Higgs in Loops

G. Quast, A. Raspereza

Course "Higgs Physics"

Lecture 6, 31/05/2012

Recap and Summary

Reminder: The Lagrangian of EW interactions

$$\mathscr{L}_{EW} = \underbrace{\bar{L}\gamma^{\mu}\, i\partial_{\mu} L + \bar{R}\gamma^{\mu}\, i\partial_{\mu} R}_{E_{kin}} \quad -$$

$$\underbrace{\frac{g}{2}\bar{L}\gamma^{\mu}\tau_{\alpha}\cdot W^{\alpha}_{\mu} L - \frac{g'}{2}\bar{L}\gamma^{\mu} Y B_{\mu} L - \frac{g'}{2}\bar{R}\gamma^{\mu} Y B_{\mu} R}_{Interaction\ with\ W^{\pm}, Z, \gamma} \quad -$$

$$\underbrace{\frac{1}{4} W^{\alpha}_{\mu\nu}\cdot W^{\mu\nu}_{\alpha} - \frac{1}{4} B_{\mu\nu}\cdot B^{\mu\nu}}_{E_{kin}\ of\ W^{\pm}, Z, \gamma\ and\ self-interaction} \quad +$$

$$\underbrace{\left|\left(i\partial_{\mu} - g\frac{1}{2}\tau_{\alpha}\cdot W^{\alpha}_{\mu} - g'\frac{Y}{2}B_{\mu}\right)\Phi\right|^{2} - V(\Phi)}_{W^{\pm}, Z, \gamma, H\ masses\ and\ couplings} \quad -$$

$$\underbrace{\left(G_1 \bar{L}\Phi R + G_2 \bar{L}\Phi_c R + \text{hermitian conjugate}\right)}_{lepton\ and\ quark\ masses\ and\ coupling\ to\ Higgs}$$

L: left-handed fermion doublet
R: right-handed fermion singlet

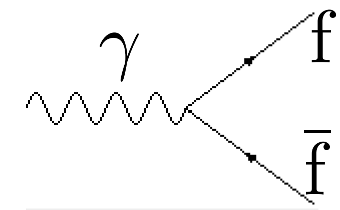
Structure of gauge boson couplings to fermions

γ f f	$ie\gamma^{\mu}$	vector coupling
W f f'	$\frac{-i\,e}{\sqrt{2}\sin\Theta_W}\gamma^{\mu}\frac{1}{2}(1-\gamma^5)$	"V-A" coupling
Z f f	$\frac{-ie}{2\,cos_W\ \sin\Theta_W}\gamma^{\mu}(g_V^{\mathrm{f}}-g_A^{\mathrm{f}}\gamma^5)$ $g_A^{\mathrm{f}}=T_3^{\mathrm{f}}\,,\qquad g_V^{\mathrm{f}}=T_3^{\mathrm{f}}-2q_{\mathrm{f}}\sin^2\Theta_W$	vector and axial vector couplings
H W W	$\frac{i\,e}{\sin\Theta_W}M_w$	
H Z Z	$\frac{-i\,eM_Z}{\cos\Theta_W\sin\Theta_W}$	
H f f	$\frac{-i\,e}{2\sin\Theta_W}\frac{m_f}{M_W}$	

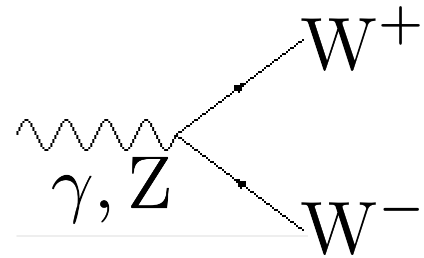
$\hbar=c=1\,;\;\; e=\sqrt{4\pi\alpha}$ with $\alpha=\frac{1}{137,\ldots}\,;\;\; g\sin\Theta_W=e\,;\;\; G_F=\frac{\sqrt{2}^2}{8{M_W}^2}$

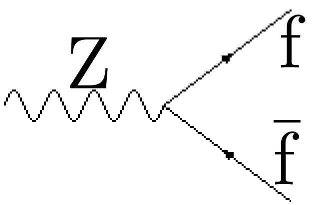
Quelle: Halzen, Martin

Reading Feynman Diagrams from Lagrangian

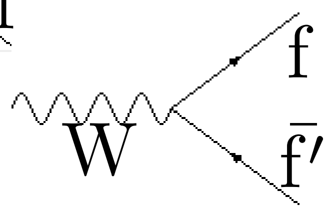


$f = e, \mu, \tau, u, d, s, c, b, t$





$f = \nu_e, e, \nu_\mu, \mu, \nu_\tau, \tau, u, d, c, s, t, b$



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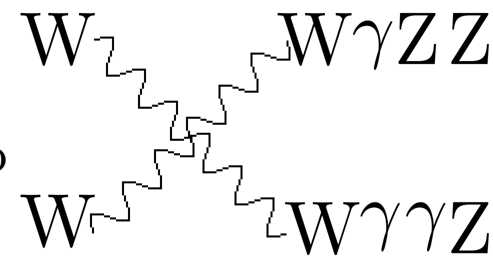
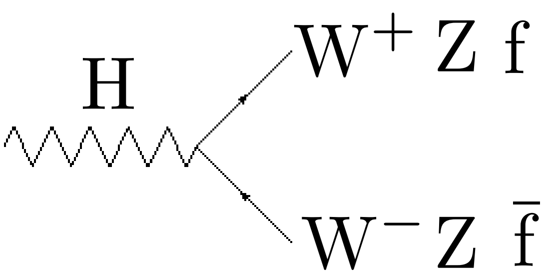
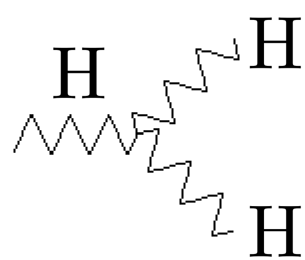


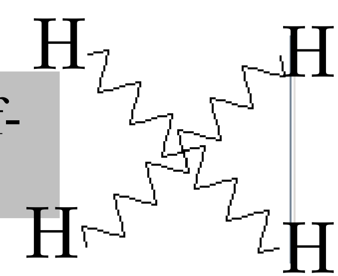
quartic couplings
(not seen yet)

Higgs couplings (not yet seen directly)





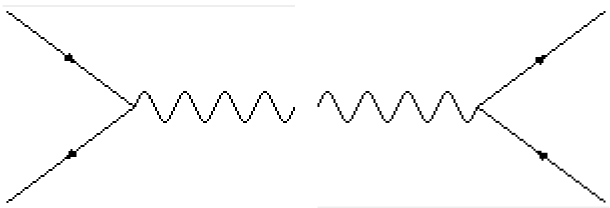
Higgs self-coupling



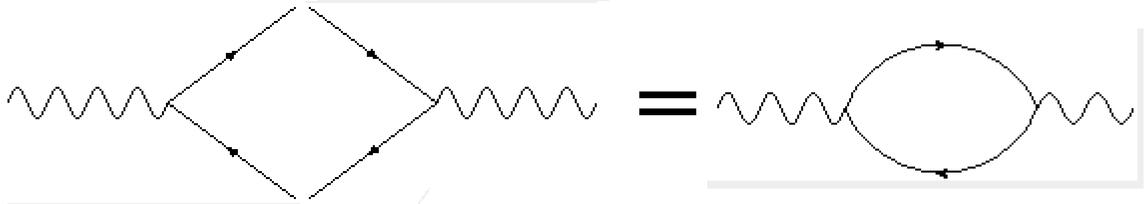
these are all "tree level couplings"

More complex diagrams constructed from these building blocks

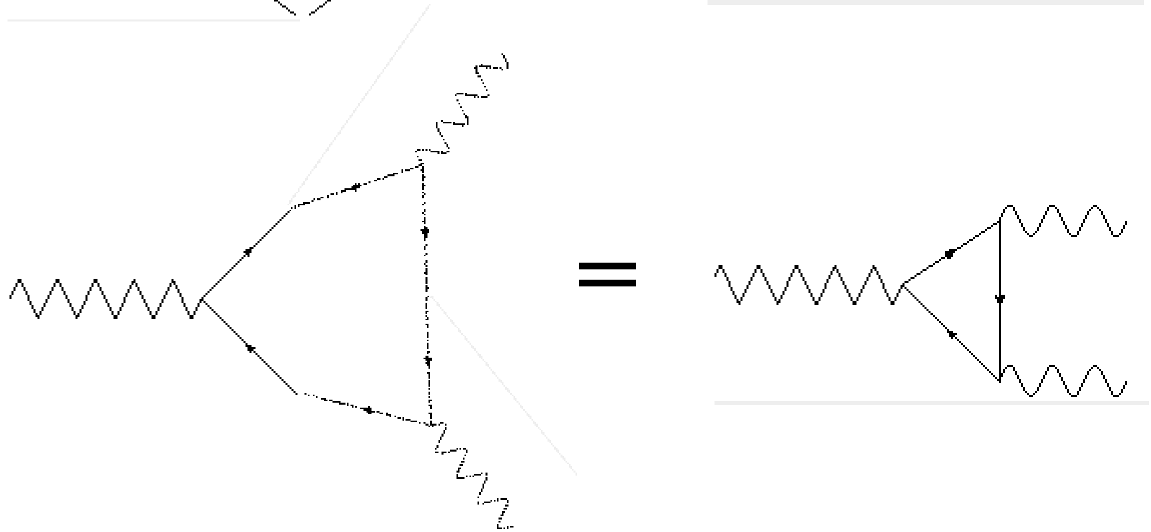
Feynman diagrams from building blocks - examples



$f\bar{f} \rightarrow f'\bar{f}'$



"fermion loop"
(modifies photon propatator)



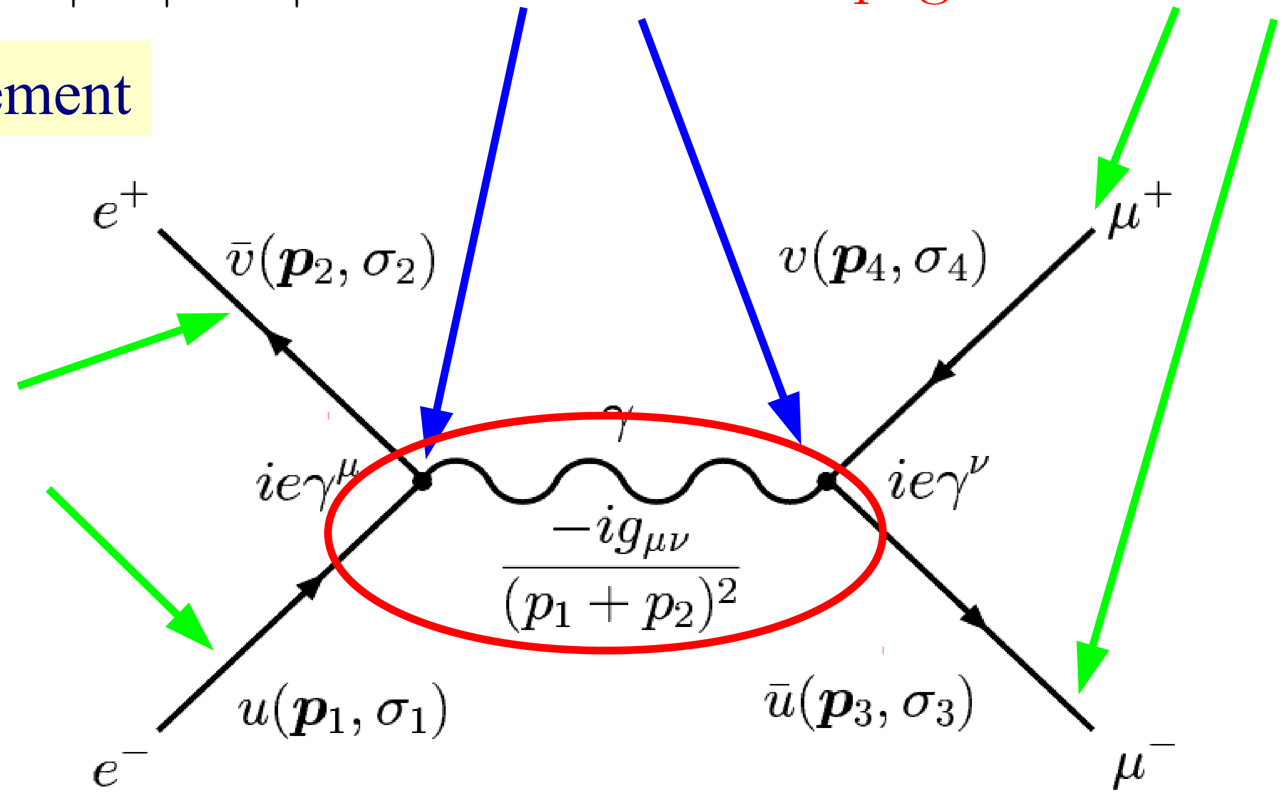
non-tree-level coupling via loop,
here: $H \rightarrow \gamma\,\gamma$

Very many combinations possible, up to an infinite number of Loops
→ enormous number of diagrams contributing to a given process

Reminder: Calculation of differential cross sections (in lowest order)

$$|\mathcal{M}|^2 = |\text{Vertex factors} \cdot \text{Propagator} \cdot \text{External lines}|^2$$

Matrix element



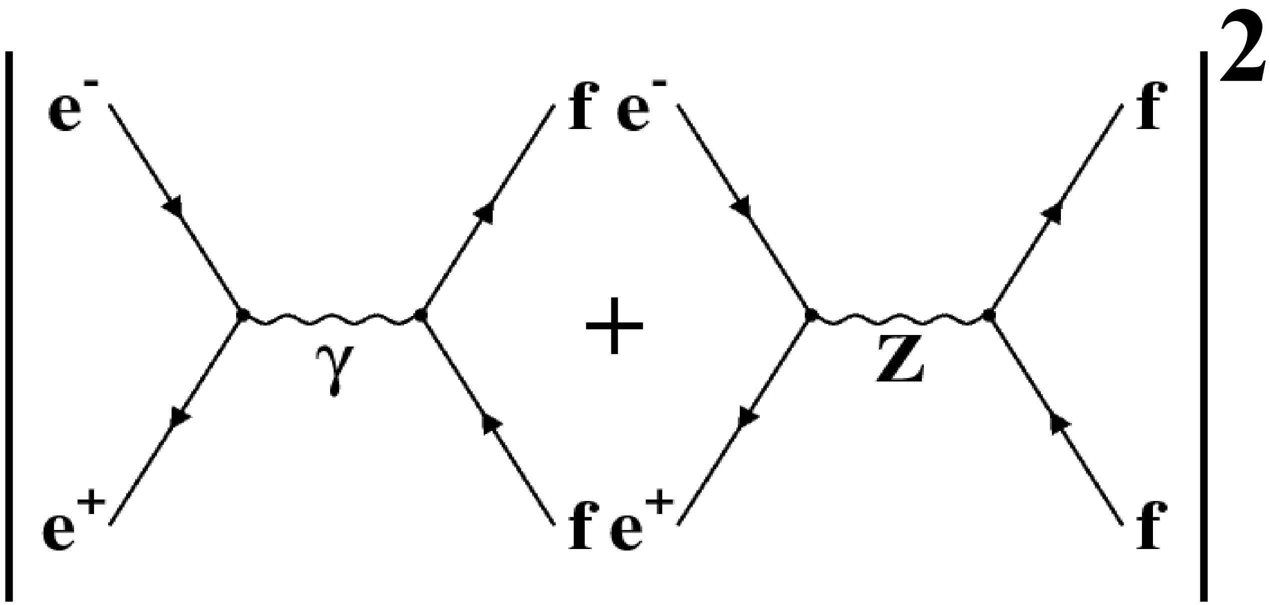
Cross Section

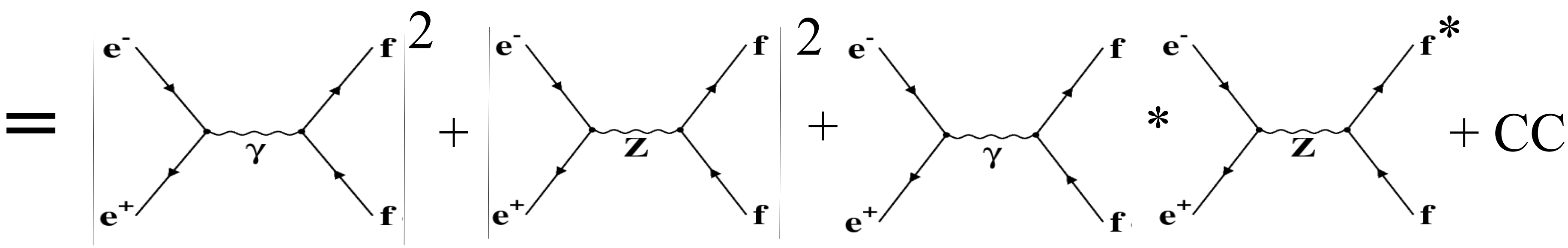
$$\sigma = \frac{|\mathcal{M}|^2 \cdot [\text{Phase space}]}{[\text{Colliding particle flux}]}$$

Standard Model processes in higher order

Example: $e^+e^- \to f\bar{f}$

$|M|^2 =$





Photon Z **Photon – Z Interference term**

Example: $e^+e^- \rightarrow f\bar{f}$ differential cross section

$$\frac{2s}{\pi}\frac{1}{N_c^{\mathrm{f}}}\frac{d\sigma_{\mathrm{ew}}}{d\cos\theta}(\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}) =$$

$$\underbrace{|\alpha|^2 (1+\cos^2\theta)}_{\gamma}$$

$$\underbrace{-8\alpha\chi(s)\left[g_{\mathrm{Ve}}g_{\mathrm{Vf}}(1+\cos^2\theta) + 2g_{\mathrm{Ae}}g_{\mathrm{Af}}\cos\theta\right]}_{\gamma - \mathrm{Z\ interference}}$$

$$\underbrace{+16|\chi(s)|^2\left[(g_{\mathrm{Ve}}^2+g_{\mathrm{Ae}}^2)(g_{\mathrm{Vf}}^2+g_{\mathrm{Af}}^2)(1+\cos^2\theta) + 8g_{\mathrm{Ve}}g_{\mathrm{Ae}}g_{\mathrm{Vf}}g_{\mathrm{Af}}\cos\theta\right]}_{\mathrm{Z}}$$

"color factor"; 3 for quarks, 1 for leptons

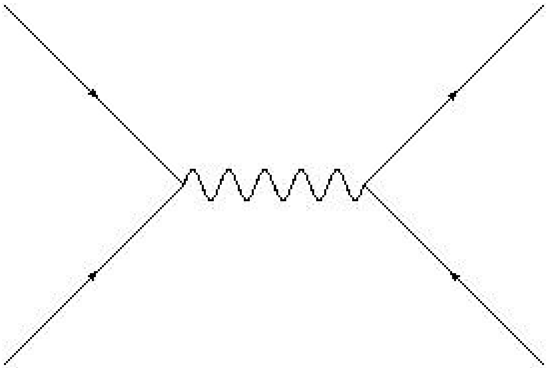
Use dimension-less (fine structure) coupling constant instead of e^2:

$$\alpha = \frac{e^2}{4\pi\epsilon_0}\frac{1}{\hbar c} \simeq \frac{1}{137}$$

with $\chi(s) = \frac{m_{\mathrm{Z}}^2}{8\pi\sqrt{2}}\frac{s}{s-m_{\mathrm{Z}}^2+i\Gamma_{\mathrm{Z}}m_{\mathrm{Z}}}$

