Neutrino Physics Needs a New Generation of Bubble Chambers with Light Nuclear Targets

DIS2023: XXX International Workshop on Deep-Inelastic Scattering and Related Subjects

Working Group 6: Future Experiments

Michigan State University

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Neutrinos and Oscillation Physics (Part One)

Paths to Beyond-the-Standard-Model Physics

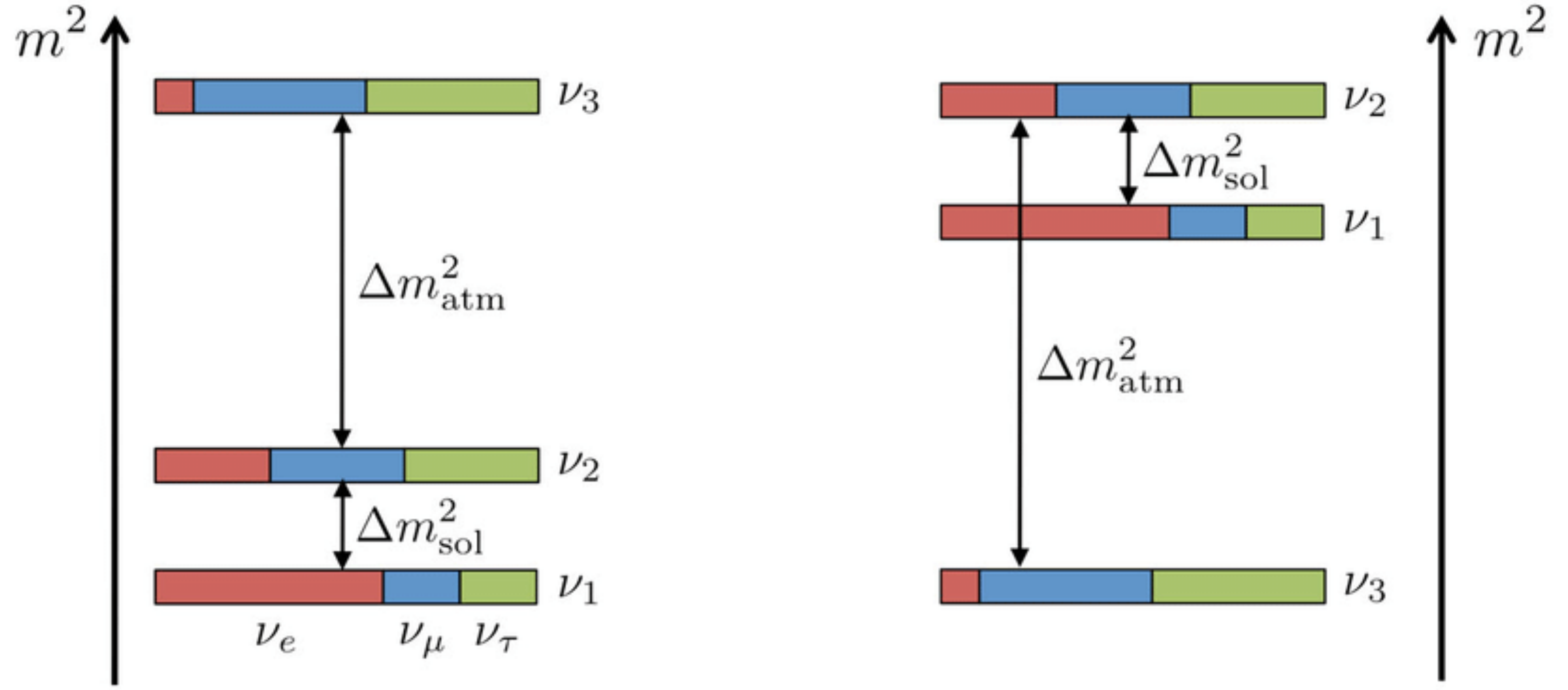
$$\mathcal{L}_{\mathrm{CC}} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha L}\gamma^\mu \nu_{\alpha L} + \mathrm{h.c.} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha L}\gamma^\mu \sum_{i=1,2,3} U_{\alpha i}\nu_{iL} + \mathrm{h.c.}$$

$$\begin{array}{cccc} \text{PMNS Matrix} & \text{Atmospheric} & \text{Reactor} & \text{Solar} \\ |U| = \begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu 1} & |U|_{\mu 2} & |U|_{\mu 3} \\ |U|_{\tau 1} & |U|_{\tau 2} & |U|_{\tau 3} \end{bmatrix} = & \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} & \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} & \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{array}$$

$$U_{\alpha i}: \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathcal{R}_{Atmos}(\theta_{23}) \cdot \mathcal{R}_{React}(\theta_{13}, \delta_{CP}) \cdot \mathcal{R}_{Solar}(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

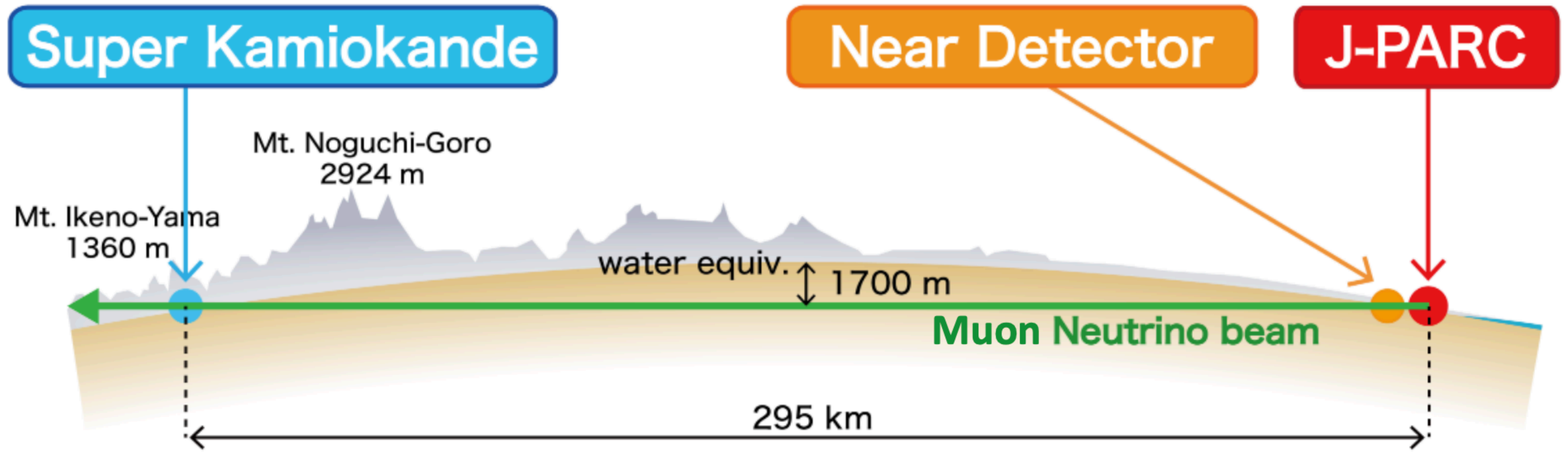
The neutrino mixing matrix has parameters and coefficients directly describing the splitting of the mass states and asymmetry between neutrino and anti-neutrinos!

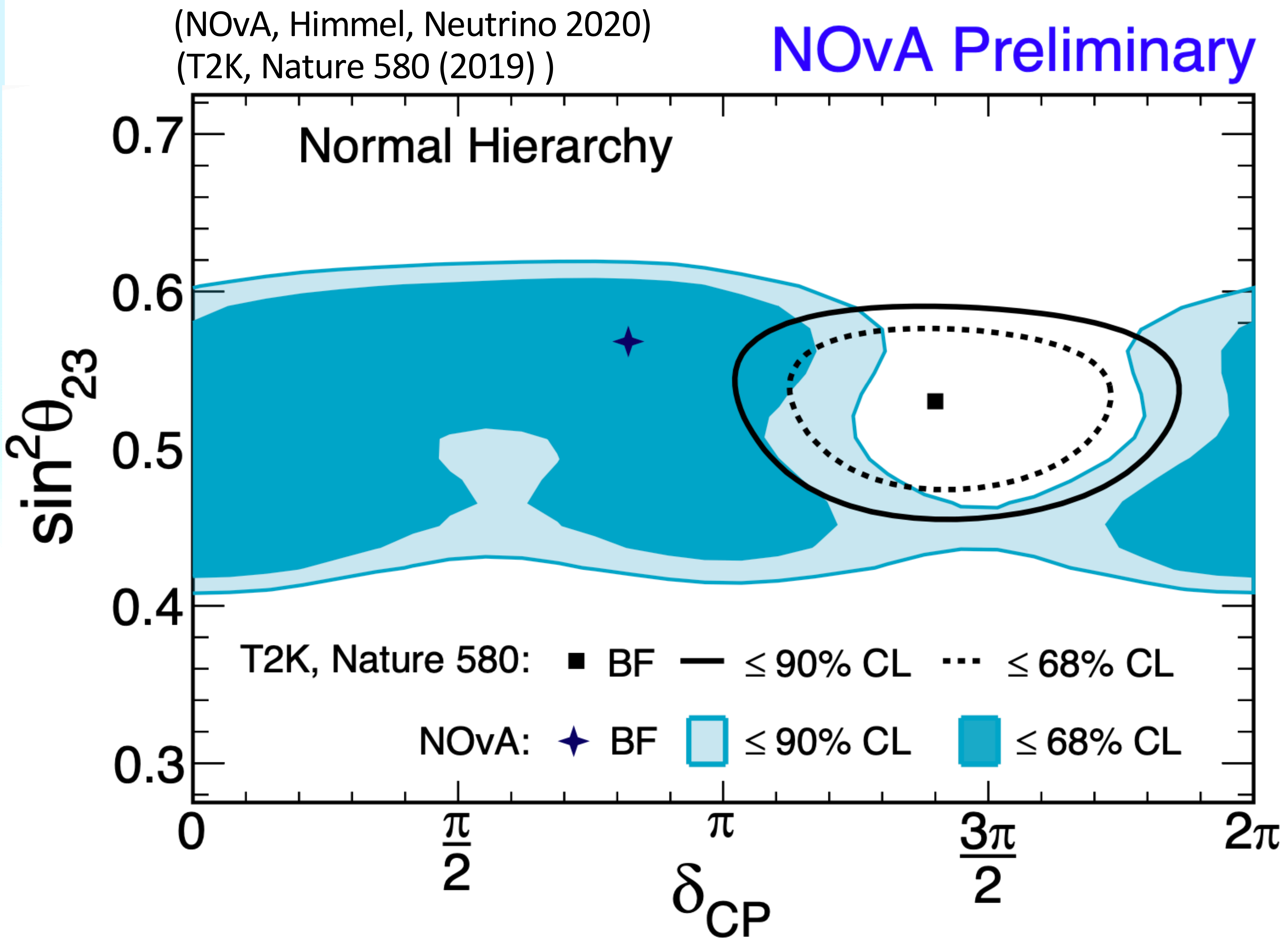
Leptonic CP-violation serves as a proof of concept for the matter-antimatter asymmetry!



Current Generation of Long-Baseline Experiments

Current State-of-the-Art Detectors and Measurements





NOvA and T2K are dual detector oscillations experiments currently taking data and producing results. As of 2020, NOvA and T2K are leaders in resolving oscillation parameters and leptonic CP-violation in the neutrino sector.

Uncertainties in an Oscillation Analysis

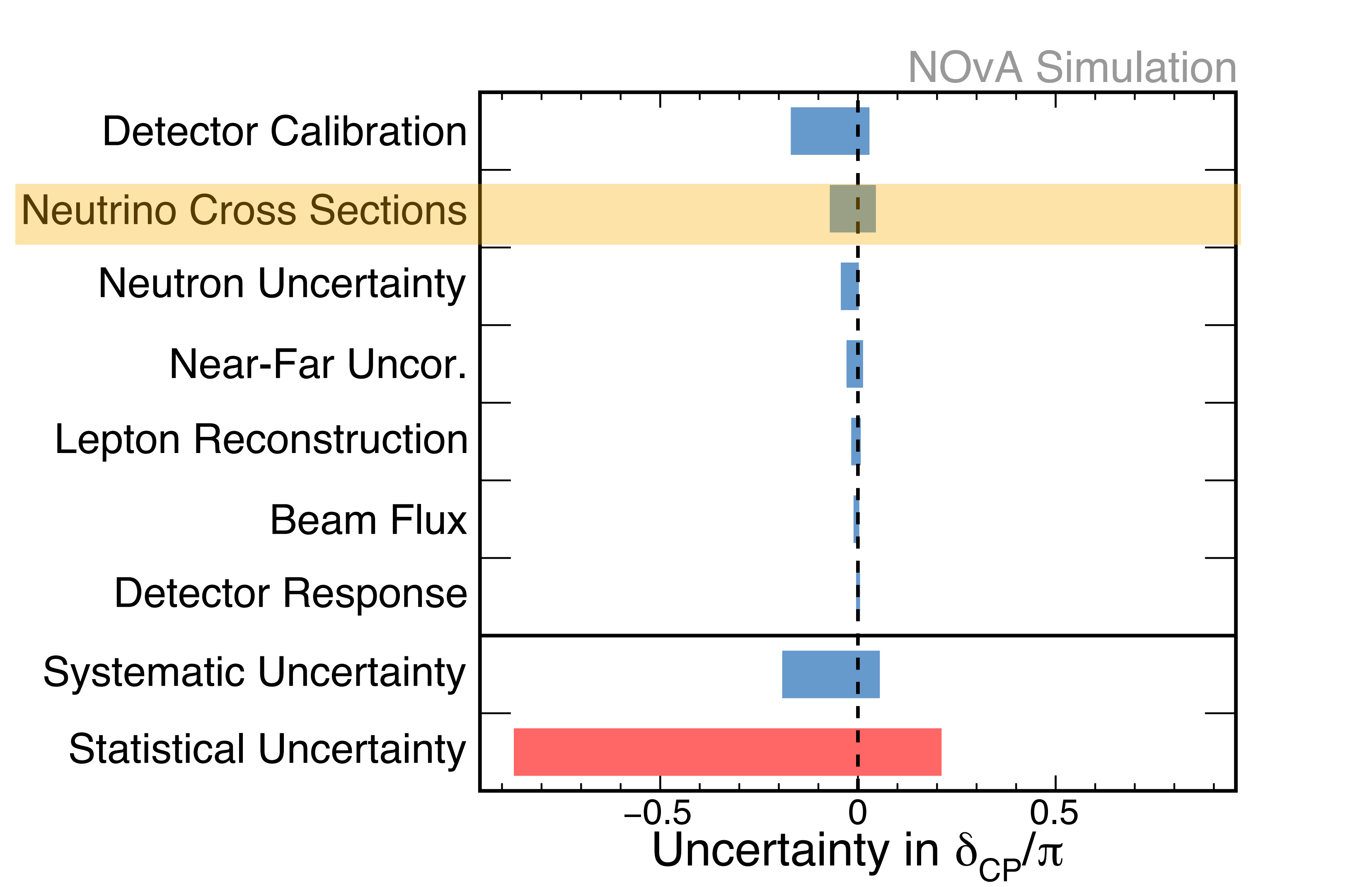
A Brief Look at Uncertainties on δ_{CP}

T2K

Supplementary Table 1: The systematic uncertainty on the predicted relative number of electron neutrino and electron antineutrino candidates in the Super-K samples with no decay electrons.

