Why Neutrino Physics Needs a Bubble Chamber with Light Nuclear Targets

Neutrino Seminar
Fermilab
April 21st, 2022

Bryan Ramson
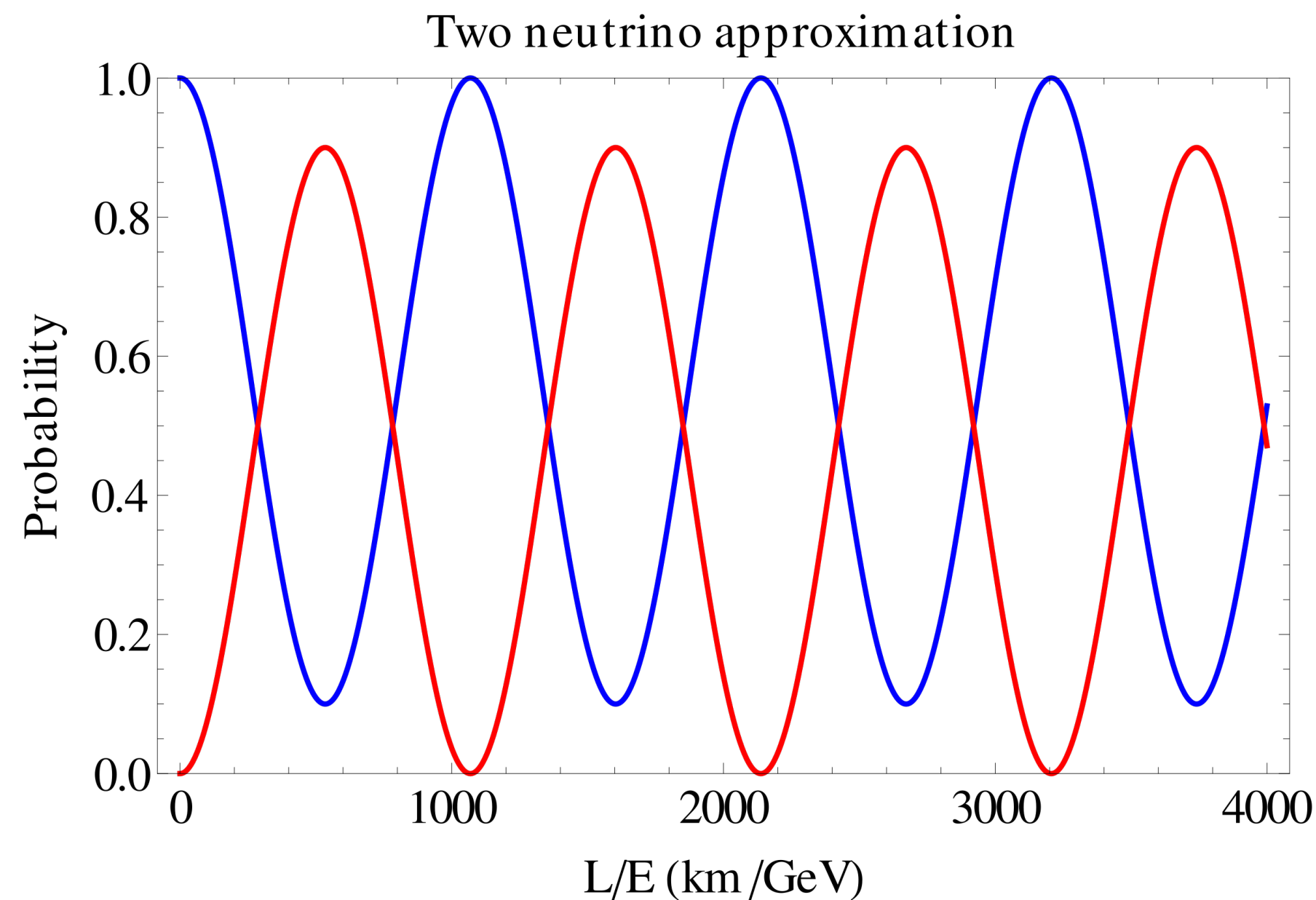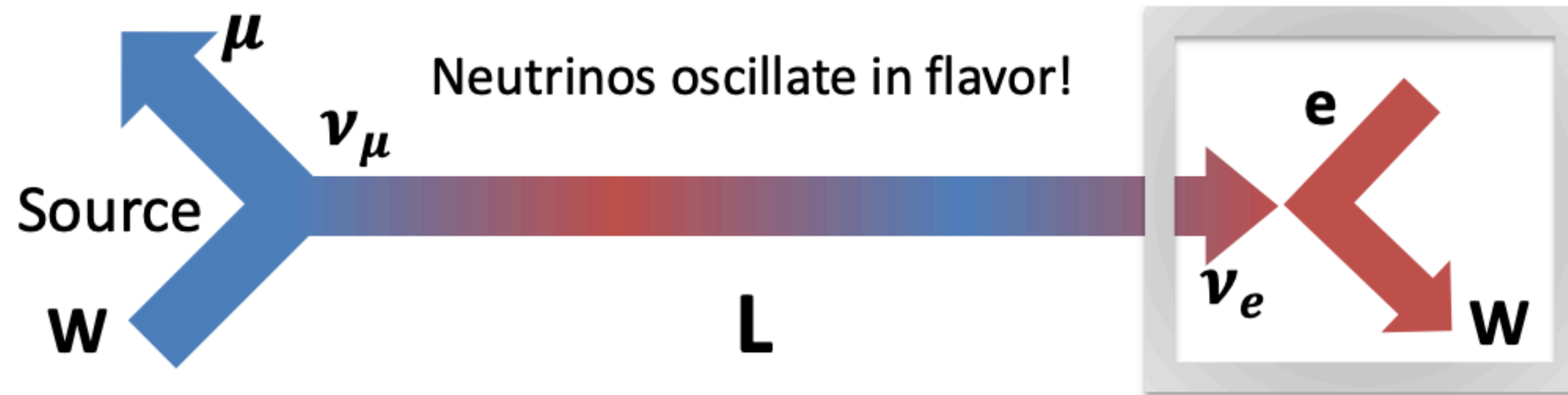**Neutrino Division**
Fermilab

🔆 Fermilab

Neutrinos and Oscillation Physics (Part One)
Paths to Beyond-the-Standard-Model Physics

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

Neutrinos oscillate in flavor!

Two neutrino approximation

If we assume only two flavor and mass states:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \mathcal{R}(\theta) \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Only one Euler angle is needed.
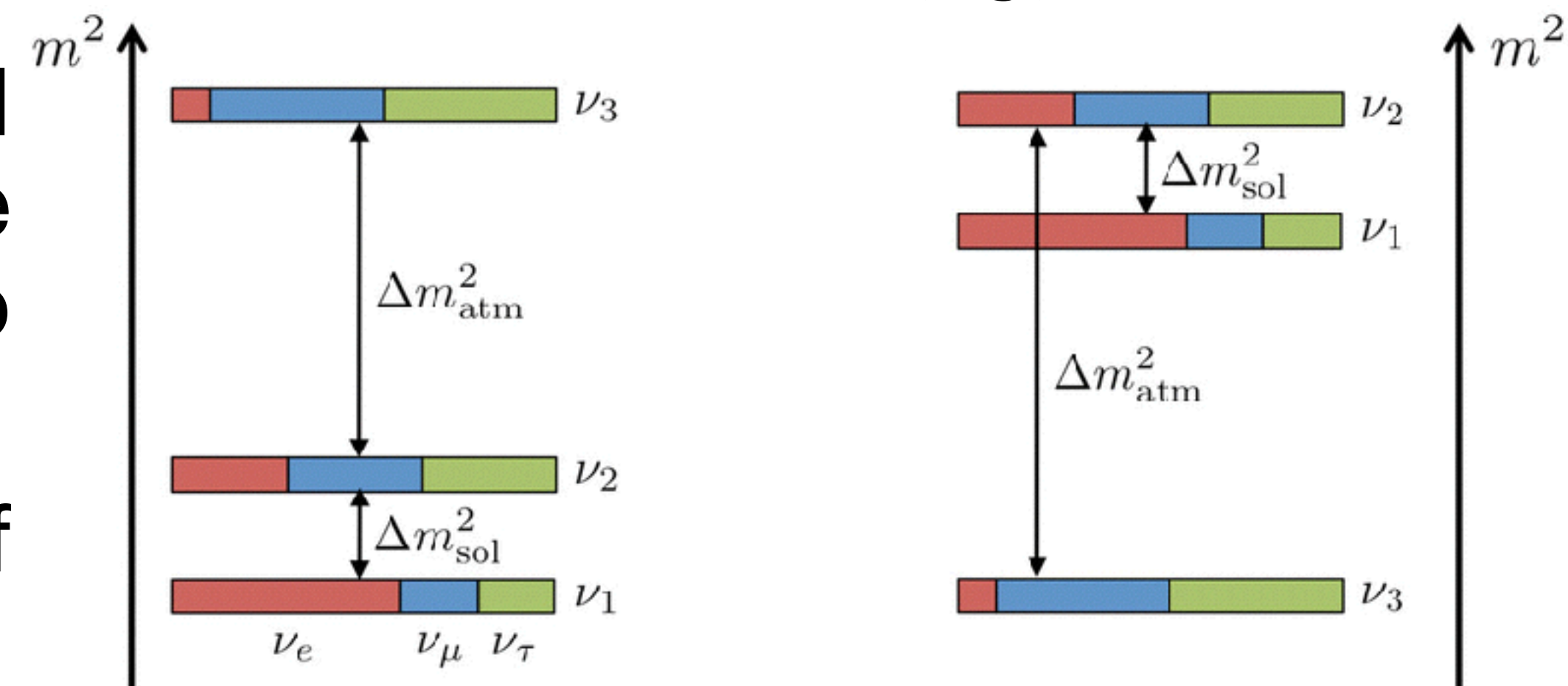
Paths to Beyond-the-Standard-Model Physics

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

PMNS Matrix $\qquad$ Atmospheric $\qquad$ Reactor $\qquad$ Solar

$$|U| = \begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu1} & |U|_{\mu2} & |U|_{\mu3} \\ |U|_{\tau1} & |U|_{\tau2} & |U|_{\tau3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

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!

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Neutrinos and Oscillation Physics (Part Three)
Paths to Beyond-the-Standard-Model Physics

PMNS Matrix

$$|U| = \begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu1} & |U|_{\mu2} & |U|_{\mu3} \\ |U|_{\tau1} & |U|_{\tau2} & |U|_{\tau3} \end{bmatrix} = \begin{bmatrix} 0.800 \to 0.845 & 0.513 \to 0.579 & 0.144 \to 0.156 \\ 0.244 \to 0.499 & 0.505 \to 0.693 & 0.631 \to 0.768 \\ 0.272 \to 0.518 & 0.471 \to 0.669 & 0.623 \to 0.761 \end{bmatrix}$$

Current 3σ CL on the best fit for the PMNS matrix gives tight constraints on the mixing angles and mass splitting.
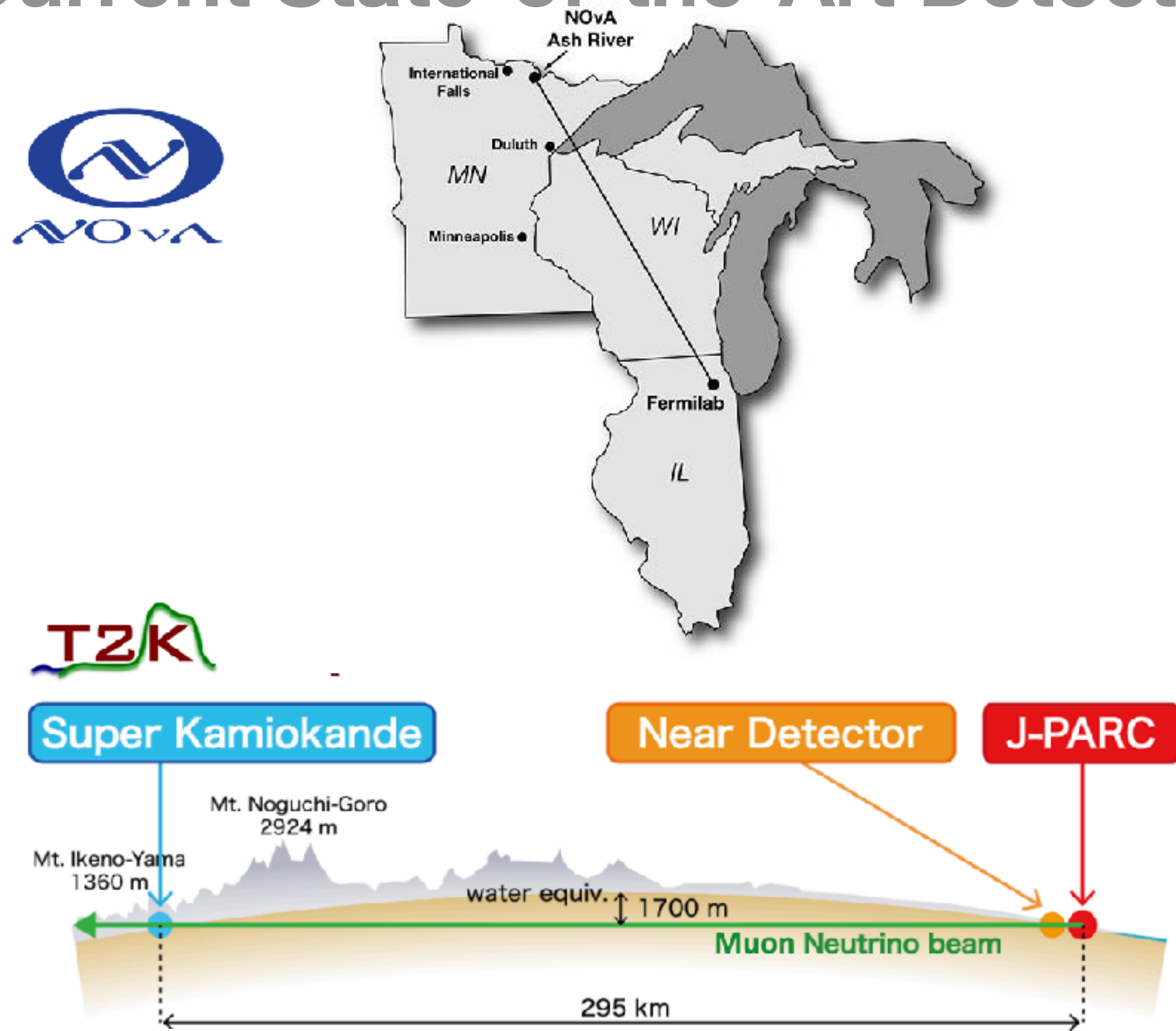
δ_{CP} and the NH/IH question are the biggest uncertainties as of Oct 2021.

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/°$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
$\theta_{23}/°$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
$\theta_{13}/°$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
$\delta_{CP}/°$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

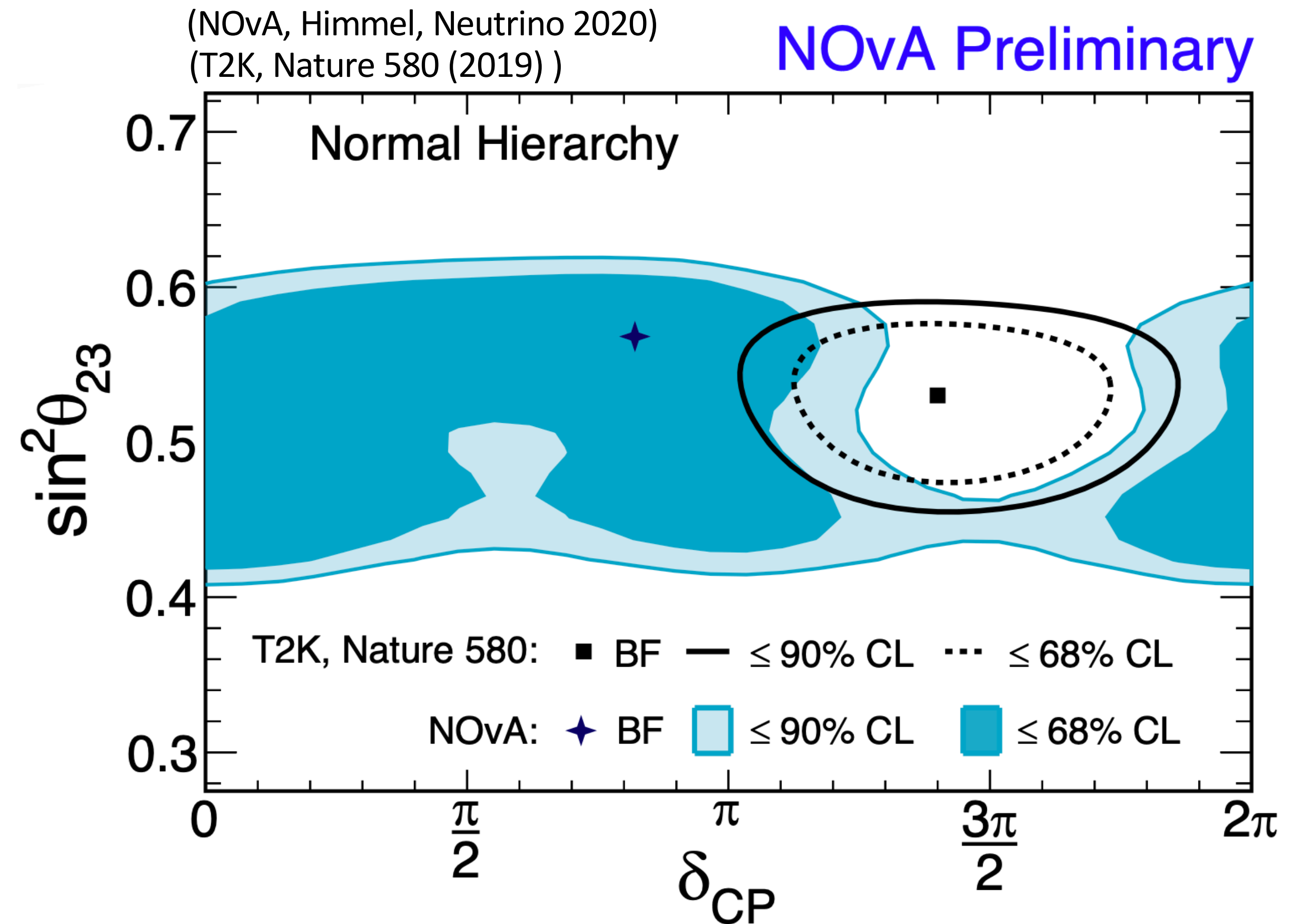NuFit 5.1, October 2021

Current Generation of Long-Baseline Experiments
Current State-of-the-Art Detectors and Measurements

NOvA
Ash River

NOvA

T2K

Super Kamiokande | Near Detector | J-PARC

Mt. Noguchi-Goro 2924 m

Mt. Ikeno-Yama 1360 m

water equiv. 1700 m

Muon Neutrino beam

295 km

T2K, Stephen Dolan, Neutrino 2020

(NOvA, Himmel, Neutrino 2020)
(T2K, Nature 580 (2019))

NOvA Preliminary

Normal Hierarchy

$\sin^2\theta_{23}$

δ_{CP}

T2K, Nature 580: ■ BF — ≤ 90% CL ⋯ ≤ 68% CL

NOvA: ✦ BF ▢ ≤ 90% CL ▢ ≤ 68% CL

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

NOvA

NOvA Simulation

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
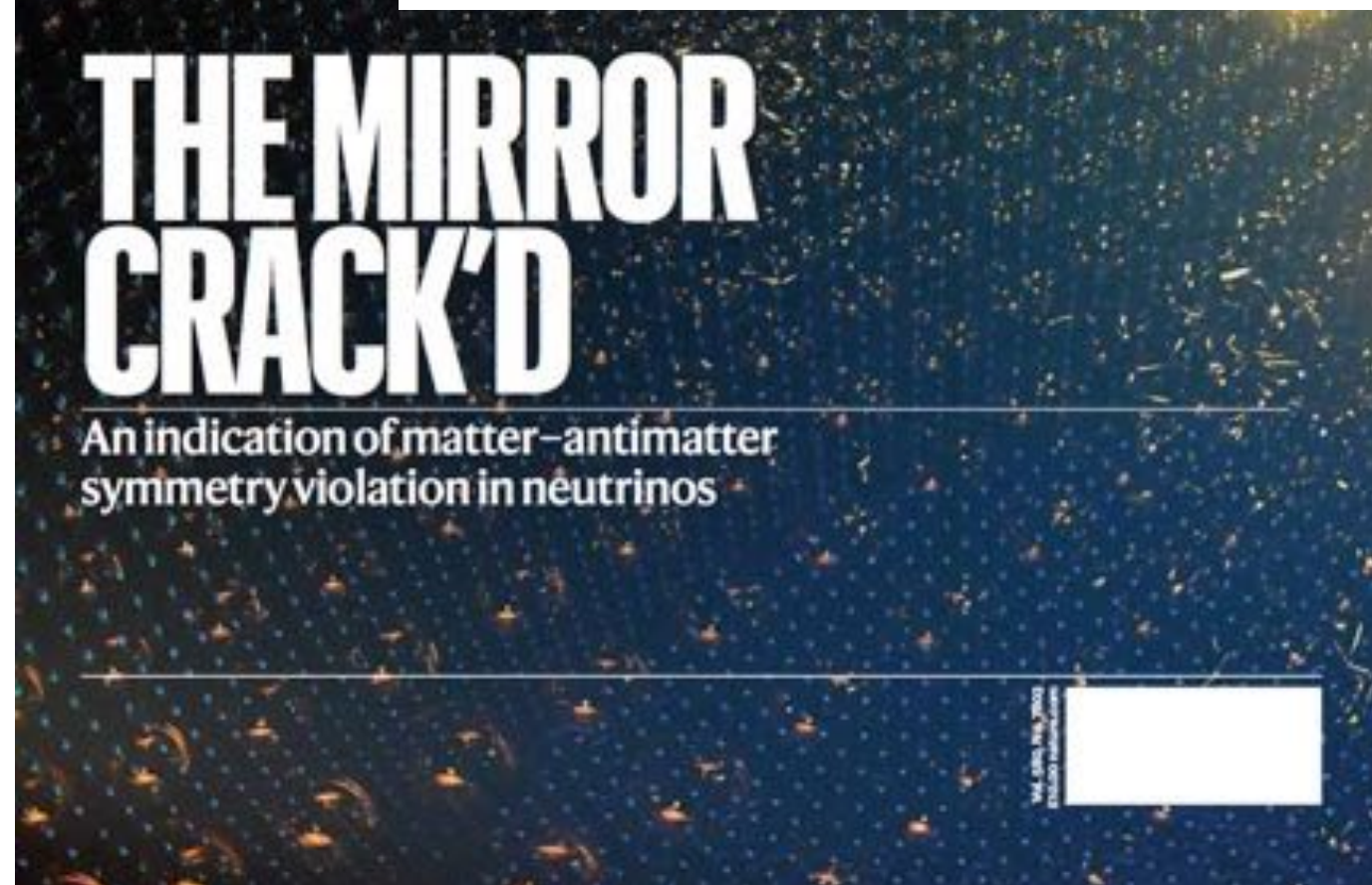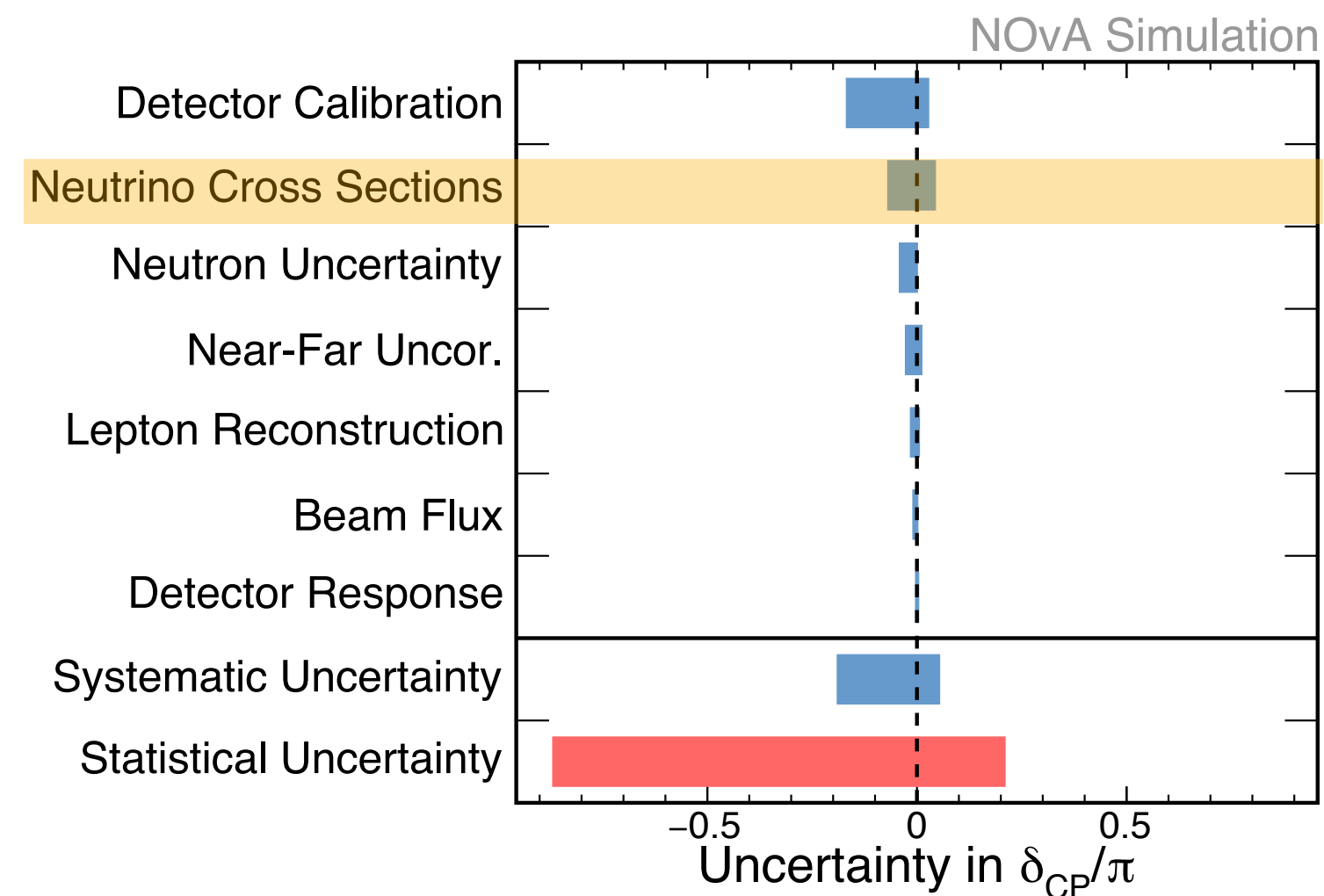
Source of Uncertainty	$\sin^2\theta_{23}$	δ_{CP}/π	$\lvert\Delta m^2_{32}\rvert\ (\times10^{-3}\ \mathrm{eV}^2)$
Beam Flux	+0.00034 / -0.0008	+0.0023 / -0.0099	+0.0014 / -0.0023
Detector Calibration	+0.005 / -0.025	+0.028 / -0.17	+0.019 / -0.019
Detector Response	+0.0016 / -0.0021	+0.0041 / -0.0035	+0.0067 / -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?

