Perspectives in High Energy Physics
-- In the light of DPF Snowmass 2021

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Chair, 2021 DPF & Snowmass Steering Group

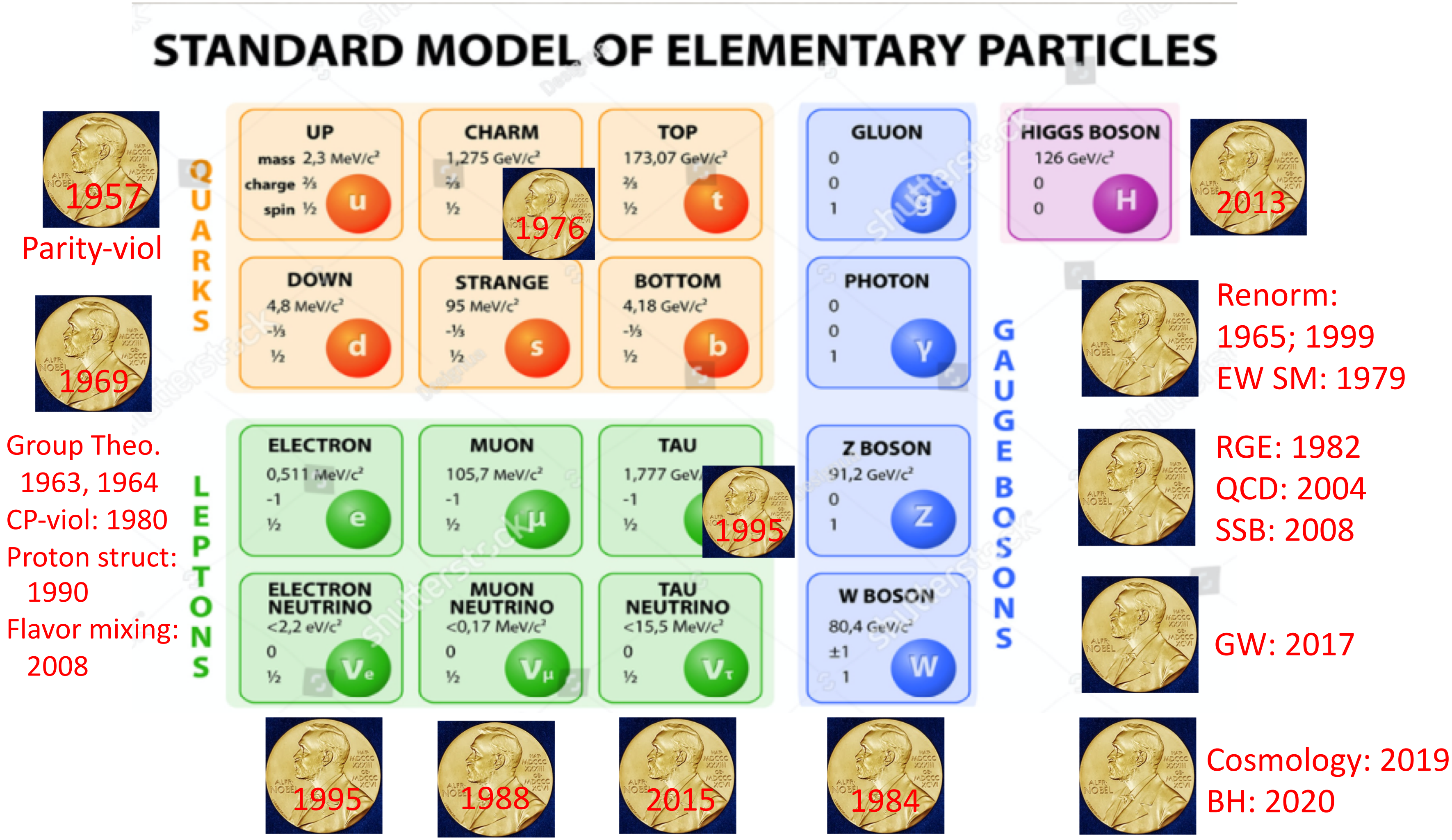
中国物理学会高能物理分会
第十一届全国会员代表大会暨学术年会

August 8, 2022

- HEP: A highly accomplished dynamic field
- HEP at a cross-road
- DPF Snowmass 2021: Building the future

HEP: A highly accomplished field

Un-interrupted discoveries for many decades



HEP: A highly dynamic field

Many fundamental questions to address

Both in theory & experimental observations:

Experimental, observational

- The underlying theory of Electroweak symmetry breaking
- The nature of EW phase transition
- Quark & lepton flavor mixing
- The nature of neutrino mass
- New sources of CP violation
- Baryon-antibaryon asymmetry
- Cosmic inflation
- Black holes

Conceptual, intellectual

- Non-perturbative QFT
- Grand unified theory
- Supersymmetry
- Quantum gravity
- The nature of space-time & extra dimension
- Superstring theory
- Synergy with Artificial Intelligence/Quantum Information Science

