

The Frontiers of Phenomenological Theory

Jesse Thaler



Snowmass Community Summer Study, University of Washington, Seattle — July 22, 2022

For this talk...

*theory is the
rigorous study of
what is possible*

For this talk...

*Phenomenological theory is the
rigorous study of
what is possible *in our Universe**

(with experiment the ultimate arbiter of what is)

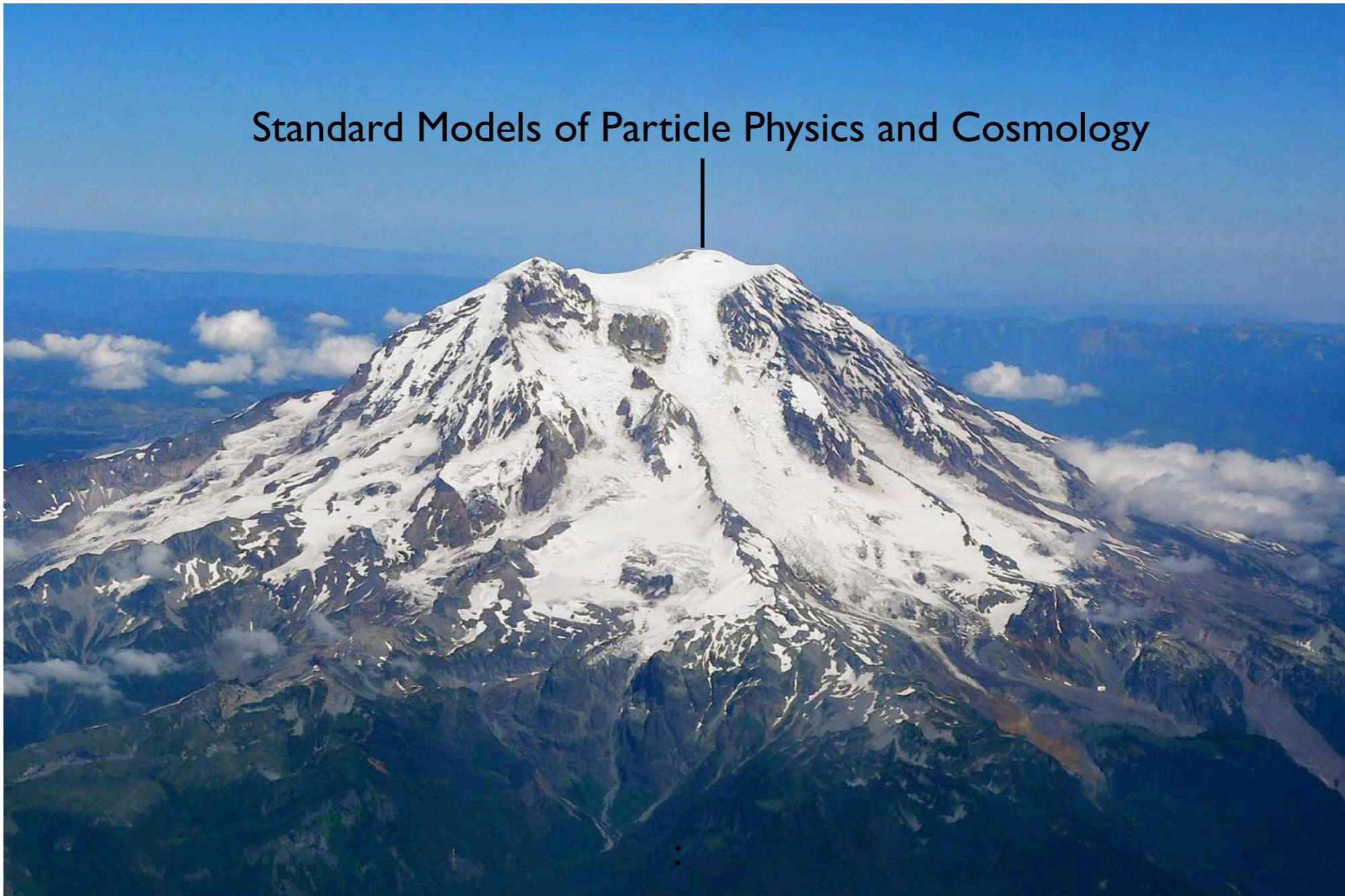
Pioneer of the Possible

Ann Nelson (1958–2019)



Summiting the “Known”

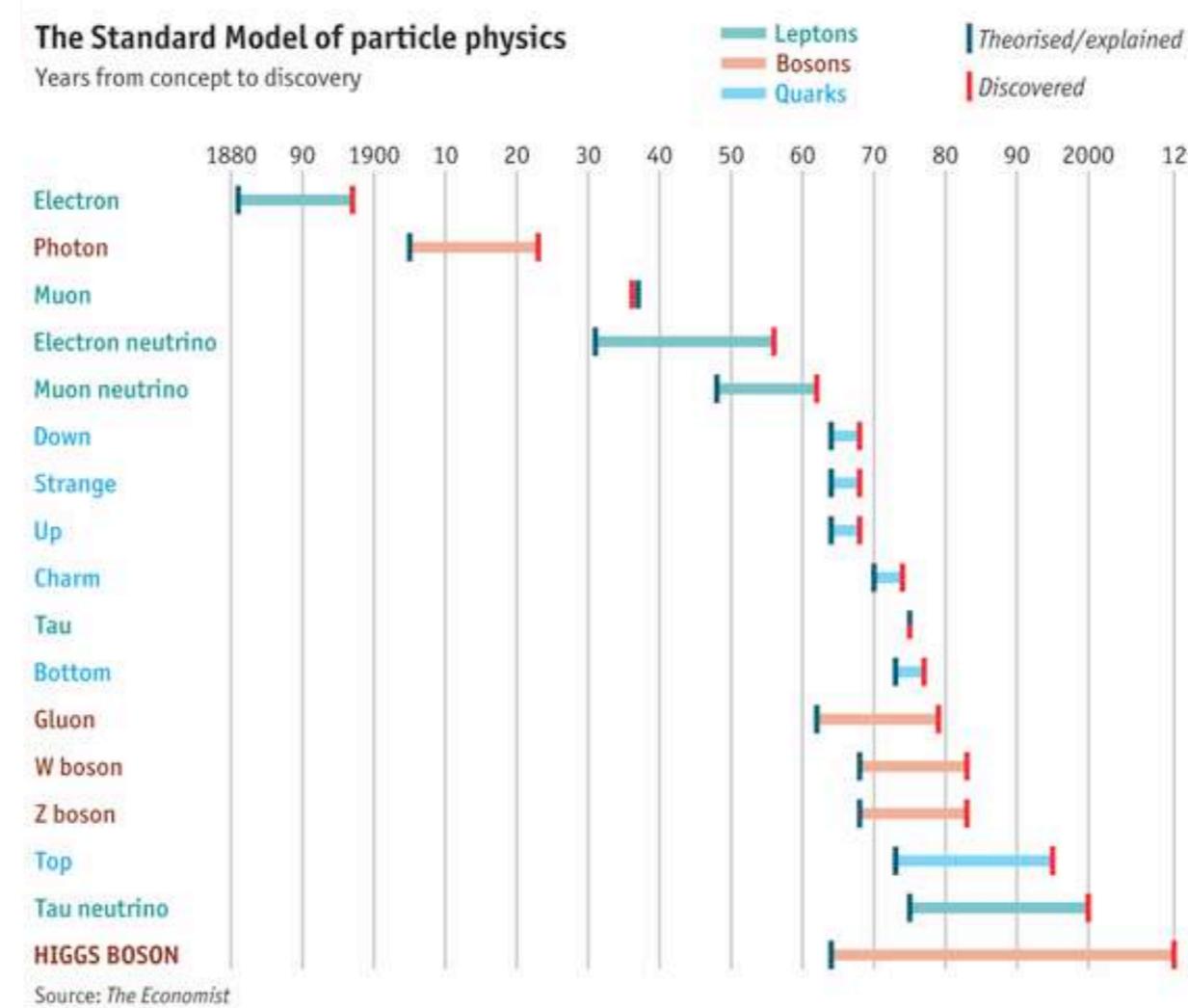
Intellectually rich and scientifically essential



Standard Models of Particle Physics and Cosmology

Why Pursue the Possible?

In addition to human curiosity about our Universe...



Rigorous speculation has a pretty good track record in high-energy physics

(Wednesday's public talk notwithstanding...)

Why Invest in the Possible?

After all, high-energy physics is ultimately an experimental science...

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

Theory **establishes the conceptual/calculational foundations** for future experiments

Theory is essential for **motivating** new experiments,
analyzing/interpreting experimental data, and
responding to experimental surprises

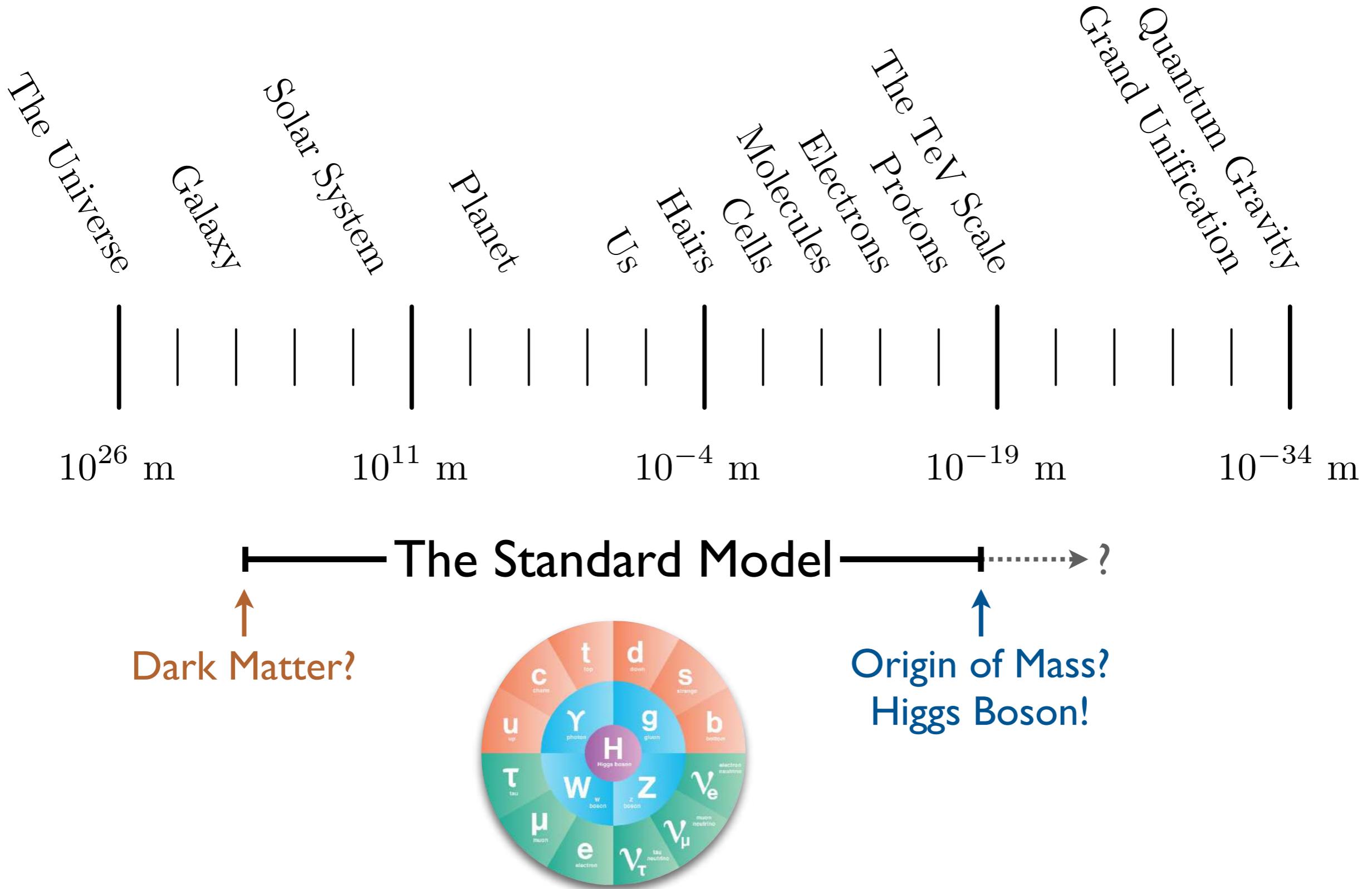
At the same time, theoretical research is a
vibrant scientific endeavor in its own right

