Energy Frontier Workplan

Snowmass Community Summer Study (CSS)

Seattle, July 17-26, 2022

Laura Reina (FSU), Meenakshi Narain (Brown U.), Alessandro Tricoli (BNL)

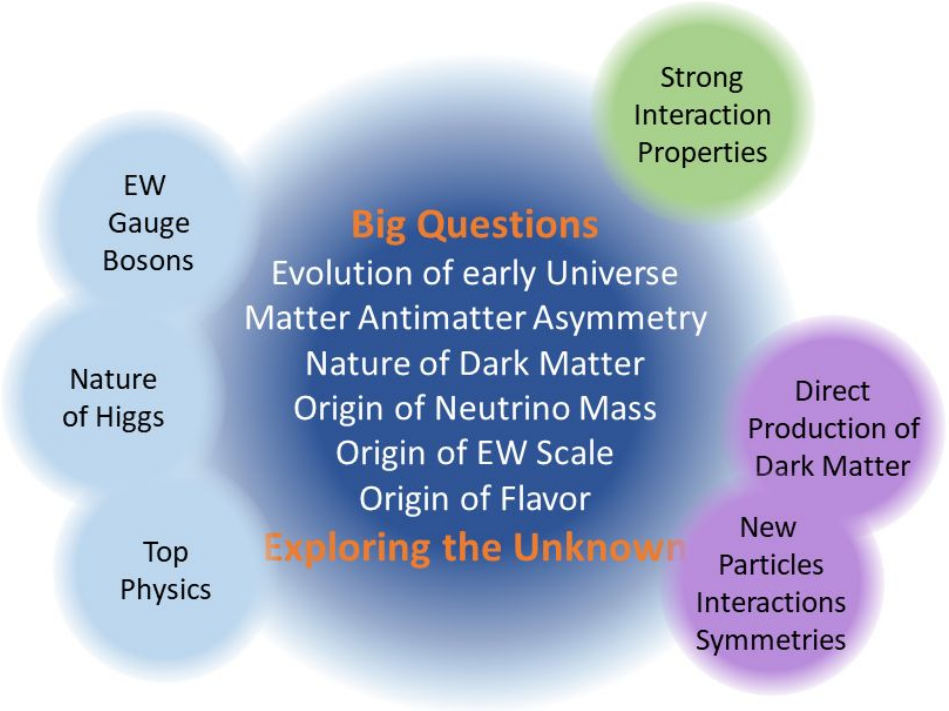
Snowmass EF wiki: https://snowmass21.org/energy/start

