The evolution of electroweak theory

Electroweak milestones –

50 years of neutral currents, 40 years of W and Z bosons

CERN

31 October, 2023

W. Hollik

Max-Planck-Institut für Physik, München

90 years anniversary

theoretical description of the weak interaction began 1933

ansatz by Enrico Fermi

$$\mathcal{H} = G\, J_\mu \cdot J^\mu$$

- $\star$ current–current interaction
- $\star$ charged current
- $\star$ universal coupling constant G

today: '"Fermi constant" G_{F}

From a phenomenological model to a fully-fledged Quantum Field Theory

1933	Fermi model
1957	incorporation of parity violation
1967 – 1973	formulation of the electroweak Standard Model
	gauge theory based on $SU(2) \times U(1)$
	W, Z masses via Higgs mechanism
	fermion masses and mixing via Yukawa couplings
1971 – 1972	proof of renormalizability
1973 –	experimental confirmation

Phases of evolution

- from Fermi's ansatz to a full theory
- from precision calculations to discoveries
- current performance and perspectives

weak interaction around 1960

- current–current interaction $\sim\ J_\mu \cdot J^\mu$
- charged current $J_\mu^\pm = V_\mu - A_\mu$ V–A structure

  Feynman, Gell-Mann 1957, Sudarshan, Marshak 1957

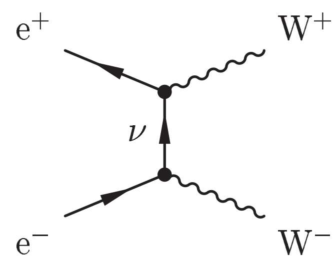
- intermediate heavy charged vectorbosons $W^\pm$ *Schwinger 1957*

  couple to J_μ^+ and J_μ^-

  analogy to QED, but obviously incomplete:

  $\rightarrow$ not renormalizable

  $\rightarrow$ bad high-energy behaviour violating unitarity



- algebra of charges $[I^+, I^-] = 2\,I^0$

  indicates $SU(2)$ with $[I^0, I^\pm] = \pm I^\pm$ isospin

  missing current $J_\mu^0 \rightarrow$ another boson W^0 = photon ?

symmetry takes over

- need for additional quantum number: hypercharge Y

  additional current J^Y and boson B^0 $\Rightarrow$ $SU(2) \times U(1)$

  $$\begin{pmatrix} A^0 \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

  Glashow 1961

  photon A^0 $\leftrightarrow$ *electromagnetic current,* $Q = \frac{Y}{2} + I_3$

  Z^0 boson $\leftrightarrow$ *weak neutral current*

- dynamics of vectorbosons: non-Abelian gauge theory

  formulated for $SU(2)$ *Yang, Mills 1954*

  but: mass = 0 for vectorbosons!

- constructed for $SU(2) \times U(1)$ *Glashow 1961*

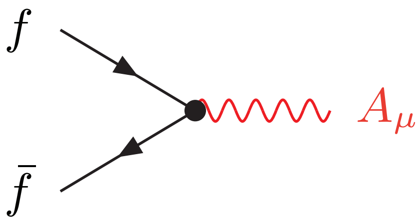
  – photon massless, $W^{\pm}$ and Z^0 massive

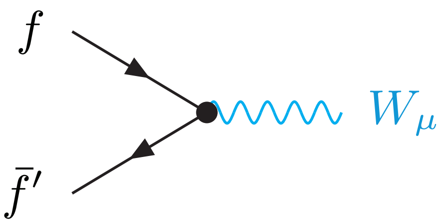
  – explicit mass terms added by hand

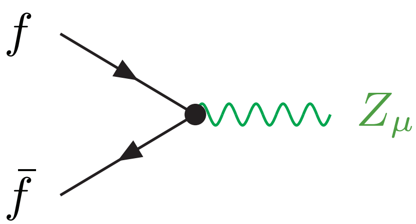
  – break gauge symmetry $\rightarrow$ not renormalizable

electroweak interactions from symmetry

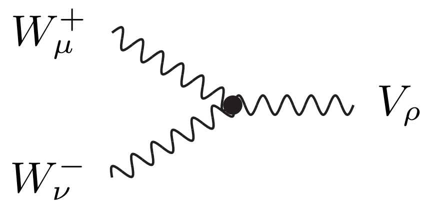
fermion–vectorbosons

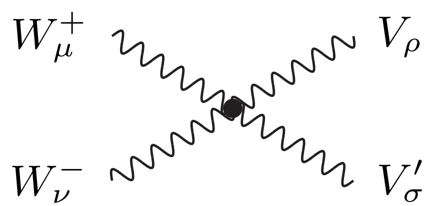






vectorboson self interactions





coupling constants: $e, \quad g = e/\sin\theta_{\mathrm{w}}$

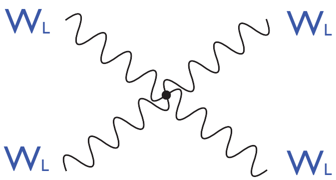
group entries: isospin I_3^f, charge Q_f

basic problem: masses of W and Z

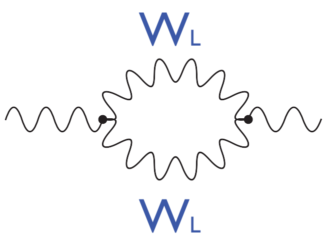
- W, Z have longitudinal polarization states

  polarization vectors of W (Z) $\epsilon_{\rm L} \sim p/M_{\rm W}$

  for large momentum p

- 

  bad high energy behaviour of WW scattering

- 

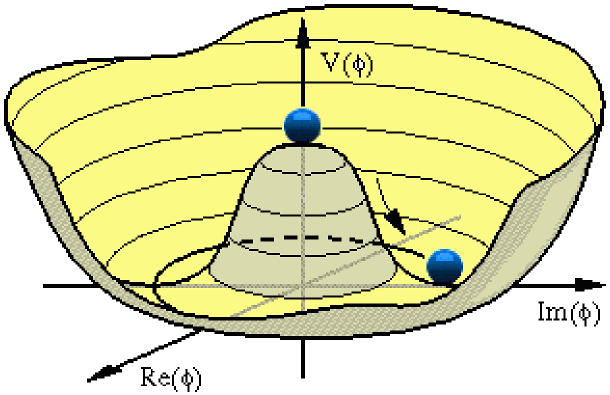
  bad divergence of loop integrals

spontaneous symmetry breaking

Brout, Englert 1964, *Higgs 1964,* *Guralnik, Hagen, Kibble 1964*

scalar field Φ with self-interaction

$$V = -\mu^2\,(\Phi^\dagger\Phi) + \lambda\,(\Phi^\dagger\Phi)^2, \quad \lambda > 0$$



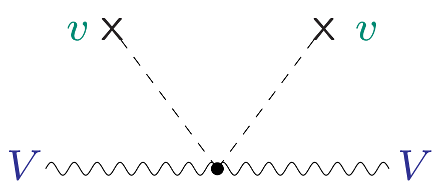
spontaneous symmetry breaking:
minimum at $v = \frac{\mu}{\sqrt{\lambda}} \neq 0$

interaction with gauge field:
gauge-invariant, renormalizable

gauge transformation $\longrightarrow$ $\Phi = v + \mathrm{H}$ physical field H

$$\Phi = v + \mathrm{H}$$

Higgs – gauge boson interaction $\sim g^2$

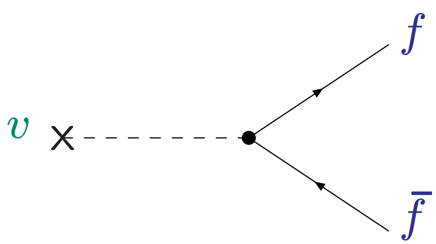


$V = W,\ Z$

$\Rightarrow$ V masses $\quad M^2 = g^2\, v^2$

residual VV–H interaction $\sim M_V$

Yukawa interaction $\sim g_f$



fermion masses $\quad m_f = g_f\, v$

residual f – H interaction

$g_f \sim m_f$

formulation of the electroweak theory

- applying current ideas to $SU(2) \times U(1)$ gauge theory

  Weinberg 1967, Salam 1968 *(formulated for leptons)*

- extension to hadrons

  assuming two quark generations: *c-quark postulated*

  Glashow, Iliopoulos, Maiani 1970

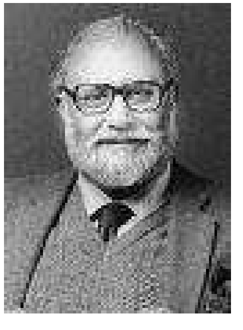
- assuming three quark generations: *t, b-quarks postulated*

  Kobayashi, Maskawa 1973

  embedding of CP-violation *(discovered 1964)*

Result: unified electroweak theory at the classical level

Nobelprize in Physics 1979 *Glashow, Salam, Weinberg*


- around 1970: **classical theory of ew interactions**

  $\longrightarrow$ weak neutral current, massive $W^{\pm}, Z^0$ bosons

- still open question: **is this kind of theory renormalizable?**

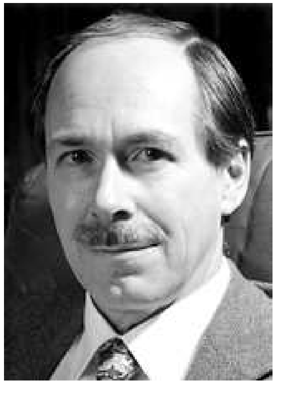
  – upgrade to the quantum level?