The pursuits of the fundamental questions drive the field: Intellectual culture, technology and society

HEP at a Cross-Road

"When you come to a fork in the road, take it!" – Yogi Berra

Good news:

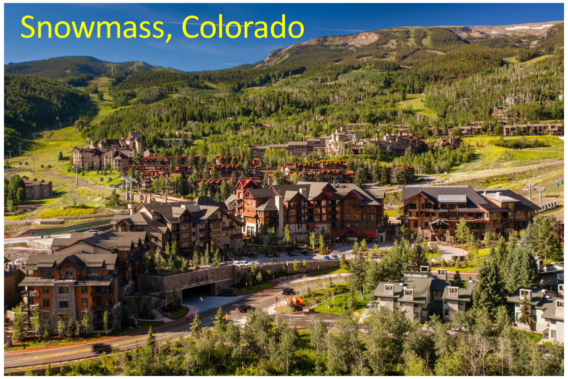
- The SM is experimentally tested to a high precision ~ TeV.
  It can be valid to an exponentially high scale, even to M_{PL} !
- DM discovered in astro/cosmological observations → BSM !
- Neutrino mass/mixing established → BSM physics !

Challenge: No clear argument for the next physics scale !

Λ_{BSM} , M_{DM} , M_{ν} ?

We must explore all directions!

Snowmass:
A Community Exercise



In June 28 - July 16, 1982, the APS DPF organized an workshop, to "assess the future of elementary particle physics, to explore the limits of our technological capabilities, and to consider the nature of future major facilities for particle physics in the US."

DPF Chair Charles Baltay:

"… The 1982 DPF Summer Study was the first attempt in recent years to bring together physicists from the whole country to consider the future of our field from the point of view of the best overall national program. The DPF Executive Committee feels that this summer study was sufficiently useful in this last respect to hold similar summer studies at appropriate times in future years."

This spearheaded the SSC exploration, and more.
The tradition continued.

Every 7-10 years, DPF leads community studies, "Snowmass"

Snowmass Goals:

To define the most important questions for the field of particle physics; to identify promising opportunities to address them.

--- it is a science process, with breadth and depth!

Last Snowmass (2013) highly successful:

(Report by December 2013)

https://www.slac.stanford.edu/econf/C1307292/

essential inputs to P5

"Particle Physics Project Prioritization Panel" (P5)

A subpanel of HEPAP

- Projects prioritized according to funding scenarios
- Science research directions in HEP
- Federal funding profile for the current and near-future projects in the decade.

P5 Report, May 2014


Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5) May 2014

Distilled from the Snowmass 2013 inputs, five Science Drivers for the field:

- **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.**

- 29 recommendations
- Projects prioritized according to funding scenarios

As a result, highly impactful on the
- Directions/achievements in HEP
- Federal funding profile enhanced

for the current and near-future projects in the decade.

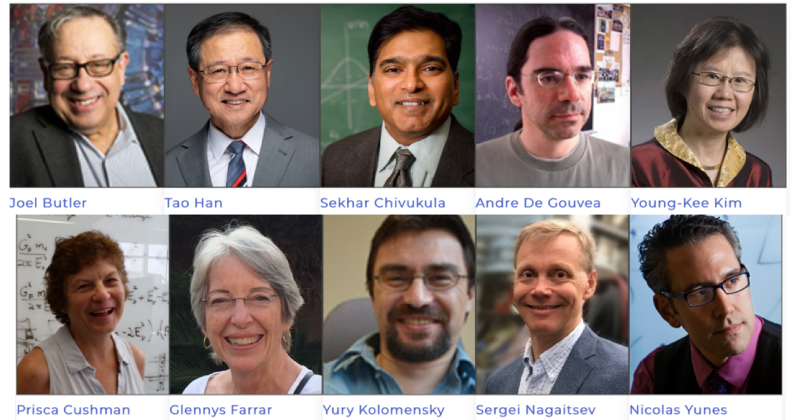
Snowmass 2021 organization

https://snowmass21.org/

Steering Group 2022

DPF 2022 Chair: Joel Butler (FNAL)
Chair-elect: R. Sekhar Chivukula (UCSD)
Vice Chair: André de Gouvêa (Northwestern)
2021 Chair: Tao Han (U Pitt)
2020 Chair: Young-Kee Kim (U Chicago)
2019 Chair: Prisca Cushman (U Minnesota)

DPB: Sergei Nagaitsev (FNAL)
DNP: Yury Kolomensky (LBNL)
DAP: Glennys Farrar (NYU)
DGRAV: Nicolas Yunes (UIUC)



