Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Report on the Strategic Planning Workshop: Particle Physics Plan

Lauren Hsu

PAC Meeting

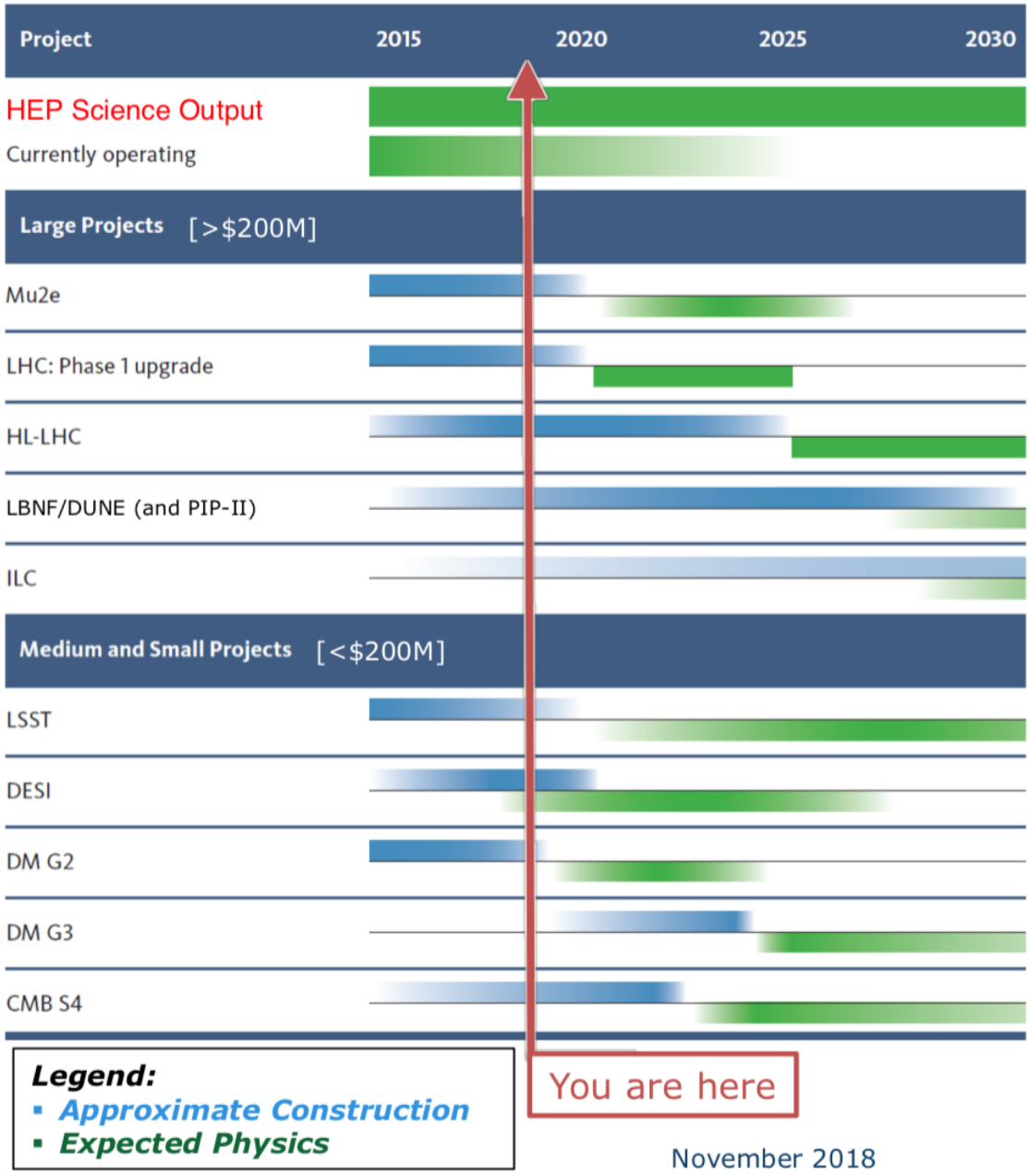
18 January 2019

What is the Annual Lab Strategic Plan?

- Defines lab goals and activities with the purpose of communicating the plan to the DOE, employees and community
- Serves as a starting point for discussion between laboratory and DOE about laboratory's future directions
- Organized by "strategic themes":
  - Accelerator Science (see Sam Posen's talk for this and detector R&D)
  - Building for Science
  - Computing for Science
  - ***Collider Science***
  - ***Cosmic Science***
  - ***Neutrino Science***
  - ***Precision Science***
  - ***Quantum Science***
- Planning covers next 10 years; Plan is reviewed and revised yearly
- This effort occurs in parallel to the SAC-coordinated retreats and focuses on nearer term plans (up to next 10 years). Existing working group structure setup in coordination with first and second SAC-organized retreats.

Lab Strategic Plan is Well-Aligned with P5

Jim Siegrist slide (Nov. 2018 HEPEP meeting)



All projects on budget & schedule

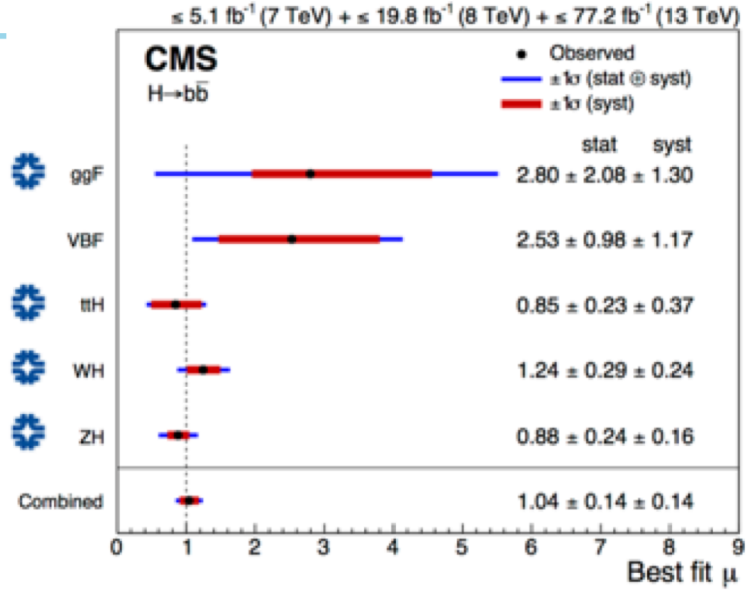
- Projects fully funded as of FY19
  - Muon g-2: 1st beam 2017
  - LHC detector upgrades: on track for 2019/20 installation
  - Mu2e : 1st data in 2020
  - LSST: full science operations 2023
  - DM-G2 (superCDMS & LZ): 1st data 2020
  - DESI: 1st light 2019
- HL-LHC accelerator and detector upgrades started on schedule
- LBNF/DUNE & PIP-II schedules advanced due to strong support by Administration & Congress
- CMB S4: developing technically-driven schedule to inform agencies, NAS Astro 2020 Decadal Survey
- DM-G3: R&D limited while fabricating G2
- ILC: cost reduction R&D while waiting for decision from Japan
- Broad portfolio of small projects running