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The Neutrino-Nucleus Cross Section Problem (Part One)
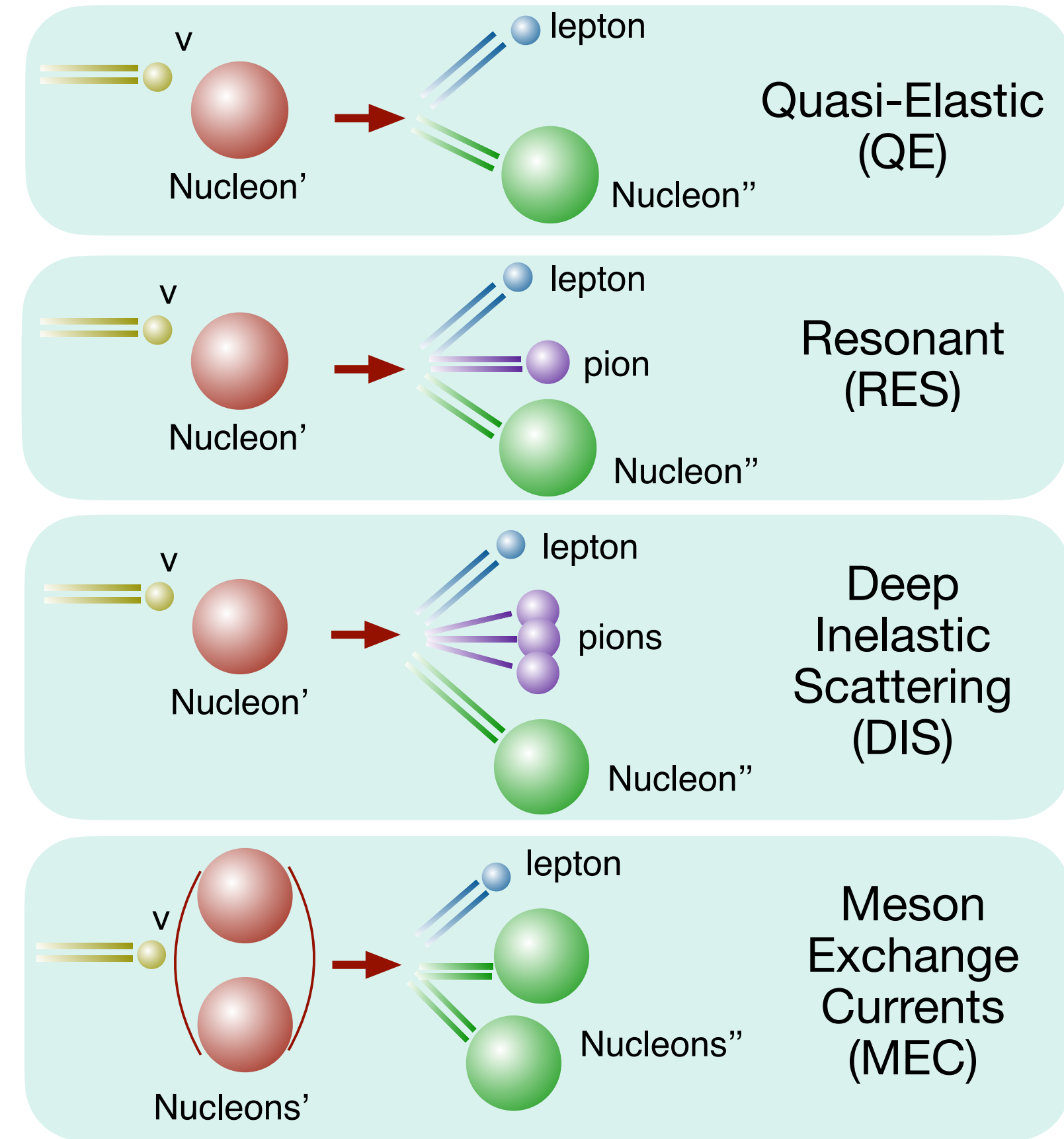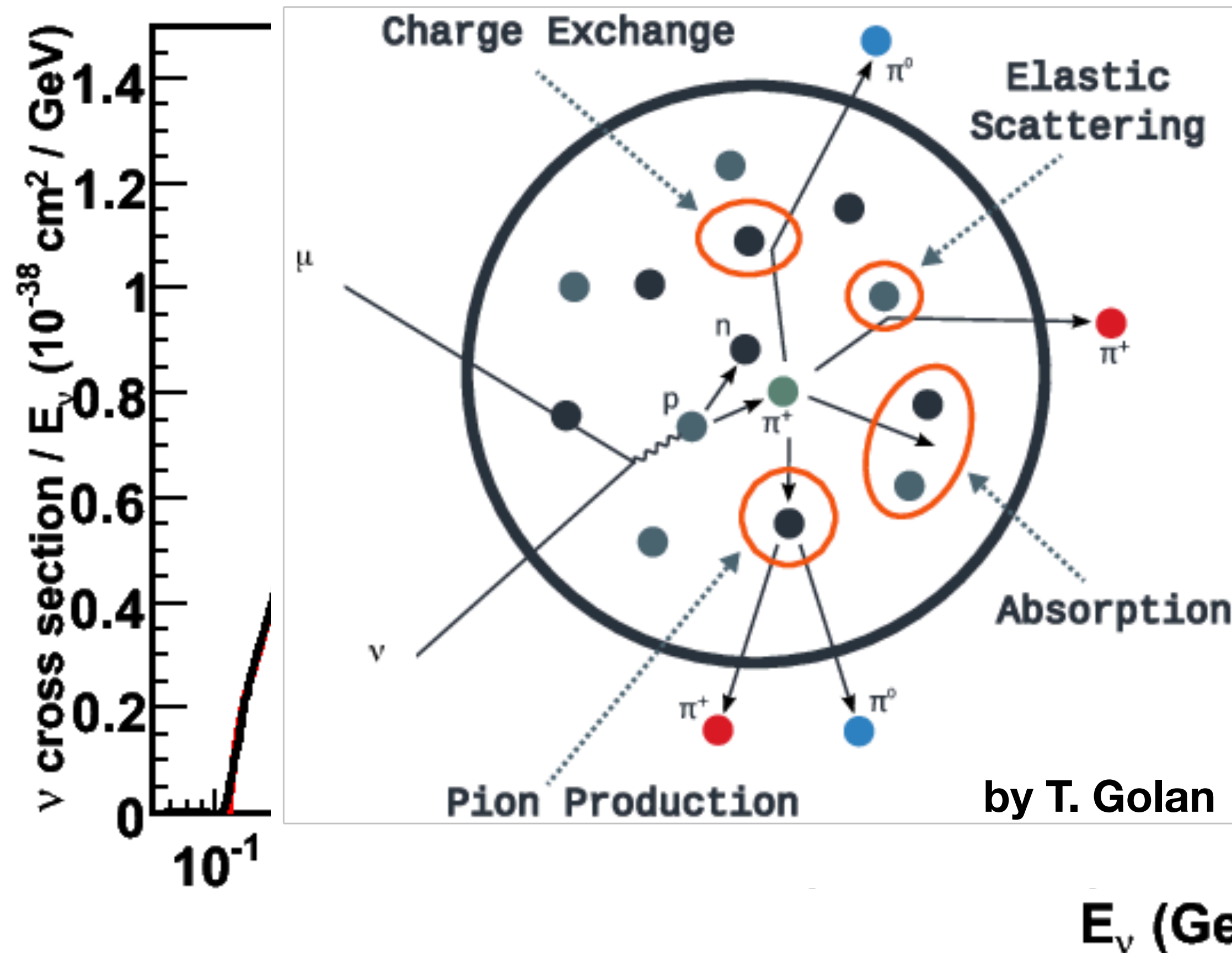
Where is the Problem?
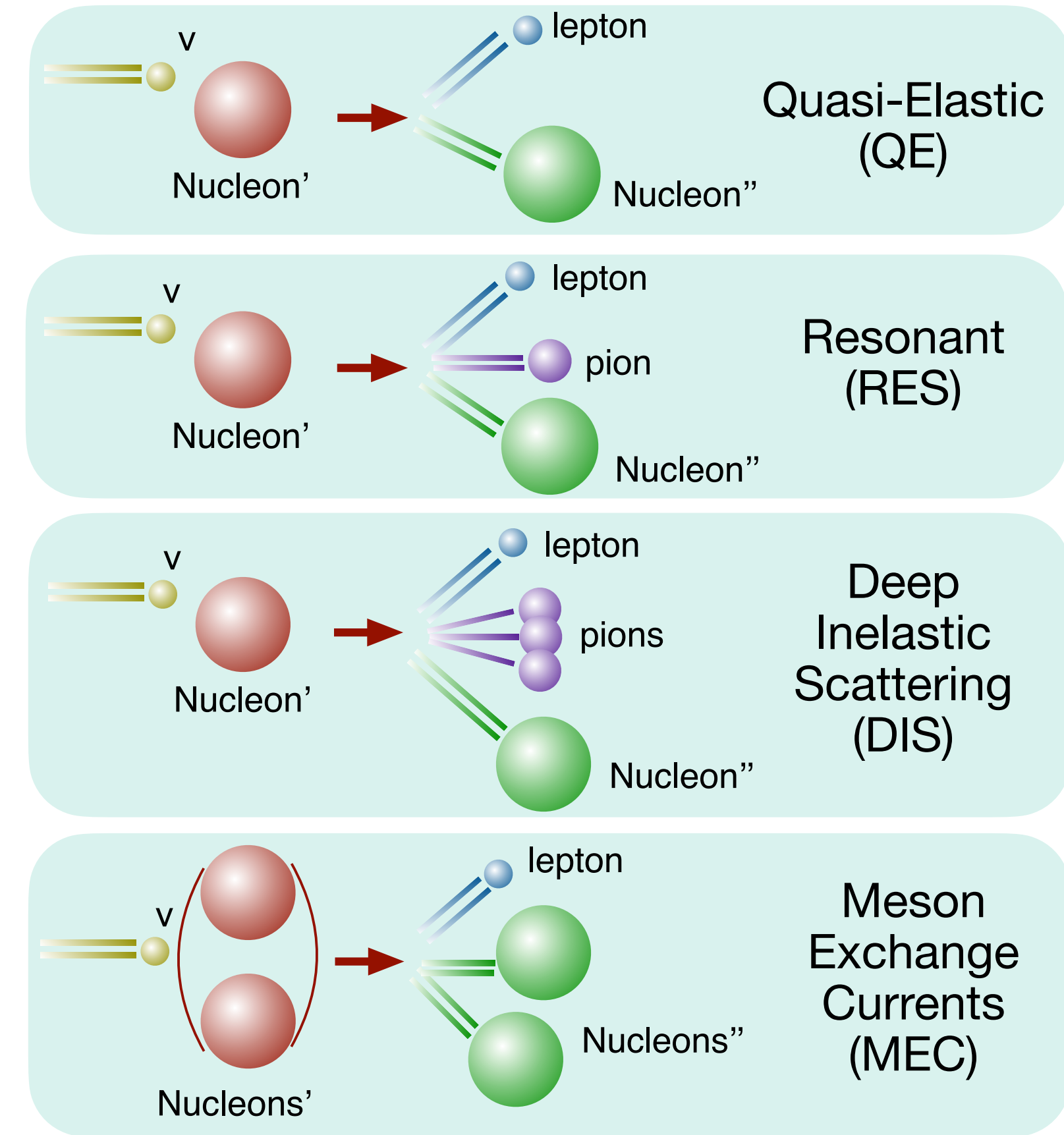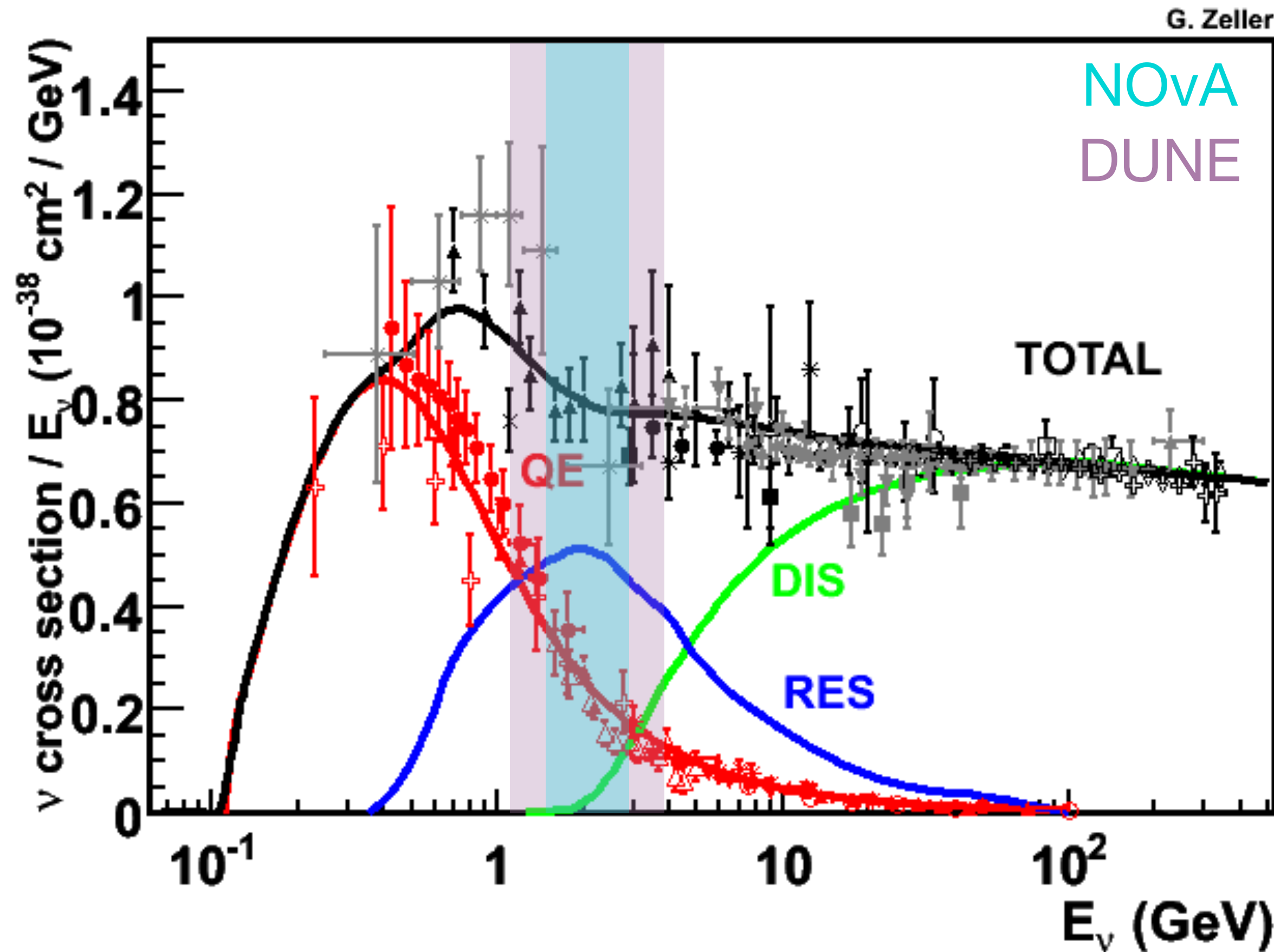
Many neutrino scattering measurements but to first order must understand interplay between four different types of scattering (QE/Elastic, RES, DIS, MEC).

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

The Neutrino-Nucleus Cross Section Problem (Part One)
Where is the Problem?

by T. Golan

Quasi-Elastic (QE)

Resonant (RES)

(RES)

Deep Inelastic Scattering (DIS)

Meson Exchange Currents (MEC)

UCL

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 nuc

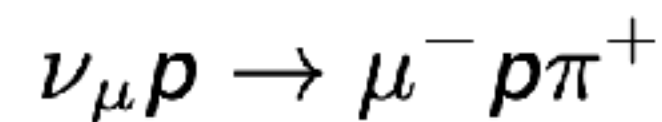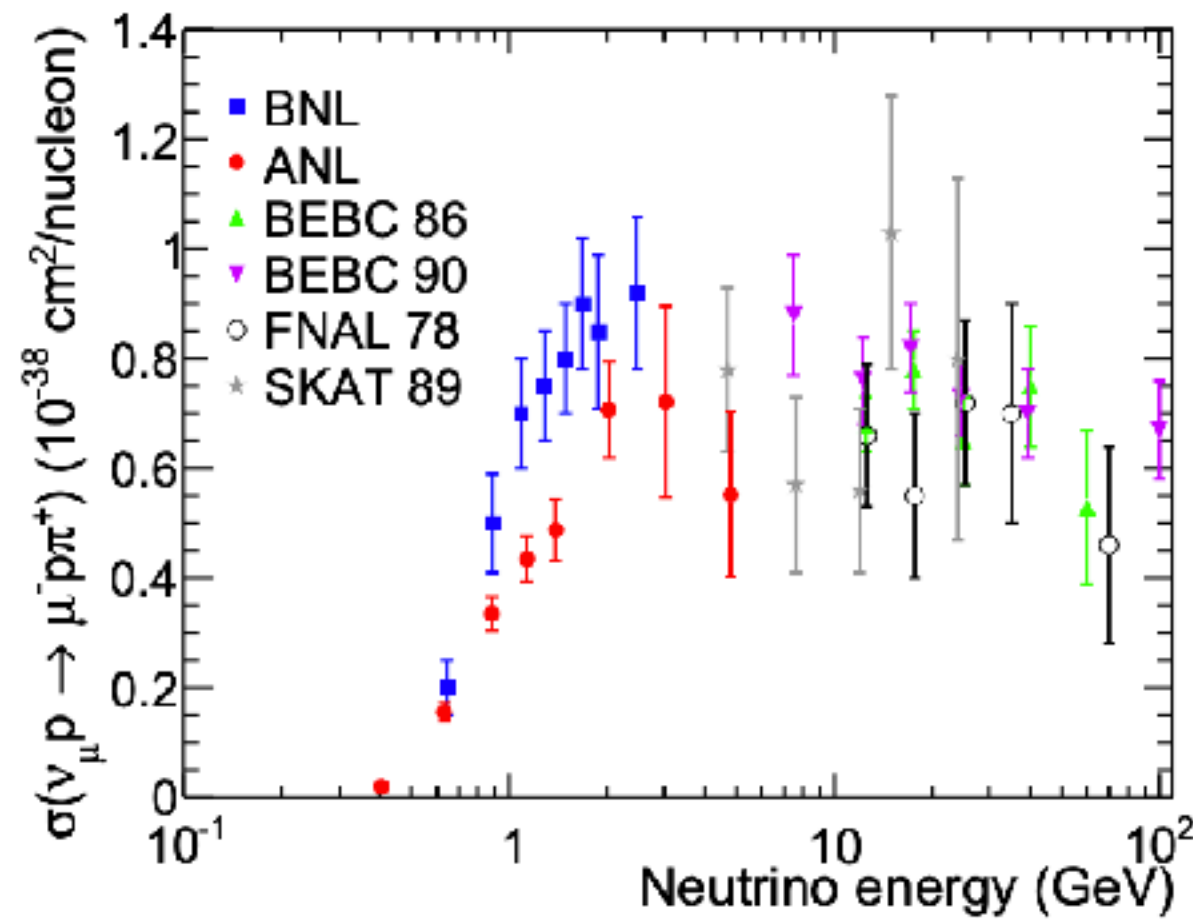# The Neutrino-Nucleus Cross-Section Problem (Part Three)
Example of the Issue with QE/Elastic scattering
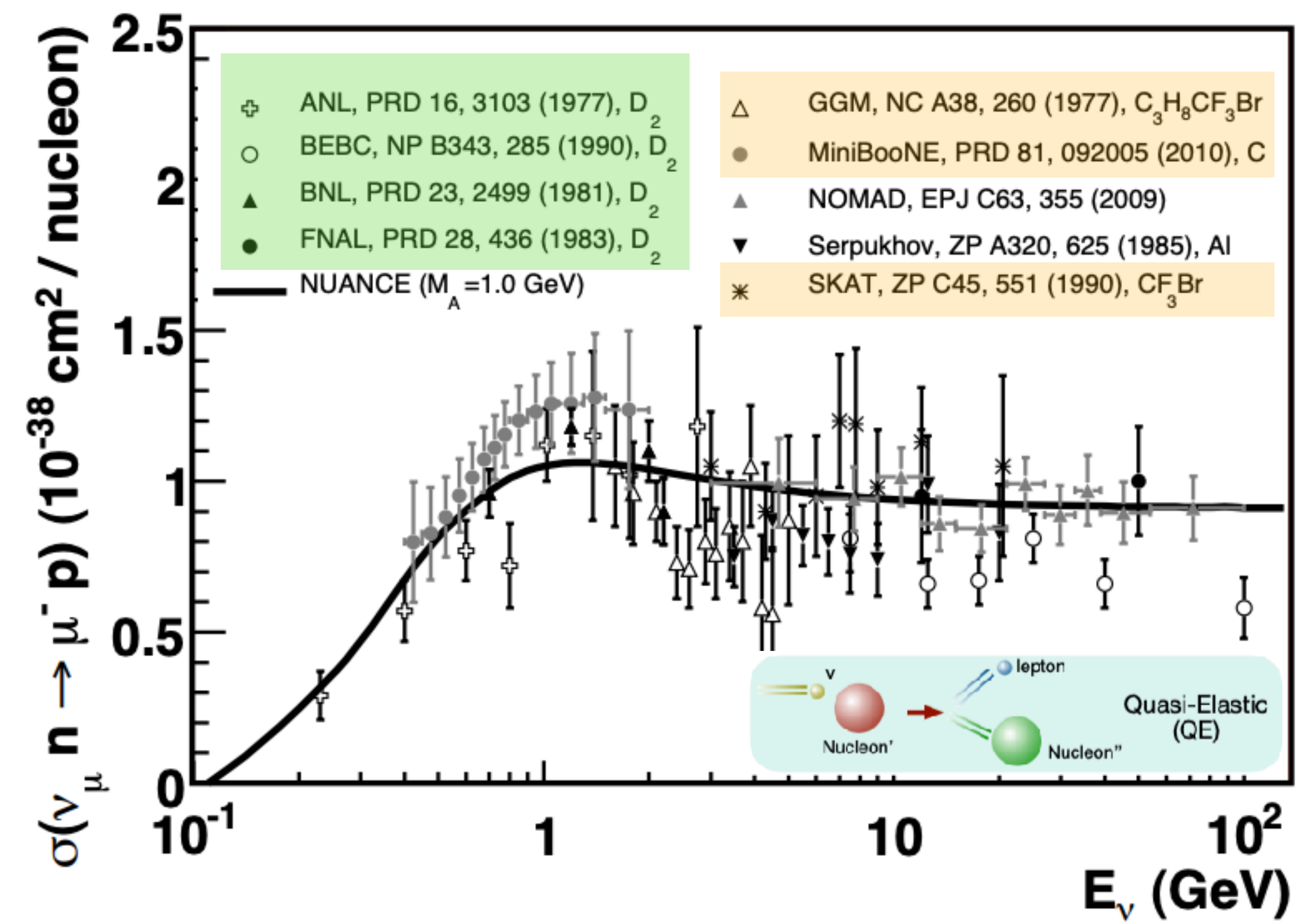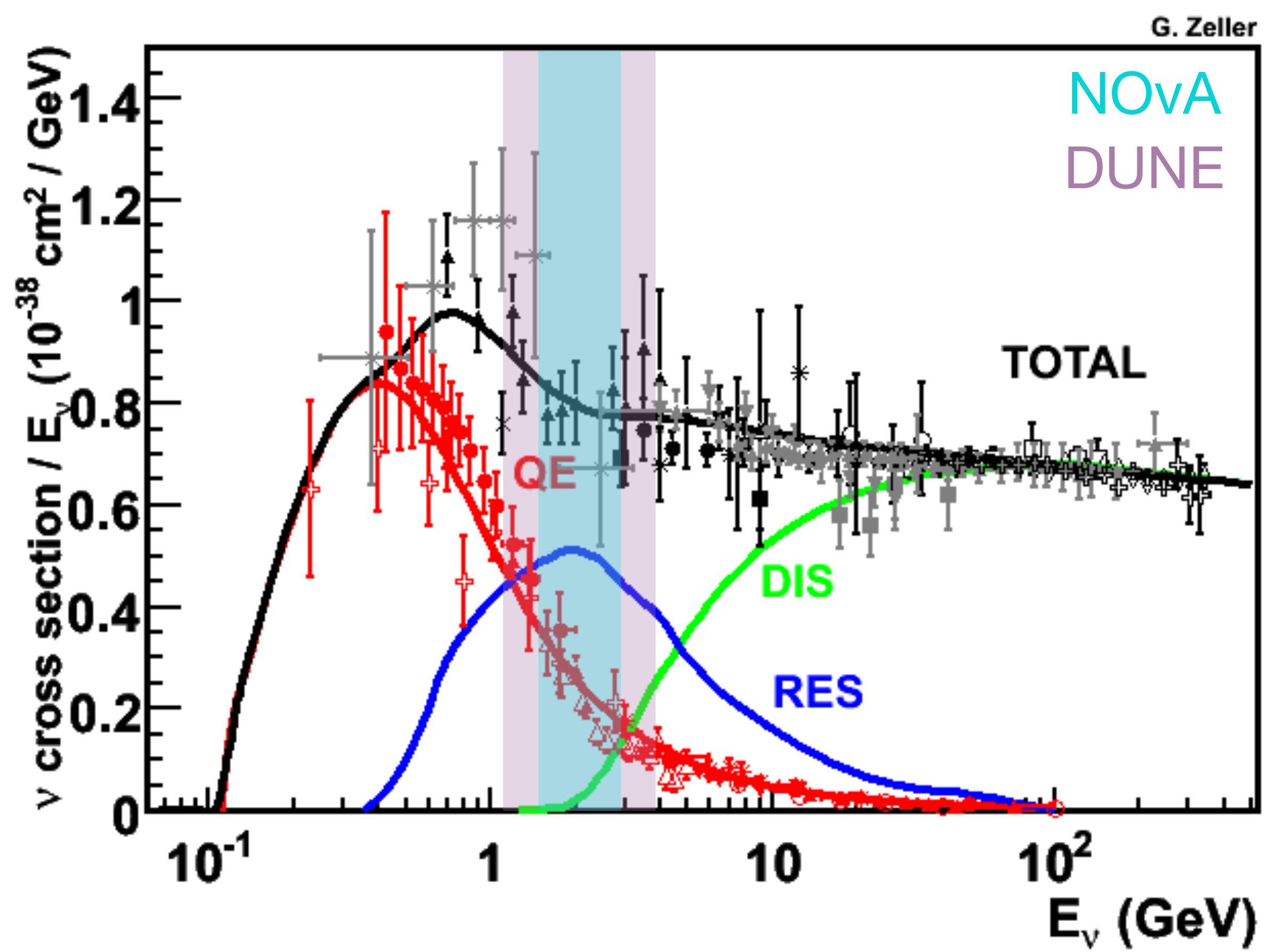
MiniBooNE Axial Mass estimated to be about 1.31 GeV with amazing statistics, however world hydrogen/deuterium data from ANL, BNL, FNAL, and BEBC put axial mass at ~1.0 GeV!
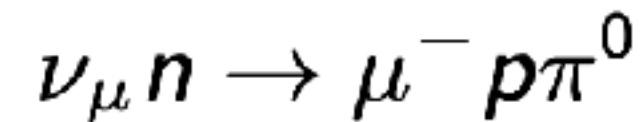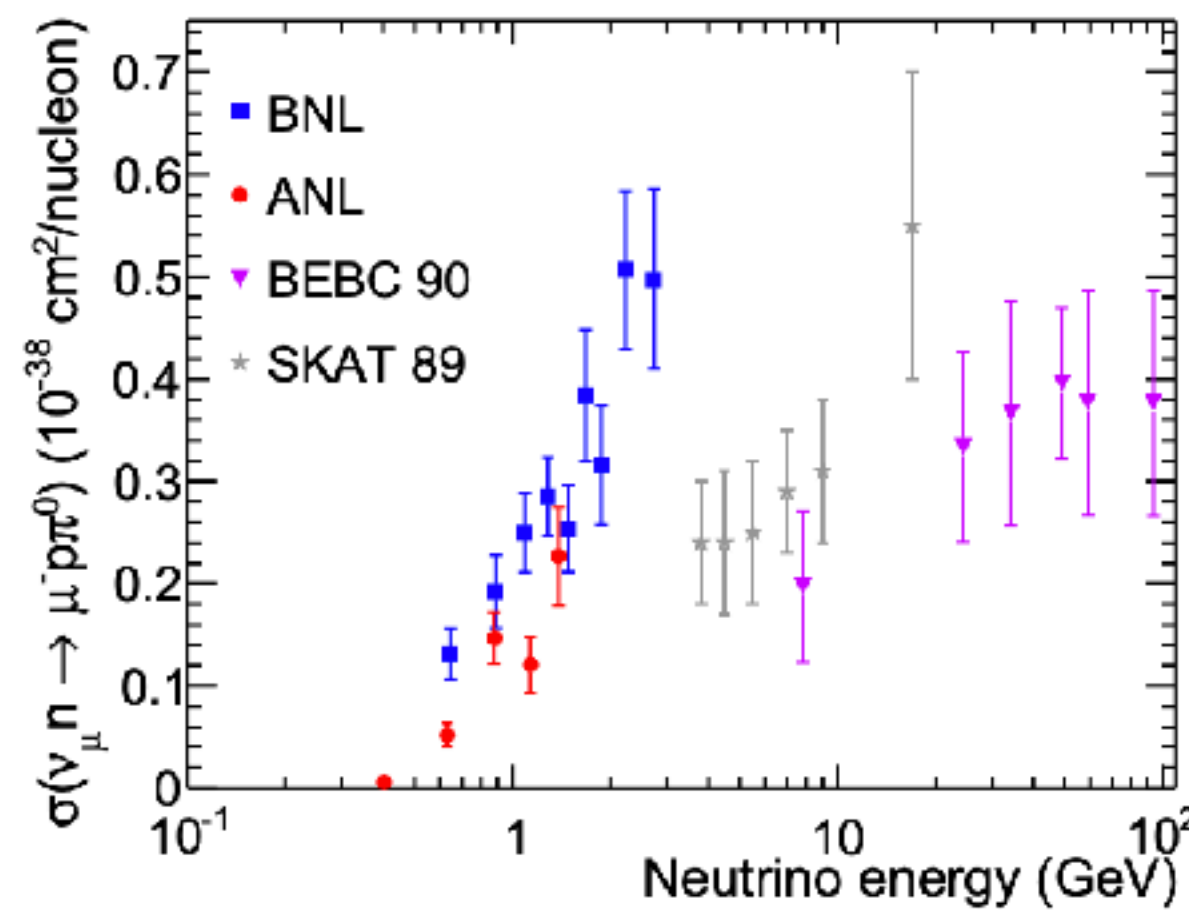
The Neutrino-Nucleus Cross-Section Problem (Part Two)
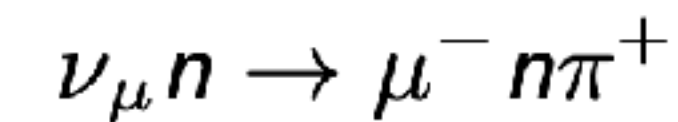## Significant Problems with Old Bubble Chamber Data

$$\nu_\mu p \to \mu^- p\pi^+ \qquad \nu_\mu n \to \mu^- p\pi^0 \qquad \nu_\mu n \to \mu^- n\pi^+$$

BNL Dataset

ANL Dataset   arXiv:1411.4482

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

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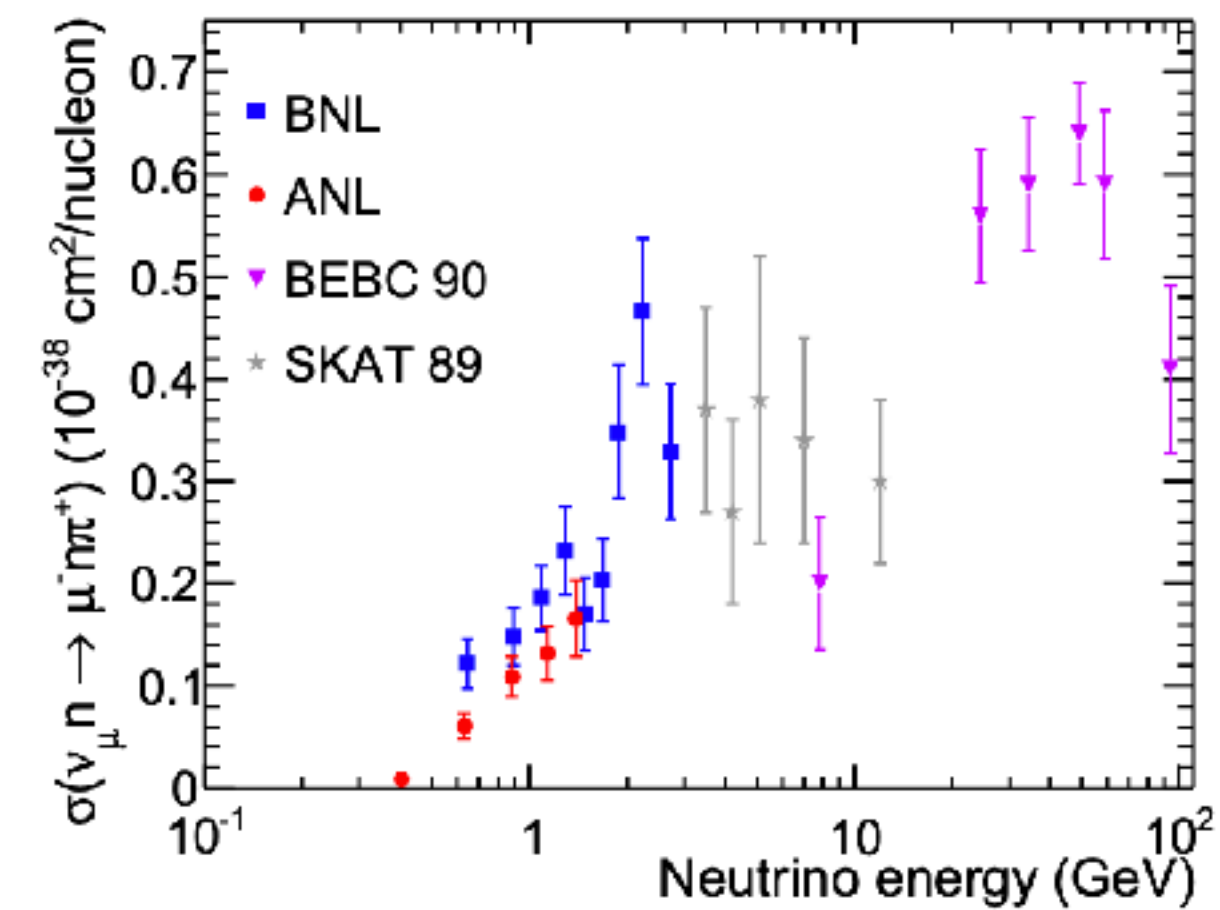
Statistics in the relevant regions for Long-Baseline experiments are low $\sim O(10^4)$ and systematic uncertainties are high.

Generator predications based on these data have low exclusionary power at DUNE/Hyper-K precision.
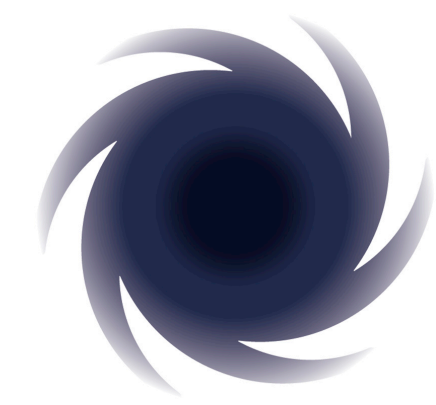
The Next Generation of Long-Baseline Experiments

DUNE: the future long-baseline oscillation experiment
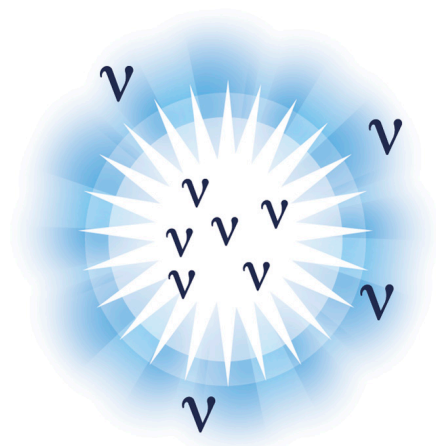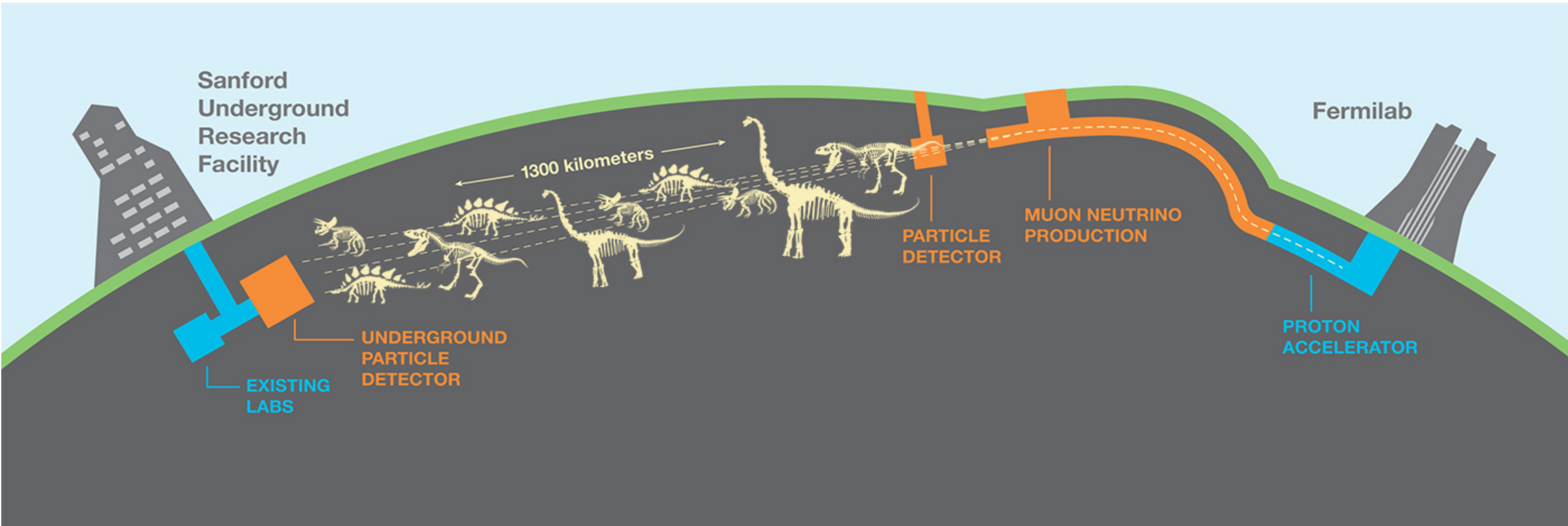
- Leptonic CP-violation ($\delta_{CP}, \Delta L = 0$?)
- Oscillation Parameters (θ_{23})
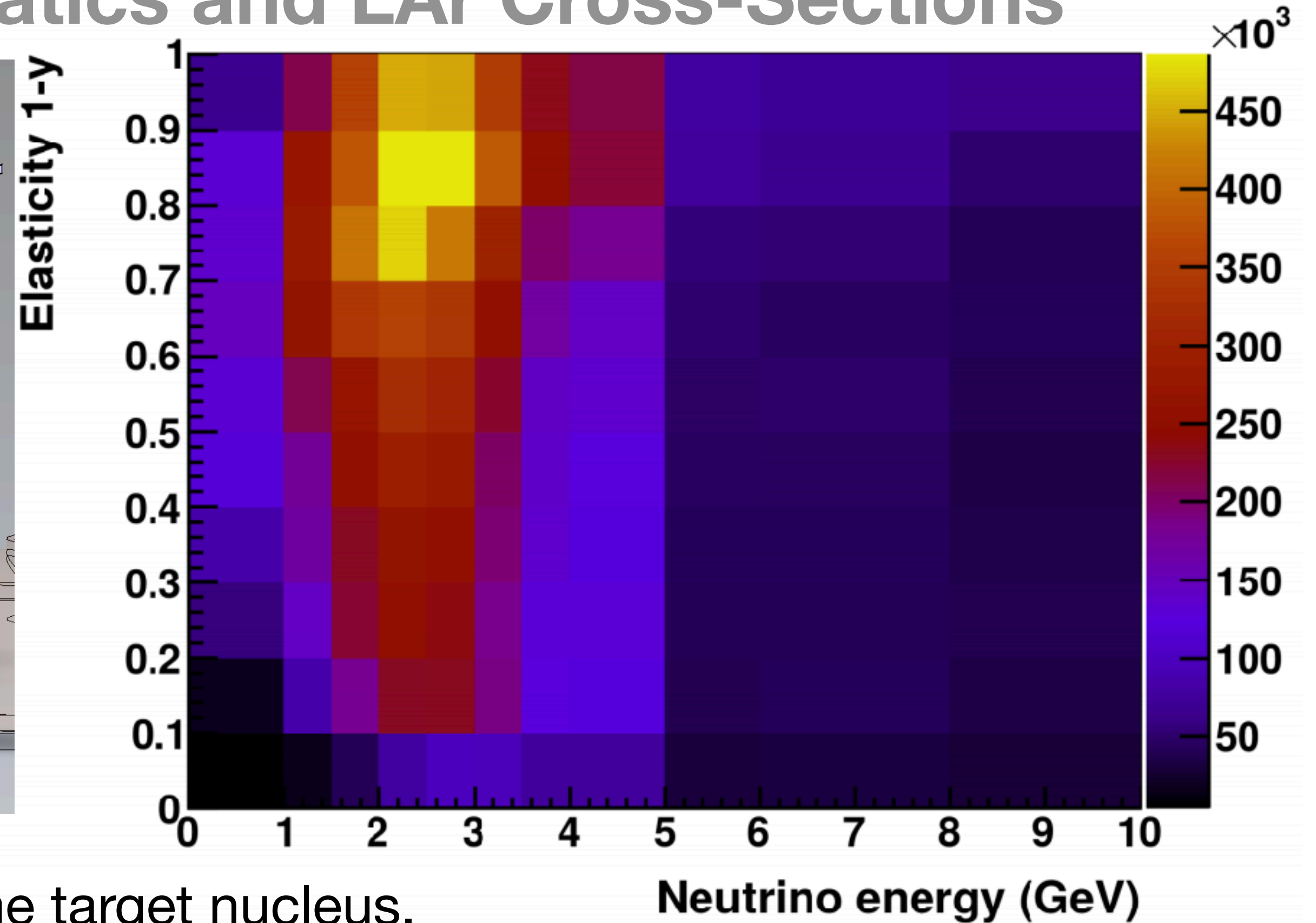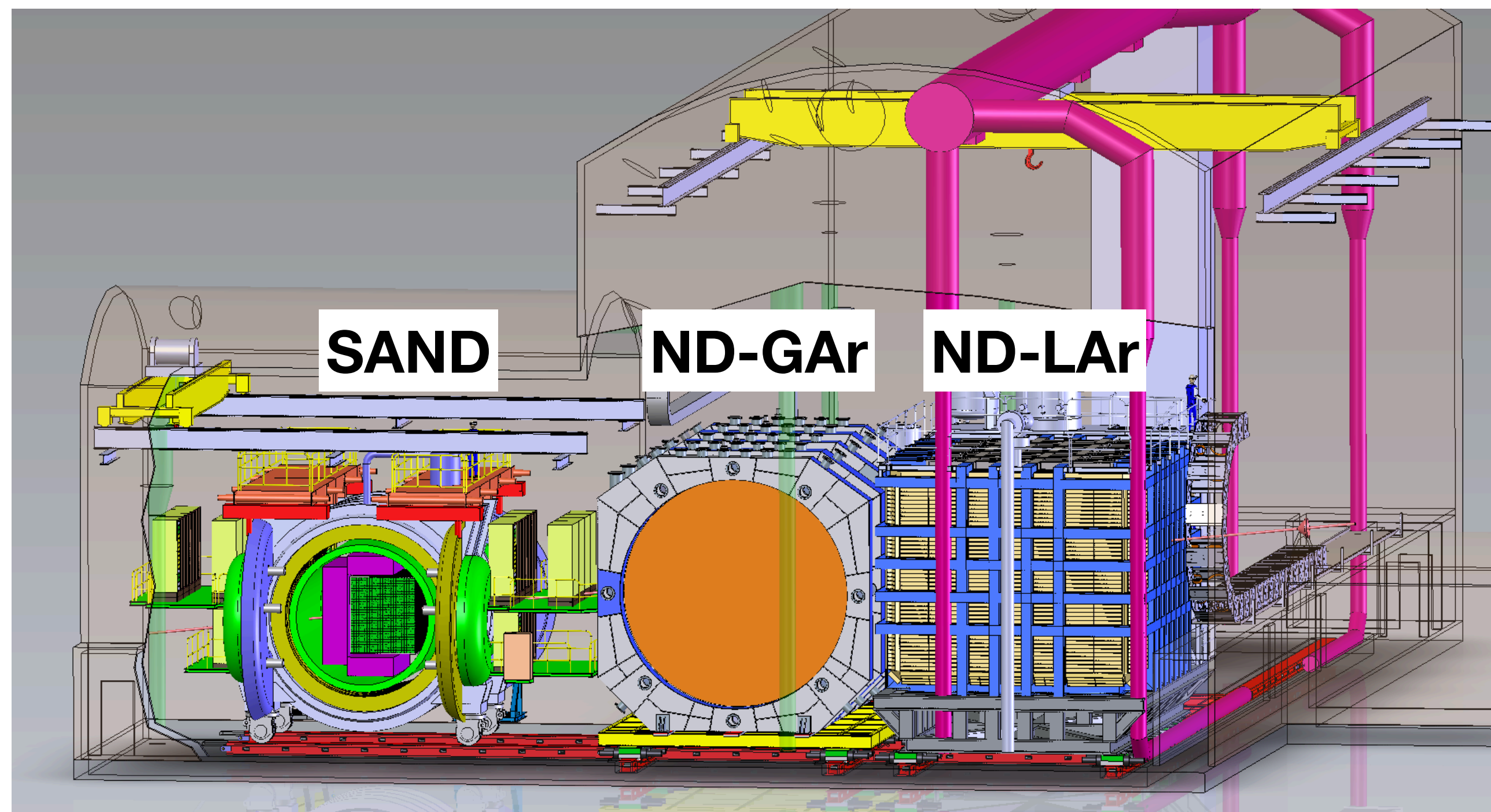- Neutrino Mass Hierarchy (NH/IH?)