Advisory Group 2022

- DPF Executive Committee
  - Secretary/Treasurer: Tulika Bose
  - Councilor: Bob Bernstein
  - Member-at-Large: Mary Bishai
  - Member-at-Large: Lauren Tompkins
  - Member-at-Large: Mayly Sanchez
  - Member-at-Large: Gordon Watts
  - Member-at-Large: Heather Gray
  - Member-at-Large: Kendall Mahn
  - Early Career Member: Julia Gonski
- Editor and Communication
  - Editor – Michael Peskin
  - Communication – Bob Bernstein
  - Technical Liaison – Sergei Chekanov

- Representatives from the Int. Community
  - Africa / Middle East
    Azwinndini Muronga, Nelson Mandela Metropolitan Univ, South Africa
  - Asia / Pacific
    Atsuko Ichikawa, Kyoto University, Japan
    Xinchou Lou, IHEP, China
  - Canada
    Heather Logan, Carleton University
  - Europe / Russia
    Val Gibson, Cavendish Laboratory, UK
    Berrie Giebels, CNRS, France
    Michelangelo Mangano, CERN
  - Latin America
    Claudio Dib, Universidad Tecnica Federico Santa Maria, Chile

Snowmass 2021 organization

10 Frontiers	80 Topical Groups
Energy Frontier	Higgs Boson properties and couplings, Higgs Boson as a portal to new physics, Heavy flavor and top quark physics, EW Precision Phys. & constraining new phys., Precision QCD, Hadronic structure and forward QCD, Heavy Ions, Model specific explorations, More general explorations, Dark Matter at colliders
Frontiers in Neutrino Physics	Neutrino Oscillations, Sterile Neutrinos, Beyond the SM, Neutrinos from Natural Sources, Neutrino Properties, Neutrino Cross Sections, Nuclear Safeguards and Other Applications, Theory of Neutrino Physics, ...icial Neutrino Sources, Neutrino Detectors
Frontiers in Rare Processes & Precision Measurements	Weak Decays of b and c, Strange and Light Quarks, Fundamental Physics and S... ...nd Lepton Number Violation, Charged Lepton Flavor Violation, Dark Sector at Low E...
Cosmic Frontier	Dark Matter: Particle-like, Dark Matter: Wave-like, Dark Mat... ...mic Acceleration: The Modern Universe, Dark Energy & Cosmic Acceler... ...rgy & Cosmic Acceleration: Complementarity of Probes and N...
Theory Frontier	String theory, quantum gravity, blac... ...es, CFT and formal QFT, Scattering amplitudes, Lattice gauge the... ...ysics, Collider phenomenology, BSM model building, Astro-particle... ...rmation science, Theory of Neutrino Physics
Accelerator Frontier	Beam Physi... ...ators for Neutrinos, Accelerators for Electroweak and Higgs Physi... ...or Physics Beyond Colliders & Rare Processes, Advanced Accelerator ...&D: RF, Magnets, Targets/Sources
Instrumentation Fron...	...on Detectors, Solid State Detectors & Tracking, Trigger and DAQ, Micro Pattern Gas ...imetry, Electronics/ASICS, Noble Elements, Cross Cutting and System Integration, Radio Detection
Computational Fronti...	...xperimental Algorithm Parallelization, Theoretical Calculations and Simulation, Machine Learning, Storage and processing resource access (Facility and Infrastructure R&D), End user analysis
Underground Facilities and Infrastructure Frontier	Underground Facilities for Neutrinos, Underground Facilities for Cosmic Frontier, Underground Detectors
Community Engagement Frontier	Applications & Industry, Career Pipeline & Development, Diversity & Inclusion, Physics Education, Public Education & Outreach, Public Policy & Government Engagement
Snowmass Early Career	to represent early career members and promote their engagement in the Snowmass 2021 process; to build a long-term HEP early career community

30 Frontier conveners, ~250 Topical Group conveners,
>40 Inter-Frontier Liaisons, ~25 Early Career Liaisons.

Broad coverage/connection in science and global community!

Snowmass 2021 activities kicked off

April 18 - 21, 2020 (APS April Meeting, DC, virtual)

- ~ 300 participants
- All frontiers / liaisons joined the preparatory activities

Snowmass Community Planning Meeting

Oct. 5-8, 2020 (FNAL, virtual)