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

NOvA



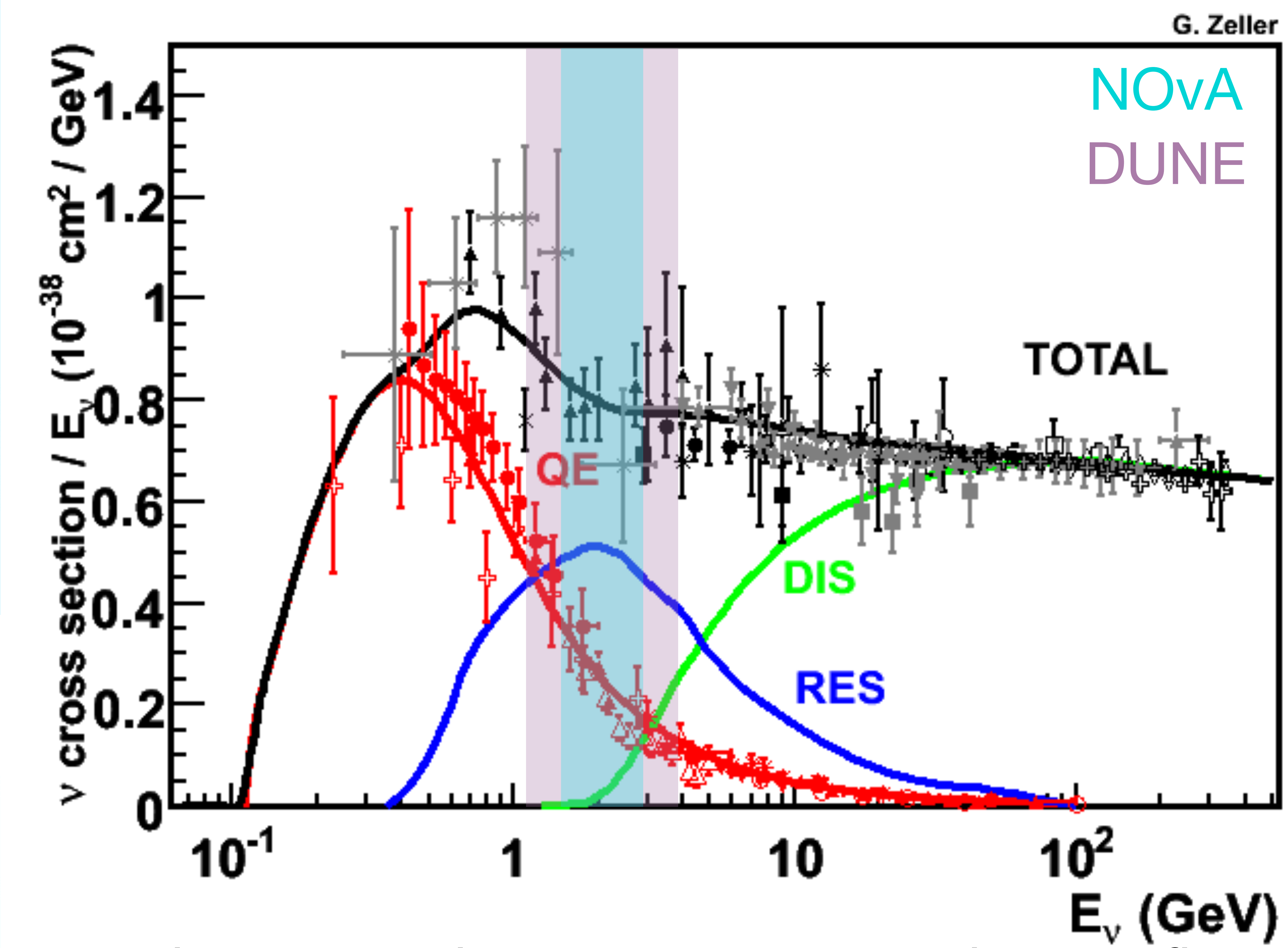
Source of Uncertainty	$\sin^2\theta_{23}$	δ_{CP}/π	$\lvert\Delta m^2_{32}\rvert$ ($\times10^{-3}$ eV^2)
Beam Flux	+0.00034 / -0.0008	+0.0023 / -0.0099	+0.0014 / -0.0023
Detector Calibration	+0.005 / -0.025	+0.028 / -0.17	+0.019 / -0.019
Detector Response	+0.0016 / -0.0021	+0.0041 / -0.0035	+0.0067 / -0.0085
Lepton Reconstruction	+0.0026 / -0.002	+0.006 / -0.016	+0.0094 / -0.015
Near-Far Uncor.	+0.002 / -0.0016	+0.012 / -0.028	+0.0013 / -0.0048
Neutrino Cross Sections	+0.0027 / -0.0034	+0.044 / -0.07	+0.0066 / -0.012
Neutron Uncertainty	+0.0049 / -0.0078	+0.0012 / -0.042	+0.011 / -0.017
Systematic Uncertainty	+0.0083 / -0.027	+0.054 / -0.19	+0.024 / -0.028
Statistical Uncertainty	+0.022 / -0.033	+0.21 / -0.87	+0.043 / -0.055

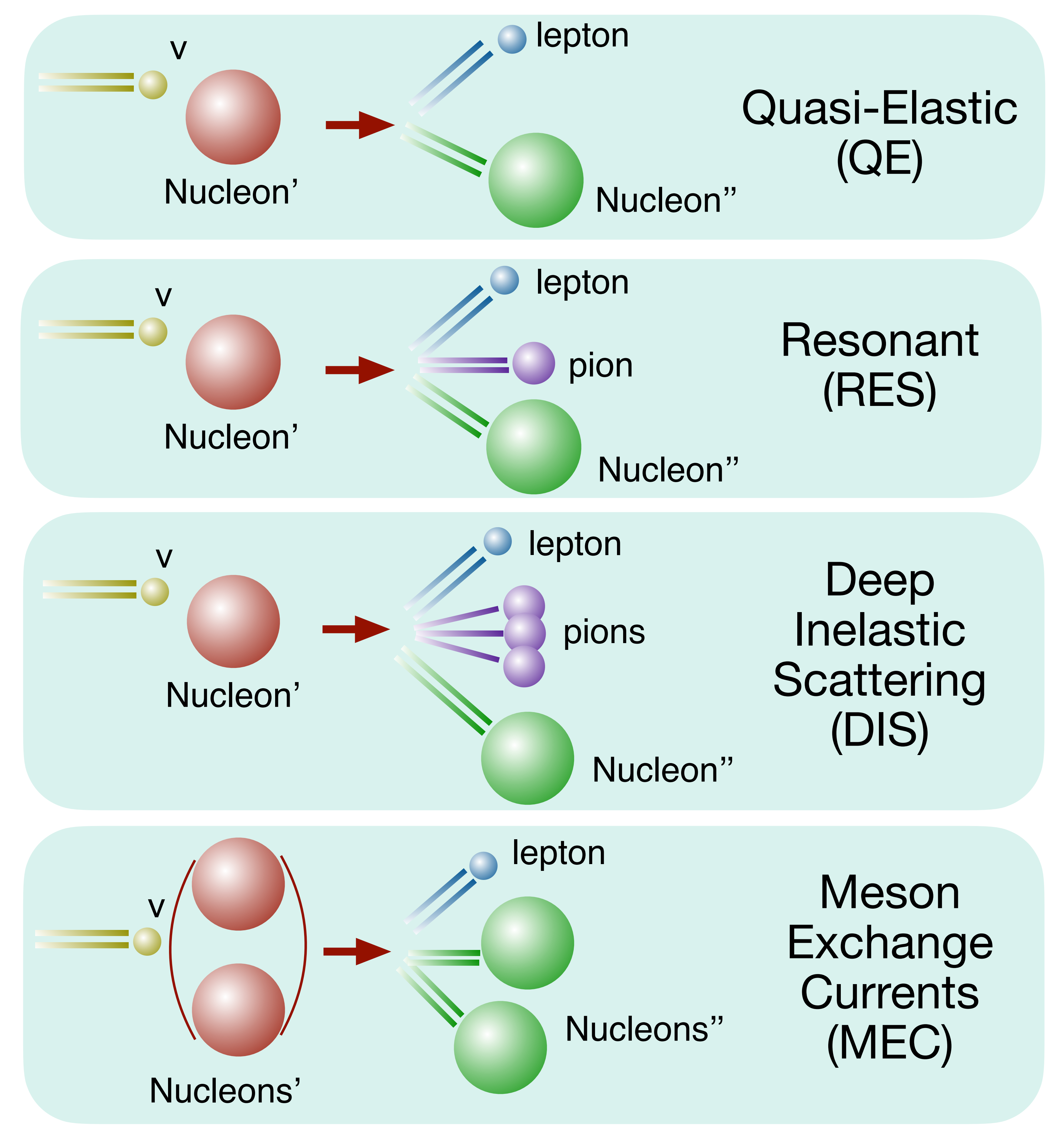
~19% of the total systematics budget

As of 2020, largest uncertainties are due to statistics limited, but the next generation of experiments will surpass the precision of current experiments! How to control the systematics budget?

The Neutrino-Nucleus Cross Section Problem (Part One)

Where is the Problem?





Many neutrino scattering measurements but to first order must understand interplay between four different types of scattering (QE/Elastic, RES, DIS, MEC).

To second order, must also deal with FSI effects (nuclear matter effects, absorption, interaction with cold nuclear matter)!

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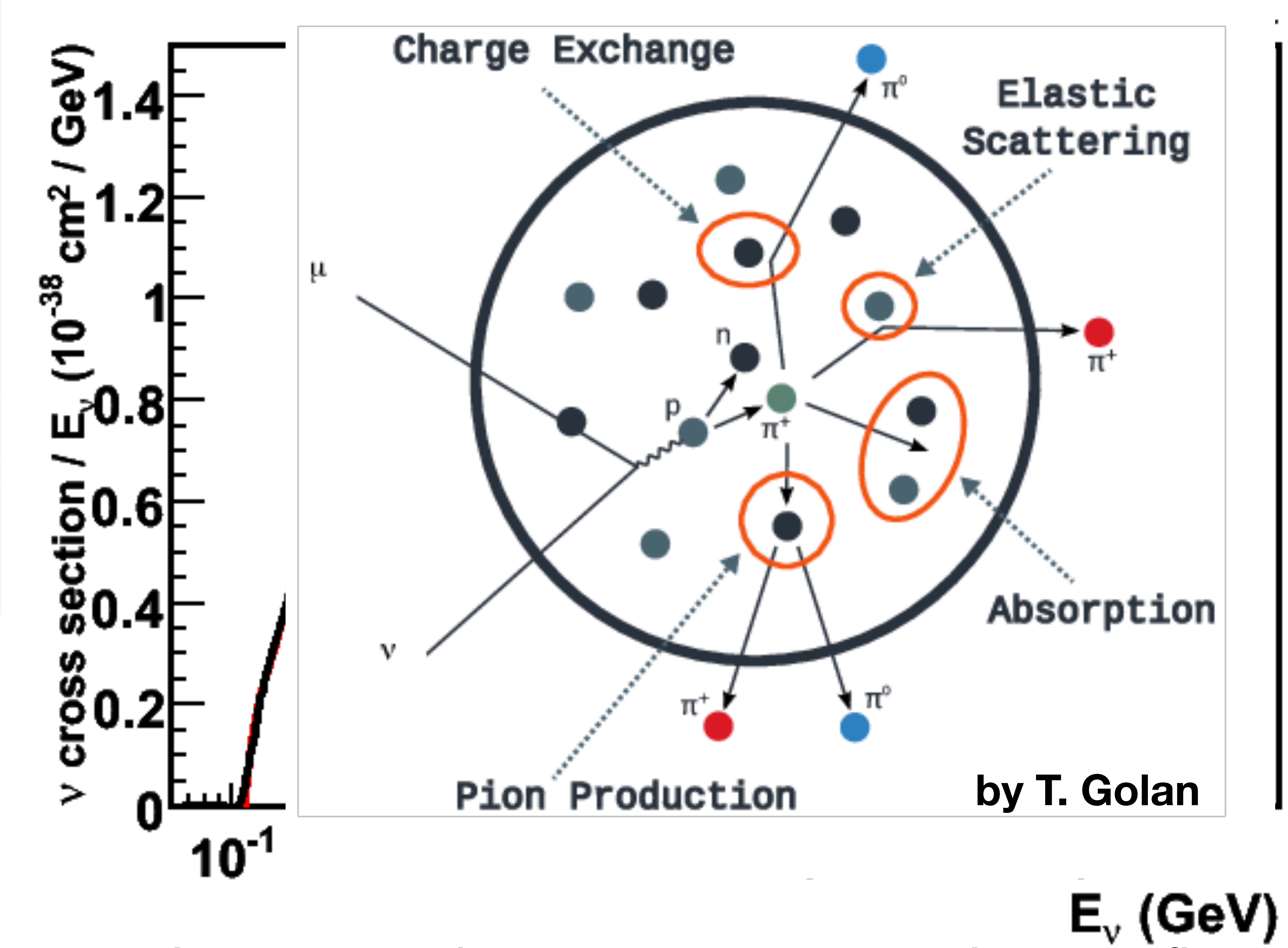

