US Particle Physics Program

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DPF 2017

U.S. DEPARTMENT OF ENERGY
Office of Science

Apologies & Credits

Only a 25 minute talk!

- Highlights & major thrusts only - not all U.S. experiments or all U.S. involvement will be covered
- Neglect rest of America's
  - Emphasize major U.S. thrusts and U.S. hosted opportunities for the worldwide community

Will draw heavily on P5 and evaluate plan today

Thanks to Andy & Dmitri for their slide decks!

Introduction

The U.S. particle physics program is guided by the strategic plan laid out in the 2014 P5 report

- Time sequence:
  - Snowmass 2013: a year-long community-wide study organized by the DPF
  - P5: another nearly year-long study, used the Snowmass study to define a strategic plan for U.S. particle physics for the next decade
- The P5 plan met success in the community, the agencies, and the stakeholders. It defines the U.S. particle physics program that is currently being executed.

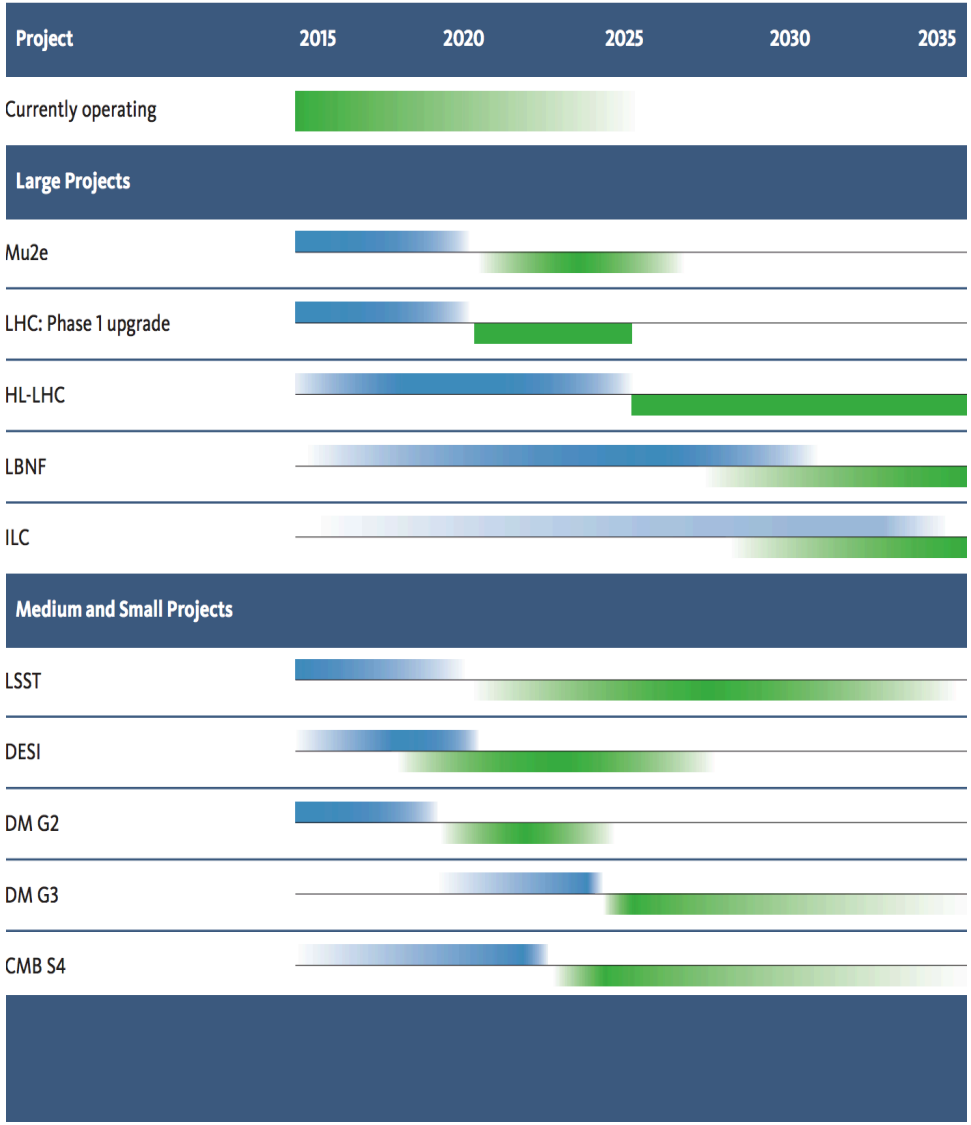
More discussion on future plans at this evening's panel

What Signaled it was Time for a new P5?

- Physics landscape changed
  - Higgs discovered at relatively low mass
  - Key Neutrino mixing angle $\sin\theta_{13}$ measured to be relatively large
  - 3 Nobel prizes: CKM, Higgs, Dark Energy
- These demonstrate importance of diversity of topics and scale

- Programmatic Changes
  - DUSEL morphed into SURF
  - JDEM did not go forward
  - Tevatron and B-Factory ceased operations
  - Budgets declined