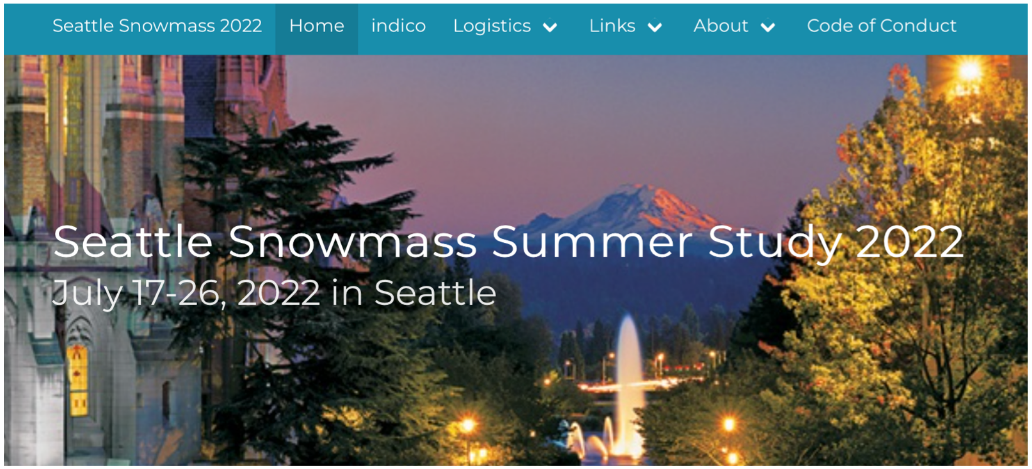
- ~ 3,000 people registered !
- 63 submissions to the "Voices from the Community"
- 25 Plenary speakers; 5 "Future Facilities" panelists
- 101 Breakout sessions
- 1,574 LOIs considered
- Call for contributed (white) Papers by March 2021

Heading to Community Summer Study (CSS) →
Snowmass 2021 in July 2021 @ UW-Seattle !
But the COVID-19 pandemic hit hard
→ Snowmass slowdown/paused for 8 months!

Community Summer Study (CSS): Snowmass 2021

July 17 – 26, 2022 @ UW – Seattle

http://seattlesnowmass2021.net



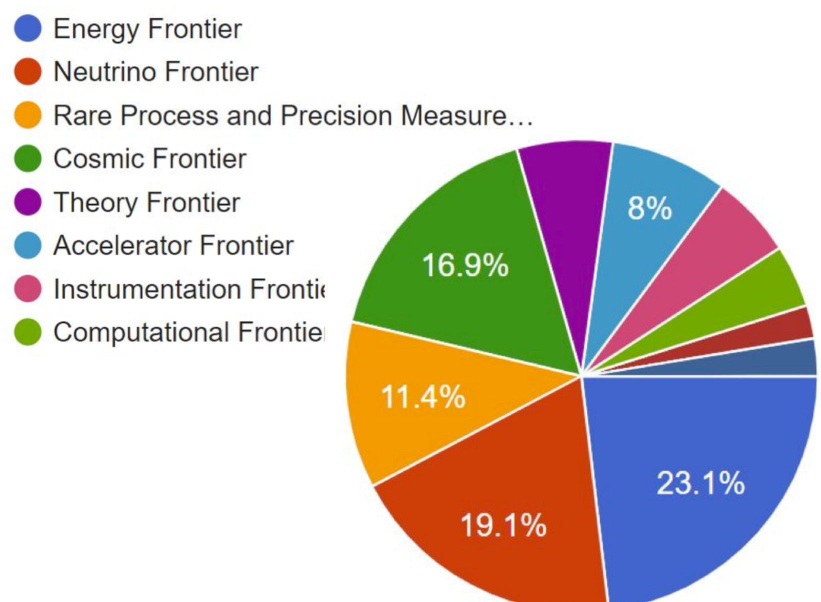
Participants

Number of in-person participants: 743

Number of virtual participants: 654

Local Organizing Committee/Volunteer/Press: 58

Total number of participants: 1397



Gordon Watts

Shih-Chieh Hsu

NOTE: This schedule is not yet final	Saturday, July 16	Sunday, July 17	Monday, July 18	Tuesday, July 19	Wednsday, July 20	Thursday, July 21	Friday, July 22	Saturday, July 23	Sunday, July 24	Monday, July 25	Tuesday, July 26
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
7:30 AM		Registration									
8:00 AM			Parallel	Parallel	Parallel	Parallel	Parallel	Parallel		Snowmass Summary (Program under development)	National Study
8:30 AM											NAS EPP Decadal study
9:00 AM		Introductory Plenary									Snowmass Summary (Program under development)
9:30 AM											
10:00 AM									Parallel		
11:00 AM											
12:00 PM		Lunch	Lunch, Poster & Exhibit	Lunch, Poster & Exhibit	Lunch, Poster & Exhibit	Lunch	Lunch	Lunch & Communicating HEP to the public and the govt.	Lunch	Lunch	Closing Remarks
1:00 PM											
2:00 PM		Introductory Plenary	Parallel 1: AI/ML Parallel 2: Underground	Panel: Careers and Training the Next Generations	Parallel 1: Neutrino Parallel 2: Rare processes	Colloquium on Rare Processes and Precision Measurements	Colloquium on Underground Physics	Colloquium on Energy Frontier Physics	Presentation: Snowmass Early Career	Panel: Interconnections with other fields	
3:00 PM											
3:30 PM			Parallel 1: The next accelerators Parallel 2: LQCD	Parallel 1: Lepton Colliders Parallel 2: Cosmic	Colloquium on Instrumentation	Colloquium on new Accelerators and R&D	Colloquium on Theory	Colloquium on Computing	Parallel 1: Underrepresented Minorities Parallel 2: Instrumentation projects	Coffee	
4:00 PM		Coffee								Talks: National, International Leaders	
	Pre-Registration	Planning US HEP: past, present, future									
5:00 PM			Coffee	Coffee		Coffee	Coffee	Coffee	Coffee		
			DEI: Talks and Panel	Colloquium on Community Engagement		Colloquium on Cosmic Frontier Probes of Fundamental Physics	Colloquium on Neutrino Physics	Quantum Information Science in HEP	talks DOE, NSF, FNAL Director, other US labs	Panel International Status and Plans	
6:00 PM											
7:00 PM			Reception & Poster & Industry Partners								
				stry Networkng	Adam Riess Public Lecture	Physics Slam		Colliderscope			
8:00 PM							Conference Dinner				
9:00 PM											

