High Energy Physics at BNL

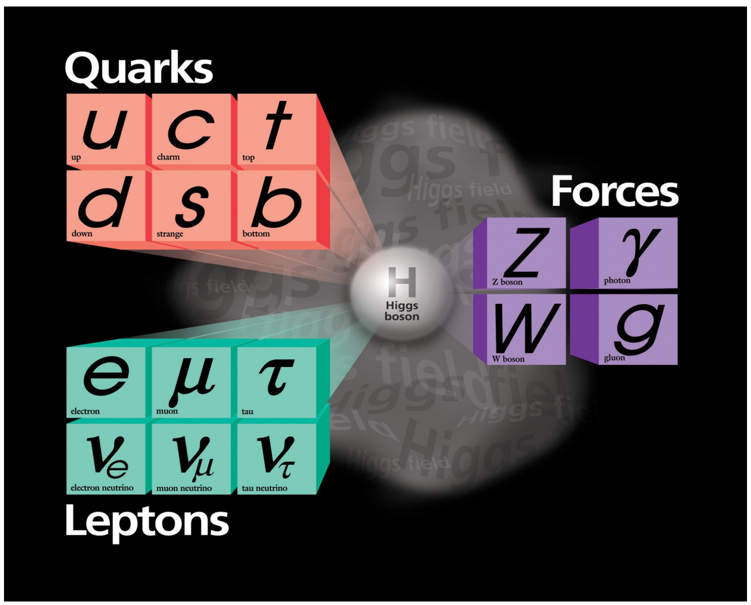
S. Dawson, BNL, June 29, 2026

Efforts at BNL

- Centered around precision tests of the Standard Model
- Searching for deviations from Standard Model
- 4 groups: High Energy Theory, Astrophysics and Cosmology, Electronic Detector Group, Omega Group

Standard Model is a framework

- Particle physics has a "Standard Model" of particles and their interactions



- Quarks come in pairs with charge 2/3 e and -1/3 e
- Each lepton has its own neutrino
- Force carriers communicate between quarks and leptons

Muon ν discovered at BNL in 1962

$p+Be \rightarrow \pi \rightarrow \mu\nu$, $\nu N \rightarrow \mu\nu$

Particle spectroscopy

- In nature, we see pions:

$$\pi^+ = (u\bar{d}) \qquad \pi^- = (d\bar{u}) \qquad \pi^0 = \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$$

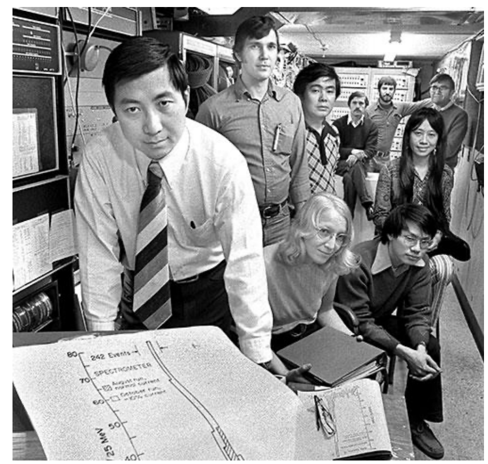
  - Pion was discovered in cosmic rays in 1947

$K^- p \to \Omega^- K^+ K^0$

- Kaons also seen in cosmic rays

$$K^+ = (u\bar{s})$$

- (sss) (Ω^-) discovered at BNL in 1964
- Heavier quarks have to be made at accelerators
- $J/\psi = (c\bar{c})$ discovered at BNL/SLAC in November, 1974

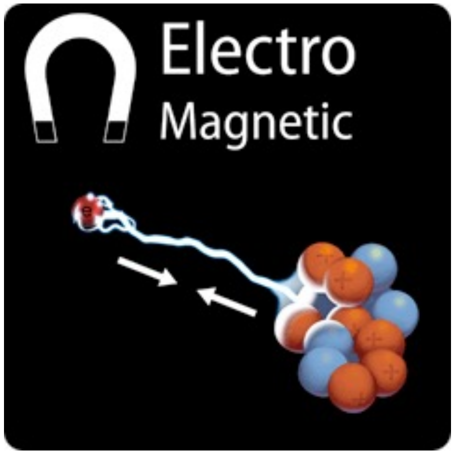


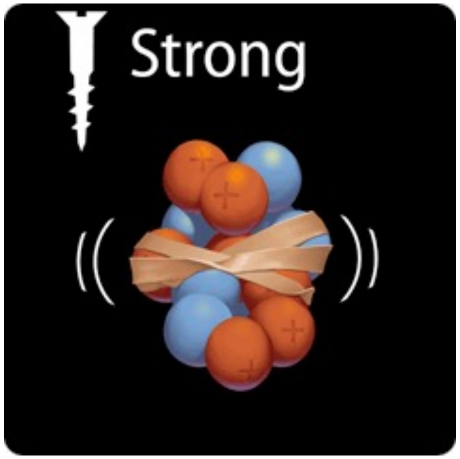
$K^- p \to \Omega^- K^+ K^0$

$pA \to e^+e^-$ (bump)

Forces

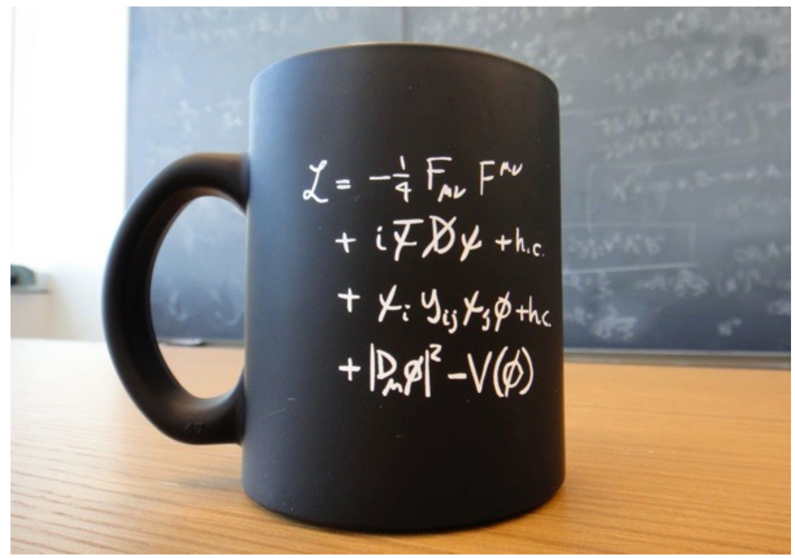
- Electromagnetism explains electricity and magnetism (Maxwell)
- Weak force explains radioactivity (Fermi, 1933)
- Strong force explains why quarks are bound in protons
- Gravity seems simple…..





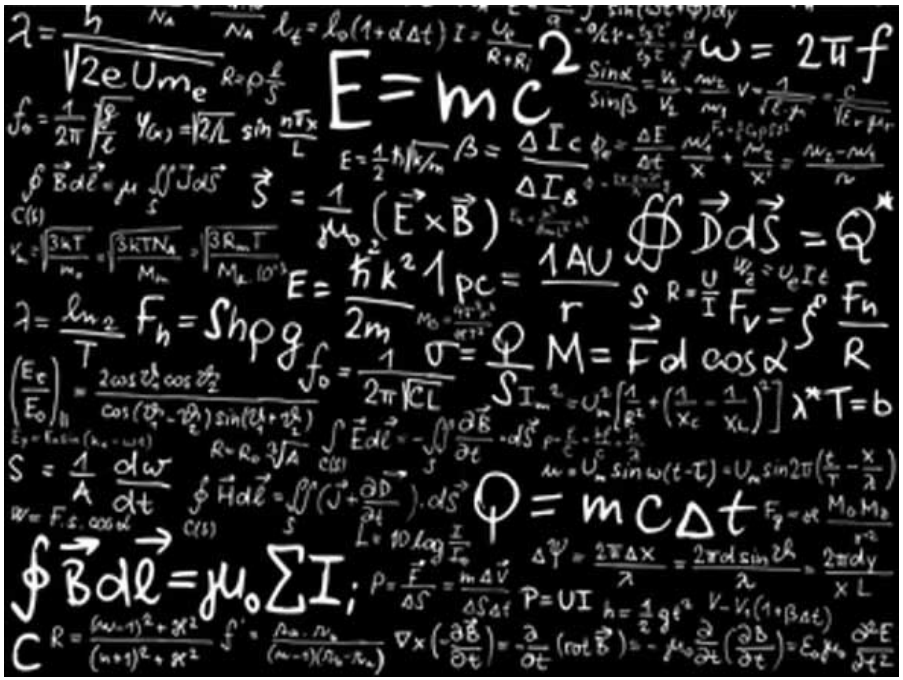
The Standard Model is Simple and predictive

- The fact that the SM is predictive has fundamental impact
  - Theory group and ATLAS group probe SM
- Neutrino masses are not part of the Standard Model and require new physics
- Understanding neutrino masses is central to the theory effort and the EDG efforts



Gauge theories for particle physics started with Yang-Mills @ BNL in 1953

Since the 1960's we have constructed a picture of how the forces interact with particles



TRUST, BUT VERIFY

The Standard Model without the Higgs has massless particles

- The gauge bosons are massless without the Higgs
  - Experimentally: M_W=80 GeV, M_Z=91 GeV, m_g, m_γ=0
- The fermions are massless without the Higgs
  - Experimentally: m_{top}=173 GeV

