Simc root branches

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Contents

1 About this file

The notes below were compiled not only by digging though the simc code itself and looking at some root files created by simc, but also by reading comments in the code and some complementary documents. Additionally, I have used simc mainly for quasi-elastic electron-proton scattering in nuclei $2 \leq A \leq 3$ and thus some of the statements below may not be completely true for other processes or nuclei. As if that was not enough, note that simc has been heavily modified by a bunch of different people, and consequently there are many different versions out there, without version control. This is to say: take these notes with a grain of salt, and check the code yourself. If you find anything wrong below, please, send me an email at: 'reynier@mit.edu'.

2 Input (constant) variables

There are some variables that are constant throughout every single simulated event in the root file. However, for convenience, they are saved as branches. Normfac (see section 7.1) also falls in this category.

2.1 Ein

Ein corresponds to the beam energy in MeV. This value is defined and copied directly from the input file.

2.2 e_spec_p & h_spec_p

e_spec_p and h_spec_p correspond to the electron (L) and hadron (R) spectrometer central momentum values in MeV/c respectively. These values are defined and copied directly from the input file.

2.3 e_spec_th & h_spec_th

e_spec_th and h_spec_th correspond to the electron (L) and hadron (R) spectrometer central angle values in degrees respectively. These values are defined and copied directly from the input file.

3 Spectrometer variables

Variables whose first two characters are e_ represent quantities corresponding to the electron in the electron arm. The same variables, but with the first two characters h_, correspond to the same quantities, this time for the hadron in the hadron arm. Variables whose last character is an i are generated variables. The same variables without the i at the end are the same quantities, but reconstructed by the spectrometers.

3.1 e_delta, h_delta, e_deltai, & h_deltai

delta (δ) is the fractional deviation from the central spectrometer momentum (p_c, defined in 2.2): $\delta = 100 \cdot [p - p_c]/p_c$. Therefore, the momentum of the particle is:

$$p = p_c \cdot [1 + \delta/100] \tag{1}$$

The variables e_delta and h_delta correspond to the reconstructed electron and hadron 'deltas' respectively. The variables e_deltai and h_deltai are the same, in this case generated.

3.2 e_yptar, h_yptar, e_yptari, & h_yptari

yptar variable characterizes the in-plane angle deviation from its central value in the spectrometer, and is given in radians. That is, the approximate relationship between yptar and the in-plane angle (θ) is:

$$\theta \approx \theta_c \pm \text{yptar} \tag{2}$$

Where + (-) is taken for the electron (proton) arm. However, this is an approximation. The actual expression is:

$$\cos\theta = \frac{\cos\theta_c - \text{yptar} \cdot \sin\theta_c \sin\phi_0}{\sqrt{1 + \text{xptar}^2 + \text{yptar}^2}} \tag{3}$$

Where ϕ_0 = 270° for the right HRS and ϕ_0 = 90° for the left HRS. That is:

$$\cos\theta_{\text{LHRS}} = \frac{\cos\theta_c - \text{e\_yptar} \cdot \sin\theta_c}{\sqrt{1 + \text{e\_xptar}^2 + \text{e\_yptar}^2}} \tag{4}$$

$$\cos\theta_{\text{RHRS}} = \frac{\cos\theta_c + \text{h\_yptar} \cdot \sin\theta_c}{\sqrt{1 + \text{h\_xptar}^2 + \text{h\_yptar}^2}} \tag{5}$$

The variables e_yptar and h_yptar correspond to the reconstructed electron and hadron 'yptars' respectively. The variables e_yptari and h_yptari are the same, in this case generated.

