The Future of HEP

J. Hewett
SSI2023
JoAnne’s personal SSI history

Attended as a student in 1984

Organizing Cmtte 2003-2015

Lectured in

1993: Top ten models constrained by b to s gamma
1995: The role of top in heavy flavor physics
2012: Supersymmetry basics
2013: The vision ahead
2023: Future of HEP
What is the world made of?
What holds the world together?
Where did we come from?

These are the questions humans have asked from the very beginning..now we have some real answers..& even more questions !
Why are there so many kinds of particles?
What is dark matter?
What is dark energy?
Why is there matter and no antimatter?
Why is CP Violation absent in QCD?
Are there extra dimensions?
Do the forces unify?
What is the nature of neutrinos?
What stabilizes the Higgs mass?
.....
The U.S. High Energy Physics program is guided by the strategic plan laid out in the 2014 P5 report.

Community Driven Strategic Process

- "Snowmass" 2013: a year-long community-wide study of science opportunities, organized by the Division of Particles and Fields of the American Physical Society
- Particle Physics Project Prioritization Panel (P5) 2014: High Energy Physics Advisory Panel (HEPAP) subpanel, prioritized scientific opportunities outlined in the Snowmass study within a budget framework

Dovetailed with

- 2010 Astronomy & Astrophysics Decadal Survey
- 2013 European Strategy for Particle Physics

Process defines strategic plan for U.S. HEP for the decade.
P5 Plan in 2023: 9 years in

P5 projects report card:

9 Projects have been completed (and transitioned to commissioning & operations)
  • Belle-2, Muon g-2, Phase I ATLAS, Phase I CMS, DESI, LZ, FACET-II, LSSTCamera, sCDMS

5 Projects at CD-2/3 (Baseline/Construction)
  • HL-AUP, HL-LHC ATLAS, HL-LHC CMS, Mu2e, PIP-II

1 Projects at CD-1 (preparing for baseline)
  • LBNF/DUNE

2 Projects at CD-0
  • CMB-S4
  • Accelerator Control Operations and Research Network at FNAL

Broad portfolio of small projects from R&D phase to operations
Next U.S. HEP Strategic Planning Process almost complete!

The U.S. High Energy Physics program will be guided by the strategic plan laid out in the 2023 P5 report

Community Driven Strategic Process

- **“Snowmass” 2020-2022**: 2 years-long community-wide study of science opportunities, organized by the Division of Particles and Fields of the American Physical Society
- **Particle Physics Project Prioritization Panel (P5) 2023**: High Energy Physics Advisory Panel (HEPAP) subpanel, prioritized scientific opportunities outlined in the Snowmass study within a budget framework

Dovetailed with

- **2021** Astronomy & Astrophysics Decadal Survey
- **2020** European Update on Strategy for Particle Physics
LHC data agree amazingly well with SM predictions

The LHC is a precision measurement machine!
SM predictions becoming very precise

Higgs cross sections now being computed to next-to-next-to-next-to-leading order (N^3LO)!
LHC data agree amazingly well with SM predictions

Nonetheless, the SM can only be considered a low-energy effective theory description of particle physics that leaves many unanswered questions about the nature of reality at distance scales shorter than $\sim$ TeV$^{-1}$.

Snowmass theory summary 2210.03075
New Physics @ the Terascale

Electroweak Symmetry breaks at energies ~ 1 TeV (SM Higgs or ???)

WW Scattering unitarized at energies ~ 1 TeV (SM Higgs or ???)

Gauge Hierarchy: Nature is fine-tuned or Higgs mass must be stabilized by New Physics ~ 1 TeV

Dark Matter: Weakly Interacting Massive Particle must have mass ~ 1 TeV to reproduce observed DM density

All things point to the Terascale!
New Physics @ the Terascale

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All things point to the Terascale!
Not all data agrees with the SM predictions

**g-2 of the muon**

New results from FNAL are extremely precise!
- 0.20 ppm precision
- 3 additional yrs of data to analyze

5.0σ from 2020 SM prediction
- SM prediction currently being updated

BSM interpretations becoming more difficult
- Many SM extensions yield wrong sign for the discrepancy
- Tension with collider data
- Evade limits with
  - compressed spectra
  - Chirality flipping new physics operators
  - A large number of new fields or large couplings
SM predictions becoming very precise

Muon g-2 theory initiative

International initiative to produce a single consensus theoretical value of $a_\mu$ within the SM

~ 150 author collaboration!

