Electron Scattering in GENIE Radiative Effects

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work in progress
The Correction is given a single interaction, thus does not depend on the target width
Radiative Effects

Theory

\[ \left( \frac{d\sigma}{d\Omega_e'} \right)_{\text{VIRTUAL}_\gamma} + \left( \frac{d\sigma}{d\Omega_e'} \right)_{\text{REAL SOFT}_\gamma} = \left( \frac{d\sigma}{d\Omega_e'} \right)_{\text{BORN}} (1 + \delta_{\text{vac}} + \delta_{\text{vertex}} + \delta_R), \]

\[
\delta_{\text{vac}} + \delta_{\text{vertex}} + \delta_R = \frac{\alpha_{\text{em}}}{\pi} \left\{ \ln \left( \frac{(\Delta E_s)^2}{E_E E'_E} \right) \left[ \ln \left( \frac{Q^2}{m^2} \right) - 1 \right] \right. \\
\left. + \frac{13}{6} \ln \left( \frac{Q^2}{m^2} \right) - \frac{28}{9} - \frac{1}{2} \ln^2 \left( \frac{E_E}{E'_E} \right) - \frac{\pi^2}{6} + Sp \left( \cos^2 \frac{\theta_e}{2} \right) \right\}
\]
Radiative Effects

Theory

Based on PHYSICAL REVIEW C, VOLUME 62, 025501
The energy loss, $\Delta E$, can be sampled using the distribution:

$$I_{int}(E, \Delta E, a) = \frac{a}{\Delta E} \left( \frac{\Delta E}{E} \right)^a$$

where $E$ is the incoming electron energy

$$a = \frac{\alpha EM}{\pi} \left[ \ln \left( \frac{Q^2}{m^2} \right) - 1 \right]$$

note: For ISR $Q^2$ has to be used before it is assigned for the event.

GENIE note: Currently using the average value of $Q^2$ for the given incoming energy.
Radiative Effects

Theory

\[ \propto P(\Delta E) \]

Probability for Energy Loss
Radiative Effects in GENIE

Initial State Radiation

For the ISR, relevant only for the electron scattering case.

Energy and momentum are omitted from the initial state probe.

note:
- not recording the probe energy before radiating a photon
- not recording the emitted photon

GENIE notes:
the change was done in two places:
- The initial state probe in InitialState using SetProbeE(energy)
- The particle at slot 0 in GHepRecord
Radiative Effects in GENIE

Final State Radiation

Final state radiation should be applicable for both electron and neutrino mode.

The final state electron was decayed, and a final state photon was added.

GENIE notes:
- The decayed electron is still recorded with a status of 3 (decayed state)
Radiative Correction

In the last iteration we’ve used all the range of the distribution, but for large energy loss our approximation is not correct.

We have to apply a cut off for the energy loss, which can be chosen as:
- 10% of the electron energy
- Peskin Energy difference in the process $E - E'$
- VanderHagen $(1-x)(E-E')$

The choice changes the small tail.

The results are shown with 10%
Due to the radiative correction the cross section for a given interaction is changed.

We’ve added a weight to each event which is dependent on the initial and final state kinematic variables.

Note: for the incoming neutrino case the weight will of course be different.
Introducing a new class
currently implemented in a private branch mit_radcorr:
  src/EVGModules/RadiativeCorrector.C
  src/EVGModules/RadiativeCorrector.h

