Penelope EM model as an option for Geant4 simulation in LarSoft

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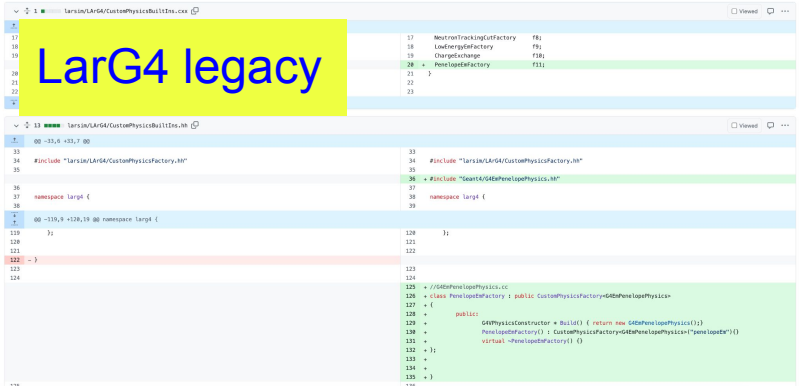
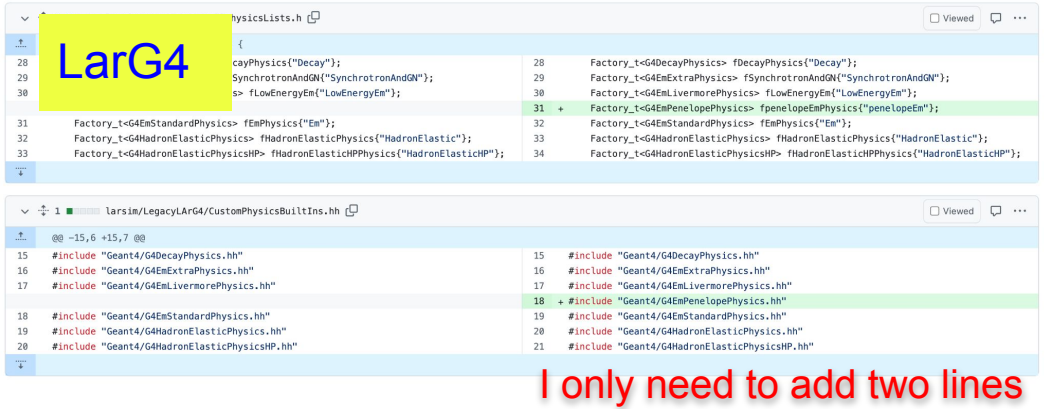
Add penelope EM model in MCC9/MCC10

- Geant4 provides many different EM model.
- LarG4 includes G4EmStandardPhysics and G4EmLivermorePhysics
- Additional EM model G4EmPenelopePhysics is added





- Detail of the code can be found in PR
  https://github.com/LArSoft/larsim/pull/139 (for MCC9)
  https://github.com/LArSoft/larsim/pull/140 (for MCC10)

EM model in Geant4

- **G4EmStandardPhysics**: The standard processes, which are optimized for high energy physics applications, often rely on parameterizations of data.
- **G4EmLivermorePhysics**: low energy processes make direct use of shell cross section data.
  - Atomic shell structure will be more important.
- The data used for the determination of cross-sections and for sampling of the final state are extracted from a set of publicly distributed evaluated data libraries:
  - EPDL97 (Evaluated Photons Data Library)
  - EPICS2014 (Evaluated Photons Data Library)
  - EPICS2017 (Evaluated Photons Data Library)
  - EEDL (Evaluated Electrons Data Library)
  - EADL (Evaluated Atomic Data Library)
  - Binding energy values based on data of Scofield

https://geant4.web.cern.ch/docs/

- The implementation of low energy processes is valid for elements with atomic number between 1 and 99, and for energies down to 10 eV, upper limit depends on the process.
  - For higher energies, the Standard models are used

Livermore data based model

- **Photon models**
  - Photo-electric effect (class `G4LivermorePhotoElectricModel`)
  - Polarized Photo-electric effect (class `G4LivermorePolarizedPhotoElectricModel`)
  - Compton scattering (class `G4LivermoreComptonModel`)
  - Compton scattering (class `G4LowEPComptonModel`)
  - Polarized Compton scattering (class `G4LivermorePolarizedComptonModel`)
  - Rayleigh scattering (class `G4LivermoreRayleighModel`)
  - Polarized Rayleigh scattering (class `G4LivermorePolarizedRayleighModel`)
  - Gamma conversion (also called pair production, class `G4LivermoreGammaConversionModel`)
  - Nuclear gamma conversion (class `G4LivermoreNuclearGammaConversionModel`)
  - Polarized gamma conversion (class `G4LivermorePolarizedGammaConversionModel`)
- **Electron models**
  - Bremsstrahlung (class `G4LivermoreBremsstrahlungModel`)
  - Ionisation and delta ray production (class `G4LivermoreIonisationModel`)