- 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_μ CC events per year**.

The LBNF/DUNE Beam
Super High-Statistics Neutrino Beam
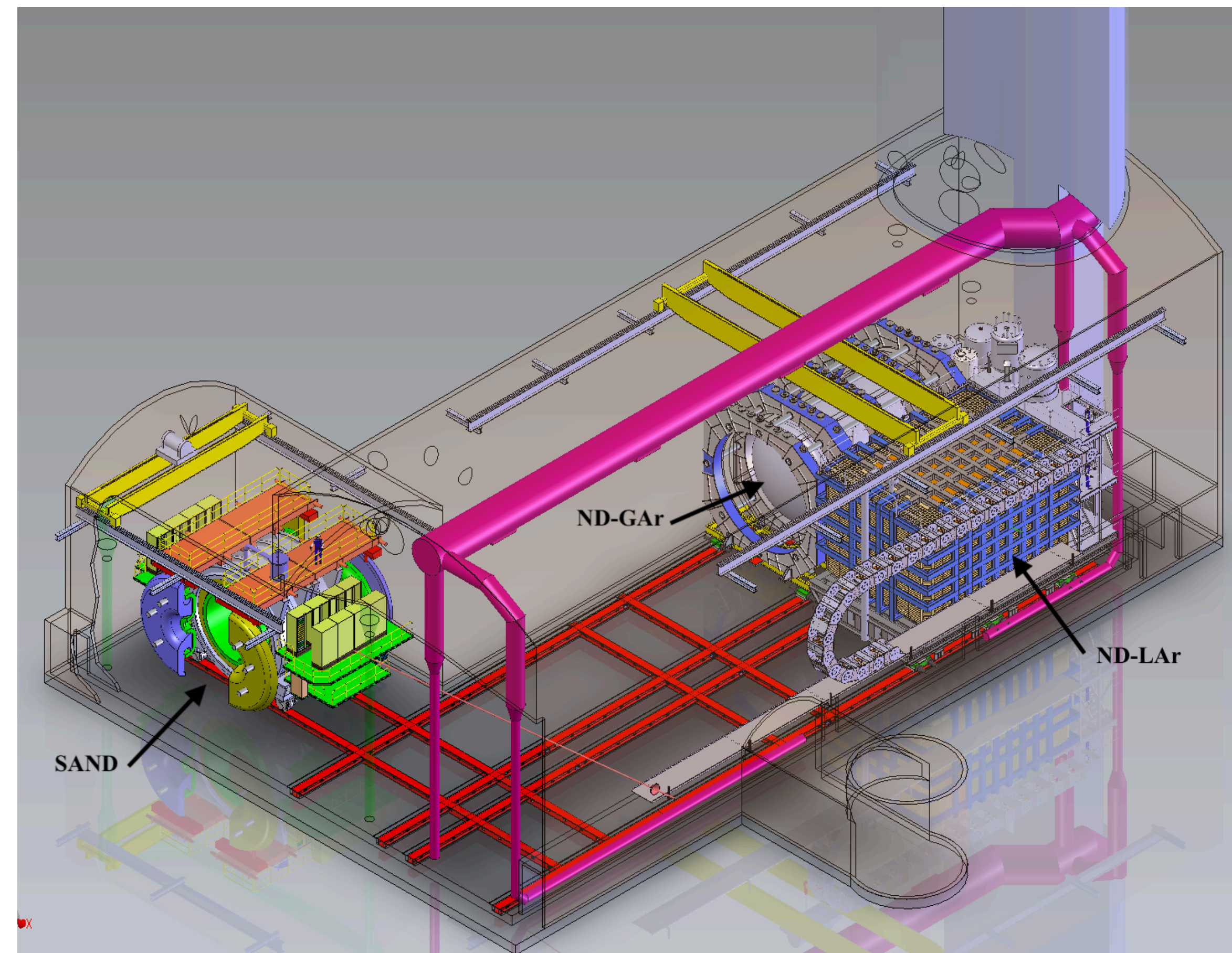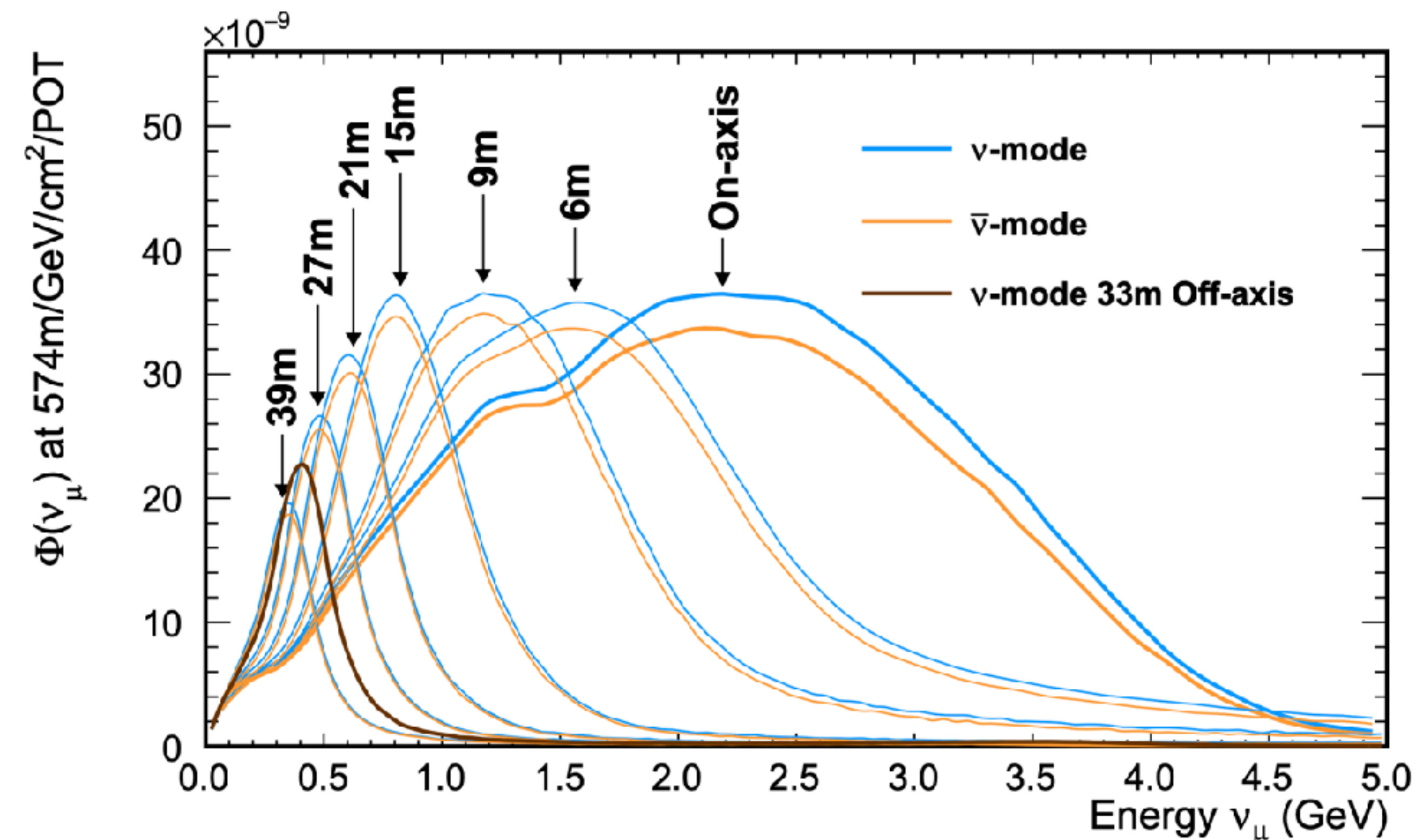
DUNE-PRISM will have the Argon detectors move in order to deconvolve the flux from the cross sections.

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

Outside possibility of moving to higher energies!

Consequences of Misunderstandings in Cross Sections
Example of an Issue with MEC in NOvA
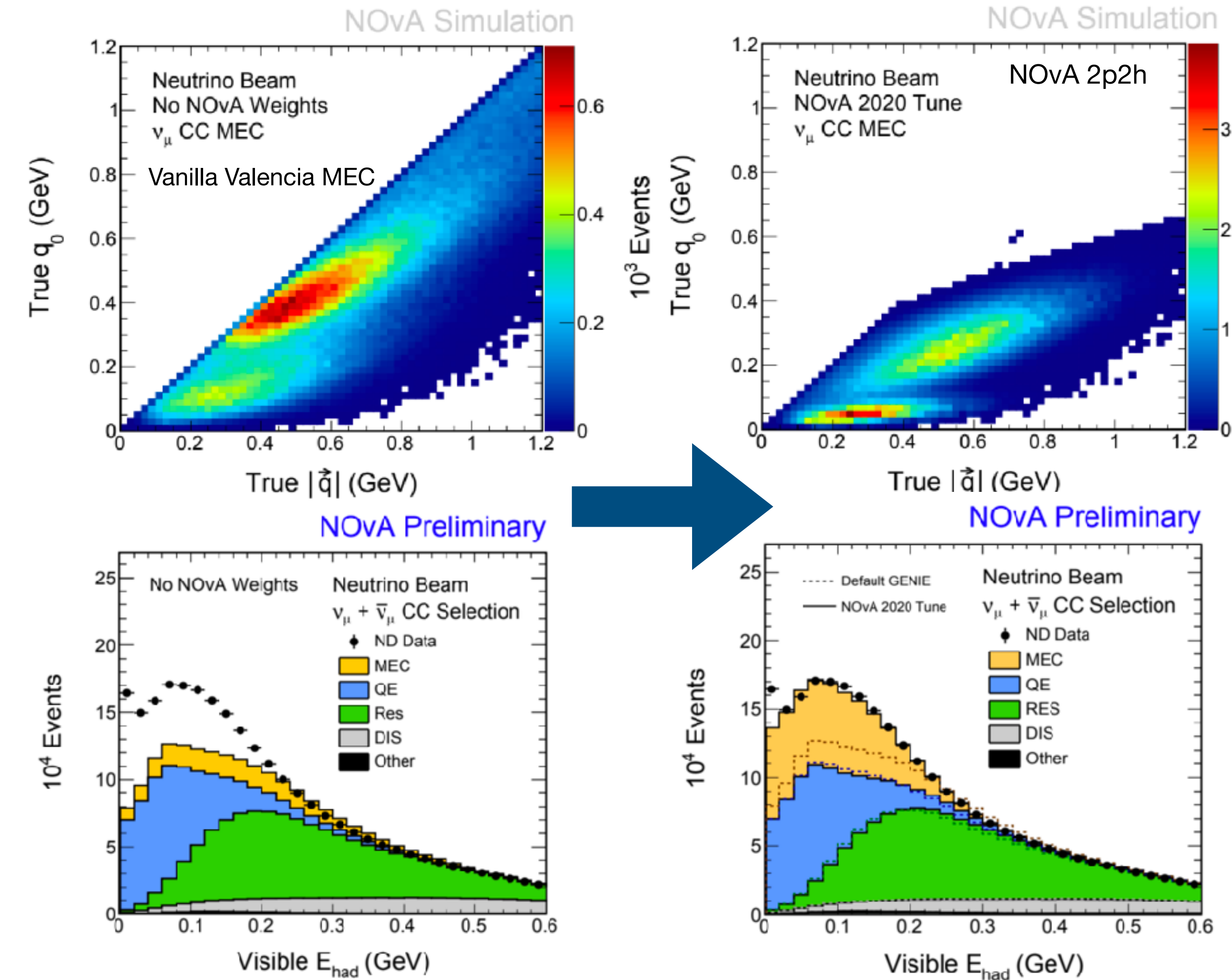

NOvA uses GENIE to model neutrino interactions, but no 'vanilla' model describes excess data.

Custom '2p2h' tune does not perfectly describe low energy bins.

MEC exists (!) but no older experiments around to bound the effect.

Each neutrino experiment *requires* significant *tunes* to match any given generator and tunes bring experiments out of agreement with each other!

Data driven corrections can not completely substitute for a fundamental understanding of the physics!

Considering Solutions

How to get Hydrogen into DUNE?

We need a detector in high intensity neutrino beam with hydrogen and deuterium to make new cross-section measurements! Options:

SAND
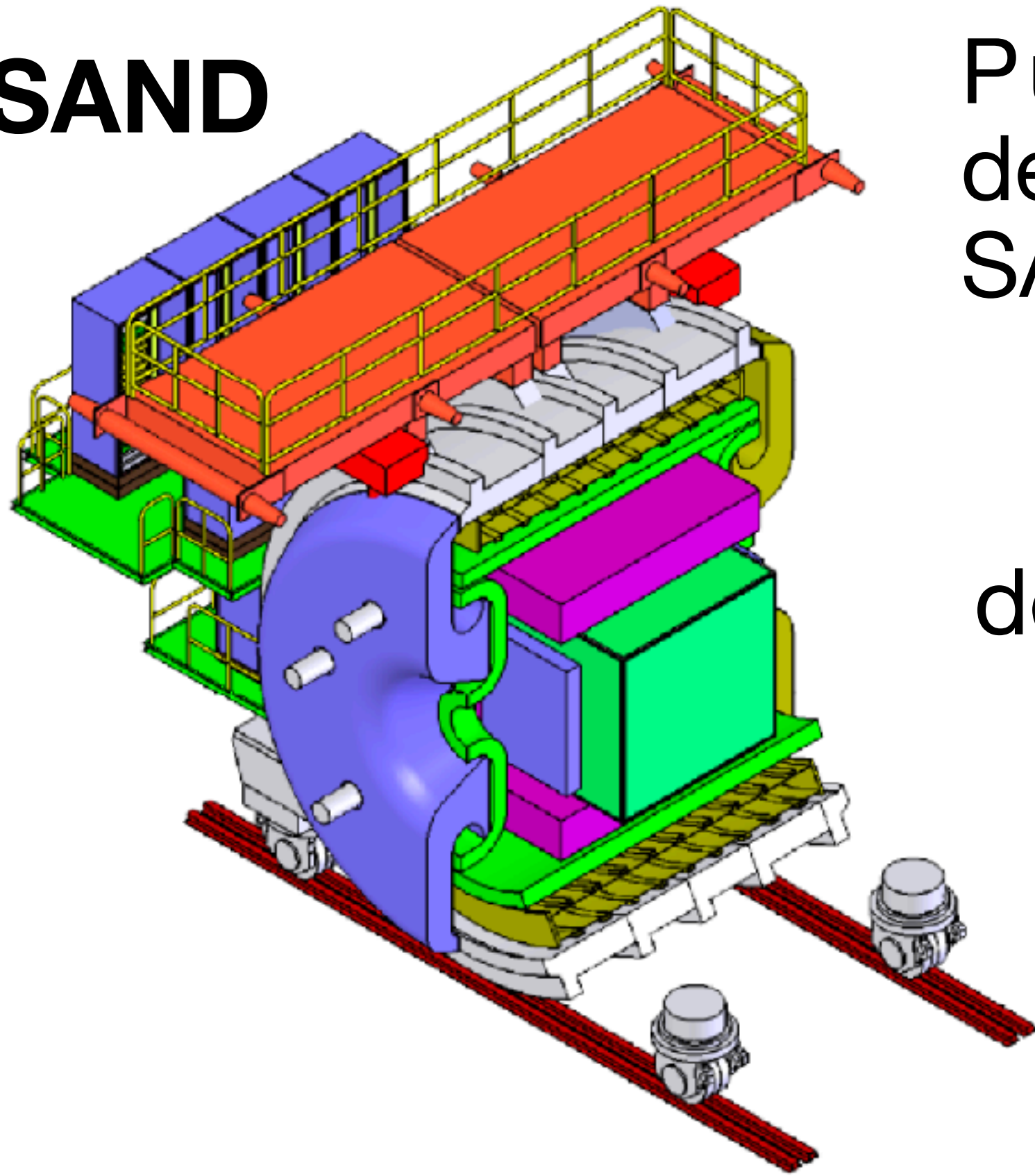
ND-GAr

Put hydrogen in an existing detector: The Strawtube Tracker in SAND (CH)?

Add hydrogen to an existing detector: Add Methane to ND-GAr (CH$_4$)?

Create new dedicated detector: Bubble Chamber (H$_2$/D$_2$+)?

I argue we should do all of these!

Considering Mixed Media Targets

Analysis of Hydrogen Integrated into Existing Detectors?

Regardless of choice, mixed media targets must involve challenging background subtraction.
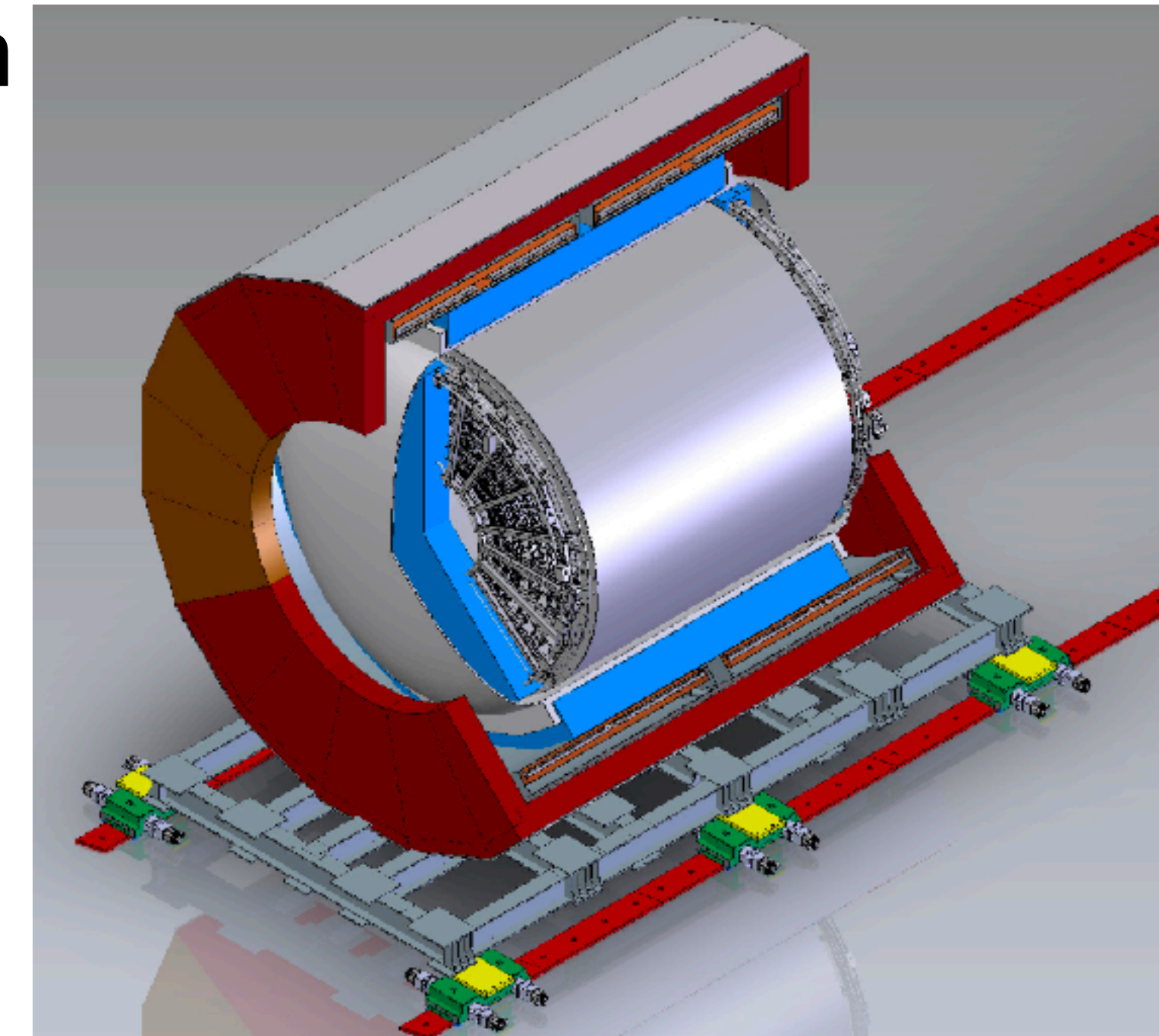
$$\{X, Y\}$$
$$= \{p, \pi^+\} \text{ for } \nu + p \rightarrow l^- + \Delta^{++}$$
$$\text{or } \{p, \pi^-\} \text{ for } \bar{\nu} + p \rightarrow l^+ + \Delta^0$$

note: area normalized!

$\nu_\mu + p \rightarrow \mu^- + \Delta^{++}$, $E_{\nu_\mu} = 1$ GeV

NuWro — H, downscaled by 10
— d
He
C
Ar
Pb
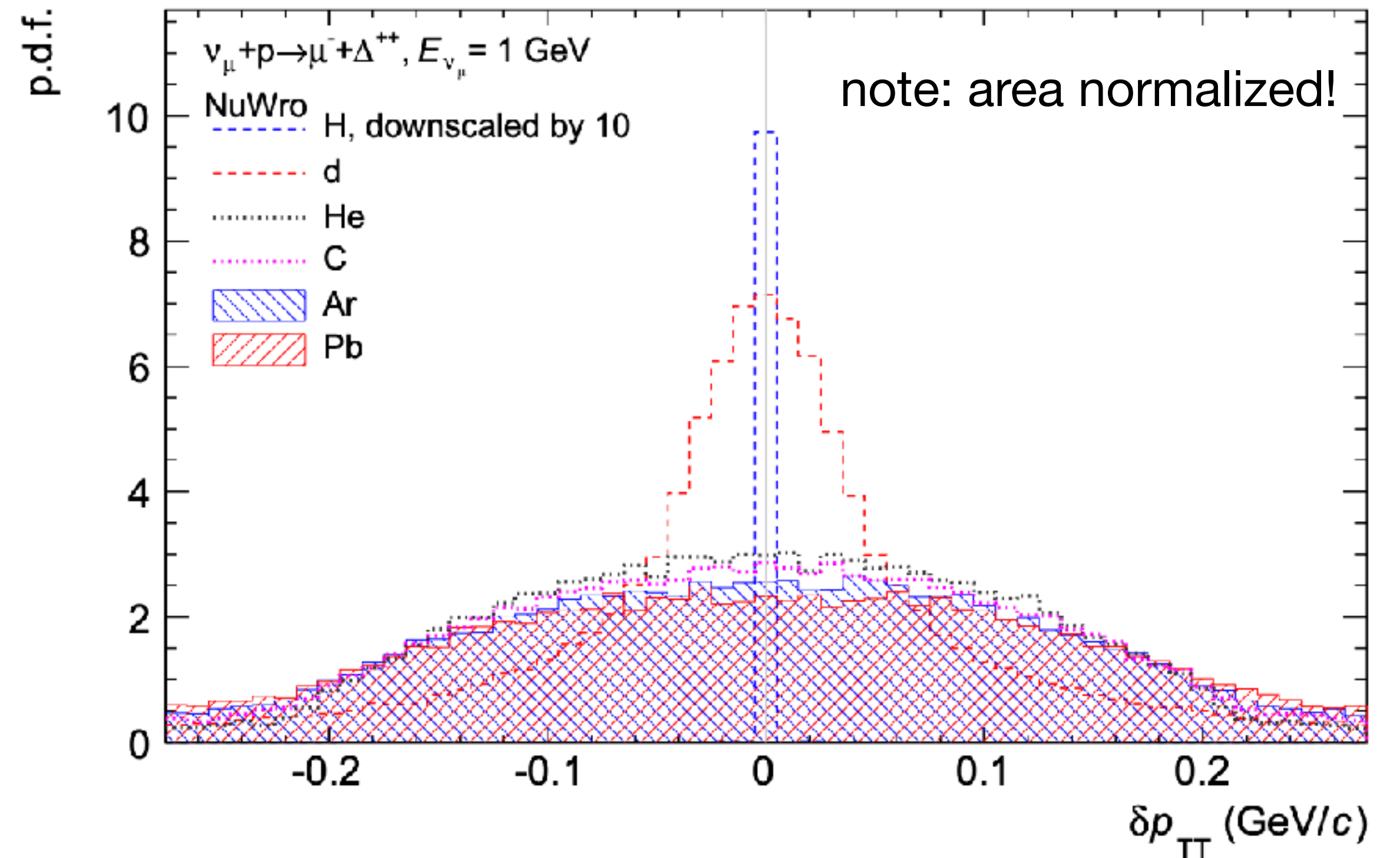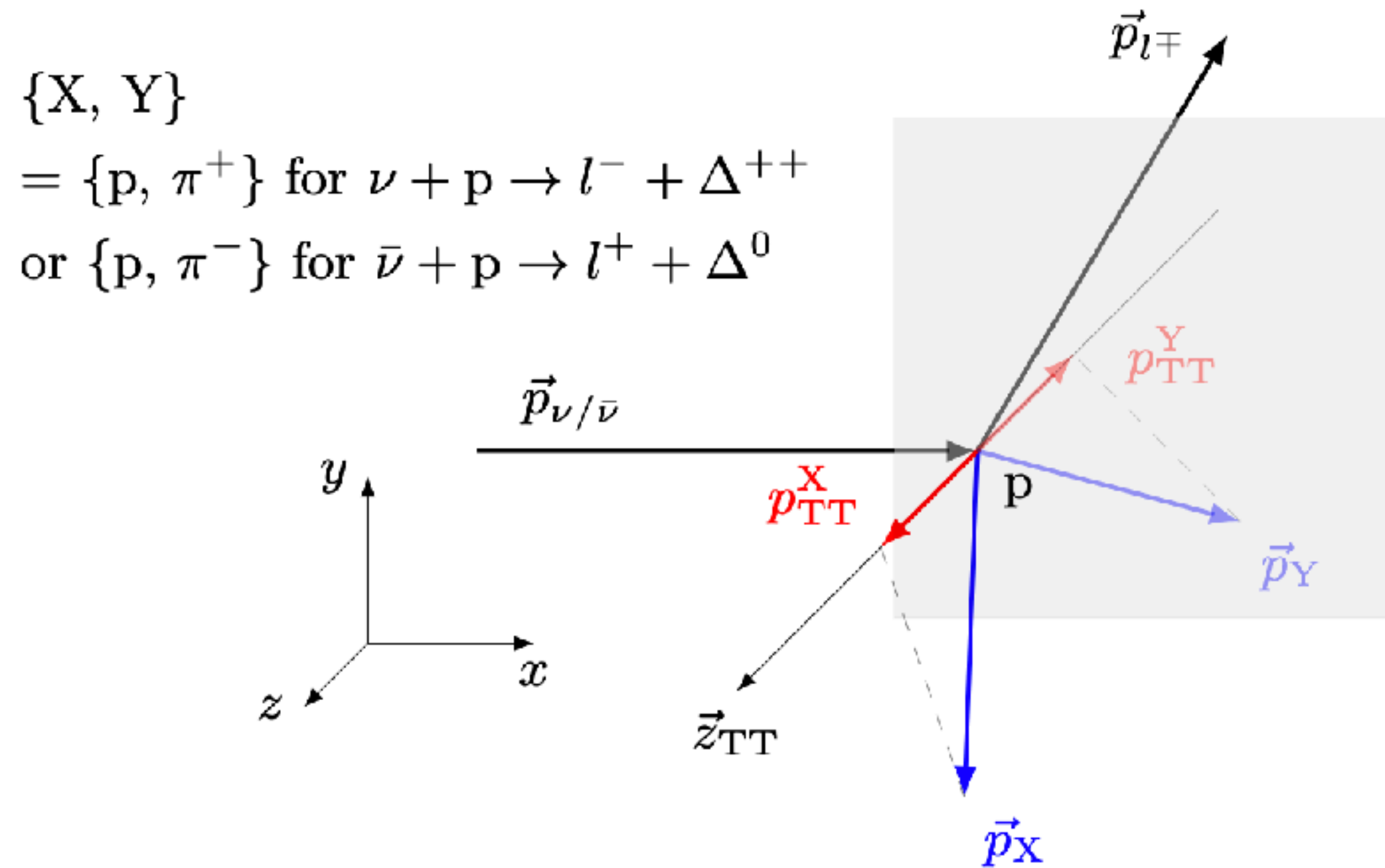
Examining component perpendicular to both neutrino and lepton momentum shows contributions from Fermi motion inside of nucleon. Adds irreducible systematics to measurements. (**also blunts understanding of quark d.o.f.,** more on that later)

Motivating a Hydrogen Bubble Chamber Prototype

A Solution to the Neutrino-Nucleus Cross-Sections Problem!

