THEORY FRONTIER

Snowmass

COMMUNITY PLANNING 2021

Nathaniel Craig (UCSB), Csaba Csaki (Cornell), Aida El-Khadra (UIUC),
on behalf of the Theory Frontier

TF Logo: P. Tanedo

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Theory Frontier Organization


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Topical Group		**Topical Group co-Conveners**			
TF01	String theory, quantum gravity, black holes	Daniel Harlow	Shamit Kachru	Juan Maldacena	
TF02	Effective field theory techniques	Patrick Draper	Ira Rothstein		
TF03	CFT and formal QFT	David Poland	Leonardo Rastelli		
TF04	Scattering amplitudes	Zvi Bern	Jaroslav Trnka		
TF05	Lattice gauge theory	Zohreh Davoudi	Taku Izubuchi	Ethan Neil	
TF06	Theory techniques for precision physics	Radja Boughezal	Zoltan Ligeti		
TF07	Collider phenomenology	Fabio Maltoni	Shufang Su	Jesse Thaler	
TF08	BSM model building	Patrick Fox	Graham Kribs	Hitoshi Murayama	
TF09	Astro-particle physics and cosmology	Dan Green	Joshua Ruderman	Ben Safdi	Jessie Shelton
TF10	Quantum information science	Simon Catterall	Roni Harnik	Veronika Hubeny	
TF11	Theory of Neutrino Physics	André de Gouvêa	Irina Mocioiu	Saori Pastore	Louis Strigari

Theory Frontier Liaisons

Energy Laura Reina (FSU)	**Neutrino Physics** Irina Mociouiu (Penn State) & Kaladi S. Babu (Oklahoma)	**Accelerator** Lian-Tao Wang (U Chicago)	**Community Engagement** Devin Walker (Dartmouth)
Rare and Precision Alexey Petrov (Wayne State)	**Cosmic** Flip Tanedo (UCR)	**Computational** Steven Gottlieb (Indiana U)	**Early Career** Rotating

+ Muon Collider Forum (Joint w/ Accelerator & Energy Frontiers)
Patrick Meade (Stony Brook) & Fabio Maltoni (Louvain/Bologna)

Theory Frontier in Snowmass

"Articulate the vibrancy of theory within HEP, both in relation to projects and on its own right.
Highlight important past developments and exciting new opportunities in the coming decade.
Facilitate theory-related activities across frontiers."

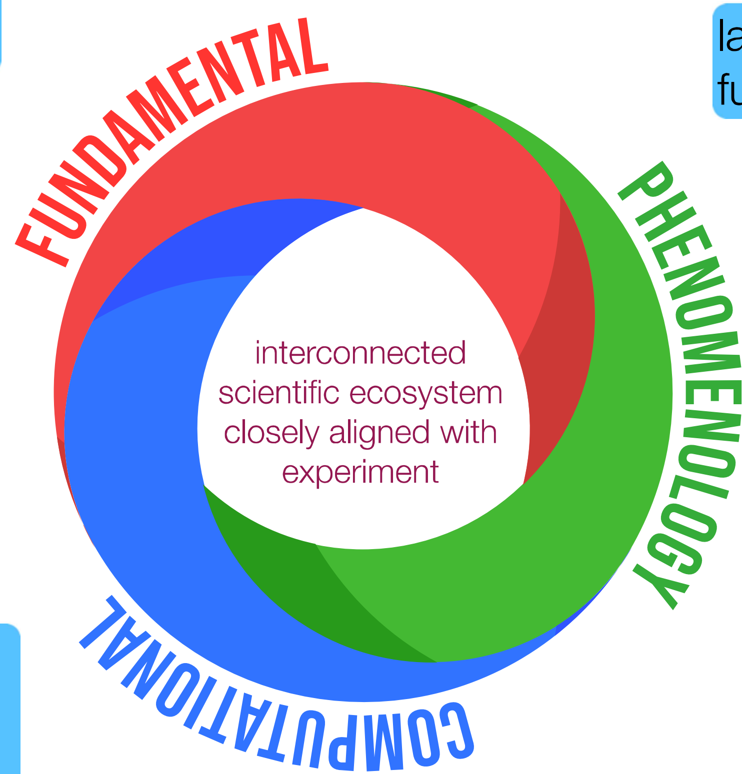
- Snowmass Town Hall & Snowmass Community Planning Meeting (2020, virtual)
- 5 virtual workshops on special topics (4 cross-frontier w/ NF, RPF)
- TF Conference at KITP (Feb. 2022, hybrid) w/ ~100 in-person participants
- Snowmass Community Summer Study (July 2022, hybrid)
- 865 subscribers to the Theory Frontier mailing list.
- 320 LOI and 150 white papers (out of 548 total) submitted to the Theory Frontier.

