LEP
The Making of a Frontier

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Abstract

Something from the past, a lot from the present,
a hint at the future.

Prelude: **Experimental** Progress

- The Exp. progress made in the **1990's** is remarkable in many ways. With the **right experiments** we can reveal the fine details of high energy phenomena.

- Around **LEP** Shutdown we known that physics at the **microscopic scale** has a basis as **rationale** as chemistry.

- Everything moves, **not by magic**, but because there is a **mechanism at work**, the **Standard Model**.

- Everything is encouraging for the major **unsolved** aspects of the breaking of electroweak gauge symmetry.

Rating ……

▷ to be compared with **our knowledge** at, say, 1989 Lepton-Photon Conference.

⋆⋆⋆⋆ – $\rho = 1$, **SM** uniqueness of **group & representations**, **renormalizable gauge theory**

– $N_\nu = 3$.

– Any deviation from **MSM** is **soft**

– Z, W bosons are **not composite**, therefore **TeV** scale severely constrained

– *stringent limits* on **new** physics

⋆⋆⋆ – one-side 95% **CL** **Higgs** upper limit 210 GeV,

– nitid evidence for **radiative corrections** beyond running of $\alpha_{\rm QED}$, therefore **SM** correct at *loop level*

– absence of evidence for **anomalous couplings**

– Lepton universality and SM couplings to quarks and leptons

– M_Z is a **fundamental** constant of nature

– **Gauge-symmetry** is **not** a low energy approximation, therefore **SM** correct and unique

Summarizing: **SM** is real before our eyes and not a
Se non è vero è ben trovato
construct

However, ... **something** should have been done better

- □ The *meaninful* mass-quantities are the locations of the **complex poles** on the **2nd** Riemann sheet,
- □ **not** the *on-shell* – like masses that enter **Breit-Wigner** propagators for **PO**-*fitting*

- ▷ All **distributions** should be recorded, if not published, and not only **de-convoluted POs**,
- ▷ What will we do, **in ten years**, with **QCD+QED** *de-convoluted* **forward-backward** asymmetries if **theory** will change?

The means by which we have achieved **our understanding** is that of using **accelerators** that go to the **basic scale**.

In a category of its own

XXX LEPEWWG activities **&** theoretical input

– **precise RC**

– **Packages**: *ALIBABA, BHLUMI, KKKMC, TOPAZ0, MIZA & ZFITTER*

– **Packages**: *Gentle, (Next)calibur, Koralw, YFSWW, Grace, RacoonWW, Wphact & WTO*

Sociology around LEP:

It is interesting to examine the **environment** in which the LEP **technology** has been developed. One way is through the **Kühn tower**.

the Pushers: higly-specialized experts, QED, QCD etc

△ △ △

the Smugglers: those who assemble a code mooncursing it

△ △ △

the Users: the experimental community at large

∇ Some sort of **universal language** has been created to allow a **meaningful** communication

A new language:

The Pseudo-Observables

- The **PO** are related to measured **cross-sections** and **asymmetries** by some deconvolution or **unfolding** procedure.

- The concept itself of **pseudo-observability** is rather difficult to define.

- One way to introduce it is to say that the experiments **measure** some **primordial** (basically **cross-sections** and thereby **asymmetries** also) quantities which are then

- **reduced** to secondary quantities under some set of **specific assumptions**.

- Within these assumptions the secondary quantities, the **PO**, also deserve the label of **observability**.

The **PO** prototype: the ρ parameter

Standard definition of the Veltman ρ-parameter

- ρ is defined as the ratio of the W and Z masses squared divided by c_θ^2. **We start by introducing a bare quantity**:

$$\rho_0 = \frac{M^2}{c_\theta^2 M_0^2}$$

- The quantities appearing in this equation must be related to experimental data.

- There is no ambiguity in what is meant by an experimental mass. There remains the experimental c_θ^2 which should be extracted from, for instance, **low-energy data**.

- In the original formulation, where everything was extracted from low-energy data ($p^2 = 0$), a ρ was introduced as

$$\rho \;=\; 1 + \frac{g^2}{16\,\pi^2 M_W^2}\left[\Sigma_{WW}(0) - \Sigma_{33}(0)\right] = 1 + \frac{g^2}{16\,\pi^2}\Delta\rho, \quad (1)$$

  where the 1 in the **r.h.s.** of the equation is actually $\rho_{\rm bare}$ in the **MSM**.