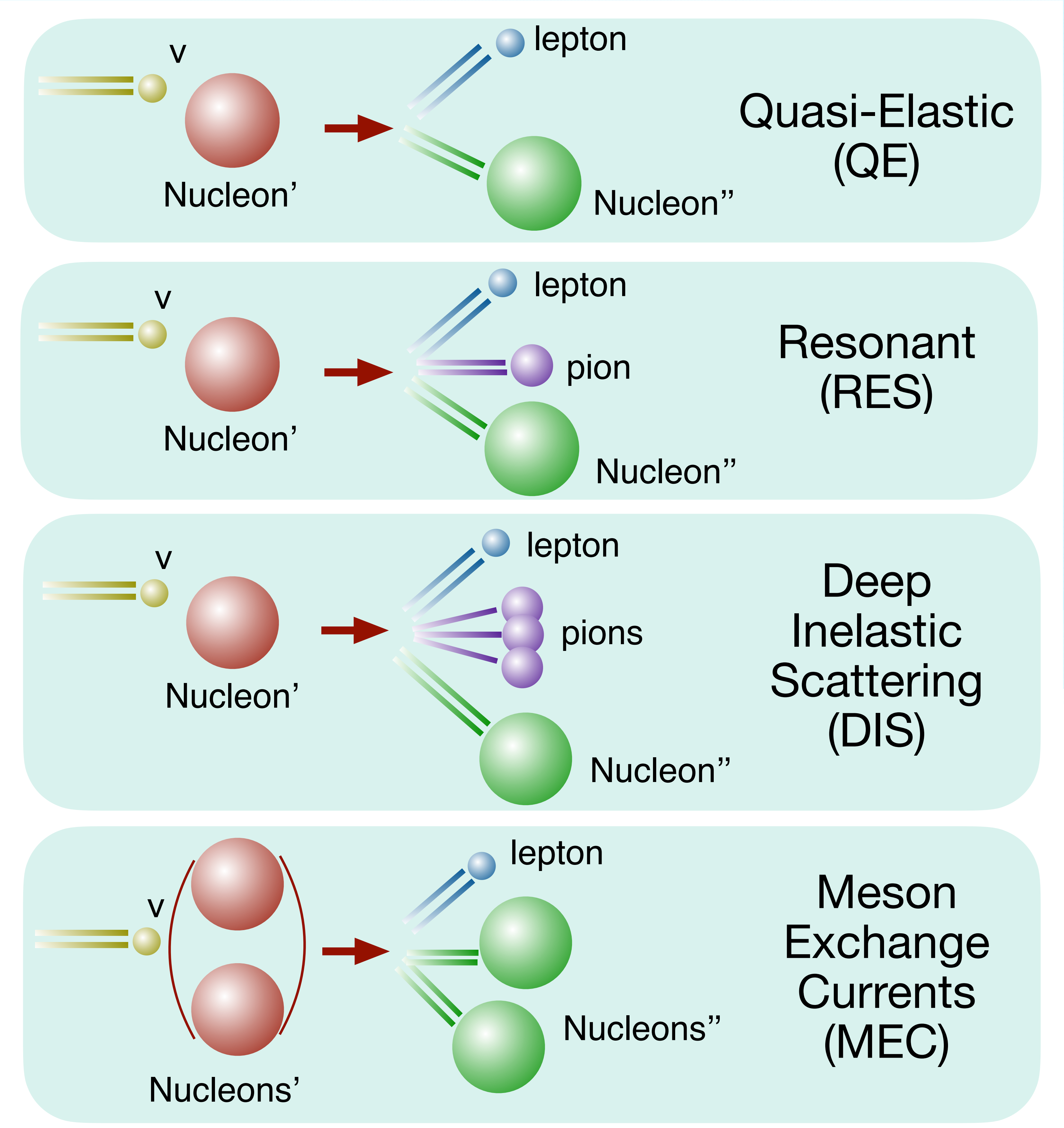

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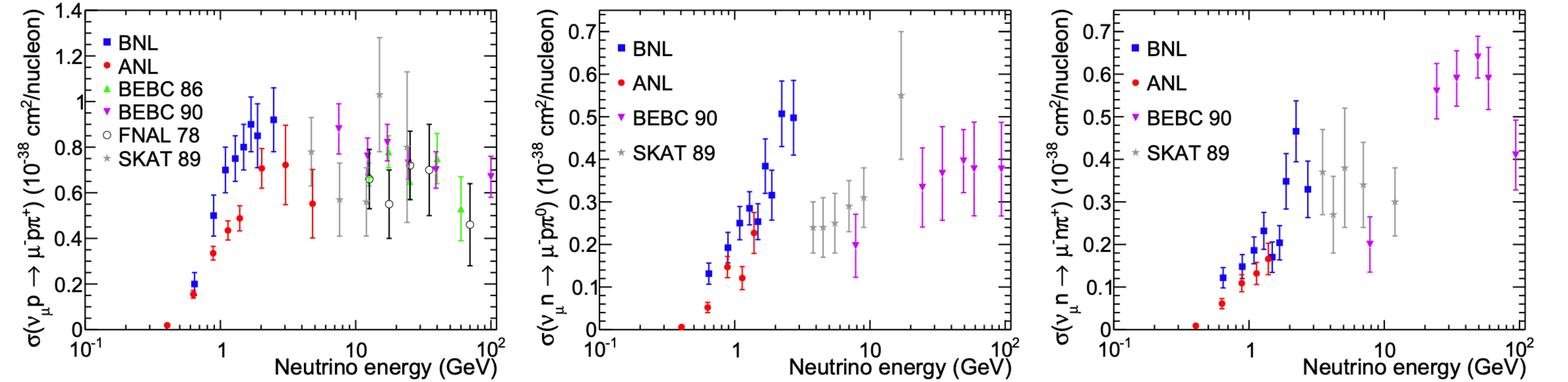
The Neutrino-Nucleus Cross-Section Problem (Part Two)

Significant Problems with Old Bubble Chamber Data



BNL Dataset

Dataset	Channel	Digitized	Published
Partial	$\nu n \to \mu^- p$	—	1276
	$\nu N \to \mu^- X$	3685.3	3723
Full	$\nu n \to \mu^- p$	2693.3	2684
	$\nu p \to \mu^- p \pi^+$	1534.7	1610

ANL Dataset arXiv:1411.4482

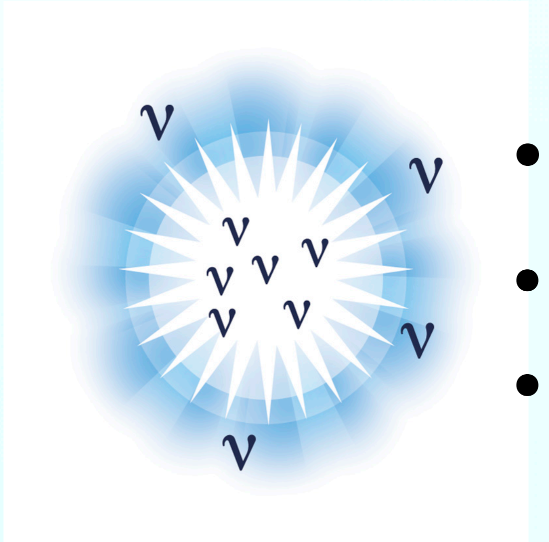
Dataset	Channel	Digitized	Published
Partial	$\nu n \to \mu^- p$	834.6	833
	$\nu p \to \mu^- p \pi^+$	395.9	398
	$\nu n \to \mu^- X^+$	1139.2	1150
	$\nu p \to \mu^- X^{++}$	453.2	457
Full	$\nu p \to \mu^- p \pi^+$	843.2	871

Statistics in the relevant regions for Long-Baseline experiments are low $\sim O(10^4)$ and systematic uncertainties are high.

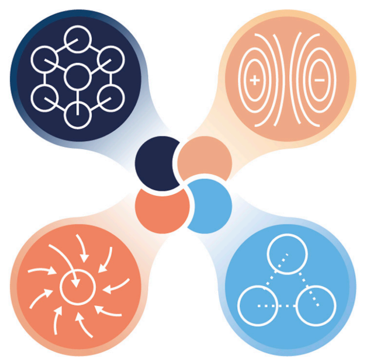
Generator predications based on these data have low exclusionary power at DUNE/Hyper-K precision.

The Next Generation of Long-Baseline Experiments

DUNE: the future long-baseline oscillation experiment



- Leptonic CP-violation (δ_{CP},$\Delta L = 0$?)
- Oscillation Parameters (θ_{23})
- Neutrino Mass Hierarchy (NH/IH?)