Penelope model in Geant4

- Penelope model is implemented according to the PENELOPE code (**PEN**etration and **E**nergy **LO**ss of **P**ositrons and **E**lectrons)
  - Specifically developed by the Barcelona group (F. Salvat et al.)
  - Great care was given to the low energy description (i.e. atomic effects, etc.)
  - Mixed approach: analytical, parametrized & database-driven
  - Includes also positrons (not described by Livermore models)
- In Geant4, G4EmPenelopePhysics provides reliable results for energies from 100 eV up to 1 GeV
  - For higher energies, the Standard models are used

Penelope 2008 based model

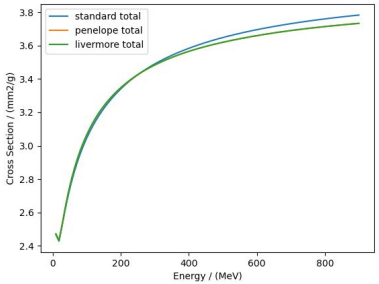
- **Photon models**
  - Compton scattering (class `G4PenelopeComptonModel`)
  - Rayleigh scattering (class `G4PenelopeRayleighModel`)
  - Gamma conversion (also called pair production, class `G4PenelopeGammaConversionModel`)
  - Photo-electric effect (class `G4PenelopePhotoElectricModel`)
- **Electron models**
  - Bremsstrahlung (class `G4PenelopeBremsstrahlungModel`)
  - Ionisation and delta ray production (class `G4PenelopeIonisationModel`)
- **Positron models**
  - Bremsstrahlung (class `G4PenelopeBremsstrahlungModel`)
  - Ionisation and delta ray production (class `G4PenelopeIonisationModel`)
  - Positron annihilation (class `G4PenelopeAnnihilationModel`)

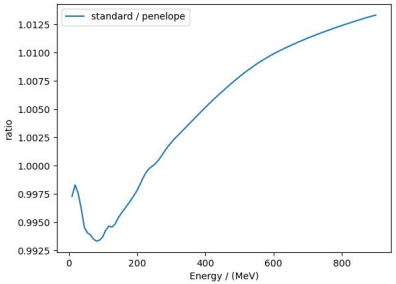
Simulation of positron

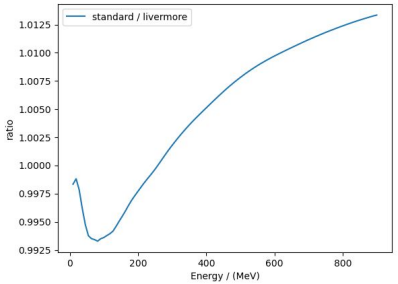
- In standard EM model, G4eplusAnnihilation performs the e+ e- annihilation when both particles are assumed at rest. It generates two back to back photons. The angular distribution is isotropic.
- Penelope model can simulation annihilation in flight. It is used a quantum theory of radiation from W. Heitler.

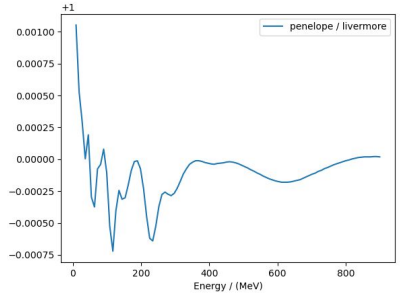
How large is the difference between different model in MicroBooNE range?

- At MicroBooNE, the energy range of photons from neutrino interaction is from few MeV to ~1 GeV
- The are about ~1% deviation of photon liquid-argon cross section among the EM models



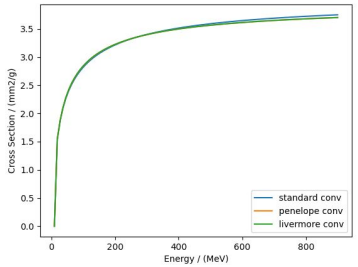


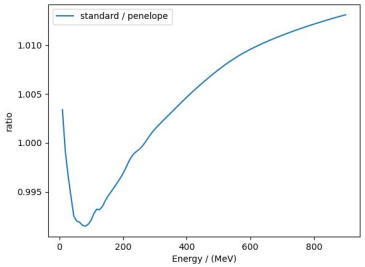


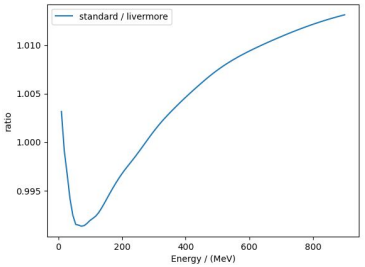


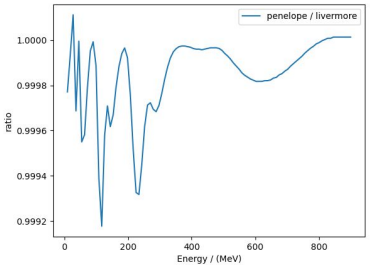
How large is the difference between different model in MicroBooNE range?