Energy Frontier: explore the TeV energy scale and beyond

to answer still open Big Questions and Explore the Unknown

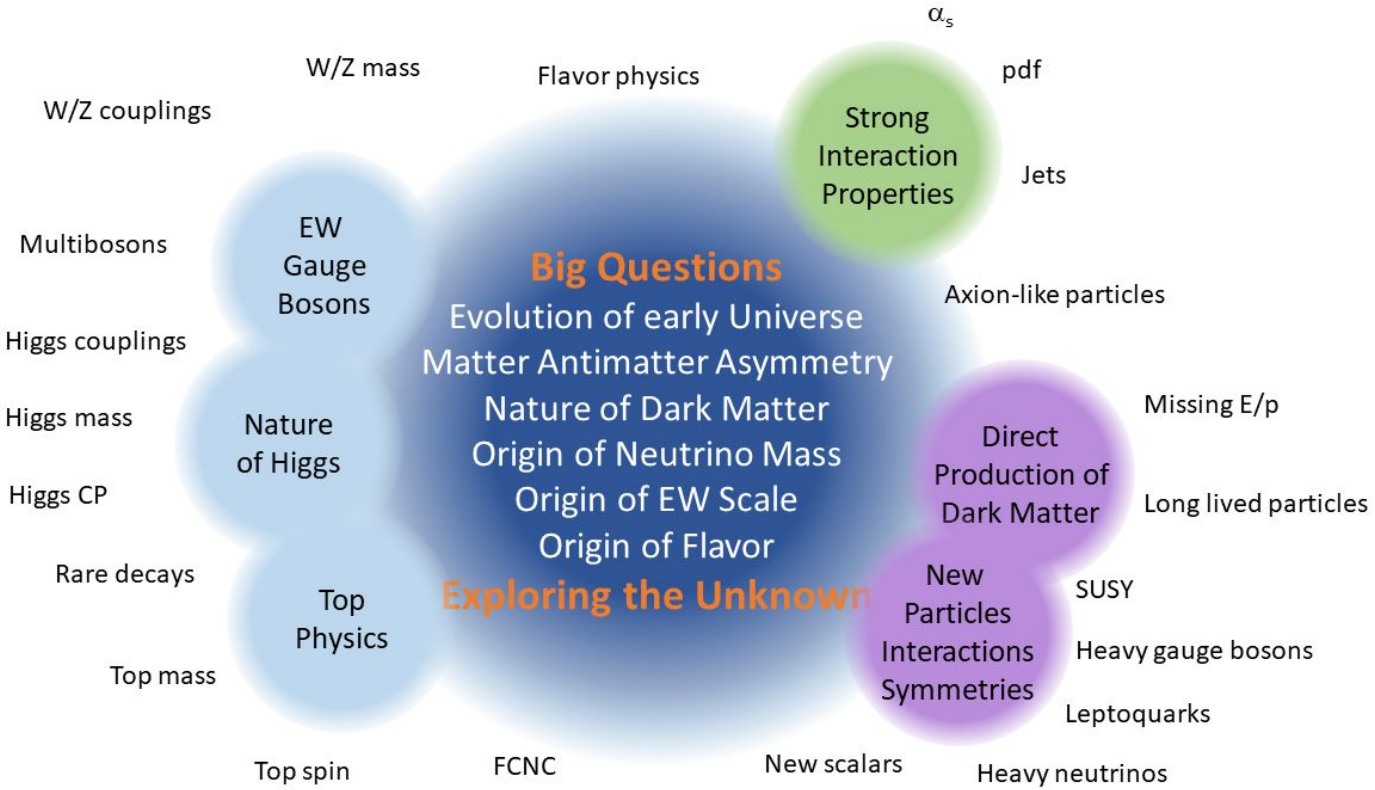
Energy Frontier: explore the TeV energy scale and beyond

Using Standard Model and Beyond Standard Model probes



Energy Frontier: explore the TeV energy scale and beyond

Through the breadth and multitude of collider physics signatures



Big Picture Questions
set at the beginning of Snowmass

- Why is physics at the energy frontier important?
- How should the US be involved in near future and far future energy-frontier machines after HL-LHC?
- What could be the energy-frontier machines that follow the HL-LHC?
- How can the US continue to play a leadership role in energy-frontier experiments?
- How can the Snowmass process help develop a plan for the energy-frontier research and convince the community about our priorities?
- Should we start entertaining the idea of a future collider in the US again? If so, what are our goals, the benefits for the US and the international community, and how can we get there?
- etc...

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**

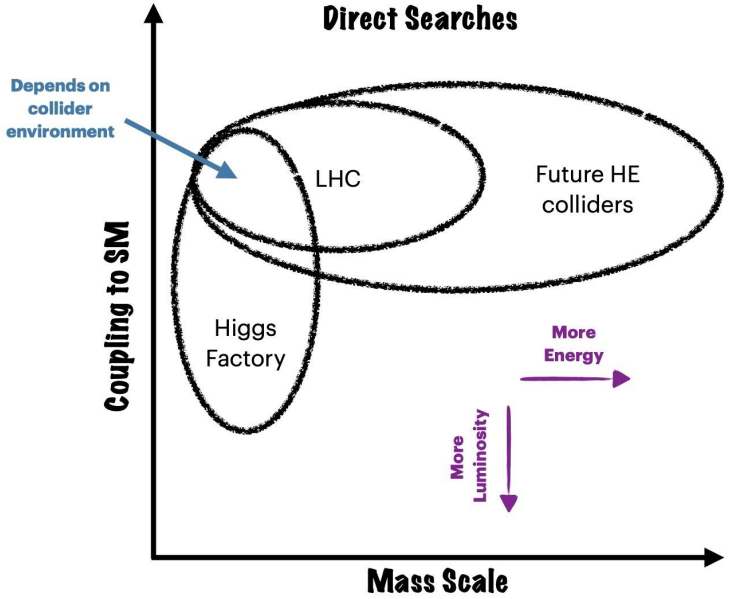
- **Search for direct evidence of BSM physics at the energy frontier**
  - Need to explore the multi-TeV scale → **Need energy**
  - Need to explore what LHC/HL-LHC may have difficulty exploring → **Need luminosity**