Part I: My Personal Snowmass

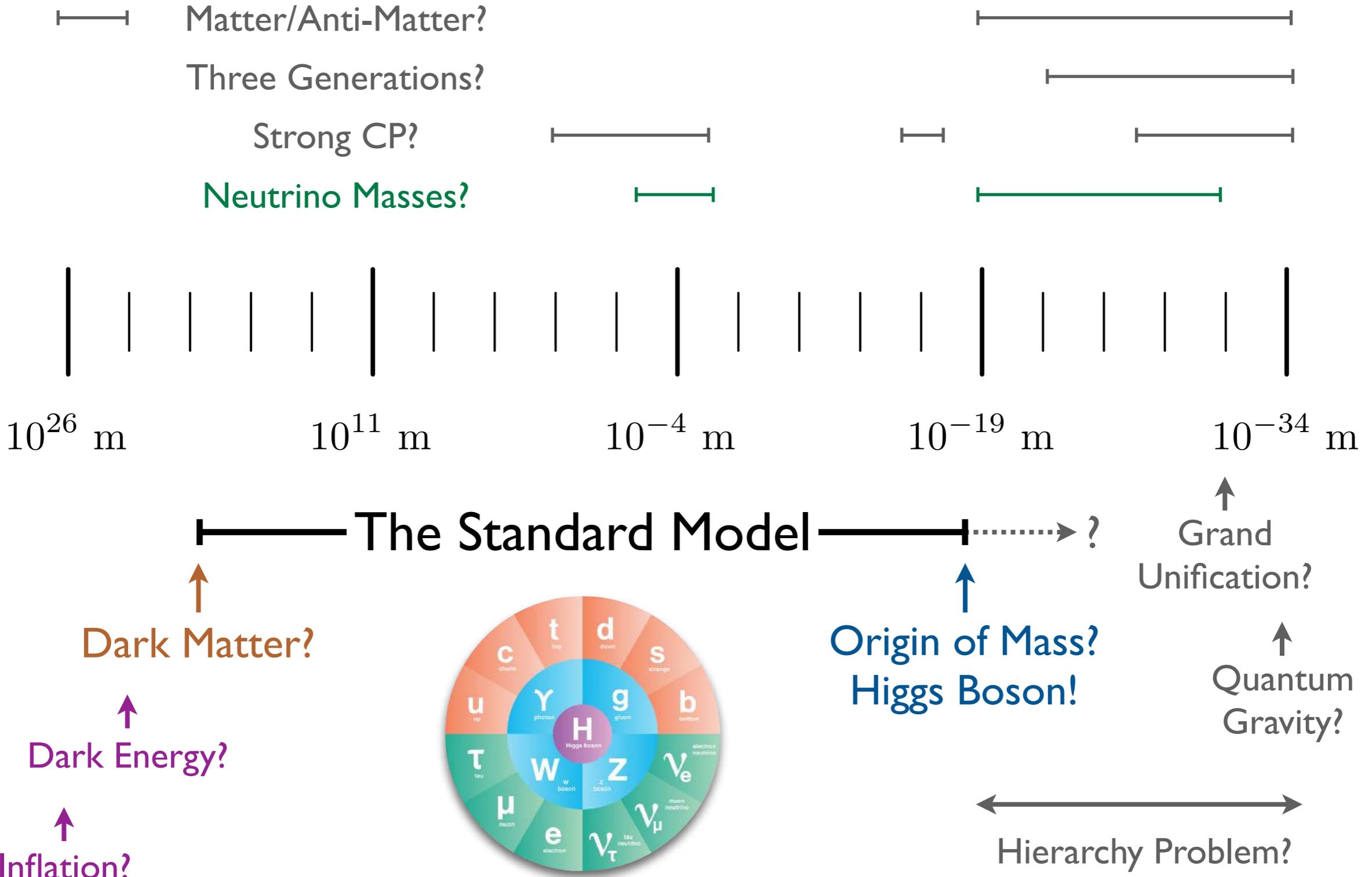
“The High Energy Physics Landscape in 2019”

Presentation to HEPAP on May 30, 2019
Slides only lightly edited, so some content 3 years out of date

The HEP Landscape (*Colloquium Edition*)



The HEP Landscape (*Colloquium Edition*)



The HEP Landscape (*QFT Edition*)

Standard Model: *Leading interactions consistent with these symmetries*

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

$$3 \times \left[q: (\mathbf{3}, \mathbf{2})_{1/6} \quad u^c: (\overline{\mathbf{3}}, \mathbf{1})_{-2/3} \quad d^c: (\overline{\mathbf{3}}, \mathbf{1})_{1/3} \quad \ell: (\mathbf{1}, \mathbf{2})_{-1/2} \quad e^c: (\mathbf{1}, \mathbf{1})_1 \right] \quad h: (\mathbf{1}, \mathbf{2})_{1/2}$$

Principles & Paradigms

Quantum Mechanics	Chiral Mass Generation
Lorentz/CPT Invariance	Quark Flavor Structure
Spin/Statistics	P/CP Violation
Locality/Causality/Unitarity	Accidental B, L Conservation
Global Symmetries*	Asymptotic Freedom
Conservation Laws	(?) Neutrino Mass Generation
Spontaneous Symmetry Breaking	(?) Dark Matter
Gauge Redundancy	(?) Strong CP
Anomaly Cancellation	(?) Baryogenesis
Renormalization Group Evolution	(?) Unification
Effective Field Theory	(?) Supersymmetry
Naturalness (??)	(?) Extended Space-time
Weak Gravity / Swampland (??)	(?) Inflation
...	...

2014 Science Drivers from P5

*Well aligned with core questions in fundamental physics
Effective road map through period of transition in US HEP*



- ▶ Use the **Higgs boson** as a new tool for discovery
- ▶ Pursue the physics associated with **neutrino mass**
- ▶ Identify the new physics of **dark matter**
- ▶ Understand **cosmic acceleration**: dark energy and inflation
- ▶ Explore the unknown: new particles, interactions, and physical principles

[\[U.S. Particle Physics: Building for Discovery\]](#)

2014 Science Drivers from P5'

with apologies to the $B \rightarrow K \mu^+ \mu^-$ anomaly

*Well aligned with core questions in fundamental physics
Effective road map through period of transition in US HEP*



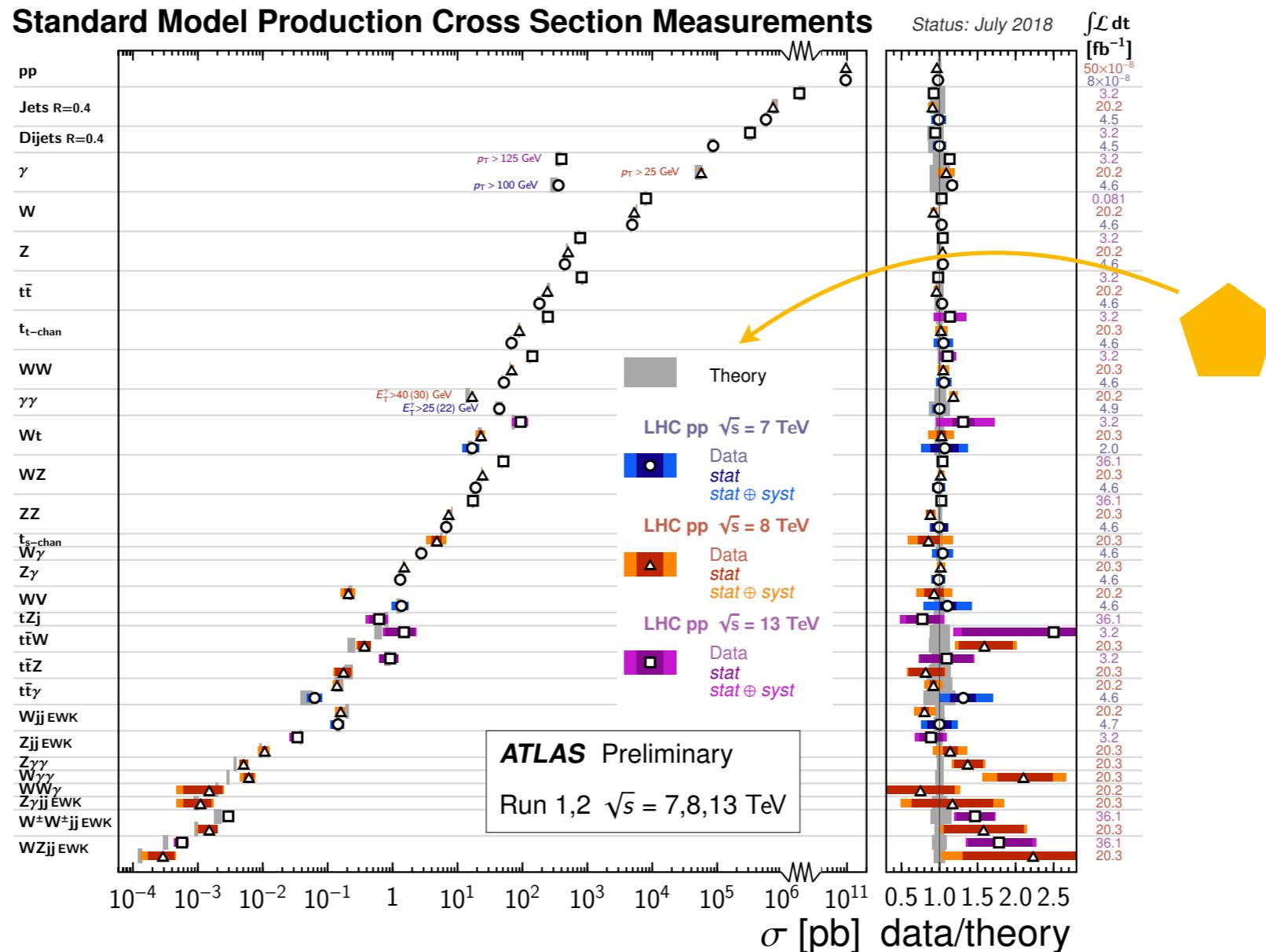
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- ▶ Develop **transformative concepts and technologies** to enable future discoveries

*In addition to reaping the physics rewards of key investments,
we are continually planting the seeds for future explorations*

[\[U.S. Particle Physics: Building for Discovery\]](#)

