Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Snowmass Energy and Accelerator Frontiers Activities

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Energy Frontier

- Like the rest of the Snowmass process limited activities between January 2021 and summer 2021

- Restarted strongly with Energy Frontier Workshop August 30 to September 3
  - https://indico.fnal.gov/event/49756/

- Week-long set of meetings and discussions about the Energy Frontier Snowmass progress, developments and future
  - Including extensive interactions between Energy Frontier and Accelerator Frontier

Recent Energy Frontier Workshop

EST time	Mon	Tue	Wed	Thur	Fri
10 -11 am	Plenary (Organisaion&Plans, EF Highlights, MC production)	Plenary (Theory needs and Progress in Accelerators)	Parallels C (a - EF01+EF02, b - EF05+EF06)	Parallels F (a - EF01+EF03+EF04, b - EF05 and EF06)	Plenary (TG Highlights)
11 -12 pm	Parallels (Global EFT Fits)	Plenary (Emerging Future Collider Projects and Progress in Instrumentation)	Parallels D (a - EF01+EF02, b - EF08+EF09)	Parallel G (a - EF07, b - EF01+EF03+EF04)	Plenary (TG Highlights)
12 -12:30 pm		Break			
12:30 - 1:00pm	Break				
1:00 - 1:30 pm		Parallels B (a - Session about dark matter summary plots, b - Session with CompF)	Parallels E (a - EF03, b- EF08+F09)	Parallels H (a - EF03+EF06, b - EF10)	Plenary (TG Highlights)
1:30 - 2:30 pm	Plenary (Physics Anomalies and Progress in Instrumentation)				
2:30 - 3 pm	Break	Break			
3 - 4:30 pm	Unstructured Discussions (Discussion with CEF (government outreach and funding)	Unstructured Discussions (Discussion with AF - Muon Collider and new ideas)	Unstructured Discussions (Discussion with AF - e+/e- and hadron colliders, HL-LHC)	Unstructured Discussions (Discussion with AF: advanced acceleration concepts and the collider options)	Unstructured Discussions (Report preparation - result presentation, e.g. plots, tables etc.)

Very close cooperation with Accelerator Frontier

Energy Frontier Groups

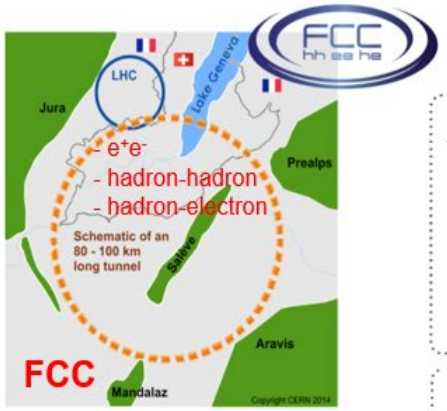
Topical Group	Co-Conveners
EF01: EW Physics: Higgs Boson properties and couplings	Sally Dawson (BNL), Andrey Korytov (U Florida), Caterina Vernieri (SLAC)
EF02: EW Physics: Higgs Boson as a portal to new physics	Patrick Meade (Stony Brook), Isobel Ojalvo (Princeton)
EF03: EW Physics: Heavy flavor and top quark physics	Reinhard Schwienhorst (MSU), Doreen Wackeroth (Buffalo)
EF04: EW Physics: EW Precision Physics and constraining new physics	Alberto Belloni (Maryland), Ayres Freitas (Pittsburgh), Junping Tian (Tokyo)
EF05: QCD and strong interactions: Precision QCD	Michael Begel (BNL), Stefan Hoeche (FNAL), Michael Schmitt (Northwestern)
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), Elliot Lipeles (UPenn), Nausheen Shah (Wayne State)
EF09: BSM: More general explorations	Tulika Bose (U Wisconsin), Zhen Liu (Maryland), Simone Pagan-Griso (LBL)
EF10: BSM: Dark Matter at colliders	Caterina Doglioni (Lund), LianTao Wang (Chicago)

Energy Frontier

- Address main questions of particle physics and science in general
  - In depth understanding of the Standard Model
    - And its limits
  - Study properties of the Higgs boson
  - Understand matter-antimatter asymmetry of the Universe
  - What is the dark matter?
  - How the world behaves at the smallest and largest distances we can study?
  - What new particles and interactions exists at even higher collision energies?

All the above relies heavily on the new high energy colliders!