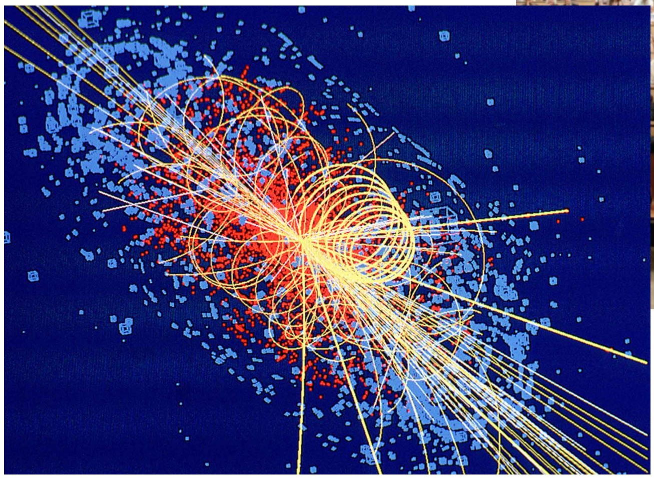
Not a small effect

The entire reason for the Higgs boson is to explain masses

Much of the effort of the theory group and the ATLAS group is centered around the Higgs boson

In the last 15 years…

- 2012: LHC discovered a Higgs boson; it appears to have predicted properties



Announced on July 4, 2012 at 9 am Geneva time

Count free parameters

- Masses of fermions: 6 quarks, 3 charged leptons
  - Also 3 x 3 mixing matrix involving quark masses (3 angles, 1 phase)
  - By definition, neutrinos are massless in the Standard Model
  - Incorporating neutrino masses requires extension of Standard Model
- 3 gauge coupling constants
- Higgs boson mass is completely free parameter
- A CP parameter

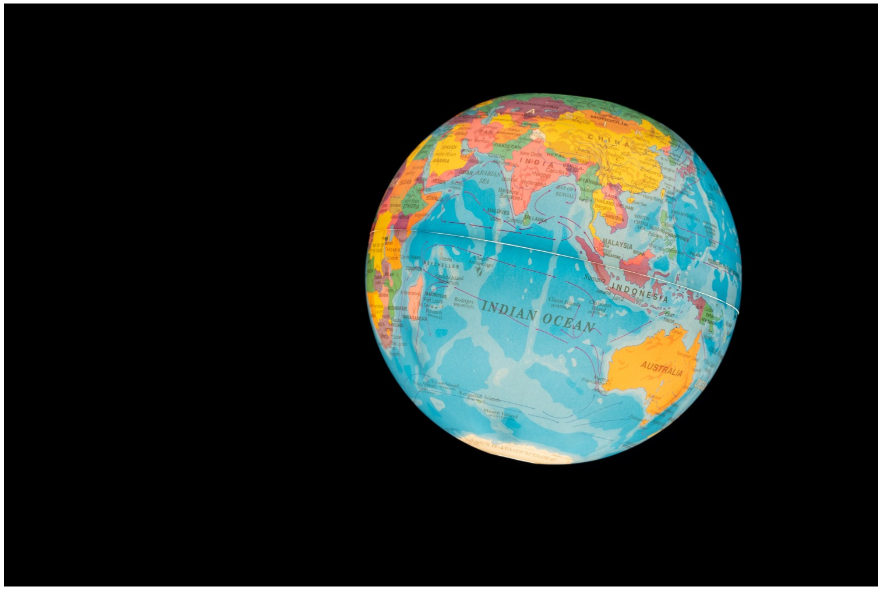
All particle interactions predicted in terms of these 18 parameters:
A PREDICTIVE THEORY

Everything we have measured

(Almost) everything is consistent with this picture of physics above 1 TeV

But we are not finished

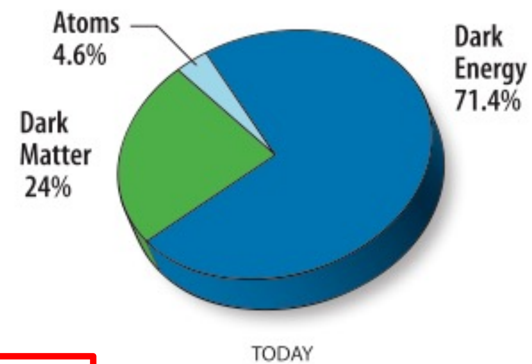
- The discovery of the Higgs changed everything
- But yet, it leaves us with many unanswered questions
- Opportunities for discovery!



It's the beginning, not the end of the story

Theorists aren't happy with SM

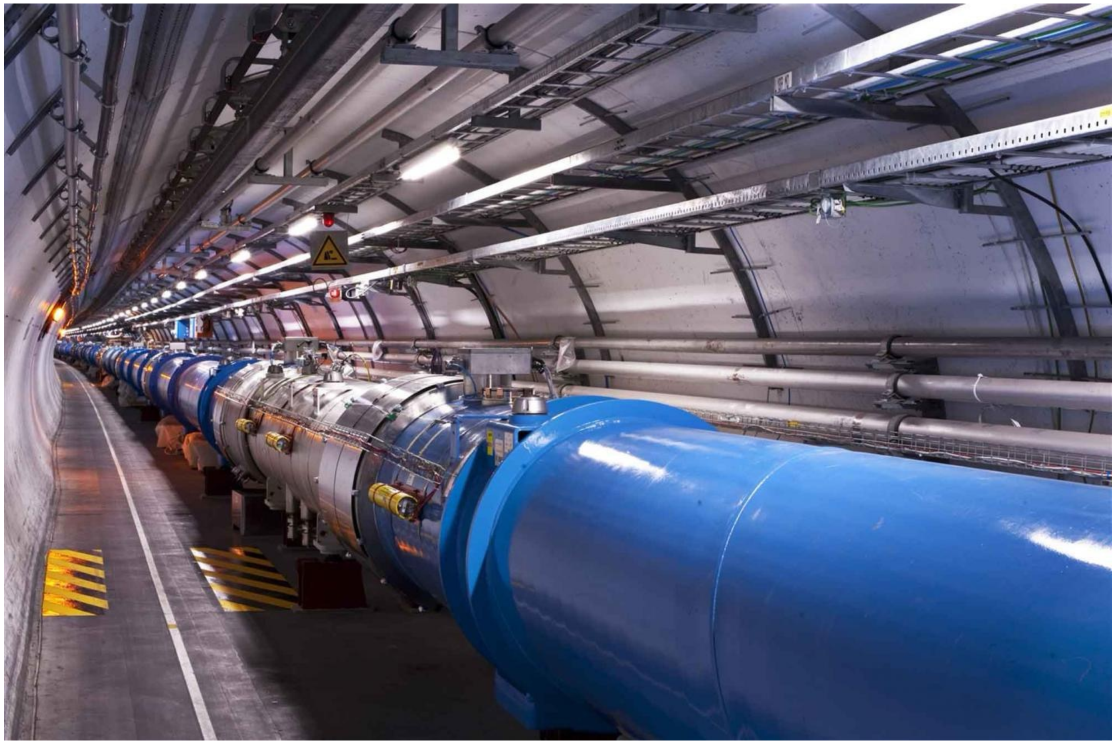
- What is dark matter and dark energy?
- Attempt to answer this question has inspired countless models



A theory of everything would answer these questions

Efforts in theory group to answer "what is dark matter?", and in Omega group to look for particles connected with explanations of dark matter