The P5 Plan

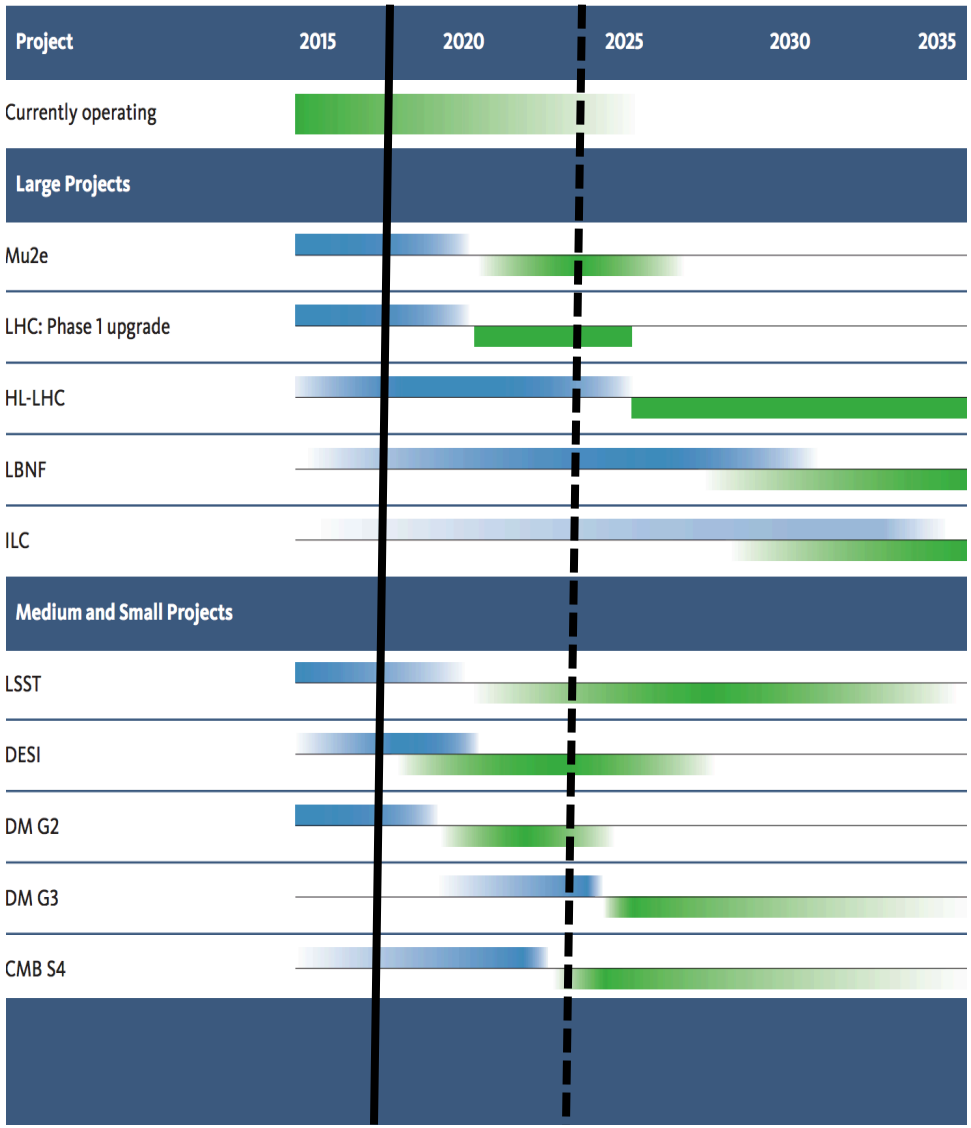


Particle Physics is Global

Centered on 5 Science Drivers

1. Higgs as a tool for discovery
2. Physics associated with Neutrino mass
3. Dark Matter
4. Dark Energy & Inflation
5. Exploring the Unknown

The P5 Plan



Particle Physics is Global

Centered on 5 Science Drivers

1. Higgs as a tool for discovery
2. Physics associated with Neutrino mass
3. Identify Dark Matter
4. Dark Energy & Inflation
5. Exploring the Unknown

Mix of projects of all scales

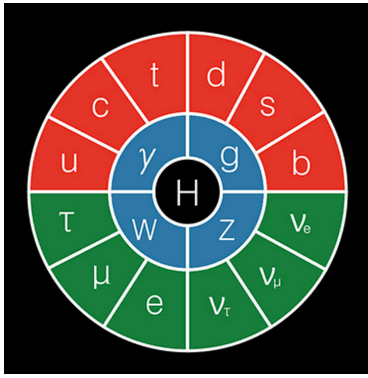
Balance Research, Operations & Projects

Using the Higgs Boson as a Tool for Discovery

The Higgs plays a special role & offers a unique portal

Its interactions must be precisely determined

- With the Standard Model particles
- With itself
- With Neutrinos
- With new particles (Dark Matter)
- Role in Vector Boson scattering
- Is there more than one?



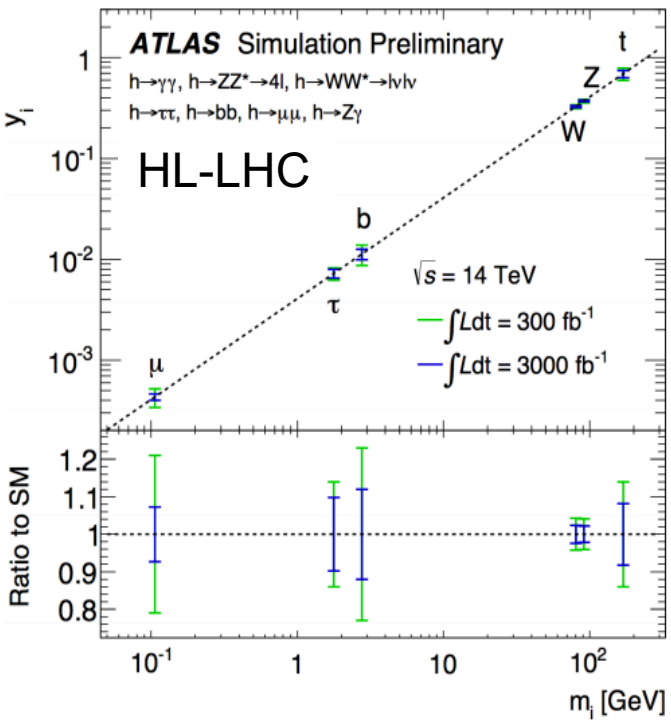
The Large Hadron Collider

The LHC is the first laboratory to use the Higgs boson as a tool for discovery

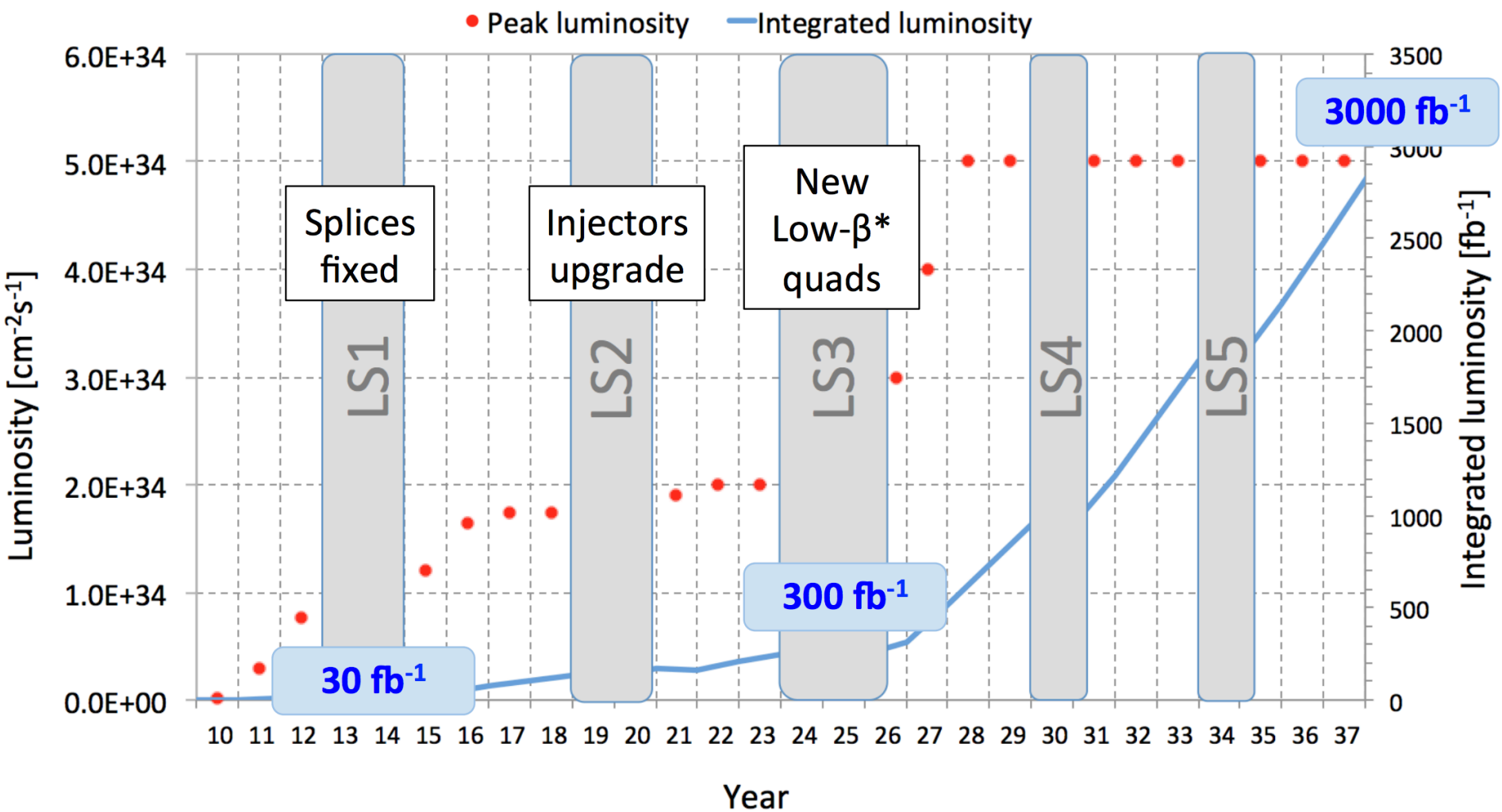
- Currently 10x more data being taken at 13 TeV
- Eventually another 10x more data at the High-Luminosity LHC

