



Report from the Theory Frontier

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& the TF Topical Group Conveners + Liaisons

SnowMass 2021 CPM 10.08.20



Aida El-Khadra
UIUC



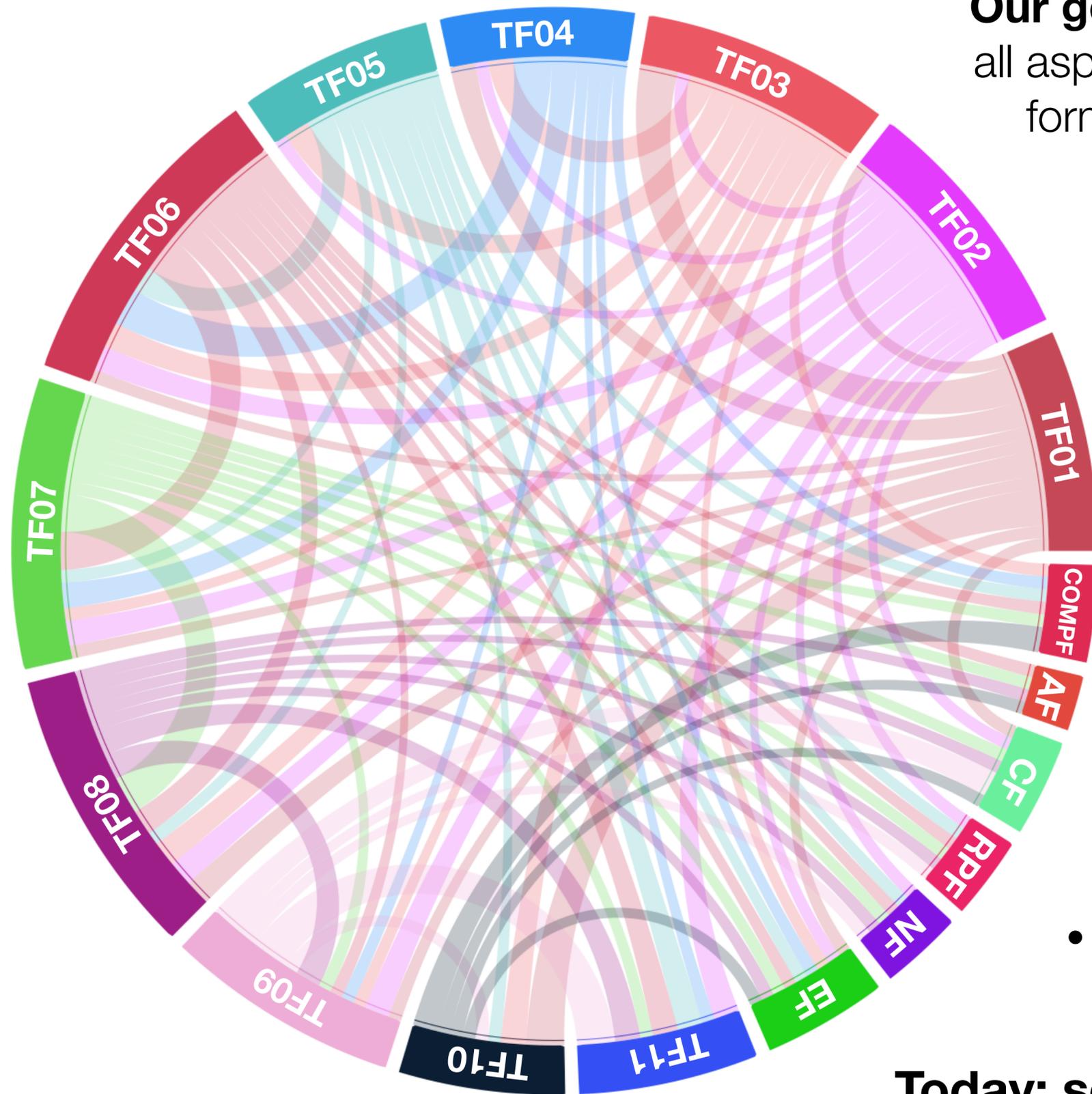
Csaba Csaki
Cornell



Nathaniel Craig
UCSB

Topical Group		Topical Group 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

Liaisons	Accelerator Lian-Tao Wang (U Chicago)	Community Engagement Devin Walker (Dartmouth)	Computational Steven Gottlieb (Indiana U)
Cosmic Flip Tanedo (UC Riverside)	Energy Laura Reina (Florida State U)	Neutrino Physics Irina Mociouiu (Penn State U) & Kaladi S. Babu (Oklahoma State U)	Rare Processes and Precision Alexey Petrov (Wayne State)



Our goal: articulate recent advances & future opportunities in all aspects of theory relevant to HEP, including particle theory, formal/foundational theory, cosmological and astro-particle theory, and quantum information science.

- 41 TF TG conveners and liaisons with other frontiers
- ~100 theorists as conveners across all frontiers and TGs
- Snowmass TF community mailing list: ~860 subscribers
- 311 LOIs (93 TF primary, 218 TF secondary)
- >70 White Papers that are actively being solicited
- ~380/295 CPM participants listing TF as primary/secondary
- 26 inter-frontier CPM breakout sessions co-organized by TF TGs

Today: select physics highlights for the coming year...

TF01: String theory, quantum gravity, black holes

Daniel Harlow, Shamit Kachru, and Juan Maldacena

Recent progress on the black hole information problem

1996: Entropy of some BHs can be counted in string theory (Strominger & Vafa).

Page curve remains elusive: the plot of the von Neumann entropy of the radiation of an evaporating black hole as a function of time. A major milestone on the way to solving the information problem

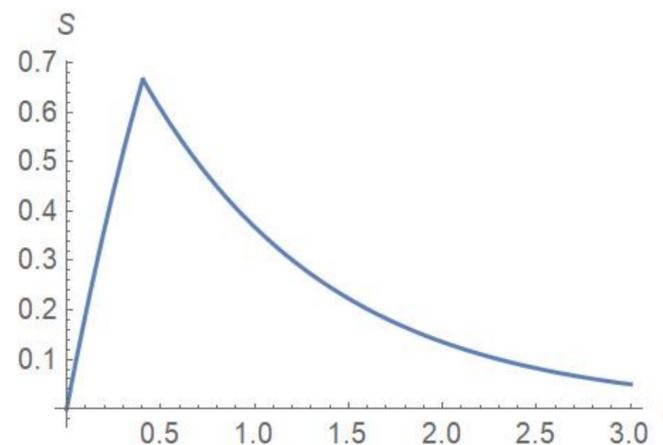
$$S(\rho_R) = \min_{X_R} \left[\text{ext}_{X_R} \left(\frac{\text{Area}(X_R) + \dots}{4G} + S_{\text{bulk}}(r(X_R)) \right) \right]$$

>100 papers clarifying and extending these results. Key lesson: extraordinary power of the Euclidean gravity path integral, which through “replica wormholes” gives one rather general motivation for the quantum extremal surface formula. Does not rely on the details of AdS/CFT, and thus can be used to explore the non-perturbative physics of black holes in more realistic backgrounds.



1976: Low-energy physics of black holes seems to lead to a contradiction with quantum unitarity (Hawking).

1997: AdS/CFT correspondence (Maldacena) indicates black hole evaporation is apparently unitary.



