Impact of a NA61/SHINE Low-E Beamline on the COHERENT experiment

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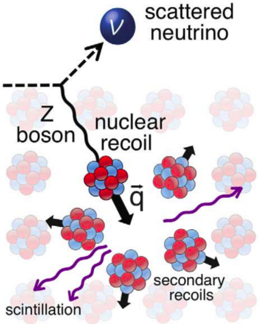
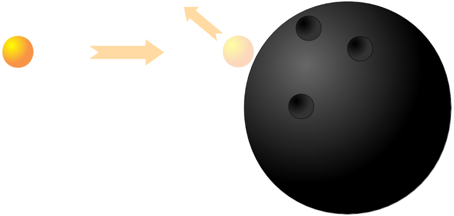
Presentation Outline

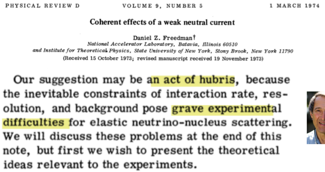
1. COHERENT and CEvNS
2. SNS Flux Simulations
3. Model validation efforts

Coherent elastic neutrino-nucleus scattering (CEvNS)

- ◇ Standard Model result: neutral-current process predicted in 1974
- ◇ No nuclear excitations, no changes to the neutrino or nucleus
- ◇ Only observable signature is the resulting nuclear recoil
- ◇ Experimental needs originally phrased as "an act of hubris":
  - ▷ Intense source of neutrinos to combat the interaction rate
  - ▷ Sensitivity to detect low-energy nuclear recoils ($\sim$10 keV)
  - ▷ Well-understood backgrounds to reject non-CEvNS events







PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

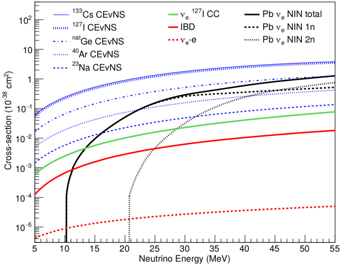
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

CEvNS Physics

$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$

- ◇ Flavor-blind interaction, with $qR < 1$
- ◇ Maximum recoil energy: $T_{\rm max} = 2E_\nu^2/(M + 2E_\nu)$
- ◇ Broad physics reach: SM tests, nuclear structure, ν properties, etc.
- ◇ Motivates detector R&D, quenching factor measurements, etc.

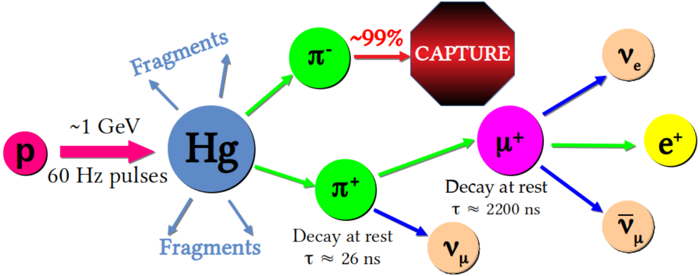


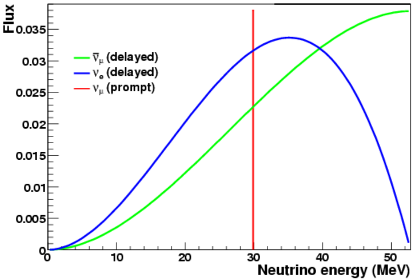
Word cloud from M. Caddedu (Magnificent CEvNS 2020)

The COHERENT Collaboration

- Formed 2013 to unambiguously measure CEvNS
- 20 institutions in USA, Canada, Russia, and South Korea