- For the Gamma Conversion scattering process

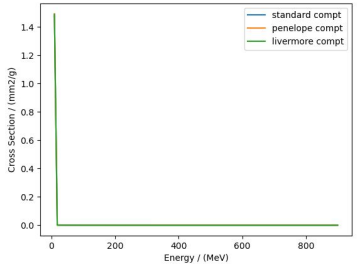


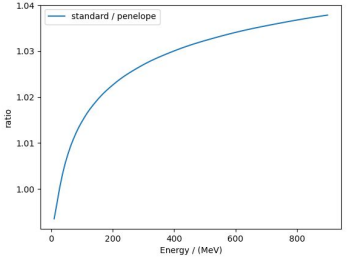


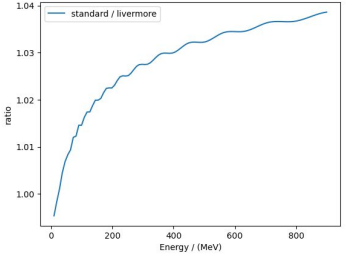


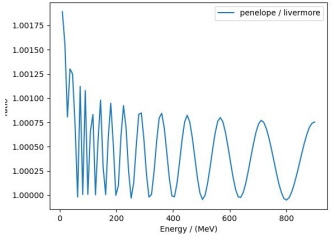


- For the Compton Scattering process









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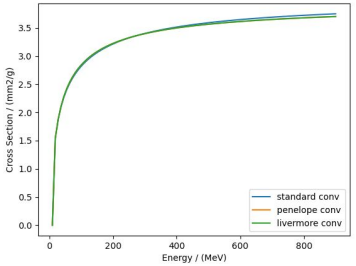
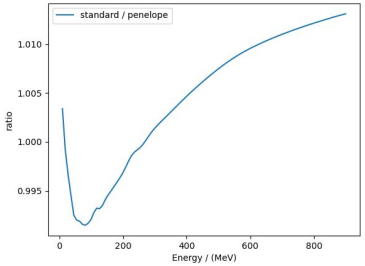
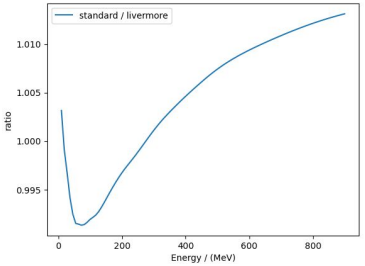
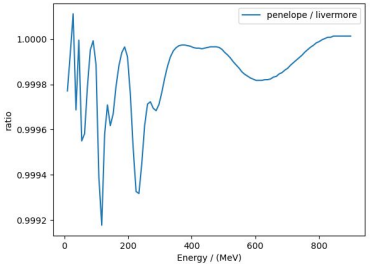
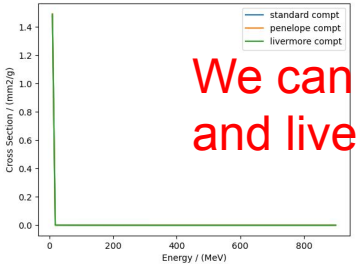


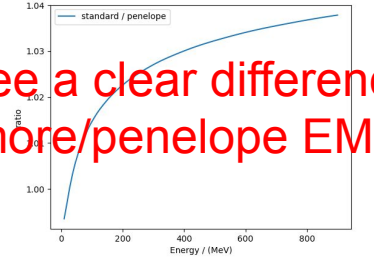


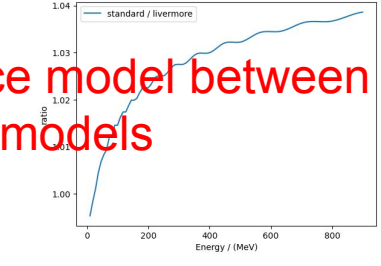


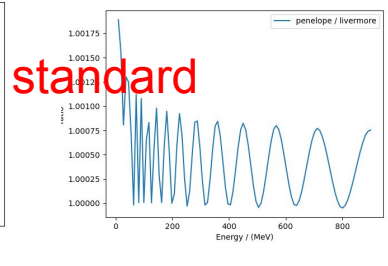


- For the Compton Scattering process









We can see a clear difference model between standard and livermore/penelope EM models