Omega group is focused on LHC

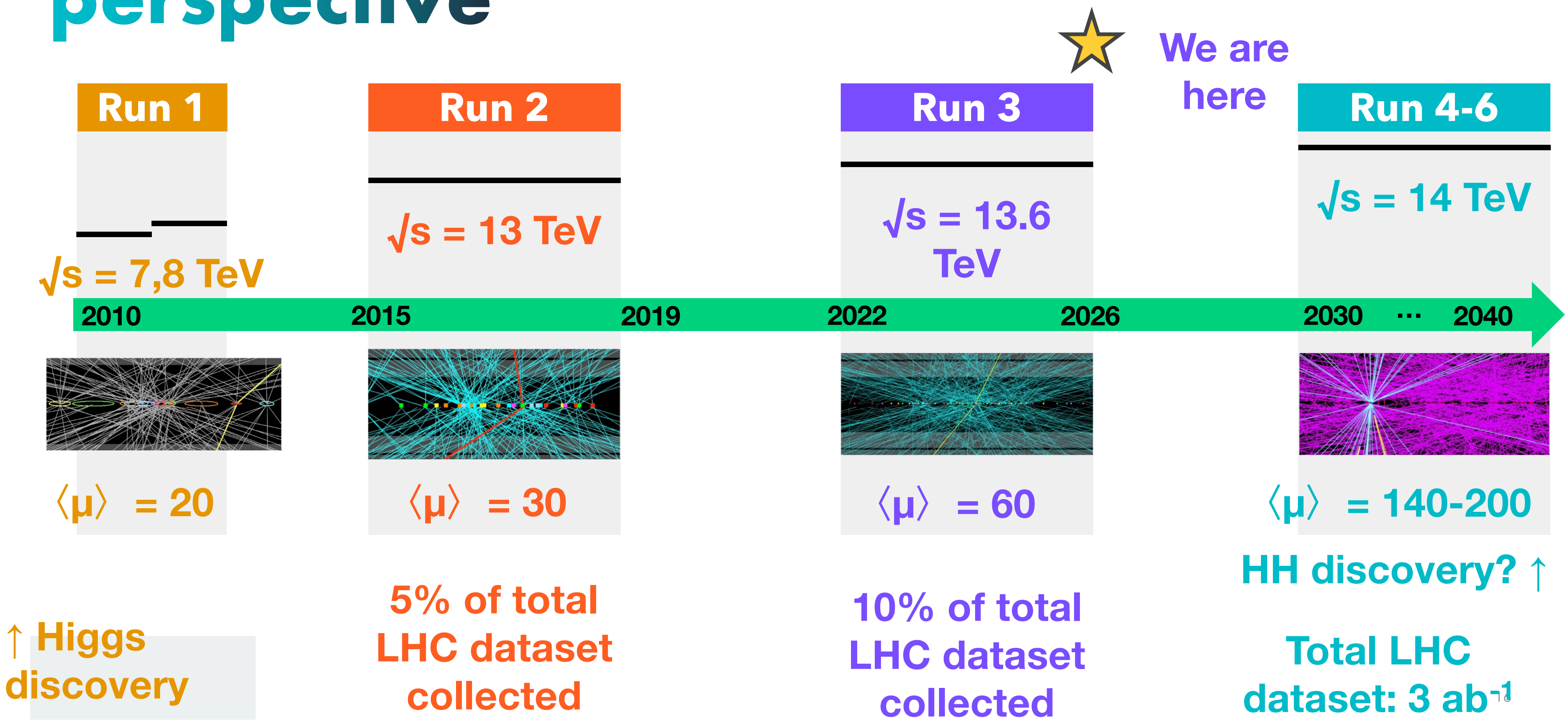


Large group ~ 70 FTE

Long-term planning

Shutdown from July, 2026 to 2030

The LHC schedule, from the ATLAS perspective



ATLAS Program at BNL

A major contributor to ATLAS since its beginning

- based on pioneering work on hadron-collider experiments — ISR in 1970's, D0 since 1980's, GEM for SSC

Essential strategy: *from physics → detector → software → performance → physics*

- our interests match with our expertise
- physics analyses benefit from our extensive detector domain knowledge

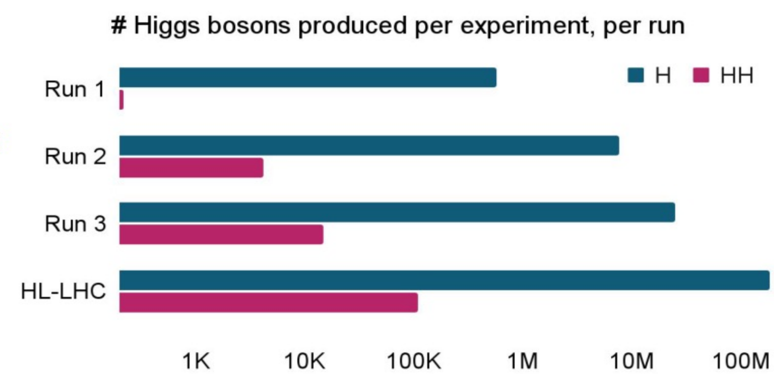
Strong presence at CERN an important factor in our success

- establishing collaborative efforts between BNL and other ATLAS institutes

BNL is well recognized in ATLAS and in broader community

oftware, trigger

- Brost, Cavaliere, and Tricoli won Early Career Awards



We're committed to long-term success of ATLAS

- only place to study Higgs and many other particles for ~20 years
- x10 data set still to come
- complex challenges remain in analysis & computing
  → excellent training ground for early career scientists

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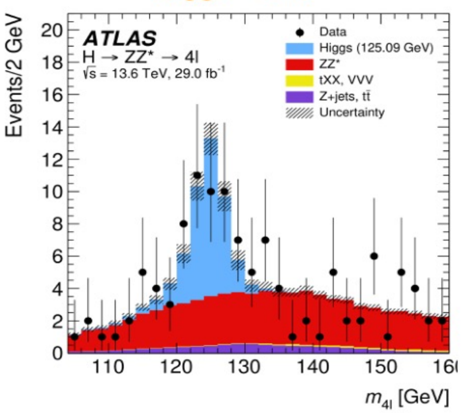
Physics

Higgs & Electroweak Symmetry Breaking is our flagship physics topic

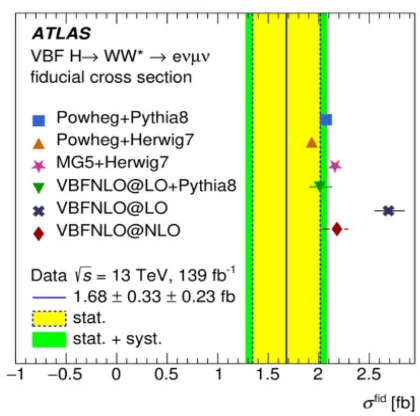
- crucial avenue to leverage in searches for new physical phenomena including Dark Matter
- aligned with P5 science drivers
- lead key analyses on ATLAS

Higgs → ZZ*



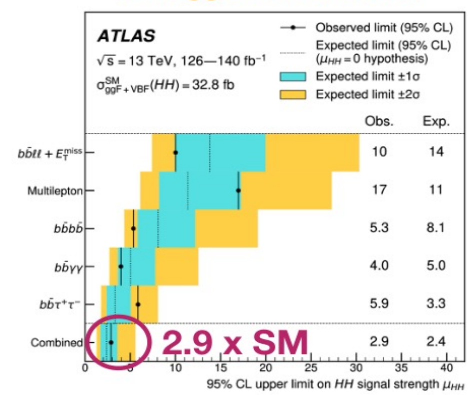
First measurements of Higgs boson using Run 3 data at √s=13.6 TeV. Highlights commissioning ATLAS Phase-I upgrades

Higgs → WW



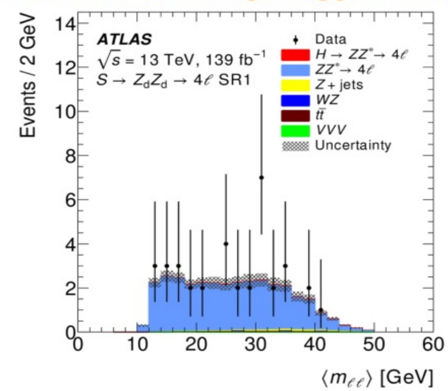
Tricoli ECA: first pure Higgs Vector Boson Fusion measurement of fiducial cross section in this channel

DiHiggs Combination



~50% better than expected from luminosity compared to previous result → driven by improved ML in object ID

Dark Matter through Higgs Portal



Search for S → Z_dZ_d → 4l. 2.7 (1.6) sigma local (global) excess.

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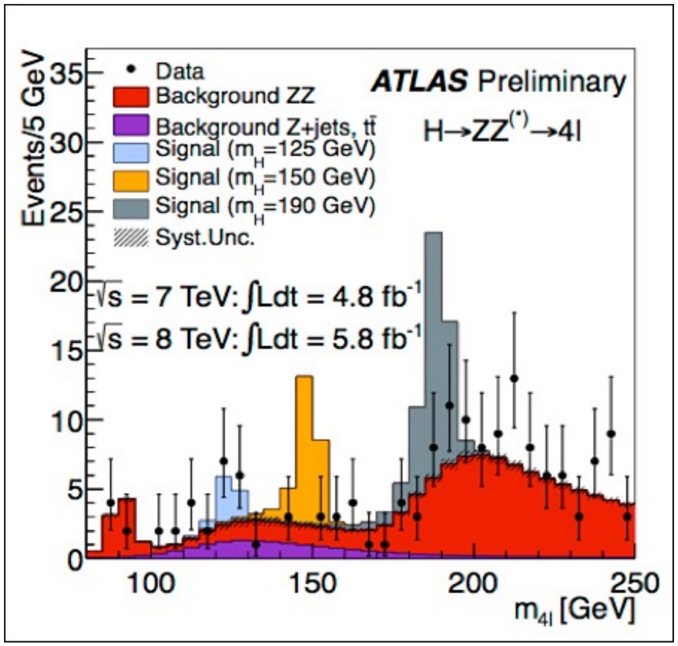
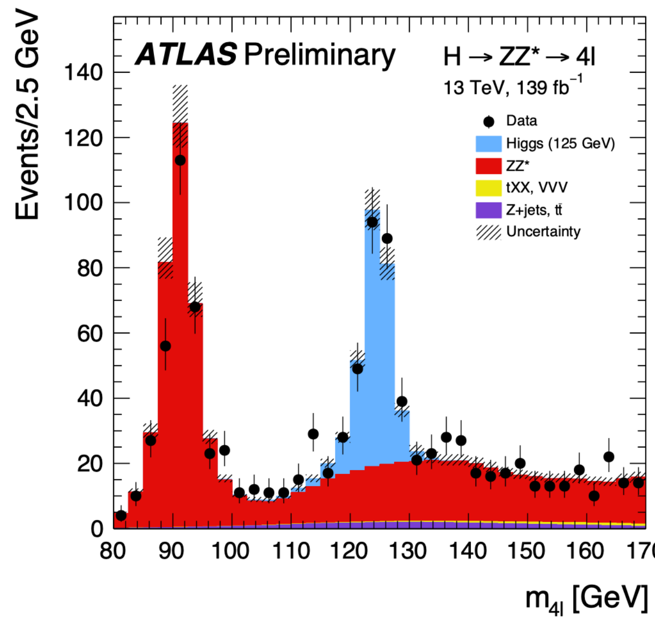
Discovery to precision

2012



2022

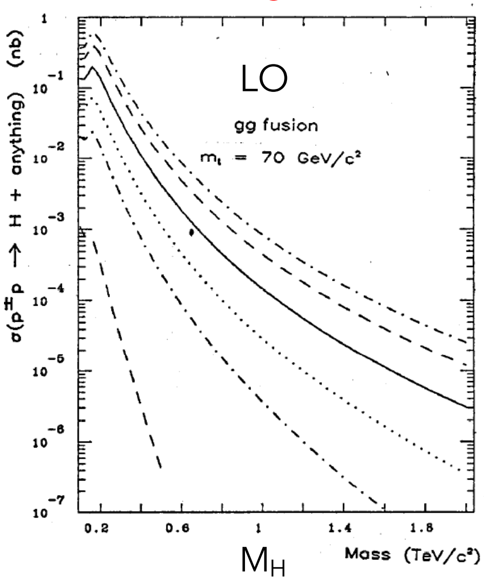


More events, smaller uncertainties

Precision physics at the LHC

- Can you do precision physics at a hadron collider? YES!