  – fundamental theory?

- breakthrough: **proof of renormalizability**

  't Hooft 1971, 't Hooft, Veltman 1972

  Nobelprize in Physics 1999




pathbreaking improvement

- ⋆ electroweak theory promoted to a consistent QFT
- ⋆ predictions beyond lowest order possible
- ⋆ quantum effects calculable like in QED *(Lamb shift, g-2)*

- need: technology for 1-loop Feynman integrals

  't Hooft, Veltman 1978 *scalar 1-, . . . 4-point integrals*

- complete 1-loop calculation for $e^+e^- \to \mu^+\mu^-$

  Passarino, Veltman 1979

  reduction method for tensor integrals to scalar integrals

  taylored to computer-aided calculations

  still being used for precision calculations (LHC, FCC. . .)

opened the era of electroweak precision physics

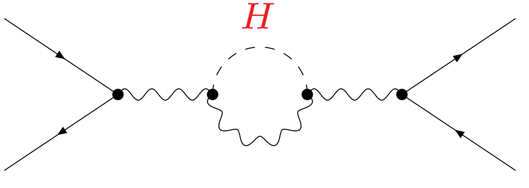
milestone: 1-loop calculation of the ρ-parameter *Veltman 1977*

for a fermion doublet (t,b) with $m_t \gg m_b$

$$\rho = \frac{M_W^2}{M_Z^2\, \cos^2\theta_W} = \frac{G_{\rm NC}}{G_{\rm CC}} = 1 + \frac{3\,G_F\,m_t^2}{8\pi^2\sqrt{2}} \simeq 1 + \mathbf{0.01}$$

information on heavy (unkown) particles

quantum corrections are sensitive also to the Higgs boson



quantum effects are detectable in precision experiments

- masses are correlated with other measureable quantities

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W}, \quad M_Z^2 = \frac{M_W^2}{\cos^2\theta_W}$$

- M_W, M_Z can be obtained from $G_F, \alpha, \sin^2\theta_W$

  since 1973: $\sin^2\theta_W$ known from neutrino scattering

  first calculations at one-loop order done in 1980

  Veltman; Antonelli, Consoli, Corbo

  limited precision, $\Delta\sin^2\theta_W \sim 0.0016$

- M_W and M_Z are correlated via G_F and α

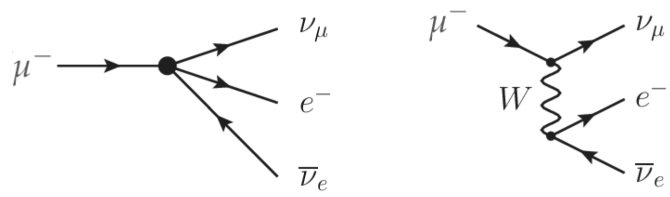
  allows to calculate M_W when M_Z is known

  since 1983 *UA1, UA2*

  since 1989 *LEP and SLC experiments*

  $\Rightarrow$ calculate M_W from M_Z, G_F, α (and more)

Fermi constant and W–Z mass correlation



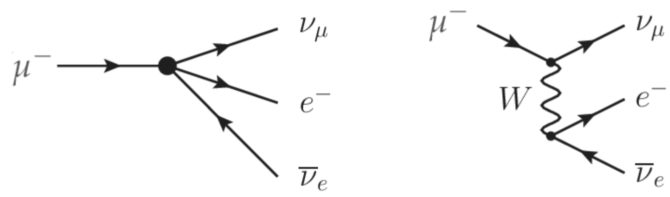
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2 \sin^2\theta_W}$$

- "on-shell scheme" *Sirlin 1980; Marciano, Sirlin 1980*

  M_W, M_Z *pole masses*

  $$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}, \qquad \frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2 \sin^2\theta_W}\left(1 + \Delta r\right)$$

Fermi constant and W–Z mass correlation



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- $\overline{MS}$ scheme

  Degrassi, Sirlin, Fanchiotti 1990; Degrassi, Gambino, Giardino 2014

  $\alpha, \sin^2\theta_W$ *running quantities at scale Q=M$_Z$*

  $$\frac{G_F}{\sqrt{2}} = \frac{\pi\hat{\alpha}}{2M_W^2 \sin^2\hat{\theta}_W}\left(1 + \Delta\hat{r}\right)$$

on-shell calculations for W mass and e^+e^- processes

Fleischer, Jegerlehner 1981

Akhundov, Bardin, Riemann 1986

Böhm, WH, Spiesberger 1986

WH 1988

Beenakker, WH 1988

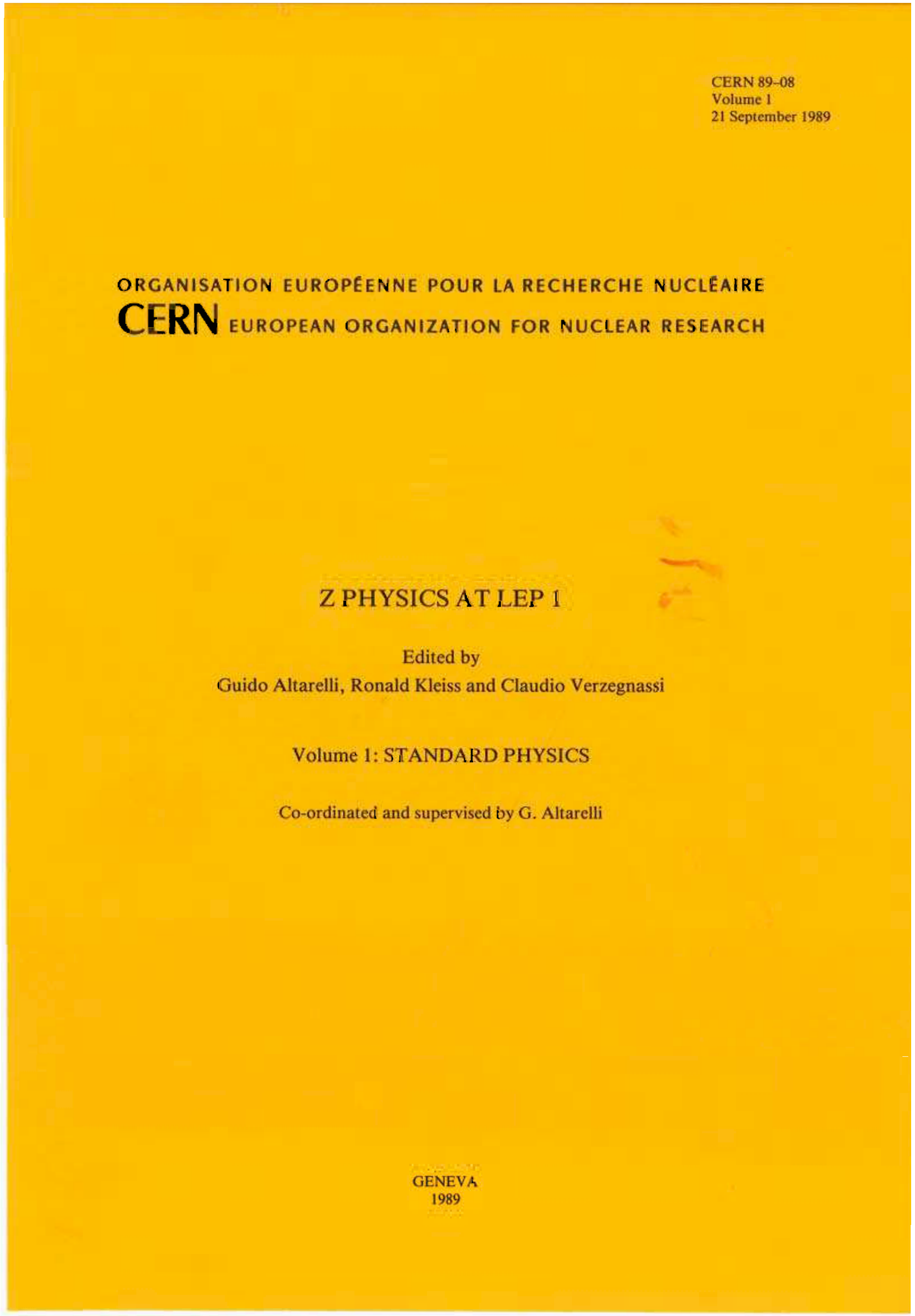
Consoli, WH, Jegerlehner 1989

Bardin, Riemann et al. since 1985 $\rightarrow$ `ZFITTER`

...