HEP Theory

unifies the frontiers of particle physics

connects to gravity, cosmology, astrophysics nuclear physics, condensed matter, AMO, computer science, statistics, data science, mathematics

advances our understanding of Nature in regimes that experiment cannot (yet) reach



lays the foundations for future experiments

central to the motivation, analysis, and interpretation of experiments

responsive: propose new directions based on data; propose/guide new experiments; develop new analysis tools

incorporates new perspectives (QI, ML) and computational technologies to extend the boundaries of our knowledge

Image Credit: P. Tanedo

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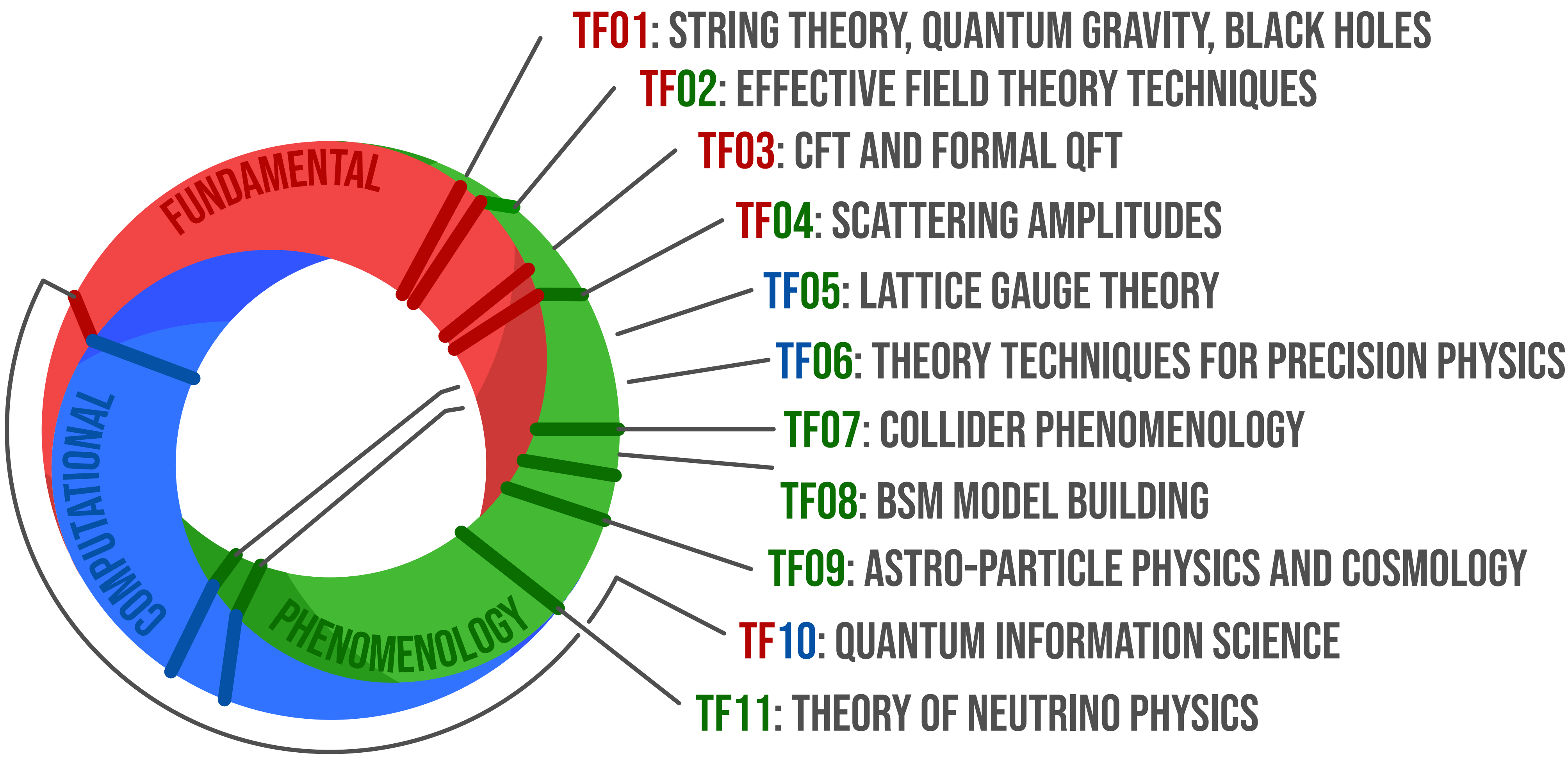
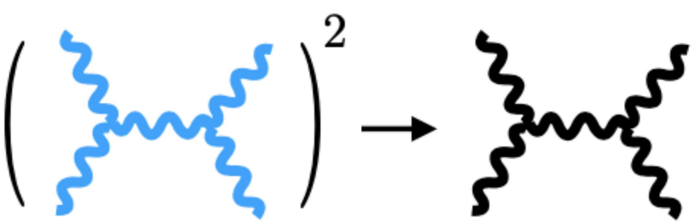
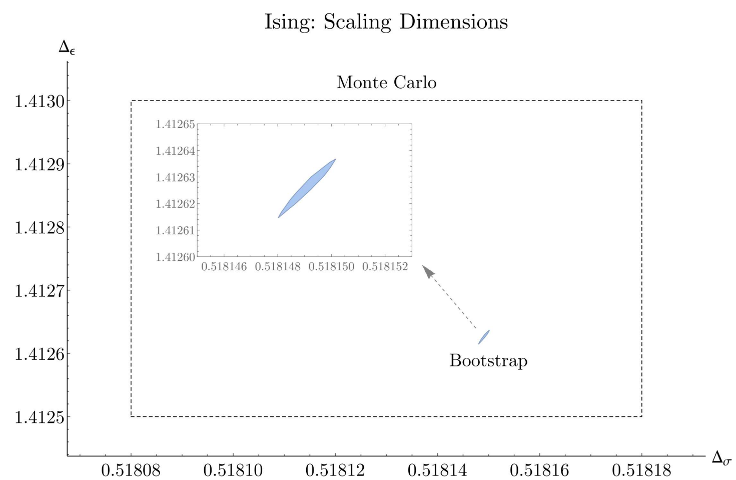


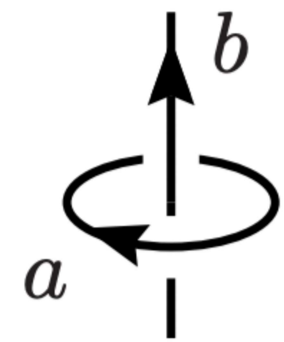
Snowmass Theory Frontier Report: https://arxiv.org/pdf/2211.05772.pdf

Select Highlights

- New perturbative and non-perturbative techniques (ranging from the double copy structure of scattering amplitudes to the advent of diverse bootstrap methods) have vastly expanded our knowledge of quantum field theory.







