Spin Correlations with Herwig++

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- Introduction.
- Rewrite of textbook style Feynman amplitude.
- Spin correlation algorithm step–by–step.
- Some remarks.

Introduction

What are spin correlations?

Example: $t\bar{t}$ production at hadron colliders.

- $\tilde{q}\bar{q} \longrightarrow t\bar{t}$: ${}^3S_1$ state $\Rightarrow$ $t\bar{t}$ spins parallel.
- $gg \longrightarrow t\bar{t}$: ${}^1S_0$ state $\Rightarrow$ $t\bar{t}$ spins antiparallel.

$\Rightarrow$ results in angular correlations among the final state particles.

We are interested in a description of these angular correlations in general.

Introduction

Two ways to calculate ME for process with many final state particles:

1. Calculate the full Feynman diagram.
2. Calculate process in several steps: production, decay, decay, . . .

Method 1
Contains all angular information from spin correlations.

Can become very complicated (automatisation under control, many tools available). *But:* phase space is bottleneck for *many* $(> 6?)$ particles.

Method 2
Fast and simple ME and phase space, only $(2 \to 2)$ processes and $(1 \to 2)$ or $(1 \to 3)$ decays.

Using the usual $|M|^2$ for $\mathrm{d}\sigma/\mathrm{d}\Phi$ or $\mathrm{d}\Gamma/\mathrm{d}\Phi$, one looses angular information.

Way out: Must use Helicity information on the ME level.

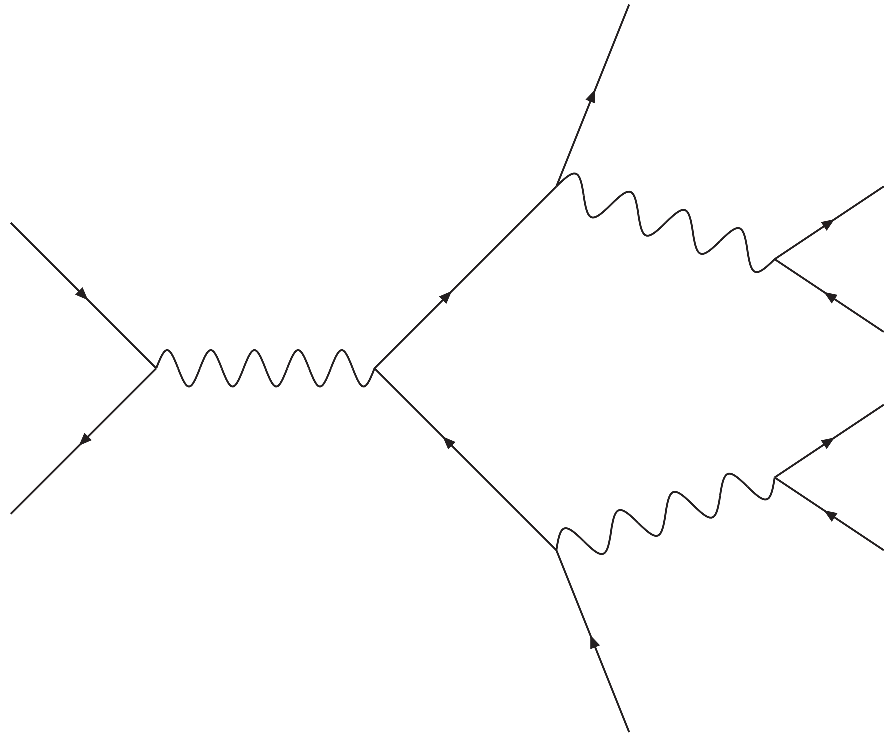
Intermediate particles on–shell — not always a viable approximation.

Plan:

- Explain the spin correlation algorithm (method 2 with some clever propagation of helicity information).
- Stick to the canonical example of $t\bar{t}$ production for this school ($e^+e^- \longrightarrow t\bar{t}$).
- Show that it really works for an even simpler example.
- What's inside Herwig++?
- Some final state distribution results.

How to describe $t\bar{t}$ events?

Calculate full ME from Feynman diagram. Process:



$$e^+e^- \to t\bar{t} \to bW^+\bar{b}W^- \to b\ell_1^+\nu_1\bar{b}\ell_2^-\bar{\nu}_2$$

$$i\mathcal{M}(\lambda_b,\lambda_{\bar{b}},\lambda_{\ell 1},\lambda_{\nu 1},\lambda_{\ell 2},\lambda_{\nu 2}) =$$

$$C\bar{u}_b\Gamma^{\mu}_{tbW}\frac{\not{p}_t + m_t}{p_t^2 - m_t^2}\;\not{J}_e\frac{\not{p}_{\bar{t}} - m_t}{p_{\bar{t}}^2 - m_t^2}\Gamma^{\nu}_{tbW}v_{\bar{b}}\frac{g_{\mu\alpha} - \frac{k_\mu k_\alpha}{m_W^2}}{p_{W+}^2 - m_W^2}\frac{g_{\nu\beta} - \frac{k_\nu k_\beta}{m_W^2}}{p_{W-}^2 - m_W^2}\bar{u}_1\Gamma_1^{\alpha}v_1\bar{u}_2\Gamma_2^{\beta}v_2$$

Textbook: sum over polarizations and square $\longrightarrow$ Dirac traces.

Polarization sums

$\longrightarrow$ Quite lengthy, four propagators require a carful sampling of phase space.
Different flavours $(1, 2)$ have to be combined.

How to simplify? First observe the polarization sums:

For fermions:

$$\sum_\lambda u_\lambda(p)\bar{u}_\lambda(p) = \not{p} + m \; , \qquad \sum_\lambda v_\lambda(p)\bar{v}_\lambda(p) = \not{p} - m \; .$$

For massive gauge bosons:

$$\sum_{\lambda(\text{physical})} \varepsilon_\mu^\lambda \varepsilon_\nu^{\lambda *} = -g_{\mu\nu} + \frac{k_\mu k_\nu}{m_W^2} \; .$$

Observe our amplitude:

$$i\mathcal{M} = C\bar{u}_b\Gamma^\mu_{tbW}\frac{\not{p}_t + m_t}{p_t^2 - m_t^2}\not{J}_e\frac{\not{p}_{\bar{t}} - m_t}{p_{\bar{t}}^2 - m_t^2}\Gamma^\nu_{tbW}v_{\bar{b}}\frac{g_{\mu\alpha} - \frac{k_\mu k_\alpha}{m_W^2}}{p_{W+}^2 - m_W^2}\frac{g_{\nu\beta} - \frac{k_\nu k_\beta}{m_W^2}}{p_{W-}^2 - m_W^2}\bar{u}_1\Gamma_1^\alpha v_1\bar{u}_2\Gamma_2^\beta v_2$$