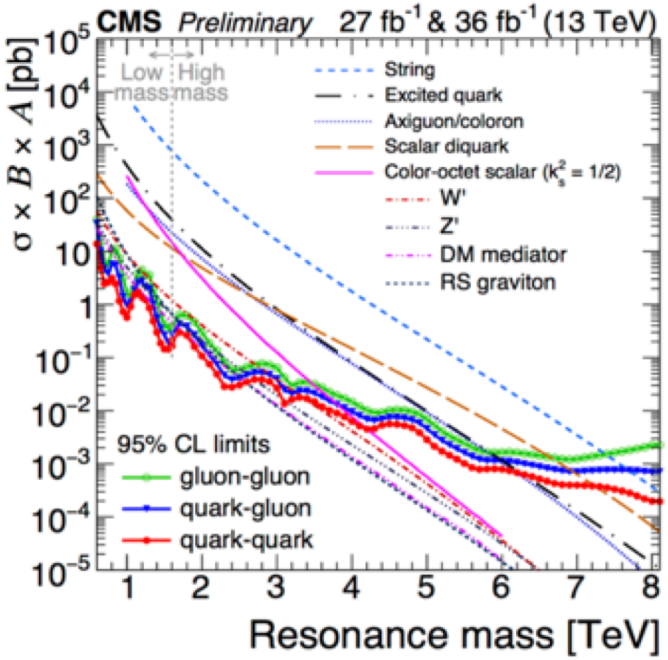
Collider Science
10 year plan

LHC Science in Run1 and Run2

- **FNAL maintains its leading role in the CMS Higgs boson program, searches for Dark Matter and for BSM, Standard Model program**
  - 4 physicists leading SUSY, Exotica, SM subgroups
  - Contributions to high profile journal publications, including the Observation of Higgs decaying to b quarks (*cover of PRL*)
- FNAL continues to educate through LPC: 60+ students & 40 facilitators attending Data Analysis School this week
- In 2018 CMS breaks publication record: 141 journal publications in one year
- **FNAL to pioneer breakthrough trigger and reconstruction techniques enabling CMS to access previously unexplored parts of BSM phase space**
  - Extending DM and BSM searches to complex signatures with displaced particles, semi-invisible jets, lepton-jets

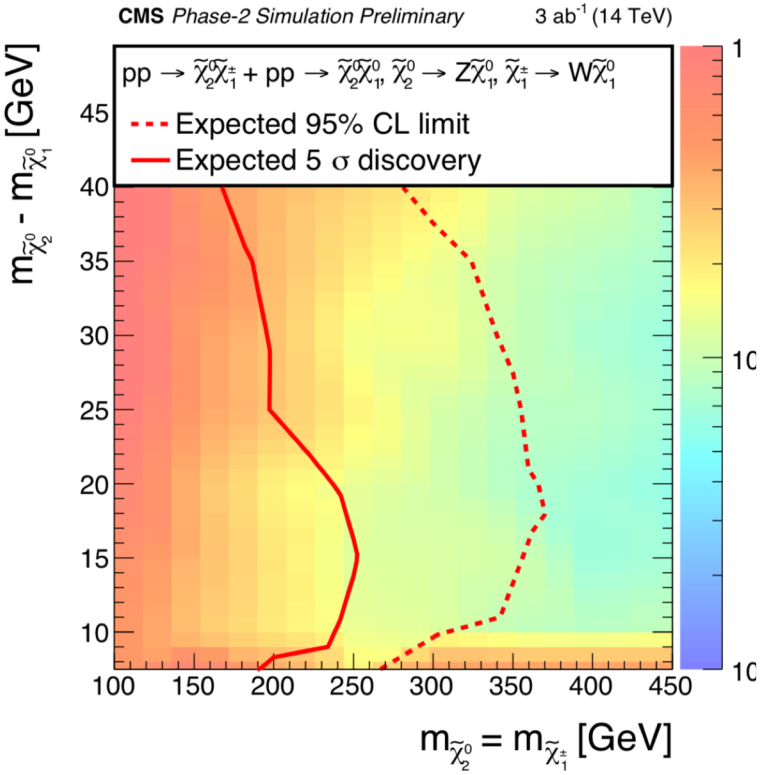
Very successful end of Run2 with > 150/fb (more than planned for Run1+Run2)

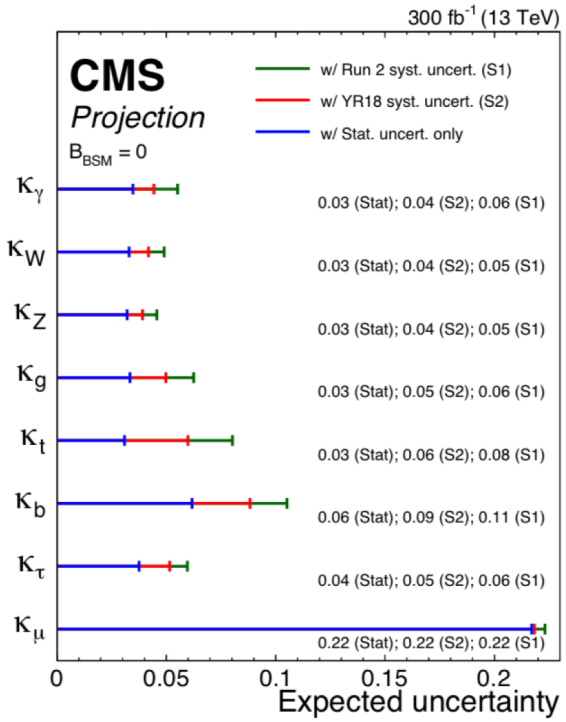


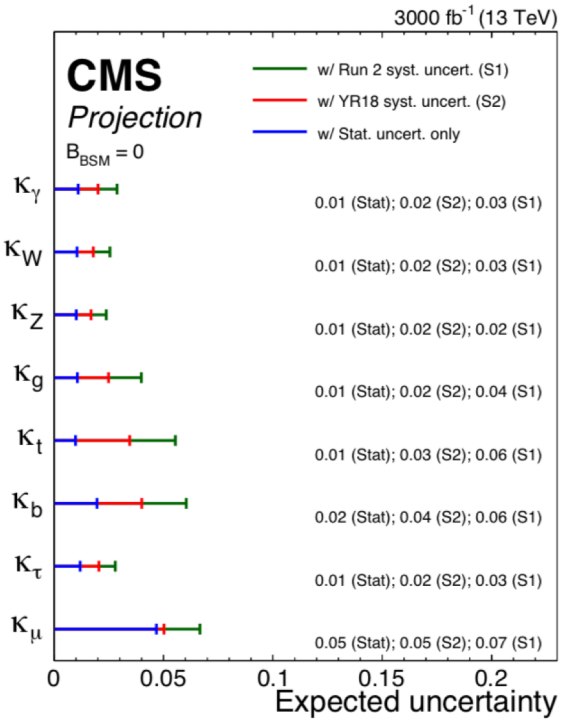


LHC Science Program in Run3 and HL-LHC

- The Fermilab group will continue to pursue research along the lines identified by P5, exploiting an upgraded detector with enhanced capabilities
  - Leadership in cutting edge usage of Machine Learning at trigger level, data quality monitoring, and object reconstruction and analysis levels
  - Enables experiment to effectively collect data more efficiently and to yield higher sensitivity in precision measurements and searches for BSM physics
  - Fermilab is additionally a leader in computing and software infrastructure development for CMS