Breit-Wigner Propagator

2 → 2 process in higher orders

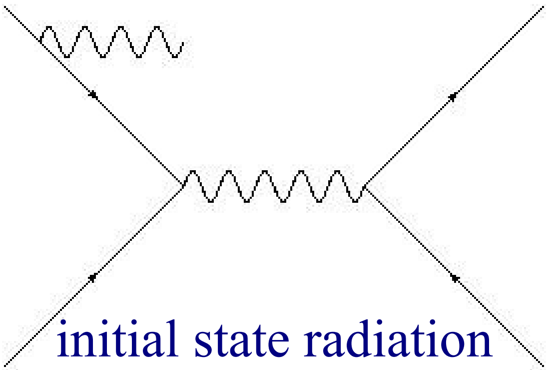


Higher order corrections

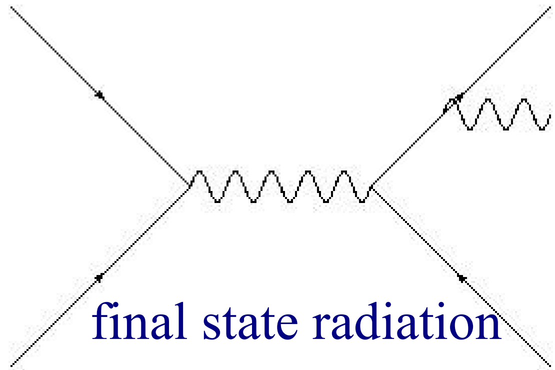
modify simple process $f\bar{f} \rightarrow f'\bar{f}'$

shown here: examples of

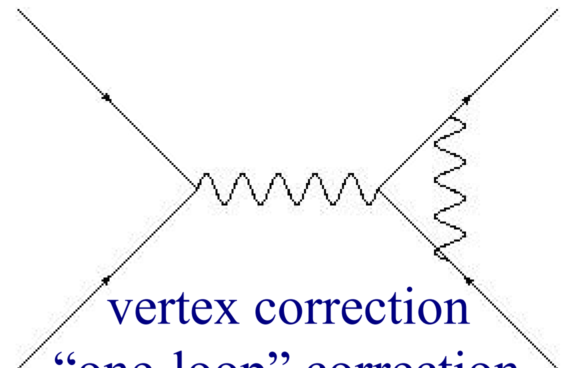
"next-to-leading order"- corrections



initial state radiation

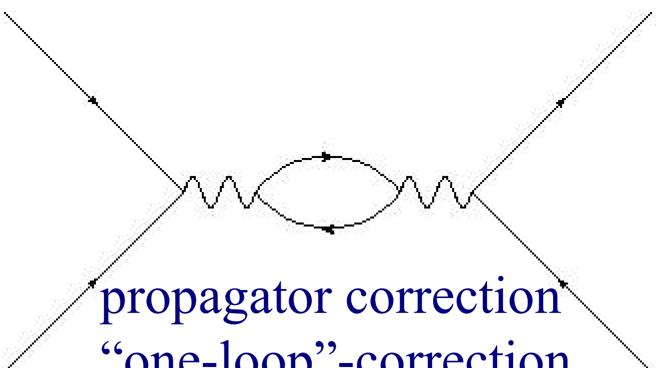


final state radiation



vertex correction

"one-loop" correction



propagator correction

"one-loop"-correction

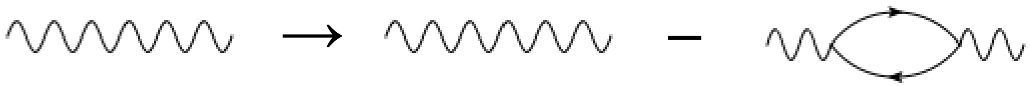
– all basic vertices can be inserted, involving all particles of the theory (fermions & bosons)

– integration over momenta of radiated particles or particles in loop

Higher-order amplitudes calculable with Feynman rules,

with the following extensions:

- **diagrams with n fermion loop receive factor $(-1)^n$**
- **integrate over 4-momenta in loops**



Integrals lead to **divergences** at low and high momenta,
$p \rightarrow 0$ or $p \rightarrow \infty$, respectively: infrared and ultraviolet divergences

handled by "rgularisation" and "renormalisation" techniques

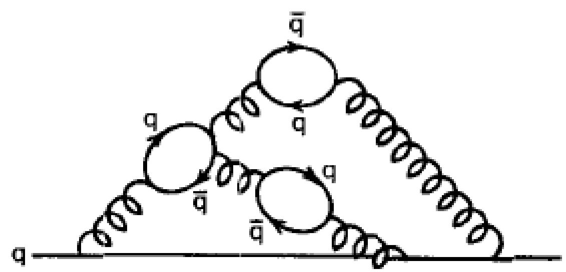
- "regularisation" of integrals to track infinities
  cutoff-parameters, or finite photon mass, or "dimensional regularisation"
- reparametrisation of physical observables (mass, charge=couplings):
  "renormalisation"
- exploit cancellations between contributions
  (e.g. diagrams involving photon, Z and neutriono-exchange in WW cross section)

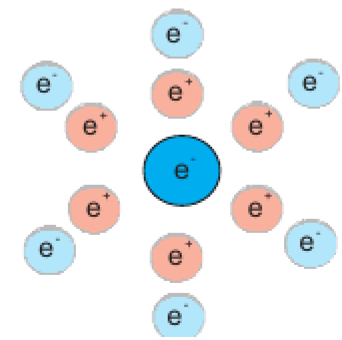
Renormalisation:

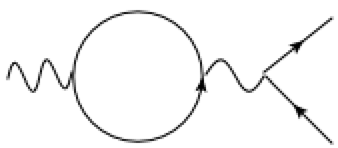
Example:

charge and magnetic moment of electron in QED

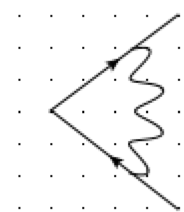
in pictures: *electron is surrounded by a cloud of virtual electrons, existing at a scale* $\Delta E \Delta t \geq \frac{\hbar}{2}$







virtual particles in loop
shield (bare) electric charge



virtual photon exchange
modifies magnetic moment

lead to experimentally well-established effects

Lamb shift

g-2 of electron $\neq 0$

Remarks on higher order calculations - Renormalisation (2)

Method: replace **bare electric charge** in lowest-order diagram by measured values in a process at a given energy scale μ^2 – re-parameterize perturbation series in terms of physical charge

Theory now depends on
– scale of the process, Q^2 ,
– and scale μ^2, at which coupling was determined

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi} \log \frac{Q^2}{\mu^2}}$$

"running coupling"

$$\alpha(M_Z{}^2) \simeq \frac{1}{129}$$

Dependence on μ^2 diminishes if higher orders taken into account, and vanishes at infinite order (governed by "renormalisation group equation").

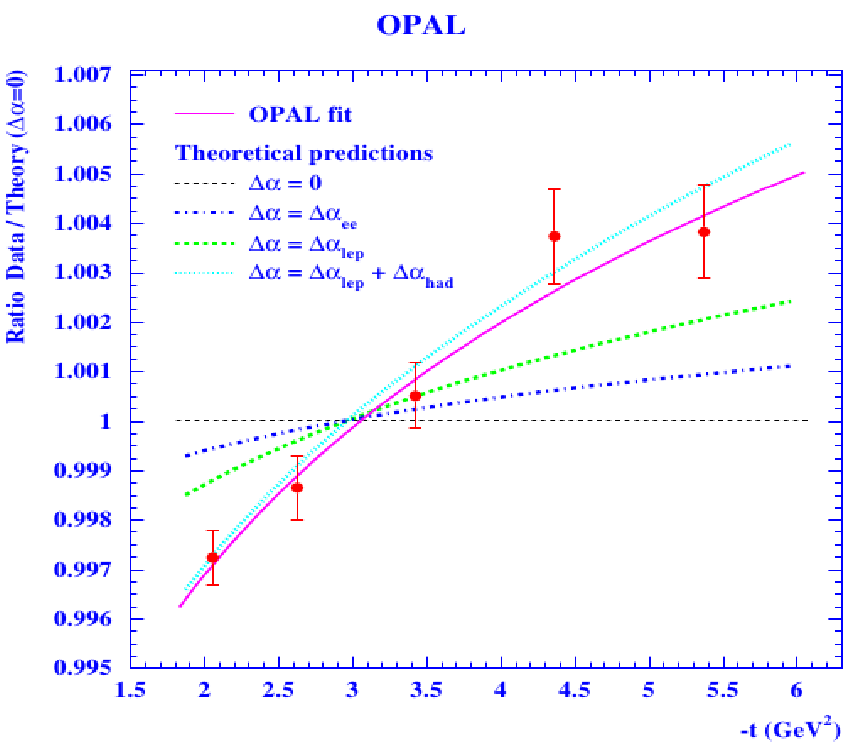
"Running couplings" absorb effect of propagator loops

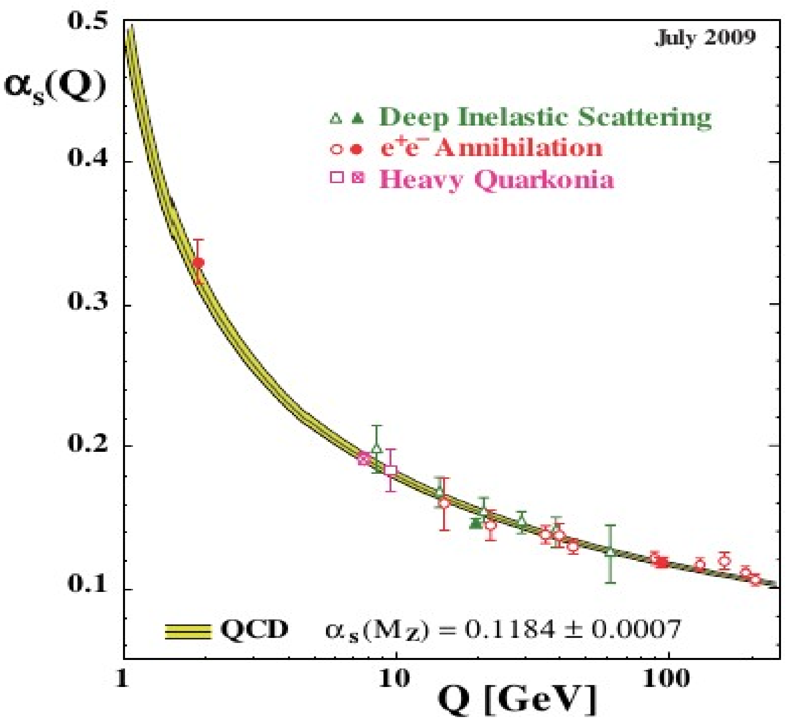
See Halzen, Martin, Chap. 7, for a brief introduction, or Theoretical Particle Physics II

Examples:

Running of

the electromagnetic and the strong coupling constants



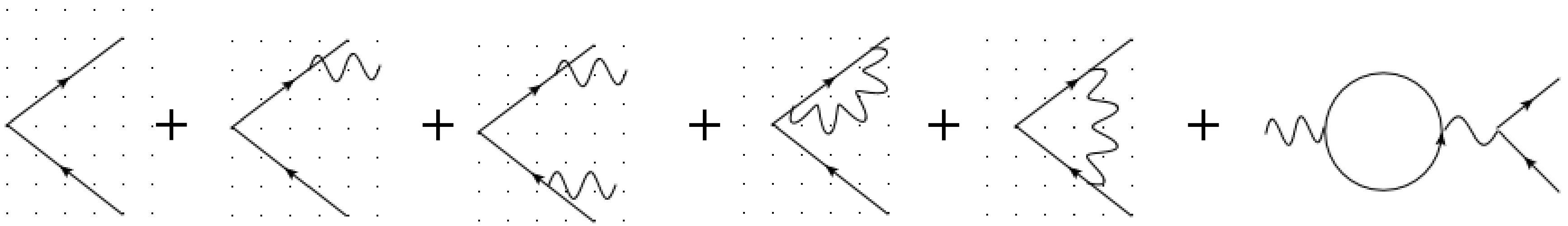


Measurement of the electromagnetic coupling constant as a function t-channel momentum transfer in $e^+e^- \to e^+e^-$ scattering

Strong coupling constant as measred at different energies and in different processes.

Remarks on higher orders - exploiting cancellations

Infrared-divergences in photon emission cancel out
if all diagrams up to given order are included

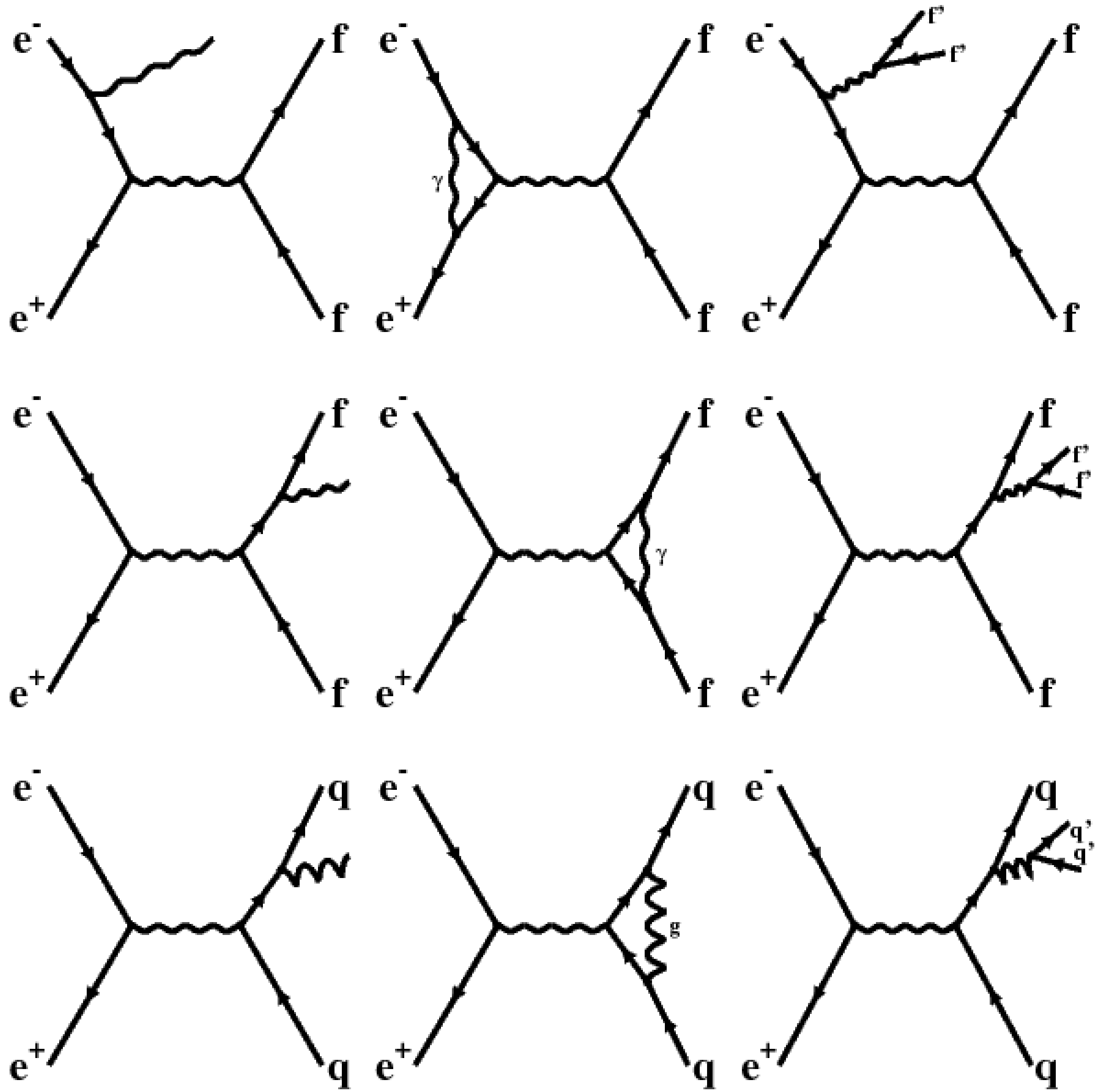


real emission   virtual photons   propagator loops

consequence of "Ward identities" in renormalizable theories

Back to $e^+e^- \rightarrow f\bar{f}$ – QED and QCD radiation

Examples of initial and final state radiation



QED corrections known to leading third order.

Corrections from strong interactions in quark final states (QCD) known to fourth order!

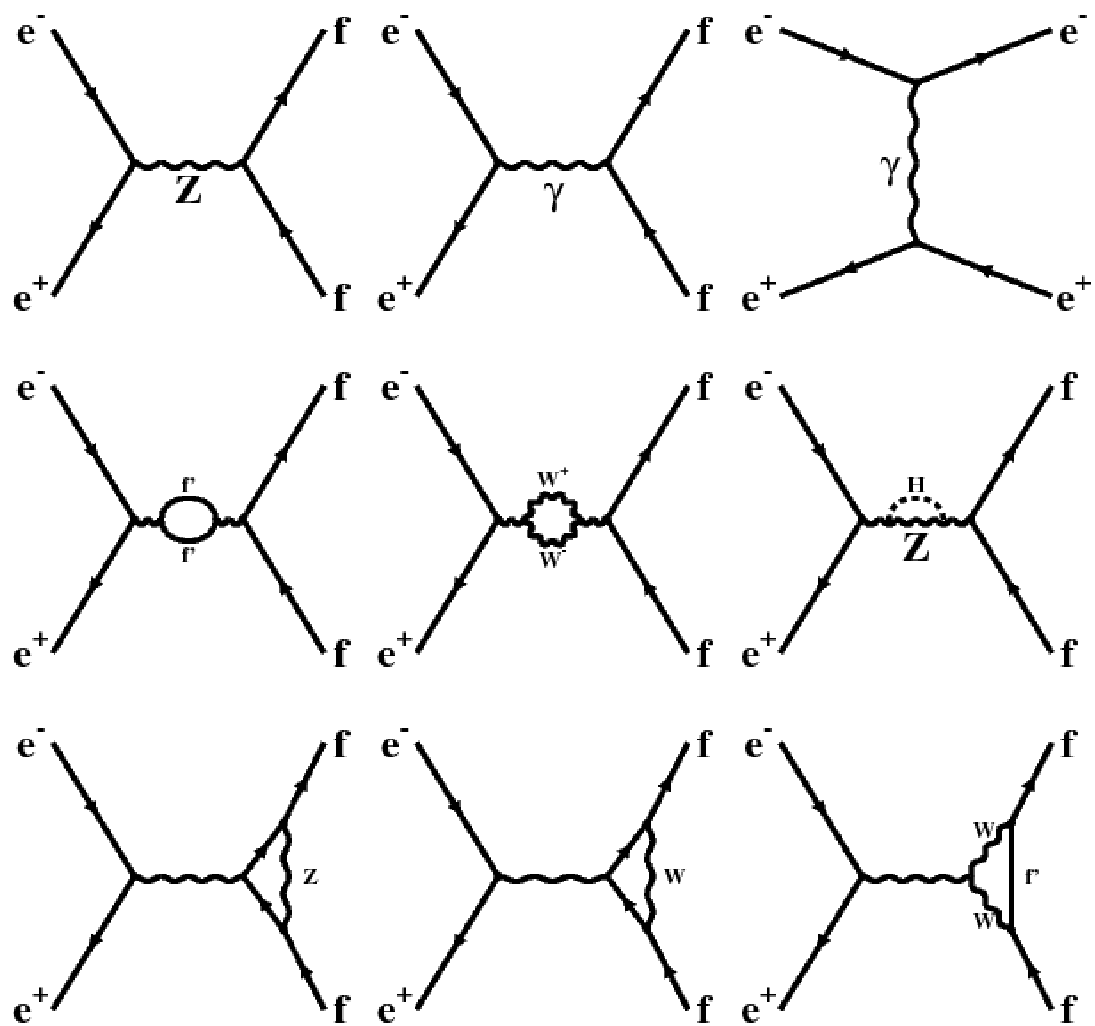
$e^+e^- \rightarrow f\bar{f}$ loop corrections

Examples of diagrams contributing to $e^+e^- \rightarrow f\bar{f}$

Via loops and radiation,
the simple 2→2 process
becomes sensitive to
all particles in the theory!