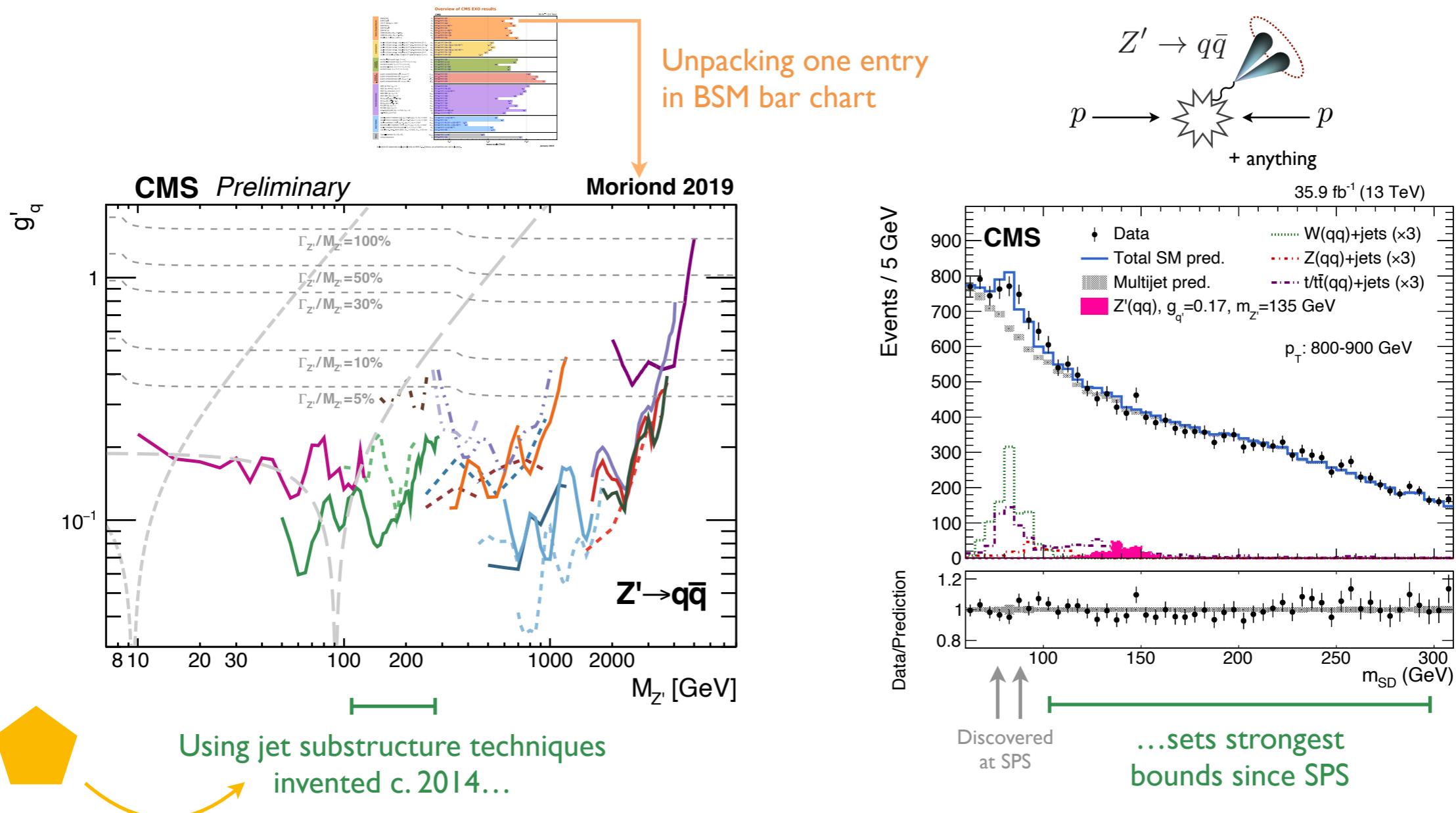
2014 → 2019: Solidification of Standard Model



LHC Run 1 & 2: Experimental and theoretical triumph!

(and much more to come with full Run 2 dataset, Run 3, and HL-LHC)

2014 → 2019: Diversification of BSM Searches

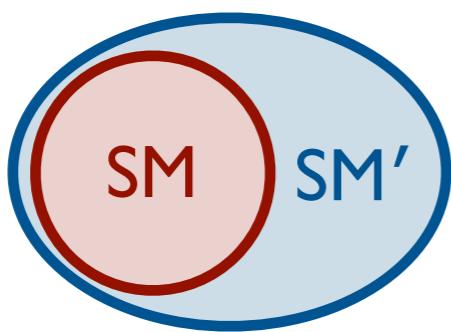


Wide range of innovative analyses with broad coverage!

2014 → 2019: Establishing New Paradigms

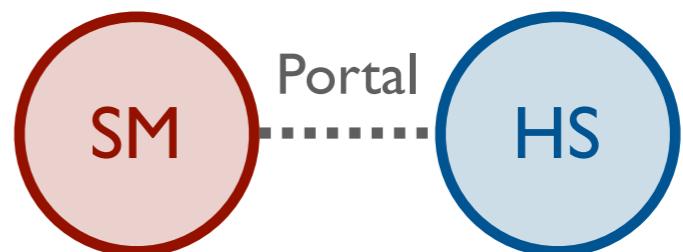
Not just a response to null results; broadening in thinking even pre-LHC

Extended Symmetries



Typical structure to address conceptual shortcomings of SM

Hidden Sectors



Arguably the generic structure of string-theoretic scenarios

Plus intermediate scenarios: split spectra, neutral naturalness, dynamic relaxation, ...

New paradigms motivate new search strategies!

2014 → 2019: Continued Effectiveness of EFTs

In the context of effective field theories, we can already...



$$\langle h \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

- ▶ Describe process of electroweak symmetry breaking
⇒ Higgs mechanism

$$c_{ij} \frac{\ell_i h \ell_j h}{M}$$

- ▶ Accommodate neutrino masses/mixing
⇒ Dimension-5 Weinberg operator (if Majorana)

$$\frac{a}{f} \frac{\alpha_s}{8\pi} G^{\mu\nu a} \tilde{G}_{\mu\nu}^a$$

- ▶ Build testable dark matter paradigms
⇒ e.g. WIMPs, hidden sectors, axions (with strong CP bonus)

$$\Lambda$$

- ▶ Accommodate current acceleration & primordial density fluctuations
⇒ Cosmological constant & single-field inflation

$$\frac{qqq\ell}{M^2}$$

- ▶ Motivate why further deviations are suppressed
⇒ Approximate symmetries (B, L, CP, GIM, MFV, ...)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

- ▶ Quantum-mechanically couple SM to gravity in weak-field limit
⇒ Einstein-Hilbert graviton with one free parameter (M_{Pl})

**Enables systematic probes
for cracks in the SM:**

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{M} \mathcal{O}_5 + \frac{1}{M^2} \mathcal{O}_6 + \dots$$

21 slides later...

Looking Towards Snowmass 2020+

*The physics priorities of our field are largely the same,
but the toolbox and targets have expanded*



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Looking Towards Snowmass 2020+

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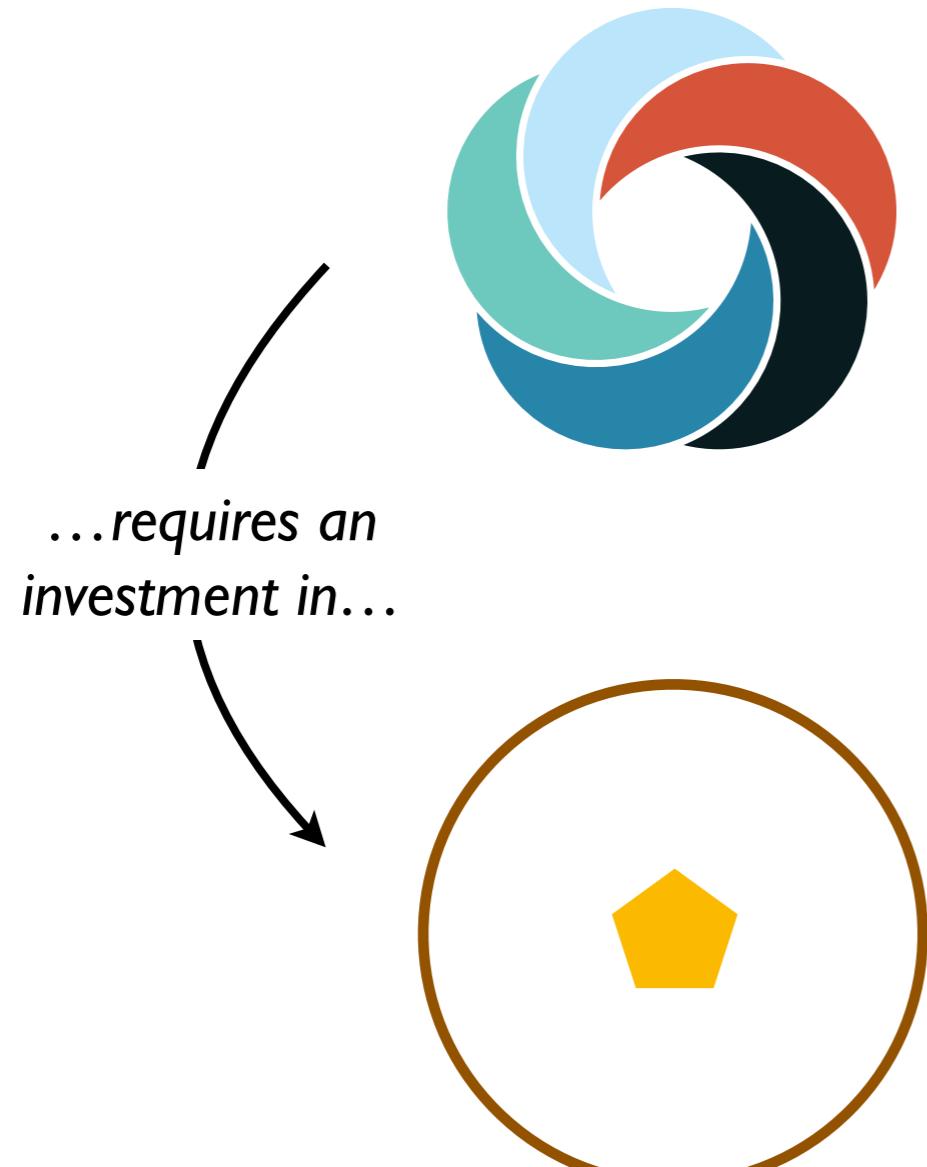
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- ▶ Develop **transformative concepts and technologies** to enable future discoveries
- ▶ Cultivate a vibrant, inclusive, and supportive **scientific community**

The success of our endeavors depends on “ 4π coverage” in identifying and cultivating talent at all career stages

1,150 days later...

Here we are (finally) at Snowmass 2022!



Energy Frontier

Neutrino Physics Frontier

Rare Processes and Precision

Cosmic Frontier

👉 **Theory Frontier** 👈

Accelerator Frontier

Instrumentation Frontier

Computational Frontier

Underground Facilities

Community Engagement

Early Career

Part II: The Frontiers of Pheno

Communicating the fruitful and essential
dialogue between theory and experiment

Mission (Im)possible

*Previous talk
by Shamit*

- TF01: String theory, quantum gravity, black holes
- TF02: Effective field theory techniques
- TF03: CFT and formal QFT
- TF04: Scattering amplitudes
- TF05: Lattice gauge theory
- TF06: Theory techniques for precision physics
- TF07: Collider phenomenology
- TF08: BSM model building
- TF09: Astro-particle physics and cosmology
- TF10: Quantum Information Science
- TF11: Theory of Neutrino Physics