Helicity amplitudes

Plugging in/reverting the polarization sums, we obtain

$$
i\mathcal{M}(\lambda\ldots) = \sum_{\text{all internal}\lambda\text{'s}} C\,\bar{u}_{\lambda b}\Gamma^{\mu}_{tbW}\frac{u_{\lambda t}\bar{u}_{\lambda t}}{p_t^2 - m_t^2}\not{J}_e\frac{v_{\lambda\bar{t}}\bar{v}_{\lambda\bar{t}}}{p_{\bar{t}}^2 - m_t^2}\Gamma^{\nu}_{tbW}v_{\lambda\bar{b}}
$$

$$
\times\frac{\varepsilon_{\mu}^{\lambda W^+}\varepsilon_{\alpha}^{\lambda W^+ *}}{p_{W+}^2 - m_W^2}\frac{\varepsilon_{\nu}^{\lambda W^-}\varepsilon_{\beta}^{\lambda W^- *}}{p_{W-}^2 - m_W^2}\bar{u}_{\lambda\ell 1}\Gamma_1^{\alpha}v_{\lambda\nu 1}\bar{u}_{\lambda\ell 2}\Gamma_2^{\beta}v_{\lambda\nu 2}\ .
$$

Rearranging and contracting open Lorentz indices gives

$$
i\mathcal{M}(\lambda\ldots) = \sum_{\text{all internal}\lambda\text{'s}} C\left(\bar{u}_{\lambda b}\Gamma_{tbW}\cdot\varepsilon^{\lambda W^+}u_{\lambda t}\right)\left(\bar{u}_{\lambda t}\not{J}_e v_{\lambda\bar{t}}\right)\left(\bar{v}_{\lambda\bar{t}}\Gamma_{tbW}\cdot\varepsilon_{\nu}^{\lambda W^-}v_{\lambda\bar{b}}\right)
$$

$$
\times\left(\bar{u}_{\lambda\ell 1}\Gamma_1\cdot\varepsilon^{\lambda W^+ *}v_{\lambda\nu 1}\right)\left(\bar{u}_{\lambda\ell 2}\Gamma_2\cdot\varepsilon^{\lambda W^- *}v_{\lambda\nu 2}\right)
$$

$$
\times\frac{1}{p_{W+}^2 - m_W^2}\frac{1}{p_{W-}^2 - m_W^2}\frac{1}{p_t^2 - m_t^2}\frac{1}{p_{\bar{t}}^2 - m_t^2}\ .
$$

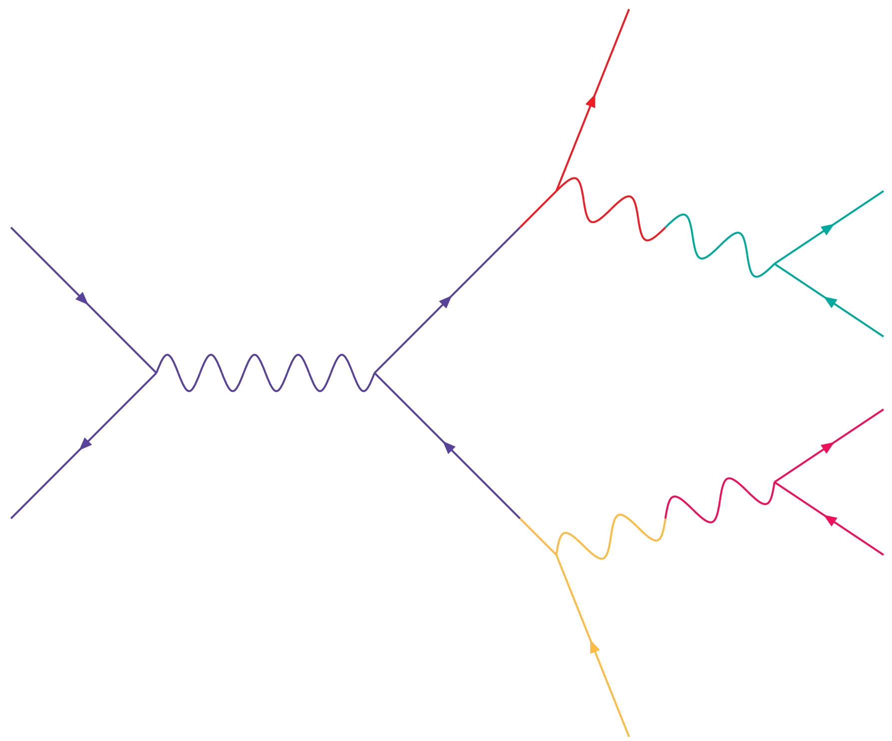
Helicity amplitudes

$$i\mathcal{M}(\lambda\ldots) = \sum_{\text{all internal}\lambda\text{'s}} N\left(\bar{u}_{\lambda t}\ \not{J}_e v_{\lambda\bar{t}}\right)\left(\bar{u}_{\lambda b}\Gamma_{tbW}\cdot\varepsilon^{\lambda W^+} u_{\lambda t}\right)\left(\bar{u}_{\lambda\ell 1}\Gamma_1\cdot\varepsilon^{\lambda W^+ *} v_{\lambda\nu 1}\right)$$

$$\times\left(\bar{v}_{\lambda\bar{t}}\Gamma_{tbW}\cdot\varepsilon_{\nu}^{\lambda W^-} v_{\lambda\bar{b}}\right)\left(\bar{u}_{\lambda\ell 2}\Gamma_2\cdot\varepsilon^{\lambda W^- *} v_{\lambda\nu 2}\right)$$

$$= \sum_{\text{all internal}\lambda\text{'s}} N'\mathcal{M}^{e^+e^-\to t\bar{t}}_{\lambda_t\lambda_{\bar{t}}}\mathcal{M}^{t\to bW^+}_{\lambda_t\lambda_{W+}}$$

$$\times\mathcal{M}^{W^+\to\ell_1^+\bar{\nu}_1}_{\lambda_{W+}}\mathcal{M}^{\bar{t}\to\bar{b}W^-}_{\lambda_{\bar{t}}\lambda_{W-}}\mathcal{M}^{W^-\to\ell_2^+\bar{\nu}_2}_{\lambda_{W-}}$$