3.3 e_xptar, h_xptar, e_xptari, & h_xptari

This variable characterizes the out-of-plane angle (ϕ) and is given in radians:

$$\phi \approx \text{xptar} \tag{6}$$

The actual expression is:

$$\phi = \tan^{-1}\left(\frac{\sin\theta_c \sin\phi_0 + \text{yptar}\cos\theta_c}{\sin\theta_c \cos\phi_0 + \text{xptar}}\right) + \delta \cdot \sin\phi_0 \tag{7}$$

Where ϕ_0 = 270° for the right HRS and ϕ_0 = 90° for the left HRS. That is:

$$\phi_{\text{LHRS}} = \tan^{-1}\left(\frac{\sin\theta_c + \text{e\_yptar}\cos\theta_c}{\text{e\_xptar}}\right) + \delta \tag{8}$$

$$\phi_{\mathrm{RHRS}} = \tan^{-1}\left(\frac{-\sin\theta_c + \mathrm{h\_yptar}\cos\theta_c}{\mathrm{h\_xptar}}\right) - \delta \tag{9}$$

where $\delta = 180\ ^\circ$ if xptar < 0 and $\delta = 0\ ^\circ$ otherwise.

The variables e_xptar and h_xptar correspond to the reconstructed electron and hadron 'xptars' respectively. The variables e_xptari and h_xptari are the same, in this case generated.

3.4 e_ytar, h_ytar, e_ytari, & h_ytari

This variable is defined such that the position of the interaction vertex along the beamline, $z_{vertex} \approx$ ytar/sin Θ_{HRS}, where Θ_{HRS} is the central angle of the spectrometer (defined in 2.3). That is, ytar is horizontal position of the particle when entering the spectrometer. This corresponds to the projection of the z-position of the interaction vertex (beam direction) onto the spectrometer coordinate system according to the spectrometer angle.

3.5 e_xfp, h_xfp, e_xpfp, h_xpfp, e_yfp, h_yfp, e_ypfp, & h_ypfp

Electron (e_) and hadron (h_) spectrometer focal plane variables: x, x', y, y'. See functions 'mc_hrsl' and 'mc_hrsr' in hrsl/mc_hrsl.f and hrsr/mc_hrsr.f respectively for details.

4 Electron and Proton physical variables

4.1 e_pf, h_pf, e_pfi, & h_pfi

e_pf and h_pf are the reconstructed electron and proton final-state momenta in units of MeV/c, determined from Eq. 1. e_pfi and h_pfi correspond to the same variables, in this case determined using generated deltas.

4.2 theta_e, theta_p, theta_ei, & theta_pi

theta_e and theta_p are the reconstructed electron and proton final-state scattering angles in degrees, determined from Eq. 3. theta_ei and theta_pi correspond to the same variables, in this case determined using generated yptars.

4.3 e_zv, h_zv, e_yv, & h_yv

Reconstructed vertex positions in cm. e_zv and h_zv are the z-component of the vertex position reconstructed by the electron and hadron spectrometers respectively. Similarly, e_yv and h_yv are the y-component of the vertex position reconstructed by the electron and hadron spectrometers respectively.

4.4 tar_x, tar_y, & tar_z

Generated vertex positions in cm. tar_x, tar_y, and tar_z are the generated x, y, and z vertex coordinates.

5 "Transfer" variables

In the (e,e'p) interaction, the incoming electron (with 4-vector e^μ) gets scattered (with 4-vector e'^μ) when interacting with a bound proton, knocking it out of the nucleus (with 4-vector p_f^μ). The interaction is mediated by a virtual photon emitted by the incoming electron (with 4-vector q^μ). This is diagrammatically shown in Fig. 1.

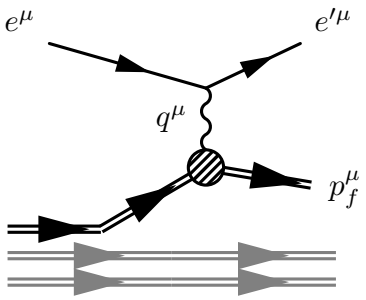

Figure 1: Quasi-elastic (e,e'p) diagram.