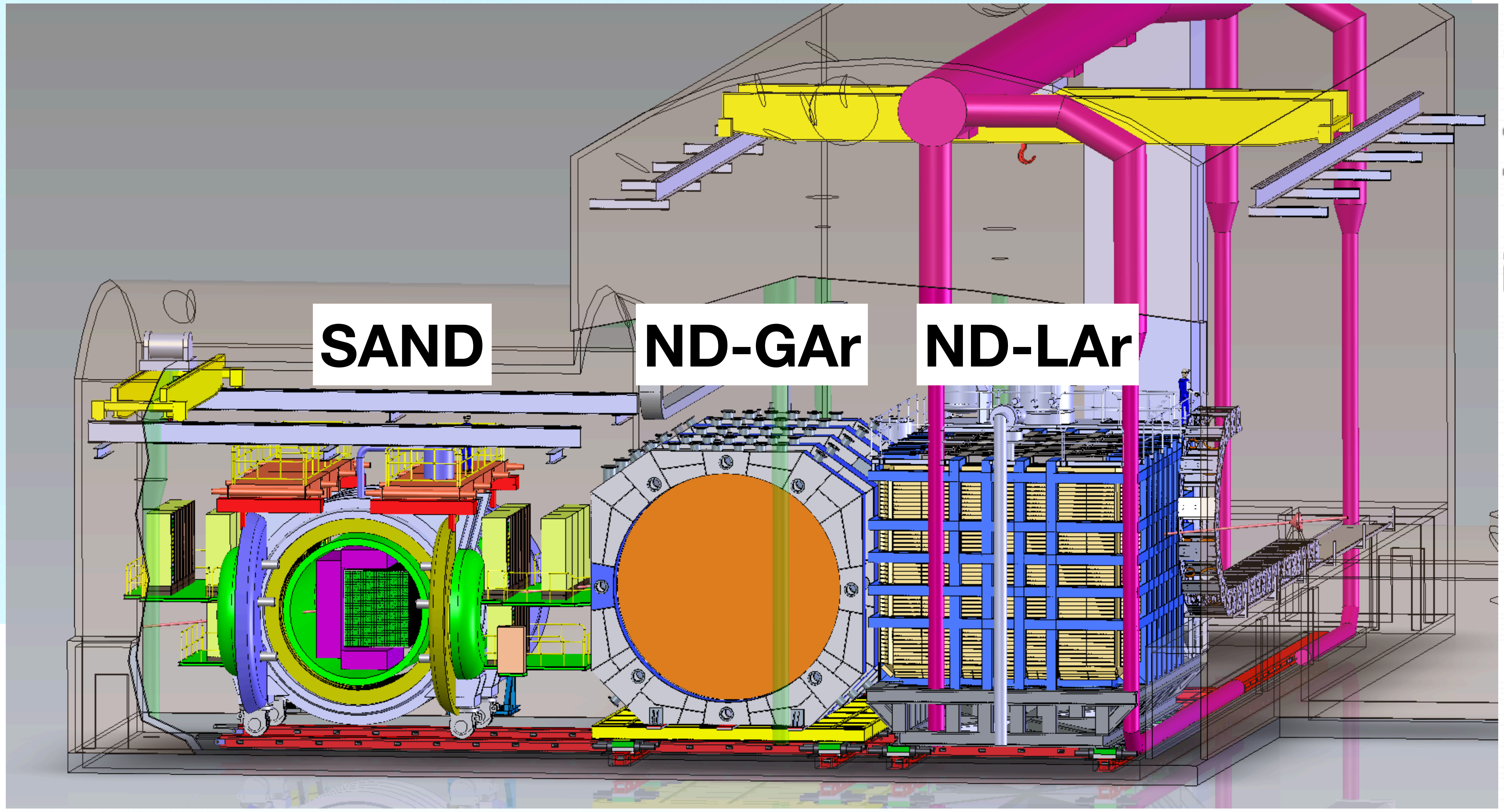


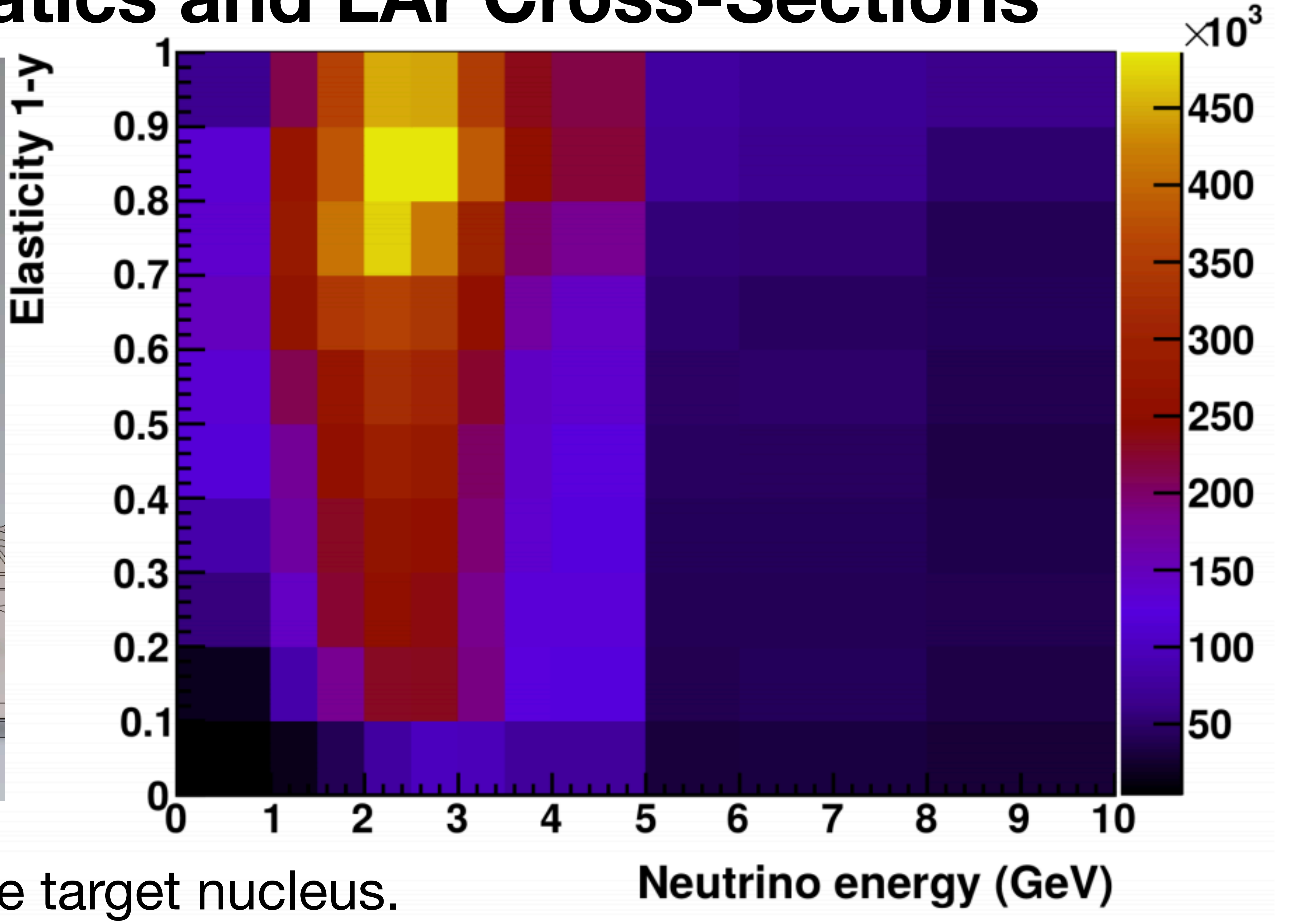
- Proton Decay (GUT?)

- Supernova Burst Neutrinos

The DUNE Near Detector (Phase 2)

Necessary to Constrain Beam Systematics and LAr Cross-Sections





ND-LAr functionally similar to FD modules with the same target nucleus.

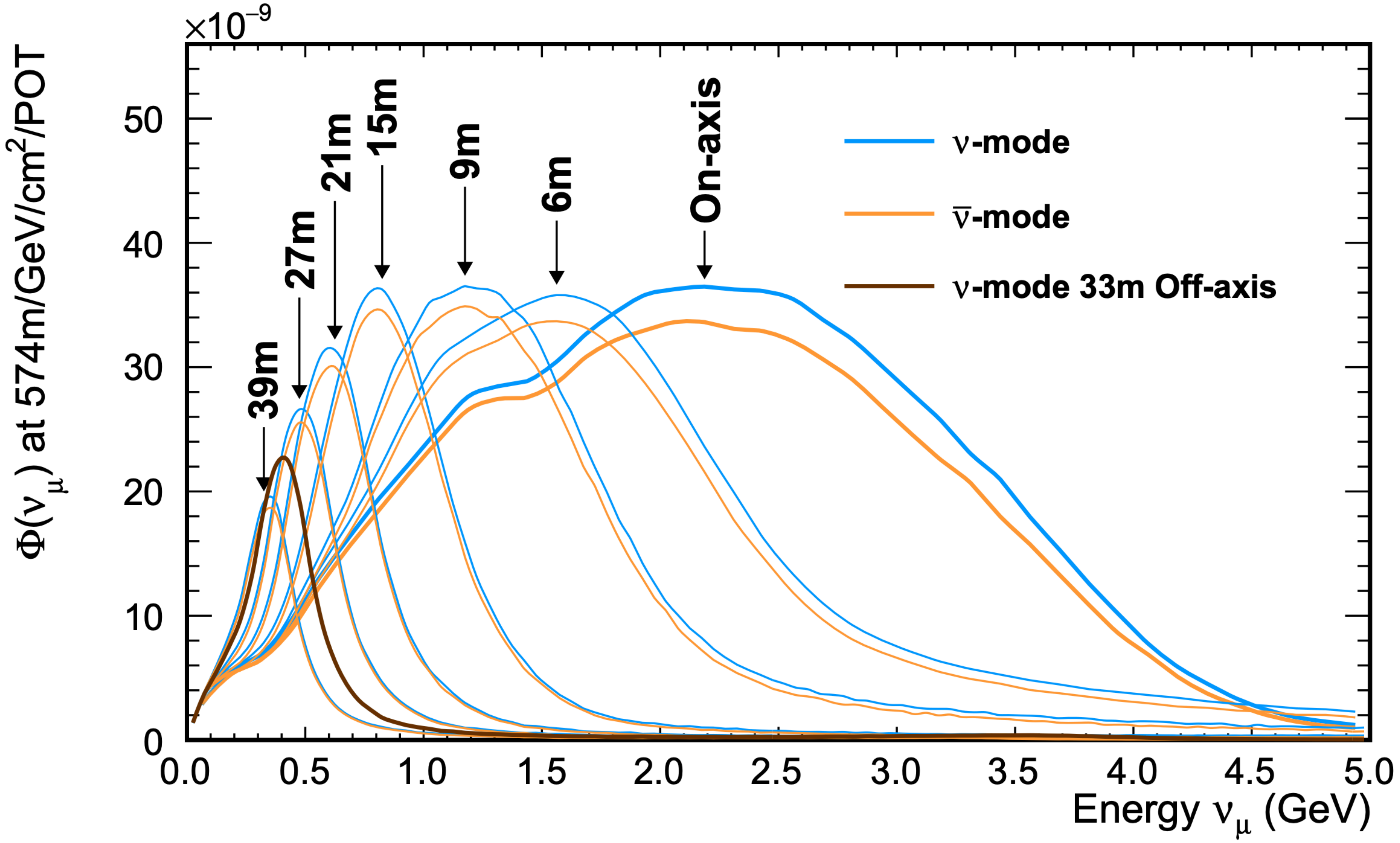
ND-GAr gives charge separation and some analysis of secondary interactions with the same target nucleus.

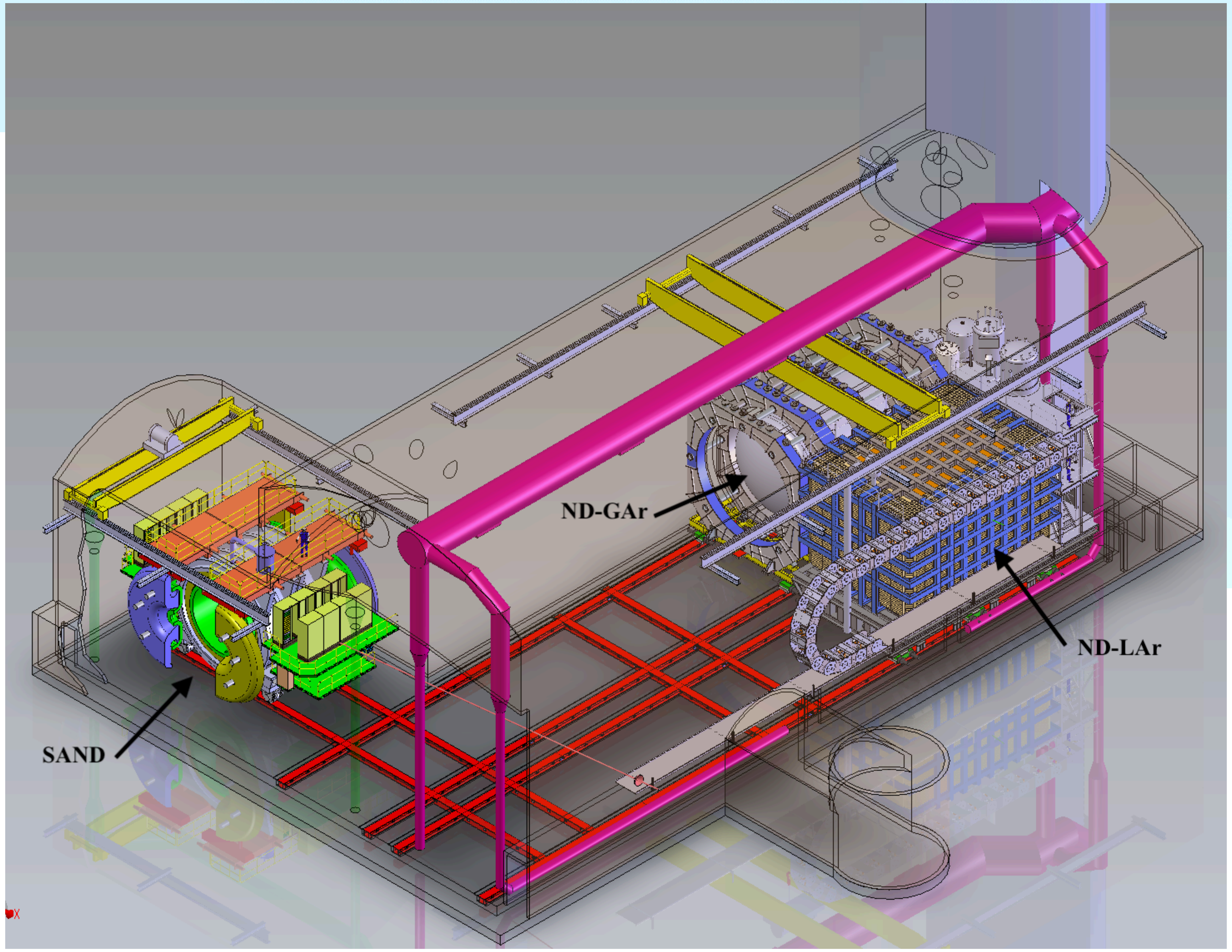
System for on-Axis Neutrino Detection (SAND) serves as always on beam monitoring system with CH

From the ND CDR, 50 tons of LAr at 1.2 MW neutrino beam should yield about **59 million ν_μCC events per *year***.

The LBNF/DUNE Beam

Super High-Statistics Neutrino Beam





DUNE-PRISM will have the Argon detectors move in order to deconvolve the flux from the cross sections.