Energy Frontier Machines: energy and precision

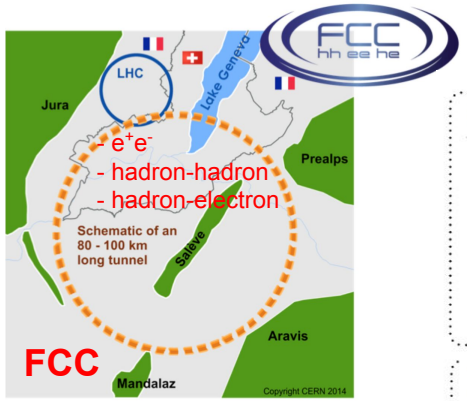
New physics can be at low and at high mass scales: Naturalness would prefer mass scale close to the EW scale, but direct searches of specific models have placed stronger bounds around 1-2 TeV.

Depending on the mass scale of new physics and the type of collider, the primary method for discovery new physics can vary.

We need to use both energy and precision.



Which machines?



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

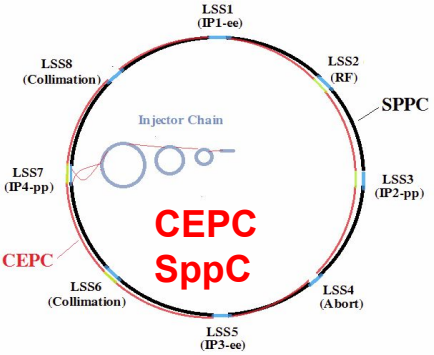
Circular

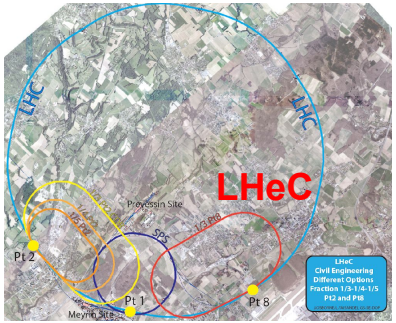
- higher luminosity
- several interaction points
- precise E-beam measurement (O(0.1MeV) via resonant depolarization)
  - $\sqrt{s}$ limited by synchroton radiation

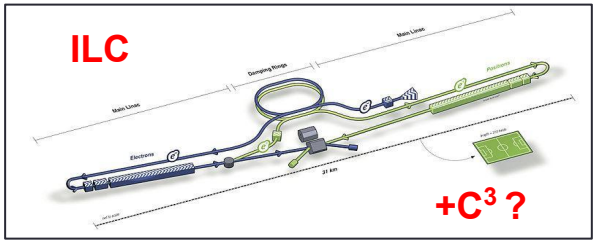
Linear

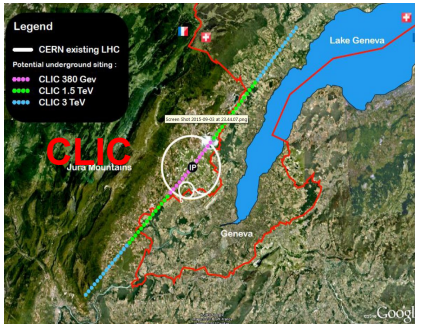
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
  - large beamsthralung
  - one IP only