2019: The quantum extremal surface formula of AdS/CFT is powerful enough to compute the Page curve for certain evaporating black holes (Penington and Almheiri/Engelhardt/Marolf/Maxfield)

TF02: Effective Field Theory Techniques

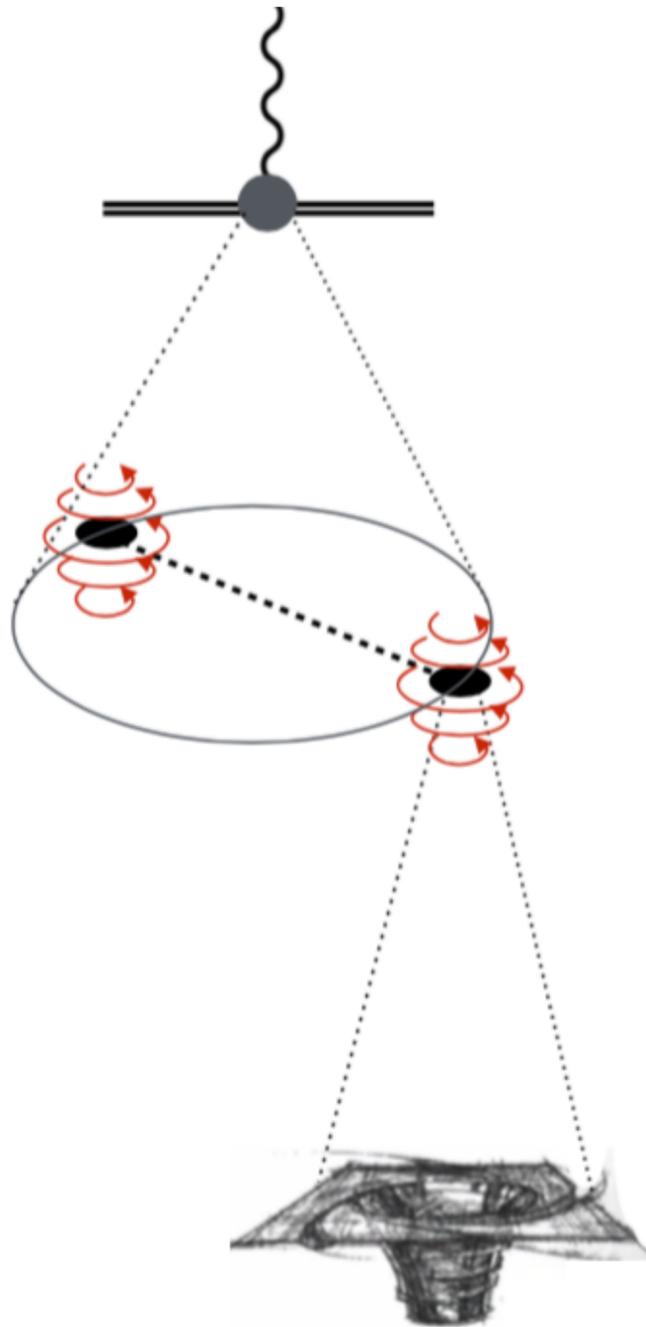
Patrick Draper and Ira Rothstein

EFT approach to Gravitational Physics

Gravitational wave observations have expedited the need for precise calculations involving gravitational interactions between compact objects. Such observations are a window on fundamental physics (exotic states of matter, QCD in extreme conditions, black hole horizon physics)

