MCC12 Neutron Tracking Cut

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Table of Contents

1 NeutronTrackingCut

2 Refactored LArG4

3 Backup

- Neutron Tracking cut limits the time and energy after which neutrons are tracked
- Can disable this by providing a custom physics list that excludes the **NeutronTrackingCut** physics
- Current cut is set to remove Neutrons with KE < 30 MeV
- **Note:** Neutron captures in ^{40}Ar produce gammas with Energy totalling 6MeV

Standard Physics List for ProtoDUNE

Standard

- Em
- FastOptical
- SynchrotronAndGN
- Ion
- Hadron
- Decay
- Hadronelastic
- Stopping
- NeutronTrackingCut

Proposed

- Em
- FastOptical
- SynchrotronAndGN
- Ion
- Hadron
- Decay
- Hadronelastic
- Stopping

- The following tables compare jobs run with the standard protoDUNE_g4_12ms_sce_datadriven.fcl vs. the same fhicl file without the NeutronTrackingCut

Comparison (10 Evt)

- CPU_HWM is the peak resident memory held by a process in RAM
  - job output refers to this as "VmHWM"

	g4_peak_CPU (MB)	detsim_peak_CPU (MB)	reco_peak_CPU (MB)
W/out NeutronCut	4190.0	3239.5	3843.5
With NeutronCut	4021.6	3145.8	3711.3
(W/out)-(With)	168.4	93.7	132.2

	g4_CPU_HWM (MB)	detsim_CPU_HWM (MB)	reco_CPU_HWM (MB)
W/out NeutronCut	3404.7	2597.2	2789.1
With NeutronCut	3149.1	2499.5	2665.5
(W/out)-(With)	255.6	97.7	123.6

	g4_CPU_time (s)	detsim_CPU_time (s)	reco_CPU_time (s)
W/out NeutronCut	1625.0	155.9	4142.8
With NeutronCut	1586.6	153.2	3881.4
(W/out)-(With)	38.4	2.7	261.4

	g4_Real_time (s)	detsim_Real_time (s)	reco_Real_time (s)
W/out NeutronCut	1678.6	177.2	3406.0
With NeutronCut	1695.0	214.0	3297.4
(W/out)-(With)	-16.42	-36.8	108.6

Percent change

- metric = CPU_vmHWM(MB) $\cdot$ CPU_time(s)

	g4_metric (MB·s)	detsim_metric (MB·s)	reco_metric (MB·s)
W/out NeutronCut	5532637	404903	11554807
With NeutronCut	4996362	382923	10345871
% change	+10.7	+5.7	+11.7

	g4_file_size (MB)	detsim_file_size (MB)	reco_file_size (MB)
W/out NeutronCut	1672	2345	2070
With NeutronCut	1595	2266	1984
(W/out)-(With)	77	79	86
% change	+4.8	+3.5	+4.3

Table of Contents

1 NeutronTrackingCut

2 Refactored LArG4

3 Backup

Refactored LArG4

Standard – **larsim/LArG4** AKA **Legacy**

- depends on nutools
- ConfigurablePhysicsList.h
- Optical simulation in Legacy was taken out of Geant and adapted from the Peter Gumplinger's original G4 implementations
  - **TheScintillationProcess** → SetScintillationYield()
  - there can be only one scintillating material in the optical simulation (LAr)

Refactored – **LArG4**

- depends on artg4tk (artg4 tool kit)
- Access to reference physics lists + extensions
- Updated OpticalPhysics in G4
  - scintillation properties are attached to the materials
  - can have any number of scintillating materials in the detector (e.g. LAr and plastic scintillator)

See Hans Wenzel's presentation from the DUNE collaboration meeting for a more comprehensive list of features and improvements of the refactored larg4 over Legacy: slides