Geant4 EM physicslist

- In MCC9, the physicslist of Geant4 is configured in fhicl
  - services_microboone_simulation.fcl

```
microboone_g4_services.LArG4Parameters.EnabledPhysics:    [ "Em",
                                                            "FastOptical",
                                                            "SynchrotronAndGN",
                                                            "Ion",
                                                            "Hadron",
                                                            "Decay",
                                                            "HadronElastic",
                                                            "Stopping"]
                                                            # Save neutrons  #"NeutronTrackingCut" ]
```

- We can use the alternative EM models by
  - Em->LowEnergyEM
  - Em->penelopeEm

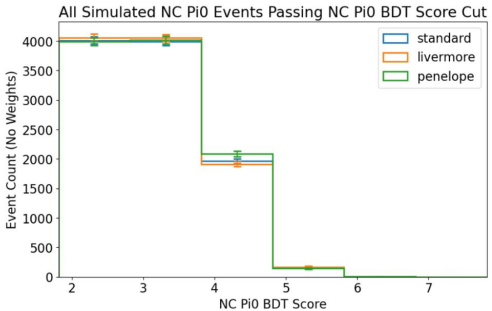
A test from MicroBooNE NCpi0 analysis

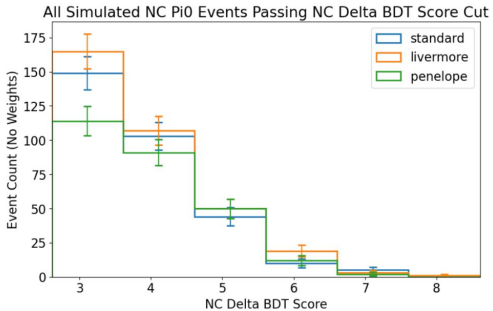
- Generated run1 MC samples and made ntuples: 28596 events in each file.

```
standard:  /exp/uboone/data/users/liangliu/Geant4/Ntuple/standard.root
livermore: /exp/uboone/data/users/liangliu/Geant4/Ntuple/livermore.root
penelope: /exp/uboone/data/users/liangliu/Geant4/Ntuple/penelope.root
```

BDT Score Distributions, Passing BDT Cuts

From Lee Hagaman





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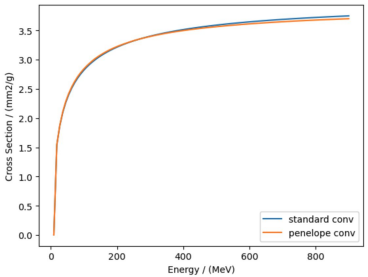
Summary

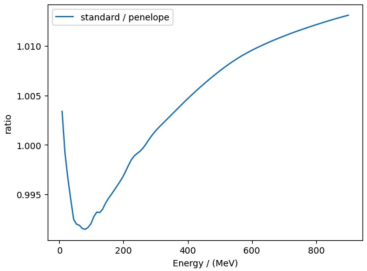
- There are ~1% deviation between the standard EM model and livermore/penelope EM model of photon liquid-argon cross section from 0 to 1 GeV. The Gamma Conversion is the dominant process in that energy range.
- Penelope EM model (G4EmPenelopePhysics) is added to larsim package.
- It can be used by modifying the fhicl files as alternative EM model in g4 simulation.
- The different EM models might lead to systematic effect in analysis involving photons or electrons in the final state.

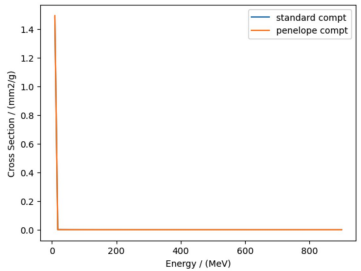
Backup

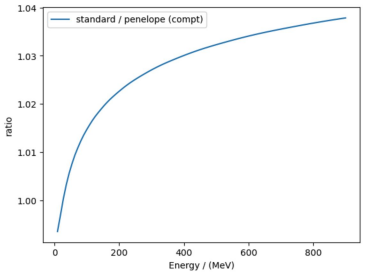
How large is the difference between different model in MicroBooNE range?

- New LEE analyses may be sensitive to details of EM modeling
- The systematic effects of the Geant4 EM model need to be revisited.
- There are ~1% difference of the g4 input conversion cross section between standard EM and penelope EM models at 0->900 MeV, more than 3% difference of the Compton scattering.









- The NCpi0 MC simulations with different EM models could tell us the impact of such difference.