The HL-LHC has a compelling and comprehensive program that includes essential measurements of Higgs Properties

- Precision probe of Standard Model & quantum effects of new physics



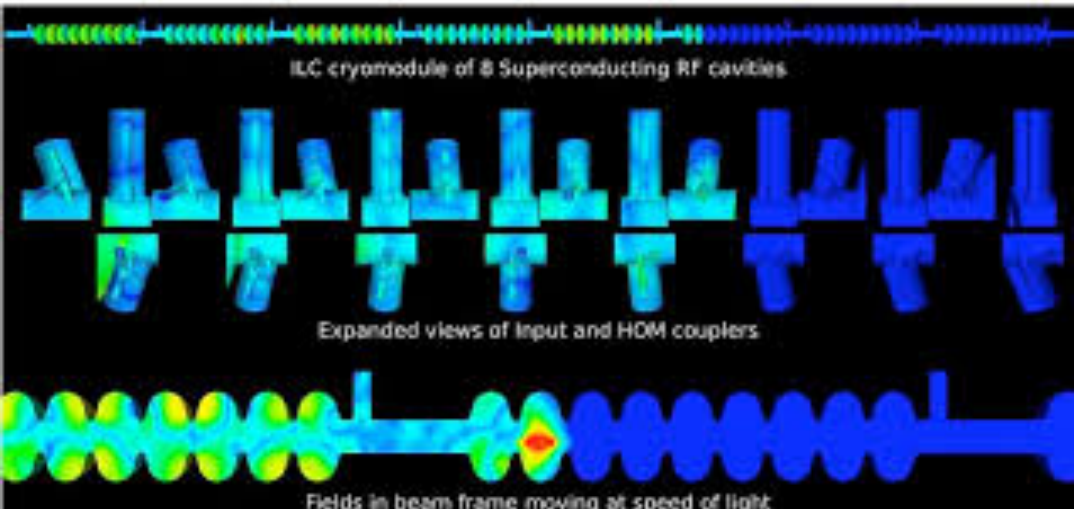
LHC Timeline

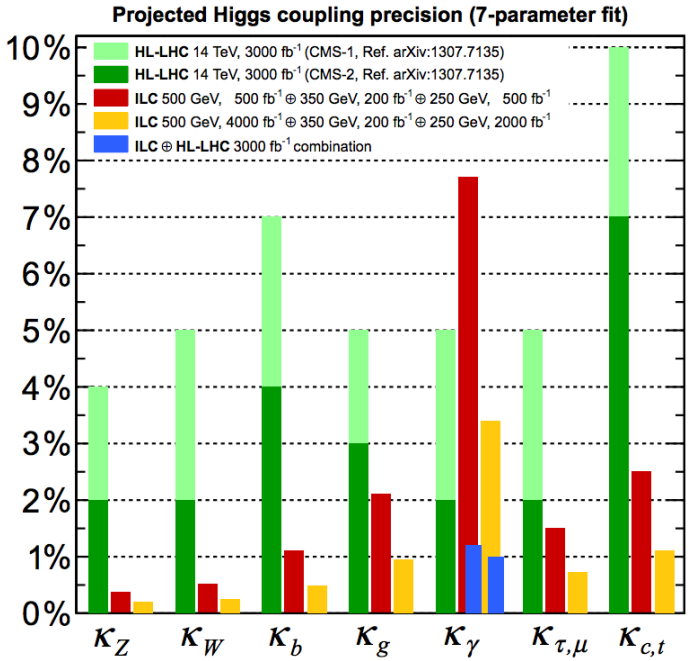


Future Electron-Positron Collider for Higgs Physics

- An e^+e^- collider can provide the next outstanding opportunity to investigate the properties of the Higgs in detail.
  - Increase the sensitivity to the Higgs boson interactions with the Standard Model particles, with particles in the dark sector, and with other new physics.
  - Reach the percent or sub-percent level in sensitivity

- Possibilities include ILC, CLIC and CepC/FCC-ee
  - ILC has most mature design
  - See talk by Komamiya





Pursue the Physics Associated with Neutrino Mass

Fundamental questions answered by diverse neutrino program

- What is the origin of neutrino mass?
- How are the neutrino masses ordered?
  - *Oscillation experiments*
- What is the absolute neutrino mass scale?
  - *Beta-decay spectrum*
  - *Cosmic surveys*
- Do neutrinos and anti-neutrinos oscillate differently?
  - *Oscillation experiments*
- Are there additional neutrino types & interactions?
  - *Oscillation experiments*
  - *Cosmic surveys*
- Are neutrinos their own antiparticles?
  - *Neutrinoless double-beta decay*

Vision: U.S. Hosted, International Neutrino Physics Program

P5 envisioned a long-term neutrino program that is:

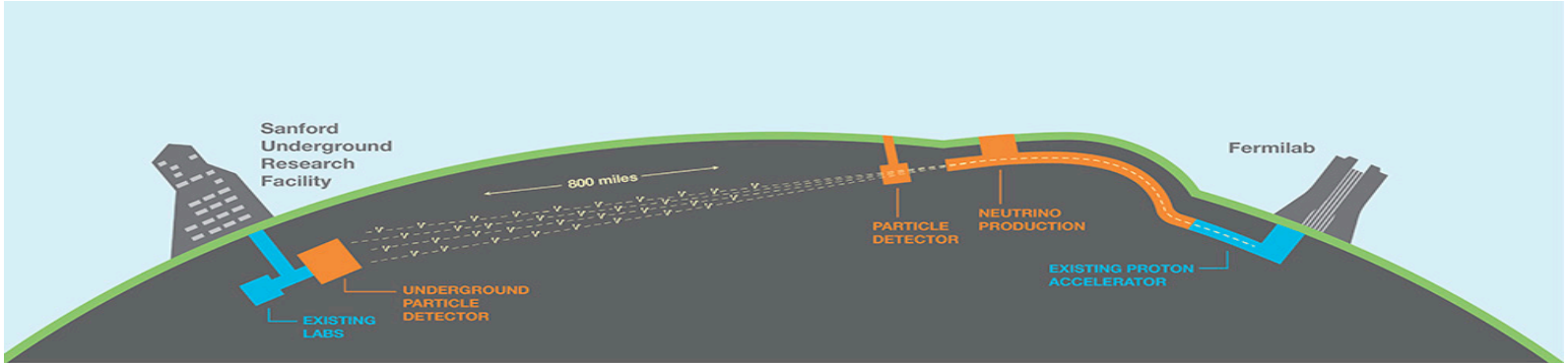
- Comprehensive: Both short- & long-baseline experiments, unified by physics, by technique and technology, and by community.
- International: Based on worldwide interest in this subject.
- Hosted by U.S.: Based on capabilities of U.S. sites
  - Beam energy and intensity capabilities of Fermilab complex
  - Quality of underground far site at SURF lab (South Dakota)

Long-Baseline Neutrino Facility

Identified by P5 as the highest priority large project in its time frame

- Centerpiece of U.S.-hosted, international neutrino program
- LBNF/DUNE is a major U.S. milestone, as it is the 1st international science facility hosted in the U.S.
- Infrastructure: beamline, cavern, cryo
- Current focus on site preparation and excavation

A powerful, wideband neutrino beam will be realized with Fermilab's **PIP-II** upgrade project, which provides very high intensities in the Fermilab accelerator complex



Deep Underground Neutrino Experiment

DUNE: 40kT LAr TPC, 4800' underground, to detect neutrino oscillation, nucleon decay, and supernova neutrinos

- Int'l. collaboration continues to grow: 970 scientists, 162 institutions, 31 nations
- Current focus on 2 full-scale prototypes, ProtoDUNE, at CERN Neutrino Platform

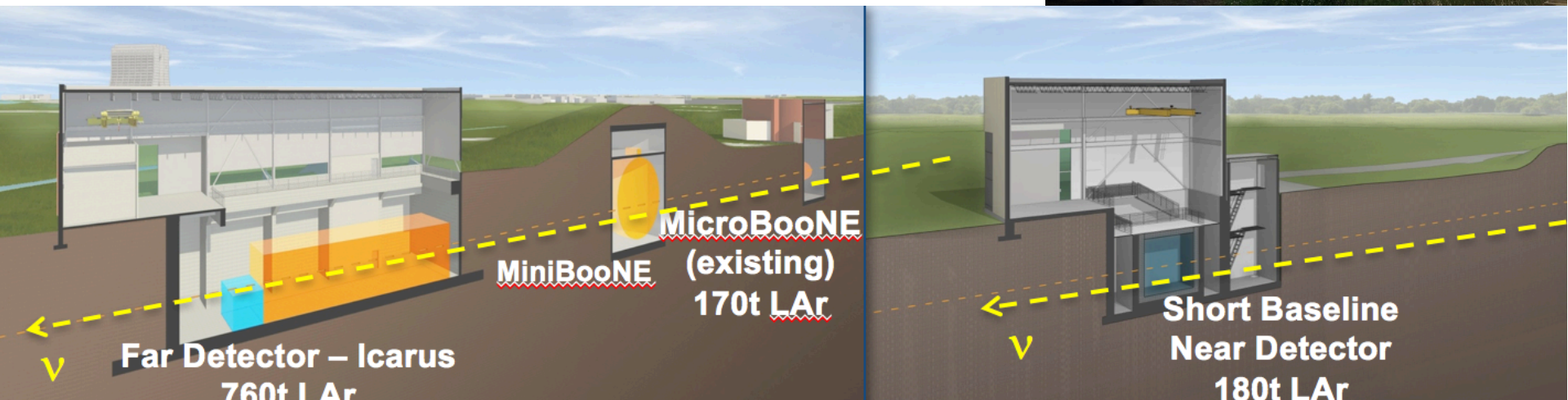
1st detector module operating at SURF in late 2024, with 1st beam in late 2026

LBNF/DUNE Groundbreaking – July 21, 2017

Short Baseline Neutrino Program

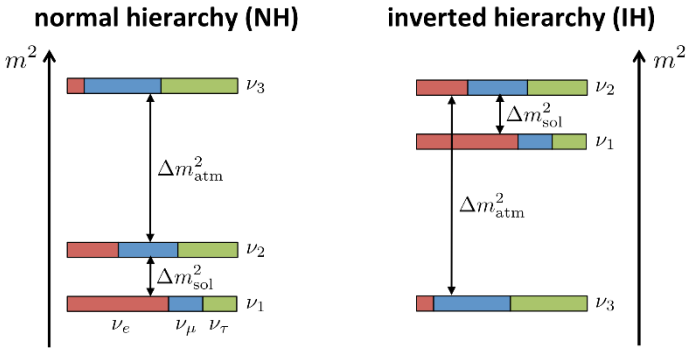
- P5: Fermilab-hosted Short Baseline Neutrino Program:
  - conclusively address experimental hints of physics beyond the 3-neutrino paradigm
  - use liquid argon to advance the technology & build the int'l. community for DUNE
- SBN Program consists of MicroBooNE, ICARUS (2017), and SBND (2018)
  - Participation of CERN through ICARUS refurbishment & CERN's Neutrino Platform.

ICARUS arrives @ FNAL!



