SHMS Geant4 for Proton Absorption Correction

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Motivation

- Goal: calculate proton absorption correction for missed 3/4 triggers in the SHMS
- Previous estimates vary from 2 – 10 %
- Comparing with the spreadsheet estimate "SHMS_Proton_Absorption_jmatter.ods"
- Advantages of Geant4:

Spreadsheet	**Geant4**
Total cross-sections	Cross-sections with angular and energy dependencies
Proton absorption	Absorption for different particles (p+ / pi+ / K+)
All stopped particles considered missing triggers	Distinguish between stopped particles and missing triggers
One momentum	Encorporates δ variation across focal plane

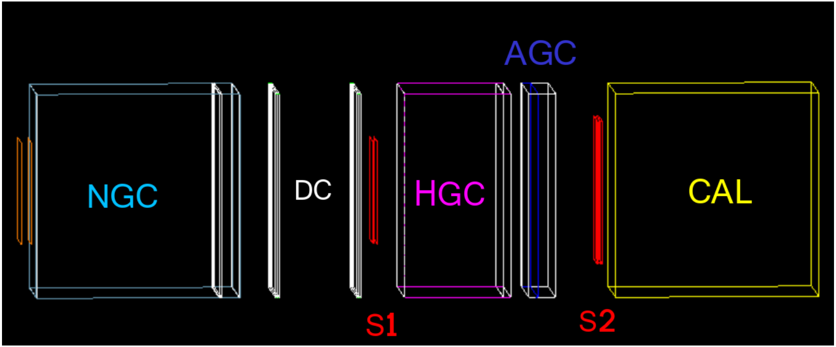
Simulation Overview

- Simple **Geant4** simulation **shmsPA**
- Based off of Geant4 example program **basic/B5**
- Physics list used is **FTFP_BERT** (current default) with added **G4OpticalPhysics** for Cherenkov process, and **G4EmLivermorePhysics** for more precise low-energy EM interactions
- Key classes:
  PADetectorConstruction (geometry)
  PAPrimaryGeneratorAction (event generation)
  PASteppingAction (actions taken per step)
- Geometry customizable: *detectors.dat* turns on/off NGC, specify aerogel tray

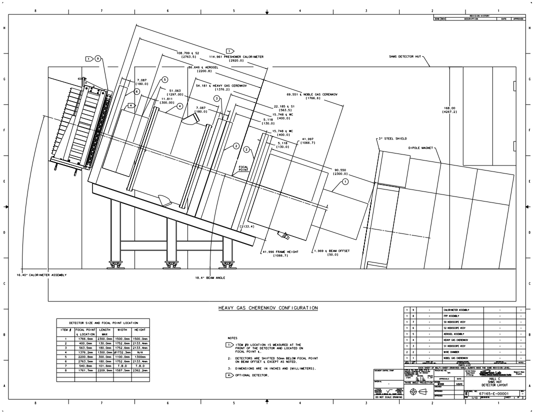
Code available here: github:acpostuma/shmsPA

Detector Construction

- Define materials: key features density & interaction lengths
- Define geometry: accurate z-dimensions and arbitrary (2×2 m) xy dimensions
- Semi-accurate z positions of each component



z-Positions



	t (cm)	z (cm)
NGC	200	-177
DC1	3.81	-40
DC2	3.81	40
S1X	0.50	56
S1Y	0.50	60
HGC	104.44	137
AGC	26.39	220
S2X	0.50	276
S2Y	2.50	280
Cal	200	392

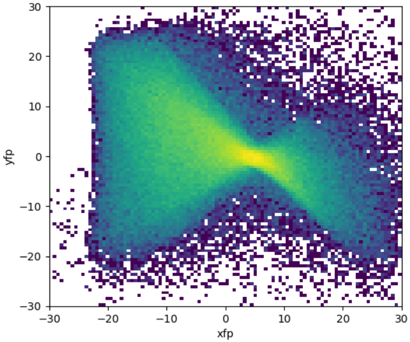
Materials Comparison

- Comparing nuclear interaction length, λ_I
- PDG source: https://pdg.lbl.gov/2004/reviews/atomicrpp.pdf
- Spreadsheet closer to PDG
- Note λ_I (cm) = λ_I (g/cm^2) $\div \rho$ (g/cm^3)