3 approaches to the Hadronic vacuum polarization and light-by-light contributions: Data-driven, lattice, and dispersive

Annual workshops to refine calculations and reach consensus

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HVP, LO}} + a_\mu^{\text{HVP, NLO}} + a_\mu^{\text{HVP, NNLO}} + a_\mu^{\text{HLbL}} + a_\mu^{\text{HLbL, NLO}}$$

$$= 116\,591\,810(43) \times 10^{-11}.$$
Model-independent analysis with one new field

<table>
<thead>
<tr>
<th>Model</th>
<th>Spin</th>
<th>$SU(3)_C \times SU(2)_L \times U(1)_Y$</th>
<th>Result for $\Delta a^\text{BNL}<em>\mu$, $\Delta a^\text{2021}</em>\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>(1, 1, 1)</td>
<td>Excluded: $\Delta a_\mu &lt; 0$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>(1, 1, 2)</td>
<td>Excluded: $\Delta a_\mu &lt; 0$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>(1, 2, −1/2)</td>
<td>Updated in Sec. 3.2</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>(1, 3, −1)</td>
<td>Excluded: $\Delta a_\mu &lt; 0$</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>(3, 1, 1/3)</td>
<td>Updated Sec. 3.3.</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>(3, 1, 4/3)</td>
<td>Excluded: LHC searches</td>
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<td>7</td>
<td>0</td>
<td>(3, 3, 1/3)</td>
<td>Excluded: LHC searches</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>(3, 2, 7/6)</td>
<td>Updated Sec. 3.3.</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>(3, 2, 1/6)</td>
<td>Excluded: LHC searches</td>
</tr>
<tr>
<td>10</td>
<td>1/2</td>
<td>(1, 1, 0)</td>
<td>Excluded: $\Delta a_\mu &lt; 0$</td>
</tr>
<tr>
<td>11</td>
<td>1/2</td>
<td>(1, 1, −1)</td>
<td>Excluded: $\Delta a_\mu$ too small</td>
</tr>
<tr>
<td>12</td>
<td>1/2</td>
<td>(1, 2, −1/2)</td>
<td>Excluded: LEP lepton mixing</td>
</tr>
<tr>
<td>13</td>
<td>1/2</td>
<td>(1, 2, −3/2)</td>
<td>Excluded: $\Delta a_\mu &lt; 0$</td>
</tr>
<tr>
<td>14</td>
<td>1/2</td>
<td>(1, 3, 0)</td>
<td>Excluded: $\Delta a_\mu &lt; 0$</td>
</tr>
<tr>
<td>15</td>
<td>1/2</td>
<td>(1, 3, −1)</td>
<td>Excluded: $\Delta a_\mu &lt; 0$</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>(1, 1, 0)</td>
<td>Special cases viable</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>(1, 2, −3/2)</td>
<td>UV completion problems</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>(1, 3, 0)</td>
<td>Excluded: LHC searches</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>(3, 1, −2/3)</td>
<td>UV completion problems</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>(3, 1, −5/3)</td>
<td>Excluded: LHC searches</td>
</tr>
<tr>
<td>21</td>
<td>1</td>
<td>(3, 2, −5/6)</td>
<td>UV completion problems</td>
</tr>
<tr>
<td>22</td>
<td>1</td>
<td>(3, 2, 1/6)</td>
<td>Excluded: $\Delta a_\mu &lt; 0$</td>
</tr>
<tr>
<td>23</td>
<td>1</td>
<td>(3, 3, −2/3)</td>
<td>Excluded: proton decay</td>
</tr>
</tbody>
</table>