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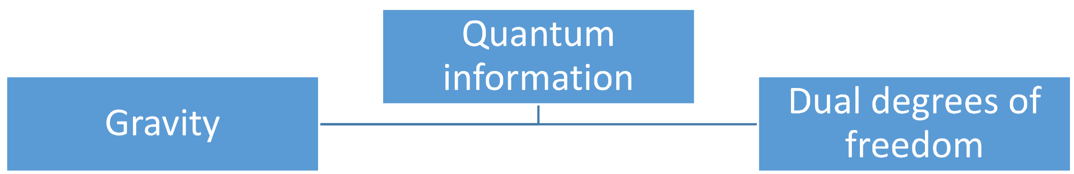
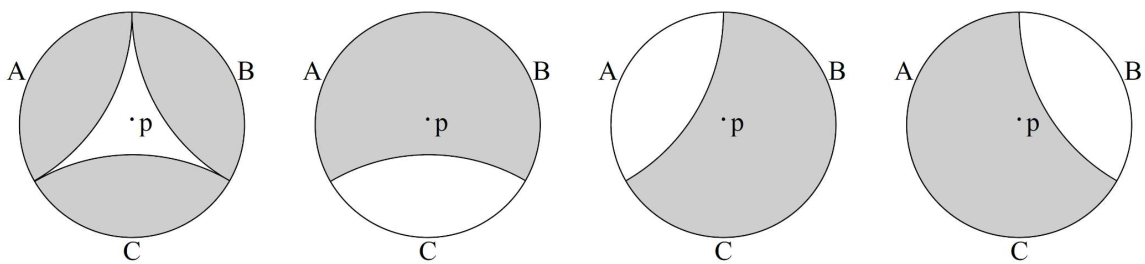
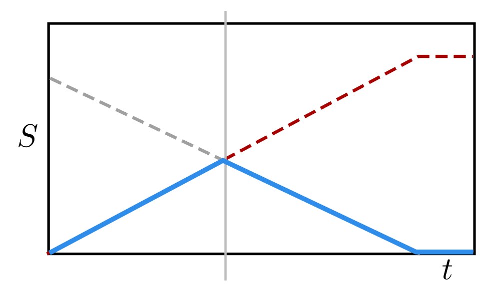
- A deeper understanding of holography and insights from quantum information have breathed new life into the longstanding quest for a complete theory of quantum gravity.







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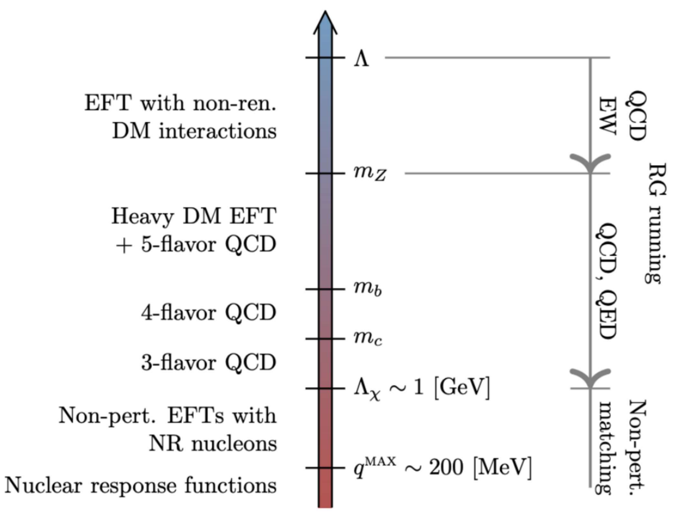
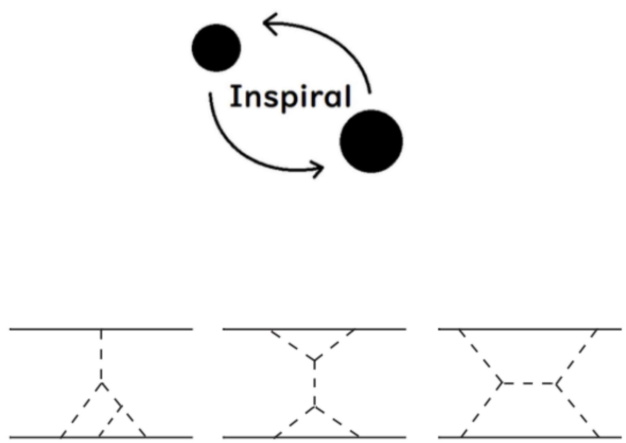
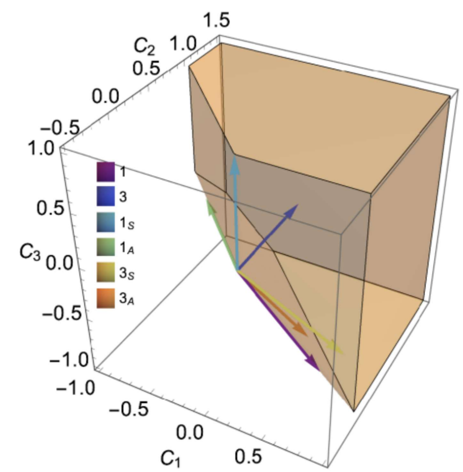
- New effective field theories have facilitated applications of QFT to high-energy scattering, Higgs physics, large-scale structure, inflation, dark matter detection, and gravitational waves.







