Bubble Chamber Detectors with Light Nuclear Targets for Neutrino Scattering

Snowmass Community Summer Study Workshop

University of Washington

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Contemporary Neutrino Physics (Part One)

Neutrino Oscillations as a paths to Beyond-the-Standard-Model Physics

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

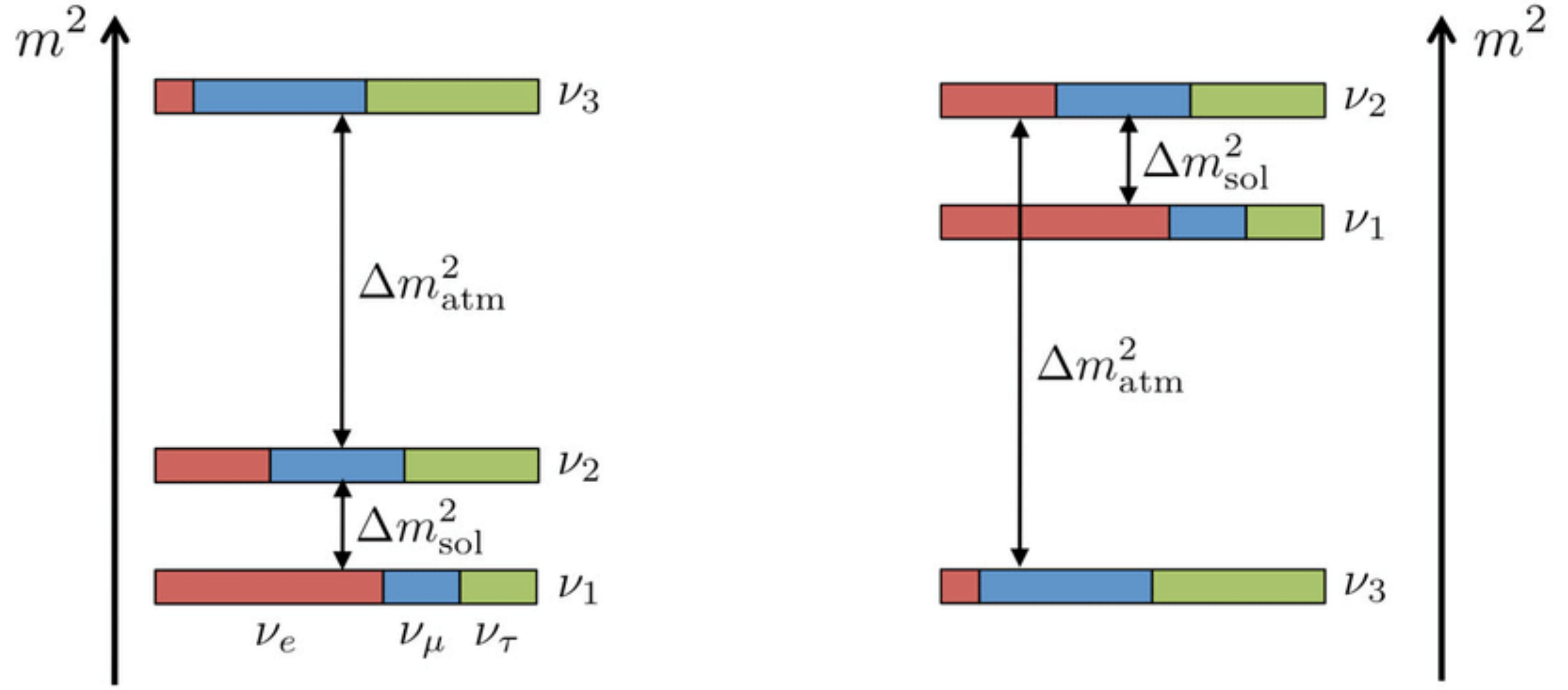
PMNS Matrix, Atmospheric, Reactor, Solar

$$|U| = \begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu 1} & |U|_{\mu 2} & |U|_{\mu 3} \\ |U|_{\tau 1} & |U|_{\tau 2} & |U|_{\tau 3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

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!



Contemporary Neutrino Physics (Part Two)

Neutrino Oscillations as a paths to Beyond-the-Standard-Model Physics

PMNS Matrix

$$|U| = \begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu 1} & |U|_{\mu 2} & |U|_{\mu 3} \\ |U|_{\tau 1} & |U|_{\tau 2} & |U|_{\tau 3} \end{bmatrix} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.144 \to 0.156 \\ 0.244 \to 0.499 & 0.505 \to 0.693 & 0.631 \to 0.768 \\ 0.272 \to 0.518 & 0.471 \to 0.669 & 0.623 \to 0.761 \end{pmatrix}$$

Current 3σ CL on the best fit for the PMNS matrix gives tight constraints on the mixing angles and mass splitting.

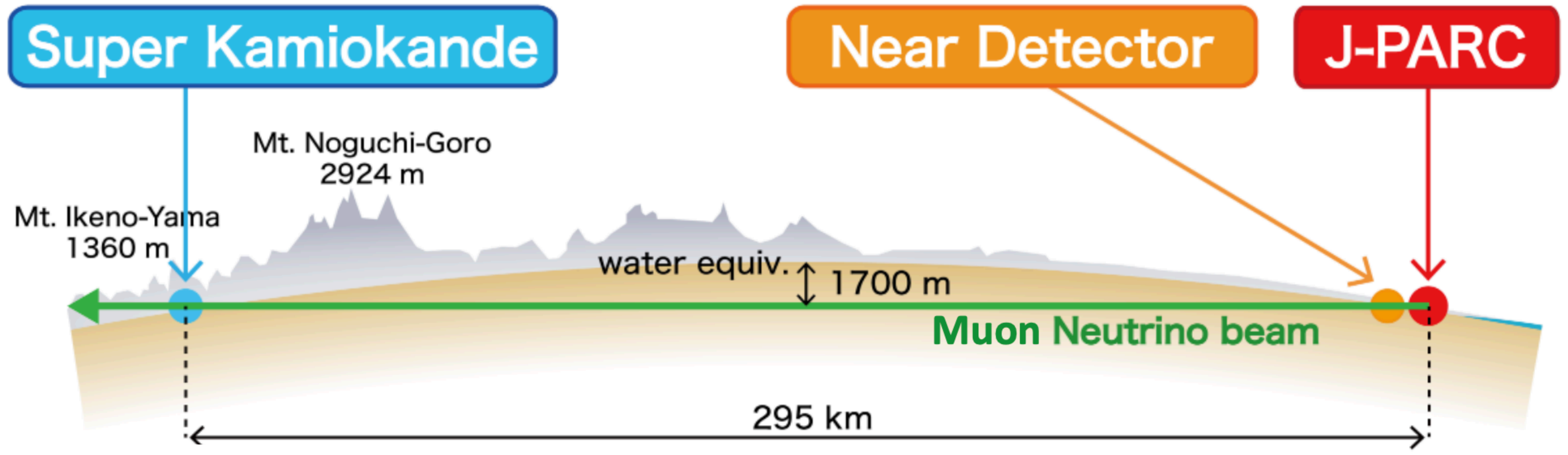
δ_{CP} and the NH/IH question are the biggest uncertainties as of Oct 2021.

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

NuFit 5.1, October 2021

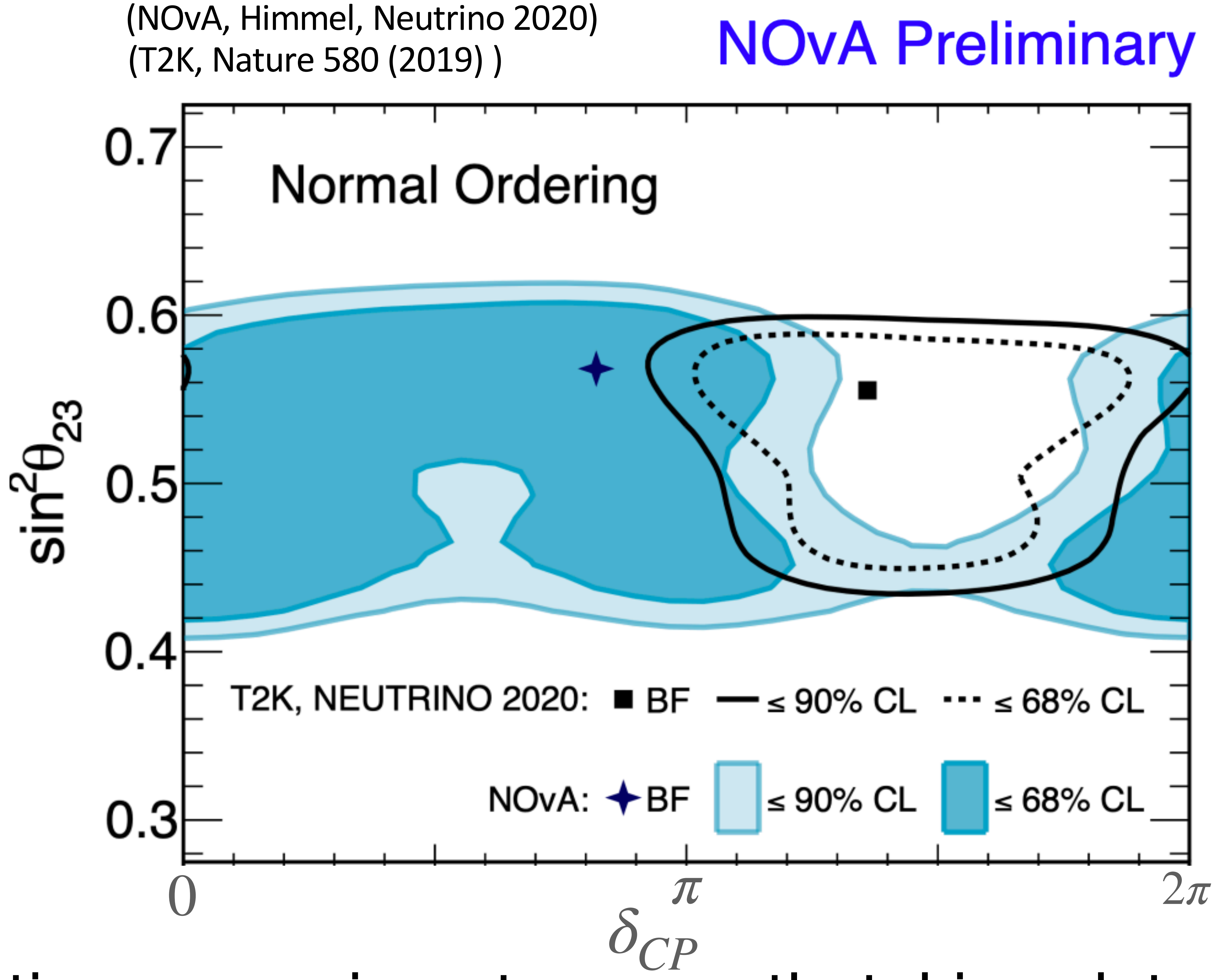
Current Generation of Long-Baseline Experiments

Current State-of-the-Art Detectors and Measurements



T2K, Stephen Dolan, Neutrino 2020

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



NOvA and T2K are dual detector oscillations experiments currently taking data and producing results. As of 2022, NOvA and T2K are leaders in resolving oscillation parameters and leptonic CP-violation using neutrinos.

Uncertainties in an Oscillation Analysis

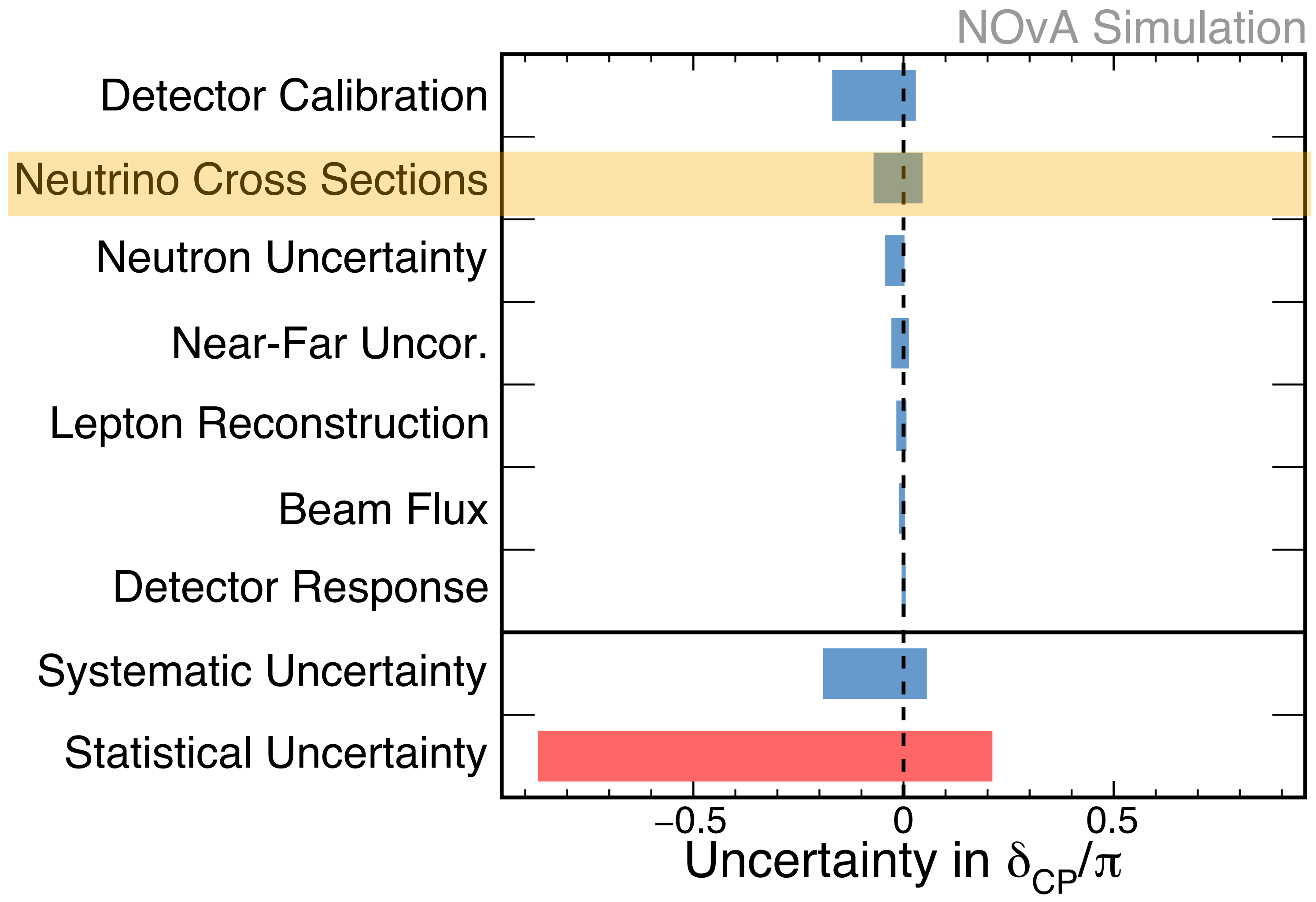
A Brief Look at Uncertainties on δ_{CP}

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



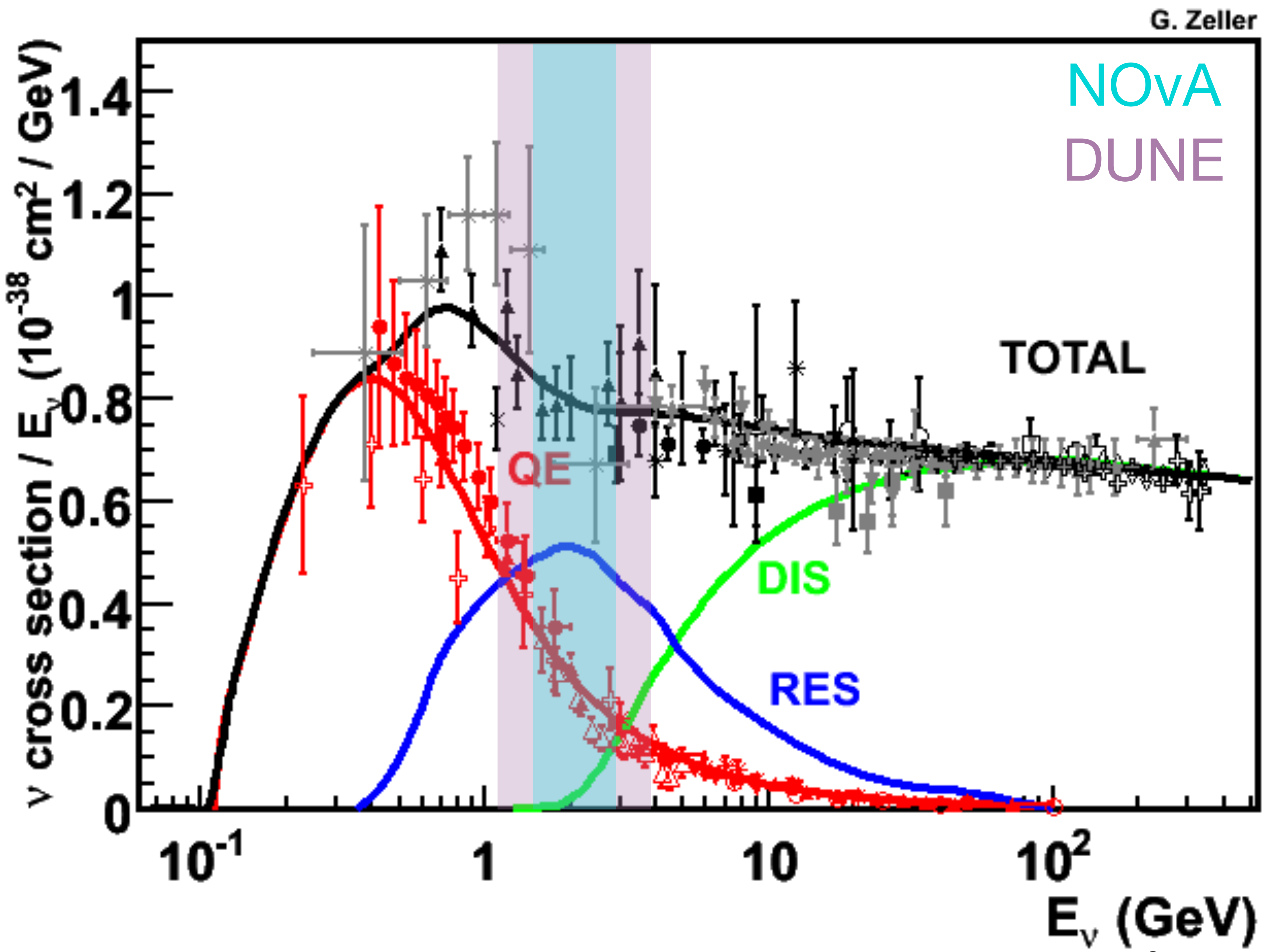
Source of Uncertainty	$\sin^2\theta_{23}$	δ_{CP}/π	$\|\Delta m^2_{32}\|$ ($\times 10^{-3}$ eV^2)
Beam Flux	+0.00034 / -0.0008	+0.0023 / -0.0099	+0.0014 / -0.0023
Detector Calibration	+0.005 / -0.025	+0.028 / -0.17	+0.019 / -0.019
Detector Response	+0.0016 / -0.0021	+0.0041 / -0.0035	+0.0067 / -0.0085
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

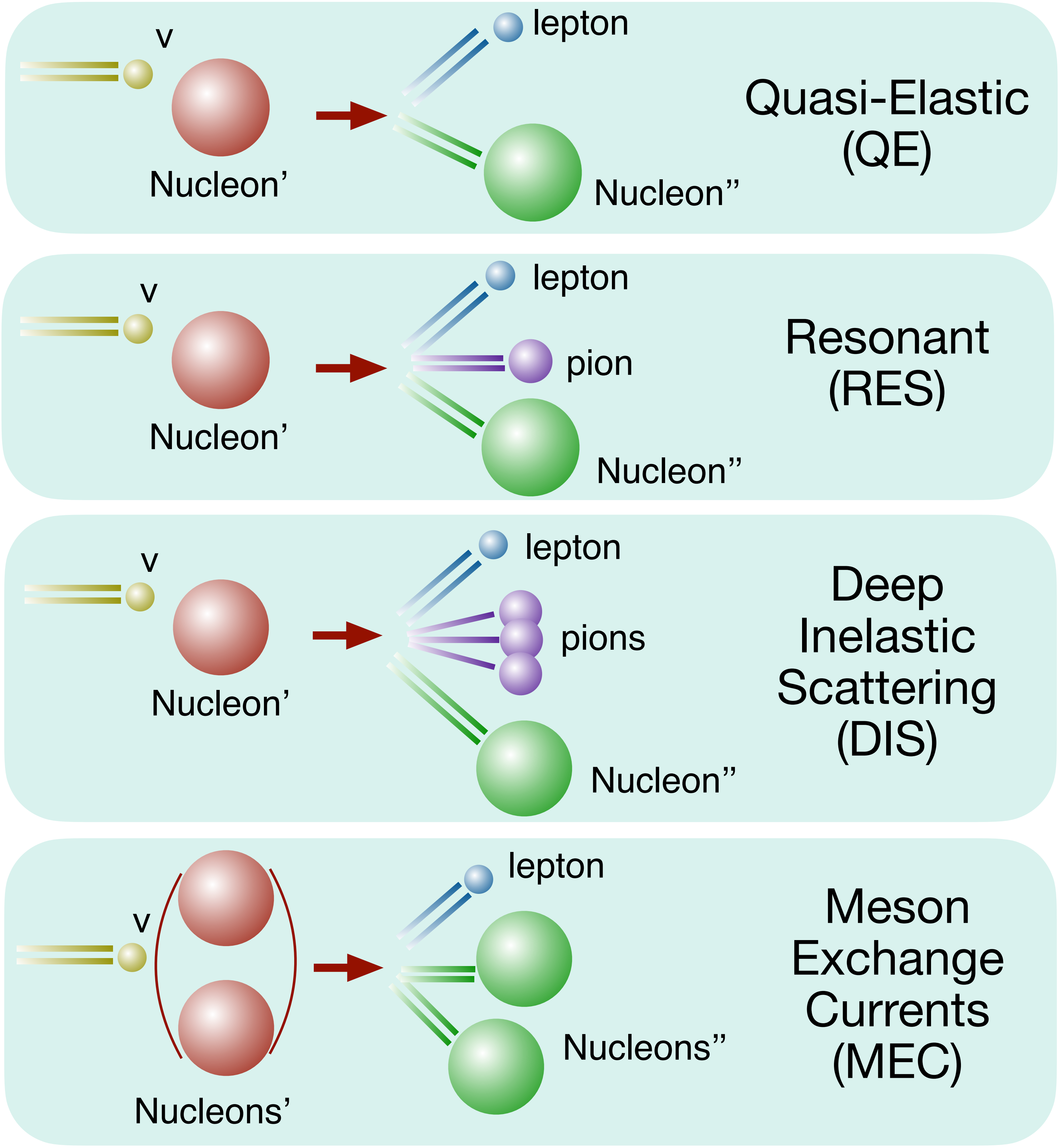
~19% of the total systematics budget

As of 2022, 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/MNI).

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)

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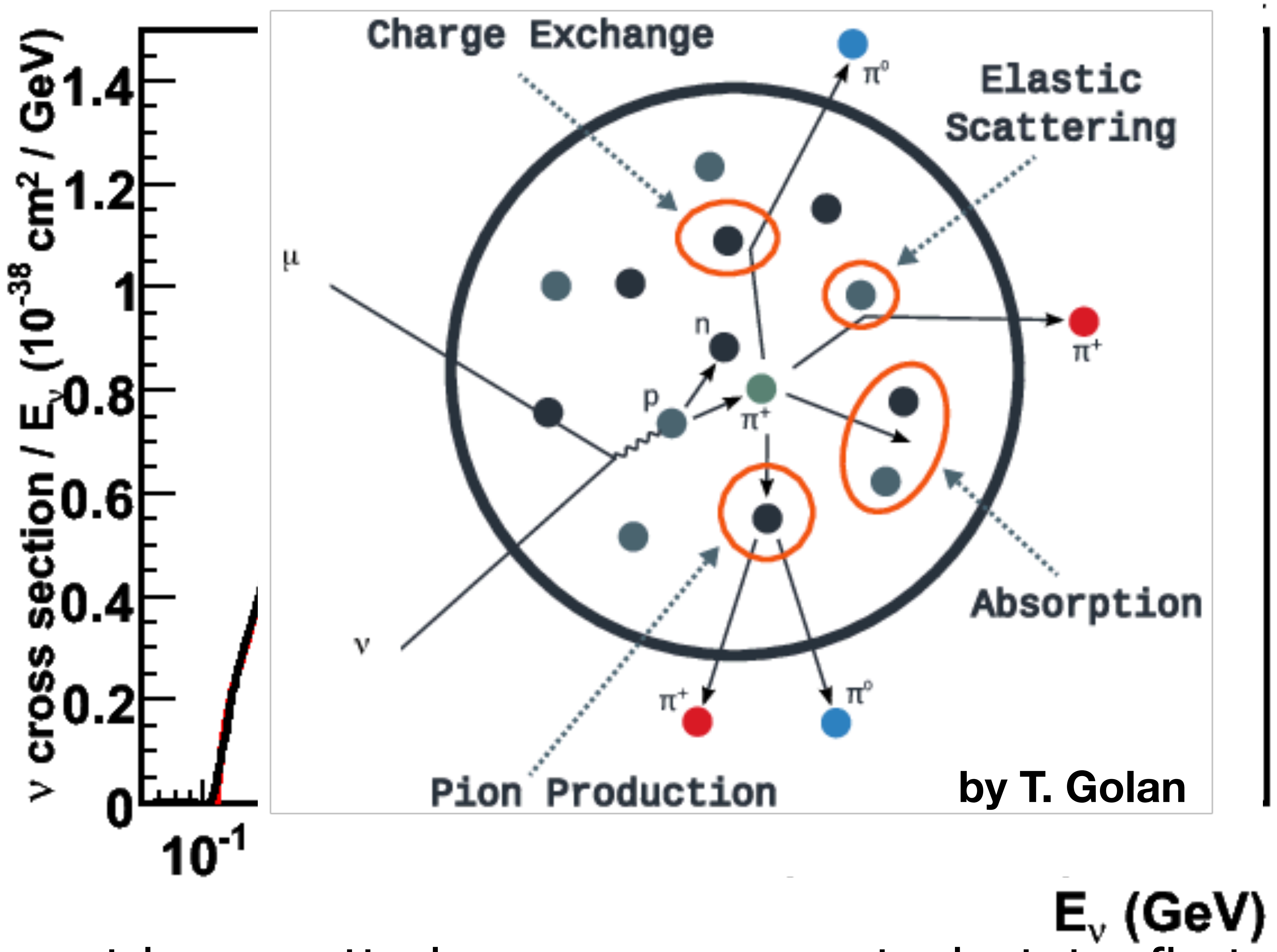

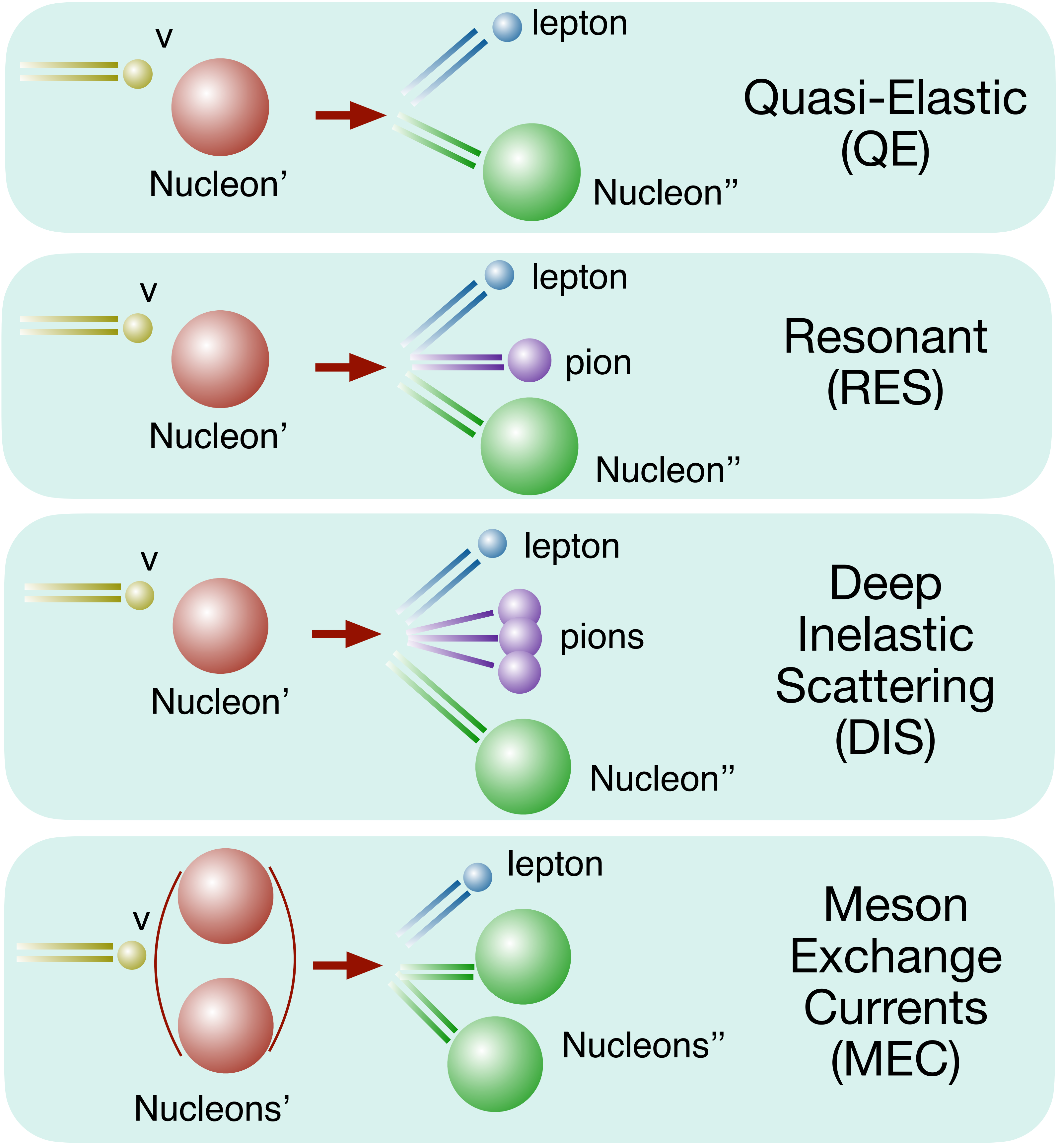

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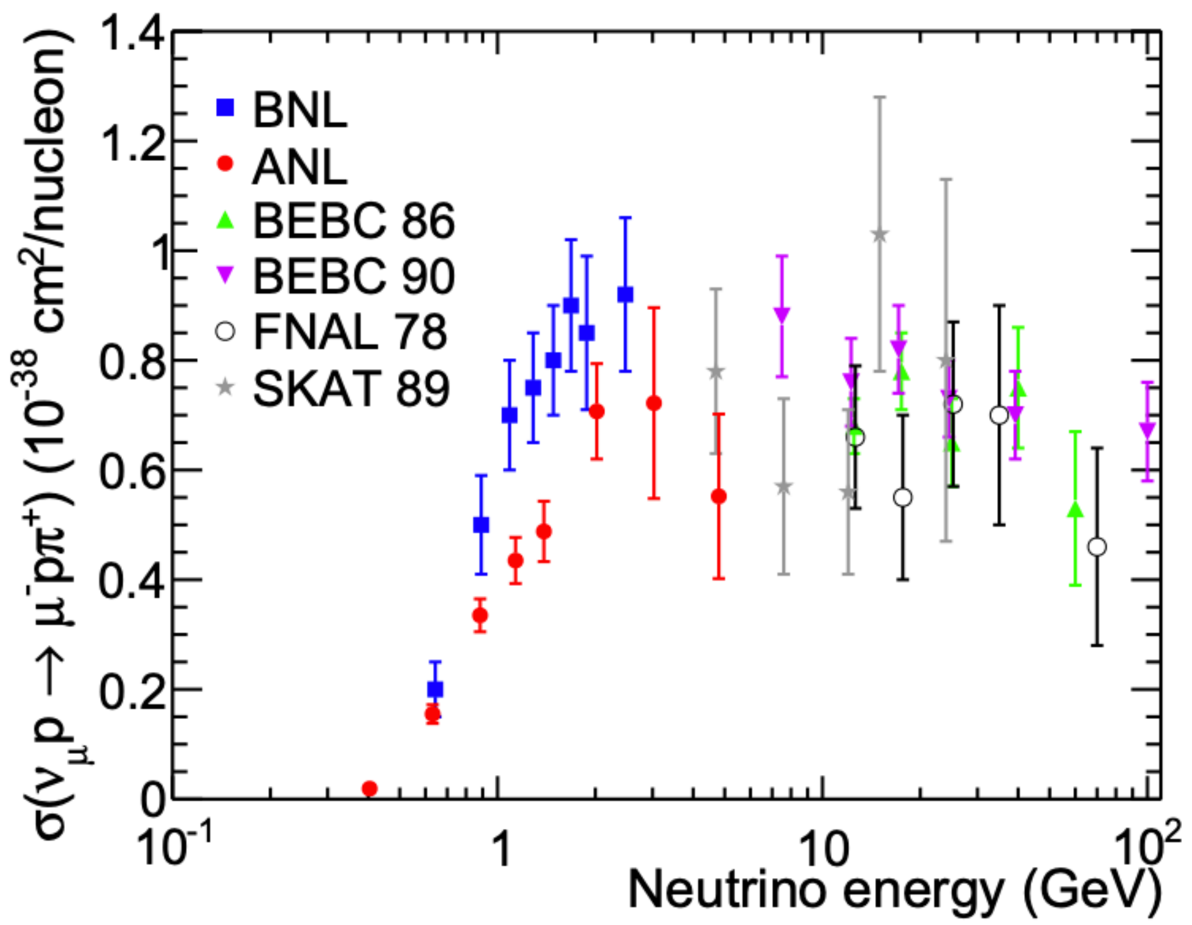
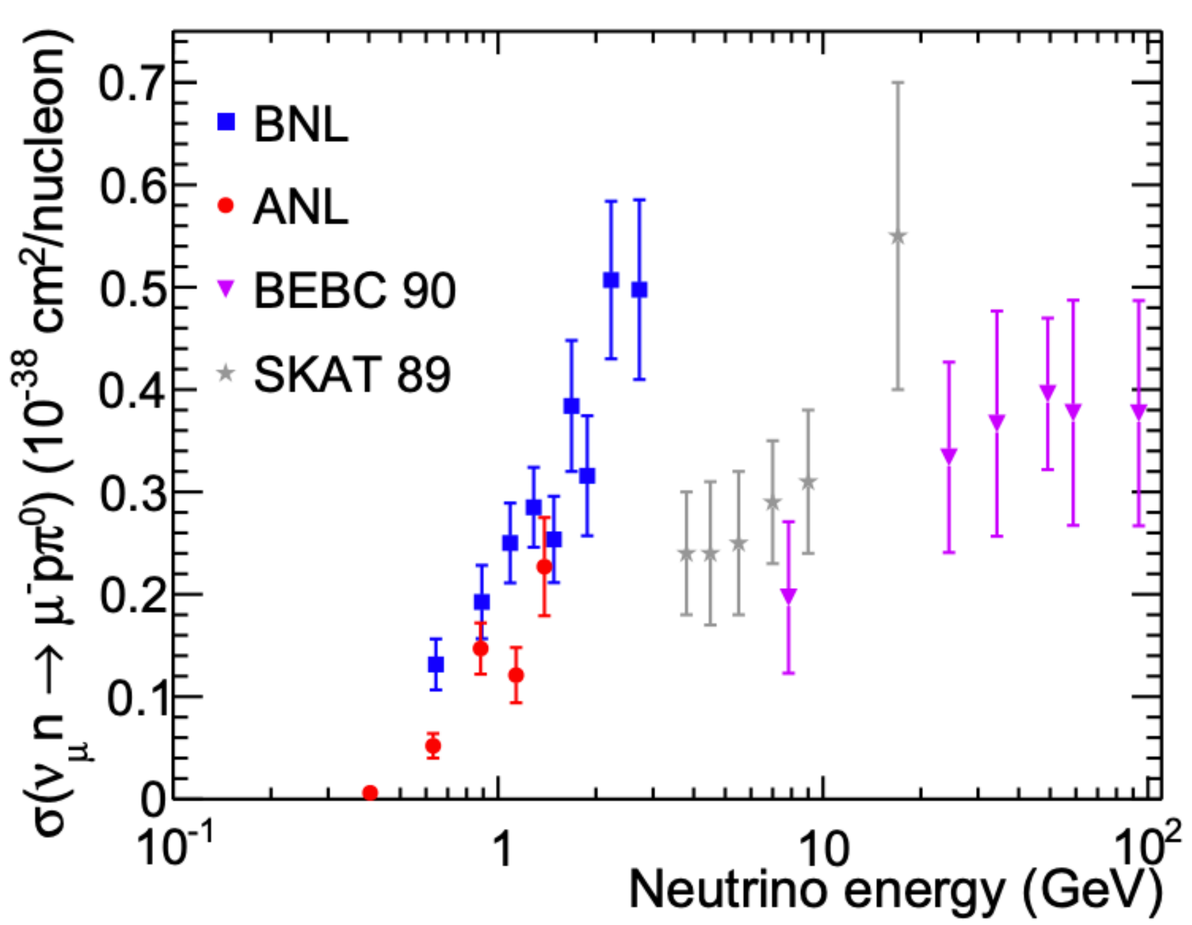
The Neutrino-Nucleus Cross-Section Problem (Part Two)