EFT methods have proven useful in various aspects of the calculation of gravitational wave templates, and has generated synergy between various sub-fields in HEP-TH.

- Higher order calculations within the Post-Newtonian (NR) and Post-Minkowskian (Expansion in G)
- EFT dynamics of QCD in extreme conditions
- Response functions for Exotic Matter



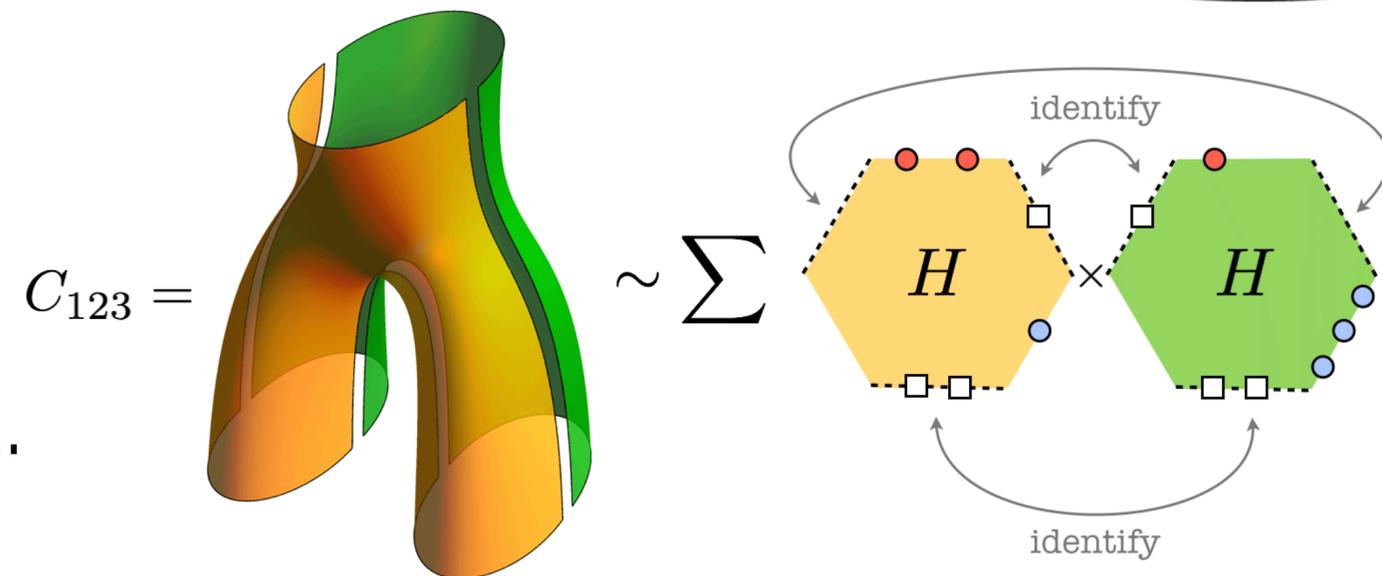
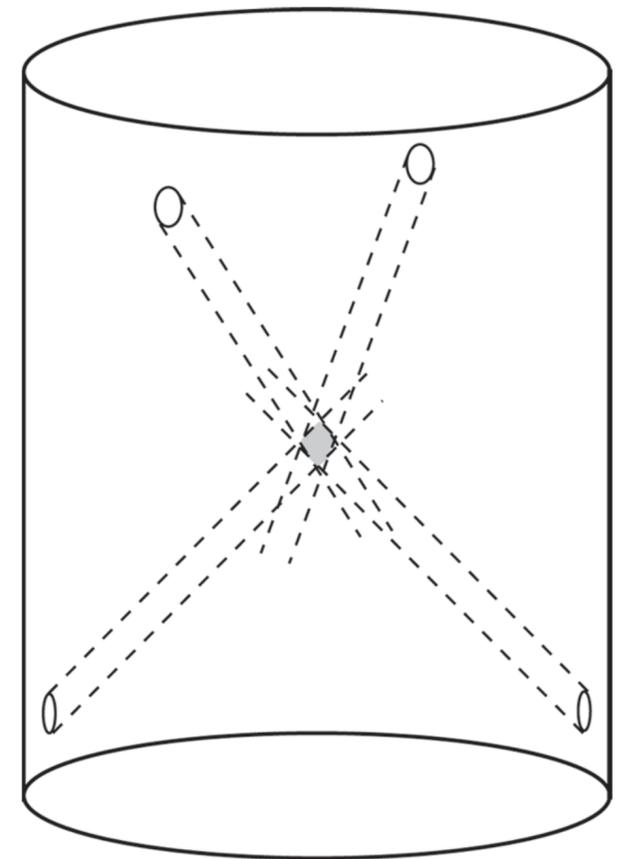
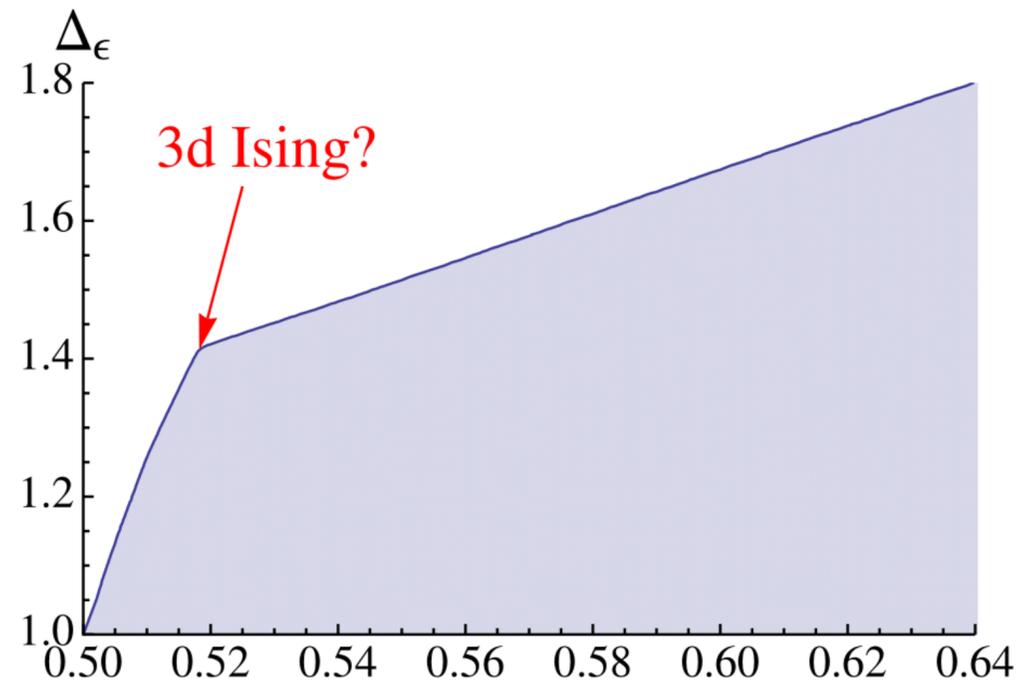
TF03: CFT and formal QFT