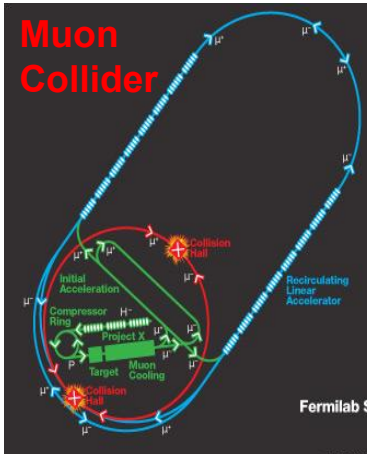
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders











Christophe Grojean — Future Measurements — 9 — Inst. Pascal, Dec. 4, 2019

Snowmass 2021:
EF Benchmark Scenarios

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

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ $\rm ab^{-1}$
HL-LHC	pp	14 TeV		6
ILC and C^3	ee	250 GeV	$\pm 80/\pm 30$	2
c.o.m almost		350 GeV	$\pm 80/\pm 30$	0.2
similar		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

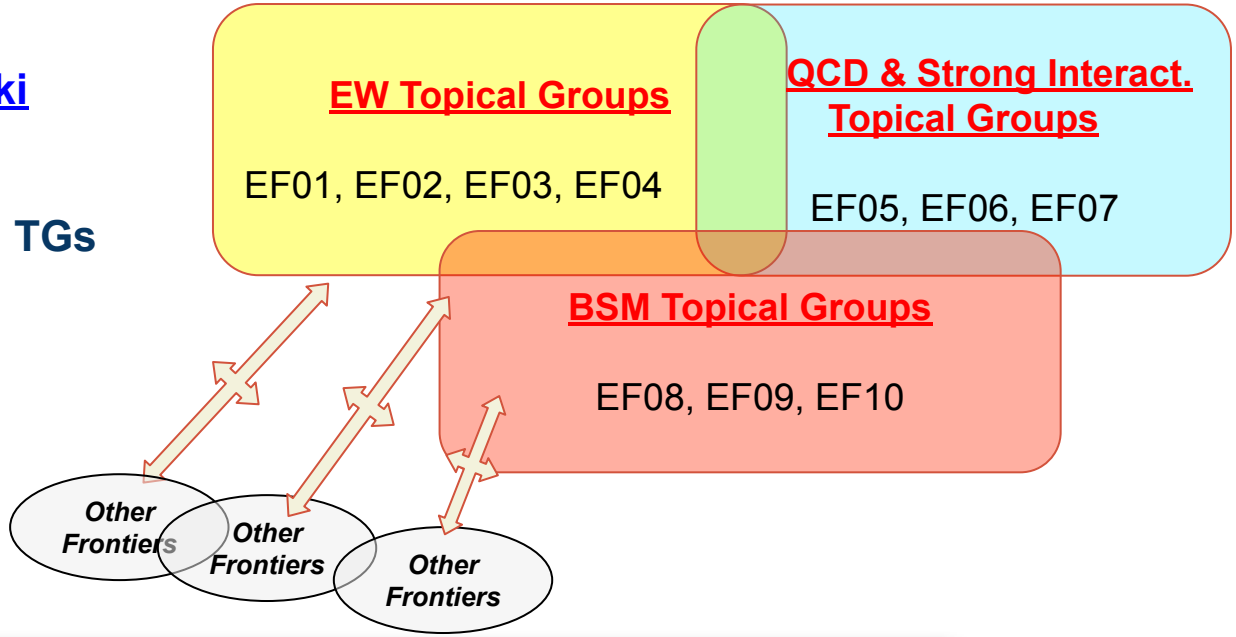
Multi-TeV colliders
(> 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\rm int}$ $\rm ab^{-1}$
HE-LHC	pp	27 TeV		15
FCC-hh	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