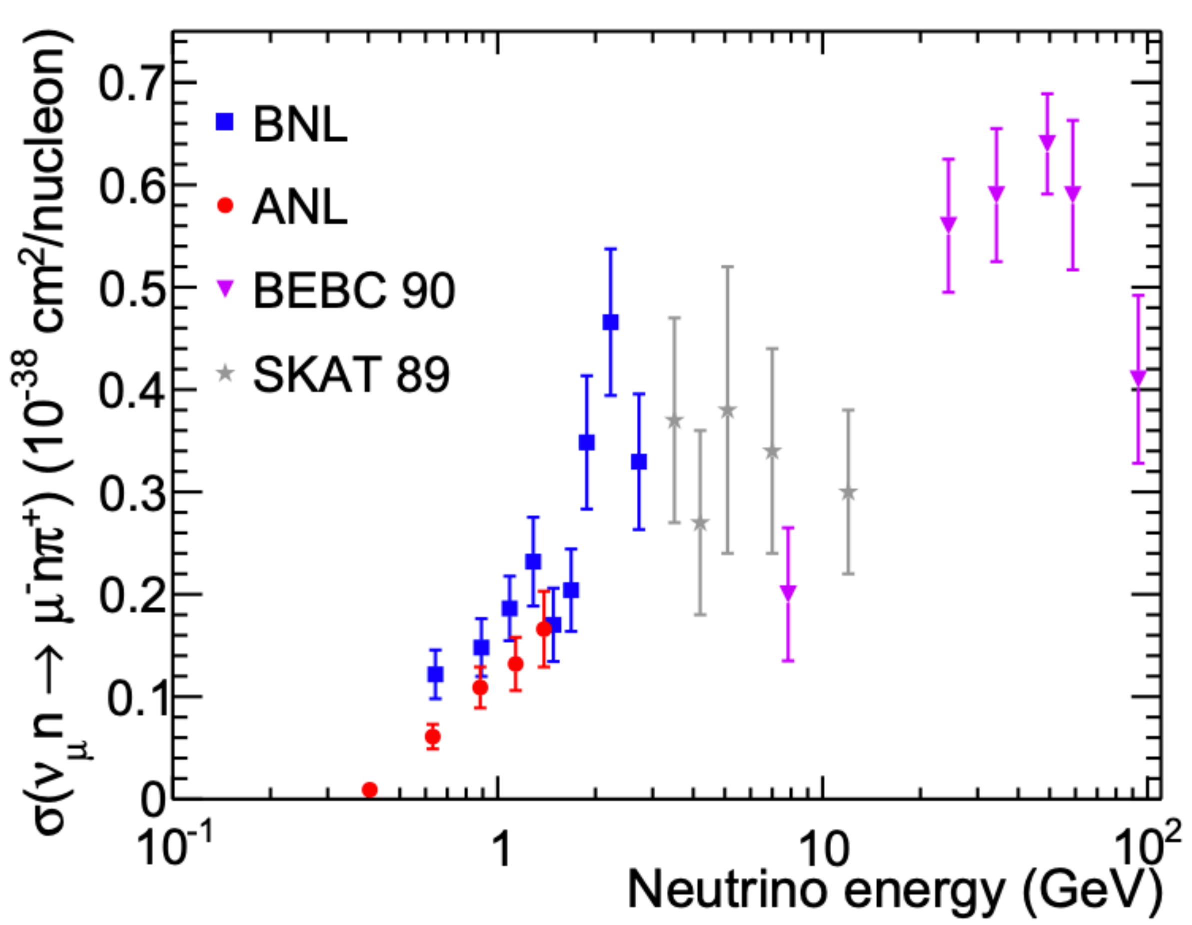
Significant Problems with Old Bubble Chamber Data



$\nu_\mu p \rightarrow \mu^- p\pi^+$



$\nu_\mu n \rightarrow \mu^- p\pi^0$



$\nu_\mu n \rightarrow \mu^- n\pi^+$

BNL Dataset

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

ANL Dataset

arXiv:1411.4482

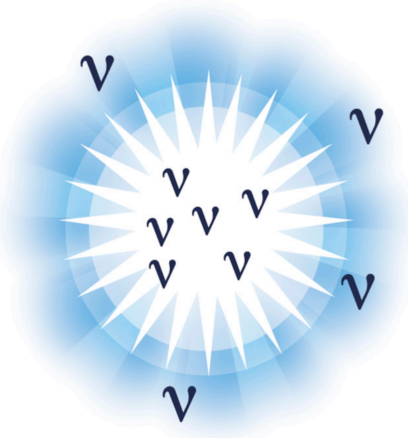
Dataset	Channel	Digitized	Published
Partial	$\nu n \rightarrow \mu^- p$	834.6	833
	$\nu p \rightarrow \mu^- p\pi^+$	395.9	398
	$\nu n \rightarrow \mu^- X^+$	1139.2	1150
	$\nu p \rightarrow \mu^- X^{++}$	453.2	457
Full	$\nu p \rightarrow \mu^- p\pi^+$	843.2	871

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

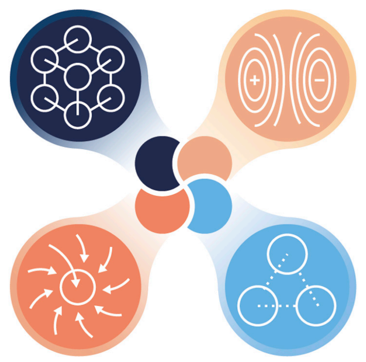
Generator predications based on these data have low exclusionary power at DUNE/Hyper-K precision.

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?)

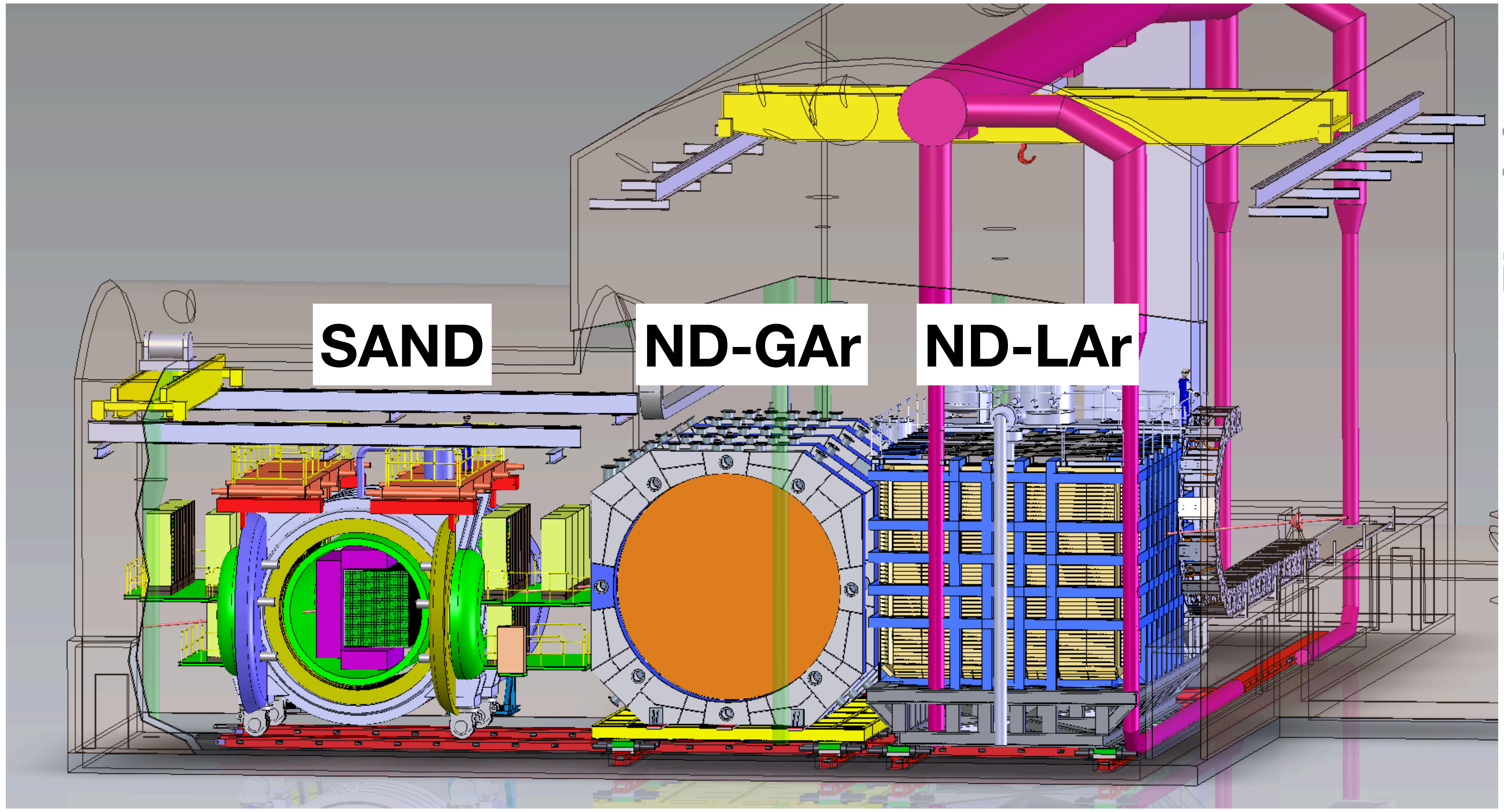


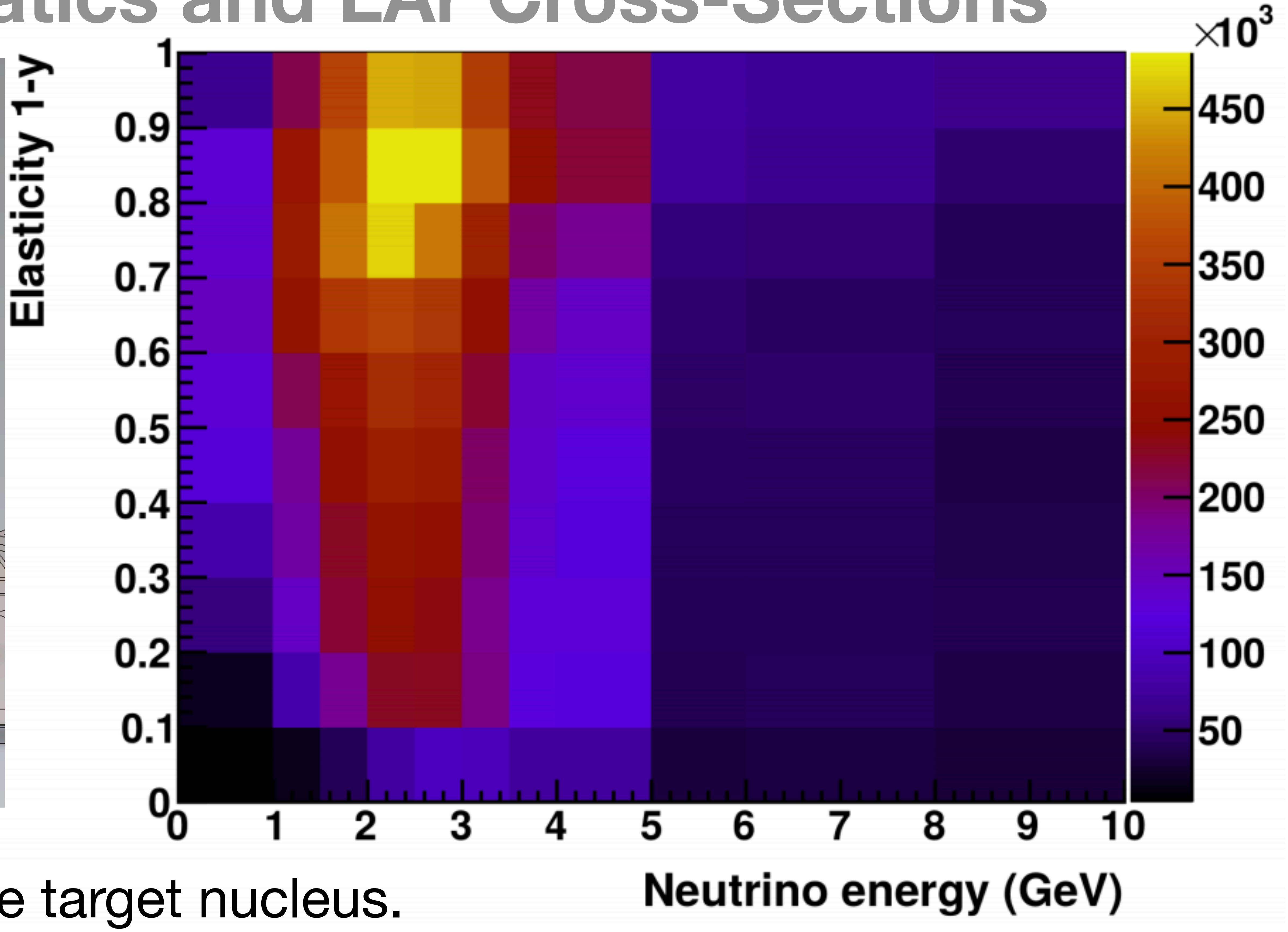
- Proton Decay (GUT?)

- 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.

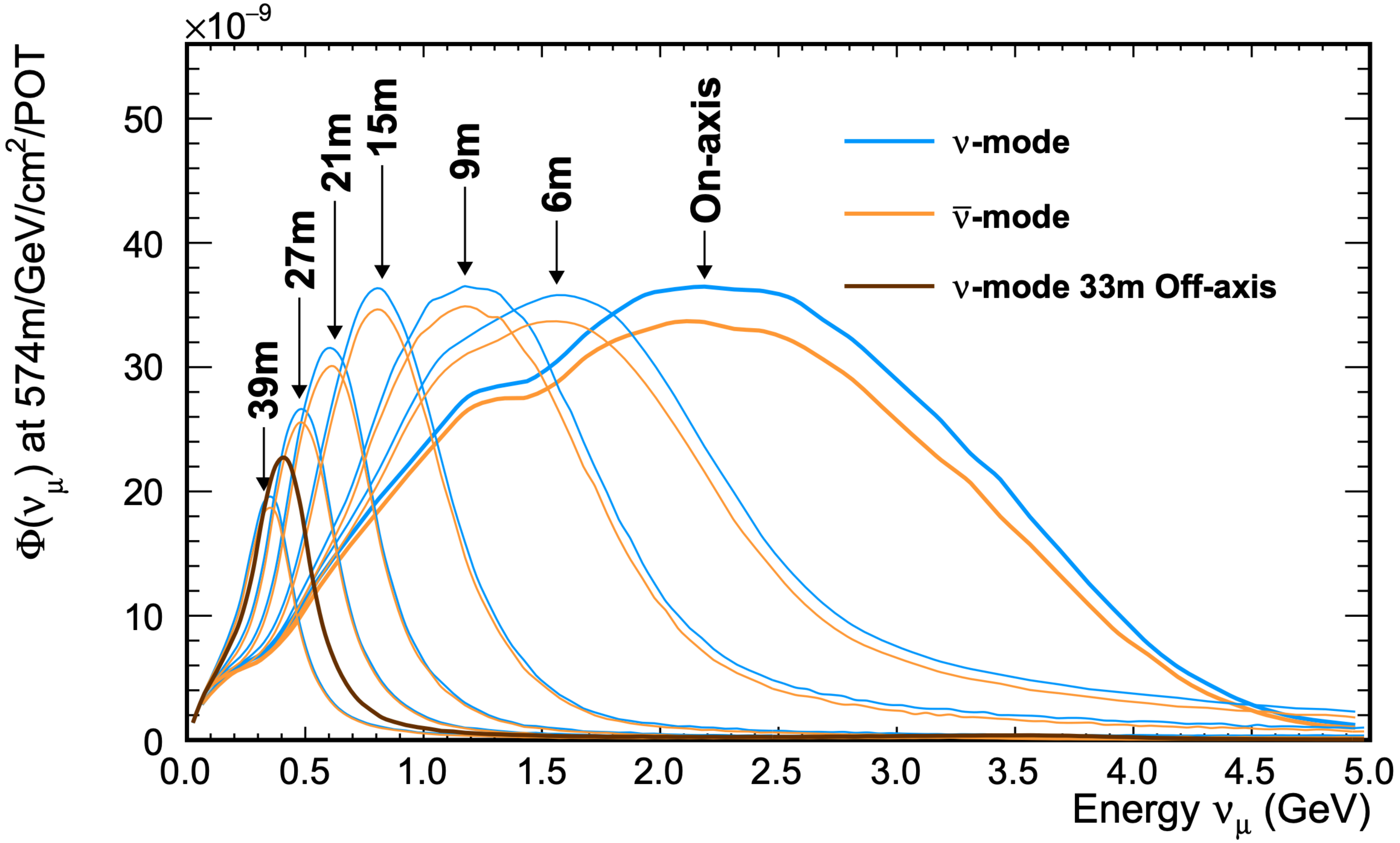
ND-GAr gives charge separation and some analysis of secondary interactions with the same target nucleus.

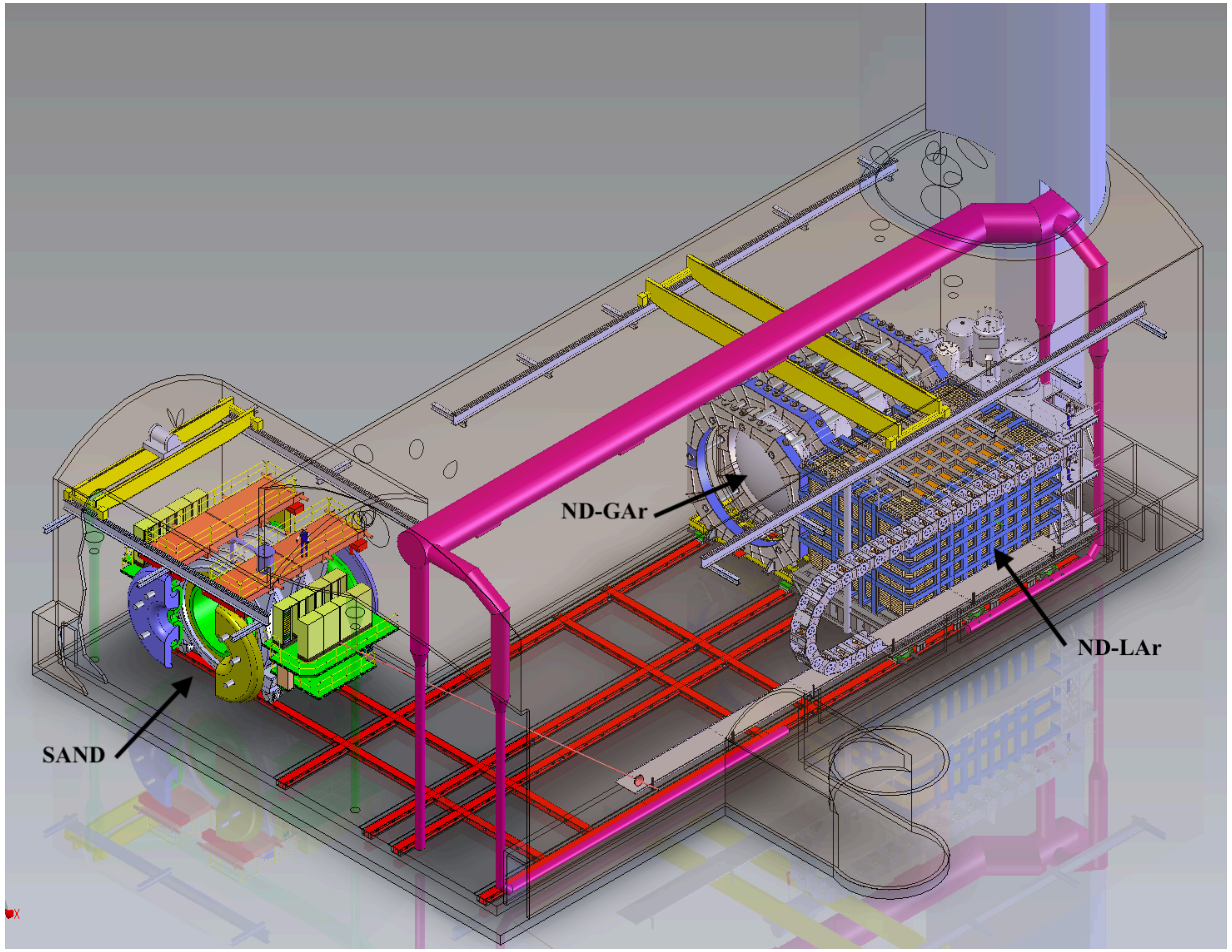
System for on-Axis Neutrino Detection (SAND) serves as always on beam monitoring system with CH

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

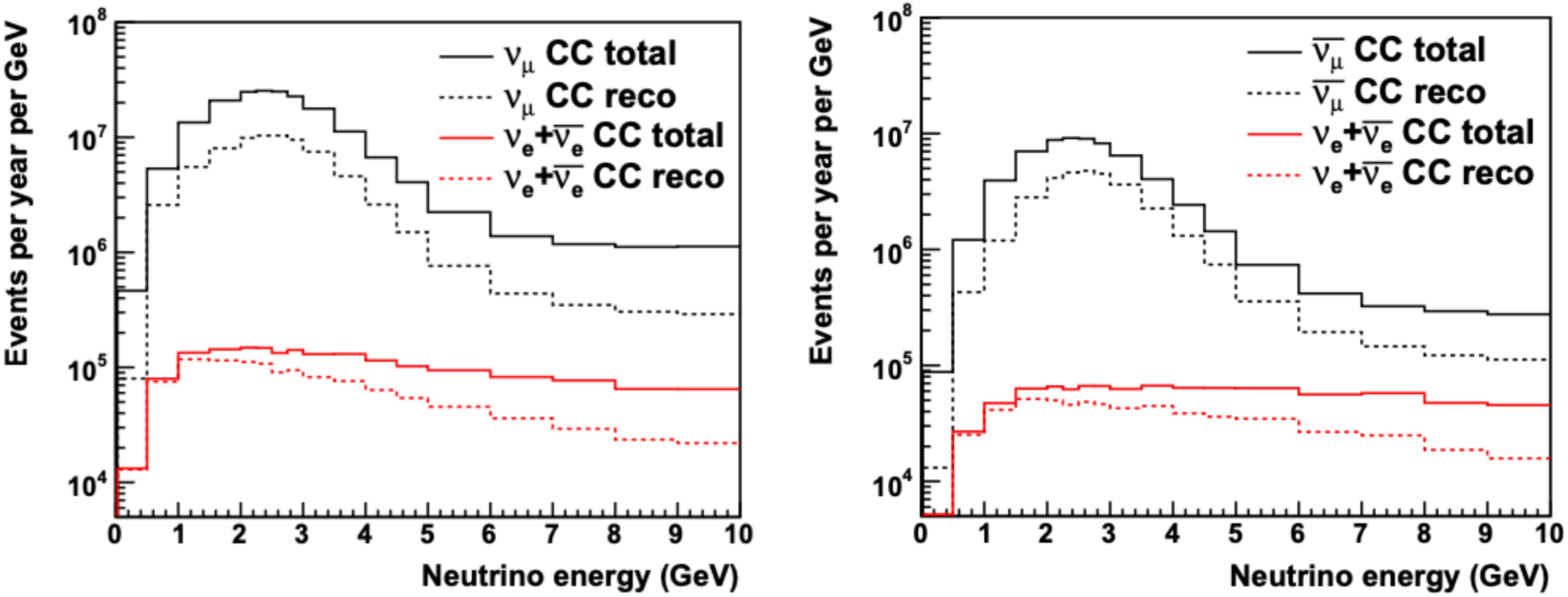
Will constrain beam flux shape and normalization to ~1%!

Phase 2 includes intensity upgrade to higher intensity!

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!).

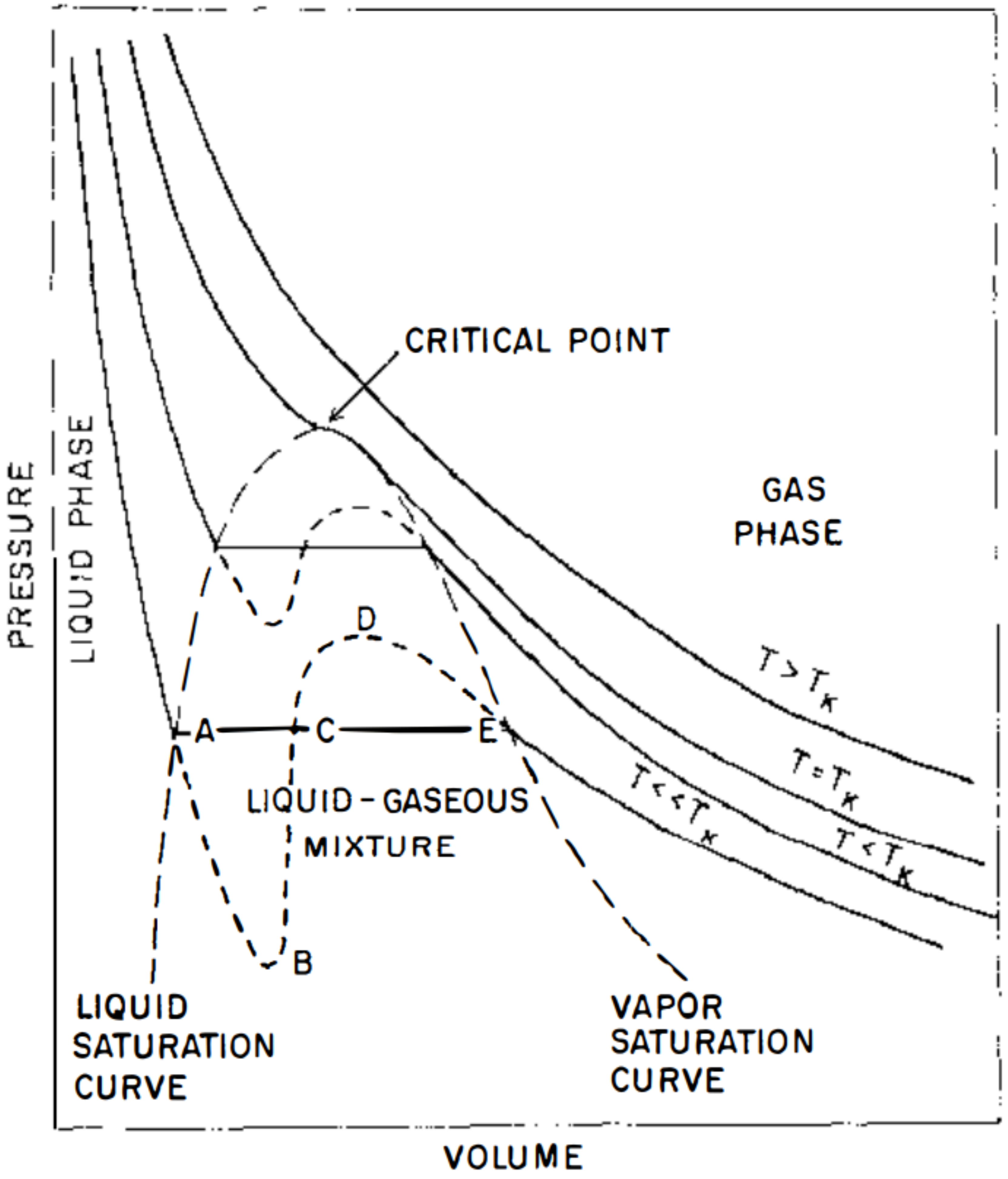
The Fermilab 15' bubble chamber had an estimated 2 tons of hydrogen.

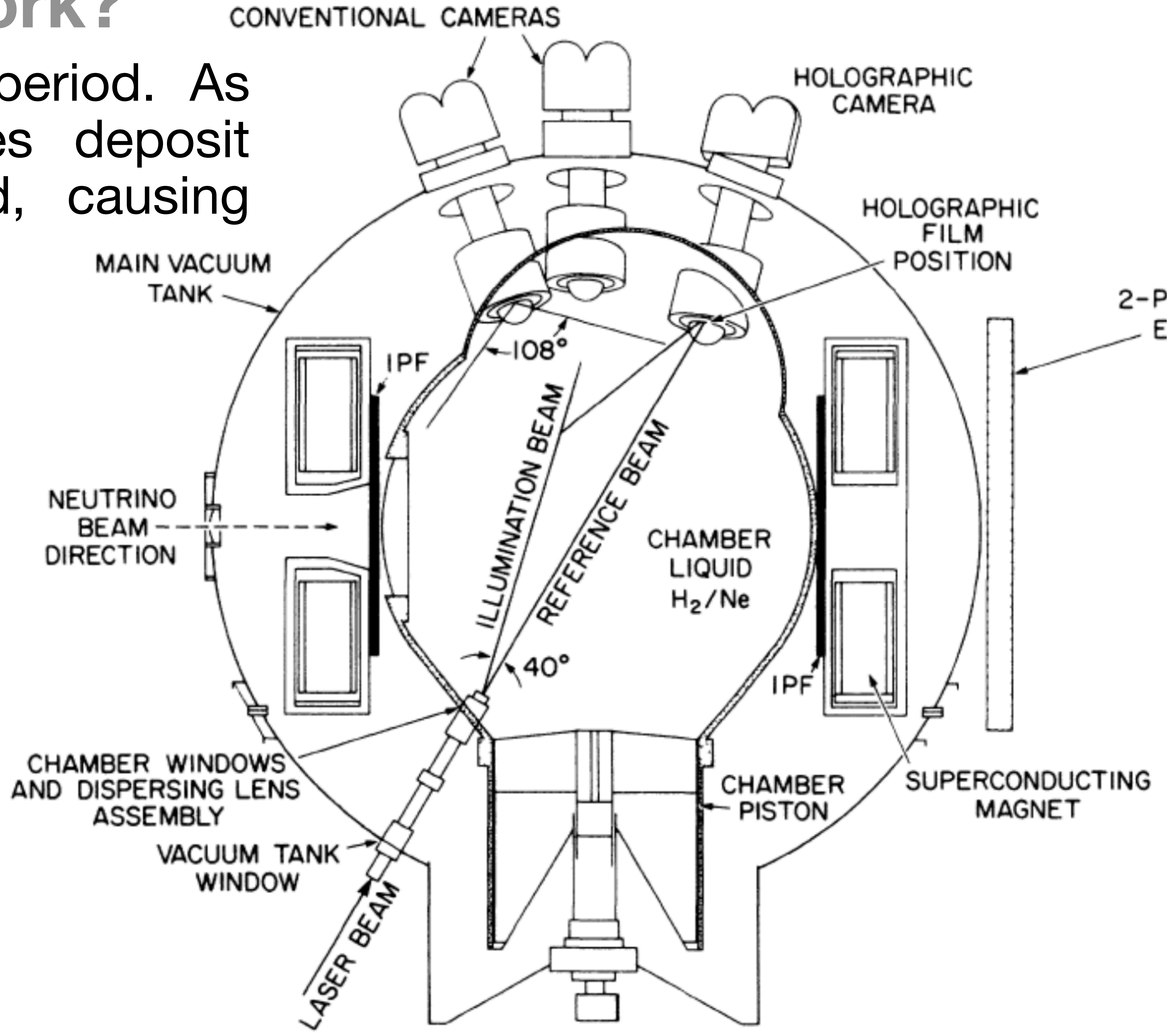
We should build a ~5L prototype!

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.



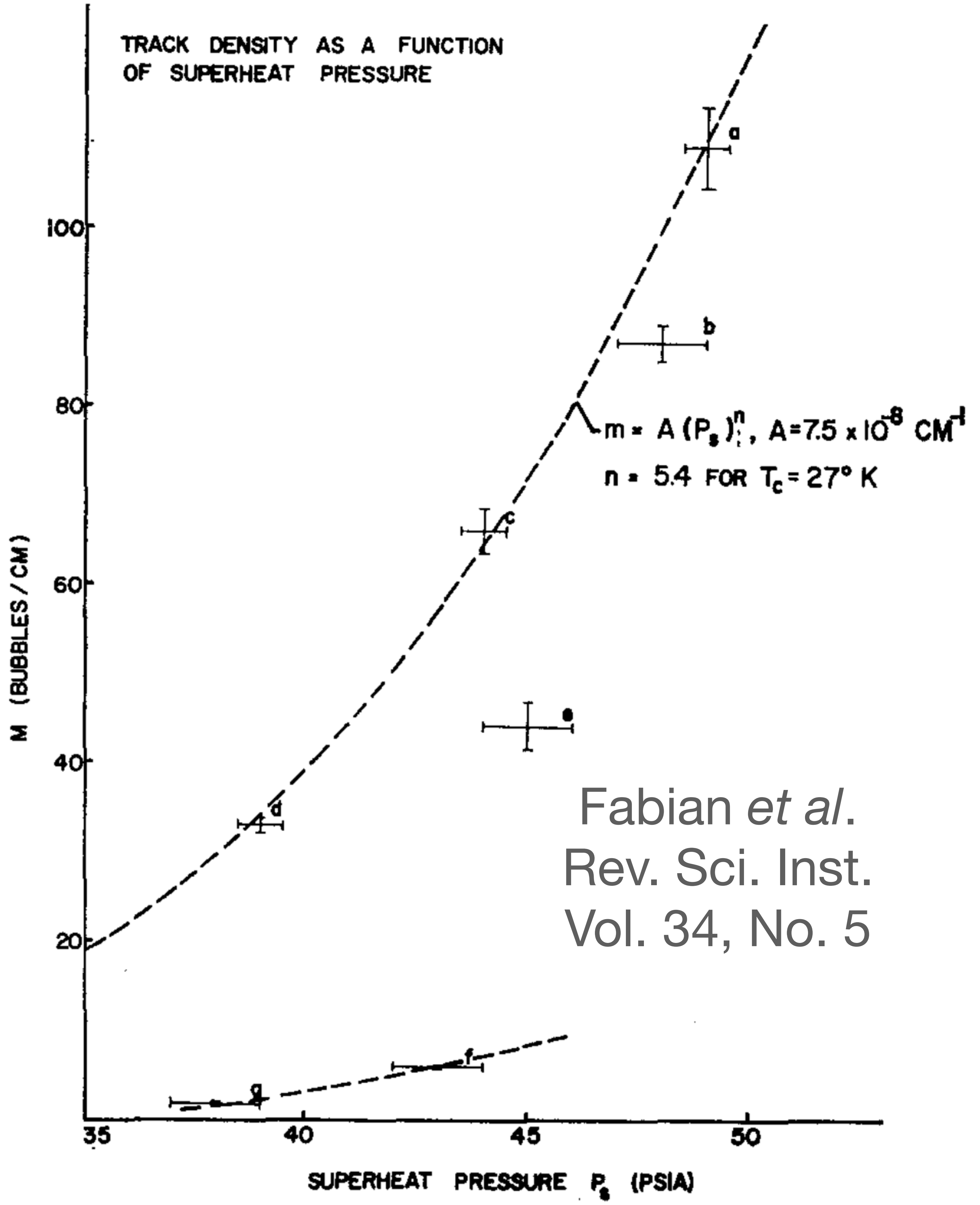


Event selection of analog pictures done *by eye* in the 60s-90s.