The Spallation Neutron Source at Oak Ridge National Laboratory

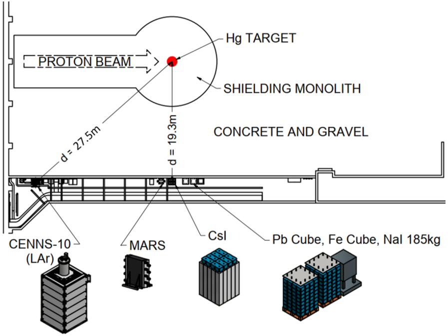


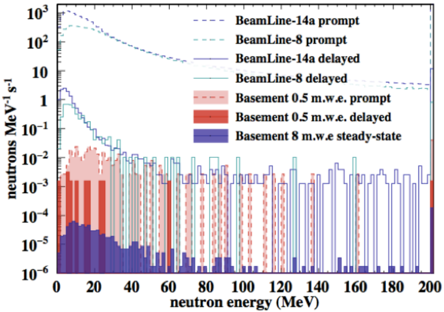


- ◇ 1.4 MW user facility at ORNL
- ◇ POT at 60 Hz, pulses ∼700 ns wide
- ◇ Pion decay-at-rest ν source
- ◇ **10% systematic on ν flux**

Neutrino Alley

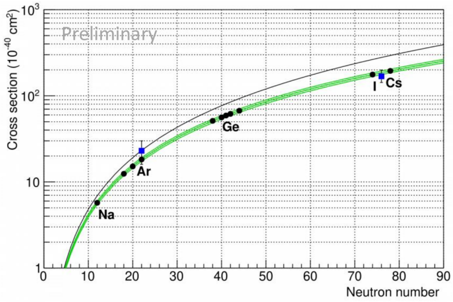
- Beam-related neutrons could cause similar signal to CEvNS
- Spallation process which creates π^+ also creates the neutrons
- Background study located a neutron-quiet hallway 20 m from the target
- Neutrino Alley: 8 m.w.e., 20 m of concrete/gravel shielding

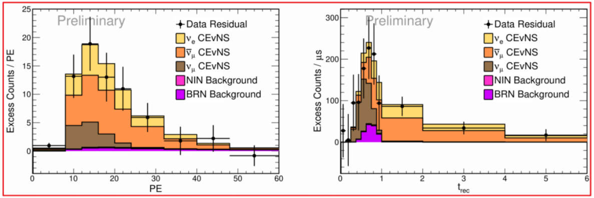


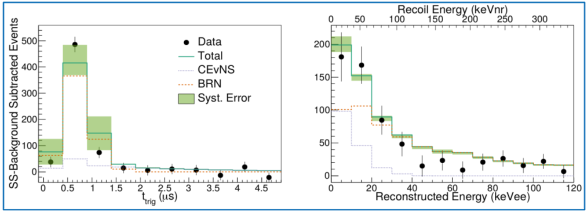


Collaboration Results and Plans

- ◇ 2017: First observation (6.7σ in CsI[Na])
  - ▷ 2020: Full dataset results above 10σ
- ◇ 2020: CEvNS in second detector (3.5σ in LAr)







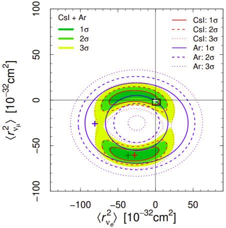
[1] A. Konovalov, "COHERENT at the SNS and CsI[Na] Effort Update", Magnificent CEvNS (2020).

[2] D. Pershey, "New Results from the COHERENT CsI[Na] Detector", Magnificent CEvNS (2020).

[3] D. Akimov et al., "First detection of coherent elastic neutrino-nucleus scattering on argon", in press at PRL (2020).

