SNS Neutrino Flux

Rebecca Rapp
Carnegie Mellon University

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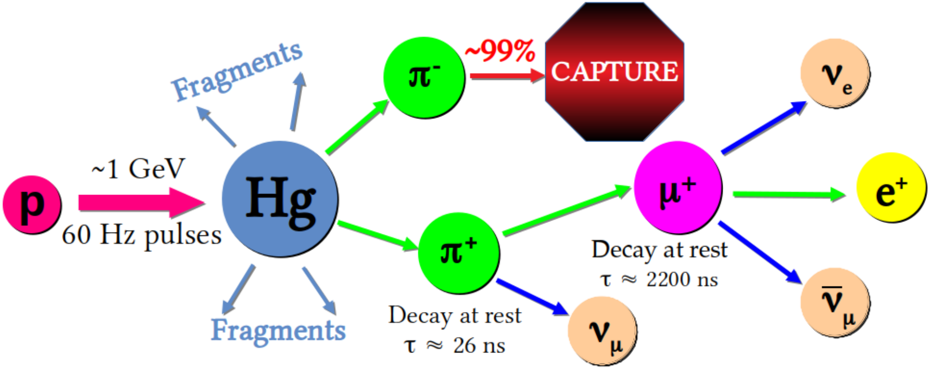
Fundamental Physics at the Second Target Station

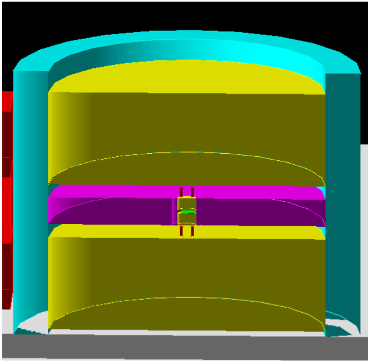
COHERENT SNS

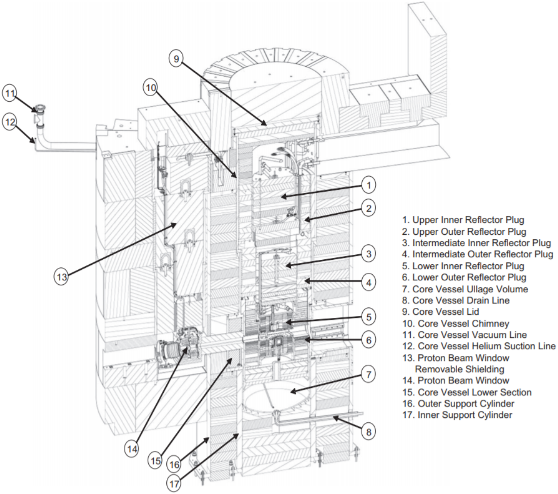
The Spallation ~~Neutron~~ NEUTRINO Source



- π^+ decay chain produces ν_μ, ν_e, and $\bar{\nu}_\mu$
- π^- decay chain prevented: mostly captured!
- If π^- decay, μ^- capture produces $\bar{\nu}_e$

ν production doesn't need the full, complex geometry!



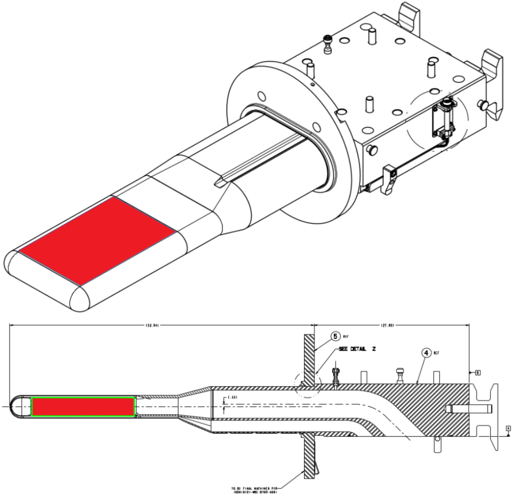


Simplified FTS to study:

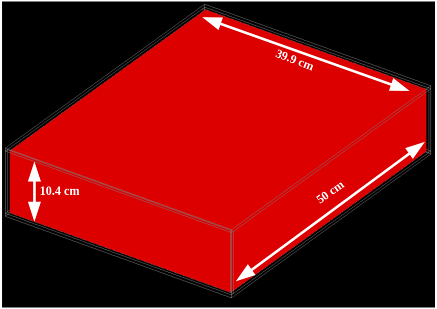
- ν production processes
- ν energy and timing

[1] J. Haines et al., "Spallation neutron source target station design, development, and commissioning", (2014).

