The PP-LEP2Poll

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Based on discussions with the PP-forum:

- M. Grünewald,
- G. Quast,
- F. Filthaut,
- D. Kellogg,
- M. Kobel,
- D. Bardin,
- A. Arbuzov

♣ This talk is about defining a common strategy for implementing **PP**, Pair-Production, in existing codes.

♢ During the last few months, or so, we had several discussions about this common strategy.

♡ Answers have been coming from F. Filthaut (on behalf of L3) and from M. Kobel (on behalf of OPAL).

♠ However, this is a field where, perhaps for the first time, nobody will start working unless a completely general consensus is reached with the experimental community.

There remain issues to be discussed if one wants to have a *realistic* implementation of pair-production (**PP**) for **2f** cross-sections at LEP 2 energies in any **SA** code. In the following I will repeat them.

Let's start with some general consideration:

⊘ There are situations where pair corrections are a very small effect due to the near-cancellation of real and virtual pairs.

⊘ Whenever the effect of pairs is of order 0.1%, it is below the LEP combined precision of any **2f** cross-section.

⊘ Whenever pairs are an issue of order 1% or more this can become important for LEP wide combinations.

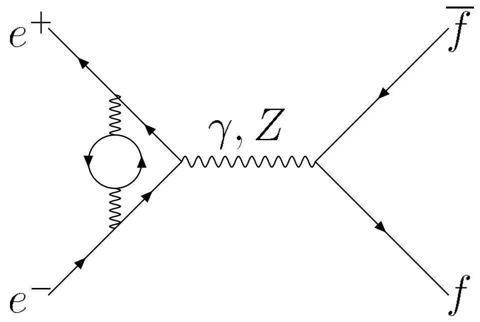
Let's continue with a simple case,

$$e^+e^- \quad \text{PP-corrections to} \quad e^+e^- \to \bar{b}b \tag{1}$$

The relevant diagrams are given in Fig. 1. To avoid confusion we will introduce the following definition:

- 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**.

Note that we include both γ and Z exchange, so that one could still distinguish between $\mathbf{ISNS}_\gamma$, $\mathbf{ISNS}_Z$ and interference. On top of real **PP** one has to include virtual e^+e^- pairs. A typical example is the following:



So far, TOPAZO *(and* ZFITTER *too) only include* **ISNS**$_\gamma$ *plus virtual, with* **ISS** *optional. The approximation is well justified around the Z-peak but now we have to move to higher energies, where new thresholds open.*

- Furthermore, one has to add a proper definition of *soft* pairs and of *hard pairs*: I would define
  - Soft(Hard) Invariant Mass **IM** pairs, or **SIM(HIM)** pairs, according to some pair mass cut.
- Of course, one could still use a soft-hard separation based on other variables[1]:

hard pair : when the energy of the pair (sum of energy of its components) is comparable with the beam energy;

[1] This is what A. Arbuzov would do.

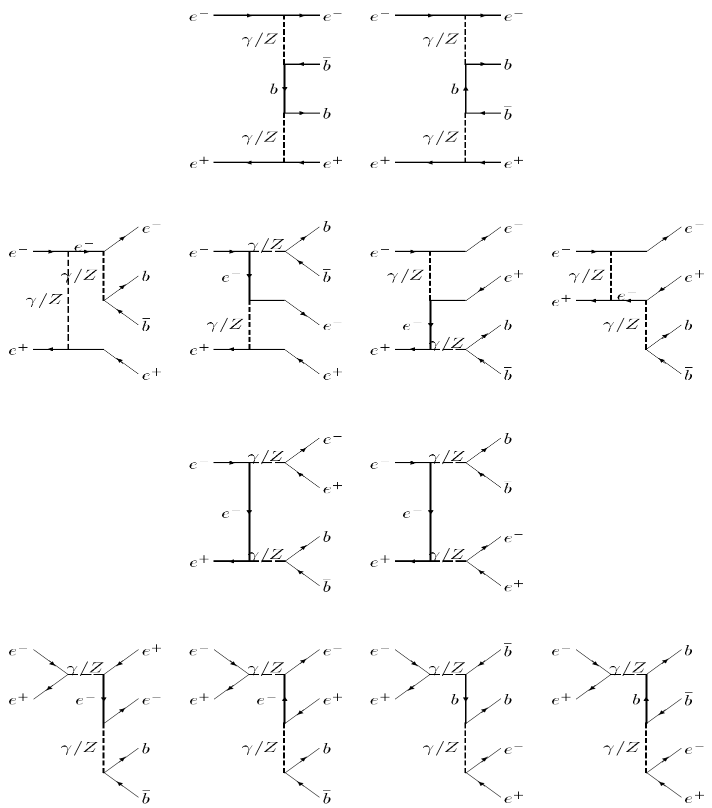


Figure 12: *Complete set of diagrams for the process* $e^+e^- \to e^+e^-b\bar{b}$.