Material	Type	λ_I (cm)		
		Spreadsheet	Geant4	PDG
Al	G4Element	39.70	38.894	39.40
PVT	G4Material	78.77	69.969	78.97
Kapton	G4Material	60.20	55.82	60.42
Aerogel (n=1.030)	Custom	680.42	670.3	677.6
Mylar	Custom	61.08	56.32	61.65
LH2	Custom	742	484	717

Event Generation

Read in focal plane variables from real data (run 5055): *xfp, yfp, xpfp, ypfp, delta*



Simulate realistic trajectories through materials!

- Define focal plane as $z = 0$, then $xfp = x(0)$, $yfp = y(0)$
- $ztar$ is chosen as center of target
- Given $xpfp = dx/dz$ and $ypfp = dy/dz$, approximate positions at target as:

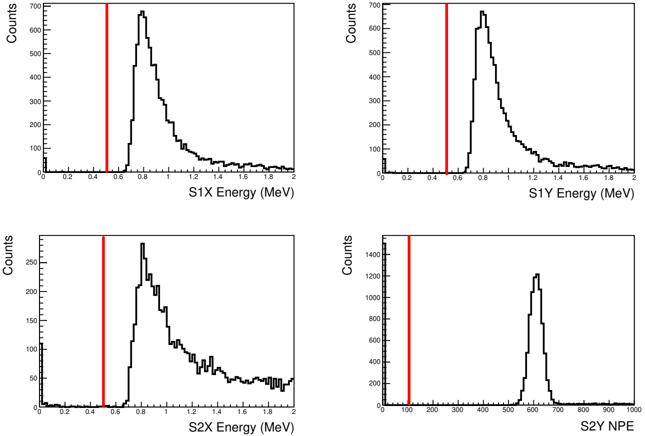
$$xtar = xfp + xpfp * ztar$$

$$ytar = yfp + ypfp * ztar$$

- Generate event at $(xtar, ytar, ztar)$ with momentum direction $(xpfp, ypfp, 1)$ and momentum $P_{\text{central}}(1 + delta/100)$

Simulation Output

- **PAHodoscopeSD**: records energy deposit and time of hit in each hodoscope
- **PASteppingAction**: records NPE in S2Y



Running Instructions

- Run interactive: *./build/shmsPA*
- Run in batch mode: *./build/shmsPA runPA.mac*
- Run ROOT script *CalcPA.C* on output file (takes filename as argument)

```
#runPA.mac
/run/initialize
/process/inactivate Decay pi+
/process/inactivate Decay kaon+
/run/physicsModified
/PA/generator/momentum 5 GeV
/PA/generator/useGenerated true
/PA/generator/setInFile
    run5055kine.txt
/gun/particle proton
/analysis/setFileName
    proton5GeV1000.root
/run/beamOn 1000
```

Simulated Trigger

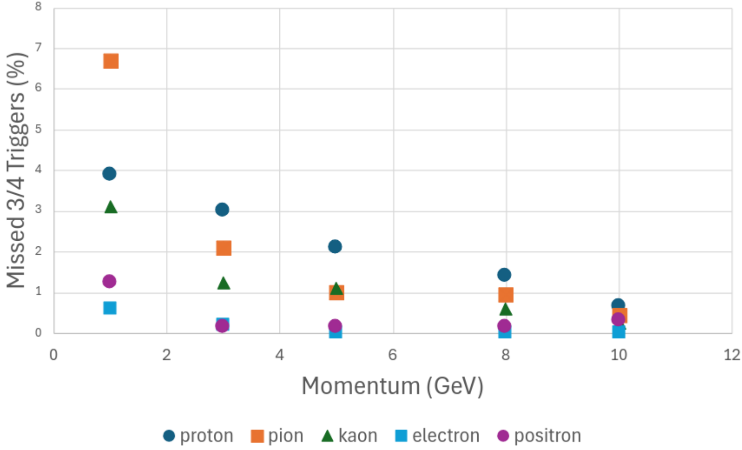
Simple 3/4 trigger on ROOT output. In event loop:

```
energy_threshold = 0.5 //MeV
npe_threshold = 100
time_window = 20; //ns
nTrig=0; //reset
//calculate time differences
dt1 = s1y_time - s1x_time;
dt2 = s2x_time - s1x_time;
dt3 = s2y_time - s1x_time;

//check hodoscopes
if (s1x_energy > energy_threshold) nTrig++;
if (s1y_energy > energy_threshold &&
    abs(dt1)<time_window)nTrig++;
if (s2x_energy > energy_threshold &&
    abs(dt2)<time_window)nTrig++;
if (NPE > npe_threshold)nTrig++;
//check 3/4
if (nTrig<3)nMissed++;
```

