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Background substraction in parity violation experiments

J. Van De Wiele and M. Morlet

Institut de Physique Nucléaire/IN2P3/CNRS, F-91406 Orsay Cedex, France

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Abstract. The importance of the knowledge of the background in parity violating (PV) experiments is shown. Some improvements in Monte Carlo simulations are presented and discussed.

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It is well known that the asymmetry in P.V. experiments due to the exchange of the Z_0 boson is small ($\approx 10^{-6} - 10^{-5}$). Much care has to be taken in the measurement of such a small quantity. Since a few years, impressive improvements in technical aspects have been achieved and some of them have been presented in this workshop. Without such improvements, the extraction of the physical quantity would be obtained with too large a systematic error and so would be meaningless.

In any experiment, simulation of all the processes which populate the "good" events as well as some "background" events, is a good tool to be sure that the experiment and in particular the experimental set-up is under control.

Simulation of very small effects is not an easy task for many reasons:

- The accuracy of the simulation depends strongly on the statistics and standard methods, which are time consuming, therefore may become inefficient.
- Some of the physical effects, which are usually considered as small and therefore are neglected, may contribute.
- It is necessary to improve the description of some processes which are usually treated only in an approximate way.
- Accurate models and data needed do not exist.

The basic formula is the following:

$$A_{\rm Phys} = A_{\rm Meas}\,\frac{1+\sum(A_i/A_0 \quad \sigma_i/\sigma_0)}{1+\sum\sigma_i/\sigma_0}$$

In this expression the index "0" stands for the elastic events and the index "i≠0" stands for any background event. If the background asymmetry vanishes, the denominator acts as a dilution factor to the physical asymmetry. As can be seen in Fig. 1, any measured spectrum of a physical quantity (energy or time of flight) shows up a the physical signal above some background events. In Table 1 A_{Phys}/A_{Meas} are given as a function of A_i/A_0 if the ratio of bad events to good events is equal to 10 %. In Fig. 2, this effect is plotted for different contamination rates. The change in the sign of A_i/A_0 could be dramatic.

In principle, it is possible to experimentally study the background but the statistical precision could be poor as compared to the elastic peak. In some cases, it is possible only to extrapolate the the background and the experimental study becomes less efficient (see Fig. 3)

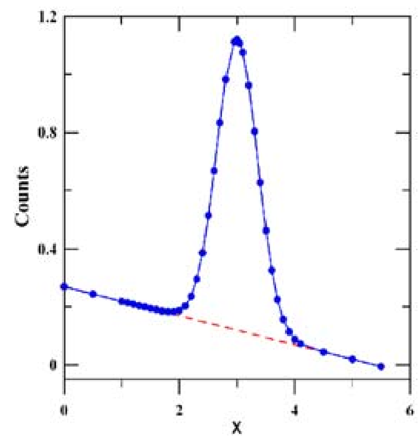

Fig. 1. Typical measured spectrum. X is a measured quantity -energy or time of flight-

Table 1. Ratio A_{Phys}/A_{Meas} as a function of A_i/A_0 for σ_i/σ_0 =10 %

A_i/A_0	A_{Phys}/A_{Meas}
-3.	0.63
-2.	0.73
-1.	0.82
0.	0.91
1.	1.00
2.	1.09
3.	1.18

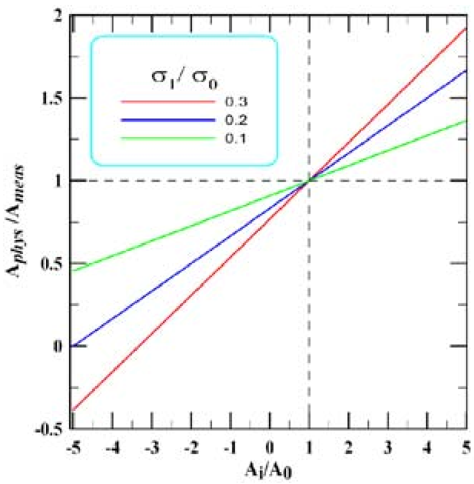

Fig. 2. Ratio A_{Phys}/A_{Meas} as a function of A_i/A_0 for several values of σ_i/σ_0

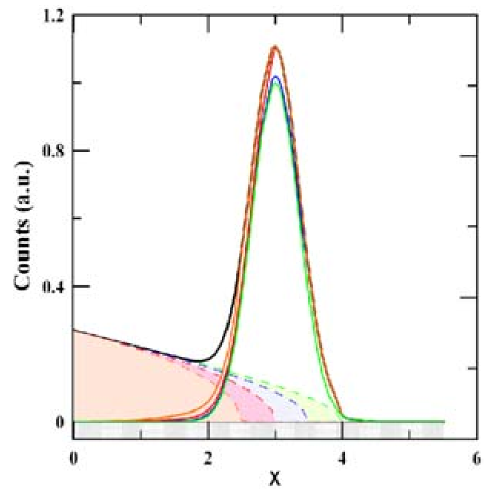

Fig. 3. Different extrapolations of the background

Monte Carlo (M.C.) simulations are supposed to be a powerful tool to understand both the elastic observables and the background features. They give complementary information to the measurement. This method is powerful if the physical laws under consideration are well known. Monte Carlo results are accurate if we are able to generate a large number of events.