The virtual photon 4-vector only depends on the incoming and scattered electrons. From energy-momentum conservation:

$$q^\mu = e^\mu - e'^\mu \equiv (\omega, \vec{q}) \tag{10}$$

5.1 nu

The transfer energy, defined in Eq. 10 as ω, is also sometimes called ν (nu), which is the information stored in this branch:

$$\text{nu} \equiv \omega = E_e - E_{e'} \equiv E_{\text{beam}} - E_{e'} \quad [\text{GeV}] \tag{11}$$

calculated using reconstructed variables.

5.2 q

This branch stores the information related to the absolute value of the 3-vector part of q^μ defined in Eq. 10:

$$\text{q} \equiv |\vec{q}| = |\vec{p}_e - \vec{p}_{e'}| \quad [\text{GeV}] \tag{12}$$

calculated using reconstructed variables.

5.3 Q2

This variable corresponds to the effective mass squared of the virtual photon ($-Q^2 = \omega^2 - |\vec{q}|^2$):

$$\text{Q2} \equiv Q^2 = -q^\mu q_\mu \quad [\text{GeV}^2] \tag{13}$$

calculated using reconstructed variables.

5.4 W

W is the invariant mass of the particle in the final state after the interaction took place.

$$W = \sqrt{(q^\mu + p_f^\mu)(q_\mu + p_{f,\mu})} \tag{14}$$

In the case of quasi-elastic (e,e'p) scattering, this corresponds to the mass of the proton. In simc, is is calculated as:

$$\mathrm{W} \equiv \sqrt{W^2} = \sqrt{m_p^2 - Q^2 + 2m_p \cdot \omega} \quad [\mathrm{GeV}] \tag{15}$$

using reconstructed variables.

5.5 xB

This is the (unitless) Bjorken scaling variable defined as:

$$\mathrm{xB} \equiv x_B = \frac{Q^2}{2m_p\omega} \tag{16}$$

calculated using reconstructed variables.

5.6 theta_pq

Angle between the knocked out proton and the q vector (see Fig. 2) in radians:

$$\mathrm{theta\_pq} \equiv \theta_{pq} = \cos^{-1}(\hat{p_p} \cdot \hat{q}) \quad [\mathrm{rad}] \tag{17}$$

5.7 phi_pq

Angle between scattering and reaction planes (see Fig. 2) in radians.

6 "Missing" variables

In simc, the missing momentum vector is defined as:

$$\vec{p}_m = \vec{p}_p - \vec{q} \tag{18}$$

6.1 Pmx, Pmy, Pmz

These are the missing momentum components in the simc lab frame:

$$\text{Pmx} \equiv p_{m,x} = p_x - q_x \quad [\text{GeV}] \tag{19}$$
$$\text{Pmy} \equiv p_{m,y} = p_y - q_y \quad [\text{GeV}] \tag{20}$$
$$\text{Pmz} \equiv p_{m,z} = p_z - q_z \quad [\text{GeV}] \tag{21}$$

where z points along the beam line, x points downward, and y points to the left.

6.2 Pm

Absolute value of the missing momentum vector:

$$\text{Pm} \equiv |\vec{p}_m| \quad [\text{GeV}] \tag{22}$$

6.3 PmPar, PmPer, PmOop

PmPar is the component of missing momentum parallel to $\vec{q}$ (transfer momentum) in units of GeV/c. Similarly, PmPer is the component of missing momentum perpendicular to $\vec{q}$ in the scattering plane in units of GeV/c. Finally, PmOop is the out-of-plane component of missing momentum in units of GeV/c perpendicular to the scattering plane. See Fig. 2:

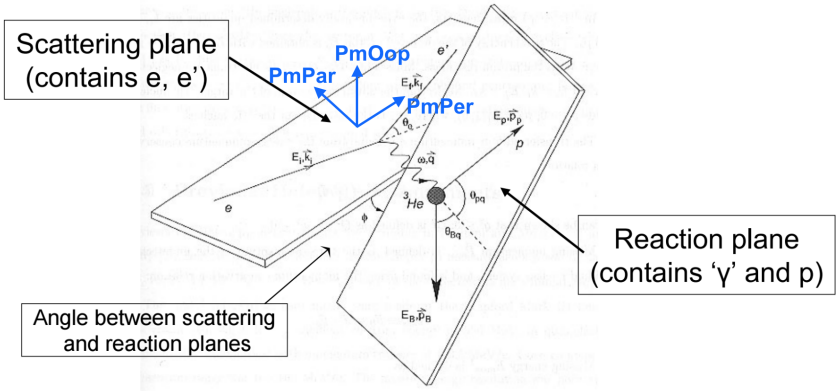

Figure 2: PmPar, PmPer & PmOop

This implies that: $\text{Pm} = \sqrt{\text{PmPar}^2 + \text{PmPer}^2 + \text{PmOop}^2}$.

6.4 Em

The variable Em describes the missing energy in units of GeV.

$$\text{Em} \equiv E_m = \omega - T_p - T_{A-1} \tag{23}$$

where $T_{A-1} = (\omega + m_A - E_p) - \sqrt{(\omega + m_A - E_p)^2 - |\vec{p}_m|^2}$ is the reconstructed kinetic energy of the residual $A-1$ system, and T_p and E_p are the measured kinetic and total energies of the outgoing proton.

6.5 theta_rq

Angle between recoil system and q in degrees:

$$\text{theta\_rq} \equiv \theta_{rq} = \cos^{-1}(-\hat{p_m} \cdot \hat{q}) \quad [\text{deg}] \tag{24}$$

7 Cross sections and Weights

Events from a root file generated with simc should be weighed by:

$$\frac{1}{n_{\text{entries}}} \Big(\text{Normfac } [\mu\text{b}^{-1}] \Big) \Big(\text{Weight } [\mu\text{b}] \Big) \tag{25}$$

where n_{entries} is the number of entries in the root file, and Normfac and Weight are defined in the next subsections. μb refers to micro-barns.

This is the correct normalization (i.e. yield or yield/bin) for the amount of beam charge put on the target (which is specified in the input file). For example, to get the total yield:

$$\text{yield} = \text{Normfac} \cdot < \text{Weight} > = \text{Normfac} \cdot \frac{\sum \text{Weight}}{\text{entries}} \tag{26}$$

is the average Weight. Then, if one wants to get the rate, one needs to determine the equivalent time for which the simulation was ran. We can get this by dividing the total charge (defined in the input file) by the beam current (charge / current = charge/(charge/time) = equivalent time). With this information:

$$\text{rate} = \text{yield} / \text{equivalent time} \tag{27}$$

7.1 Normfac

Normfac is calculated once when simc is run, and is a constant value corresponding to:

$$\text{Normfac} = \text{Luminosity} \times \frac{n_{\text{success}}}{n_{\text{generated}}} \quad [\mu\text{b}^{-1}] \tag{28}$$

and it's saved as a branch only for convenience. n_{success} and $n_{\text{generated}}$ are the number of generated and the number of successful events respectively.

Luminosity is given by:

$$\text{Luminosity} = \frac{Q}{\text{Targ\_factor}} \quad [\mu\text{b}^{-1}] \tag{29}$$

where Q is the total electron charge delivered (in units of mC) defined in the input file, and the target factor, Targ_factor, is defined as:

$$\text{Targ\_factor} = \frac{\Big(m_{tar}\ [\text{amu}]\Big)}{C\Big(\frac{\text{targ abundancy }[\%]}{100}\Big)\Big(\text{targ thickness }[\frac{\text{mg}}{\text{cm}^2}]\Big)} \cos\theta_{\text{tar}} \quad [\mu\text{b mC}] \tag{30}$$