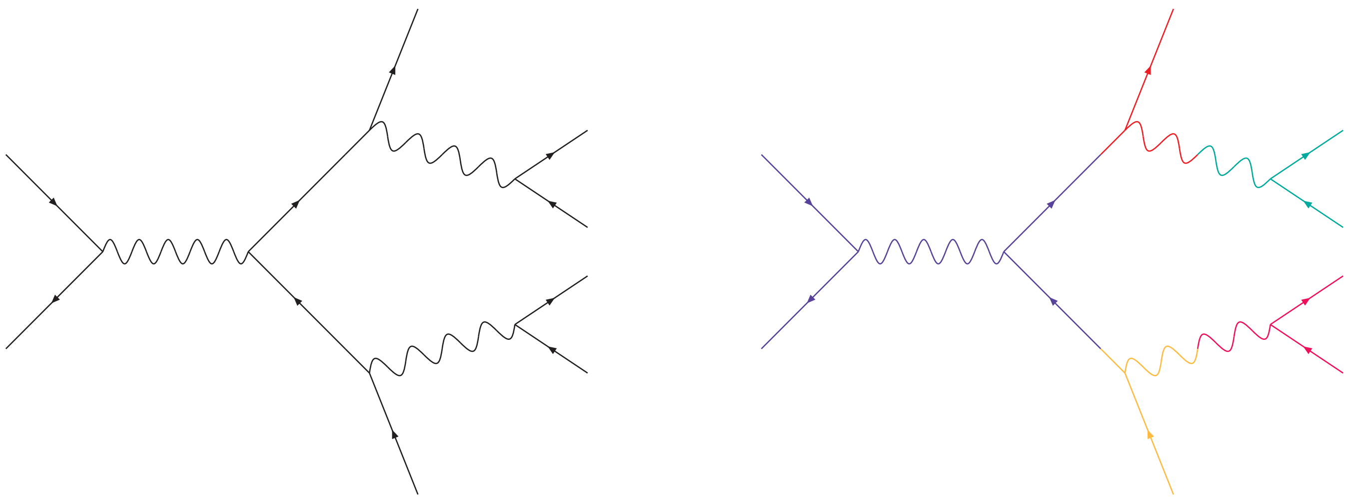


Here: propagator factors absorbed in N'. Later we consider the *zero width approximation* $\longrightarrow$ particles on–shell. The propagator is absorbed by the intermediate phase space integration.

So far

So far we have learnt:

- Ordinary Feynman diagram breaks up into several well-defined subamplitudes (in the narrow–width approximation!).
- Must keep explicit helicity information for this! ("square, then sum" vs "sum, then square")
- Clearly: Independent subamplitudes, with spin averaging, would give a different result.
- *Note:* we put intermediate particles on–shell, i.e. take the limit of width $\rightarrow 0$. Well justifyable for many cases ($\rightarrow$ examples later).



Next step $\longrightarrow$ use these helicity amplitudes to do sequential decays but *keep* spin correlations among the subamplitudes.

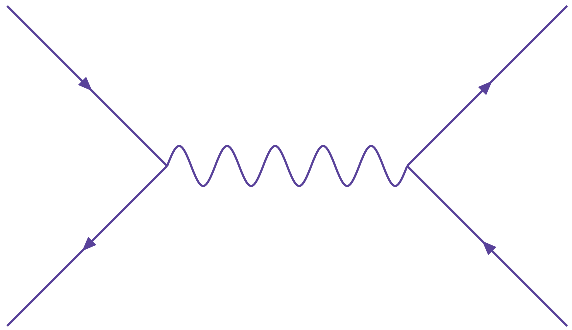
Spin Correlation Algorithm

P Richardson, JHEP 0111,029 (2001), based on J Collins NPB304,794 (1988), IG Knowles NPB304,767 (1988), NPB310,571 (1988).

- General algorithm to achieve the goal we have formulated.
- Originally invented to adjust spin correlations in parton showers.
- Now most important for the case of ME with many legs, the case we are considering here.
- Implemented in Herwig++.
- We will discuss this algorithm for the special case of $e^+e^- \to t\bar{t}$. With hints towards the general implementation.

Spin Correlation Algorithm

Step 1: generate hard process from spin averaged ME. A spin density ρ for the incoming particles might be included here already. For unpolarised initial state, one simply uses $\rho_{\kappa,\kappa'} = \delta_{\kappa,\kappa'}/2$.



Generate momenta of t, $\bar{t}$ from the usual cross–section integral

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi} = \frac{(2\pi)^4}{2s} \int \frac{d^3 p_t}{(2\pi)^3 2E_t} \frac{d^3 p_{\bar{t}}}{(2\pi)^3 2E_{\bar{t}}} \mathcal{M}^{e^+e^- \to t\bar{t}}_{\lambda_t \lambda_{\bar{t}}} \mathcal{M}^{*e^+e^- \to t\bar{t}}_{\lambda_t \lambda_{\bar{t}}} .$$

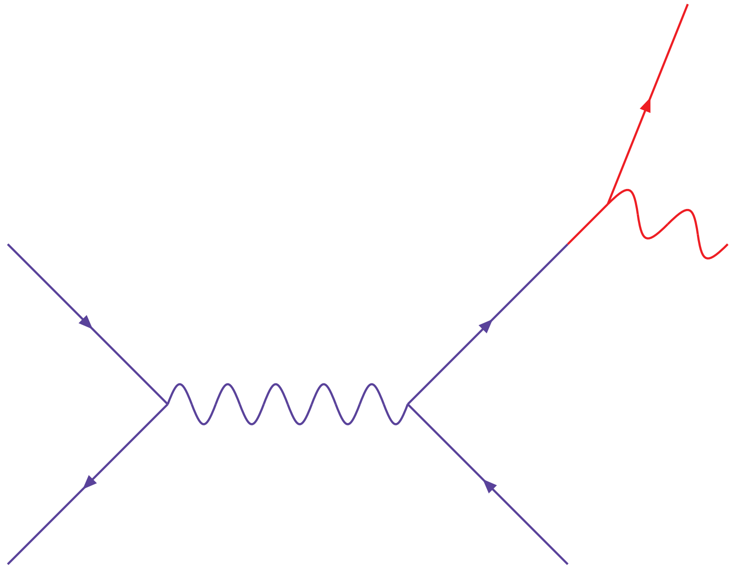
Note: repeated spin indices (here λ_t, $\lambda_{\bar{t}}$) are summed over.

Spin Correlation Algorithm

Step 2: select one final state partice at random (say the t). Calculate the spin density matrix

$$\rho^t_{\lambda_t \lambda'_t} = \frac{1}{N} \mathcal{M}^{e^+e^- \to t\bar{t}}_{\lambda_t \lambda_{\bar{t}}} \mathcal{M}^{*e^+e^- \to t\bar{t}}_{\lambda'_t \lambda_{\bar{t}}} .$$

N chosen such that $\mathrm{Tr}\rho = 1$. $\rho_{\kappa,\kappa'}$ would enter here if non–trivial.