Neutron Study

- Produced various samples of 10 MeV neutrons at the center of TPC1 (larsoft numbering, APA3-active)
- **Issue 1:** simb::MCParticle->EndProcess() for secondary neutrons often returns *FastScintillation*
- **Issue 2:** Some neutrons ending with FastScintillation processes come to rest in the ProtoDUNEFoam
- **Issue 3:** At rest neutrons subsequently decay... ($n \rightarrow p + e^{-} + \overline{\nu}_e$)
  - Neutron EndProcess is still marked as FastScintillation
  - simb::MCParticle→Process() for proton, e^{-}, and $\overline{\nu}_e$ returns *Decay*

```
root [16] NeutronAna->Scan("event:((pdg>1E9) ? (pdg-1E9) : pdg):TrackId:Mother:NumberDaughters:G4Process:G4FinalProcess:EndPointx:EndPointy:EndPoin
|| Mother==2) && (G4Process==\"Decay\" || TrackId==2)")
************************************************************************************************************************************
*    Row   * Instance *     event * ((pdg>1E9 *   TrackId *    Mother * NumberDau * G4Process * G4FinalPr * EndPointx * EndPointy * EndPointz *
************************************************************************************************************************************
*        3 *        1 *         4 *      2112 *         2 *         1 *        61 * neutronIn * FastScint * 17.854642 * 277.86615 * -83.53598 *
*        3 *       68 *         4 *      2212 *        69 *         2 *         0 *     Decay * FastScint * 17.854642 * 277.86615 * -83.53598 *
*        3 *       69 *         4 *       -12 *        70 *         2 *         0 *     Decay * CoupledTr * 1870.1999 * 1778.8261 * -827.6646 *
*        3 *       70 *         4 *        11 *        71 *         2 *         0 *     Decay * FastScint * 17.853923 * 277.33258 * -83.36968 *
************************************************************************************************************************************
```

Issues with Legacy

- TheScintilliationProcess is not defined as an *AlongStep* Process. . .
  - Rather, it is defined as both a *PostStep* and an *AtRest* process
  - Why?
- OpticalPhysics live in a “Parallel World(Geometry)” (_nowires.gdml)

```
    if (fTheScintillationProcess->IsApplicable(*particle)) {
  pmanager->AddProcess(fTheScintillationProcess);
  pmanager->SetProcessOrderingToLast(fTheScintillationProcess, idxAtRest);
  pmanager->SetProcessOrderingToLast(fTheScintillationProcess, idxPostStep);
  //  mf::LogInfo("OpticalPhysics")<<"OpticalPhysics : Scintillation applicable : " << particleName;
    }
```

Excerpt from the OpticalPhysics : G4VPhysicsConstuctor

First Attempt with ProtoDUNE

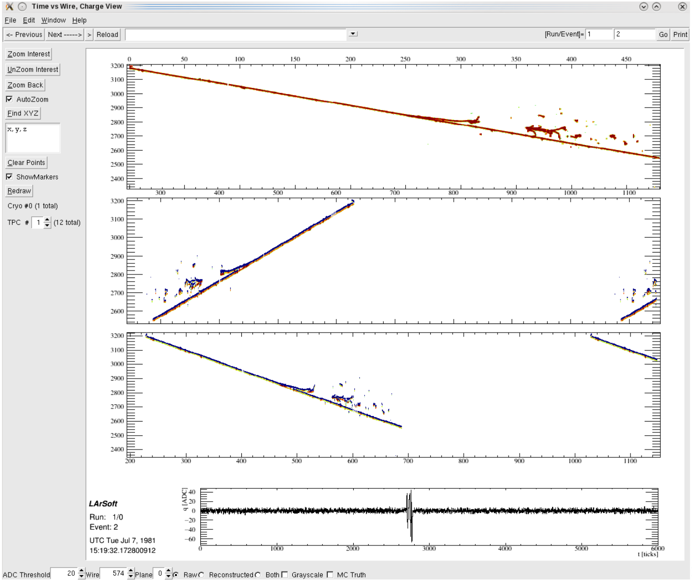
Penn University of Pennsylvania

- Hans provided an example refactorization of the 3x1x1 detector
  - see Larsoft Feature #22466
- Declared the Liquid Argon volumes as charge sensitive detectors
  - **protodune_v5_refactored.gdml**
  - **protodune_v5_refactored_nowires.gdml**
- Neglected the optical aspect of the simulation, for simplicity
- Redefined the protoDUNE services in the same spirit as the example provided by Hans
- Created corresponding G4→Reconstruction fhicl files
- Also a modified version of the protoDUNE event display fhcil
  - **protoDUNE_refactored_g4.fcl**
  - **protoDUNE_refactored_detsim.fcl**
  - **protoDUNE_refactored_reco.fcl**
  - **evd_refactored_protoDUNE.fcl**

```
<structure>
  <volume name="volTPCActive">
    <materialref ref="LAr"/>
    <solidref ref="InnerActive"/>
    <auxiliary auxtype="SensDet" auxvalue="SimEnergyDeposit"/>
    <auxiliary auxtype="StepLimit" auxvalue="0.01"/>
    <auxiliary auxtype="Efield" auxvalue="500."/>
  </volume>
```