Cosmic Science
10 year plan

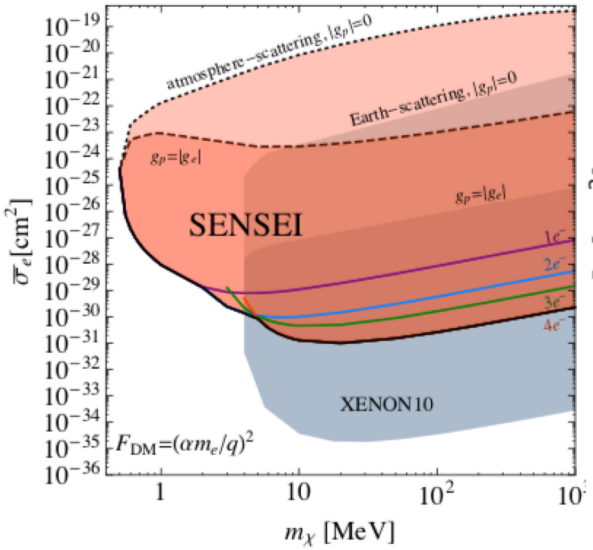
Summary of Cosmic 10-year plan

See Josh Frieman's talk for details on Cosmic steering committee conclusions

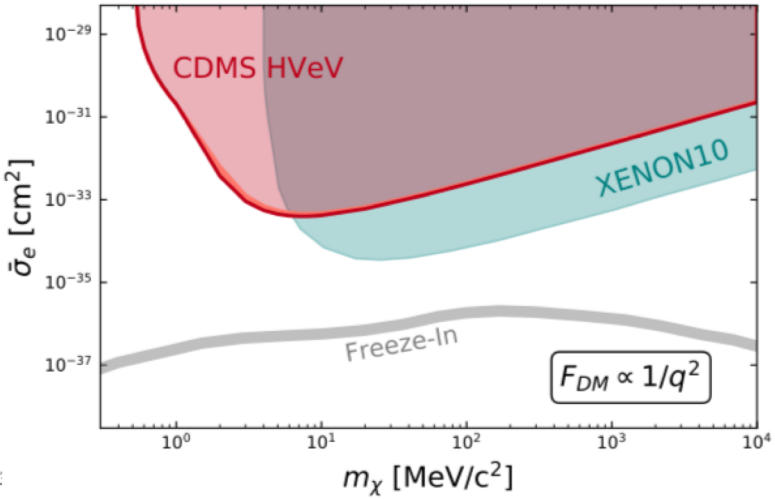
- **Drive towards discovery of dark matter**
  - *Leadership in low-mass dark matter and axion searches*
  - *Analysis of data sets (SuperCDMS, SENSEI, LZ) to discover, or constrain, the nature of Dark Matter*
  - *Develop theoretical models that narrow range of particle candidates*
- **Leadership in Cosmic Microwave Background**
  - *Lead operation of stage-3 CMB (SPT-3G) experiment*
  - *Complete operations and science analysis of SPT-3G survey*
  - *Have a leading role in stage-4 (CMB-S4) program*
  - *Advance detector and readout technical development for CMB-S4*
- **Understanding Cosmic Acceleration and the Physics of Neutrinos**
  - *Lead effort to constrain dark energy using DES, leverage experience for LSST science*
  - *Lead a stage-5 dark energy experiment (mid-scale spectroscopic survey) to follow-up DES, LSST*
  - *Extract cosmological constraints on dark energy and neutrinos from cosmic science experiments*

Cosmic Science Recent Achievements

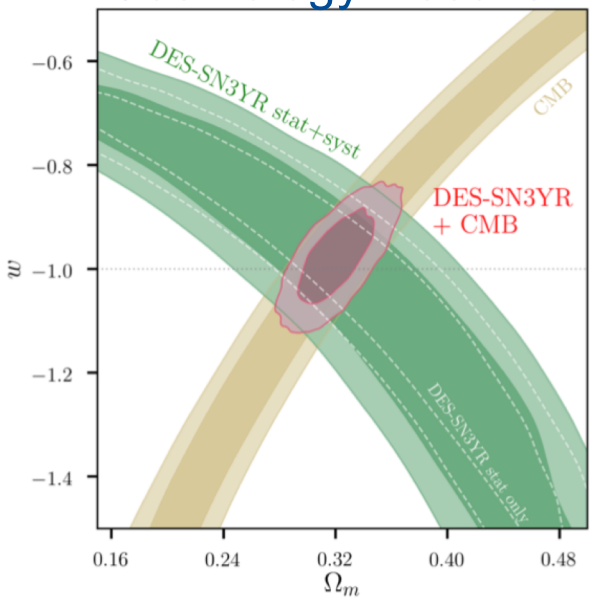
First results from SENSEI



Sub-GeV DM search with SuperCDMS

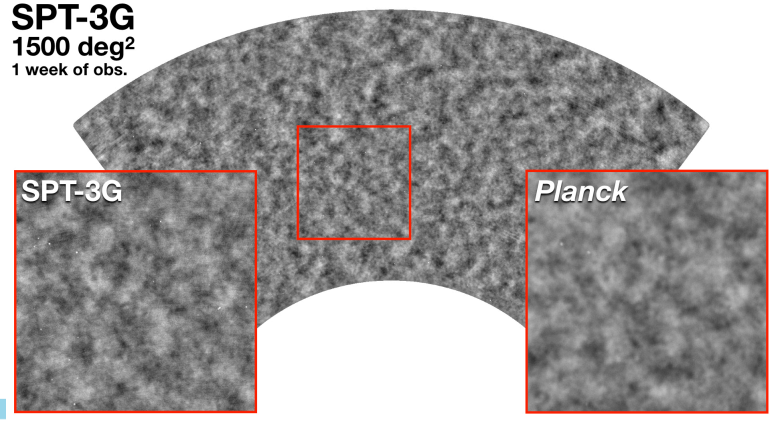


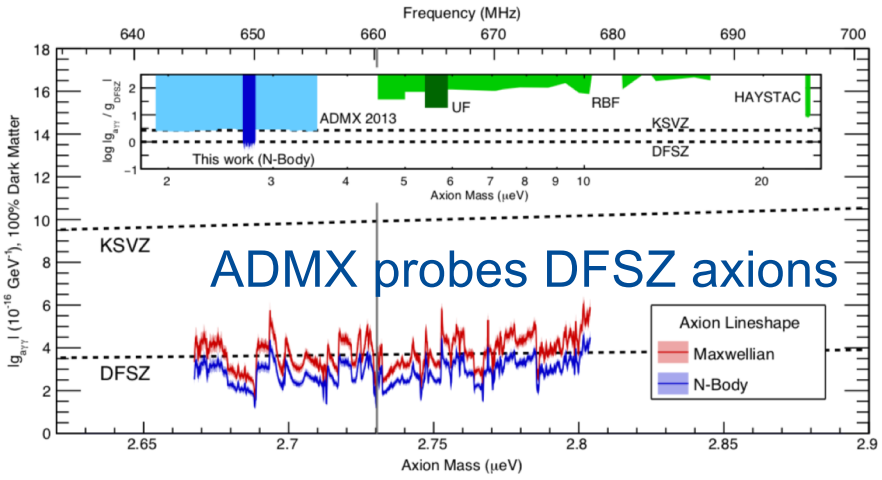
DES Supernovae Cosmology Results



The SPT-3G 1500 deg² Survey

SPT-3G data is deeper than Planck with only 1 week of observations!