Known to leading
two-loop contributions!

Must calculate a large
number of diagrams
contributing to same
(experimental) final
states.



From Standard Model in lowest order ...

Model parameters:

- e electron charge, or fine structure constant $\alpha = \frac{e^2}{4\pi\epsilon_0}\frac{1}{\hbar c} \simeq \frac{1}{137}$
- M_W } or, alternatively G_F Fermi constant
- M_Z } or, alternatively $\sin^2\Theta_W$ weak mixing angle
- 12 fermion masses
  ↔ 12 Higgs-Fermion Yukawa couplings
- quark-mixing (CKM) matrix, 4 angles
  ↔ Higgs Yukawa Couplings
- Lepton mixing matrix $m_\nu \neq 0$!(?)
- Strong coupling constant α_s

in total: 25 parameters

Relations in lowest order:

$$\frac{G_F}{\sqrt{2}} = \frac{\alpha}{2\sin^2\Theta_W M_W^2}$$

$$\sin^2\Theta_W = 1 - \frac{{M_W}^2}{{M_Z}^2}$$

… to Standard Model in higher order

Introduce running couplings: $\alpha(M_Z)$, $G_F\,(M_Z)$

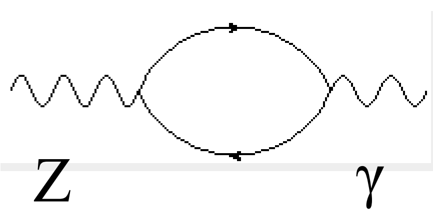
keep $\sin^2\Theta_W := 1 - \frac{{M_W}^2}{M_Z^2}$ as definition "on-shell weak angle"

with "radiative corrections" $\Delta r = \Delta\alpha + r_W$ 2nd relation becomes:

$$M_Z^2 \sin^2\Theta_W \cos^2\Theta_W = \frac{\pi\alpha^{(0)}}{\sqrt{2}G_F}\cdot\frac{1}{1-\Delta r}$$

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

There are other variants of an "effective weak angle":



+ vertex corrections:

$$\sin^2\Theta_W^{\mathrm{eff,f}} = \frac{1}{4}\left(1 - \frac{g_v^{\mathrm{eff,f}}}{g_a^{\mathrm{eff,f}}}\right)$$

from couplings measured in experiment

Observables in higher order

Results in modifications of couplings:

$$g_a^{\mathrm{f}} = T_3 \rightarrow g_a^{\mathrm{eff,f}} = \sqrt{\rho^{\mathrm{eff,f}}} T_3 \qquad \rho^{\mathrm{eff}} = 1 + \Delta\rho$$

$$g_v^{\mathrm{f}} = T_3 - 2q_f \sin^2\Theta_W \rightarrow g_v^{\mathrm{eff,f}} = \sqrt{\rho^{\mathrm{eff,f}}}(T_3 - 2q_f \sin^2\Theta_W^{\mathrm{eff,f}})$$

$\Delta r_w,\ \Delta\rho$ and $\sin^2\Theta_W^{\mathrm{eff}}$

absorb higher orders to very good approximation

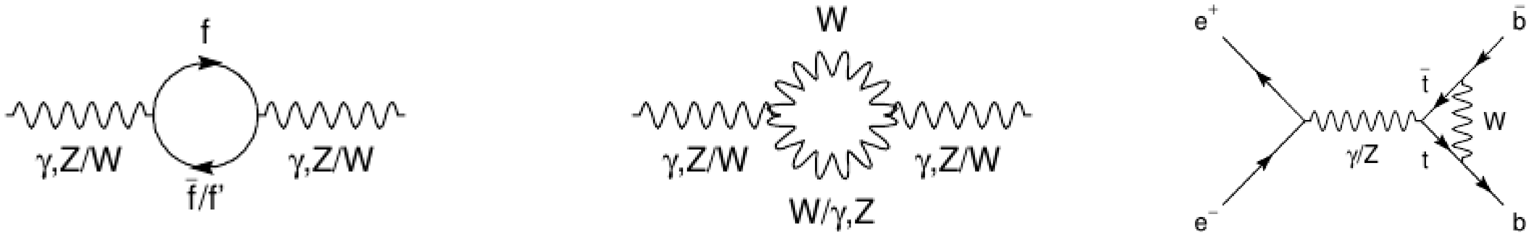
Radiative corrections depend

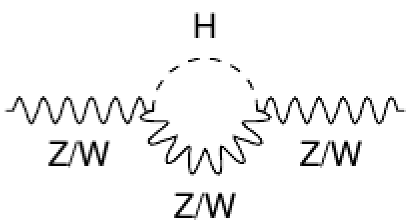
- **quadratically** on top mass
- **only logarithmically** on M_H

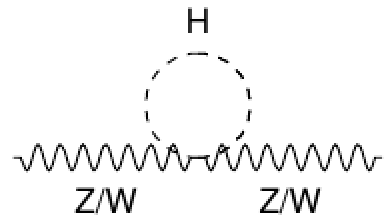
$$\text{e.g. } \Delta r_W(M_t, M_H) = \frac{3\alpha\cos^2\Theta_W}{16\pi\sin^4\Theta_W}\frac{{M_t}^2}{{M_W}^2} + \frac{11\alpha}{48\pi\sin^2\Theta_W}\log\frac{{M_H}^2}{{M_W}^2} + \dots$$

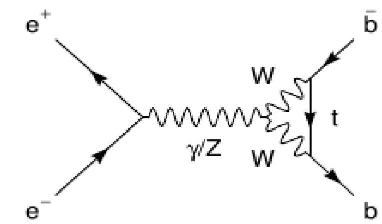
Software implementations of higher-order calculations exist to calculate Observables $\mathcal{O}(\alpha, G_F, M_Z, M_{\mathrm{top}}, M_{\mathrm{H}}, \ldots)$

Differential cross section near Z resonance in higher orders









Corrections

to boson propagators and vertex-corrections,

as shown above, and many others, absorbed into

- modified Breit-Wigner with s-dependent width
- "running" electromagnetic and strong coupling constants
- effective Z-couplings:

$$\mathcal{G}_{\mathrm{Vf}} = \sqrt{\mathcal{R}_{\mathrm{f}}}\,(T_3^{\mathrm{f}} - 2Q_{\mathrm{f}}\mathcal{K}_{\mathrm{f}}\sin^2\theta_{\mathrm{W}})$$

$$\mathcal{G}_{\mathrm{Af}} = \sqrt{\mathcal{R}_{\mathrm{f}}}\,T_3^{\mathrm{f}}\,.$$

with complex form factors R_{f} , K_{f}

dominant real parts can be extracted from measurements as "effective Z couplings"

Effective Parametrization of differential cross section near Z resonance

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

Form of tree-level formula retained !

$$\underbrace{|\alpha(s)|^2\,(1+\cos^2\theta)}_{\gamma}$$

$$\underbrace{-8\Re\left\{\alpha^*(s)\chi(s)\left[\mathcal{G}_{\mathrm{V}e}\mathcal{G}_{\mathrm{V}f}(1+\cos^2\theta)+2\mathcal{G}_{\mathrm{A}e}\mathcal{G}_{\mathrm{A}f}\cos\theta\right]\right\}}_{\gamma-\mathrm{Z\ interference}}$$

$$\underbrace{\begin{array}{c}+16|\chi(s)|^2\left[(|\mathcal{G}_{\mathrm{V}e}|^2+|\mathcal{G}_{\mathrm{A}e}|^2)(|\mathcal{G}_{\mathrm{V}f}|^2+|\mathcal{G}_{\mathrm{A}f}|^2)(1+\cos^2\theta)\right.\\ \left.+8\Re\left\{\mathcal{G}_{\mathrm{V}e}{\mathcal{G}_{\mathrm{A}e}}^*\right\}\Re\left\{\mathcal{G}_{\mathrm{V}f}{\mathcal{G}_{\mathrm{A}f}}^*\right\}\cos\theta\right]\end{array}}_{\mathrm{Z}}$$

with $\chi(s) = \frac{m_{\mathrm{Z}}^2}{8\pi\sqrt{2}}\frac{s}{s-m_{\mathrm{Z}}^2+is\Gamma_{\mathrm{Z}}/m_{\mathrm{Z}}}$ Breit-Wigner with s-dependent width

Literature: "Z Pole Report" by LEP EW Working group and the LEP collaborations furthermore:

partial decay widths

$$\Gamma_{\mathrm{f}}^{(ew)} = N_c^{\mathrm{f}} \frac{G_F {m_Z}^3}{6\sqrt{2}\pi} \left({g_V^{\mathrm{eff}}}^2 + {g_A^{\mathrm{eff}}}^2 \right)$$

receive radiative corrections for real photon and gluon emmission:

$$\Gamma_{\mathrm{f}} = \Gamma_{\mathrm{f}}^{(ew)} \cdot \left(1 + \frac{3}{4\pi} q_{\mathrm{f}}^2 \alpha(m_Z) + \ldots \right)$$

$$\cdot \left(1 + \frac{\alpha_s(m_Z)}{\pi} + \ldots \right)$$

last factor for quarks only

Important to remember:

Via **radiative and loop corrections**
effective couplings (i.e. corrections to tree-level couplings)
depend on all parameters of the theory, in particular:
- **top quark mass** (→ prediction of top mass before top quark discovery)
- **Higgs boson mass**

Measurements in $e^+ e^-$ at LEP – the four experiments

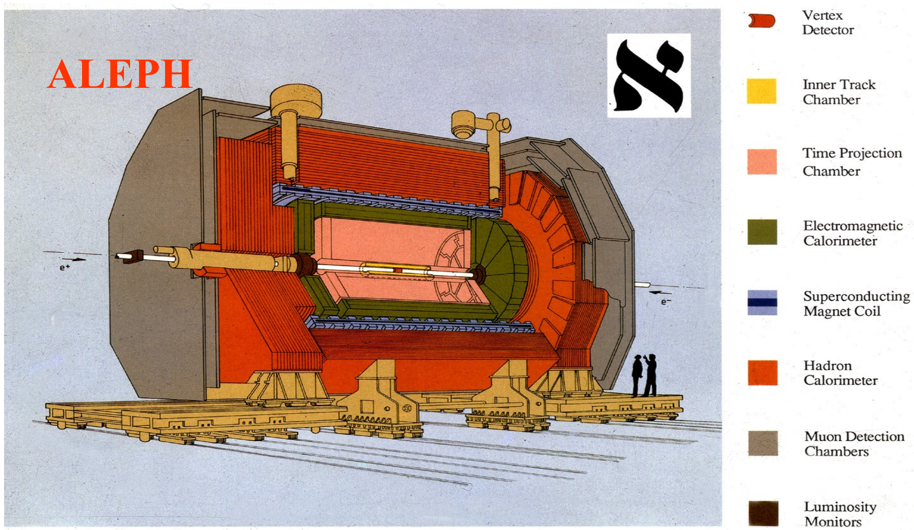
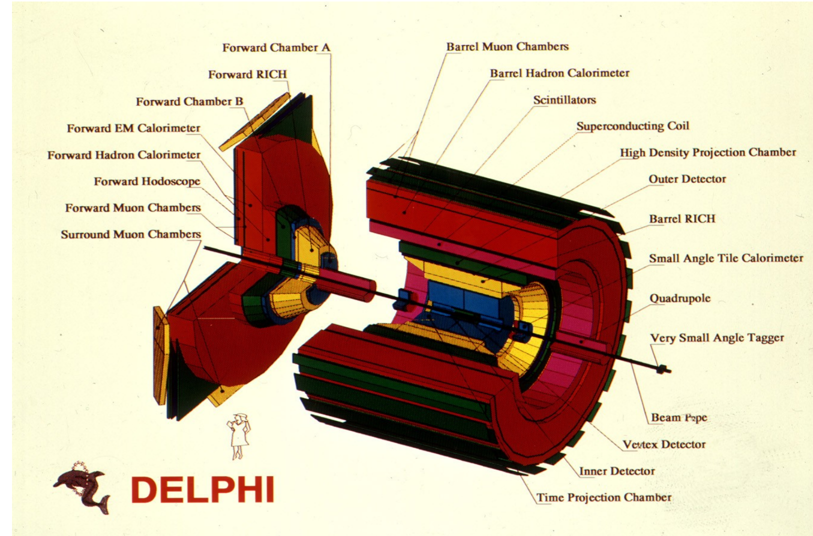
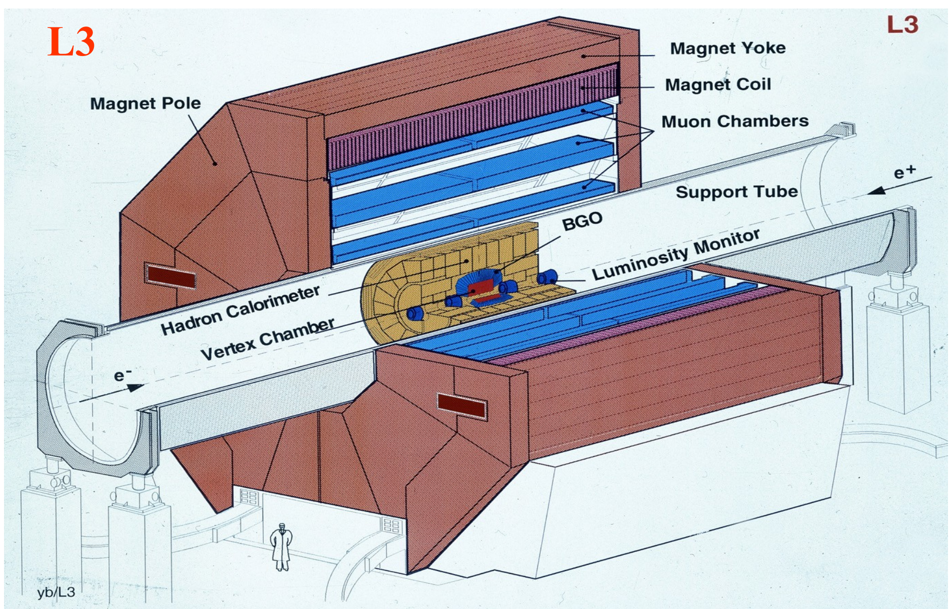
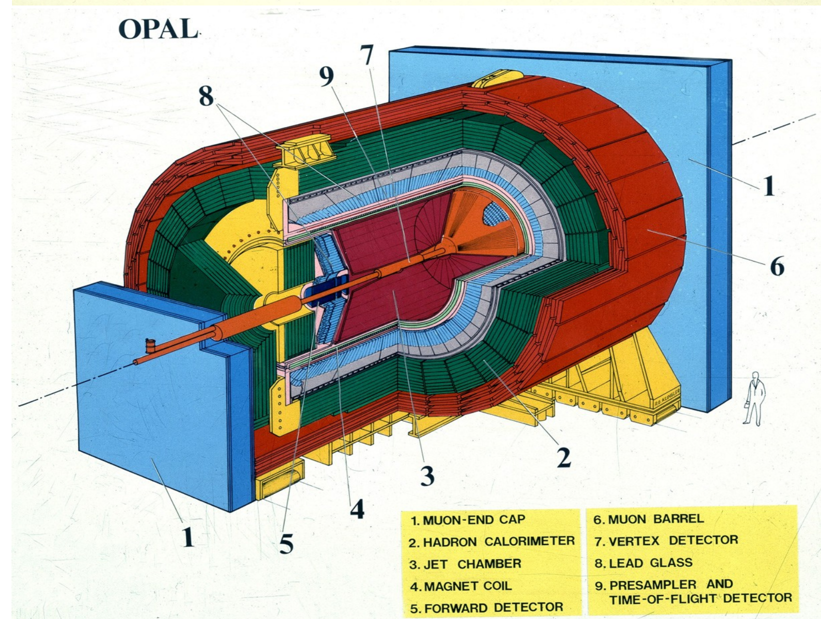


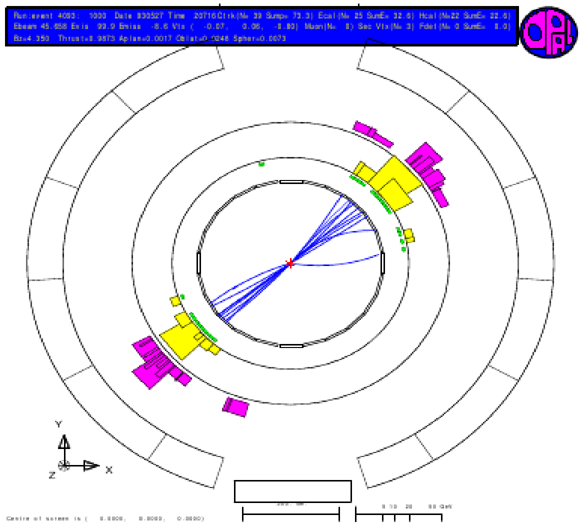
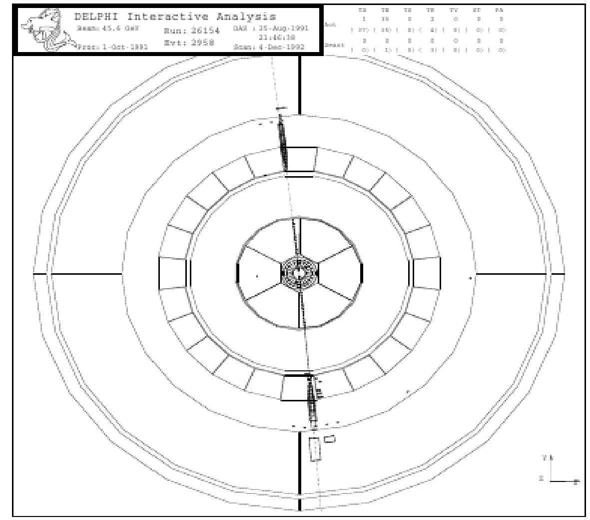
Fig. 1 - The ALEPH Detector