Athron et al, 2104.03691
Model-independent analysis with 2 new fields of different spins

<table>
<thead>
<tr>
<th>$(SU(3)_C \times SU(2)_L \times U(1)<em>Y)</em>\text{spin}$</th>
<th>$+\mathbb{Z}<em>2$ Result for $\Delta a^\text{BNL}</em>\mu$, $\Delta a^\text{2021}_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(1, 1, 0)<em>0 - (1, 1, -1)</em>{1/2}$</td>
<td>No Yes</td>
</tr>
<tr>
<td>$(1, 1, -1)<em>0 - (1, 1, 0)</em>{1/2}$</td>
<td>Both</td>
</tr>
<tr>
<td>$(1, 2, -1/2)<em>{0} - (1, 1, 0)</em>{1/2}$</td>
<td>Both</td>
</tr>
<tr>
<td>$(1, 1, 0)<em>0 - (1, 2, -1/2)</em>{1/2}$</td>
<td>No Yes</td>
</tr>
<tr>
<td>$(1, 2, -1/2)<em>{0} - (1, 1, -1)</em>{1/2}$</td>
<td>No Yes</td>
</tr>
<tr>
<td>$(1, 1, -1)<em>0 - (1, 2, -1/2)</em>{1/2}$</td>
<td>Excluded: LEP search</td>
</tr>
<tr>
<td>$(1, 2, -1/2)<em>{0} - (1, 2, -1/2)</em>{1/2}$</td>
<td>Excluded: LHC searches</td>
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<tr>
<td>$(1, 2, -1/2)<em>{0} - (1, 3, 0)</em>{1/2}$</td>
<td>No Yes</td>
</tr>
<tr>
<td>$(1, 2, -1/2)<em>{0} - (1, 3, -1)</em>{1/2}$</td>
<td>No Yes</td>
</tr>
<tr>
<td>$(1, 3, 0)<em>{0} - (1, 2, -1/2)</em>{1/2}$</td>
<td>Excluded: LHC searches + LEP contact interactions</td>
</tr>
<tr>
<td>$(1, 3, 0)<em>{0} - (1, 3, -1)</em>{1/2}$</td>
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<td>No Yes</td>
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</tr>
<tr>
<td>$(1, 3, -1)<em>{1/2} - (1, 3, 0)</em>{1}$</td>
<td>No</td>
</tr>
</tbody>
</table>

Athon et al., 2104.03691
Features of MSSM models compatible with the excess

- Approach 2σ region with large \( \tan\beta \) near 50
- Very large \( \tan\beta >> 50 \)
- Tune slepton masses so that slepton and LSP are close
- Light charginos, \( m_{\chi^{\pm}_{1,2}} < m_{\text{slepton}} \)

Dickinson et al., 2207.05103

Bino-Wino dark matter

Chakraborti, Heinemeyer, Saha
Not all data agrees with the SM predictions

W-Boson mass measurement

7σ from SM EW fit prediction!
Flurry of theory activity!

Indirect determinations of Higgs mass

EW fits to the oblique parameters

De Blas et al, 2204.04204
Correlations between $M_W$ and g-2

2HDM with leptophilic Higgs

MSSM

Babu et al., 2204.05303

Bagnaschi et al., 2203.15710
THE JURY IS OUT
The Higgs Boson as a tool for discovery

Precision Higgs physics is key for BSM physics
Precision Higgs measurements at future colliders

Dawson et al., 2209.07510
Typical mass scales probed by precision Higgs coupling measurements

Size of Higgs Coupling deviations?