Event rate can be estimated from the DUNE ND-LAr event rate!
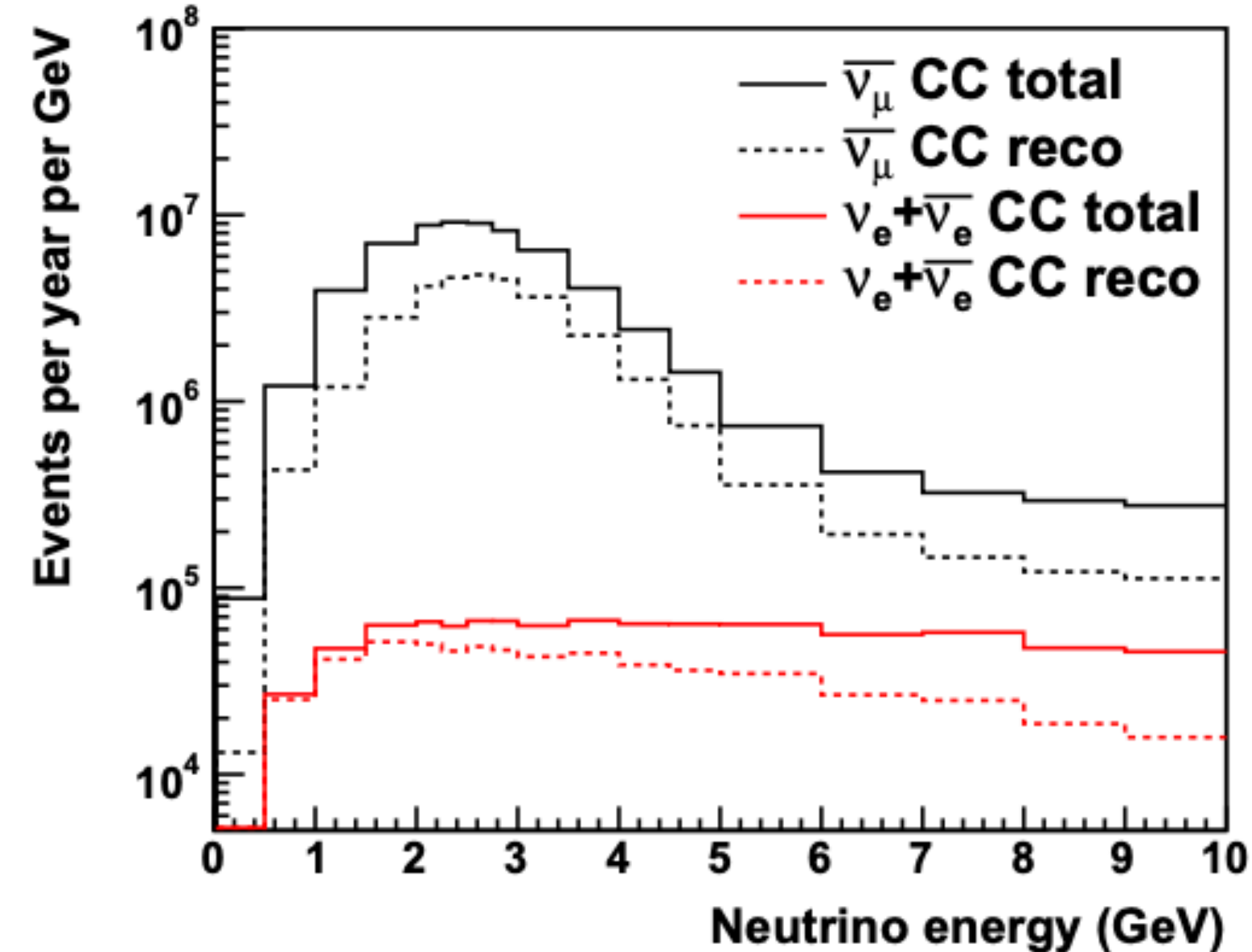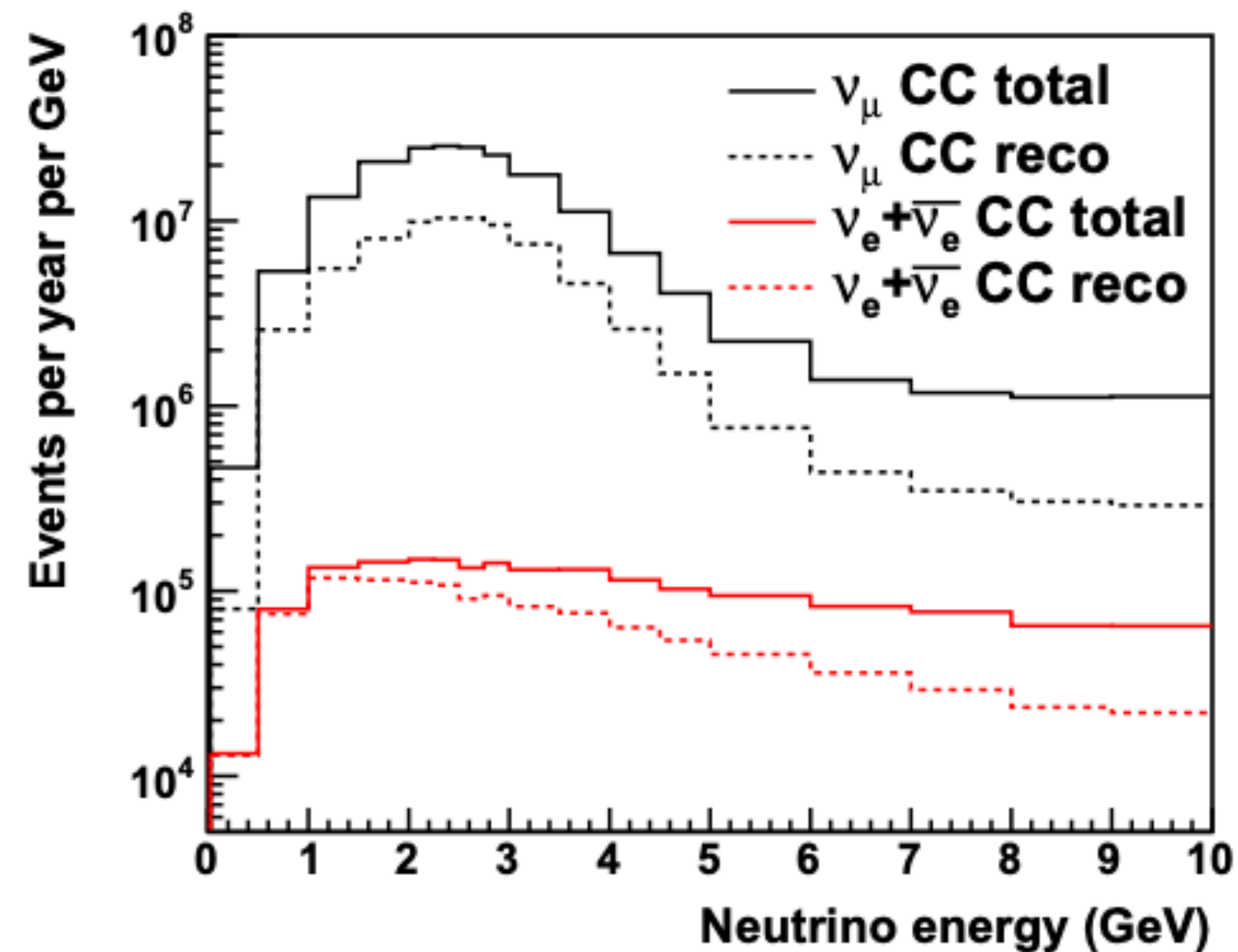
We get about 60k events per year for each ton of LH$_2$ at *perfect efficiency* (about two-fifths of MiniBooNE's entire contribution every year!).

The Fermilab 15' bubble chamber had an estimated 3.5 tons of hydrogen.

We should build a <10L prototype!

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.

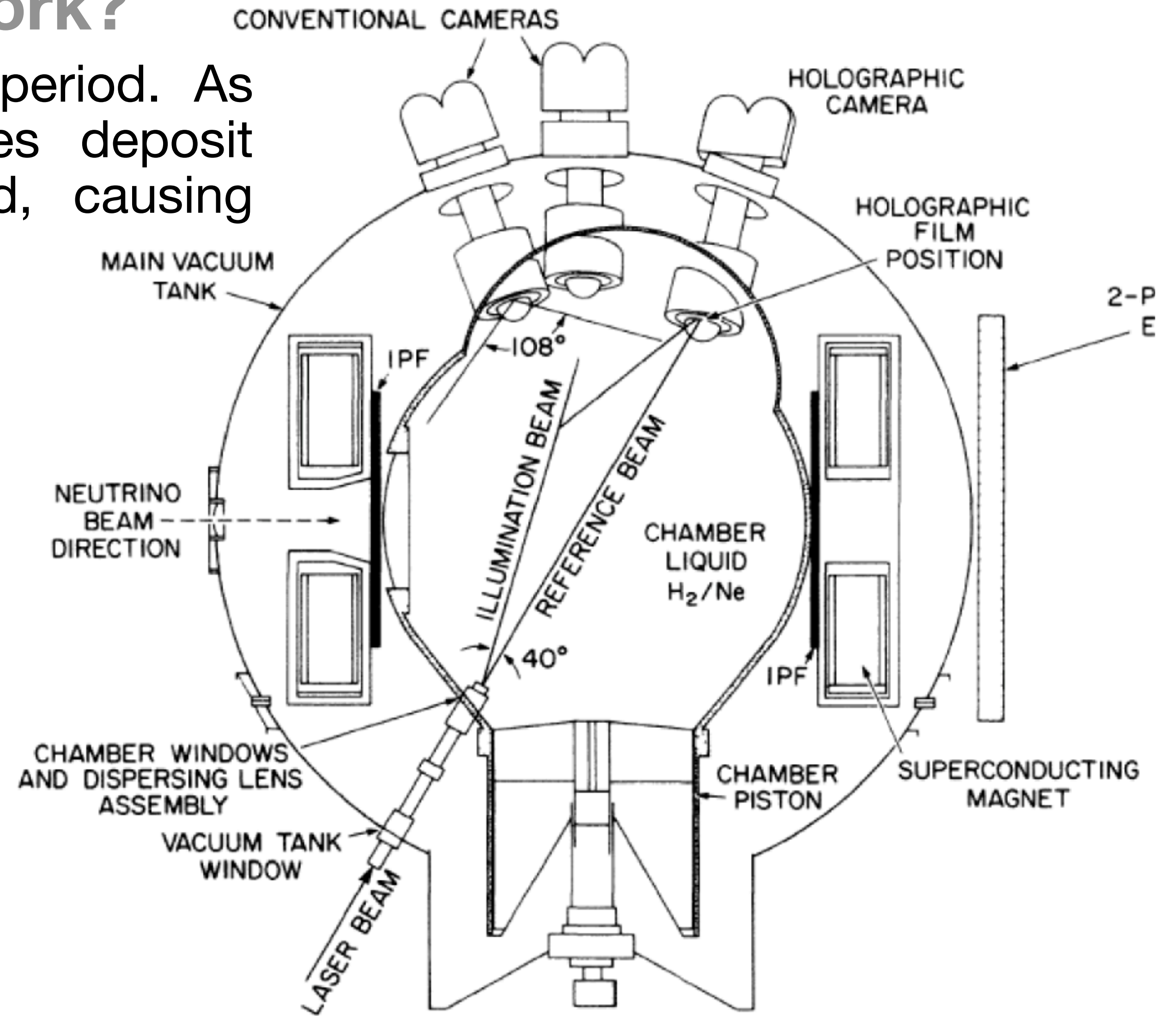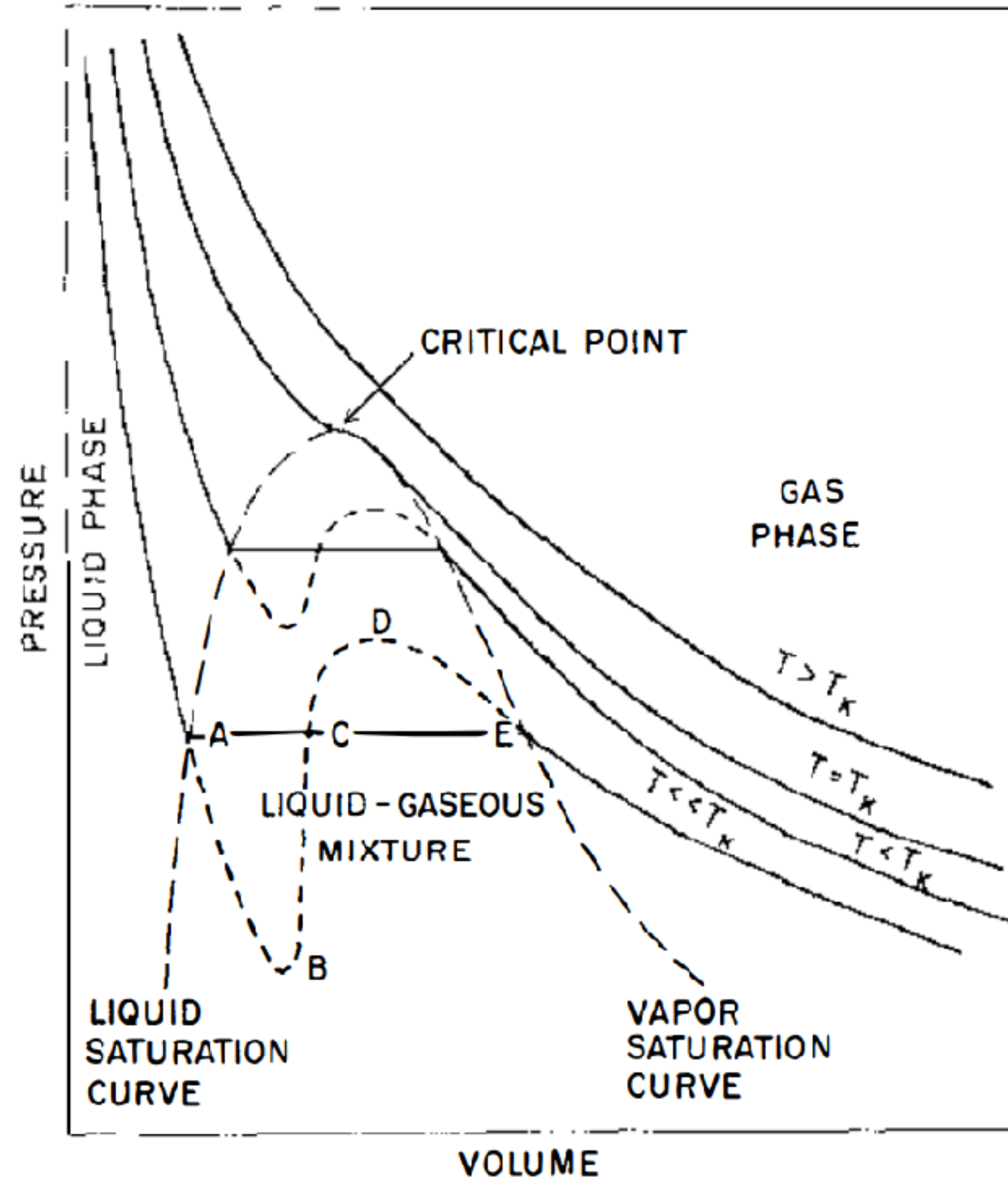Event selection of analog pictures done *by eye* in the 60s-90s.

Bubble Microphysics

A Tunable Medium

Charge deposits on metastable, "microbubble" medium causes bubble nucleation, the size and density are controlled by the state of the working fluid.

Fabian *et al.*
Rev. Sci. Inst.
Vol. 34, No. 5

Ballam and Watt.
Ann. Rev. Nucl.
Sci. 27

Older experiments used bubble density as a way to measure energy deposition in the medium.
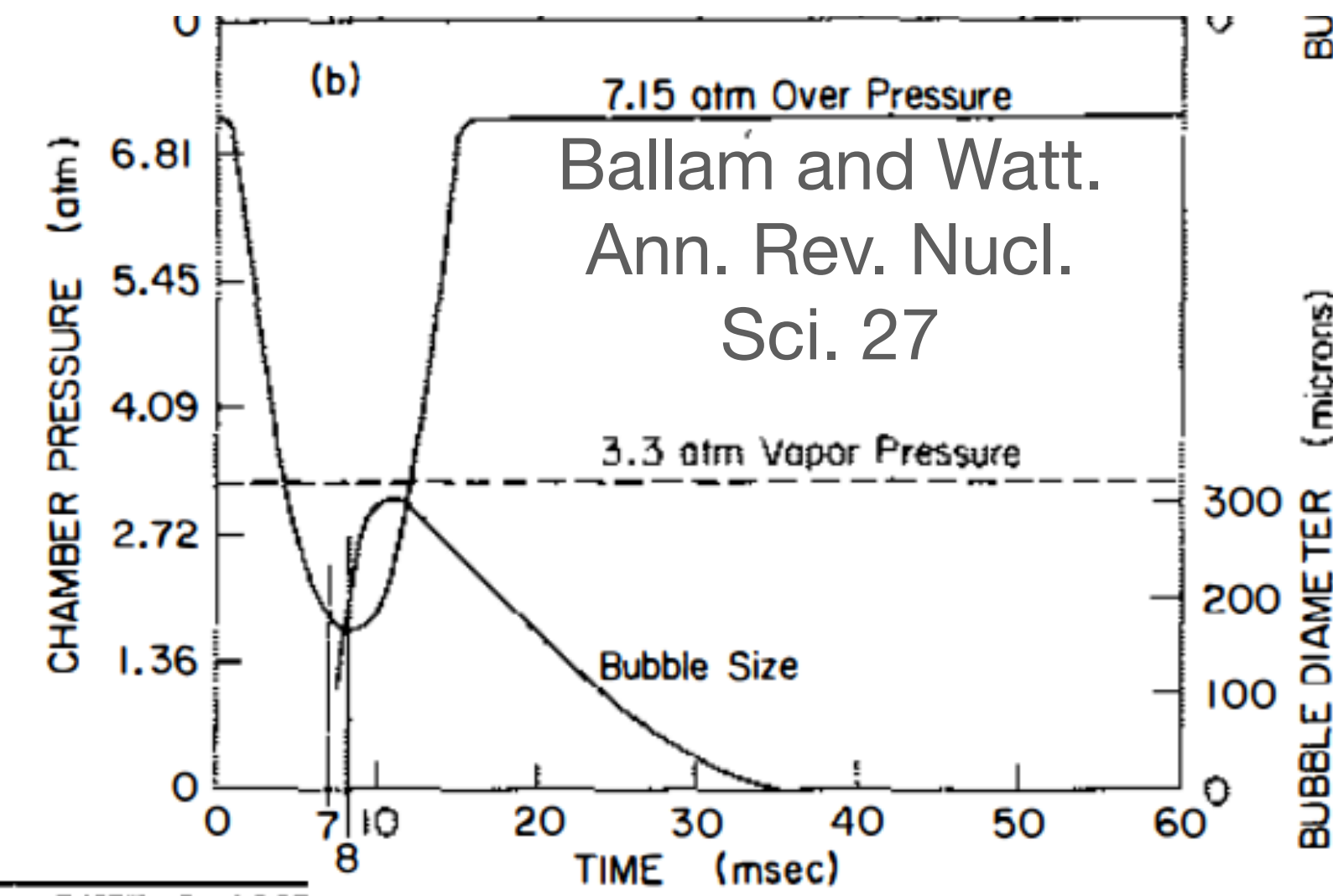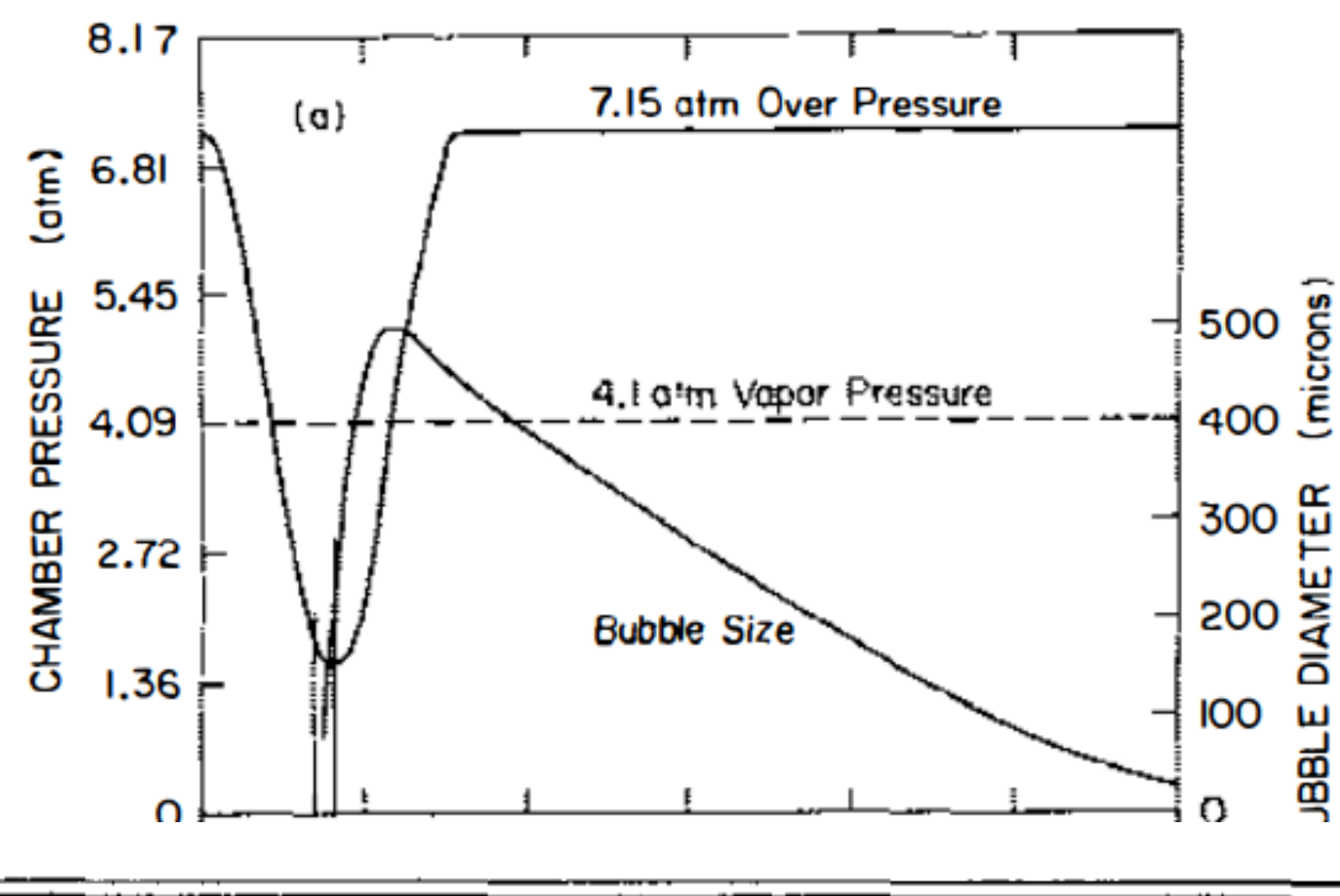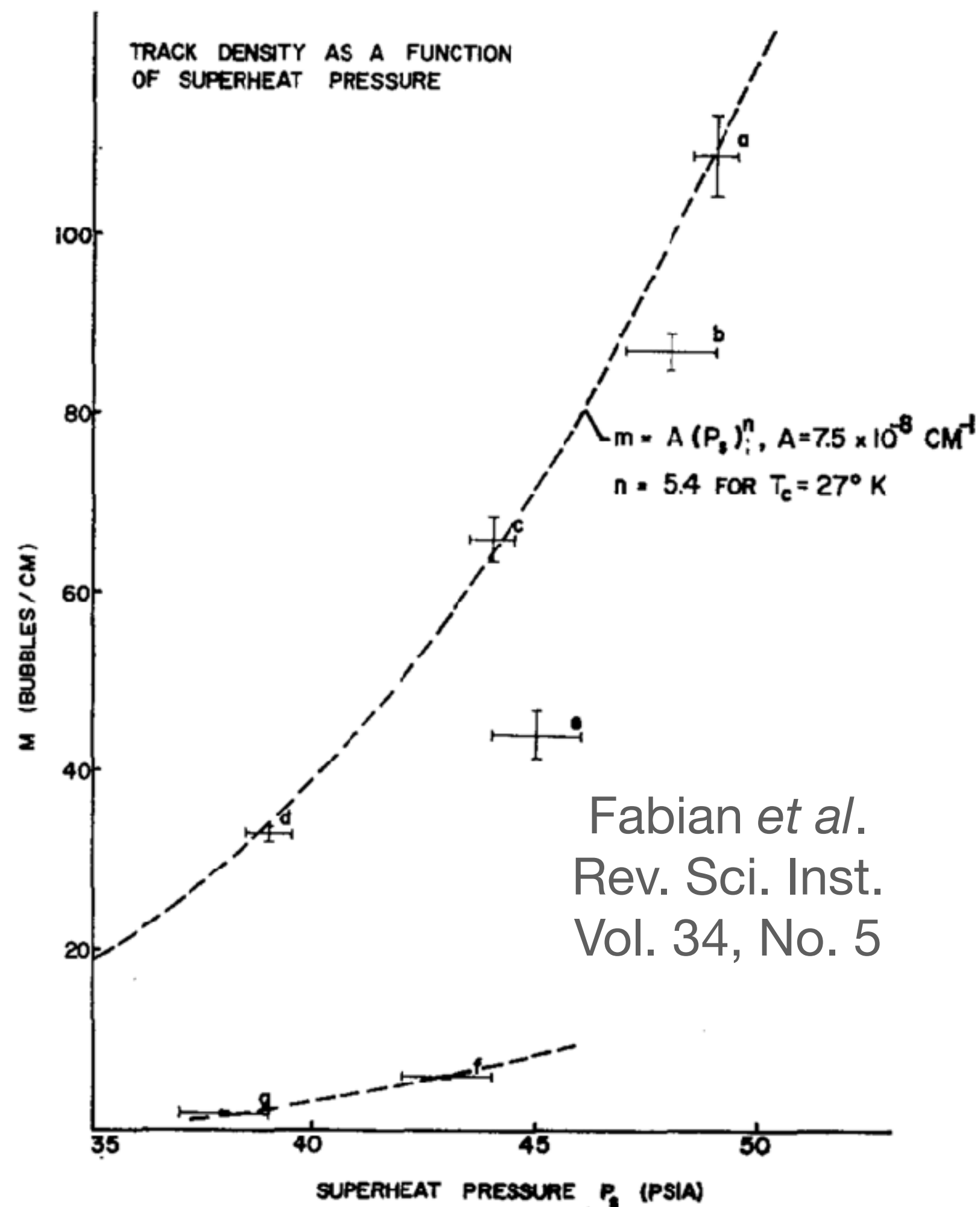
Symbol used	Expanded pressure (psia)	Chamber temperature (°K)	Beam	
a	22	27.04	2.0 BeV/c	p
b	18	26.60	1.0 BeV/c	π^-
c	27	26.93	2.0 BeV/c	p
d	31	26.92	2.0 BeV/c	p
e	14	26.07	1.0 BeV/c	π^-
f	7	25.23	2.0 BeV/c	p
g	11	25.14	2.0 BeV/c	p

The Current Generation of Chambers (Part One)

Updates to Bubble Chamber Technology!

Newer chambers have focus on dark matter and novel detector design!

PICO

Labels on diagram:
- To Hydraulic Cart
- Bellows
- Acoustic Sensors
- Pressure Vessel
- Fused Silica Jar
- Cooling Coils
- Propylene Glycol (hydraulic fluid)
- Water (buffer)
- CF_3I (target)
- Cameras
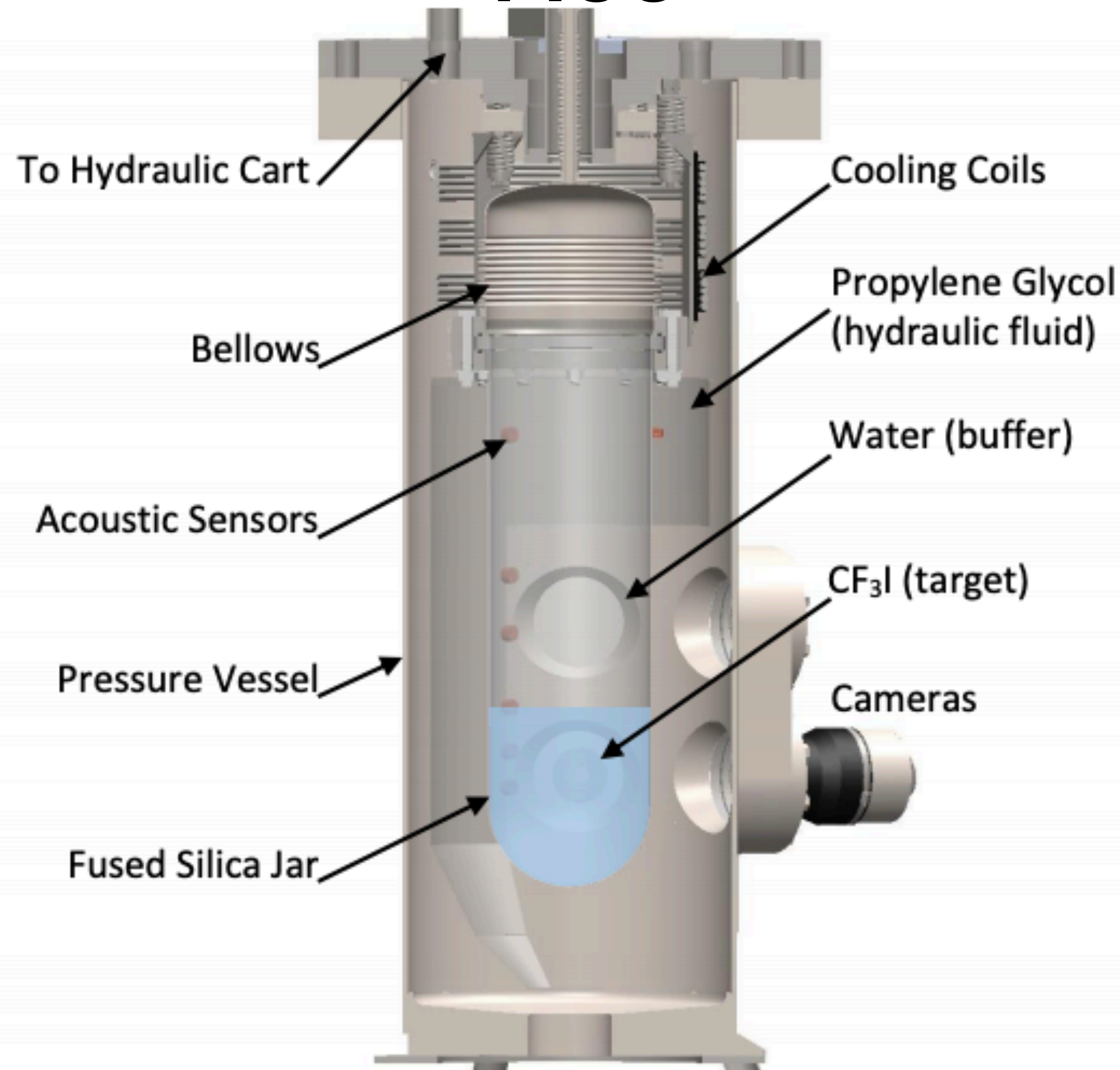
Unsuitable for cross sections measurements without further development (different operational regime).

Still at prototype stages, various sizes, largest prototype is 60L.

Transparent silica glass jar for containment of liquid target.

Acoustic Signals from Alphas in Fast Radon Decay Chain

Legend:
- 1st in chain
- 2nd in chain
- 3rd in chain

Axes: AP vs Frequency [kHz]

The Current Generation of Chambers (Part Two)

Updates to Bubble Chamber Technology!