As Snowmass 2021 is wraping up: My overview

Path ahead:

- High Energy frontier & Accelerator technology
- Neutrino frontier
- Precision and rare processes
- Cosmic frontier
- Theory frontier

- Computational frontier
- Instrumentation & Detector technology
- Underground labs
- Community engagement
- Plus: Snowmass early career group

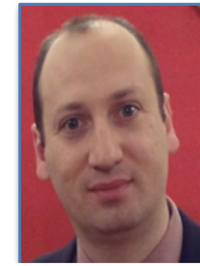
Energy Frontier

EF will explore the TeV energy scale and beyond. Our sharply focused agenda includes understanding the heaviest particles of the Standard Model (SM), as well as exploring physics beyond the SM to discover new particles and interactions, including unraveling the mystery of dark matter.

Co-Conveners

Meenakshi Narain (Brown U)

Laura Reina (FSU)



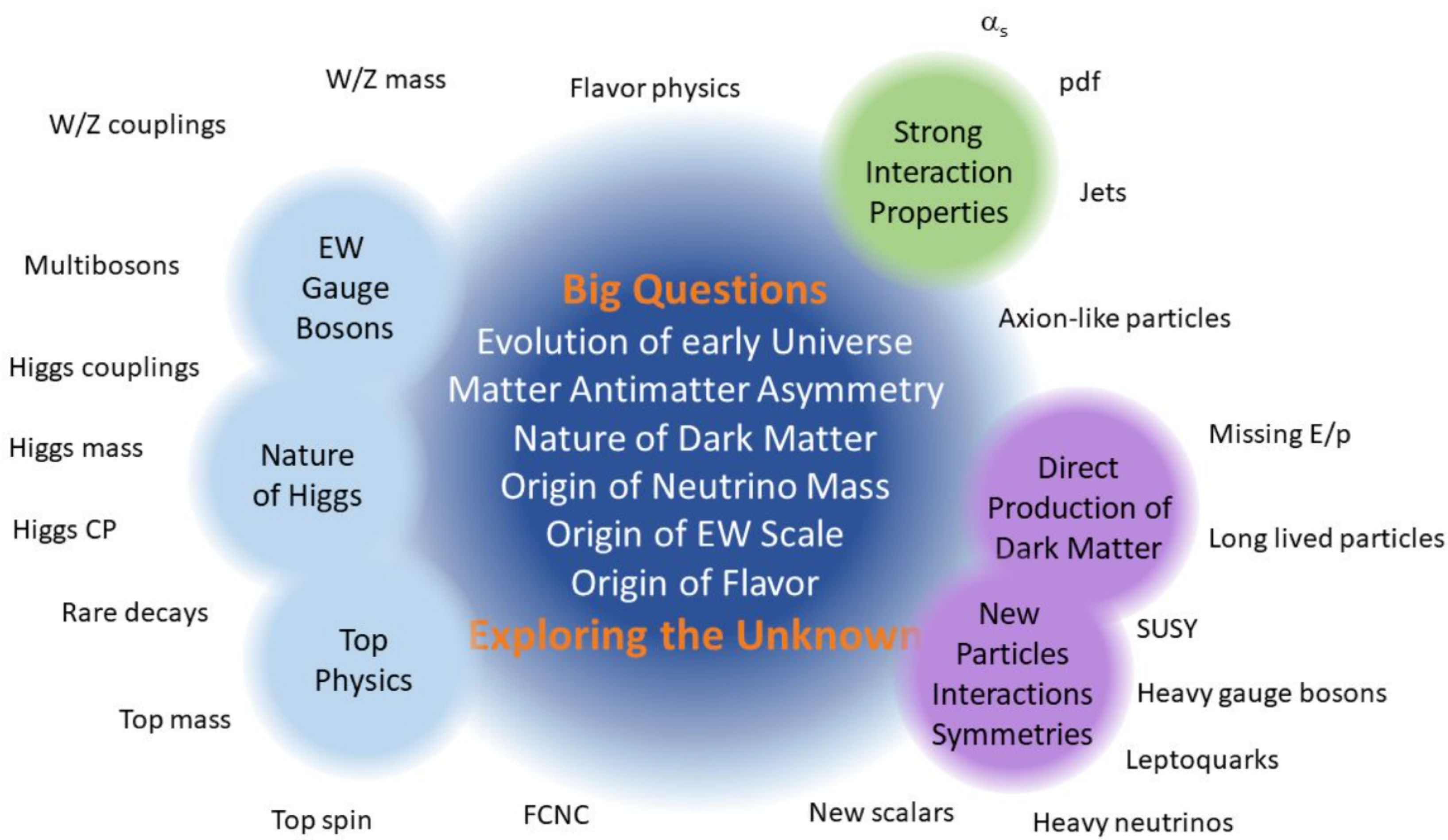
Alessandro Tricoli (BNL)