1984



M_H

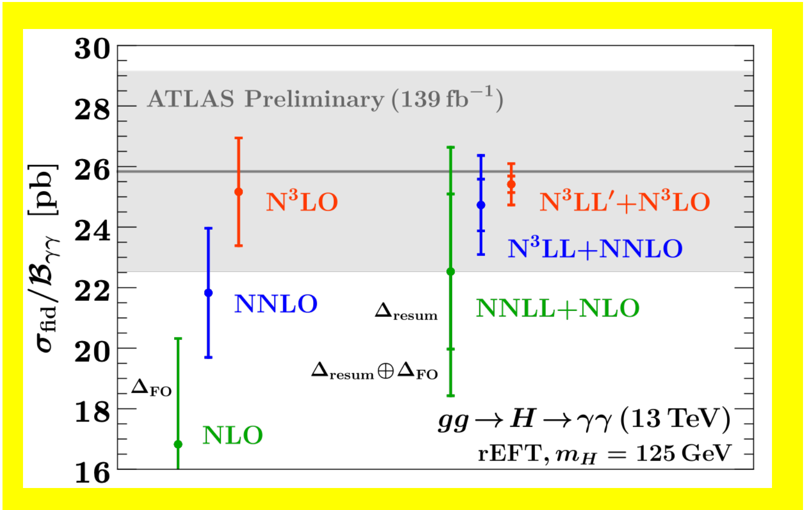
$\sqrt{S}$=2,10,20,40,70,100 TeV

EHLO

Major lesson from last 14 years at LHC: Higgs physics is precision physics

Despite progress, theory uncertainties are expected to dominate Higgs results at LHC

2025



Current uncertainty ~O(3%)

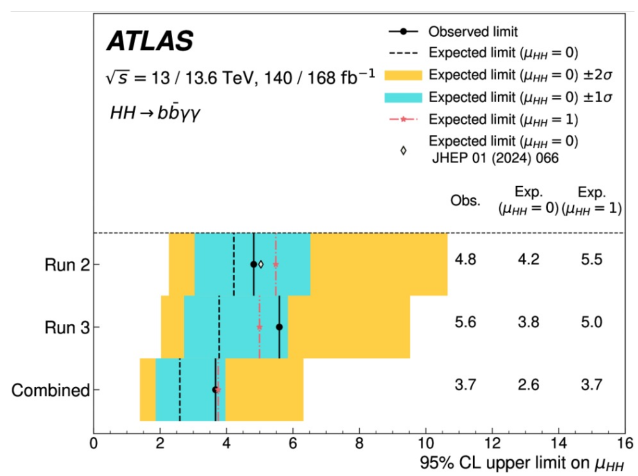
Synergy of Omega group and Theory Group

Searching for Higgs pair production

- **Higgs pair production is rare in the Standard Model**
  - 1000x more rare than producing one Higgs!
  - Direct access to the Higgs self-coupling ← PREDICTED
- **Why are we searching for it already, then?**
  - If we observe this process now, it's a clear sign of new physics

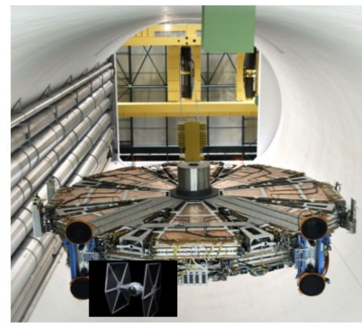
Eventual measurement of HH production needed to verify accuracy of SM

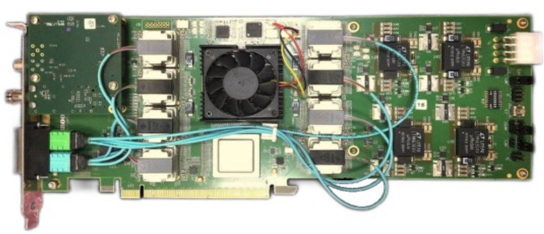
Major effort of BNL ATLAS GROUP

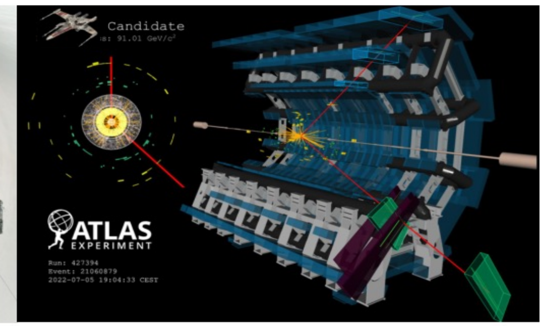


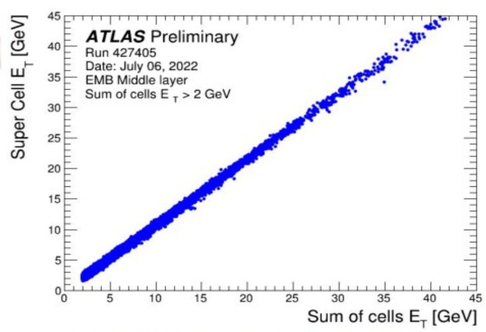
Operating LHC Run 3

BNL had many crucial Phase-I Upgrade deliverables for Run 3 based upon our scope from original construction:



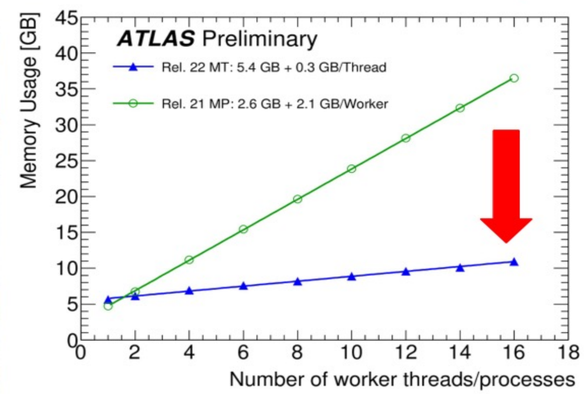






Linearity of LTDB supercell energies vs precision readout.

Jennifer Roloff (PD) installing the gFEX module at CERN.



Improvement in memory utilization from multi-threaded code.

U.S. ATLAS

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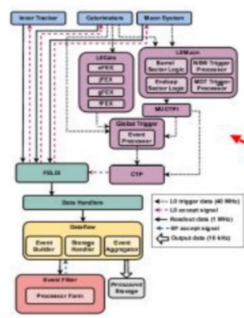
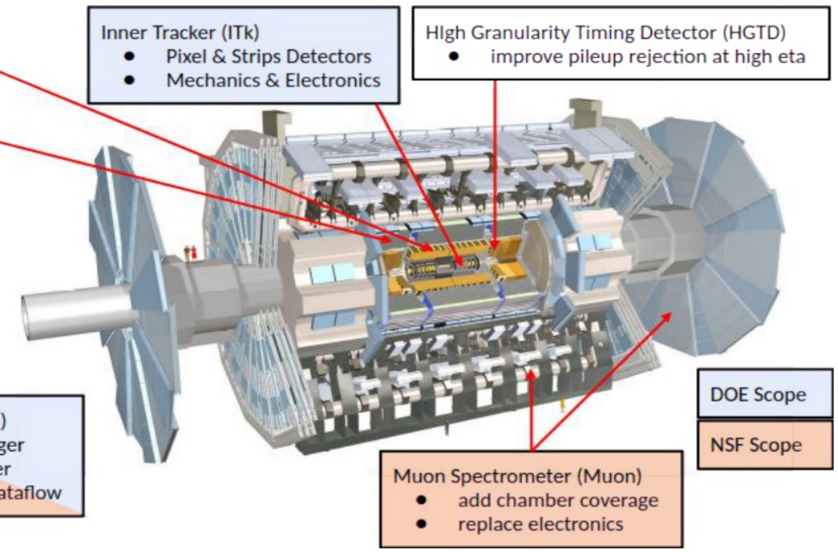
ANL, Arizona, UT Arlington, UT Austin, Berkeley, LBNL , Boston, Boulder, Brandeis, BNL, Chicago, Columbia, Duke, CalState Consortium (East Bay, Sacramento, Stanislaus), Harvard, Indiana, Iowa, LLNL, Louisiana Tech, Louisville, U Mass Amherst, Michigan, Michigan State, NYU, New Mexico, Northern Illinois, Ohio State, Oklahoma, Oklahoma State, Oregon, Pennsylvania, Pittsburgh, SLAC, UC Santa Cruz, Washington, Washington College, SMU, Stanford, Stony Brook, Tufts, UC Irvine, UI Urbana Champaign, Westmont College, Wisconsin, Yale