Why is ρ so important?

- ▷ The ρ-parameter of **Eq.(1)** is finite for $\xi = 1$ and numerically very close to the *experimental* one, in any scheme where the counter-terms are prescribed. The main correction is due to the **top quark mass**.

- ▷ Usually we do not attach any particular relevance to **bare parameters**, only the **renormalized Lagrangian** predicts meaningful—measurable—quantities.

- ▷ However, the ρ-**parameter** of the **MSM** plays a special role. It is finite because of a *residual symmetry* which is nothing but the usual **isospin invariance**.

- ▷ Individual components are by themselves infinite, but the combination occurring in this equation for the ρ-parameter is finite, as it should be.

The inner structure of the theory

▷ In general ρ_0, can be represented as follows,

$$\rho_0 \;=\; \rho_{\rm exp}\,(1-\delta\rho)\,,$$

where $\rho_{\rm exp}$ is the data point which depends on the **IPS** and $\delta\rho$ is finite and computable.

▷ These two facts define ρ also as a **physical observable**.

▷ It is a consequence of isospin invariance that the vector boson masses are not both free parameters.

▷ To discuss the *bare* ρ-**parameter** we always need four data points and here we want to present an explicit example. From the α, G_F and M_Z **IPS** (IPS$_Z$) we derive

$$s^2_\theta \;=\; \sin^2\theta_1 = \overline{s}^2 + \Delta^{(1)},$$

where $\overline{s}^2$ is known and where $\Delta^{(1)}$ represents the corresponding corrections induced by loop diagrams in IPS$_1$. Starting from M_W we derive another solution:

$$s^2_\theta \;=\; \sin^2\theta_2 = \frac{\pi\alpha}{\sqrt{2}\,G_F M^2_W} + \Delta^{(2)}.$$

▷ In computing $\rho_{\rm bare}$ we use the IPS_1 for the ratio M^2/M_0^2 and

$$s_\theta^2 = \sin^2\theta_2 = \frac{\pi\alpha}{\sqrt{2}\,G_F M_W^2} + \Delta^{(2)}.$$

for c_θ^2. In this way we arrive at the following equations:

$$\rho_0 = \frac{\cos^2\theta_1}{\cos^2\theta_2} = \rho_{\rm exp}\,\left(1 - \delta\rho\right),$$

$$\rho_{\rm exp} = \frac{1}{2}\,\frac{G_F M_Z^2 + \sqrt{G_F M_Z^2\left(G_F M_Z^2 - 2\sqrt{2}\,\pi\alpha\right)}}{G_F M_Z^2 - \dfrac{\pi\alpha M_Z^2}{\sqrt{2}M_W^2}},$$

and where $\delta\rho$ accounts for the correction factors $\Delta^{(1,2)}$. Once $\rho_{\rm exp}$ is substituted and $\delta\rho$ computed then we can test the consistency of the **MSM** by looking at deviations from $\rho_0 = 1$.

▷ If we move away from a **MSM**, then we should write $\rho_0 \geq 1/(2\,I)$, where I is the *highest weak isospin* found among the **Higgs particles**.

▷ The tree relation $\rho = 1$ is essentially a consequence of isospin invariance also in the **Higgs sector** after **EWSB**. Only isospin breaking effects, such as $m_t \neq m_b$, will affect the ρ-parameter.

Frequently forgotten aspects

- ▷ The single *most celebrated* figure of the LEP era required **theorists** (**experimenters**) to bridge in a meaningful way the gap towards the **experimental** (**theoretical**) side of particle physics.
- ▷ At this scale it was an **unprecedented phenomenon** which changed forever our way of working.
- ▷ At this level of **precision**, *discovery theoretical physics* must be sustained by *background theoretical physics*.
- ▷ The level of accuracy and architectural complexity of *theoretical* MC has no comparison with the previous era.
- ▷ To a large extent **phenomenology** is a void science in absence of data taking (*the sleep of experimenters generates monsters*).

Nevertheless the **next cycle** should be marked by a return to *pure* theoretical speculations (**extra-dimensions?**)

but we will never be the same again

if we do not forget how to match our new ideas, immediately, with the reality of the experimental side . . . . . . and now we have much better tools.