Momentum Dependence

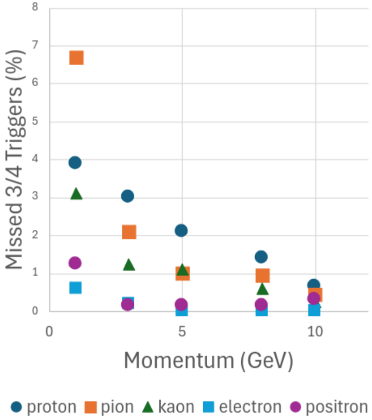
Calculate missed triggers for different SHMS momenta, particle type.
With no NGC, 2000 events/sample:



Momentum dependence is unexpected
→ should be roughly constant above 1 GeV.

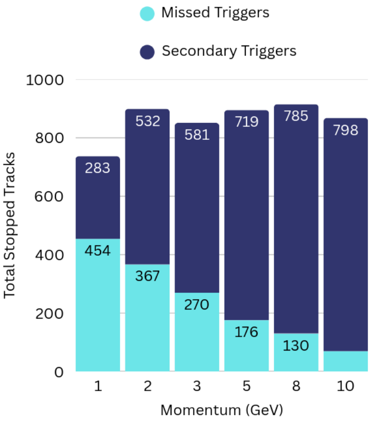
Particle Dependence

- Electron has very little absorption, as expected
- Positrons absorbed slightly more than electrons: annihilation
- Pion shows large absorption spike at 1 GeV - presumably from large pion absorption cross-section in resonance region
- SIMC already includes pion, kaon decay - turned off in simulation



Interesting Discovery

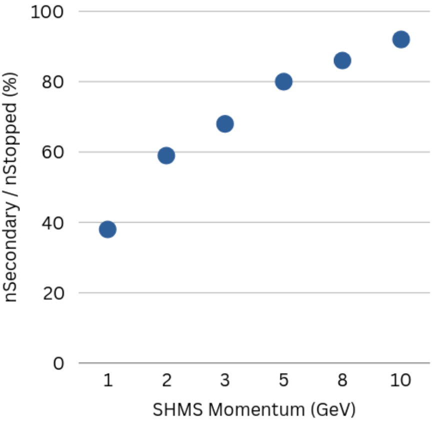
- Using Geant4 tracking information: similar number of primary p^+ tracks stop before S2Y, regardless of momentum
- However, missed 3/4 triggers are momentum dependent
- Some stopped tracks produce a secondary track
- The fraction of stopped tracks causing a trigger via a secondary particle is momentum dependent



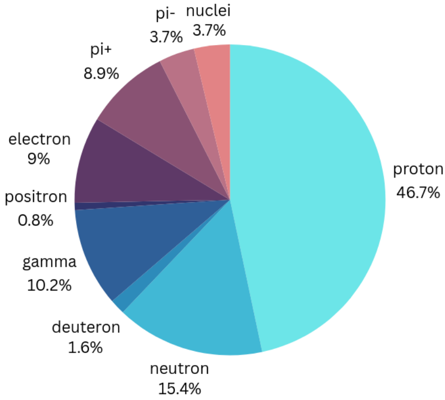
Total proton absorption ≈ 8.8% (with NGC) or 7.5% (no NGC) across $1 < P_{SHMS} < 10$ GeV

Secondary Tracks

Fraction of stopped tracks which still trigger via secondary track:



Type of secondary particle which causes a hit in a hodoscope:



Plots for proton as the incident particle. Right plot sums secondaries across momenta.