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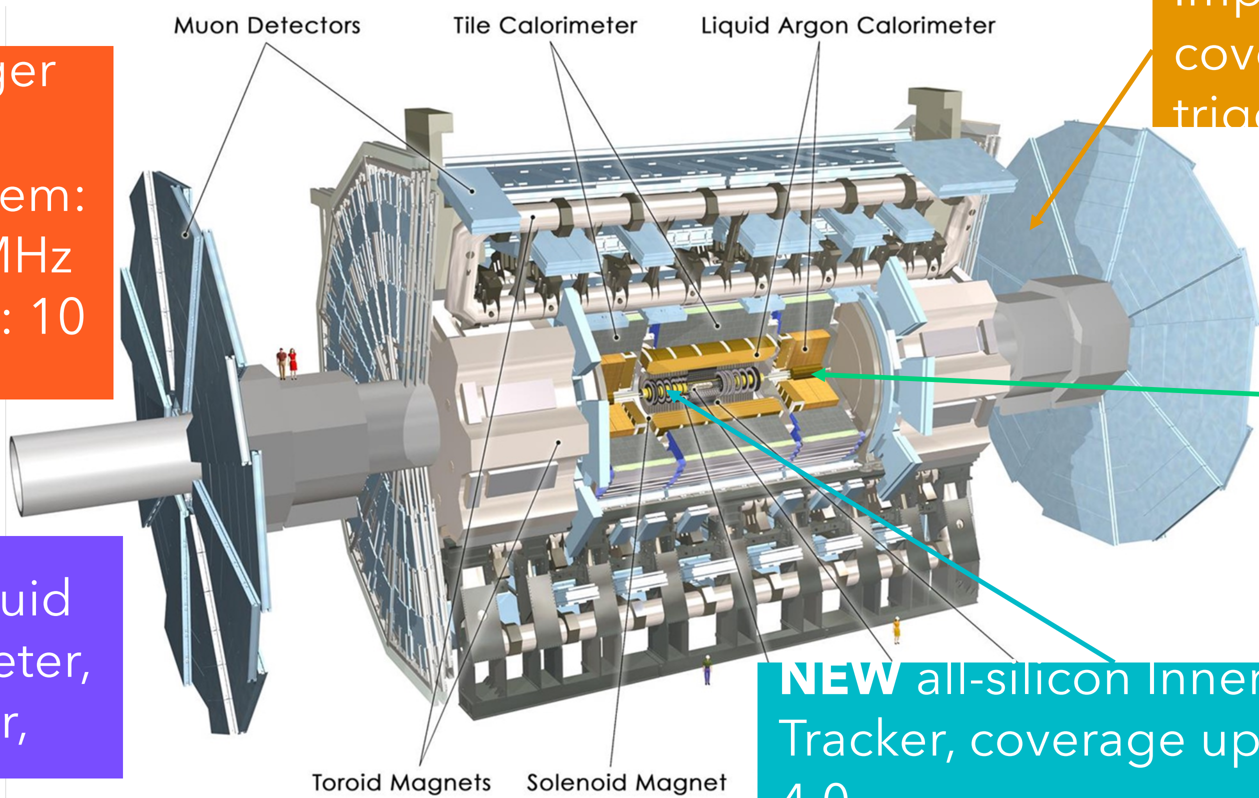
ATLAS Detector Upgrade

Upgraded Trigger and Data Acquisition system:

- L0 rate: 1 MHz
- Event Filter: 10 kHz

Upgraded electronics: Liquid Argon Calorimeter, Tile Calorimeter, Muon system



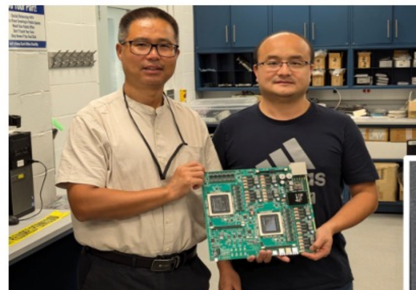
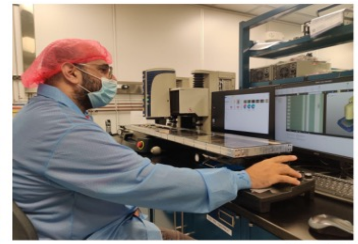
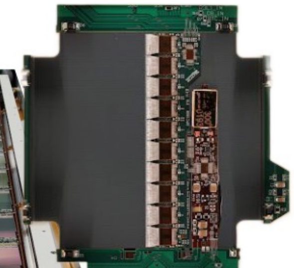
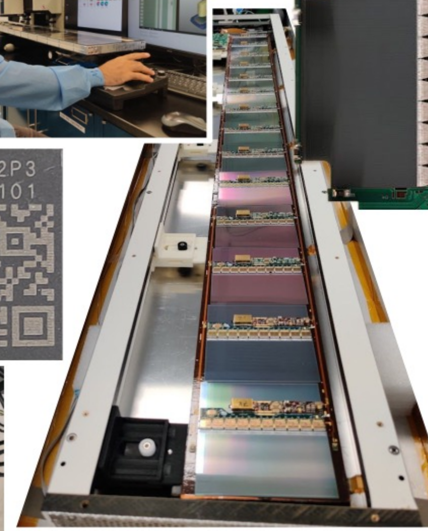
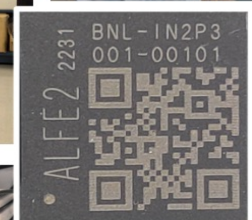
Improved muon coverage and trigger

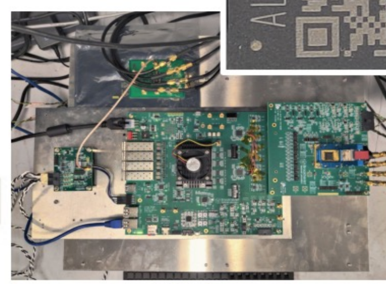
NEW endcap high - granularity timing detector

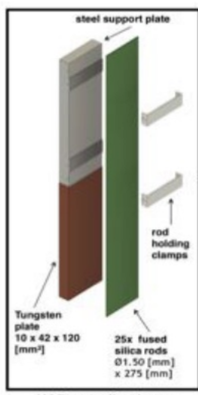
NEW all-silicon Inner Tracker, coverage up to |η|= 4.0

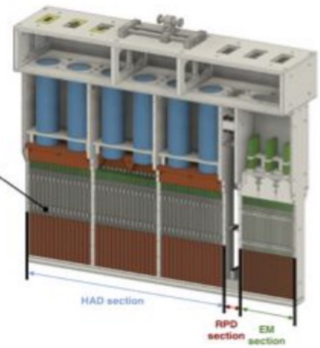
Executing HL-LHC Upgrade

Significant contributions in ATLAS & U.S. ATLAS Projects



HAD sampling layer


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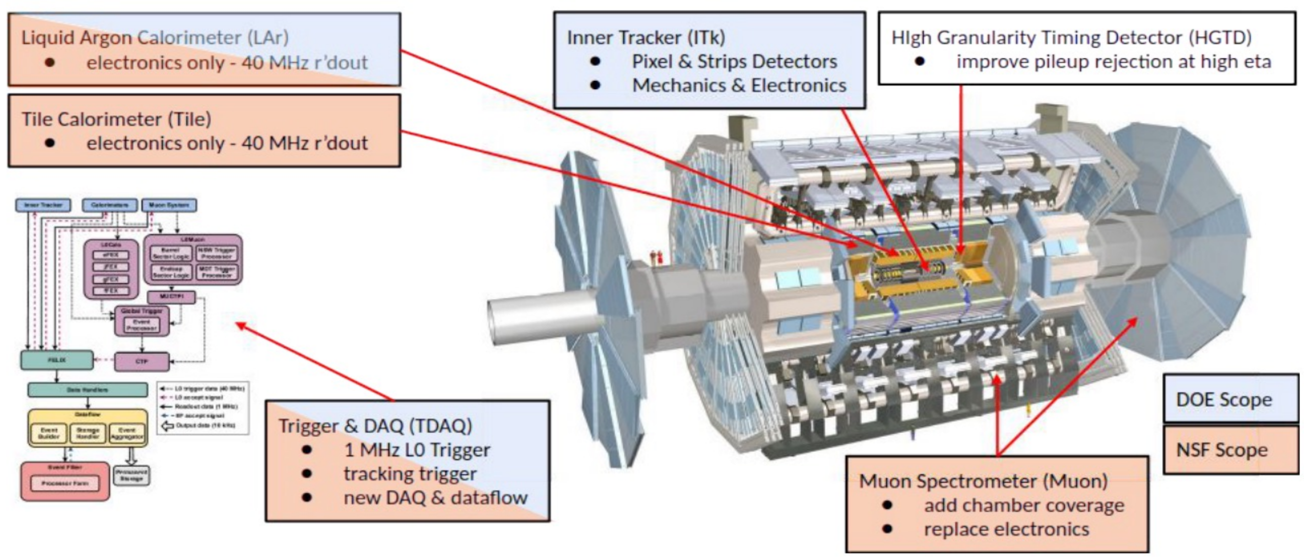
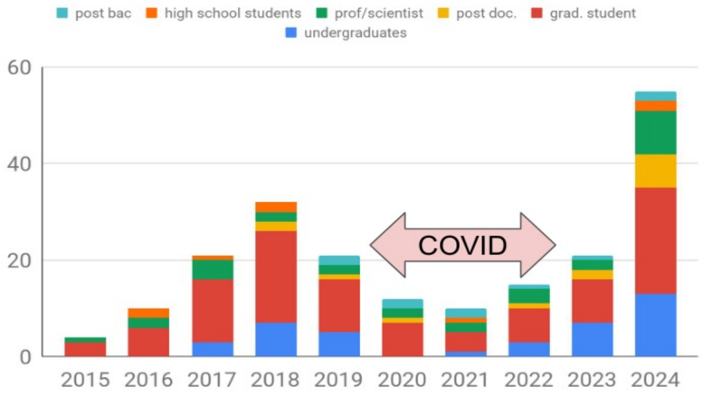
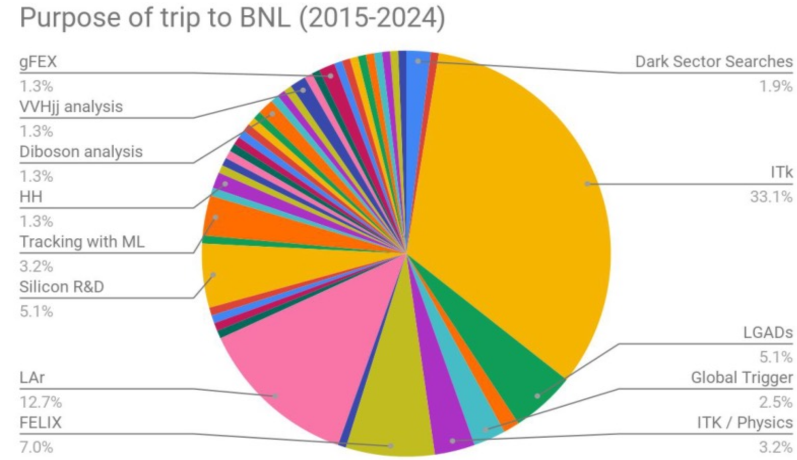


