AF <> theory

LianTao Wang University of Chicago

Snowmass Theory Frontier Workshop. KITP, Santa Barbara. Feb 24, 2022

AF-TF connection

TF: theory advances \Rightarrow fundamental questions

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- Big accelerator facilities have been and will continue to be front and center for the future advances.
- Testing theory ideas, discoveries lead to new theories.



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- Testing theory ideas, discoveries lead to new theories.



AF: accelerators design, feasibility, cost, ...

Accelerator Frontier

Frontier Conveners

Name	Institution	email
Steve Gourlay	Lawrence Berkeley National Laboratory	sagourlay[at]lbl.gov
Tor Raubenheimer	SLAC National Accelerator Laboratory	tor[at]slac.stanford.edu
Vladimir Shiltsev	Fermi National Accelerator Laboratory	shiltsev[at]fnal.gov

Description

The Accelerator Frontier 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 as well as the progress of core accelerator technology, including RF, magnets, targets and sources. Participants will submit Lol, contributed papers, take part in corresponding workshops and events, contribute to writing summaries and take part in the general Snowmass'21 events.

Each AF Working group will address the overall questions:

- 1. What is needed to advance the physics?
- 2. What is currently available (state of the art) around the world?
- 3. What new accelerator facilities could be available on the next decade (or next next decade)?
- 4. What R&D would enable these future opportunities?
- 5. What are the time and cost scales of the R&D and associated test facilities as well as the time and cost scale of the facility?

Topical groups, Group Conveners, and Liasons

- AF1: Beam Physics and Accelerator Education
- AF2: Accelerators for Neutrinos
- AF3: Accelerators for EW/Higgs
- AF4: Multi-TeV Colliders
- AF5: Accelerators for PBC and Rare Processes
- AF6: Advanced Accelerator Concepts
- AF7: Accelerator Technology R&D
 - AF7-RF : RF Accelerator Technology R&D

+ implementation task force (ITF)

White papers in TF in this area

TF7: collider phenomenology

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TOPIC	AUTHORS	Т
Observables		C
Geometric strategies for collider data analysis	Jesse Thaler (MIT)	C
Theoretical perspective on machine learning for data	Andrew Larkoski (Reed)	E
New developments in kinematic observables	Doojin Kim (Texas A&M)	F
New kinematic representations of jets and events	Tao Liu (HKUST)	N
Calculations		P
Interface of theory calculations with experimental me	tl Simone Marzani (Genova)	E
Electroweak at very high energy and EW parton show	v Tao Han (Pittsburg)	S
Needs and trends in QED resummation	Stefano Frixione (Genova), Eric Laenen (NIKHEF)	Г
Factorization	George Sterman (Stony Brook)	E
Higher order QCD calculations inspired by aspects of	f No coordinator identified yet	
Generators		
NNLO+NNLL event generators	Giulia Zanderighi (Munich)	
First-principles simulations with machine learning	Tilman Plehn (Heiderer): Model building	1
Interpretation		-
Anomaly detection with machine learning		
Opportunities for theory studies with public collider	Early Universe Model-Building (with TF09)	
Fully differential likelihood techniques	Weak Gravity Conjecture, Swampland and Impli	Ca
BSM Signatures	Elavor Modol Building (with TE06)	
Ultra-exotics and forgotten signatures at colliders N		
Model dependent vs. model independent approach	Neutral Naturalness	
	Strong Coupling, Model Building, and Lattice	

TF2: EFT techniques

TOPIC	AUTHORS
Constraints on IR physics from UV consistency	Matt Reece
EFT of dark matter	Mikhail Solon
HEP/CMT connections	Riccardo Penco
Naturalness	Nathaniel Craig
EFTs of gravity	Walter Goldberger
SMEFT	Will Shepherd
EFT of cosmology (with TF09)	Mehrdad Mirbabayi and Marko Simonovic

ntorprototion	_		
		AUTHORS	TITL
Anomaly detection with machine learning	-		
Opportunities for theory studies with public collider	Early Universe Model-Building (with TF09)	David Curtin, Eric Kuflik, Yonit Hochberg, Neal Weiner, and Keisuke Harigaya	
Fully differential likelihood techniques	Weak Gravity Conjecture, Swampland and Implications for Theory	Patrick Draper, Isabel Garcia-Garcia, Matthew Reece	
3SM Signatures			
Jltra-exotics and forgotten signatures at colliders N	Flavor Model Building (with TF06)	Wolfgang Altmannshofer, Jure Zupan	
Nodel dependent vs. model independent approach	Neutral Naturalness	Brian Batell, Chris Verhaaren	
	Strong Coupling, Model Building, and Lattice	Graham Kribs, Ethan Neil	
	Axion Model Building	Prateek Agrawal, JiJi Fan, Anson Hook, Junwu Huang, Gustavo Marques Tavares	s
	Neutrino Model Building [tentative] (with TF11)	Kaladi Babu, Marco Drewes, Julia Gehrlein (?)	
	Models of Baryogenesis	Gilly Elor, Seyda Ipek	
	Relaxion/Clockwork [tentative]	Claudia Frugiuele, Gilad Perez	