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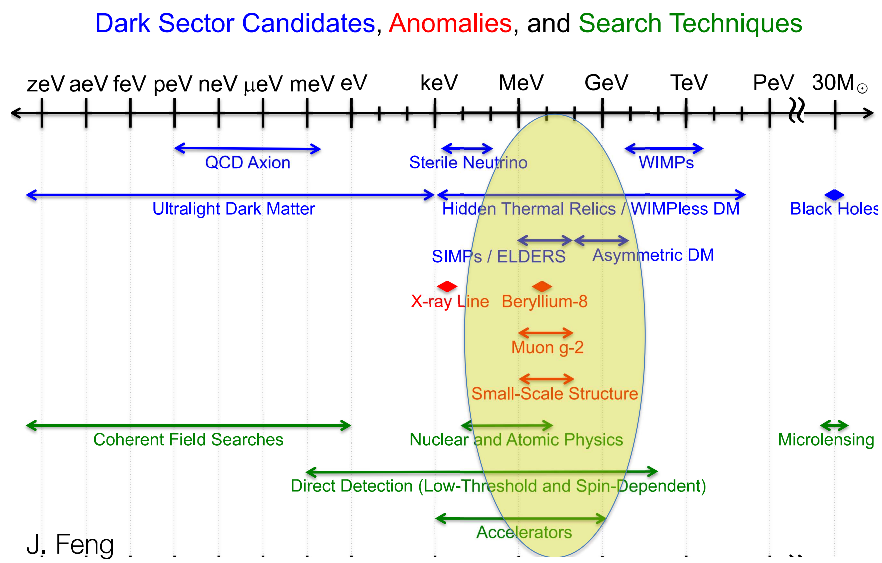
- Dark matter theory is undergoing a renaissance with the exploration of the full range of allowed DM masses, numerous portals to dark sectors, and novel interaction mechanisms.

Advances in dark matter phenomenology have gone hand in hand with new proposals for dark matter experiments leveraging quantum sensing, often envisioned and implemented by theorists.



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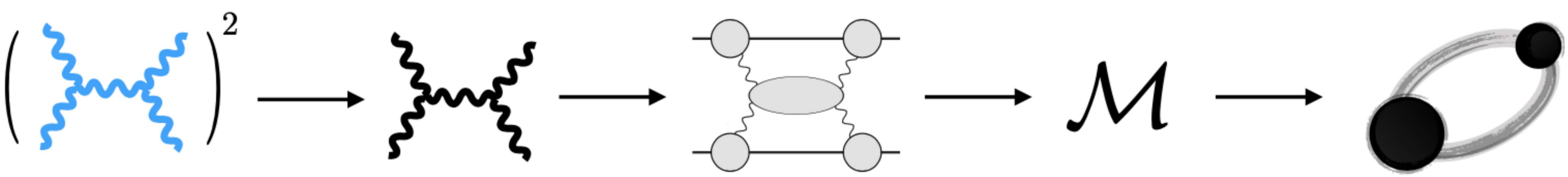
- The discovery of gravitational waves has catalyzed rapid progress in precision calculations via scattering amplitudes and inspired the use of gravitational waves to study particle physics inaccessible via planned colliders. Exciting opportunities for testing new physics at diverse scales are also being explored with current and future CMB and LSS data.



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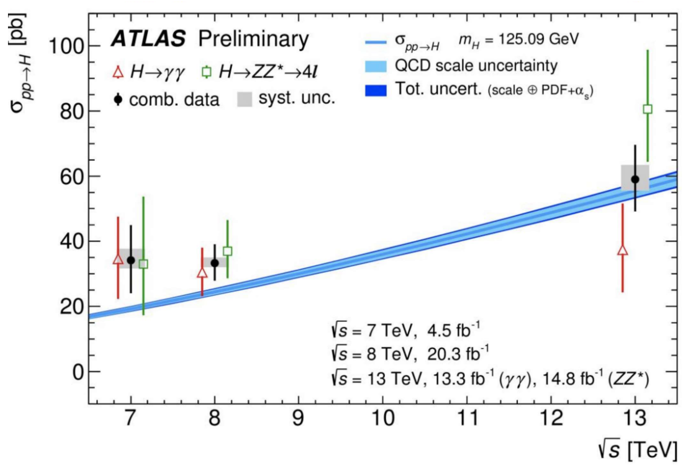
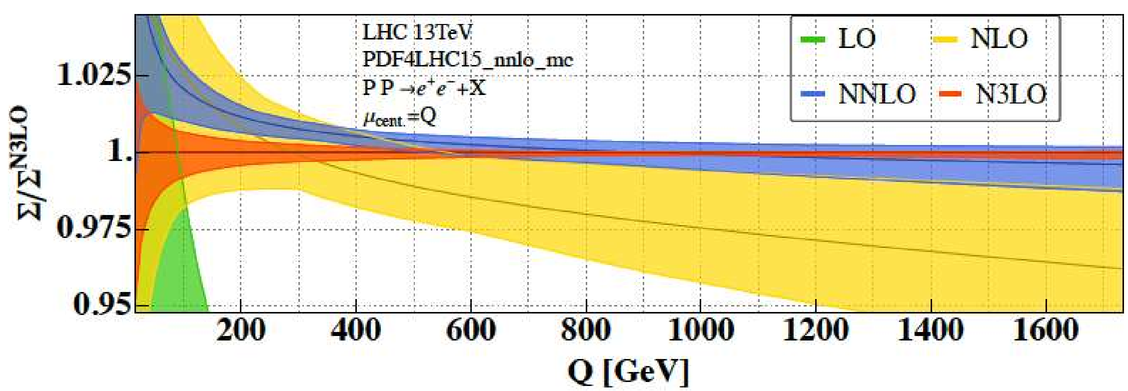
- In precision collider theory the calculation of cross sections to the NNLO and beyond in QCD has now become possible, unlocking the door to unprecedented tests of the SM. A prime example where cross-fertilization between phenomenology and fundamental theory has accelerated progress in both areas.