M.C. is based on a one-to-one correspondence between uniform random number $\eta \in]0,1[$ and a physical law. For example, in one dimension

$$\eta = \frac{\mathcal{N}}{\mathcal{D}}, \quad \mathcal{N} = \int_{x_{min}}^{x} f(x')\ dx', \quad \mathcal{D} = \int_{x_{min}}^{x_{max}} f(x')\ dx',$$

and in two dimensions:

$$\eta_1 = \frac{\mathcal{N}_1}{\mathcal{D}_1}, \quad \mathcal{N}_1 = \int_{x_{1min}}^{x_1} f_1(x_1')\ dx_1', \quad \mathcal{D}_1 = \int_{x_{1min}}^{x_{1max}} f_1(x_1')\ dx_1',$$

$$\text{with } f_1(x_1) = \int_{x_{2min}(x_1)}^{x_2} f(x_1, x_2')\ dx_2', \qquad \text{and } \eta_2 = \frac{\mathcal{N}_2}{\mathcal{D}_2},$$

with

$$\mathcal{N}_2 = \int_{x_{2min}(x_1)}^{x_2} f(x_1, x_2')\ dx_2', \quad \mathcal{D}_2 = \int_{x_{2min}(x_1)}^{x_{2max}(x_1)} f(x_1, x_2')\ dx_2'.$$

Using the definition of M.C. method is time consuming because we need to invert the expression in the numerator to get the physical quantity. To increase the efficiency of the M.C. method, it is possible to introduce some weights W to take into account of the cross-sections.

Example 1: $a + b \longrightarrow 1 + 2$

$$\eta_\theta = \frac{\theta_1 - \theta_{1min}}{[\Delta\theta_1]}, \quad \eta_\phi = \frac{\phi_1 - \phi_{1min}}{[\Delta\phi_1]},$$

$$W = \frac{\mathcal{L}}{N_T}\ [\Delta\theta_1]\ [\Delta\phi_1]\ \frac{d^2\sigma}{d\Omega_1}\ \sin\theta_1.$$

where $\mathcal{L}$, N_T are respectively the luminosity and the number of random events. $[\Delta\theta_1] = \theta_{1max} - \theta_{1min}$ is the angular range for the polar angle and $[\Delta\phi_1] = \phi_{1max}(\theta_1) - \phi_{1min}(\theta_1)$ is the angular range for the azimuthal angle.

Example 2: $a + b \longrightarrow 1 + 2 + 3$

$$\eta_\theta = \frac{\theta_1 - \theta_{1min}}{[\Delta\theta_1]}, \qquad \eta_\phi = \frac{\phi_1 - \phi_{1min}}{[\Delta\phi_1]},$$

$$\eta_E = \frac{E_1 - E_{1min}(\theta_1)}{[\Delta E_1]},$$

$$W = \frac{\mathcal{L}}{N_T}\ [\Delta\theta_1]\ [\Delta\phi_1]\ [\Delta E_1]\ \frac{d^3\sigma}{d\Omega_1\ dE_1}\ \sin\theta_1.$$

$[\Delta E_1] = E_{1max}(\theta_1) - E_{1min}(\theta_1)$ is the energy range. The two methods are equivalent when these weights are correctly introduced.

Another method to improve the efficiency of the simulation is to calculate the cross-sections of the needed processes. In the following part, we will concentrate on the A4- and the G^0 experiment and will give some specific examples.

