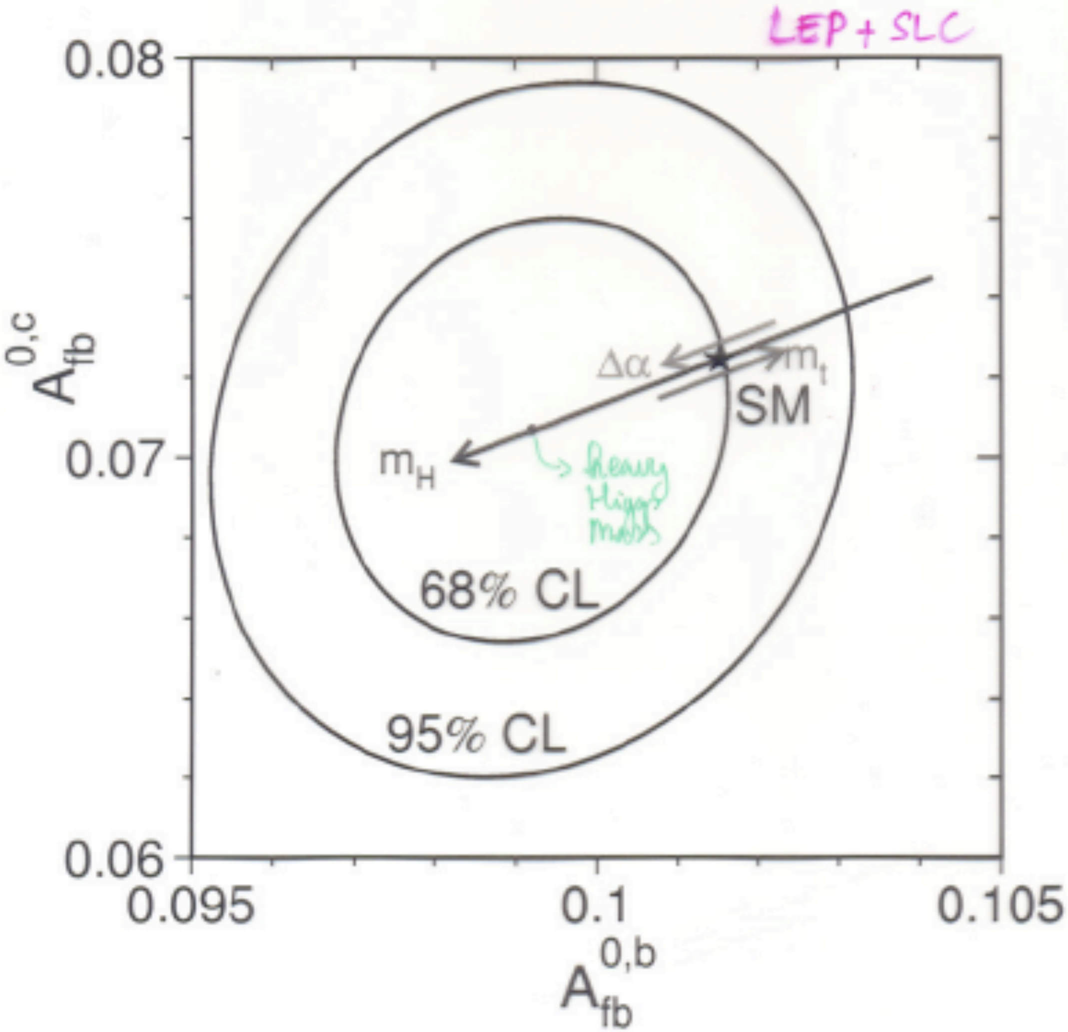


Figure 5.15: $\mathcal{A}_b$ and $\mathcal{A}_c$ measurements used in the heavy flavour combination, corrected for their dependence on parameters evaluated in the multi-parameter fit described in the text. The dotted lines indicate the size of the systematic error.

FINAL VALUES FOR R_b^0, R_c^0, $A_{FB}^{0,b}$, $A_{FB}^{0,c}$, A_b, A_c ARE OBTAIN FROM A MULTIPARAMETER FIT

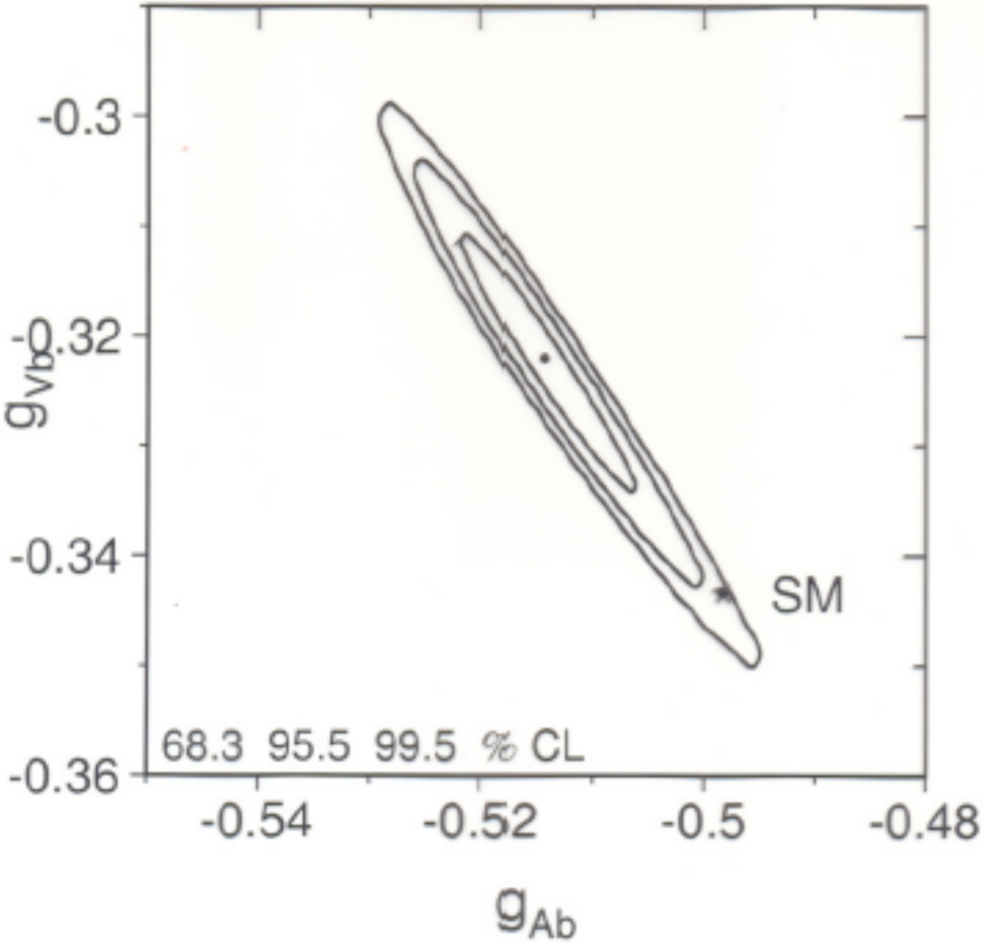
→ GOOD AGREEMENT ILLUSTRATED BELOW

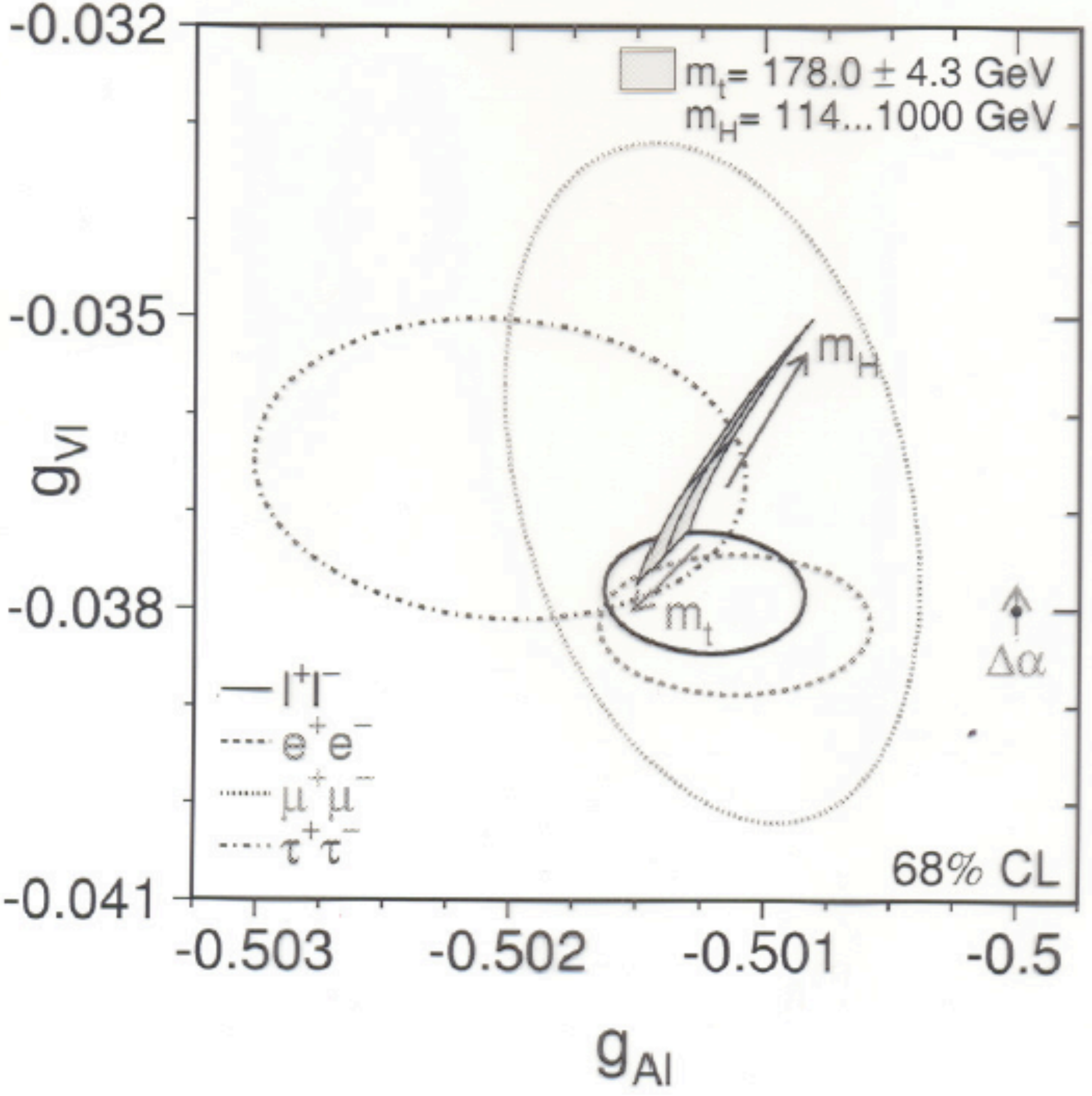


WITH THE SM EQUATIONS WE HAVE SEEN WE CAN TRANSFORM THE PSEUDO-OBSERVABLES INTO EFFECTIVE COUPLINGS OF THE NEUTRAL WEAK CURRENT :

A_f , (g_{Vf}, g_{Af}) , (g_{Lf}, g_{Rf}) , ρ_f , $\sin^2\theta_{eff}^f$

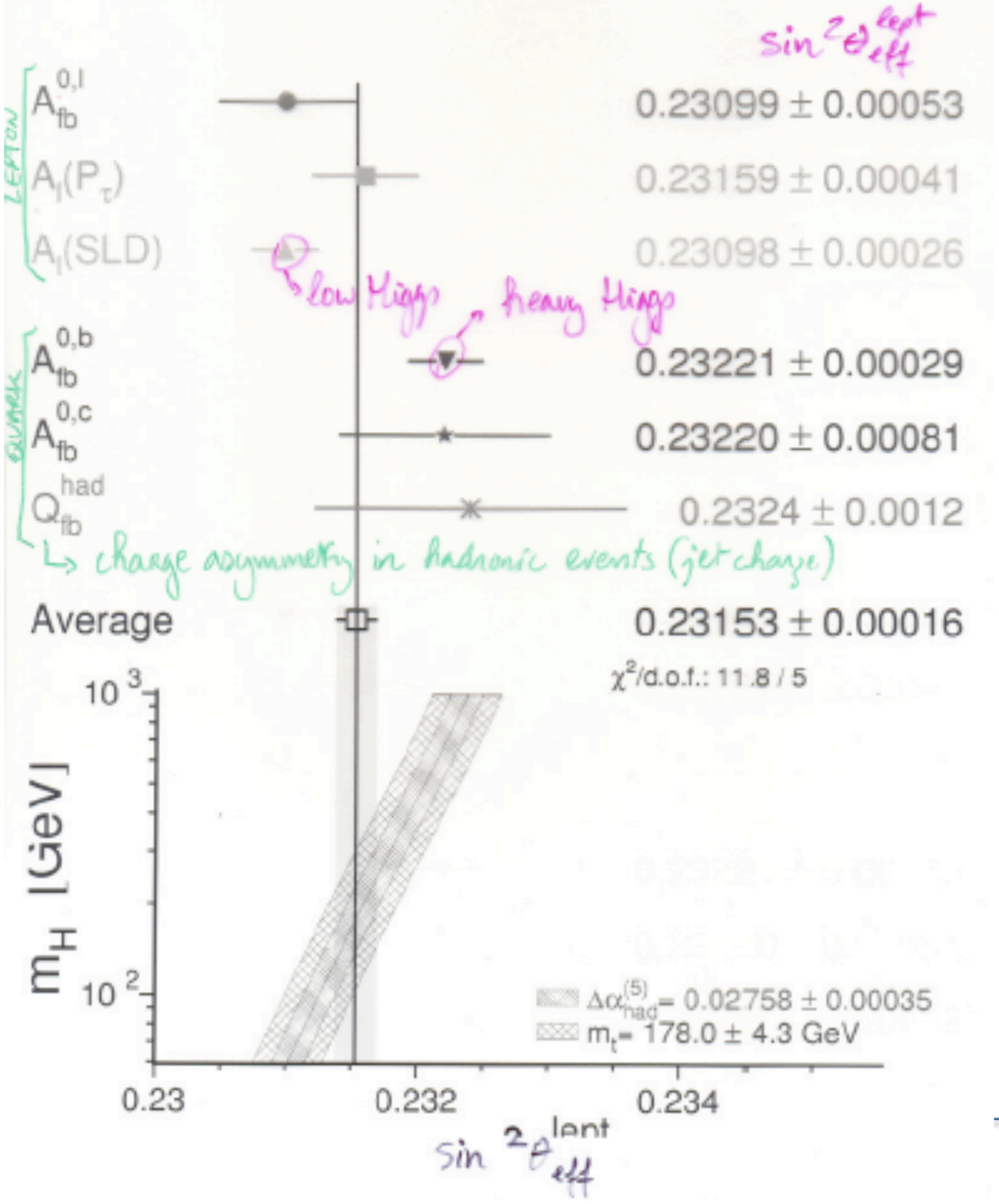
↓ ↓ EXAMPLES

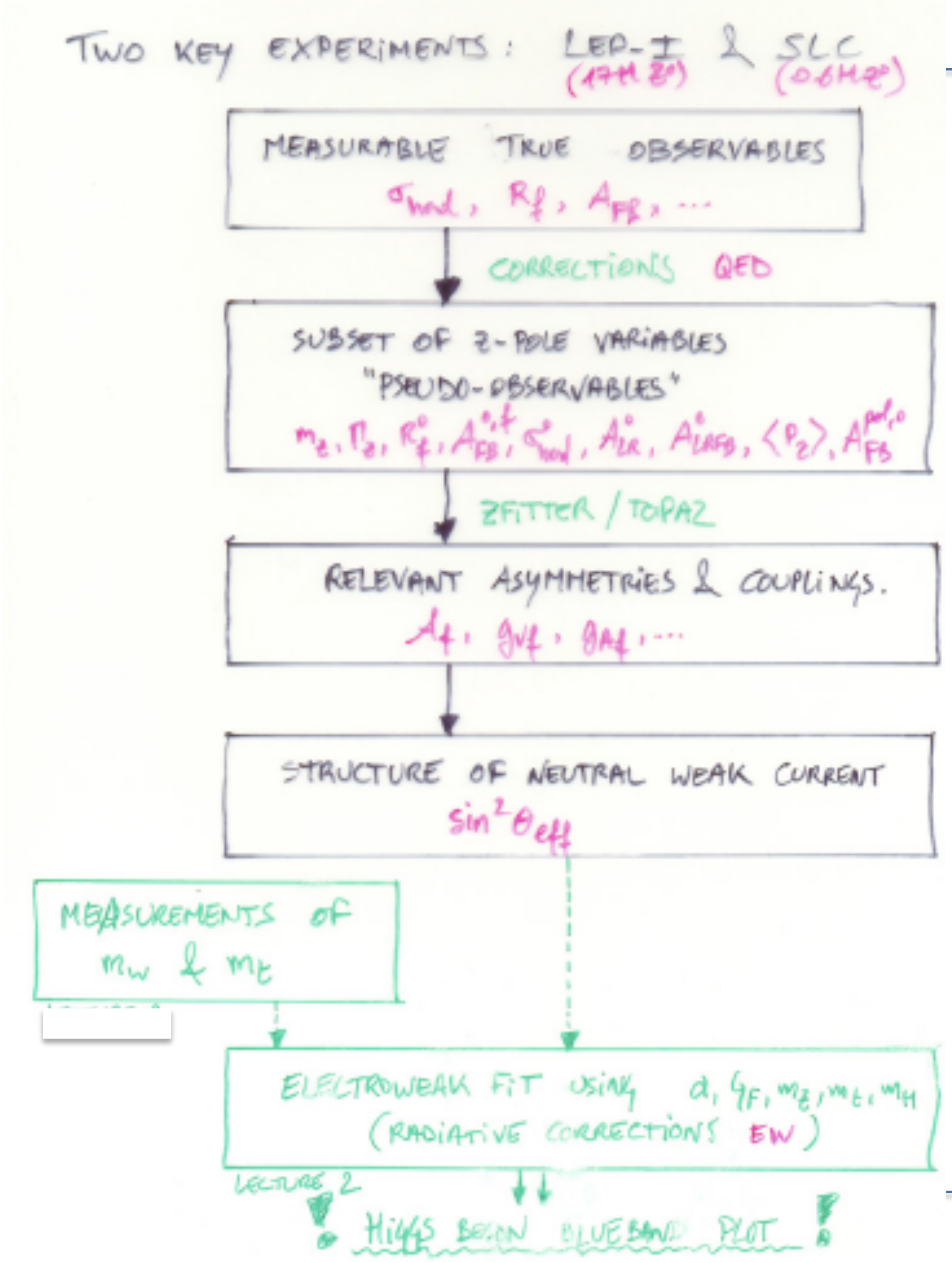




-0.032
-0.035
-0.038
-0.041
g_{Vl}
-0.503
-0.502
-0.501
-0.5
g_{Al}
m_t= 178.0 ± 4.3 GeV
m_H= 114...1000 GeV
m_H
m_t
$\Delta\alpha$
l^+l^-
e^+e^-
$\mu^+\mu^-$
$\tau^+\tau^-$
68% CL