Simulating the Target

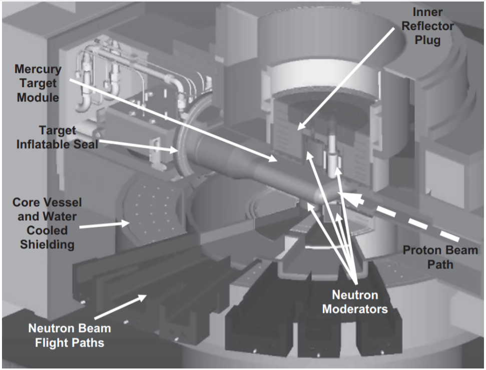


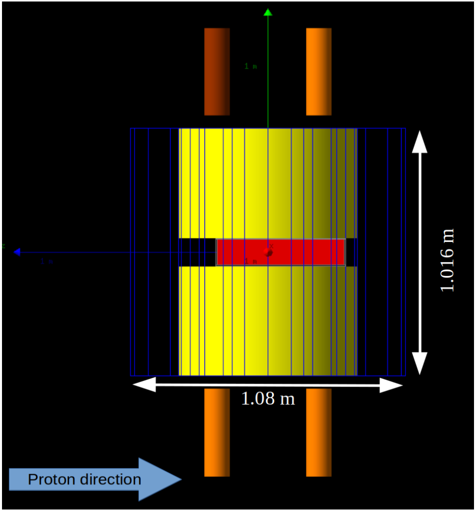
- Red: LHg target
- Green: Steel (95% Fe, 5% C)



[2] *ORNL Technical Drawings*, 2005.

Simulating the Target – Adding immediate surroundings

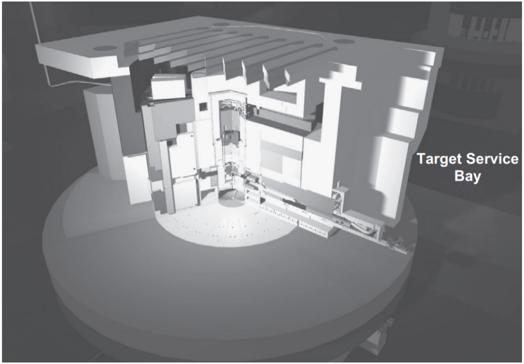


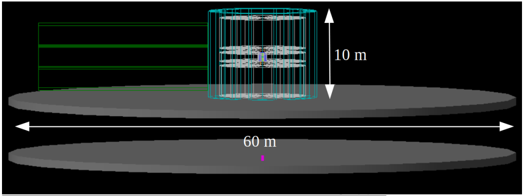


- ◇ Blue: 95% Steel, 5% D_2O Cylinder
- ◇ Yellow: 90% Be, 10% D_2O plugs
- ◇ Orange: LH_2 Moderators
- ◇ Brown: H_2O Moderator

[3] J. Haines et al., “Spallation neutron source target station design, development, and commissioning”, (2014).

Some larger structures are included

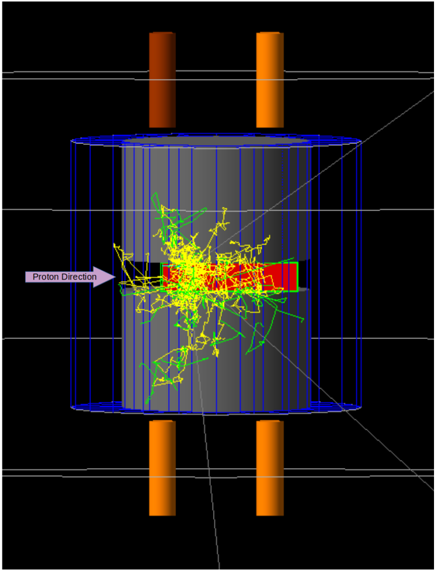


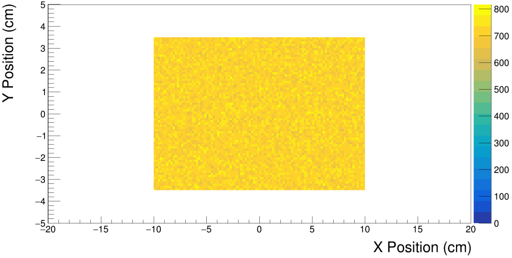


- White: Steel reflectors
- Cyan: Concrete room
- Gray: Concrete floors
- Pink: CsI location (as vacuum)
- Green: Proton beam shielding
- **Missing:** Proton beam window

[4] J. Haines et al., "Spallation neutron source target station design, development, and commissioning", (2014).