David Poland and Leonardo Rastelli

- Many different “Bootstrap” programs:

- Conformal Bootstrap
- Modular Bootstrap
- S-Matrix Bootstrap
- Integrable (Hexagon) Bootstrap
- SCFT Operator Algebra Bootstrap
- String Amplitudes Bootstrap
- Cosmological Bootstrap

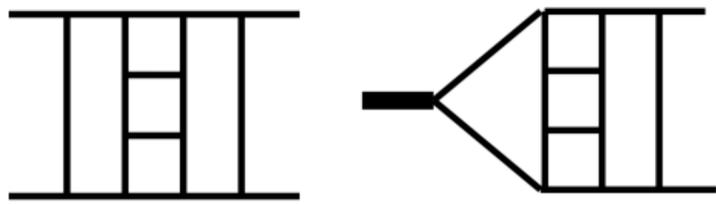
- Numerous synergies, overlaps, shared techniques, intuitions, sources of inspiration, ...



TF04: Scattering amplitudes

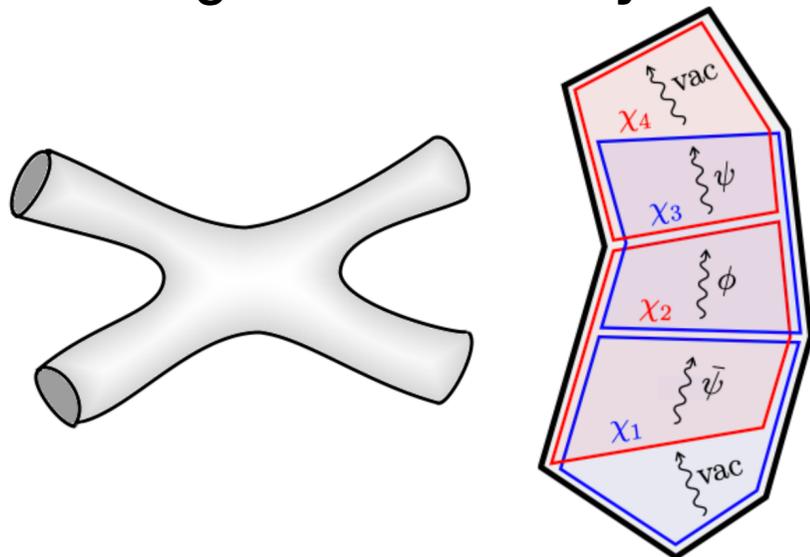
Zvi Bern and Jaroslav Trnka

Multi-loop amplitudes in QFT

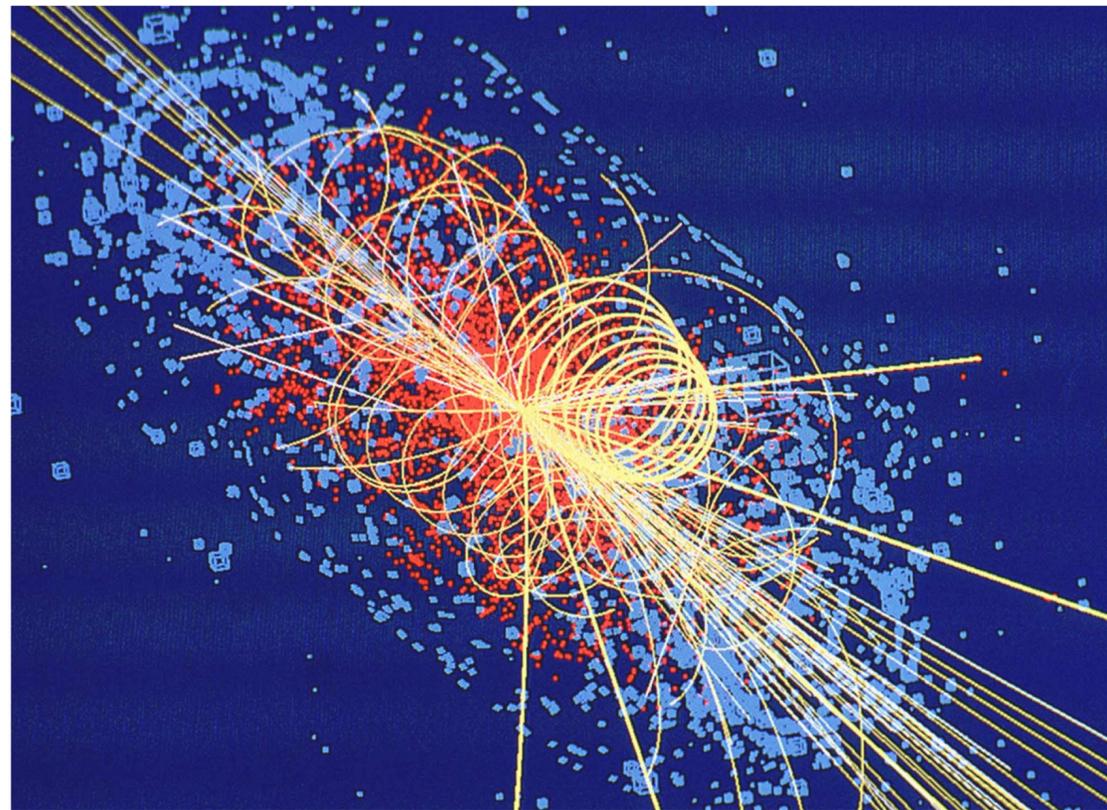


$$g^2 - 2\zeta_2 g^4 + 22\zeta_4 g^6 - [219\zeta_6 + 8(\zeta_3)^2] g^8 + \dots$$

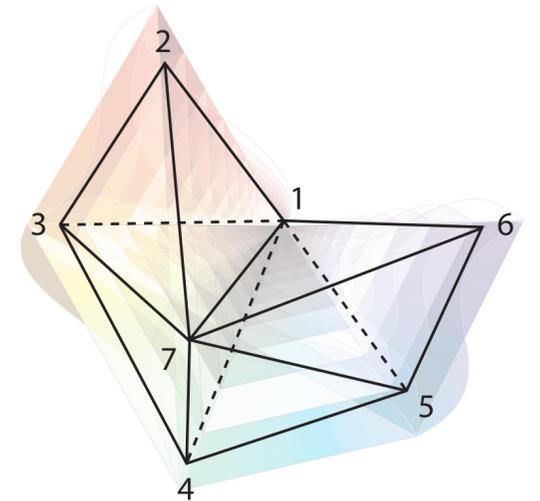
String amplitudes, integrability, solving N=4 SYM theory



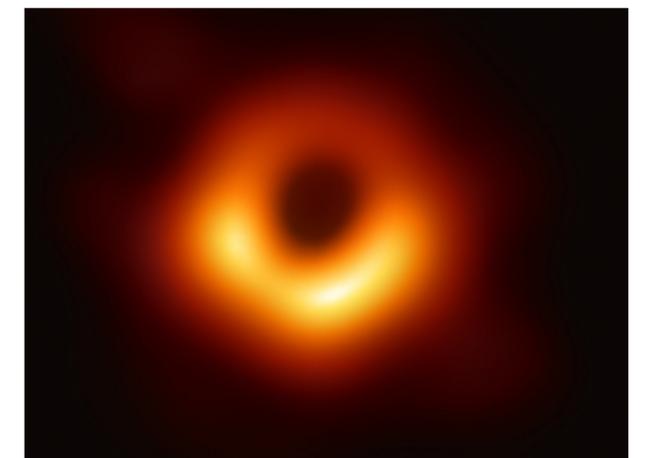
Particle scattering at colliders,
LHC physics



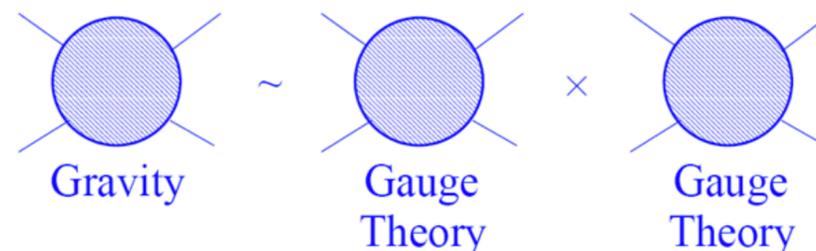
New mathematical structures,
Amplituhedron