Step 3: Decay this particle. Generate the momenta of the final state particles according to

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi} = \frac{(2\pi)^4}{2m_t} \int \frac{d^3 p_b}{(2\pi)^3 2E_b} \frac{d^3 p_{W+}}{(2\pi)^3 2E_{W+}} \rho^t_{\lambda_t \lambda'_t} \mathcal{M}^{t \to bW^+}_{\lambda_t \lambda_{W+}} \mathcal{M}^{*t \to bW^+}_{\lambda'_t \lambda_{W+}},$$

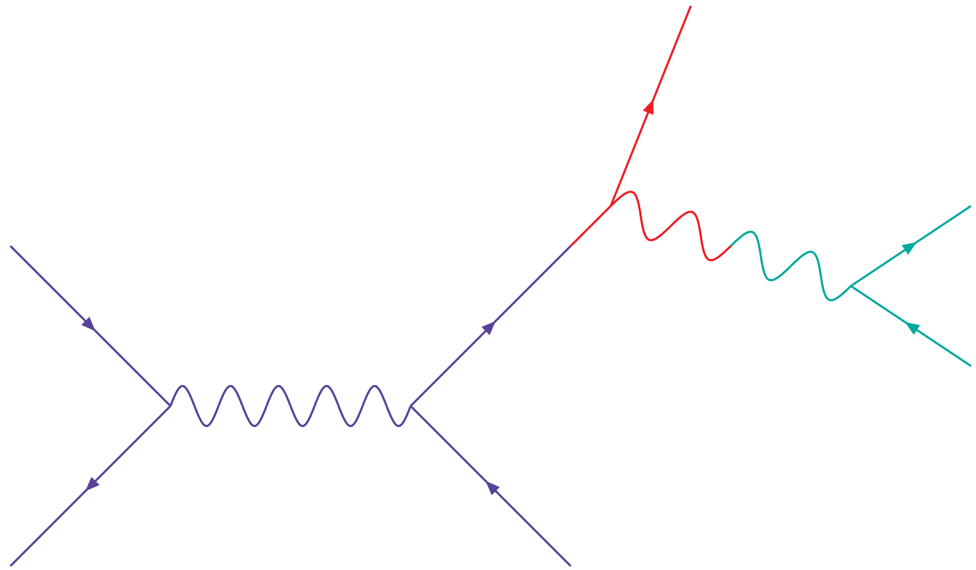
The spin density $\rho^t_{\lambda_t \lambda'_t}$ ensures the proper correlations with the incoming particles.

Spin Correlation Algorithm

Step 4: Pick one of the final state particles and calculate the new spin density. Here only for the W^+, as the b is already stable.

$$\rho^{W^+}_{\lambda_{W^+}\lambda'_{W^+}} = \frac{1}{N}\rho^t_{\lambda_t\lambda'_t}\mathcal{M}^{t\to bW^+}_{\lambda_t\lambda_{W^+}}\mathcal{M}^{*t\to bW^+}_{\lambda'_t\lambda'_{W^+}}\ .$$

Input for the Step 3 again. (λ_b, λ'_b not displayed here, they have been silently contracted with a $\delta_{\lambda_b,\lambda'_b}$ already, come back to this later.)



Step 3: Decay this particle. Generate the momenta of the final state particles according to

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi} = \frac{(2\pi)^4}{2m_{W^+}}\int\frac{d^3p_{\ell^+}}{(2\pi)^3 2E_{\ell^+}}\frac{d^3p_{\nu_\ell}}{(2\pi)^3 2E_{\nu_\ell}}\rho^{W^+}_{\lambda_{W^+}\lambda'_{W^+}}\mathcal{M}^{W^+\to\ell^+\nu_\ell}_{\lambda_{W^+}}\mathcal{M}^{*W^+\to\ell^+\nu_\ell}_{\lambda'_{W^+}},$$

The spin density $\rho^{W^+}_{\lambda_{W^+}\lambda'_{W^+}}$ now ensures the proper correlations with the t and the beam.

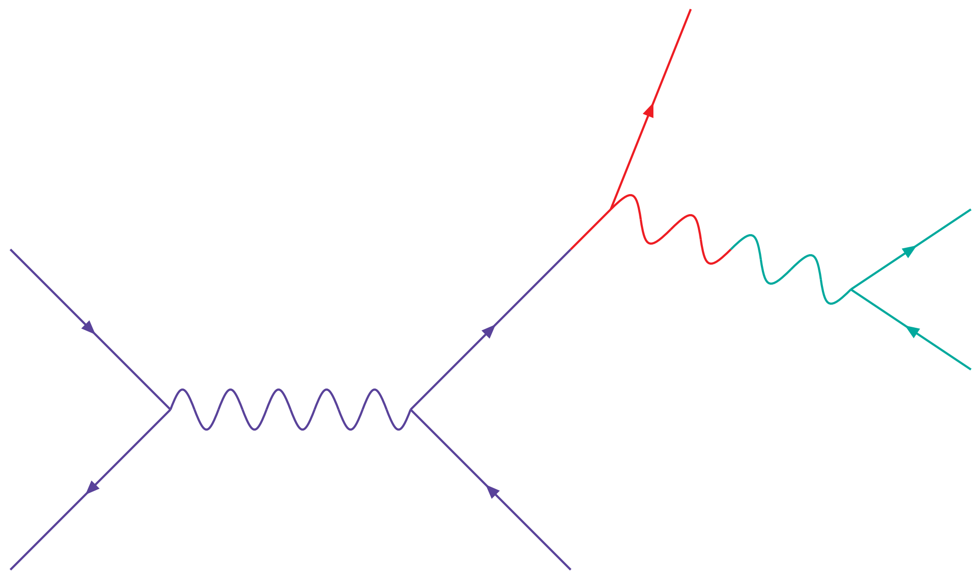
Steps 3 and 4 are repeated until all particles in a decay chain are stable. In our example this is now the case.

Spin Correlation Algorithm

Now the spin information has to be carried back up the tree.
Step 5: Calculate the decay density matrix. For the W^+ this is

$$D^{W^+}_{\lambda_{W+}\lambda'_{W+}} = \frac{1}{N}\mathcal{M}^{t\to bW^+}_{\lambda_t\lambda_{W+}}\mathcal{M}^{*t\to bW^+}_{\lambda_t\lambda'_{W+}},$$

This will be used in the other branches of the tree.



Step 6: if there were other unstable particles in the t decay, we would calculate a new spin density matrix as in Step 4 and Step 3, but here the decay matrix $D^{W^+}_{\lambda_{W+}\lambda'_{W+}}$ would enter, where previously we implicitly set this to $\delta_{\lambda_{W+}\lambda'_{W+}}$. This would then enter the calculation of the final state momenta of this decay etc.