Generating Events



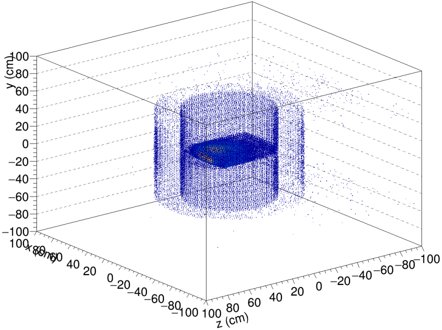


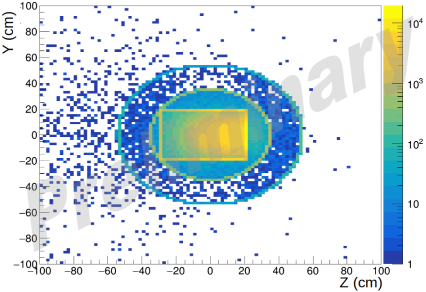
- ◇ Proton directed along $-z$
- ◇ $z = 20$ cm: edge of Hg target
- ◇ Distributed in xy across Hg target face
- ◇ Yellow track: neutron
- ◇ Green track: γ
- ◇ Gray track: ν

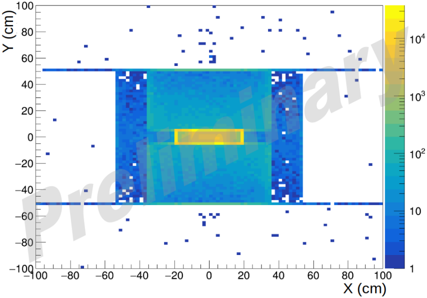
Computational Decisions

- Simulate individual, 1 GeV protons, use QGSP_BERT physics list
- Store information for ν and ν-producing particles (π, μ, K, Λ)
- Kill non-ν-producing particles after 1 m from target
- Output file size ~70 MB per million POT and contains:
  - Kinetic energy and direction at emission
  - Global time (time since $p + \text{Hg}$) at emission
  - Parent particle and creation process
  - Kinetic energy and global time at destruction
  - Destruction process
  - Coordinates of creation and destruction

ν Production Positions

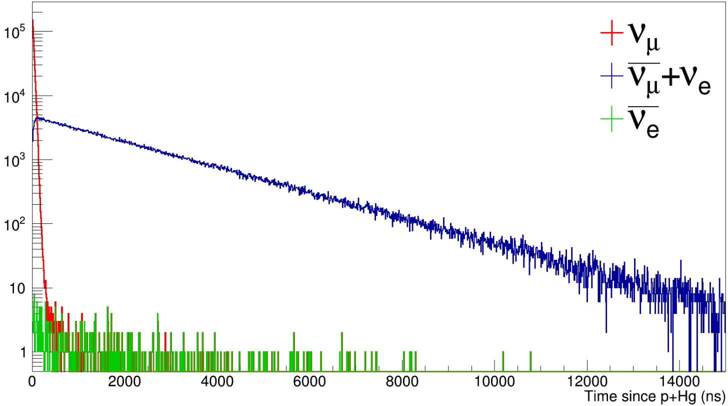






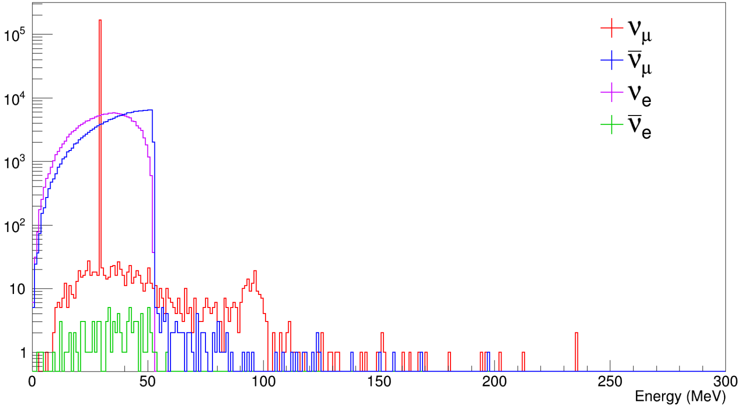
- ◇ ν produced primarily in Hg
- ◇ Some ν from the moderators
- ◇ Very few ν from outer volumes

Time of emission for SNS ν



- "Prompt" (ν_μ) and "Delayed" ($\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$) regions
- Exclude $\bar{\nu}_e$ produced more than 20 μs after $p + \text{Hg}$