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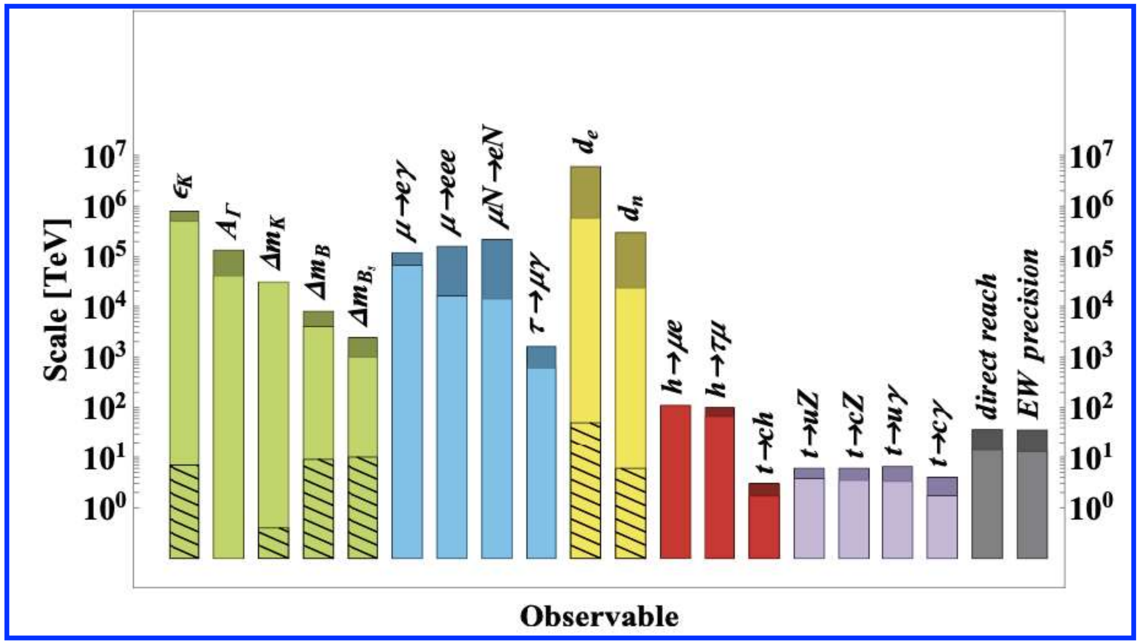
- Precision flavor physics has been the cradle of many of our most powerful effective field theory tools including HQET, SCET, now enabling advanced theoretical analyses to obtain sensitivity to promising BSM candidate theories.



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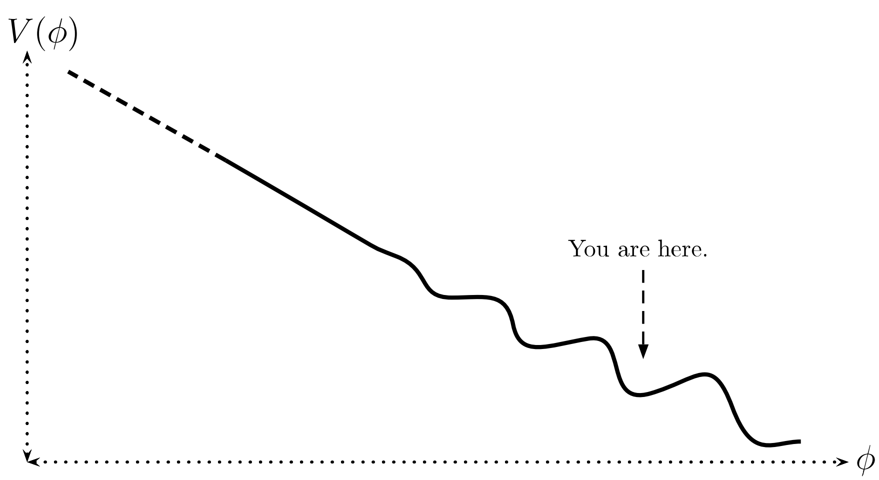
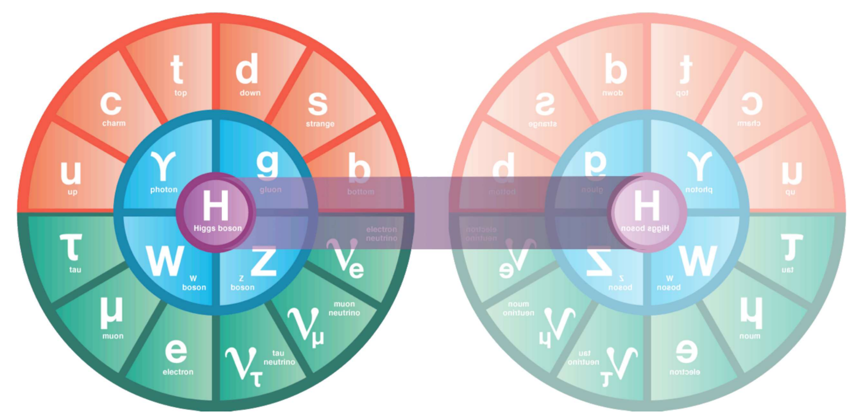
- The search for physics beyond the Standard Model has broadened considerably with the advent of novel concepts like neutral naturalness or cosmological selection of the electroweak vacuum.