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Figure 1: The process $e^+e^- \to \overline{b}be^+e^-$

collinear pair : when the angles of both pair components (with respect to the $e^-(e^+)$) beam direction) are small: $\theta_{+,-} < \theta_0 \ll 1 (\theta_0 \gg m_e/E_{\text{beam}})$.

- ∇ L3 would be strongly in favour of applying as simple cuts as possible, cuts on **IM** of the secondary pair only. There is not much difference between an ISR γ and a γ that fluctuates into a low-mass fermion pair.

- ∇ M. Kobel adds a third option: $\rightarrow$ *definition from Feynman diagrams*. Furthermore he states that, having only the first two choices, the mass cuts are clearly favorable. In addition, they have the virtue, that mass cuts can be found, which nearly 1 : 1 correspond to choosing certain, e.g. ZZ rejection. So they leave the option open, to easily convert the realistic measurements in terms of kinematic variables into an idealized measurement of a set of Feynman diagrams.

In my understanding[2], also very hard **SIM** pairs are **2f** *signal* for two reasons:

1. most of the pairs are still in the beam-pipe or very forward, where it is impossible to distinguish them from γs;

[2]As explained to me by M. Kobel

2. for those pairs which end up in the detector, the majority will be **SIM** electron pairs.

Therefore, the first question is:

Q1 *How do we separate* **2f** signal *from* **4f** background *in our upgrading? According to* **IM** *cuts (***IMC***) or according to energy/angles?*

The ADLO/TH **Poll** gives, so far, $3\star$ to **IMC**.

Strictly related to the previous question is the following quest for an *operative*, universally accepted, separation of various contributions. Consider again the process $e^+e^- \to \overline{b}be^+e^-$; the total cross-section contributes to three different processes:

▷ genuine **4f** events;

▷ e^+e^- PP-correction to $e^+e^- \to \overline{b}b$;

▷ $\overline{b}b$ PP-correction to Bhabha scattering.

A *naive* separation, easy-to-implement, would be the following. Let the process be specified by

$$e^+e^- \to \overline{b}b(Q2) + e^+e^-(q^2) \tag{2}$$

If I do not care about energies/angles I can integrate and reduce the cross-section to a two-fold integral with the following boundaries:

$$
\begin{aligned}
4\,m_b^2 &< Q^2 < (\sqrt{s} - 2\,m_e)^2, \\
4\,m_e^2 &< q^2 < (\sqrt{s} - \sqrt{Q^2})^2.
\end{aligned} \tag{3}
$$

Next, I will introduce two cuts z_p, z_s, i.e. primary and secondary cuts and I will define

♯ e^+e^- PP-correction to $e^+e^- \to \overline{b}b$:

$$
z_p\, s < Q^2 < (\sqrt{s}-2\,m_e)^2, 4\,m_e^2 < q^2 < \min\{z_s\, s\,,\,(\sqrt{s}-\sqrt{Q^2})^2\}. \tag{4}
$$

♯ $\overline{b}b$ PP-correction to Bhabha scattering:

$$
z_p\, s < q^2 < (\sqrt{s}-2\,m_b)^2, 4\,m_b^2 < Q^2 < \min\{z_s\, s\,,\,(\sqrt{s}-\sqrt{q^2})^2\}. \tag{5}
$$

♯ while the remaining portion of the phase space is *background*.

Therefore, we have the next question:

Q2 *Does this criterion suffice in matching the experimental needs? That would be nice. Or, do you actually need a* **different separation** *based, e.g., on requirements like to have visible energy less than something.***OR***. a net visible momentum along the beam axis* $|p_z|$ *greater than something else*[3] *?*

Here, we register the following opinions:

L3 is perfectly happy with a pair of z_p, z_s cuts. The possibility to make a clean conceptual *signal-background* separation is more important than the possibility to follow all possible experimental cuts to make this separation in practice.

OPAL Yes, sure. This is what OPAL is already doing. z_p is their s'/s cut (0.7225 for high s', 0.01 for inclusive) and $z_s * s = (70\ \text{GeV})^2$ is chosen constant to reject ZZ, i.e. their z_s is s-dependent. With this definition each event is *signal* to at most one **2f** final state. However, the question here is:

Should all diagrams fulfilling these mass cuts be regarded as *signal*, or should we better exclude

[3] As I was told by D. Kellogg

ISS and **MP**?