Our experience in the 1990's

- $\triangleright$ we can view *EW physics* directly and not by **indirectly** matching low energy experimental results to **obscure** theoretical predictions (see what happened before),
- $\triangleright$ the **SM** provides a *rationale description* of **particles** and their **interactions** in terms of **18** parameters,
- $\triangleright$ (*experiments have examined the particles and exhibited their properties*)
- $\triangleright$ of the 2 parameters associated with the **Higgs sector** only one is *truly unknown*
- $\triangleright$ Despite *math. consistency* the **SM** cannot provide a description of *EWSB*
- $\triangleright$ Yet **precision data** severely constrain M_H
- $\triangleright$ **SM** is believed to be an *effective theory* valid $< (\ll ?)\,\Lambda$, **precision data** point towards a smooth behavior (**no weird ideas will work**)

Discovery versus Precision

Missing the **Higgs boson** is, **to a large extent**, irrelevant but for your Nobel prize.

▷ Since there is a **rationale** at **microscopic scale** we have faith that the mechanism for **EW symmetry breaking** is within reach of discovery,

▷ the **Higgs** tells us that an **electron** is different from a **muon** but does not **explain** why,

▷ the explanation could be **anything** but it must be **simple** and the **SM** must be *smoothly imbedded in it*.

▷ Even more, any *new magic* can be immediately (with some optimism) filtered through a layer of **very precise** estimations of the MSM **background** leading to some **unambiguous signal**.

It is well known that

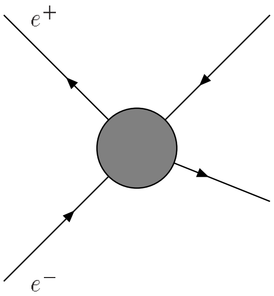
- The **theory** $\equiv$ **SM** $\ominus$ **Higgs** is *UV* divergent;
- *New physics* must cancel this **divergence**, a *non-trivial* task;
- the **Higgs** mechanism is the most *simple* and *economical* example of *New physics*;
- Other **mechanisms** fall equivalently into two categories: $\Lambda_{\text{NP}} \sim M_H$ or Λ_{NP} **unconstrained**

However some *strange* stuff is required and **LEP** has shown no evidence for it.

PRESENT STATUS of RC

by the way, where are we?

PCP Report hep-ph/9902452



one-loop $\Longrightarrow$ ALL

two-loop $\Longrightarrow$ LO + NLO

+ re-summations

IS QED, **SF-method** (or **equivalent**)
FS QED, **available**
IS $\otimes$ FS QED

Fine Points in QED for $2 \to 2$

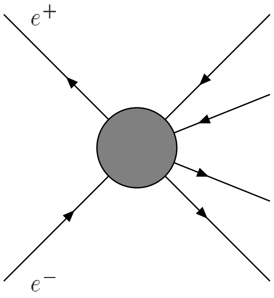
s-channel $\mathcal{O}\left(\alpha^2 L^n\right)$, $n = 0, 1, 2$ (Calculations), $\mathcal{O}\left(\alpha^3 L^3\right)$

important for Z **lineshape**

Differences and uncertainties amount to at most $\pm 0.1\,\mathrm{MeV}$ on M_Z and Γ_Z and $\pm 0.01\%$ on σ_{h}^0 (**MIZA, TOPAZ0** and **ZFITTER**) LEP EWWG/LS 2000-01

non-annihilation (Bhabha) both **SF** and **PS** have been analyzed, uncertainty estimated to be **0.061%** (**BHLUMI**)

FULL two-loop EW needed for **GigaZ** ($10^9 Z$ events),
Numerical evaluation of **FD**?



$e^+e^- \to 4\,\mathbf{f}$ **Born** $\Longrightarrow$ **ALL** processes

$\mathcal{O}(\alpha)$ EW $\Longrightarrow$ **only in DPA for** WW **signal**

$e^+e^- \to 4\mathrm{f} + \gamma \Longrightarrow$ **ALL**

hep-ph/0005309

Fine Points in QED for $2 \to 4$

for $e^+e^- \to WW \to 4\,f \;\to$ **see DPA**

for generic $e^+e^- \to 4\,f \;\to$ **s – channel SF**

$\to$ *i.e.* **LL approximation**

♢ the latter strictly applicable only if **ISR** can be separated (may lead to **excess** of **ISR**)

♢ **preliminar** investigations towards **non–s SF** by **GRACE** and **SWAP** **hep-ph/0005309**

Bulk of the effect but *ad hoc*

How well do we know realistic observables in $e^+e^- \to 2\mathrm{f}$?