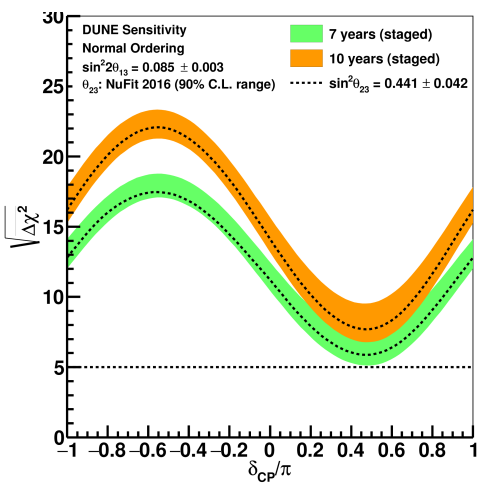
Neutrino Oscillation Physics

Short- and long-baseline oscillation experiments probe several of the essential questions

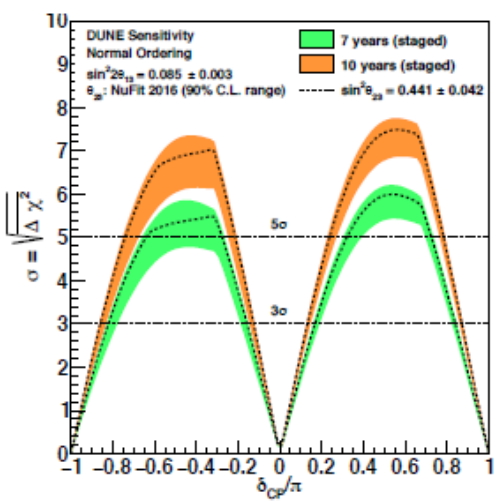


- How are the neutrinos masses ordered?
- Do neutrinos and antineutrinos oscillate differently?
- Are there additional neutrino types & interactions?

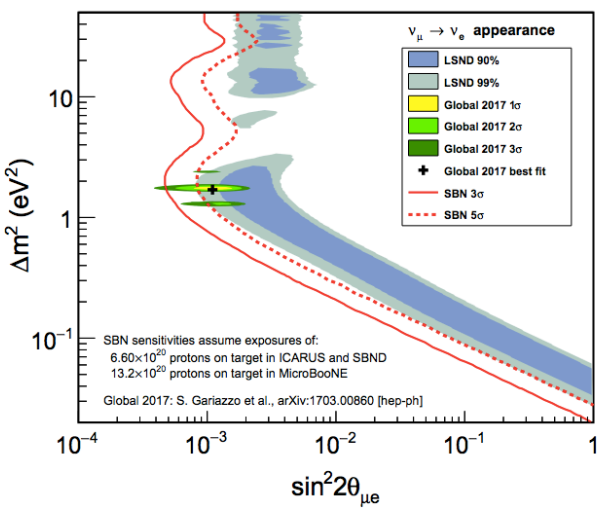
DUNE Mass Hierarchy Sensitivity



CP Violation Sensitivity



SBN Sensitivity



Small Projects Portfolio: Neutrinos

- Identified key opportunities with small projects

PROSPECT
Precision Oscillation and Spectrum Experiment

Precision measurements of flux & energy spectrum of antineutrinos from reactors

annie

Neutron yield of atmospheric neutrino interactions in gadolinium-doped water

Neutrino program demonstrates importance of diversity from small to ultra-large scale projects.

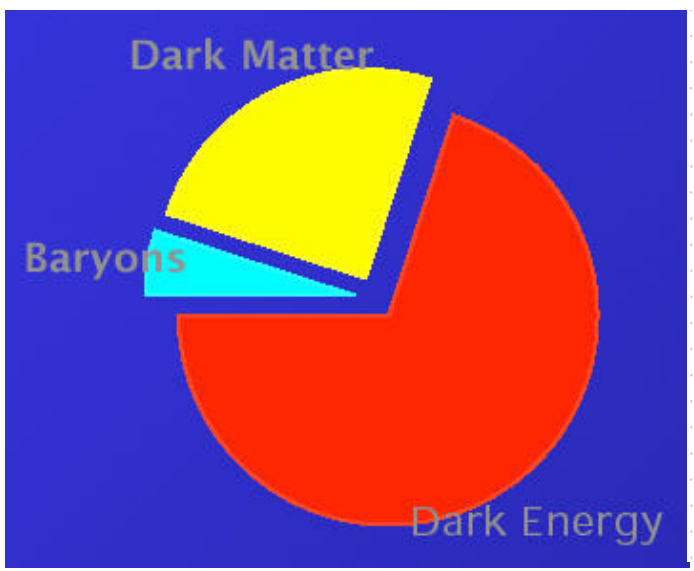
Identify the Physics of Dark Matter

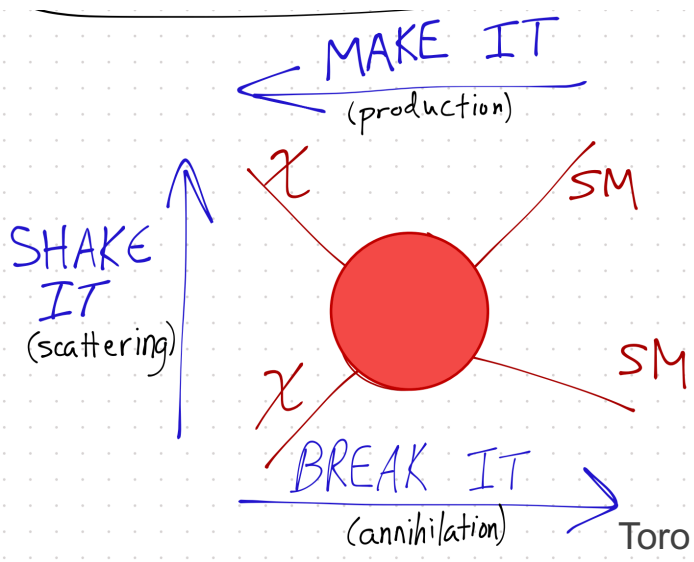
Dark Matter is ~85% of the matter in the universe

New physics that we know exists!

DM could lie anywhere – WIMPs, axions, sterile neutrinos etc

Need robust complementary suite of experiments to probe as much parameter space as possible