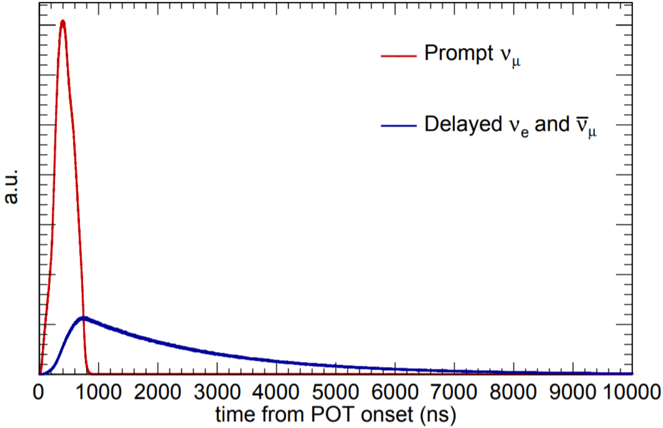
Energy Spectra for SNS ν created within 20 μs of p+Hg



- Most ν have energy between 0 and 50 MeV
- Small flux of $\bar{\nu}_e$ compared to other flavors

ν Timing from proton bunches

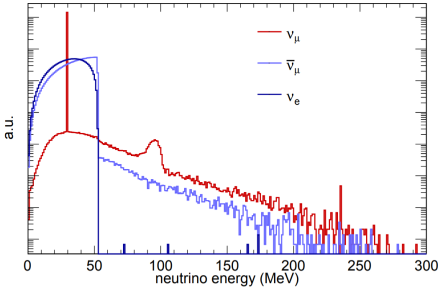
- Geant4 simulates one proton at a time, but SNS has 1 μs beam spills!
- Convolve simulation output with beam profile



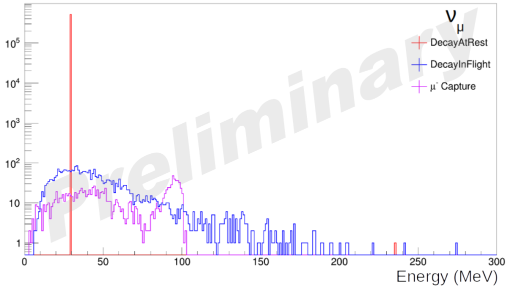
[5] D. Akimov et al., "COHERENT 2018 at the Spallation Neutron Source", arXiv:1803.09183v2, 2018.

Separating the ν Energy Spectrum

- $\sim$100 million protons-on-target
- Energy spectra for ν_μ, $\bar{\nu}_\mu$, and ν_e

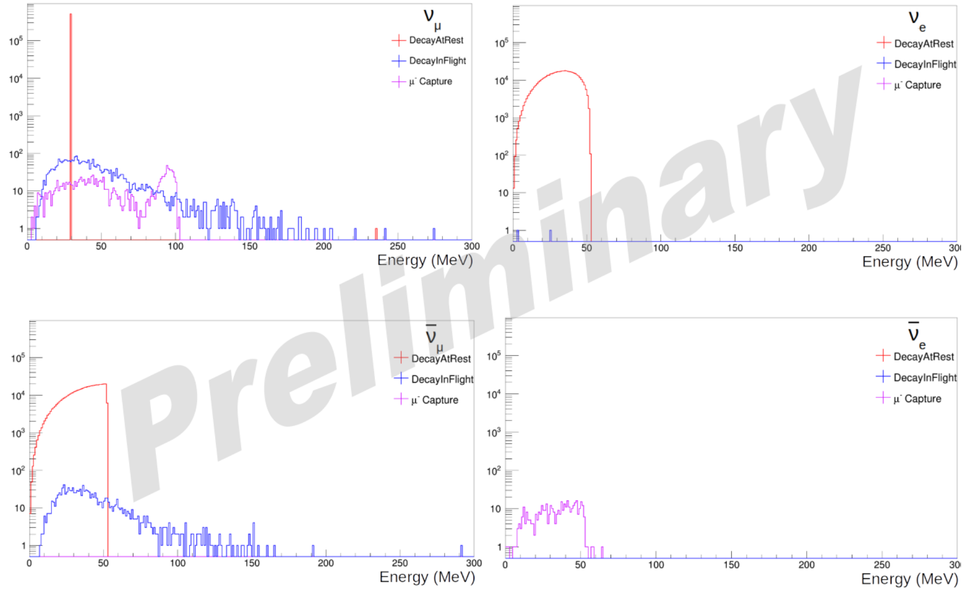


- $\sim$6 million protons-on-target
- Only ν_μ (Red line on left plot)



- **Goal:** Fit analytic form for decay-in-flight/μ^- flux contributions
- Use Michel spectrum to describe decay-at-rest contributions
- Much faster to convolve with the xscn than histograms