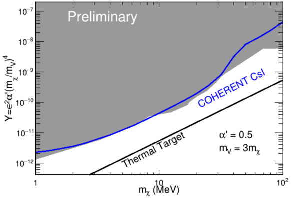
Impact of the first CEvNS Observations

ν Properties



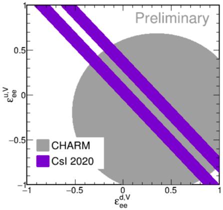
Plot from arXiv:2005.01645

Accelerator DM



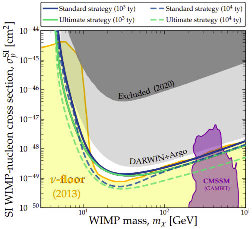
Plot from Magnificent CEvNS 2020

Non-standard Interactions



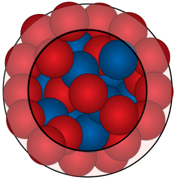
Plot from Magnificent CEvNS 2020

WIMP Background



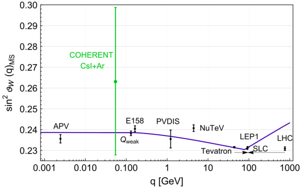
Plot from arXiv:2002.07499

Neutron Distribution



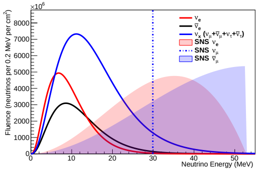
Details in arXiv:2005.01645

Weak Mixing Angle



Plot from arXiv:2005.01645

Supernova Neutrinos



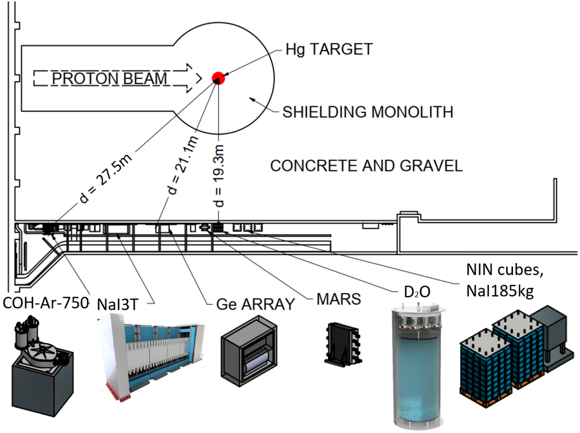
Plot from K. Scholberg

- Sterile searches
- Monitor reactors
- Non-proliferation

⋮

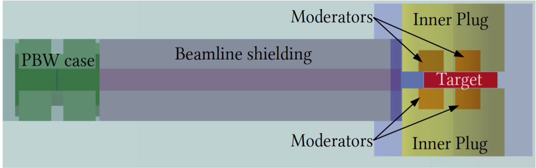
What comes next?

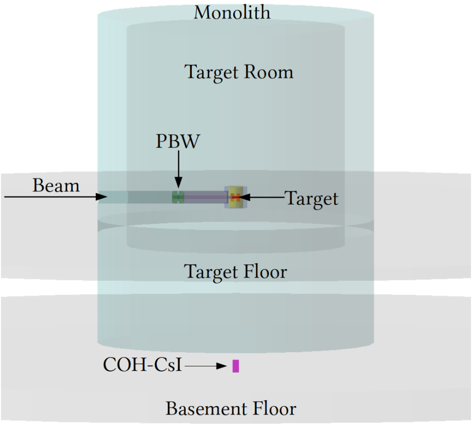
- Precision CEvNS:
  - Larger, more sensitive detectors
  - **Reduce neutrino flux systematic**
  - Improve background characterization
- Additional cross-section measurements:
  - CC interactions for supernova detection
  - Neutrino-induced-neutrons in shielding



Simulating the Spallation Neutr*ino* Source

- Geant4 Simulation of the Spallation Neutron Source
- Simplified geometric model from ORNL tech drawings
- **Goal:** model ν production from 1 GeV p interactions
- Model similar to LAHET, assigned 10% systematic



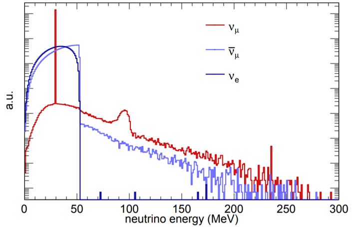


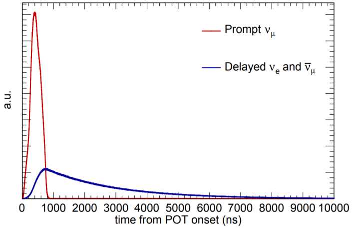
FTS ν Production: Flux, Breakdown, and Spectra