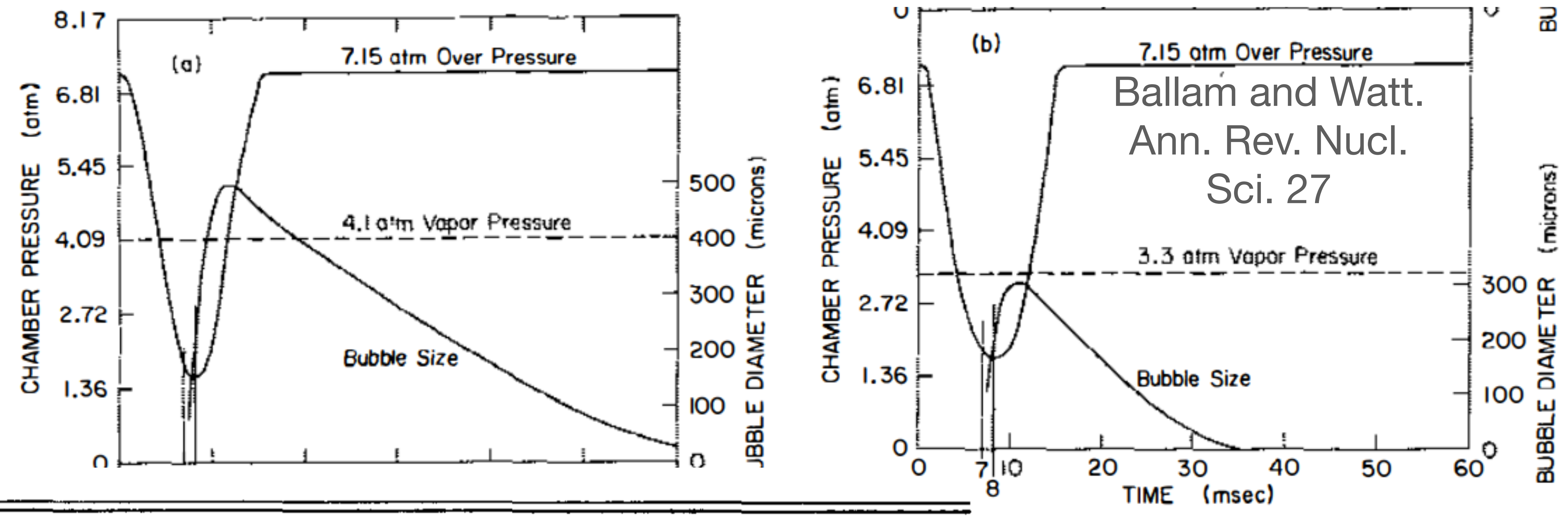
Bubble Microphysics

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

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

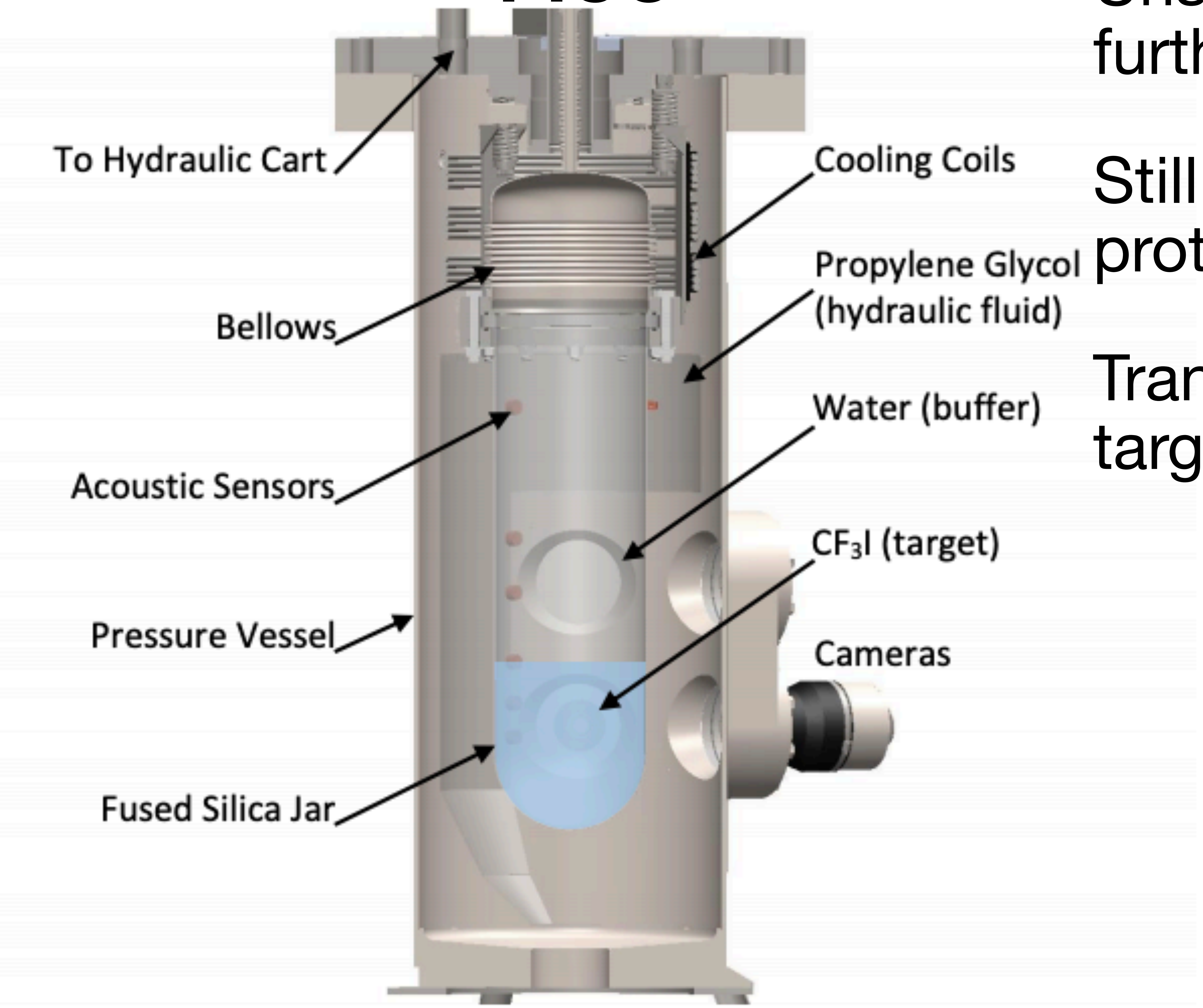
Older experiments used bubble density as a way to measure energy deposition in the medium.

The Current Generation of Chambers (Part One)

Updates to Bubble Chamber Technology!

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

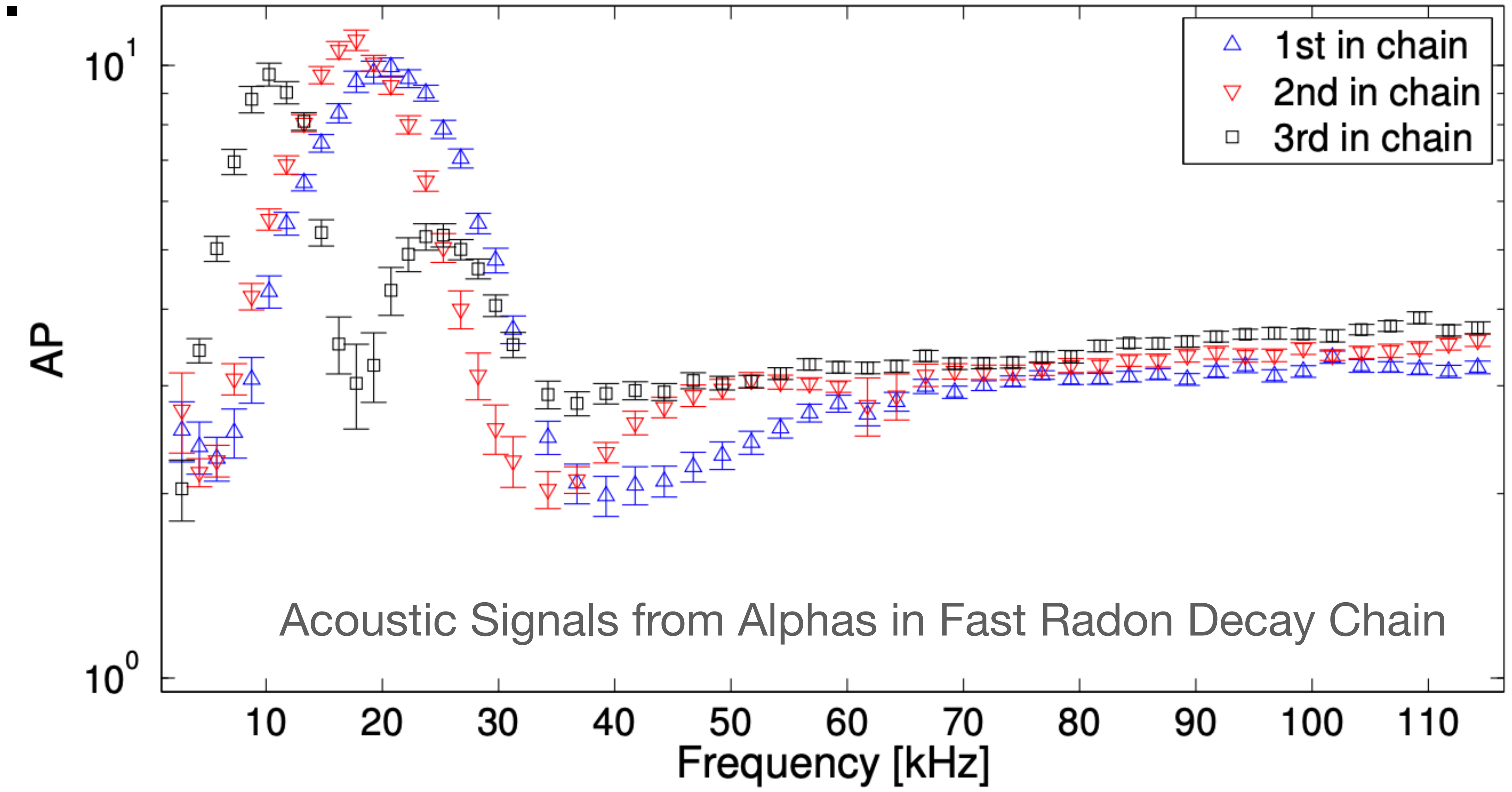
PICO



Unsuitable for cross sections measurements without further development (different operational regime).

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

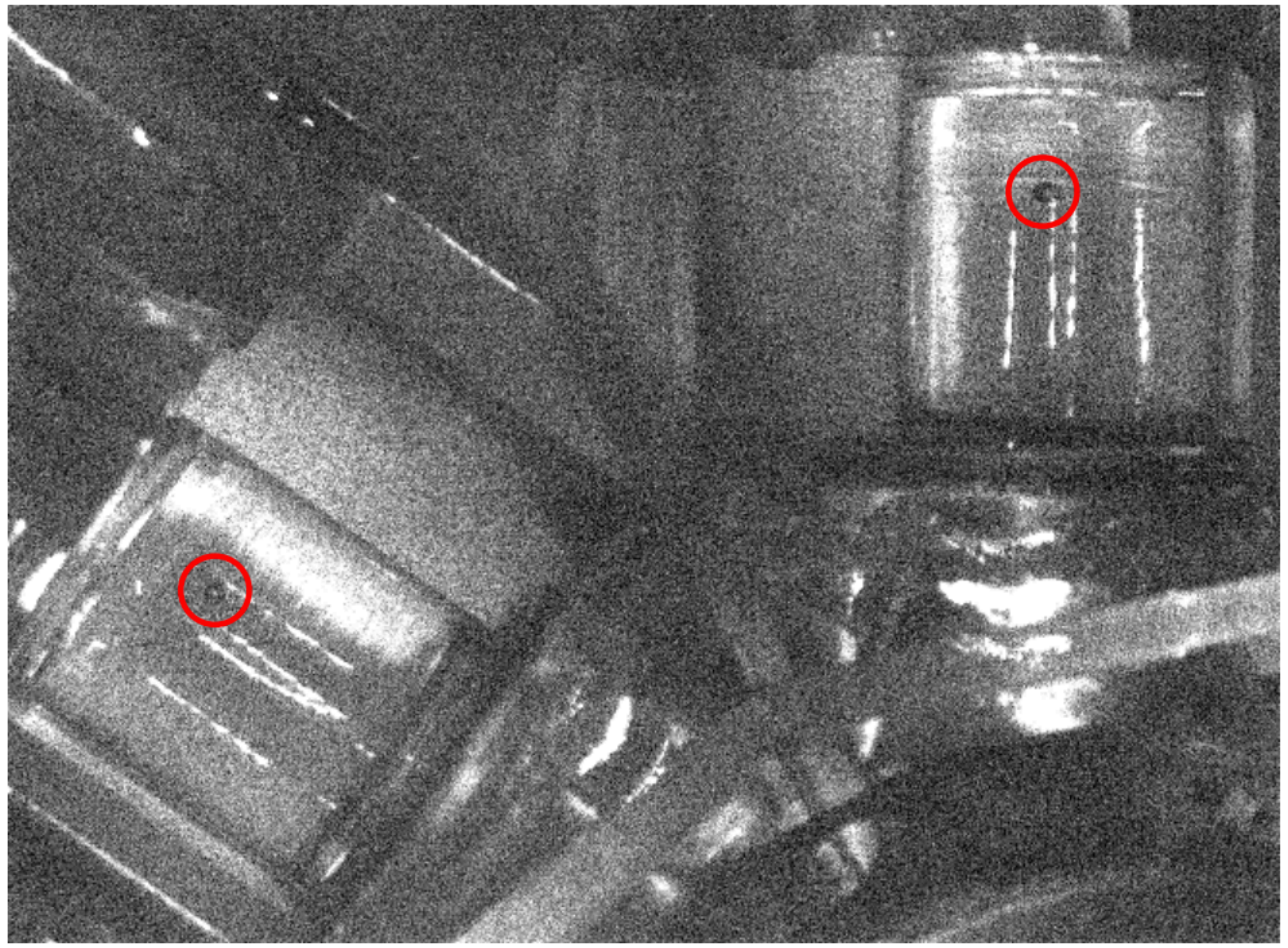
Transparent silica glass jar for containment of liquid target.

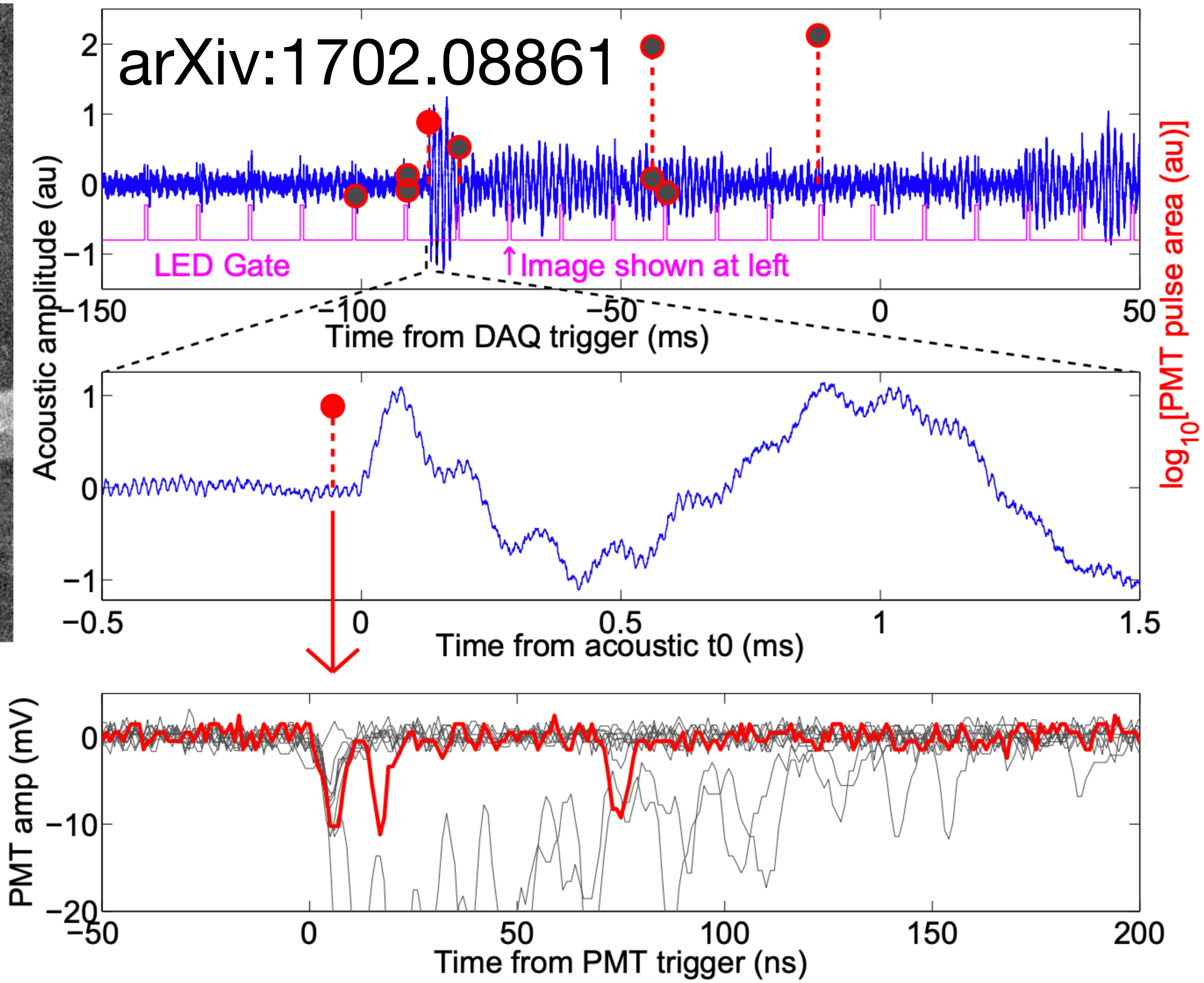


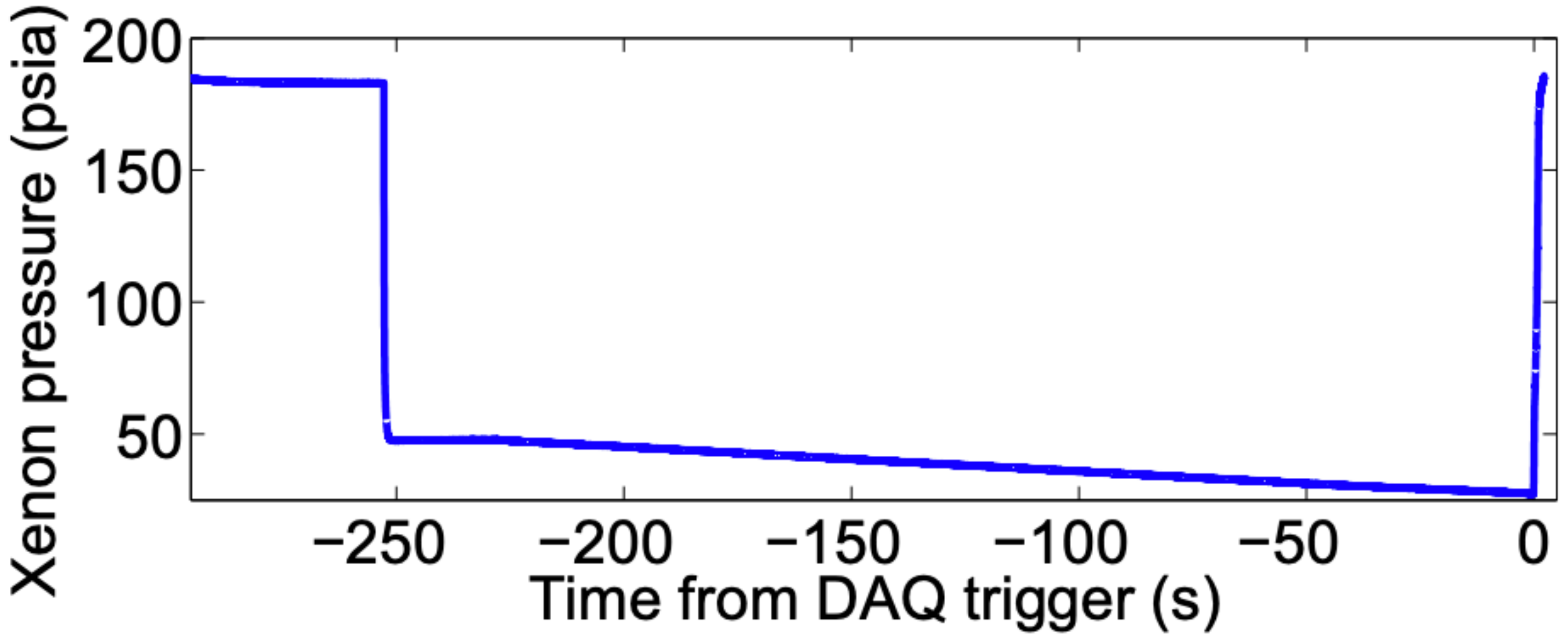
The Current Generation of Chambers (Part Two)

Updates to Bubble Chamber Technology!

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



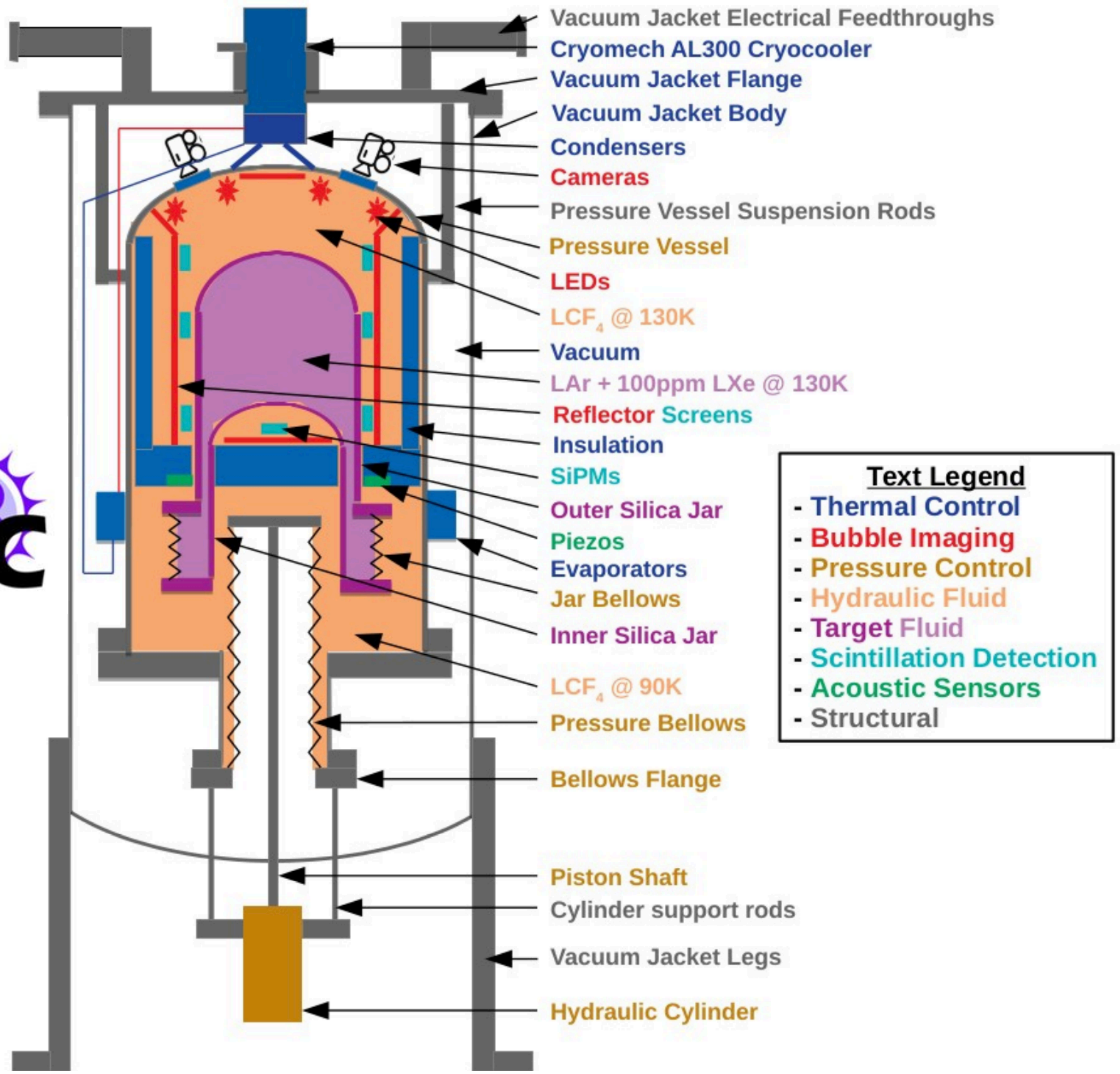




Scintillating Bubble Chamber (SBC) 30g prototype with xenon shows acoustic modeling and scintillation photon counters!

The Current Generation of Chambers (Part Three)

The Scintillating Bubble Chamber (SBC)!



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

"Clean" style inner jar in pressure vessel

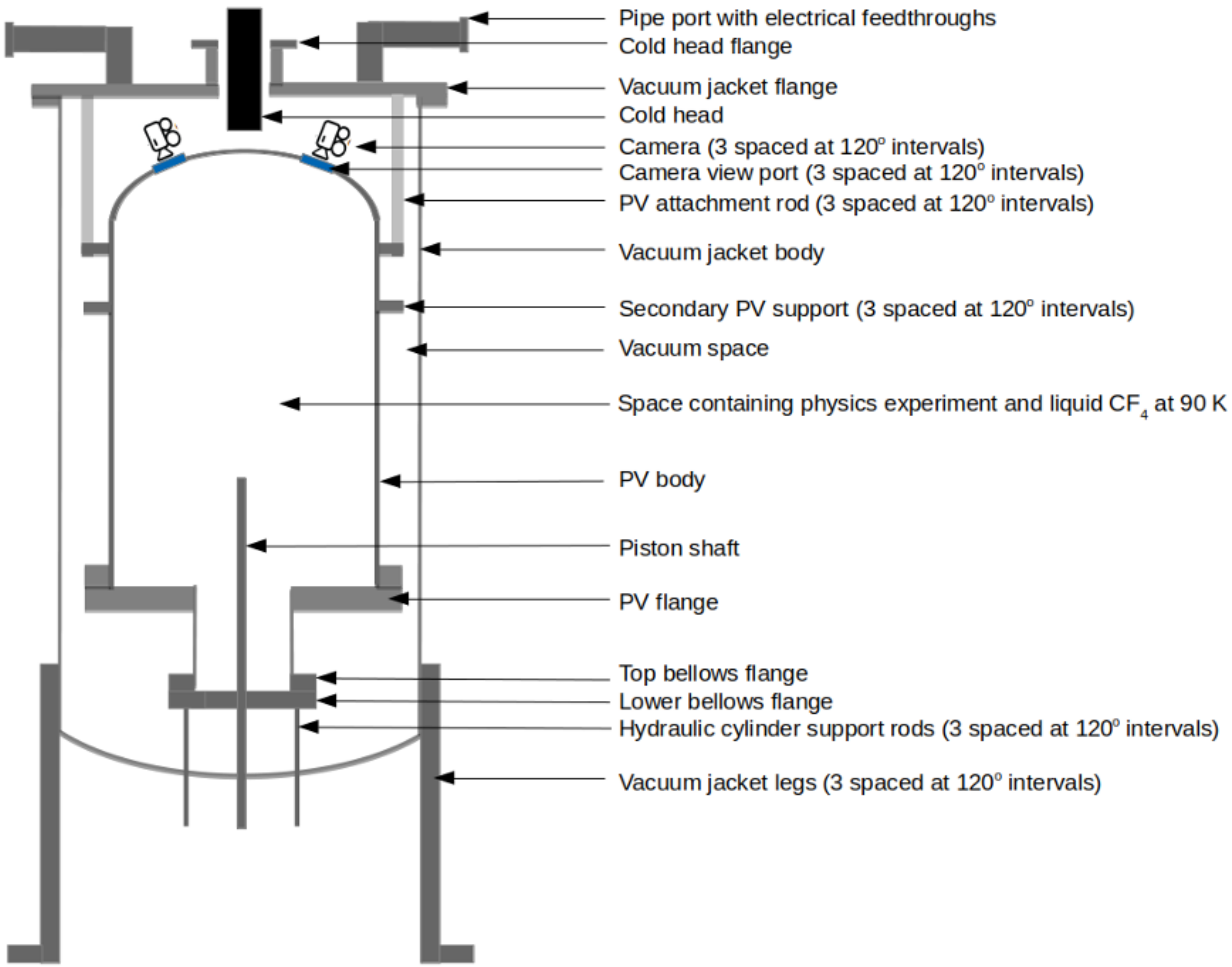
Refrigerator integrated into flange and attached to pressure vessel along with cameras.

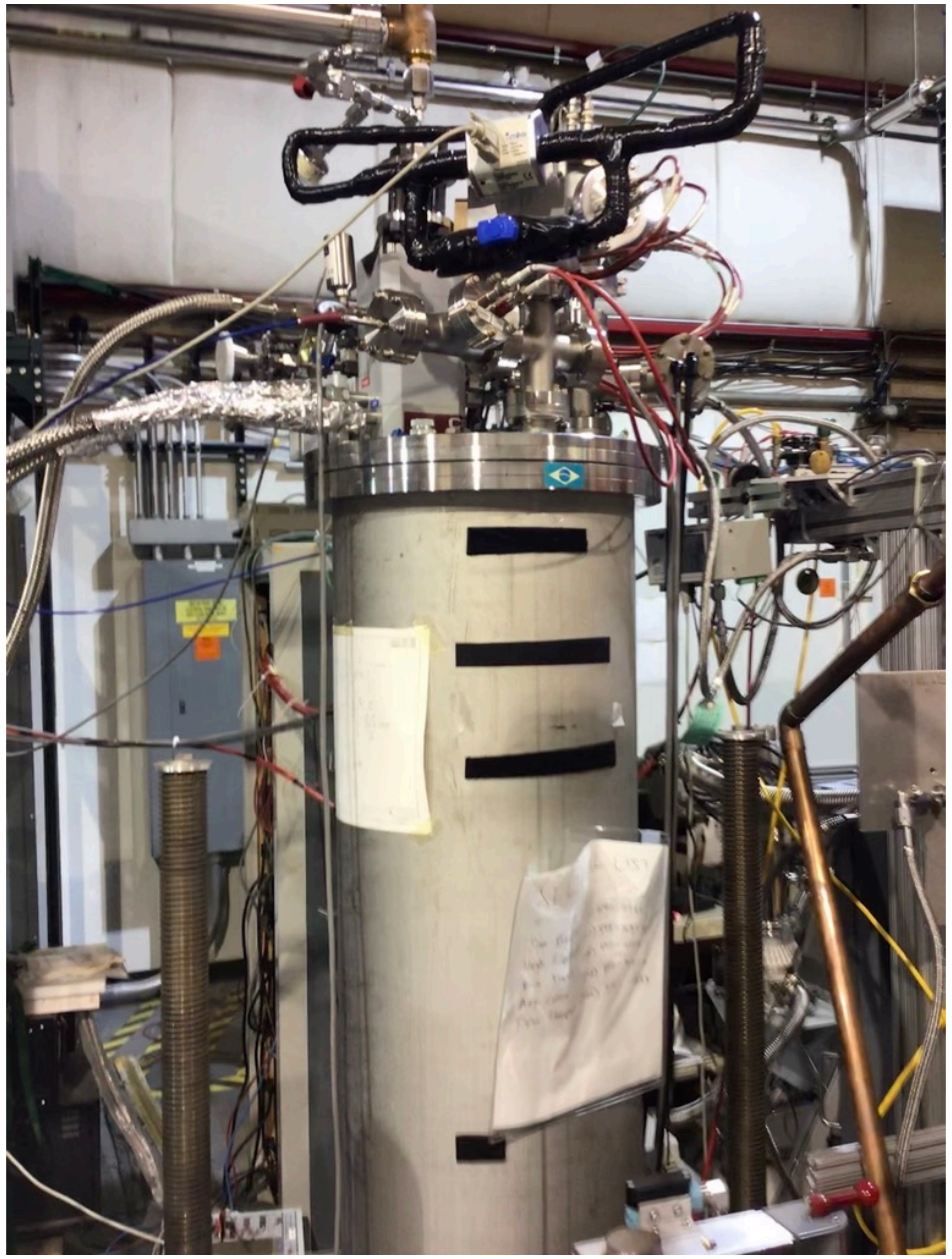
Hydraulic cylinder attached to pressure vessel and a carbon flouride hydraulic fluid is used to offset the temperature gradient.

Achievable live times ~1 hour.

Plan for building a MMBC prototype

Updates to “Dirty” Bubble Chamber Technology!





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

Objectives for Building a MMBC

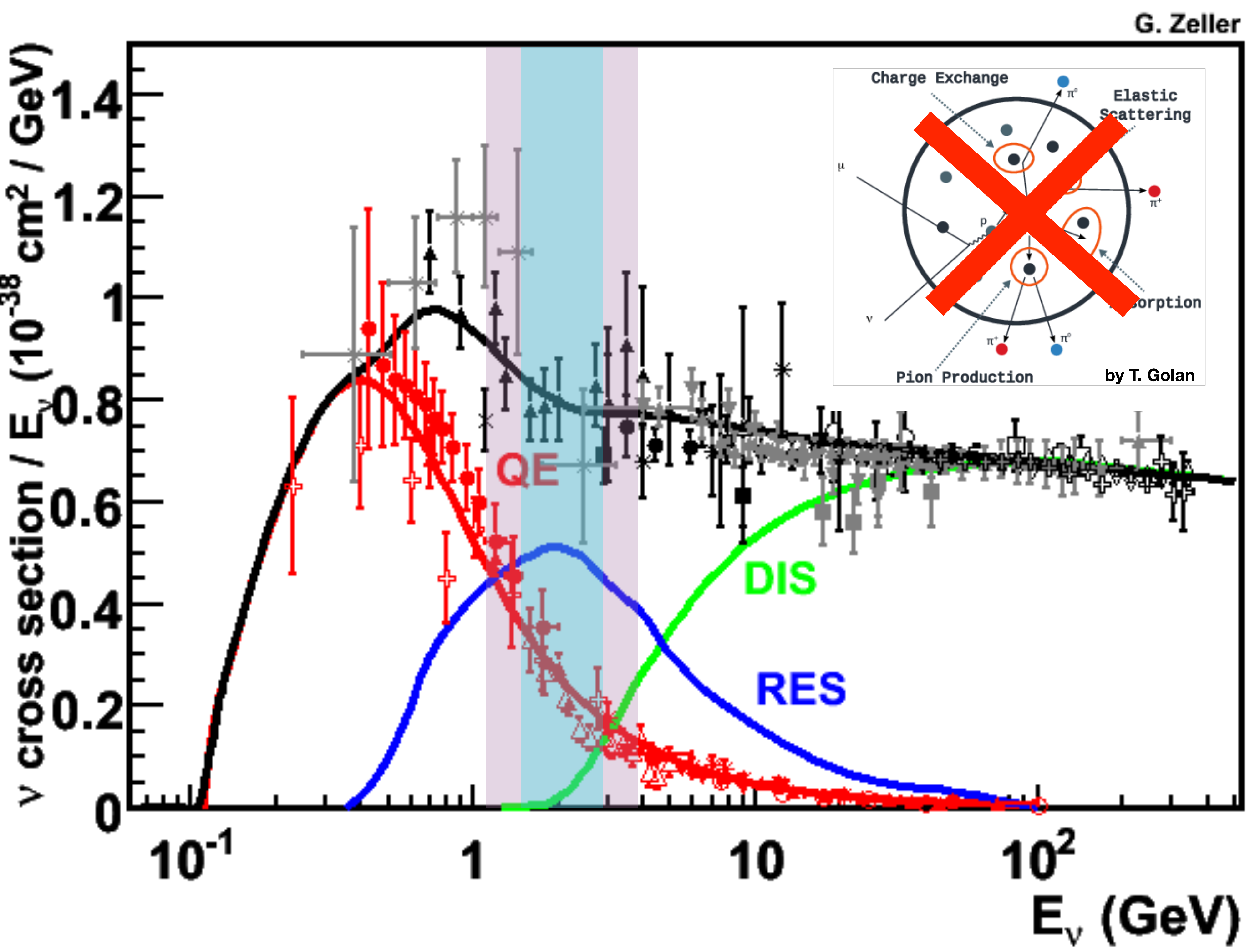
Current goals of the newly funded project!