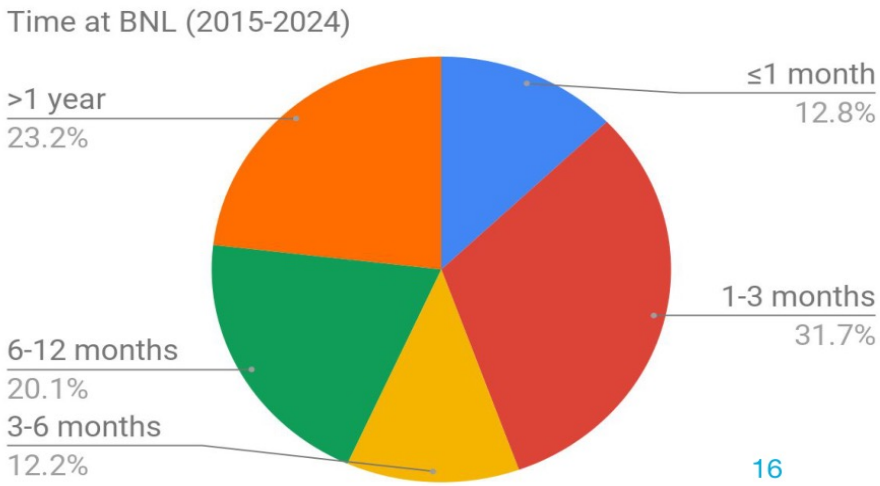
U.S. ATLAS Center

BNL is one of four host laboratories

- hosted ~55 long-term visitors in FY24
    - UMass Amherst, Arizona, Bard, Brandeis, CERN, UC Davis, Duke, Florida International, Indiana, Helsinki,Hiroshima, McGill, New Mexico, NYU, NCSU, Oregon, Nikhef, SUNY Old Westbury, SMU, Yale
    - *African School of Physics:* ITNA Senegal, Johannesburg, Lomé Togo, Mohammed V, Nairobi







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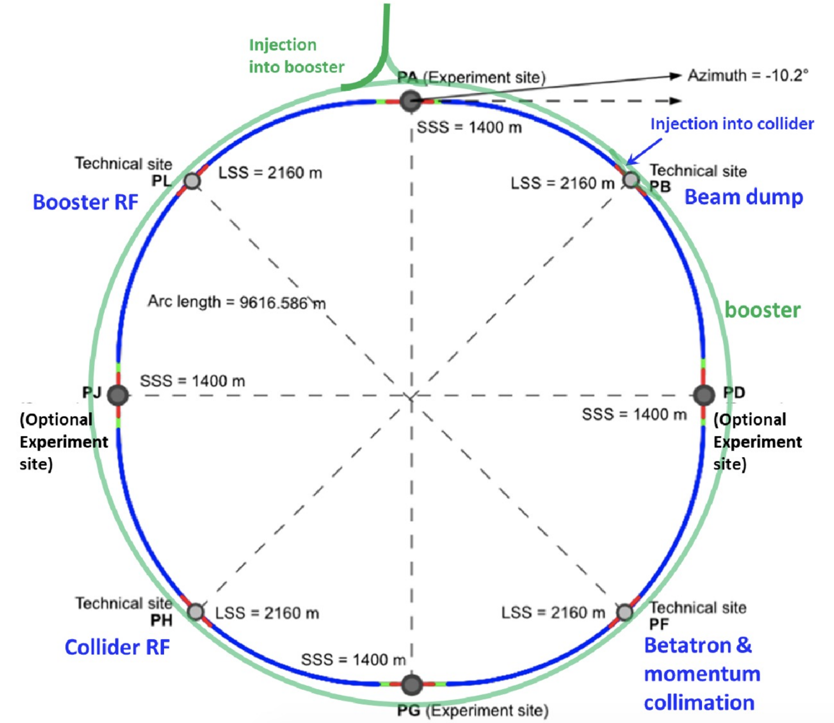
Future Circular Collider (FCC)

- Proposed 91 km collider near CERN
  - 4 interaction points
- Planned to start shortly after HL-LHC operations end
- **Stage 1:** e^+e^- Higgs (& electroweak & top) factory to run at 4(+) energy points
- **Stage 2:** O(100 TeV) proton-proton

BNL Omega group heavily involved in planning for future detectors @ FCC-ee



FCC-ee baseline

FCC-ee run plan

Z	WW	ZH	ttbar
(88-95 GeV)	(158-162 GeV)	(240 GeV)	(345-365 GeV)
205 ab^{-1}	19.2 ab^{-1}	10.8 ab^{-1}	2.7 ab^{-1}

- **4 yrs @ Z (LEP1 data accumulated every 2 minutes - 10^{13} Z)**
    - Z mass, width, electroweak precision measurements, flavor
- **2 yrs @ WW (10^8 W)**
    - W mass, W width, electroweak precision measurements
- **3 yrs @ ZH (10^6 $e^+e^- \rightarrow ZH$)**
    - Model-independent Higgs xs, Higgs couplings, Higgs self-coupling input
- **5 yrs @ ttbar (10^6 ttbar pairs)**
    - Top mass, top width, WW→H, Higgs self-coupling input
- **s-channel H? (5000 $e^+e^- \rightarrow H$ in 5? years)**

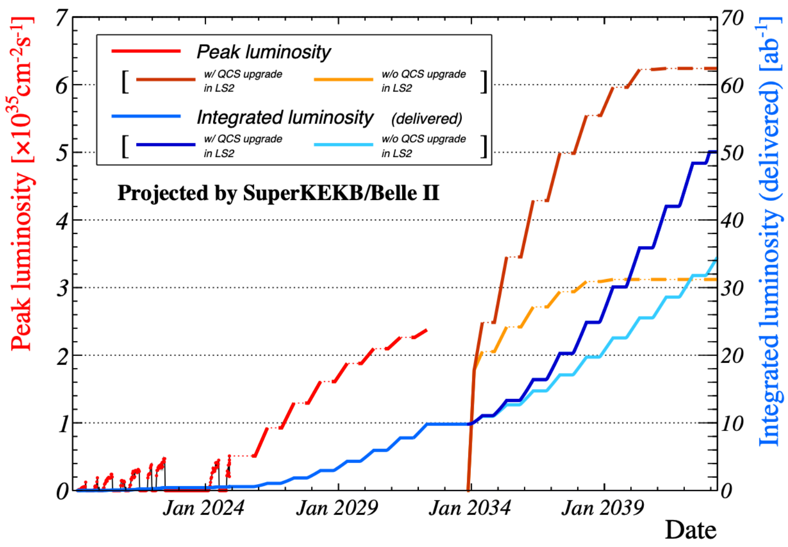
Electronic Detector group

- Long history of kaon physics
- Currently, major effort is neutrino physics at DUNE experiment
  - Leadership in other neutrino experiments
- Smaller effort on Belle-II in Japan

Belle-II at BNL

Belle-II is $e^+ e^-$ collider with energy at $\Upsilon(4S)$ resonance (10.58 GeV) looking for $B\overline{B}$ pairs

BNL supports US computing /US operations for Belle-II



Long term program

Do neutrinos really oscillate?