Spin Correlation Algorithm

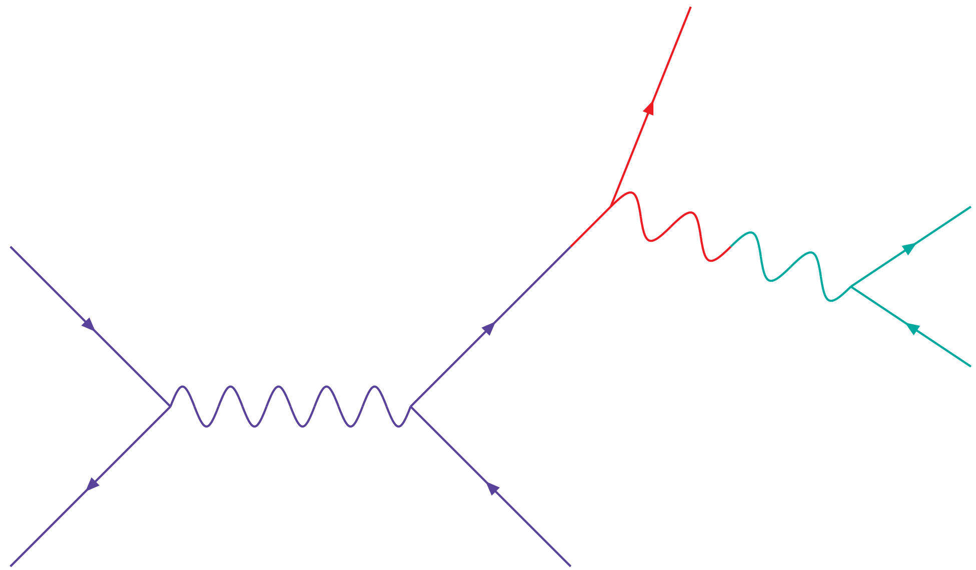
Step 7: we eventually will reach the hard process again. Now we calculate the decay matrix

$$D^t_{\lambda_t\lambda'_t} = \frac{1}{N}\mathcal{M}^{t\to bW^+}_{\lambda_t\lambda_{W^+}}\mathcal{M}^{*t\to bW^+}_{\lambda'_t\lambda'_{W^+}}D^{W^+}_{\lambda_{W^+}\lambda'_{W^+}}.$$

using this we calculate the spin density matrix

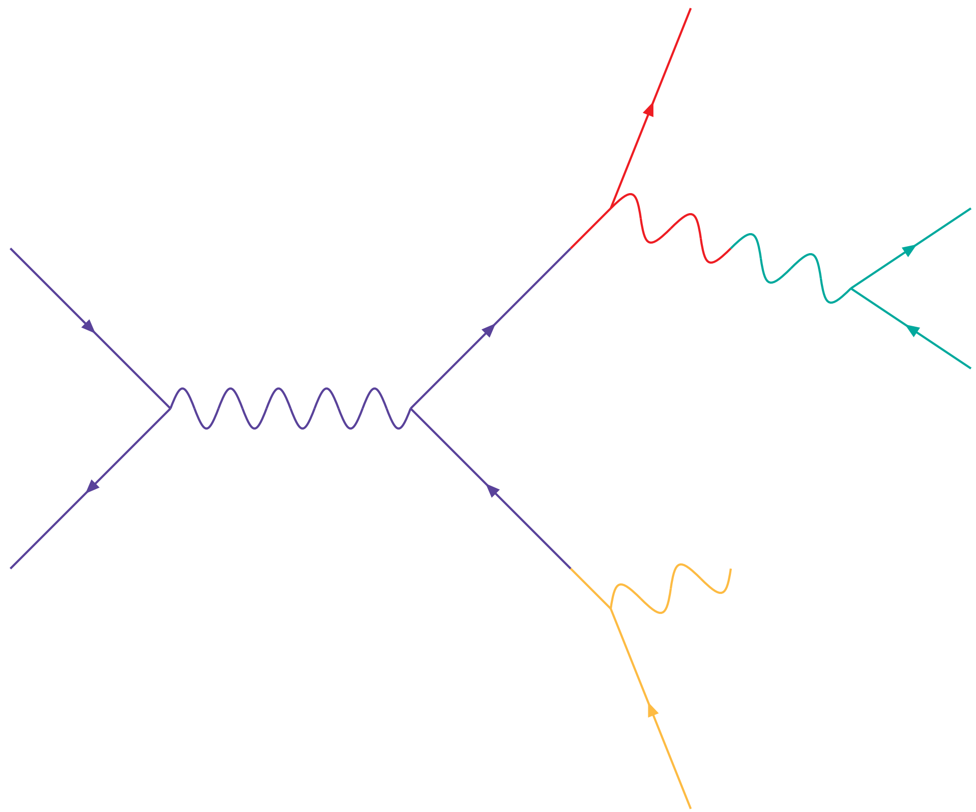
$$\rho^{\bar{t}}_{\lambda_{\bar{t}}\lambda'_{\bar{t}}} = \frac{1}{N}\mathcal{M}^{e^+e^-\to t\bar{t}}_{\lambda_t\lambda_{\bar{t}}}\mathcal{M}^{*e^+e^-\to t\bar{t}}_{\lambda'_t\lambda'_{\bar{t}}}D^t_{\lambda_t\lambda'_t}$$

(compare t case where we implicitly used the identity $\delta_{\lambda_t\lambda'_t}$ instead of $D^t_{\lambda_t\lambda'_t}$!)



Spin Correlation Algorithm

Back to Step 3: $\bar{t}$ decay, now using the spin density matrix $\rho^{\bar{t}}_{\lambda_{\bar{t}}\lambda_{\bar{t}}}$. This transports the spin information from the first branch to the second.

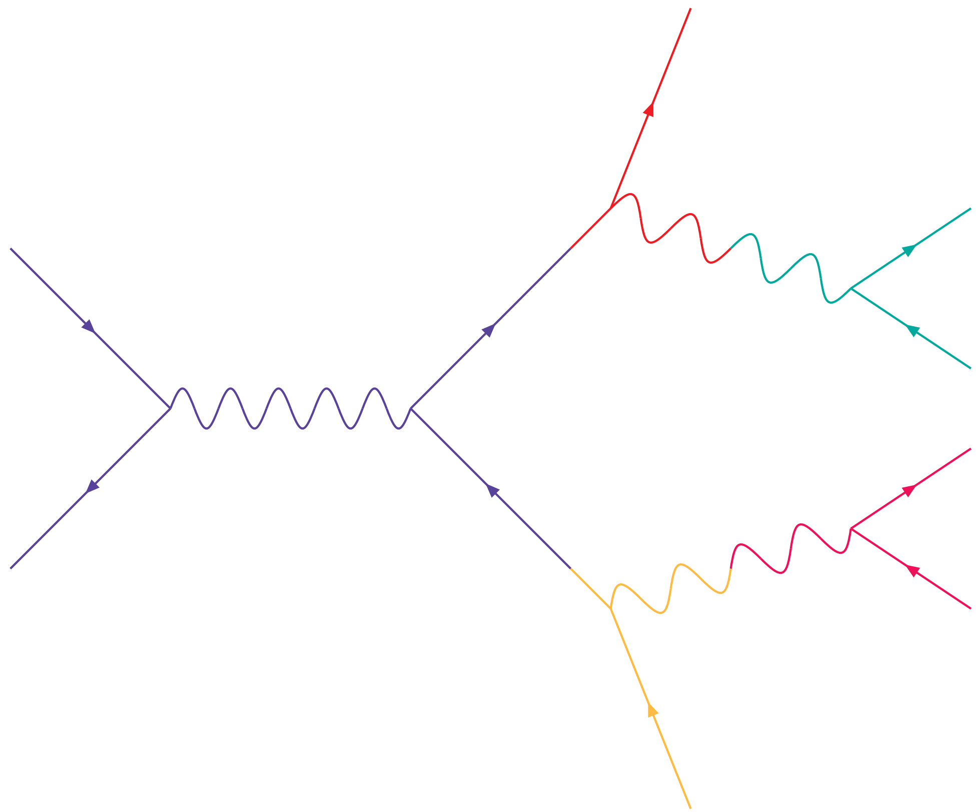


Generate the momenta of the final state particles of the $\bar{t}$ decay according to