Topical Group Activities

- General Energy Frontier Wiki
- Electroweak TGs
  - EF01, EF02, EF03, EF04
- QCD and Strong Interaction TGs
  - EF05, EF06, EF07
- BSM TGs
  - EF08, EF09, EF10



Multiple Activities

- See Topical Group Wiki pages and indico meeting agendas for details of ongoing activities
- EF calendar and communications via mailing lists and Slack

The Energy Frontier Group (I)

- **EF Convenors**: *Laura Reina (FSU), Meenakshi Narain (Brown U.), Alessandro Tricoli (BNL)*
- **10 Topical Groups (TGs)**:

Topical Group	Co-Conveners
EF01: EW Physics: Higgs Boson properties and couplings	**Sally Dawson (BNL), 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), Antonio Boveia (Ohio State)**

The Energy Frontier Group (II)

Other Frontier	Liaisons
Neutrino Physics Frontier	André de Gouvêa (Northwestern)
Rare Processes and Precision	Manuel Franco Sevilla (Maryland)
Cosmic Frontier	Caterina Doglioni (Lund), Antonio Boveia (Ohio State)
Theory Frontier	Laura Reina (FSU)
Accelerator Frontier	Dmitri Denisov (BNL), Meenakshi Narain (Brown)
Computational Frontier	Peter Onyisi (U.Texas)
Instrumentation Frontier	Caterina Vernieri (SLAC), Maksym Titov (CEA Saclay)
Community Engagement Frontier	Daniel Whiteson (UCI), Sergei Gleyzer (Alabama)

Muon Collider Forum Coordinators

EF: **Kevin Black** (U. Wisconsin-Madison), **Sergo Jindariani** (Fermilab)
AF: **Derun Li** (LBNL), **Diktys Stratakis** (Fermilab)
TF: **Patrick Meade** (Stony Brook U.), **Fabio Maltoni** (Louvain U., Bologna)

e+e- Collider Forum Coordinators

EF: **Maria Chamizo Llatas** (BNL), **Sridhara Dasu** (Wisconsin)
AF: **Emilio Nanni** (SLAC), **John Power** (ANL)
IF: **Ulrich Heintz** (Brown), **Steve Wagner** (Colorado)

Early Career Representative

- **Grace Cumming** (U.Virginia)
- **Matt Le Blanc** (U.Arizona)

Monte Carlo task force and production team

Coordinated by **John Stupak** (U. Oklahoma)
1) Assess the MC needs ⇒ **"Task force"**
2) Produce MC samples ⇒ **"Production Team"**

LOI's and Contributed Papers

- **Letters of Intent (LOI) submitted to EF**
  - **376 received** - see list here
  - **268 have EF as primary**
  - **Cross-frontier LOIs**:
    TF (21), AF (20), IF(17), RF (16),
    CF (14), NF (11), CompF (9)
- **LOIs have contributed to shaping Topical Group activities**

- **149 Contributed Papers**
  - Some contributions were combined by TG convenors in single submissions
    ⇒ number of papers submitted to a TG is not a measure of effort/interest by community

EF Group	Contributed Papers
EF01 (SM Higgs)	20
EF02 (BSM Higgs)	8
EF03 (Top)	10
EF04 (EW)	13
EF05 (precision QCD)	2
EF06 (Had interaction & fwd QCD)	8
EF07 (Heavy Ions)	3
EF08 (Model specific BSM)	13
EF09 (Model independent BSM)	26
EF10 (DM)	14
EF General	32
TOTAL	149

Energy Frontier Meetings leading to CSS

2020

- Energy Frontier **Kick-off Meeting**, May 21, 2020, see agenda
- **Energy Frontier Workshop "Open Questions and New Ideas"**, July 20-22, 2020,
- **Snowmass CPM Meeting**: **EF Report** (Oct. 2020): focus points and key questions.