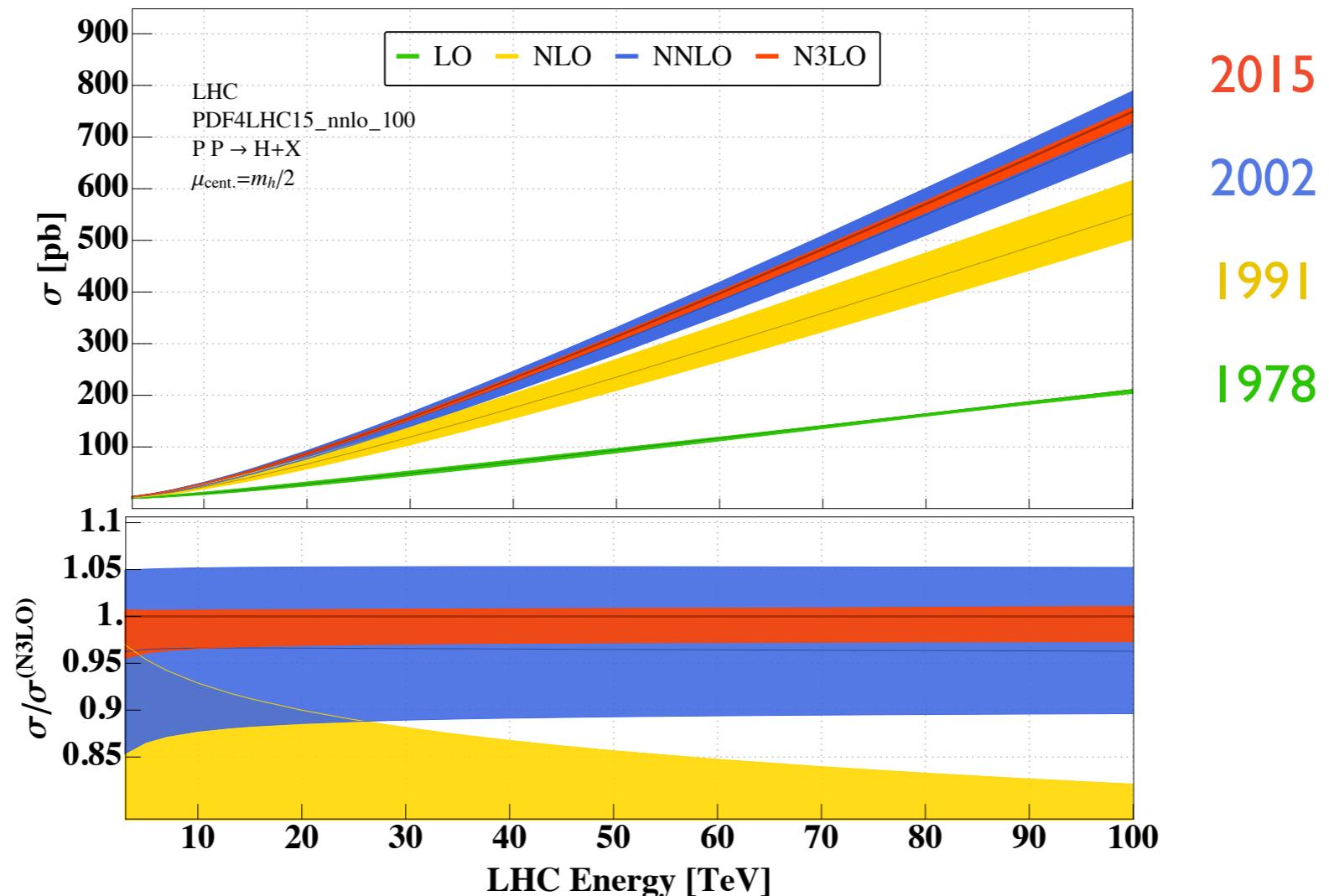
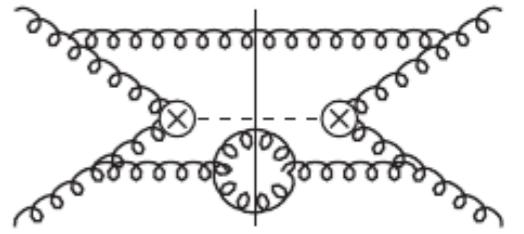
Examples are idiosyncratic, just like theoretical research

Caveats: Ideas belong to many people; references are links in the PDF

Thanks to TF conveners/liaisons for feedback; apologies for omissions

Cue the TF montage!

Higgs: From Discovery to Precision

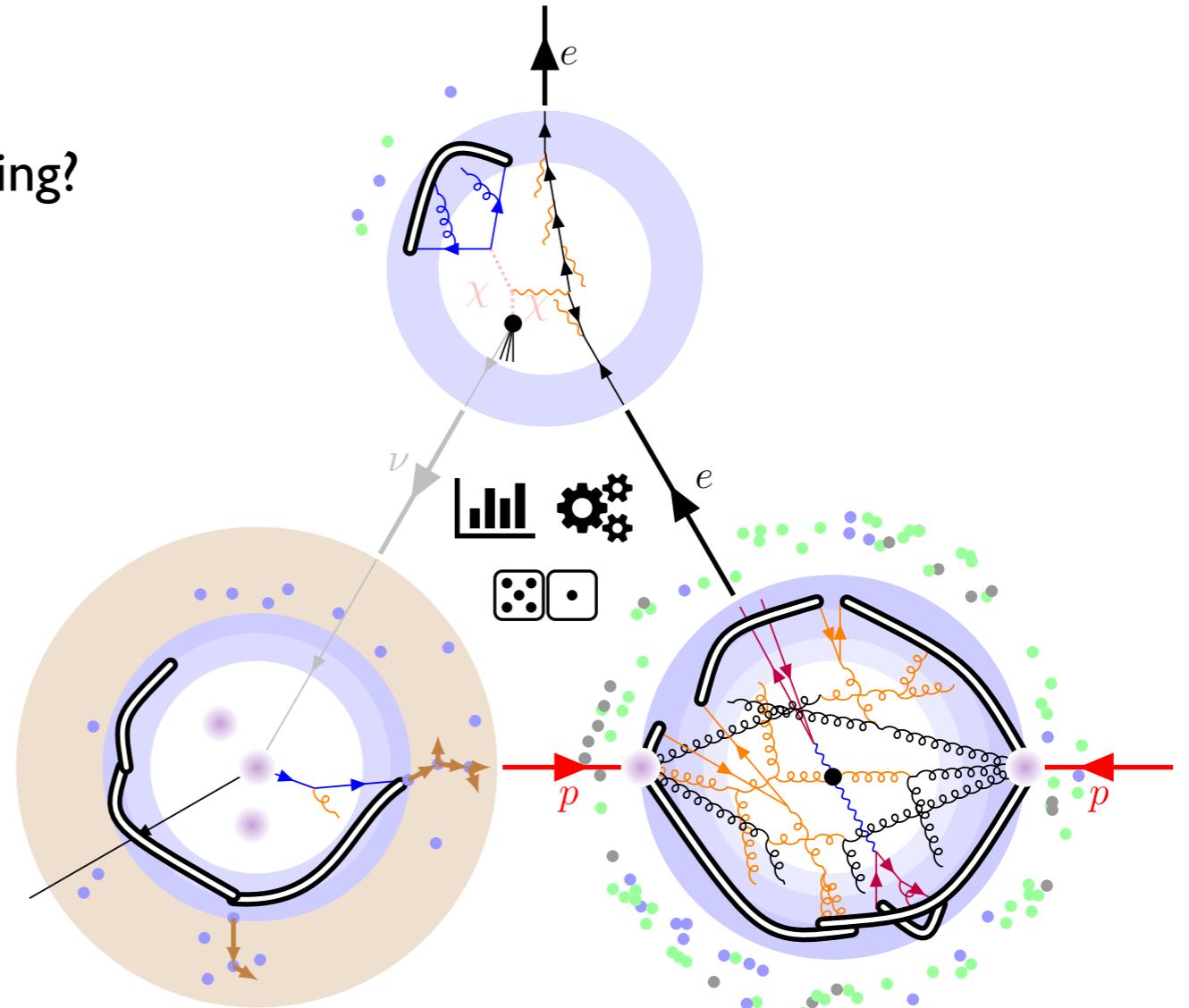
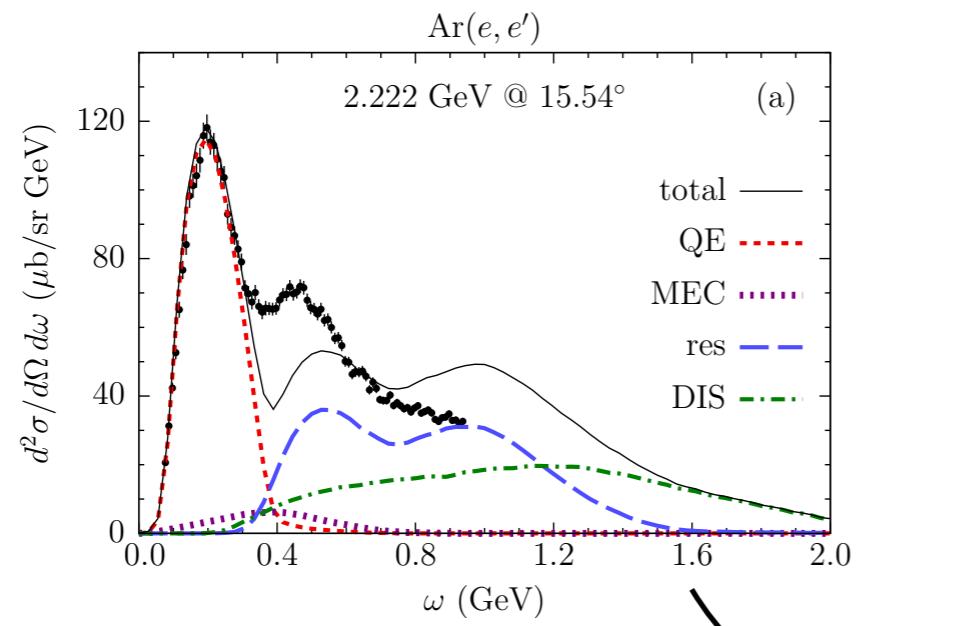


Multi-loop, multi-leg, and multi-log calculations are reaching unprecedented accuracy, essential to interpret measurements

The Frontiers of Event Generation

Enabling the US long-baseline program

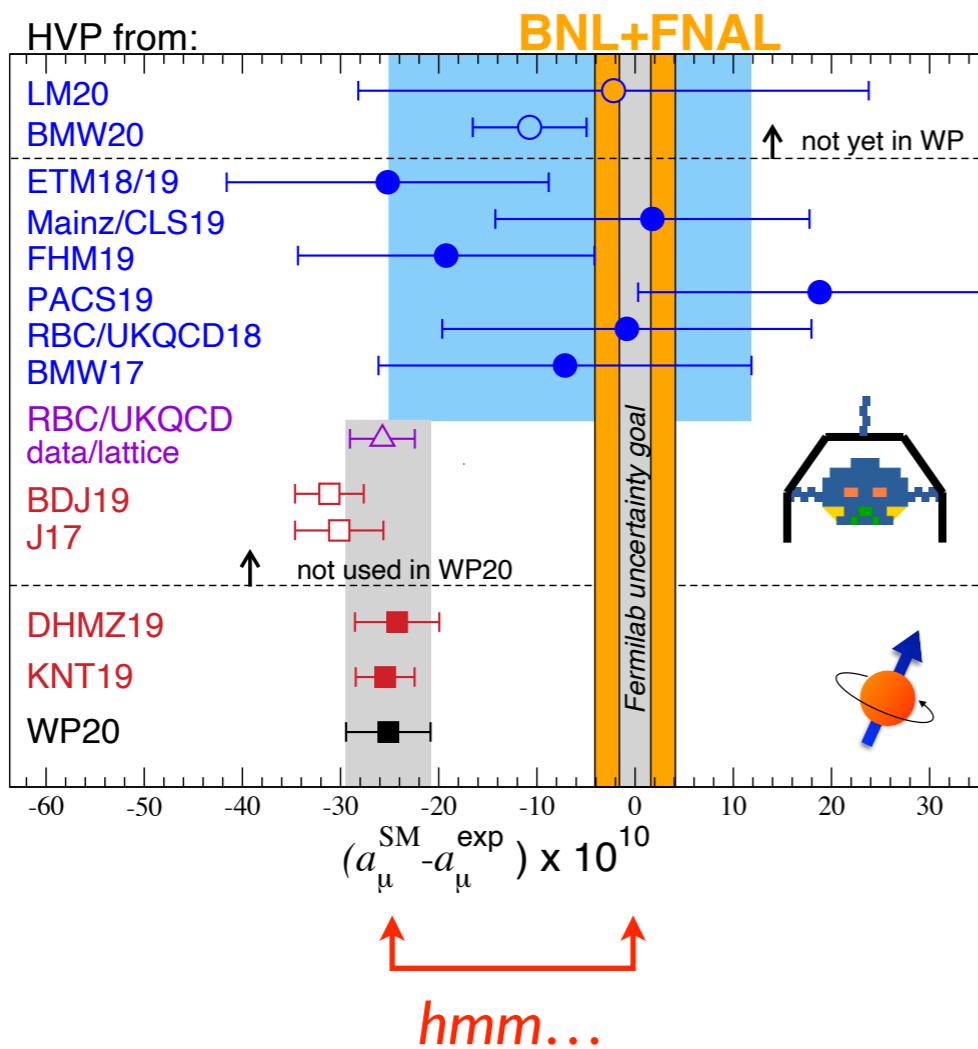
Are we ready for neutrino-Argon scattering?