Neutrino Science
10 year plan

Neutrino Science Goals:

Deliver & exploit world's highest power beams for neutrino science

- PIP-I (700 kW), ✓ accelerator complex upgrades (900 kW), PIP-II (>1 MW), PIP-III (multi-megawatt)
- Continue exploration of neutrino mixing parameters with NOvA beam running through 2025, followed by DUNE

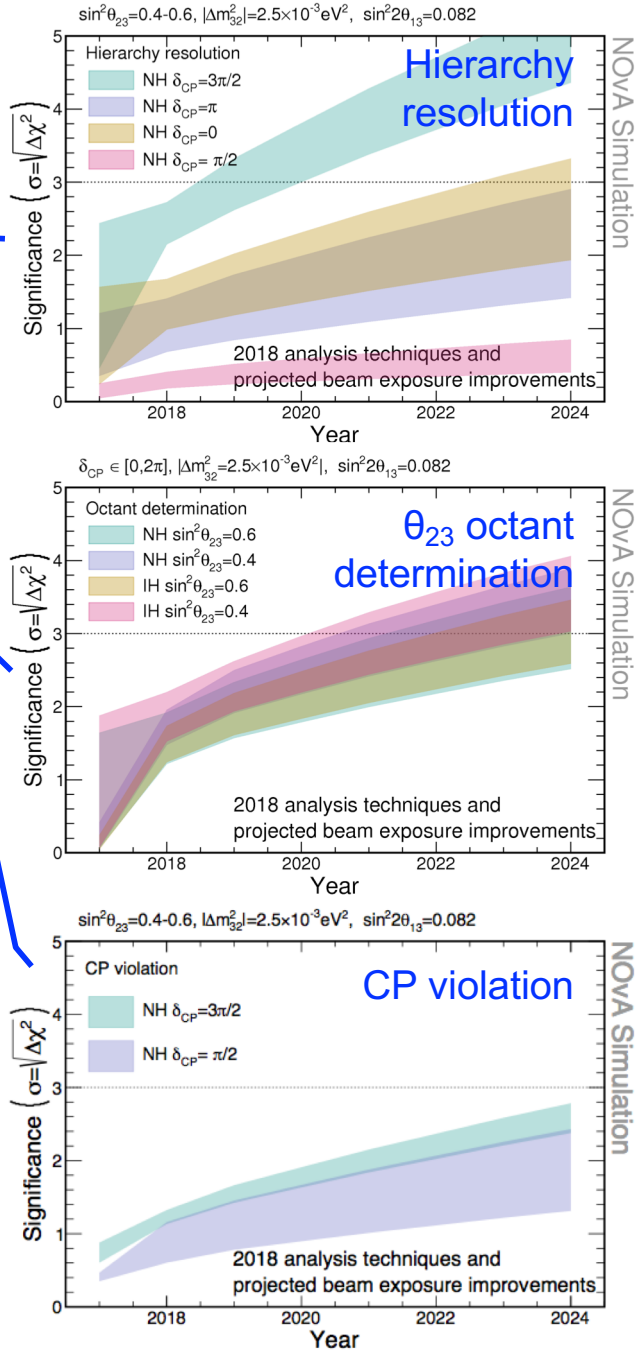
Fully exploit the short-baseline neutrino program:

- MicroBooNE, SBND and ICARUS complete a 3-detector suite to fully probe the sterile neutrino hypothesis
- Understand all we can about LAr technology & significantly advance our understanding of GeV-scale **ν**-nucleus interactions
- *See talks by Steve Brice and Ornella Palamara for more*

Deliver LBNF/DUNE:

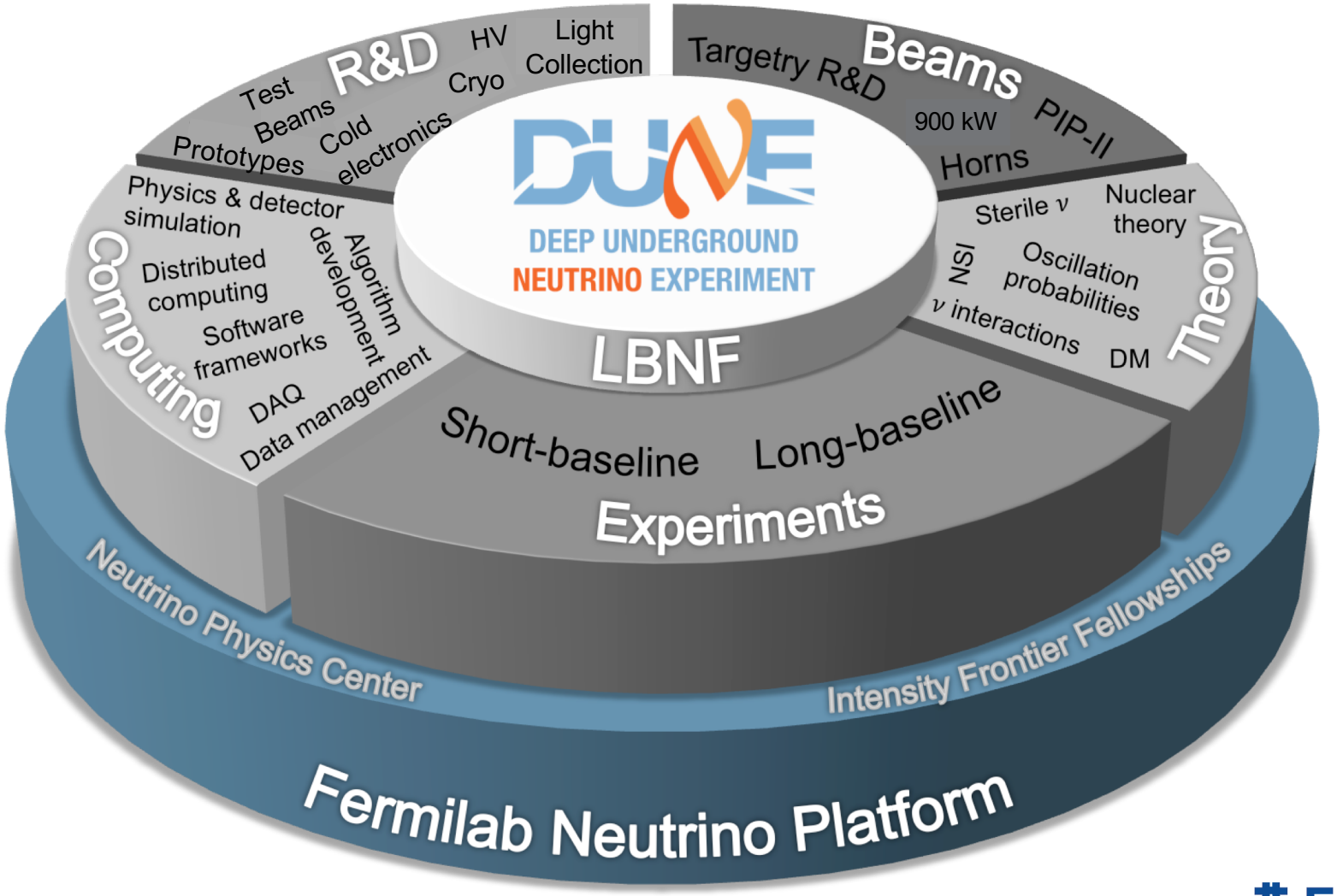
- Commission protoDUNE in time for beam operations at CERN ✓ *see talk by Flavio Cavanna for more*
- International Project Milestone: beam on with two LAr detectors in 2026
- *See talk by Hugh Montgomery for more*