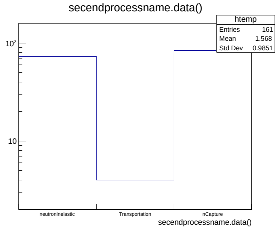
Inner Active TPC volume

Example Event : 6GeV μ^-

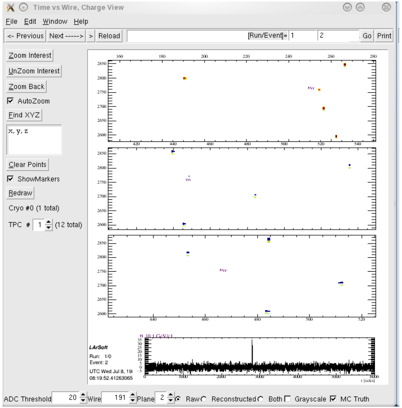


Revisiting the Neutron Simulations

- Disabled Neutron time-based cut
- Using the same gen stage input Root file, ran it through the refactored simulation chain
- Selected QGSP_BERT_HP reference physics list
- No more neutron decays!



EndProcess for 10MeV neutrons simulated in the refactored framework



To Do

```xml
<materials>
    <material name="LAr" formula="LAr">
        <property name="RINDEX" ref="ArINDEX"/>
        <property name="SLOWCOMPONENT" ref="SCINT"/>
        <property name="SCINTILLATIONYIELD" ref="SY" />
        <property name="RESOLUTIONSCALE" ref="RS" />
        <property name="SLOWTIMECONSTANT" ref="STC" />
        <property name="YIELDRATIO" ref="YR" />
        <D value="1.40" unit="g/cm3"/>
        <fraction n="1.0000" ref="G4_Ar"/>
    </material>
    <material name="Iron" formula="Iron">
        <property name="RINDEX" ref="ArINDEX"/>
        <D value="4.0" unit="g/cm3"/>
        <fraction n="1.0000" ref="G4_Fe"/>
    </material>
    <material name="Silicon" formula="Si">
        <property name="RINDEX" ref="ArINDEX"/>
        <D value="2.33" unit="g/cm3"/>
        <fraction n="1.0000" ref="G4_Si"/>
    </material>
    <element name="Oxygen"   formula="O"  Z="8.">
        <atom value="16.0"/>
    </element>
    <element name="Nitrogen" formula="N"  Z="7.">
        <atom value="14.01"/>
    </element>
    <element name="Fluorine" formula="F"  Z="9.">
        <atom value="18.9984032"/>
    </element>
    <element name="Lead"     formula="Pb" Z="82.">
        <atom value="207.20"/>
    </element>
    <material name="PbF2">
        <property name="RINDEX" ref="RINDEX"/>
        <D value="7.77" unit="g/cm3"/>
        <composite n="1" ref="Lead"/>
        <composite n="2" ref="Fluorine"/>
    </material>
</materials>
```

Optical materical properties

- Define the optical properties of the relevant materials in the geomtry file
- Consider ways to provide physical properties as configuration parameters for the G4 stage
  - E.g. for now the E-field is hard-coded in the geometry file
- Purge refactored services
- Continue validation process
- Compare resource usage between the new and the legacy frameworks
- Write up the process of switching to the refactored larg4 and make it available to other LArTPC experiments as an example with the full simulation chain (G4 $\rightarrow$ reconstruction)

The process of adding "new physics" to the Legacy LArG4 is quite convoluted, and prone to breaking changes. Paul Russo and I added the "HadronHP" (High Precision) physics alternative to the standard "Hadron" physics for the purpose of doing Neutron studies. Both handle the hadronic inelastic interactions.

- **HadronHP** – High Precision Inelastic Scattering for hadrons – added to larsim as of Feb. 25
- **HadronElasticHP** – High Precision Elastic Scattering (Neutrons only) (currently in feature branch)
- **HadronElasticPHP** – High Precision Elastic Scattering for various particles (currently in feature branch)

Conclusions

- Removal of the NeutronTrackingCut in MCC12 results in a ~10% increase in resources and ~5% increase in file size
- Legacy Optical Simulation is, as it stands, inadequate for High Precision neutron studies
- Geant4 and charge drift/readout simulation in the new framework looks promising
- Switching from Legacy (larsim/LArG4) to the refactored larg4 is quite straight-forward
- It is much easier to do a more thourough job of defining physics in the refactored larg4 than with Legacy (larsim/LArG4)

Many thanks to both Paul Russo and Hans Wenzel for their guidance and continued support.