$\Rightarrow$ **Z Physics at LEP 1 (1989)**

- *Z line shape*
- *forward–backward asymmetries*
- *MC generators*
- ...


CERN 89-08
Volume 1
21 September 1989

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Z PHYSICS AT LEP 1

Edited by
Guido Altarelli, Ronald Kleiss and Claudio Verzegnassi

Volume 1: STANDARD PHYSICS

Co-ordinated and supervised by G. Altarelli

GENEVA
1989

Yellow Book coordinated
by Guido Altarelli

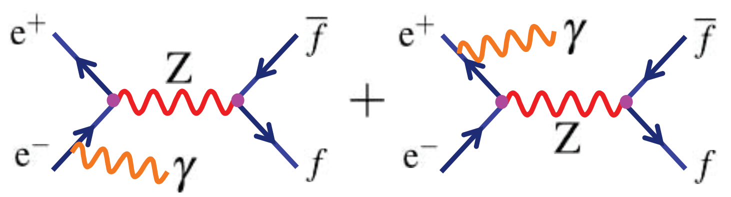
to make sure that
every needed aspect
was prepared for
the LEP experiments

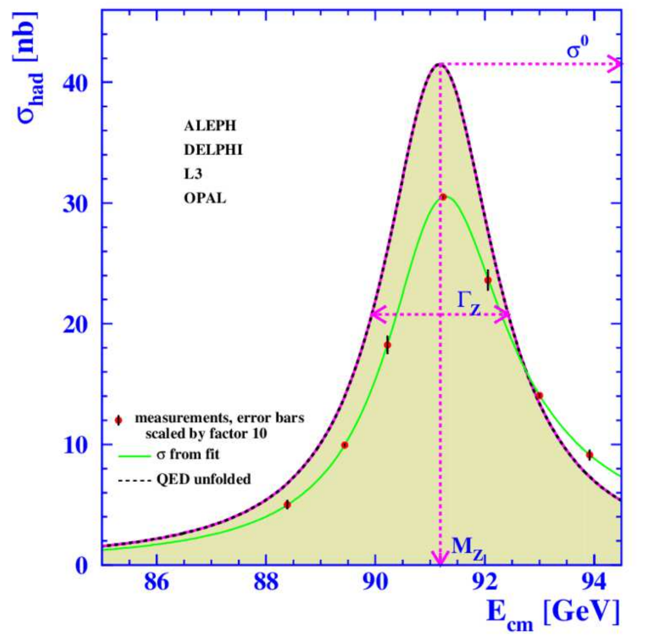
Z lineshape measurements $\Rightarrow$ mass M_Z and width Γ_Z

QED corrections

distort the line shape

initial state radiation





$$\sigma(s) = \int_0^1 dz\, H(z)\, \sigma(zs)$$

provided by theory

Berends, Kleiss, . . .

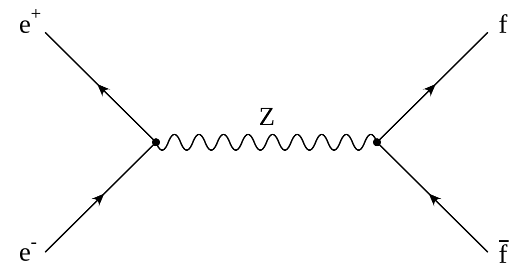
Jadach, Ward, . . . `KORALZ`

Bardin, Rieman, . . . `ZFITTER`

codes including multiple radiation

Z resonance observables

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



- effective Z boson couplings with higher-order $\Delta g_{V,A}$

$$g_V^f \to g_V^f + \Delta g_V^f, \qquad g_A^f \to g_A^f + \Delta g_A^f$$

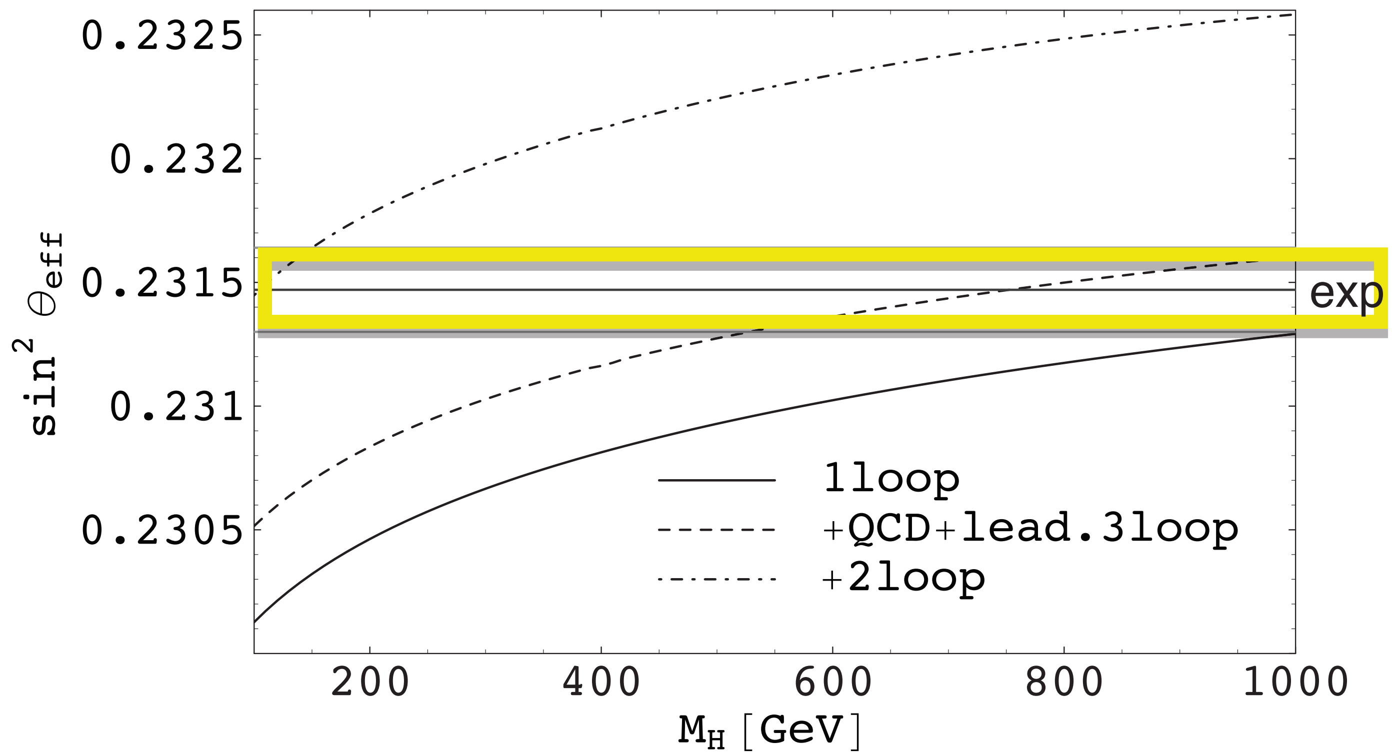
- effective ew mixing angle (for $f = e$):

$$\sin^2\theta_{\text{eff}} = \frac{1}{4}\left(1 - \text{Re}\,\frac{g_V^e}{g_A^e}\right) = 1 - \frac{M_W^2}{M_Z^2} + \frac{M_W^2}{M_Z^2}\,\Delta\rho + \cdots$$