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi} = \frac{(2\pi)^4}{2m_t}\int \frac{d^3p_b}{(2\pi)^3 2E_b}\frac{d^3p_{W+}}{(2\pi)^3 2E_{W+}}\rho^{\bar{t}}_{\lambda_{\bar{t}}\lambda'_{\bar{t}}}\mathcal{M}^{\bar{t}\to\bar{b}W^-}_{\lambda_{\bar{t}}\lambda_{W^-}}\mathcal{M}^{*\bar{t}\to\bar{b}W^-}_{\lambda'_{\bar{t}}\lambda_{W^-}} \ .$$

Spin Correlation Algorithm

Now Step 4: new ρ matrix for the W^- and Step 3: W^- decay according to the proper phase space integral.



With more than 2 particles in the final state of the hard process we would eventually get back to Step 7 and then up the next decay chain. Here we are finished.

Even simpler example

Why is this equivalent to using the full ME? (using only the on–shell limit).

Consider production process of particles 1 and 2 (with polarization) with subsequent decay into 2 polarized particles,

$$12 \to (3A)(4B) \ .$$

Particles A and B are unpolarized, so no helicity index for them.

With production ME M and Decay MEs $\Gamma^{(1)}$, $\Gamma^{(2)}$ we will write the total ME as

$$|\mathcal{M}_{\lambda_3\lambda_4}|^2 = |\Gamma^{(1)}_{\lambda_3\lambda_1} M_{\lambda_1\lambda_2} \Gamma^{(2)}_{\lambda_2\lambda_4}|^2 \ .$$

Now we do the algorithm, step–by–step.

Even simpler example

- Production according to

$$|M|^2 = M_{\lambda_1\lambda_2} M^*_{\lambda_2\lambda_1}$$

- Calculate Spin density matrix

$$\rho^{(1)}_{\lambda_1\lambda_1'} = \frac{M_{\lambda_1\lambda_2} M^*_{\lambda_2\lambda_1'}}{M_{\lambda_1\lambda_2} M^*_{\lambda_2\lambda_1}} = \frac{M_{\lambda_1\lambda_2} M^*_{\lambda_2\lambda_1'}}{|M|^2}$$

- Now Decay of 1 according to "$\rho \cdot |\Gamma|^2$",

$$\frac{M_{\lambda_1\lambda_2} M^*_{\lambda_2\lambda_1'}}{|M|^2} \Gamma^{(1)}_{\lambda_3\lambda_1} \Gamma^{*(1)}_{\lambda_1'\lambda_3}$$

- But, with conditional probability, that $1, 2$ have been already produced, so our total probability density is now

$$|M|^2 \frac{M_{\lambda_1\lambda_2} M^*_{\lambda_2\lambda_1'}}{|M|^2} \Gamma^{(1)}_{\lambda_3\lambda_1} \Gamma^{*(1)}_{\lambda_1'\lambda_3} = M_{\lambda_1\lambda_2} M^*_{\lambda_2\lambda_1'} \Gamma^{(1)}_{\lambda_3\lambda_1} \Gamma^{*(1)}_{\lambda_1'\lambda_3} = \Gamma^{(1)}_{\lambda_3\lambda_1} M_{\lambda_1\lambda_2} M^*_{\lambda_2\lambda_1'} \Gamma^{*(1)}_{\lambda_1'\lambda_3}$$

$$= (\Gamma^{(1)} \cdot M)_{\lambda_3\lambda_2} (\Gamma^{(1)} \cdot M)^*_{\lambda_2\lambda_3} = |\Gamma^{(1)} \cdot M|^2$$

Even simpler example

- Now we need the decay matrix of the first decay, in order to propagate the information to the second decay:

$$D_{\lambda_1\lambda_1'} = \frac{\Gamma^{(1)}_{\lambda_3\lambda_1}\Gamma^{*(1)}_{\lambda_1'\lambda_3}}{\Gamma^{(1)}_{\lambda_3\lambda_1}\Gamma^{*(1)}_{\lambda_1\lambda_3}} = \frac{\Gamma^{(1)}_{\lambda_3\lambda_1}\Gamma^{*(1)}_{\lambda_1'\lambda_3}}{|\Gamma^{(1)}|^2}$$

- This goes into the spin density matrix for the second decay:

$$\rho_{\lambda_2\lambda_2'} = N M_{\lambda_1\lambda_2} M^*_{\lambda_2'\lambda_1'} D_{\lambda_1\lambda_1'}$$

  Plug in D and simplify:

$$\rho_{\lambda_2\lambda_2'} = N M_{\lambda_1\lambda_2} M^*_{\lambda_2'\lambda_1'} \frac{\Gamma^{(1)}_{\lambda_3\lambda_1}\Gamma^{*(1)}_{\lambda_1'\lambda_3}}{|\Gamma^{(1)}|^2} = N \frac{\Gamma^{(1)}_{\lambda_3\lambda_1} M_{\lambda_1\lambda_2} M^*_{\lambda_2'\lambda_1'} \Gamma^{*(1)}_{\lambda_1'\lambda_3}}{|\Gamma^{(1)}|^2}$$

$$= \frac{|\Gamma^{(1)}|^2}{|(\Gamma^{(1)}\cdot M)|^2} \frac{(\Gamma^{(1)}\cdot M)_{\lambda_3\lambda_2}(\Gamma^{(1)}\cdot M)^*_{\lambda_2'\lambda_3}}{|\Gamma^{(1)}|^2} = \frac{(\Gamma^{(1)}\cdot M)_{\lambda_3\lambda_2}(\Gamma^{(1)}\cdot M)^*_{\lambda_2'\lambda_3}}{|(\Gamma^{(1)}\cdot M)|^2}$$

Even simpler example

- Now decay of 2 according to "$\rho \cdot |\Gamma|^2$",

$$\rho_{\lambda_2\lambda_2'}\Gamma^{(2)}_{\lambda_2\lambda_4}\Gamma^{*(2)}_{\lambda_4\lambda_2'} = \frac{\Gamma^{(1)}_{\lambda_3\lambda_1}M_{\lambda_1\lambda_2}M^*_{\lambda_2'\lambda_1'}\Gamma^{*(1)}_{\lambda_1'\lambda_3}}{|(\Gamma^{(1)}\cdot M)|^2}\Gamma^{(2)}_{\lambda_2\lambda_4}\Gamma^{*(2)}_{\lambda_4\lambda_2'}$$

$$= \frac{\Gamma^{(1)}_{\lambda_3\lambda_1}M_{\lambda_1\lambda_2}\Gamma^{(2)}_{\lambda_2\lambda_4}\Gamma^{*(2)}_{\lambda_4\lambda_2'}M^*_{\lambda_2'\lambda_1'}\Gamma^{*(1)}_{\lambda_1'\lambda_3}}{|(\Gamma^{(1)}\cdot M)|^2}$$

- Multiply with $|(\Gamma^{(1)}\cdot M)|^2$ as we generate this under the condition that the production and the first decay have already happened,

$$|\Gamma^{(1)}_{\lambda_3\lambda_1}M_{\lambda_1\lambda_2}\Gamma^{(2)}_{\lambda_2\lambda_4}|^2 \ ,$$

  we arrive at our full matrix element!