PUTTING THE ASYMMETRIES TOGETHER




TWO KEY EXPERIMENTS : LEP-I & SLC
(17M Z°) (0.6M Z°)
MEASURABLE TRUE OBSERVABLES
σ_{had}, R_f, A_{FB}, ...
CORRECTIONS QED
SUBSET OF Z-POLE VARIABLES
"PSEUDO-OBSERVABLES"
m_Z, Γ_Z, R_f^0, $A_{FB}^{0,f}$, σ_{had}^0, A_{LR}^0, A_{LRFB}^0, $\langle P_\tau \rangle$, $A_{FB}^{pol,0}$
ZFITTER / TOPAZ
RELEVANT ASYMMETRIES & COUPLINGS.
A_f, g_{Vf}, g_{Af}, ...
STRUCTURE OF NEUTRAL WEAK CURRENT
$\sin^2\theta_{eff}$
MEASUREMENTS OF
m_W & m_t
ELECTROWEAK FIT USING α, G_F, m_Z, m_t, m_H
(RADIATIVE CORRECTIONS EW)
LECTURE 2
HIGGS BOSON BLUEBAND PLOT

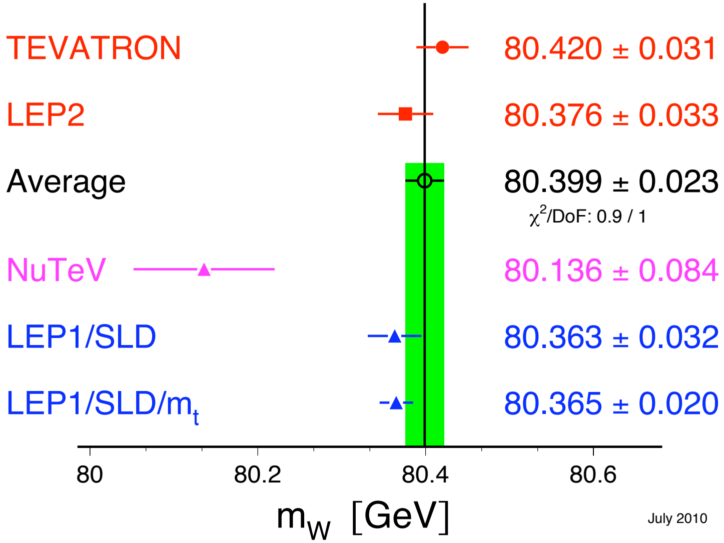
The general concept of the ElectroWeak fit

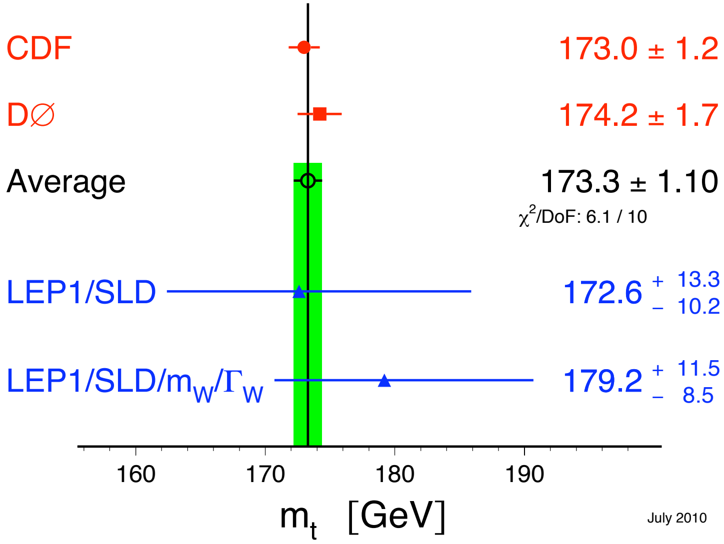
- Aim is to predict the Standard Model parameters which are not predicted by the theory (eg. m_H) and this via measurements and Standard Model relations.
- The measured observables ($\sin^2\theta_{W,eff}$, m_W, ...) do depend on the free Standard Model parameters (m_t, m_H, α, G_F, m_Z).
- Hence we can constrain the value of the remaining unknown free parameters (m_H).
- All measurements should predict the same Standard Model parameter values to believe in the consistency of the Standard Model.
- This is done within a global least-square fit: *the EW fit*

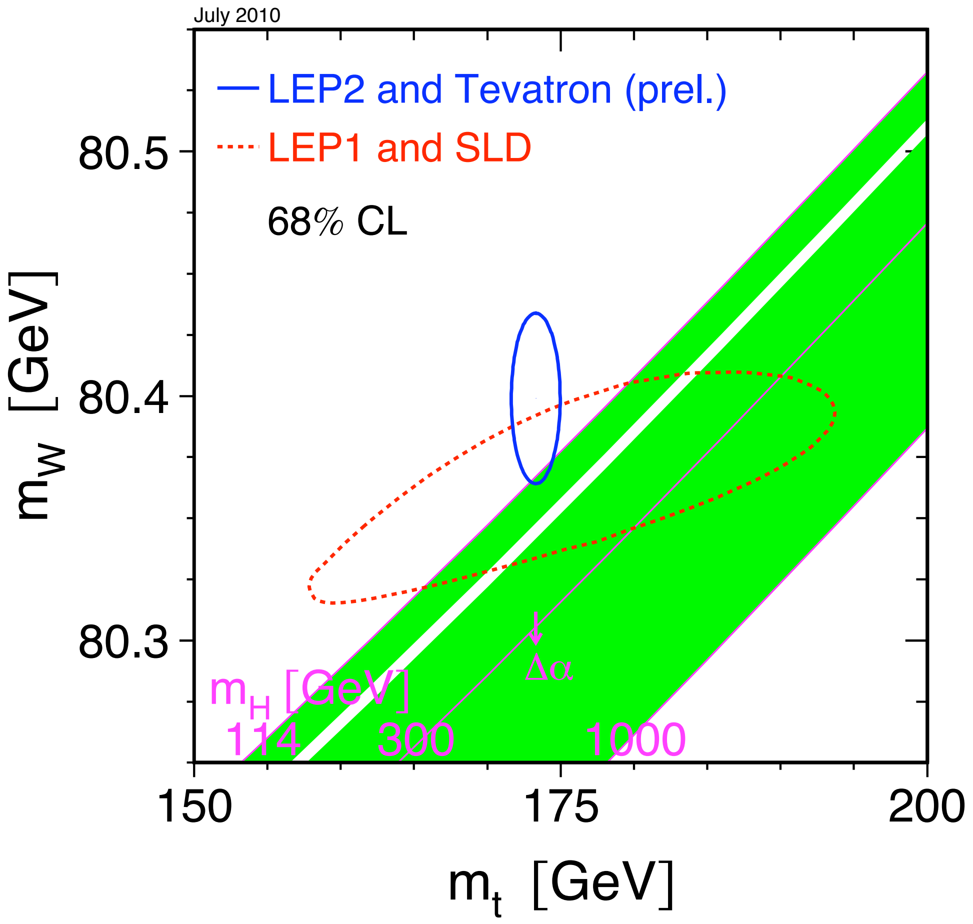
- Example

m_W measured ↔ $m_W = m_W(m_t, m_H, \alpha, G_F, m_Z)$

The general concept of the ElectroWeak fit







The free parameters in the fit

- The Standard Model gives a unified description of Electro-Magnetic & Weak interactions, hence the weak coupling is related to the EM coupling → only 2 coupling constants remain independent
  1) α : EM interactions (fine structure constant)
  2) α_s : strong interactions

- Among the fermion masses only the top quark mass plays an important role (all others are well enough determined and can be assumed fixed) as they have $m_f << m_Z$ and do not influence the observations at high energies significant: m_t

- Among the boson masses the Z boson mass (m_Z) is very well measured while the W boson mass not that presice. The free parameter m_W has been replaced by G_F, hence m_W becomes a quantity derived from the SM relations or the EW fit.

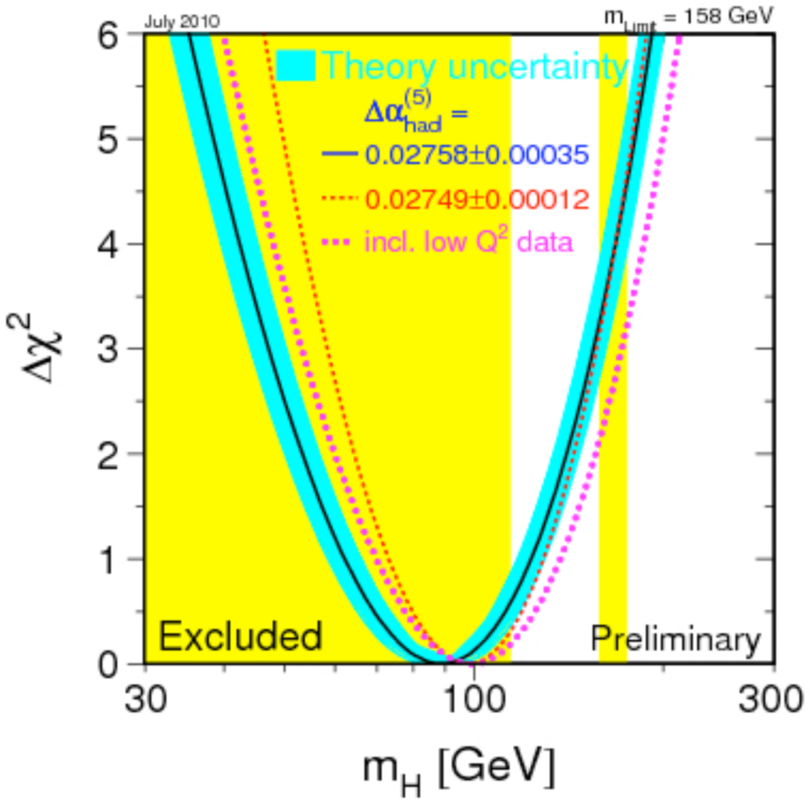
- The Higgs boson mass (m_H).

→ the free parameters are $\alpha_s(m_Z^2)$, $\alpha(m_Z^2)$, m_Z, m_t, m_H, G_F

The ElectroWeak fit: the result

- Five relevant input parameters of the Standard Model relations

  $\alpha_s(m_Z^2)$, $\alpha(m_Z^2)$, m_Z, m_t, m_H, G_F
- Given these parameters we can obtain indirect measurements of the observables measured directly by LEP, SLC, Tevatron.



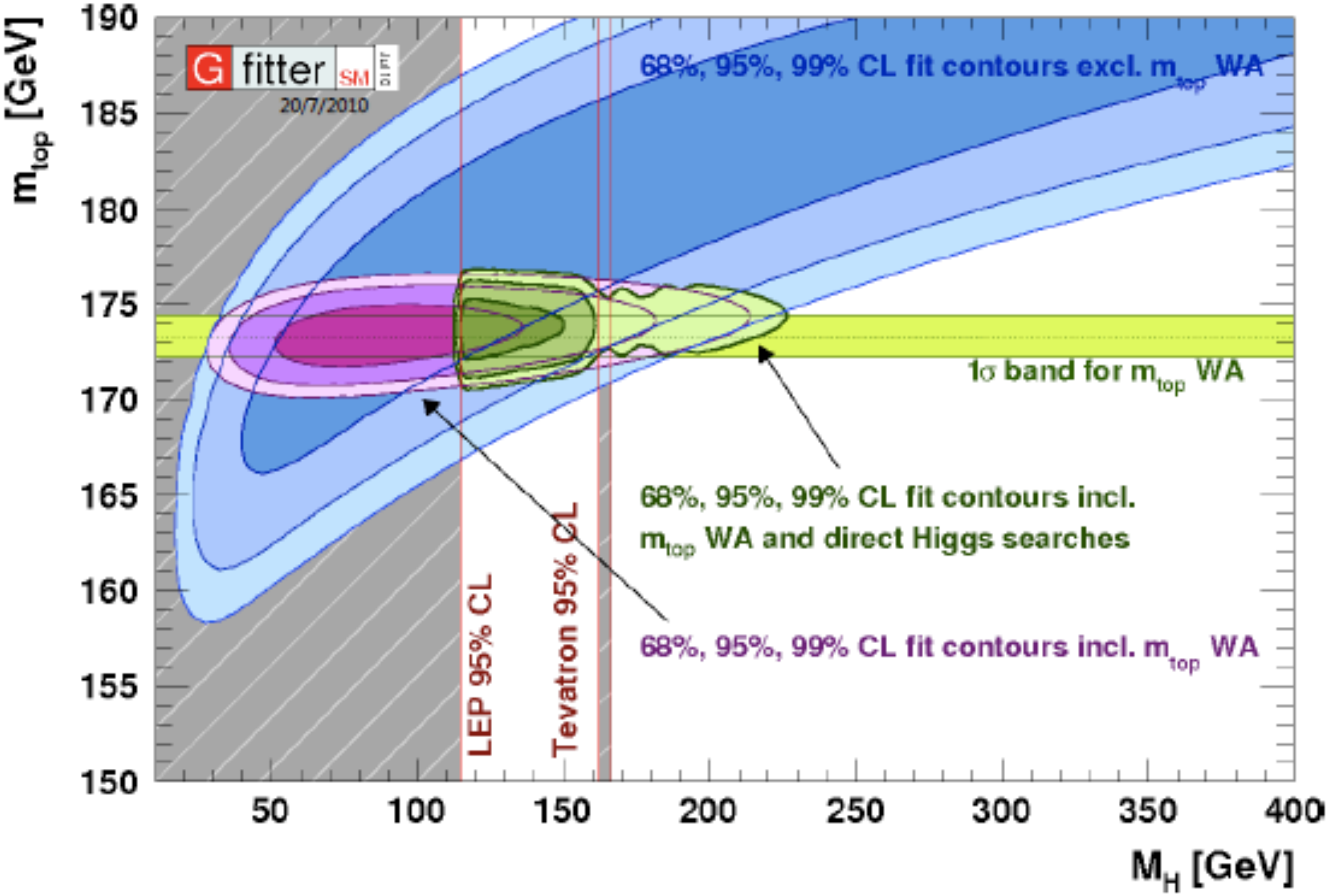
- These predictions go through radiative corrections calculated to some precision