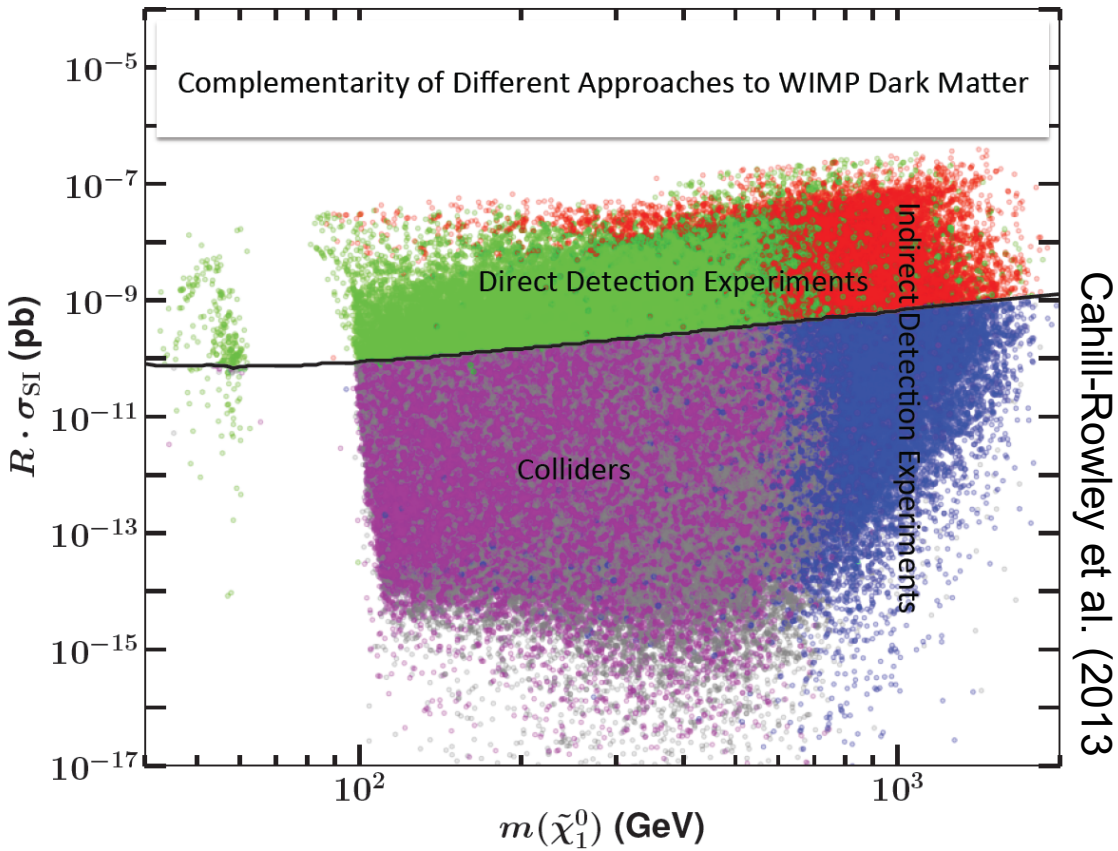




Complementarity of DM search techniques

Dark Matter Complementarity

Different experimental approaches are sensitive to different dark matter candidates with different characteristics, and provide us with different types of information: involves cosmic, energy, intensity & theory fontiers!



Different SUSY models are probed by different experiments

Progression of Direct Detection exp'ts G1 → G2 → G3

G2 Expt's include: ADMX, LZ, Super-CDMS-SNOLab

Small Projects Portfolio: Dark Matter

New Ideas for Searches in New DM Parameter Regions

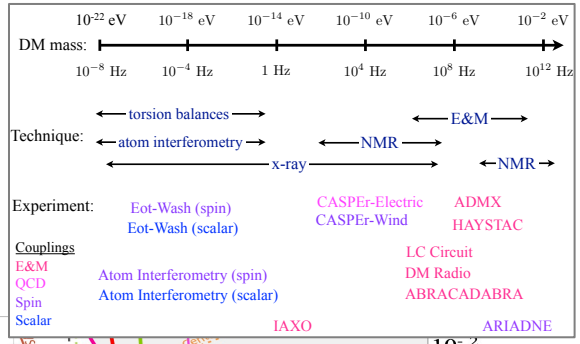
Cosmic Visions DM March Workshop
Investigating low-cost, high impact exp'ts

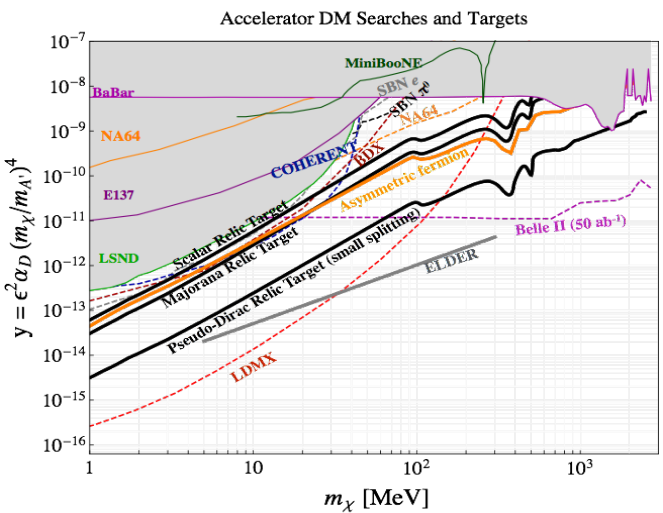
U.S. Cosmic Visions: New Ideas in Dark Matter

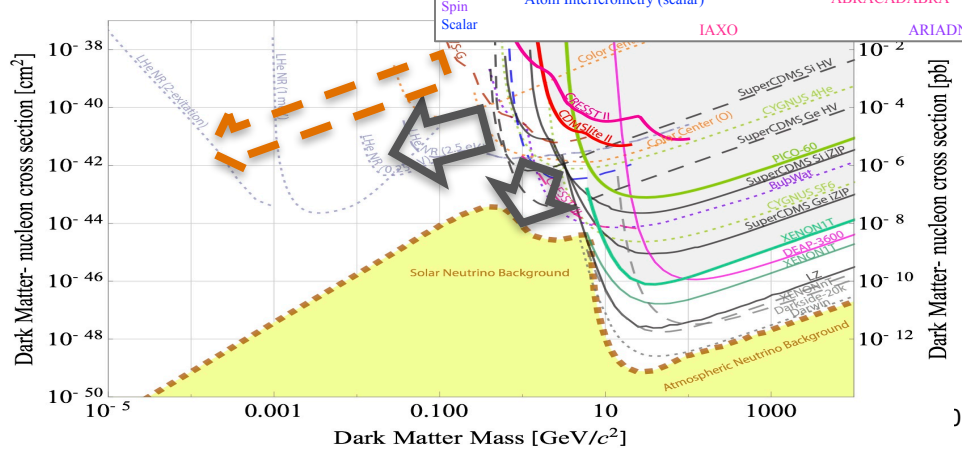
23-25 March 2017 *Stamp Student Union, University of Maryland, College Park*
US/Eastern timezone

Three areas of opportunities to probe identified targets

1. New Avenues in Direct Detection
2. Ultra-low mass (sub-eV) DM Detection
3. DM Production at accelerators







Understanding Cosmic Acceleration: Dark Energy & Inflation

Two epochs of accelerated expansion of the universe:

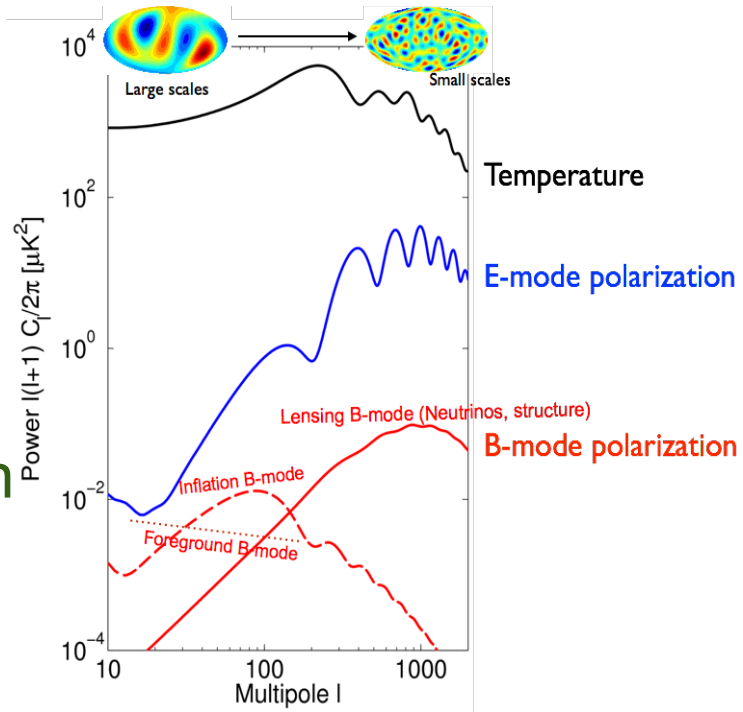
- Primordial (inflation) – first fraction of a second of the universe
  - Cause is unknown – new physics at ultra-high energies
- Dark Energy – began more recently and continues today
  - Einstein's constant or something else evolving with time

2 sets of primordial ripples probe Inflation

- Gravitational waves
- Density waves
- Waves imprint characteristic polarization

Suite of expt's with increasing precision

Stage 2 → Stage 3 → Stage 4



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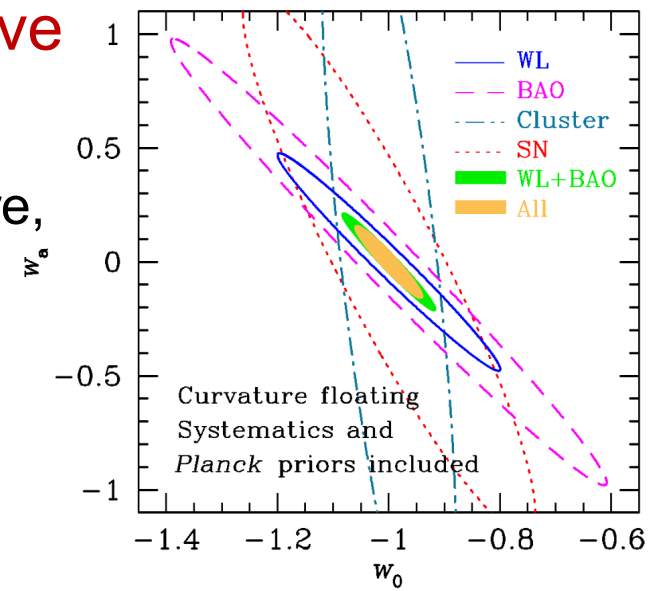
5 Cosmological probes yield deeper understanding of the nature of dark energy & will observe dynamical behavior of dark energy

- Weak Lensing, Clusters, Large Scale Structure, Strong Lensing, Type 1a Supernovae



Suite of expt's with increasing precision

DES/BOSS → DESI → LSST

Exploring the Unknown

New Particles, Interactions & Physical Principles

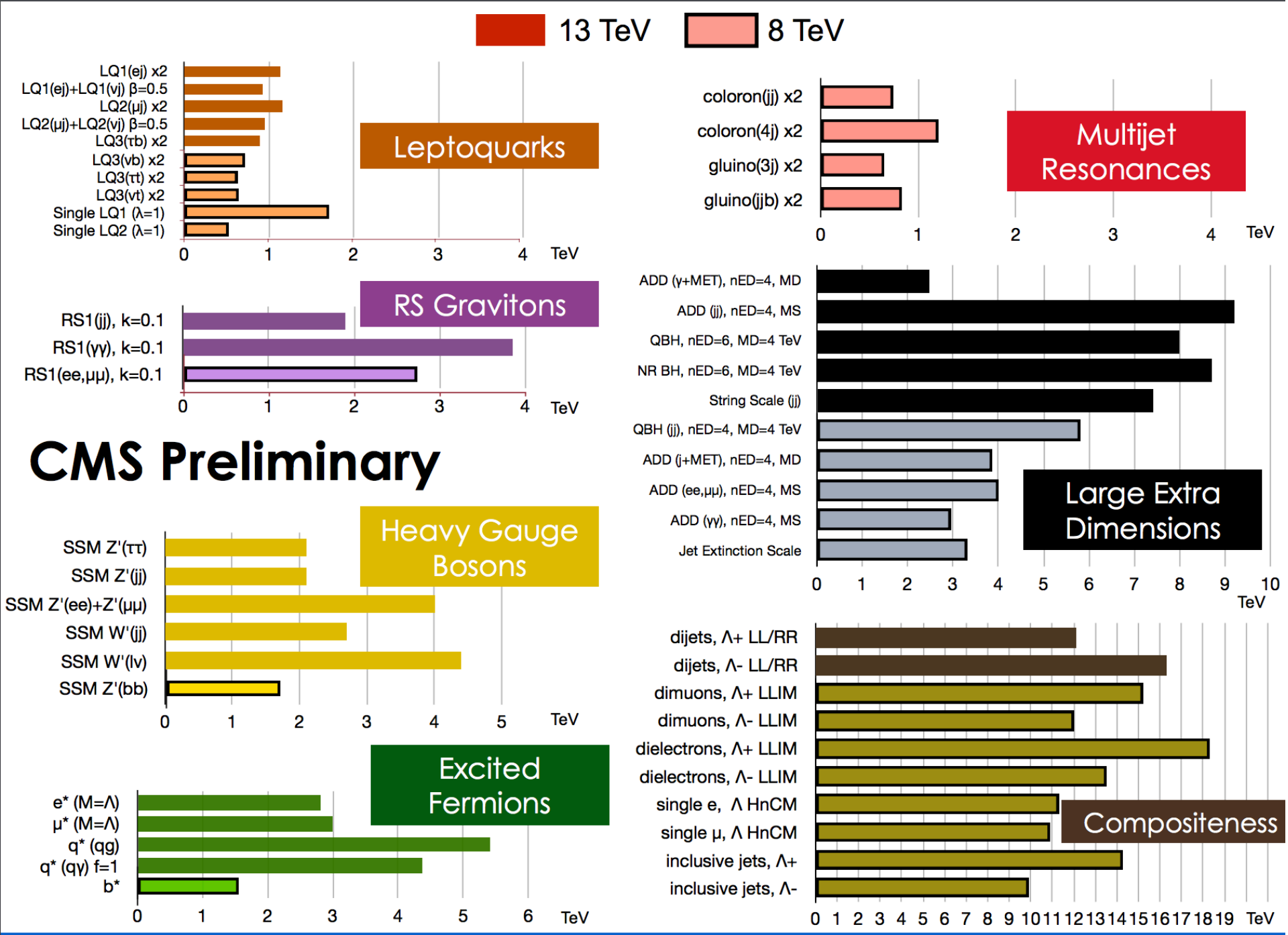
Clear indicators of physics beyond the Standard Model that invite exploration