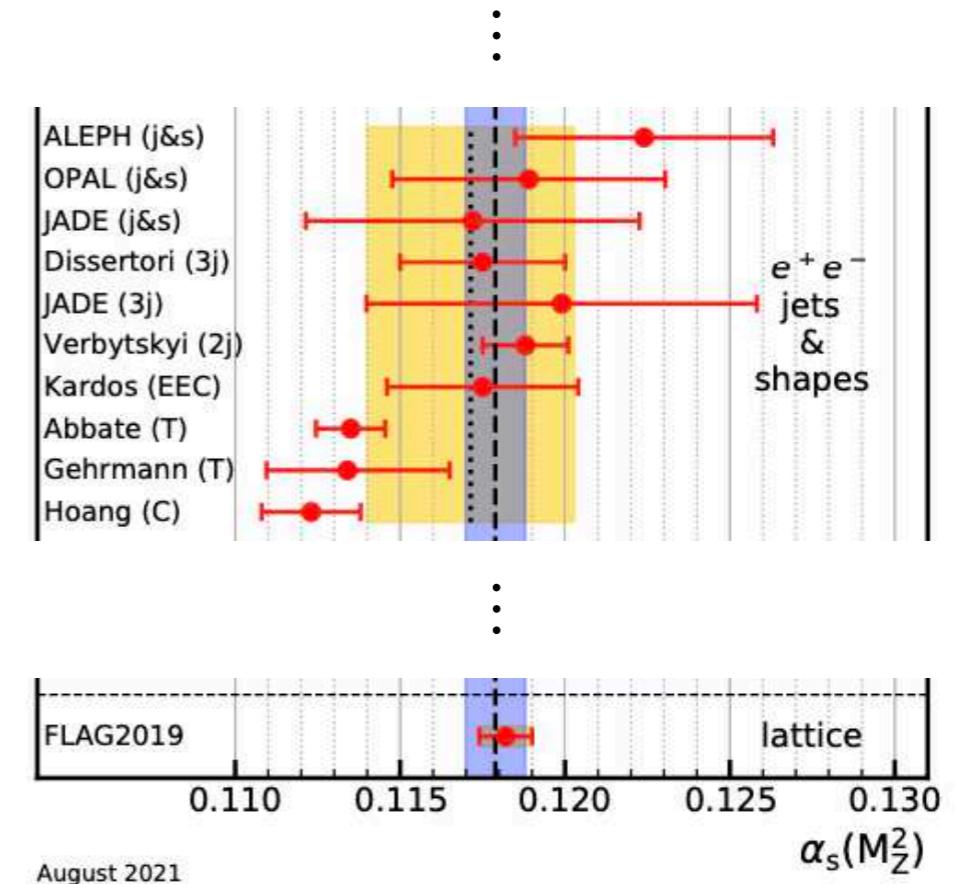
*Progress towards synthesizing high-energy parton showers
with non-perturbative modeling and lattice inputs*

Puzzles in (Non-)Perturbative QCD

Muon Anomalous Moment



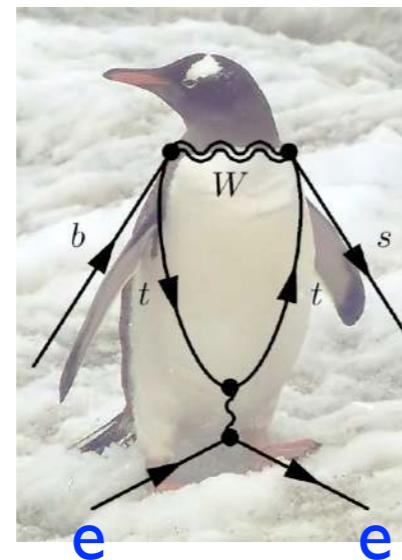
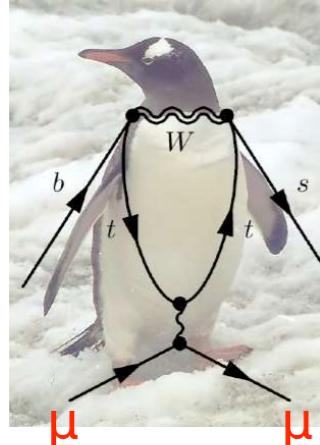
Strong Coupling Constant



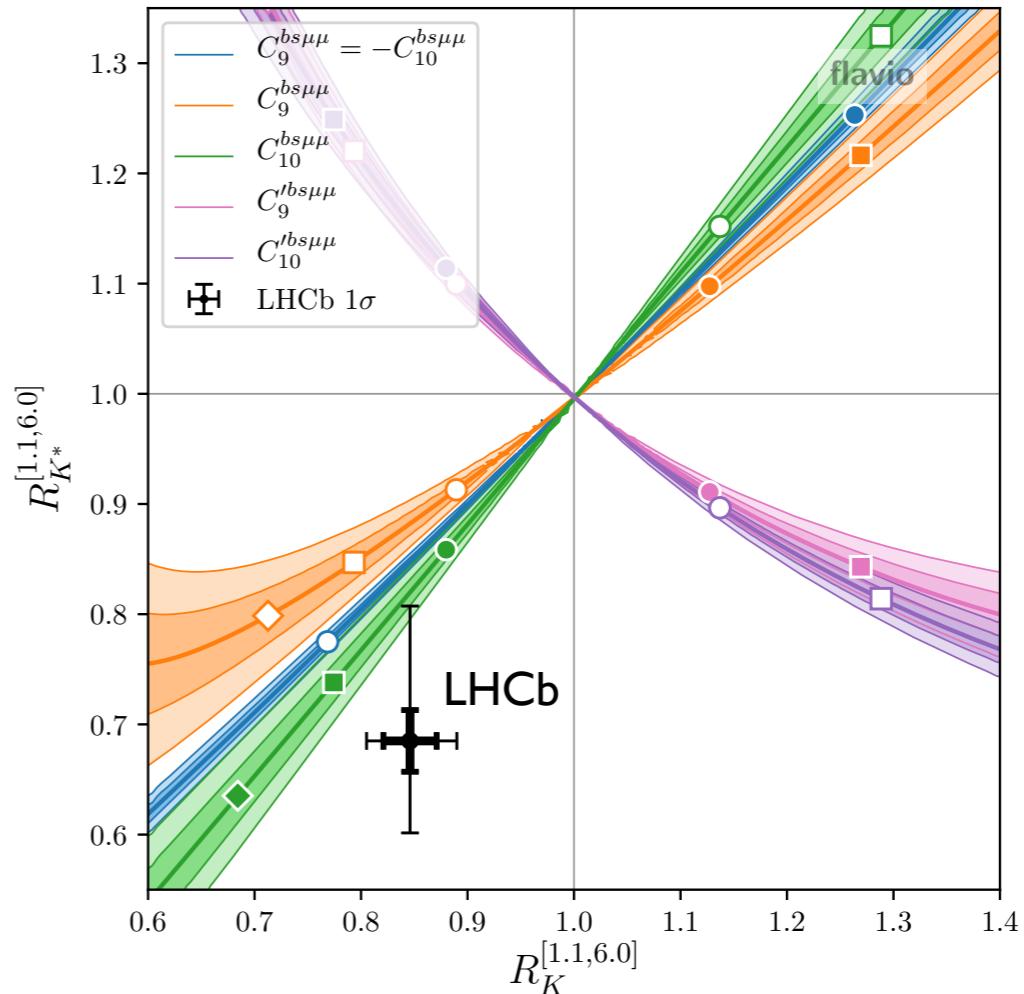
Advances in lattice gauge theory are enabling new ways to overconstrain the Standard Model

Who Ordered That?!

Violations of lepton universality in B decays?



Continued effectiveness of EFTs...

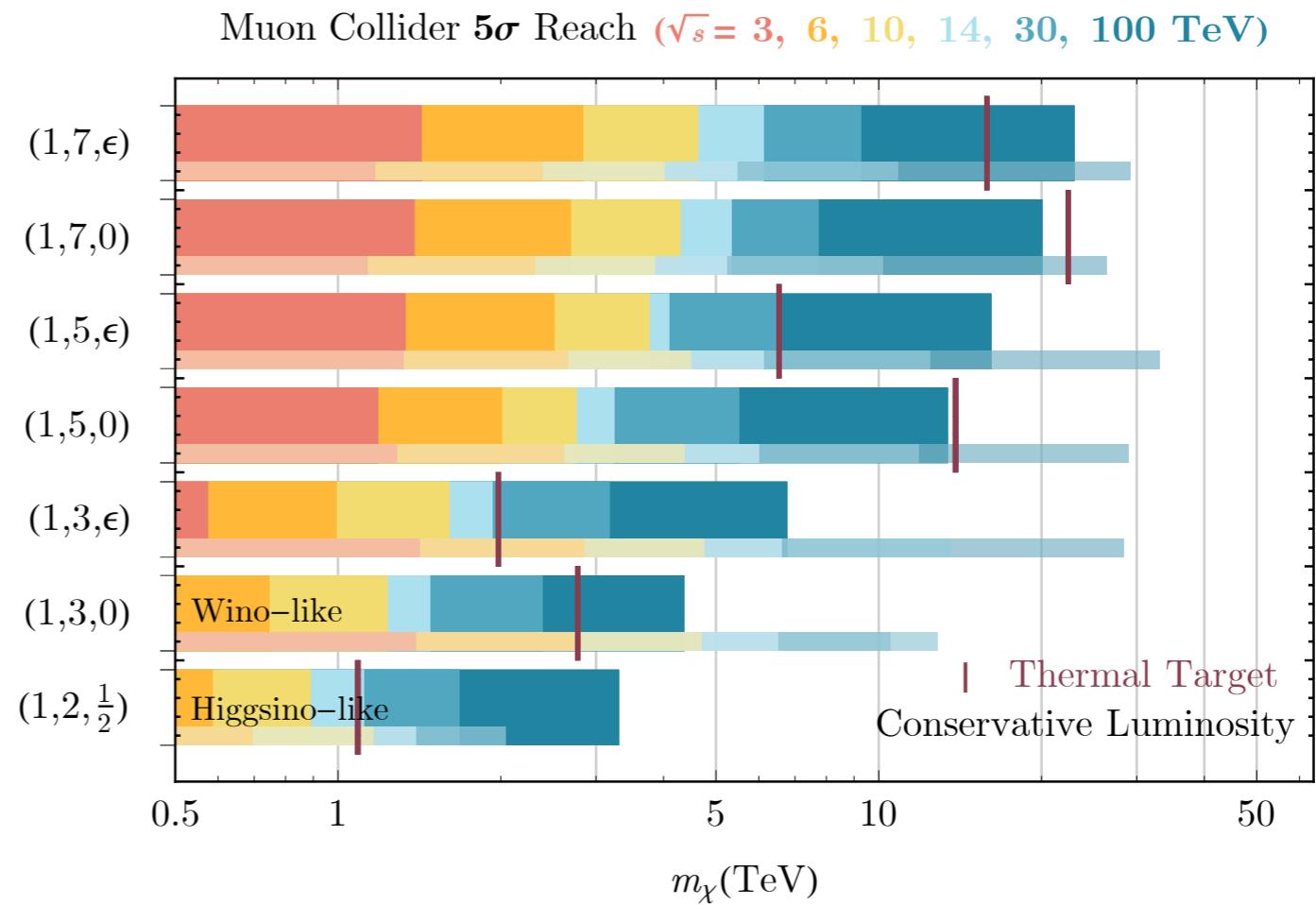


*Experimental puzzle launches mini-industry of theory work,
breaking down old prejudices and inspiring new analyses*

Planning for the (Far) Future



Muon Collider Reach for WIMP Dark Matter



*To guide multi-generational voyages into the unknown,
theory is erecting lighthouses on the shore*

Continued Importance of the Possible

Theory is essential for **motivating** new experiments,
analyzing/interpreting experimental data, and
responding to experimental surprises

At the same time, theoretical research is a
vibrant scientific endeavor in its own right



@FlipTanedo:
Hooray for pentagons!