- With 1.011 GeV protons, simulations predict 0.265 ν/POT
- SNS capability of 1.55×10^{14} p/pulse $\implies$ $2.5 \times 10^{15} \nu$/s

	ν / POT	DAR %	DIF %	μ^- Cap or DIO %	β Decay %
ν_μ	0.0886	98.9362	0.7768	0.2869	—
$\bar{\nu}_\mu$	0.0886	99.7115	0.2885	—	—
ν_e	0.0884	99.9988	0.0012	—	—
$\bar{\nu}_e$	0.0001	—	0.2075	73.2126	26.5799

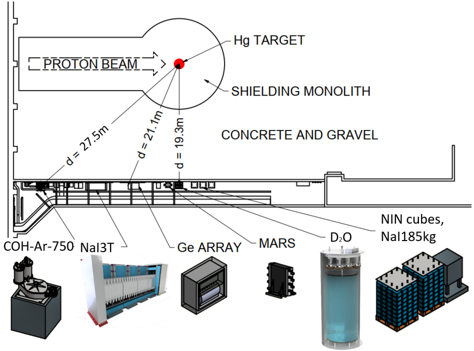
	π^+ %	μ^+ %	π^- %	μ^- %	K^+ %	n %
ν_μ	99.7125	—	—	0.2872	0.0003	—
$\bar{\nu}_\mu$	—	99.7127	0.2873	—	—	—
ν_e	—	99.9999	—	—	0.0001	—
$\bar{\nu}_e$	—	—	—	73.4201	—	26.5799

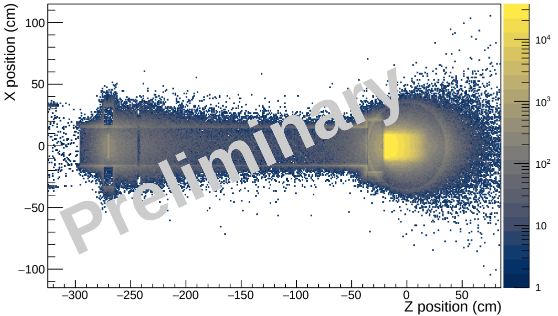


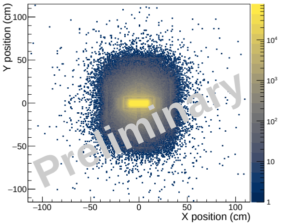


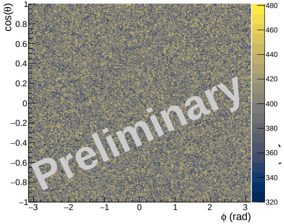
FTS ν Production: Position and Angular Distributions

- ν primarily produced within 1 m of the target
- COHERENT detectors $\sim$20 m from target
- Working to quantify position-related effects



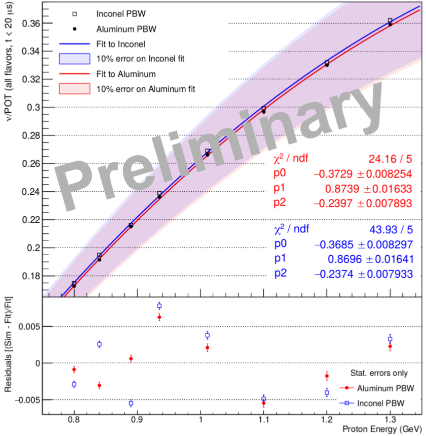




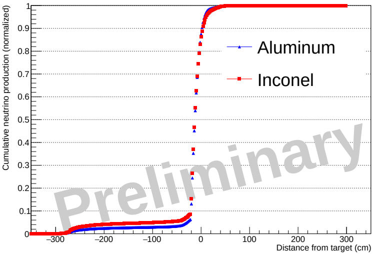


FTS ν Production: Dependence on PBW and Proton Energy

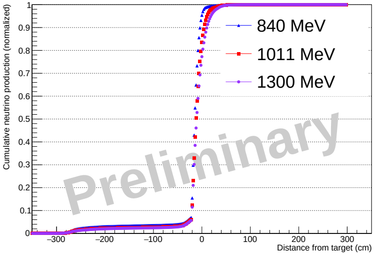
- The proton-beam-window has featured multiple designs:
  - Inconel films from April 2006 – January 2017
  - Aluminum plate from January 2017 – April 2020
  - Inconel design from April 2020 – present
- Proton energy for COHERENT runtime $\in$ [800, 1011] MeV
- Proton Power Upgrade: Energy increase 1.3 GeV by 2024