2021

- **EF slowed down activities in 2021 until June**
  - Community continued to work collaboratively
  - Monte Carlo production activities continued to support EF needs
  - Occasional and informal Topical Group 'conversations' to assure scientific continuity and support of ongoing activities
- **EF restart workshop** - August 30-Sep 3, 2021

2022 - Building towards the CSS and Reports

- **EF Workshop, Brown University. March 28 - April 1 2022**
  - Planning towards EF reports (frontier and Topical Group), Building EF vision
- **EF Topical Group Convener Meeting - FNAL - June 6-7 2022**
  - Formulating the EF report
- **EF Meeting with Representative of Future Project Proponents - Stony Brook U., June 13-15 2022**
  - Discussing EF vision
- **EF community meeting pre-CSS - June 24 2022 (virtual)**
  - Presenting draft of EF reports (frontier and Topical Group)

Snowmass Agora on Future Colliders

Series of events jointly organized by AF and EF, hosted by the Future Colliders initiative at Fermilab, to discuss both near and far future collider proposals, in different stages of development, synergistically grouped into five categories:

- **e+e- linear colliders** (Dec. 15, 2021): https://indico.fnal.gov/event/52161/
- **e+e- circular colliders** (Jan. 19, 2022) https://indico.fnal.gov/event/52534/
- **μ+μ- colliders** (Feb. 16, 2022): https://indico.fnal.gov/event/53010/
- **circular pp and ep colliders** (Mar 16, 2022): https://indico.fnal.gov/event/53473/
- **advanced colliders** (April 13, 2022): https://indico.fnal.gov/event/53848/

⇒ Critical discussions of physics reach, challenges and R&D required, synergies with global context and local resources, timeframe, cost projection.

EF Schedule at CSS

- All EF Sessions at CSS are summarised in this Sheet

In-depth discussions of Topical Group Results

Day	EF Parallel Session	Time	Room
Mon, 7-18	EF Strong Interactions I	8am-noon	238 MGH
Mon, 7-18	EF Higgs and BSM I	8am-noon	332 HUB
Wed,7-20	EF TOP I	8am-noon	210 Kane
Wed, 7-20	EF EWK I	8am-noon	130 Kane
Wed, 7-20	EF BSM II - non DM	8am-10 am	220 Kane
Thu, 7-21	EF EWK II	8am-12pm	210 Kane
Thur, 7-21	EF DM Discussion	10am-12pm	110 Kane
Fri, 7-22	EF BSM IV	8am-9am	102 JHN
Fri, 7-22	EF BSM V	9am-10am	022 JHN
Sat, 7-23	EF Discussion and Summaries (ie EF plenary)	8am-noon	130 Kane

Overview of EF Reports and discussion of EF Vision

Day	EF Plenary Session	Time	Room
Tue, 7-19	Lepton Colliders	3:30pm-5:00pm	120 Kane
Sat, 7-23	Physics on the Energy Frontier	2pm-3:30pm	130 Kane
Mon, 7-25	Panel: Physics Highlights from the Frontiers	8:00-9:30am	130 Kane
Tue, 7-26	Panel: Large Exp./Facilities & timelines	9:00-10:00am	130 Kane
Tue, 7-26	Panel: Mid/Small Exp./Facilities & timelines	10:30-11:30am	130 Kane

e+e- and muon colliders (motivations, status and discussions)

1) Physics case for Higgs Factories
2) Physics case for EF Multi-TeV colliders

Panel Discussions with presentation of EF Vision

XFrontier Discussions at CSS

- All EF Sessions at CSS are summarised in this Sheet

- Fri, 7-22, 12:30pm-1:45pm, ***"DOE Program Manager meeting: Energy Frontier"***