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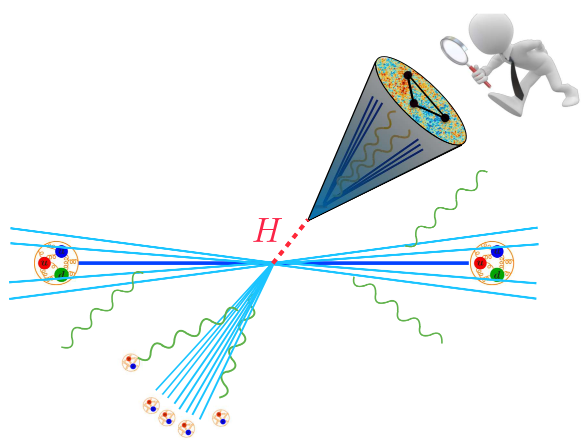
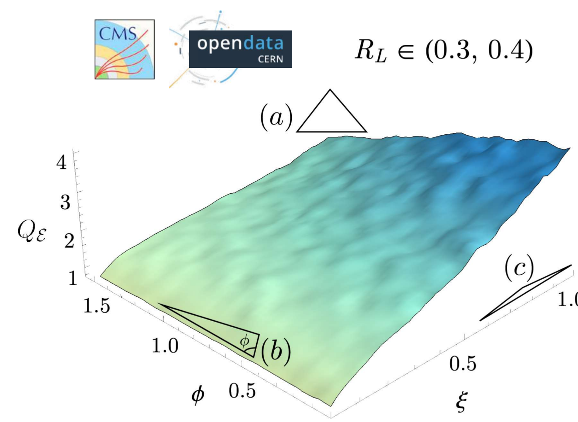
- Collider phenomenology has led to many new collider observables including diverse forms of jet substructure and the emerging field of multi-point correlators, and is employing widespread innovations in computational theory to leverage machine learning and artificial intelligence.





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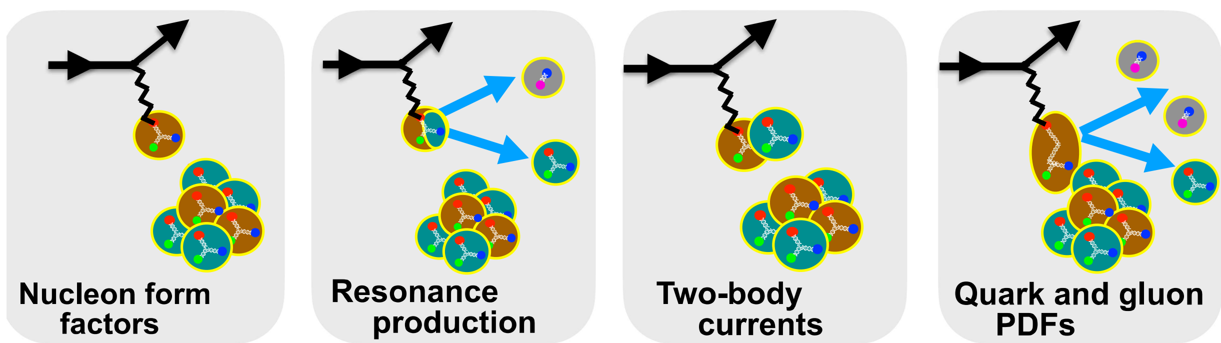
- A theory-driven, coordinated program combining nuclear effective theory, lattice QCD, perturbative QCD, and event generation to quantify the multi-scale nuclear cross sections at the needed precision level has been launched, that will allow us to unlock the full potential of the present and future neutrino physics program.