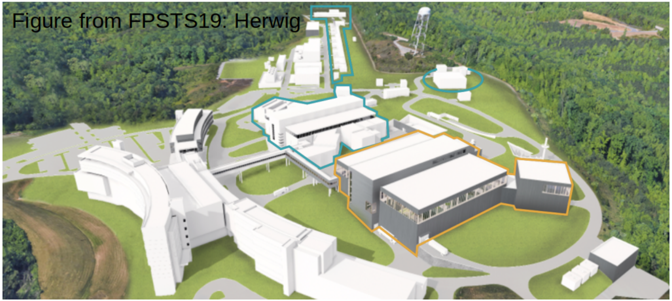
1.011 GeV p, varied PBW:

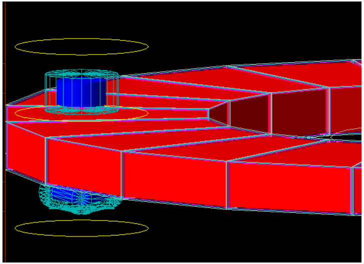


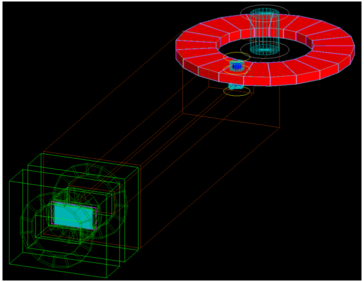
Aluminum PBW, varied energy:



SNS Second Target Station







- ◇ Known details from FPSTS-19 Workshop, much unknown
- ◇ 21-wedge rotating target assembly made of dense W
- ◇ Neutron moderators on top of active target wedge
- ◇ POT at 15 Hz, 1.3 GeV protons, pion decay-at-rest source
- ◇ With aluminum PBW design, preliminary 0.14 $\{\nu_\mu, \bar{\nu}_\mu, \nu_e\}$ / POT

Physics model validations

- **No data for pion production on Hg from 1 GeV incident protons**
- The Hadron Production Experiment ran at CERN's Proton Synchrotron from 2000 - 2002
  - Measured pion production from proton-nucleus collisions at varied beam energies
  - TPC calibration considerations generated a subgroup: HARP-CDP
  - We compare our simulations to the 3 GeV results for both HARP and HARP-CDP

- Test the following precompounded Geant4.10.06 physics lists to validate their pion production:

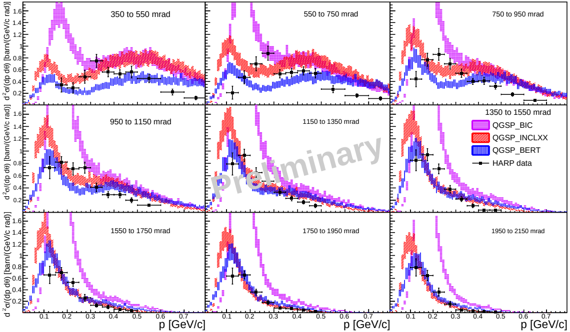
QGSP_BERT
- Bertini Cascade
- Recommended for hadrons
- Nucleus modeled as the sum of particle-hole states

QGSP_BIC
- Binary Cascade
- Fermi gas model of nuclei
- More secondary production of protons and neutrons