Determine properties, masses, and mixing matrix of 3 known neutrinos
(**Hierarchy resolution, θ23 octant determination, CP violation)**



"All paths lead to DUNE" – for the next 10 years

DUNE is the highest priority project, with entire FNAL neutrino program working coherently towards building it

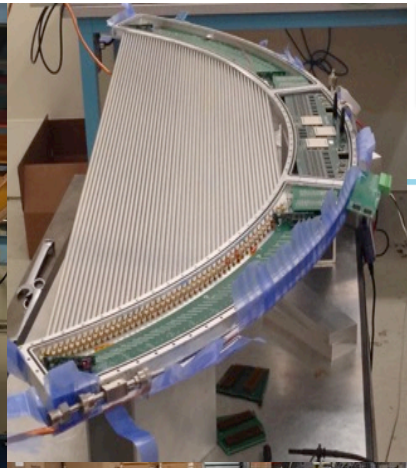


Precision Science
10 year plan

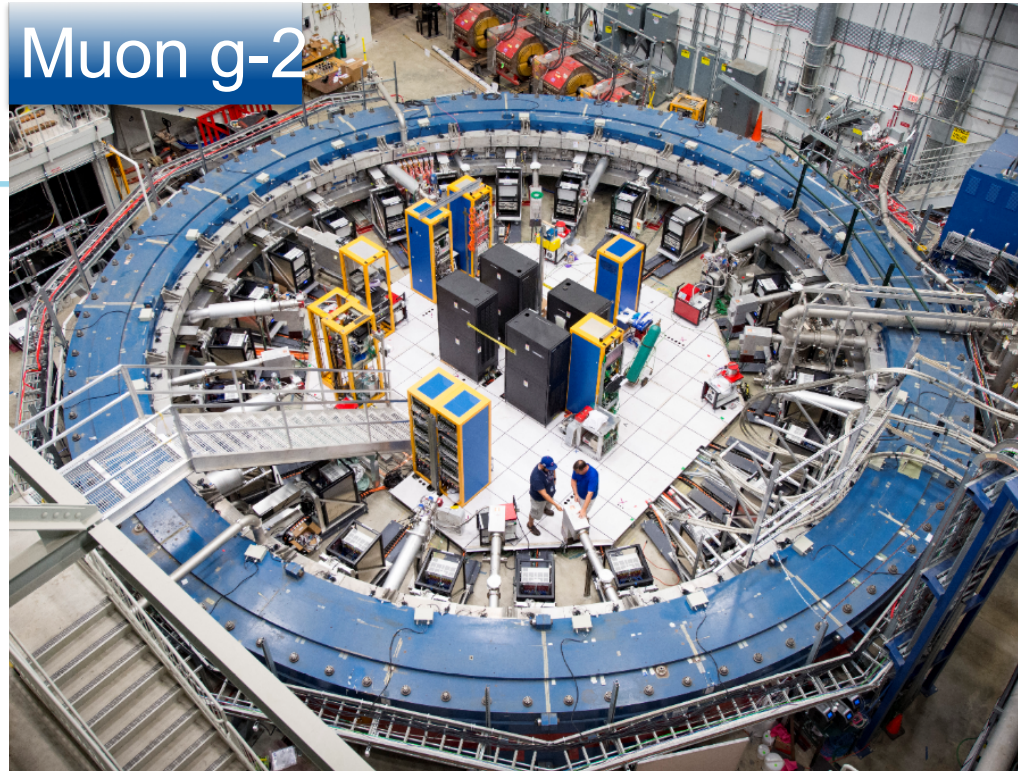
Precision Science 10 year plan

1) Perform the most precise measurement of muon g-2
   - ✓ Complete the Muon g-2 Project ✓
   - – Collect data set 10x larger than Brookhaven experiment by 2019 and 20x larger by 2020
   - – Publish first results exceeding BNL precision
2) Perform the highest sensitivity search for charged lepton flavor violation with Mu2e
   - – Complete the Mu2e Project by 2022 and develop a preliminary operations plan
   - – Collect a data set enabling the world's best limit on CLFV by 2023 and factor 10,000 improvement by 2026
3) Provide high intensity and high quality beams for precision experiments
   - – Complete the Muon Campus by 2019
   - – Begin commissioning Mu2e beam line with protons by 2020
4) Plan the next generation of precision experiments at Fermilab
   - ✓ Propose Mu2e-II upgrades to the PAC ✓
   - – Secure funding to advance R&D for Mu2e-II and develop preliminary design in preparation for next P5
   - – Investigate new precision experiments for the muon campus as inputs to the Snowmass process
5) Facilitate the growth of a strong and vibrant precision science user community
   - ✓ Execute hiring plan to ensure lab-based leadership in experimental operations and data analysis ✓
   - – Lead development of tools for data processing and analysis for Muon g-2 by 2018 and Mu2e by 2019
   - – Provide additional office and lab space for the growing user community
6) Improve theoretical SM and BSM predictions for Precision Science observables
   - – Calculate leading order hadronic vacuum polarization contribution to Muon g-2 with total error <1%
   - – Develop models for new physics that have observable effects in current and future experiments

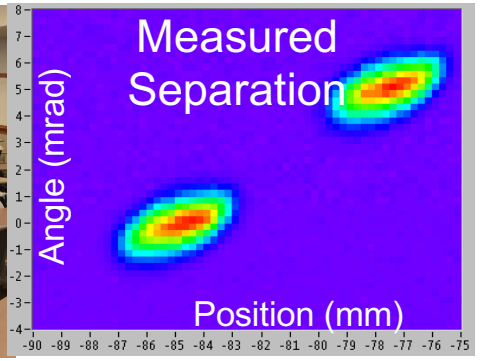
Mu2e



Muon g-2



Mu2e-II



Theory

Most precise lattice-QCD calculation :

-$K \to \pi l \nu$ form factor

-u, d, s, and b-quark masses

-B0 and Bs-meson leptonic decay const.