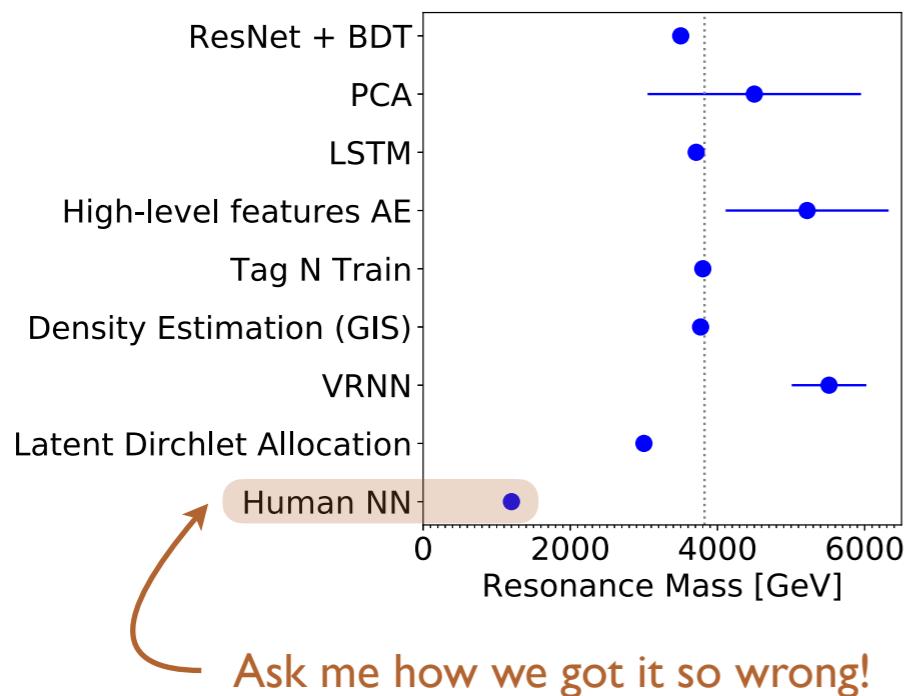
Part III: The Expansion of Theory

Communicating the ways that phenomenology
is evolving since the last Snowmass

Yet another TF montage!

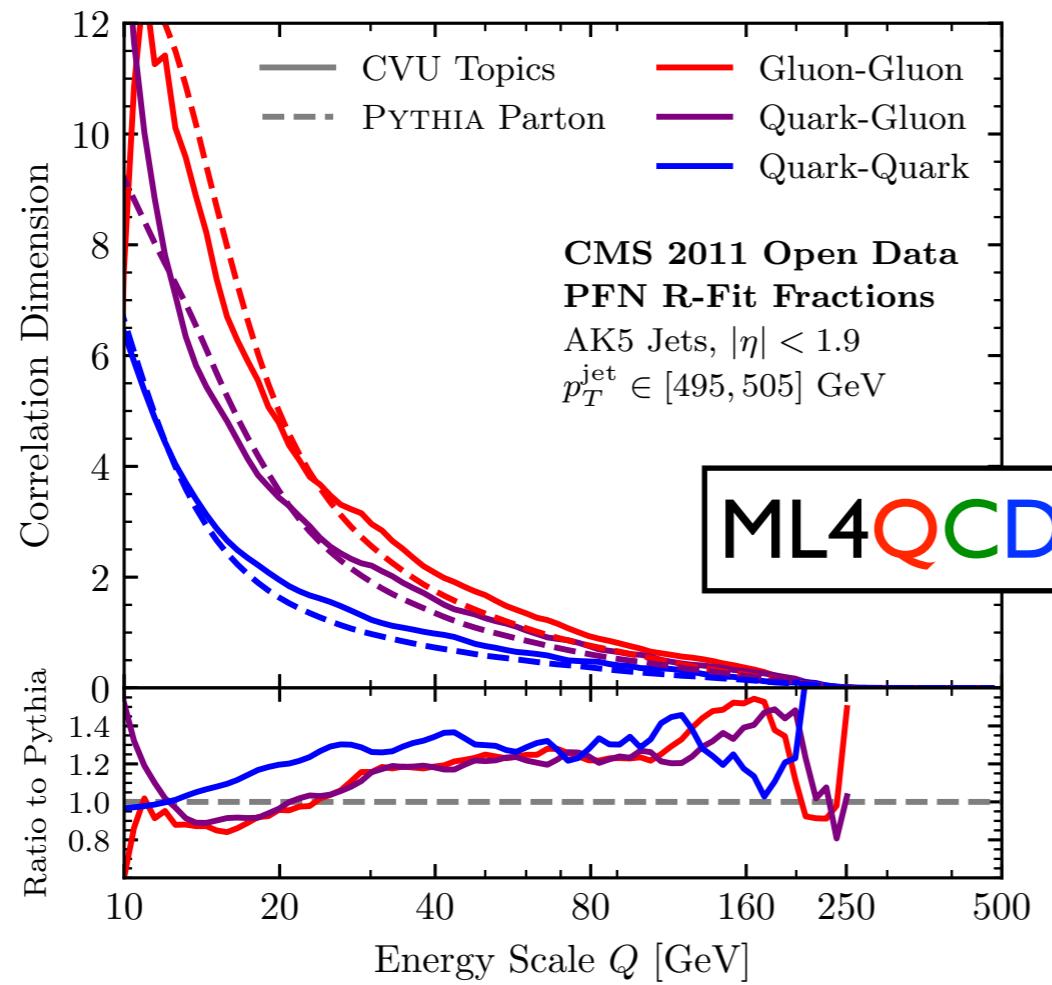
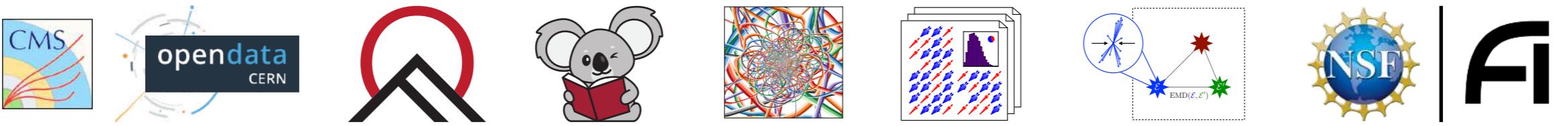
The Rise of Modern Machine Learning

E.g. Anomaly Detection at the LHC Olympics 2020

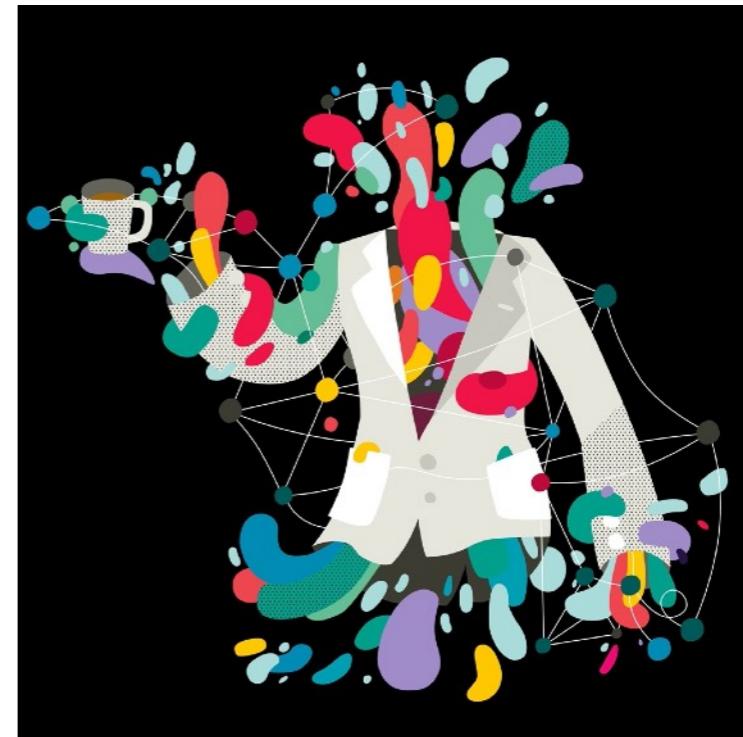


Not just “more of the same”
Galvanizing conceptual shifts in our data-rich field

The Rise of Modern Machine Learning



A New Category of
“Data Physicist”?

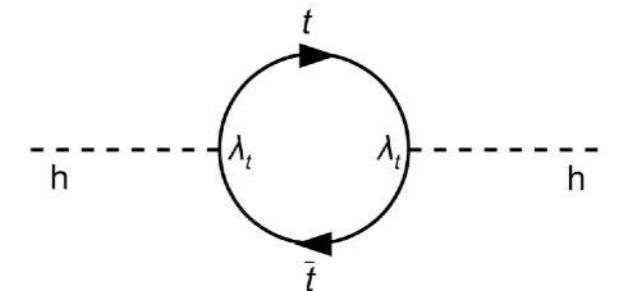


Revisiting Fine Tuning

Is naturalness a reliable guide into the unknown?

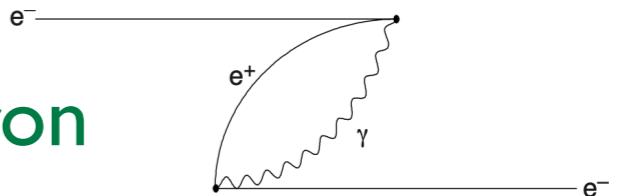


Higgs



vs.

Electron

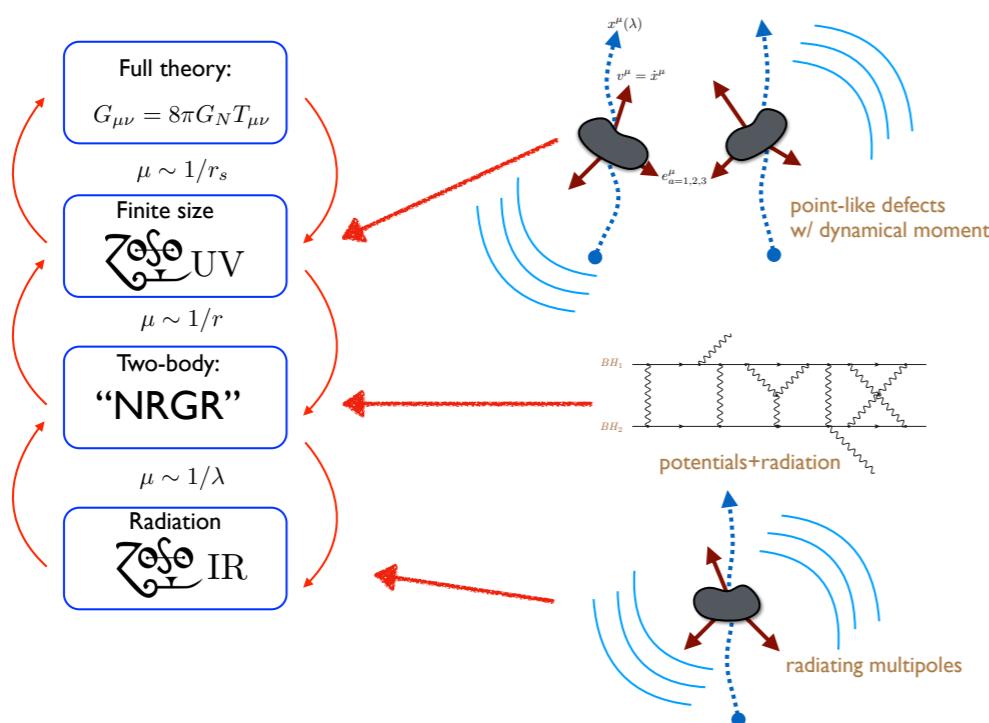


Absence of global symmetries in quantum gravity challenges paradigm of technical naturalness! Implications for flavor physics?