- codes for precision calculations

ZFITTER	*Bardin, Riemann, et al. (1989 ff)*
TOPAZ0	*Montagna, Piccinini, Nicrosini, Passarino, Pittau (1993 ff)*
BHM	*Burgers, WH, Martinez (1989 ff)*
EXPOSTAR	*Kennedy, Lynn (1989)*

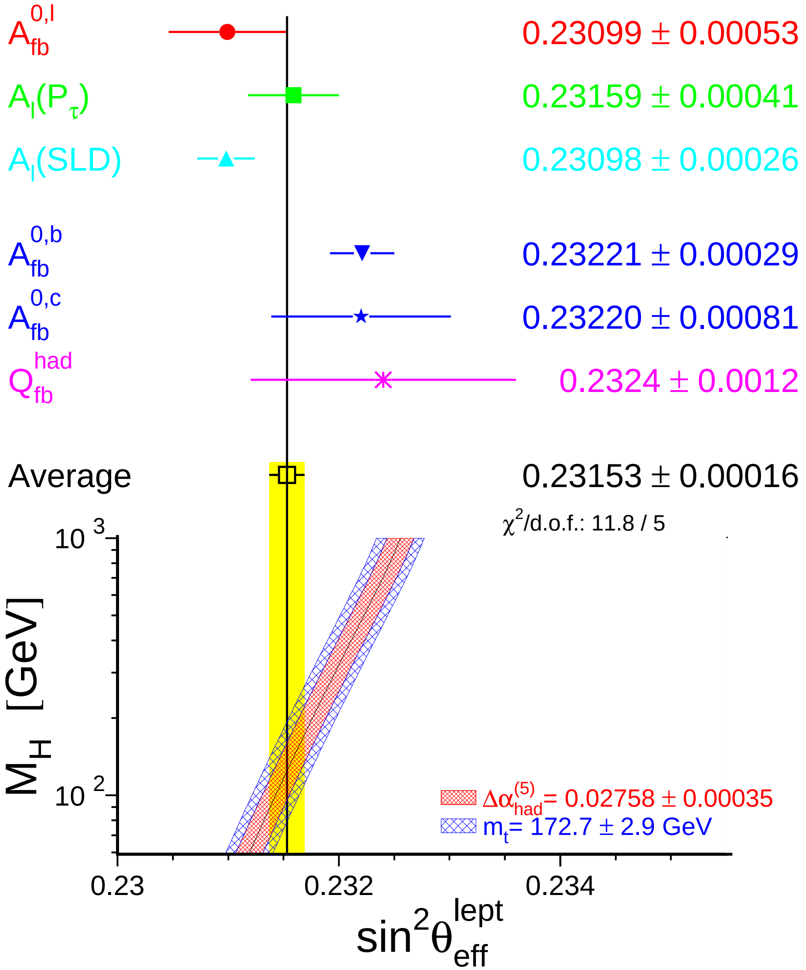
impact of higher-order contributions



lowest order: $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = 0.22305 \pm 0.00023$ *(PDG 2022)*

exp. value: $\sin^2\theta_{\rm eff} = 0.23153 \pm 0.00016$

quantum effects are established with compelling significance



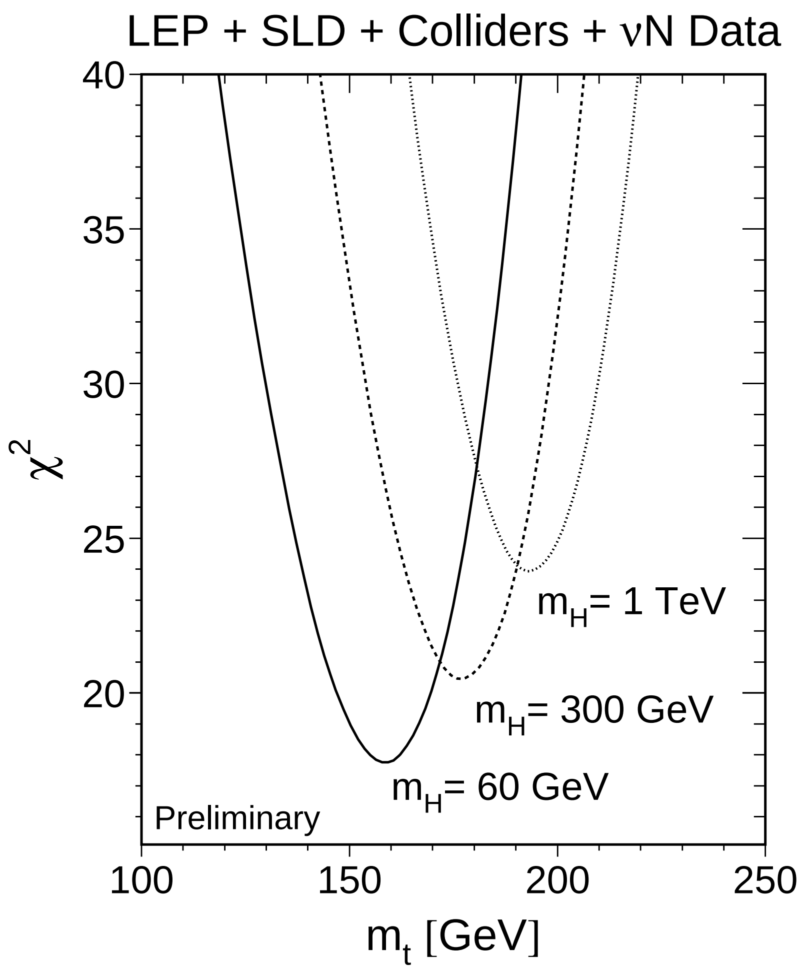
LEP ELECTROWEAK
WORKING GROUP

D.Schaile, R.Clare, M.Grünewald

combination of data from the individual experiments

analysis with tools provided by theory before the top quark was discovered (< 1995):

indirect mass determination $\Rightarrow$ $\mathrm{m_t} = 178 \pm 8\,^{+17}_{-20}\,\mathrm{GeV}$



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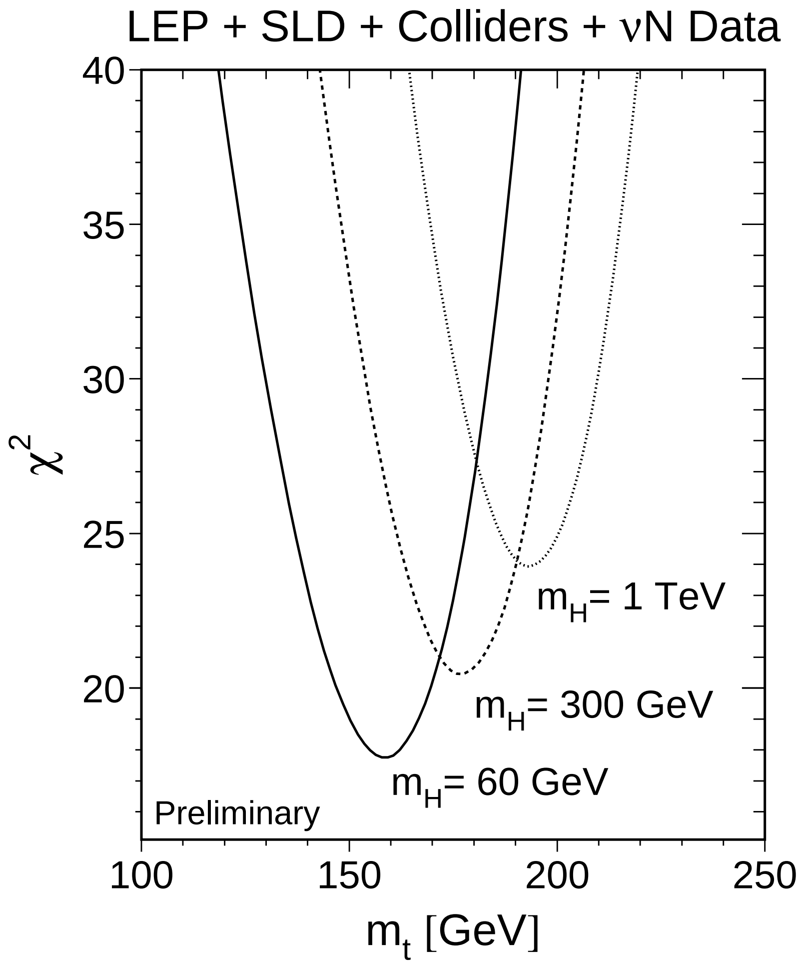

top discovery: *Tevatron 1995* $\mathrm{m_t} = 180 \pm 12\,\mathrm{GeV}$

before the top quark was discovered (< 1995):