Newer chambers have focus on dark matter and novel detector design!
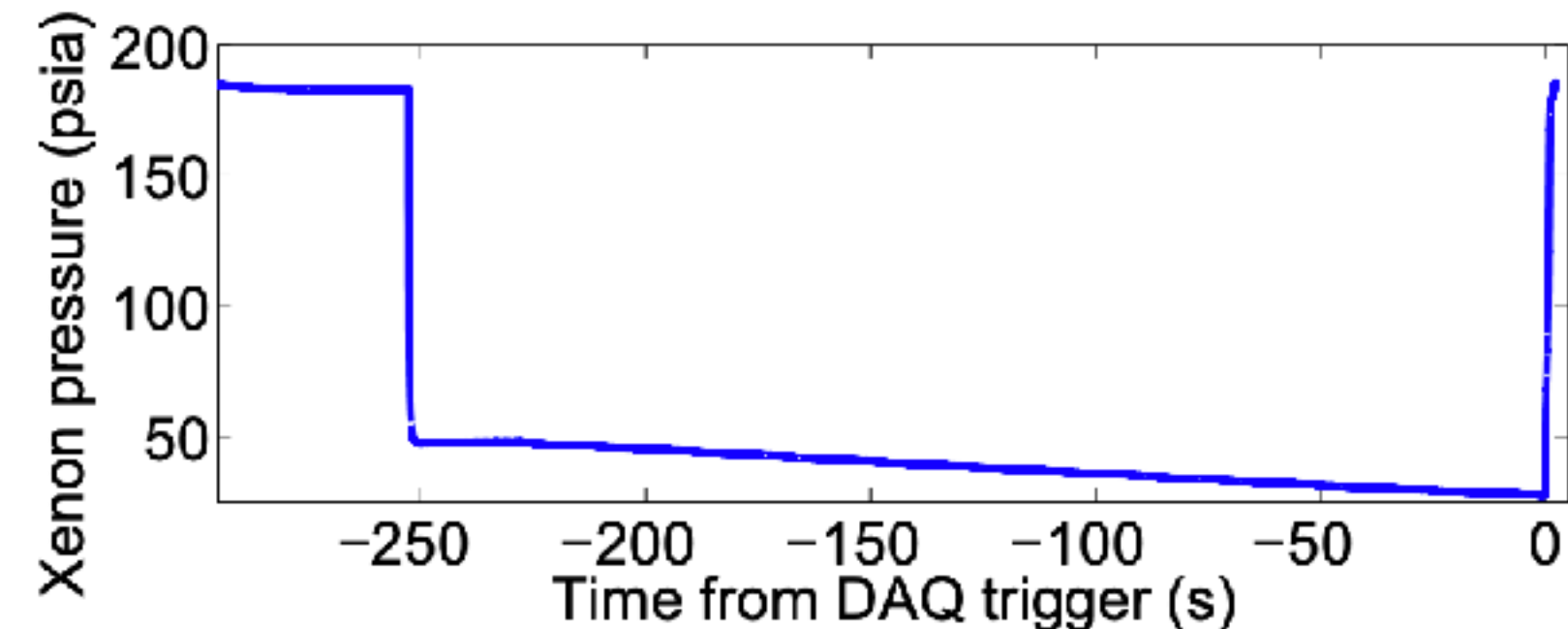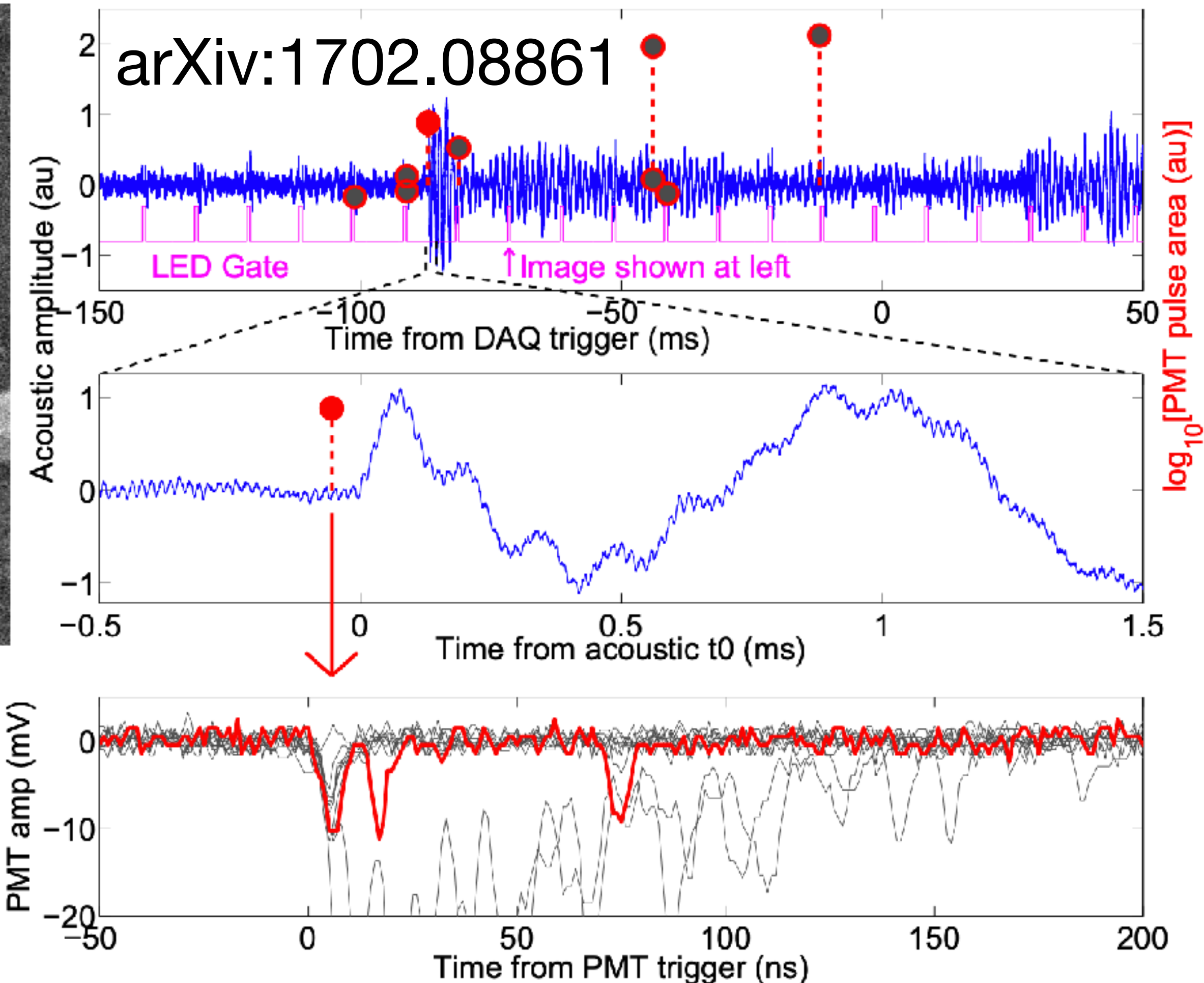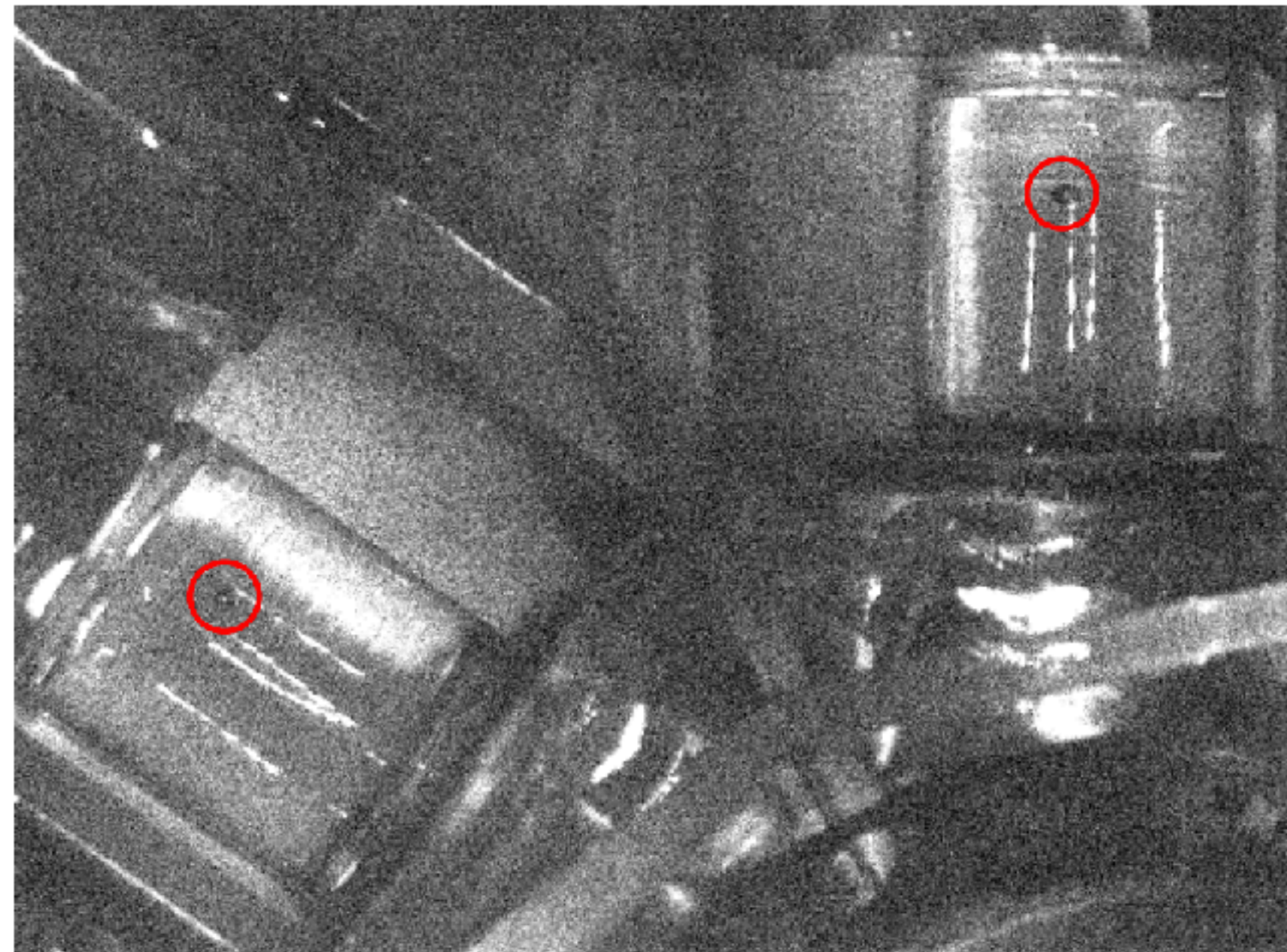
Scintillating Bubble Chamber (SBC) 30g prototype with xenon shows acoustic modeling and scintillation photon counters!

The Current Generation of Chambers (Part Three)

The Scintillating Bubble Chamber (SBC)!
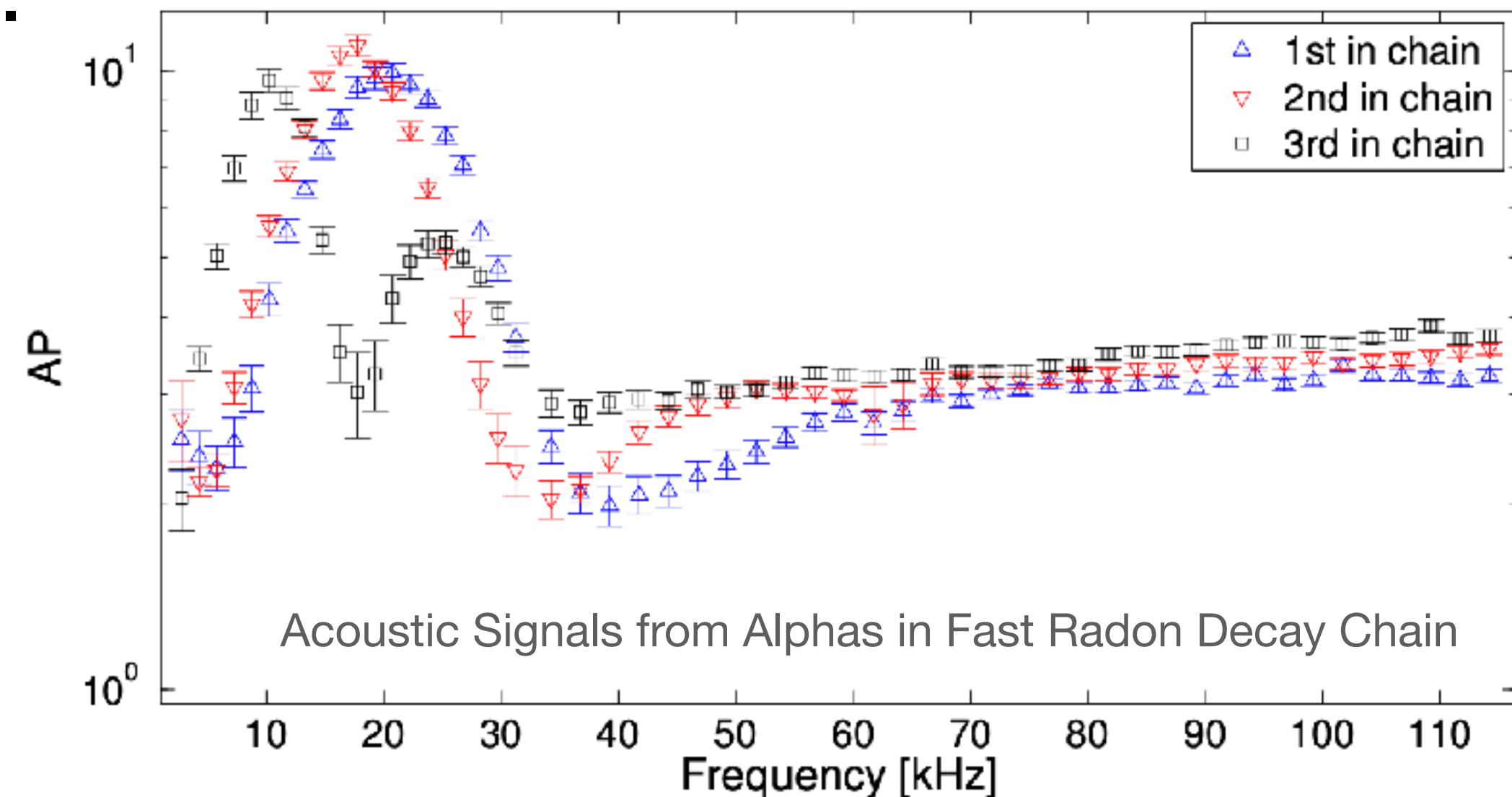

Text labels (top to bottom):
- Vacuum Jacket Electrical Feedthroughs
- Cryomech AL300 Cryocooler
- Vacuum Jacket Flange
- Vacuum Jacket Body
- Condensers
- Cameras
- Pressure Vessel Suspension Rods
- Pressure Vessel
- LEDs
- LCF_4 @ 130K
- Vacuum
- LAr + 100ppm LXe @ 130K
- Reflector Screens
- Insulation
- SiPMs
- Outer Silica Jar
- Piezos
- Evaporators
- Jar Bellows
- Inner Silica Jar
- LCF_4 @ 90K
- Pressure Bellows
- Bellows Flange
- Piston Shaft
- Cylinder support rods
- Vacuum Jacket Legs
- Hydraulic Cylinder

Text Legend
- Thermal Control
- Bubble Imaging
- Pressure Control
- Hydraulic Fluid
- Target Fluid
- Scintillation Detection
- Acoustic Sensors
- Structural

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.

Plan for building a MMBC prototype
Updates to "Dirty" Bubble Chamber Technology!
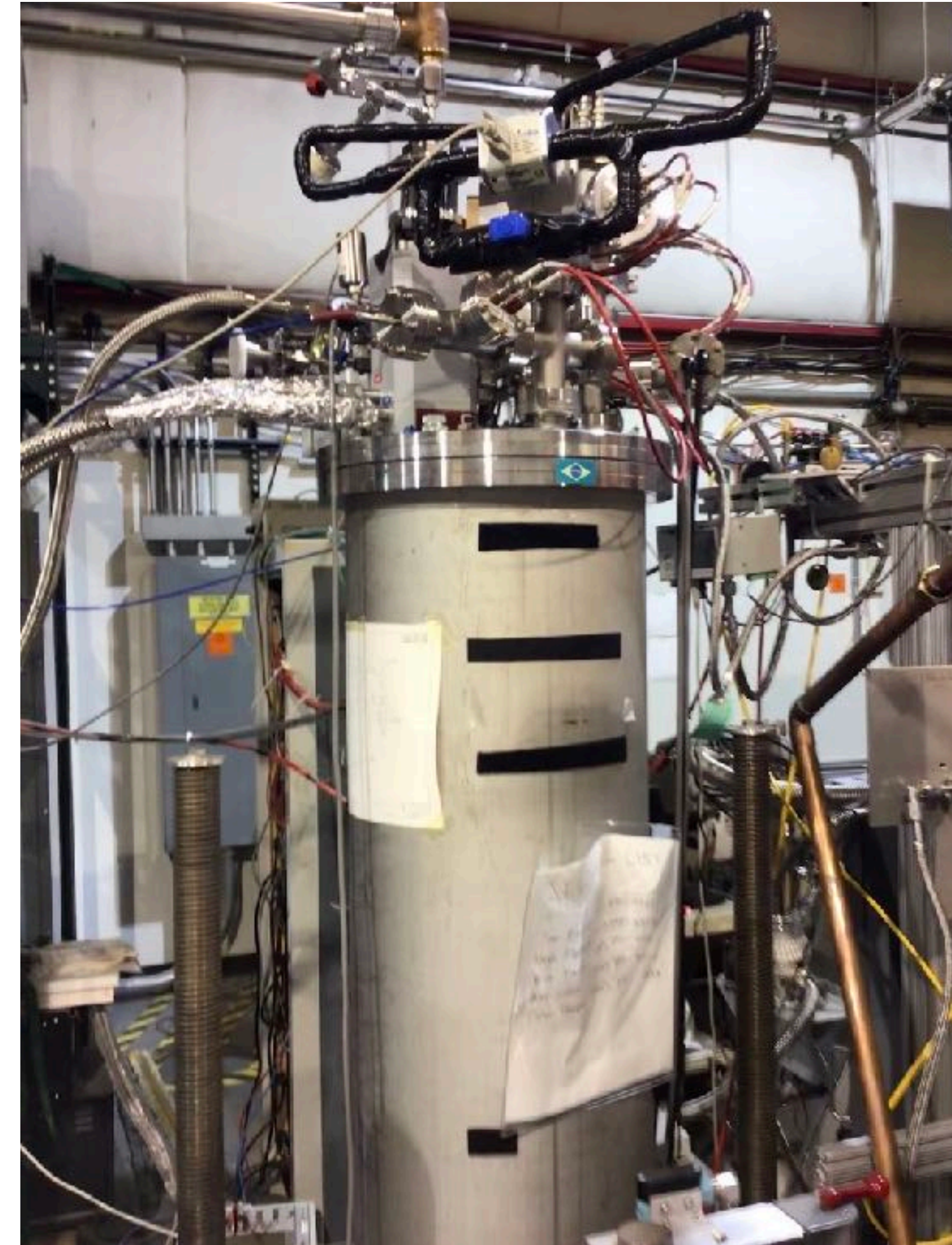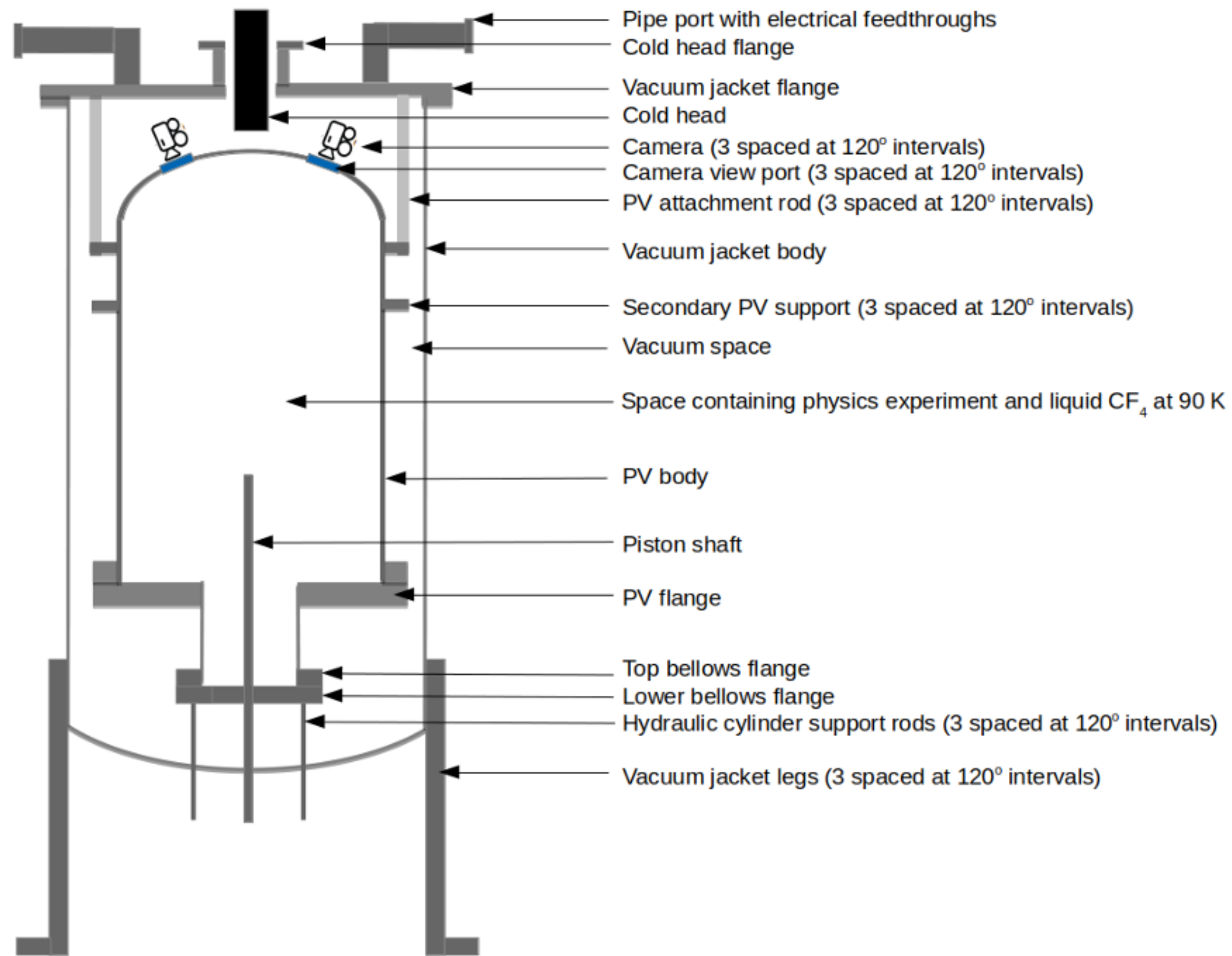

Pipe port with electrical feedthroughs
Cold head flange
Vacuum jacket flange
Cold head
Camera (3 spaced at 120° intervals)
Camera view port (3 spaced at 120° intervals)
PV attachment rod (3 spaced at 120° intervals)

Vacuum jacket body

Secondary PV support (3 spaced at 120° intervals)

Vacuum space

Space containing physics experiment and liquid CF_4 at 90 K

PV body

Piston shaft

PV flange

Top bellows flange
Lower bellows flange
Hydraulic cylinder support rods (3 spaced at 120° intervals)

Vacuum jacket legs (3 spaced at 120° intervals)

Initial plan is to use the SBC pressure vessel design in another previously available vacuum jacket in the old MiniBooNE Hall or PC4.

Objectives for Building a MMBC
Current goals of the newly funded project!

In the process of finalizing the project scope!

- **First Objective (FY23.5)** A fully leak checked, pressure ready, and vacuum ready device in MiniBooNE Hall.
- **Second Objective (FY23.5)** Device active time long enough to capture an entire spill from the LBNF beam (at minimum 10 microseconds).
- **Third Objective (FY24.0)** 1 Hz cycling time.
- **Fourth Objective (FY24.0)** Minimum possible cycling time.
- **Fifth Objective (FY24.0/FY24.5)** Maximum active time without interior changes. Polish, coating, or plating and retest maximum active time.
- **Sixth Objective (FY25/FY25.5)** Precision track reconstruction on cosmic ray muons.
- **Seventh objective (FY25/FY25.5)** sync to the Fermilab Testbeam clock and observe hadron decays.

Where to Put It?
The Biggest Challenge Toward Building It!
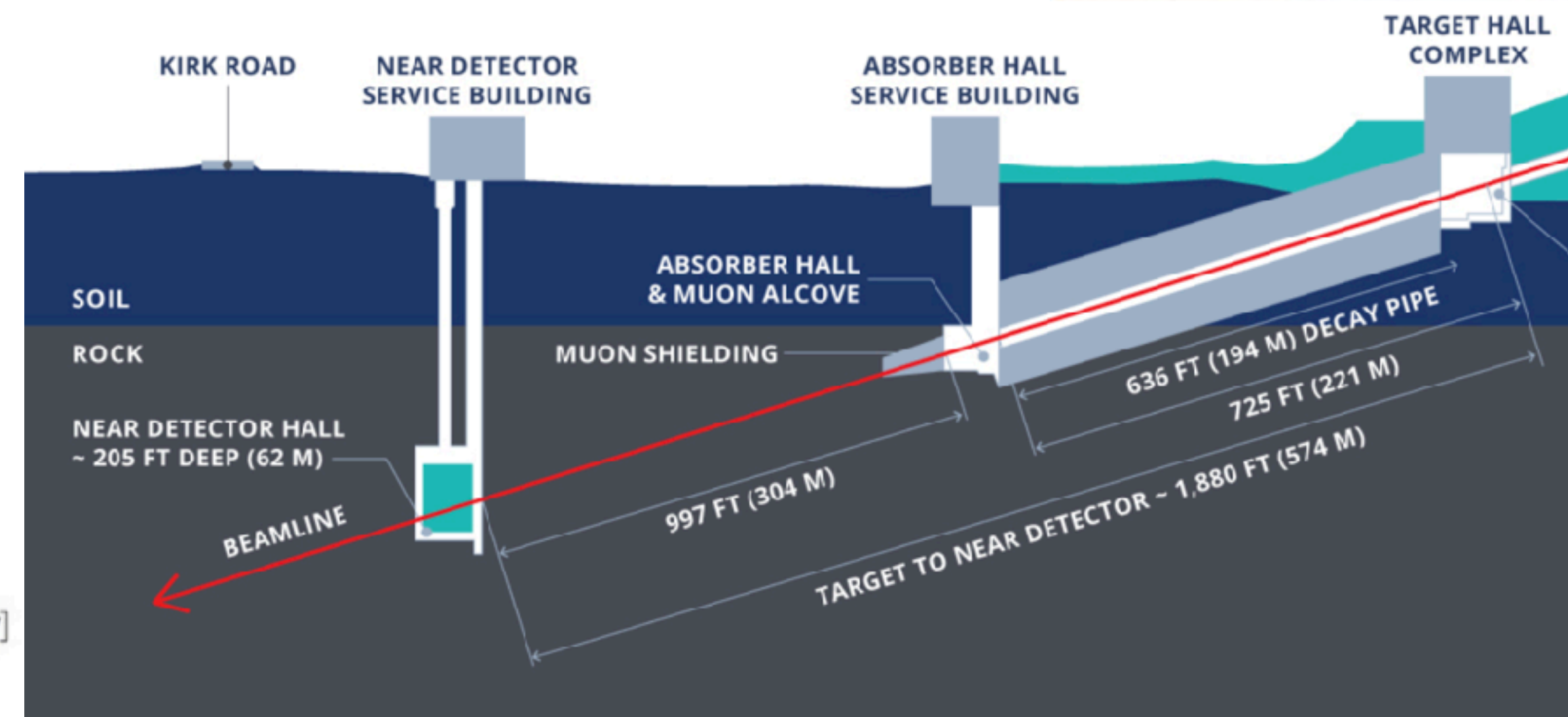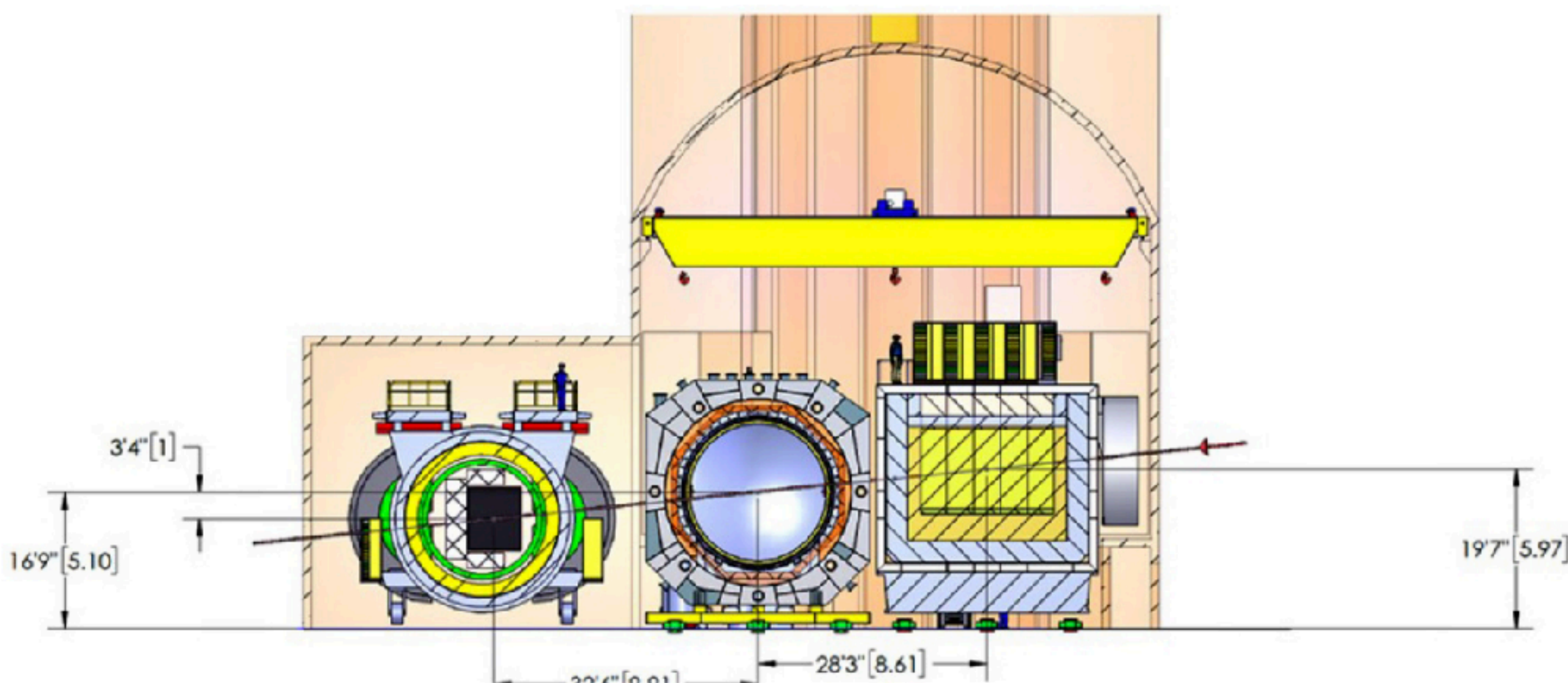
**Problem 1**: Detector would be in direct path of LBNF beam, 62m underground.

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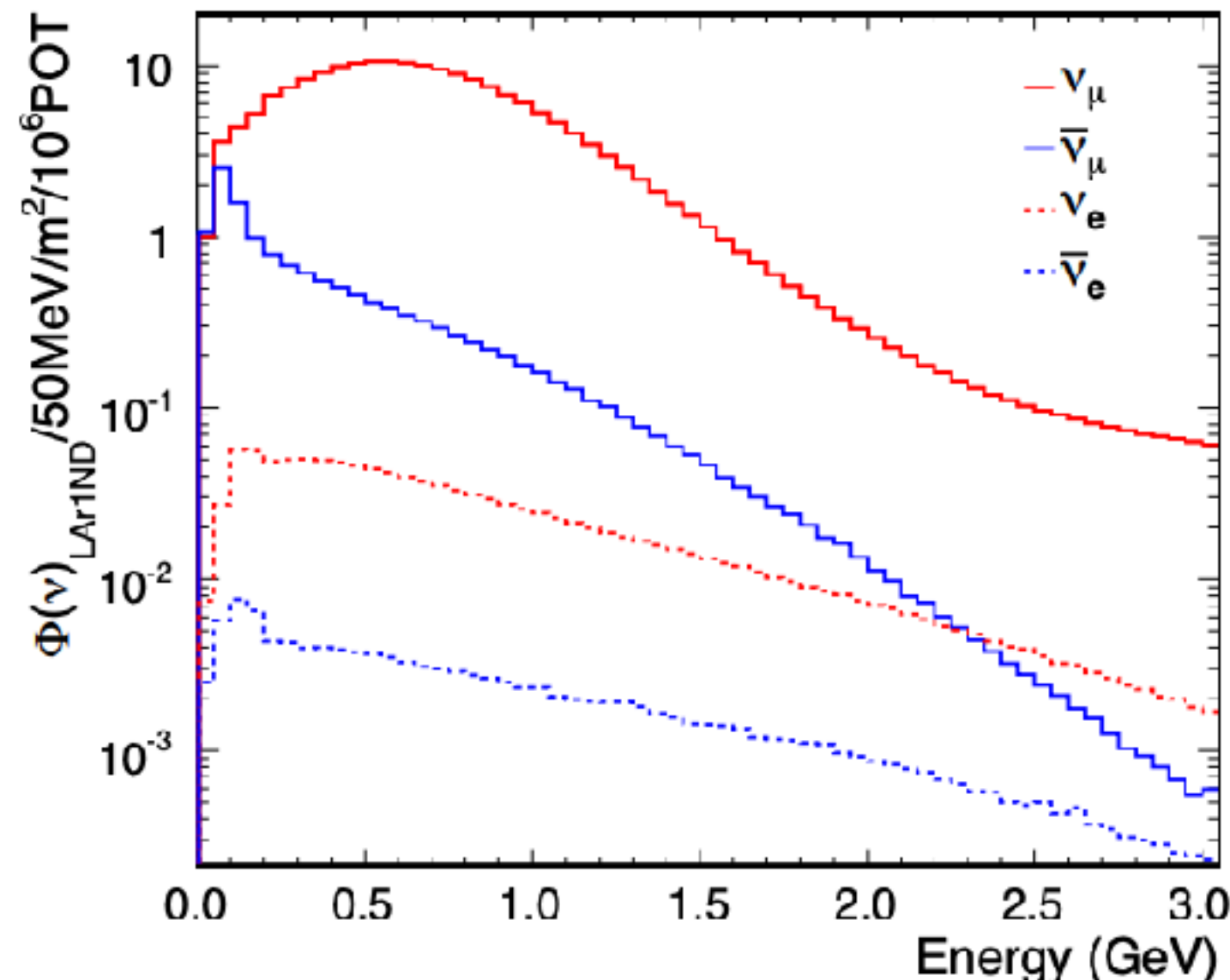
Build somewhere else (**Dedicated Underground Hall or On the Surface?**)

Biggest Challenges: Source of Neutrinos?
Different Options for Beam at Fermilab
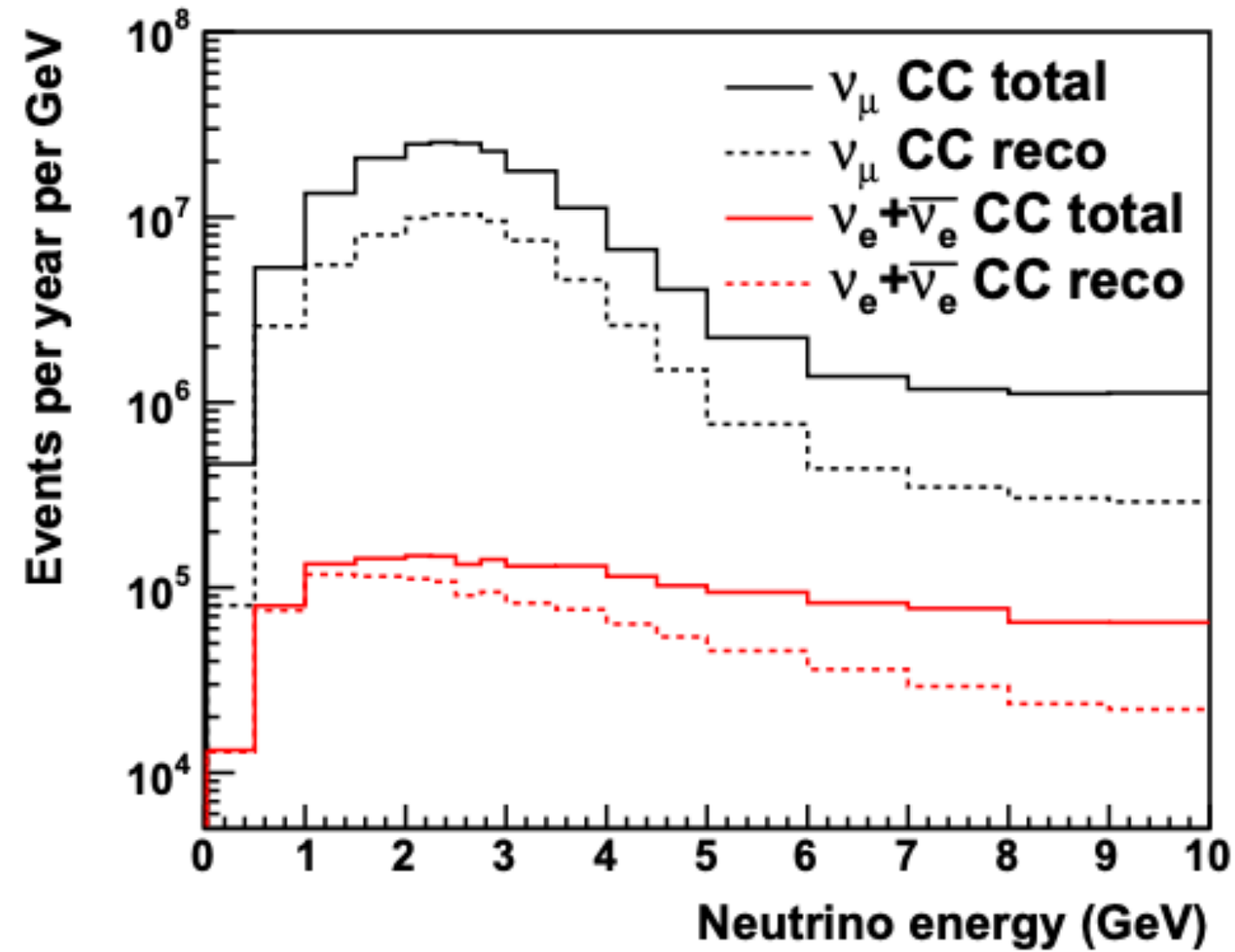
Assuming LBNF beam has a similar structure to NuMI beam but is more intense, 6×10^{13} POT/Spill in 9.5 μs at 0.75 Hz rep rate, indicates about an event more or less every second at minimum.