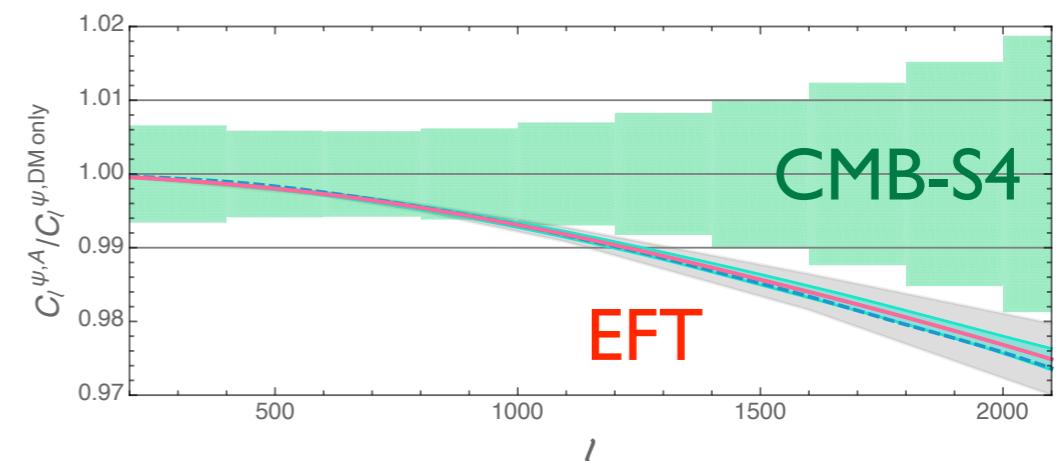
Expanding the EFT Toolbox

Building on successes of HQET, NRQCD, SCET, SMEFT, HEFT, etc.

Gravitational Waves



Large Scale Structure

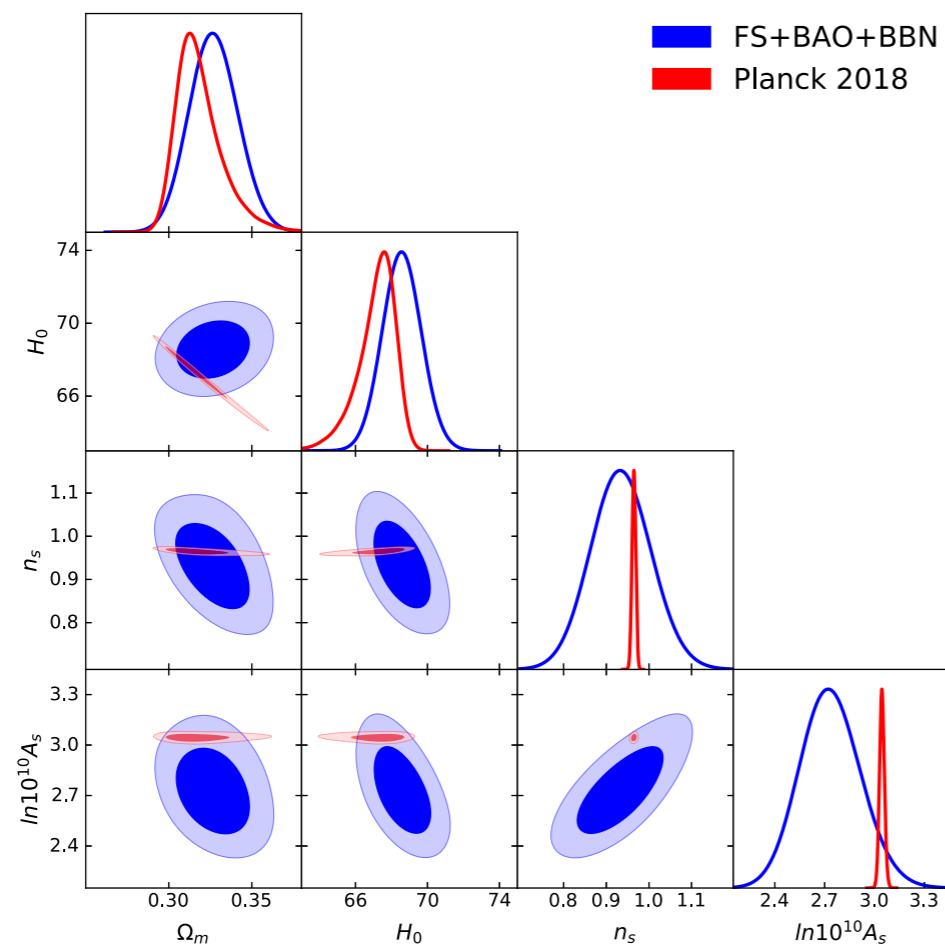


*Hierarchies of scales are ubiquitous in science
EFTs have broad impact beyond traditional HEP applications*

Expanding the EFT Toolbox

Building on successes of HQET, NRQCD, SCET, SMEFT, HEFT, etc.

Reminder that **data analysis spans theory and experiment**

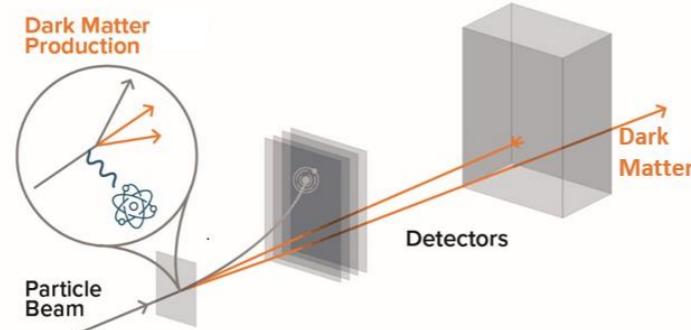
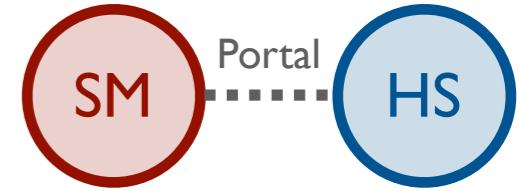


- ← Single author theory paper
- ← 181 author experimental paper

Especially true in astro-particle physics and cosmology;
increasingly true for collider phenomenology with open data

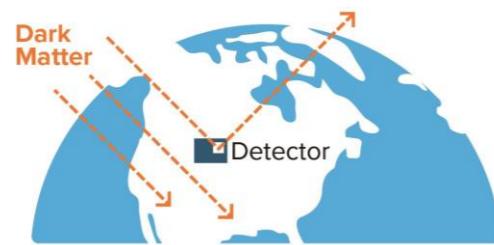
*What is good for the science
should also be good for careers*

G2': Venturing into the Dark Sector



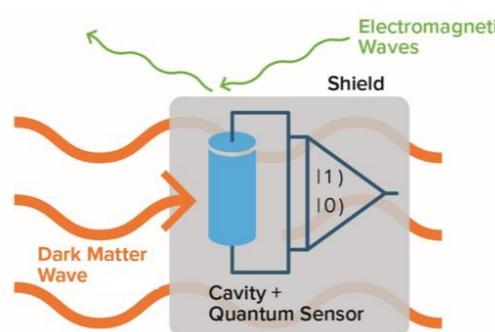
Production/Detection Experiments
(make dark matter beams)

Neutrino connections



Low Threshold Direct Detection
(sub-GeV dark matter)

Quantum connections



Ultralight Dark Matter Detection
(sub-eV coherent fields)

Theorists are collaborating on a new generation of experiments, from conception to design, to analysis, to interpretation

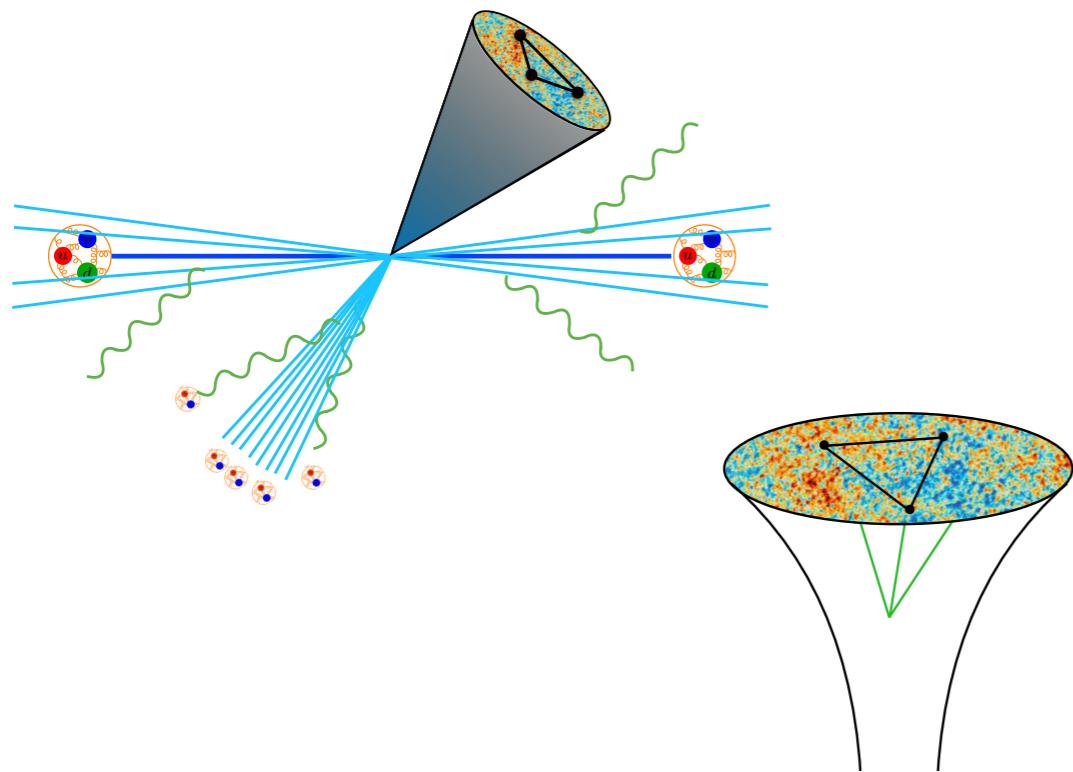
Deep breath, Jesse...

“And then there is using everything.”