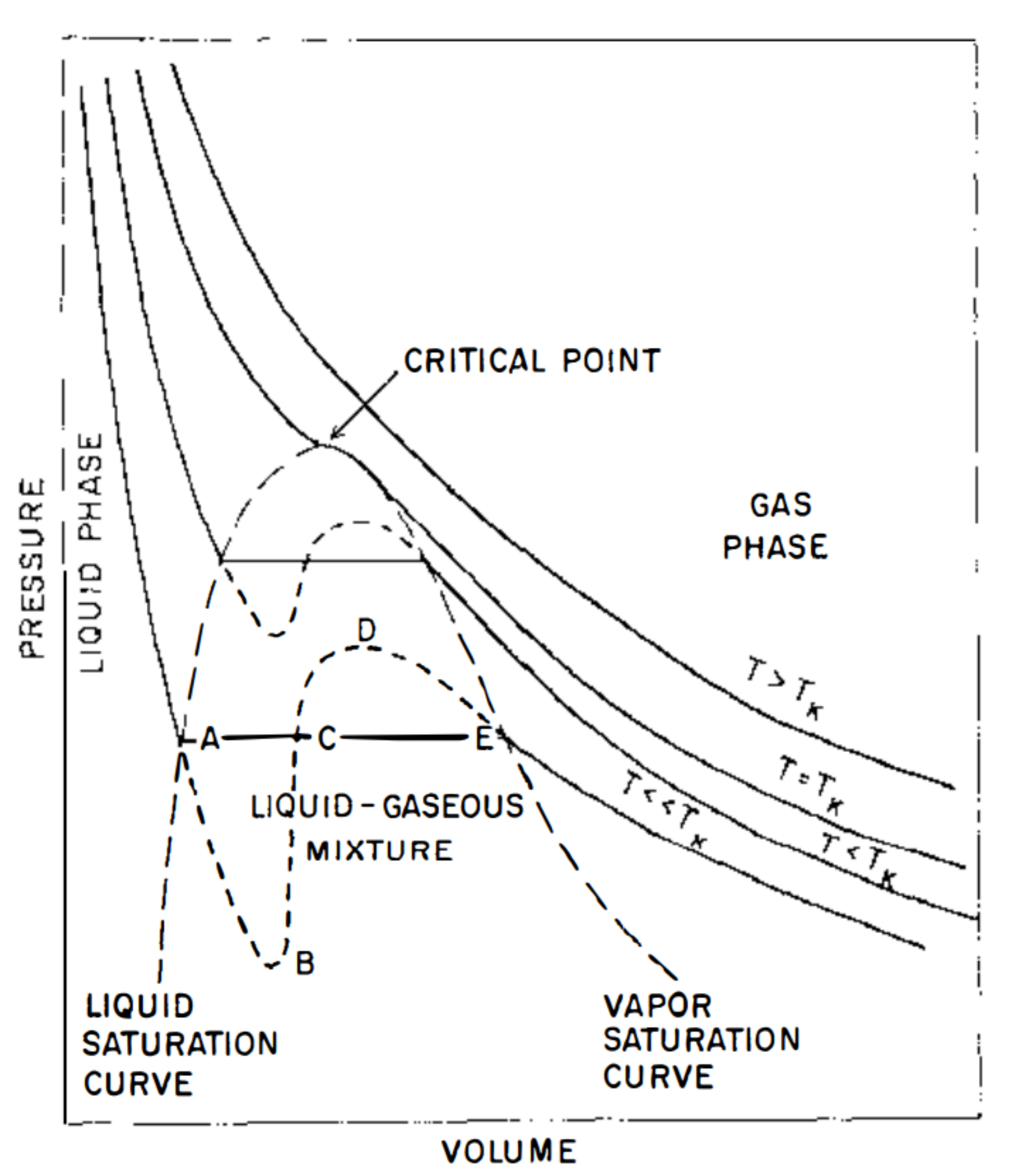
Will constrain beam flux shape and normalization to ~1%!

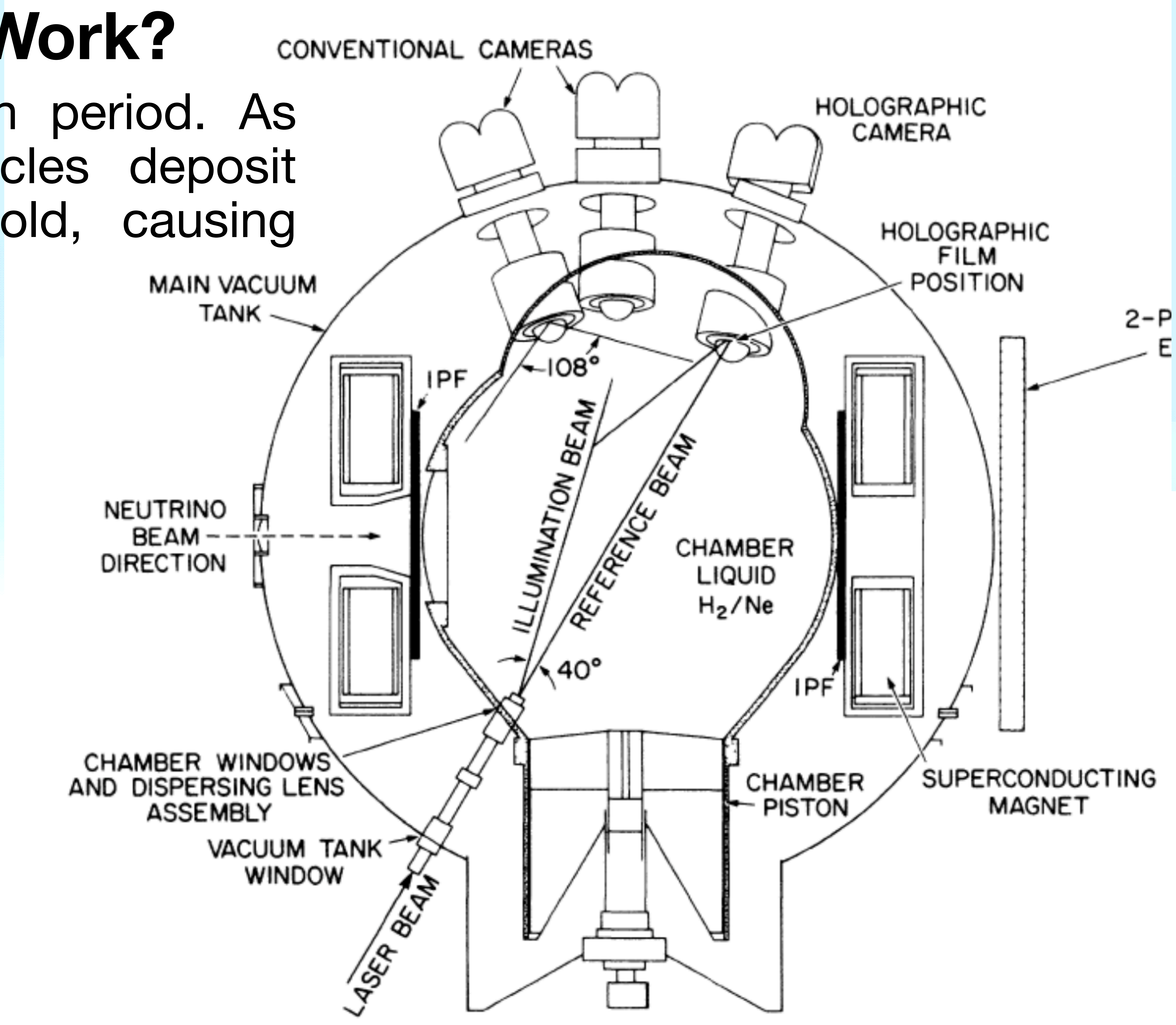
Outside possibility of moving to higher energies!

Historic Chamber Design

How Did the "Dirty" Chambers Work?

Superheated fluid prepared for expansion period. As piston expands, ionizing (charged) particles deposit energy and overcome nucleation threshold, causing bubbles.

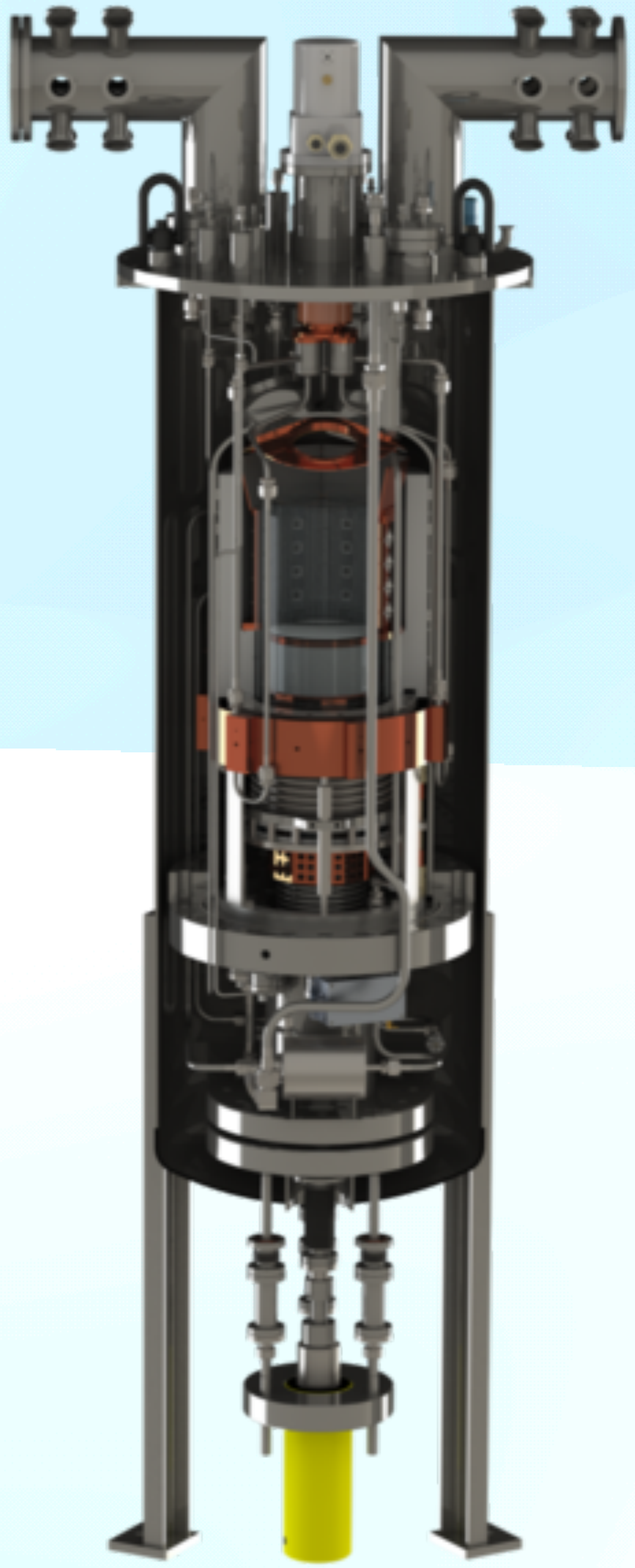


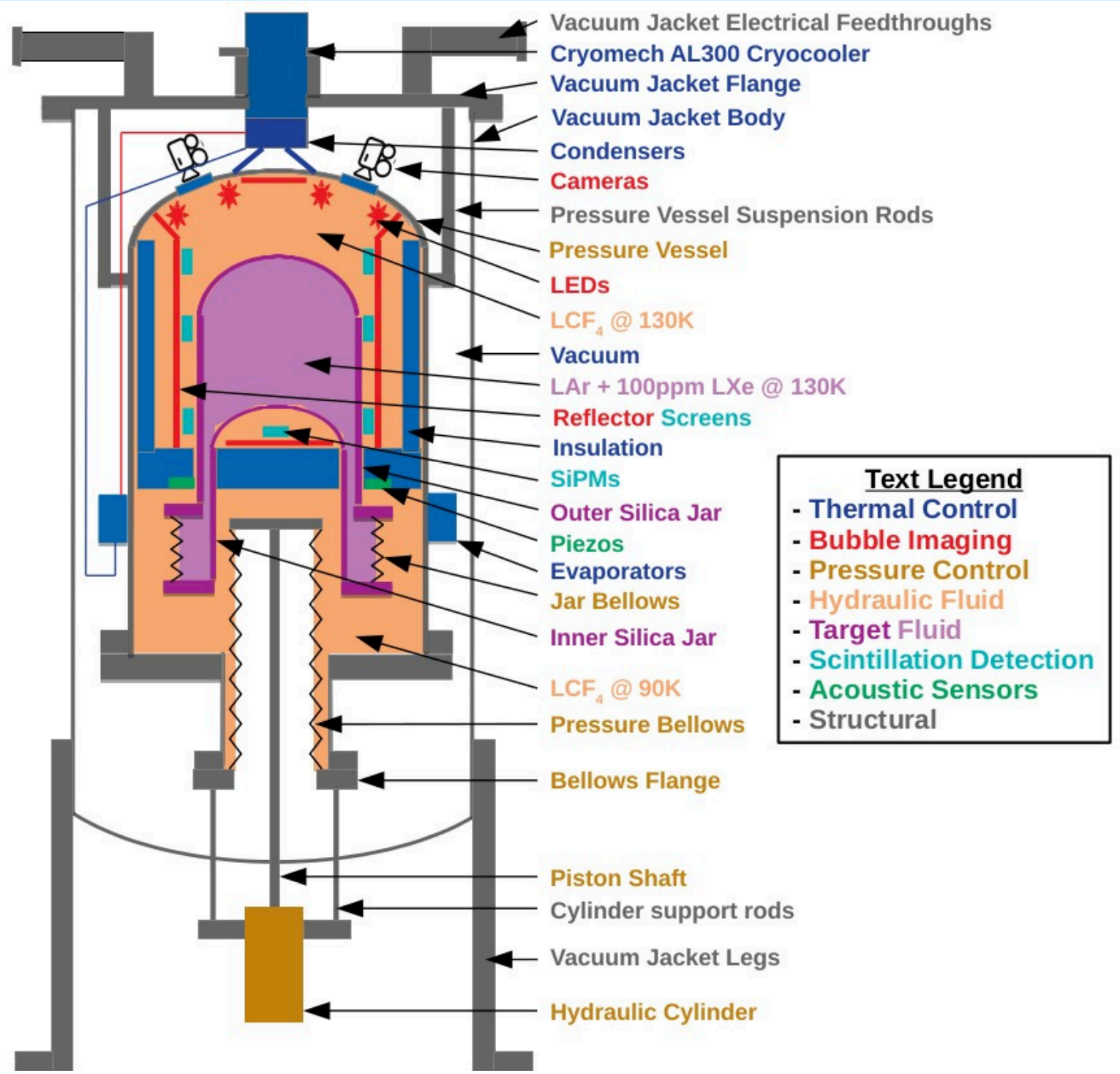


Event selection of analog pictures done *by eye* in the 60s-90s.