  → **blueband in the plot**

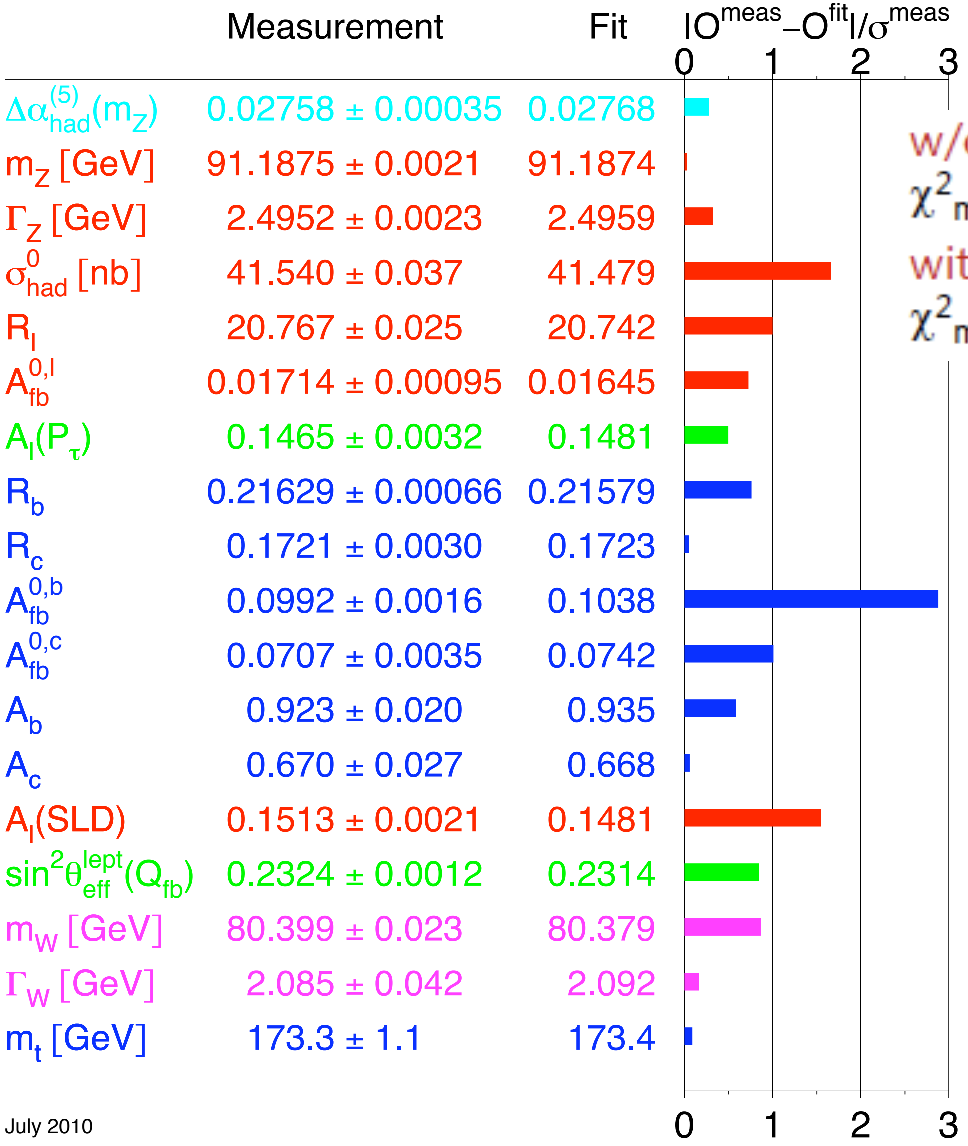
  (eg. 2-loop fermionic and bosonic corrections for the calculation of m_W)
- On each of the input parameters there is some uncertainty, hence we derive a confidence interval where the observed quantity should have its value give the SM relations

  → **reflected in the $\Delta\chi^2(m_H)$**

Top quark mass is very important



Interpretation



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
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	41.479
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
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	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

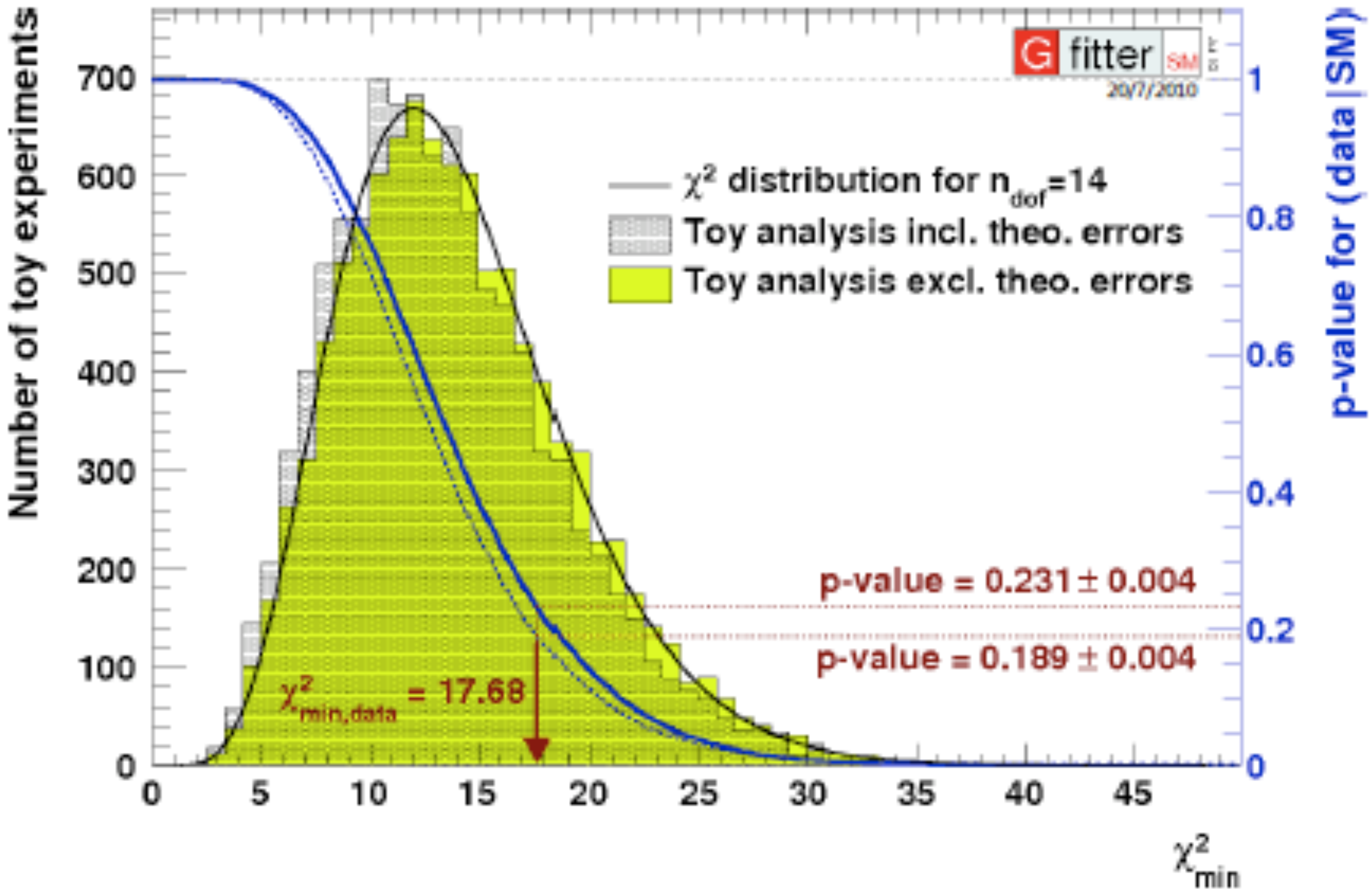
w/o direct Higgs searches:

$\chi^2_{min}=16.4 \rightarrow \mathrm{Prob}(\chi^2_{min},13)=0.23$

with direct Higgs searches:

$\chi^2_{min}=17.8 \rightarrow \mathrm{Prob}(\chi^2_{min},14)=0.22$

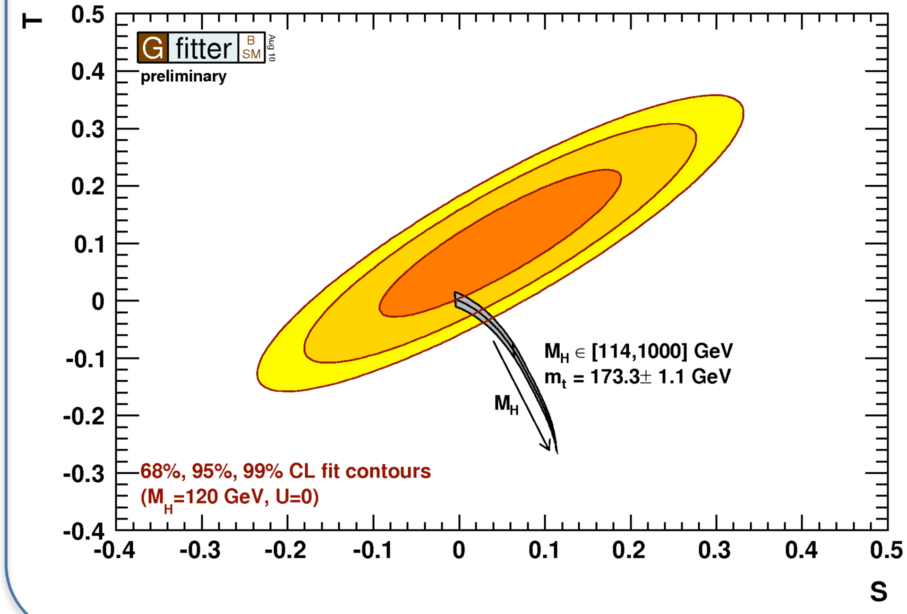
Statistical interpretation: consistency of the SM

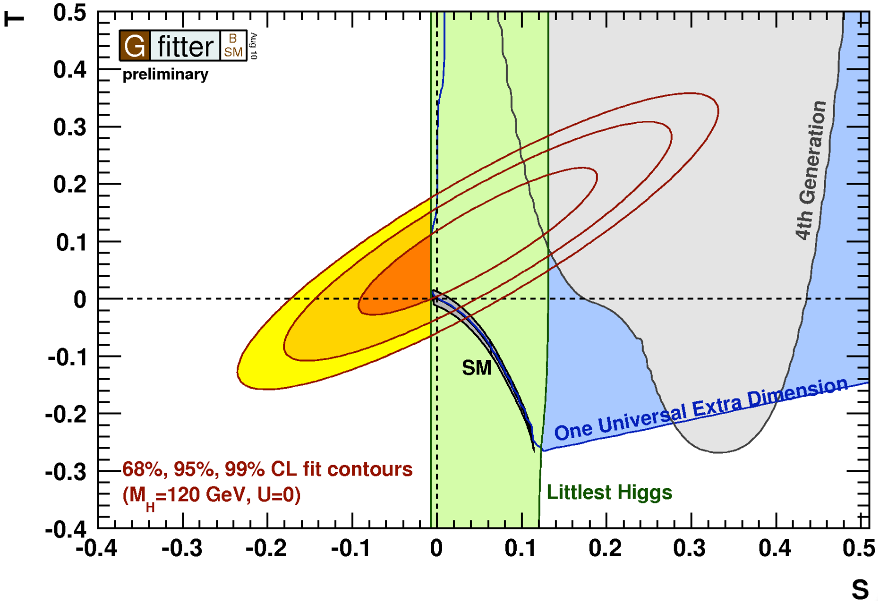


Summary of the day

Although new particles or new phenomena are not visible yet, one can test their possible presence in radiative loops in the processes we observe today. The loop corrections make the observed variables dependent on yet unobserved phenomena given a pre-defined model (in this case we have studied the Standard Model).

Similar techniques can be applied on other models (eg. website http://gfitter.desy.de/).





Theoretical constraints on the Higgs boson mass

Aim:

- Get a feeling how one can test that a theory is consistent.
- How far can we stretch the EW theory until it does not make sense anymore?
- Example for the yet unobserved Higgs sector in the Standard Model, but techniques can be applied elsewhere

Content:

- Perturbativity & unitarity
- The triviality bound
- The vacuum stability bound
- The fine tuning constraints

Perturbative constraint & unitarity

The scattering of vector bosons at high energies is divergent due to their longitudinal polarization. Take V = W or Z traveling in the z-direction with 3-momentum magnitude k.

$$k^{\mu} = (E_k; \vec{k}) = (E_k; 0, 0, k)$$

with

$$E_k^2 = k^2 - m_V^2$$

The three polarization vectors are (resp. right handed, left handed and longitudinal):

$$\begin{aligned} \epsilon_{+}^{\mu}(\vec{k}) &= \frac{1}{\sqrt{2}}(0; 1, i, 0) \\ \epsilon_{-}^{\mu}(\vec{k}) &= \frac{1}{\sqrt{2}}(0; 1, -i, 0) \\ \epsilon_{L}^{\mu}(\vec{k}) &= \frac{1}{m_V}(k; 0, 0, E_k) \end{aligned}$$

which satisfy (a,b = +, - , L)

$$\begin{aligned} k_{\mu}\epsilon_{a}^{\mu}(\vec{k}) &= 0 \\ \epsilon_{a}^{\mu}(\vec{k})\epsilon_{b\mu}^{*}(\vec{k}) &= -\delta_{ab} \end{aligned}$$

Addendum: Polarization for massless particles

$\varepsilon^\mu = (\varepsilon^0, \vec{\varepsilon})$ polarization vector

satisfies the Lorentz condition $k \cdot \varepsilon = 0$ (from $\partial_\mu A^\mu = 0$ as choice for the gauge)

↓

$$A^\mu = N \varepsilon^\mu e^{-ik\cdot x}$$

(plane wave)

$$\begin{cases} \vec{\varepsilon}^{(1)} = (1,0,0) \\ \vec{\varepsilon}^{(2)} = (0,1,0) \end{cases} \rightsquigarrow \text{alternative choice} \Rightarrow \begin{cases} \vec{\varepsilon}(\lambda=+1) = -\frac{1}{\sqrt{2}}(1,i,0) \\ \vec{\varepsilon}(\lambda=-1) = \frac{1}{\sqrt{2}}(1,-i,0) \end{cases}$$

↓

"helicity"

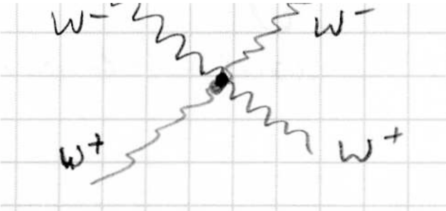
(spin projection along the direction of motion)

For massive particles also a longitudinal component.

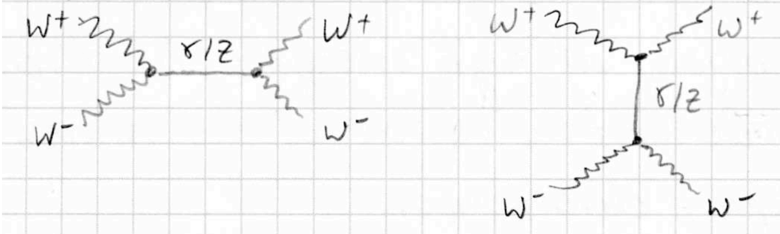
Perturbative constraint & unitarity

When $E_k \gg m_V$ the longitudinal polarization is divergent. Diagrams with external vector bosons have divergent cross sections. Consider the process $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$

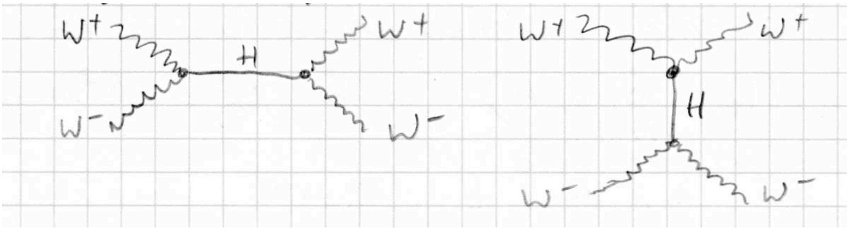
(i) Four point interaction



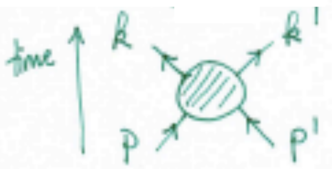
(ii) Gauge exchange of photon/Z in the s- and t-channel



(iii) Higgs exchange in the s- and t-channel



Addendum: Mandelstam variables (Peskin & Schroeder p.156-158)



$$\left.\begin{aligned} s &= (p+p')^2 = (k+k')^2 \\ t &= (k-p)^2 = (k'-p')^2 \\ u &= (k'-p)^2 = (k-p')^2 \end{aligned}\right\}$$

t: usually defined as the difference (squared) between the momenta of the most similar initial & final state particle

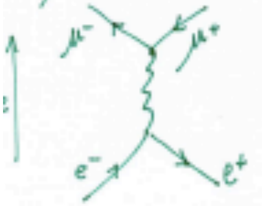
s: squared total momentum of the process

In the limit of massless particles: $k^2 = p^2 = k'^2 = p'^2 = 0$

ie. $k^2 = E_k^2 - \vec{k}^2 = m^2 = 0$

$$\hookrightarrow \left\{\begin{aligned} s &= (p+p')^2 = q^2 \\ t &= -2p.k = -2p'.k' \\ u &= -2p'.k = -2p.k' \end{aligned}\right.$$

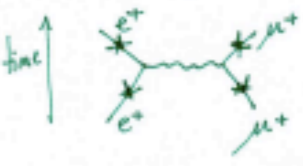
process $e^+e^- \to \mu^-\mu^+$:



$$\frac{1}{4}\sum_{\text{spins}} |\mathcal{M}|^2 = \frac{8e^4}{s^2}\left[\left(\frac{t}{2}\right)^2 + \left(\frac{u}{2}\right)^2\right]$$

"s-channel"

to obtain the squared matrix element for the process $e^+\mu^+ \to e^+\mu^+$ we can simply rotate the Feynmann diagram & change the interpretation of the Mandelstam variables ($t \leftrightarrow s$)

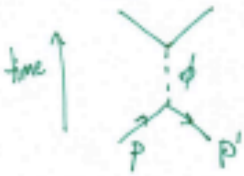


$$\frac{1}{4}\sum_{\text{spins}} |\mathcal{M}|^2 = \frac{8e^4}{t^2}\left[\left(\frac{s}{2}\right)^2 + \left(\frac{u}{2}\right)^2\right]$$

"t-channel"

Although quite different processes, the formulation is straight forward.