— Gertrude Stein

Reaching Across Disciplines

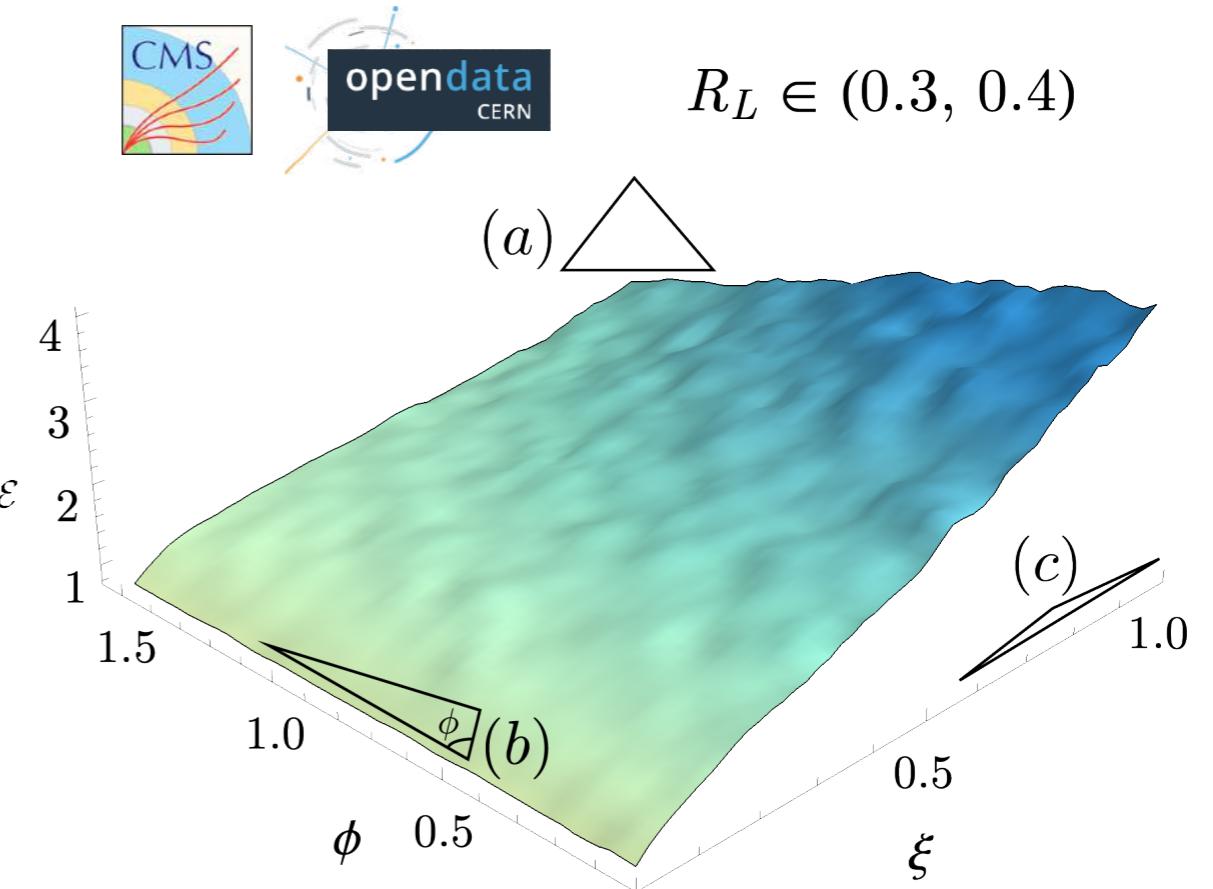
“Non-Gaussianities” in collider energy flux



↔ UV to IR ↔

Technique from
collider physics
and QCD

Interpreted
through lens of
cosmology



↔ Theory to Experiment ↔

Computed
through lens of
conformal field theory

Analyzed
with public
collider data

↔ Phenomenological to Formal ↔



Theory Frontier:
Linking what is possible to what is

Take Home Messages

Theory has played, and will continue to play,
a **phenomenally** important role in high-energy physics



Investments in the possible
drive the science drivers



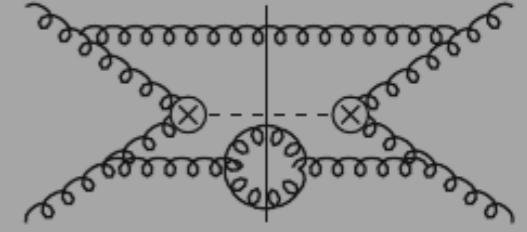
Theory empowers experiment;
Experiment inspires theory



HEP theory is a vibrant
intellectual community

Apologies that I skipped these!

Higgs: From Discovery to Precision



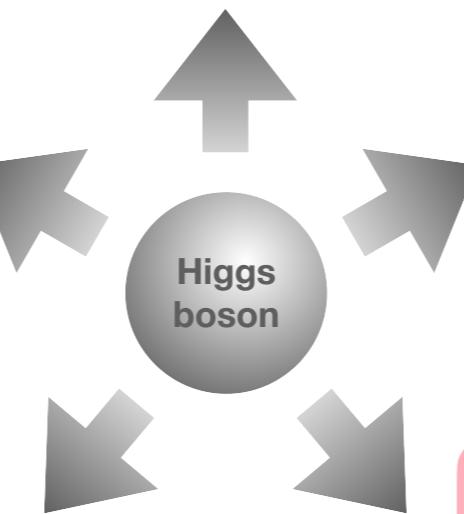
To Enlightenment?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs decay into pairs of quarks and leptons with distinct flavours (for example, $H \rightarrow \mu^+\tau^-$)?

What is dark matter?

- Can the Higgs provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs?



What is the origin of the early-universe inflation?

- Is the Higgs connected to the mechanism that drives inflation?
- Are there any imprints in cosmological observations?

Why is the electroweak interaction so much stronger than gravity?

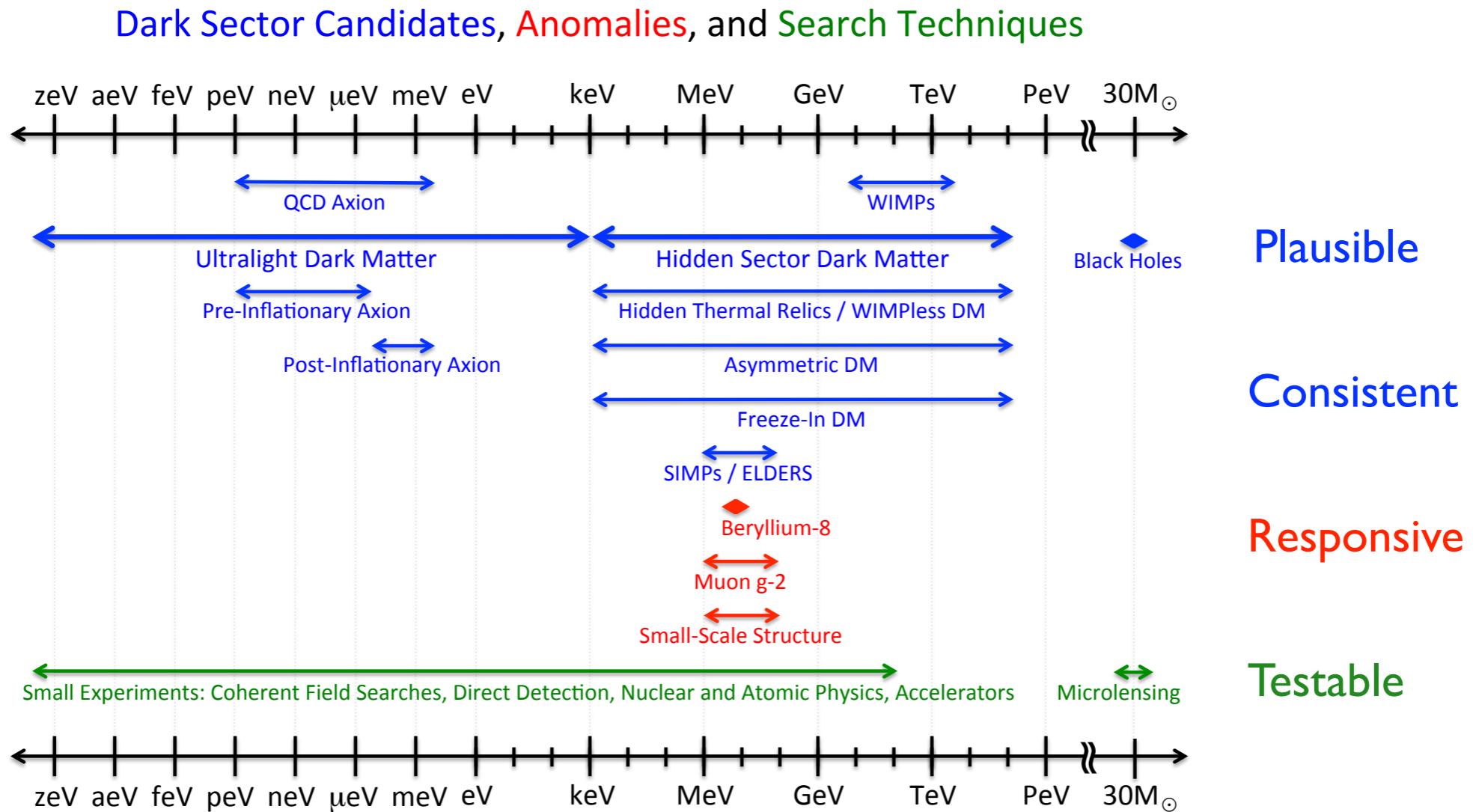
- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs with the W and Z?

Why is there more matter than antimatter in the universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-universe electroweak phase transition?
- Are there multiple Higgs sectors?

Dark Matter Across Scales

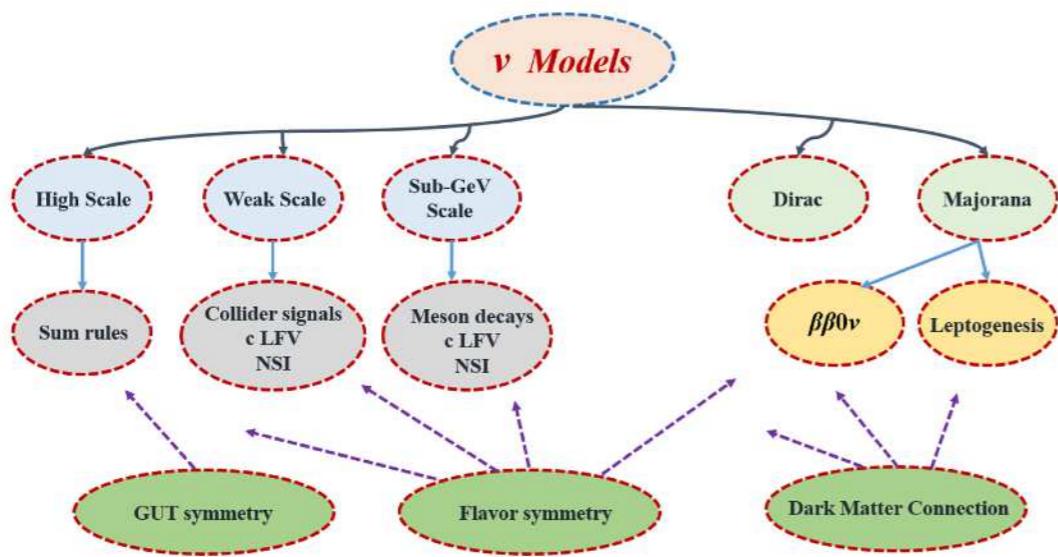
Creative scenarios with unique cosmological histories



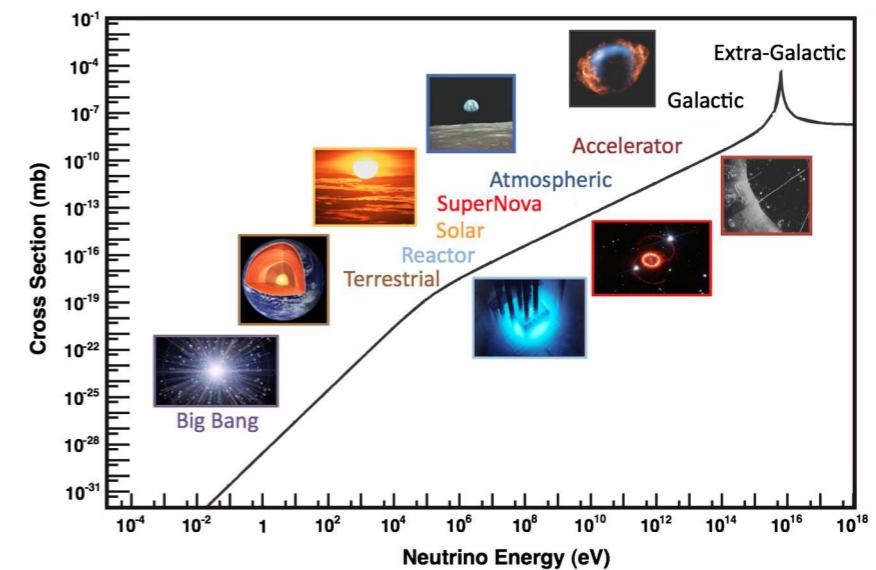
*Turning questions about the Universe into
broad set of concrete search strategies*

Expanding the Scope of Neutrino Theory

From Model Building...



...to Cross Sections...



...to Oscillations in Astrophysical Environments...

Going beyond the three neutrino paradigm also means going beyond the traditional toolbox of HEP theory