Topical Group			Topical Group co-Conveners		
EF01	EW Physics	Higgs Boson properties and couplings	Sally Dawson (BNL)	Andrey Korytov (U Florida)	Caterina Vernieri (SLAC)
EF02	EW Physics	Higgs Boson as a portal to new physics	Patrick Meade (Stony Brook)	Isobel Ojalvo (Princeton)	
EF03	EW Physics	Heavy flavor and top quark physics	Reinhard Schwienhorst (MSU)	Doreen Wackeroth (Buffalo)	
EF04	EW Physics	EW Precision Phys. & constraining new phys.	Alberto Belloni (Maryland)	Ayres Freitas (Pittsburgh)	Junping Tian (Tokyo)
EF05	QCD and Strong Interactions	Precision QCD	Michael Begel (BNL)	Stefan Hoeche (FNAL)	Michael Schmitt (NW)
EF06	QCD and Strong Interactions	Hadronic structure and forward QCD	Huey-Wen Lin (MSU)	Pavel Nadolsky (SMU)	Christophe Royon (Kansas)
EF07	QCD and Strong Interactions	Heavy Ions	Yen-Jie Lee (MIT)	Swagato Mukherjee (BNL)	
EF08	BSM	Model specific explorations	Jim Hirschauer (FNAL)	Elliott Lipeles (UPenn)	Nausheen Shah (Wayne State)
EF09	BSM	More general explorations	Tulika Bose (UW-Madison)	Zhen Liu (Maryland)	Simone Griso (LBL)
EF10	BSM	Dark Matter at colliders	Caterina Doglioni (Lund)	LianTao Wang (Chicago)	Antonio Boveia (Ohio State)

Energy Frontier

Energy Frontier: explore the TeV energy scale and beyond

Through the breadth and multitude of collider physics signatures



Energy Frontier

Energy Frontier Machines

Discoveries at the Energy Frontier are enabled by the development of new accelerators and detector instrumentation.