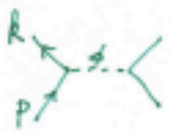
s-channel



$$\mathcal{M} \sim \frac{1}{s - m_\phi^2}$$

depends on $s = E_{cm}^2$

t-channel



$$\mathcal{M} \sim \frac{1}{t - m_\phi^2}$$

$t = -2p^2(1-\cos\theta)$

u-channel

$$\mathcal{M} \sim \frac{1}{u - m_\phi^2}$$

$u = -2p^2(1+\cos\theta)$

relations

$$s+t+u = \sum_{i=1}^{4} m_i^2$$

Perturbative constraint & unitarity

The amplitude can be written as (S.Weinberg, Vol.1, sec 3.7)

$$\mathcal{A} = \mathcal{A}^{(2)} s^2 + \mathcal{A}^{(1)} s + \mathcal{A}^{(0)}$$

From computations we learn that (when $s, t >> m_V^2, m_h^2$)

$$\begin{array}{lcl} \mathcal{A}^{(2)} & \longrightarrow & 0 \\ \mathcal{A}^{(1)} & \longrightarrow & 0 \\ \mathcal{A}^{(0)} & \longrightarrow & -\frac{2m_h^2}{v^2} \simeq -4\lambda \end{array}$$

Perfect cancellation between the diagrams. But the amplitude remains proportional to the Higgs boson mass. If the Higgs boson mass is too large the theory becomes strongly interacting and we cannot perform expansions versus λ.

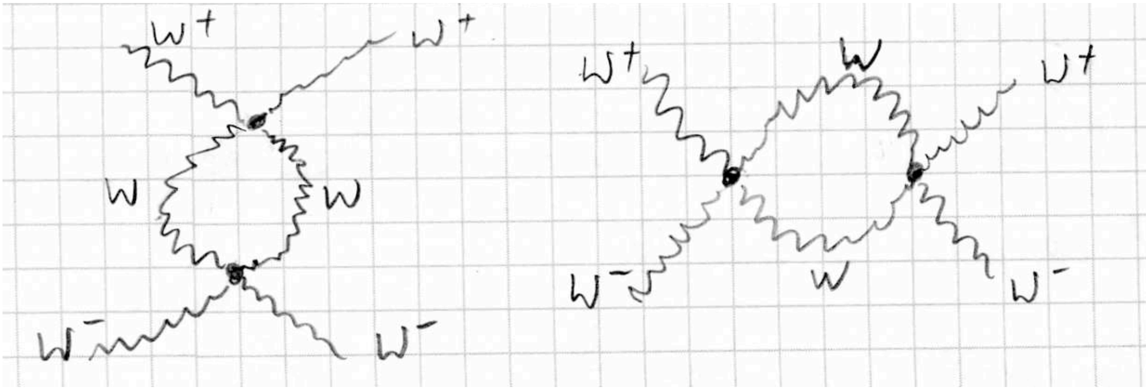
Perturbative constraint & unitarity

At the loop level the process

$$W^+W^- \rightarrow (WW)_{loop} \rightarrow W^+W^-$$

has an amplitude of

$$\frac{2\lambda^2}{16\pi^2}$$



The one-loop amplitude becomes equal to the tree-level amplitude when $\lambda \sim 16\,\pi^2$, hence the Electro-Weak theory should break down when $m_h > 4.6$ TeV.

More rigorous via partial wave analysis: $m_h < 870$ GeV
When taking also the WW→ZZ process into account: $m_h < 710$ GeV

The triviality bound

The couplings should remain finite at all energy scales Q.

$$g_i = (0.41; 0.64; 1.2)$$
$$y_t = \sqrt{2}\frac{m_t}{v} \simeq 1$$
$$\lambda = \frac{m_h^2}{2v^2}$$

Via the renormalization group equations we can evolve the couplings to higher scales Q.

$$t = ln\left(\frac{Q}{Q_0}\right)$$

$$\begin{aligned}
\frac{dg_1}{dt} &= \frac{41}{10}\frac{g_1^3}{16\pi^2} \\
\frac{dg_2}{dt} &= -\frac{19}{6}\frac{g_2^3}{16\pi^2} \\
\frac{dg_3}{dt} &= -7\frac{g_3^3}{16\pi^2} \\
\frac{dy_t}{dt} &= \frac{y_t}{16\pi^2}\left(-\frac{17}{20}g_1^2 - \frac{9}{4}g_2^2 - 8g_3^2 + \frac{9}{2}y_t^2\right) \\
\frac{d\lambda}{dt} &= \frac{1}{16\pi^2}\left(24\lambda^2 - \lambda\left(\frac{9}{5}g_1^2 + 9g_2^2 + 12y_t^2\right) + \frac{9}{8}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2g_2^2 + g_2^4\right) - 6y_t^4\right)
\end{aligned}$$

For large Higgs boson masses the term λ^2 dominates and after integration one obtains Landau pole or a limit on the value of Q for which the theory is still valid.

$$Q_{LP} = m_h exp\left(\frac{4\pi^2 v^2}{3m_h^2}\right)$$

The vacuum stability bound

When the Higgs boson mass is light the term -6y_t^4 will dominate:

$$\frac{d\lambda}{dt} \simeq -\frac{1}{16\pi^2} 6y_t^4$$

hence for higher scales Q the value of λ could become negative, hence the vacuum instable (V<0). With the constraint λ(Q)>0 for all values of Q we obtain an underlimit on the Higgs boson mass. After integrating the part of the RGE which is λ independent from Q_0 to Q we obtain:

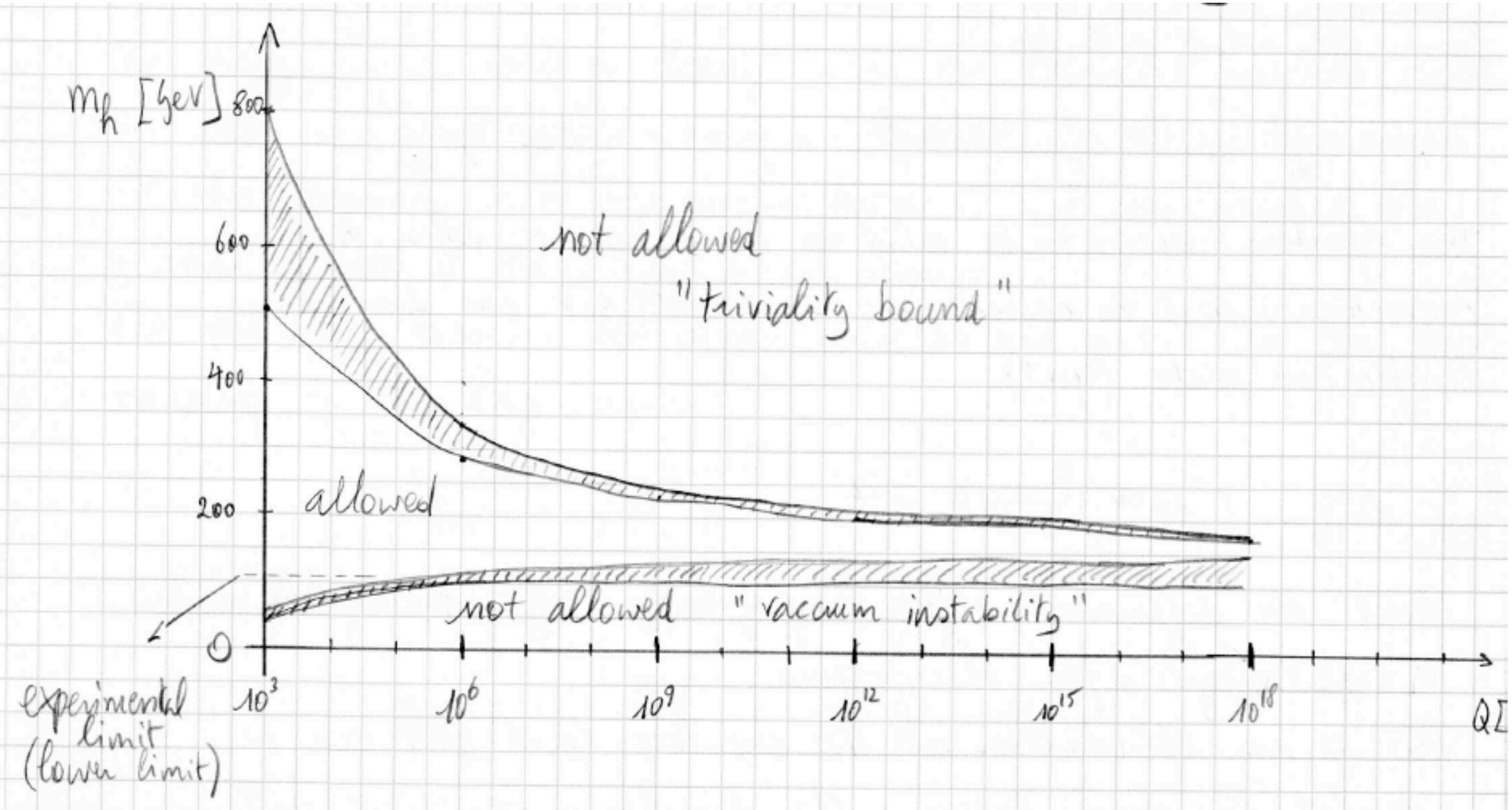
$$m_h^2 > \frac{v^2}{8\pi^2} \left(\frac{9}{8} \left(\frac{3}{25} g_1^4 + \frac{2}{5} g_1^2 g_2^2 + g_2^4 \right) - 6y_t^4 \right) ln \left(\frac{Q}{Q_0} \right)$$

Hence a lower limit for the Higgs boson mass for a given Q scale to keep the vacuum stable (without the presence of new physics phenomena beyond the Standard Model).

The full calculations at higher order (more loops) is done.

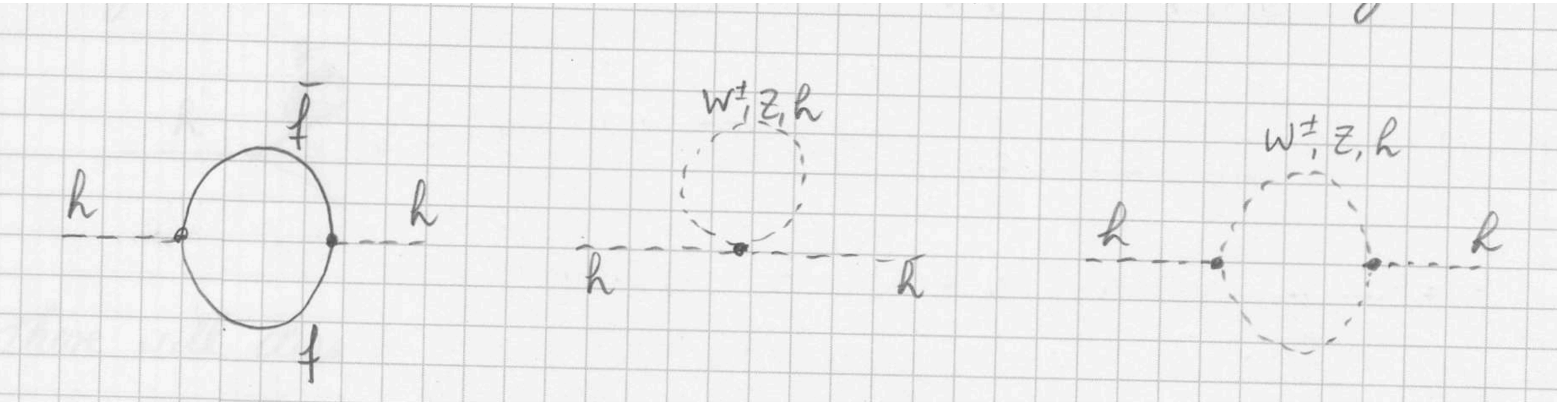
All together: theoretical bounds on the Higgs boson mass

If the Higgs boson is to be found at 60 GeV then this means the vacuum is instable in the absence of new physics. Only when the mass is between 130-180 GeV the vacuum can remain stable up to the Planck scale.



The fine-tuning constraint

The radiative corrections to the Higgs boson mass induce a fine tuning problem. At one loop



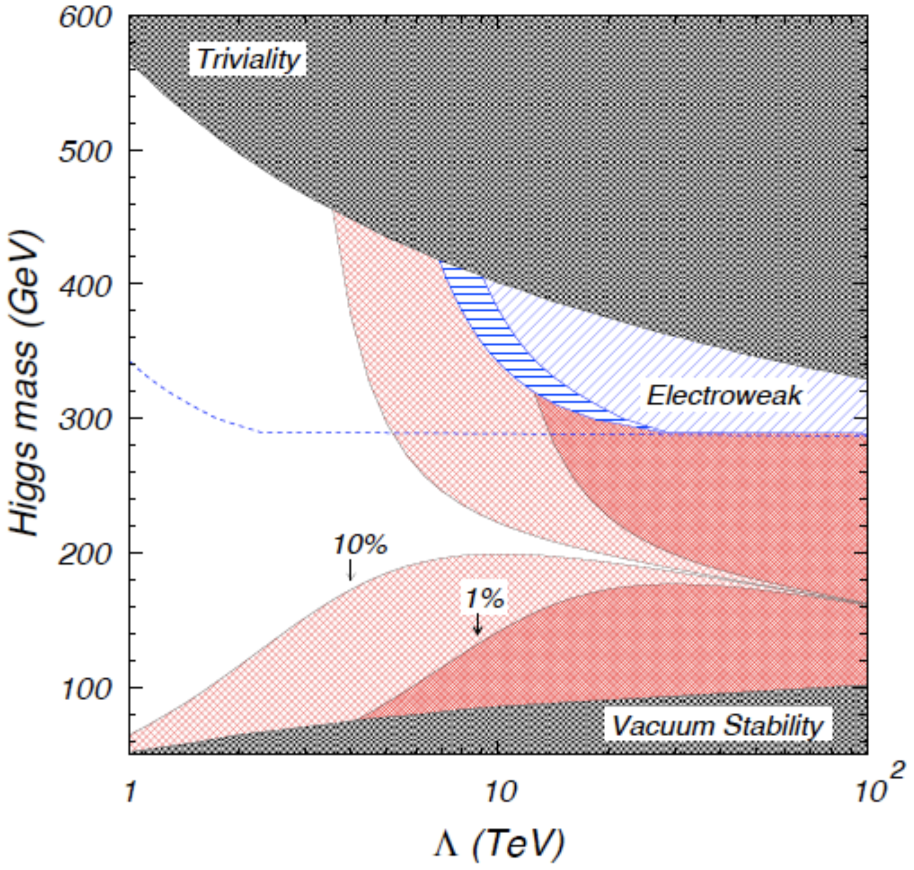
The integral can be cut-off at a momentum scale Λ

$$m_h^2 = (m_h^0)^2 + \frac{3\Lambda^2}{8\pi^2 v^2}\left(m_h^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right)$$

hence to cancel this we need m_h^2 ~ (320 GeV)^2
To cancel the radiative terms up to the GUT scale Λ ~ 10^{16} GeV we need to cancel up to 32 digits after the comma.

The fine-tuning constraint

Requesting up to 10% (or 1%) fine-tuning the allowed range for the validity of the Standard Model is reduced.



4

Phenomenology of the Standard Model Higgs boson

Aim:

- Main decay properties of the Higgs boson
- Be able to calculate towards the phenomenology of Higgs physics

Content:

- Decays to quarks & leptons
- Decays to Electro-Weak gauge bosons
- Loop induced decays into photons and gluons

The decay of Higgs bosons

The Higgs boson couplings are directly proportional to the mass of the particles involved, hence it tends to decay to the heaviest particle allowed by phase-space.

