Science Highlights: Frontier Summaries and Panel Discussion

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- Brief Introduction
- Frontier Physics Highlights: CF, EF, NF, RPF, TF
- Discussion and Questions

A lot of Particle Physics is Missing in the Standard Model

- Why Electroweak Symmetry Breaking occurs?
  What is the history of the Electroweak Phase Transition ?
- The reason for the Hierarchy in Fermion Masses and their Flavor Structure
- The Nature of Dark Matter
- The origin of the Matter-Antimatter Asymmetry
- The generation of Neutrino Masses
- The cause of the Universe's accelerated expansion - Dark Energy
- What are the quantum properties of Gravity?
- What caused Cosmic Inflation after the Big Bang?

The SM is silent about all the above, BSM physics is at the core of it all

Each Frontier physics highlights aims at deciphering many of these mysteries and their approaches are in many ways complementary to each other

BSM example: Dark Matter

Theory Frontier: which are possible dark matter candidates and possible associated dark sectors, and their corresponding experimental signatures?

Cosmic Frontier: can we refine our understand of its properties based on cosmic observations? e.g., self-interactions or its interactions with the SM

Energy Frontier: can we produce and infer the presence of potential dark matter or other dark sector particles at the LHC?

Neutrino Physics Frontier: are there sterile neutrinos and can they be dark matter candidates? Are dark sector effects already affecting neutrino experiments e.g., the MiniBooNE anomaly?

Rare and Precision Frontier: can we probe flavor violation effects that may be predicted by TeV scale BSM theories of dark matter?

BSM example: Matter-antimatter asymmetry

Theory Frontier: which are viable models for baryogenesis/leptogenesis and what do they imply for experiments?

Cosmic Frontier: can we find gravitational wave signals from early universe first order phase transitions?

Energy Frontier: can we discover an extended Higgs sector that points towards electroweak baryogenesis? Can we probe models of new gauge forces and dark sectors, or Supersymmetry, that allows for electroweak baryogenesis?

Neutrino Physics Frontier: is there leptonic CP violation and what is the implication for leptogenesis models? What is the mass hierarchy, and are neutrinos Majorana?

Rare and Precision Frontier: can we detect electric dipole moments induced by new CP violation phases required for electroweak baryogenesis?

BSM example: Neutrino mass generation

Theory Frontier: which are the viable models of neutrino mass generation and what do they imply for experiments?

Cosmic Frontier: can we measure the sum of neutrino masses from cosmic observations?

Energy Frontier: can discover new heavy neutral fermions possibly related to see-saw mass generation mechanisms?

Neutrino Physics Frontier: what is the mass hierarchy, and are neutrinos Majorana?

Rare and Precision Frontier: is there charged lepton flavor violation signaling a whole new sector related to neutrinos as well?

Possible Discovery Menu in the coming decade from current HEP program

LHC

- Higgs cousins of many types with many possible implications
- Dark matter, dark sector, feebly-interacting particles, long-lived particles
- New forces (gauge bosons)
- New kind of scalars or fermions
- Higgs boson is composite
- Higgs flavor violation, Higgs CP violation
- Lepton flavor Violation signals
- Etc.

* Some items may be related to the Muon g-2 result

* Other accelerator-based experiments will add uniquely

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Neutrinos

- SBN results to make a definite statement about the MiniBooNE anomaly and its many possible BSM interpretations
- Other current anomalies could be resolved/confirmed
- Mass ordering to be better known from global fits, but a definitive result only possible if no tension in combined data
- CP violation still uncertain

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Rare and Flavor

- Charged LFV
- Lepton Number violation
- Quark Flavor opportunities

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- Direct dark matter searches could discover one or more kinds of DM particles
- A full and varied slate of dark matter new initiatives for light DM will be in mature stages and may have discoveries
- Some fixed target accelerator-based experiments running/complete and may have discoveries

* A discovery in direct detection exp., LHC, SBN, DUNE, other accelerator-based or indirect dark matter searches, cosmic probes of DM, will have immediate implications for all other experiments. Applies both to DM and dark sector/forces

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Cosmic

- Unique probes of dark matter properties, interactions with the SM and with itself
- Even better limits or measure the sum of neutrino masses from cosmic probes
- Dark energy is dynamical
- Dynamics of inflation; primordial B-modes either observed of better constrained
- Resolve the Hubble tension, which may be an indication of physics beyond the SM
- Better measurement of N_{eff} (relevant for light relics)
- Gravitational waves as a window to early phase transitions

The growing importance of cross-cutting activities

- Theory is a cross-cutting area that integrates into everything we do in HEP
- This is also true for Instrumentation and Computation which will be summarized in the next panel (lots of great pictures!)
- More recently AI/machine learning has begun to assume a similar role
- And Quantum Science shows similar promise !

Some observations

- We are probing many of the deepest secrets of our universe
- HEP is a very exciting field with a strong program, as recognized by our stakeholders and other communities
- The HEP program is broad by design, both to maximize discoveries and make the science connections we will need to make sense out of discoveries
- With so much discovery potential in the coming decade, we are planning for success, being ambitious, but being realistic about timescales
- An exciting field with multiple Noble Prize worthy discoveries can provide the momentum to launch many new initiatives

Great advancements since Snowmass 2013. We are ready for the next P5 exercise

Frontier Physics Highlights: CF, EF, NF, RPF, TF

- **Summary of the physics highlights / Big ideas**, which define their vision for 2025-2035 and 10 years after 2035.
- **Summary on experiments proposed to investigate them** and their proposed timelines (timelines = R&D, construction and data collection).
- **Comment on the mapping of each frontier's science on the current P5 science drivers and possible new directions.**
- Together discuss if the collective physics highlights from all Frontiers may reaffirm the P5 science drivers or points towards a need to reformulate/extend them.

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Thank you !