The Current Generation of Chambers

The Scintillating Bubble Chamber (SBC)





SBC designed to use Xenon doped Liquid Argon as the working fluid

“Clean” style inner jar in pressure vessel

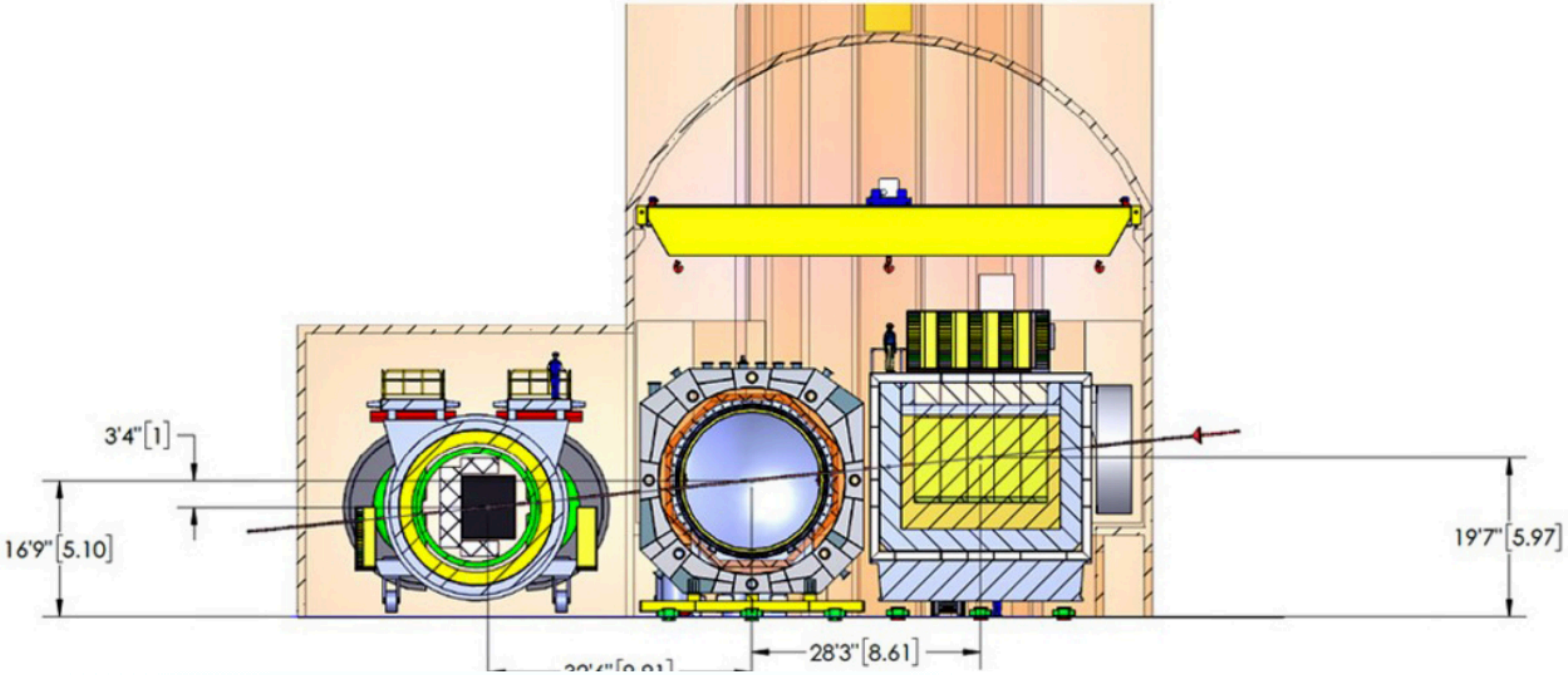
Refrigerator integrated into flange and attached to pressure vessel along with cameras.

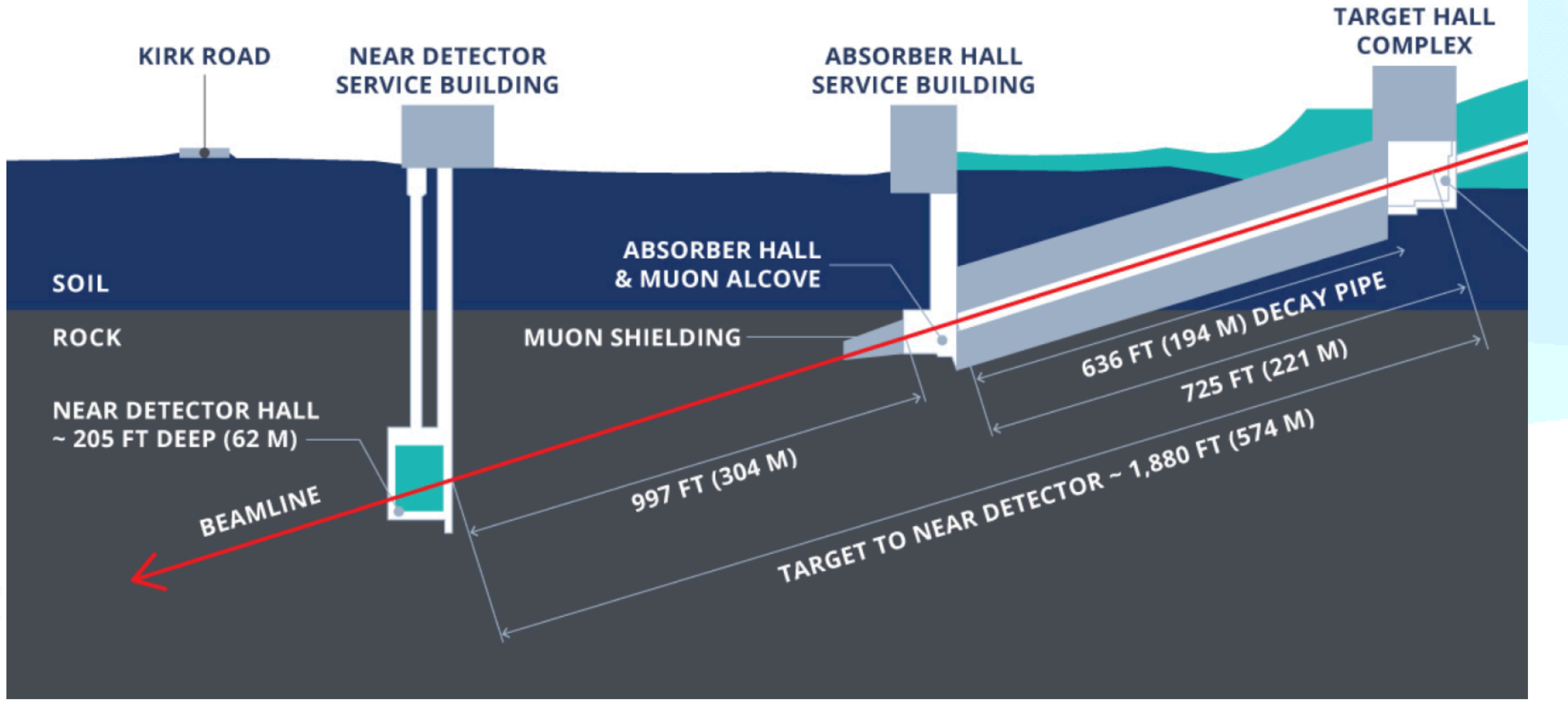
Hydraulic cylinder attached to pressure vessel and a carbon flouride hydraulic fluid is used to offset the temperature gradient.

Achievable live times ~1 hour.

Where to Put It?

The Biggest Challenge Toward Building It!





Problem 1: Detector would be in direct path of LBNF beam, 62m underground.

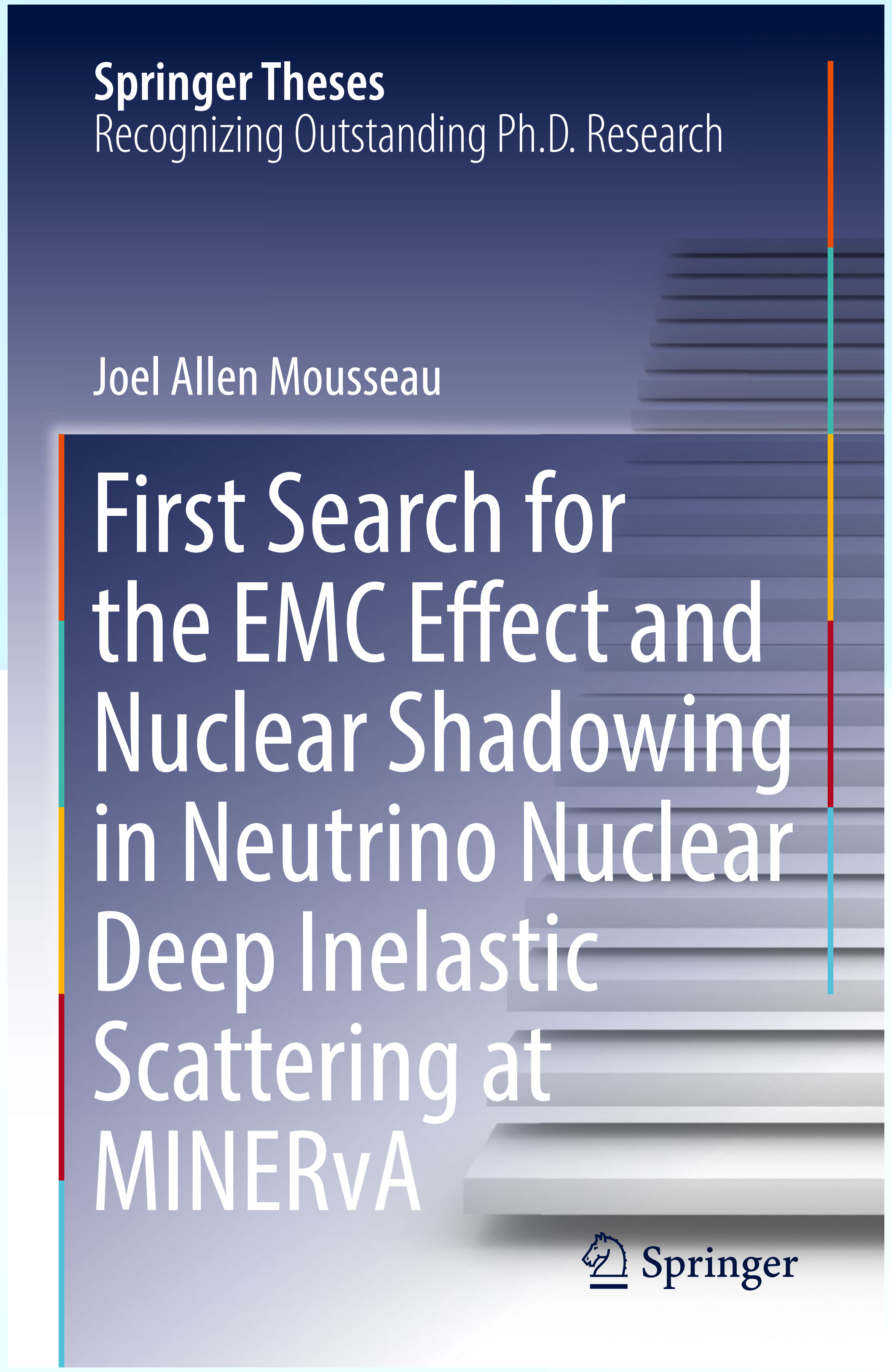
DOE safety guidelines allow only 15 gal/~57L to be used underground without additional safety measures.

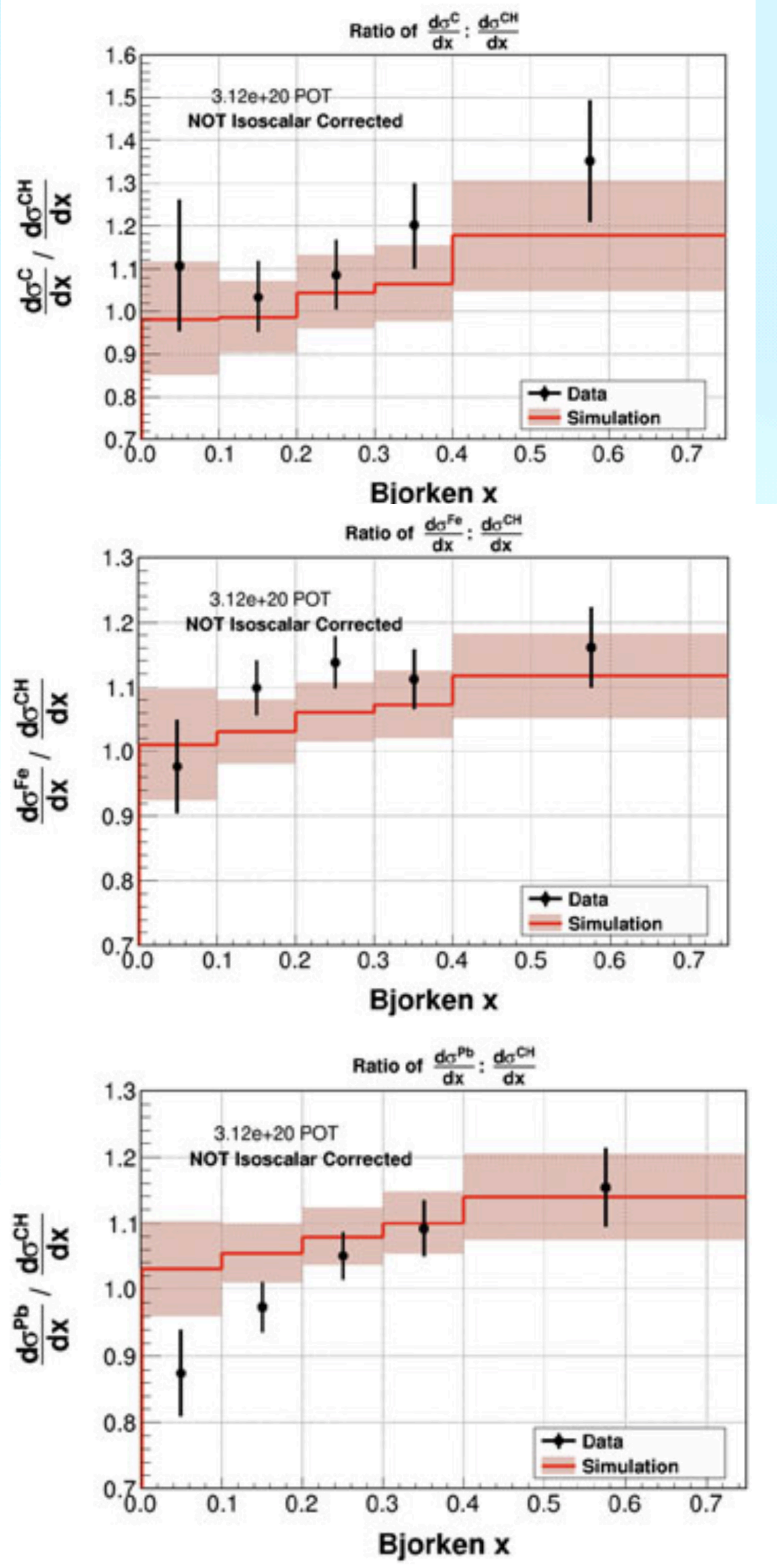
Problem 2: There doesn't seem to be much space in the ND Hall underground for detector or supporting equipment.