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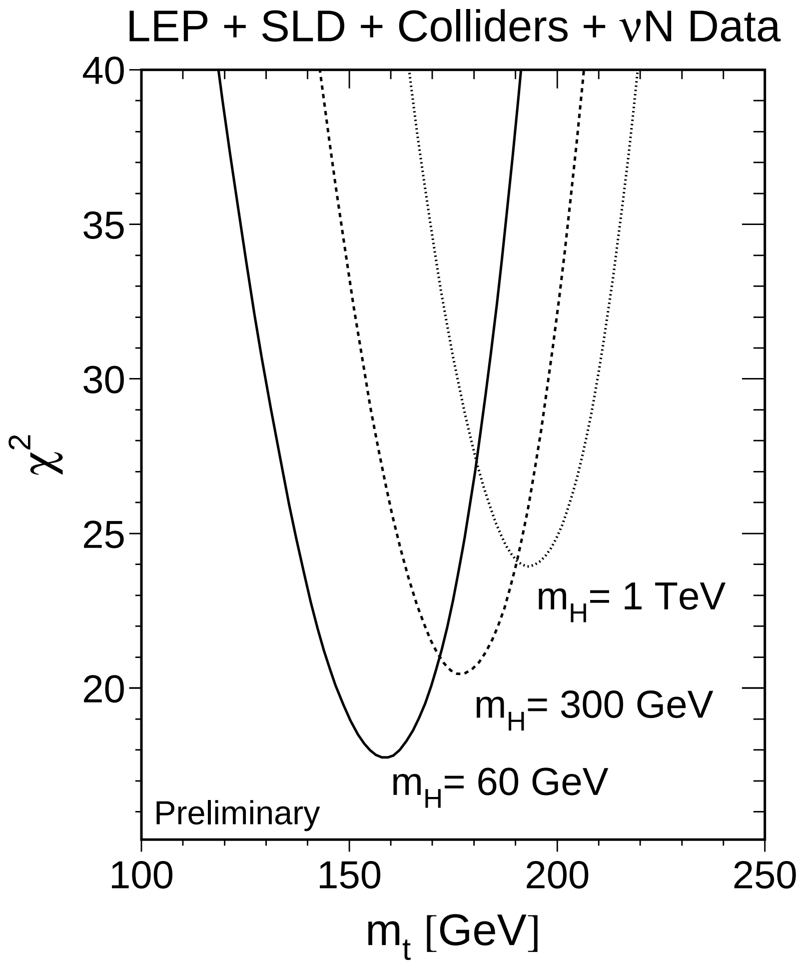
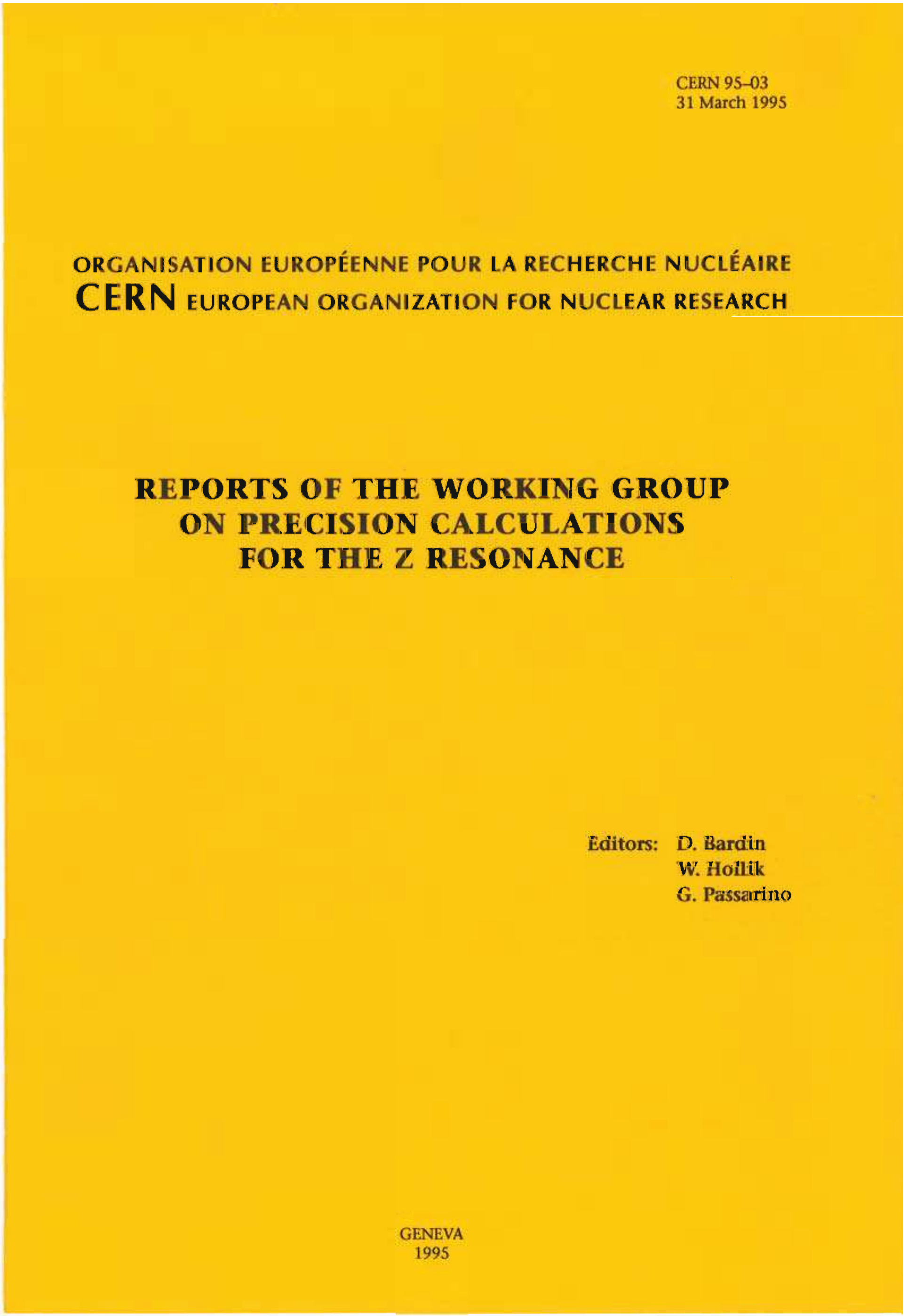


top discovery: *Tevatron 1995* $\mathrm{m_t} = 180 \pm 12\,\mathrm{GeV}$

today: *PDG 2022* $\mathrm{m_t} = 172.69 \pm 0.30\,\mathrm{GeV}$


CERN 95-03
31 March 1995

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

REPORTS OF THE WORKING GROUP ON PRECISION CALCULATIONS FOR THE Z RESONANCE

Editors: D. Bardin
W. Hollik
G. Passarino

GENEVA
1995

triggered by LEPEWWG

updated codes for precision observables

systematic estimate of theoretical errors

$\Rightarrow$ *“blueband plot”*

The first blueband plot

global fit to the Higgs-boson mass after the top discovery (ICHEP 1996)

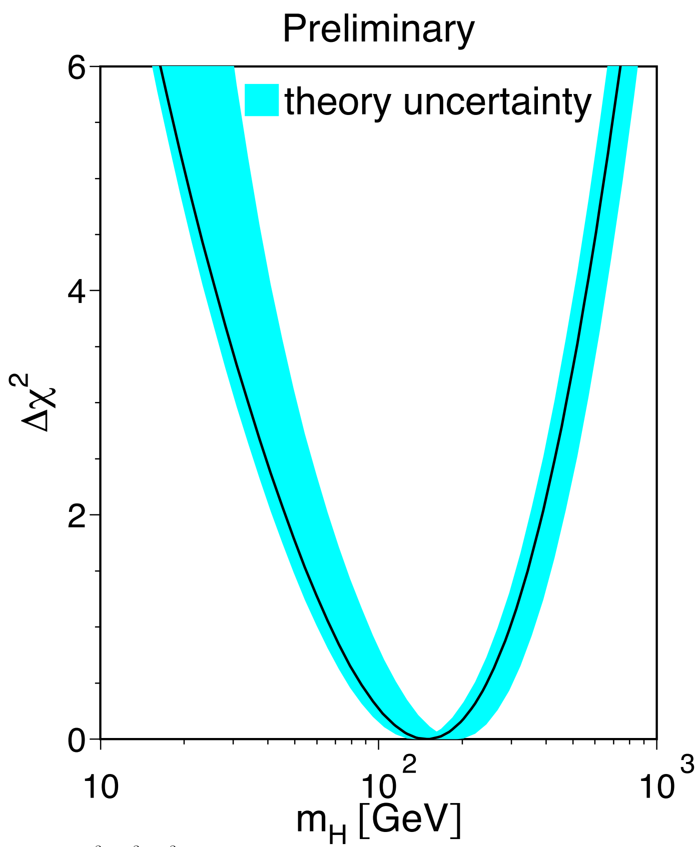


Figure 9: $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ *vs.* $m_{\rm H}$ curve. The line is the result of the fit using all data (last column of Table 22); the band represents an estimate of the theoretical error due to missing higher order corrections.