- Pretty **well** around the Z **peak**
- Reasonably well **up to LEP 2 energies**, but **fermion-pair** corrections are not really under control.

Let's see the general state of PP

- Let's start from a simple case, e^+e^- **PP**-corrections to $e^+e^- \to \bar{b}b$.
  - ▷ diagrams of the first row are termed **Multi-Peripheral**, or **MP**;
  - ▷ diagrams of the second row are termed **Initial State Singlet**, or **ISS**;
  - ▷ diagrams of the third row are termed **Initial State Non-Singlet**, or **ISNS**;
  - ▷ diagrams of the fourth row are termed **Final State**, or **FS**.

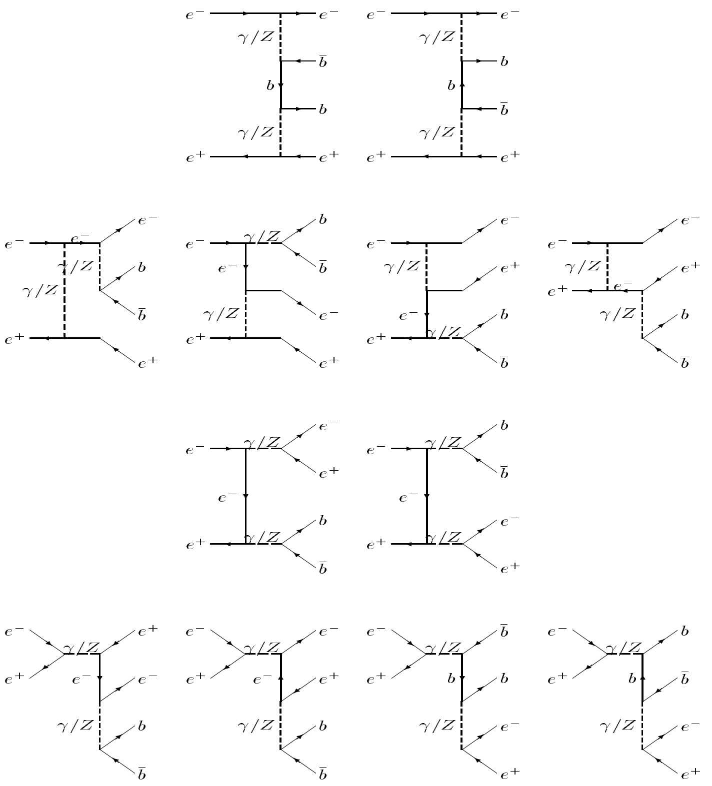


Figure 12: *Complete set of diagrams for the process* $e^+e^- \to e^+e^-b\bar{b}$.

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- Note that we include both γ and Z exchange.
- On top of **real pair production** one has to include **virtual** e^+e^- pairs.

Let's compare as a typical example the sum of **virtual** and **real** pair corrections for **primary** hadrons and **primary** muons at $\sqrt{(s)} = 189$ **GeV**.

Table 1: Relative virtual + real pair corrections in per mill of the total cross-section for the process $e^+e^- \to$hadrons at $\sqrt{s} = 189$ GeV for different signal definitions. A – means that this definition is not accessible in the respective program.

definition	GENTLE	ZFITTER	TOPAZ0	GENTLE	ZFITTER	TOPAZ0
R_{cut}	0.01			0.7225		
A) diagram, $s' = M^2_{\mathrm{prop}}$	14.72	15.76	16.42	-1.13	-0.92	-0.98
B) diagram, $s' = M^2_{\mathrm{inv}}$	14.74	15.82	–	-1.45	-1.20	–
C) cuts, $P_{\mathrm{cut}} = 0.15$	14.64	–	–	-1.45	–	–
D) cuts, $P_{\mathrm{cut}} = 0.10$	14.45	–	–	-1.45	–	–
$\delta_{\mathrm{B}} - \delta_{\mathrm{A}}$	0.02	0.06	–	-0.32	-0.29	–
$\delta_{\mathrm{B}} - \delta_{\mathrm{C}}$	0.10	–	–	< 0.0001	–	–
$\delta_{\mathrm{B}} - \delta_{\mathrm{D}}$	0.29	–	–	< 0.0001	–	–