Tree level origin

\[ \frac{v^2}{M^2} \]

Loop level

\[ \frac{1}{(4\pi)^2} \frac{v^2}{M^2} \]

SM Neutral e.g. scalar singlet

\[ \approx \left( \frac{\lambda_{h^2 s}^2}{2M^2} \right) \frac{v^2}{M^2} \]

\[ M \lesssim 1.7 \text{ TeV} \]

\[ M \lesssim 5.5 \text{ TeV} \]

SM Charged e.g. 2HDM

\[ \approx \left( \frac{\lambda_{h^2 u}^2 v^2}{M^2} \right) \frac{v^2}{M^2} \]

\[ M \lesssim 0.8 \text{ TeV} \]

\[ M \lesssim 1.4 \text{ TeV} \]

SM Neutral e.g. scalar singlet

\[ \approx \left( \frac{\lambda_{h^2 s}^2}{48\pi^2} \right) \frac{v^2}{M^2} \]

\[ M \lesssim 0.1 \text{ TeV} \]

\[ M \lesssim 0.4 \text{ TeV} \]

SM Charged w/ SM loop e.g. stops in SUSY

\[ \approx \frac{1}{4m_t^2} \]

\[ M \lesssim 0.9 \text{ TeV} \]

\[ M \lesssim 2.8 \text{ TeV} \]

Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

\[ \delta \eta_{SM} \approx 1\% \]

\[ \delta \eta_{SM} \approx 0.1\% \]

Dawson et al., 2209.07510
Higgs couplings in the pMSSM

Higgs coupling measurements sensitive to models with masses up to ten's of TeV

pMSSM scan: 0.1-25 TeV for non-colored sparticles and 0.2-50 TeV for sparticles with color

Dickinson et al., 2207.05103
H → bb in the pMSSM

Fraction of scan points within 1% of SM

Narain et al, 2211.11084
What to do about the hierarchy problem?

Quantum corrections to scalars e.g. mass

\[ \delta m_{\phi}^2 \propto c_1 \Lambda_{NP}^2 + c_2 M_{Pl}^2 \]
What to do about the hierarchy problem?

I’m open to good ideas!

Quantum corrections to scalars e.g. mass

\[ \delta m^2_\phi \propto c_1 \Lambda^2_{NP} + c_2 M^2_{Pl} \]
What to do about the hierarchy problem?

I’m open to good ideas!

Choices:

- New physics properties render it inaccessible to current experiment
- New physics is just out of kinematic reach to current experiment
- We don’t have the right ideas - not thinking the right way
- Nature is fine-tuned

\[ \delta m^2 \phi \propto c_1 \Lambda^2_{NP} + c_2 M^2_{Pl} \]
THE JURY IS OUT
Effective Field Theories: Global fits of new physics

Model independent description of new physics

Wilson expansion, in powers of the cut-off scale and new physics encoded in the Wilson coefficients

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d=5}^{\infty} \sum_{i} \frac{C_i(d)}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} \]

A complete basis of operators with \( d=5-8 \) totals 2499 operators! 84 operators for one generation only and 59 if CP is also conserved

Example of the power of this approach taking one operator at a time

Future limits on leptoquark coupling/mass

Belloni et al, 2209.08078
precision reach on effective couplings from SMEFT global fit

subscripts denote luminosity in ab^(-1)
Z & WW denote Z-pole & WW threshold

Belloni et al., 2209.08078
Operators involved in top-quark production and decay

Shaded bars are global fit

Belloni et al, 2209.08078
Future Collider sensitivity to new physics

Composite Higgs: EFT Approach

Phenomenology governed by 2 parameters:

Compositeness scale and coupling

Universal new gauge boson

Direct and indirect production

Narain et al., 2211.11084
Supersymmetry reach at future colliders
Reminder that neutrino masses are Dim-5 operators in the SM and are themselves an example of new physics.