From amplitudes to classical
gravity, LIGO physics



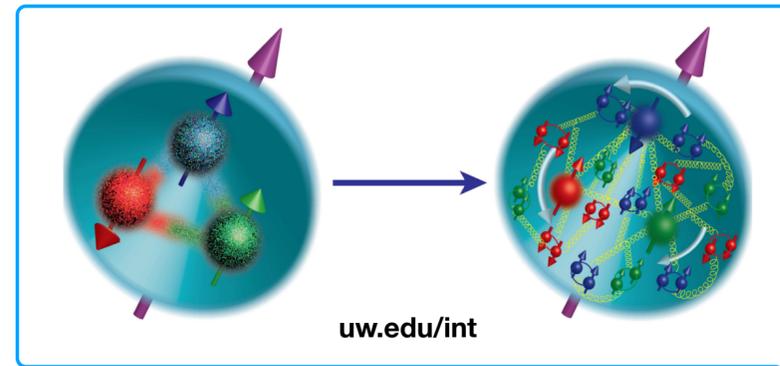
Color-kinematics duality



TF05: Lattice gauge theory

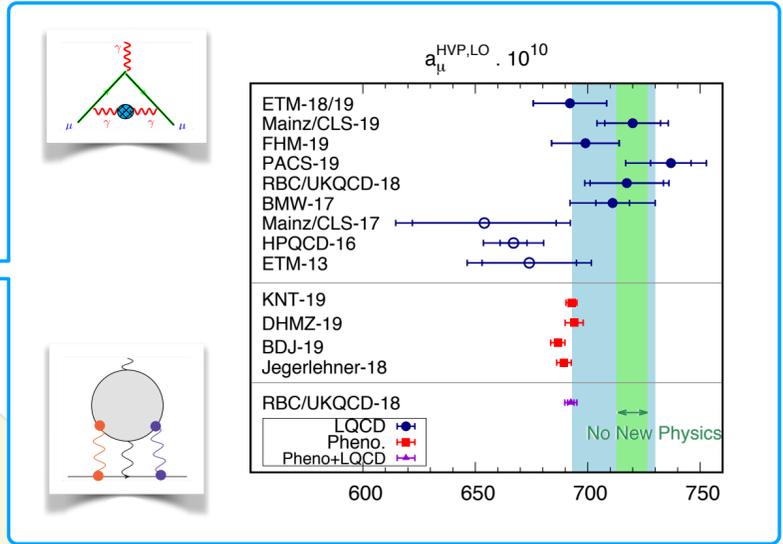
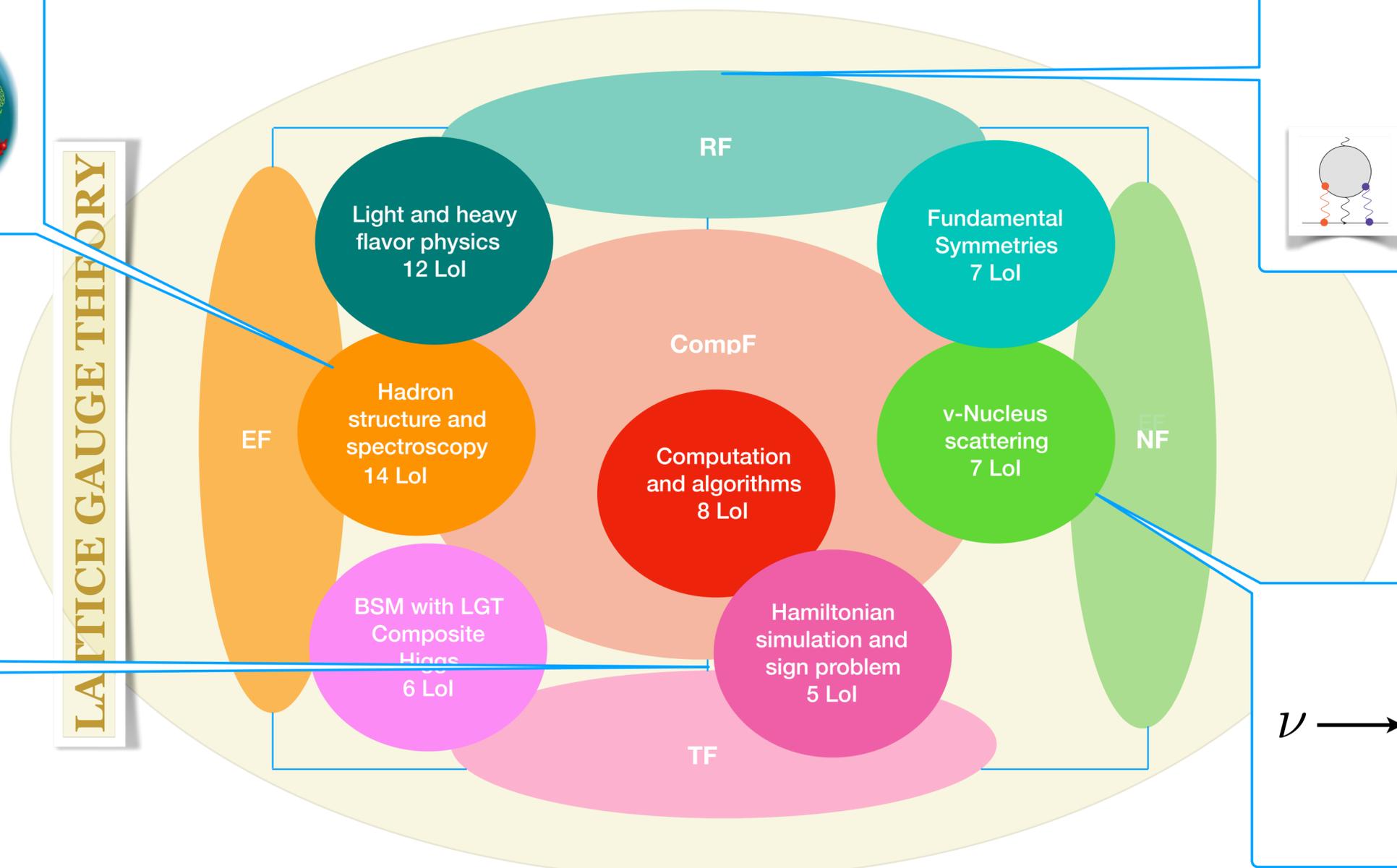
Zohreh Davoudi, Taku Izubuchi, and Ethan Neil

In addition to many existing exciting directions with direct impact on experimental program, a few new themes will become an integrated part of the LGT portfolio in the coming decade.