For the vector bosons we have the hVV term in the Lagrangian

$$\mathcal{L}_{hVV} = \sqrt{\sqrt{2}G_F} m_V^2 h V^\mu V_\mu$$

While for the fermions the couplings are given as

$$g_{hf\overline{f}} \sim \frac{m_f}{v} = \sqrt{\sqrt{2}G_F} m_f$$

with

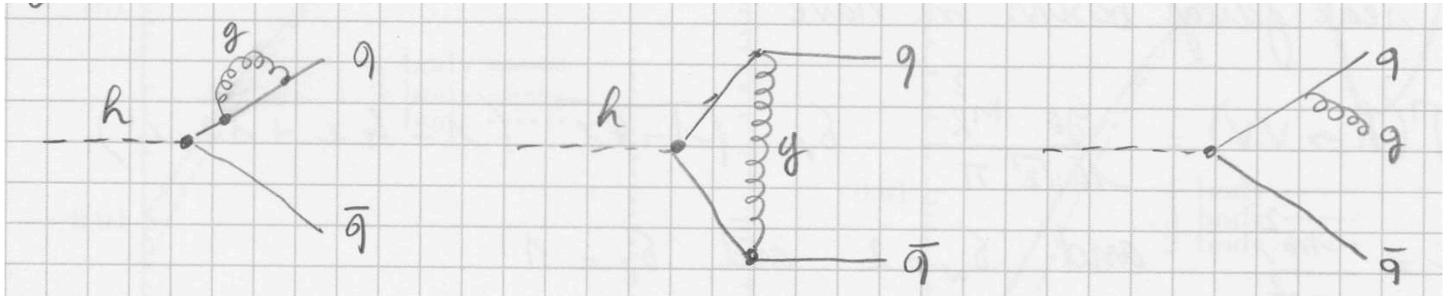
$$G_F = \frac{g^2}{\sqrt{32} m_W^2}$$

The decay of Higgs bosons into quarks & leptons

Born approximation:

$$\Gamma_{Born}(h \to f\overline{f}) = \frac{G_F N_C}{4\sqrt{2}\pi} m_h m_f^2 \beta_f^3 \qquad \beta_f = \sqrt{1 - \frac{4m_f^2}{m_h^2}}$$

with N$_c$ a color factor.
There are loop corrections to this from diagrams like



The decay width becomes

$$\Gamma_{NLO}(h \to q\overline{q}) = \frac{3G_F}{4\sqrt{2}\pi} m_h m_q^2 \left[1 + \frac{4}{3}\frac{\alpha_s}{\pi}\left(\frac{9}{4} + \frac{3}{2} log \frac{m_q^2}{m_h^2}\right)\right]$$

Absorb the large logarithms into a redefinition of the quark masses, MSbar scheme

$$m_q \longrightarrow \overline{m_q}(m_h)$$

The decay of Higgs bosons into quarks & leptons

After QCD radiative corrections up to 3rd order

$$\Gamma(h \to q\overline{q}) = \frac{3G_F}{4\sqrt{2}\pi} m_h \overline{m}_q^2(m_h)\left[1 + \Delta_{q\overline{q}} + \Delta_h^2\right]$$

With

$$\Delta_{q\overline{q}} = 5.67\frac{\overline{\alpha}_s}{\pi} + (35.94 - 1.36N_f)\frac{\overline{\alpha}_s^2}{\pi^2} + \left(164.14 - 25.77N_f + 0.26N_f^2\right)\frac{\overline{\alpha}_s^3}{\pi^3}$$

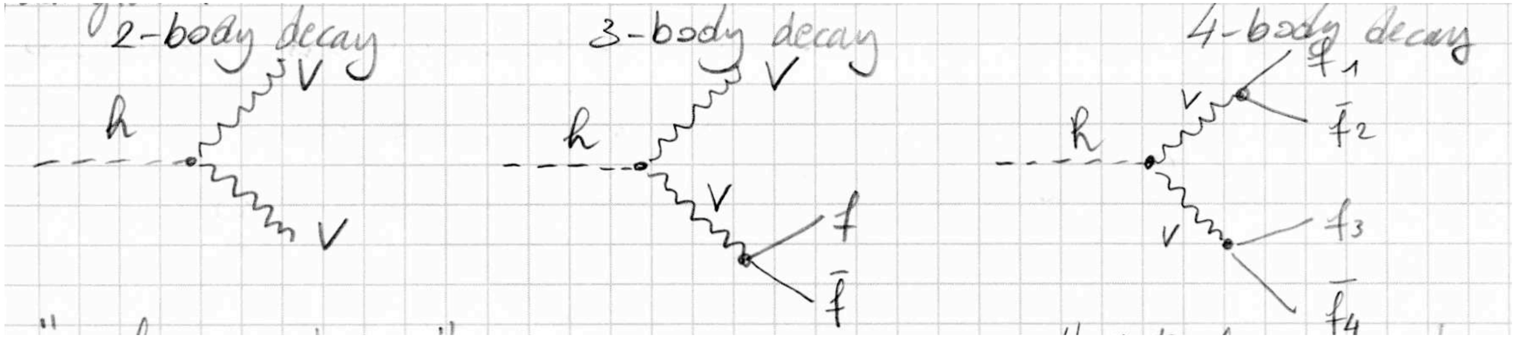
$$\Delta_h^2 = \frac{\overline{\alpha}_s^2}{\pi^2}\left[1.57 - \frac{2}{3}log\left(\frac{m_h^2}{m_t^2}\right) + \frac{1}{9}log^2\left(\frac{\overline{m}_q^2}{m_h^2}\right)\right]$$

$$\overline{\alpha}_s = \alpha_s(m_h)$$

N_f the number of accessible fermion flavours

The decay of Higgs bosons into Electro-Weak gauge bosons

The decay widths are directly proportional to the hVV terms in the Lagrangian. Difference between "real" and "virtual" gauge bosons:



For two real bosons

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

$$x = \frac{m_V^2}{m_h^2} \qquad \delta_W = 2 \qquad \delta_Z = 1$$

Hence when the Higgs boson mass is much larger than the mass of the vector bosons, we have

$$\Gamma(h \to WW) \simeq 2 \cdot \Gamma(h \to ZZ)$$

The decay of Higgs bosons into Electro-Weak gauge bosons

For large Higgs boson masses

$$\Gamma(h \to WW + ZZ) \simeq 0.5TeV \left(\frac{m_h}{1TeV}\right)^3$$

the width becomes similar to the mass itself around m_h=1.4 TeV. When there is a 3-body decay one of the vector bosons is off-shell, hence the branching ratio can be non-zero below the kinematic threshold

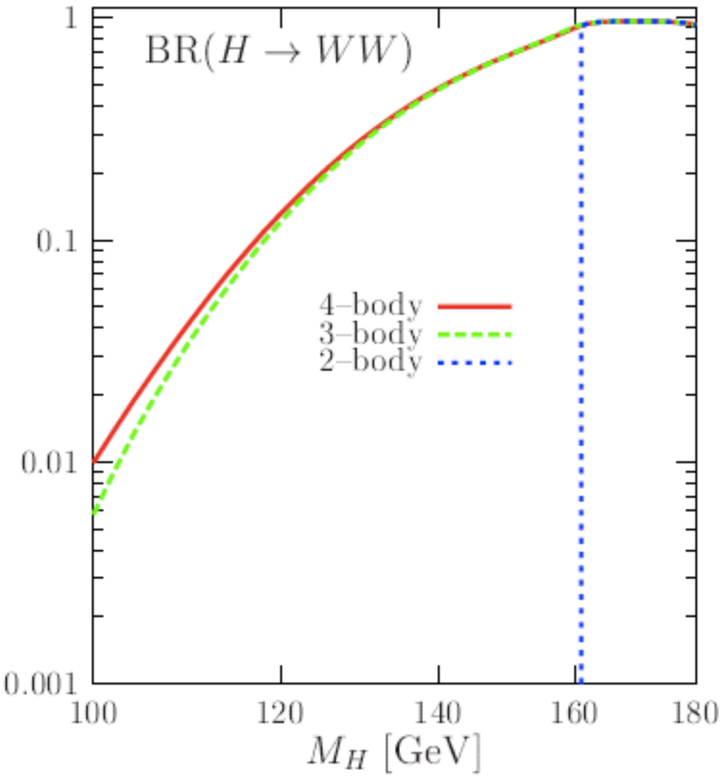
$$\Gamma(h \to VV^*) = \frac{3G_F^2 m_V^4}{16\pi^3} m_h \delta'_V R_T(x)$$

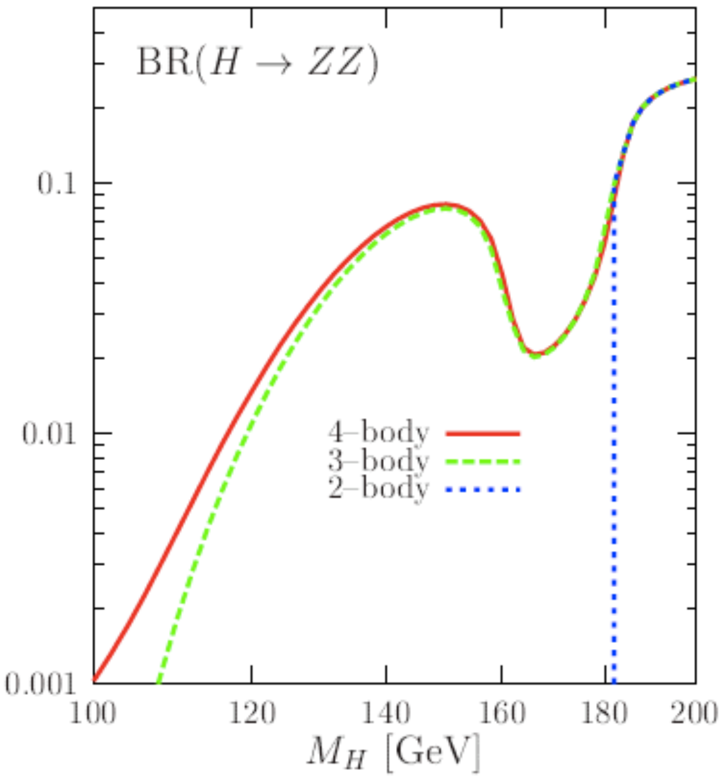
with

$$\delta'_W = 1 \qquad \delta'_Z = \frac{7}{12} - \frac{10}{9} sin^2\theta_W + \frac{40}{9} sin^4\theta_W$$

$$R_T(x) = \frac{3(1-8x+20x^2)}{\sqrt{4x-1}} arccos\left(\frac{3x-1}{2x^{3/2}}\right) - \frac{1-x}{2x}(2-13x+47x^2) - \frac{3}{2}(1-6x+4x^2)log(x)$$

The decay of Higgs bosons into Electro-Weak gauge bosons

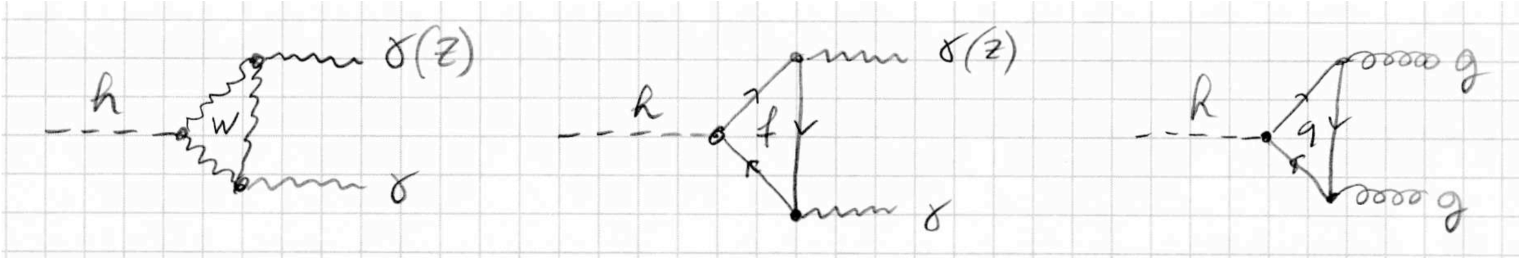




Reference for these and following plots: arXiv:hep-ph/0503172v2

Loop induced decays into photons and gluons

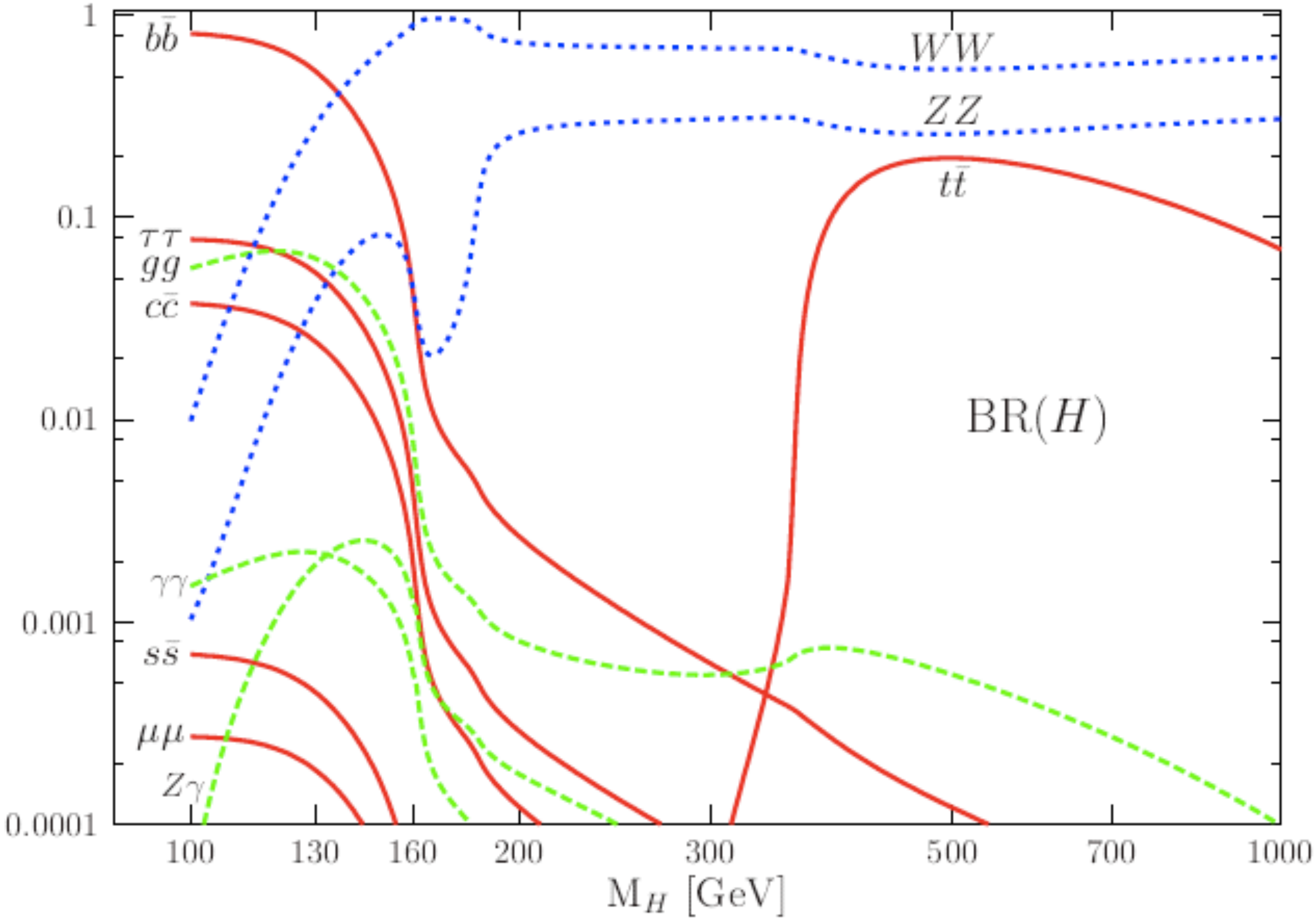
Photons and gluons are massless hence do not couple to the Higgs boson, nevertheless they can appear in loops:



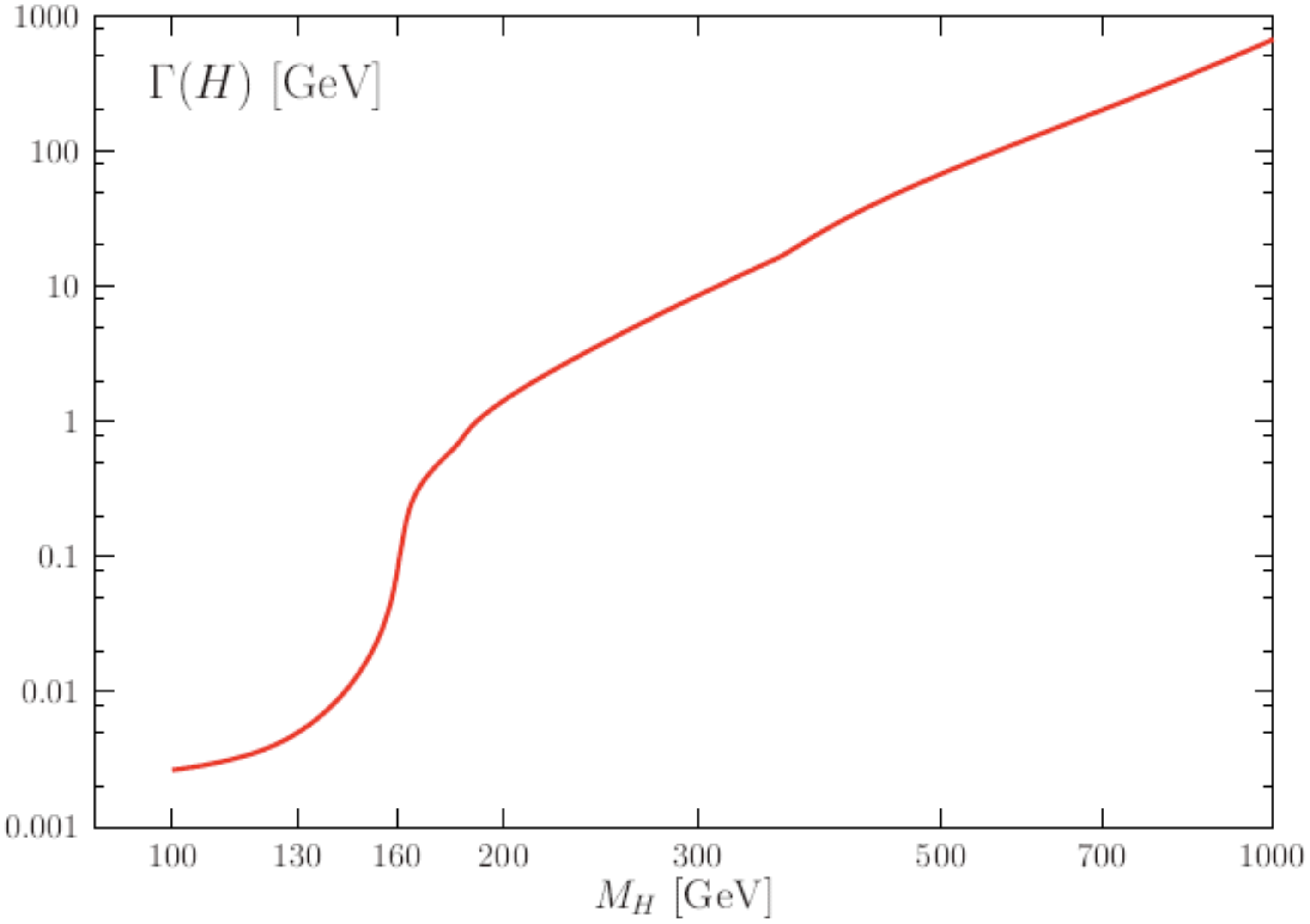
These diagrams contribute according to the mass of the particles in these loops. Hence we can probe physics far beyond the scale of the mass of the Higgs boson. For example the new heavy charged or colored particles appearing in models beyond the Standard Model.