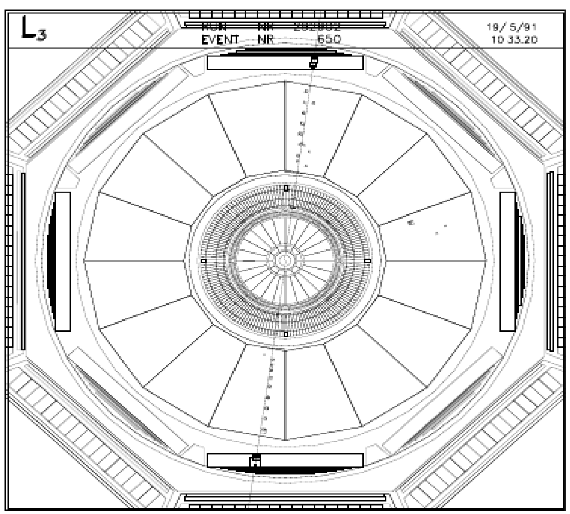


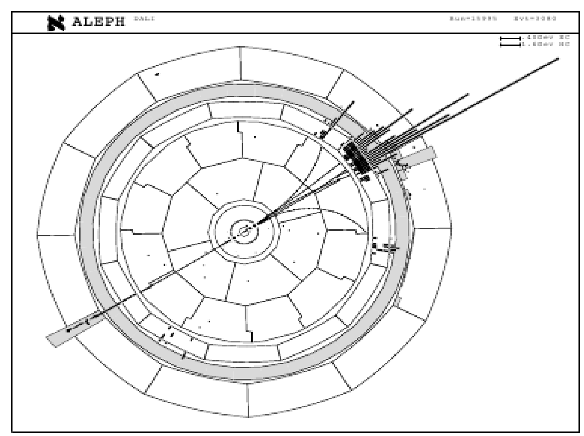


Measurements in $e^+ e^-$ at LEP

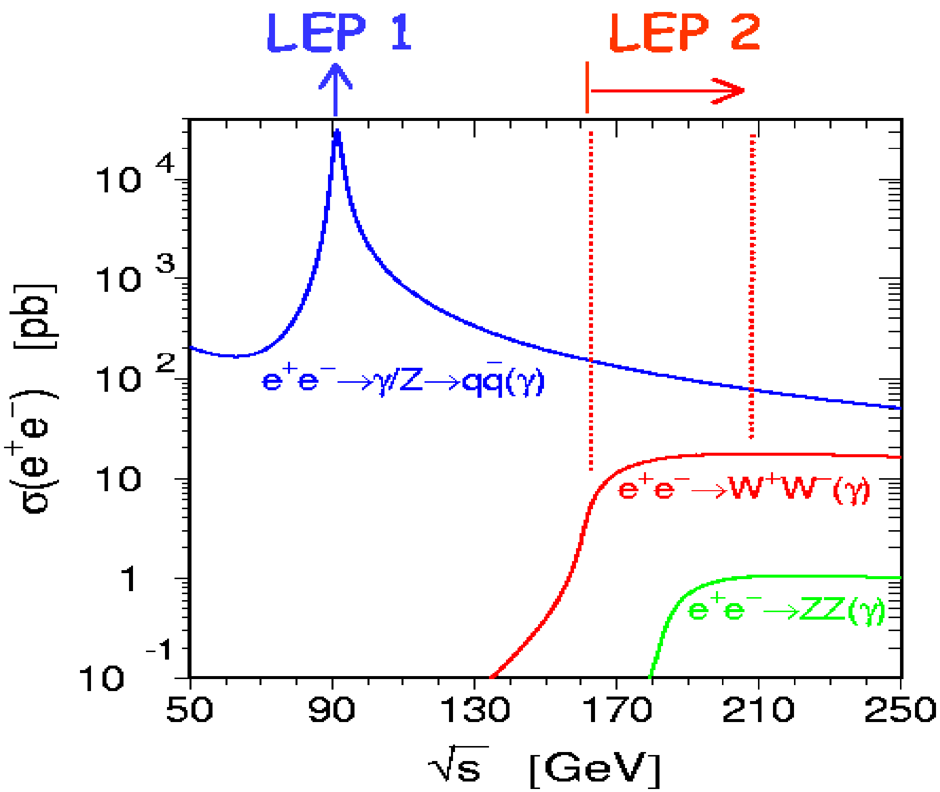



Event Displays from LEP experiments



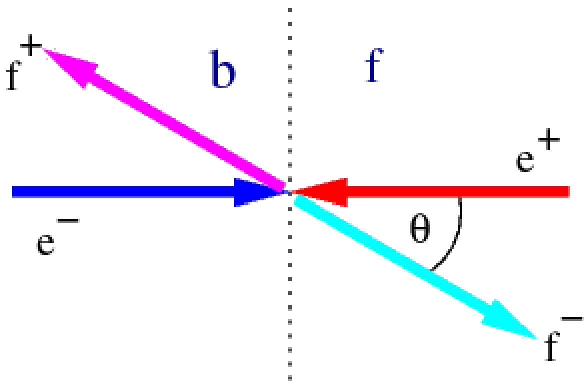


Measurements in $e^+ e^-$ at LEP



LEP 1: measurement of Z boson parameters (16 million Z's)

LEP 2: measurement of W and Z boson pair production, W boson Parameters (40'000 W pairs)



total cross section

$$\sigma_{tot} \equiv \int_{-1}^{1} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

depends on (1+cos^2 Θ) terms only

Forward-backward asymmetry

$$A_{FB} \equiv \frac{\int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta}{\sigma_{tot}}$$

depends on cos^2 Θ terms only

Principle:

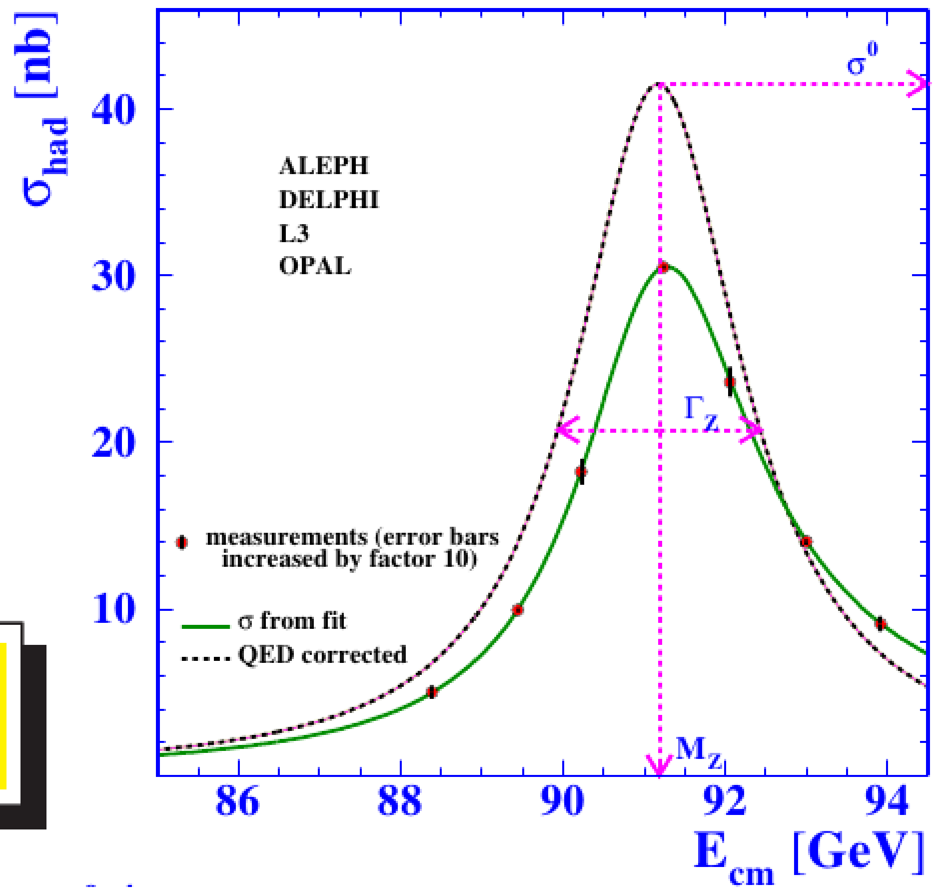
Extract combinations of Z-couplings to fermions form measurements of σ_{tot} and A_{FB} in different channels and at different energies

Precision measurements: Z line shape

Measurement of cross sections:

- Determine canditate events for signal process
- Subtract background passing selection critetea
- Determine selection efficiency: from Monte- Carlo simulation or using "data-driven" mehtods
- Normalize corrected number of signal events to luminosity

$$\sigma(E_i) = \frac{N^{cand}_{f\bar{f}}(E_i) - N^{bkg}_{f\bar{f}}(E_i)}{\varepsilon_{ac}(E_i)} \frac{1}{\int L\,(E_i)},$$



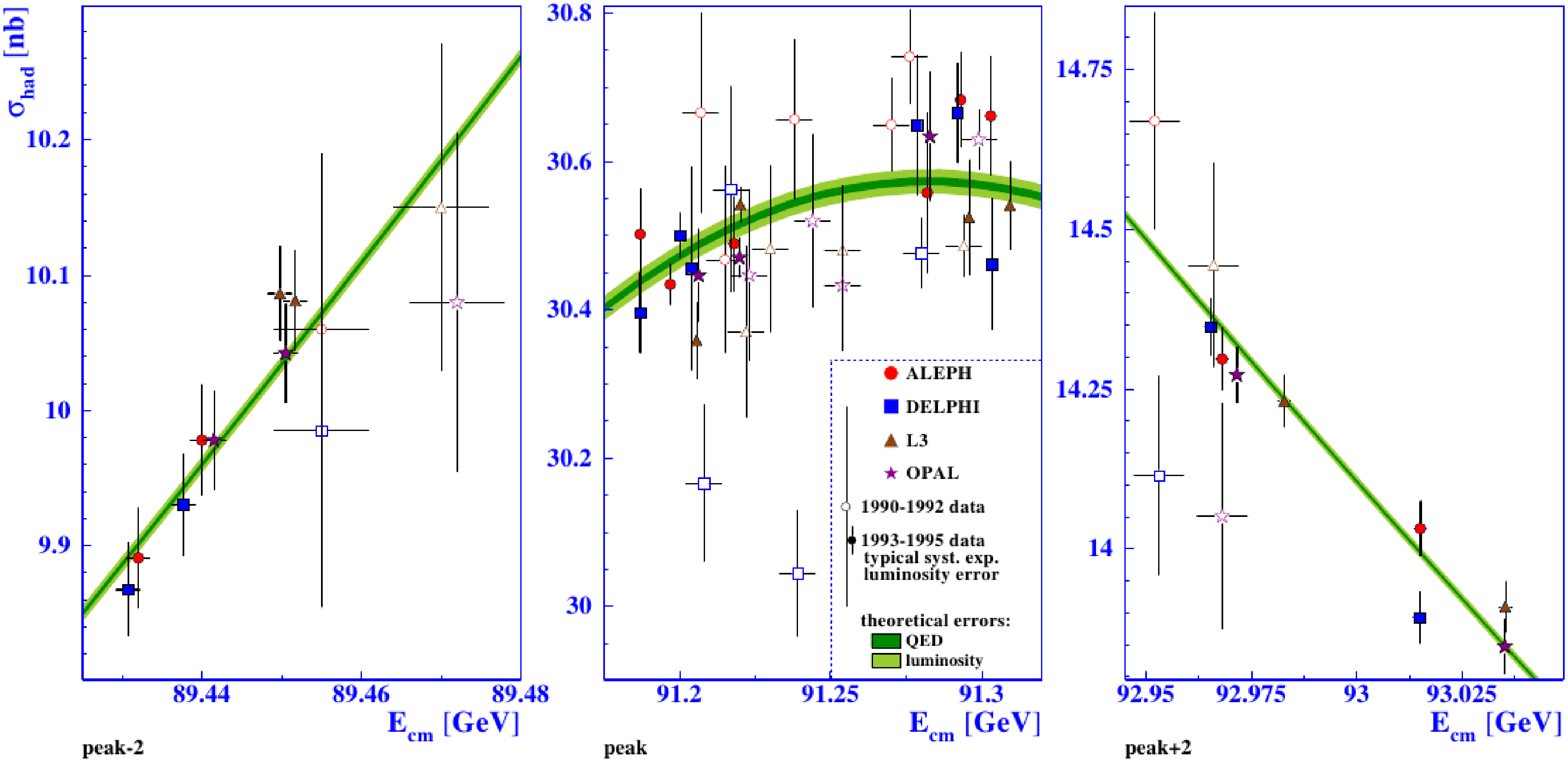
Luminosity determination:

count number of events in reference reaction with well-known cross section: $\int L = n_{ref} / \sigma_{ref}$

reference reaction @ LEP: $e^+e^- \rightarrow e^+e^-$ at small angles ("Bhabha scattering

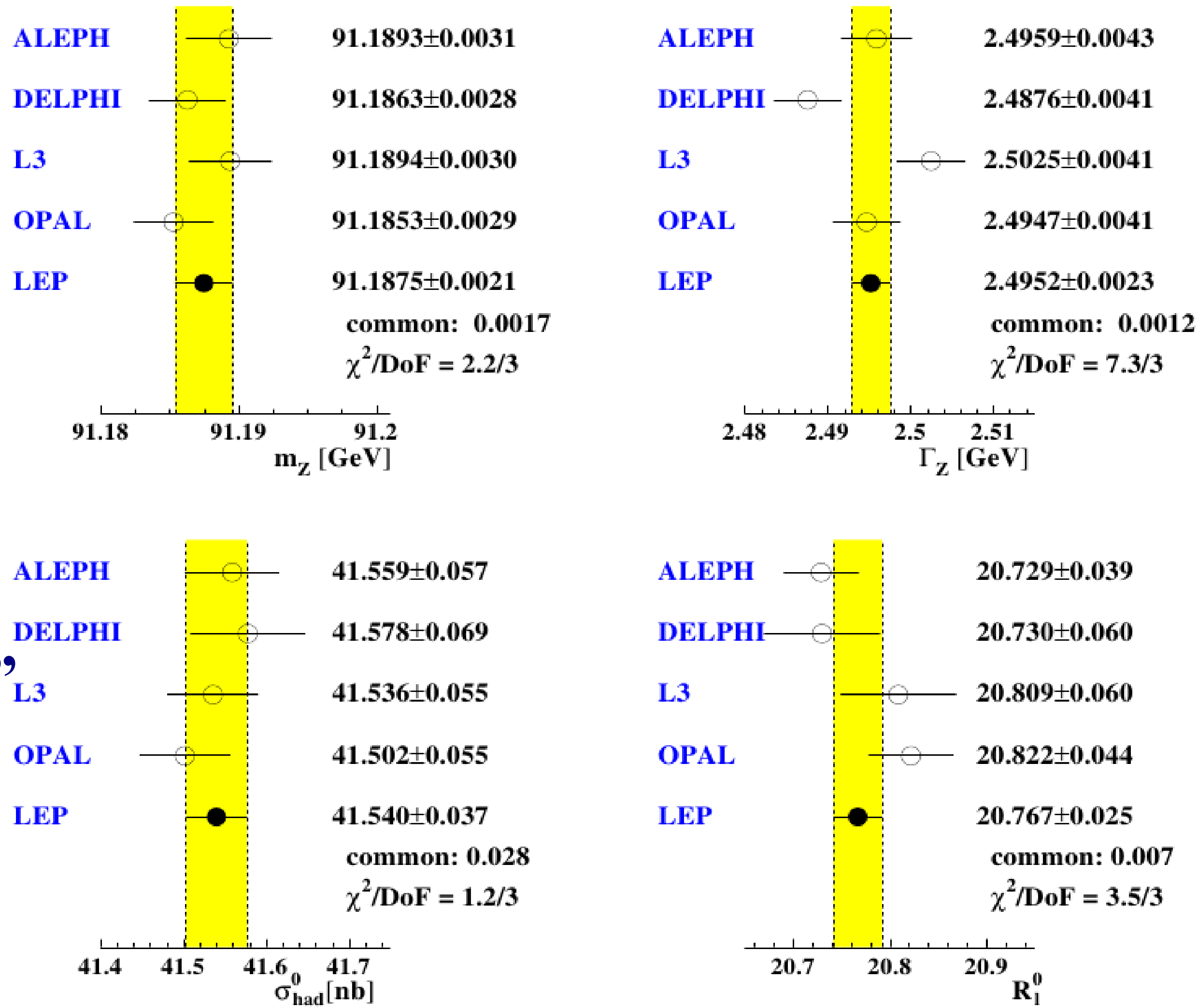
photonic corrections are large, but well known theoretically

Precision measurements: Z line shape



The challenge: combining more than 800 individual measurements

(different channels, CM-energies and data taking periods)



Parametrization of cross section using **"pseudo-observables"**

- m_Z
- Γ_Z
- $\sigma^o_{had} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$
- $R_e = \Gamma_{had} / \Gamma_{ee}$
- $R_\mu = \Gamma_{had} / \Gamma_{\mu\mu}$
- $R_\tau = \Gamma_{had} / \Gamma_{\tau\tau}$

partial decay width

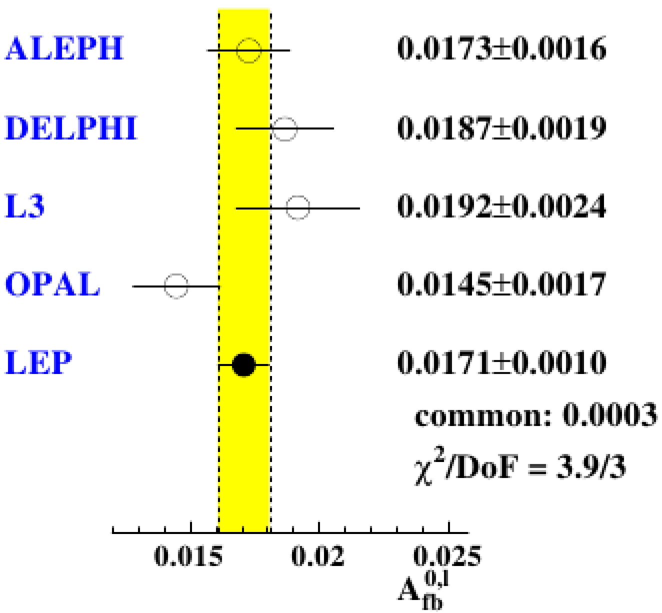
$\Gamma_{ff} \propto \left(g_{Vf}^2 + g_{Af}^2\right)$ for f=e, μ, τ