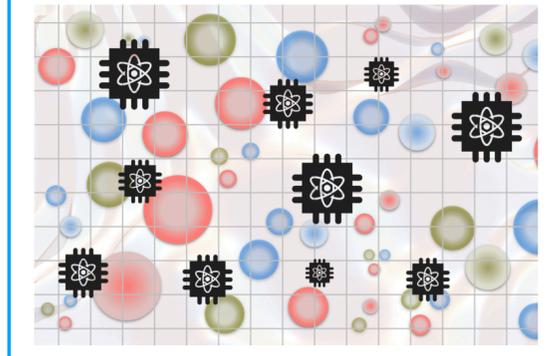


Structure functions, e.g., PDFs

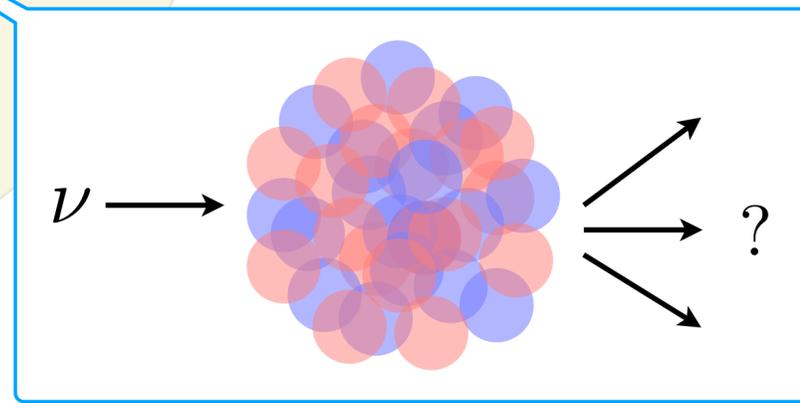
LATTICE GAUGE THEORY



Hadronic contributions to muon anomalous magnetic moment



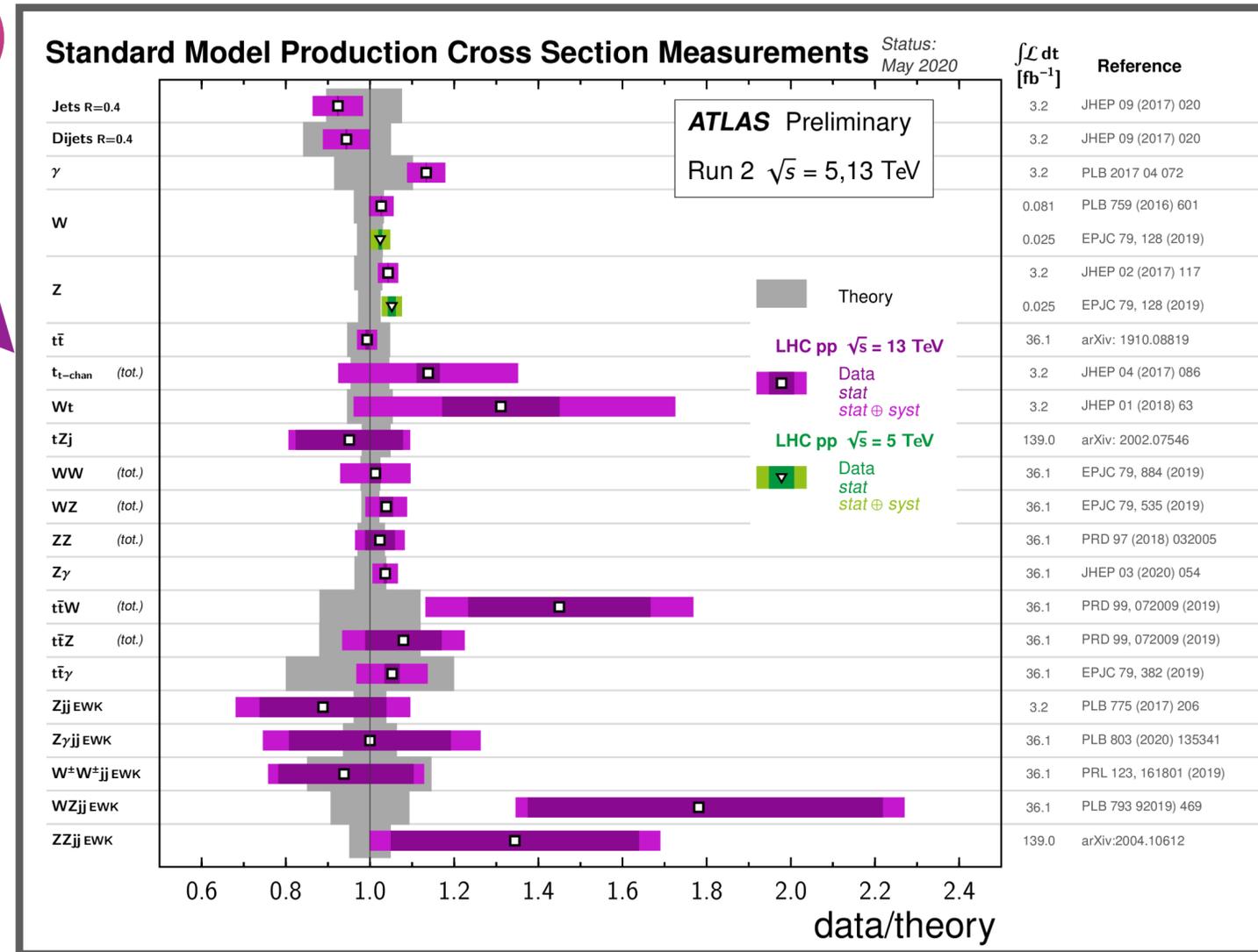
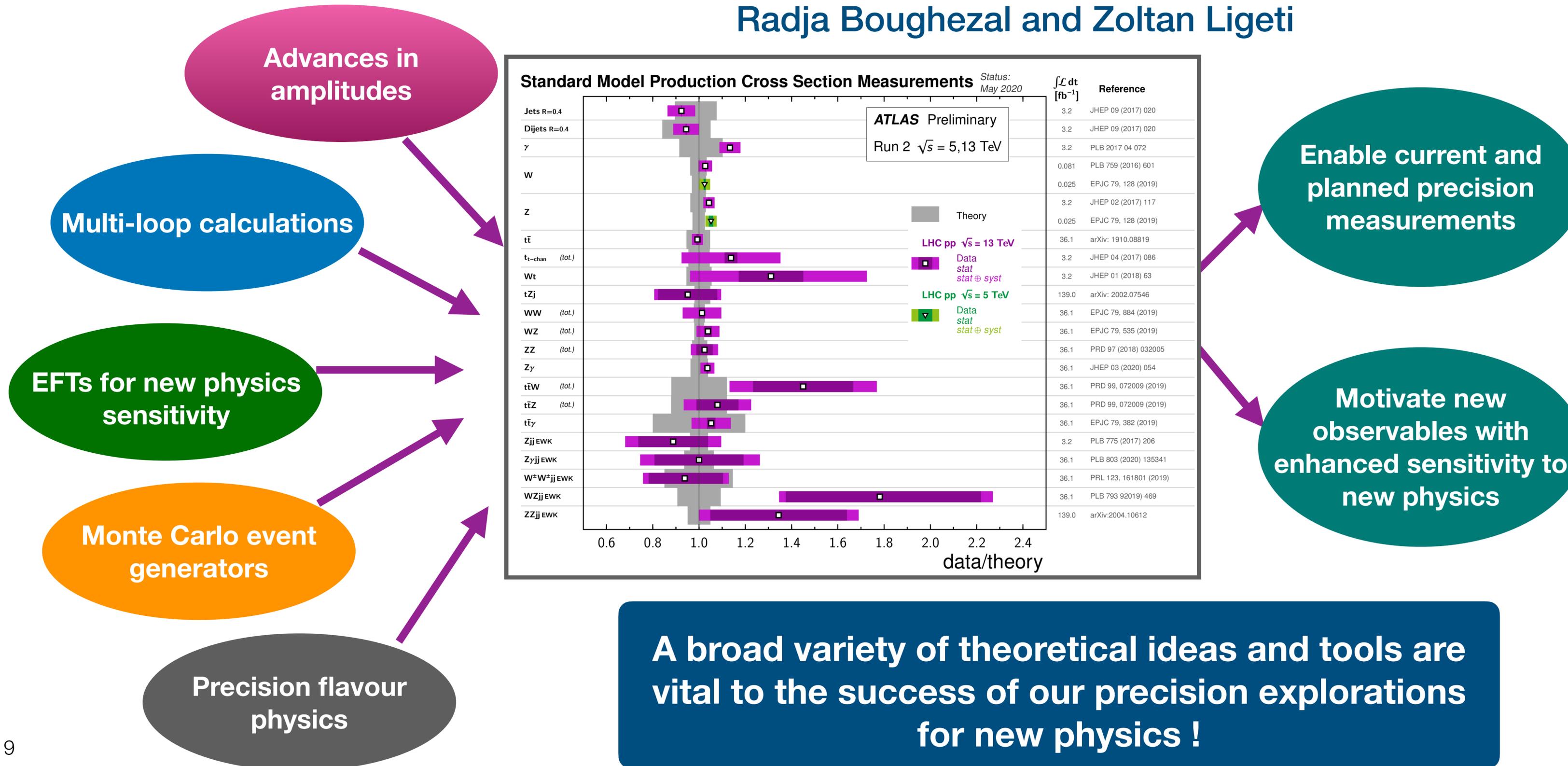
New strategies in computing and simulation, including the use of ML and quantum computing