Where do Events Stop?

Compare percentage of **total stopped tracks** per volume (proton):

	Geant4	Calc
target	6.0	7.5
HB entrance	1.0	0.8
dipole exit	1.6	1.6
Noble Gas Cer	**14.6**	**14.1**
entrance	0.2	0.1
gas	3.4	3
mirror	7.6	8.3
support	3.4	2.9
exit	0.2	0.1
Drift Chambers	**3.6**	**4.8**
entrance	0	0.05
gas	0.2	0.07
wires	0.02	1.1
cathode	3.4	3.6
exit	0.04	0.05

	Geant4	Calc
Heavy Gas Cer	**28.7**	**27.7**
entrance	2.9	3.1
gas	14.7	13.2
mirror	8.3	8.3
exit	2.9	3.1
Aerogel Cer	**24.0**	**25.5**
entrance	3.6	4
tray (n=1.030)	15.6	16.2
air gap	0.3	0.3
exit	4.4	5
Hodoscopes	**20.5**	**17.1**
S1X	6.6	5.7
S1Y	7.5	5.7
S2X	6.4	5.7

“Proton Absorption" Correction

- So if most stopped tracks produce a secondary trigger, then what correction should be applied?
- Need to determine what fraction of secondary particles would pass PID cuts - added output to Geant4 tree

  NGCNPE: total NPE generated in NGC active volume

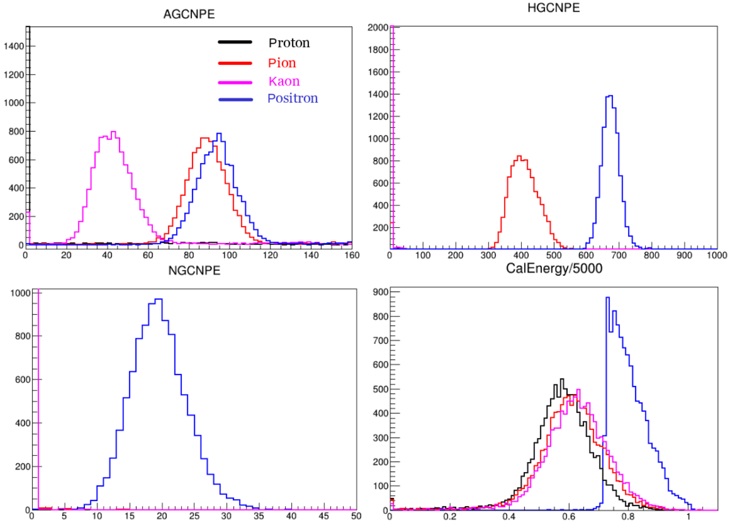
  HGCNPE: total NPE generated in HGC active volume

  AGCNPE: total NPE generated in aerogel tray

  CalEnergy: total energy deposited in calorimeter (MeV)
- Correction depends on input particle type:
  missed events = missed 3/4 triggers + 3/4 triggers with wrong PID
- Assuming Geant4 output represents true identity of secondary particle

Additional Output

At P=5 GeV, 10000 events/sample:



Track Classification

pion: AGC NPE > 10, HGC NPE > 10
kaon: AGC NPE > 10, HGC NPE < 10
proton: AGC NPE < 10, HGC NPE < 10
positron: NGC NPE > 5, AGC NPE >10, HGC NPE >10, CalEnergy/P > 0.7

No set of conditions satisfied: contaminated track (secondary of different type created partway through detector stack)

Preliminary Results

Input: 10K event sample, initial particle proton.