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.

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(10^8) from ND-LAr/ND-GAr.

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

A boon to neutrino physics!

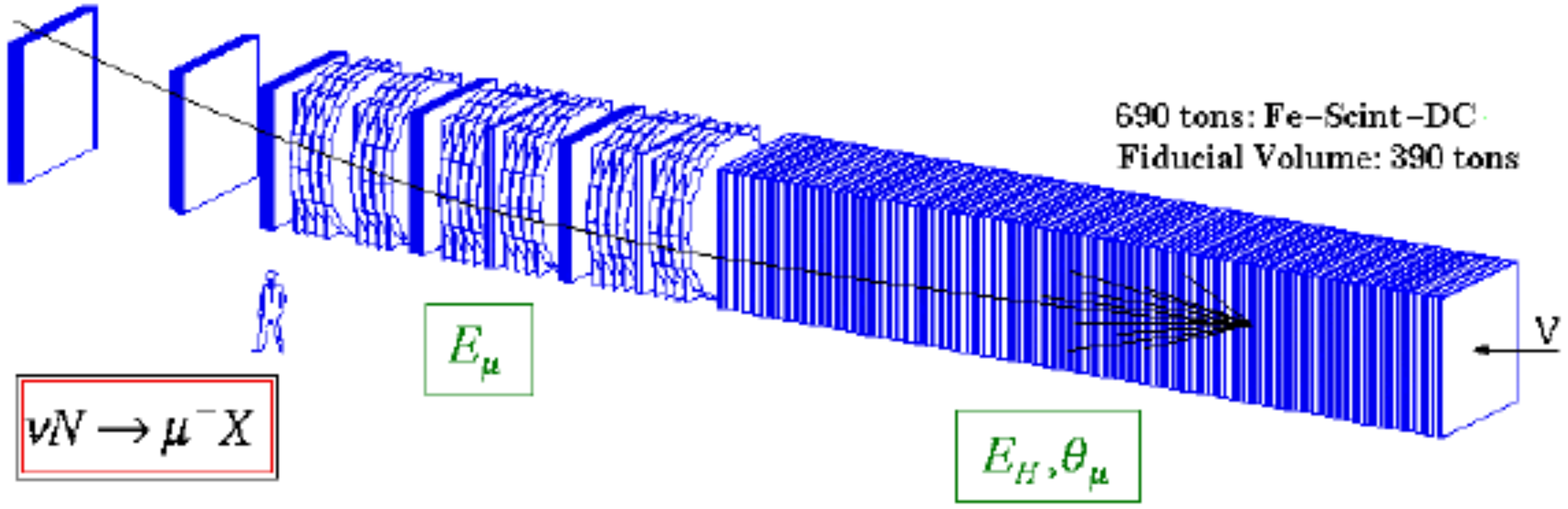
The NuTeV Experiment: Precision Electroweak Pioneer

A highly precise direct measurement of the weak mixing angle!

Neutrino DIS has clean access to the Weinberg angle through the Paschos-Wolfenstein ratio!

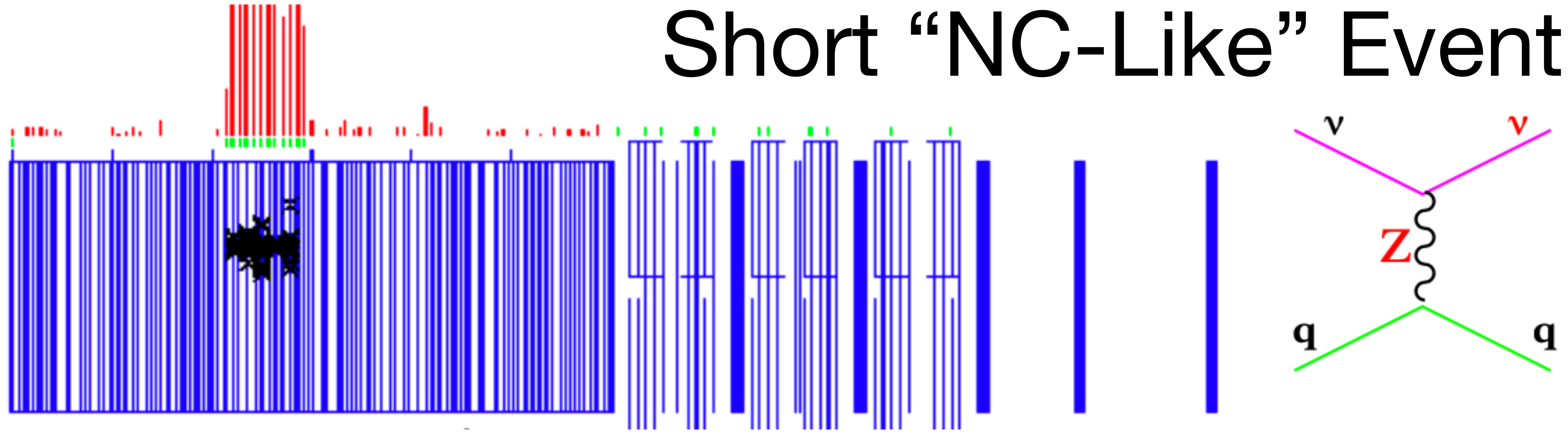
$$R^{-} \equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\overline{\nu}_\mu N \to \overline{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\overline{\nu}_\mu N \to \mu^+ X)} = \frac{1}{2} - \sin^2\theta_W = 1 - \frac{{M_W}^2}{{M_Z}^2}$$

NuTeV Experiment measured the Paschos-Wolfenstein ratio on Fe through a comparison of "long" and "short" events, found a $\sim 3\sigma$ offset from the standard model!

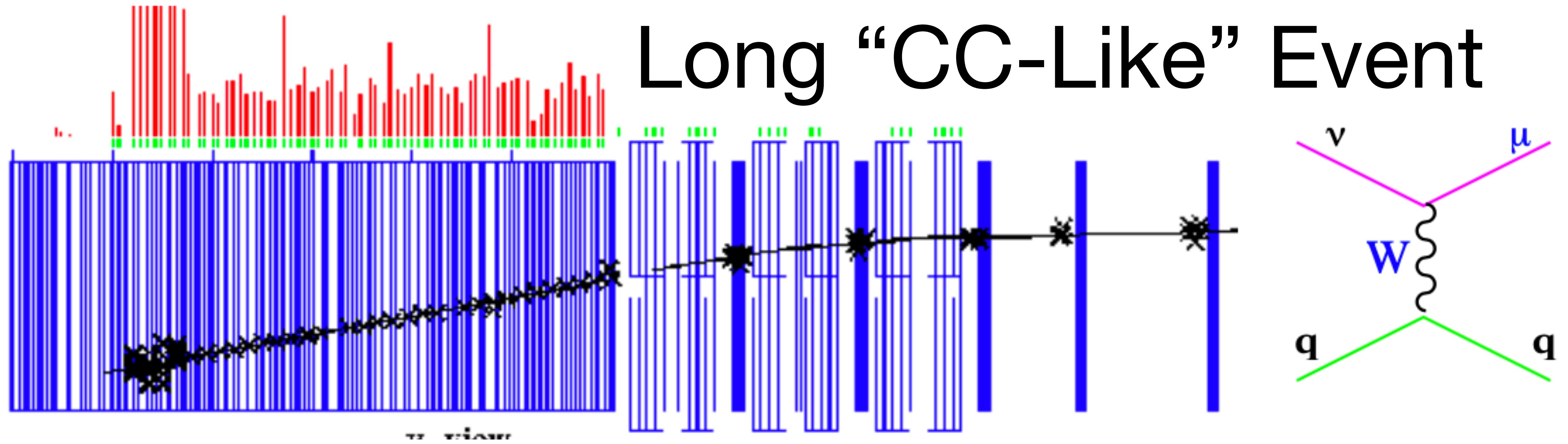


(G. Zeller, Thesis, 2002)

Short "NC-Like" Event



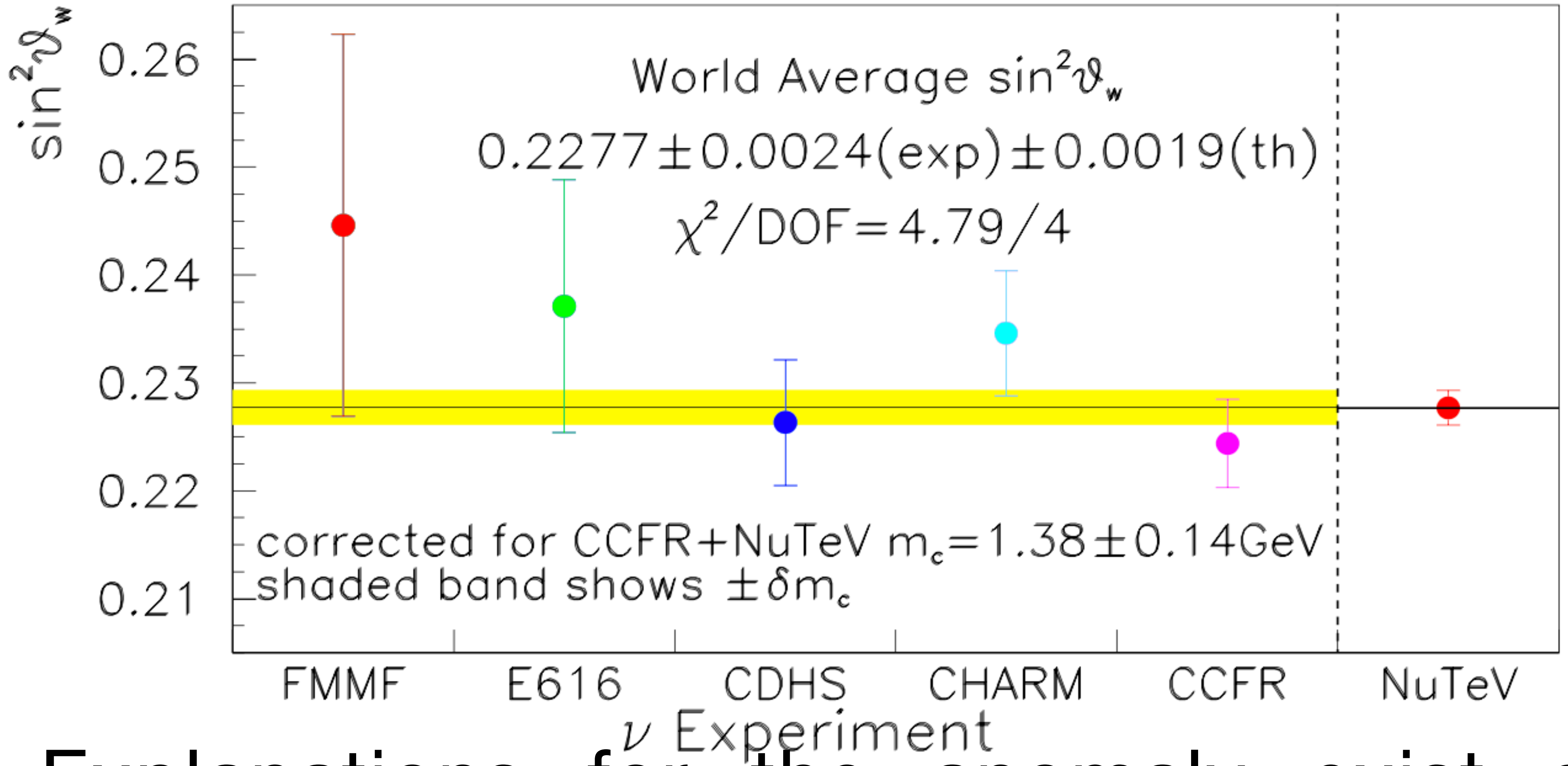
Long "CC-Like" Event



The NuTeV Anomaly *in Context*

New and Complementary Physics?

(G. Zeller, Thesis, 2002)



Broad strokes on experiment highlights:

High energy events, 20 GeV<E_{vis}<180 GeV from 800 GeV Tevatron Beam.

Measurement was **~1.62 million CC** and **~351 thousand NC** events.

Two largest corrections are mis-ID of CC/NC events (30%) and beam contamination by ν_e (10%)

Explanations for the anomaly exist and they have implications for PVDIS (arXiv:0908.3198v3):

Nuclear Effects - Excess neutrons in the experiment steel contribute nuclear modifications on the order of 1σ.

Charge Symmetry Violation - Mass difference of u/d disturbs charge symmetry assumption and QED splitting on the order of 1σ.

Asymmetry in Strangeness - Dearth of measurements with strangeness, unknown if s and anti-s have similar contributions, on the order of 1σ

The NuTeV Anomaly *in Present Context*

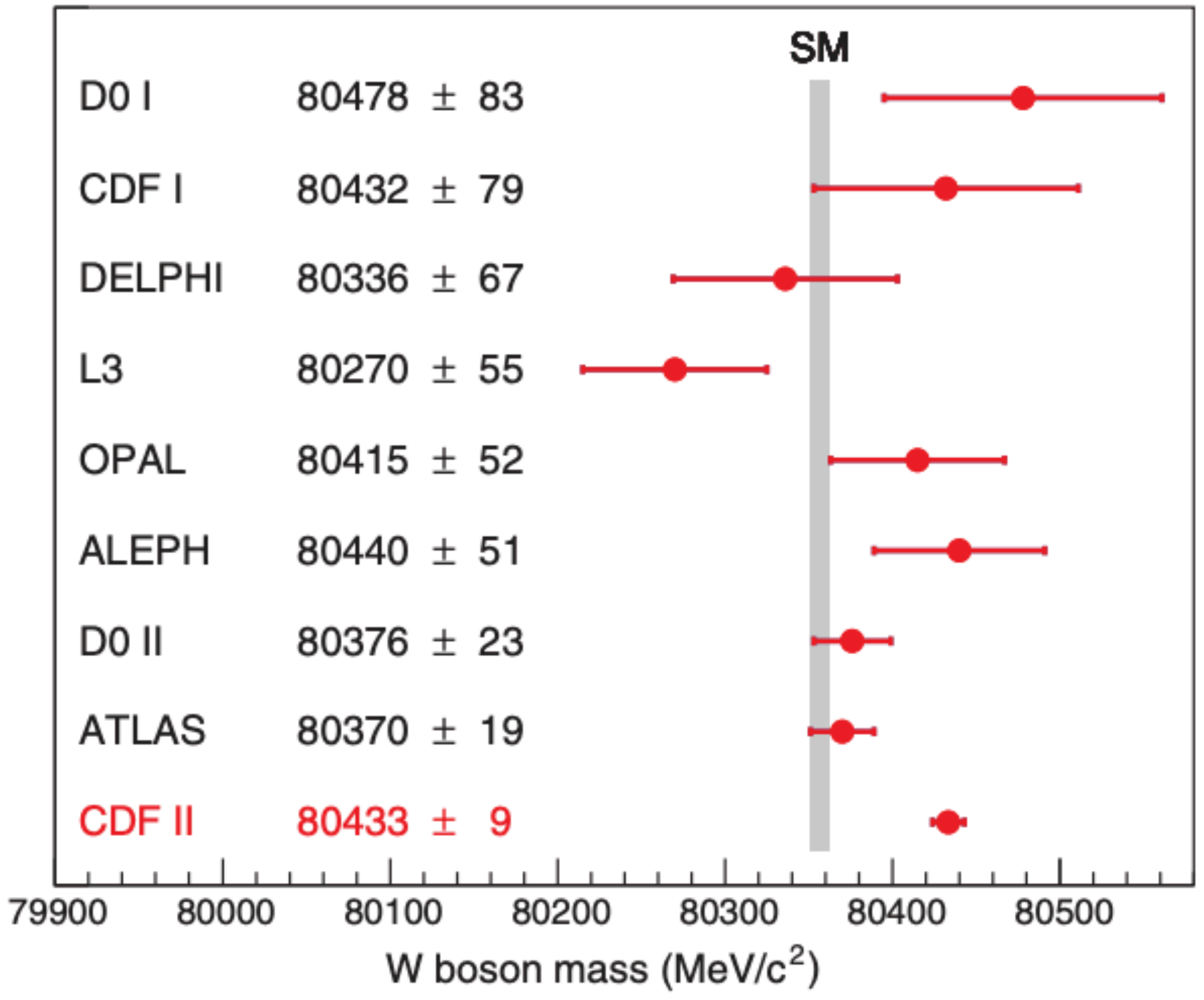
Recent Interest in the NuTeV Anomaly with New Measurements of W-Mass!

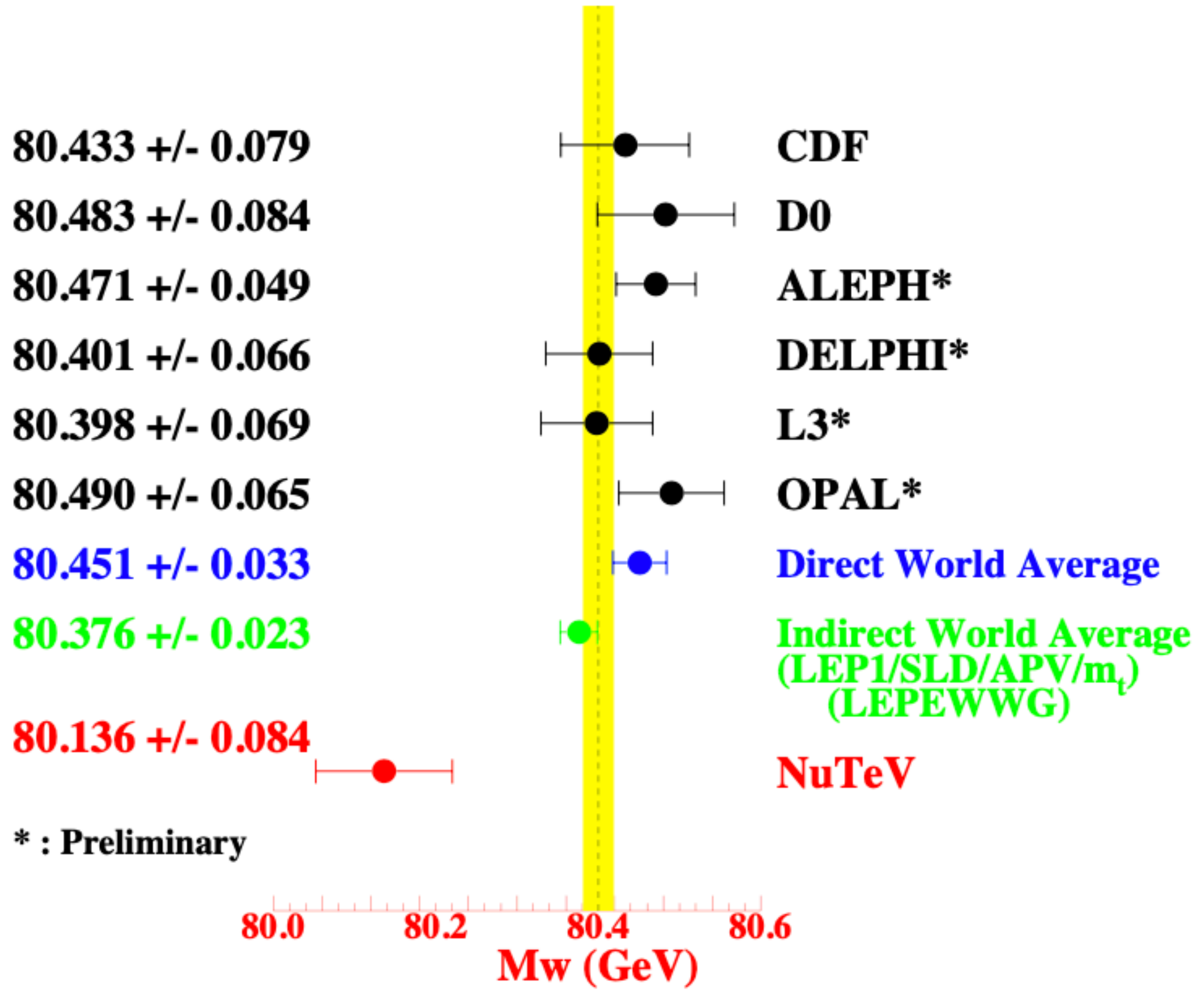
NuTeV measurement also gives an indirect measurement of the W-Mass by fixing the mass of the Z.

Recent measurement of W-Mass by CDF II drives new interest in NuTeV experiment: is there new physics hiding in the W to which neutrinos might *also* be sensitive?

Investigating W-mass measurement, allows us to update the measurement and address all three of the previous issues. **Strangeness and CSV also affect PVDIS.**

(CDF Collaboration, 2022)





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 an increase in precision.

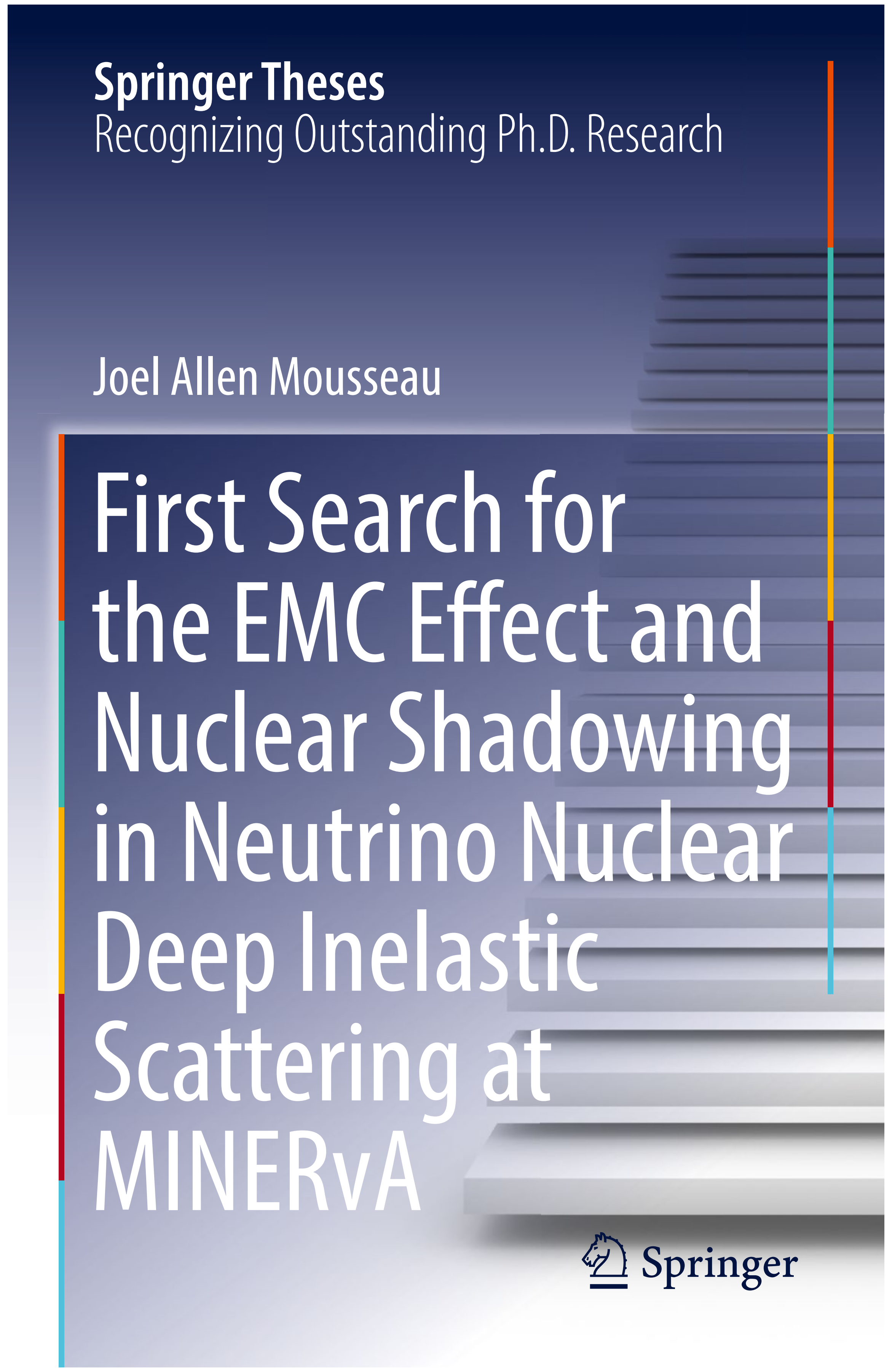
A bubble chamber physics program is robust, novel, and complementary to measurements in nuclear physics, including measurements made at JLab, the EIC, and the Forward Physics Facility.

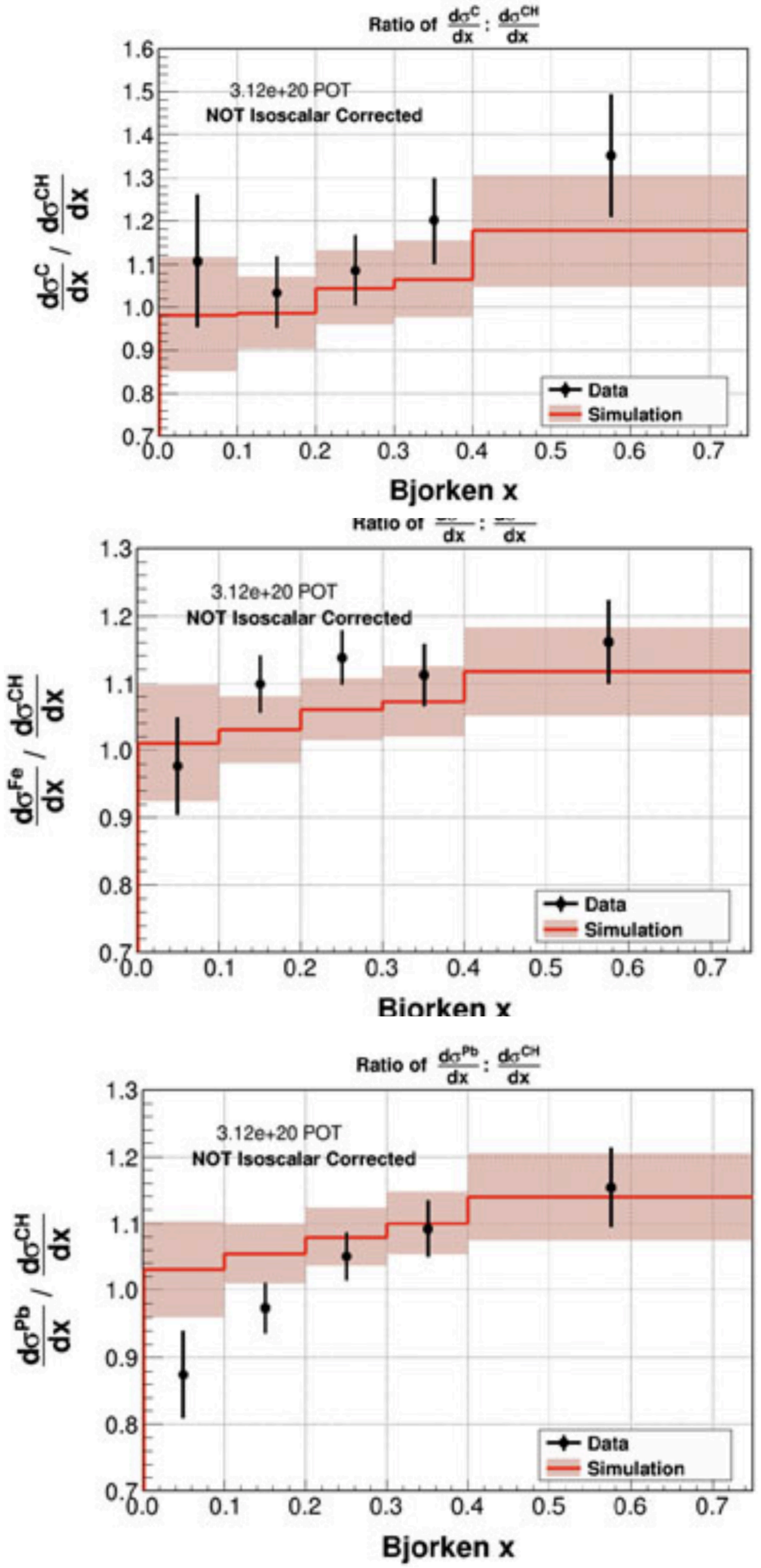
Please checkout the Snowmass White Papers!
Hydrogen/Deuterium Cross Sections: https://arxiv.org/abs/2203.11298
Bubble Chamber: https://arxiv.org/abs/2203.11319

Backup

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?

Neutrinos Act Like Polarized Electrons?

Another way of accessing electroweak physics.

Neutrino scattering can be handled similarly to PVDIS *except with inherent longitudinal* polarization:

Neutrino-DIS

$$\frac{d^2\sigma^{\nu,\overline{\nu}}}{dx\,dy} = \frac{G_F^2 ME}{\pi\,(1+Q^2/M_{W,Z}^2)^2}\left[\begin{array}{c}\frac{y^2}{2}2xF_1(x,Q^2)+\left(1-y-\frac{Mxy}{2E}\right)F_2(x,Q^2)\\ \pm y\left(1-\frac{y}{2}\right)xF_3(x,Q^2)\end{array}\right]$$

Formaggio & Zeller (2012)

Unpolarized eDIS

$$\frac{d^2\sigma}{dxdy} = \frac{4\pi\alpha^2 S}{Q^4}[xy^2F_1(x,Q^2)+(1-y-xy\frac{M^2}{S})F_2(x,Q^2)$$

PVDIS gains similar structure by introducing polarization but has interference of vector and axial contributions from the quark and electron. Parity violation is in these terms.

(D. Wang, Thesis, 2013)

Polarized eDIS

$$A_{PV} = \left(\frac{3G_FQ^2}{10\sqrt{2}\pi\alpha}\right)[(2C_{1u}-C_{1d})+Y_3(2C_{2u}-C_{2d})]$$

$$\begin{aligned}
C_{1u} &= 2g_A^e g_V^u = 2(-\frac{1}{2})(\frac{1}{2}-\frac{4}{3}\sin^2\theta_W) = -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W\\
C_{2u} &= 2g_V^e g_A^u = 2(-\frac{1}{2}+2\sin^2\theta_W)(\frac{1}{2}) = -\frac{1}{2}+2\sin^2\theta_W\\
C_{1d} &= 2g_A^e g_V^d = 2(-\frac{1}{2})(-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W) = \frac{1}{2}-\frac{2}{3}\sin^2\theta_W\\
C_{2d} &= 2g_V^e g_A^d = 2(-\frac{1}{2}+2\sin^2\theta_W)(-\frac{1}{2}) = \frac{1}{2}-2\sin^2\theta_W
\end{aligned}$$

*Assuming no nucleon sea, ***charge symmetry***, and an isoscalar target.

Neutrinos cannot *directly* contribute here but provide complementary indirect probes of EW physics!

Neutrinos as a Novel Nuclear Probe

Precision Selection of Quark Flavor

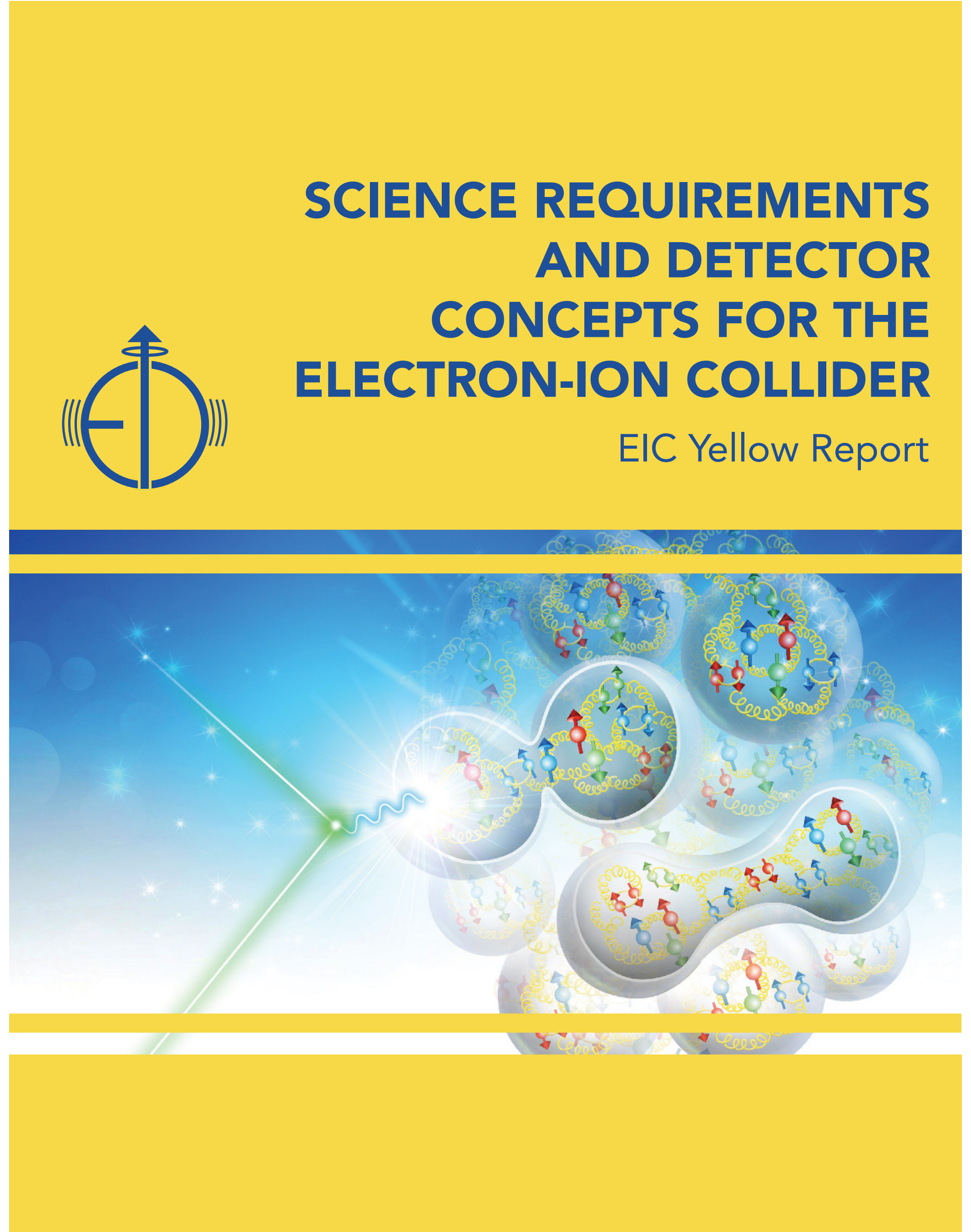
$$\frac{d\sigma_{CC}^{\nu/\bar{\nu}}}{dx\,dy} = \frac{G_F^2\, s}{2\pi\,(1+Q^2/M_W^2)^2}\left[F_1^{CC}\, x\, y^2 + F_2^{CC}\left(1 - y - \frac{Mxy}{2E}\right) \pm F_3^{CC}\, xy\,\left(1-\frac{y}{2}\right)\right]$$

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

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

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

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



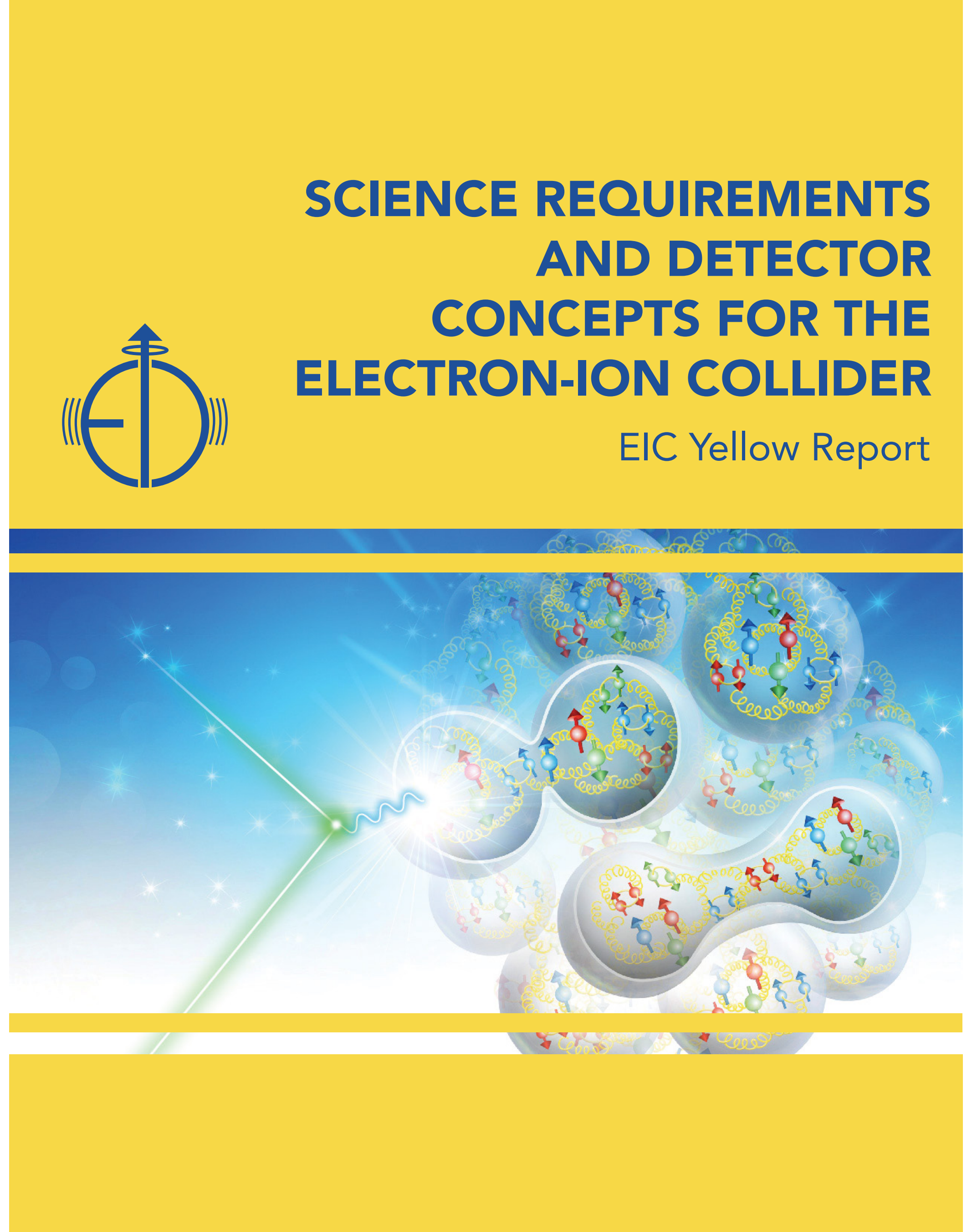
Complementarity especially attractive in DIS region where quark flavor and handedness is selectable!