Table of Contents

1 NeutronTrackingCut

2 Refactored LArG4

3 Backup

Refactored Physics Constructor

```
artg4tk::PhysicsListService::PhysicsListService(fhicl::ParameterSet const & p, art::ActivityRegistry &) :
  PhysicsListName_( p.get<std::string>("PhysicsListName","FTFP_BERT")),
  DumpList_( p.get<bool>("DumpList",false)),
  enableNeutronLimit_(p.get<bool>("enableNeutronLimit",true)),
  NeutronTimeLimit_(p.get<double>("NeutronTimeLimit",10.*microsecond)),
  NeutronKinELimit_(p.get<double>("NeutronKinELimit",0.0)),
  enableStepLimit_(p.get<bool>("enableStepLimit",true)),
  enableOptical_(p.get<bool>("enableOptical",true)),
  enableCerenkov_( p.get<bool>("enableCerenkov",false)),
  CerenkovStackPhotons_( p.get<bool>("CerenkovStackPhotons",false)),
  CerenkovMaxNumPhotons_(p.get<int>(" CerenkovMaxNumPhotons",100)),
  CerenkovMaxBetaChange_(p.get<double>("CerenkovMaxBetaChange",10.0)),
  CerenkovTrackSecondariesFirst_( p.get<bool>("CerenkovTrackSecondariesFirst",false)),
  enableScintillation_( p.get<bool>("enableScintillation",true)),
  ScintillationStackPhotons_( p.get<bool>("ScintillationStackPhotons",false)),
  ScintillationByParticleType_( p.get<bool>("ScintillationByParticleType",true)),
  ScintillationTrackInfo_( p.get<bool>("ScintillationTrackInfo",false)),
  ScintillationTrackSecondariesFirst_( p.get<bool>("ScintillationTrackSecondariesFirst",false)),
  enableAbsorption_( p.get<bool>("enableAbsorption",false)),
  enableRayleigh_( p.get<bool>("enableRayleigh",false)),
  enableMieHG_( p.get<bool>("enableMieHG",false)),
  enableBoundary_( p.get<bool>("enableBoundary",false)),
  enableWLS_( p.get<bool>("enableWLS",false)),
  BoundaryInvokeSD_( p.get<bool>("BoundaryInvokeSD",false)),
  verbositylevel_( p.get<int>("Verbosity",0)),
  WLSProfile_( p.get<std::string>("WLSProfile","delta"))
{}
```

OpFastScintillation

```
  ////////////
  // Methods
  ////////////

// AtRestDoIt
// ----------
//
  G4VParticleChange*
  OpFastScintillation::AtRestDoIt(const G4Track& aTrack, const G4Step& aStep)

  // This routine simply calls the equivalent PostStepDoIt since all the
  // necessary information resides in aStep.GetTotalEnergyDeposit()

  {
    return OpFastScintillation::PostStepDoIt(aTrack, aStep);
  }

// PostStepDoIt
// -------------
//
  G4VParticleChange*
  OpFastScintillation::PostStepDoIt(const G4Track& aTrack, const G4Step& aStep)
  // This routine is called for each tracking step of a charged particle
  // in a scintillator. A Poisson/Gauss-distributed number of photons is
  // generated according to the scintillation yield formula, distributed
  // evenly along the track segment and uniformly into 4pi.

  {
    aParticleChange.Initialize(aTrack);

    // Check that we are in a material with a properties table, if not
    // just return
    const G4Material* aMaterial = aTrack.GetMaterial();
    G4MaterialPropertiesTable* aMaterialPropertiesTable =
      aMaterial->GetMaterialPropertiesTable();
    if (!aMaterialPropertiesTable)
      return G4VRestDiscreteProcess::PostStepDoIt(aTrack, aStep);

    G4StepPoint* pPreStepPoint  = aStep.GetPreStepPoint();

    G4ThreeVector x0 = pPreStepPoint->GetPosition();
    G4ThreeVector p0 = aStep.GetDeltaPosition().unit();
```

G4 Printout

```
From G4:
    ********************************************************************************
    * G4Track Information:   Particle = neutron,   Track ID = 18,   Parent ID = 12
    ********************************************************************************

    Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
        0 -1.49e+03 4.39e+03      832     0.172        0        0         0 volTPCActiveInner_PV initStep
        1 -1.46e+03  4.4e+03      768     0.158        0     72.3      72.3 volTPCActiveInner_PV hadElastic
        2 -1.45e+03 4.39e+03      788     0.146        0     23.3      95.6 volTPCActiveInner_PV hadElastic
....
       86 -1.74e+03 5.82e+03     -643  3.43e-11        0     64.1  1.65e+04 volFoamPadding_PV hadElastic
       87 -1.72e+03 5.87e+03     -621  2.82e-11        0     53.8  1.65e+04 volFoamPadding_PV hadElastic
       88 -1.75e+03 5.86e+03     -604         0        0     30.8  1.65e+04 volFoamPadding_PV hadElastic
       89 -1.75e+03 5.86e+03     -604         0        0        0  1.65e+04 volFoamPadding_PV FastScintillation
```