- At the same time, we must address what *has to go in the calculation* and what is *already subtracted from the data*.
- We have to define the exact content of PP-corrections to be inserted in the upgradings of the **SA** codes.
- Then, you apply a *theory* correction, actually a subtraction obtained from MC, to go to *signal* definitions as employed by `TOPAZO/ZFITTER`.
- This is what is done now, the only problem being that the present *signal* definition in `TOPAZO/ZFITTER` is not good enough for LEP 2.

Typical example?

△ Using **IM** cuts one finds relatively large corrections (around 5% or more), most of which ares due to the **MP** process.

△ So, if the situation remains unaltered, you will have to apply a rather large subtraction, which is rather unnatural.

△ Of course, we can take the **MP** into account, but only if some *reasonable* cut is applied to $M(\bar{b}b)$.

Example

- At 200 GeV the double resonant

$$e^+e^- \to ZZ \to e^+e^-\bar{b}b, \tag{6}$$

 cross-section, i.e. the NC02 MC, is about 10^-2 **pb**, while the total **MP**, that you don't get with a NC02 MC, is about 1 **pb** compared with a σ_{had} of $80-90$ **pb**.

- However, this huge increase in cross-section is caused by hadronic two-γ collision processes. Thus the **IM** of the $\bar{b}b$ system will be very low, peaking toward $2\,m_b$. The bulk of the cross section will be around 10 GeV invariant $\bar{b}b$ **IM**.

- Therefore, the 1 pb cross-section is not dominated by a high-**IM** system, and for high enough **IM** cut we could include MP as well in our codes, the low-**IM** is dealt with (at the level of subtraction), I hope, by NC02 γ^*/Z^* plus PHOJET for the MP stuff[4] (it won't be realistic to have PHOJET implemented in our codes).

Now we move to another topic, flavor misinterpretation. *Only short answers, so far.*

[4] As I was told by M. Grünewald.

- Suppose that I want all radiative corrections to the hadronic cross-section. Here I have the following problem:

  - ☐ Events of the type

    $$e^+e^- \to u\overline{d} \quad +e \quad \text{in the beam pipe} \quad +\nu, \quad (7)$$

    how are they considered? Can you say that $u+\overline{d}$ cannot come from $e^+e^- \to Z(\gamma)$ and therefore exclude them?

Q3 *I assume that this type of events ends up in the total sample but not necessarily in the high-energy sample, but what to do? Clearly, this would require the proper inclusion of CC20, in a single-W configuration.*

L3 Why single-W events should be included in the *signal* definition? Let the experiments make up their mind about how they want to subtract this *background*. The available MC programs should allow to do this perfectly well.

OPAL Preferably, all **CC** diagrams should be *background*, even if they lead to a final state which is common with **NC** diagrams. This *background* (including its interference) could e.g. be subtracted by MC.

Finally we come to the most complicate configurations,

$$e^+e^- \to \overline{q}q\bar{Q}Q, \tag{8}$$

or even worst,

$$e^+e^- \to \overline{q}_1q_1\overline{q}_2q_2, \qquad \text{e.g.} \quad uuuu \tag{9}$$

etc. configurations. Before discussing it, however, there is a repetition of the previous question:

Q4 *Events of the type $e^+e^- \to \overline{u}d\overline{s}c$, should they be regarded as* background *or as* signal *when the* **IM** *of any of the pairs is sufficiently high?*

L3 same answer as before. But they agree that things become more complicated in the case of, e.g., $\overline{u}d\overline{d}u$ events, which do lead to the same final state.

OPAL Again, all **CC** diagrams should be *background*, even if they lead to a final state which is common with **NC** diagrams (e.g. $u\overline{u}d\overline{d}$).

Despite previous answers, I would like to generalize our previous separation of the **2f** *signal* from the **4f** *background*. I foresee two options:

⊙ We require that *at least* one pair has an **IM** greater than $z_p\, s$. But only the $\overline{q}q$ pairs or, should we also include the $\overline{q}Q$ pairs? And what about the $qQ, \overline{q}Q$ pairs?

⊙ We require that *at least* one pair has an **IM** greater than $z_p\, s$ while all remaining configurations have **IM** less than $z_s\, s$.

Now we come to the really difficult part of the problem.

♯♯ Since arbitrarily low **SIM** pairs are allowed, in both cases, a *parton-level* calculation **cannot** be accurate enough.