Day	XFrontier EF Session	Time	Room
Mon, 7-18	XF CEF Feedback	8am-noon	334 HUB
Mon, 7-18	XF: Report of the Accelerator Frontier Implementation Task Force (IF)	3:35pm-5pm	
Tue, 7-19	XF DM Complementarity	8am-noon	220 Kane
Tue, 7-19	XF Energy Frontier - Theory Frontier	8am-noon	175 JHN
Wed, 7-20	XF Long Lived Particles (RF-EF)	10am-noon	340 HUB
Thu, 7-21	XF Flavor anomalies and exotics at colliders	8am-10am	241 Kane
Thu, 7-21	XF EF-CompF Big Experiments	8am-10am	110 Kane
Thu, 7-21	XF Detectors and MDI and Plots (IF-EF-AF)	8am-12pm	337 HUB
Thu, 7-21	XF timing and tracking detectors (IF-EF-RF)	8am-10am	340 Kane
Thu, 7-21	XF CLFV and heavy states (RF-EF-AF)	10am-12pm	231 MGH
Thu, 7-22	XF Flavor anomalies & exotics (RF-EF-TF)	10am-12pm	241 MGH
Fri, 7-22	NF-EF Cross-cutting issues	8am-10am	
Fri, 7-22	AF-EF Accelerator R&D Overseas	8am-10am	337 HUB
Fri, 7-22	combined EF/AF report discussion	10am-12pm	022 JHN
Fri, 7-22	hadrons & exotic hadrons (RF-EF-TF)	10am-12pm	248 MGH
Sun, 7-24	XF: AF Future Colliders R&D Program Initiative	10am-noon	120 Kane

Preliminary Drafts of EF Reports and CSS Goals

- **1st Report Drafts public since June 22**
  - Shared documents made available for commenting by community
- **2nd Report Versions were circulated on Sat, July 16**
  - Including comments received in share documents or private communications
- **Plan to collect further comments and feedback at CSS**

  ⇒ Circulate 3rd Version by August 5 (close to final modulo editorial work)

- **One EF Report**
- **Topical Group Reports**
  a. **Higgs Boson (EF01+EF02)**
  b. **Top & HF (EF03)**
  c. **EW (EF04)**
  d. **QCD (EF05+EF06+EF07)**
  e. **BSM (EF08=EF09+EF10)**
- **Lepton Collider Forum Reports**
  a. **Muon Collider**
  b. **e+e- Collider**

Report Drafts available in EF Wiki page - Final Reports
together with **shared documents for further commenting** by community
⇒ All posted comments will be addressed

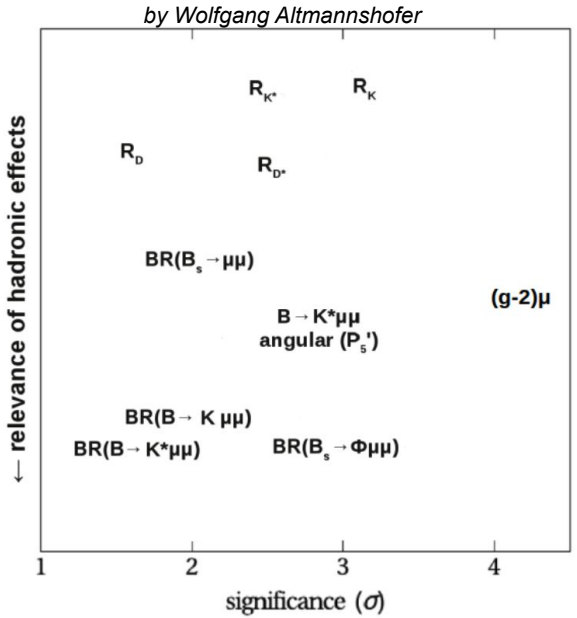
CSS Goal for the EF:
⇒ Converge on a broadly agreed EF vision, based on community input and synergistically with other Frontiers

To further contribute to EF deliberations and to EF and TG Reports:
1. **Join discussions in Parallel & Plenary EF sessions as well as XFrontier meetings**
2. **Append your comments to any of the Reports into respective shared documents (see above link to Wiki)**

Backup

Probing the energy scale for new physics

- **Landscape changed since we started Snowmass → Evidence of the breaking of the SM in the lepton flavor sector?**