Possible probe of nucleon intrinsic strangeness, this could mean *strange form factors*.

Spin and Polarization

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.

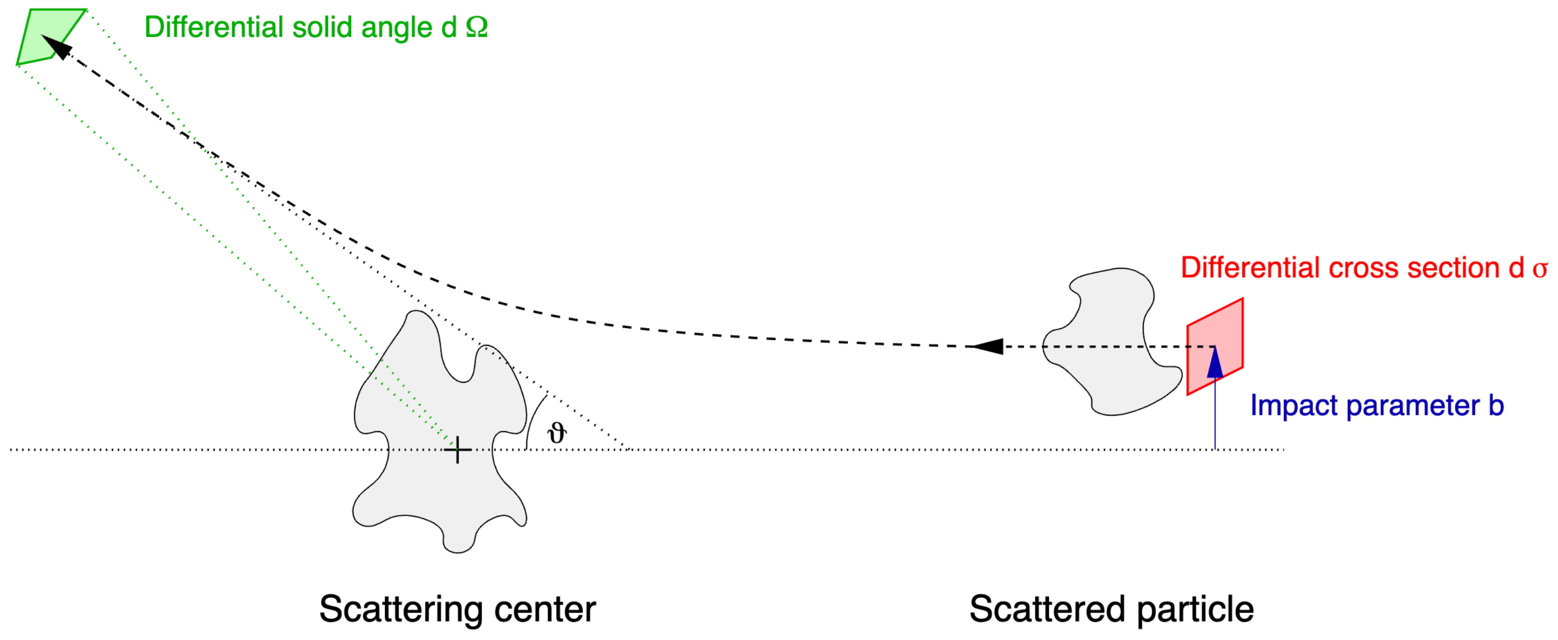


N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

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

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

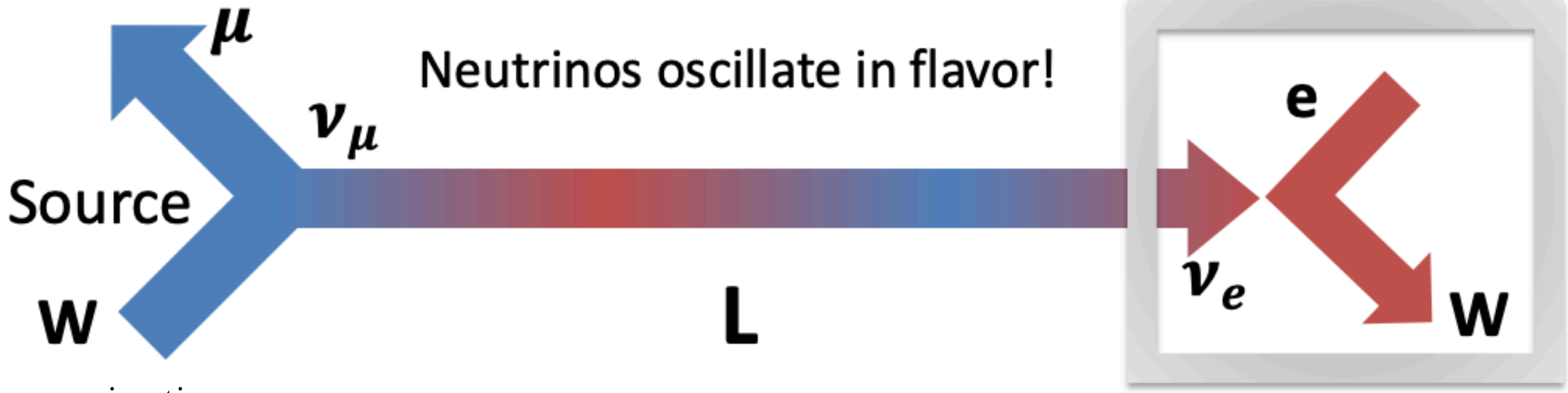
$$\Phi^{[i\sigma^{i+}\gamma_5]} = S_\perp^j h_1(x, k_\perp^2) + S_z \frac{k_\perp^j}{M} h_{1L}^\perp(x, k_\perp^2) + \frac{\epsilon_T^{ji} k_\perp^i}{M} h_1^\perp(x, k_\perp^2) + S_\perp^i \frac{2k_\perp^i k_\perp^j - k^2\delta^{ij}}{2M^2} h_{1T}^\perp(x, k_\perp^2),$$

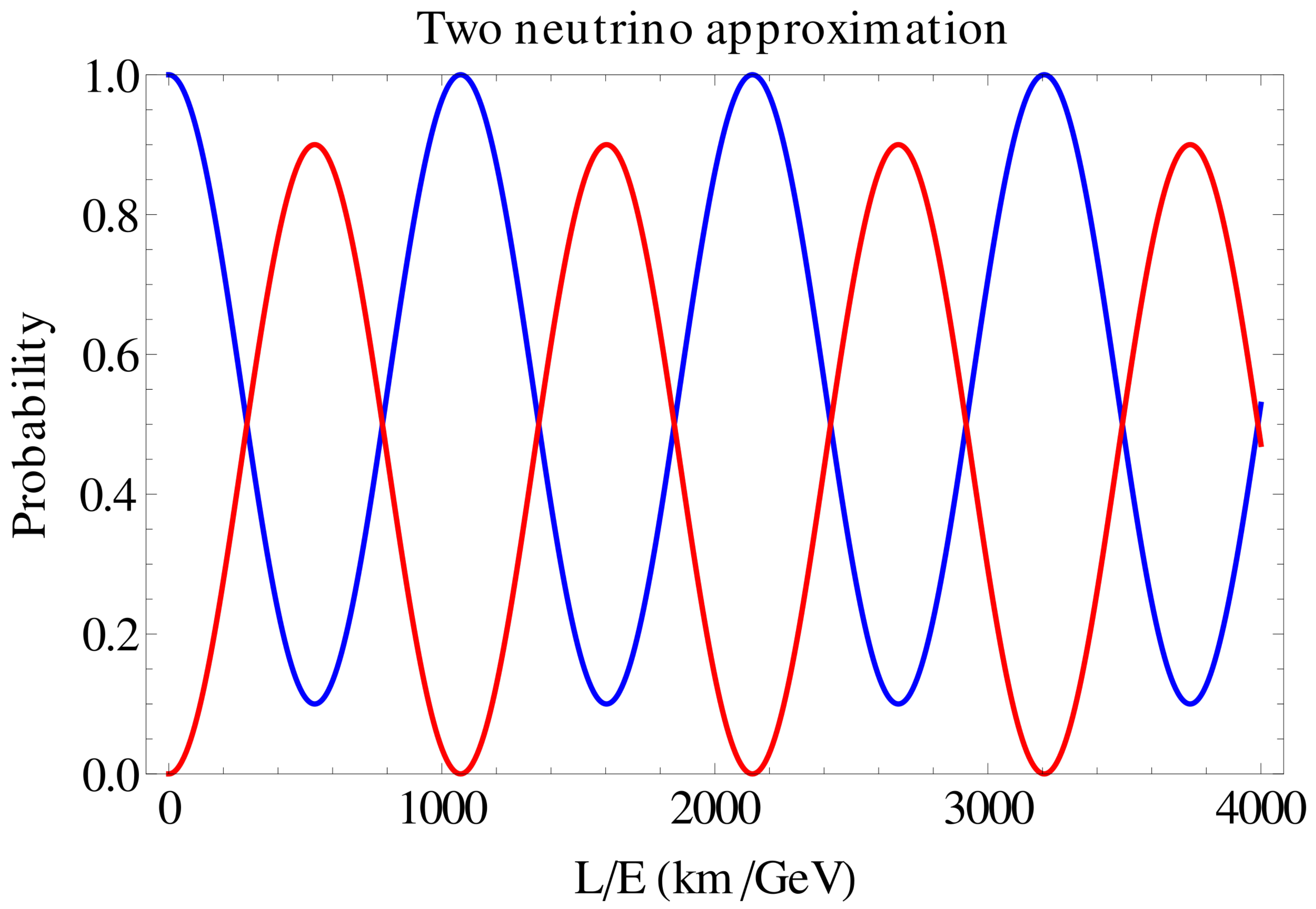


Contemporary Neutrino Physics (Part One)

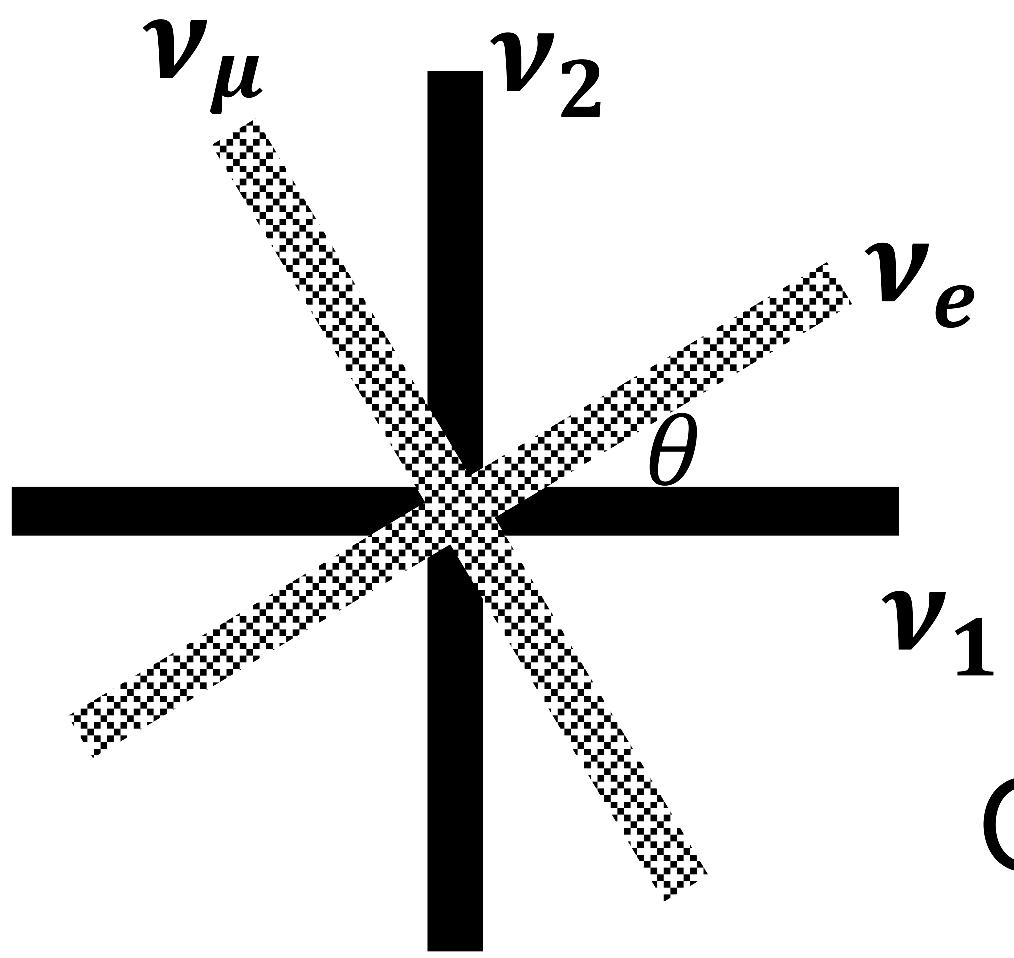
Neutrino Oscillations as a paths to Beyond-the-Standard-Model Physics

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





If we assume only two flavor and mass states:



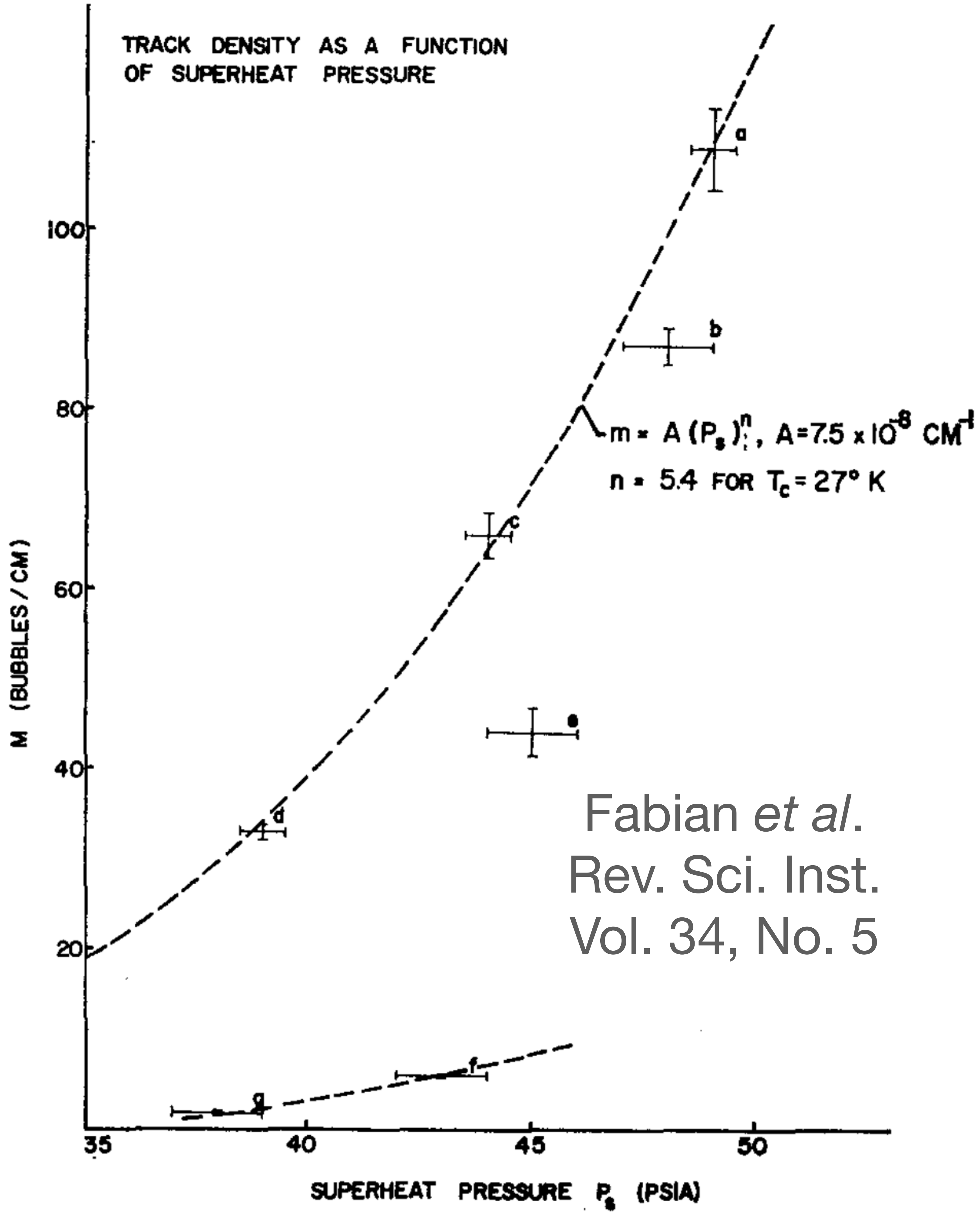
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \mathcal{R}(\theta) \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Only one Euler angle is needed.

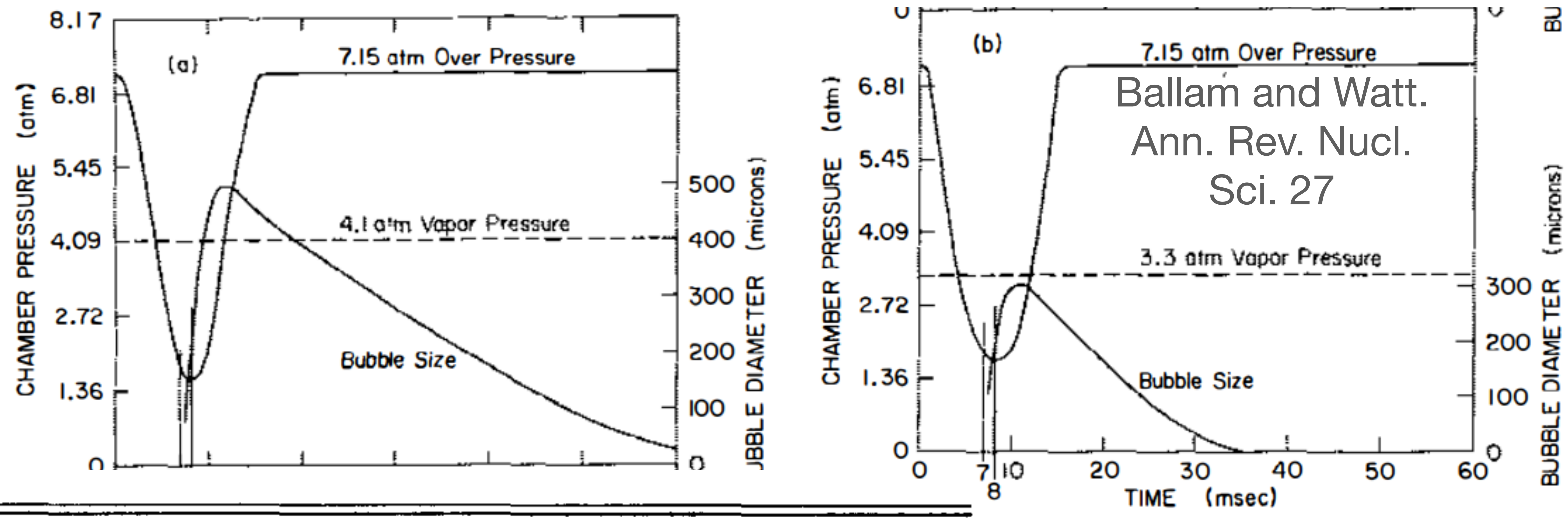
Bubble Microphysics

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



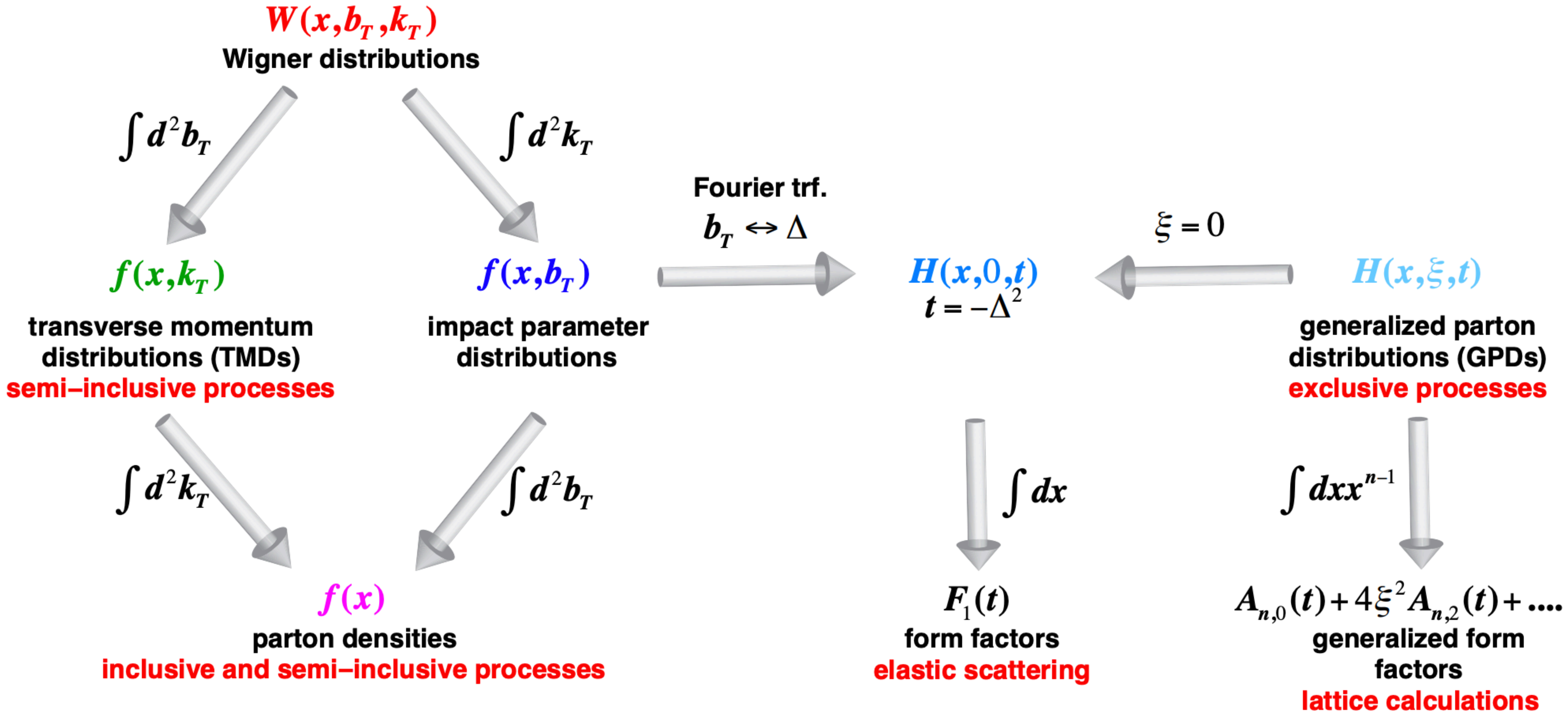
Ballam and Watt.
Ann. Rev. Nucl.
Sci. 27

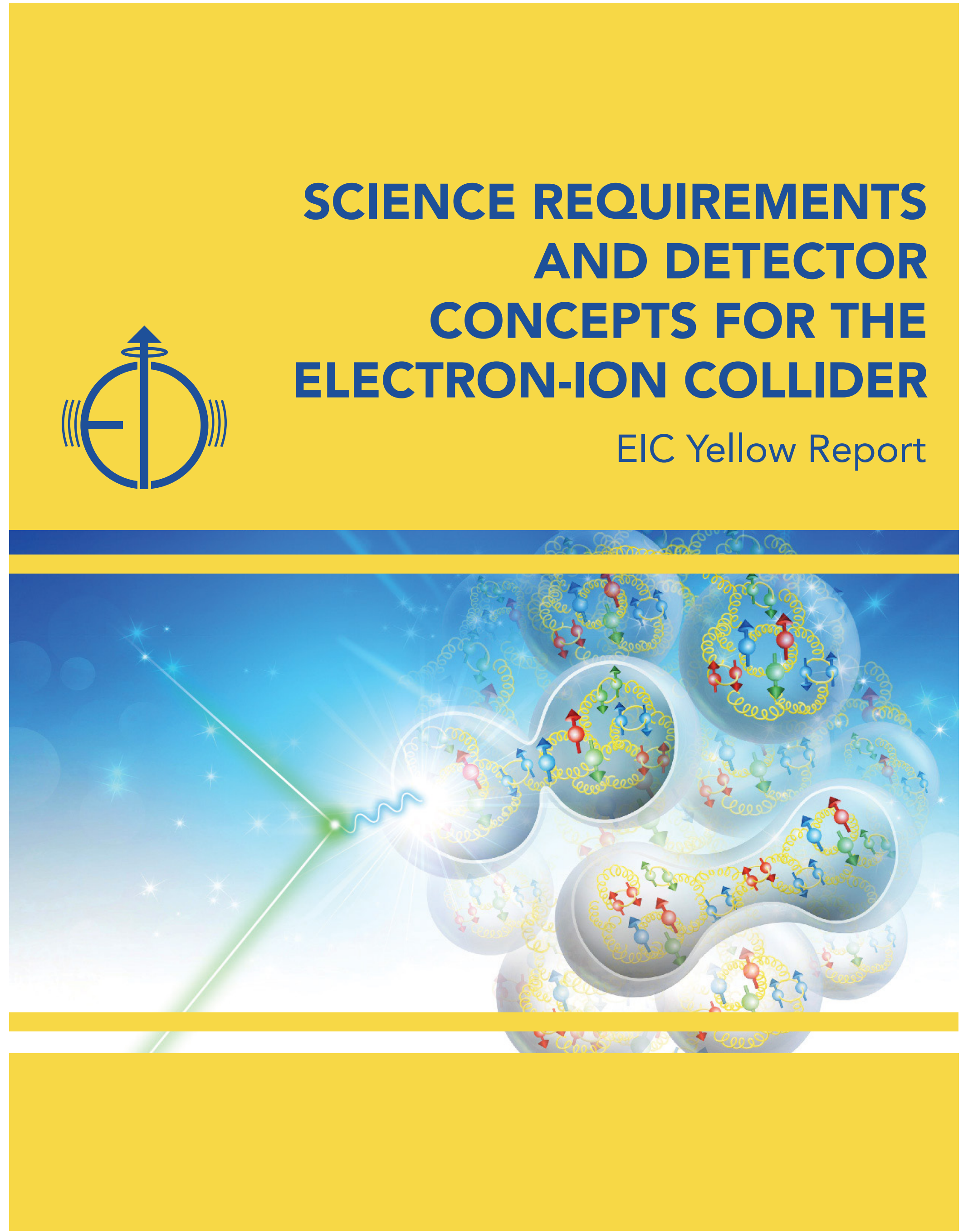
Symbol used	Expanded pressure (psia)	Chamber temperature (°K)	Beam
a	22	27.04	2.0 BeV/c p
b	18	26.60	1.0 BeV/c π^-
c	27	26.93	2.0 BeV/c p
d	31	26.92	2.0 BeV/c p
e	14	26.07	1.0 BeV/c π^-
f	7	25.23	2.0 BeV/c p
g	11	25.14	2.0 BeV/c p

Older experiments used bubble density as a way to measure energy deposition in the medium.

Spin and Polarization (Part Three)

Theoretical Expansion to Scattering and the Concept of the Nucleon

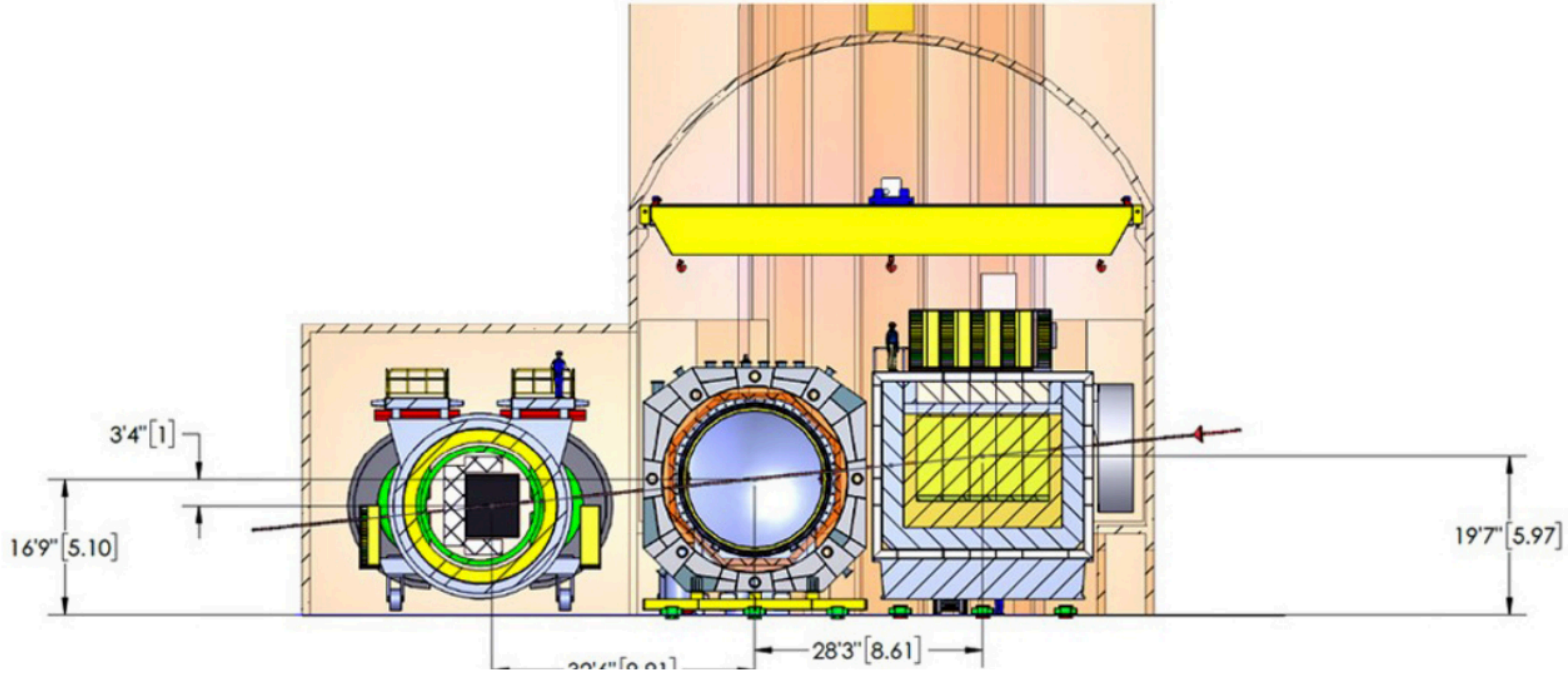


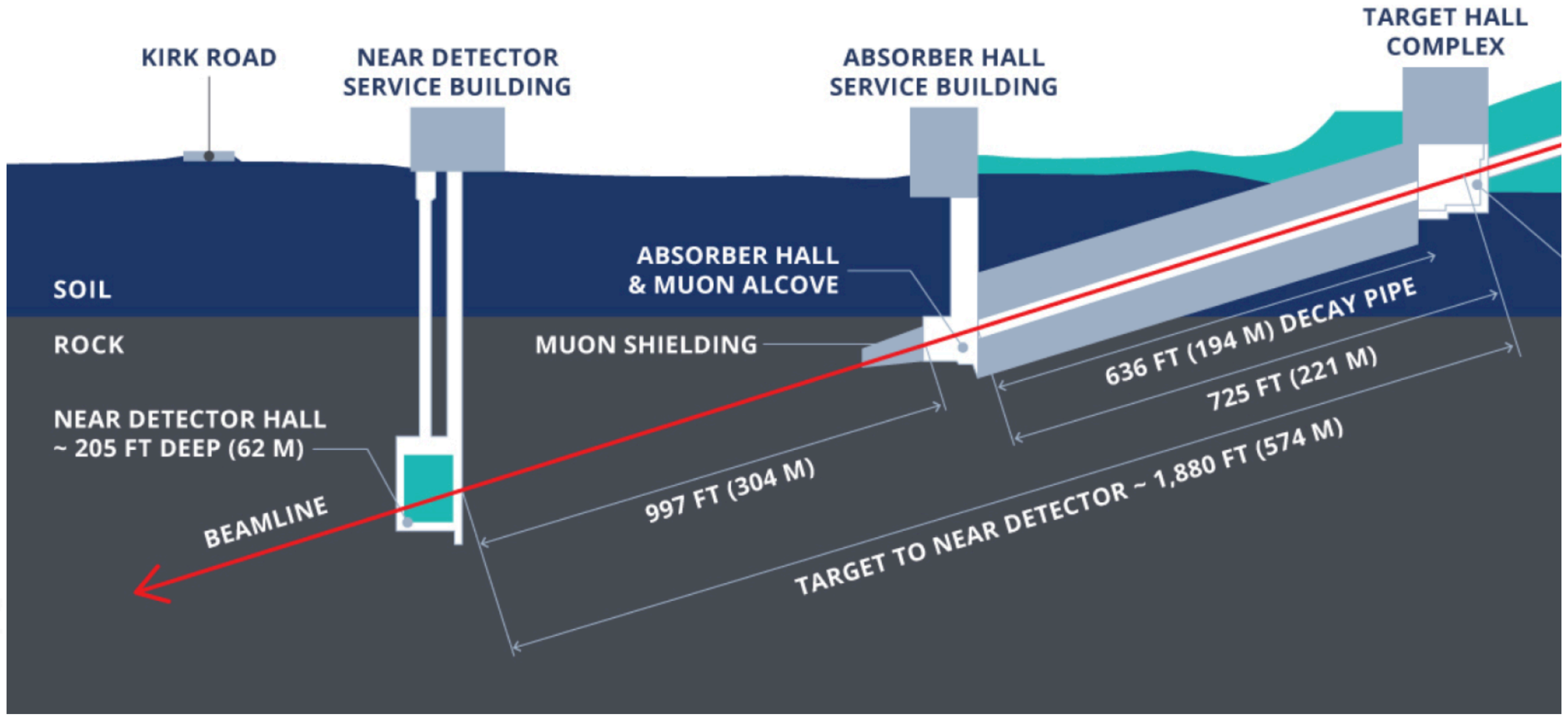


Formulation of GPDs from mapping of the nucleon gives new dimensions to scattering and information about the complicated spin structure of the nucleon.