Build somewhere else (**Dedicated Underground Hall or On the Surface?**)

Measurement of Nuclear Modification with Neutrinos

Contributions to Nucleon Structure





Shadowing and EMC Effect show nuclear modifications to cross sections dependent on the size of the nucleus!

Investigation from MINERvA shows shadowing in low-x region but demonstration of EMC effect is inconclusive.

Bubble chamber would be perfect instrument for investigation of nuclear modification with (anti)neutrinos!

Argon, Xenon, and Flourine based compounds already demonstrated as possible targets, consider other noble gasses?

Possible to do with QE and resonant scattering? What do we learn?

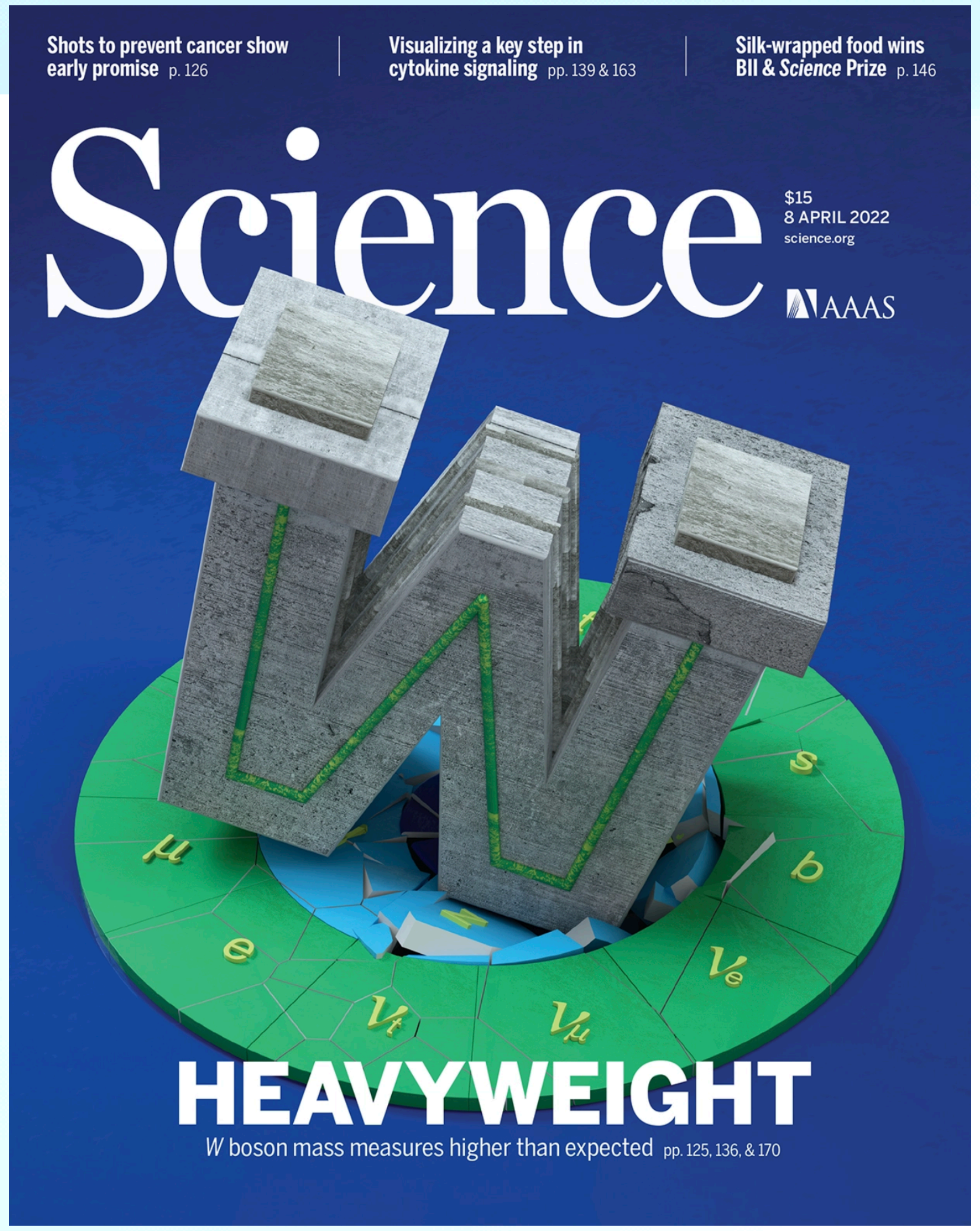
Measurement of the NuTeV Anomaly

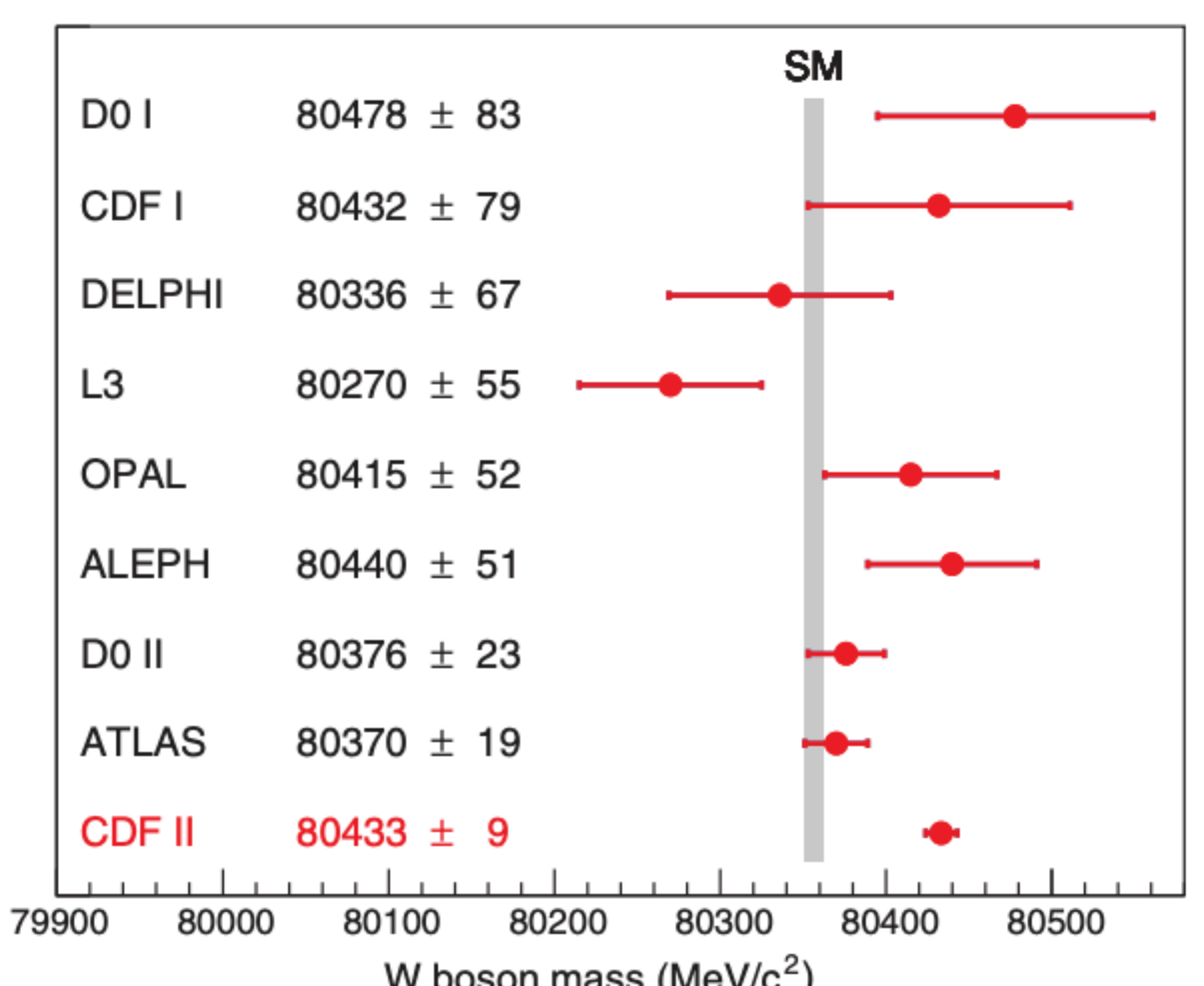
Another Path to Beyond the Standard Model Physics

Neutrino DIS has clean access to the weak mixing/Weinberg angle because *it only* couples to $W^{\pm}$ and Z!

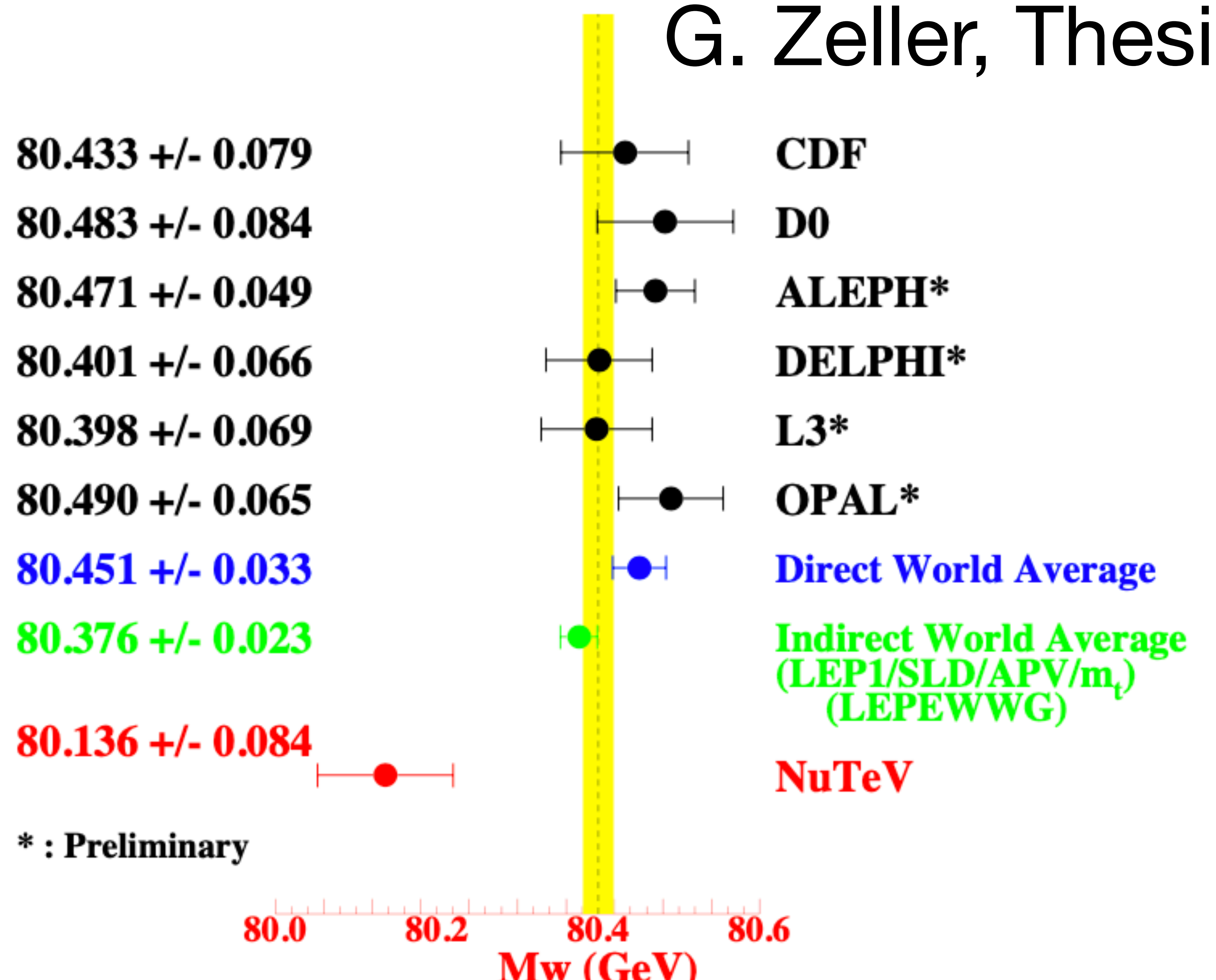
NuTeV Experiment measured the Paschos-Wolfenstein ratio on Fe through a comparison of CC to NC events for $\bar{\nu}/\nu$ and found a $\sim 3\sigma$ offset from the standard model!

$$\frac{1}{2} - \sin^2\theta_W \approx \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}}$$