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CERN-PPE/96-183
December 6, 1996

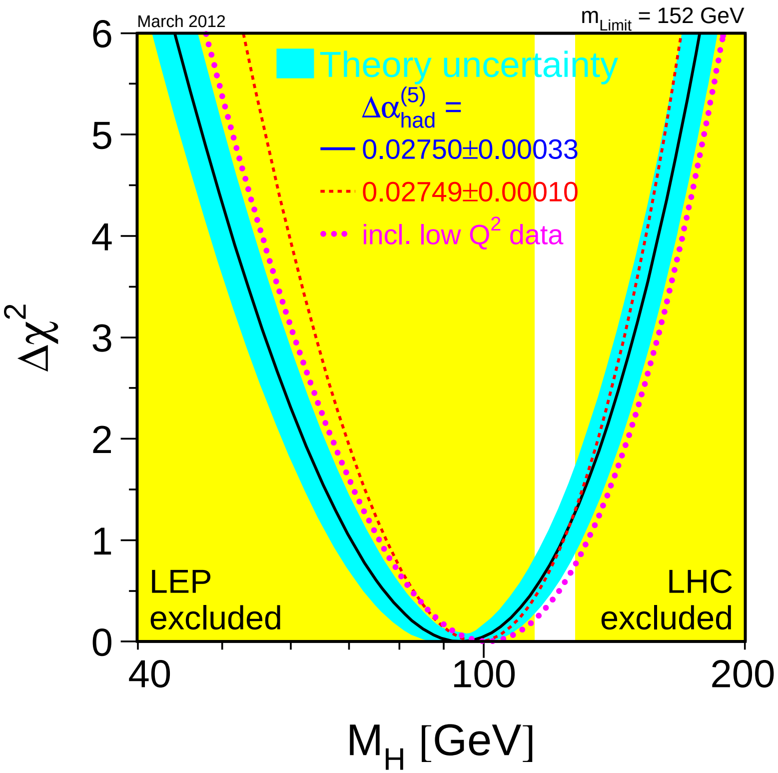
A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model

The LEP Collaborations* ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group† and the SLD Heavy Flavour Group‡.

Prepared from Contributions to the 28th International Conference on High Energy Physics, Warsaw, Poland, 25-31 July 1996.

The last blueband plot

before the Higgs boson discovery in summer 2012



$$M_H < 152 \text{ GeV } (95\%\text{C.L.})$$

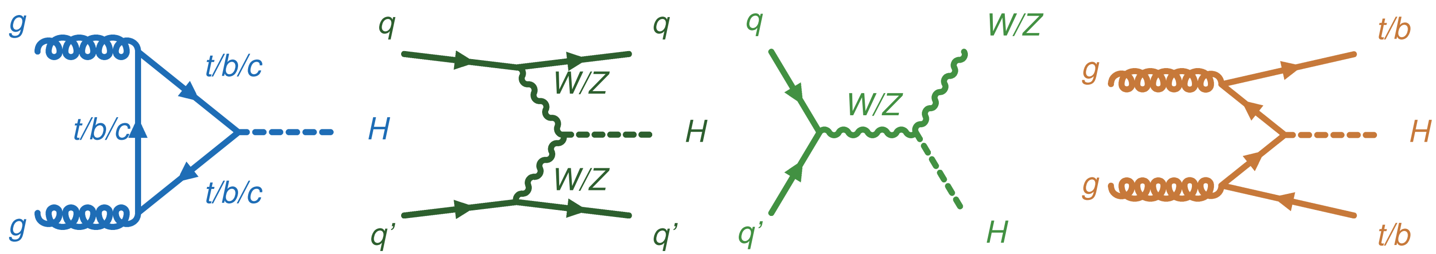
$$M_H = 94^{+29}_{-24} \text{ GeV}$$

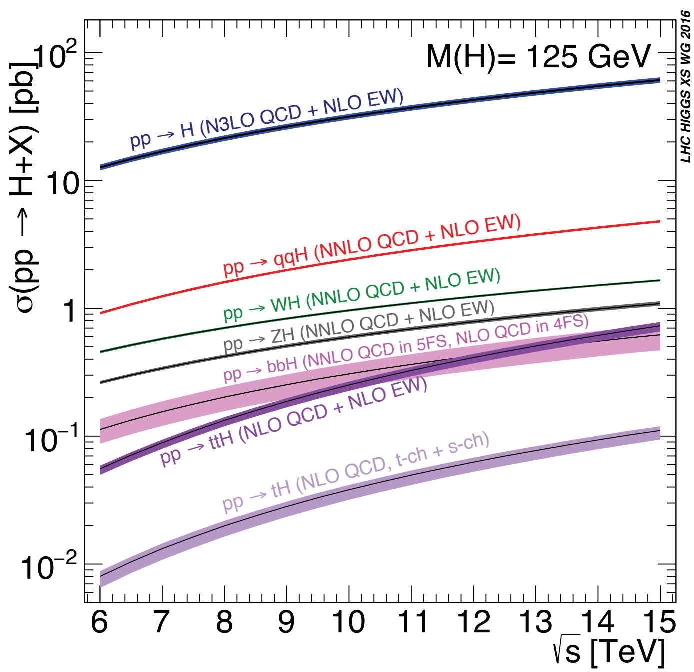
ATLAS 2012: $M_H = 126.0 \pm 0.4 \pm 0.4 \,\text{GeV}$