♭ Under the simplified assumption that one pair (the Q^2 one) is **HIM** enough and that the remaining one (the q^2 one) is **SIM** enough we can write the cross-section as

$$
\begin{aligned}
\frac{d\sigma_f}{dq^2 dQ^2} &= \left(\frac{\alpha}{\pi}\right)^2 \sigma_f(Q^2) \frac{R_{\rm had}(q^2)}{3\, s q^2}\, f\left(s, Q^2, q^2\right) \\
f\left(s, Q^2, q^2\right) &= \frac{s + (Q^2 + q^2)}{s - Q^2 - q^2} \ln \frac{s - Q^2 - q^2 + \sqrt{\lambda}}{s - Q^2 - q^2 - \sqrt{\lambda}} - 2\sqrt{\lambda} \\
\lambda &= \lambda\left(s, Q^2, q^2\right). \qquad (10)
\end{aligned}
$$

♮ Clearly we face two problems, one conceptual and another practical. The first problem will be referred to as the *double-counting problem*[5].

– At the parton level, we have $e^+e^- \to \overline{q}q\bar{Q}Q$ and, for instance we want to sum over q in order to define the Q-line shape.

– However, when we also sum over Q in order to have the full hadronic line shape, proper care must be taken in order to avoid *double-counting*.

– At the *parton level* this can be done but one should remember that we actually compute

$$e^+e^- \to \bar{Q}Q + \text{hadrons}, \tag{11}$$

through $R_{\text{had(s)}}$, and the problem is, by far, more severe.

– Therefore, we have a typical situation where $\sqrt{(Q^2)} > 20$ GeV and $2\,m_\pi < \sqrt{(q^2)} < 170$ GeV. Thus, yes, we have to agree on what should happen once $R_{\text{had}}(s)$ is called for low s.

– Yes, you could use your favorite MC but it will be missing virtual pairs and, frankly speaking, I do not see of it could be properly interfaced with

[5]There was a quite long mail from M. Grünewald about it.

our **SA**. After all **ISNS** pairs are supposed to sit in the *signal*, not in the MC.

- After some investigation I have found that there is no black-box-tool code for $R_{\rm had}(s)$ available on the market. I need a black-box-routine for $R_{\rm had}$ at hand, which combine its parametrizations using data for the low energy continuum and the resonances with recent results from perturbative QCD for the high energies above the $\overline{b}b$ threshold.

  You may wonder why, all of the sudden, this interest in having $R_{\rm had}(s)$?

- Well, if I do not have it then I am bound to KKKS and to the description of hadron radiation in terms of moments. This description is, again, well justified around the Z-resonance and for reasonably high values of the $z_{\rm min}$ parameter where one, quite arbitrarily, defines a *primary* pair and a *secondary* one.

- If $z_{\rm min}$ is high enough, greater than 0.25, there is no overlapping in the hadronic line-shape, i.e. no double-counting. If, however, $z_{\rm min} < 0.25$[6], I simply do not know how to deal with *double-counting* in the KKKS formulation and, even worst, I will not be able to properly account for the *equal-flavor* contribution.

[6] Question raised by M. Grünewald.

This last comment introduces an additional question:

Q5 *At least in principle, we can introduce three different cuts, i.e. s'/s for initial state QED radiation and z_p, z_s* for **PP**. From a theoretical point of view, there is no problem here. However, during the last few weeks, some sort of debate has been in the air. We, better you, should reach an agreement: *one common cut* ($s'/s = z_{\min}$), *two cuts* ($s'/s \neq z_{\min}$ *but also* $s'/s = z_p$ *and* z_s) *or three cuts* ($s'/s \neq z_p \neq z_s$)?[7]

L3 A priori, F. Filthaut would be in favour of having the same cut on the primary pair for pair corrections as for photonic corrections. On the other hand, M. Grünewald would like different cuts.

OPAL says: *our choice is clearly two cuts* $s'/s = z_p$, *and* z_s *to reject* ZZ *pairs*. If we then regard the higher mass pair as the primary pair, there is no overlap problem. There is an pairing ambiguity for four identical fermions.

This can only be resolved with the help of event weights. But, having a need to involve event weights anyway, there is no reason to stay with

[7] Avoiding a different treatment of γs and pairs seems to be M. Kobel's favorite solution. Pending a serious upgrading of the **SA** codes $s'/s \neq z_{\min}$ seems to encounter M. Grünewald's favor.

(arbitrary) kinematic cuts.
One could also resort to a definition in terms of diagrams. The kinematic cuts, which will mimic very close what the diagrams give, are then only useful as experimental tool to select events.