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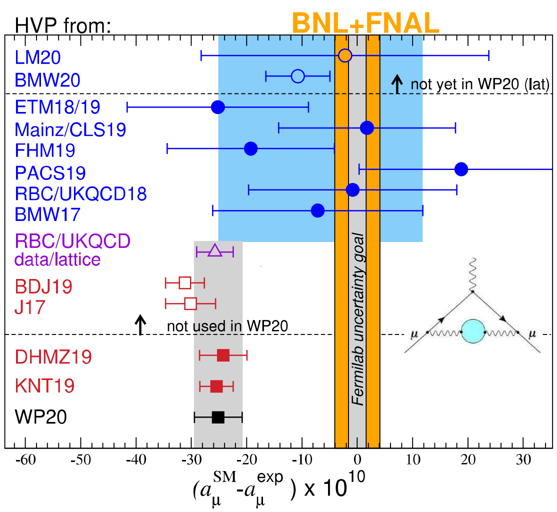
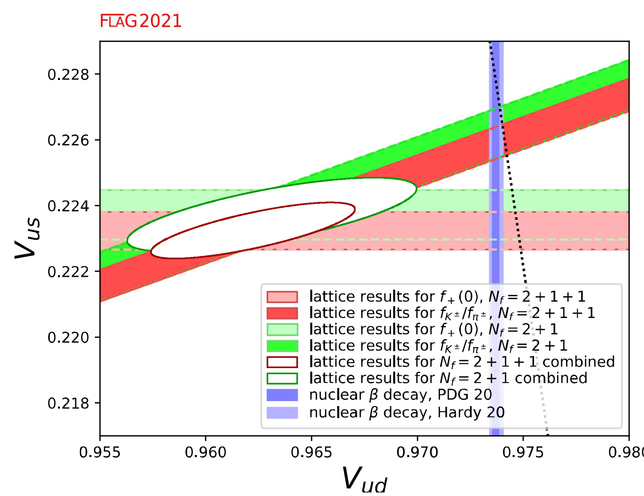
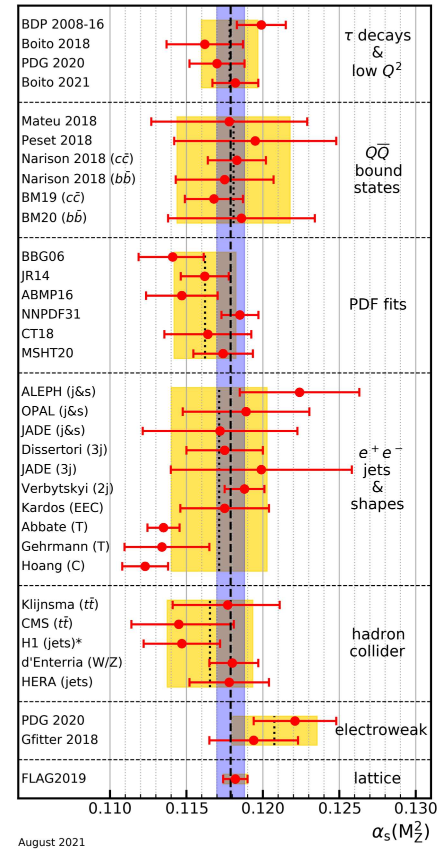
- Lattice QCD has become a powerful tool for precision physics, yielding precise SM predictions that reveal surprising new tensions in quark- and lepton-flavor physics.







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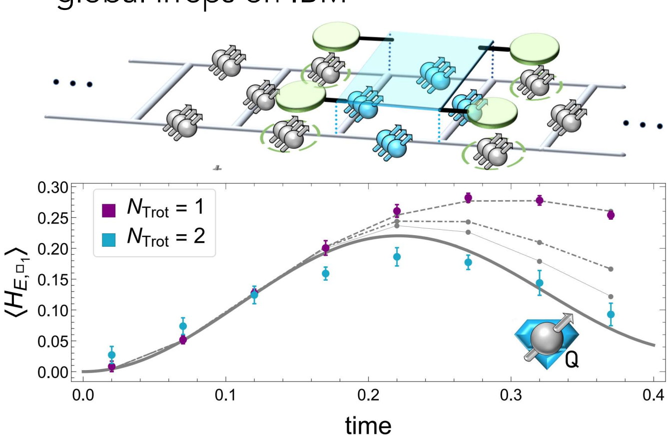
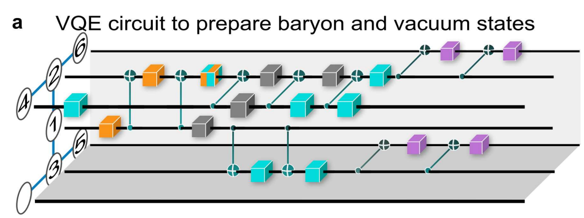
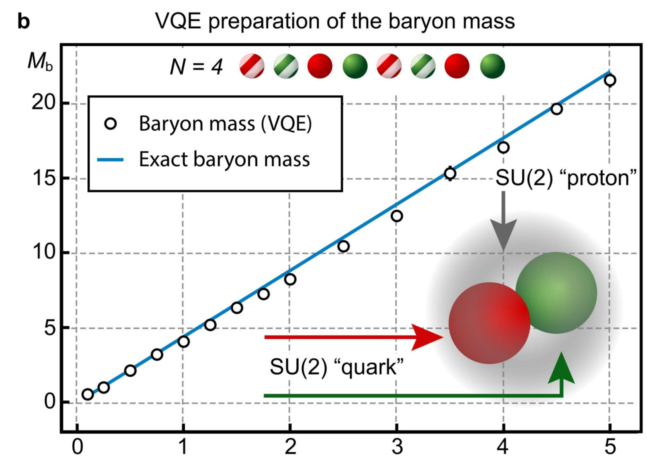
- Efforts to develop the methods and theoretical foundations for quantum simulations of quantum field theories relevant to high energy theory are already yielding intriguing results on currently available hardware, with great promise in the decades to come.