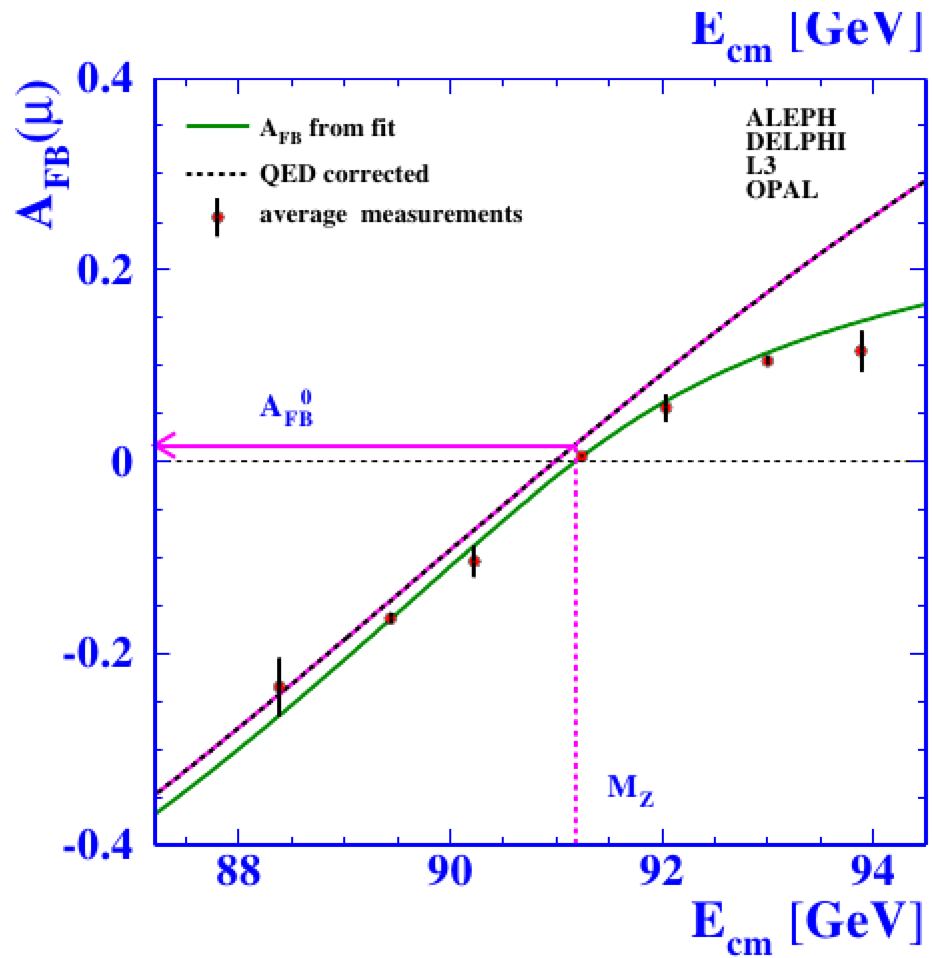
Precision measurements: forward-backward asymmetries of lepton pairs

$$A_{FB} = \frac{N_{forw} - N_{back}}{N_{tot}} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta}{\sigma_{tot}}$$

pseudo-observables:

$$A_{FB}^{0,f} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \quad \text{with} \quad \mathcal{A}_f = \frac{2 g_{Vf}/g_{Af}}{1 + \left(g_{Vf}/g_{Af}\right)^2}$$





More Precision measurements – tau lepton polarisation

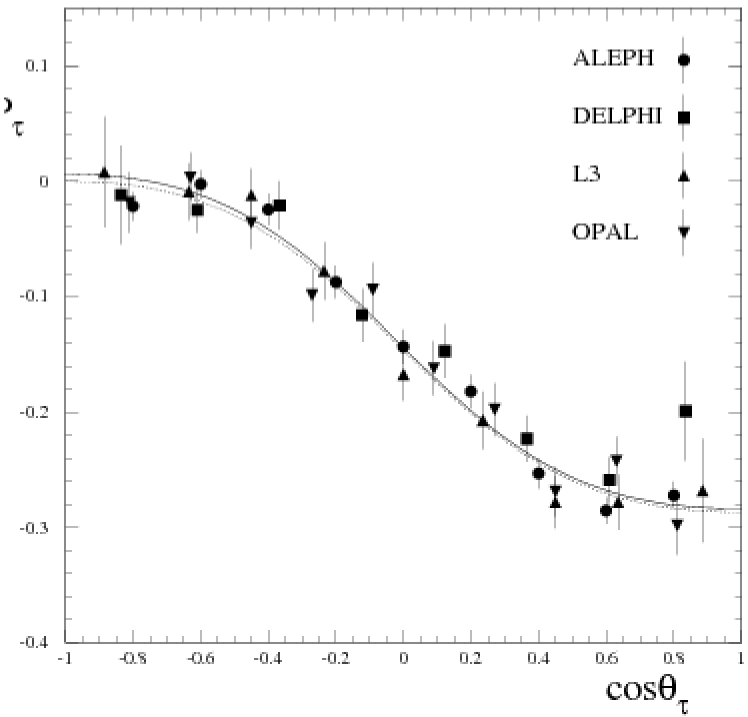
in $e^+e^- \rightarrow \tau^+\tau^-$:

Spin in final state can be measured assuming V-A structure in τ decay

average τ polarization depends on e and τ couplings

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{1+\cos^2\theta + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

Measured P_τ vs $\cos\theta_\tau$



allows precise measurement of vector and axial vector couplings of τ to Z !

More Precision measurements – with polarized e-beam

Measurements at SLAC linear collider:

polarized **e^-** colliding with unpolarized **e^+** at $\sqrt{s}=M_Z$

measurements analogous to LEP, but

can determine σ and A_{FB} for left- and right-handed **e^-**

observables at SLAC:

$$A_{LR} = \frac{1}{\mathcal{P}_e} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \propto \mathcal{A}_e$$

$$A_{fb,LR} = \frac{1}{\mathcal{P}_e} \left(A_{fb,L} - A_{fb,R} \right) \propto \mathcal{A}_f$$

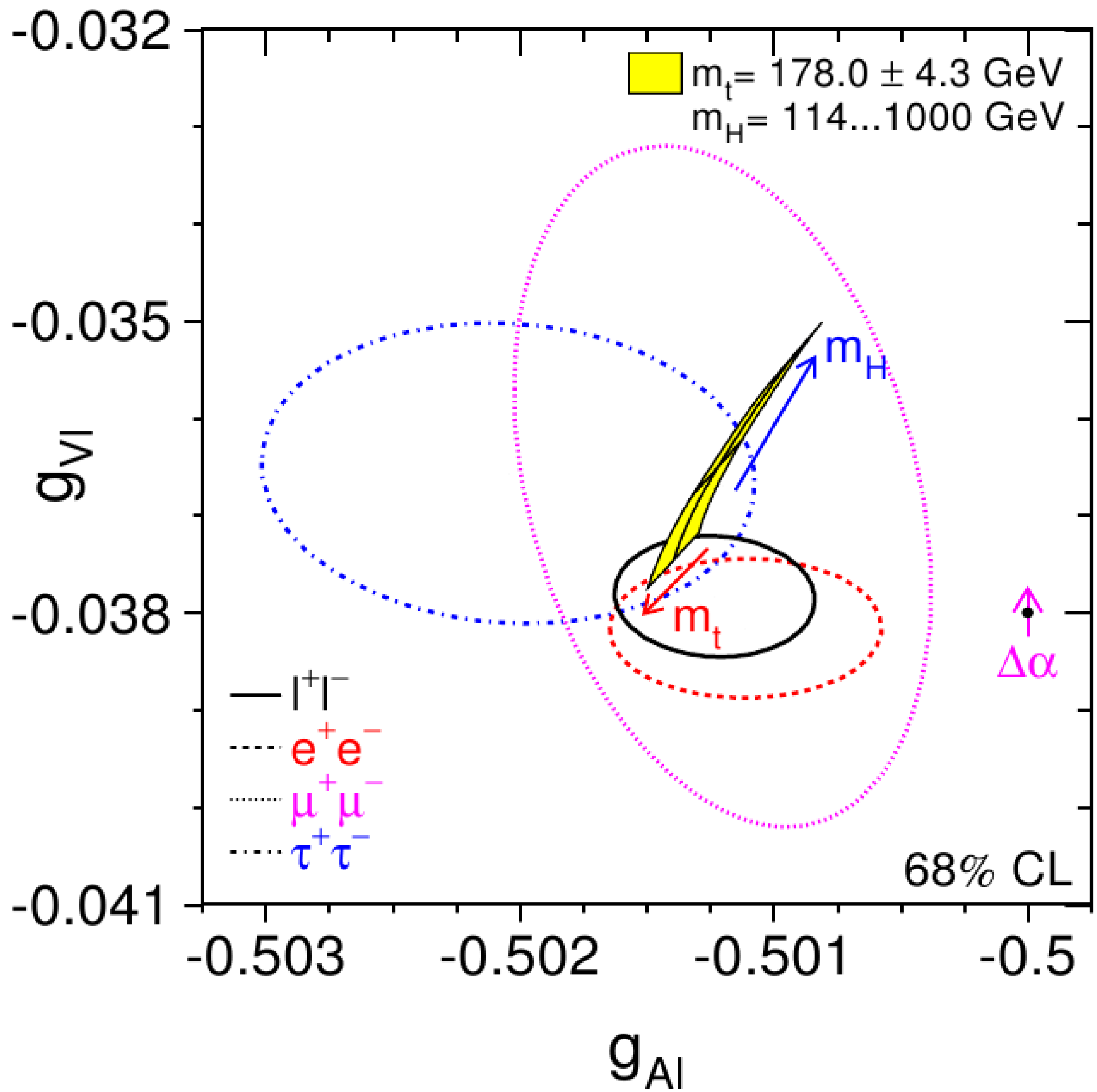
A_{LR} is most sensitive single measurement to $\sin^2\theta_W^{eff}$

Determination of lepton couplings to Z boson

Combination of previously shown measurements gives most precise values of lepton couplings.

Consistent with "lepton universality" → combine all into leptonic g_V and g_A

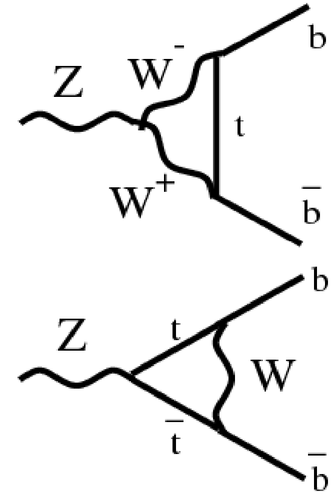
Measurements are sensitive to top and Higgs boson masses

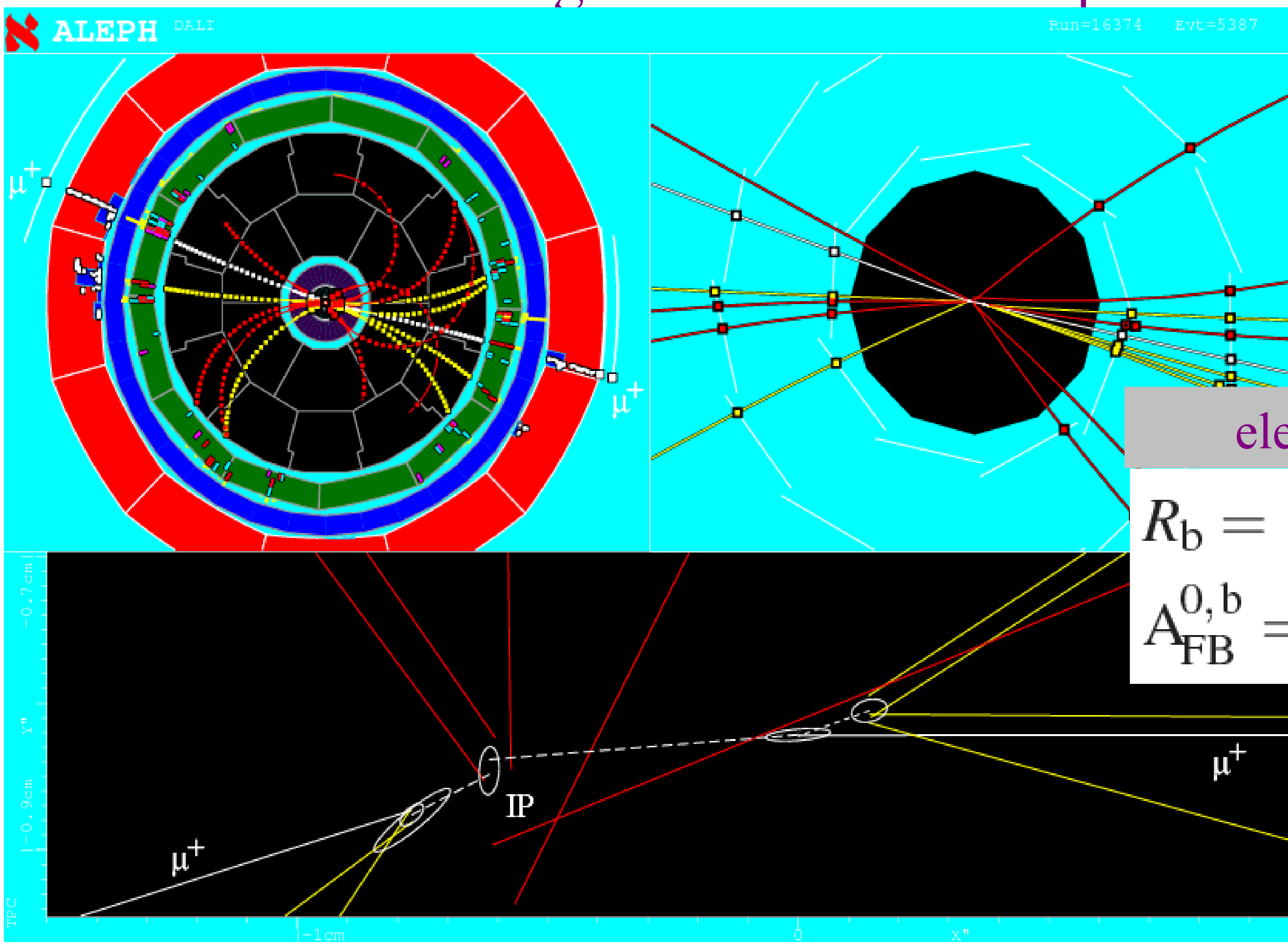


More Precision measurements – heavy quarks

b-quarks – are (relatively) long-lived
– are heavy
– decay in cascades → can be distinguished from other quarks

special relation to top quark:





electroweak observables

$$R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} \Rightarrow \rho_b$$

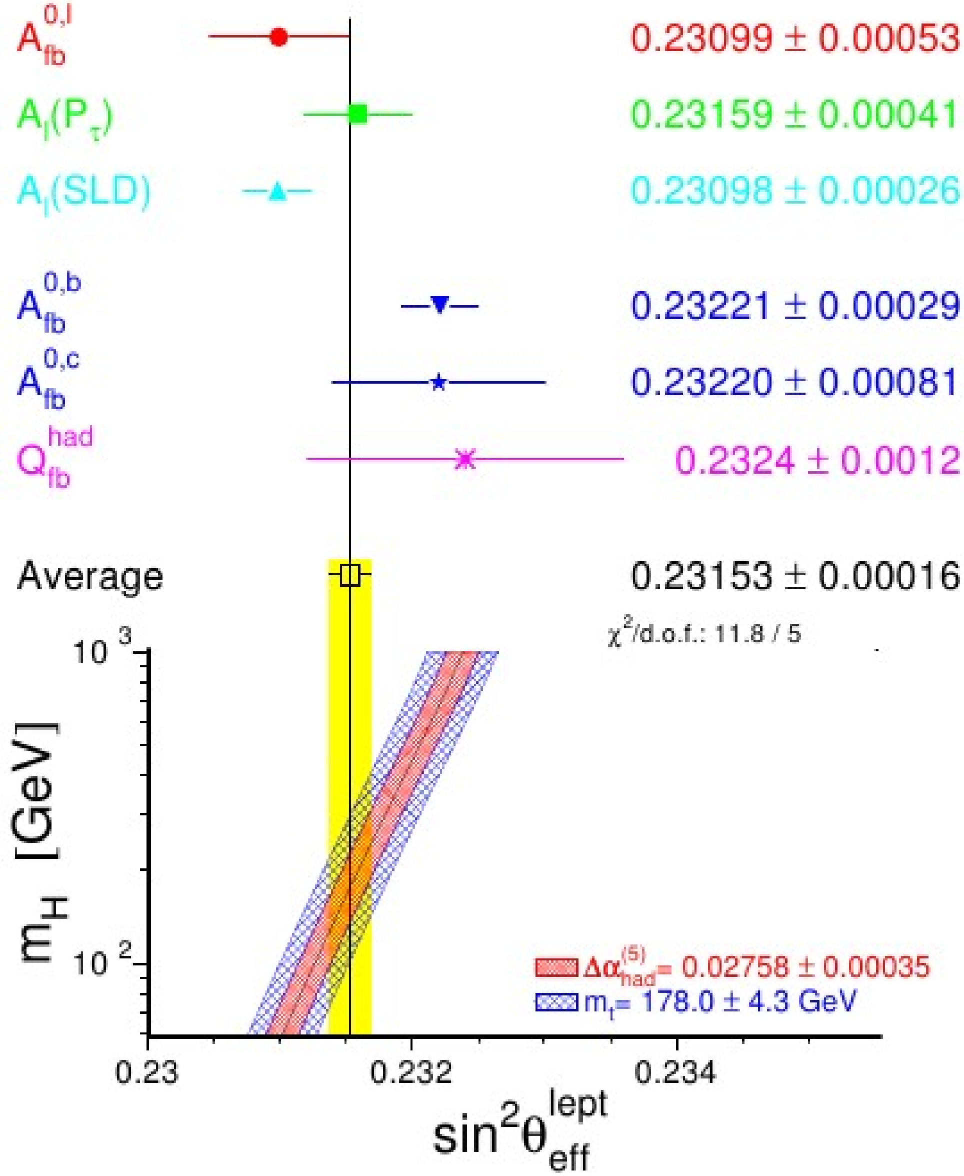
$$A_{FB}^{0,b} = \frac{4}{3}\mathcal{A}_e\mathcal{A}_b \Rightarrow \sin^2\theta_{eff}^{lept}$$

Summary of asymmetry-type measurements

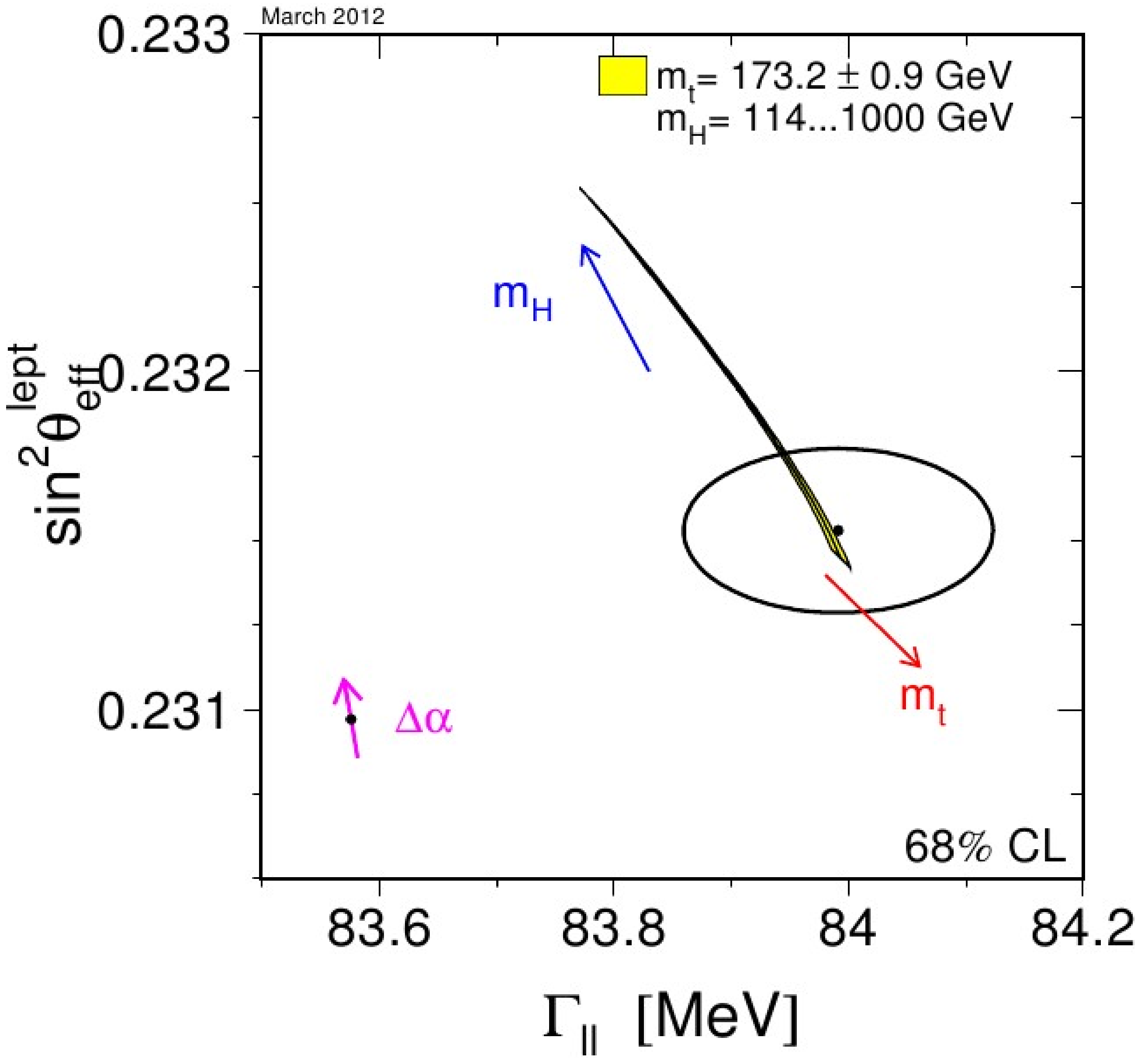
Asymmetry-type measurements depend on vector and axial vector couplings, g_V and g_A, and hence on $\sin^2\theta_W{}^{eff}$

Average of $\sin^2\theta_W{}^{eff}$ very sensitive to Higgs mass

There is, however, some "tension" between the most precise measurements !