First calculation of:

-higher-order HVP contribution to muon g-2

- strong isospin breaking correction to the HVP contribution to g-2 at the physical up- and down-quark masses

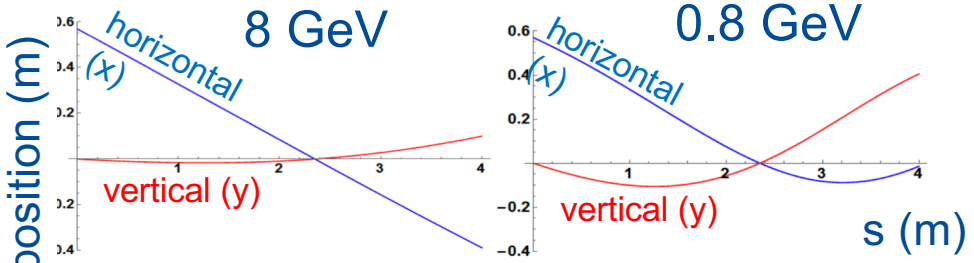
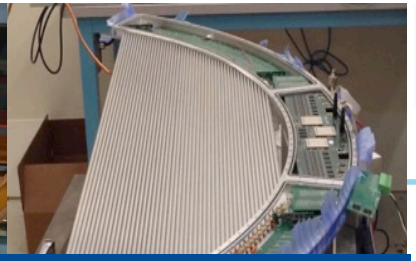
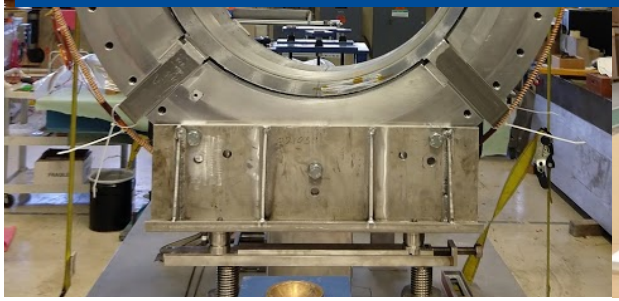


FIGURE 6. x-y coordinates through PS for 8 GeV protons (left) and 0.8 GeV protons (right). Target is at –2.35m

Mu2e

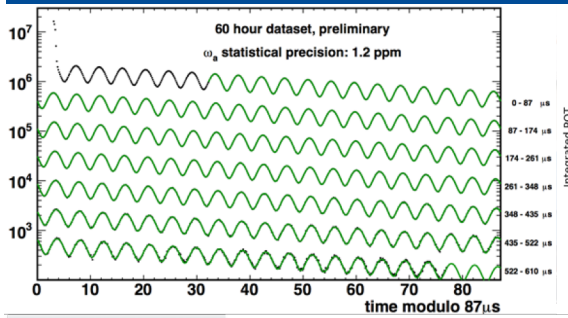


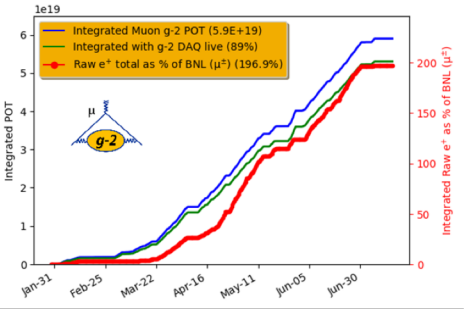
~30,000 straws complete
HAB commissioned, TS Magnets arriving ~32 km scintillator extruded



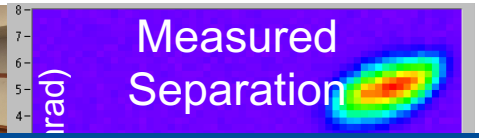
Muon g-2

Finished commissioning experiment
Collected 2x BNL in raw statistics
FY18 Shutdown Upgrades:
-Cryogenics, kickers, quads, momentum cooling wedge





Mu2e-II



Two workshops >70 participants each

Task force initiated to develop conceptual design for proton beamline and target

Proposal to use PIP2IT to measure

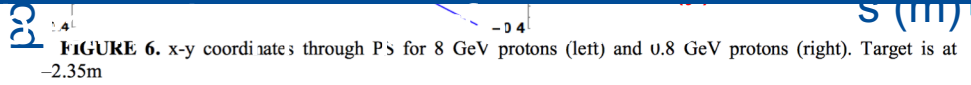


FIGURE 6. x-y coordinates through PS for 8 GeV protons (left) and 0.8 GeV protons (right). Target is at –2.35m

Theory

Most precise lattice-QCD calculation :
-$K \to \pi l \nu$ form factor

Multiple publications

More in progress…

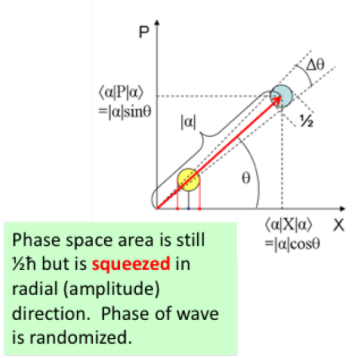
- strong isospin breaking correction to the HVP contribution to g-2 at the physical up- and down-quark masses

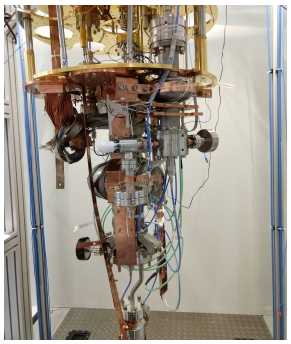
Quantum Science
10 year plan

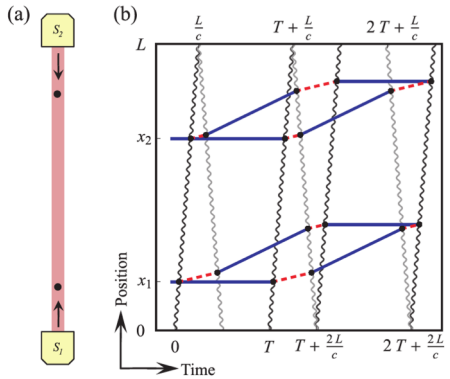
Quantum Science Goals:

Leverage Fermilab's core capabilities to yield results in quantum science on short term while building for HEP in longer term

- **Applications of Quantum Sensors**: Adapt quantum technologies, including squeezing and entanglement, to enable new fundamental physics experiments.
- **Superconducting Quantum Systems**: Leverage Fermilab's expertise to advance superconducting materials and resonators for dramatic improvements in coherence times, quantum error correction, and scalability of superconducting quantum systems.
- **Applications of Quantum Computing**: Identify most promising HEP applications on near-term quantum digital and analog computers; develop algorithms and experience with state-of-the-art machines; find HEP applications with demonstrated quantum advantages that could evolve into "quantum accelerator" modules in HEPCloud.
- **Develop quantum simulations:** that express the foundational Quantum Science connections to black holes, wormholes, emergent spacetime, and quantum field theory.