The module is being called twice:
<param_set name="QEL-eEM">
  <param type="string" name="VldContext"></param>
  <param type="int" name="NModules">14</param>
  <param type="alg" name="Module-0">genie::InitialStateAppender/Default</param>
  <param type="alg" name="Module-1">genie::RadiativeCorrector/ISR</param>
  <param type="alg" name="Module-2">genie::VertexGenerator/Default</param>
  <param type="alg" name="Module-3">genie::FermiMover/Default</param>
  <param type="alg" name="Module-4">genie::QELKinematicsGenerator/EM-Default</param>
  <param type="alg" name="Module-5">genie::QELPrimaryLeptonGenerator/Default</param>
  <param type="alg" name="Module-6">genie::QELHadronicSystemGenerator/Default</param>
  <param type="alg" name="Module-7">genie::PauliBlocker/Default</param>
  <param type="alg" name="Module-8">genie::UnstableParticleDecayer/BeforeHadronTransport</param>
  <param type="alg" name="Module-9">genie::NucDeExcitationSim/Default</param>
  <param type="alg" name="Module-10">genie::HadronTransporter/Default</param>
  <param type="alg" name="Module-11">genie::NucBindEnergyAggregator/Default</param>
  <param type="alg" name="Module-12">genie::UnstableParticleDecayer/AfterHadronTransport</param>
  <param type="alg" name="Module-13">genie::RadiativeCorrector/FSR</param>
  <param type="alg" name="ILstGen">genie::QELInteractionListGenerator/EM-Default</param>
</param_set>
Radiative Effects in GENIE

Results initial state electron energy
Radiative Effects in GENIE

Results

\[ p \]

\[ ^4\text{He} \]
Radiative Effects in GENIE

Results

\[ E_e = 3 \text{ GeV} \]
\[ E_e = 5 \text{ GeV} \]
\[ E_e = 7 \text{ GeV} \]
Radiative Effects in GENIE
Results $Q^2$ for events with scattering angle $> 5^\circ$
Radiative Effects in GENIE

Results
Radiative Effects in GENIE

Results - final state photon

\[ p \]

\[ ^4 \text{He} \]
Radiative Effects in GENIE

Current Status

Incubator Projects

Incubator projects are in-house development activities or community development efforts led by the GENIE WG Coordinators and overseen by the GENIE board. An incubator project is the unique route for any physics or software development into any of the GENIE suite products (Generator, Comparisons, Tuning).

This page serves the purpose of informing the community of the scope and breadth of the GENIE development programme. Community members that have a wish to contribute to GENIE and identify the need for a new project are strongly encouraged to contact the GENIE WG Coordinators who, upon fully defining the scope and specification, can launch new incubator projects.

Currently in incubation: 23 projects

- Project: radiative_effects_for_electron_scattering
  Description: Adding radiative effects to electron scattering processes in GENIE.
  Developers: Adi Ashkenazi (MIT)
  Reporting: NPWG
  Target release: GENIE/Generator v3.0.0
  Documentation: internal wiki

- Project: electron_scattering_form_factors
  Description: Update Form Factors (FFs) for electron scattering processes in GENIE, and enable future similar updates
  Developers: Adi Ashkenazi (MIT)
  Reporting: NPWG
  Target release: GENIE/Generator v3.0.0
  Documentation: internal wiki

p    He
Radiative Effects in GENIE

Future Steps

- Improve the ISR implementation:
  - Generate Q2 value
  - Calculate the energy loss,
  - Generate a new Q2 based on the new electron energy
  - Weight the event accordingly
- Compare simulation to Deuterium data, hopefully
- Add the complementary neutrino FSR case
- Update to newest published Form Factors
Back Up
Radiative Effects in GENIE

Data Comparison

FIG. 6. A series of measurements of the $^1$H cross section is shown. In the region below the pion-production threshold only the radiative tail of the elastic peak contributes. The solid line shows the predicted radiative tail found from the formalism of Mo and Tsai (Ref. 21) and a parametrization of previous $^1$H elastic scattering cross sections (Ref. 23). The agreement is found to be good, indicating that the radiative properties of the target are well understood and that no unexpected background exists.
Radiative Effects in GENIE

Data Comparison

![Graph showing data comparison between GENIE default and + radiative correction](image-url)
Radiative Effects

Theory

![Graph showing the dependence of \( \langle Q^2 \rangle \) on E [GeV]](image)

Note: there is a \( Q^2 > 0.02 \text{ GeV}^2 \) cut.