where m_{tar} [amu] is the target mass (defined in the input file), targ abundancy [%] is the target purity (defined in the input file), targ thickness $[\frac{\text{mg}}{\text{cm}^2}]$ is the target length (defined in the input file), $\cos\theta_{\text{tar}}$ is used to specify of the target cell is skewed (defined in the input file), and C is a conversion constant defined as:

$$\begin{aligned} C &= \Big(6.02296\times10^{20}\ \frac{\text{amu}}{\text{mg}}\Big)\times\Big(10^{-30}\ \frac{\text{cm}^2}{\mu\text{b}}\Big)/\Big(\text{electron charge [mC]}\Big) &(31)\\ &= 3.7591\times10^{6}\ \frac{\text{amu}}{\text{mg}}\frac{\text{cm}^2}{\mu\text{b}}\frac{1}{\text{mC}} &(32)\end{aligned}$$

7.2 Weight

Unlike 'Normfac', which is constant per simc run, Weight is a per-event weighing factor related to the cross section of the simulated process in the Plane-Wave Impulse Approximation (PWIA) and corrections (phase-space, Coulomb, ...).

$$\text{Weight} = \Big(\text{sig}\Big)\Big(\text{Jacobian\_corr}\Big)\Big(\text{Genweight}\Big)\Big(\text{coul\_corr}\Big)\Big(\text{targ\_weight}\Big) \quad [\mu\text{b}] \tag{33}$$

Here, targ_weight is a correction for number of nucleons involved for pion and kaon production. In the case of quasi-elastic scattering (which is the process I study, and thus the main focus of this document), targ_weight is always set to one. The rest of the factors in Eq. 33 are described below (since they are all branches).

7.2.1 sig

In the PWIA, the cross section for quasi-elastic electron scattering off a proton bound in a nucleus A is written in the factorized way [1]:

$$\frac{d^6\sigma}{d\omega dE_p d\Omega_e d\Omega_p} = K\sigma_{ep}S(|\vec{p}_i|,E_i) \tag{34}$$

where σ_{ep} is the cross-section for scattering an electron from a bound proton, $K = E_p|\vec{p}_p|$ is a kinematical factor, $d\Omega_e$ and $d\Omega_p$ are the electron and proton solid angles respectively, and $S(|\vec{p}_i|,E_i)$ is the spectral function (probability to find a proton in the nucleus with momentum $|\vec{p}_i|$ and separation energy E_i). In the PWIA, these values correspond to missing momentum and energy: $|\vec{p}_i| = |\vec{p}_m|$ and $E_i \equiv E_m$ (see section 6 for the definition of these variables). The branch sig corresponds to this equation:

$$\text{sig} = \Big(\text{sigcc}\Big)\Big(\text{SF\_weight}\Big)\Big(\text{Jacobian}\Big) \tag{35}$$

7.2.2 sigcc

There are several prescriptions for σ_{ep} from Eq. 34. The most common one, which is the one used in simc, is the off-shell De Forest cross section [2]. There are two versions of this cross section referred to as "CC1" and "CC2" (i.e. $\sigma_{ep} = \sigma_{CC}$). This is where the name of these branches comes from.

However, the information encoded in these branches does not correspond to the DeForest cross section for the event. Instead, the information stored corresponds to:

$$\text{sigcc} = \sigma_{CC} \times K \quad [\frac{\mu\text{b}}{\text{sr}^2} \times \text{MeV}^2] \tag{36}$$

where K is the kinematical factor defined above in Eq. 34, and sr corresponds to steradians. The difference between sigcc & sigcc_recon is that they are calculated with generated and reconstructed variables respectively.

7.2.3 SF_weight

This branch describes the weight from the spectral function:

$$\text{SF\_weight} = Z \times \text{transparency} \times S(|\vec{p}_m|, E_m) \tag{37}$$

where Z corresponds to the number of protons in the target nucleus, and transparency accounts for known reductions in the cross section. transparency is a variable which can be defined in the input file, or otherwise defined as 1 by default. The spectral function in this equation is normalized to 1.