ν -nucleus cross sections

TF06: Theory techniques for precision physics

Radja Boughezal and Zoltan Ligeti

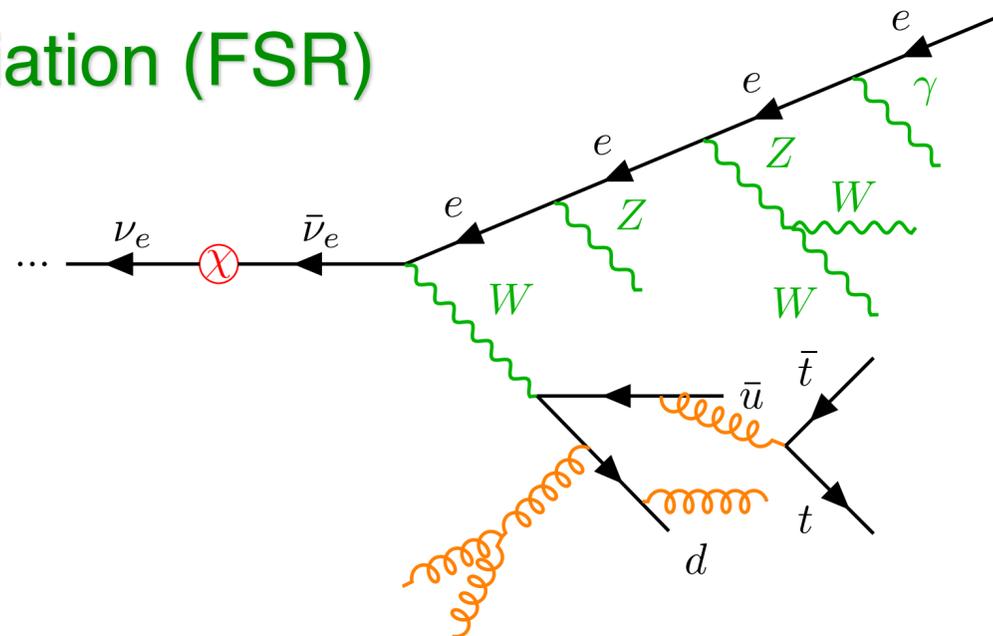


TF07: Collider phenomenology

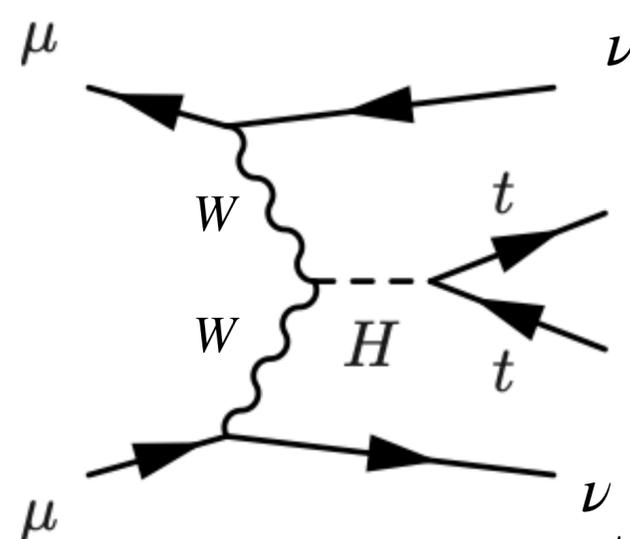
Fabio Maltoni, Shufang Su, and Jesse Thaler

Example Snowmass Focus Effort: [Electroweak Effects at High Energy](#)

● Final state radiation (FSR)



● Initial state radiation (ISR)



Electroweak (EW) effects can become quite large at high energies \Rightarrow $O(1)$ impact for $Q \gg m_{W/Z}$

Currently: Many [exploratory studies](#) in the literature, with very different formal approaches, which have not been compared yet

Future target: [Systematic studies](#) to quantify EW effects in processes at very high energies, such as from very heavy [dark matter annihilation \(FSR\)](#) or at future [multi-TeV lepton colliders \(ISR\)](#)

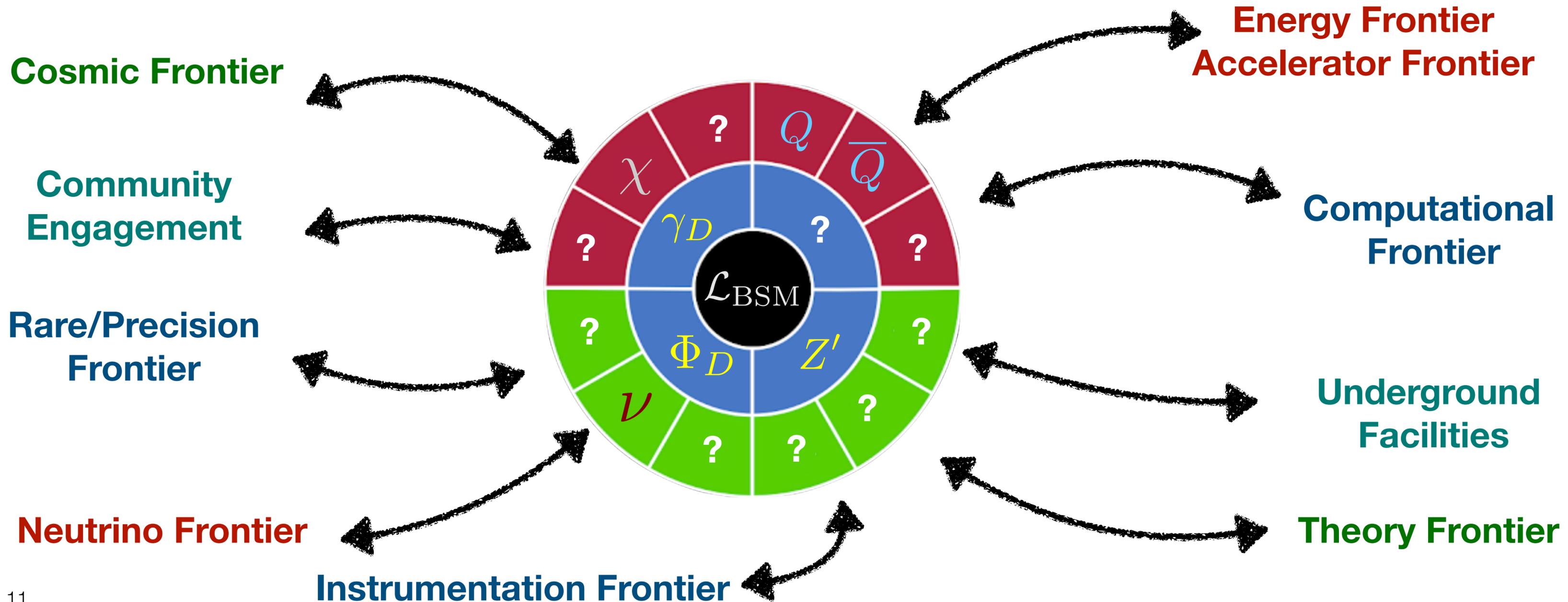
Future target: [Complete implementation](#) of EW showers in Monte Carlo generators (space-like and time-like)

[First meeting held within TF07](#) with a lot of discussion and interest!