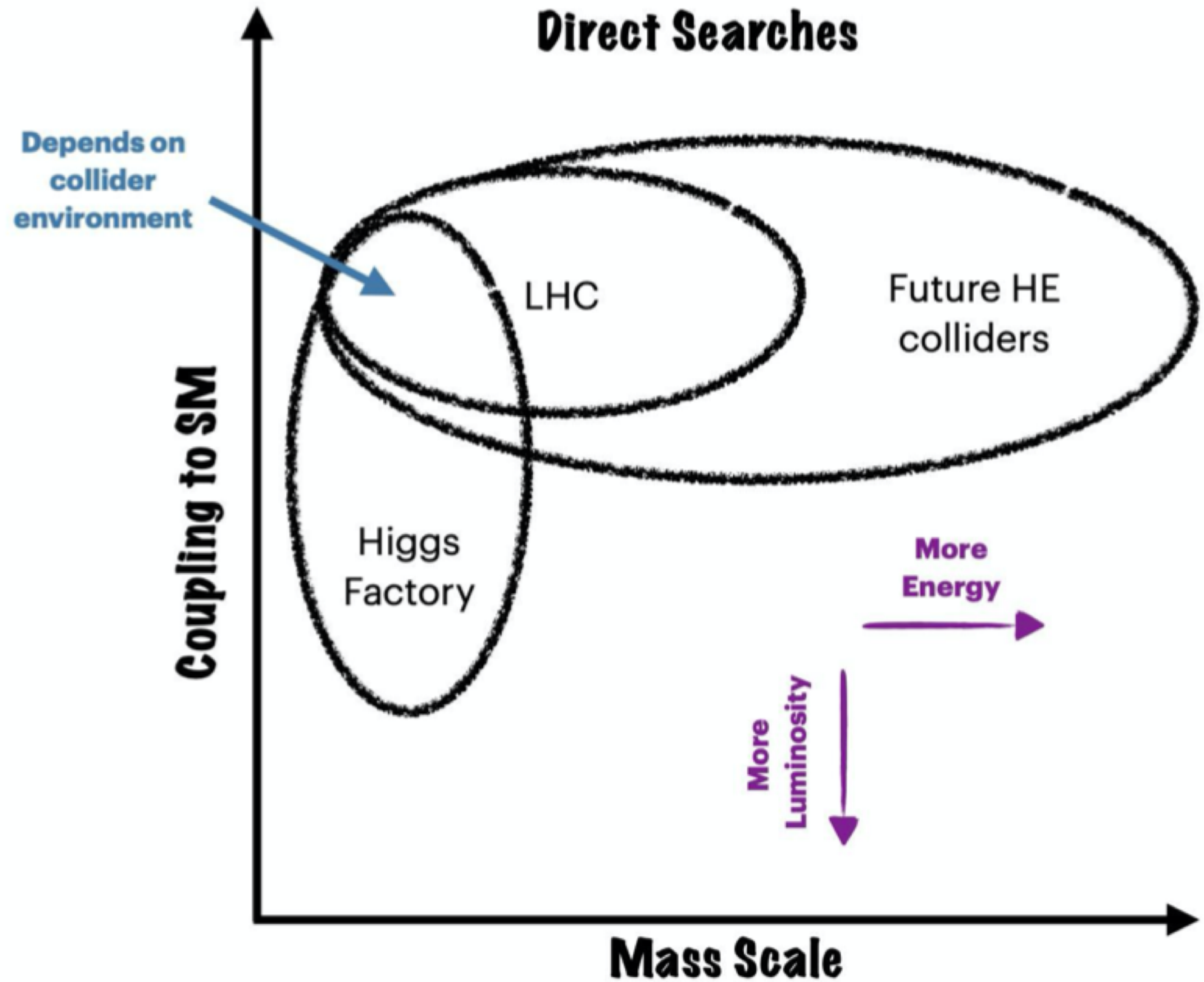
EF explorations should proceed along **two main complementary directions:**

- **Study known phenomena at high energies looking for indirect evidence of BSM physics**
  - Need factories of Higgs bosons (and other SM particles)
  - Need high precision to probe the TeV scale and beyond

  → **Need both luminosity and energy**

- **Search for direct evidence of BSM physics at the energy frontier**
  - Need to explore the multi-TeV scale → **Need energy**
  - Need to explore what LHC/HL-LHC may have difficulty exploring → **Need luminosity**

Energy Frontier



Accelerator Frontier

AF activities include discussions on high-energy hadron and lepton colliders, high-intensity beams for neutrino research and for the “Physics Beyond Colliders”, accelerator technologies, science, education and outreach.

Co-Conveners

Steve Gourlay (LBNL)

Tor Raubenheimer (SLAC)

Vladimir Shiltsev (FNAL)

Topical Group		Topical Group co-Conveners		
AF01	Beam Phys & Accel. Education	Z. Huang (Stanford)	M. Bei (GSI)	S. Lund (MSU)
AF02	Accelerators for Neutrinos	J. Galambos (ORNL)	B. Zwaska (FNAL)	G. Arduini (CERN)
AF03	Accelerators for EW/Higgs	M. Ross (SLAC)	Q. Qin (IHEP, Beijing)	Georg Hoffstaetter (Cornell)
AF04	Multi-TeV Colliders Jingyu Tang (IHEP)	M. Palmer (BNL)	A. Valishev (FNAL)	N. Pastrone (INFN, Torino)
AF05	Accelerators for PBC and Rare Processes	E. Prebys (UC Davis)	M. Lamont (CERN)	Richard Milner (MIT)
AF06	Advanced Accelerator Concepts	C. Geddes (LBNL)	M. Hogan (SLAC)	P. Musumeci (UCLA)
AF07	Accelerator Technology R&D			
	Sub-group RF	E. Nanny (SLAC)	S. Posen (FNAL)	H. Weise (DESY)
	Sub-Group Magnets	G. Sabbi (LBNL)	S. Zlobin (FNAL)	S. Izquierdo Bermudez (CERN)
	Sub-Group Targets/Sources	C. Barbier (ORNL)	Y. Sun (ANL)	F. Pellemoine (FNAL)

Implementation Task Force (ITF) established

What Machine?