7.2.4 Jacobian

This Jacobian takes into account that events are generated in a set of variables (i.e. spectrometer coordinates yptar and xptar), while the cross section is differential in a different set of variables (i.e. dΩ). In general, we have:

$$\text{Jacobian} = \frac{1}{r_e^3 \times r_p^3} \tag{38}$$

where:

$$r_e = \sqrt{1 + \text{e\_yptar}^2 + \text{e\_xptar}^2} \tag{39}$$

$$r_p = \sqrt{1 + \text{h\_yptar}^2 + \text{h\_xptar}^2} \tag{40}$$

In the case of (e,e'p) scattering off deuteron or 2-body breakup in the case of helium-3, there is an extra factor which corresponds to $|\partial E_p / \partial E_m|$.

7.2.5 Jacobian_corr

The Jacobian correction is identical to Eq. 38. Nothing else is multiplied to this correction, not even in the case of (e,e'p) scattering off deuteron or 2-body breakup in the case of helium-3, in which an additional factor is multiplied to the Jacobian itself.

7.2.6 Genweight

This correction takes into account the fact that the generated and true energy (momentum) limits are not the same. This branch includes factors of the type:

$$\frac{E^{\text{true}}_{\text{max}} - E^{\text{true}}_{\text{min}}}{E^{\text{gen}}_{\text{max}} - E^{\text{gen}}_{\text{min}}} \tag{41}$$

In the case of (e,e'p) scattering off deuteron or 2-body breakup in the case of helium-3, there is one of these factors to account for the electron energy. In the case of 3-body breakup scattering off helium-3 and heavier nuclei, there is also another factor like this one to account for the proton energy.

7.2.7 coul_corr

Coulomb corrections. This is implemented as:

$$\text{coul\_corr} = (1 + \frac{< \text{Coulomb} >}{E_{\text{beam}}})^2 \tag{42}$$

where

$$< \text{Coulomb} >= 0.75 \times 1.5 \times \frac{(Z-1)\alpha\hbar c}{1.1 \times A^{1/3} + 0.86 \times A^{-1/3}} \tag{43}$$

where Z and A are the total number of protons and nucleons in the nuclear target respectively, α is the fine-structure constant, $\hbar$ is the reduced Planck constant, and c is the speed of light in vacuum. This coulomb correction implementation is based on [3].

7.3 sigcc_recon

The same as sigcc, but calculated with reconstructed variables.

7.4 SF_weight_recon

This branch is identical to SF_weight. I'm not sure who created these two outputs or why.

7.5 sig_recon

Laget model cross section. I haven't used this (i.e. this branch is empty in my simc root files), so I'm not familiar with the details. More details can be found in code: LagetXsec.f.

8 Other variables

8.1 corrsing

"Corrected singles", defined as:

$$\text{corrsing} = E_p - \frac{m_p E_{\text{beam}}}{2E_{\text{beam}} \sin^2(\theta_e/2) + m_p} \quad [\text{GeV}] \tag{44}$$

8.2 fry

y raster position in cm

8.3 radphot

Energy lost in the radiative processes in GeV.

8.4 epsilon

$$\text{epsilon} = \frac{1}{1 + 2 \times (1 + \omega^2/Q^2) \times tan^2(\theta_e/2)} \tag{45}$$

References

[1] J. J. Kelly, "Nucleon knockout by intermediate-energy electrons," *Adv. Nucl. Phys.*, vol. 23, pp. 75–294, 1996. [,75(1996)].

[2] T. De Forest, "Off-Shell electron Nucleon Cross-Sections. The Impulse Approximation," *Nucl. Phys. A*, vol. 392, pp. 232–248, 1983.

[3] A. Aste, C. von Arx, and D. Trautmann, "Coulomb distortion of relativistic electrons in the nuclear electrostatic field," *Eur. Phys. J.*, vol. A26, pp. 167–178, 2005.