G. Zeller, Thesis



Neutrinos as a Novel Probe

Precision Selection of Quark Flavor

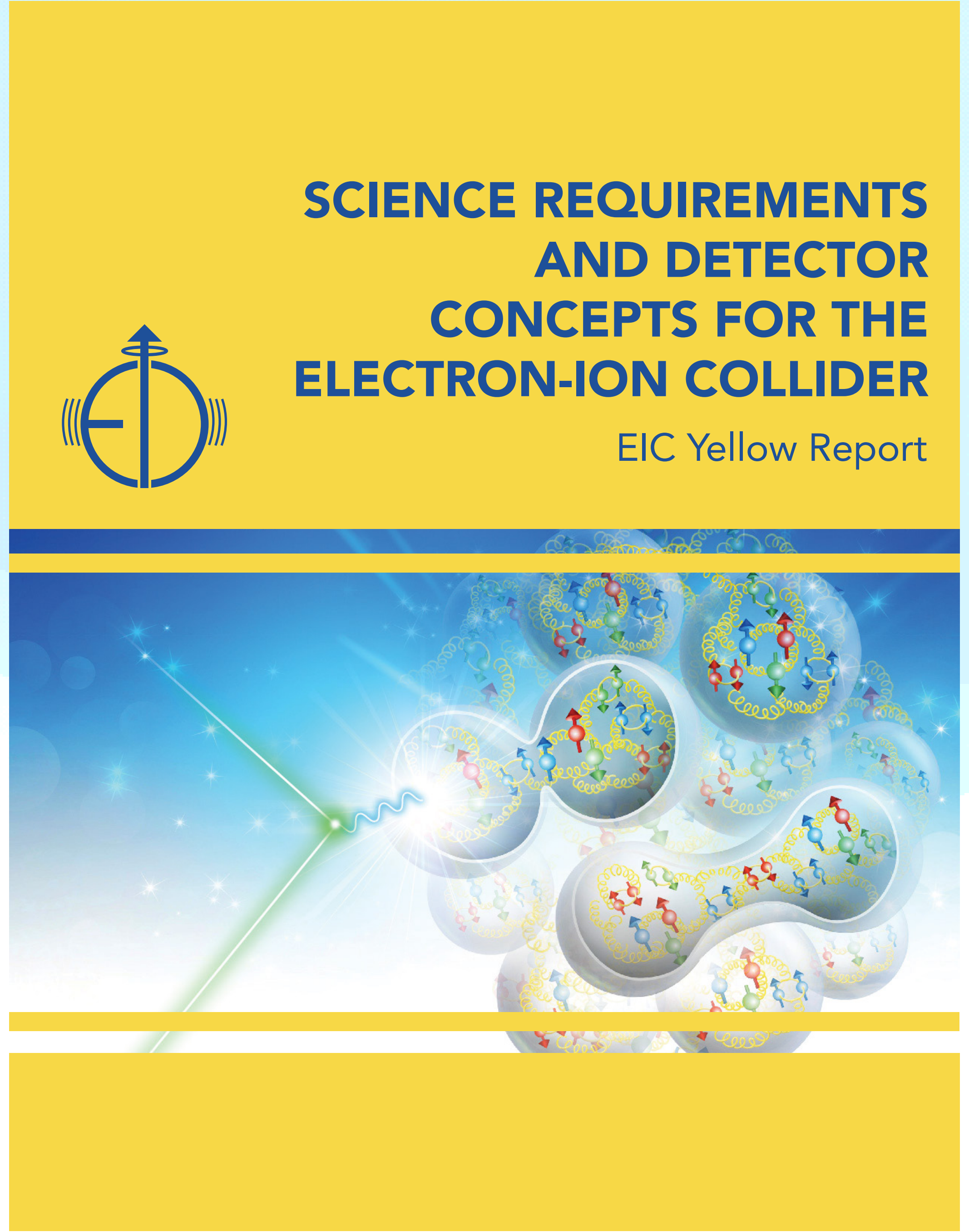
$$\frac{d\sigma^{\nu/\bar{\nu}}_{CC}}{dx\,dy} = \frac{G_F^2\, s}{2\pi\,(1+Q^2/M_W^2)^2}\left[F_1^{CC}\,x\,y^2 + F_2^{CC}\left(1-y-\frac{Mxy}{2E}\right) \pm F_3^{CC}\,xy\,\left(1-\frac{y}{2}\right)\right]$$

$$F_2^{\nu p\,(CC)} = 2x\,(d+s+\bar{u}+\bar{c}),\quad xF_3^{\nu p\,(CC)} = 2x\,(d+s-\bar{u}-\bar{c}),$$

$$F_2^{\bar{\nu} p\,(CC)} = 2x\,(u+c+\bar{d}+\bar{s}),\quad xF_3^{\bar{\nu} p\,(CC)} = 2x\,(u+c-\bar{d}-\bar{s}),$$

$$F_2^{\nu/\bar{\nu}\,p\,(NC)} = 2x\left[(u_L^2+u_R^2)\,(u^+ + c^+) + (d_L^2+d_R^2)\,(d^+ + s^+)\right]$$

$$xF_3^{\nu/\bar{\nu}\,p\,(NC)} = 2x\left[(u_L^2-u_R^2)\,(u^- + c^-) + (d_L^2-d_R^2)\,(d^- + s^-)\right]$$

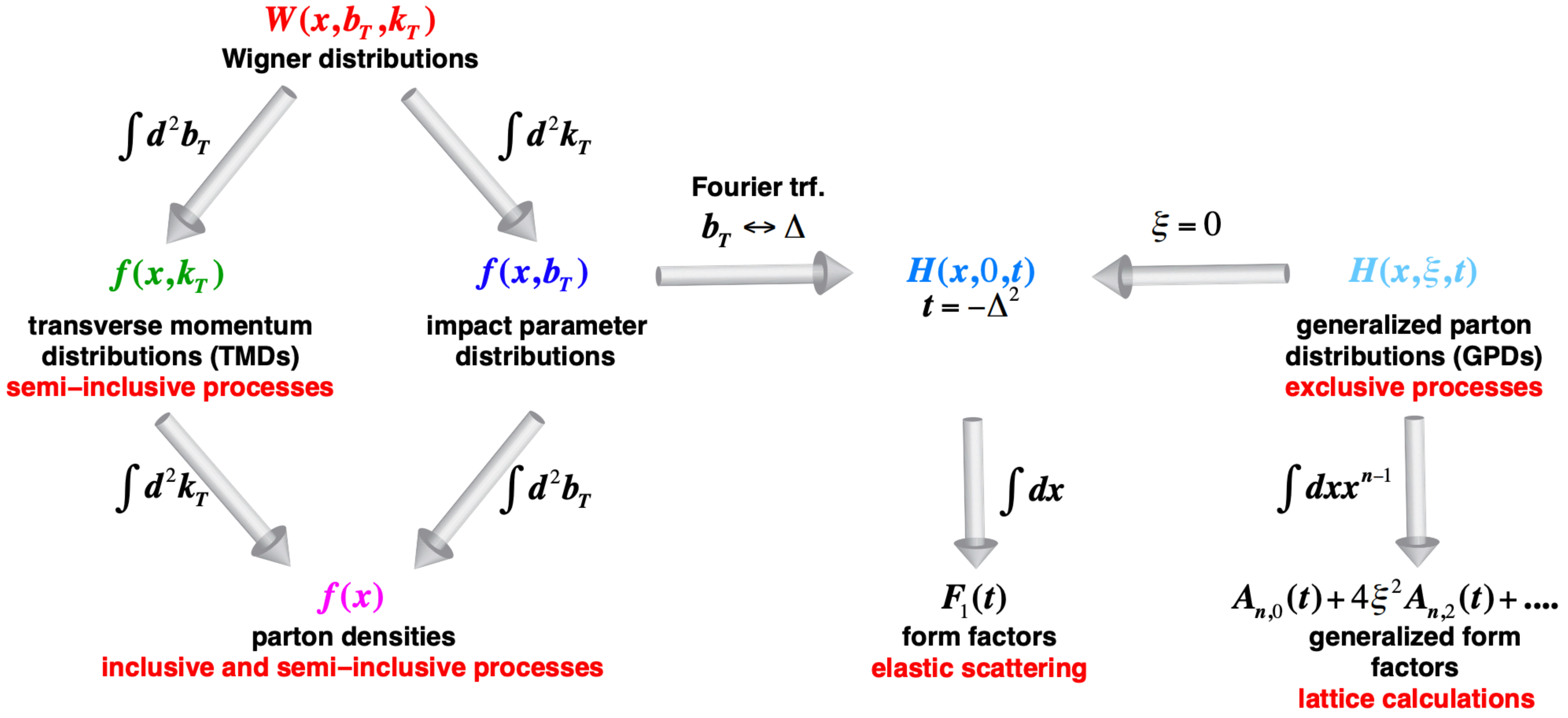


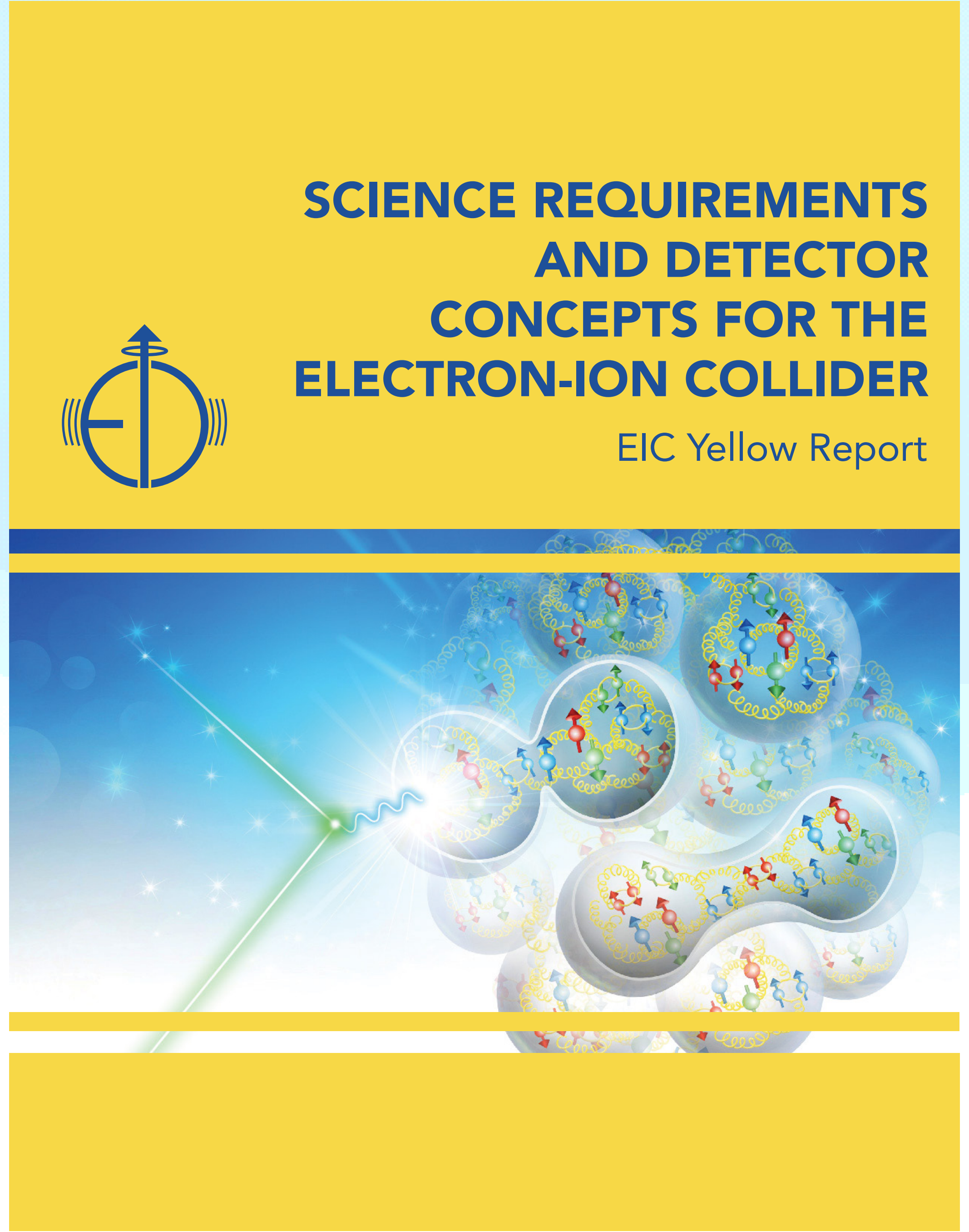
Complementarity especially attractive in DIS region where quark flavor is selectable!

Clean probe of strangeness, path toward *strange form factors*.

Spin and Polarization

Theoretical Expansion to Scattering and the Concept of the Nucleon





Formulation of GPDs from mapping of the nucleon gives new dimensions to scattering and information about the complicated spin structure of the nucleon.

Summary and Conclusion

Current neutrino cross-section sample underlying neutrino event generators does not have the precision to effectively constrain measurements from the next generation of long-baseline neutrino oscillations experiments.

Next generation experiments will have their own robust cross-section measurements, but measurements on light nuclear targets will allow for a better understanding of the underlying nucleon structure and a reduction in systematics.

A bubble chamber physics program is robust, novel, and complementary to measurements that will be done by the Electron Ion Collider

Building a 5L Hydrogen Modern Modular Bubble Chamber Design Study at Fermilab Right Now!

Project Management (Notion)
Document Server (Google Drive)
Meetings Thursdays at 10 AM CT

Please checkout the Snowmass White Papers!
Hydrogen/Deuterium Cross Sections: https://arxiv.org/abs/2203.11298
Bubble Chamber: https://arxiv.org/abs/2203.11319