TF08: BSM model building

Patrick Fox, Graham Kribs, and Hitoshi Murayama

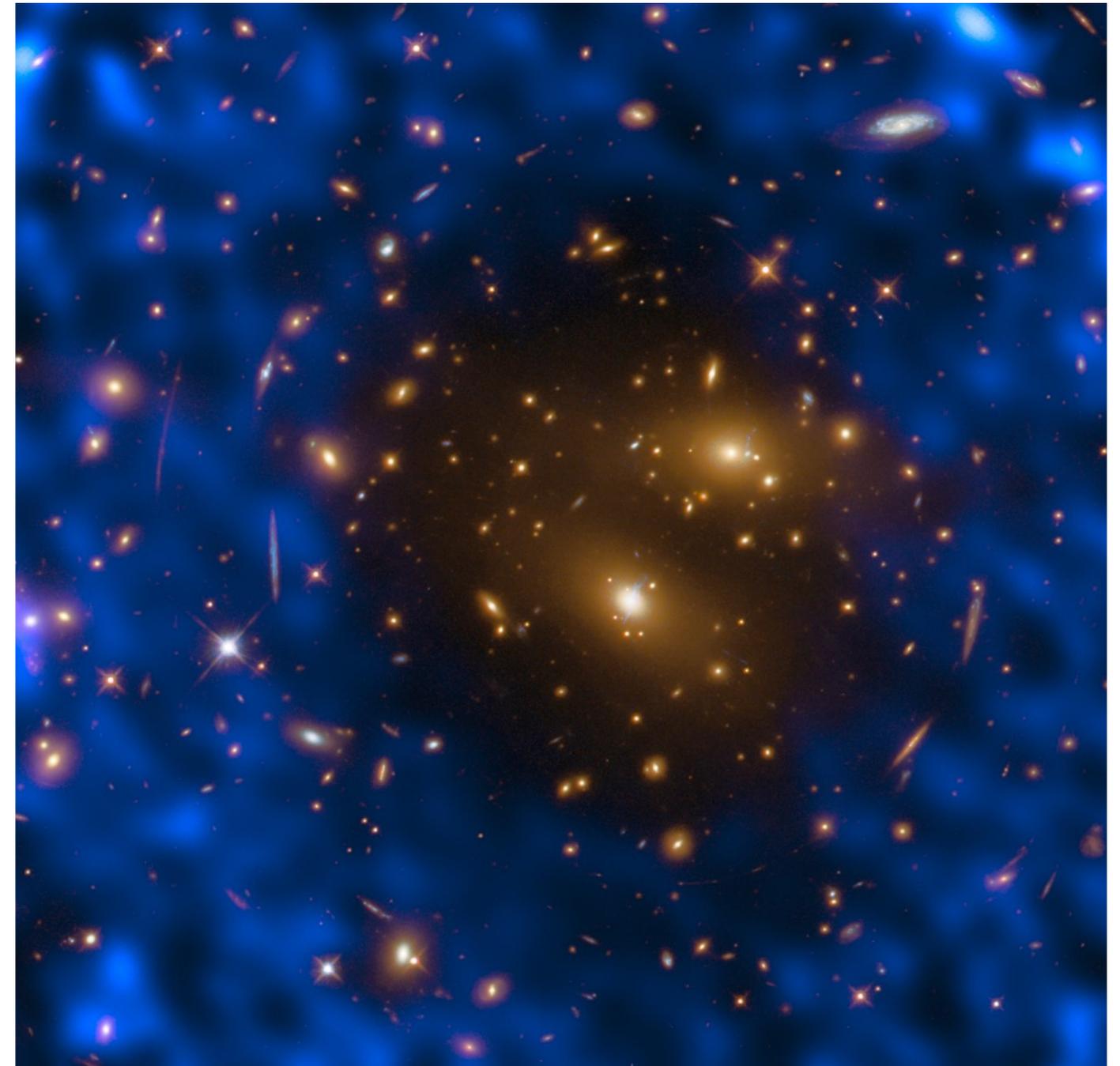
As the Lagrangian that describes New Physics (e.g. the dark sector) is uncovered, the major focus of TF08 becomes the focus of the whole field



TF09: Astro-particle physics & cosmology

Dan Green, Josh Ruderman,
Ben Safdi, and Jessie Shelton

- Expanding and exploring new frontiers
 - Theory driving new experiments
 - Expanding uses of astrophysical data
 - Exploring new directions in theory space
- New theoretical tools
 - Emerging connections with formal theory (e.g., new uses of holography, bootstrap, EFT)
 - New directions in simulations



TF10: Quantum Information Science

Simon Catterall, Roni Harnik, and Veronika Hubeny

- Geometrization of entanglement:
 - Many aspects of quantum entanglement captured by simple geometric constructs in higher dimensional gravity.
 - Holographic encoding of bulk spacetime as a quantum error correcting code.
 - Novel insights into black hole information and spacetime emergence.
 - New teleportation protocols as spacetime wormholes.



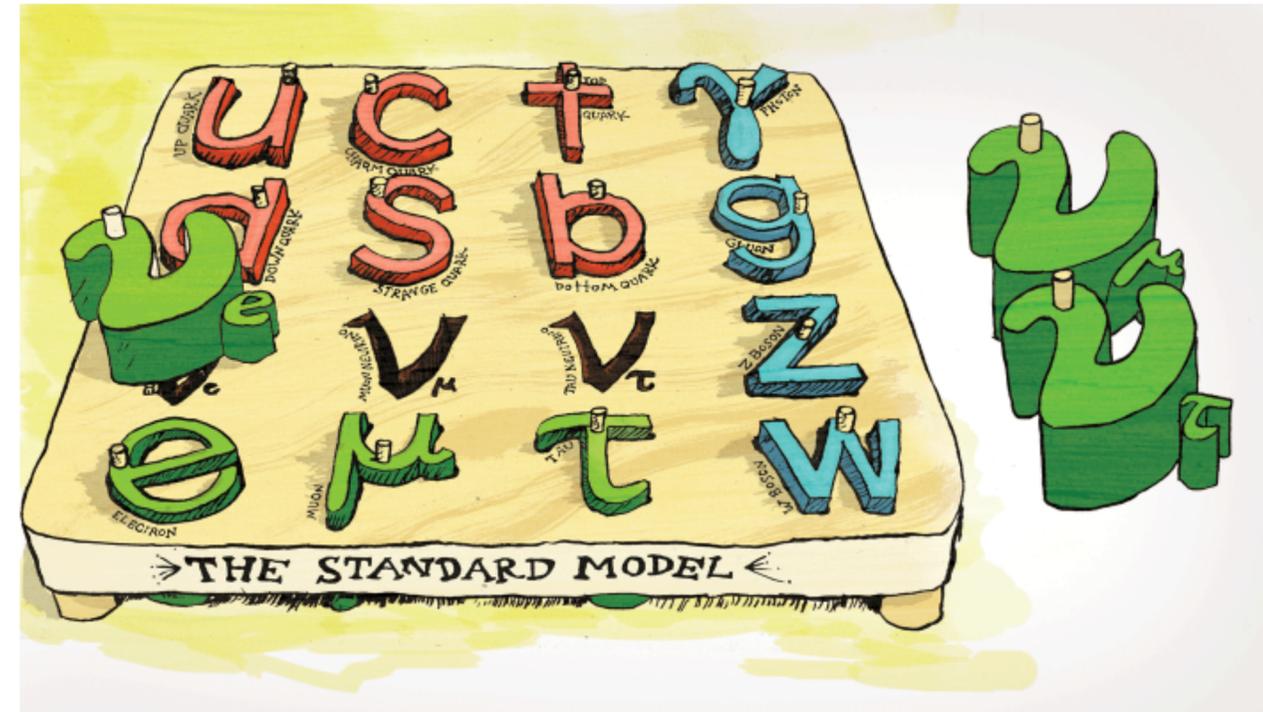
TWON

TF11: Theory of neutrino physics

André de Gouvêa, Irina Mocioiu, Saori Pastore, and Louis Strigari

Two key questions:

- How do we take full advantage of percent-level neutrino oscillation experiments? Can we determine neutrino-nucleus cross sections that are relevant for these experiments?
- Interplay with other areas of nuclear physics (neutrino properties from double beta decay), particle physics (links to dark matter and collider physics), astroparticle physics (ultra-high energy neutrinos and supernova neutrinos), and cosmology (neutrino properties from cosmic surveys, including effective numbers of neutrinos and neutrino masses).



Next steps for TF

- **Before CPM:** Town hall kickoff (7/31), workshops by TF07 (9/15), TF11 (9/21-23).
- **Ongoing:** Focus on developing contributed papers. New ideas welcome!
- **Ongoing:** Additional small focused workshops by TGs. Under development: Joint CompF/EF/NF/RPF/TF workshop on LGT; RPF/TF workshop on $|V_{ub}|$, $|V_{cb}|$; AF/EF/TF workshop on energy frontier discovery machines.
- **After CPM:** Develop detailed timeline for TG summary drafts, TF summary drafts, gathering feedback from community. Coordinate with other frontiers via liaisons.
- **March 17-19 2021:** TF meeting @ KITP (hybrid or online TBD). Highlight theoretical developments, consolidate TF contributed papers, coordinate theory activities across all frontiers. *All physicists welcome.*