Demonstrated for this simple case that the algorithm works!

Remarks

- Algorithm very general.
- Not limited to $2 \longrightarrow 2$ hard scattering.
- Not limited to $1 \longrightarrow 2$ decays.
- In fact, in Herwig++ the t decays in a 3 body decay with an off–shell W.

Implementation

In Herwig++ a number of basic Matrixelements and decayers are implemeted based on HELAS like helicity amplitudes. They allow to calculate and then carry spin correlations through perturbative production and decay chains in general.

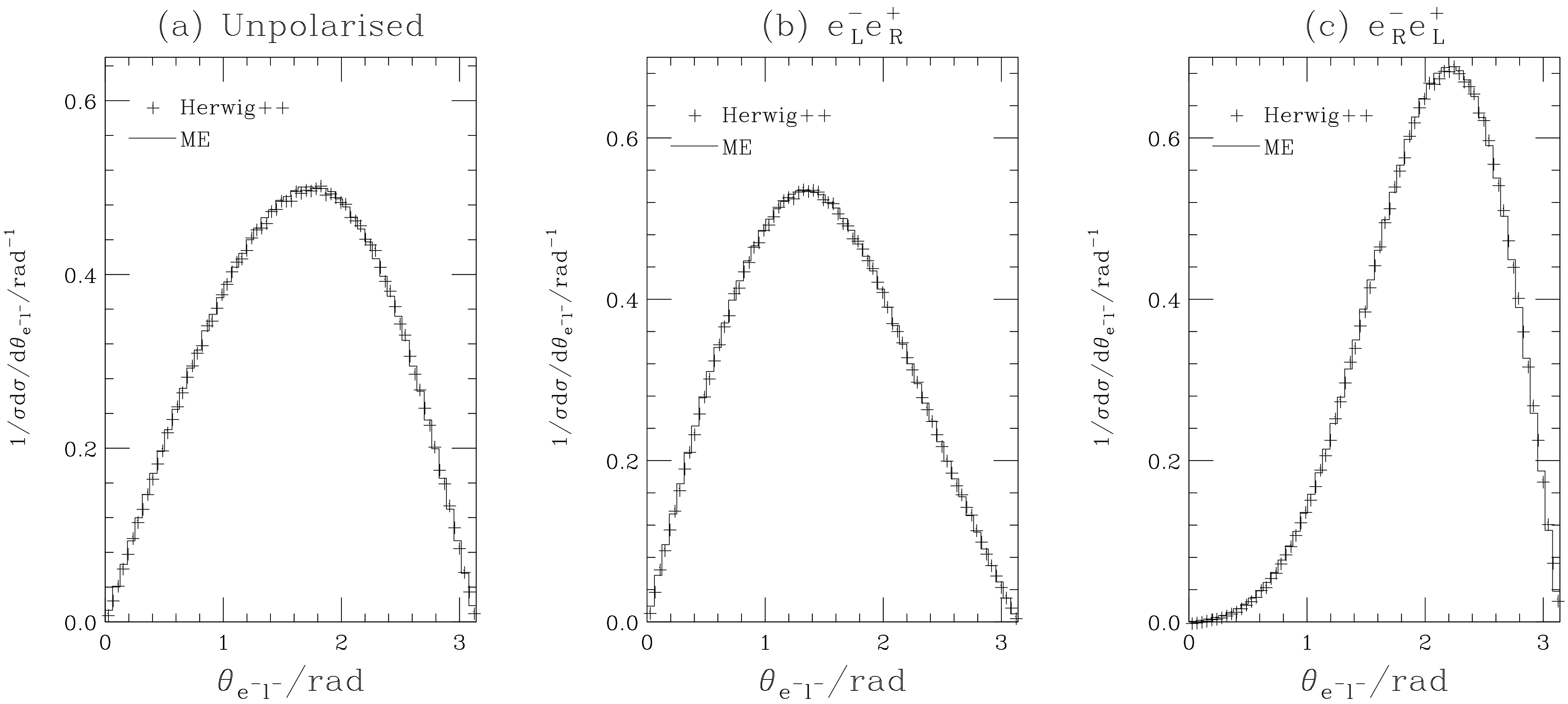
We have SM spin correlations in

- t decays.
- τ decays.
- h_0 decays.

Spin informaion is always stored in production and decay vertices "behind the scenes". Only complex matrices are stored for a single phase space point.