Two signatures

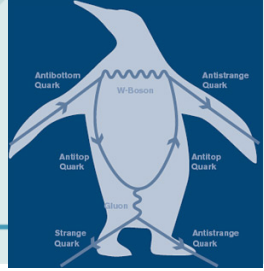
- Direct production of new particles at colliders
- Indirect quantum effects of new particles

A Cellar of Ideas for New Physics: Theory

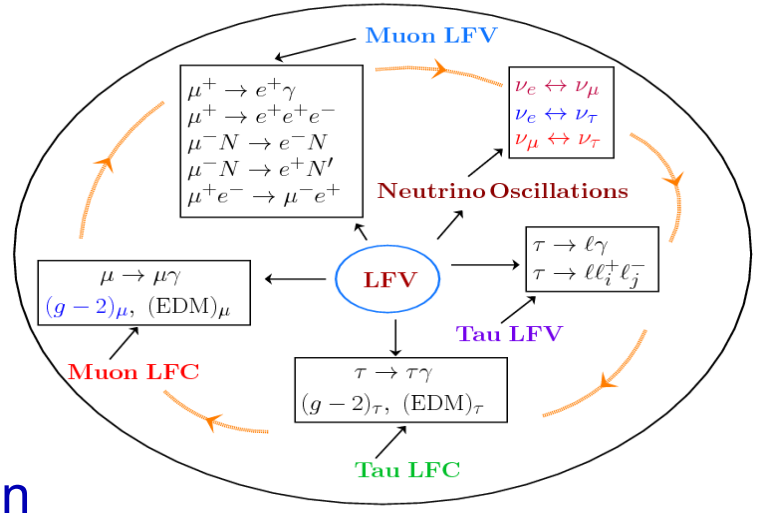
’67	The Standard Model	a classic! aged to perfection
~~’77~~	~~Vin de Technicolor~~	better drink now
’70’s	Supersymmetry: MSSM	mature, balanced, well developed - the Wino’s choice
’90’s	SUSY Beyond MSSM	svinters blend
’90’s	CP Violating Higgs	all upfront, no finish lacks symmetry
’98	Extra Dimensions	bold, peppery, spicy uncertain terrior
’02	Little Higgs	complex structure
’03	Fat Higgs	young, still tannic needs to develop
~~’03~~	~~Higgsless~~	sleeper of the vintage what a surprise!
’04	Split Supersymmetry	finely-tuned
’05	Twin Higgs	double the taste

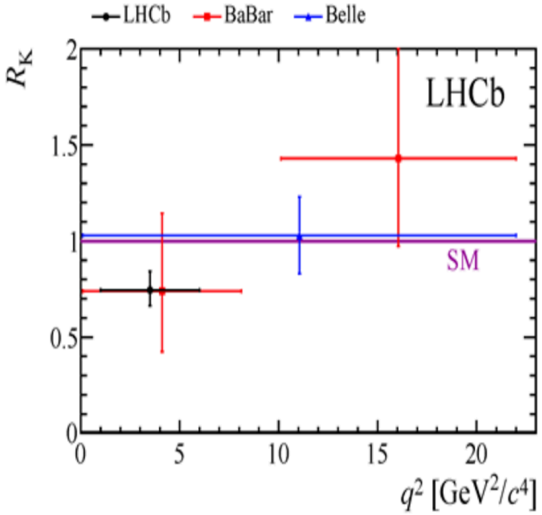

13 TeV
8 TeV
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(vj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(vj) β=0.5
LQ3(τb) x2
LQ3(vb) x2
LQ3(τt) x2
LQ3(vt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
0 1 2 3 4 TeV
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4 TeV
RS Gravitons
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
0 1 2 3 4 TeV
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
0 1 2 3 4 5 6 7 8 9 10 TeV
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lv)
SSM Z'(bb)
0 1 2 3 4 5 TeV
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
0 1 2 3 4 5 6 TeV
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV

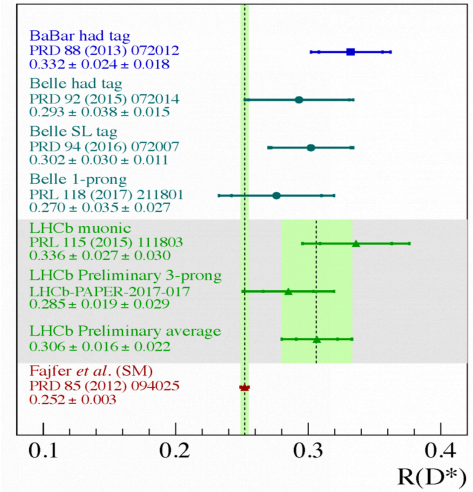
Quantum Effects of New Particles



- Charged Lepton Flavor Violation
  - Muon to electron conversion
    - On schedule for start of operations
- Precision Measurements of Charged Lepton Properties
  - Anomalous magnetic moment of the muon
    - Data taking has begun! 3.5σ discrepancy with SM to be resolved
- Heavy quark physics
  - LHCb, BelleII
  - 2-3 σ anomalies from LHCb on lepton universallity







Enablers

Are key to our future success

Advances in:

- Acceleration
  - High-field superconductiong magnets
  - Plasma/Laser Wakefield acceleration
- Computing
  - Quantum computing is the next revolution!
- Detector R&D
  - New techniques bring new experimental possibilities

All must be maintained at the appropriate level

Theoretical Physics

New ideas yield new experiments

Precise calculation of signal and background quantifies discovery

- U.S. is a scientific center of excellence in theoretical physics
  - Broad view across subdisciplines, connected to & defining programs
- Provide support to US & International HEP programs
- Provide center of excellence for training young scientists

Healthy U.S. theory program must be maintained for health of overall program

Nothing is possible without theory

P5: Where are we today?

The P5 plan has endurance

- Accepted by the community
- Followed by the funding agencies
- Accepted in Congress

  The FY18 Senate appropriations bill states:

  The Committee strongly supports the Secretary's efforts to advance the recommendations of the Particle Physics Project Prioritization Panel Report, which established clear priorities for the domestic particle physics program

Plan requires a delicate balance

- breadth and mix of project scale
- healthy theory program
- enablers
- balance between research, operations, projects

Summary

- The P5 plan is an amazingly diverse array of exciting science with yuge discovery potential
- It is progressing well so far

We are on a good track – keep up the momentum!