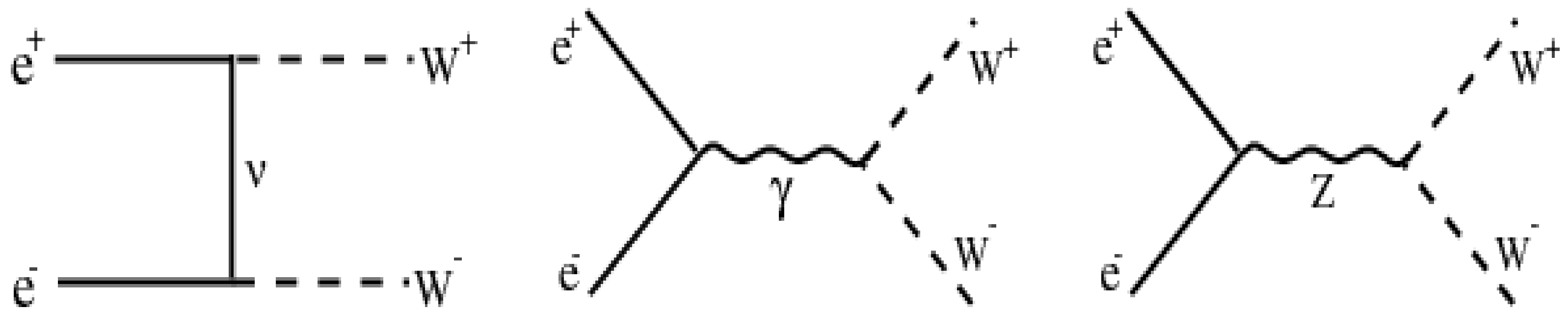


Combination of precision measurements: Γ_{lept} and $\sin^2\theta_W^{eff}$



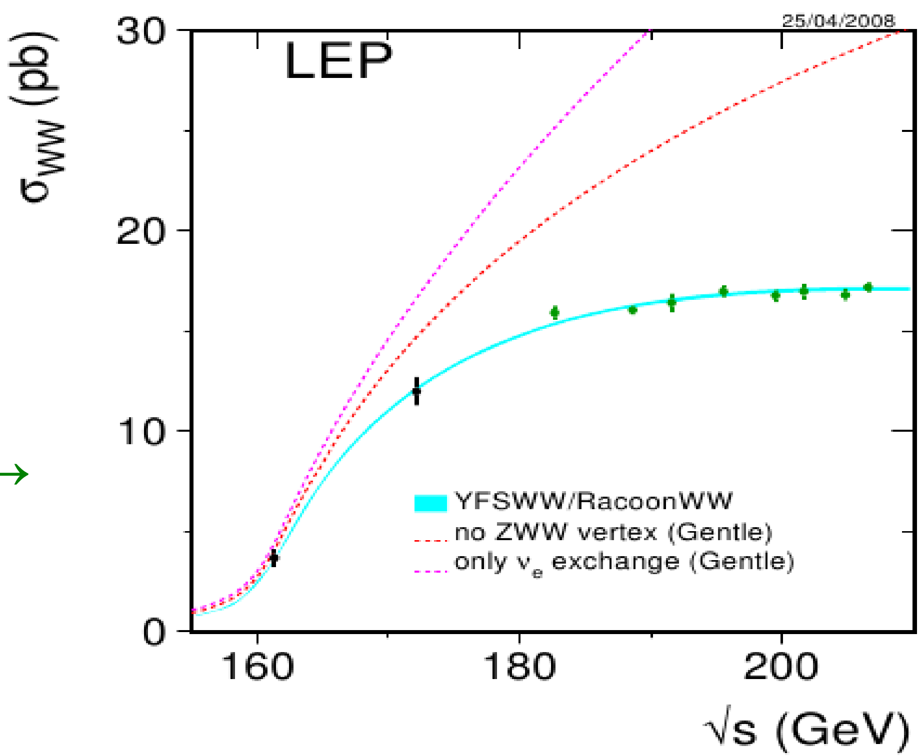
Γ_{lept} and $\sin^2\theta_W^{eff}$ together provide strong constraint on Higgs mass !

W pair production at LEP II



$e^+e^- \rightarrow W^+W^-$ cross section in EW theory remains finite only if photon, Z and neutrino exchange are all taken into account -

experimentally well confirmed →



Remark: there is also a Higgs diagram, but negligible in e^+e^- !

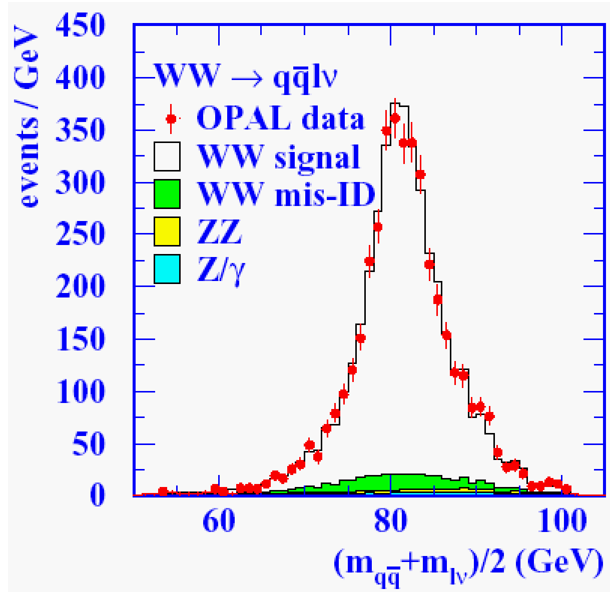
W Boson mass

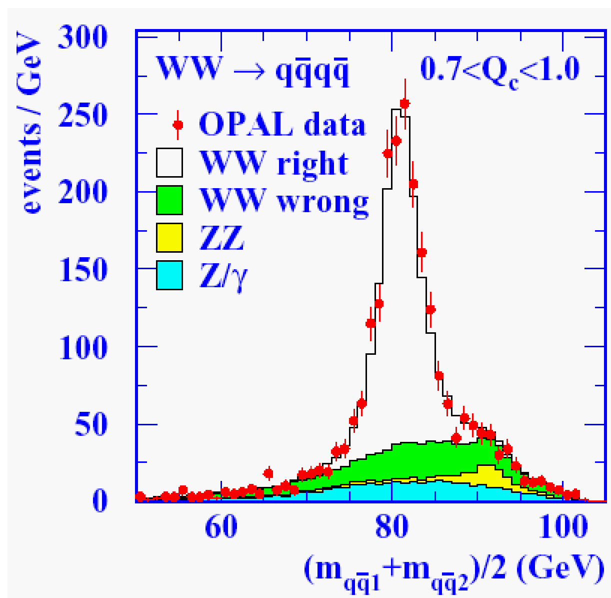
W-Boson mass

from reconstructed objects in detectors by LEP experiments ALEPH, DELPHI, L3 and OPAL and by Tevatron experiments CDF & D0

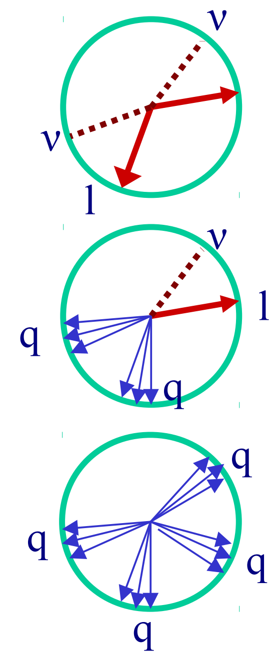
(LHC not yet ...)

very difficult, dominated by systematic errors





@LEP: W pair events:

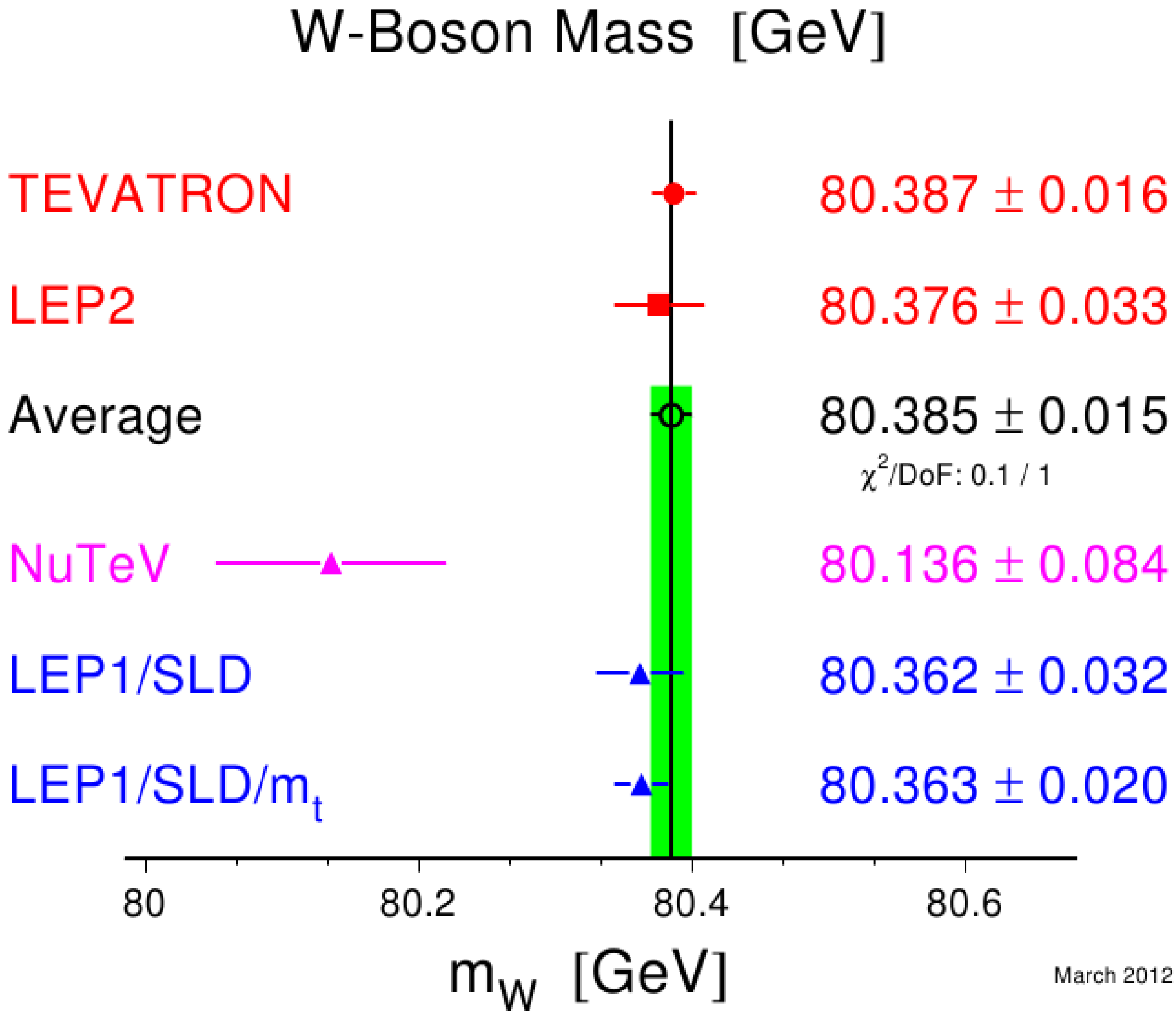


BR ~ 10%

BR ~ 44%

BR ~ 46%

W Boson mass – world average 2012



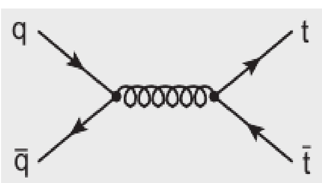
Remember: Relevance of W mass: determines on-shell weak angle

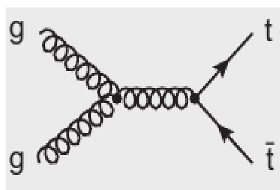
One more ingredient: need the top quark mass

top quark mass

measured from reconstructed objects in detectors by Tevatron experiments CDF & D0 (LHC on the way ...)

– top quarks (mostly) produced in pairs via $q\bar{q}$ or gg





– dominant decay:

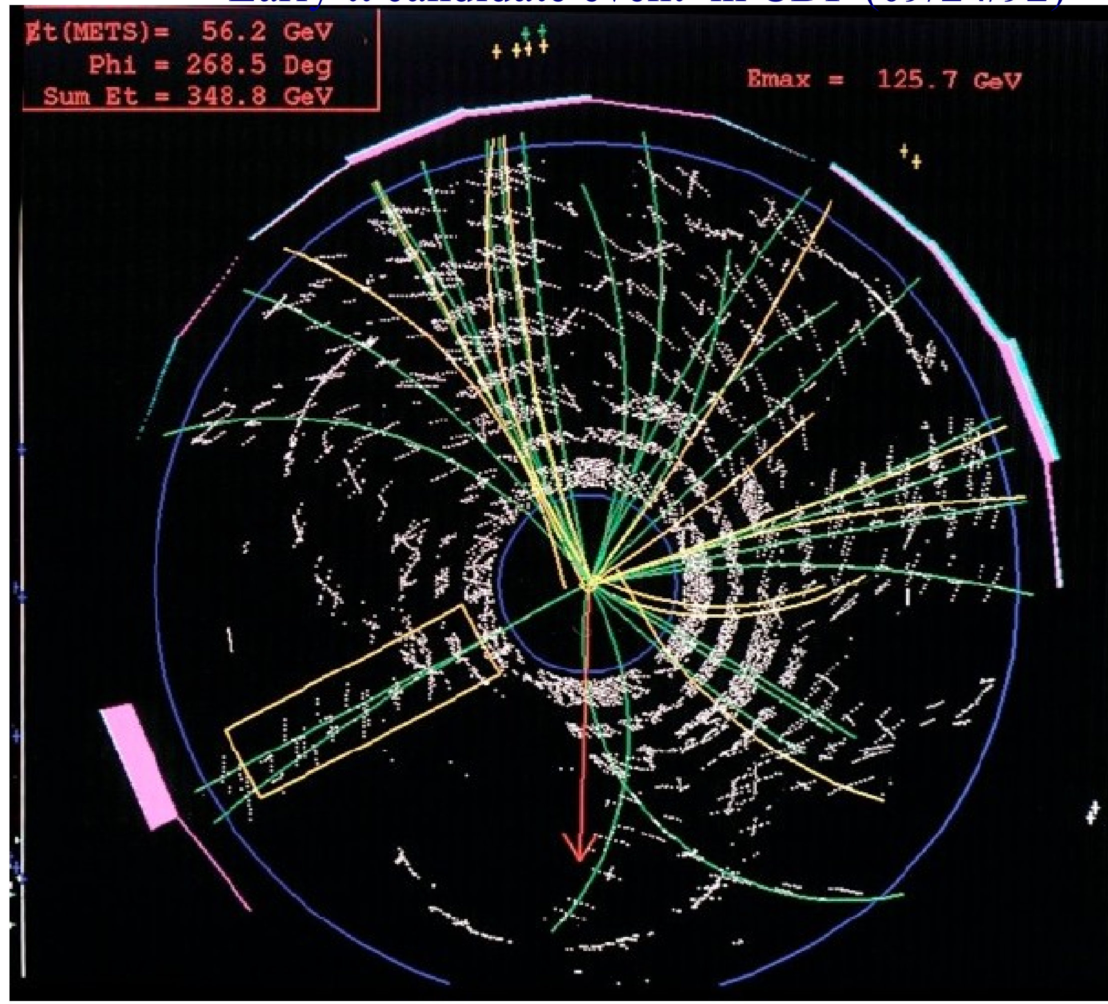
$t \rightarrow b + W^{+}$

$W \rightarrow q\bar{q}'$ or $l\nu$

signatures studied:

- fully hadronic
- lepton + jets
- di-lepton

Early $t\bar{t}$ candidate event in CDF (09/24/92)



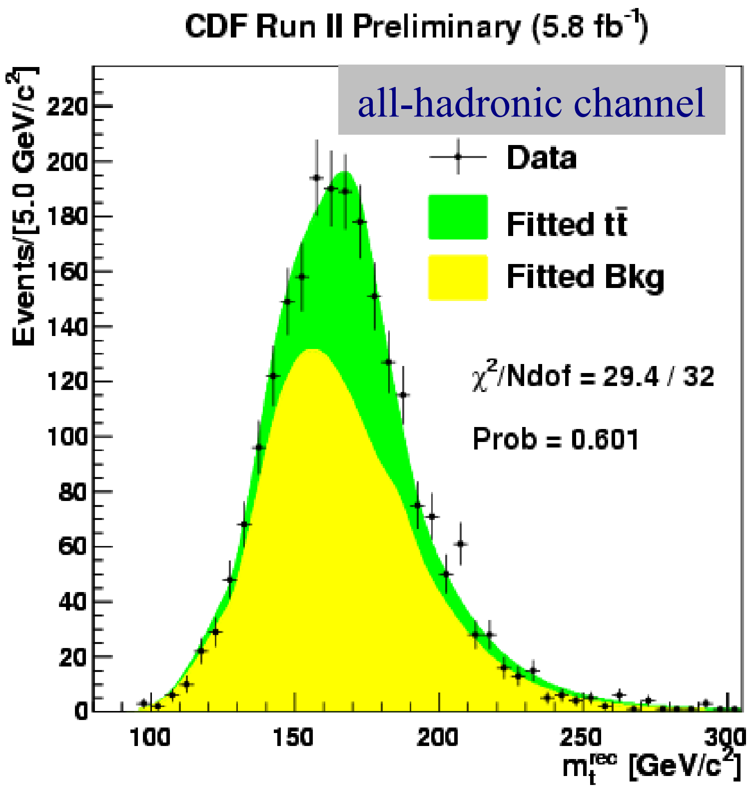
Signature: "lepton +jets"