<table>
<thead>
<tr>
<th>BSM Scenario</th>
<th>Sources</th>
<th>Signatures</th>
<th>Example Experiments</th>
</tr>
</thead>
</table>
| HNL [1]      | Colliders | HNL decay | ATLAS, CMS, FASER, Belle II, ...
| Nuclear decays | | Nuclear decay kinematics | KATRIN/TRISTAN, HUNTER, ...
| Fixed target  | | HNL decay | DUNE ND, SHIP, ICARUS, ...
| Atm. & solar  | | Distorted recoil spectrum | DUNE, HK, IceCube/DeepCore, ...
| v's          | | HNL decay, double bangs | DUNE, HK, IceCube/DeepCore, ...
| Early Universe | | Cosmological parameters \(N_{\nu}\) | Simons Observatory, CMB-S4, ...
| Non-unitarity [2] | Beam & Atm. v's | Deviations from 3-v mixing \(\text{ND} \, \text{& FND}\) | DUNE, ESSr5B, HK, ...
| LED [2]      | Reactor v's | Distortion of oscillated spectra \(\text{FD} \, \text{& ND}\) | JUNO, TAO, ...
| Beam v's     | | Icecube, KM3NeT | DUNE, ...
| Atm. v's     | Anomalous matter effects | DUNE, ...
| NSI & light mediators [3, 4] | Reactor & Spallation sources | Distortion of CE/NS rate | COHERENT, CONNIE, CONUS, ...
| Solar, Beam, Atm. & SN v's | | Anomalous matter effects | DARWIN, DUNE, T2HK, HK, IceCube, ...
| Beam v's     | | Anomalous appearance, \(\nu \rightarrow e\) scattering, tridents | DUNE ND, T2HK ND, IsodAR, ...
| Collider v's | | Distortion of CC spectrum | FASERv, ...
| Long-range forces [2] | Solar & Atm \(\nu\) | Anomalous matter potential | HK, JUNO, DUNE, ...
| UHE Astrophysical v's | | Distorted flavor ratios | HE Neutrino Telescopes |
| \(\nu\)-DM interact. [3] | Reactor & solar v's | Distorted oscillated spectra, or time-dependent oscillation params. | JUNO, ...
| Beam \(\nu\) | | DUNE, ...
| UHE Astrophysical v's | Distorted flavor ratios & spectra | HE & UHE Neutrino Telescopes |
| \(\nu\) self interact. [3, 14] | SN v's | SN extra energy loss, distortion in neutrino spectra | DUNE, HK, JUNO, ...
| UHE Astrophysical v's | Distorted spectra | HE & UHE \(\nu\) telescopes |
| Early Universe | Effects on CMB, BBN, & structure formation | CORE, PICO, CMB-S4 |
| Beam & Collider v's | Missing energy & \(p_T\) in \(\nu\) scattering | DUNE ND, Forward Physics Facility, ...
| \(\nu\) decay [3] | Reactor & DAR v's | Distortion of oscillated spectra | JUNO, IsodAR, ...
| Beam \(\nu\) | | DUNE, MOMENT, ESSr5B, HK, ...
| Atm. v's | | INO-ICAL, KM3NeT-ORCA, ...
| UHE Astrophysical v's | Different \(\nu\) and \(\bar{\nu}\) oscill. params. | IceCube, DUNE, ...
| Beam v's | | DUNE, ESSr5B, HK, ...
| Atm. v's | | IceCube, DUNE, ...
| UHE Astrophysical v's | Distorted flavor ratios & spectra | HE & UHE Neutrino Telescopes |
| CPT violation [2] | Beam v's | Different \(\nu\) and \(\bar{\nu}\) oscill. params. | IceCube, DUNE, ...
| Atm. v's | | DUNE, ESSr5B, HK, ...
| UHE Astrophysical v's | Distorted flavor ratios & spectra | HE & UHE Neutrino Telescopes |
| Lorentz violation [2] | Beam v's | Sidereal modulation of event rate | IceCube, DUNE, ...
| Atm. v's | | DUNE, ESSr5B, HK, ...
| UHE Astrophysical v's | Distorted flavor ratios & spectra, velocity dispersion | HE & UHE Neutrino Telescopes |
| Quantum decoh. [2] | Reactor & DAR v's | Distortion of oscillated spectra | JUNO, IsodAR, ...
| Beam \(\nu\) | | DUNE, ...
| Atm. v's | | KM3NeT, IceCube, HK, ...
| UHE Astrophysical v's | Distorted flavor ratios | HE Neutrino Telescopes |
| B violation [5] | Detector mass | Nucleon decay, \(n \rightarrow \nu\) oscillations | DUNE, HK, JUNO, ...
| Dark Matter [6, 7] | DM annihilation, DM decay | Excess of \(\nu\)'s from Sun or Earth | DUNE, HK, IceCube ...
| Boosted DM, slow-moving DM | | Scattering, or up-scattering & decay | DUNE, T2HK, SB, FASERv, ...
| Fixed target | Decay | DUNE, T2HK, SB, FASERv, ...
| Scattering, or up-scattering & decay | | DUNE, T2HK, SB, FASERv, ...
| Milli-charged particles [7] | Fixed target | Scattering | DUNE ND, T2HK ND, ...
| Atmosphere | | DUNE, HK, JUNO, ...