TH My point[8] is that, for $s' = 0.01\, s$, the kinematics of **ISS** pairs is such that the created pair goes at a very small angle with respect to the incoming e^- (or e^+) and disappears in the beam pipe; the final state hadrons (or muons) have a boost along the beam axis, $|p_z| = 0.99 E_{\rm beam}$. This can be simulated with a IS collinear γ emission with 0.99 energy fraction with respect to $E_{\rm beam}$, the kinematics is the same!
Therefore, I prefer not to distinguish between s'/s and $z_{\rm min}$, i.e. to handle **SIM** pairs like γs, the same s' cut applied for pair + $\overline{f} f$ as for $\gamma + \overline{f} f$.

Tentative conclusions:

⌢ The whole **4f** must be included to compute the **2f** cross-sections;

⌣ The whole **4f** is to be divided into two components, *signal* and *background*.

[8] Actually, A. Arbuzov's point.

– For our purposes their definition is peculiar, *signal* is what you have implemented into the **SA** codes.

  This raises a serious question: ZFITTER is used to define the SM predictions and TOPAZ0 for benchmarking. This works, as long as we have different but equivalent implementations of the same effect, however this time we could violate this rule by having different *signals* and *backgrounds*. It is matter of life when we move to interface **4f** codes with **2f** codes, in case of TOPAZ0 the partner being WTO with full access to the **4f** processes.

– *background* is what one subtracts by using a MC, typically GRC4f.

We go from one extreme solution to the other:

- $\mathit{background} = \emptyset$, if everything is included in the **SA**. **MP** is an example of something difficult to implement into the **SA** if low-**IM** regions are required.
- $\mathit{signal} = \mathbf{ISNS}$, i.e. everything else (large effects) is subtracted by MC. However, using different MC programs would bring to subtractions that dif-

fer by some per-cent, which then would have to be regarded as a *theoretical* systematic uncertainty[9].

- Furthermore, you will have to use the MC in region of **SIM** pairs leading to large soft and collinear effects that are, eventually, compensated by the virtual pairs.
  It takes some optimism to trust the MC over there, although preliminar observations[10] seem to indicate that this procedure may work:

  1. one has to take the MC, subtract everything but ISNS pairs and compare with **SA**.
  2. The two predictions must agree at the level of the effect of virtual pairs, from 0.2% up to some 0.6% if one believes in fudge factors.
  3. Most important, the rule in this field is[11] that *any virtual+real pair effect from the* **SA** *must not exceed the MC prediction* (virtual effects are negative!).

- Intermediate solutions can be found but they are *companion-code* dependent.

[9]As F. Filthaut, points out
[10]F. Filthaut, again.
[11]Thanks to M. Kobel for this observation.

In principle, we should be able to implement **PP** according to the following recipe:

A Include virtual+soft(**SIM**) (up to some **IM** Δ for all mass-divergent pairs, e.g. $\gamma^* \to \overline{f}f$) pairs with a complete **2f** calculation.

B The contributions not in A are then included with a two, three cuts procedure through a **4f** calculation (merging with the **2f** code).

C The contributions that are already contained in A, are included with **IM**s $> \Delta$.

- One could decide to count as *background* **4f** processes from *true* e^+e^- annihilation (e.g. ZZ, WW) and **4f** processes via $e-\gamma$ collisions (e.g. $(e)eZ, (e)\nu W$). However this distinction is based on selecting sub-sets of diagrams to be used for the **2f** *signal* definition. I do not think that we should define the *signal* according to the kind diagrams it originates from. We need a definition based on **measurable quantities**, so we should not exclude a set of diagrams, we should exclude the kinematical region where that particular set dominates.

signal $>$ **ISNS** could be included *without* having to resort to the **full** stuff.

- $\ominus$ One can loose some insight on which subsets of diagrams are really dominant and we know the *reliability* of effective approximations.
- $\ominus$ In **NC48** we have:

  8 **MP** diagrams,

  16 single- or non-resonant **bremsstrahlung** diagrams,

  8 single- or double-resonant **conversion** diagrams,

  16 single- or non-resonant **annihilation** diagrams.
- $\ominus$ **Interferences** are found to be negligible at LEP 2, even without cuts:

$$\begin{aligned}\max_{I\in\mathrm{NC48}} &< 25\,\mathrm{fb}, \quad \text{at} \quad \sqrt{s} = 200\,\mathrm{GeV}, \\ < I >_{I\in\mathrm{NC48}} &< 1\,\mathrm{fb}.\end{aligned} \tag{12}$$

- $\ominus$ Available approximations are:
  - Equivalent-photon for **MP**; excellent agreement with exact.
  - Narrow-width for **Brem, Con, Ann**.

⊖ Adding the approximate formulas for **MP** and single-double-**Con** *incoherently* the total cross-section is reproduced within 5%, i.e. the *th. uncertainty* on this part of **PP** is estimated to be 5%.