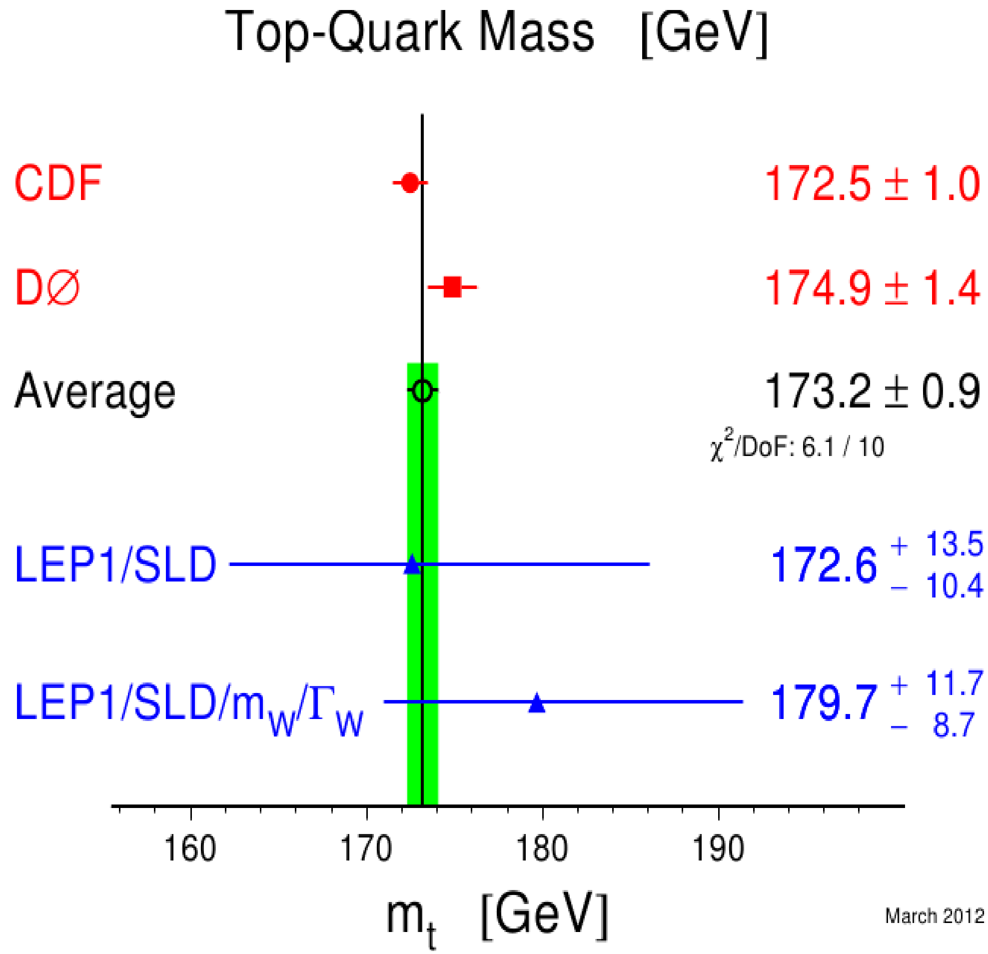
– 1 lepton – four jets

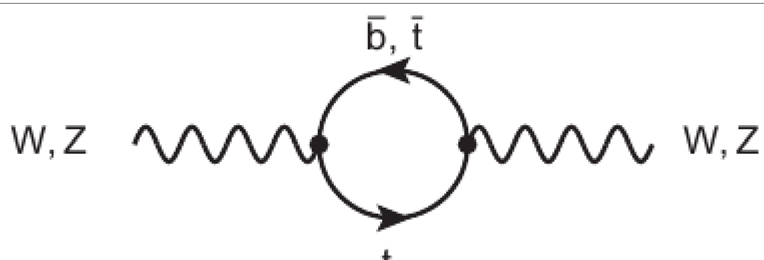
– missing transverse energy

One more ingredient: top quark mass

Example of observed mass distribution:







Remember: dominant radiative corrections arise from top ($\sim G_F m_t^2$) !

Top quark mass from loop corrections ...

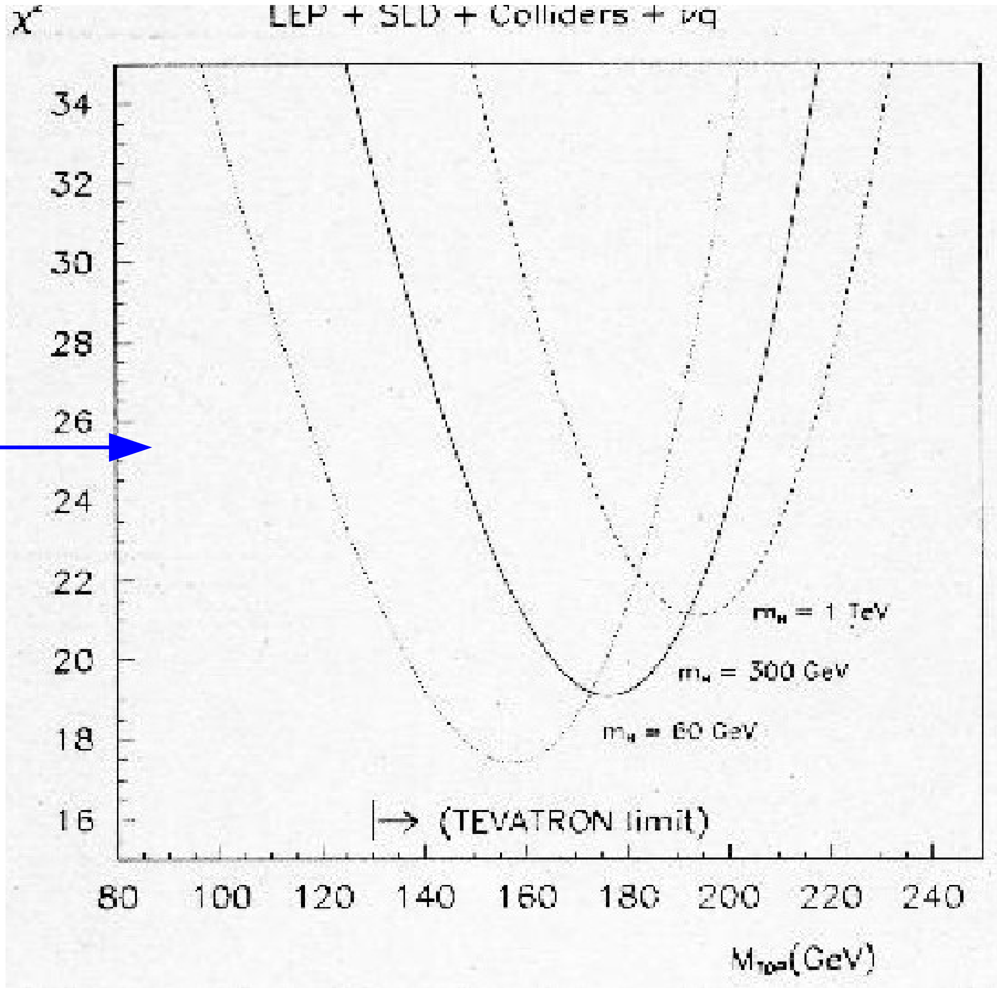
… at Moriond conference
in March 1994:

direct search for top at Tevatron:

$m_t > 130\,\mathrm{GeV}/c^2$

from **radiative corrections**:

$m_t = 177 \pm 11\,^{+18}_{-19}{}_{\mathrm{Higgs}}\;\mathrm{GeV}/c^2$



a little later in summer, direct **observation** of top quark (CDF):

$m_t = 174 \pm 10\,^{+13}_{-12}{}_{\mathrm{syst}}\;\mathrm{GeV}/c^2$

Excellent agreement between
top from loops and from direct measurement!

M_H from individual precision measurements

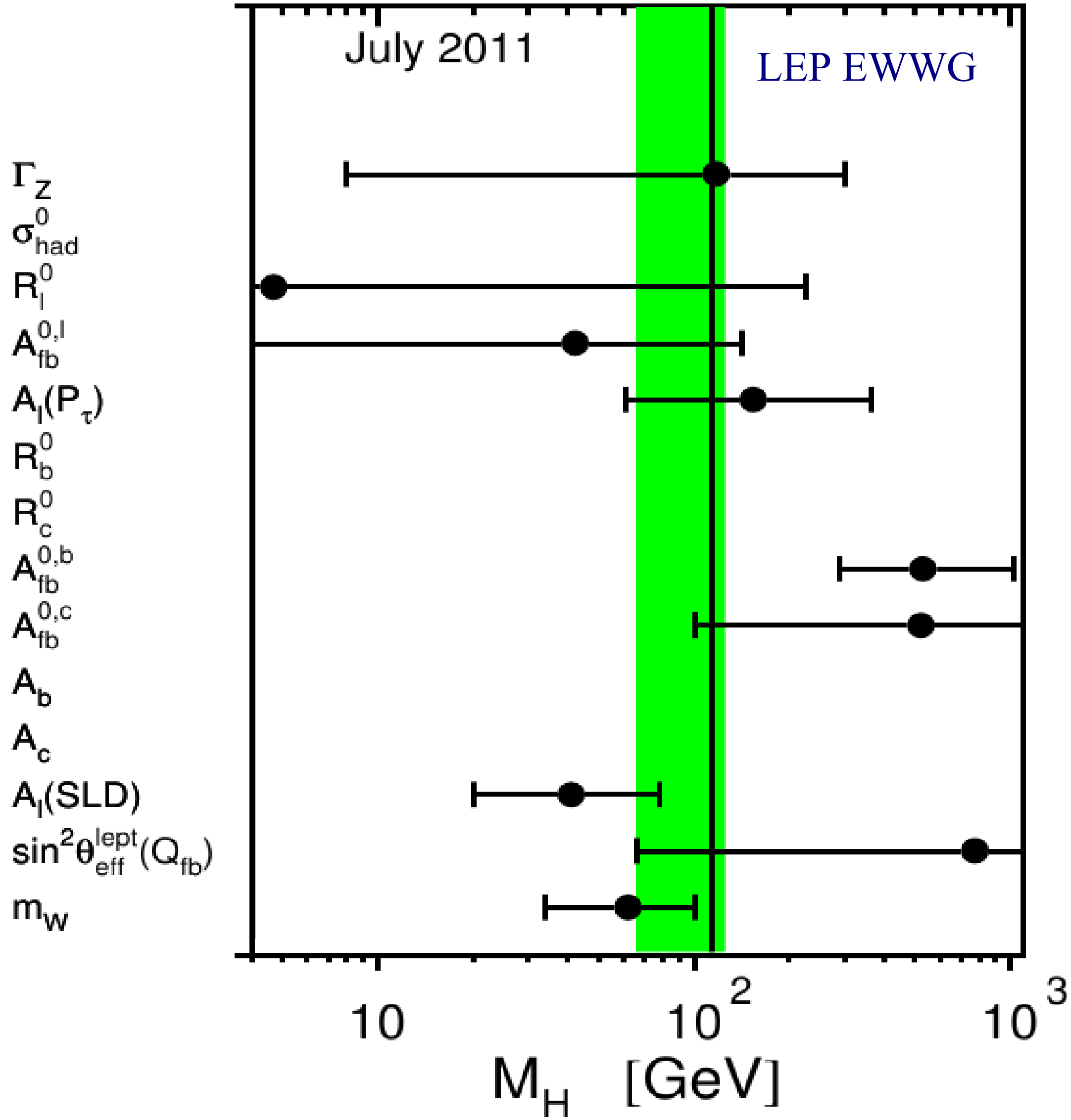
With known top mass, can now disentangle radiative effects from top and Higgs

(provided nothing else is in the loops …)

→

M_H from precision measurements

with large errors



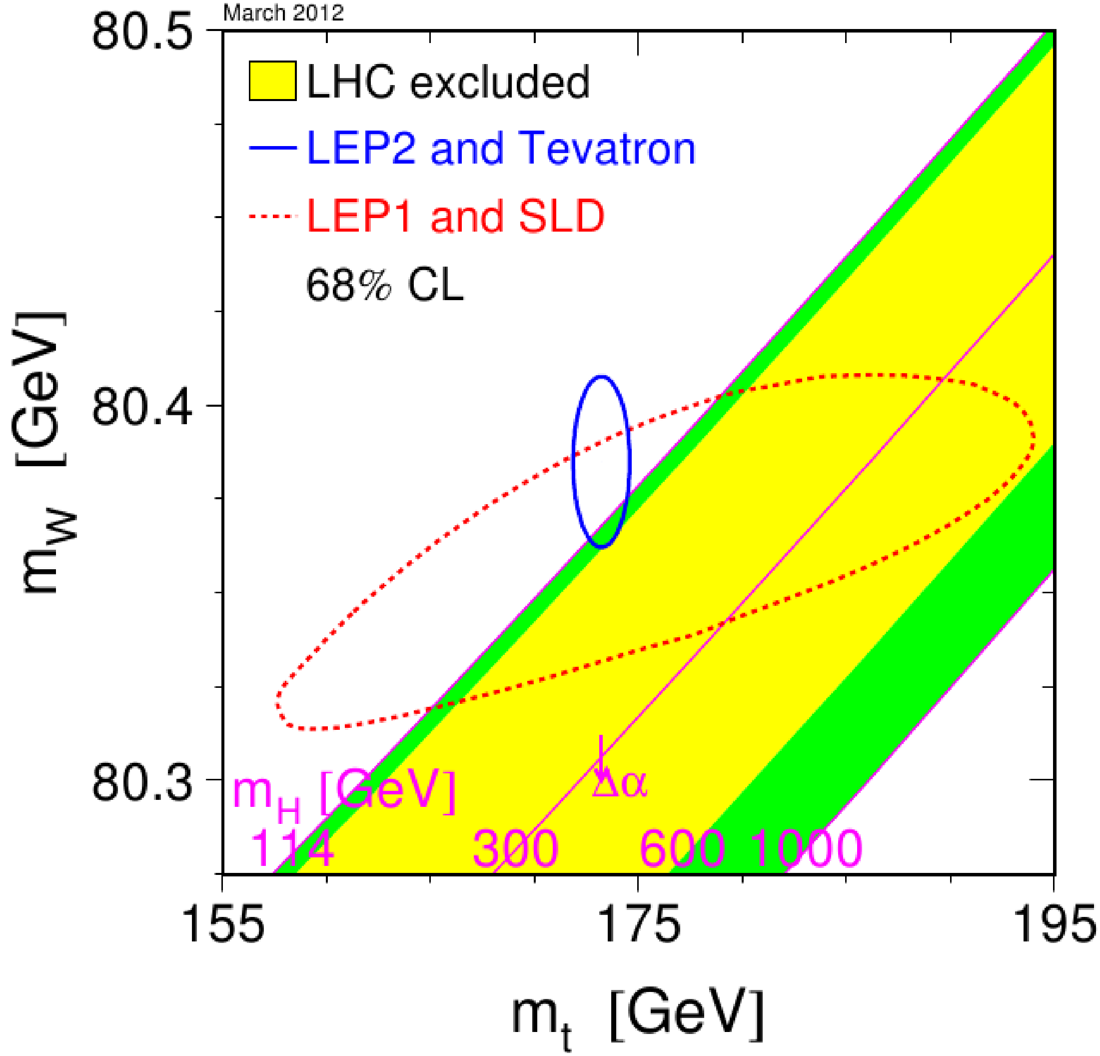
Putting it all together ….

... in a rather complicated plot:

top quark vs. W boson mass

1. direct measurements
2. indirect determination from precision variables: $O:=O(\alpha, G_F, M_Z, m_t, M_H)$ solved numerically ("Newton's method) for m_t and M_H (using SM)
3. W mass predicted for different values of M_H

nice consistency check, prefers low value for Higgs mass !



Putting it all together ….

… in an overall fit

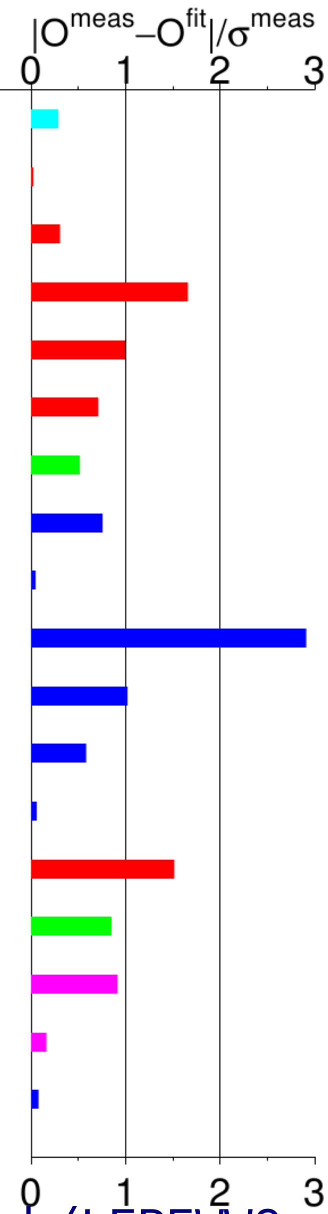
of Higgs boson mass within the minimal Standard Model

"pull plot" and overall value of χ^2 to identify potential problems

good overall consistency,

but there is one "outlier"; the measurement of the b-quark forward backward asymmerty.

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1039
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



July 2011

http://lepewwg.web.cern.ch/LEPEWWG

Putting it all together ….