BNB has much lower intensity beam and at a lower energy but at a higher repitition rate, 5×10^{12} POT/Spill in 1.6 μs at 5-20 Hz rep rate which is much faster than older chambers could cycle.

Note: Also includes contributions from highly off-axis NuMI Beam.

Measurement of Absolute Neutrino Cross Sections
Resolution of Underlying Neutrino-Nucleus Interaction Uncertainties
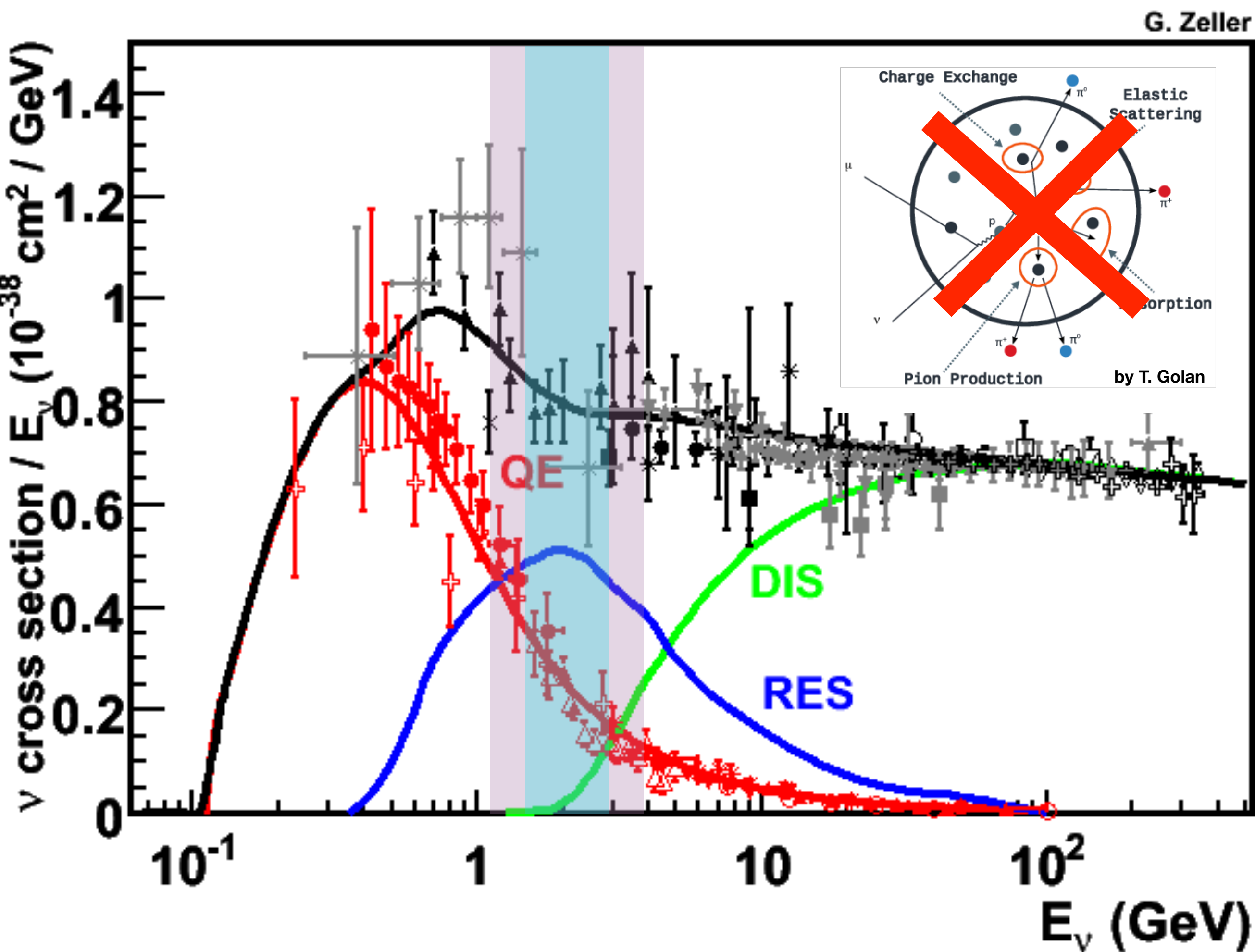
New dataset would be largest (anti)neutrino H_2/D_2 sample ever made, surpassing current world data in the relevant regions by at least a couple orders of magnitude!

Resolve tension in current experiments by factorizing underlying cross-section physics from secondary nuclear effects/FSI.

Helps to properly constrain possible largest cross-section dataset to ever exist ~$O(10^7)$ from ND-LAr/ND-GAr.

Needs isoscalar (D_2) nucleus to completely disentangle but also get absolute minimum of MEC contributions.

A boon to generator developers!
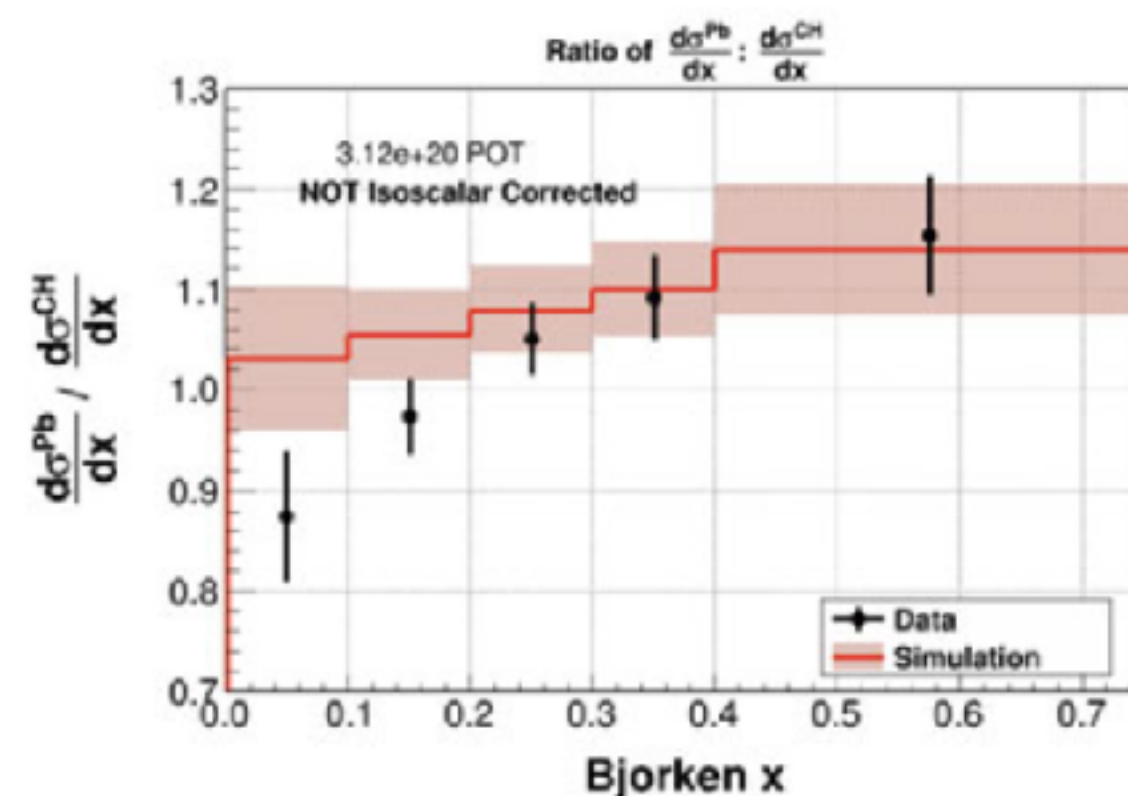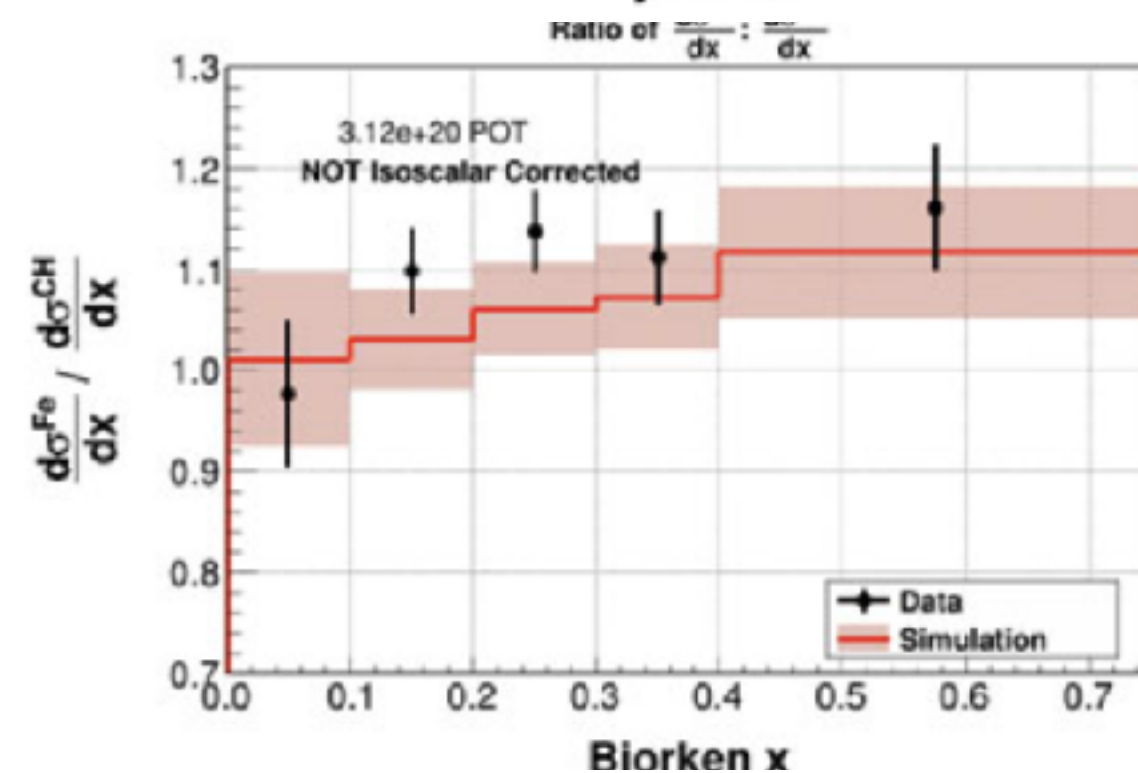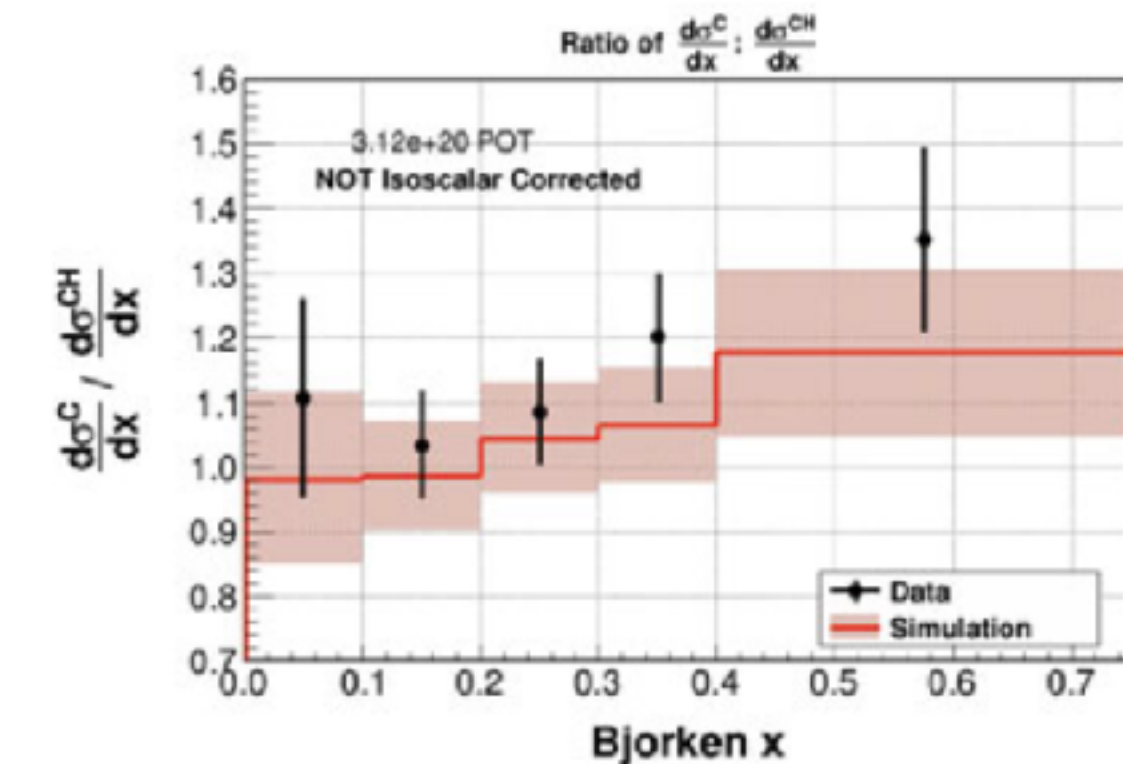
Measurement of Nuclear Modification with Neutrinos
Contributions to Nucleon Structure

Ratio of $\frac{d\sigma^C}{dx} : \frac{d\sigma^{CH}}{dx}$

3.12e+20 POT
NOT Isoscalar Corrected

$\frac{d\sigma^C}{dx} / \frac{d\sigma^{CH}}{dx}$

Bjorken x

Ratio of $\frac{d\sigma^{Fe}}{dx} : \frac{d\sigma^{CH}}{dx}$

3.12e+20 POT
NOT Isoscalar Corrected

$\frac{d\sigma^{Fe}}{dx} / \frac{d\sigma^{CH}}{dx}$

Bjorken x

Ratio of $\frac{d\sigma^{Pb}}{dx} : \frac{d\sigma^{CH}}{dx}$

3.12e+20 POT
NOT Isoscalar Corrected

$\frac{d\sigma^{Pb}}{dx} / \frac{d\sigma^{CH}}{dx}$

Bjorken x

Data
Simulation

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?

Springer Theses
Recognizing Outstanding Ph.D. Research

Joel Allen Mousseau

First Search for the EMC Effect and Nuclear Shadowing in Neutrino Nuclear Deep Inelastic Scattering at MINERvA

Springer
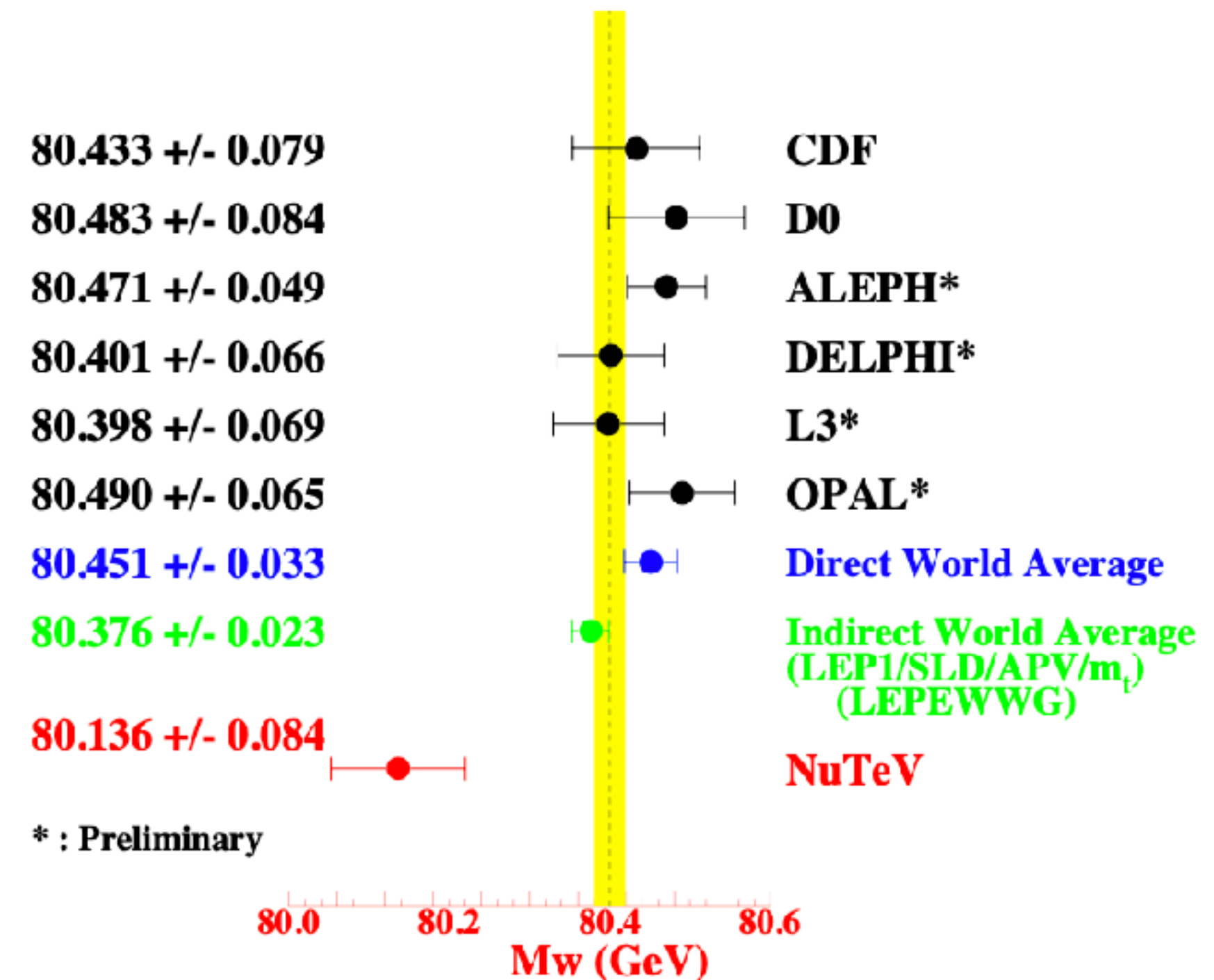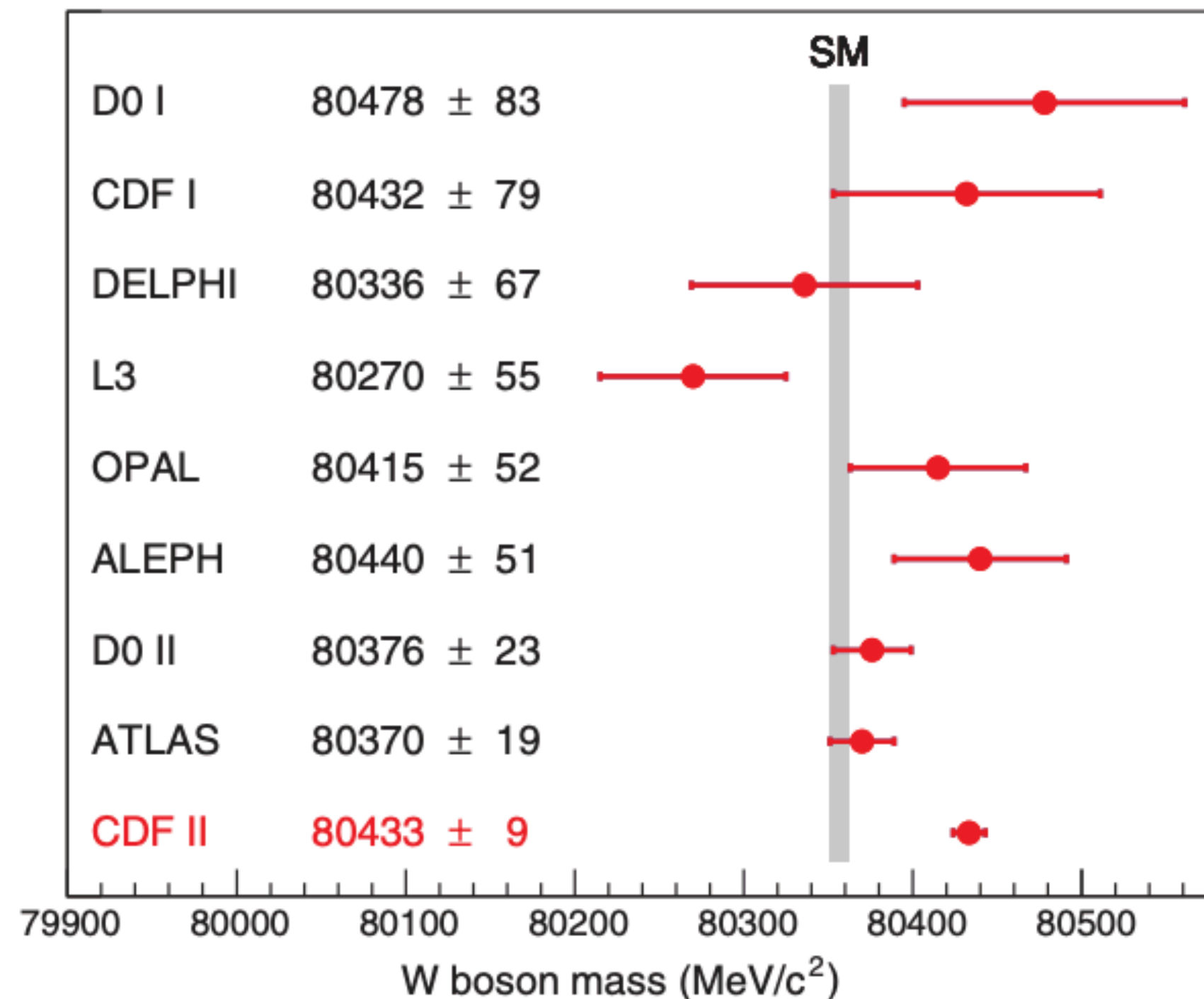
28

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!

$$\sin^2\theta_W = \frac{1}{2} - \left(\frac{m_W}{m_Z}\right)^2 = \frac{1}{2} - \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}}$$

From G. Zeller's Doctoral Thesis

D0 I	80478 ± 83	
CDF I	80432 ± 79	
DELPHI	80336 ± 67	
L3	80270 ± 55	
OPAL	80415 ± 52	
ALEPH	80440 ± 51	
D0 II	80376 ± 23	
ATLAS	80370 ± 19	
CDF II	80433 ± 9	

W boson mass (MeV/c²)

|	
80.433 +/- 0.079	CDF
80.483 +/- 0.084	D0
80.471 +/- 0.049	ALEPH*
80.401 +/- 0.066	DELPHI*
80.398 +/- 0.069	L3*
80.490 +/- 0.065	OPAL*
80.451 +/- 0.033	Direct World Average
80.376 +/- 0.023	Indirect World Average (LEP1/SLD/APV/mₜ) (LEPEWWG)
80.136 +/- 0.084	NuTeV

* : Preliminary

Mw (GeV)

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Spin and Polarization (Part One)
Spin Structure as a Cross Check for Neutrino Measurements

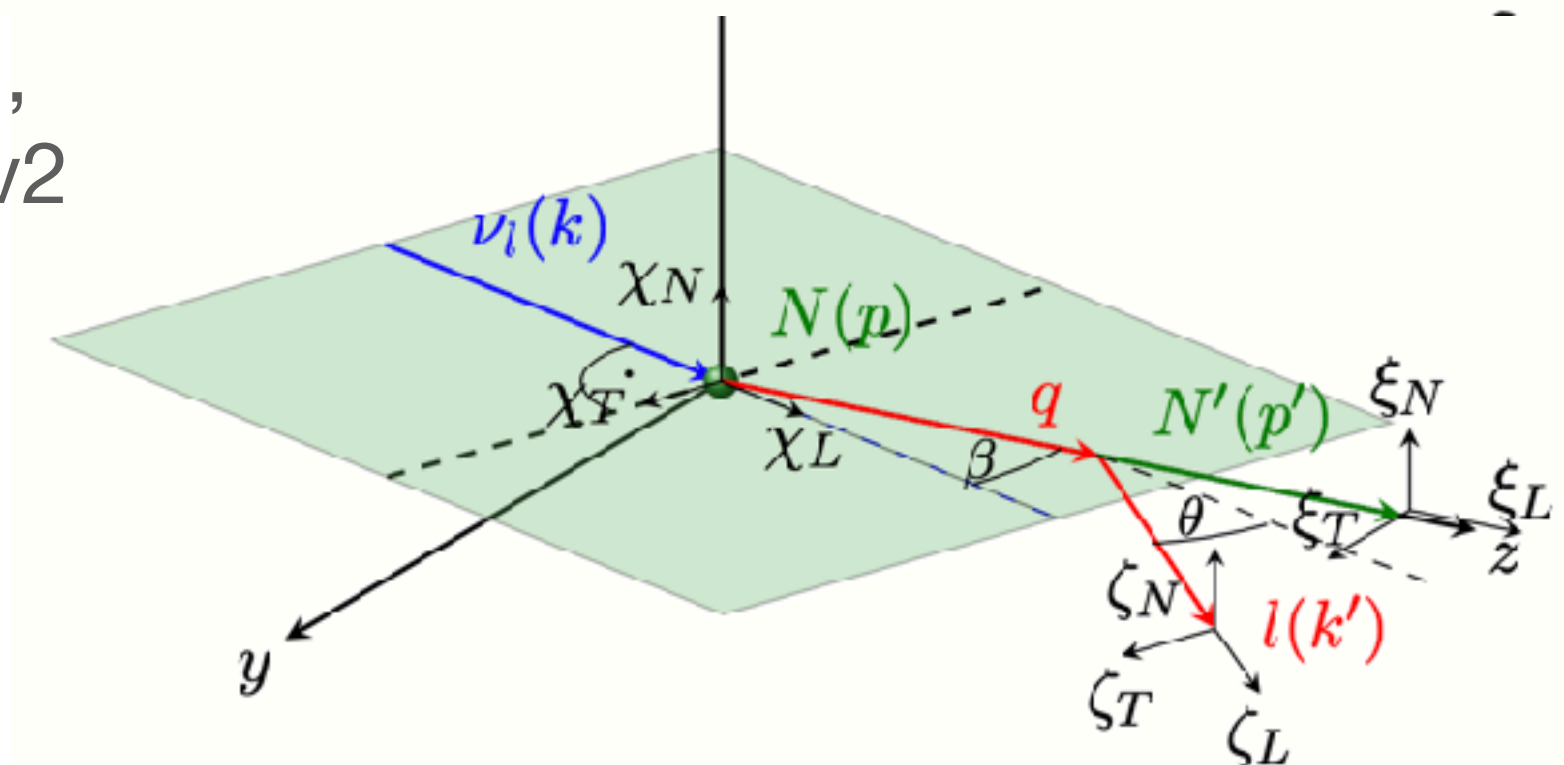Spin and polarization can be factorized in the cross section into spin directions given the source.

Polarization of lepton, target nucleon, or recoil nucleon in one of the three directions, longitudinal, transverse, or the normal directions.

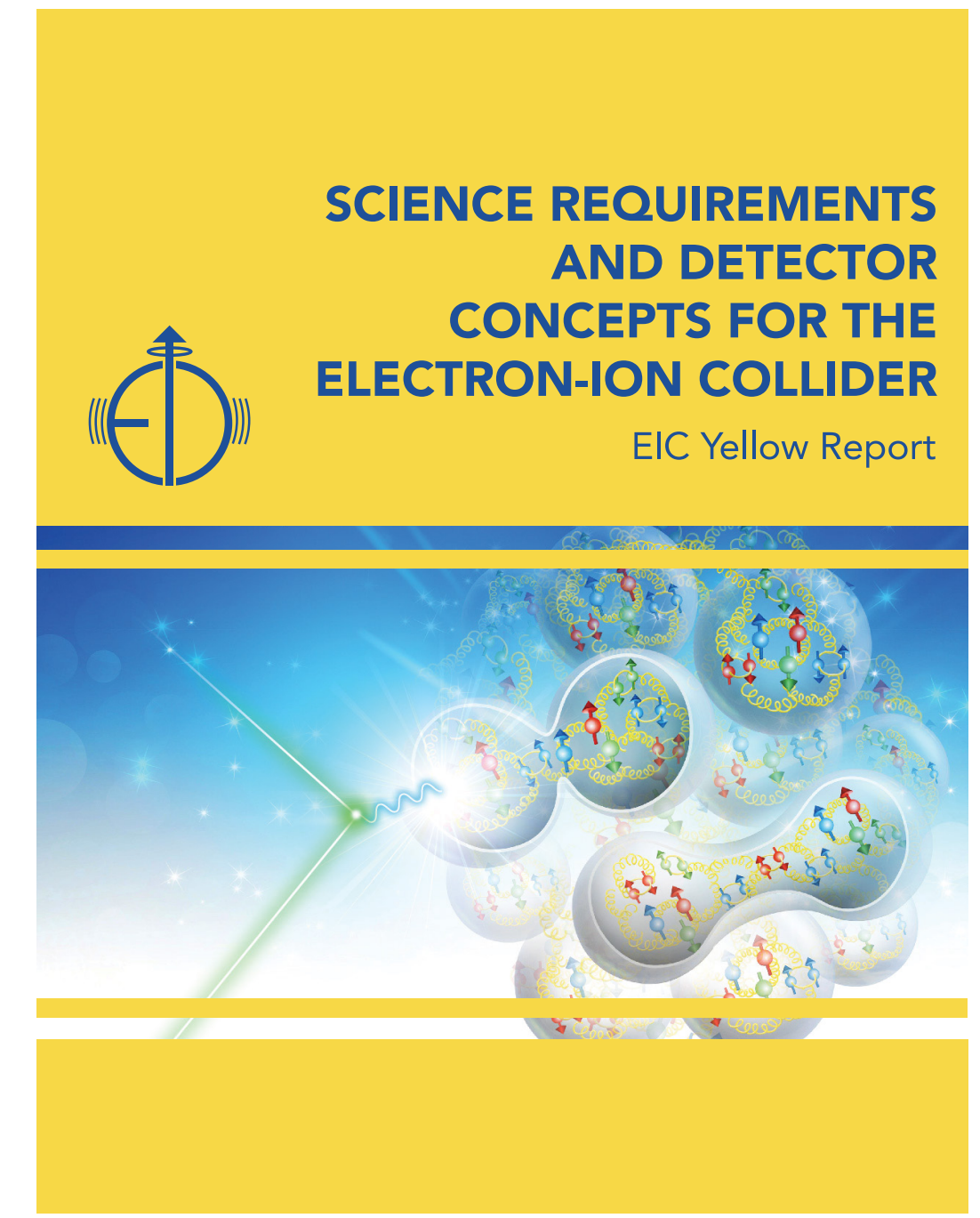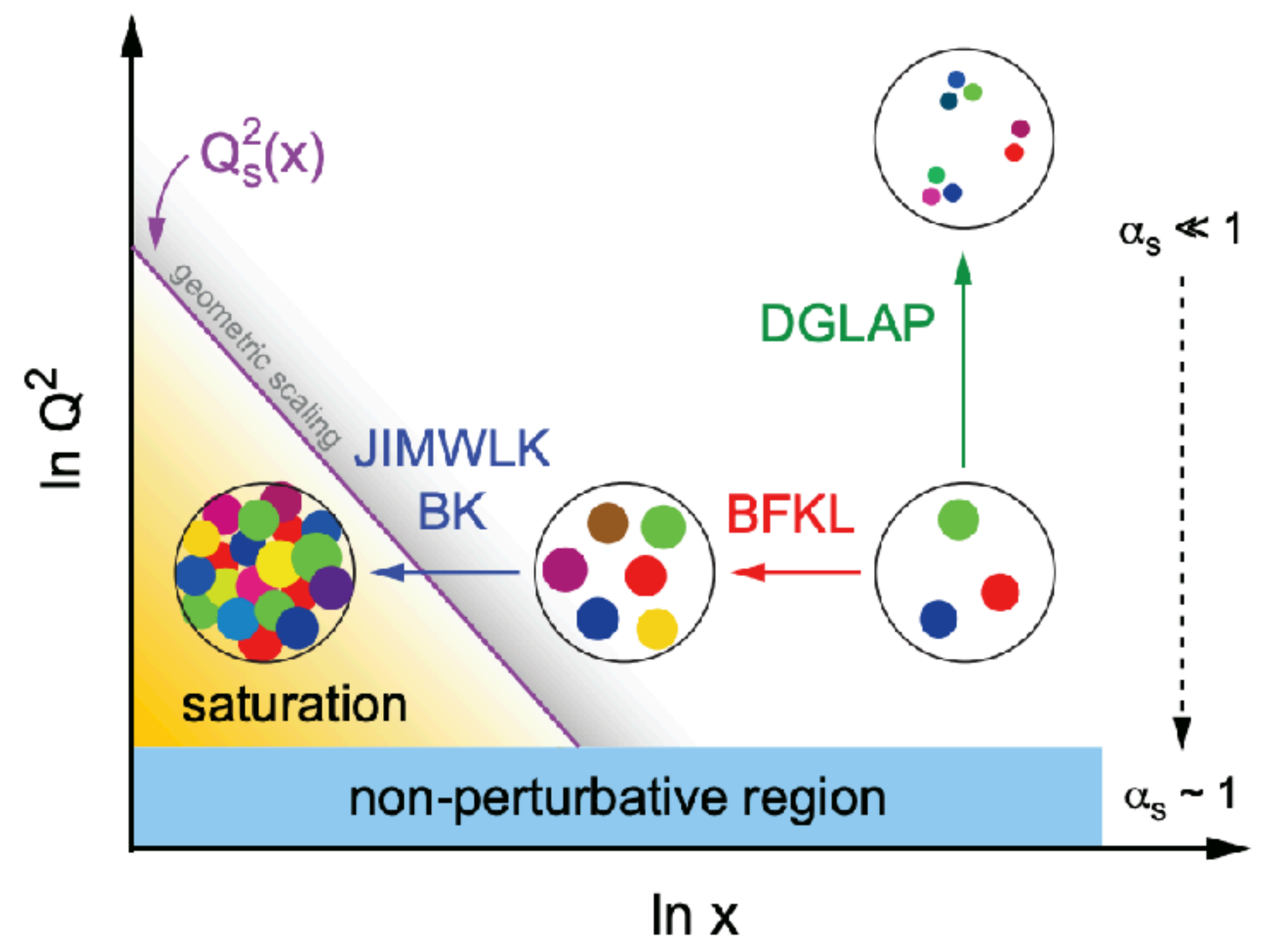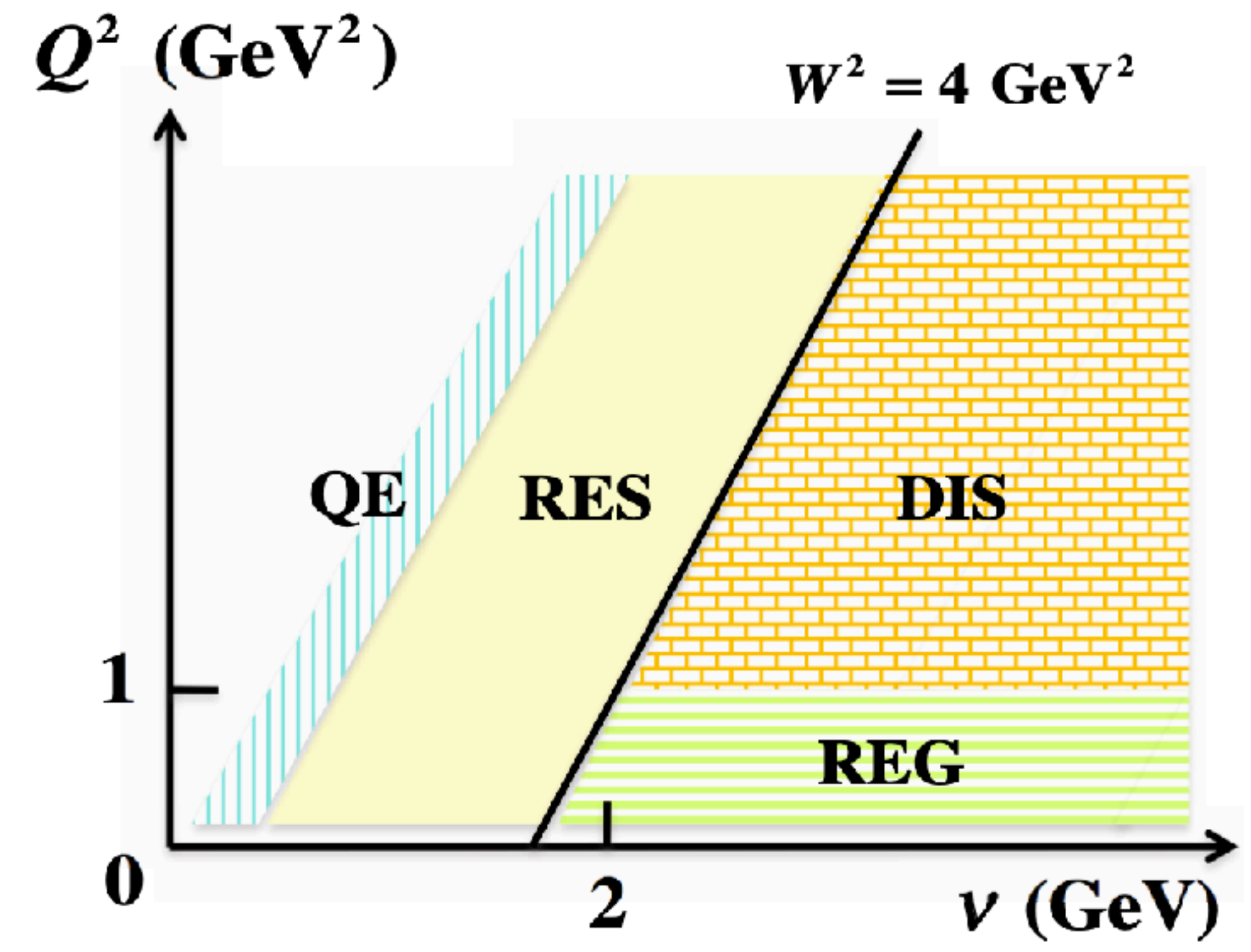One use is the determination of scattering parameters as a *function of polarization*.
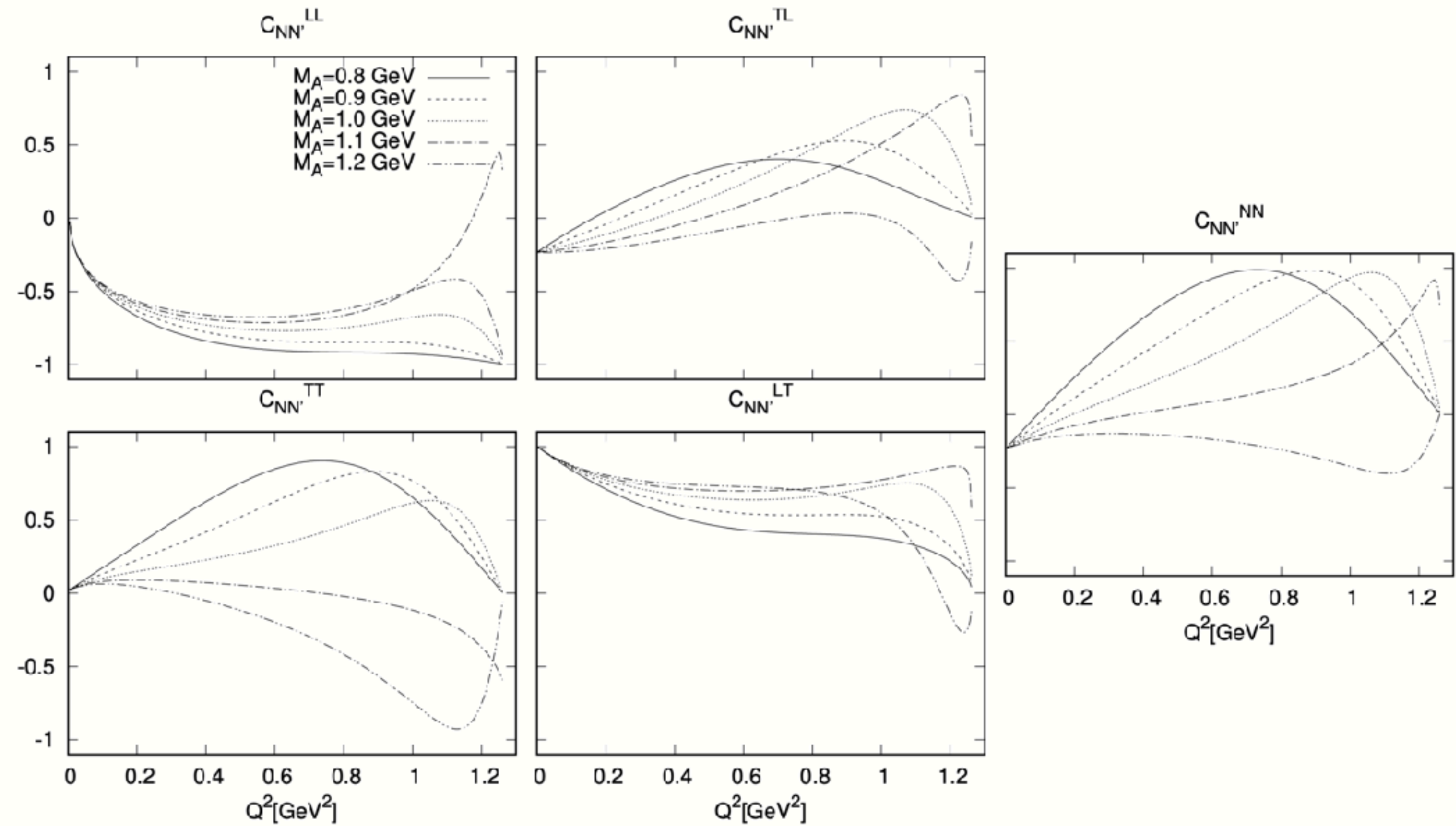
Graczyk & Kowal,
arXiv:1902.03671v2