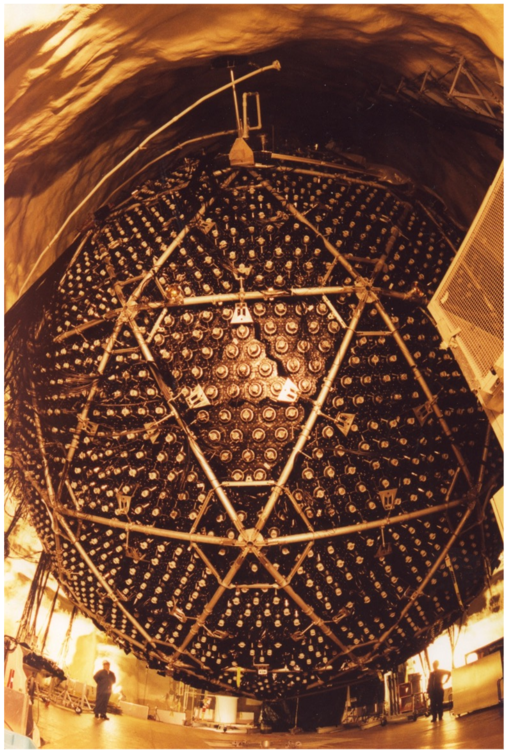
Can a ν_μ turn into a ν_e?

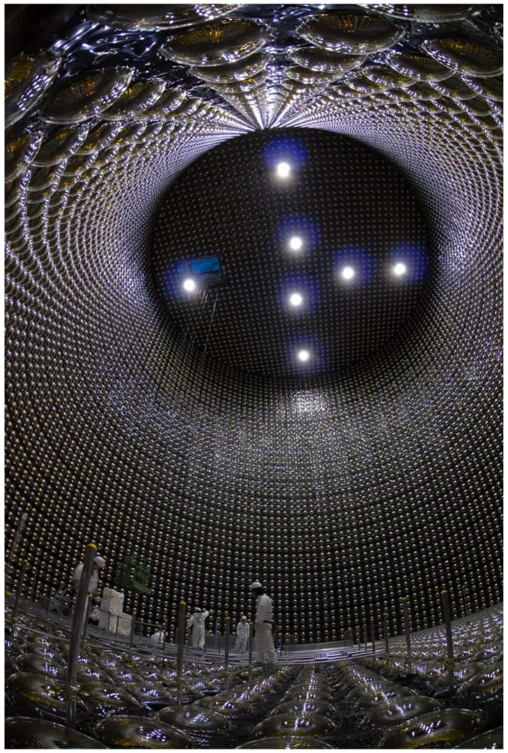
Yes! **SNO** looked at channels sensitive to all neutrino flavours from the Sun, and **Super Kamiokande** showed **strong dependence for oscillation on the path length** from production to detection

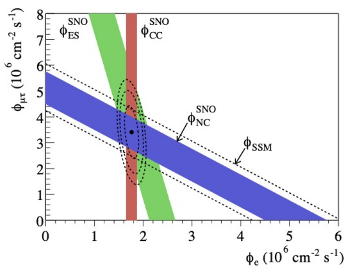
The 2015 Nobel Prize for Physics was awarded to **Arthur B McDonald (director of SNOlab)** and **Takaaki Kajita (SuperKamiokande):**

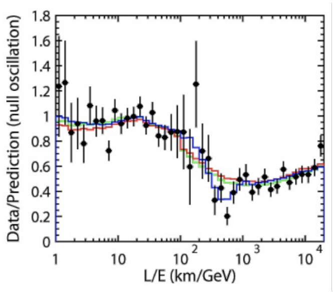
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

This is considered the start of "modern neutrino physics"!







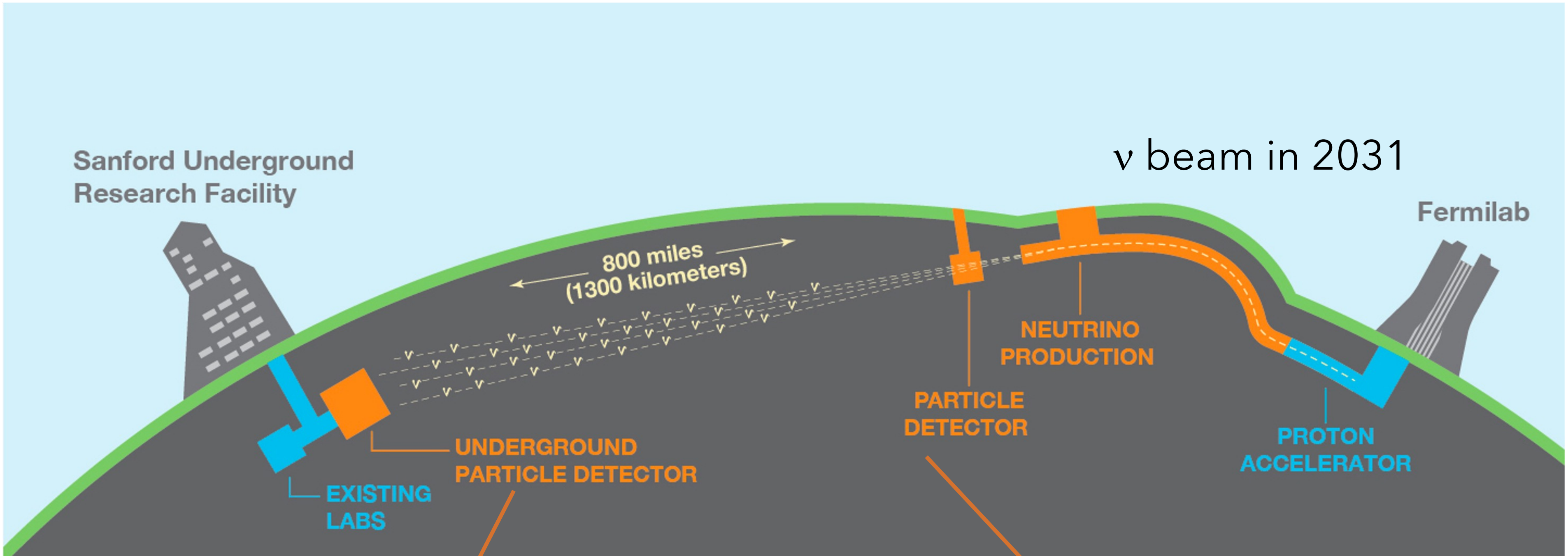


Neutrinos

- What is a Neutrino?
- Neutrinos have flavors?
- Neutrinos have mass?
- Neutrino Sources?
- How do Neutrinos interact?
    - (Only very weakly)
- Can we see Neutrinos?
    - (Hard since they only interact weakly)

Theory/EDG efforts to understand neutrino masses and mixing

DUNE Experimental Design

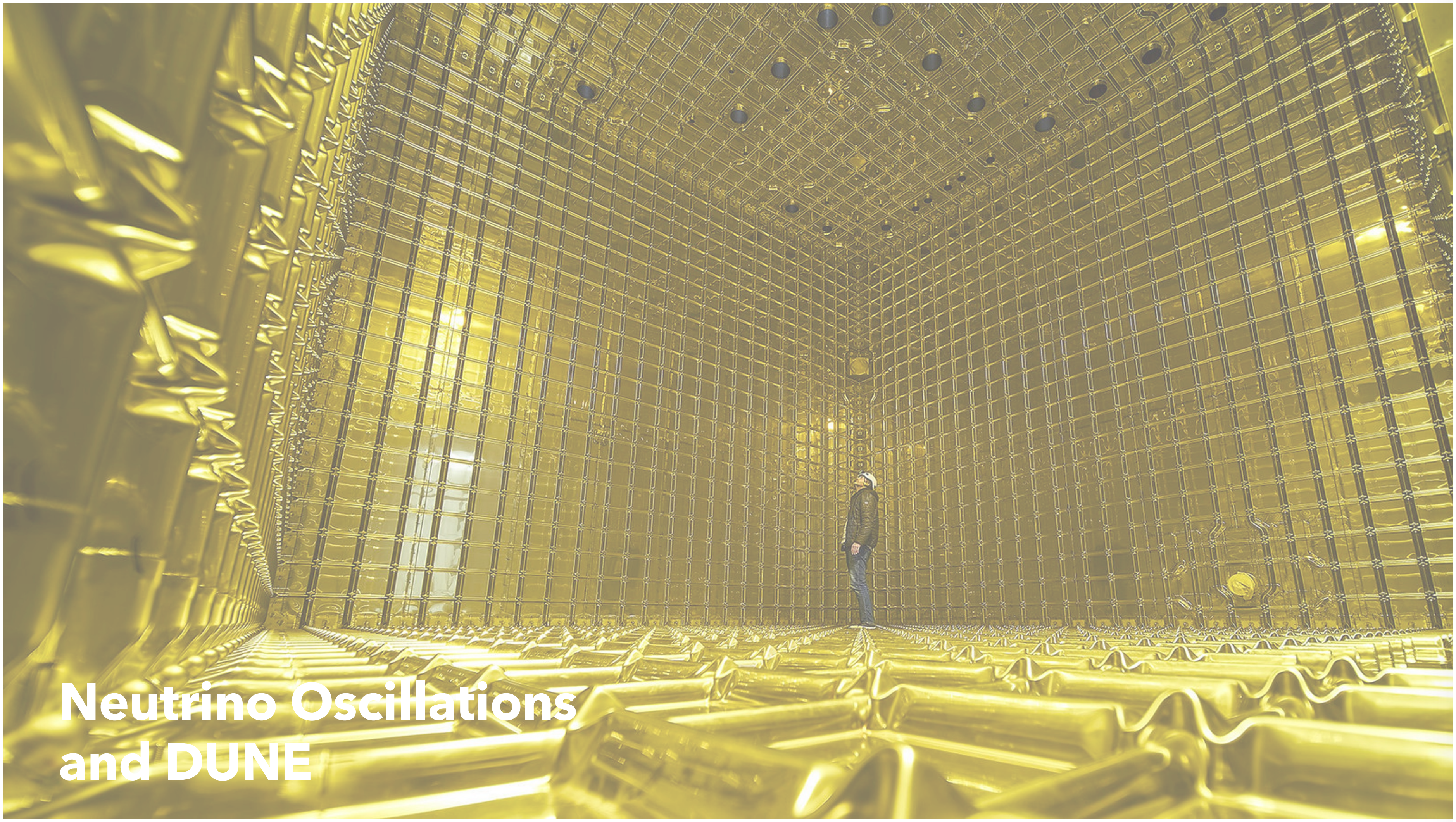


Far Site

- *1300km from the proton source*
- *very large LAr TPCs (each 17 ktons)*
- *underground in South Dakota*