Highlights of Recent Activities and Awards

See talks by: Panagiotis Spentzouris, Roni Harnik and Anna Grassellino and Jason Hogan for more details

Fermilab-led DOE QuantiSED grants:

- Develop qubits for single-photon readout for axion detector – Aaron Chou
- SRF cavities to develop qubits with ultra-long coherence times - Alex Romanenko
- Application of quantum computing simulations to particle theory – Marcela Carena
- Quantum computers for machine learning – Gabe Perdue
- Skipper CCD's for quantum imaging

DOE Early Career awards related to Quantum Science (2018):

- Qubits for single-photon readout for axion and neutrino detectors – Daniel Bowring
- Skipper CCD's for 10-kg neutrino detectors – Javier Tiffenberg

Backup

Software and Computing (LHC and HL-LHC)

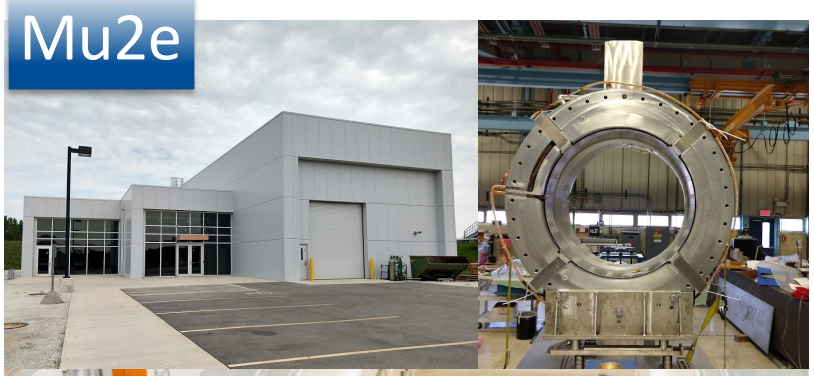
- **FNAL is responsible to deploy the US CMS T1 at a scale and availability consistent with the commitment to the Worldwide LHC Computing Grid**
  - Custodial responsibility of > 50 PB of CMS data
  - Providing access to > 30 PB of disk and > 20,000 cores of compute power for CMS
- FNAL enables the US-CMS physics community to perform **analysis on the LPC resources**
  - > 700 users
- **FNAL is a leader in the development of CMS software for reconstruction and analysis**
  - Optimized simulation to reduce the needed computing resources and extend the physics capabilities of the experiment
  - (Only) experimental framework using multi-threading in production, running on GRID resources, commercial cloud resources and the US leadership class facility supercomputers
  - SW R&D to utilize GPUS and FPGAs for detector signal reconstruction like tracking
- **FNAL is the leader in the development of computing infrastructure software for CMS**
  - Covering central production and data handling infrastructure SW and cooperating with community efforts (*e.g*. Open Science Grid)
  - Involved in collaborations with industry and other science partners in utilizing Big Data technologies

Muon Precision Science Experiments

Muon g-2

- Make ultra-precise measurements
- Sensitive to a_μ to 140 ppb
- >3σ discrepancy to >5σ
- 7 Countries, 34 Institutions
- 192 Collaborators

Mu2e



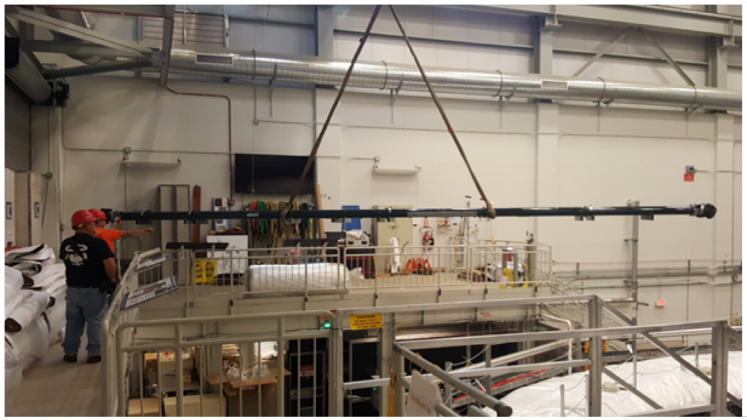
- Search for rare or forbidden processes
- Sensitive to $\mu^- N \rightarrow e^- N$ to 7×10^{-17}
- Factor of 10000 improvement
- 6 Countries, 40 Institutions
- 240 Collaborators

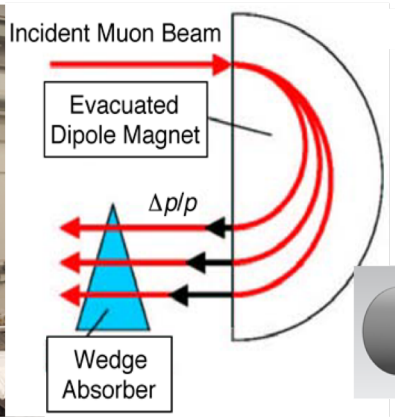
Goal 2: Perform the most precise measurement of muon g-2

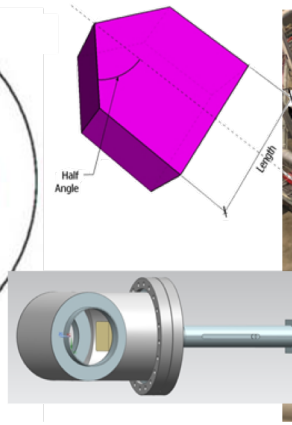
- Collect a data set 10x as large as the Brookhaven E821 experiment (FY19)

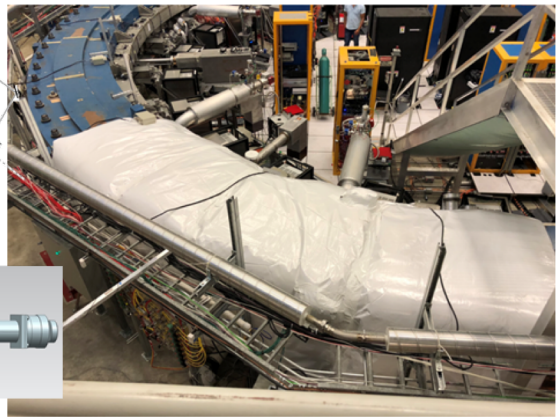
FY18 Shutdown Upgrades

- Cryogenic upgrades for quench-free operations
- Electrostatic quadrupole improvements
- Redesign and refurbished in-ring kickers (aiming for 30% higher kick)
- Momentum cooling wedges installed in beamline (20-40% simulated increase in muon flux)









Goal 4: Plan the next generation of precision experiments at Fermilab

✓ FY18: Propose Mu2e-II upgrades to the PAC

- June: Directorate initiated Task Force-develop a conceptual design for the proton beam line and target

-Chairs: S. Werkema, R. Zwaska
-Main challenges: beam trajectory & 100 kW-capable target
-Final report due early 2019