Looks like these diagrams are only relevant when $m_h < 130$ GeV.

All together: branching ratios



All together: total decay width



All together: zoom into the branching ratios

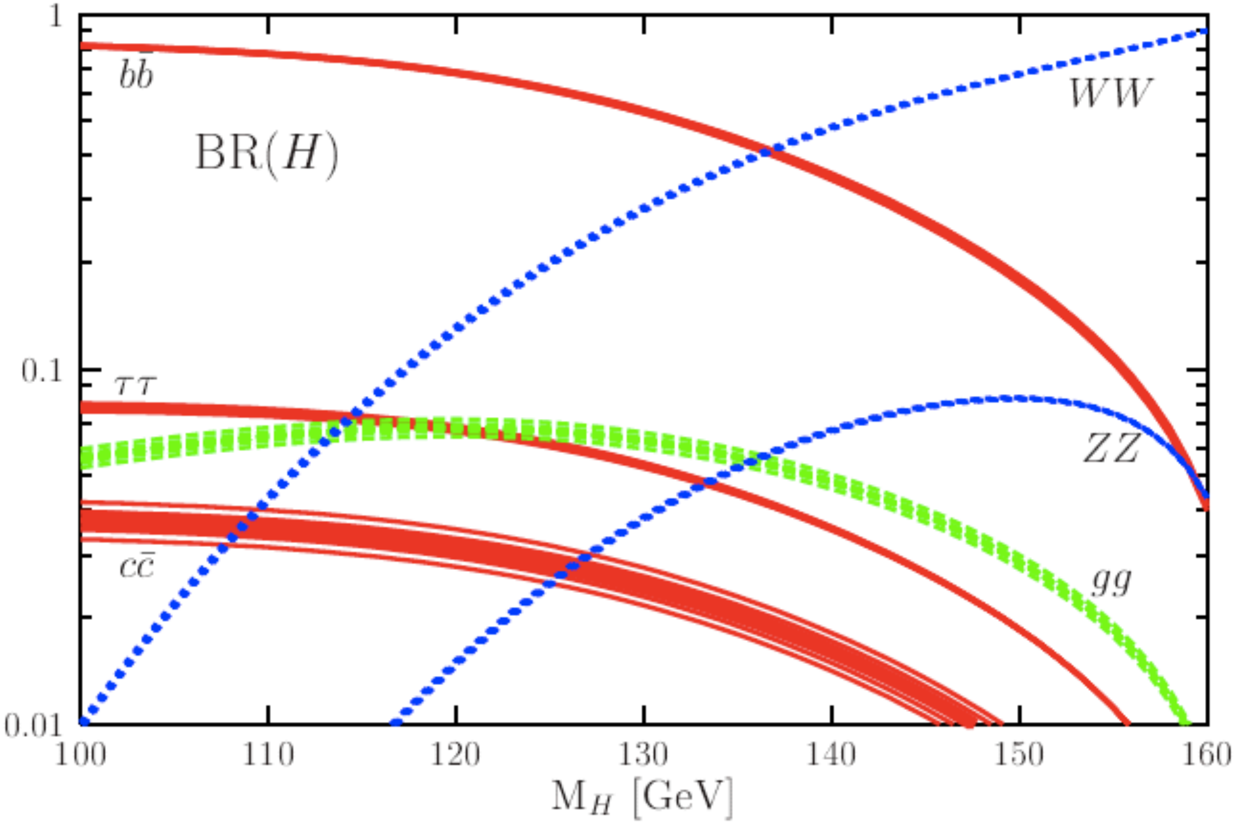


Figure 2.27: The SM Higgs boson decay branching ratios in the low and intermediate Higgs mass range including the uncertainties from the quark masses $m_t = 178 \pm 4.3$ *GeV,* $m_b = 4.88 \pm 0.07$ *GeV and* $m_c = 1.64 \pm 0.07$ *GeV as well as from* $\alpha_s(M_Z) = 0.1172 \pm 0.002$.

Searching for the Standard Model Higgs boson

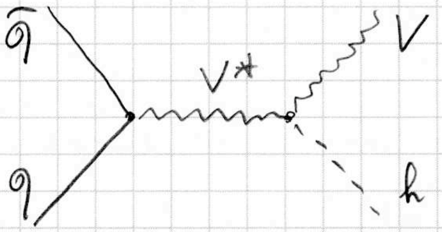
Aim:

- Learn how with a phenomenological approach one can identify the relevant experimental signatures to search for (in this case) Higgs bosons
- Experiments are designed to discover phenomena (eg. the Higgs boson), hence we have to be able to judge on the experimental design parameters needed to make this discovery possible

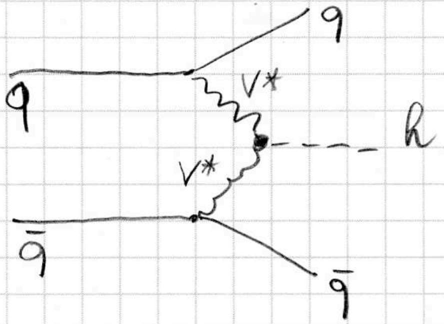
Exercise (typical exam question):

Can we discover the Standard Model Higgs boson at the LHC (14 TeV) in the pp→ttH channel? Try to estimate the significance of this process after some event selection enhancing this signal. Which integrated luminosity is needed to have a significance larger than 5. Motivate your arguments.

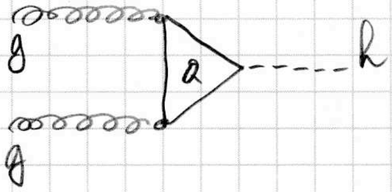
Main Higgs boson production processes



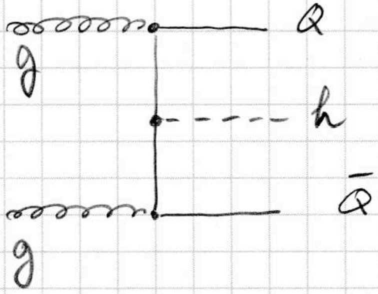
"associated production with W/Z bosons"



"weak vector boson fusion production"

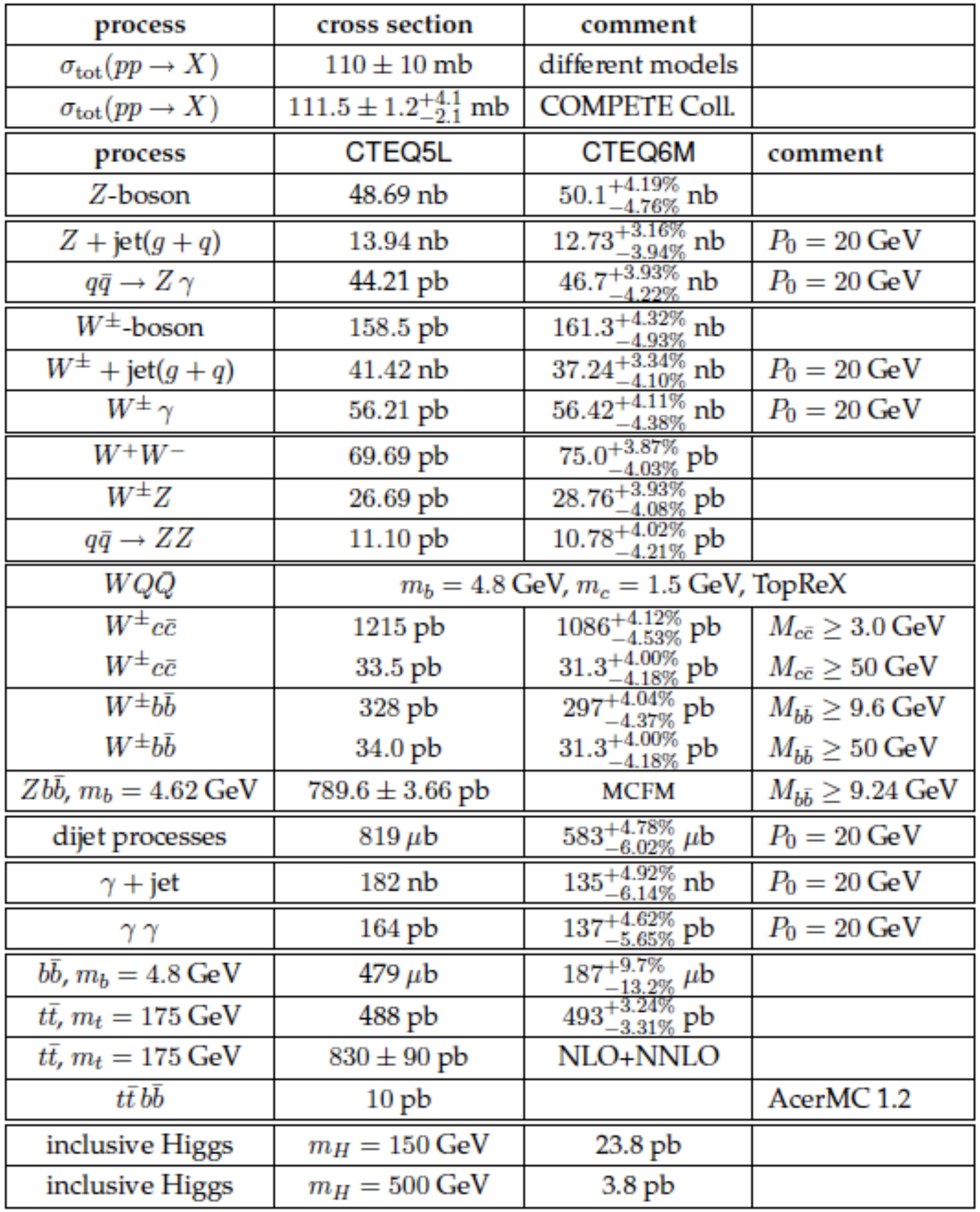


"gluon-gluon fusion"



"associated production with heavy top or bottom quarks"

Main background processes (LHC@14TeV)



process	cross section	comment	
$\sigma_{\text{tot}}(pp \to X)$	110 ± 10 mb	different models	
$\sigma_{\text{tot}}(pp \to X)$	$111.5 \pm 1.2^{+4.1}_{-2.1}$ mb	COMPETE Coll.	
process	CTEQ5L	CTEQ6M	**comment**
Z-boson	48.69 nb	$50.1^{+4.19\%}_{-4.76\%}$ nb	
$Z + \text{jet}(g+q)$	13.94 nb	$12.73^{+3.16\%}_{-3.94\%}$ nb	$P_0 = 20$ GeV
$q\bar{q} \to Z\gamma$	44.21 pb	$46.7^{+3.93\%}_{-4.22\%}$ nb	$P_0 = 20$ GeV
$W^{\pm}$-boson	158.5 pb	$161.3^{+4.32\%}_{-4.93\%}$ nb	
$W^{\pm} + \text{jet}(g+q)$	41.42 nb	$37.24^{+3.34\%}_{-4.10\%}$ nb	$P_0 = 20$ GeV
$W^{\pm}\gamma$	56.21 pb	$56.42^{+4.11\%}_{-4.38\%}$ nb	$P_0 = 20$ GeV
W^+W^-	69.69 pb	$75.0^{+3.87\%}_{-4.03\%}$ pb	
$W^{\pm}Z$	26.69 pb	$28.76^{+3.93\%}_{-4.08\%}$ pb	
$q\bar{q} \to ZZ$	11.10 pb	$10.78^{+4.02\%}_{-4.21\%}$ pb	
$WQ\bar{Q}$	$m_b = 4.8$ GeV, $m_c = 1.5$ GeV, TopReX		
$W^{\pm}c\bar{c}$	1215 pb	$1086^{+4.12\%}_{-4.53\%}$ pb	$M_{c\bar{c}} \geq 3.0$ GeV
$W^{\pm}c\bar{c}$	33.5 pb	$31.3^{+4.00\%}_{-4.18\%}$ pb	$M_{c\bar{c}} \geq 50$ GeV
$W^{\pm}b\bar{b}$	328 pb	$297^{+4.04\%}_{-4.37\%}$ pb	$M_{b\bar{b}} \geq 9.6$ GeV
$W^{\pm}b\bar{b}$	34.0 pb	$31.3^{+4.00\%}_{-4.18\%}$ pb	$M_{b\bar{b}} \geq 50$ GeV
$Zb\bar{b}$, $m_b = 4.62$ GeV	789.6 ± 3.66 pb	MCFM	$M_{b\bar{b}} \geq 9.24$ GeV
dijet processes	819 μb	$583^{+4.78\%}_{-6.02\%}$ μb	$P_0 = 20$ GeV
$\gamma + \text{jet}$	182 nb	$135^{+4.92\%}_{-6.14\%}$ nb	$P_0 = 20$ GeV
$\gamma\gamma$	164 pb	$137^{+4.62\%}_{-5.65\%}$ pb	$P_0 = 20$ GeV
$b\bar{b}$, $m_b = 4.8$ GeV	479 μb	$187^{+9.7\%}_{-13.2\%}$ μb	
$t\bar{t}$, $m_t = 175$ GeV	488 pb	$493^{+3.24\%}_{-3.31\%}$ pb	
$t\bar{t}$, $m_t = 175$ GeV	830 ± 90 pb	NLO+NNLO	
$t\bar{t}b\bar{b}$	10 pb		AcerMC 1.2
inclusive Higgs	$m_H = 150$ GeV	23.8 pb	
inclusive Higgs	$m_H = 500$ GeV	3.8 pb	

Main channels involve a lepton (electron or muon) because the amount of jet production at the LHC is enormous.

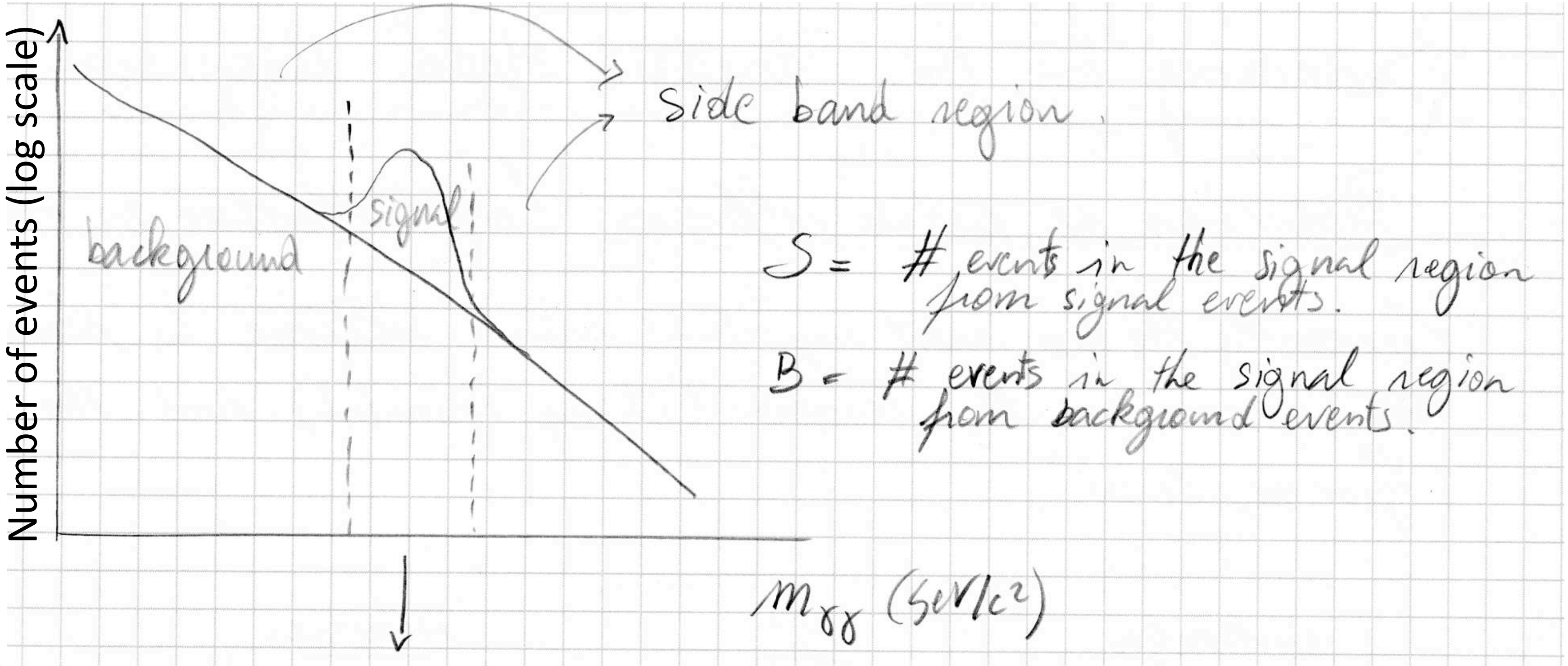
Hence need at least one lepton in the final state of the process where we look for the Higgs boson.