In the A4 experiment [4], the rate of inelastic electron produced by one pion electro-production $e + p \longrightarrow e' + p' + \pi^0$ and $e + p \longrightarrow e' + n' + \pi^+$ reactions has been measured and calculations with effective lagrangians for E_e lower than 1 GeV are accurate enough. It is more difficult to calculate the number of photons coming from the π^0 decay. With an electromagnetic shower calorimeter, it is impossible to disentangle electrons and photons. A part of these photons have the same energy as the elastic electrons and thus contribute to the background under the elastic peak. The standard method – calculation of the π^0 electro-production followed by π^0 decay after Lorentz boost - is not appropriate to calculate the rate of photons if we want to take into account energy loss and external radiative corrections. Furthermore, it is impossible

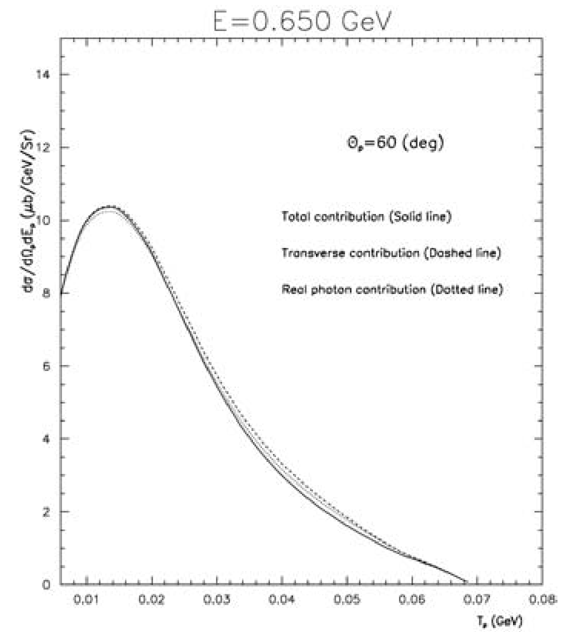

Fig. 4. Inclusive proton differential cross-section at 650 MeV

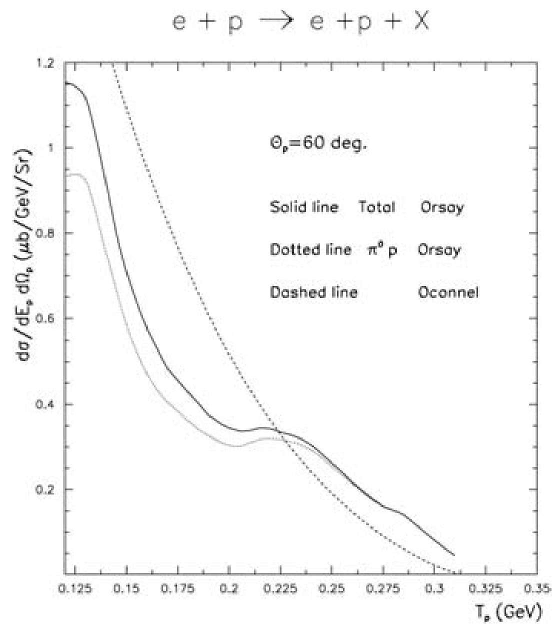

Fig. 5. Comparison between our calculation and the EPC code developed by LightBody and O'Connel

to estimate the false asymmetry carried by the photons. Nevertheless, it is possible to include all these effects if we calculate directly the photon production cross-section (the lagrangian for the $\pi^0 \longrightarrow 2\gamma$ is known):

$$\frac{d^3\sigma}{d\Omega_\gamma\ dE_\gamma} = \int \frac{d^3\sigma(h_e)}{d\Omega_{\pi^0}\ dE_{\pi^0}}\ \mathcal{K}\ \delta\big(\ \widetilde{E}_\gamma - E_\gamma\ \big)\ d\Omega_{\pi^0}\ dE_{\pi^0},$$

$$\mathcal{K} = \frac{m_\pi^2}{4\pi}\frac{1}{E_{\pi^0} - p_{\pi^0}\mathbf{u}_{\pi^0}\cdot\mathbf{u}_\gamma}, \quad \widetilde{E}_\gamma = \frac{m_\pi^2}{E_{\pi^0} - p_{\pi^0}\mathbf{u}_{\pi^0}\cdot\mathbf{u}_\gamma}.$$

The π^0 differential cross-section, which depends on the helicity of the incident electron beam, is calculated through the models described above. From such accurate calculations, we conclude that the photon contamination does not depend on the helicity and acts only as a dilution factor. We note here that the inclusive pion or proton cross-sections has to be calculated by replacing the usual flux factor Γ which is divergent when $\theta_{e'} \to 0$ and $m_e = 0$ by $\overline{\Gamma}$:

$$\Gamma\ =\ \frac{\alpha}{2\pi^2}\frac{E'_e}{E_e}\frac{E_\gamma}{Q^2}\frac{1}{1-\varepsilon}\ \longrightarrow \overline{\Gamma} = \frac{\alpha}{8\pi^2}\frac{|\mathbf{p'}_e|}{|\mathbf{p}_e|}E_\gamma F_{virt}.$$

The expression of F_{virt} is given in [1].