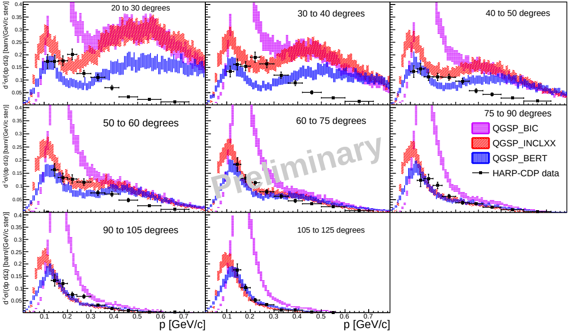
QGSP_INCLXX
- Liege Intranuclear Cascade
- Well tested for spallation
- Geant4 implementation not tested for light nuclei

HARP and HARP-CDP Double Differential Comparisons

HARP



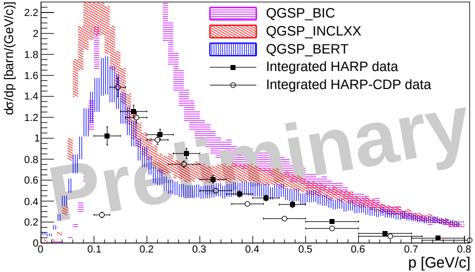
HARP-CDP

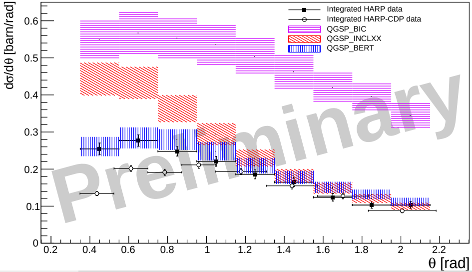


- ◇ HARP and HARP-CDP analyses use different binning choices
- ◇ 10% uncertainty on simulation predictions shown

HARP and HARP-CDP Single Differential Comparisons

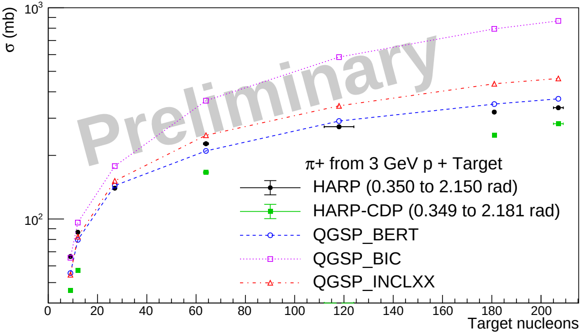
- ◇ SNS: π^+ stop and decay-at-rest inside the dense Hg
- ◇ Our ν flux is insensitive to both angle and momentum
- ◇ Integrations: $\theta \in [0.35, 2.15]$ rad and $p \in [0.1, 0.8]$ GeV/c
- ◇ No physics list predicts shape of $d\sigma/dp$ of Pb
- ◇ QGSP_INCLXX poorly predicts shape of $d\sigma/d\theta$ of Pb
- ◇ QGSP_BIC demonstrates poor overall normalization

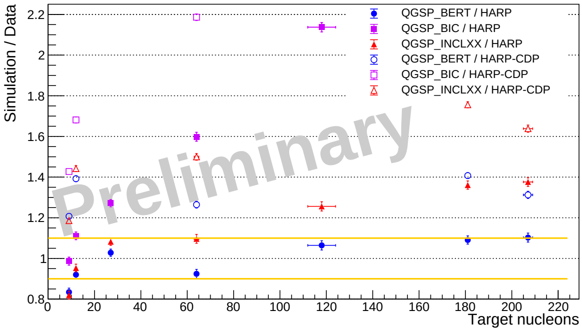




HARP and HARP-CDP Cross-section Comparisons

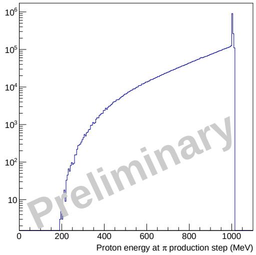
- Integrate over $\theta \in [0.35, 2.15]$ rad and $p \in [0.1, 0.8]$ GeV/c
- Generally, all models overpredict HARP and HARP-CDP measurements
- QGSP_BERT consistent with HARP data within 10% uncertainty
- Still well above SNS energies – not a direct comparison to COHERENT conditions