Separated Energy Spectra for all ν within 20 μs of p + Hg



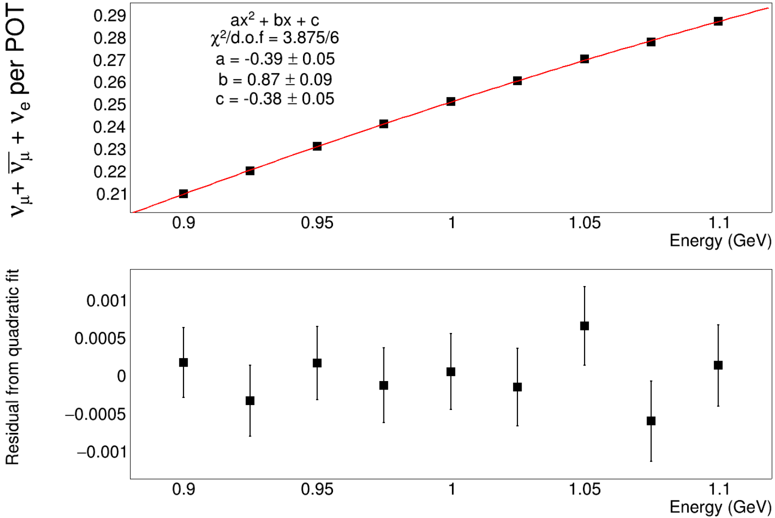
Breakdown of SNS ν production 20 μs of $p + \text{Hg}$

Particle	# per POT	DAR	DIF	μ^- Capture
ν_μ	0.08364	99.152%	0.605%	0.243%
$\bar{\nu}_\mu$	0.08364	99.757%	0.243%	0
ν_e	0.08344	99.9996%	0.0004%	0
$\bar{\nu}_e$	> 0.00006	0	0	100%

- Calculated from ~6 million protons on target
- Results are consistent with prior studies (~100 million protons-on-target)
- *Much* smaller DIF/μ^- capture contributions than other existing facilities
- $\bar{\nu}_e$ flux is likely larger; missing materials $\Longrightarrow$ missing β decays
- Using the simulation output, convert ν per POT into a more useable form:

$$4.3 \times 10^7 \ \nu/\text{cm}^2/\text{s at 20 m from the target}$$

ν flux depends on the proton energy



The uncertainty in our calculation

- **No data exists for $\pi^{\pm}$ production from 1 GeV protons on Hg**
- LAHET also implemented Bertini cascade model
- Discrepancies were found between LAHET and world data
- Assigned conservative 10% systematic on our calculated SNS ν flux
- Strategies:
  - Update comparisons of our simulation to world data
  - Compare our simulation to LAHET predictions
  - Contribute to world data: measure SNS ν flux

Improving ν flux uncertainty: Simulation

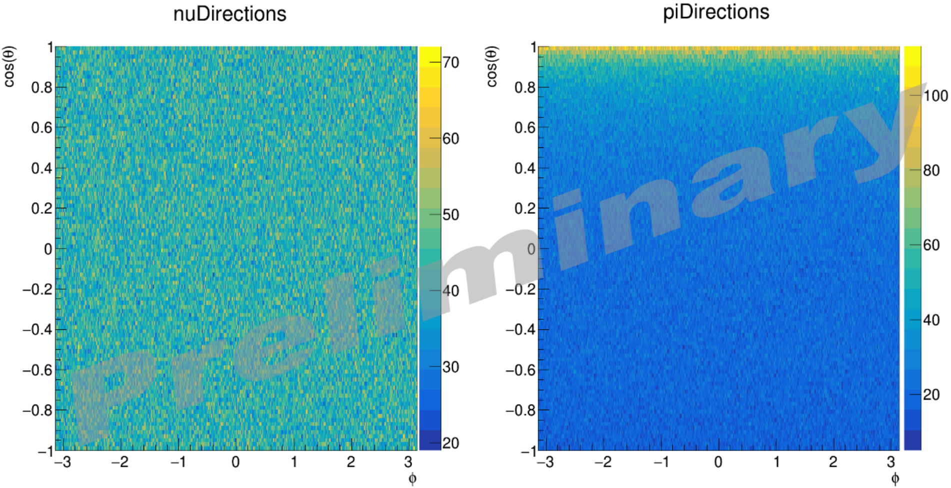
- HARP: measured $\pi^{\pm}$ production
  - Proton energies from 3 - 12 GeV
  - Limited $\pi^{\pm}$ momenta and production angle
  - Targets listed in righthand table
  - Comparisons to Geant4.7.1
  - Normalization between data/sim shown below

Beryllium
Carbon
Nitrogen
Oxygen
Aluminum
Copper
Tin
Tantalum
Lead

Model	Be (3 GeV)		Ta (3 GeV)		Be (5 GeV)		Ta (5 GeV)		Be (8 GeV)		Ta (8 GeV)		Be (12 GeV)		Ta (12 GeV)	
	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-
Bertini	0.35	1.02	0.45	0.53	0.70	1.12	0.29	0.35	1.22	1.54	0.84	1.08	1.75	1.81	1.27	1.50