Where to Put It?

The Biggest Challenge Toward Building It!





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

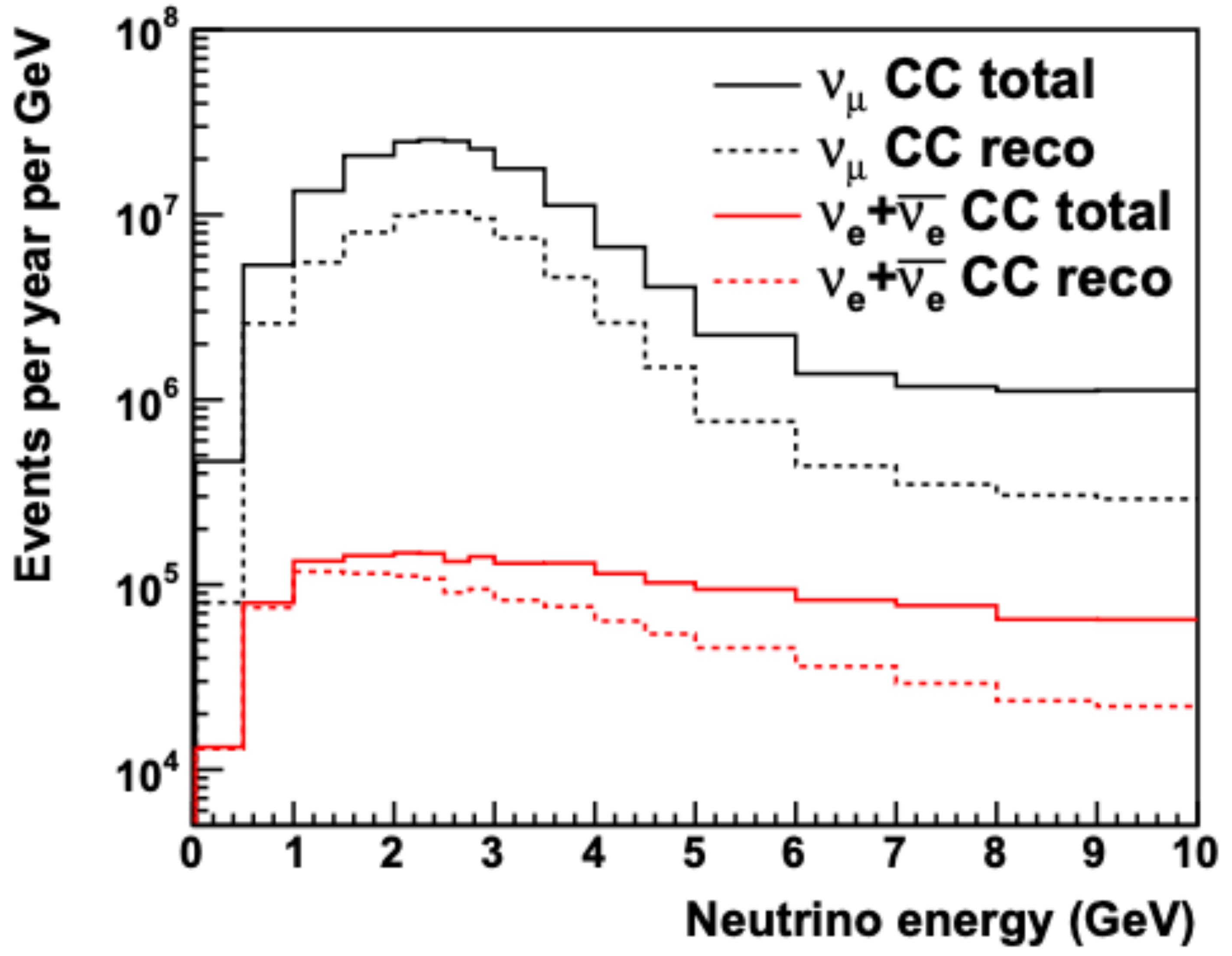
DOE safety guidelines allow only 15 gal/~57L to be used underground without additional safety measures.

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

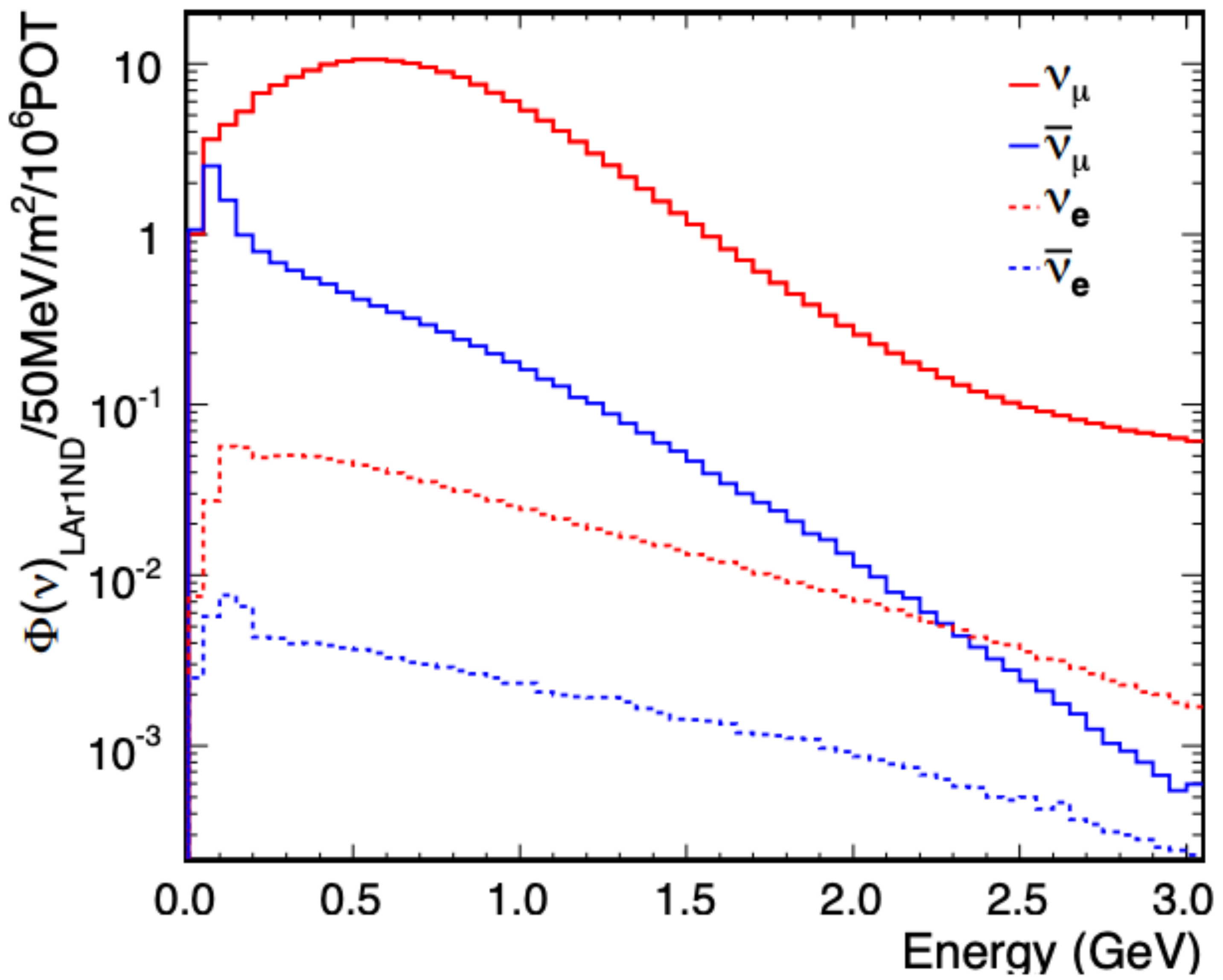
Build somewhere else (**Dedicated Underground Hall or On the Surface?**)

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.

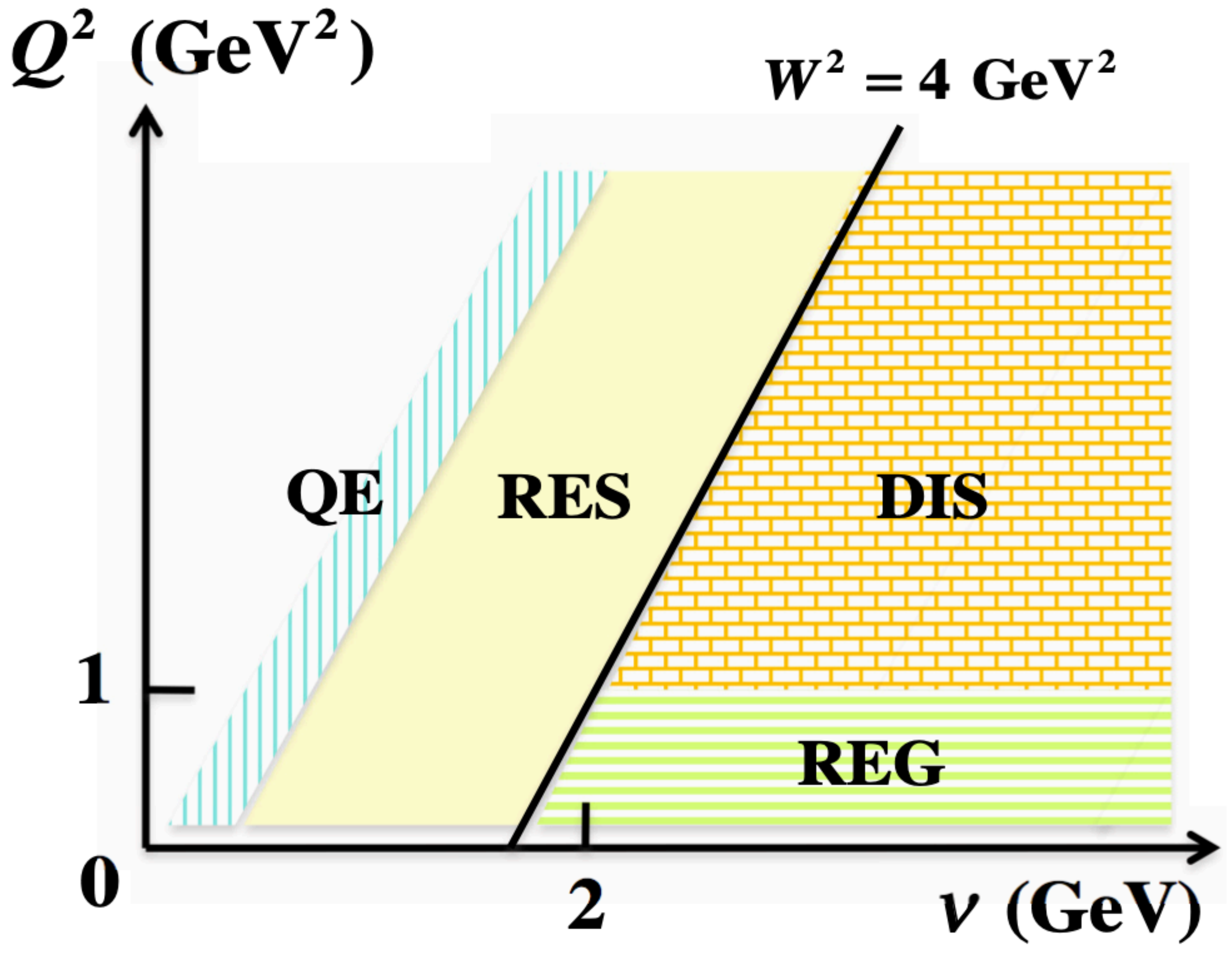


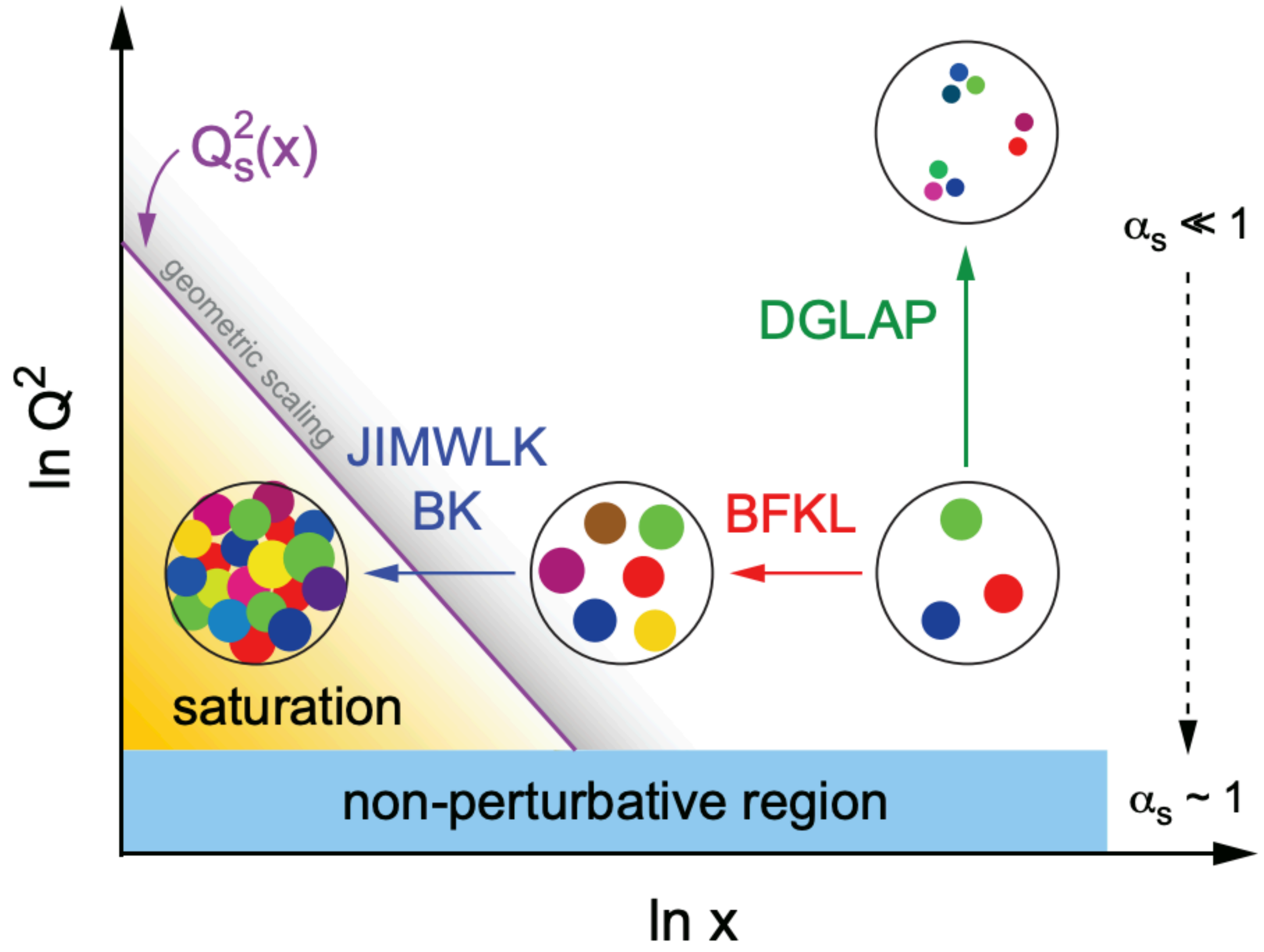
BNB has much lower intensity beam and at a lower energy but at a higher repitition rate, 5×10^{12} POT/Spill in 1.6 μs at 5-20 Hz rep rate which is much faster than older chambers could cycle.

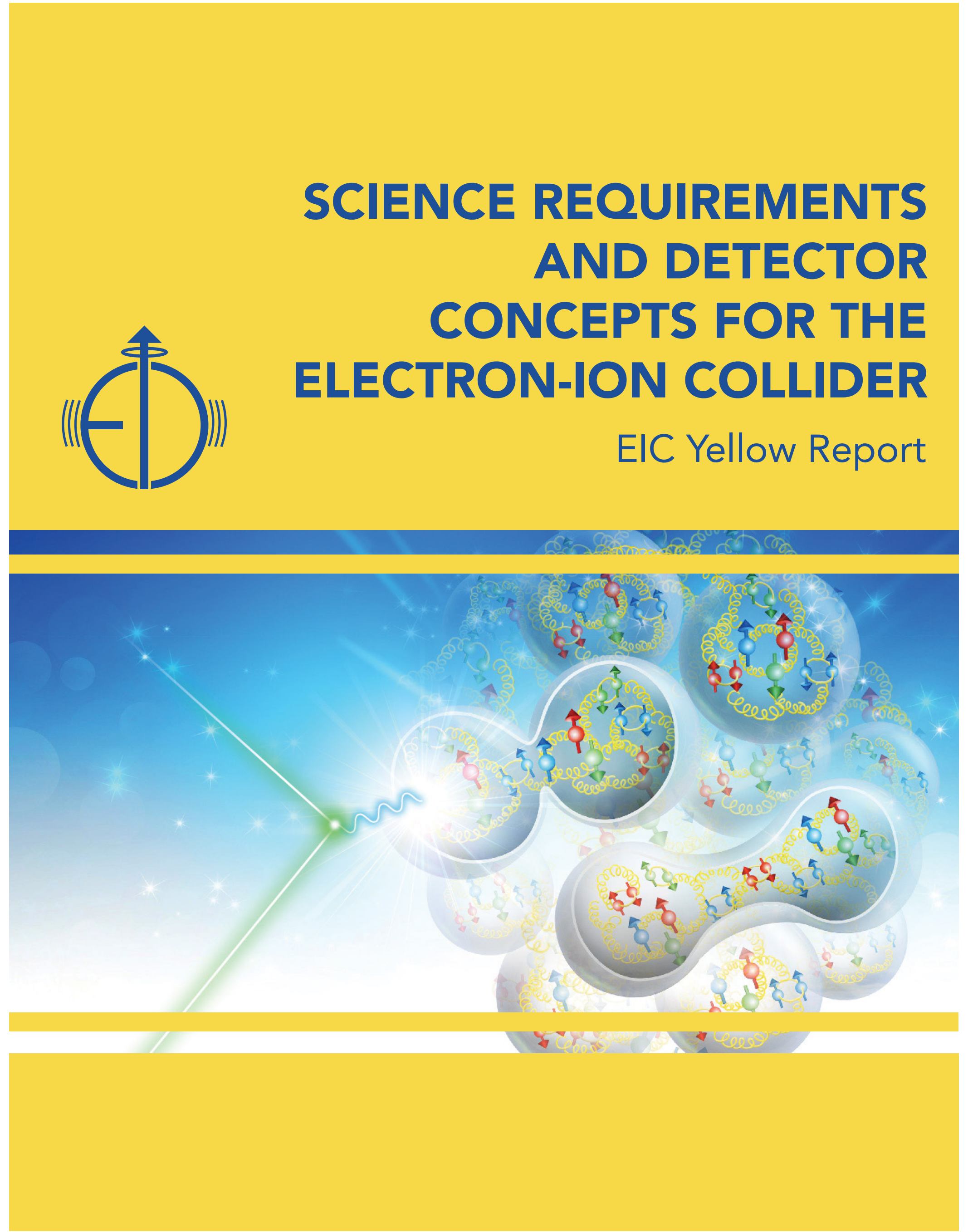
Note: Also includes contributions from highly off-axis NuMI Beam.

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.

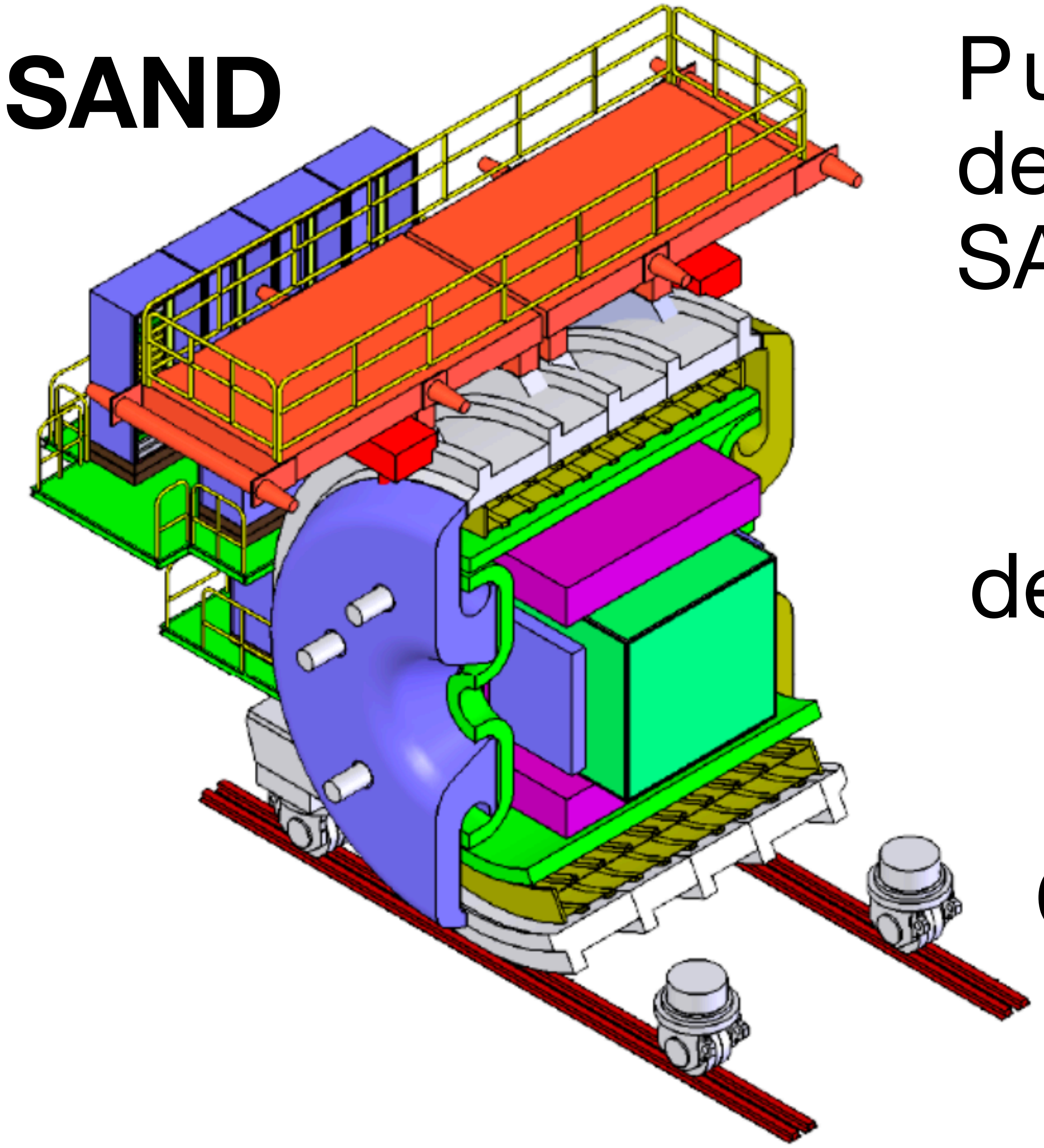
Neutrinos are a novel probe in this region, only probe with access to the axial-vector components/form factors/currents!

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



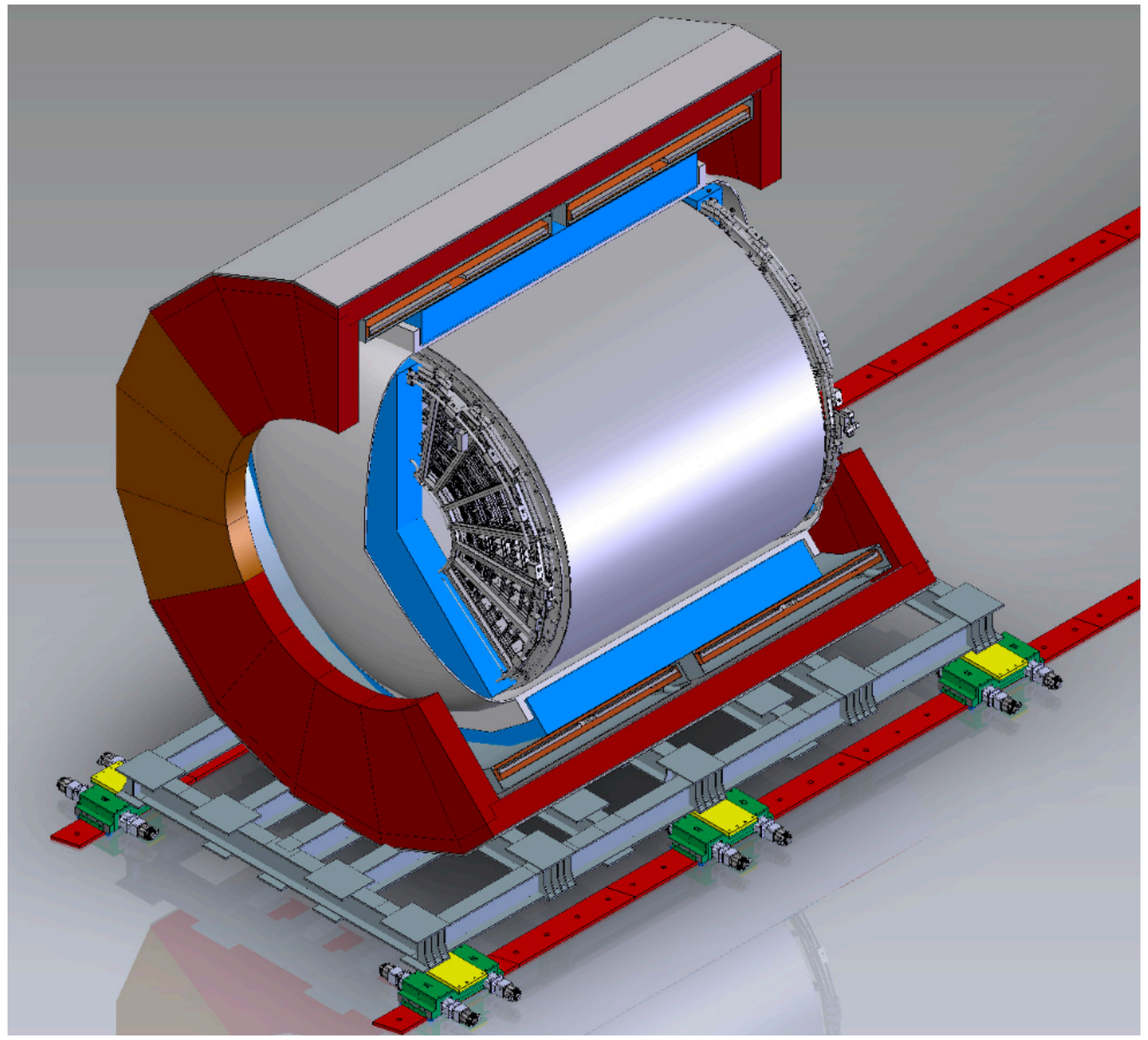
Put hydrogen in an existing detector: The Strawtube Tracker in SAND (CH)?

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!

ND-GAr



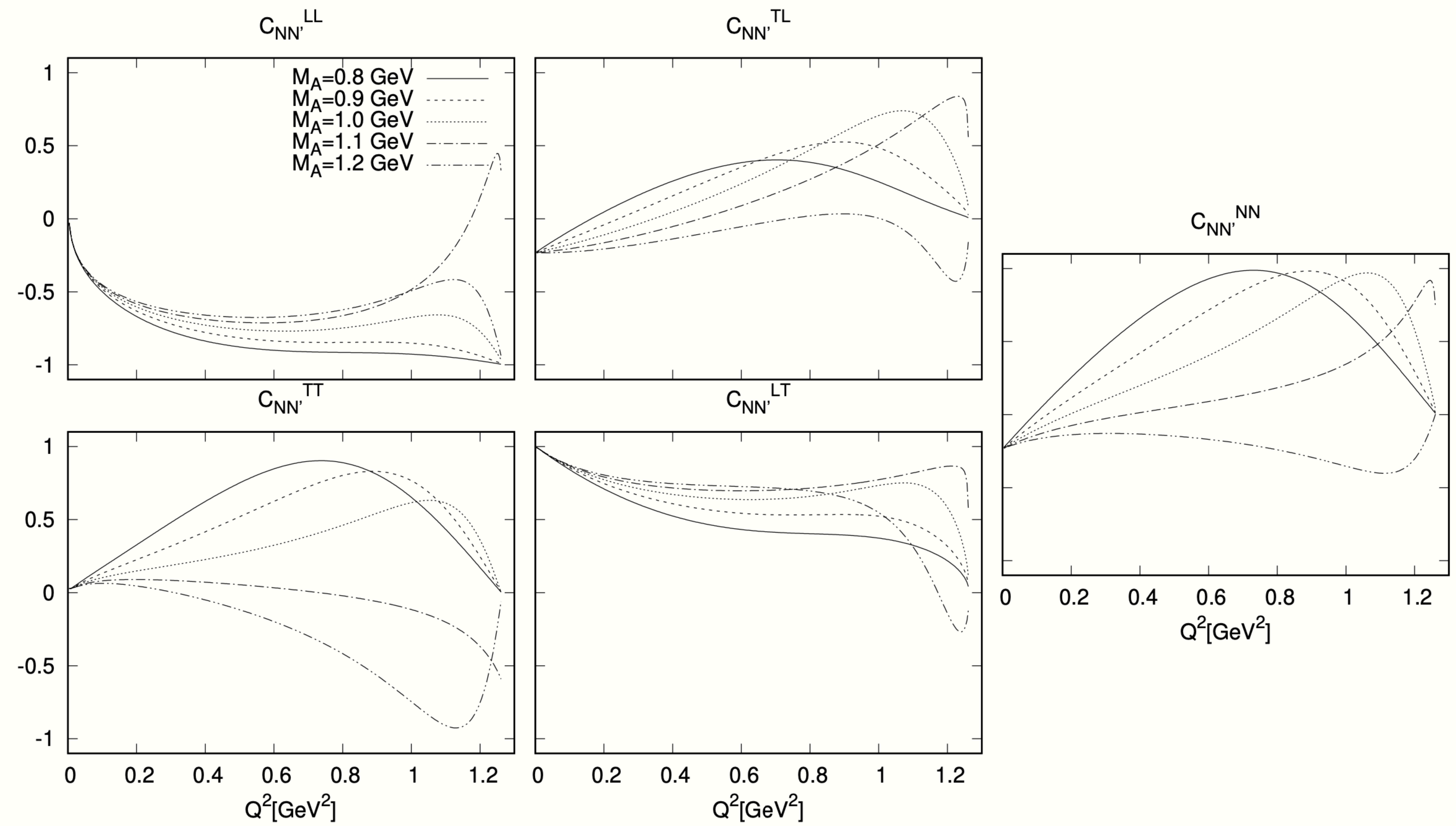
Spin and Polarization (Part One)

Spin Structure as a Cross Check for Neutrino Measurements

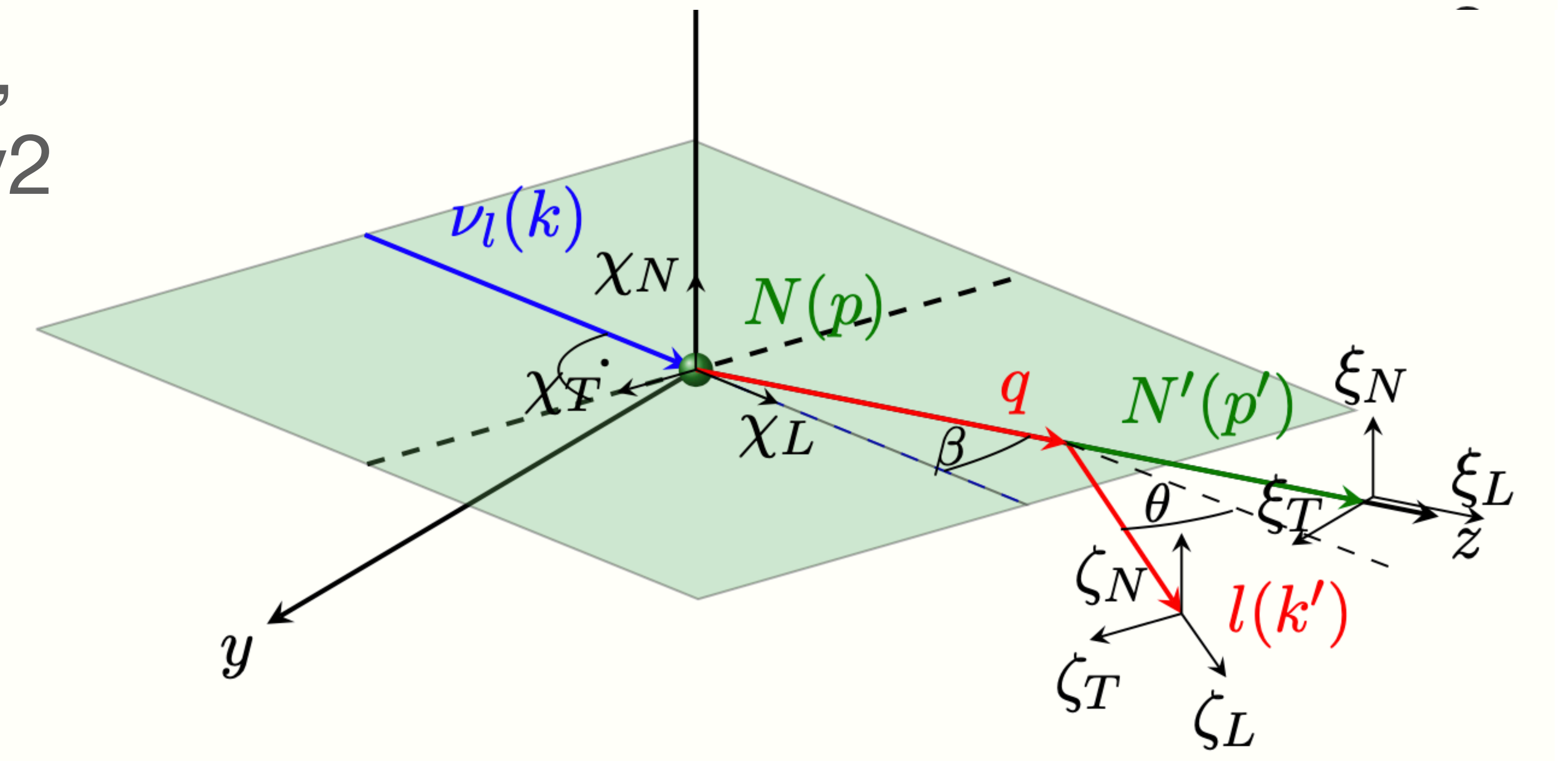
Spin and polarization can be factorized in the cross section into spin directions given the source.