In G^0 experiment phase I, with an electron beam at 3 GeV, we are interested to know the inclusive pion and proton cross-section. Unfortunately, at such an energy, the cross-section is not well known and the calculations performed with effective lagrangians on one hand, accurate at energies below 1 GeV, and with Regge models on the other hand, well suited at energies greater than 5-6 GeV, are not very reliable. LightBody and O'Connel have developed a code (EPC) to compute such cross-sections but it is based on high energy data and the validity of the extrapolation to our energy is questionable. We have developed a code with an other approach. The inclusive spectrum is obtained by integrating the five times differential cross-section over the electron angles. Because of the exchange of a virtual photon in the electro-production reaction, the main contribution in the integration is expected to come from the terms with small values of q^2. We then assume that the square of the matrix element may be extracted from photo-production measurements which exist between 200 MeV and 3 GeV [2]. We have checked this approximation at an energy of 650 MeV where an exact calculation with an effective lagrangian can be used. The results are displayed in Fig. 4. The agreement between electro-production and photo-production is better than 5%. An event generator based on this model has been written for the G^0 collaboration. The angular distribution of one pion photo-production data have been included. For two pion (or more) photo-production reactions, there are only few angular distribution data but several measurements of the total cross-section exist. All the channels up to 3 pions have been included. A comparison with the EPC code is shown in Fig. 5. The Time of Flight (TOF) proton spectrum includes, in addition to the electro-production, some contribution from photo-production reactions. This photo-production is due to the competition, in any material, between electro-production of the incoming electron and the real bremsstrahlung photons. The rate of inelastic protons is proportional to the number of bremsstrahlung photons, more precisely to $I_\gamma(E_0, E_\gamma, t)$ which is the number of photons in the energy bin E_γ, $E_\gamma + dE_\gamma$ after an electron, initially with an an energy E_0, has passed through a target of thickness t measured in unit of the radiation

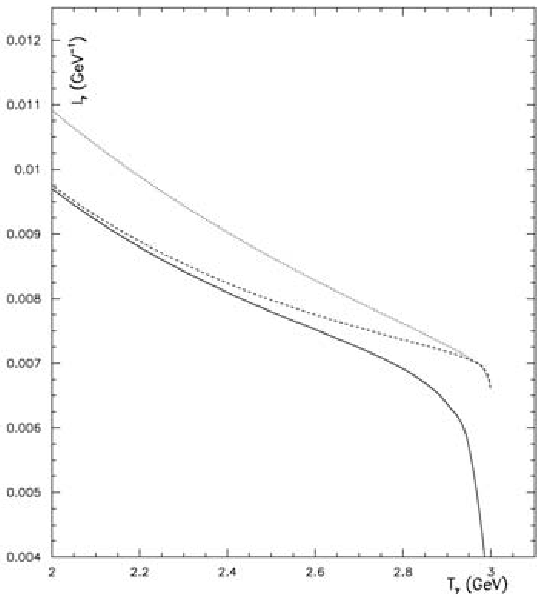

Fig. 6. Value of $I_\gamma(E_0, E_\gamma, t)$ for a LH_2 target (t=20 cm, E_0= 3 GeV) as a function of E_γ: Approximate formula (*dotted line*), complete screening approximation (*dashed line*) and exact calculation (*solid line*)

length of the material [3]. This number of photons is also proportional to the bremsstrahlung cross-section:

$$\frac{d\sigma_b}{dE_\gamma}(E, E_\gamma) = \frac{A}{NX_0}\frac{1}{E_\gamma}\Big(y^2 - \frac{4}{3}y + \frac{4}{3}\Big)\ g(y), \qquad y = \frac{E_\gamma}{E}$$

where X_0 is the radiation length of the material. In the standard calculations, we assume a complete screening approximation, with $g(y) = 1$. Within this approximation, Tsai and Van Whitis have derived an analytical expression:

$$[I_\gamma(E_0, E_\gamma, t)]_{approx} = \frac{1}{E_\gamma}\ \frac{(1 - \frac{E_\gamma}{E_0})^{\frac{4}{3}t} - e^{-\frac{7}{9}t}}{\frac{7}{9} + \frac{4}{3}\ln(1 - \frac{E_\gamma}{E_0})}$$

As was stated by Y. Tsai, this approximate expression may be a poor if the detailed shape at the high-energy tip of the Bremsstrahlung is needed. This is our case because high-energy inelastic protons, produced by high-energy photons, will have the same TOF compared to elastic protons. We have performed some exact calculations of $I_\gamma(E_0, E_\gamma, t)$ and new expressions have been derived for hydrogen and aluminium. For this material, we have used the Thomas-Fermi Molière Model [3]. Comparison between the approximate expression, the complete screening case and the exact calculation for liquid hydrogen is shown in Fig. 6. The approximate formula or the complete screening calculations overestimate the high-energy number of photons.

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