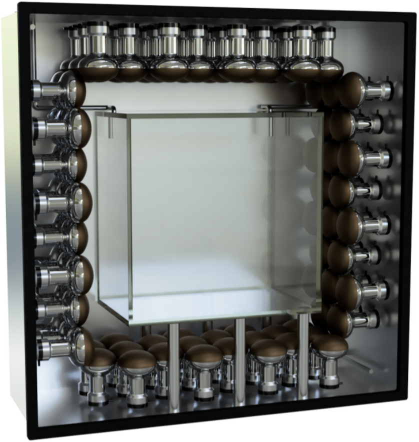
[6] M. Apollonio et al., "Forward production of charged pions with incident protons on nuclear targets at the CERN Proton Synchrotron", Phys. Rev. C **80** (2009).

Adding Direction Information



- ◇ ν created $<$ 1 m from origin – neglecting position effects for now
- ◇ **Goal:** Compare HARP data to Geant4.10.04 sim results

Improving ν flux uncertainty: Planned Experiment



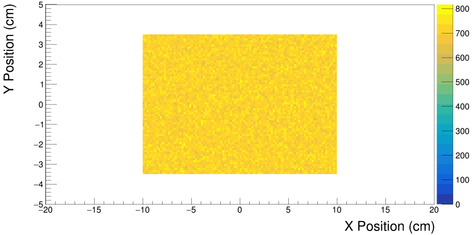
Mockup from Eric Day, CMU

- D$_2$O detector in Neutrino Alley
- Study $\nu_e + d \rightarrow p + p + e^-$
- Calculated 2-3% uncertainty on xscn
- $\# \nu_e \implies \# \mu^+ \implies \# \pi^+$
- $3 \times (\# \nu_e) \approx \# \nu_{\text{TOTAL}}$

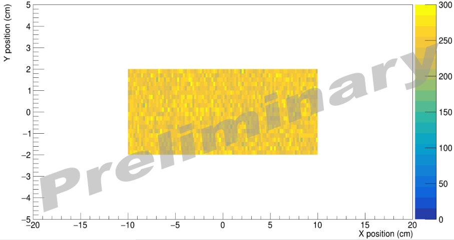
Evaluating STS Flux – Introducting a W target

- Need to change the geometry to represent the STS!
- First order estimate:
  - Change material from Hg to W
  - Shrink target to 6 cm thickness (alter beam profile)
  - Ramp up proton energy to 1.3 GeV
  - Keep FTS moderator suite
- ν production very similar to FTS – isotropic, stopped-pion, pulsed ν source

FTS Simulated Beam Profile



STS Simulated Beam Profile



Energy Upgrade – 1.3 GeV Protons

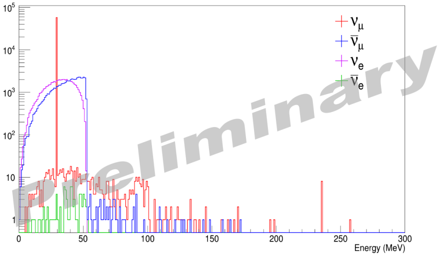
500000 POT, ν production within 20 μs of p + target

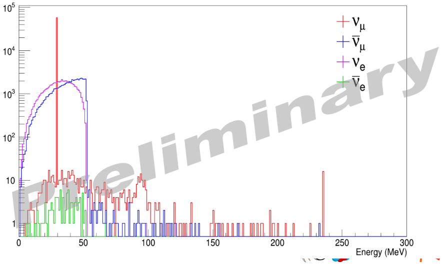
Hg target

Particle	# per POT	DAR
ν_μ	0.1164	98.74%
$\bar{\nu}_\mu$	0.1164	99.63%
ν_e	0.1159	100%
$\bar{\nu}_e$	$>$ 0.0002	0%

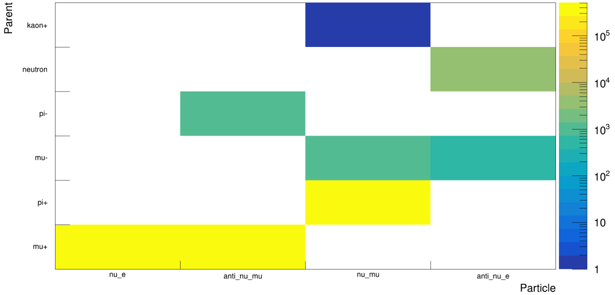
W target

Particle	# per POT	DAR
ν_μ	0.1167	98.81%
$\bar{\nu}_\mu$	0.1167	99.62%
ν_e	0.1162	100%
$\bar{\nu}_e$	$>$ 0.0002	0%