Table 1: Summary of the most significant experimental signatures for the BSM scenarios covered here. Examples experiment sensitive to each scenario are also provided (see references for the full list). Abbreviations: Atm. = Atmospheric, Baryon number. CC = Charged Current, CE=NS=Coherent Elastic \(\nu\)-Nucleon Scattering, DM = Dark Matter, FD = Far Detector, HE = High Energy, LED = Large Extra Dimensions, ND = Near Detector, NS = Non-Standard Interactions, SN = Supernovae, UHE = Ultra-High Energy, DAR = Decay at rest.
Very little is known about the ingredients of the Universe

**Content fractions of the Universe.....TODAY!**

- Dark matter: 25%
- Atomic matter: 5%
- Dark energy: 69%
- Neutrinos: 0.1%
- Photons: 0.01%
- Black holes: 0.005%

**DM Observations**

- Rotation curves
- Clusters of galaxies
- CMB
- Type 1a Supernovae

*IMHO*
What is the nature of Dark Matter?

A most compelling question in particle physics today*

<table>
<thead>
<tr>
<th></th>
<th>Electron</th>
<th>Dark Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>spin</td>
<td>fermion</td>
<td>boson or fermion?</td>
</tr>
<tr>
<td>mass</td>
<td>511 keV/c²</td>
<td>( \sim (10^{-22} - 10^{28}) ) eV/c² heavier if composite or a black hole</td>
</tr>
<tr>
<td>forces</td>
<td>gravity, photon, W, Z</td>
<td>gravity, ???</td>
</tr>
<tr>
<td>other states part of same sector?</td>
<td>many!</td>
<td>???</td>
</tr>
</tbody>
</table>

* Solely the opinion of JLH and does not represent the view of any organization
No shortage of ideas: An overwhelming abundance of DM theories with wildly different DM particle properties and masses

Any DM candidate must be non-relativistic, weakly-coupled to the SM, and stable

Organized by source of particle physics models that contains the DM, where many of the models have distinctive signatures from the non-DM model components.
DM theoretical landscape has undergone an inflationary epoch

Vast landscape of models beyond top-down approach from other new physics motivations

Interaction mechanisms

- Classic freeze-out: Thermal equilibrium with the SM through $2 \rightarrow 2$ interactions, or DM may annihilate via a secondary state
- Forbidden DM: DM mass slightly below outgoing SM state
- Cannibalism: Strong influence from $3 \rightarrow 2$ or $4 \rightarrow 2$ interactions
- Freeze-in: DM is not thermal
- Asymmetric: Common origin for DM and baryon content of the Universe
- Sommerfeld enhancement: Long-range forces arise in non-relativistic limit
- Inelastic DM: Kinematics affects direct detection exp’ts

Small subset of widely-studied classes of models

- R-parity conserving supersymmetry, NMSSM, composite Higgs theories (extra dimensions)
- Strong-coupled composite DM – dark mesons/baryons, glueballs
- Atomic/Mirror DM – atom-like bound states
- Light (<GeV) DM, dark photons
- Axions and axion-like-particles
- Sterile neutrinos
- Ultraheavy DM
- Dynamical DM
- Hidden sectors and a multi-temperature universe
- FIMP, SIMP, ELDERS
Explosion of models & search techniques has necessitated a new view
New technologies cover new theory targets with small-scale exp’ts
New detector concepts target wave-like Dark Matter
New detector concepts target particle-like Dark Matter