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma_0}{dQ^2}\left(1 + \mathcal{P}_l^\mu s_\mu^l + \mathcal{T}_N^\mu s_\mu^N + \mathcal{P}_{N'}^\mu s_\mu^{N'} + s_\mu^l s_\nu^{N'} \mathcal{A}_{lN'}^{\mu\nu} + \right.$$
$$\left. + s_\mu^l s_\nu^N \mathcal{B}_{lN}^{\mu\nu} + s_\mu^N s_\nu^{N'} \mathcal{C}_{NN'}^{\mu\nu} + s_\mu^l s_\nu^N s_\alpha^{N'} \mathcal{D}_{lNN'}^{\mu\nu\alpha}\right)$$

Complementarity to the Electron-Ion Collider

A (Very) Broad Physics Program

Neutrinos from LBNF probe well into the non-perturbative region and give complementary kinematics at a range of Bjorken-x in DIS.

Neutrinos are a novel probe in this region, only probe with access to the axial-vector components/form factors/currents!

Neutrinos as a Novel Probe
Precision Selection of Quark Flavor

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

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

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

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

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

SCIENCE REQUIREMENTS
AND DETECTOR
CONCEPTS FOR THE
ELECTRON-ION COLLIDER

EIC Yellow Report

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

Possible probe of nucleon intrinsic strangeness, this could mean *strange form factors*.
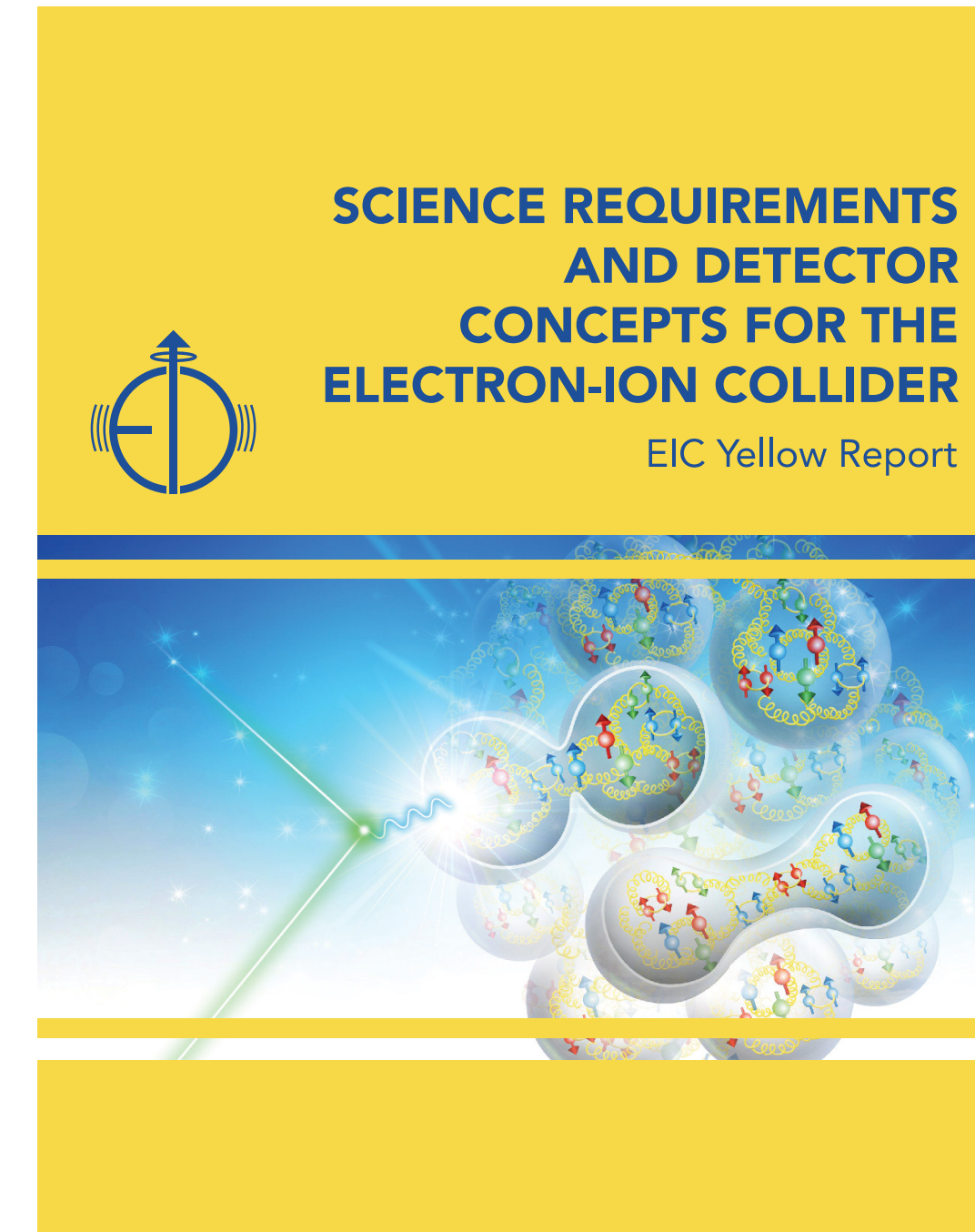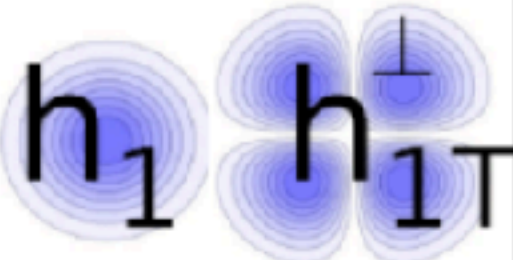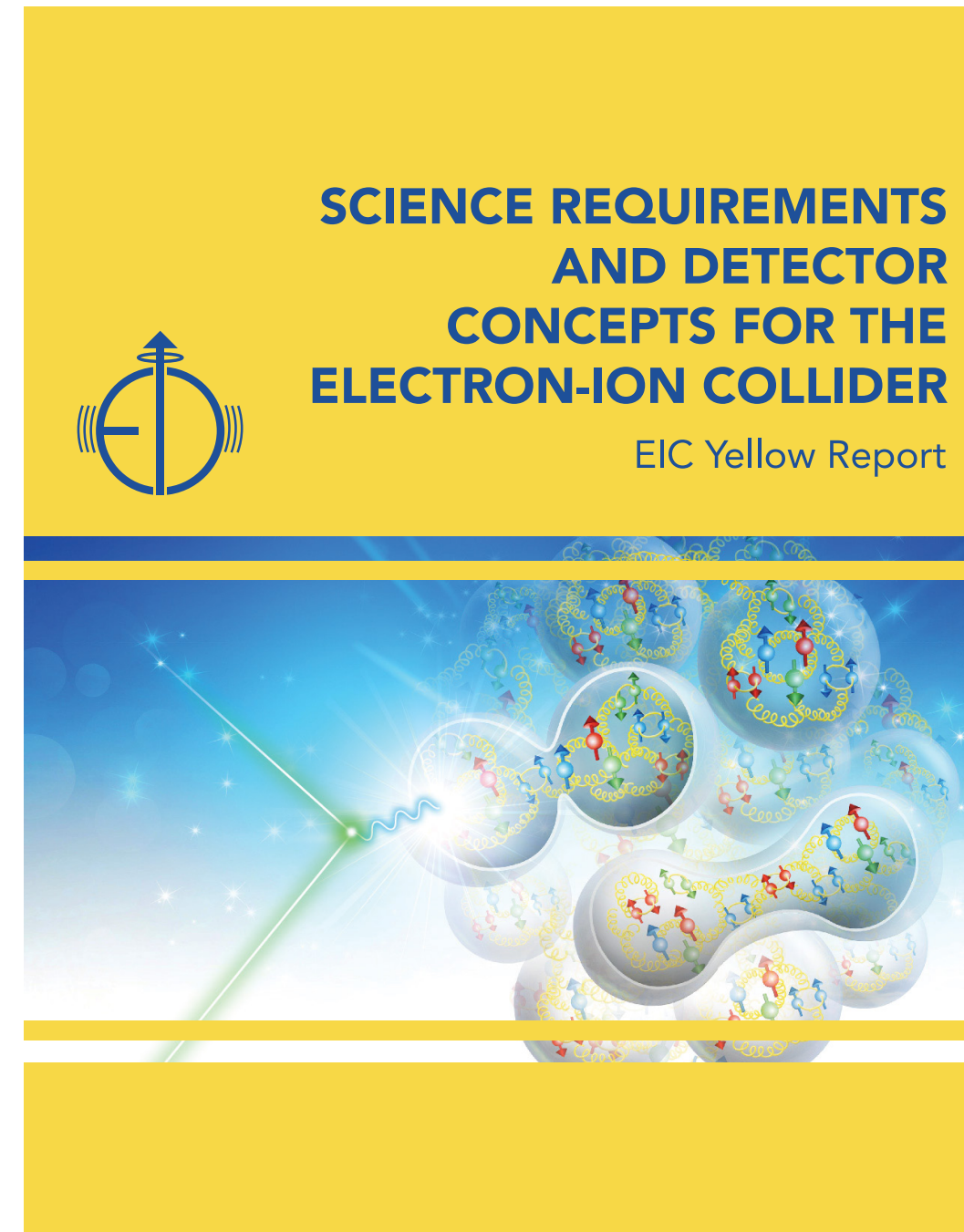
Spin and Polarization (Part Two)
Applications to Nucleon Structure

If we consider quark, nucleon, and gluon momentum and interactions in 3D (as opposed to only longitudinally) in regimes where the transverse energy scale is much smaller than the interaction energy, we get access to **Transverse Momentum Dependent** correlations.

$$\Phi^{[\gamma^+]} = f_1(x, k_\perp^2) - \frac{\epsilon_T^{ij} k_\perp^i S_\perp^j}{M} f_{1T}^\perp(x, k_\perp^2)$$

$$\Phi^{[\gamma^+ \gamma_5]} = S_z g_1(x, k_\perp^2) + \frac{k_\perp \cdot S_\perp}{M} g_{1T}(x, k_\perp^2)$$

$$\Phi^{[i\sigma^{i+}\gamma_5]} = S_\perp^j h_1(x, k_\perp^2) + S_z \frac{k_\perp^j}{M} h_{1L}^\perp(x, k_\perp^2)$$

$$+ \frac{\epsilon_T^{ji} k_\perp^i}{M} h_1^\perp(x, k_\perp^2) + S_\perp^i \frac{2k_\perp^i k_\perp^j - k^2 \delta^{ij}}{2M^2} h_{1T}^\perp(x, k_\perp^2),$$

Differential solid angle d Ω

Differential cross section d σ

Impact parameter b

Scattering center   Scattered particle
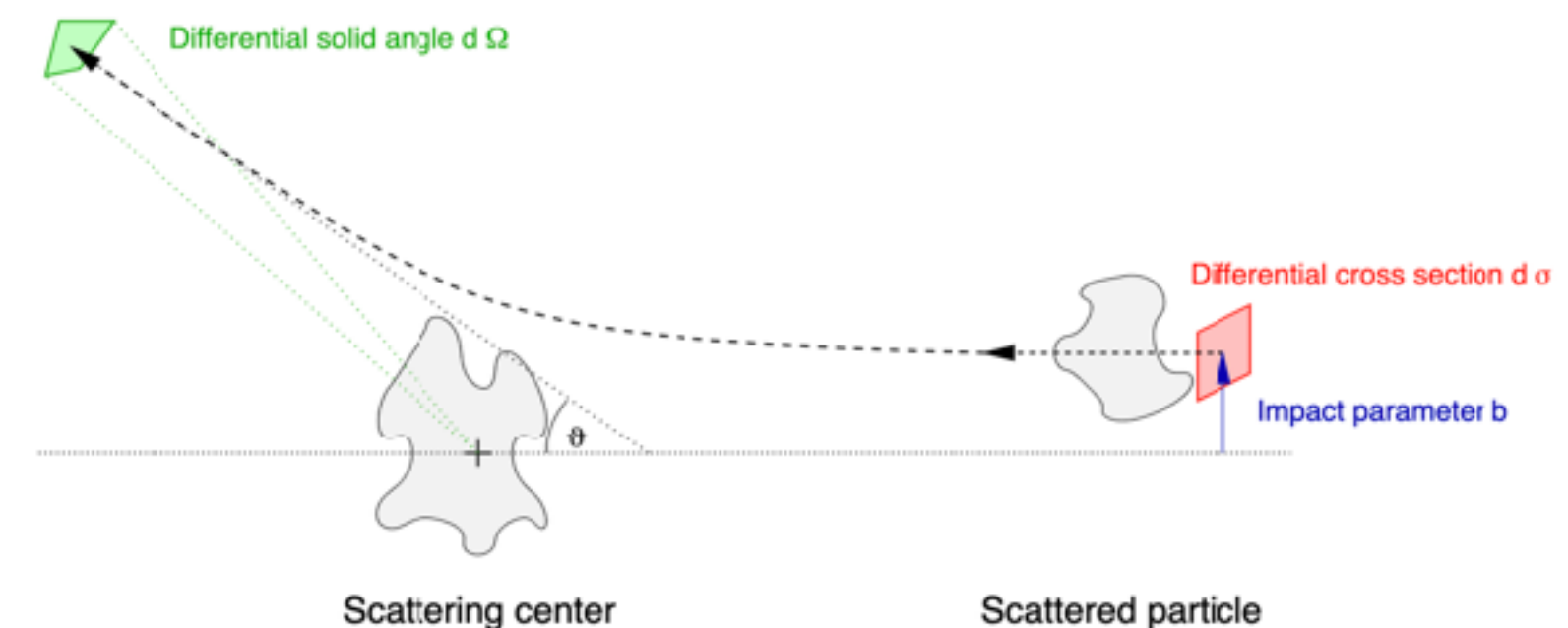
Spin and Polarization (Part Three)

Theoretical Expansion to Scattering and the Concept of the Nucleon

$W(x, b_T, k_T)$
Wigner distributions

$\int d^2 b_T$ $\int d^2 k_T$

Fourier trf.
$b_T \leftrightarrow \Delta$

$\xi = 0$

$f(x, k_T)$ $f(x, b_T)$ $H(x, 0, t)$ $H(x, \xi, t)$
$t = -\Delta^2$

transverse momentum distributions (TMDs)
semi–inclusive processes

impact parameter distributions

generalized parton distributions (GPDs)
exclusive processes

$\int d^2 k_T$ $\int d^2 b_T$ $\int dx$ $\int dx\, x^{n-1}$

$f(x)$ $F_1(t)$ $A_{n,0}(t) + 4\xi^2 A_{n,2}(t) + ...$

parton densities
inclusive and semi–inclusive processes

form factors
elastic scattering

generalized form factors
lattice calculations

SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER
EIC Yellow Report

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 cross-section sample underlying 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 few options exist for the measurement of scattering on light nuclear targets but the most robust will be the development of a new bubble chamber.

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

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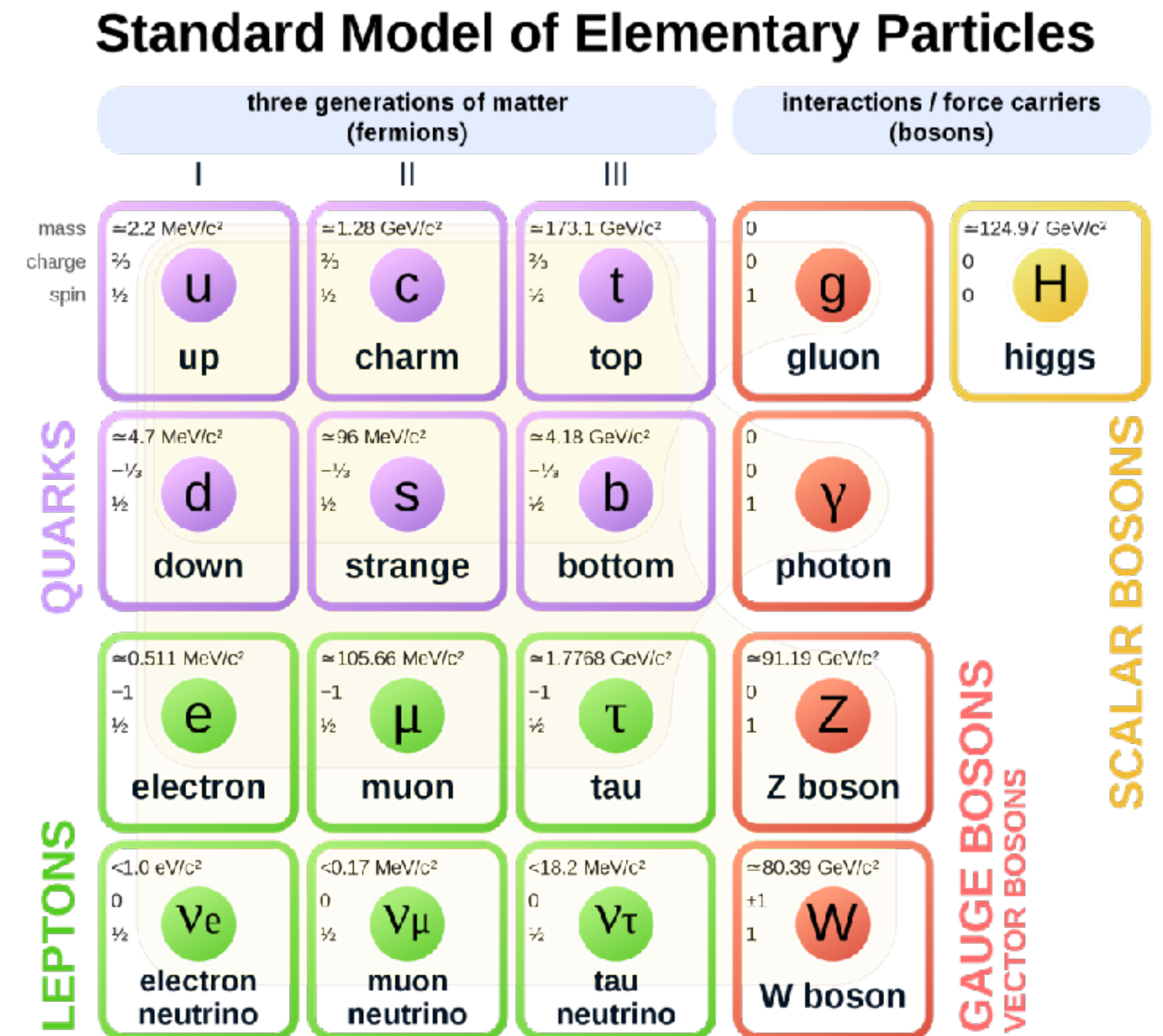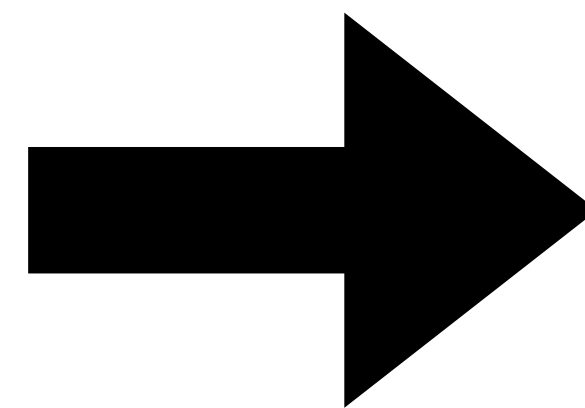**Hydrogen/Deuterium Cross Sections: https://arxiv.org/abs/2203.11298**
Bubble Chamber: https://arxiv.org/abs/2203.11319
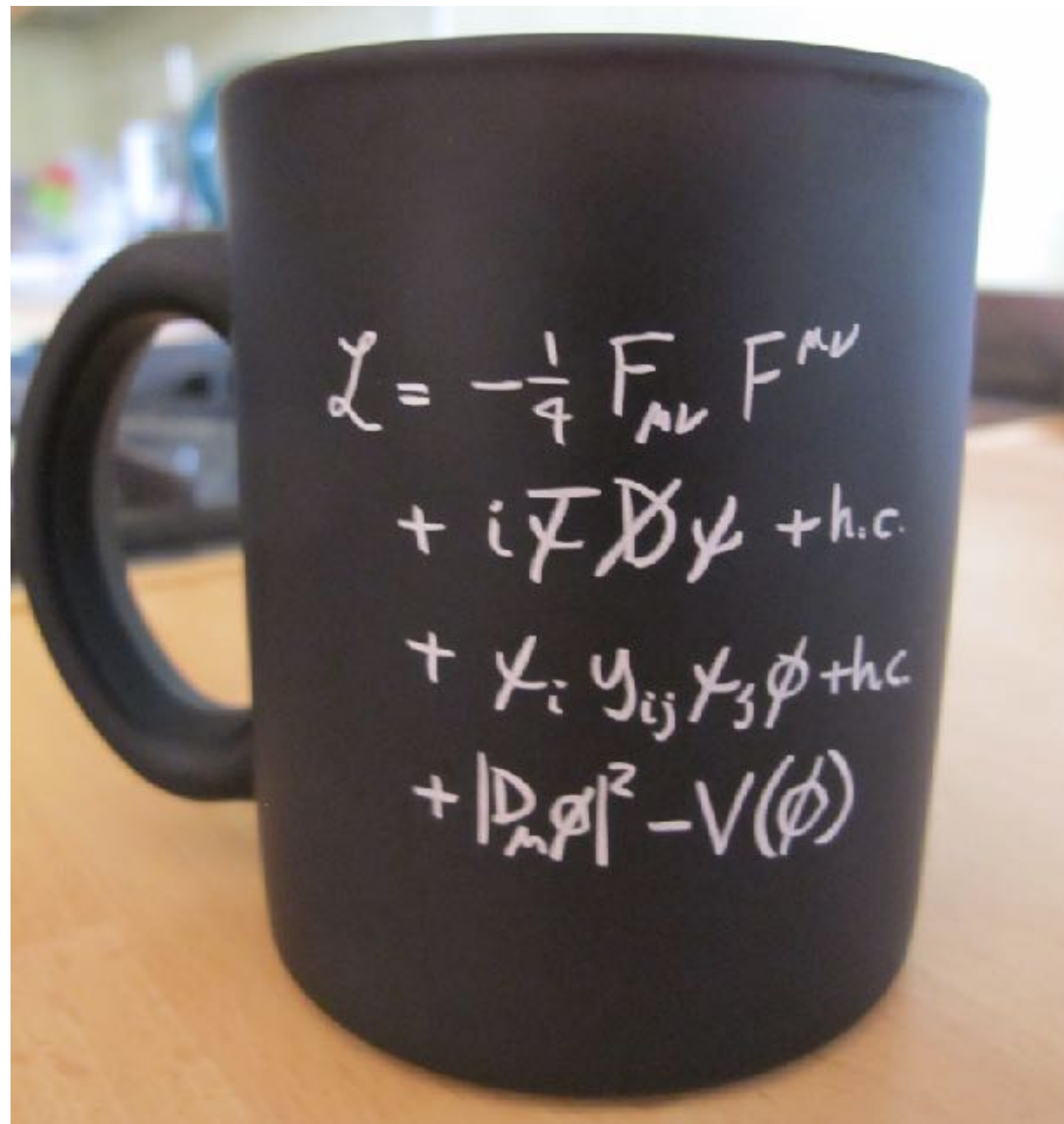
Backup

A Brief Introduction to Particle Physics
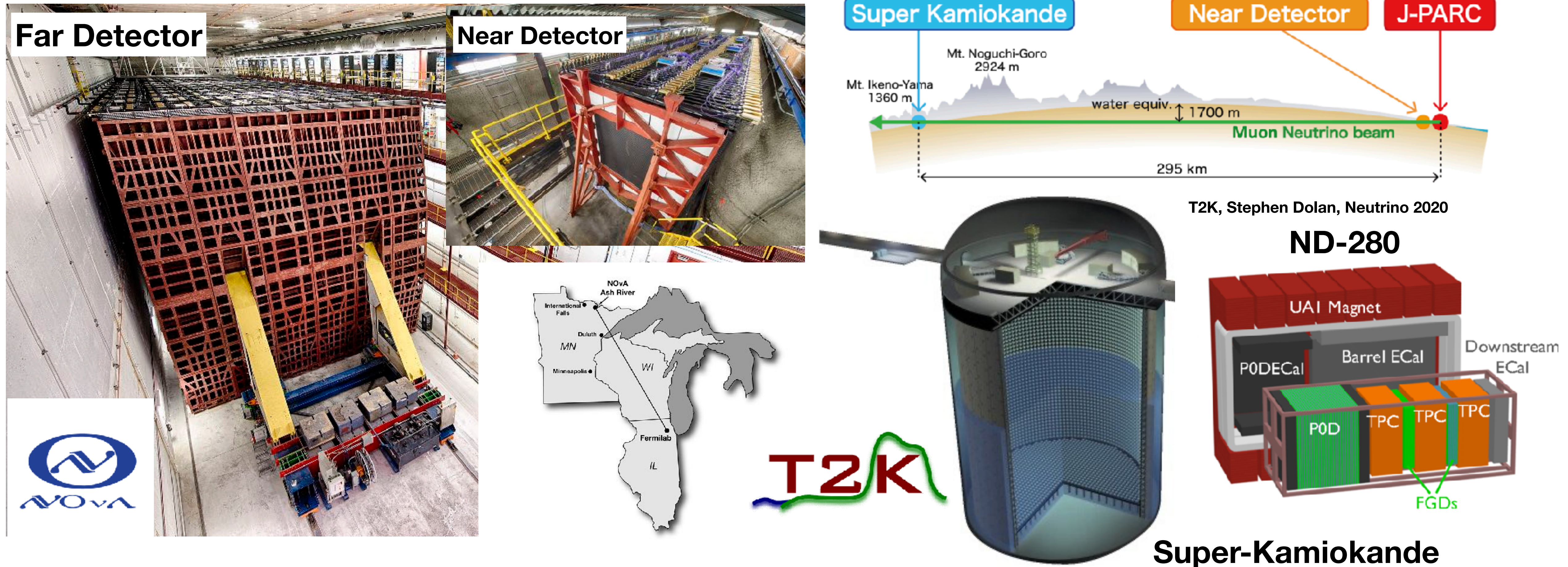## The Theory of *Almost Everything*

The Standard Model is the crown jewel of particle physics!

It describes the underlying symmetries governing the scattering of particles from each other and only excludes *gravity*. **Doing particle physics means testing the standard model.**

Current Generation of Long-Baseline Experiments
Current State-of-the-Art Detectors and Measurements

Far Detector

Near Detector

Super Kamiokande

Near Detector

J-PARC

Mt. Noguchi-Goro 2924 m

Mt. Ikeno-Yama 1360 m

water equiv. ↕ 1700 m

Muon Neutrino beam

295 km

T2K, Stephen Dolan, Neutrino 2020

ND-280

UA1 Magnet

PODECal

Barrel ECal

Downstream ECal

P0D   TPC   TPC   TPC

FGDs

NOvA Ash River
International Falls
Duluth
MN
Minneapolis
WI
Fermilab
IL

T2K

Super-Kamiokande

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.