Many Exciting Options…



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

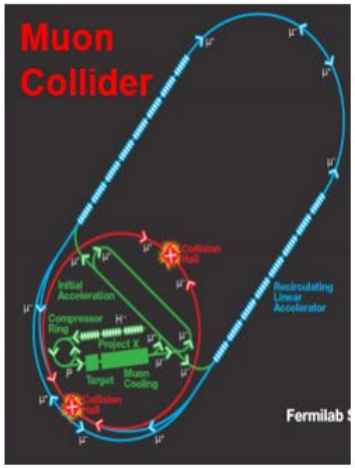
Circular

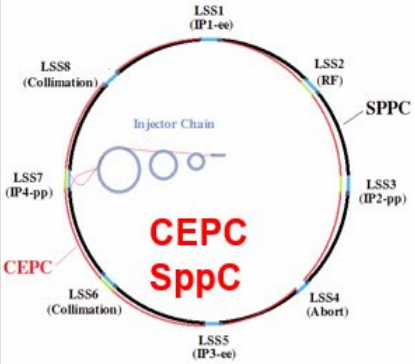
- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
  - $\sqrt{s}$ limited by synchroton radiation

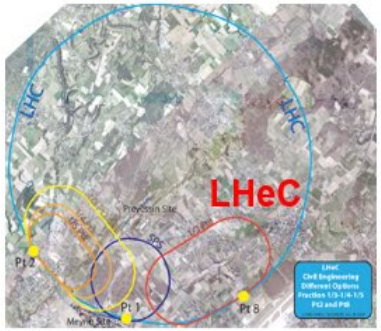
Linear

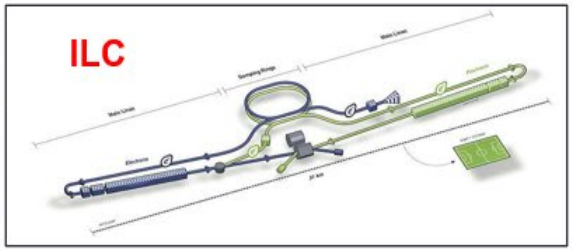
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
  - large beamsthralung
  - one IP only

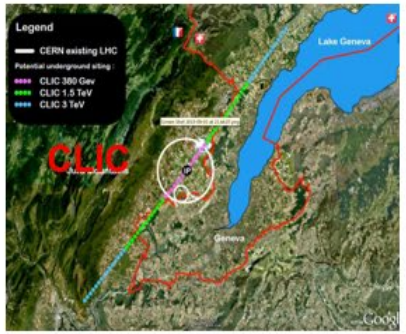
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders











- gamma-gamma colliders?

Challenges

- We are not building energy frontier colliders for ~30 years

- Two main challenges
  - New colliders are not cheap
  - There is no single ”best” option for the future collider

Recent Developments

- Renewed interest in a muon collider
  - Higgs factory
  - Next energy frontier collider
    - Effective partonic collision energy of the muon collider is much higher vs the same energy hadron collider
  - Snowmass formed “Muon Collider Forum”
- Active developments around the globe
  - CERN/Europe
  - Japan
  - China
- Re-thinking options for colliders in US
  - Fermilab’s site fillers

Accelerator Benchmark Parameters

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV 350 GeV 500 GeV 1 TeV	±80/±30 ±80/±30 ±80/±30 ±80/±20	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	±80/0 ±80/0 ±80/0	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV 2 M_{top}		150 10 5 1.5

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
FCC-hh	pp	100 TeV		30
LHeC FCC-eh	ep ep	1.3 TeV 3.5 TeV		1 2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV 10 TeV 14 TeV 30 TeV		1 10 20 90

Note for muon-collider: It is important to note that the plan is not to run subsequently at the various c.o.m etc. These are reference points to explore and assess the physics potential and technology. The luminosity can be varied to determine how best to exploit the physics potential.

- Other options to explore
  - Muon collider at a very high energy (>30 TeV)
  - FCCpp >150 TeV and ~75 TeV
  - Very high energy e^+e^- collider
  - Other emerging ideas: γγ collider, and the C3 e^+e^- collider (C3=Cool Copper Collider)

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Fermilab's Site Fillers

Circumference ≳16 km

1. e+e- Site Filler Higgs Factory
2. Muon Collider Higgs Factory
3. Muon Collider 3-8 TeV
4. pp Site Filler Collider 24-28 TeV

Linear ~ 7 km

Higgs Factories +

1. C3 (Cool Copper) linear collider
2. NC RF (CLIC-K) Collider
3. SRF-TW linear collider

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Close Interactions with Accelerator Frontier Implementation Task Force

- Led by Thomas Roser
- Document/compare options for future colliders
  - Including energy, luminosity, cost, power consumption, etc.