Atomic systems

Ionizations with $q \sim a m_p \sim 4 \text{ keV}, \Delta E \sim a^2 m_p \sim 10 \text{ eV}$

Molecular systems

Excitations and ionizations with $q \sim 1 - 10 \text{ keV}, \Delta E \sim 1 - 10 \text{ eV}$

Vibrational modes with $\Delta E \sim 0.1 - 1 \text{ eV}, q \lesssim 10 - 100 \text{ keV}$

Bond breaking with $\Delta E \gtrsim 10 \text{ eV}, q \gtrsim 100 \text{ keV}$

Condensed matter systems

Excitations with $q \lesssim 10 \text{ keV}, \Delta E \lesssim 10 \text{ eV}$

Vibrational modes with $\Delta E \lesssim 0.2 \text{ eV}, q \lesssim 10 - 100 \text{ keV}$

Multi-phonon regime

Bond breaking with $\Delta E \gtrsim 10 \text{ eV}, q \gtrsim 100 \text{ keV}$

keV

MeV

$\text{Dark matter scattering}$

MeV

$\text{Dark matter absorption}$

eV

keV

Chou et al., 2211.09978
Dark Sector physics at high-intensity experiments

Summary of accelerator facilities, experiments, and detector signatures

Modest upgrades enable transformative physics
Definitive search for high-mass WIMPs with mature technology

Search for WIMPs down to the neutrino fog
- Nearly indistinguishable background from astrophysical neutrinos

Proposed ~100 tonne scale Liquid Xenon TPC

Systematic limit imposed by coherent scattering of astrophysical neutrinos
Imperative to cover as much of this parameter space as possible!
Dark Matter signatures in other experiments

Portal Dark Matter and rare Higgs decays

Dark Matter interactions with SM through kinetic mixing portal necessitates existence of massive portal matter which carry both dark and SM charges

- Direct production of heavy portal matter at LHC
- Influence on rare Higgs decays

Celestial bodies as Dark Matter detectors

Massive objects trap Dark Matter and it then annihilates

- Heats object, radiation escapes
- Observable signatures in exo-planets, neutron stars, brown dwarfs, solar system

Rizzo, 2202.02222

Leane et al, 2104.02068, 2010.00015
Mass spectrum of dark halos can provide information on DM properties through observation of dwarf galaxies, stellar streams, strong lensing.

Microlensing will provide sensitivity to macroscopic compact objects.
P5 Process, Activities, Timetable and Rollout

Hitoshi Murayama

HEPAP meeting, virtual, Aug 7, 2023
It is a great panel!
Principles in deliberations

• Optimization of science within the boundary conditions
  • Everything is on the table, nothing is off the table
• Attention to balance among
  • Different areas
  • Different sizes
  • Domestic vs international
  • Project and Research
• Actionable recommendations on DEI
• Decisions based on consensus
  • Never relied on voting
Budget Scenarios

Assuming 3% escalation in Research, Facilities & Ops
P5 Charge

Merge aspirations of Snowmass Community Study with realistic budget scenarios

Summary of the 2021-22 U.S. HEP Community Planning Exercise

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<th>Decadal Overview of Future Large-Scale Projects</th>
<th>Snowmass Summary Report, Butler et al</th>
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P5 Budget Scenarios

High Scenario: Follows FY 2022 Chips and Science Act Authorization FY 2023-27, then +3% inflation through FY 2033

Low Scenario: Begins with FY 2023 Enacted, then +2% inflation through FY 2033
THE JURY IS OUT
Summary

Some philosophy after researching BSM for 38 years(!)

We are at a bit of a crossroads
Nature has given us numerous puzzles which require BSM
We believe BSM exists and SM is an effective theory
Yet every clue towards a direction seems to evaporate with time and data
We are waiting for a BSM breakthrough, experimentally or theoretically

Theorists mainly focusing on EFTs, Dark Matter, neutrinos, and thinking of newer ideas
The 2023 P5 will point towards our future experimental directions
Whatever the future holds....

.....it will strongly involve AI/ML