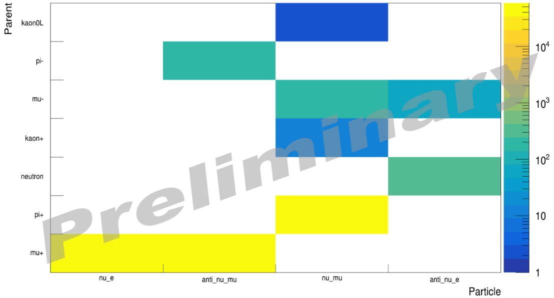


Effects of 1.3 GeV $p + \text{Hg}$ – ν Parents



1 GeV, 6.1 million POT

1.3 GeV, 0.5 million POT



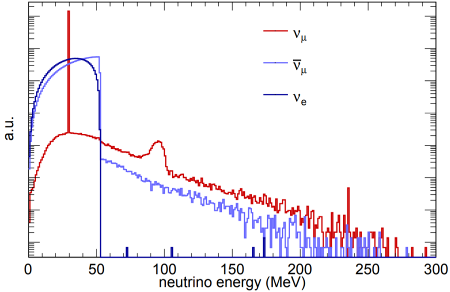
Summary

- ◇ Geant4 simulation is a useful tool for understanding the ν flux at the FTS
- ◇ The flux simulation has limitations – need to update world data
- ◇ Add proton beam window geometry to monitor proton energy loss
- ◇ "Easy" transition to STS: update geometry and proton energy
- ◇ Early estimate: ν production from $p + \mathrm{W}$ is similar to $p + \mathrm{Hg}$
- ◇ Actual production will depend on moderator suite – need to implement
- ◇ Advantage of STS: optimize shielding/location for ν physics

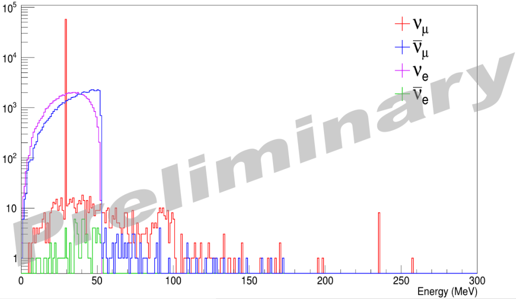
Thank You!