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

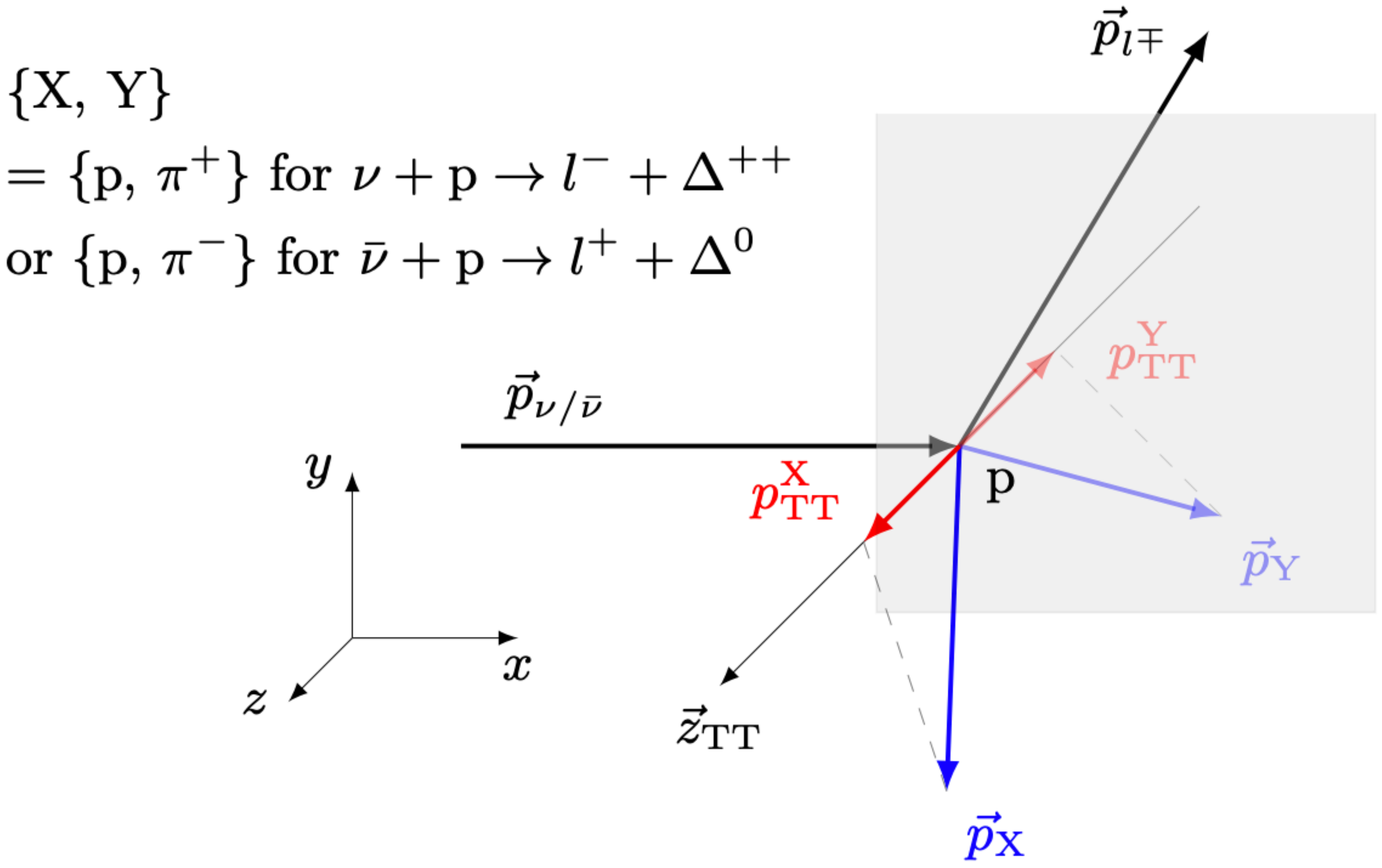


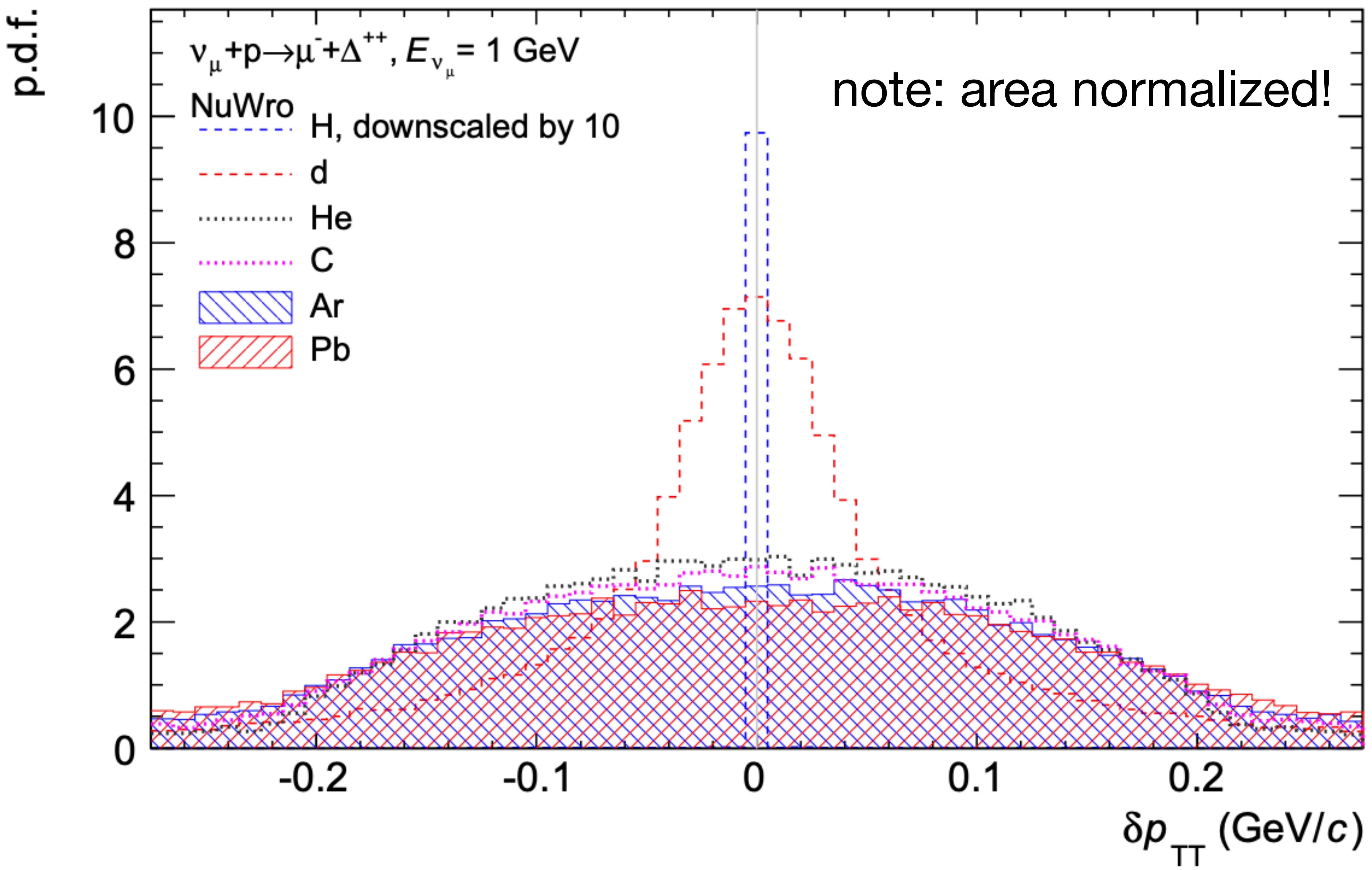
$$\frac{d\sigma}{dQ^2} = \frac{d\sigma_0}{dQ^2}\Big(1 + \mathcal{P}_l^\mu s_\mu^l + \mathcal{T}_N^\mu s_\mu^N + \mathcal{P}_{N'}^\mu s_\mu^{N'} + s_\mu^l s_\nu^{N'} \mathcal{A}_{lN'}^{\mu\nu} + $$
$$+ \quad s_\mu^l s_\nu^N \mathcal{B}_{lN}^{\mu\nu} + s_\mu^N s_\nu^{N'} \mathcal{C}_{NN'}^{\mu\nu} + s_\mu^l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

Considering Mixed Media Targets

Analysis of Hydrogen Integrated into Existing Detectors?

Regardless of choice, mixed media targets must involve challenging background subtraction.

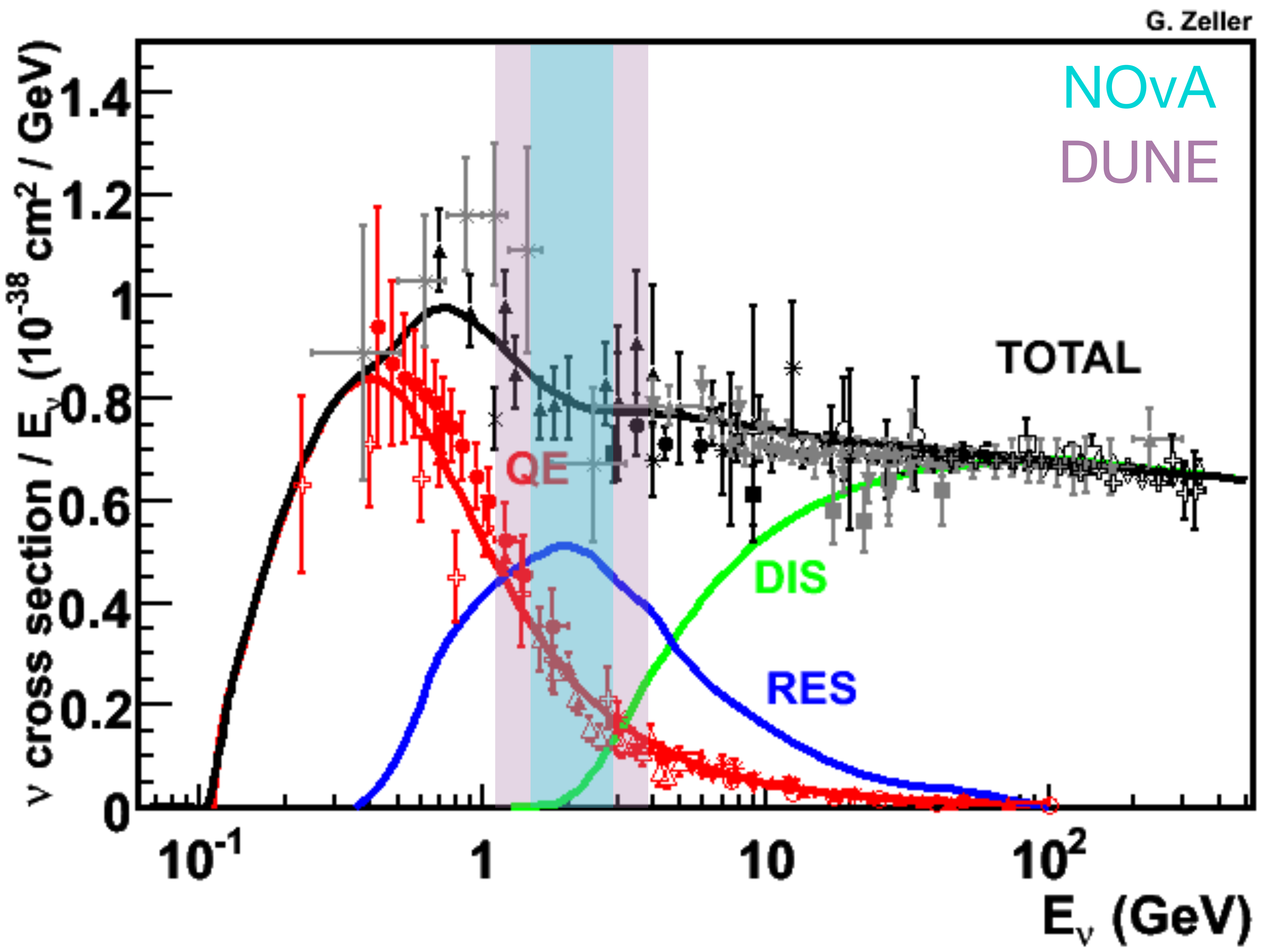


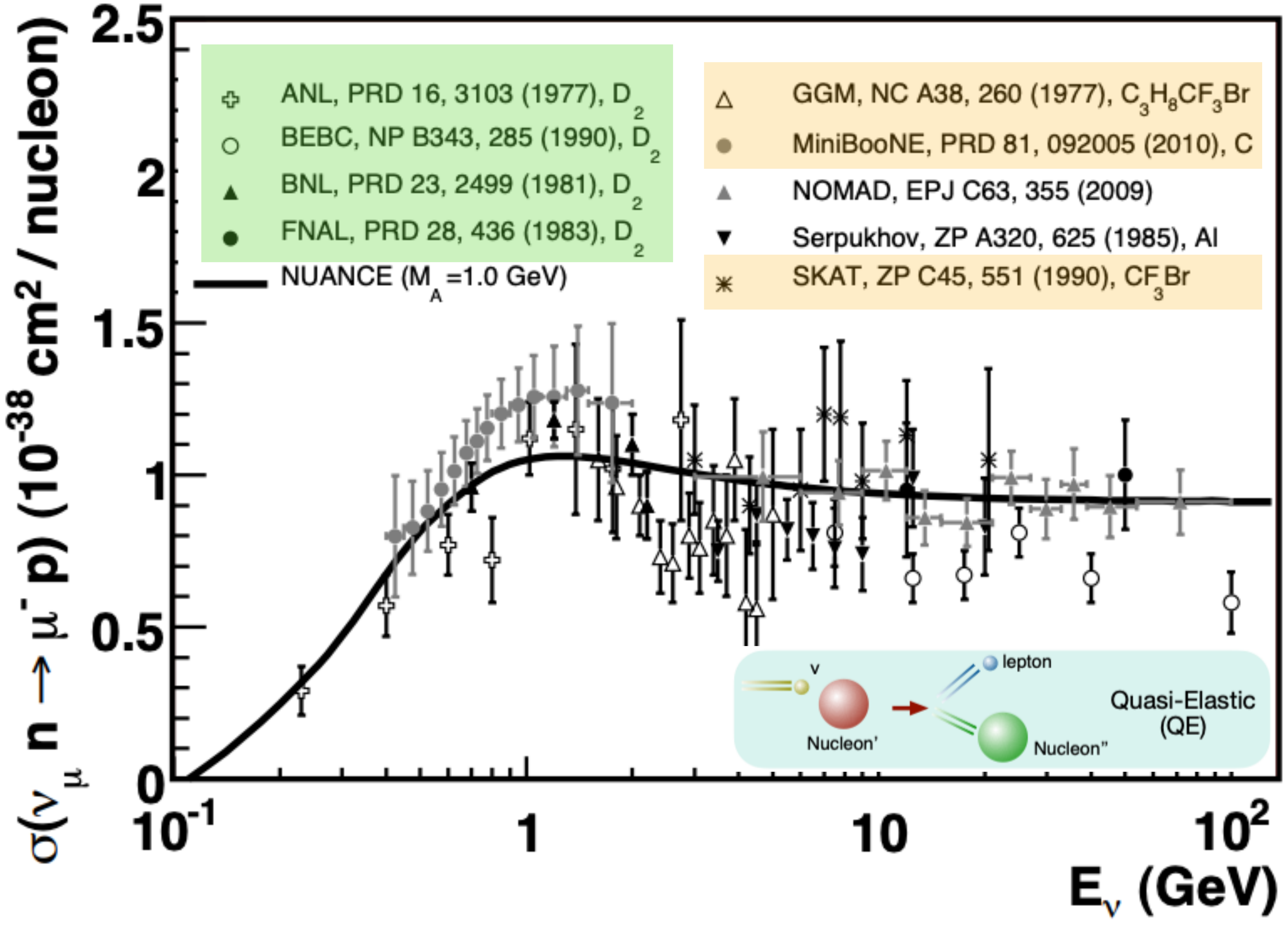


Examining component perpendicular to both neutrino and lepton momentum shows contributions from Fermi motion inside of nucleon. Adds irreducible systematics to measurements. (**also blunts understanding of quark d.o.f.,** more on that later)

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

Example of the Issue with QE/Elastic scattering

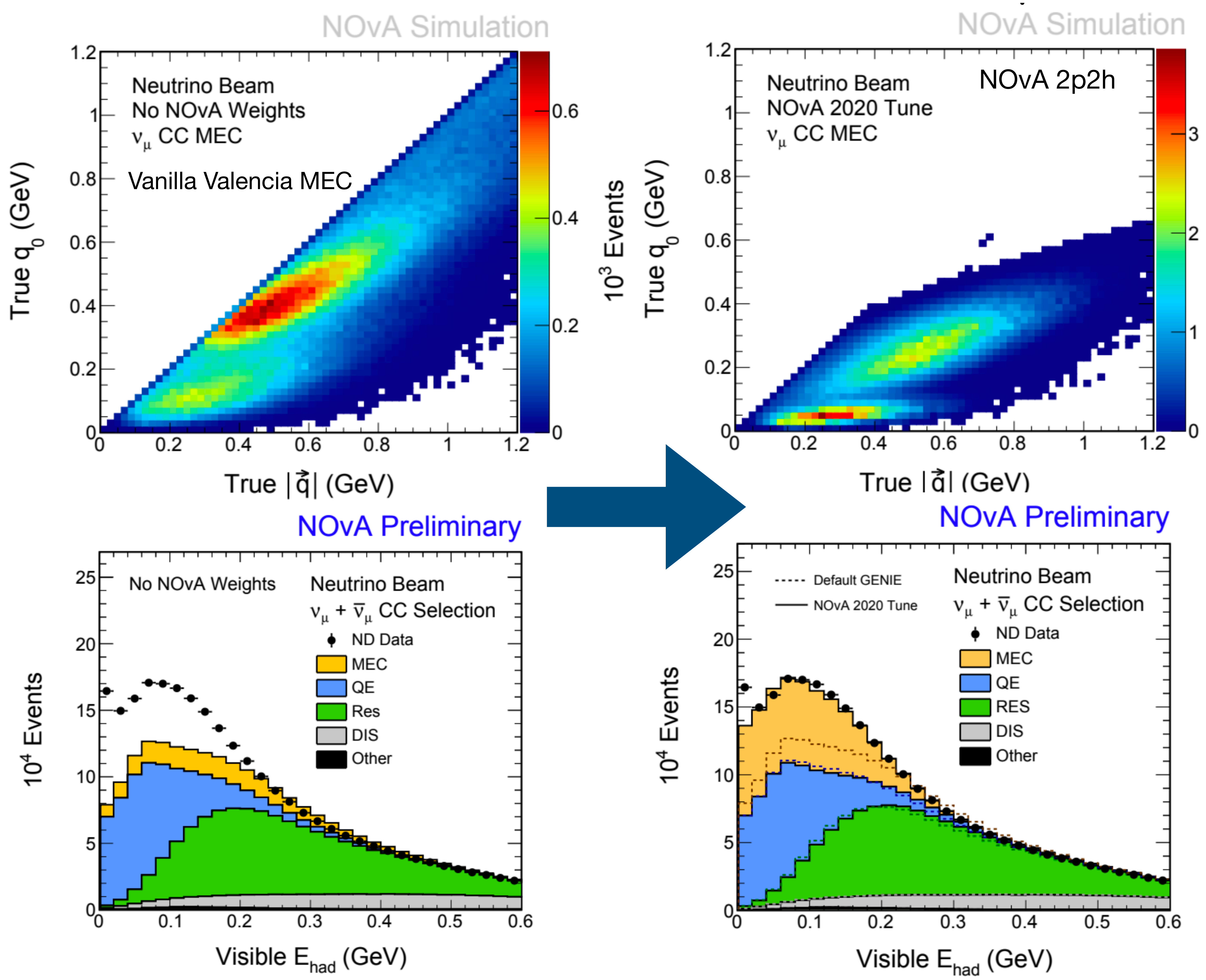




MiniBooNE Axial Mass estimated to be about 1.31 GeV with amazing statistics, however world hydrogen/deuterium data from ANL, BNL, FNAL, and BEBC put axial mass at ~1.0 GeV!

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.

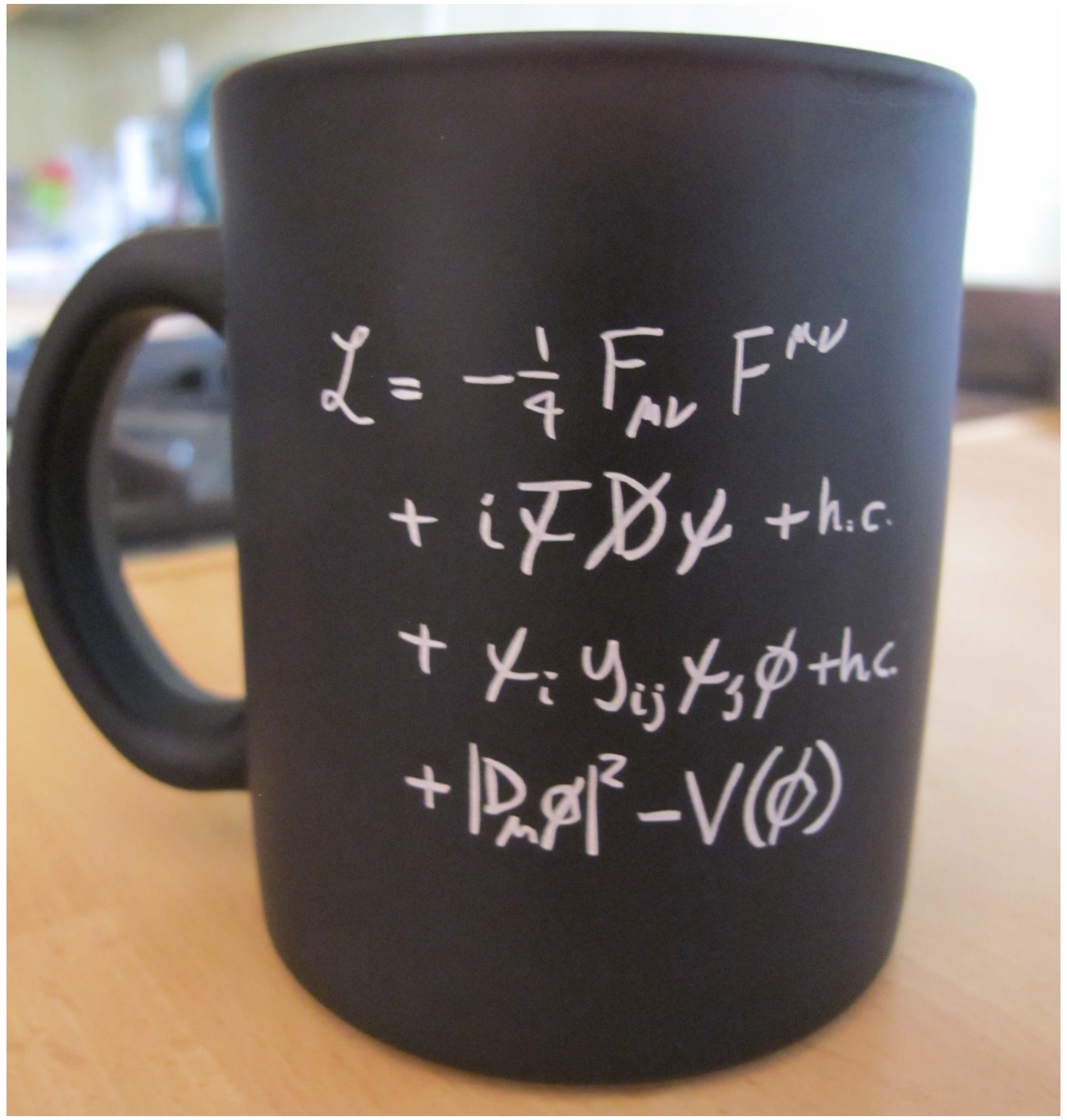
Each neutrino experiment *requires* significant *tunes* to match any given generator and tunes bring experiments out of agreement with each other!

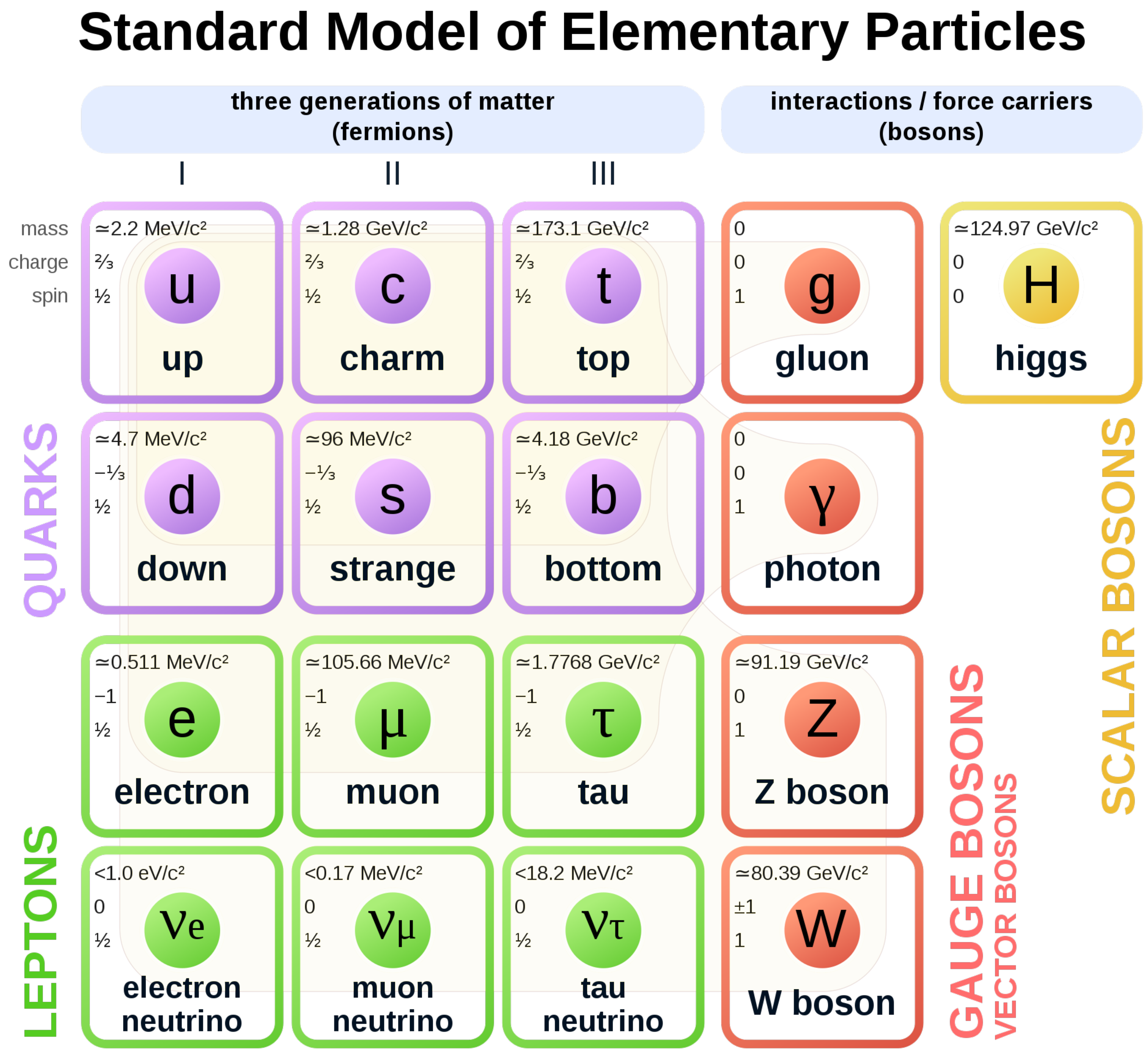
Data driven corrections can not completely substitute for a fundamental understanding of the physics!

A Brief Introduction to Particle Physics

The Theory of *Almost Everything*

The Standard Model is the crown jewel of particle physics!

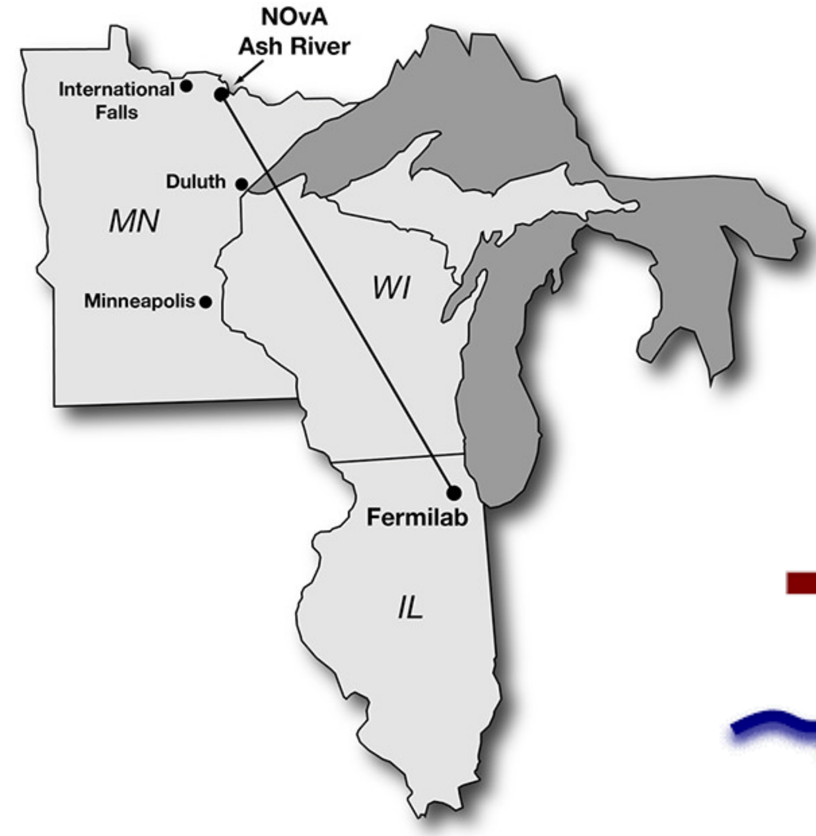


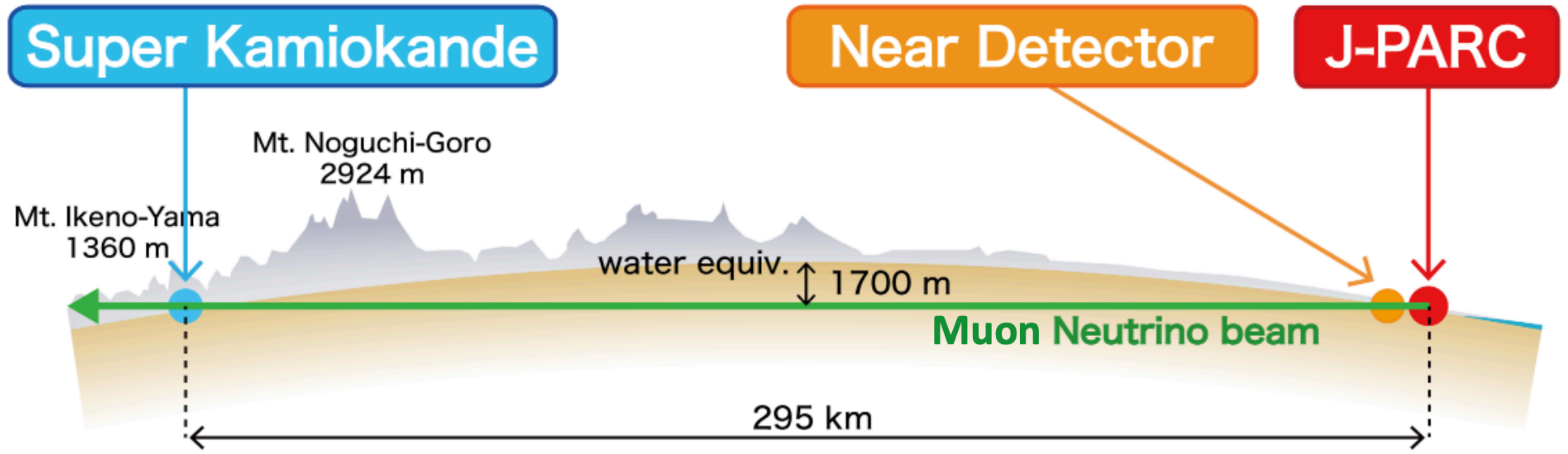


It describes the underlying symmetries governing the scattering of particles from each other and only excludes *gravity*. ***Doing particle physics means testing the standard model.***

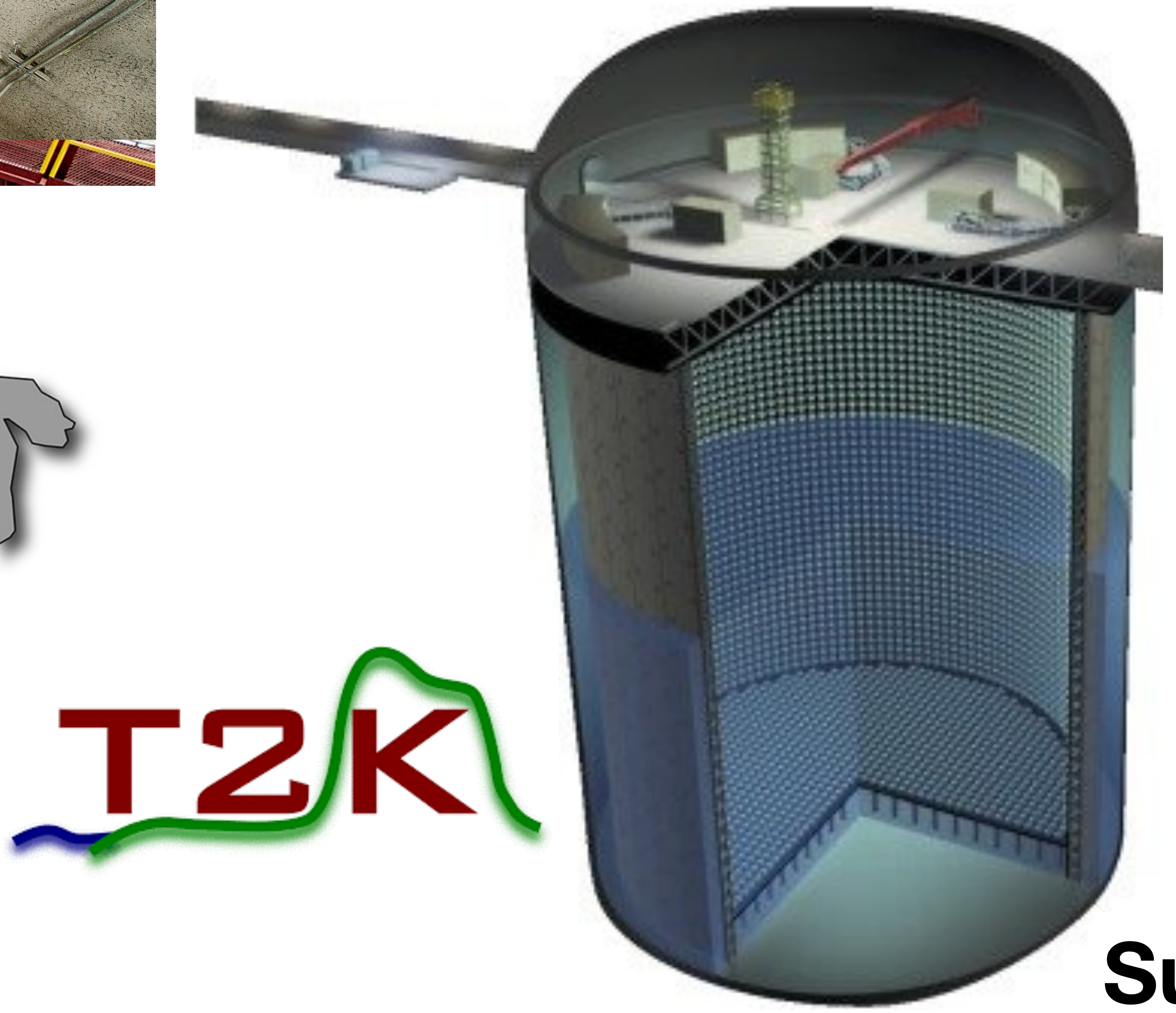
Current Generation of Long-Baseline Experiments