Correction: missed 3/4 triggers + 3/4 triggers with wrong PID

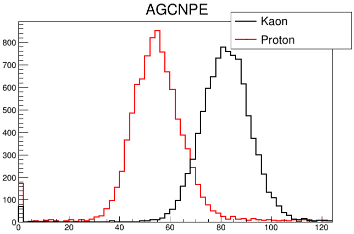
P (GeV)	Stopped tracks (%)	Missed triggers (%)	Correction (%)
2	8.75	4.44	5
3	8.43	3.14	4.76
5	8.23	1.79	6.45
8	9.49	1.28	**100**
10	8.39	0.92	**98**

Complications at High Momentum

- At SHMS momentum above 6.3 GeV, p/K discrimination becomes more difficult, since protons will Cherenkov in the aerogel
- Issue for both KaonLT and PionLT, e.g. for KaonLT Q^2=5.5, W=3.02, P_{SHMS}=6.755(low ϵ)/6.842(high ϵ)
- arXiv:1607.05264 (Horn et. al. AGC paper) "The tray combination will allow for identification of kaons from 1 GeV/c up to 7.2 GeV/c"

TABLE I: Threshold momenta P_{Th} for Čerenkov radiation for charged muons, pions, kaons, and protons in aerogel of four refractive indices ranging from n=1.011 to 1.030.

Particle	P_{Th} n=1.030	P_{Th} n=1.020	P_{Th} n=1.015	P_{Th} n=1.011
μ	0.428	0.526	0.608	0.711
π	0.565	0.692	0.803	0.935
K	2.000	2.453	2.840	3.315
p	3.802	4.667	5.379	6.307



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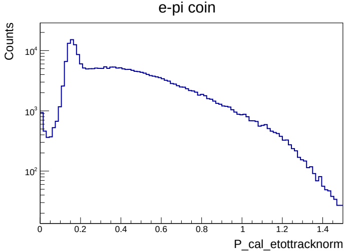
EXTRA SLIDES

S2Y Validation (In Progress)

- Lots of absorption in S2Y: around 6% of total events
- These events still form a 3/4 trigger, and could be used to validate simulation
- Need to determine how many events stopped in S2Y produce secondaries

KaonLT data (e.g. Q^2=3, W=3.14, shown right) shows spike at *P_cal_etottracknorm==0*, but with proper PID and MMpi. Could correspond to tracks stopping in S2Y, but corresponds to <1% of total.



With AGC, MMpi, coin time cuts

Event Generation Code

From PAPrimaryGeneratorAction::GeneratePrimaries(G4Event* event)

```
G4double P0 = fMomentum; //read central momentum
G4double Pmom = P0*(1.0+delta[nev]/100.); //event momentum
G4double Ekin = sqrt(Pmom*Pmom + mass*mass)-mass;

//calculate gun position, momentum
G4double posX = xfp[nev]/100. + xpfp[nev]*ztar; //x at ztar
G4double posY = yfp[nev]/100. +ypfp[nev]*ztar; //y at ztar
G4double momX = xpfp[nev]; //dx/dz
G4double momY = ypfp[nev]; //dy/dz
G4double momZ = 1; //dz/dz
auto Pvec = G4ThreeVector(momX, momY, momZ);
auto Xvec = G4ThreeVector(posX*m,posY*m,ztar*m);

//assign these quantities to the event
fParticleGun->SetParticleEnergy(Ekin);
fParticleGun->SetParticleMomentumDirection(Pvec);
fParticleGun->SetParticlePosition(Xvec);
```

Cherenkov Photon Counting

From PASteppingAction::UserSteppingAction(const G4Step* step)

```
// loop over secondaries, create statistics
const std::vector<const G4Track*>* secondaries =
   step->GetSecondaryInCurrentStep();

//count NPE this step
G4int npe_temp = 0;
for (auto sec : *secondaries) {
    if (sec->GetDynamicParticle()->GetParticleDefinition()
        == opticalphoton){
        if (sec->GetCreatorProcess()->GetProcessName().
        compare("Cerenkov")==0)npe_temp+=1;
    }
}
NPE+=npe_temp; //add to total NPE

//if end of track, fill ntuple with total NPE
if (step->IsLastStepInVolume())
    analysisManager->FillNtupleIColumn(8,NPE);
    NPE=0; //reset for next step
```