Near Site

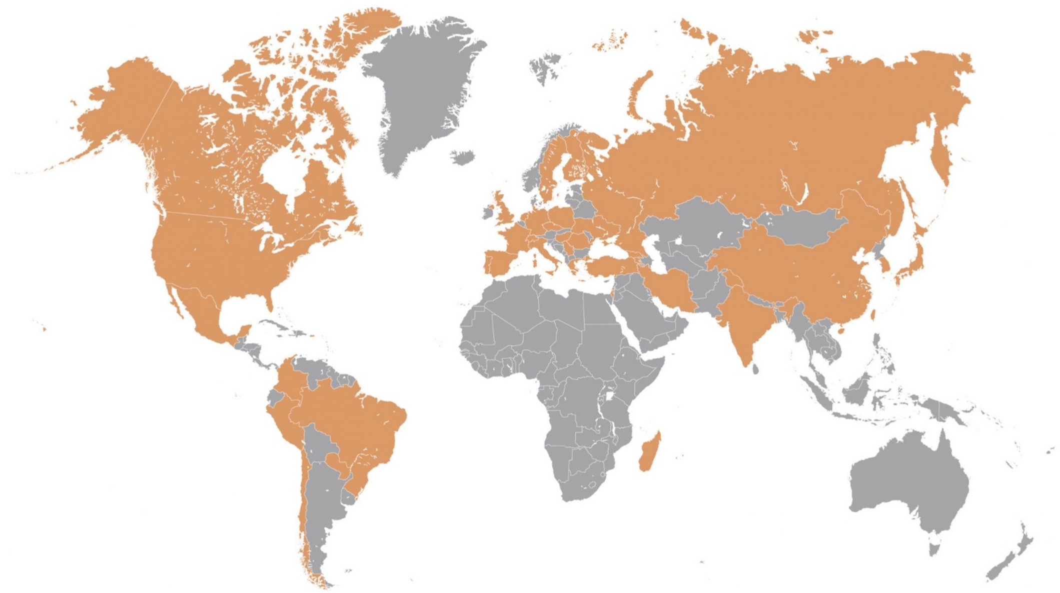
- *550m from proton source*
- *on-site at Fermilab*
- *both stationary & moveable detectors*



Neutrino Oscillations and DUNE

Mateus F. Carneiro

DEEP UNDERGROUND NEUTRINO EXPERIMENT

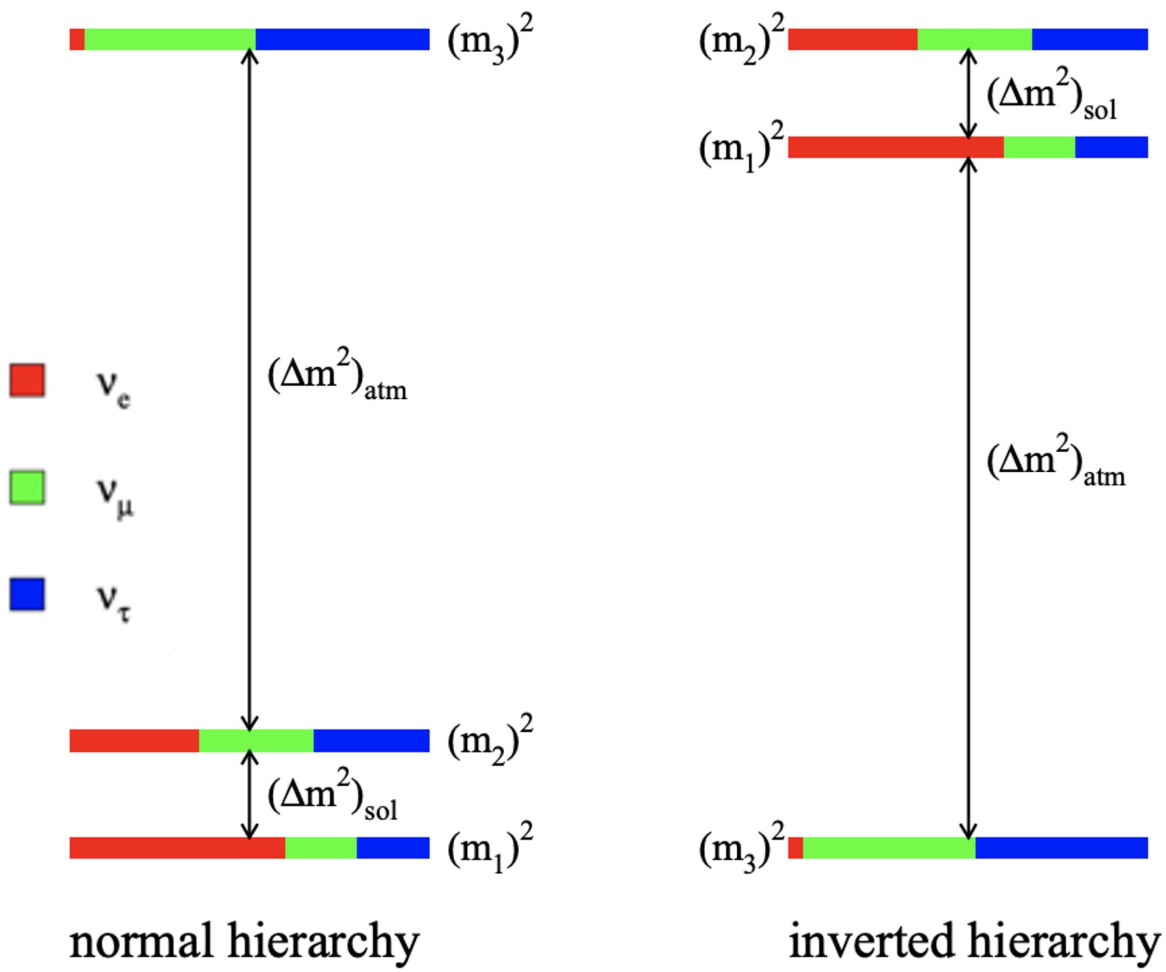


The DUNE Science Collaboration is currently made up of over **1400 collaborators from over 200 institutions in over 30 countries**

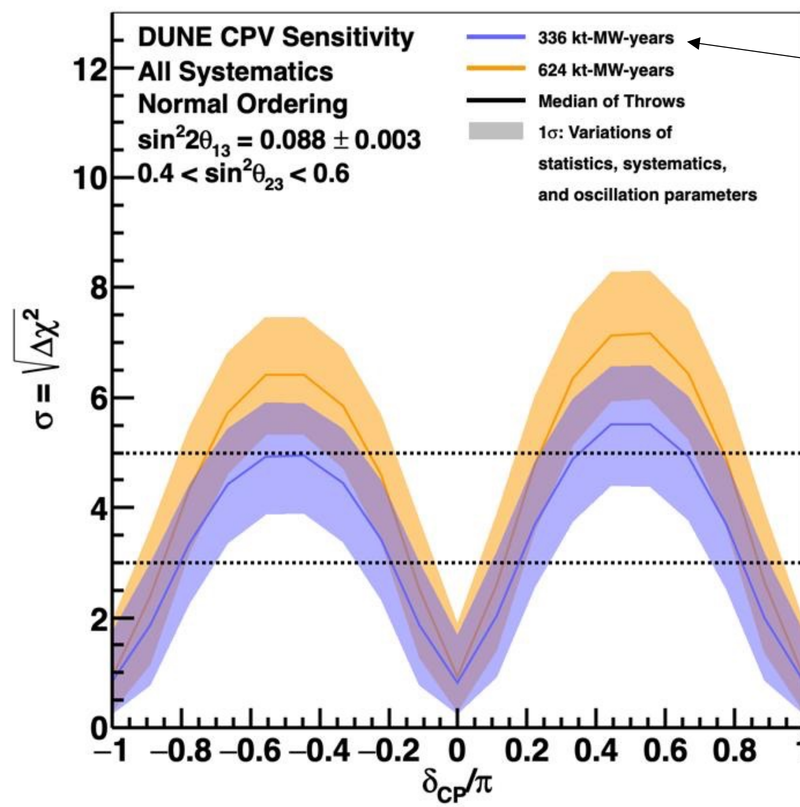
Organizing the neutrinos

From different experiments we have some of the parameters of neutrino oscillation measured

We still have parameters to measure, including the absolute **mass of the neutrino**, and the **mass ordering**



CP Violation in the neutrino sector at DUNE?



Roughly 10 years of running with full detector

Long term project

To go further

- Need to improve precision on Higgs measurements
- Need to see double Higgs production
- Need to improve quantum tests of Standard Model (both in neutrino sector and with precision measurements at LHC)
- Anticipating measurements of neutrino masses, mixing and CP violation at DUNE

- Many challenges for the future, and BNL is planning for the future.