Current State-of-the-Art Detectors and Measurements

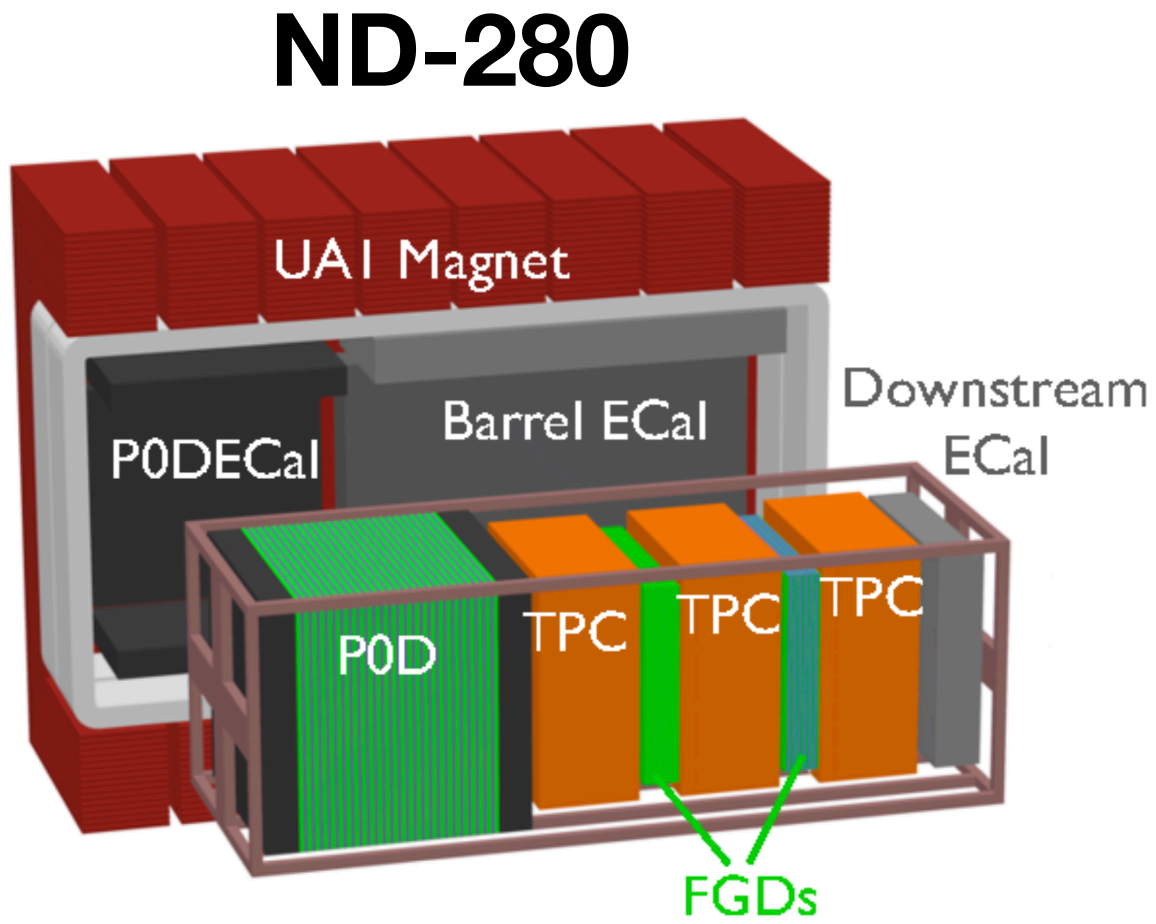




T2K, Stephen Dolan, Neutrino 2020



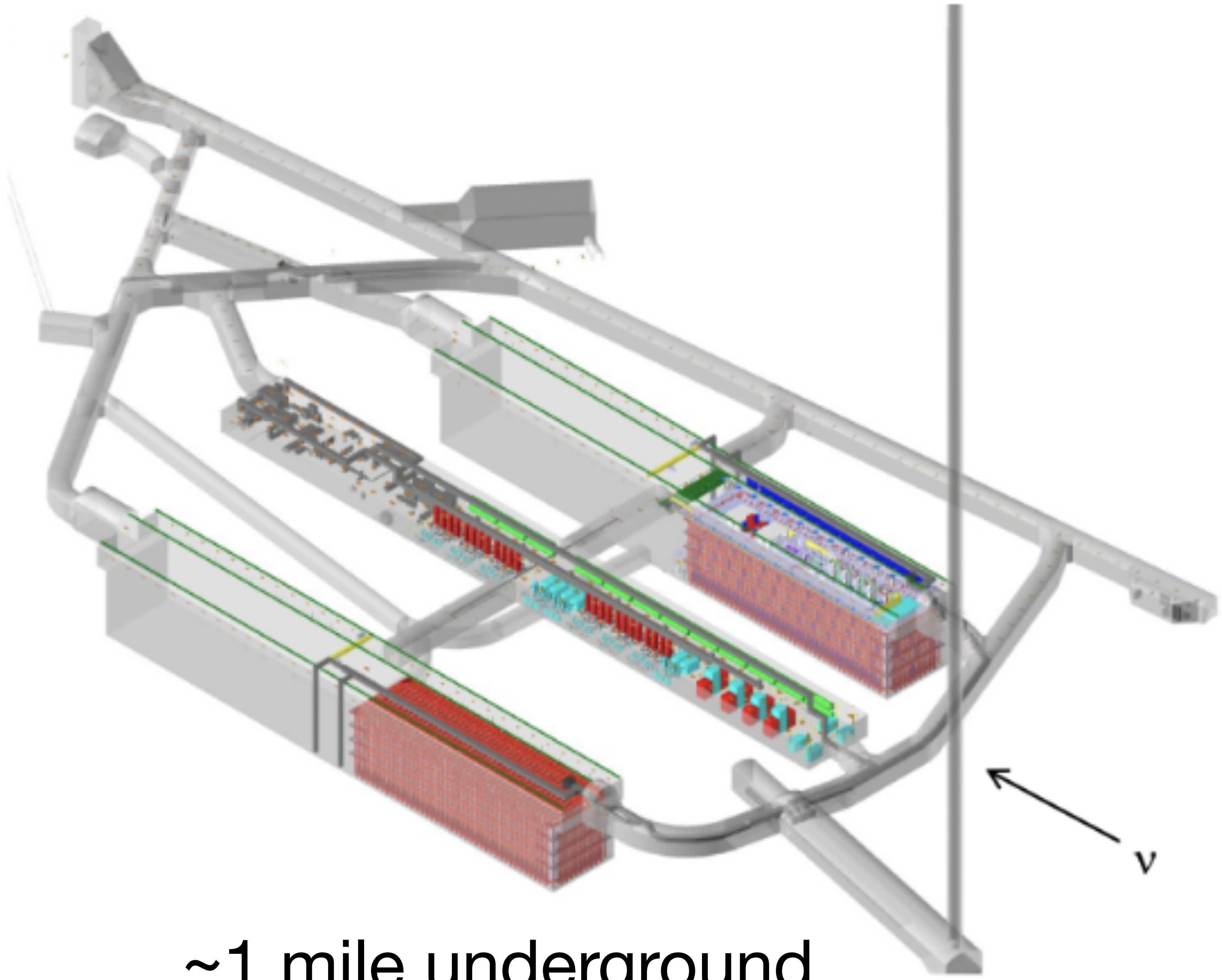
Super-Kamiokande

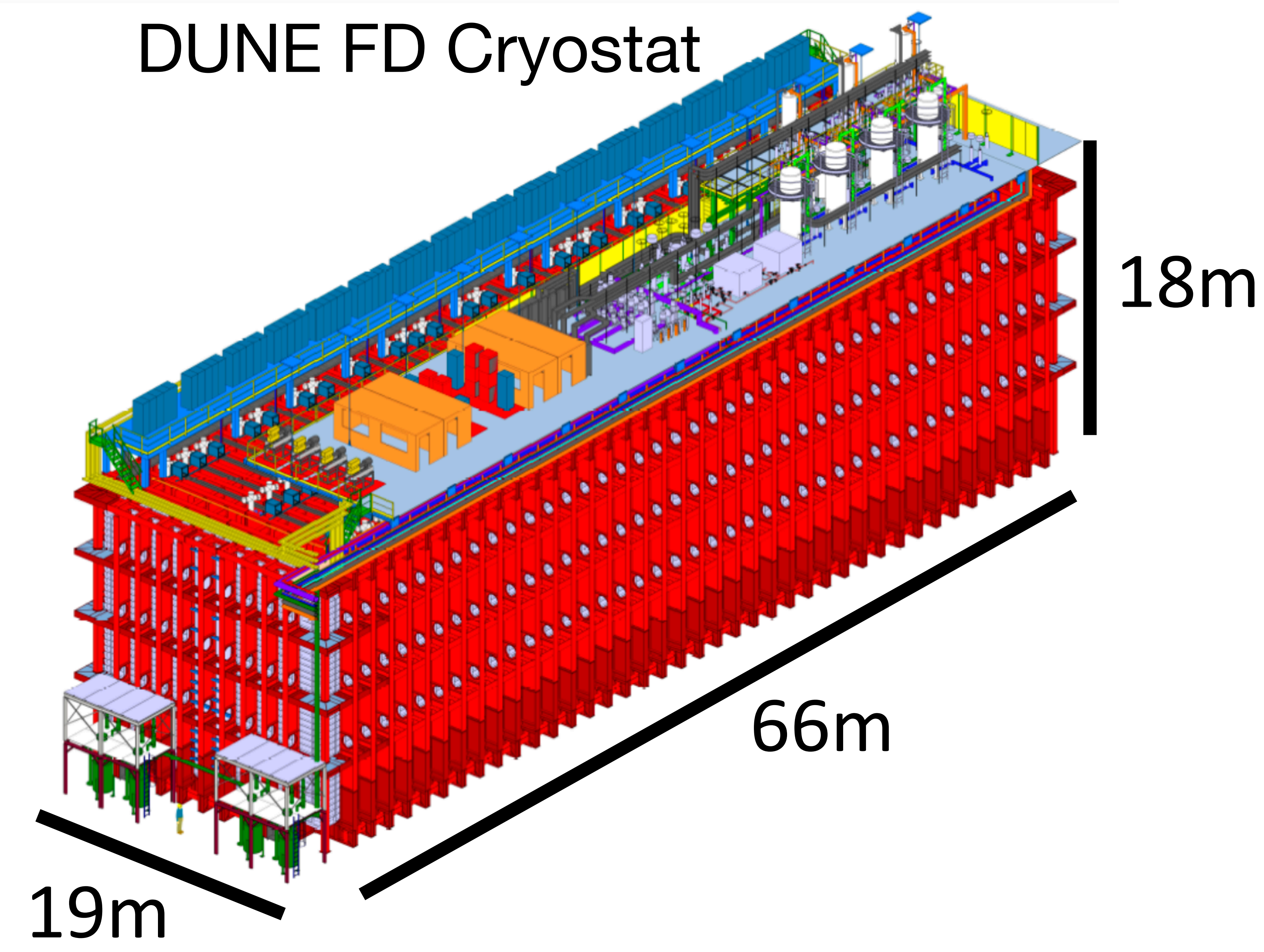


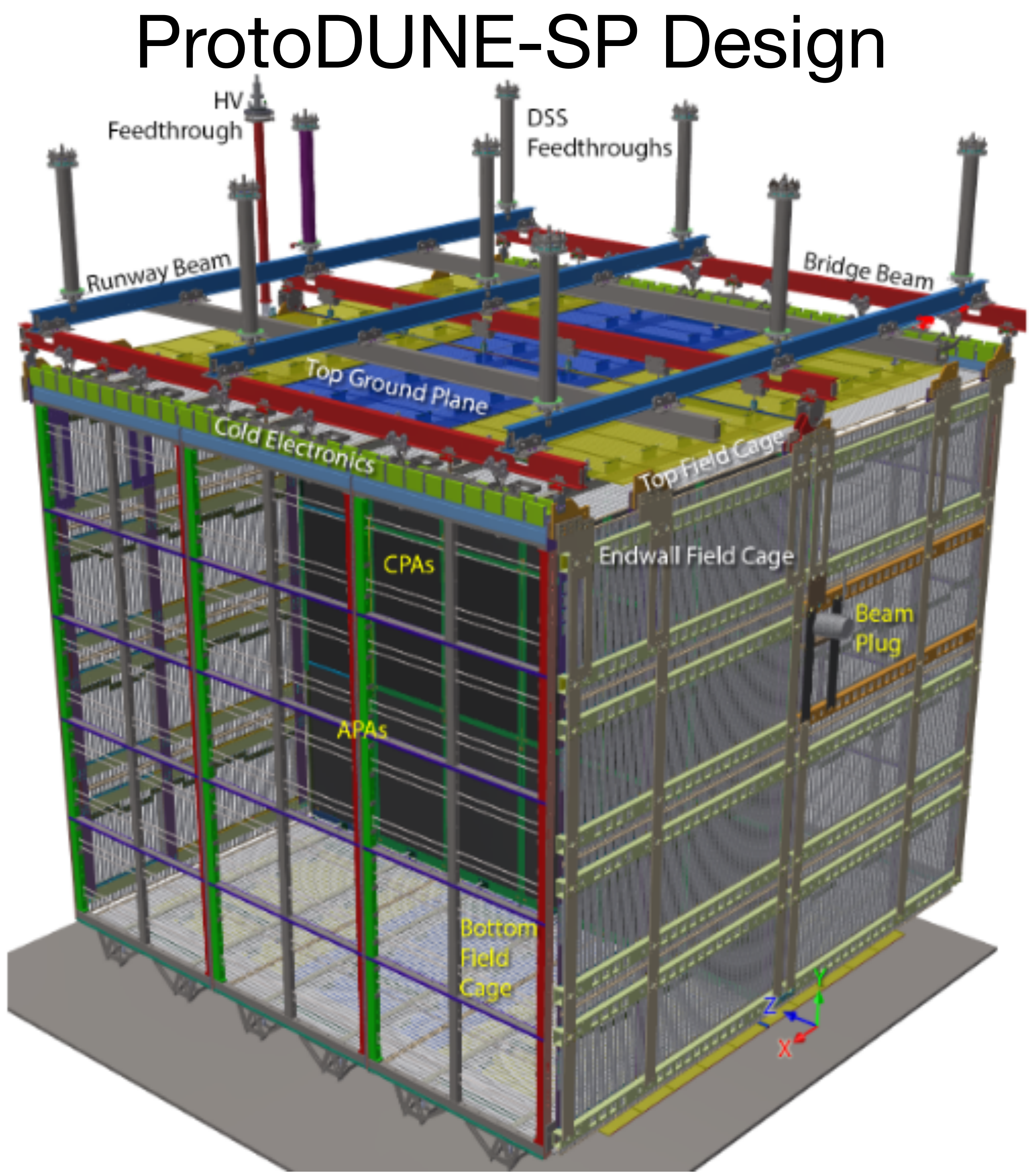
NOvA and T2K are dual detector oscillations experiments currently taking data and producing results. As of 2020, NOvA and T2K are leaders in resolving oscillation parameters and leptonic CP-violation in the neutrino sector.

The DUNE Far Detector

Necessary for Observation of Oscillations







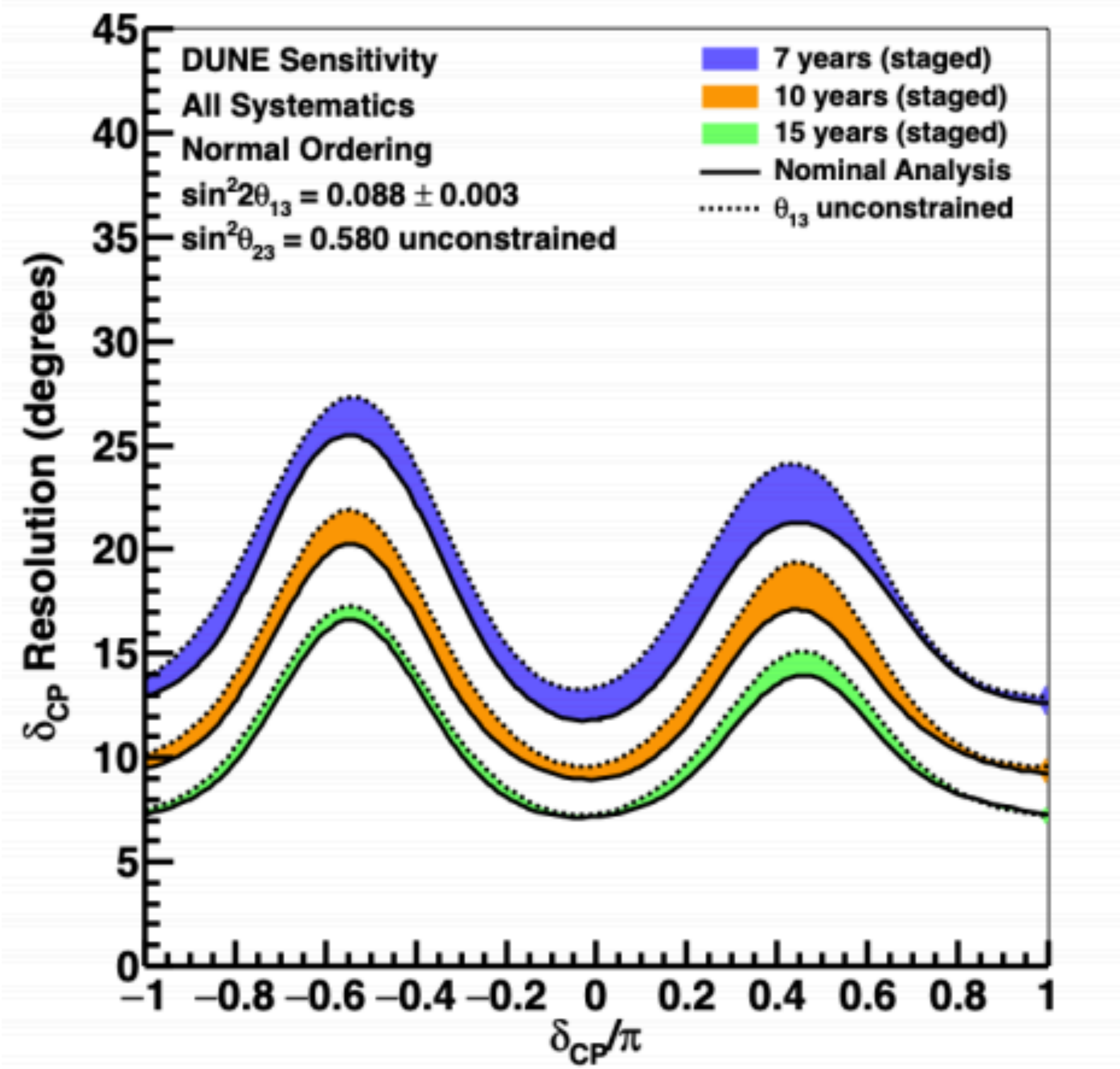
FD designed to directly observe ν_μ disappearance and ν_e appearance over ~800 mile baseline!

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?

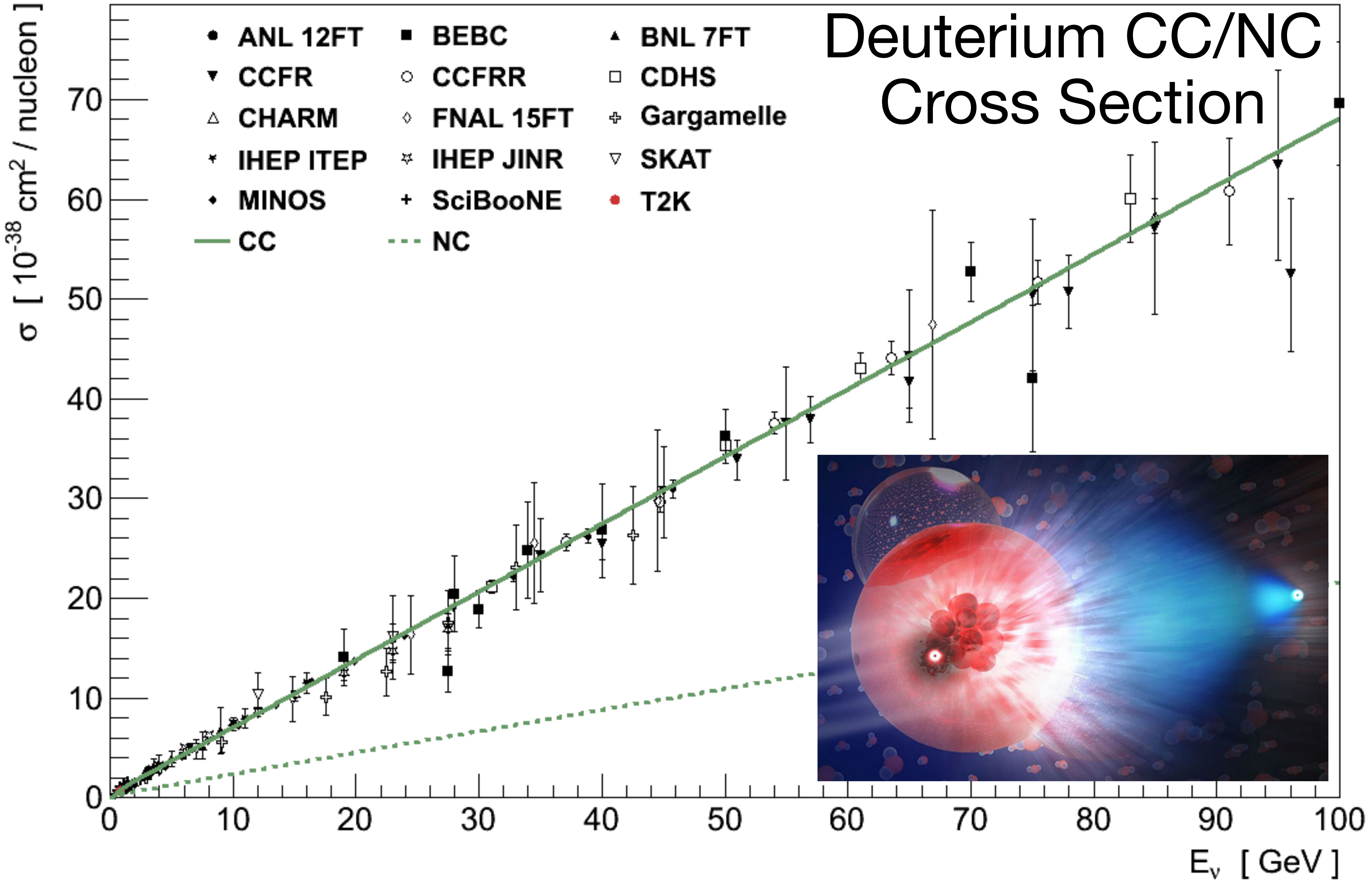


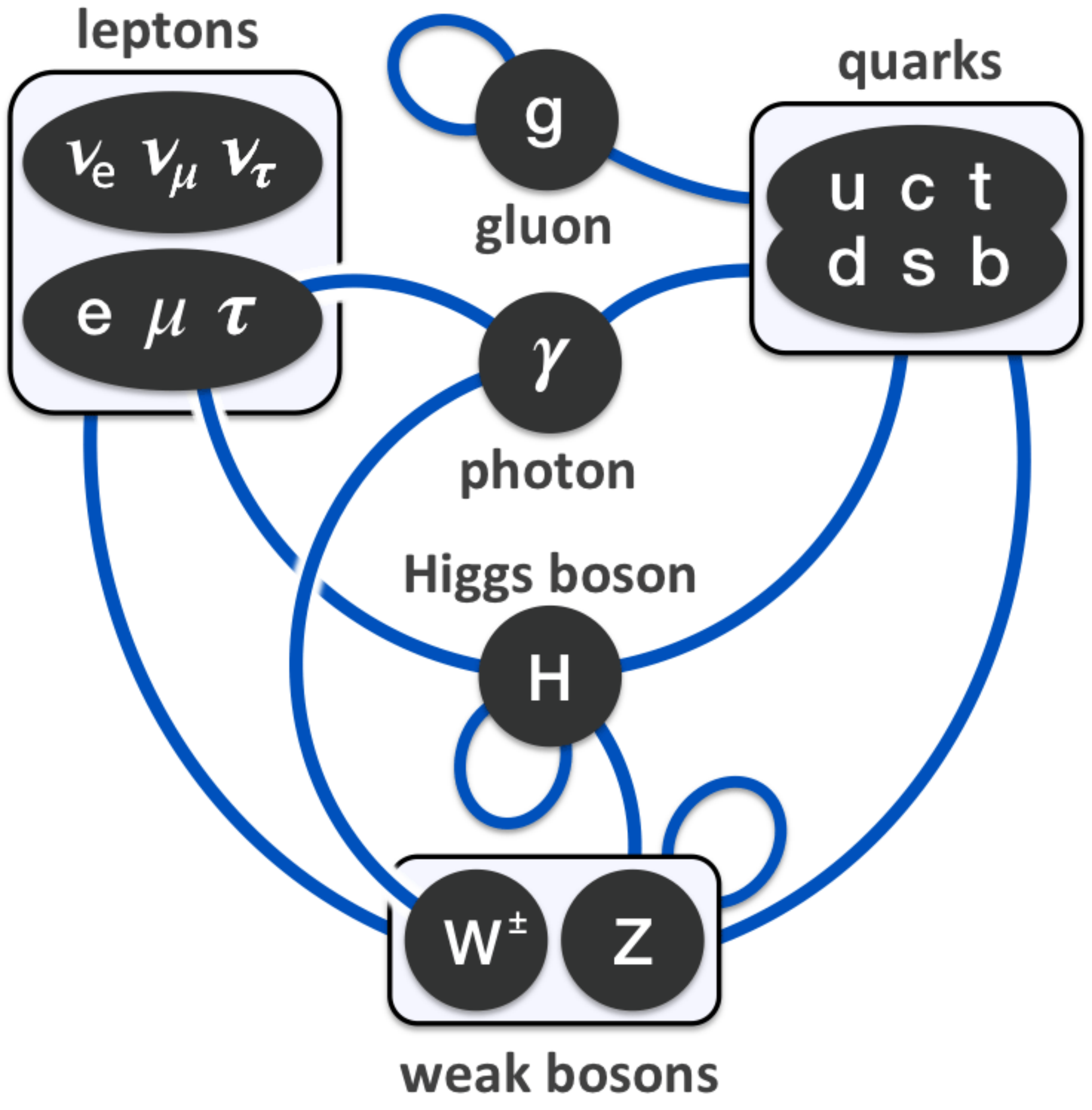
Physics Milestone	Exposure (staged years)
5σ mass ordering ($\delta_{CP} = -\pi/2$)	1
5σ mass ordering (100% of δ_{CP} values)	2
3σ CPV ($\delta_{CP} = -\pi/2$)	3
3σ CPV (50% of δ_{CP} values)	5
5σ CPV ($\delta_{CP} = -\pi/2$)	7
5σ CPV (50% of δ_{CP} values)	10
3σ CPV (75% of δ_{CP} values)	13
δ_{CP} 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



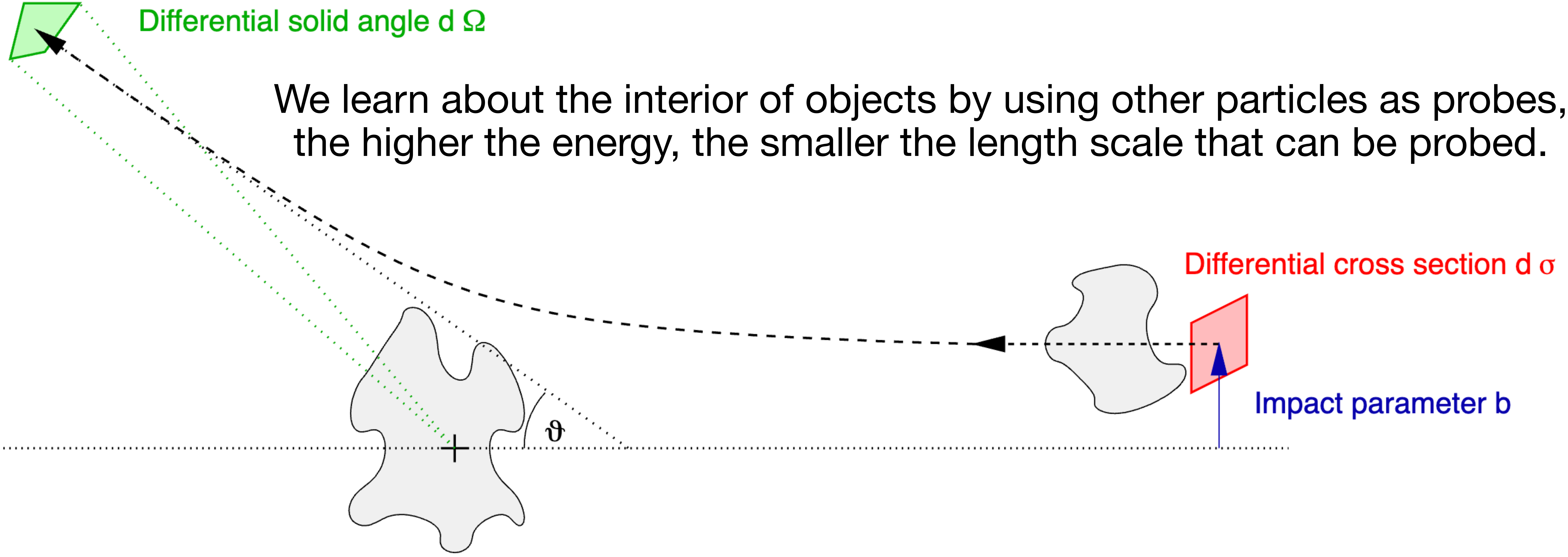


Neutrinos have a very low cross-section and thus interact very rarely compared to other types of particles (10^{-14} difference from electron scattering). *Very difficult to measure.*

Particle Physics, Scattering, and Cross Sections

Particle Scattering is How We Learn About the Universe

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.



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

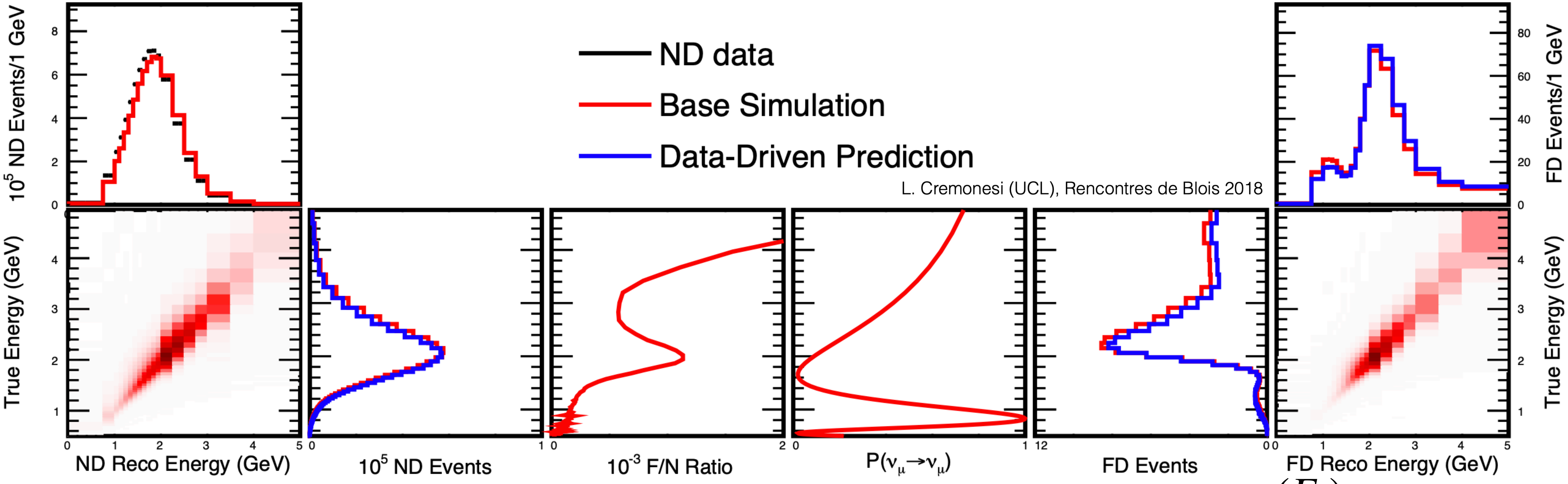
How to Do an Oscillations Analysis

A Brief Conceptual Overview for Experiments Like DUNE

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

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

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



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

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

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

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.

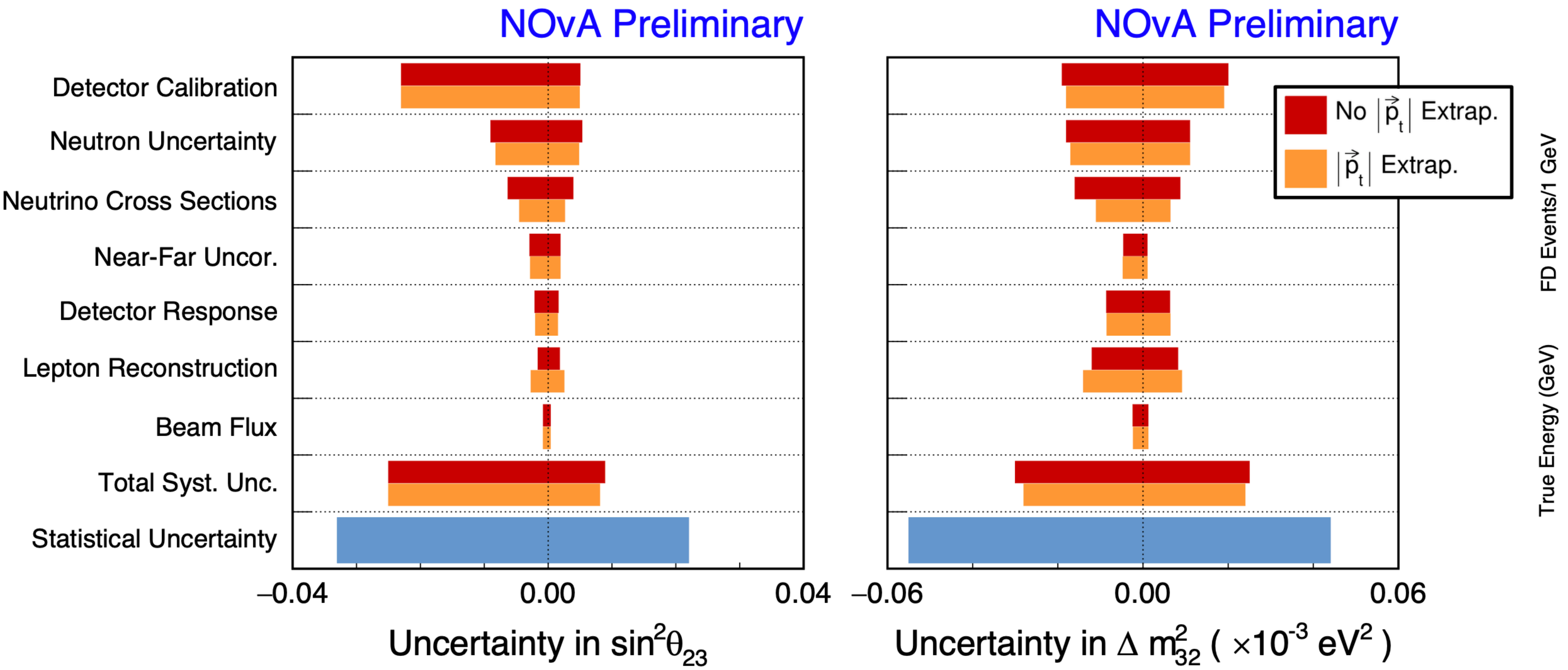
Hard to detect neutral particles.

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!