D_2O Demonstrator at the SNS

Model from Eric Day, CMU



Component	Material	Dimensions	π^+ fraction
Target	Hg	$39.9 \times 10.4 \times 50.0$ cm^3	0.9300
Target Casing	Steel	$40.9 \times 11.4 \times 51.0$ cm^3	0.0037
Inner Plug	95% Be, 5% D_2O	70.0 cm ∅, 45 cm	0.0046
Inner Plug	95% Be, 5% D_2O	70.0 cm ∅, 45 cm	0.0046
Moderator	H_2O	$4.0 \times 13.9 \times 17.1$ cm^3	0.0001
Moderator (3)	H_2	$4.0 \times 13.9 \times 17.1$ cm^3	0.0003
Reflector	90% Steel, 10% D_2O	108 cm ∅, 101.6 cm	0.0170
PBW	Al, Steel	$64.7 \times 54.6 \times 52.2$ cm^3	0.0397

Preliminary

- ◇ Monoenergetic thin-target measurements help, but aren't the full story
- ◇ D_2O Cherenkov detector studying $\nu_e + d \to p + p + e^-$ (known to 2-3%)
- ◇ Demonstrator designed around space constraints of Neutrino Alley
- ◇ Will experimentally normalize SNS ν flux and benchmark simulations
- ◇ One module cannot resolve relative contributions from PBW vs. target

COHERENT and NA61/SHINE

- Reducing the 10% systematic on the ν flux required for precision CEvNS
- COHERENT will measure ν flux at the SNS before the beam energy increases in 2024 (D_2O)
- Hadron production data at 1 GeV will benefit our simulation and design efforts
- Interested in full cross-section: all product angles and momenta
- Some specific interests for understanding SNS ν flux:

Component	Materials	Incident proton energy
FTS target	Hg	$\leq$1.3 GeV
STS target	W	$\leq$1.3 GeV
Aluminum window	Al	1 and 1.3 GeV
Inconel window	Ni, Cr, Fe	1 and 1.3 GeV
Shielding	Fe, C	$\leq$1.3 GeV

Thank you!

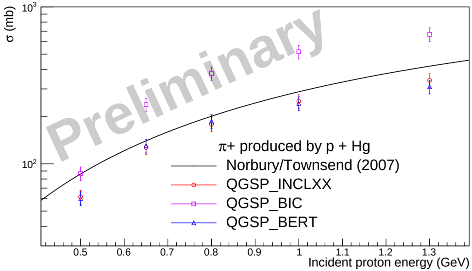
This work is supported by DE-SC0010118.

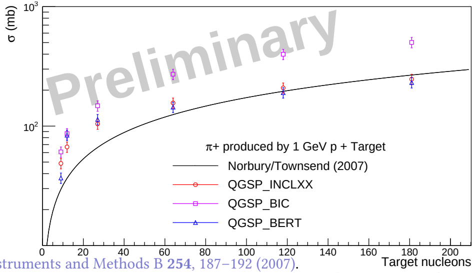
Backup Slides

Norbury-Townsend Comparisons

- ◇ Study of π production in nucleus-nucleus collisions
- ◇ Parameterization for π^+ valid from 0.4 - 2.1 AGeV
- ◇ Inputs for our fixed target scenario:
  - ▷ $A_i(=1)$: number of nucleons incident
  - ▷ A_t: number of nucleons in target
  - ▷ E_i: energy of incident particle

$$\frac{\sigma_{\pi^+}}{\text{mb}} = \frac{(A_i A_t)^{2.2/3}}{0.00717 + 0.0652\frac{\log(E_i/\text{GeV})}{E_i/\text{GeV}} + \frac{0.162}{(E_i/\text{GeV})^2}}$$





[4] J. W. Norbury et al., "Parameterized total cross sections for pion production in nuclear collisions", Nucl. Instruments and Methods B **254**, 187–192 (2007).