For this presentation I’ve taken the average \( Q^2 \) over all the range but for a specific comparison to an experiment we should take \( Q^2 \) for a given angular range.
Form Factors

electron scattering simulation is available for:
EM interaction only (no weak interaction)

The default Form Factor was compared to the AMT Form Factor

GENIE branch mit_formfactors was updated with a new class:
AMTFormFactorsModel

In order to use is one should modify ./config/UserPhysicsOptions.xml
with:

```xml
<param type="alg" name="ElasticFormFactorsModel"> genie::AMTFormFactorsModel </param>
```
Radiative Effects in GENIE

Results - $Q^2$

The difference between the different kinematics are not shown as most of the events are with very small scattering angle and high value of $Q^2$. The differences will be shown in the next slide.
Form Factors
Results EMQE ep

![Graph of cross-sections vs. electron energy](image)

- \( \sigma_{e,H} \) [10^{-38} cm^2]
- \( E_e \) [GeV]
- GENIE default FF
- AMT FF
Form Factors

Results EMQE $e^{40}$Ar

\[ \sigma_{e,A^{40}} [10^{-38} \text{ cm}^2] \]

\[ E_e [\text{GeV}] \]

- GENIE default FF
- AMT FF
2. Based on L. W. Mo and Y. S. Tsai, SLAC-PUB-380.

\[ I(E, \Delta E, t) = \frac{1}{E} \frac{\ln(\frac{E}{E-\Delta E})^{\frac{t}{\ln 2}} - 1}{\Gamma\left(\frac{t}{\ln 2}\right)} \]

where \( t \) is target thickness in radiation lengths
energy difference as limit to energy loss
Radiative Effects in GENIE
Results $E_e = 5$ GeV initial state electron energy
Radiative Effects in GENIE

Results

\[ p \quad ^4\text{He} \]
Radiative Effects in GENIE

Results
Radiative Effects in GENIE

Results - final state photon

\[ p \]  
\[ ^4 \text{He} \]
Radiative Effects in GENIE

Results - $Q^2$

$p$ and $^4$He data show the effect of radiative corrections on the cross-section as a function of $Q^2$.
Radiative Effects in GENIE
Results $Q^2$ for events with scattering angle $> 5^\circ$
Radiative Effects in GENIE

Results

$p$

${^4}\text{He}$
full range of energy loss
Radiative Effects in GENIE
Results $E_e = 5$ GeV initial state electron energy

$E_e = 3$ GeV
$E_e = 5$ GeV
$E_e = 7$ GeV

$p$

$^4$He
Radiative Effects in GENIE

Results

\[
E_e' - E_e = 10^{-9} - 10^{-6} [\text{GeV}]
\]

- For \( E_e = 3 \text{ GeV} \)
  - Solid line
  - + radiative correction
- For \( E_e = 5 \text{ GeV} \)
  - Dotted line
  - + radiative correction
- For \( E_e = 7 \text{ GeV} \)
  - Dashed line
  - + radiative correction

p

\( E_e = 3 \text{ GeV} \)
\( E_e = 5 \text{ GeV} \)
\( E_e = 7 \text{ GeV} \)

\(^4\text{He}\)

\( E_e' - E_e = 10^{-9} - 10^{-6} [\text{GeV}]
\]

\( E_e = 3 \text{ GeV} \)
\( E_e = 5 \text{ GeV} \)
\( E_e = 7 \text{ GeV} \)
Radiative Effects in GENIE

Results

\[ p \]

\[ ^4\text{He} \]
Radiative Effects in GENIE

Results - final state photon

![Graphs showing radiative effects for different energies](image)

- For protons ($p$), the graphs indicate the distribution of final state photon energies ($E_r$) for different incident energies ($E_i$), showing the effects of radiative corrections.
- For $^4$He, similar distributions are shown, highlighting the impact of radiative corrections on the final state photon energies.

These graphs illustrate the importance of accounting for radiative corrections in the final state photon spectra, especially at higher incident energies.
Radiative Effects in GENIE

Results - $Q^2$

$p$ and $^4\text{He}$
Radiative Effects in GENIE
Results $Q^2$ for events with scattering angle $> 5^\circ$