Searching for the Standard Model Higgs boson

The estimation of the amount of signal event $\hat{S}$ is obtained from the remainder after subtracting the estimated background component $\hat{B}$ from the event sample with N events after a specific event selection :

$$\hat{S} = N - \hat{B} \qquad Significance = \frac{\hat{S}}{\sqrt{\hat{S} + \hat{B}}}$$

Background estimate for example from side-band analysis.



S = # events in the signal region from signal events.

B = # events in the signal region from background events.

Cross sections for Higgs boson production

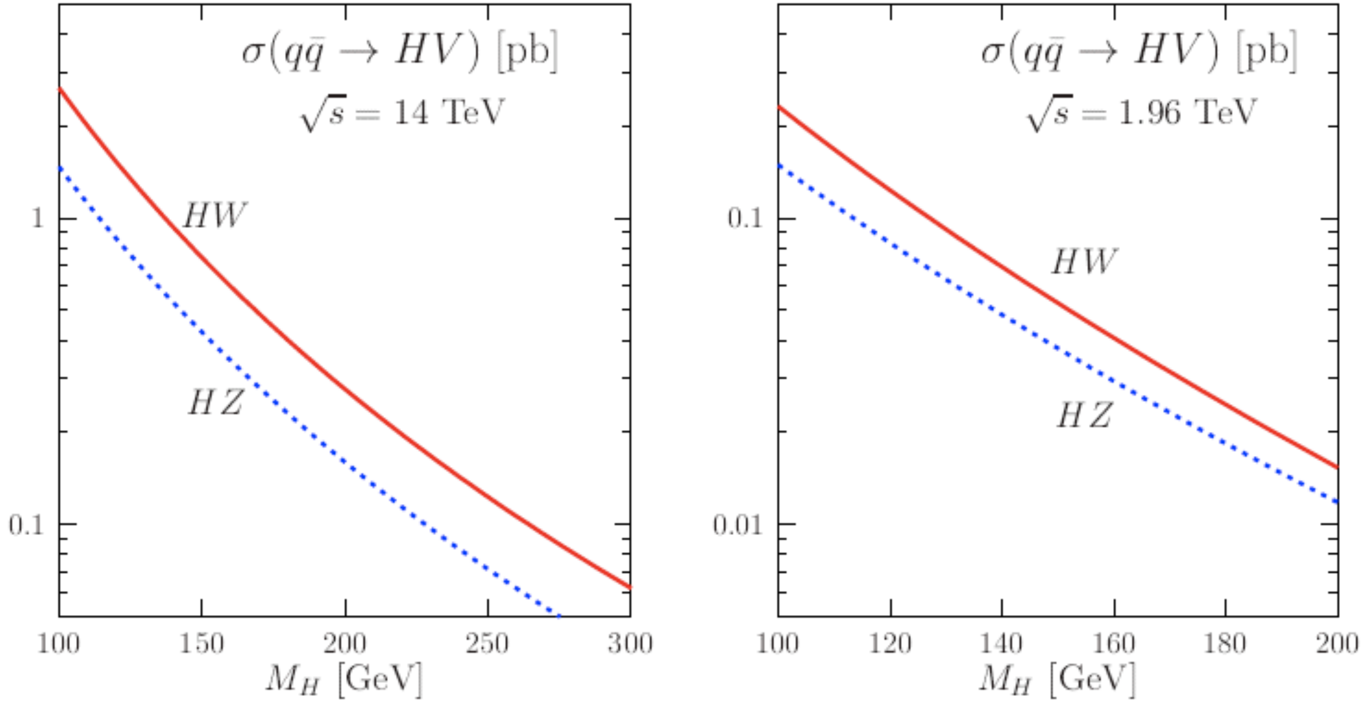


Figure 3.3: Total production cross sections of Higgs bosons in the strahlung $q\bar{q} \to H + W/Z$ *processes at leading order at the LHC (left) and at the Tevatron (right). For* $q\bar{q} \to HW$, *the final states with both* W^+ *and* W^- *have been added. The MRST set of PDFs has been used.*

Cross sections for Higgs boson production

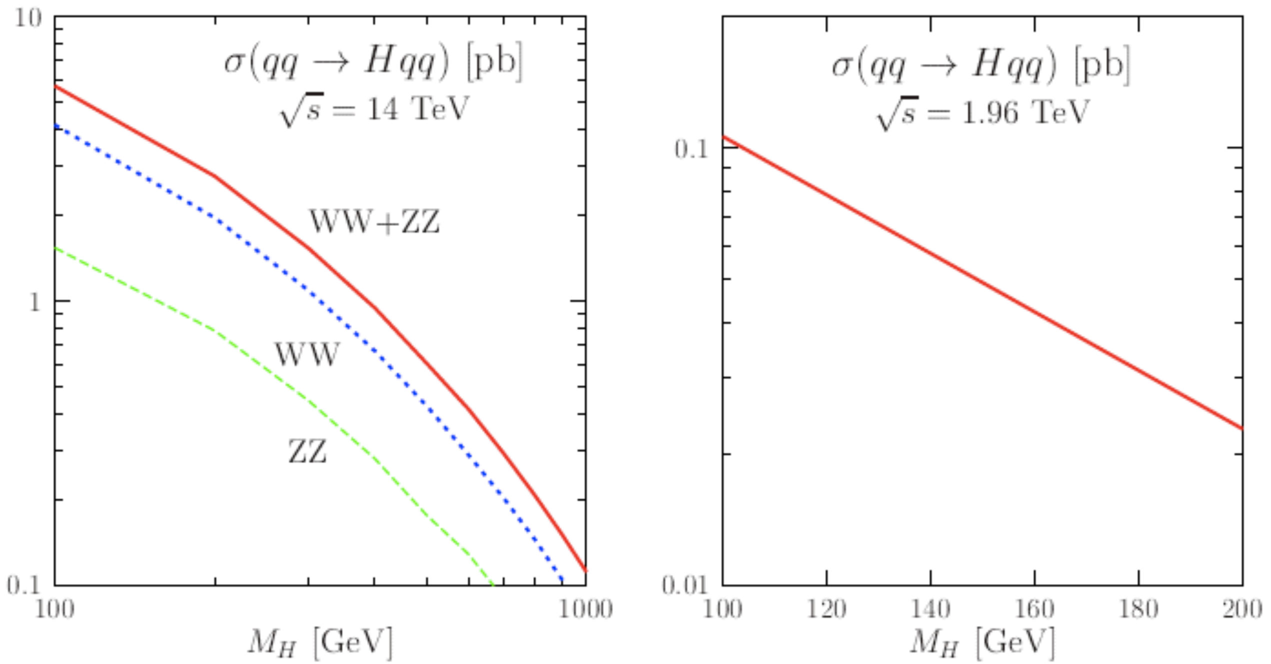


Figure 3.12: Individual and total cross sections in the vector fusion $qq \to V^*V^* \to Hqq$ *processes at leading order at the LHC (left) and total cross section at the Tevatron (right).*

Cross sections for Higgs boson production

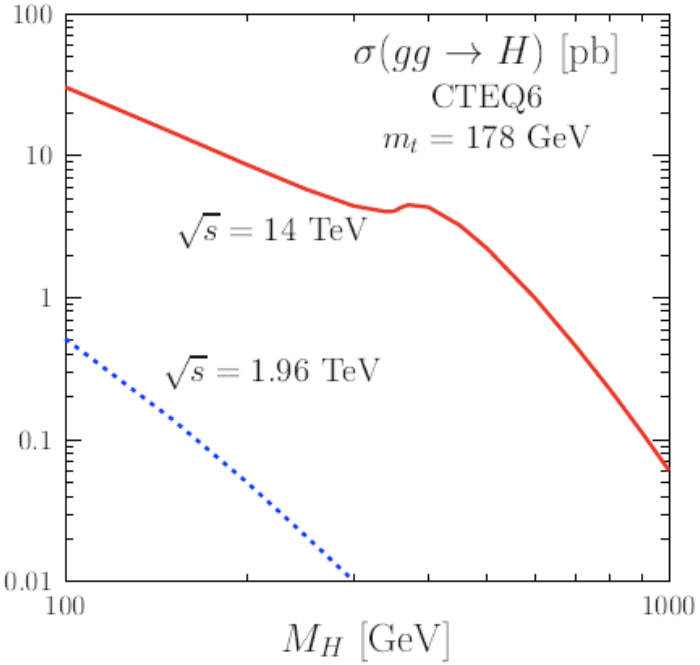


Figure 3.18: The hadronic production cross section for the gg fusion process at LO as a function of M_H *at the LHC and the Tevatron. The inputs are* $m_t = 178$ *GeV,* $m_b = 4.88$ *GeV, the CTEQ set of PDFs has been used and the scales are fixed to* $\mu_R = \mu_F = M_H$.

Cross sections for Higgs boson production

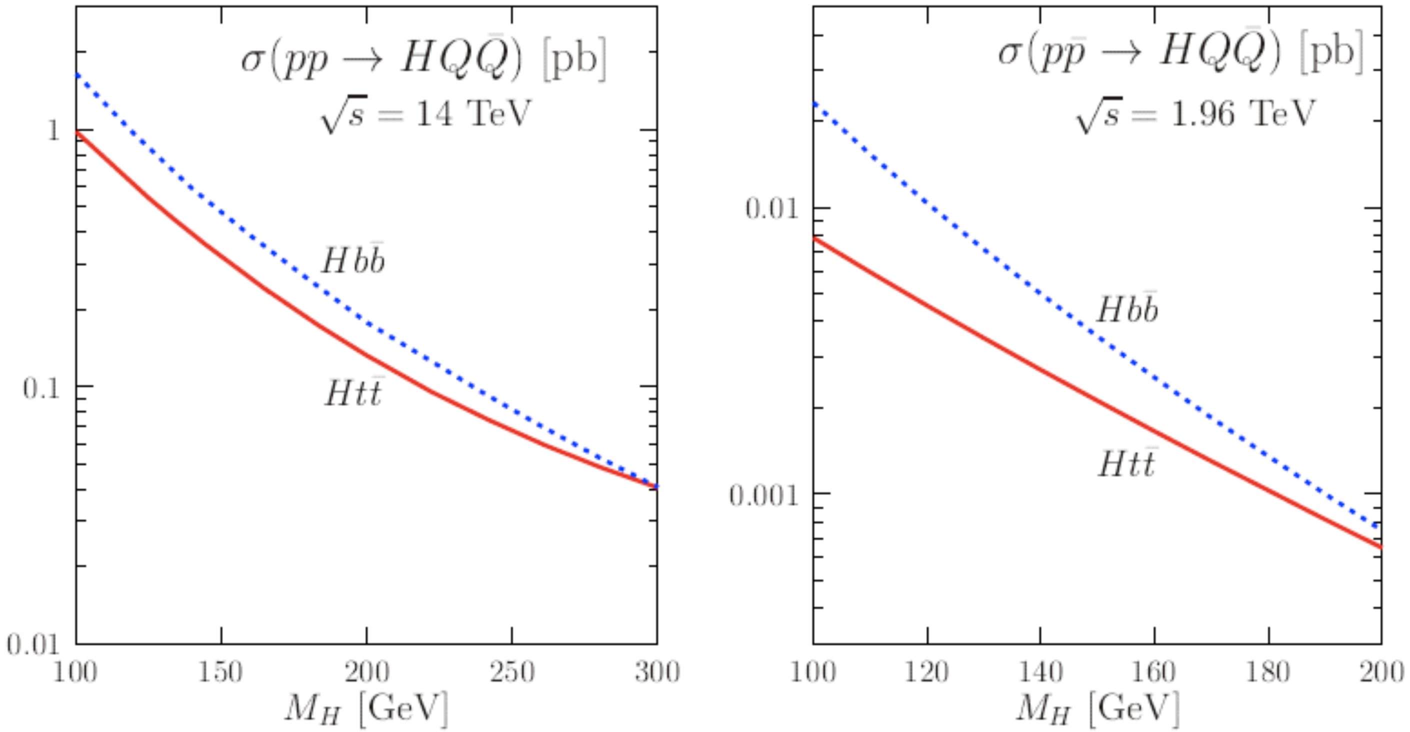


Figure 3.30: The $t\bar{t}H$ and $b\bar{b}H$ production cross sections at the LHC (left) and the Tevatron (right). The pole quark masses in the Yukawa couplings are set to $m_t = 178$ GeV and $m_b = 4.88$ GeV and the MRST PDFs are used. The renormalization and factorization scales have been set to $\mu_{R,F} = m_t + \frac{1}{2}M_H$ for $pp \to t\bar{t}H$ and $\mu_{R,F} = \frac{1}{2}m_b + \frac{1}{4}M_H$ for $pp \to b\bar{b}H$.

Cross sections for Higgs boson production

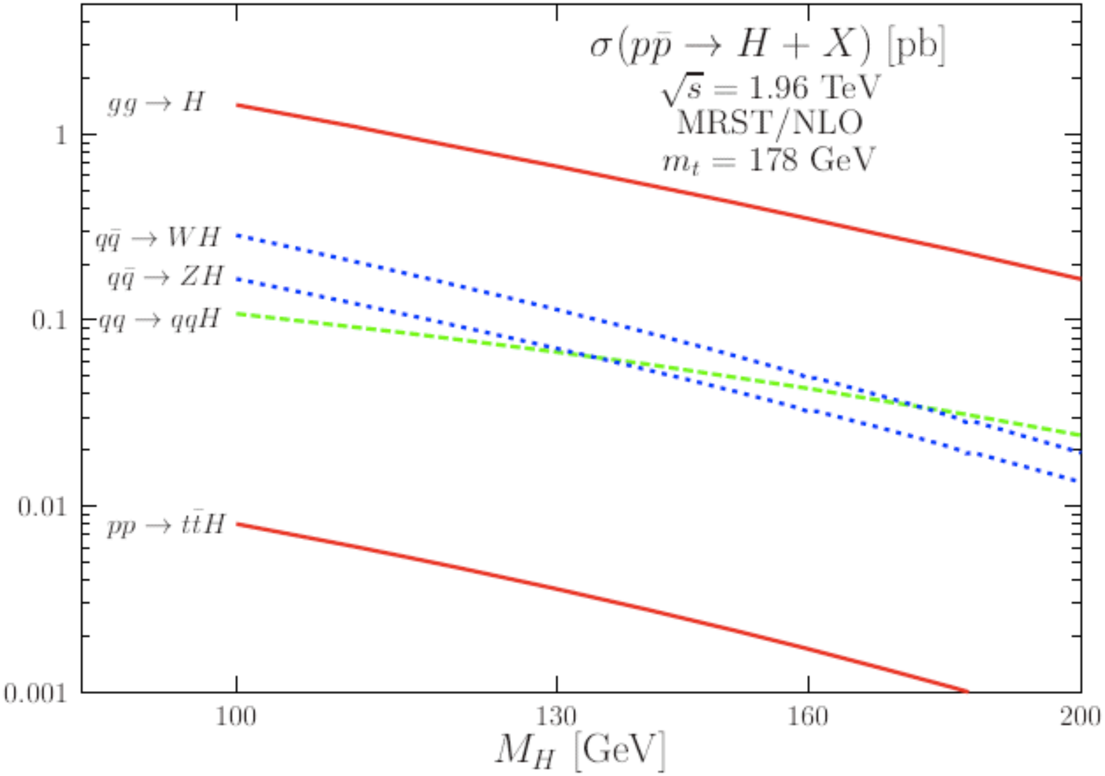


Figure 3.46: The Higgs boson production cross sections at the Tevatron in the dominant mechanisms as a function of M_H. They are (almost) at NLO with $m_t = 178$ GeV and the MRST set of PDFs has been used. The scales are as described in the text.