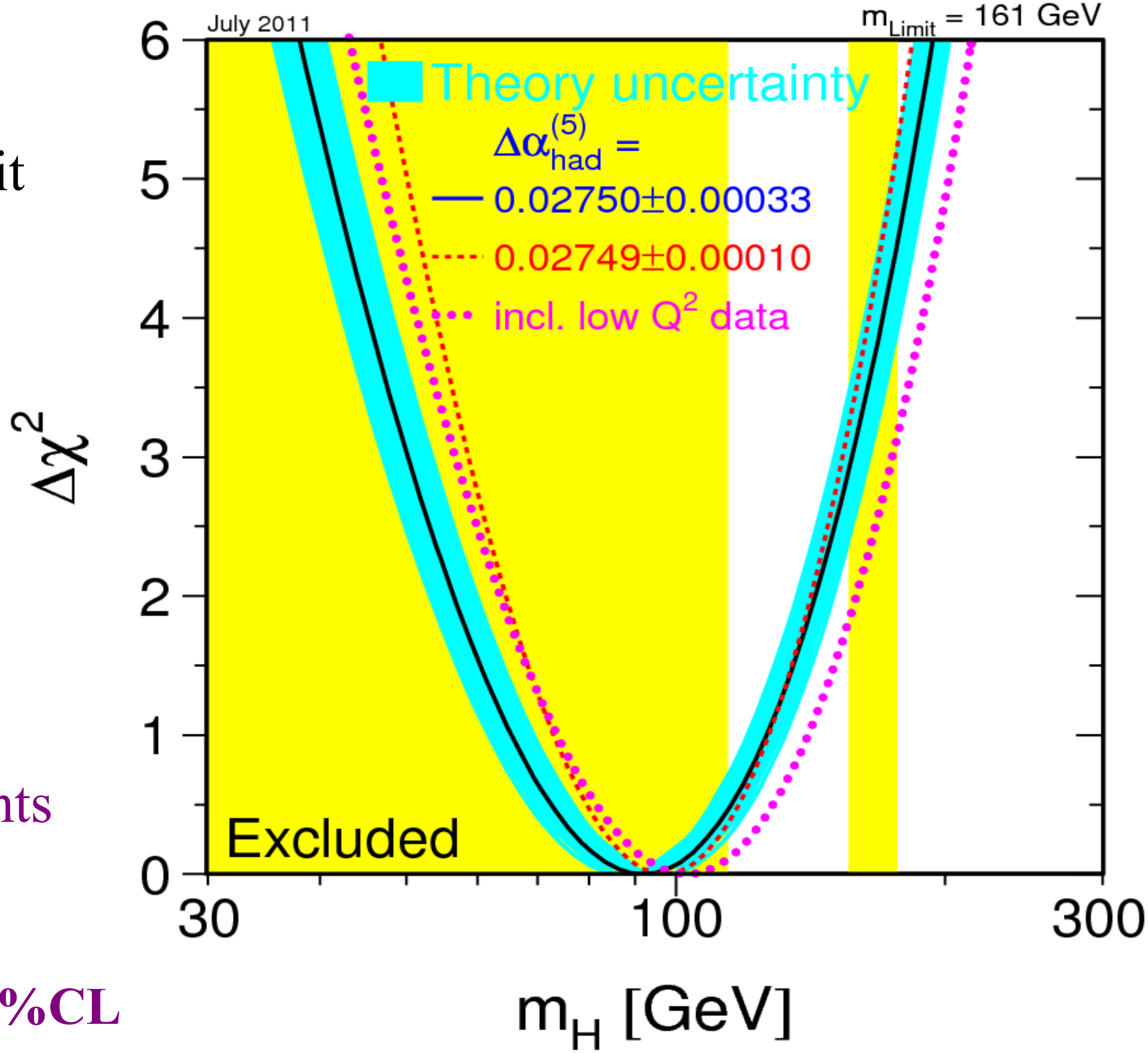
… profiled χ^2

for M_H from overall fit within the minimal Standard Model

"Blue Band Plot"

Precision measurements predict mSM Higgs boson to be light,

M_H <161GeV/c^2@95%CL



Conclusions on results from precision measurements

Standard Model established as a renormalizable field theory:

– in agreement with (almost) all experimental results, prec. ~0.1%

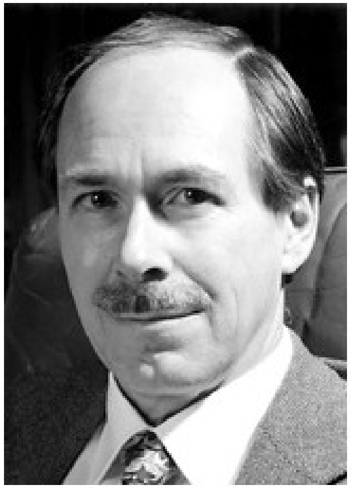
– quantum corrections seen and well established

– indirect determination of top quark mass

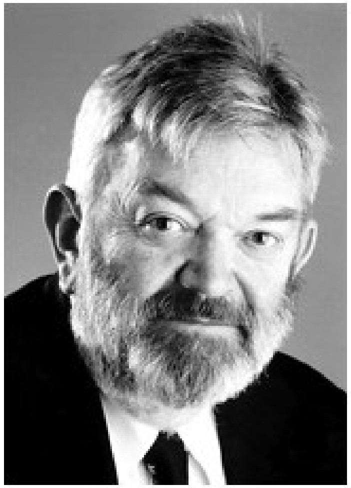
– triple gauge boson couplings confirmed with prec. 1%

– precision measurement constrain Higgs to be light

Theoretical work on proof of renormalizability awarded with Nobel prize in 1999



Gerardus 't Hooft



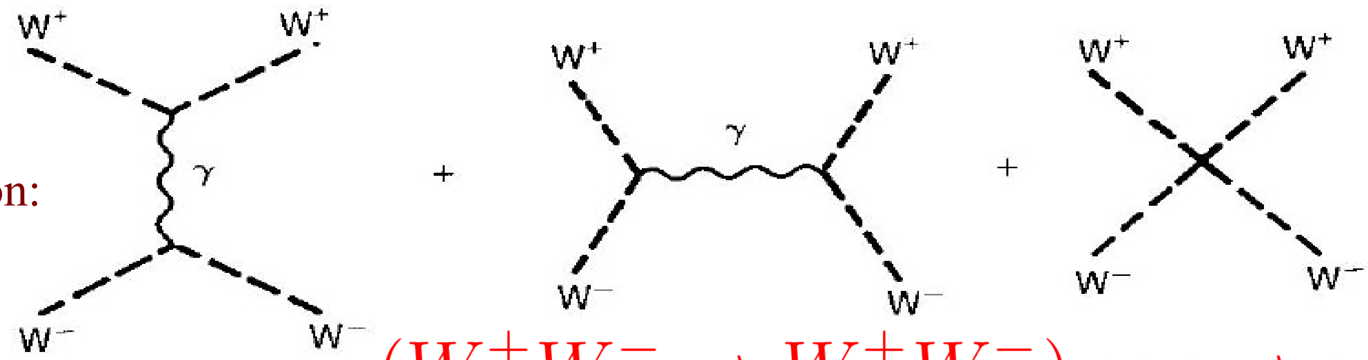
Martinus J.G. Veltman

The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman *"for elucidating the quantum structure of electroweak interactions in physics"*

Theoretical constraints on Higgs boson mass

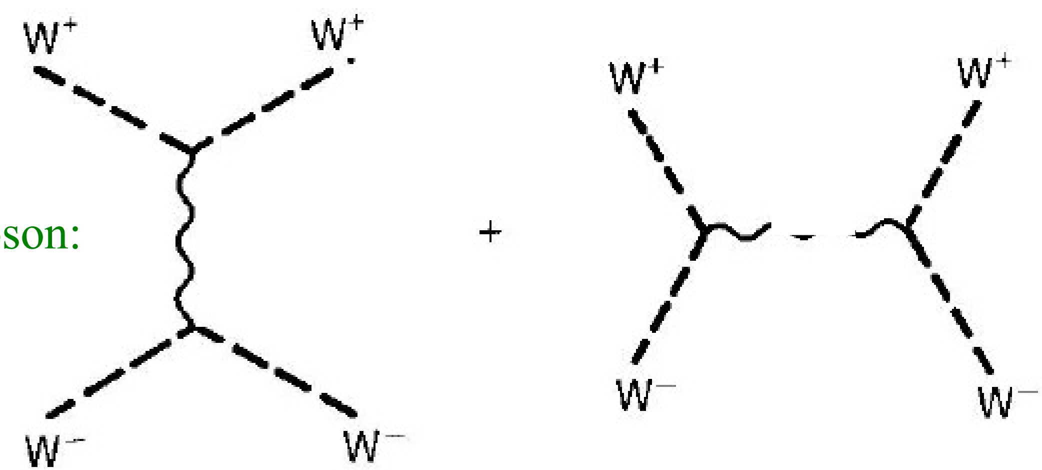
Diagrams with Higgs-Boson prevent divergencies:

Without Higgs boson:



$$\sigma(W^+W^- \to W^+W^-) \propto s \to \infty$$

additonal diagrams involving Higgs boson:

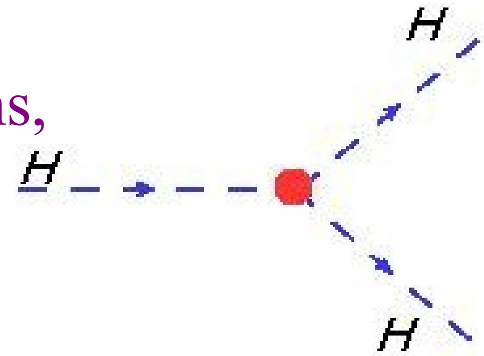


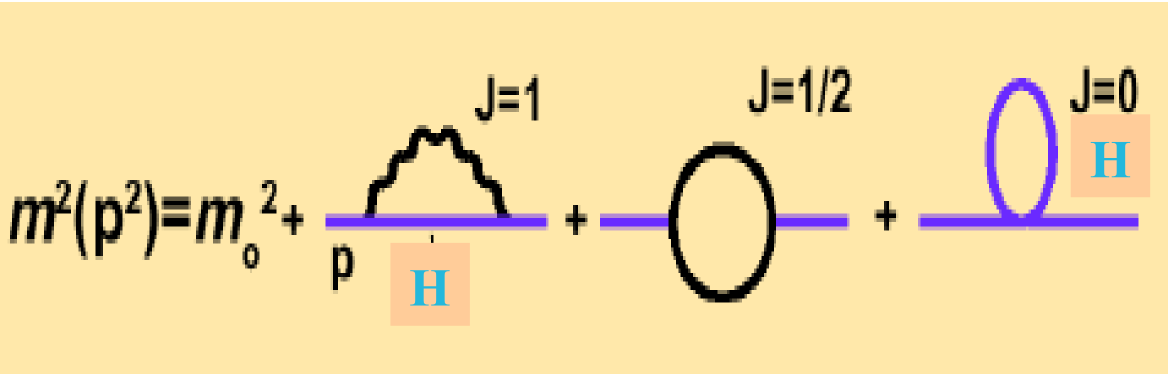
Cross section for WW scattering remains finite

Higgs must not be too heavy:: $<\sim 1$ TeV/c²

Theoretical constraints M_H loop corrections

Higgs propagator affeced by higher order corrections,
in particular from Higgs self couplings





Higgs in loops couples to itself with strength proportional to Higgs mass →
large corrections to Higgs mass and Higgs potential

– high Higgs mass: Higgs self-coupling becomes strongly interacting,
breakdown of perturbation theory

– small Higgs mass: Higgs self-coupling becomes negative
→ unstable vacuum
(in contradiction to age of universe)

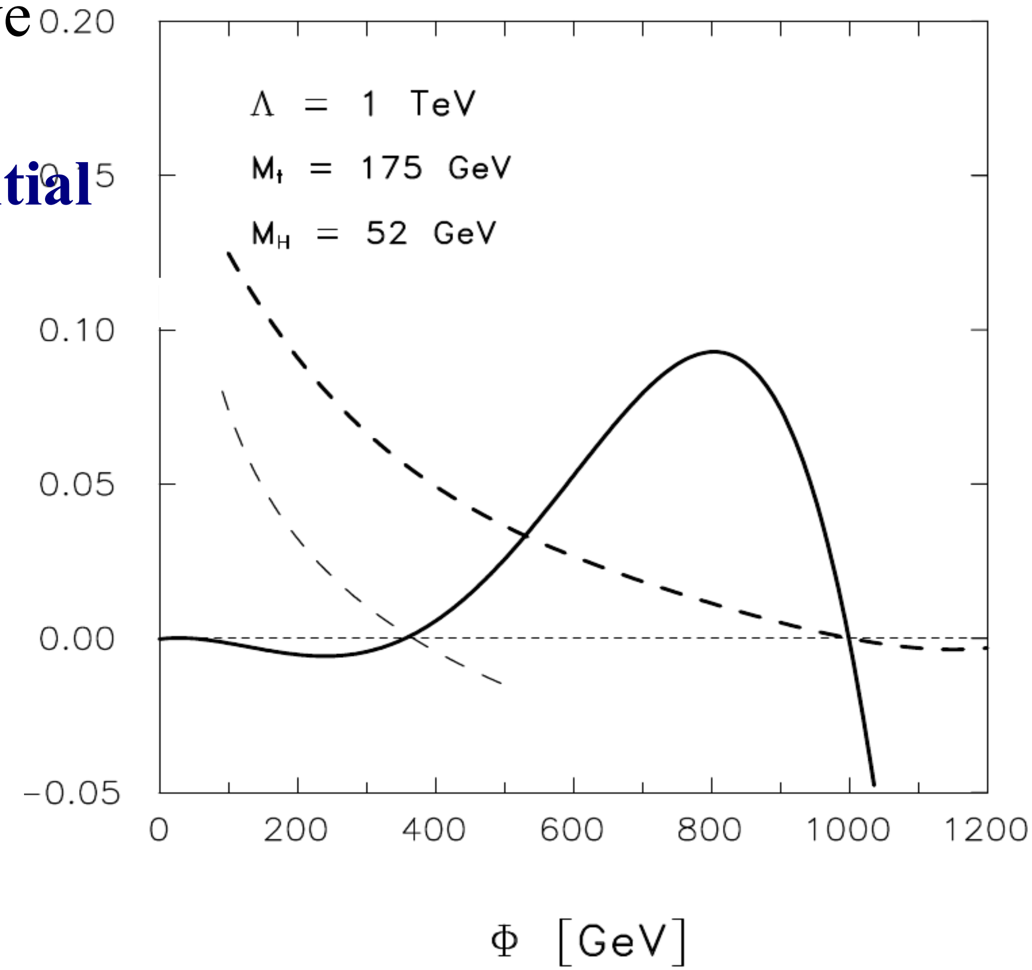
Theoretical constraints on M_H – vacuum stability

Example of renormalized Higgs Potential
Casas, Espinosa, Quiros (1996)

Loops (in particular top) drive quartic coupling negative above some scale Λ for small M_H

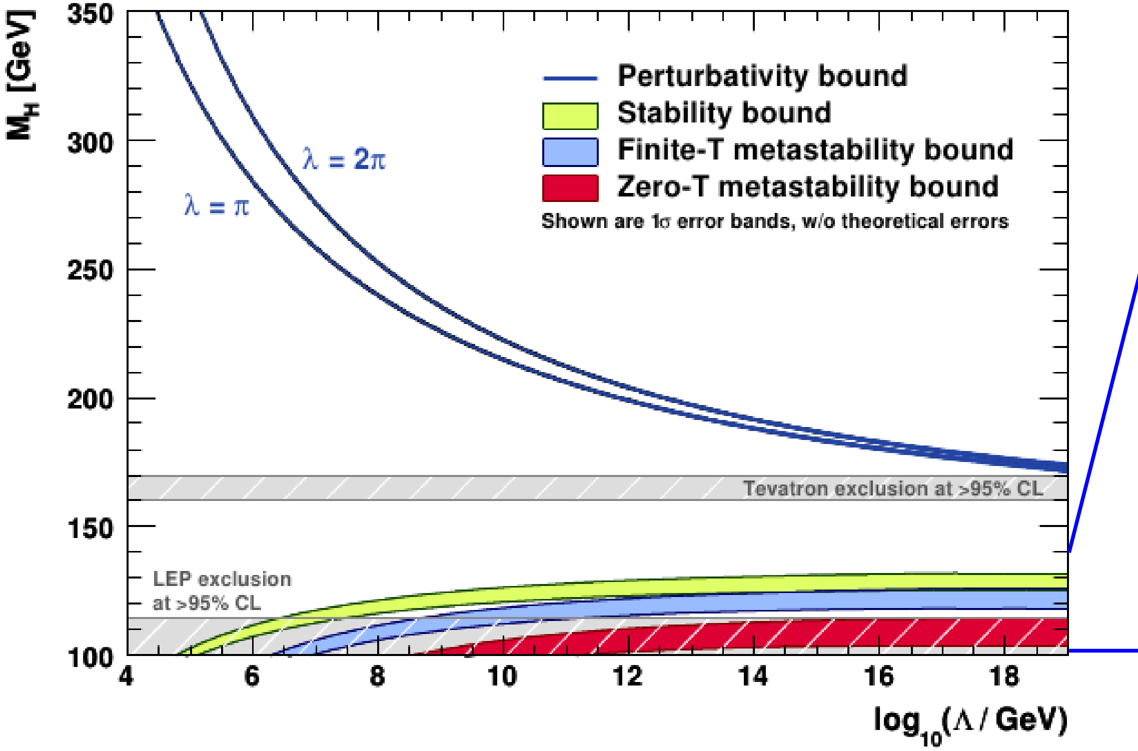
→ renormalized **Higgs potential** is either unbounded (inconsistent with the existence of the universe)

or in local minimum "false vacuum", (assume tunneling time > 14 billion years to derive limit on M_H)

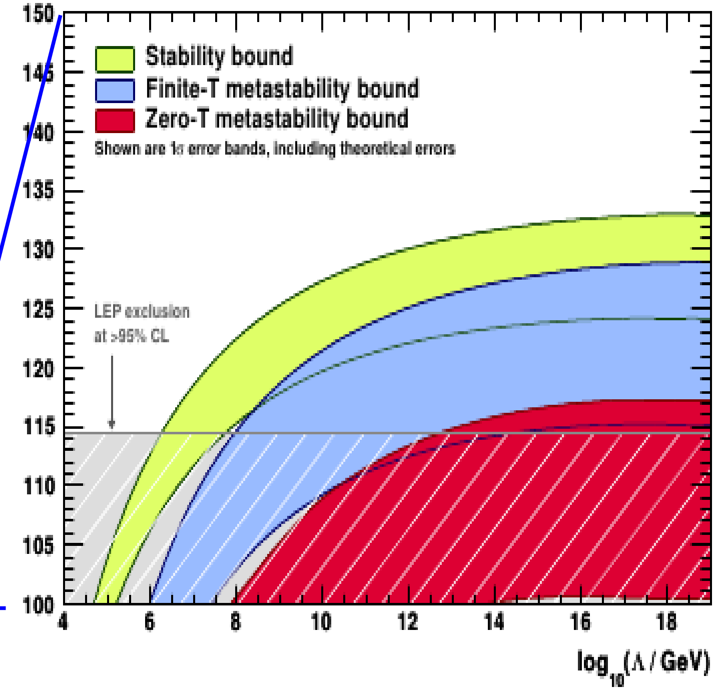


Theoretical constraints on M_H – vacuum stability

→ beyond **energy scale Λ** new Physics must be present



J. Ellis et al. CERN-PH-TH/2009-058



→ corridor of allowed values of Higgs mass within Standard Model

Final remarks

We know that the Standard Model is incomplete:

– no candidate for dark matter

(would have to be heavy, stable and only weakly interacting)

– no explanation of "dark energy"

– inclusion of gravity causes problems

(Why are Higgs mass and Boson masses so "small" compared to the relevant scale, the Planck mass?)

There must be new physics, even if the Higgs boson will be found one day at a mass making the Standard Model self-consistent).

Summary:

Standard Model looks fine and gauge couplings and Higgs mechanism appear to work, although the model is clearly incomplete.

To be done:

– discovery of Higgs boson
– determination of Yukwa couplings to fermions
– test Higgs potential via measurement of Higgs self couplings

Will the model show inconsistencies and thus point to way to extend it, or will it remain to be a self-consistent theory for the part of reality it describes ?