Figures from Dave Neuffer

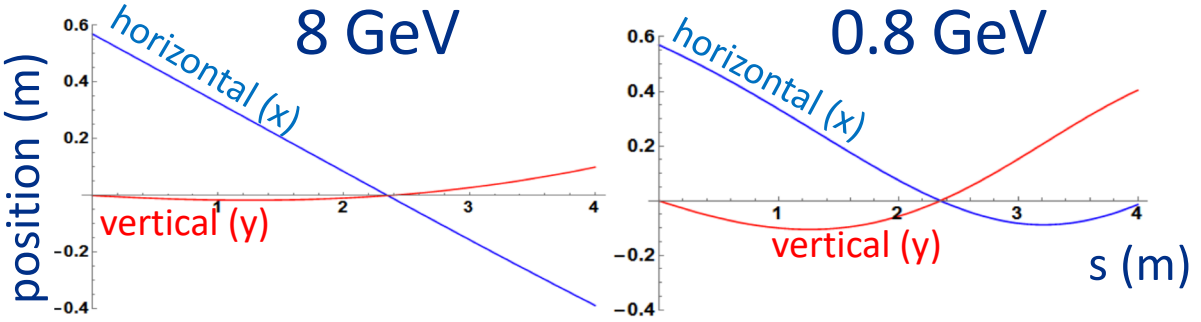
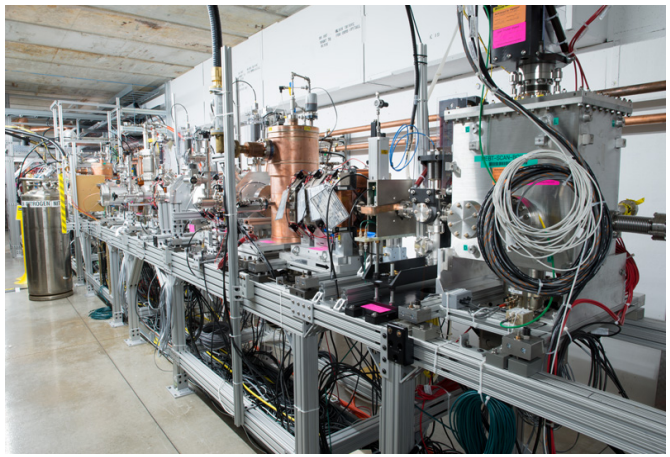
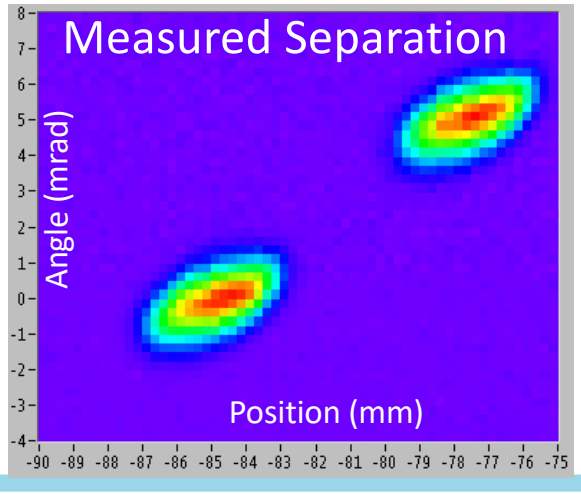
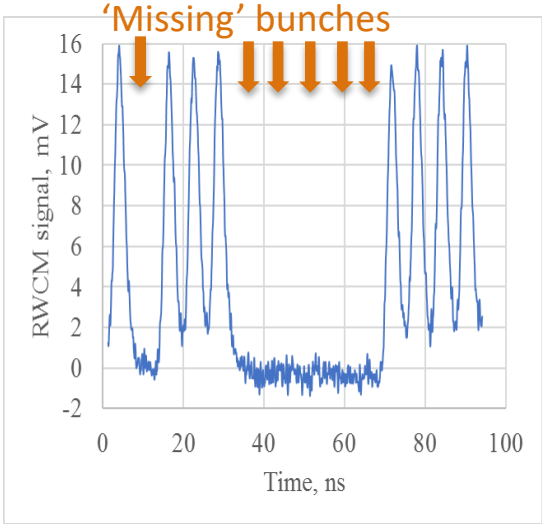


FIGURE 6. x-y coordinates through PS for 8 GeV protons (left) and 0.8 GeV protons (right). Target is at =2.35m

- Sep-2018 : Developed proposal to measure extinction performance of the beam chopper using PIP2IT – important for Mu2e-II







Goal 5: Facilitate the growth of a strong and vibrant precision science user community

- Lead efforts to develop user friendly access to data and tools for data processing and analysis sufficient for Muon g-2 by 2018 and for Mu2e by 2019 (FY19)

– Working to enable simulation production at High Performance Computing Centers such as NERSC (National Energy Research Scientific Computing Center at LBL) and ALCF (Argonne Leadership Computing Facility)
– Hired an Applications Physicist to further these efforts
– Collaborate with Scientific Computing Division to optimally access the Fermilab computing resources including data storage and job execution
  - Provide feedback and testing for community tools in these areas
  - For example, g-2 uses POMS - Production Operations Management Service - a web based system for launching production workflows with monitoring and bookkeeping
– Muon g-2 and Mu2e participate in the twice-per-year FIFE (Fabric for Frontier Experiments) Workshops lead by SCD. These workshops provide training on the community tools and new features as well as a forum to give feedback.
– First release of Mu2e simulation using multi-threaded Geant4; at an HPC facility such as THETA (ANL) or CORI II (NERSC) -about 2.4x throughput compared to single threaded G4.
– Designed new workflows and data products for simulation, reconstruction and analysis
– Organized and executed a Mock Data Challenge in the summer of 2018 (MDC2018)
  - MDC2018 also enables us to do the first studies on alignment and calibration; these will start soon
  - Next generation tutorials will be based on the output of MDC2018
  - Planning underway for MDC2019 which will exercise more elements of alignment and calibration
– Developed a prototype conditions data base to support the alignment and calibration studies

Goal 6: Improve theoretical SM and BSM predictions for Precision Science Observables

- Calculate leading order hadronic vacuum polarization contribution to muon g-2 with total error below 1%(FY20)
- Develop models for new physics that have observable effects in Muon g-2 and Mu2e and beyond(FY26 and beyond)

Publications:

- Most precise lattice-QCD calculation of the $K \to \pi l \nu$ form factor. https://arxiv.org/abs/1809.02827
- Most precise lattice-QCD calculations of u, d, s, and b-quark masses. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.98.054517
- Most precise lattice-QCD calculations of B0 and Bs-meson leptonic decay constants. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.98.074512
- First lattice-QCD calculation of the higher-order HVP contribution to muon g-2 https://journals.aps.org/prd/abstract/10.1103/PhysRevD.98.094503
- First calculation of the strong isospin breaking correction to the HVP contribution to g-2 at the physical up- and down-quark masses https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.152001

Works in progress:

- Update of 2016 lattice-QCD calculation of light-quark connected contribution to muon g-2 with finer lattice spacing. (c.f. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.96.034516). Anticipate posting to arXiv in December.

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