Backup Slides

Comparing Spectrum of 1 GeV and 1.3 GeV $p + \text{Hg}$

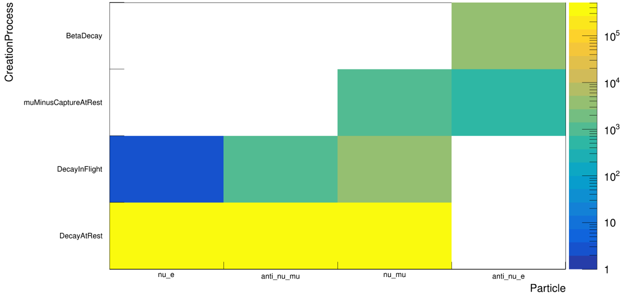


1 GeV, 100 million POT



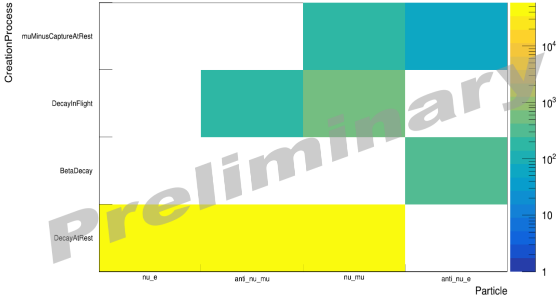
1.3 GeV, 0.5 million POT

Effects of 1.3 GeV $p + \mathrm{Hg} - \nu$ Creation Processes

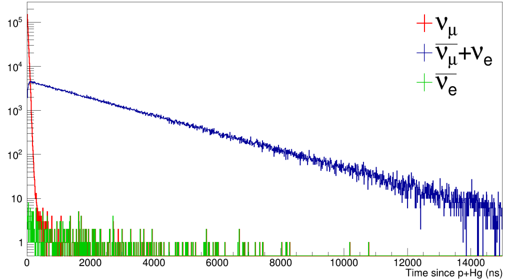


1 GeV, 6.1 million POT

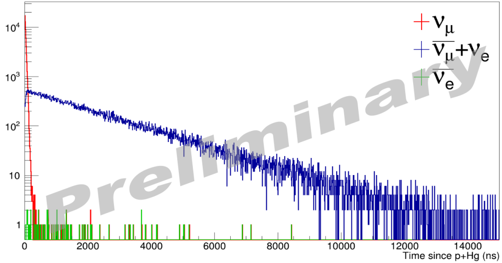
1.3 GeV, 0.5 million POT



Effects of 1.3 GeV $p + \text{Hg}$ – ν Timing

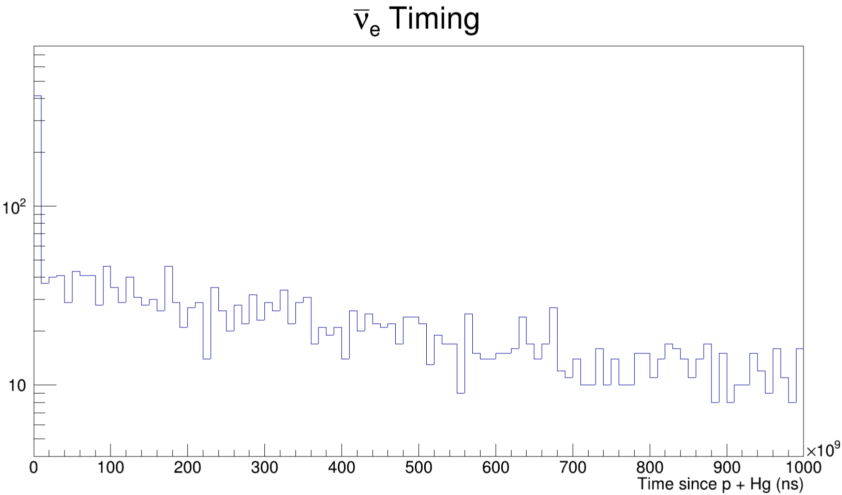


1 GeV, 6.1 million POT



1.3 GeV, 0.5 million POT

$\bar{\nu}_e$ Timing at FTS



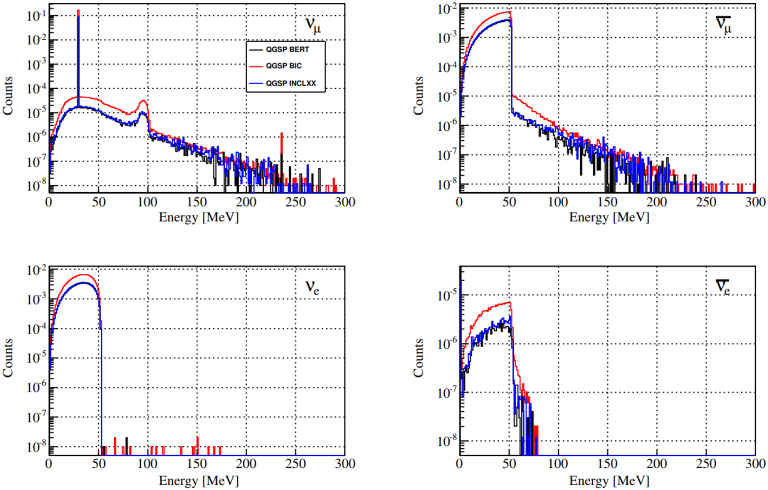
Geant4 Physics Lists: QGSP_???

◇ **Q**uark **G**luon **S**tring (E $>$ 10 GeV) + **P**recompound (E $<$ 150 MeV)

BERT	INCLXX	BIC
Applicable to proton, neutrons, pions, kaons, and hyperon in the energy range up to 10 GeV.	Applicable to nucleon-, pion- and light-ion-induced reactions in the kinetic-energy range up to 3 GeV.	Applicable to p, n in energy range upto 10 GeV and for pions up to 1.3 GeV.
Target nucleus is treated as an average nuclear medium.	Generates final states for inelastic scattering of nucleons, pions and light nuclei on nuclei. Well tested for spallation studies.	Target nucleus is modeled as a three dimensional and isotropic object.
The excitons (particle-hole) states are added after each collision.	C++ version of Liege Intra-nuclear cascade. Uses ABLA code for nuclear de-excitation.	The nucleons are placed in space according to nuclear density and the nucleon momentum is calculated according to Fermi gas model.
Path lengths of the nucleons in the nucleus are sampled according to the local density and free nucleon-nucleon cross sections.	Not applicable to light nuclei GEANT4 implementation is not yet well tested.	The primary particles interact with nucleons in binary collisions producing resonances which decay according to their lifetime producing secondary particles.
In the end of the cascade, the excited nucleus is represented as a sum of particle hole states, which is then decayed by pre-equilibrium, fission, and evaporation method.		The secondary particles re-scatter with nucleons creating a cascade.

[7] S. Agostinelli et al., "GEANT4: A Simulation toolkit", Nucl. Instrum. Meth. **A506**, 250–303 (2003).

Comparing Physics Options



QGSP_BERT chosen based on community validation efforts

[8] D. Rimal, M. McIntyre, and H. Ray, *SNS Neutrino Flux Simulation: Internal Technical Note*, 2015.