Table 2: Relative virtual + real pair corrections in per mill of the total cross-section for the process $e^+e^- \to \mu^+\mu^-$ at $\sqrt{s} = 189$ GeV for different signal definitions. A – means that this definition is not accessible in the respective program.

definition	GENTLE	ZFITTER	TOPAZ0	GENTLE	ZFITTER	TOPAZ0
R_{cut}	0.01			0.7225		
A) diagram, $s' = M^2_{\mathrm{prop}}$	10.73	11.73	12.26	-1.37	-1.00	-0.98
B) diagram, $s' = M^2_{\mathrm{inv}}$	10.84	11.96	–	-2.58	-2.05	–
C) cuts, $P_{\mathrm{cut}} = 0.15$	10.72	–	–	-2.58	–	–
D) cuts, $P_{\mathrm{cut}} = 0.10$	10.57	–	–	-2.58	–	–
$\delta_{\mathrm{B}} - \delta_{\mathrm{A}}$	0.11	0.23	–	-1.21	-1.05	–
$\delta_{\mathrm{B}} - \delta_{\mathrm{C}}$	0.12	–	–	< 0.0001	–	–
$\delta_{\mathrm{B}} - \delta_{\mathrm{D}}$	0.27	–	–	< 0.0001	–	–

The comparison between **GENTLE, ZFITTER**, and **TOPAZ0** for the **diagram-based** definition reveals **maximum differences** of **1.7 (1.5) per mill** for **inclusive hadrons (muons)** and **0.2 (0.4) per mill** for **high** s' **hadrons (muons)**.

$\boxed{\textbf{caveat: PP to be completed}}$

expressly at **higher energies** and above **vector boson** thresholds.

$\boxed{\textbf{Some evolutionary development would be:}}$

- □ **4f** MC to be **fully** interfaced with **2f** MC

Even if LEP will not be running another year ......

(again) Rating . . . . . .

$\star\star\star\star\star$ – **PO fitters**

$\star\star\star\star$ – $e^+e^- \to \overline{f}f$ **semianalytical**

– **QED** $\oplus$ **QCD external blocks**

$\star\star\star$ – $e^+e^- \to \overline{f}f$ **model independent**

– $e^+e^- \to \overline{f}f$ **true MC**

– $e^+e^- \to WW \to 4\mathrm{f}$ **DPA**

– **next-to-leading two-loop EW**

– **Fermion-Loop**

$\star\star$ – $e^+e^- \to \overline{f}_1 f_2 \overline{f}_3 f_4$ **Born**

– **Single-W** with **Fermion-Loop**

$\star$ – **Single-W** without **Fermion-Loop**

– ZZ without **DPA**

$-\star$ – **All** *ad hoc*, **effective** solutions that mimic **our ignorance**.

Theory: the remaining of the day

we have been moving from a **mediaeval architecture** of radiative corrections

to the **renaissance** of **LEP period** and now one should not indulge in deciphering the intimate meaning of the **last digit** in the **last fit** of the **LEPEWWG**.

A new **frontier** is at the horizon: most likely it is goodbye to the one man show. Running a new **RC** project will be a little like running an experiment.

Why our future will be different

△ While some smart idea should come out, during the *theory* cycle, for

EWSB, families, fermion masses, hierarchy, supersymmetry breaking, gravity

$$\mathbf{SM} \subset \quad ???$$

△ *experiment-oriented* developments should not be frozen – during *this cycle* many times we made it *just in time*!

△ … and our **RC** technology is practically saturated.

△ **Examples?**:

- □ **one-loop** for $e^+e^- \to 4\,\mathrm{f}$ has not been generated during *LEP cycle*,
- □ **FULL two-loop** EW is still in very preliminar **R&D**

$\boxed{\textbf{There is more}}$:

△ **POs** at 10^{-5} *exp precision* require

- □ 10^{-6} *th accuracy*, or
- □ **Two** independent calculations by **two** independent groups with **two** different methods.

△ This is back to *sociology*:

- □ It *cannot* be done without an *unmatched* collaboration between the **two** communities,

  without waiting for the last week before Moriond, ICHEP, etc
- □ Nobody wants to *risk* the *career* of a whole group on that.