Hadrons

- large mass reach ⇒ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇒ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇒ measurement?
- polarized beams (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇒ EW couplings

Circular

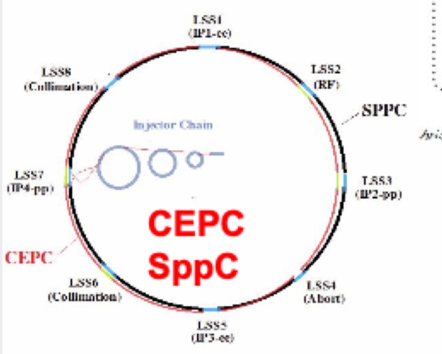
- higher luminosity
- several interaction points
- precise E-beam measurement (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchroton radiation

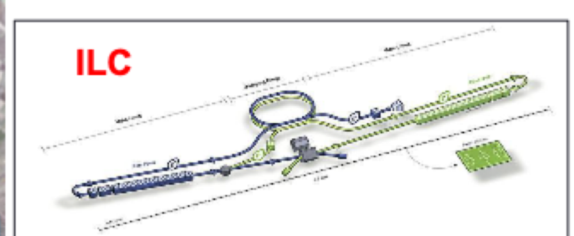
Linear

- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

Christophe Grojean   Future Measurements   4   Inst. Pascal, Dec. 4, 2019





- Added C^3
- Gamma-gamma?
- Advanced colliders?

ITF report:

(ITF = Implementation Task Force @ AF)

Higgs-boson factories
(up to 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3 c.o.m almost similar	ee	250 GeV	$\pm 80/\pm 30$	2
		350 GeV	$\pm 80/\pm 30$	0.2
		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Multi-TeV colliders
(> 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV		15
FCC-hh/SppC	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5
		3.0 TeV	$\pm 80/0$	5
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10

Timelines is taken from the ITF report from AF.

From the ITF Report Draft: Higgs factories

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	280
ILC-0.25	0.25	2.7	0-2	<12	7-12	110
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
FCChh-100	100	30	>10	>25	30-50	~560

FCCee: 2-4 IPs
all LCs: 1 IP

Disclaimer: luminosity and power consumption values have not been reviewed by ITF

Estimated Total Project Cost
No escalation
No contingency

NB: HELEN, C^3 m.b. 85% of ILC but in the same range category

From the ITF Report: HE colliders

Disclaimer: luminosity and power consumption values have not been reviewed by ITF

all LCs: 1 IP

MC-3/14: 2 IPs

FCChh: 2-4 IPs

Estimated

Total Project Cost

No escalation

No contingency

NB: broad ranges

	CME (TeV)	Lumi per IP	Years, pre-project	Years to 1st	Cost Range	Electric Power
CERC(ERL)	0.24	078	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-FNAL	6-10	20	>10	19-24	12-18	O(300)
MC-10-IMCC	10-14	20	>10	>25	12-18	O(300)
FCChh-100	100	30	>10	>25	30-50	~560

NEUTRINO FRONTIER ORGANIZATION

- Conveners:
  - Patrick Huber (Virginia Tech)
  - Kate Scholberg (Duke)
  - Elizabeth Worcester (BNL)



- Topical Groups
  - NF01: Neutrino Oscillations
  - NF02: Understanding Experimental Neutrino Anomalies
  - NF03: Beyond the SM
  - NF04: Neutrinos from Natural Sources
  - NF05: Neutrino Properties
  - NF06: Neutrino Interaction Cross Sections
  - NF07: Applications
  - NF08→TF11: Neutrino Theory
  - NF09: Artificial Neutrino Sources
  - NF10: Neutrino Detectors
  - +liaisons to all other frontiers & SEC

See NF wiki – https://snowmass21.org/neutrino/start – for names of topical group conveners, names of liaisons, report drafts, and all things NF

The science drivers for NF

- What are the neutrino masses?
- Are neutrinos their own antiparticles?
- How are the masses ordered?
- What is the origin of neutrino mass and flavor?
- Do neutrinos and antineutrinos oscillate differently?
- Discovering new particles and interactions
- Neutrinos as messengers

Significant growth in activity since last Snowmass

MAJOR THEMES IN NEUTRINO FRONTIER

- A defining and somewhat unique aspect of NF is breadth and balance of effort across a wide range of physics topics, timescales, sizes, and costs, with significant need for collaboration with other frontiers and across boundaries of what is typically considered particle physics
- Physics beyond the (3-neutrino) Standard Model is emerging as a major focus of NF – this includes investigation of anomalies in neutrino oscillation measurements, precision measurements of neutrino oscillation that are sensitive to new particles and interactions, and use of neutrino experiments to search for other new physics, such as dark matter
- Use of neutrinos as messengers carrying information about otherwise inaccessible systems, particularly as participants in multi-messenger astronomy, is a growing area of interest in NF

MAJOR THEMES IN NEUTRINO FRONTIER

- DUNE/LBNF is the largest project in the NF portfolio, with extensive investment from the US and international partners to make precision neutrino oscillation measurements as well as a broad program of astrophysics topics and BSM searches. Snowmass/P5 will be particularly focused on the 2nd phase of DUNE, which is necessary to achieve the full DUNE physics scope, and which also offers opportunities to expand the physics scope beyond that initially envisioned
- There is significant synergy with other frontiers/fields in detector, accelerator, and computing development
- Community engagement is critical for the success of NF
- Early career scientists are central to all of the ongoing and planned research in NF