Complementarity with other Frontiers

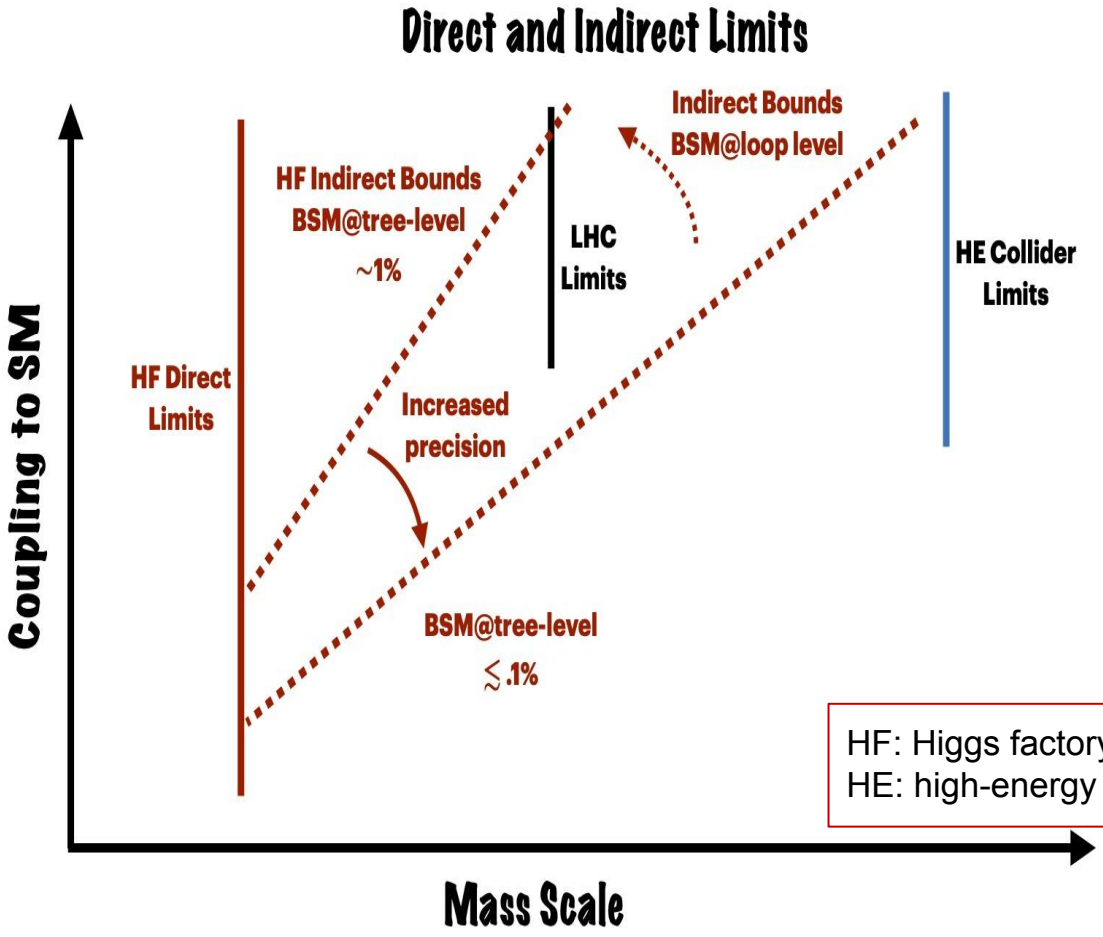
While slow at the start, the energy frontier is ultimately needed to "win the race"

Patrick Meade

Nevertheless if we get indirect hints from existing or planned experiments its important to know how to test them!

Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

- **Broad reach of Collider physics**: colliders are needed to test models across a broad range of observables
- **Unique complementarity** between electroweak precision fits and flavor observables etc.



In a simplified picture:

New physics at tree level:
$\delta\eta_{SM} \sim g^2_{BSM} E^2/M^2$

New physics at loop level:
$\delta\eta_{SM} \sim 1/16\pi^2 \times g^2_{BSM} E^2/M^2$

HF: Higgs factory
HE: high-energy or multi-TeV collider