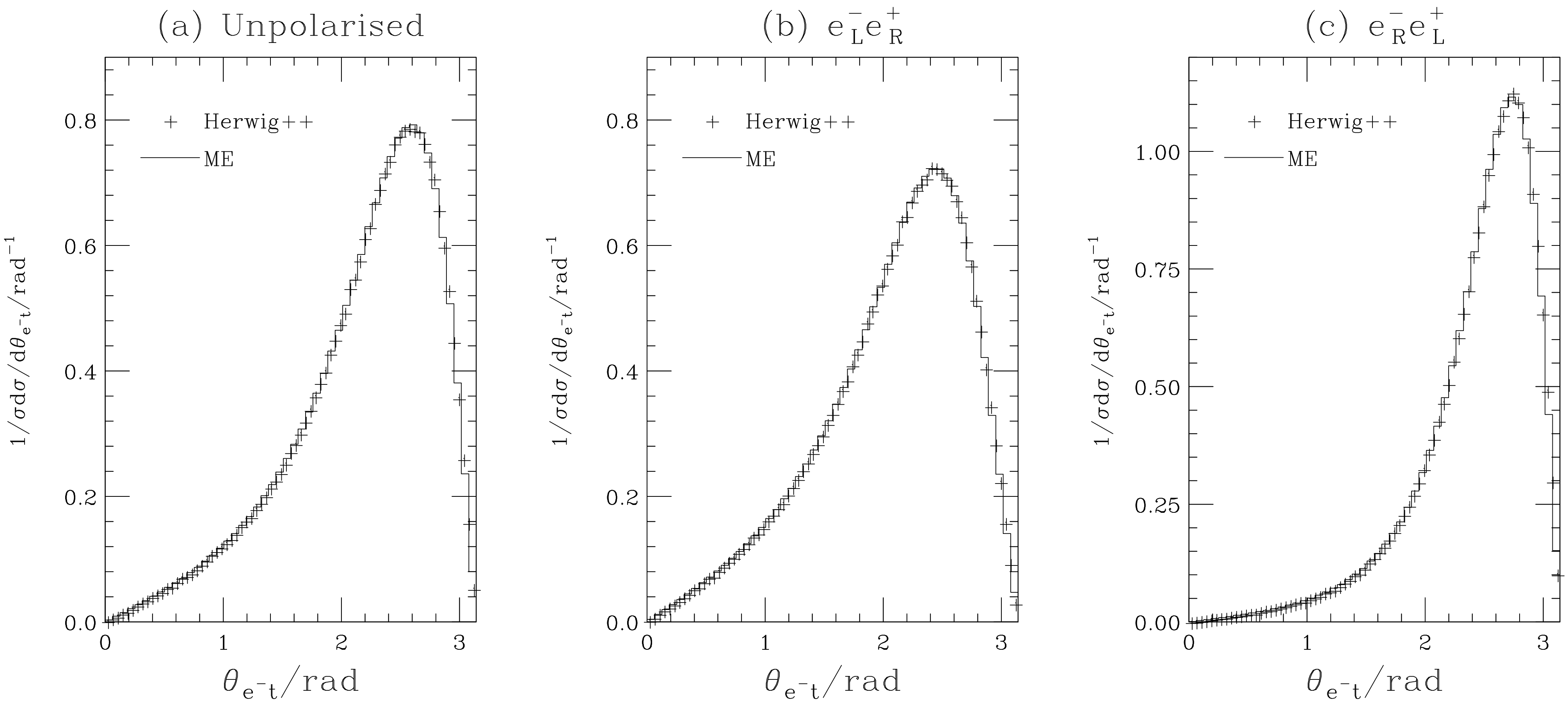
No implementation for spin correlations in the parton shower (not yet finished). Works along the same lines. Historically the first approach in the literature (Collins, Knowles).

Some results



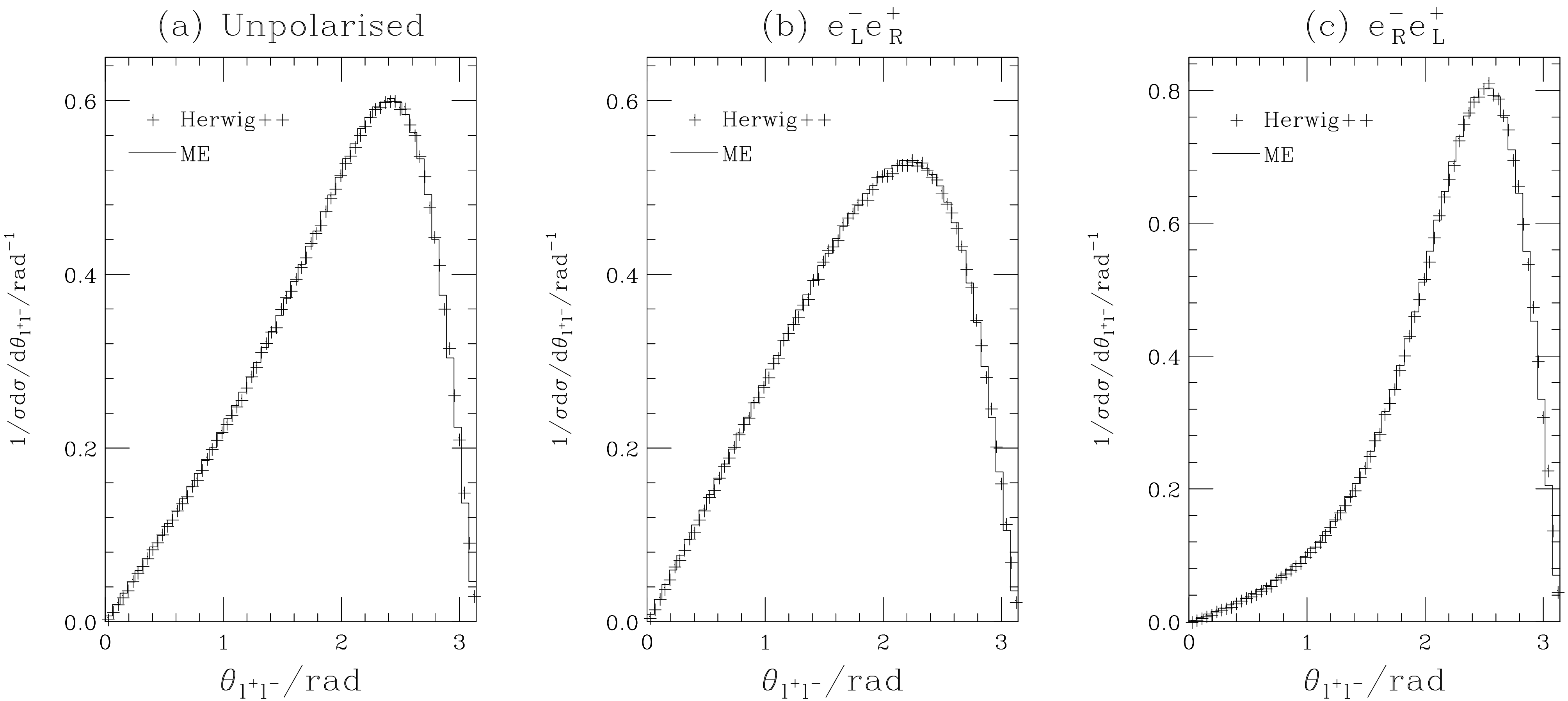
Beam–lepton angle in $e^+e^- \to t\bar{t} \to b\bar{b}l^+\nu_l l^-\bar{\nu}_l$ in the lab, $\sqrt{s} = 500\,\mathrm{GeV}$ for different beam polarisations. ME = full 6 body ME. Correct implementation of $\bar{t}$ decay chain.

Some results



Lepton–top top angle. Correct implementation of $\bar{t}$ spin density matrix and handover to t.

Some results



Angle between the outgoing lepton and anti–lepton. Correct implementation of $\bar{t}$ decay matrix that is carried through t decay chain.

SUSY decay chains

Important for determining properties of SUSY particles at the LHC.

Angular distributions of final state leptons $\longrightarrow$ invariant mass spectra $\longrightarrow$ edges and endpoints for SUSY mass determinations.

Summary

- Spin correlations in MC as a tool to generate processes with many particles in the final state.
- Preserves angular information whilst generating a sequence of decays.
- Narrow width approximation often well justified (works well for the examples we have studied).
- Built into perturbative SM and BSM production/decay process in Herwig++.