CMS 2012: $M_H = 125.3 \pm 0.4 \pm 0.5 \,\text{GeV}$

today (PDG 2022) $M_H = 125.25 \pm 0.17 \,\text{GeV}$

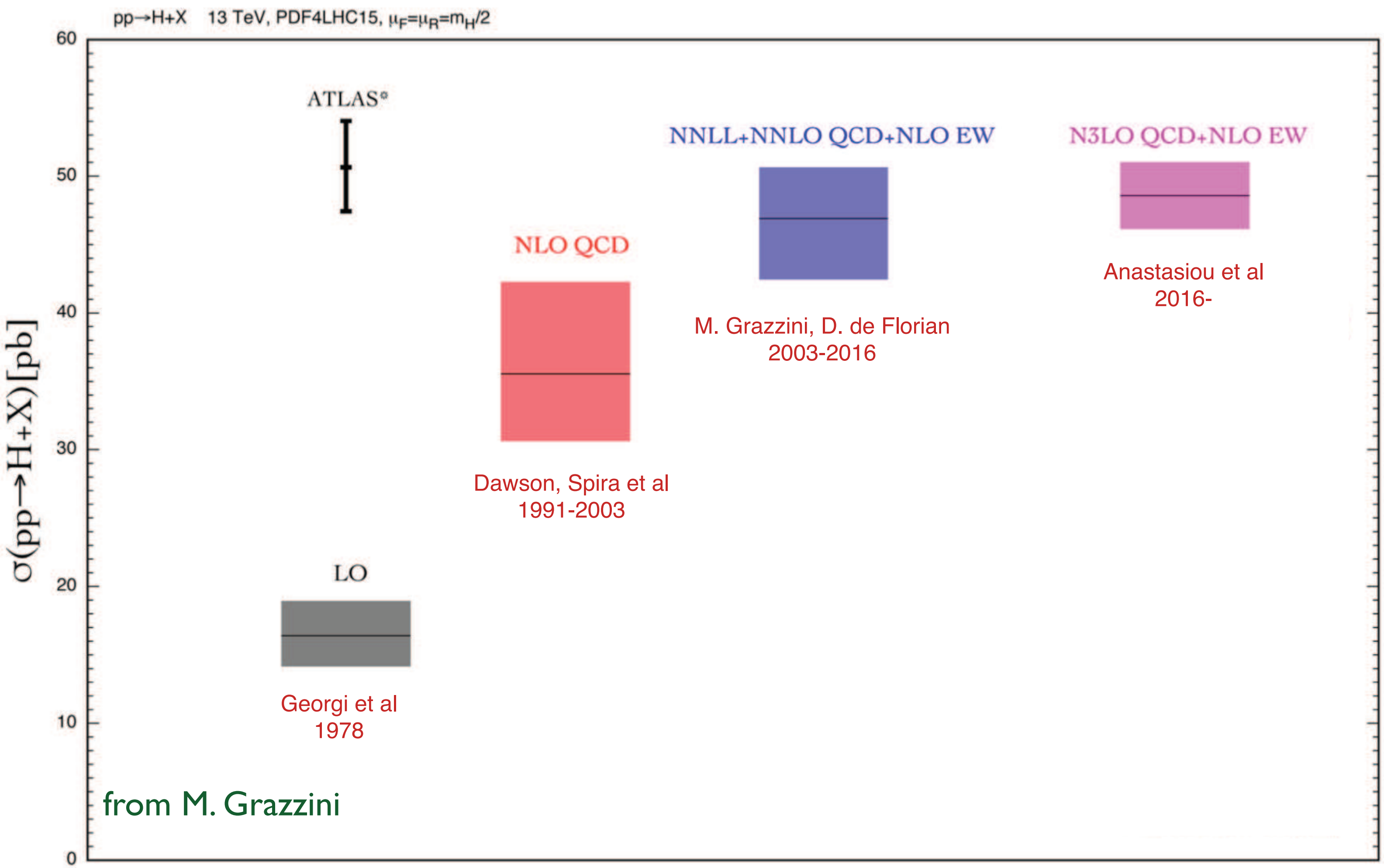
Higgs boson production at the LHC





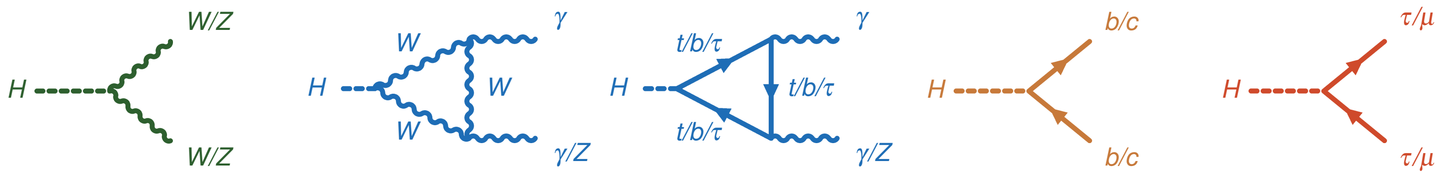
theory predictions with higher orders from QCD (4-loop) and ew (2-loop)

Handbook of Higgs Cross Sections Vol. 4
De Florian et al.
CERN Yellow Report 2017-002

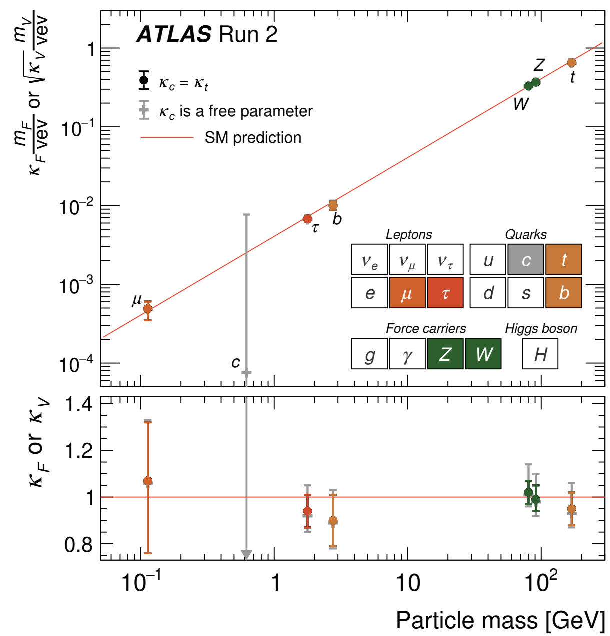


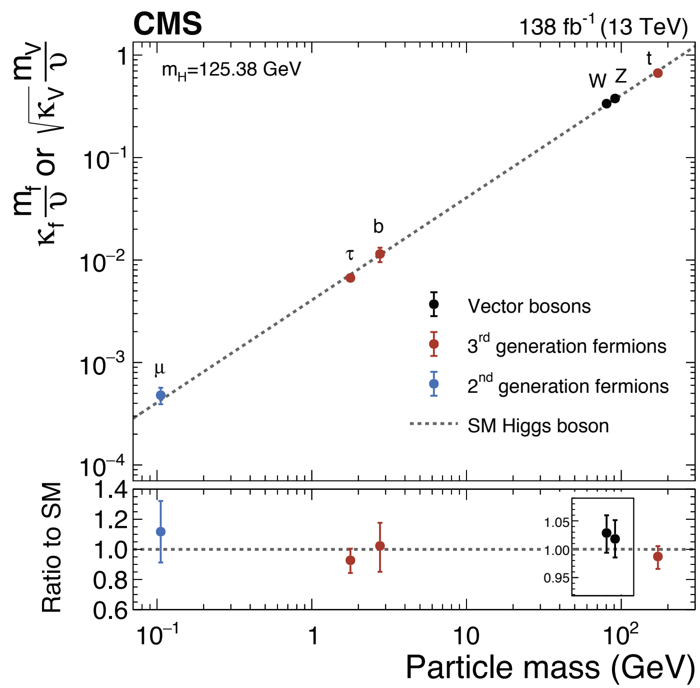
incomplete higher-order calculations provoke wrong conclusions!

Higgs boson decays



predictions with higher orders *in: Handbook of Higgs Cross sections Vol. 4*

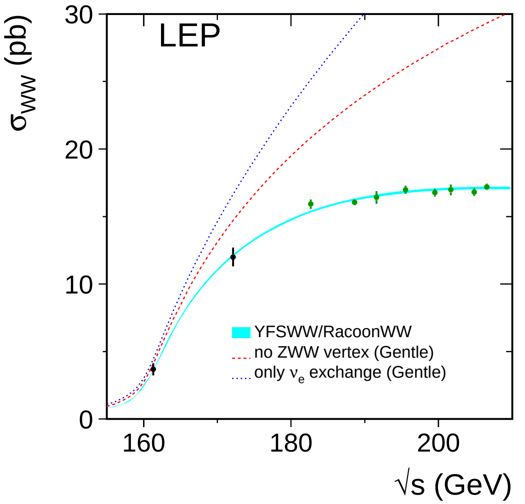




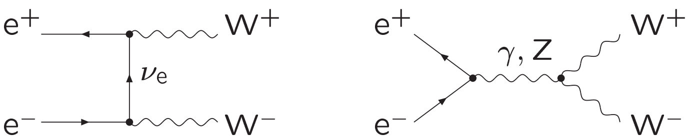
measurements: couplings scale with masses as predicted
by the ew theory

EW theory: what has been established

- coupling structure from local $SU(2) \times U(1)$ gauge symmetry
  - ⋆ vectorboson– fermion couplings
  - ⋆ cubic vectorboson self-couplings



$$e + e^- \to WW \; (\to 4\,f)$$



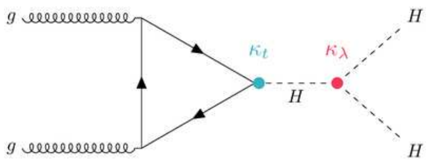
theo: RacoonWW — *Denner et al.*
Gentle — *Bardin et al.*
YFSWW — *Jadach et al.*
(codes with h.o.)