The DUNE Far Detector
Necessary for Observation of Oscillations

ProtoDUNE-SP Design

DUNE FD Cryostat


18m

66m

19m

~1 mile underground

ν
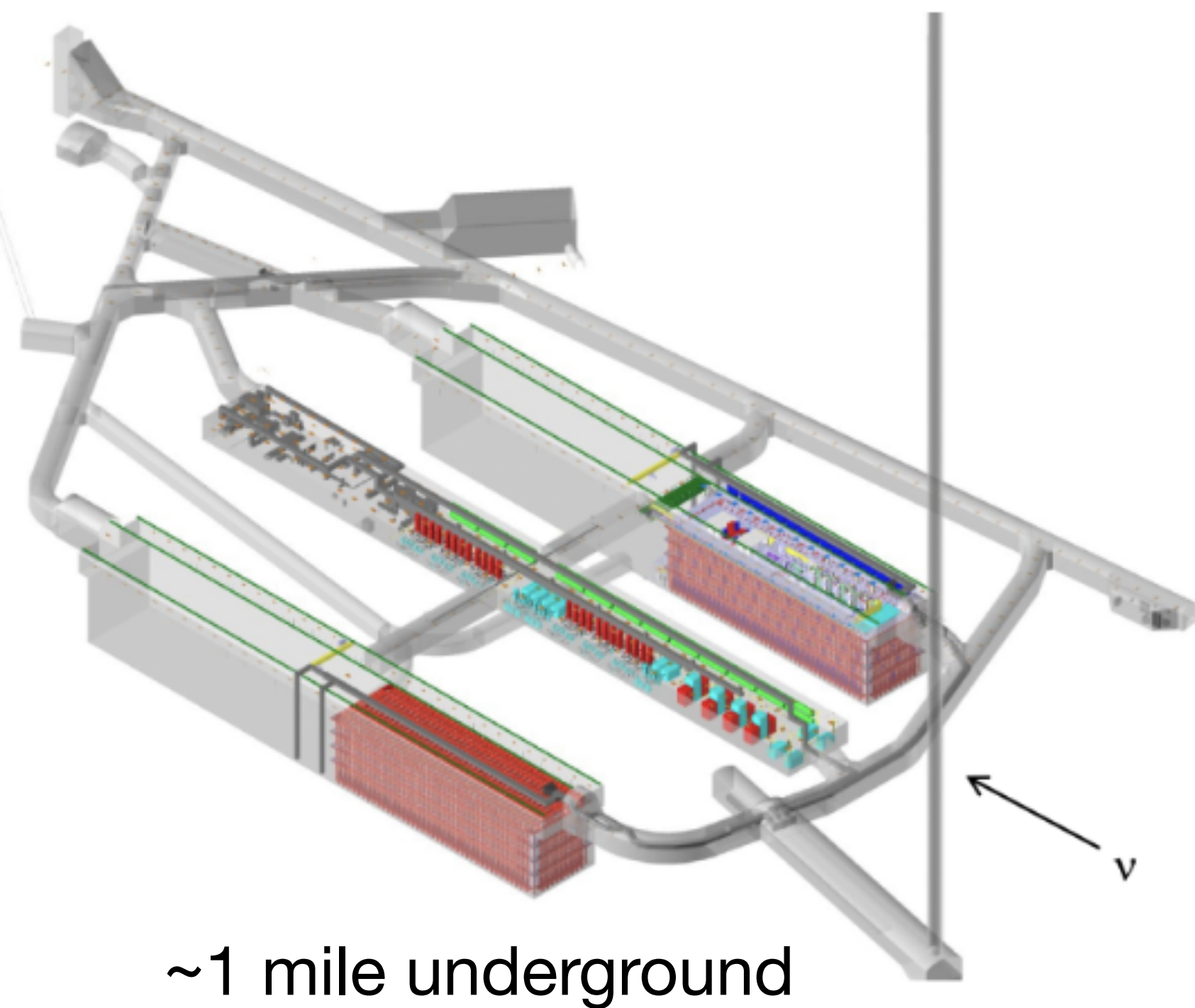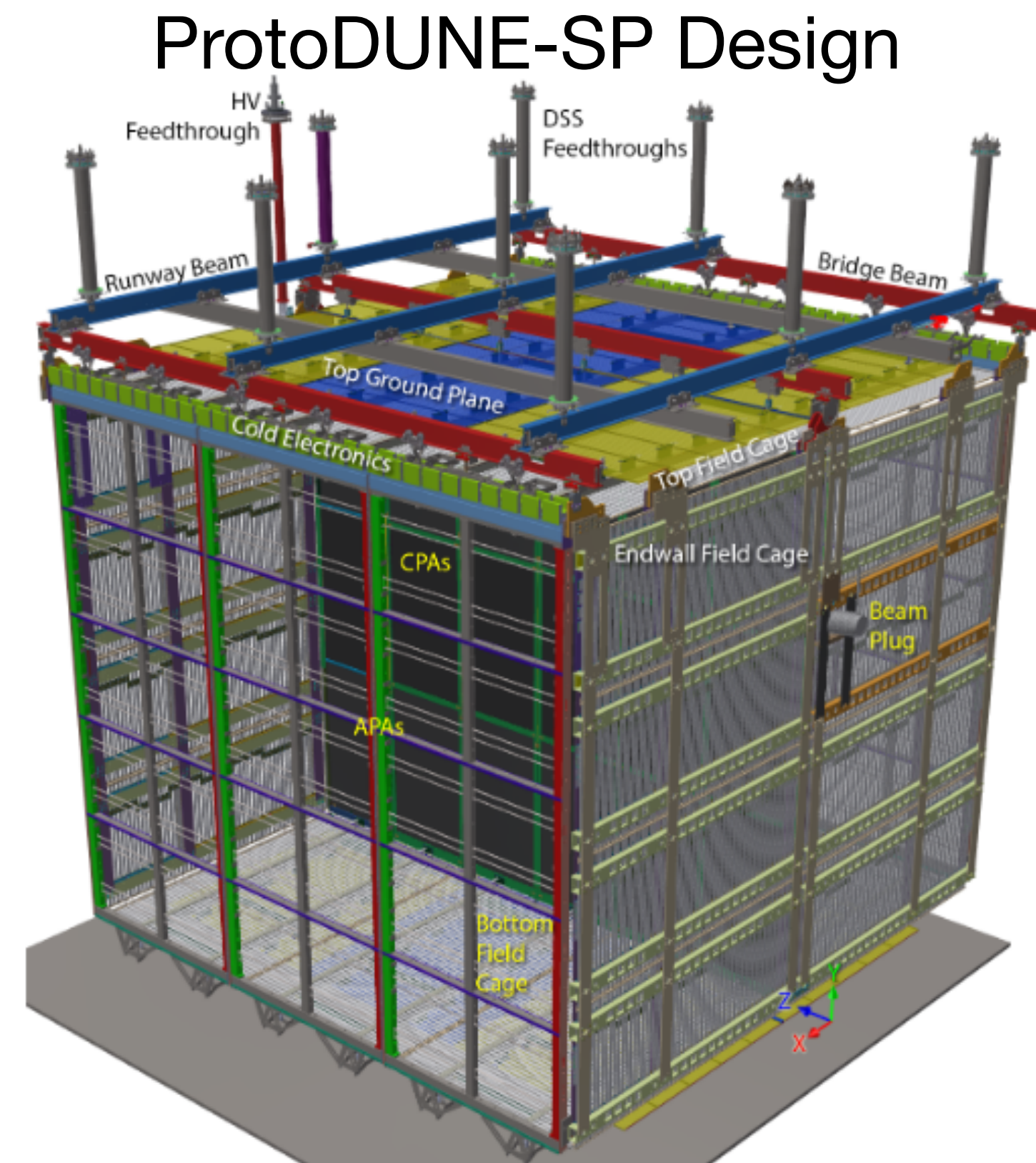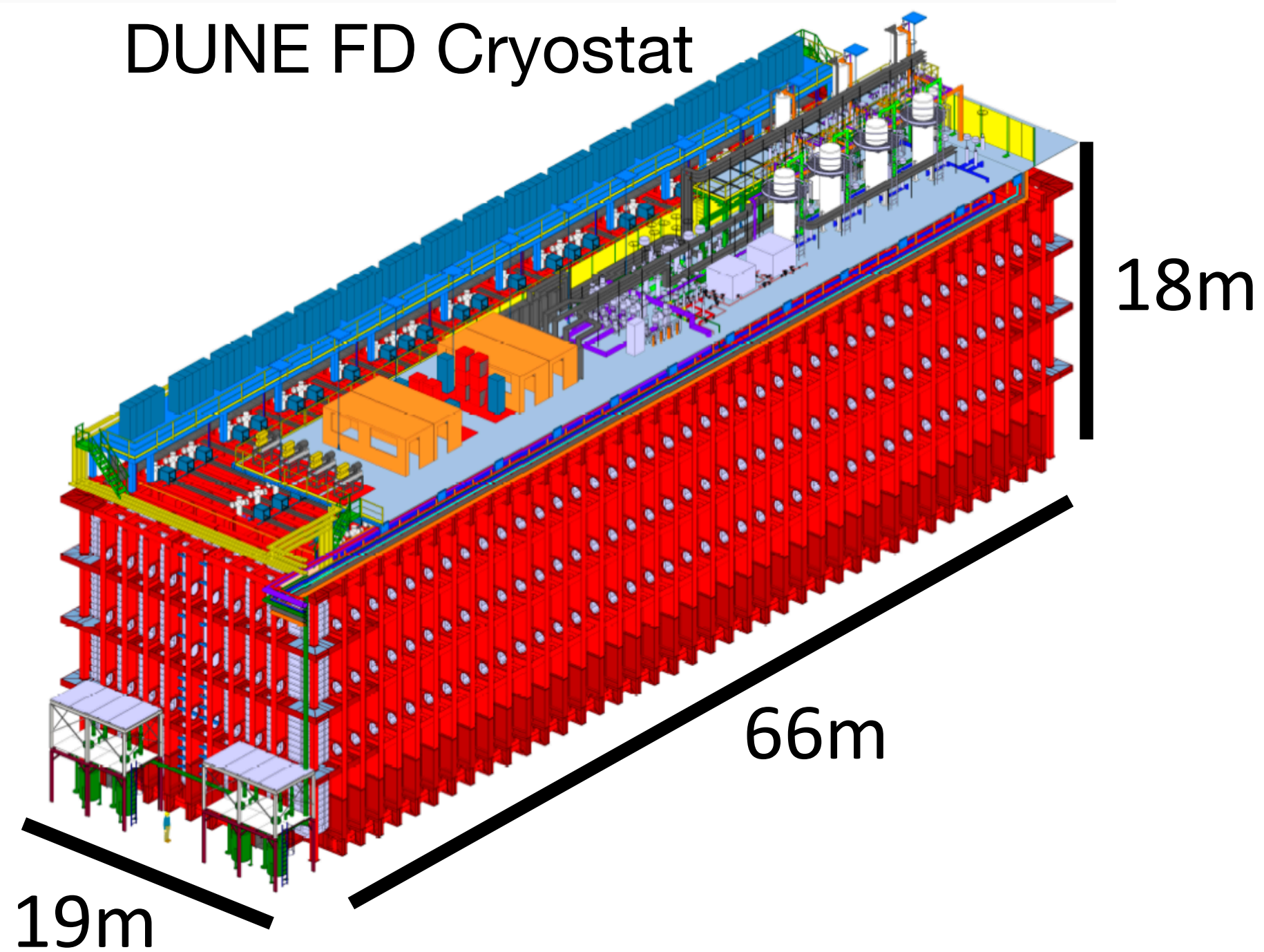
FD designed to directly observe ν_μ disappearance and ν_e appearance over ~800 mile baseline!

Four-17 kt fiducial volume detectors, first and second modules are planned to be single phase (HD/VD), with the other modules still in planning.

First prototype of single phase FD published ensemble study in 2020!

Very Optimistic ~~Expected~~ DUNE Sensitivities

## Last Generation of Accelerator Driven Long-Baseline Experiments?
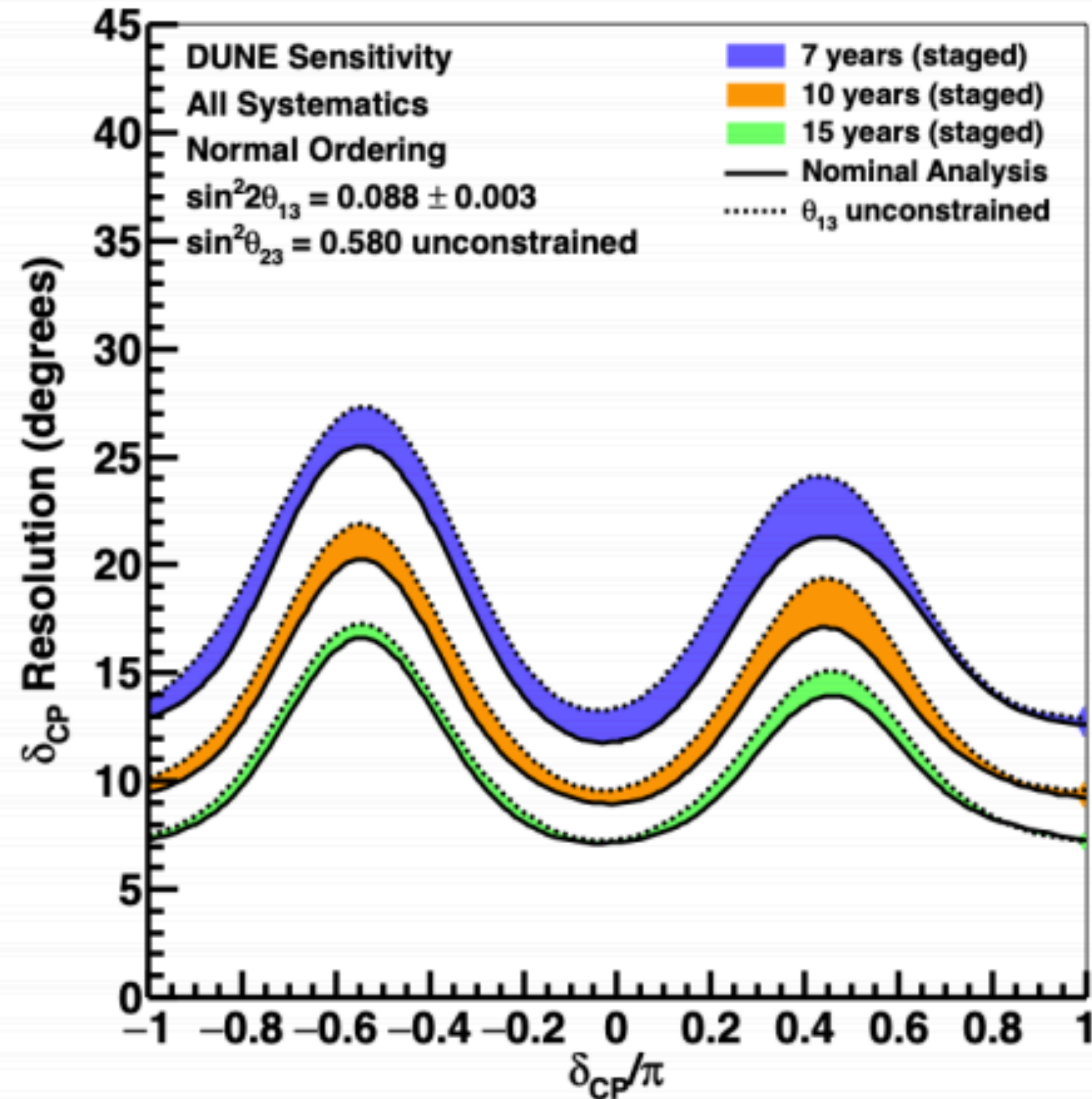
| Physics Milestone	Exposure (staged years)
5σ mass ordering ($\delta_{CP} = -\pi/2$)	1
5σ mass ordering (100% of δ_{CP} values)	2
3σ CPV ($\delta_{CP} = -\pi/2$)	3
3σ CPV (50% of δ_{CP} values)	5
5σ CPV ($\delta_{CP} = -\pi/2$)	7
5σ CPV (50% of δ_{CP} values)	10
3σ CPV (75% of δ_{CP} values)	13
δ_{CP} resolution of 10 degrees ($\delta_{CP} = 0$)	8
δ_{CP} resolution of 20 degrees ($\delta_{CP} = -\pi/2$)	12
$\sin^2 2\theta_{13}$ resolution of 0.004	15

DUNE will have the statistical power to measure to 5σ significance or significantly constrain the mass hierarchy and PMNS elements, including δ_{CP}!

Introduction to Neutrinos
The *Ghostly* Elementary Particle
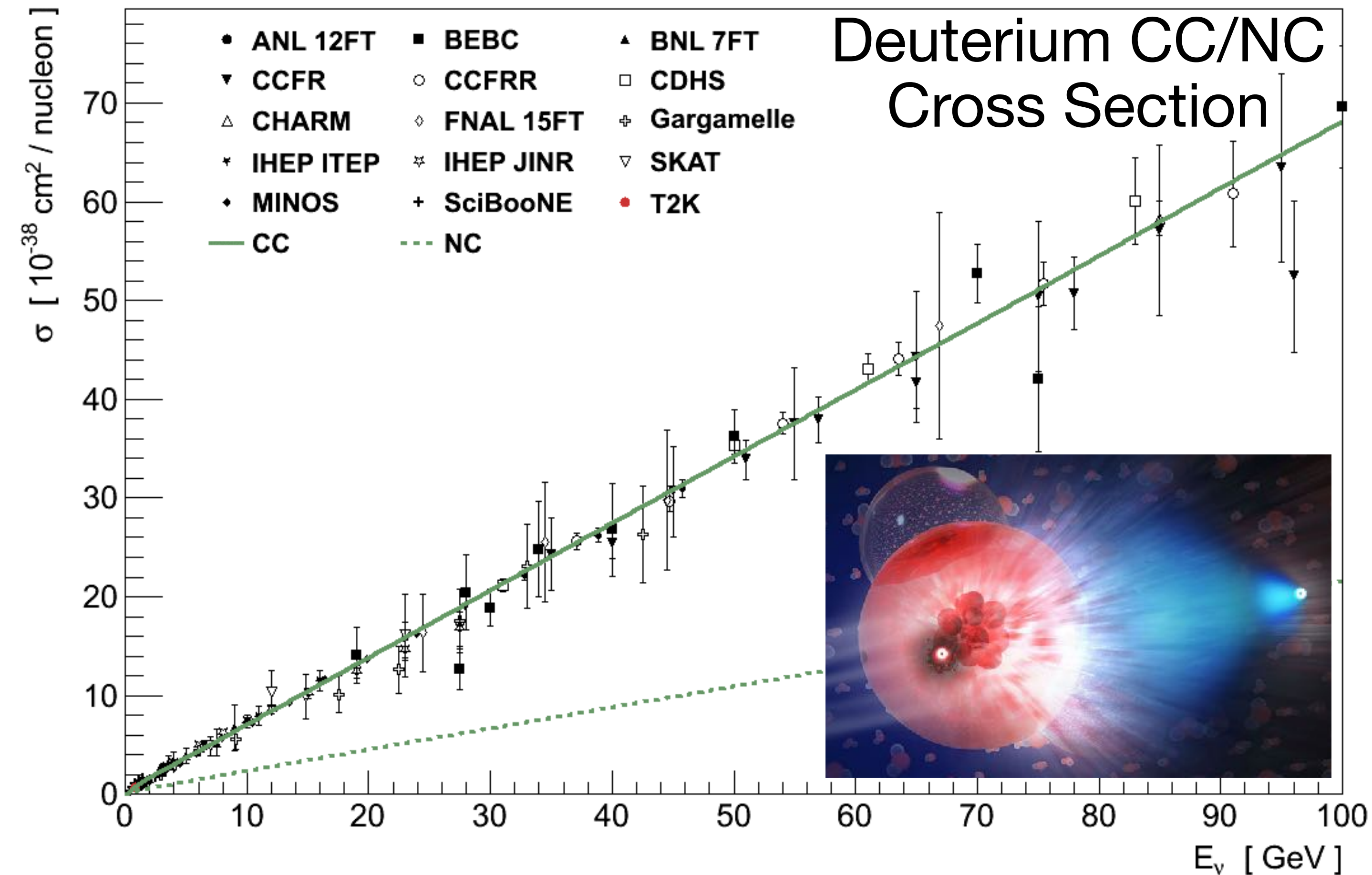
Standard model interaction map

Deuterium CC/NC Cross Section
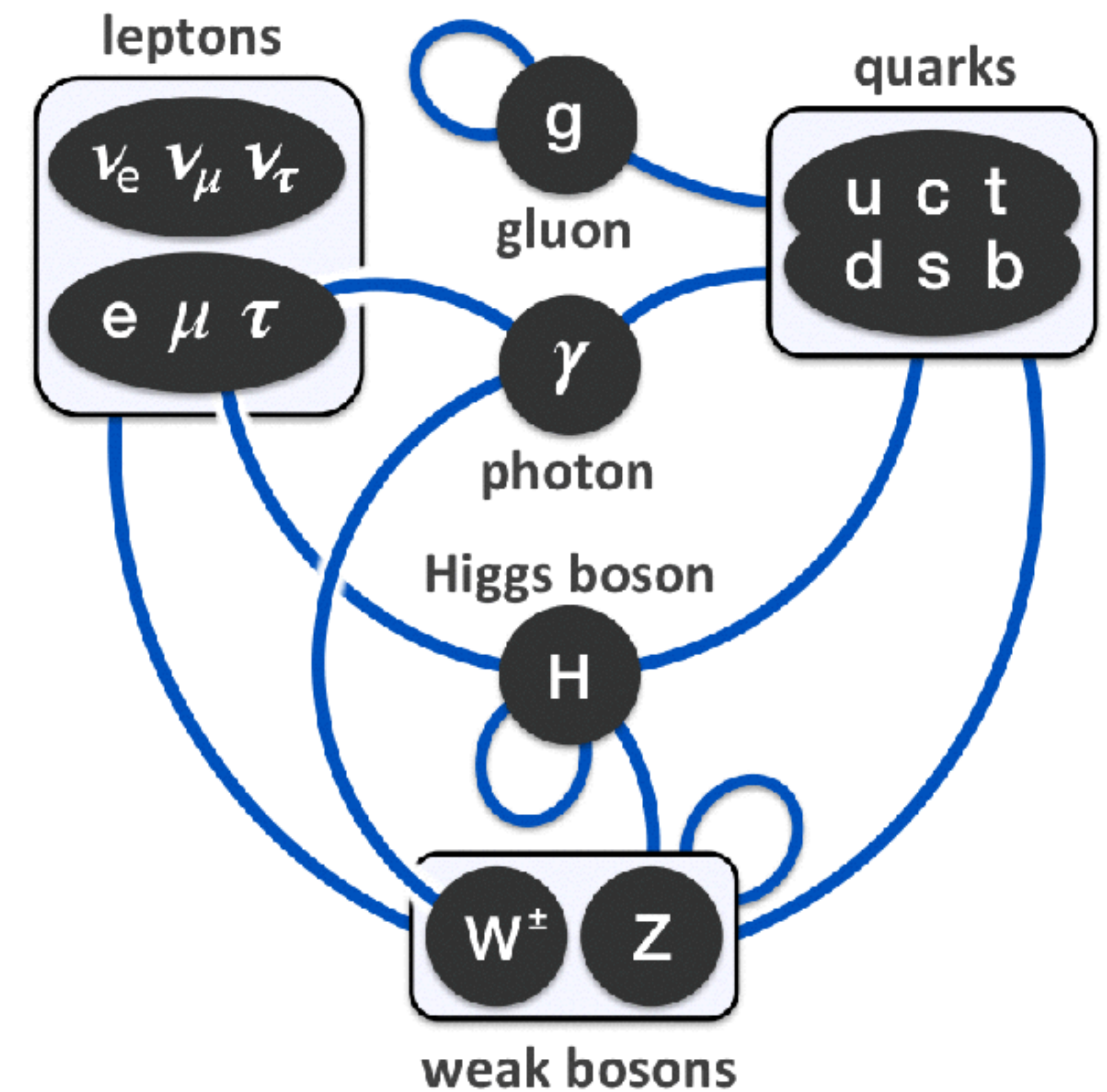
Neutrinos have a very low cross-section and thus interact very rarely compared to other types of particles (10^{-14} difference from electron scattering). *Very difficult to measure.*

Particle Physics, Scattering, and Cross Sections
Particle Scattering is How We Learn About the Universe

Differential solid angle d Ω

We learn about the interior of objects by using other particles as probes,
the higher the energy, the smaller the length scale that can be probed.

Differential cross section d σ

Impact parameter b
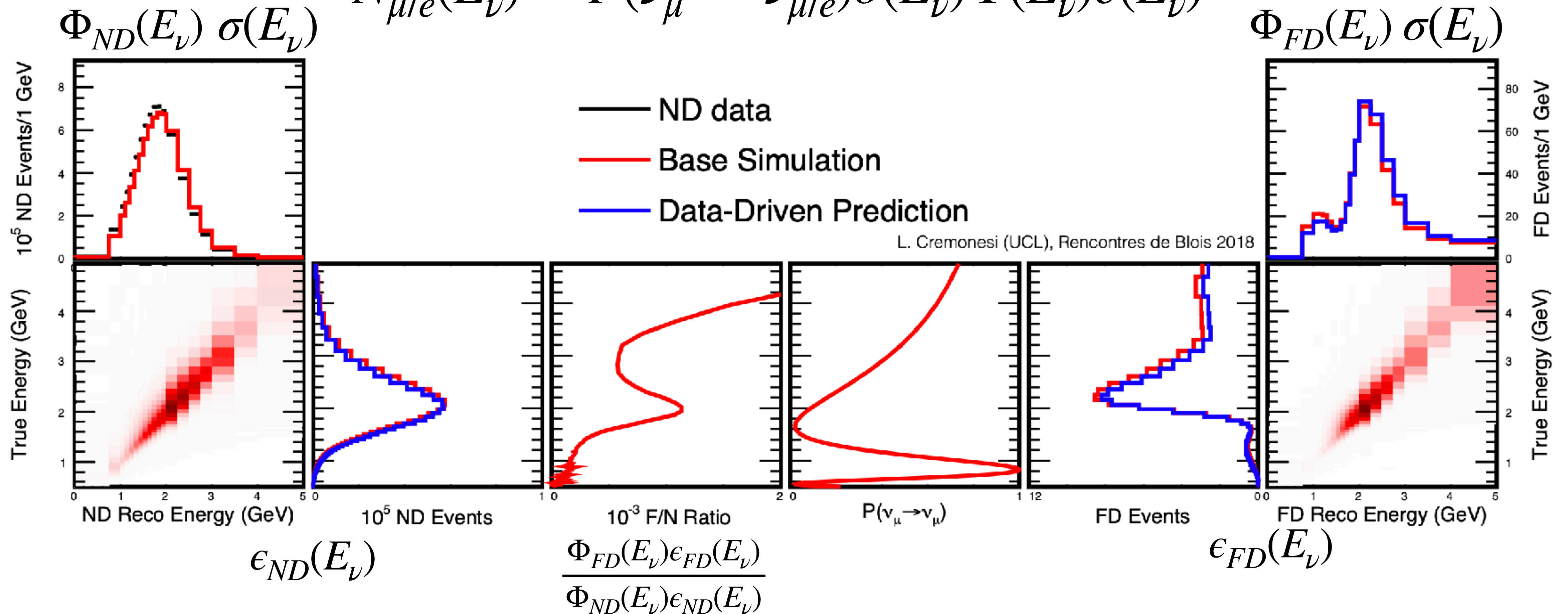
ϑ
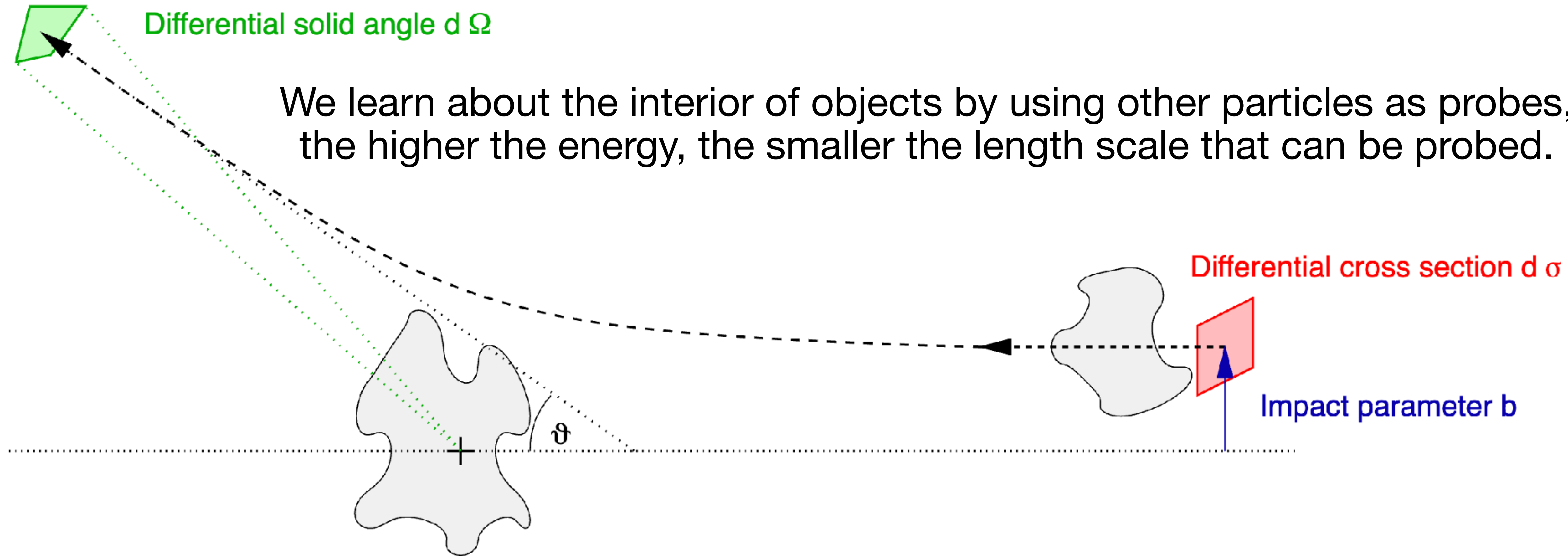
Scattering center

Scattered particle

We encode information about the probability of particles scattering in *cross sections*
which can be measured differentially with respect to various kinematics.

How to Do an Oscillations Analysis

A Brief Conceptual Overview for Experiments Like DUNE

$$N_{\mu/e}(E_\nu) = P(\nu_\mu \to \nu_{\mu/e})\sigma(E_\nu)\Phi(E_\nu)\epsilon(E_\nu)$$

$\Phi_{ND}(E_\nu)\ \sigma(E_\nu)$

$\Phi_{FD}(E_\nu)\ \sigma(E_\nu)$

ND data — Base Simulation — Data-Driven Prediction

L. Cremonesi (UCL), Rencontres de Blois 2018

$\epsilon_{ND}(E_\nu)$

$\dfrac{\Phi_{FD}(E_\nu)\epsilon_{FD}(E_\nu)}{\Phi_{ND}(E_\nu)\epsilon_{ND}(E_\nu)}$

$\epsilon_{FD}(E_\nu)$

Major questions about whether uncertainties on flux, acceptance, and efficiency can be tightly controlled across **all** long baseline experiments.

Old Style Versus New Style
advantages and disadvantages

Advantages

With strong magnet (>2T), high detection efficiency for most charged tracks.

High precision reconstruction ~300 microns vertex resolution, possible to go higher resolution.

Particle ID dependent on bubble density, directly controllable by expansion time.

Large significant history of successful use.

Disadvantages

Will require additional detectors to measure high energy/hadronic calorimetry and muons.

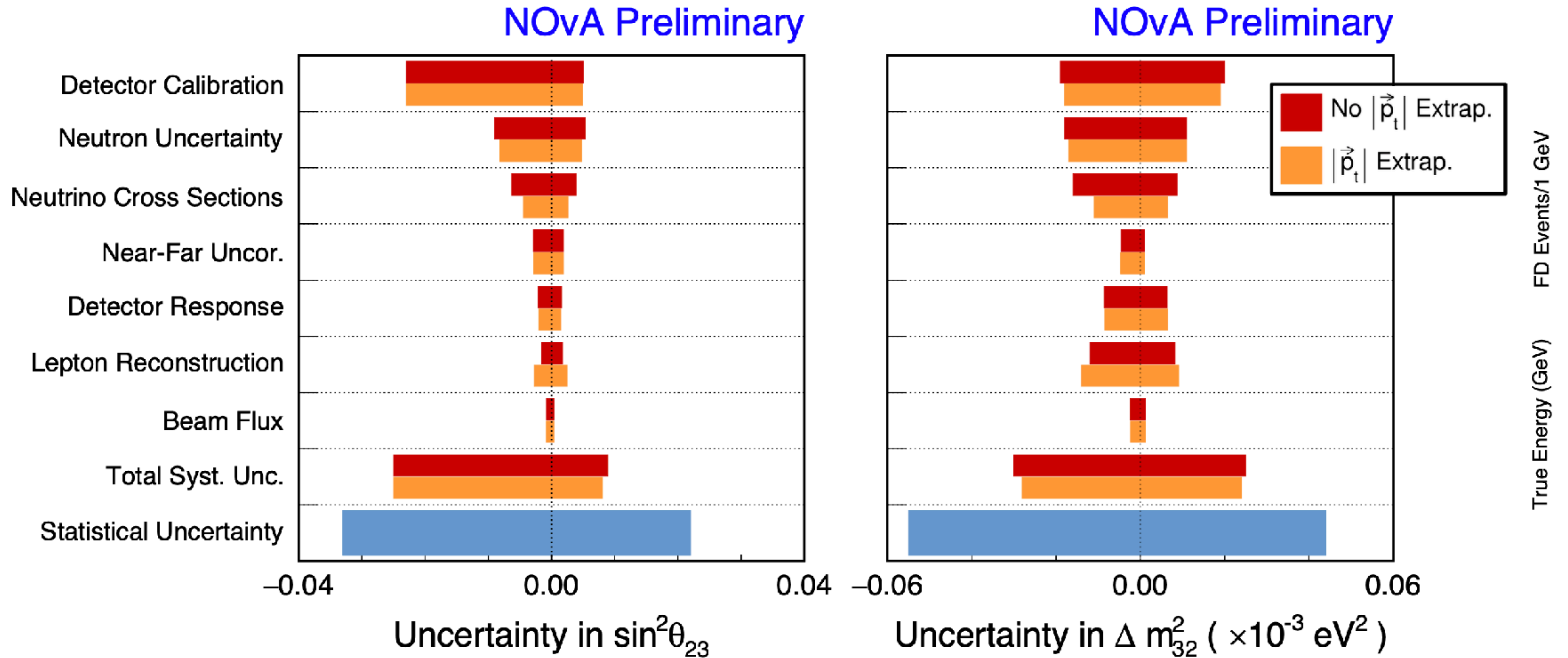Slow 1-2s reset time depending on size.

Hard to detect neutral particles.

Distortion across larger chambers, as chamber gets larger distortion gets worse.

Expansion time limited by bubble nucleation at walls.

Uncertainties in an Oscillations Analysis

How Well Does NOvA Do?

Biggest uncertainties in θ_{23} and Δm^2_{32} are from detector calibration and neutron uncertainties, all measurements are currently statistics limited!