Real-time dynamic of pure SU(2) with global irreps on IBM



Low-lying spectrum of SU(2) with matter in 1+1 D on IBM





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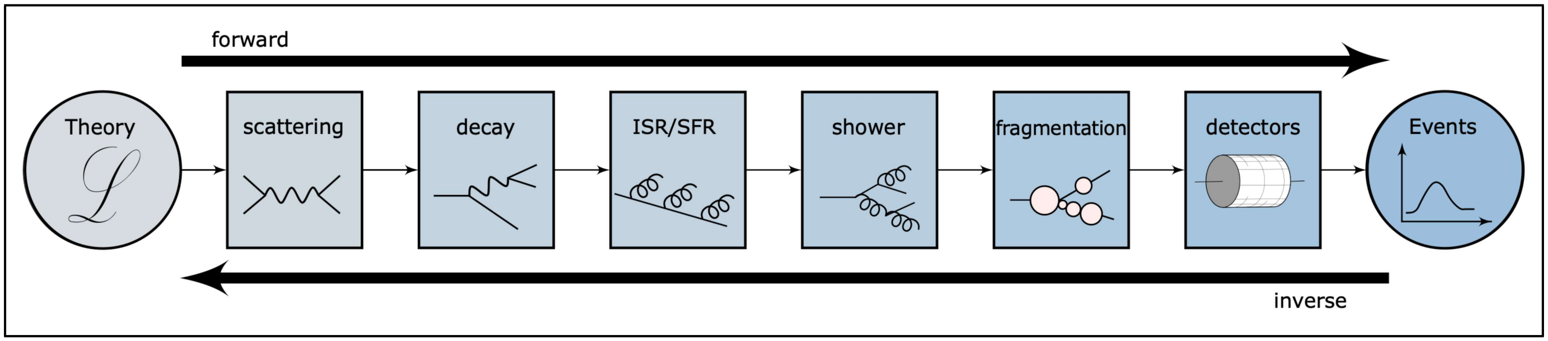
- Innovations in the theory of machine learning (AI/ML), such as the development of (gauge) symmetry equivariant architectures, driven by theoretical work in lattice field theory, collider phenomenology, and other areas, may have transformative impact on computations in high energy theory and beyond.



P5' diagram courtesy of Jesse Thaler

Looking Forward: HEP Theory Goals

- Advance our understanding of Nature by pursuing a broad and balanced program of theoretical research covering the entire spectrum of particle physics, from fundamental to phenomenological to computational theory.
- Connect the frontiers of particle physics and enable the comparison of data across different scales.
- Explore new research directions, incorporate new developments from adjacent fields, and build new bridges to gravity, cosmology, astrophysics, quantum information, nuclear physics, AMO, condensed matter physics, statistics, computer science, data science, and mathematics.

HEP Theory Goals

- Fulfill the theory needs of current and planned experiments, from motivation to analysis to interpretation, and be responsive to their results.
- Envision and motivate future experiments, and furnish the tools necessary for their success.
- Pursue exploratory research, reflecting theory as a vibrant intellectual endeavor in its own right.

P5’ diagram courtesy of Jesse Thaler

HEP Theory Goals

- Sustain US leadership in the international theory community.
- Cultivate a vibrant, inclusive, and supportive scientific community, developing “4π coverage” in identifying and fostering talent at all career stages.
- Maintain a program across HEP that trains students and junior scientists, providing them with continuing physics opportunities that empower them to contribute to science.

Critical Needs

1. Support for the essential role of theory similar to (and at least as strong as) recommended by the European Strategy Update, both in relation to projects and in its own right.

European Strategy Update

4 Other essential scientific activities for particle physics

B. Theoretical physics is an essential driver of particle physics that opens new, daring lines of research, motivates experimental searches and provides the tools needed to fully exploit experimental results. It also plays an important role in capturing the imagination of the public and inspiring young researchers. The success of the field depends on dedicated theoretical work and intense collaboration between the theoretical and experimental communities. ***Europe should continue to vigorously support a broad programme of theoretical research covering the full spectrum of particle physics from abstract to phenomenological topics. The pursuit of new research directions should be encouraged and links with fields such as cosmology, astroparticle physics, and nuclear physics fostered. Both exploratory research and theoretical research with direct impact on experiments should be supported, including recognition for the activity of providing and developing computational tools.***

Critical Needs

2. Support for a balanced program of Projects and Research, as both are essential to the health of the field.

3. Support for people, especially early career, who are the key "infrastructure" of Research.

4. Support for targeted funding advancing the physics goals.
(E.g. LQCD Project, LHC Theory Initiative, Neutrino Theory Network, QIS, AI/ML, Exascale Computing Project, SciDAC…)

- Theory **unifies the frontiers** of particle physics. It is essential to the conception, execution, and interpretation of current experiments and a driver of new, enabling technologies.

- Theory **lays the foundations** for future experiments and **advances our understanding** of Nature in regimes that experiment has yet to reach.

- The past decade has seen remarkable (and interconnected) progress across all facets of high-energy theory, laying the groundwork for a **coming decade of immense promise.**

- The theory community in the United States has been central to recent developments and is poised to play a leading role in the years to come. **Such leadership is invaluable and cannot be taken for granted.**

- **We do not know what Nature has in store for us.** We will be in the best position to realize the promise of the coming decade with **strong, sustained support for all aspects of theory.**

Thank you!