Higgs factory concepts / proposals

Name	Details	POC	AF Group
CepC	e+e-, $\sqrt{s} = 0.24$ TeV, L= 3.0×10^{34}	Jie Gao (gaoj@ihep.ac.cn)	AF3
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.38$ TeV, L= 1.5×10^{34}	Steinar Stapnes (Steinar.Stapnes@cern.ch)	AF3
Circular ERL ee collider	e+e-, $\sqrt{s} = 0.24$ TeV, L= 73×10^{34}	Thomas Roser (roser@bnl.gov)	AF3
FCC-ee	e+e-, $\sqrt{s} = 0.24$ TeV, L= 17×10^{34}	Katsunobu Oide (katsunobu.oide@ern.ch)	AF3
gamma gamma	X-ray FEL-based $\gamma\gamma$ collider	Tim Barklow (timb@slac.stanford.edu)	AF3
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.25$ TeV, L= 1.4×10^{34}	Shin-ichi Michizono (shinichiro.michizono@kek.jp	AF3
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 0.1×10^{34}	Oliver Bruening (oliver.bruening@cern.ch)	AF3
MC (Higgs factory)	$\mu\mu$, $\sqrt{s} = 0.13$ TeV, L= 0.01×10^{34}	Mark Palmer (mpalmer@bnl.gov)	AF3

High Energy Concepts/Proposals

Name	Details	POC	AF Group
Cryo-Cooled Copper (C^3) linac	e+e-, $\sqrt{s} = 2$ TeV, L= 4.5×10^{34}	Emilio Nanni (nanni@slac.Stanford.edu)	AF3
High Energy CLIC	e+e-, $\sqrt{s} = 1.5 - 3$ TeV, L= 5.9×10^{34}	S.Stapnes (steinar.stapnes@cern.ch)	AF4
High Energy ILC	e+e-, $\sqrt{s} = 1 - 3$ TeV	Hassan Padamsee (hsp3@cornell.edu)	AF4
FCC-hh	pp, $\sqrt{s} = 100$ TeV, L= 30×10^{34}	M.Benedikt (Michael.Benedikt@cern.ch)	AF4
SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10×10^{34}	J.Tang (tangjy@ihep.ac.cn)	AF4
Collider-in-Sea	pp, $\sqrt{s} = 500$ TeV, L= 50×10^{34}	P.McIntyre mcintyre@physics.tamu.edu	AF4
Gamma-gamma	??	W.Krasny (mieczyslaw.witold.krasny@cern.ch)	AF4
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 1×10^{34}	Oliver Bruening (oliver.bruening@cern.ch)	AF4
FCC-eh	ep, $\sqrt{s} = 3.5$ TeV, L= 1×10^{34}	Oliver Bruening (oliver.bruening@cern.ch)	AF4
CEPC-SPPpC-eh	ep, $\sqrt{s} = 6$ TeV, L= 4.5×10^{33}	Y.Zhang (yzhang@jlab.org)	AF4
VHE-ep	ep, $\sqrt{s} = 9$ TeV		AF4
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s} = 1.5$ TeV, L= 1×10^{34}	D.Schulte (daniel.schulte@cern.ch)	AF4
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s} = 3$ TeV, L= 2×10^{34}	D.Schulte (daniel.schulte@cern.ch)	AF4
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20×10^{34}	D.Schulte (daniel.schulte@cern.ch)	AF4
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20×10^{34}	D.Schulte (daniel.schulte@cern.ch)	AF4
LWFA-LC (e+e- and $\gamma\gamma$)	Laser driven plasmas; e+e-, $\sqrt{s} = 1 - 30$ TeV	Carl Schroeder (CBSchroeder@lbl.gov)	AF6
PWFA-LC (e+e- and $\gamma\gamma$)	Beam driven plasmas; e+e-, $\sqrt{s} = 1 - 30$ TeV	Gessner, Spencer J. (sgess@slac.edu)	AF6
SWFA-LC	Structure wakefields; e+e-, $\sqrt{s} = 1 - 30$ TeV	Chunguang Jing (jingchg@anl.gov)	AF6

Summary

- Energy Frontier works closely with Accelerator Frontier on multiple topics
  - The goal is the submission of Snowmass reports for the future energy frontier colliders and/or related R&D

- Excellent progress since the resumption of Snowmass activities
  - Continuing development of mature proposals
  - New options are under development, including Fermilab's site fillers
  - Muon collider forum started full-scale activities
  - Implementation Task Force is making excellent progress