Cross sections for Higgs boson production

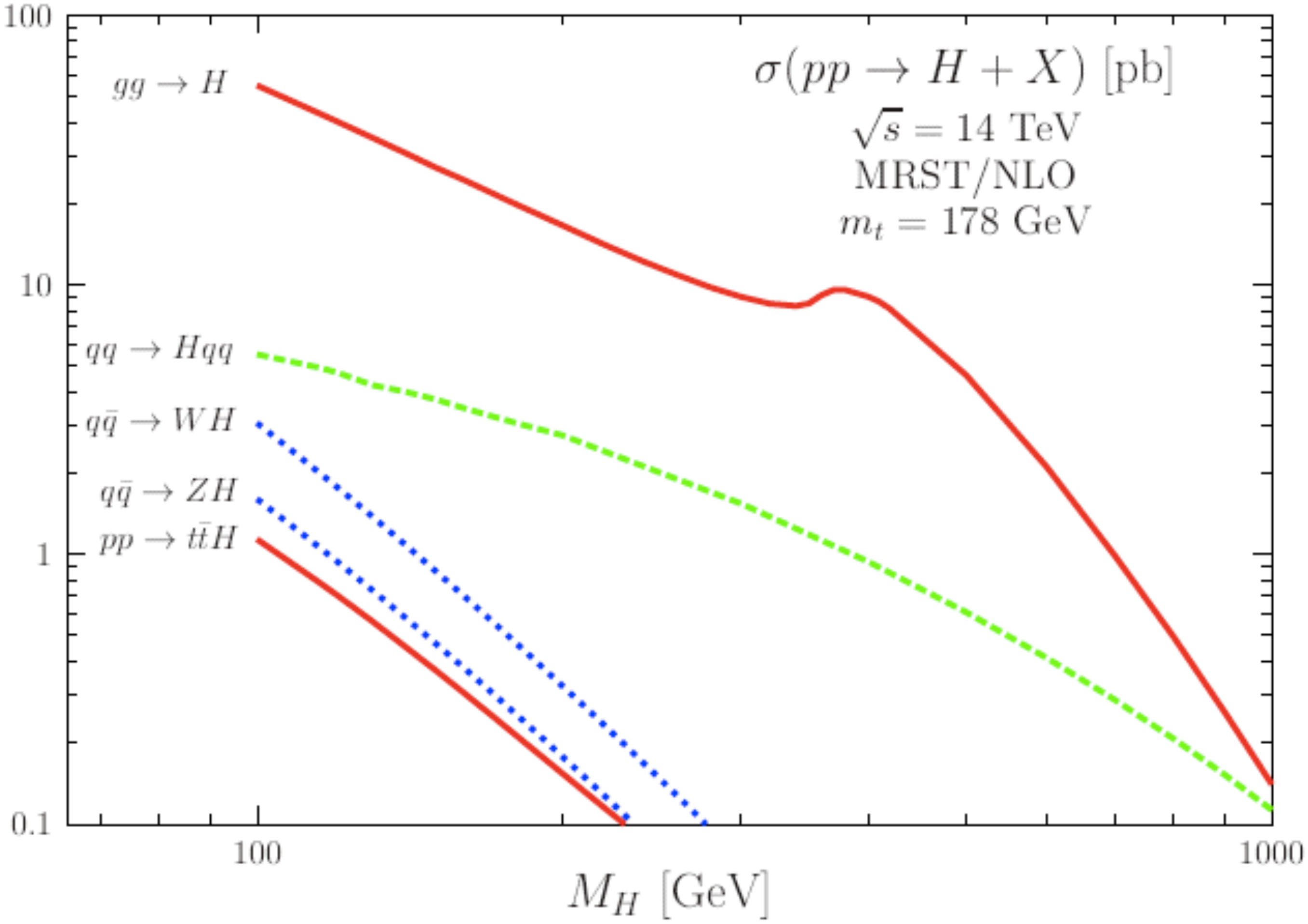
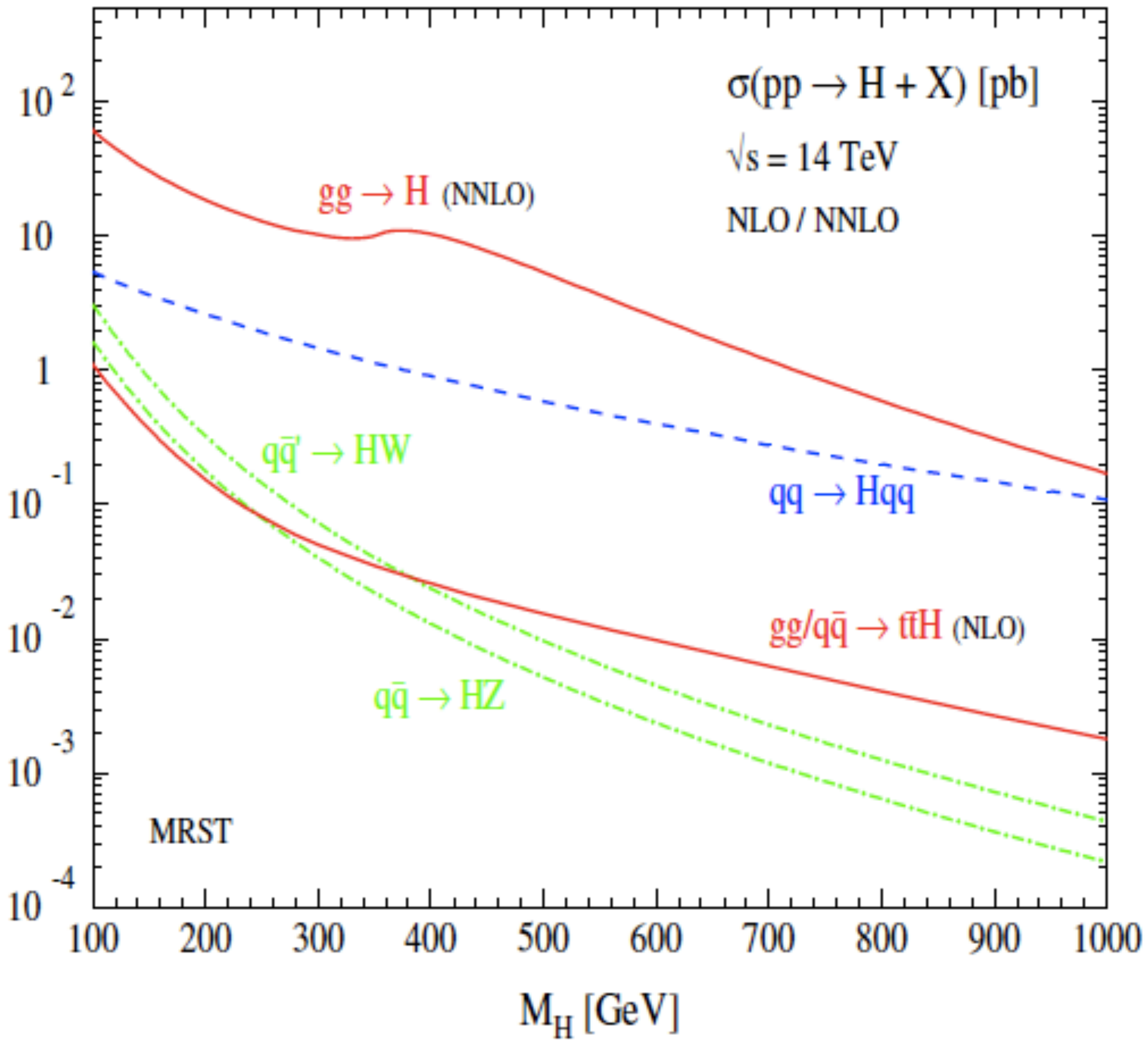


Figure 3.47: The same as Fig. 3.46 but for the LHC.

Cross sections for Higgs boson production



Reconstruction efficiencies

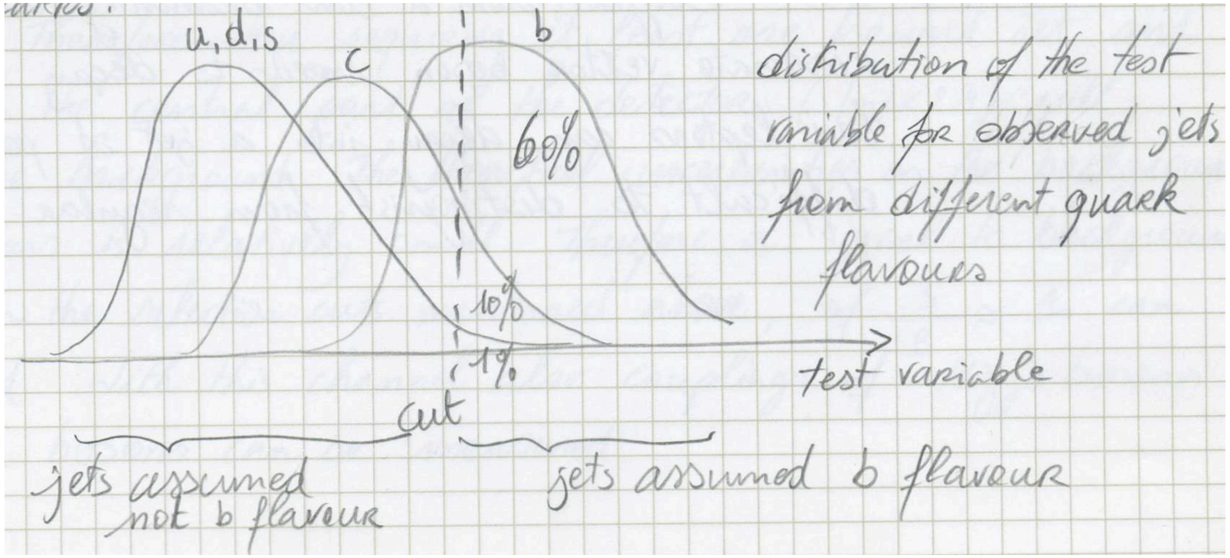
The reconstruction and identification of physical objects is never perfectly efficient (eg. detector acceptance). Below some benchmark numbers.

Isolated leptons (from W or Z decays) have ~80% efficiency to be reconstructed when the transverse momentum is above 20 GeV.

Jets with a transverse momentum above 30 GeV will be reconstructed in 90%, but will individually radiate in ~15% of the cases gluons, hence loosing their kinematic information for mass reconstruction.

B-flavoured jets can be identified with an efficiency of about ~50%, while c-jets will be mis-identified as b-jets in 10% of the cases and udsg-jets in 1% of the cases.

b-tagging at hadron colliders



Discovery potential for SM Higgs boson

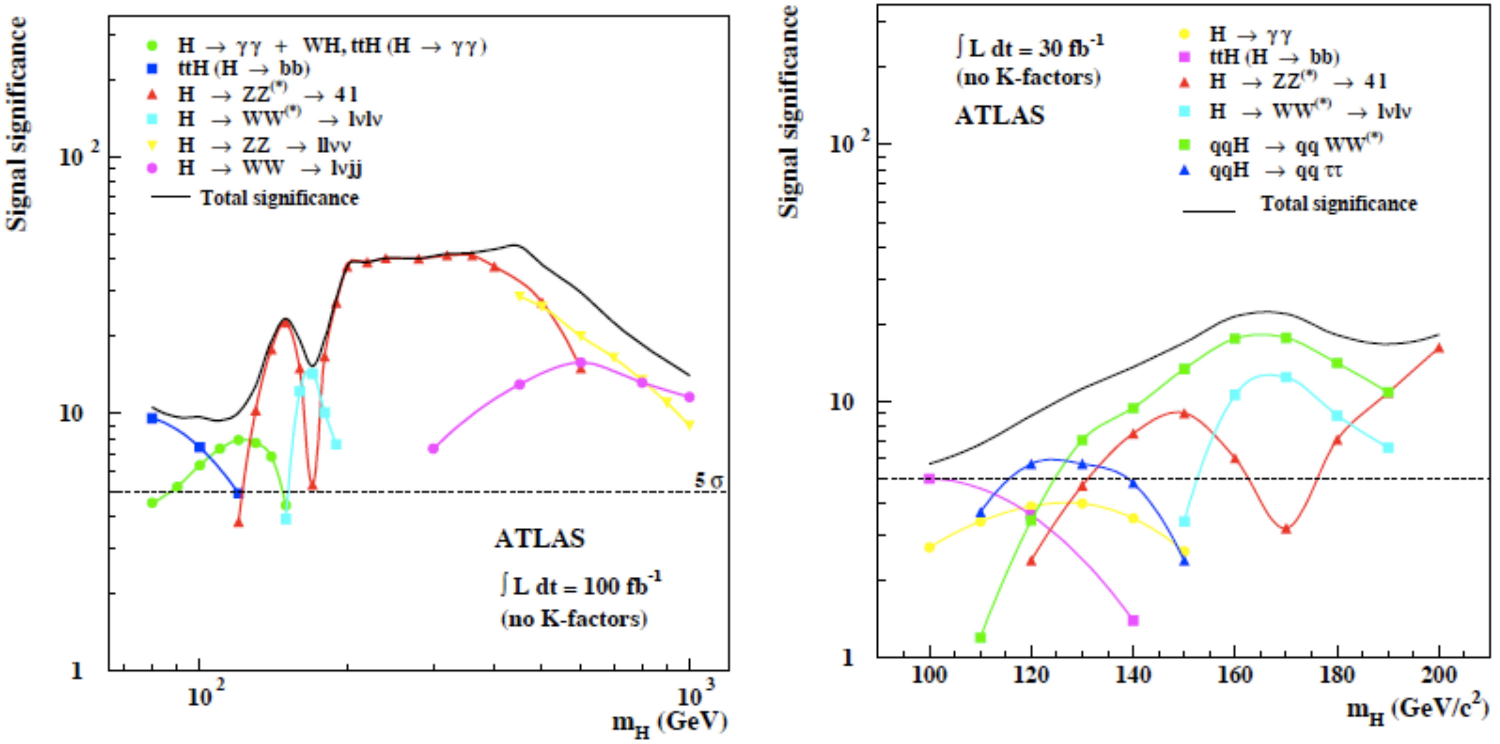


Figure 3.49: The significance for the SM Higgs boson discovery in various channels in ATLAS as a function of M_H. Left: the significance for 100 fb^{-1} data and with no vector boson fusion channel included and right: for 30 fb^{-1} data in the $M_H \leq 200$ GeV range with the $qq \rightarrow qqH$ channels included [234].

Discovery potential for SM Higgs boson

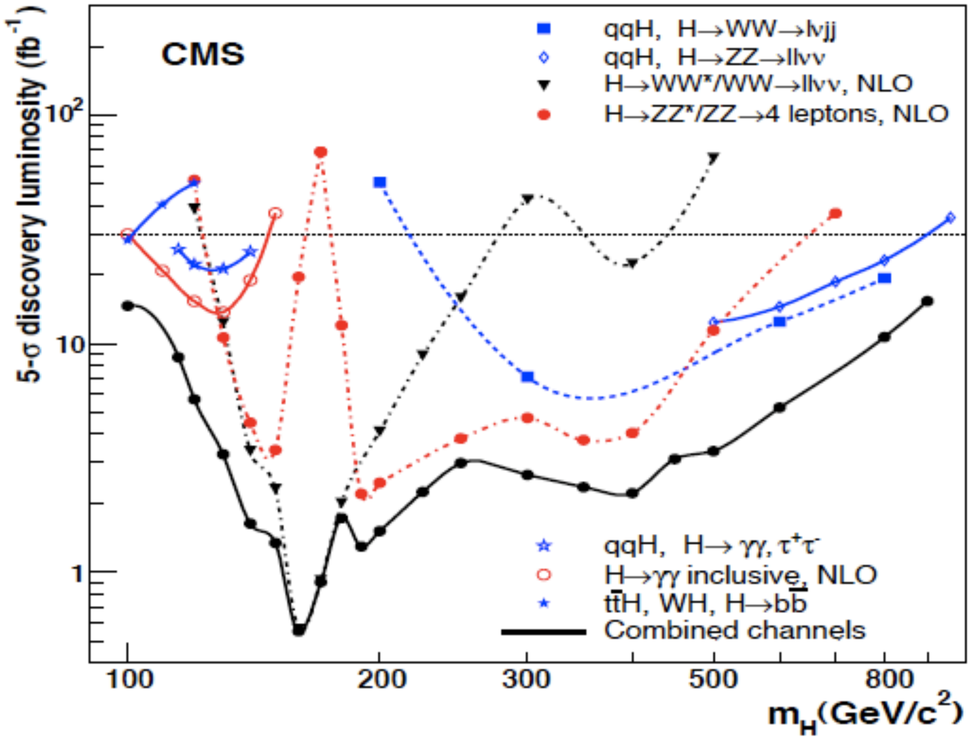


Figure 3.50: The required integrated luminosity that is needed to achieve a 5σ discovery signal in CMS using various detection channels as a function of M_H [235].

6

Two Higgs Doublet Models (2HDM)

Aim:

- A first example of how the Standard Model can be extended

References:

- …

7

Problems with the Standard Model

Aim:

- **Learn to use a phenomenological approach to identify the problems of a model (eg. Standard Model)**

References:

- …

Quick introduction to Supersymmetry

Aim:

- Extend the Standard Model with supersymmetry and learn its particle content
- Learn the Minimal Supersymmetric Standard Model (MSSM)
- Get to know its parameter space

References:

- …

The Higgs sector in Supersymmetric Models (MSSM)

Aim:

- **Extend the Higgs sector which you know very well to the MSSM**

References:

- …

Constraints on the MSSM & its Higgs sector

Aim:

- **What do we know about the MSSM Higgs sector**
- **How to approach these searches from a phenomenological angle**

References:

- …