- signals from gauge-symmetry breaking
  - ⋆ existence of a Higgs boson
  - ⋆ couplings to gauge bosons as predicted by Higgs mechanism
  - ⋆ couplings to fermions as predicted by Yukawa interactions

EW theory: what is missing

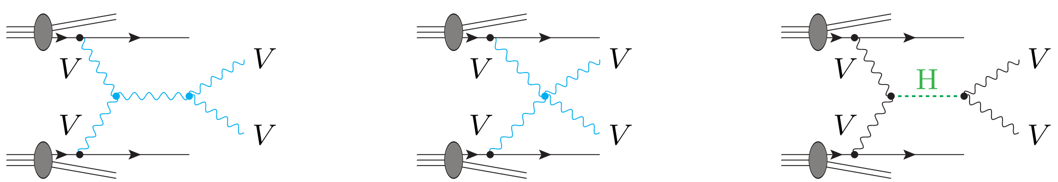
- Higgs couplings with higher precision, in particular
  Yukawa couplings of light fermions

- Higgsboson self-coupling ($\rightarrow$ scalar potential)



appears in HH-pair production

- vectorboson scattering at high energies
  goes to the core of electroweak symmetry breaking



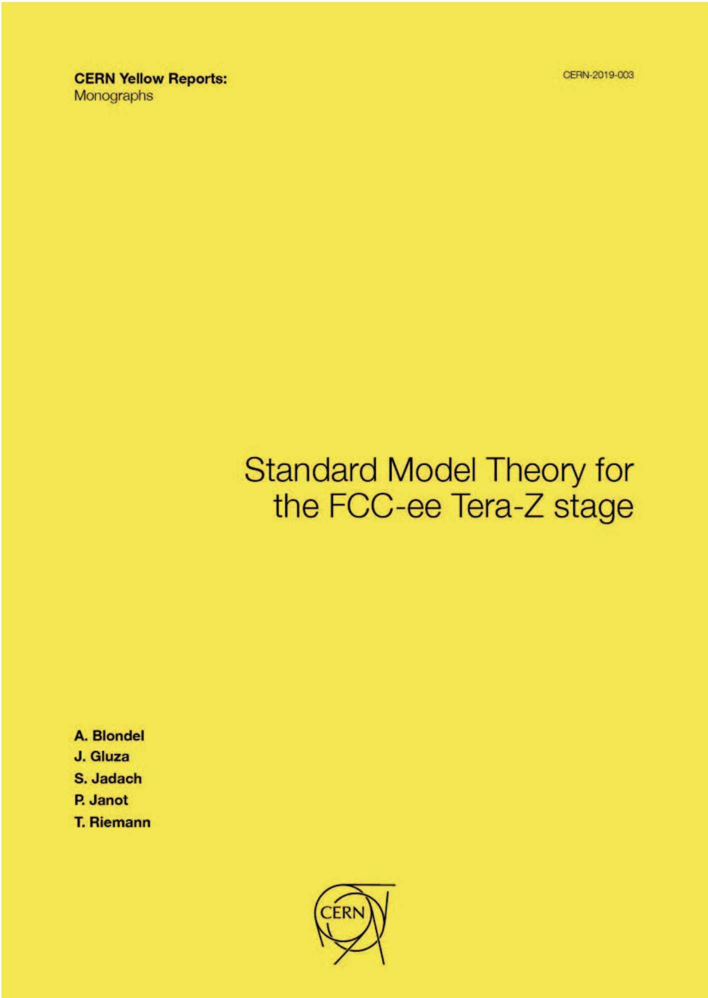
six-particle final states + higher orders (radiation processes and loops)
new techniques invented for multi-leg and multi-loop calulations

- LHC: processes already observed
  precision studies in forthcoming LHC runs

Concluding remarks

- EW theory: a result of close work in theory and experiment
  - – built on basic principles *(unitarity, renormalizability, symmetry)*
  - – accompanied by continous flow of new exp results
  - – a textbook case: from predictions to discoveries
- EW precision physics prepared the ground for discoveries
  - – unprecedented precision measurements
  - – challenge for theory $\rightarrow$ era of precision calculations
  - – new style of theoretical work
- convincing concept $\rightarrow$ great success
  - – confirmation as a working quantum field theory
  - – indirect access to heavy particles
  - – can be repeated for BSM physics?

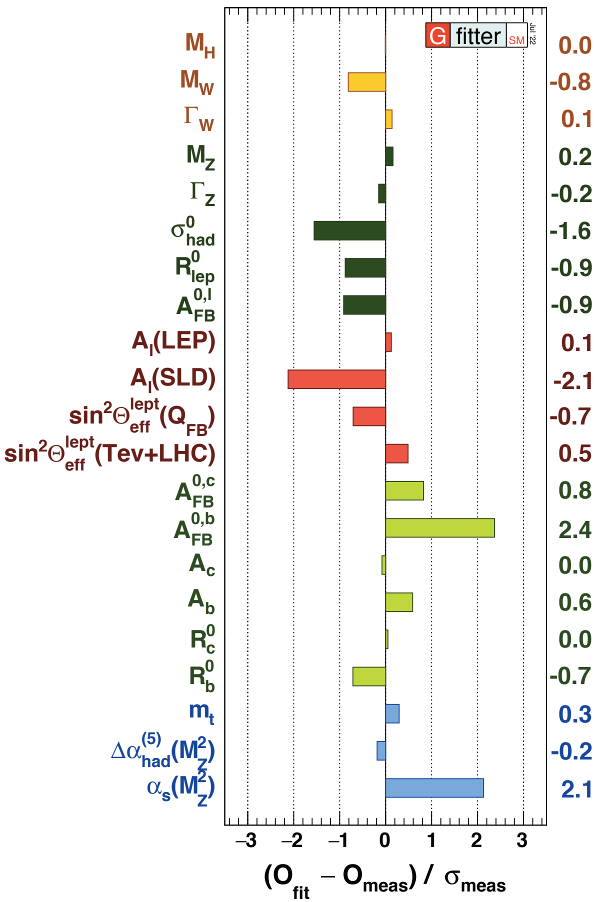
activities preparing the future . . .



exp. error	*now*	*FCC*
M_W [MeV]	12	1
$\sin^2\theta_{\rm eff}$ $[10^{-5}]$	16	0.6

- need:
  theory calculations
  with one loop more

additional slides



[ICHEP 2022]

with $\mathrm{M_H}$, precision observables are now uniquely determined

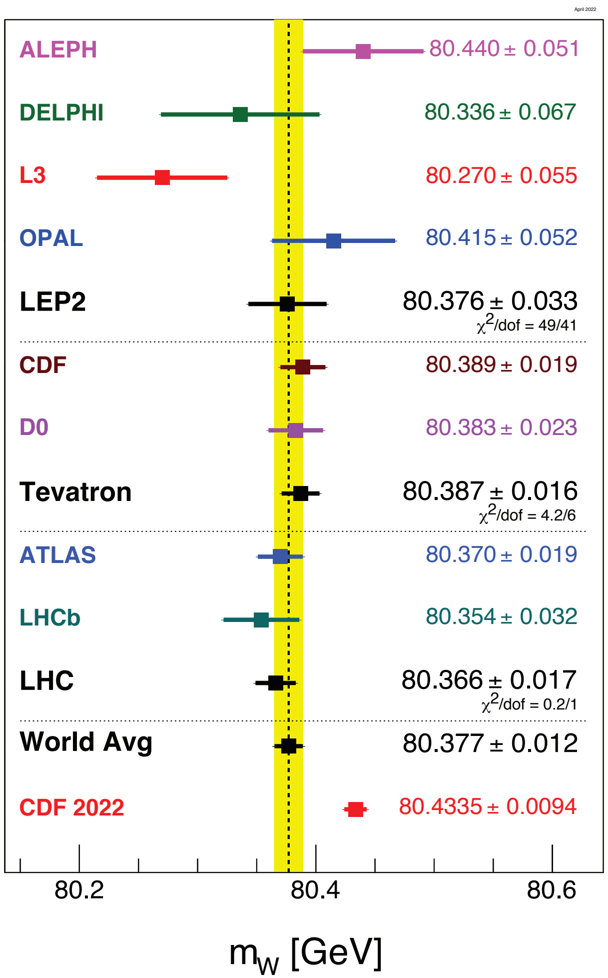
global fits are consistency tests with increasing accuracy from LHC

theory predictions with all known h.o. contributions are available as parametrizations in terms of the input quantities

Dubovyk,Freitas et al. 2019

codes for global fits

HEPfit, Gfitter, . . .



theory:

$$M_W = 80.353 \pm 0.005 \pm 0.004\,\mathrm{GeV}$$