TF6: theory techniques for precision physics

TOPIC	Author	TITLE
The path to N3LO precision	Fabrizio Caola, Claude Duhr, Xiaohui Liu, Frank Petriello, Stefan Weinzierl	
Future prospects for parton showers	Simone Alioli, Zoltan Nagy, Dave Soper, Bryan Webber	
Theoretical developments in the SMEFT at dimension-8 and beyond	Alioli, Durieux, Martin, Melia, Mereghetti, Murayama, Murphy, Petriello, Shadmi, Shepherd et al	
Proton structure at the precision frontier (with EF06)	Alekhin, Ball, Blumlein, Cooper-Sarkar, Forte, Nadolsky, Thorne, Ubiali, Yuan, et al	
Resummation for future colliders	Thomas Becher, Andrea Ferroglia, Xiaohui Liu, Alexandre Penin, Felix Ringer, Robert Szafron e	et al
Flavor model building (with TF08)	Wolfgang Altmannshofer, Jure Zupan	

Focus: theoretical techniques

Full list of white papers

Theory and future collider

- No dedicated discussion on the experimental (accelerator) facilities within the TF.
 - ▶ More in the energy frontier.

Involvement of theory

- No dedicated discussion on the experimental (accelerator) facilities within the TF.
 - ▶ More in the energy frontier.

At the same time:

- Future collider has been a focus for many theorists.

Many accelerator related activities in Snowmass 21

Snov	wmass Agora or	n Future Colliders: Muon Colliders	⊞ Tuesday Aug 24, 2021, 10:0	0 AM → T2:00 PM US/Central	
			Description The meeting is de	dicated to physics and technology of a 125 GeV mu+mu- Higgs factory.	
Februar US/Central ti	y 16, 2022 mezone	Enter your search term Q	Join Zoom Meetii	ig LINK	
Overvi	ew Snov	vmass Agora #3 on Future Colliders: Muon Colliders will held on 16 February, 2022. Please	10:00 AM → 10:10 AM News		© 10m
Tim	Snowmass Ago	ora on Future Colliders: Circular e+e- Colliders	Speakers: Der Patrick Meade	un Li (LBNL), Diktys Stratakis (Fermi National Accelerator Laboratory), Fabio Maltoni (Universite' catholique de Louvain), Kevin Black, (Storry Brook University), Sergo Jindariani (FNAL)	
Cor			🕒 MuonColli	derNews	
Re <u>c</u> Par	January 19, 2022 US/Central timezone	Enter your search term Q	10:10 AM → 10:40 AM Physics at the Speakers: 7he	e 125 GeV Muon Collider	© 30m
Fer			🕑 muon125ł	ilggs_Mu	
Cor	Overview	Snowmass Agora #2 on Future Colliders: Circular e+e- Colliders will held on 19 January, 2022. Please		form 105 Colda multi Told Mure Collidar	0.00
APS	Link to Questions	register for the event to receive the ZOOM link to attend. The registration will be open throughout the event.	TO:40 AM → TE:10 AM Technology: Speaker: Mark	C Palmer (Brookhaven National Laboratory)	() 30m
DPI	Timetable	Coorder does for submitting questions should of time is at the link bars	Higgs_Fac	tory_125	
(CF	Snowmass	s Agora on Future Colliders: Linear e+e- Colliders	11:10 AM → 11:30 AM 125-GeV Hig Speaker: Niko P 125GeV_H	gs Factory Magnet Protection and Machine-Detector Interface lai Mokhov (Fermilab) IF_Mokho	() 20m
	December 15, 2021 US/Central timezone	Enter your search term	٩		

Overview	In the context of the Snowmass 2021 Community Planning Exercise, the Accelerator and Energy
Timetable	Frontiers are pleased to announce a series of events, intended for all Snowmass participants, to
Contribution List	childany discuss physics and technical aspects of different HEP conder concepts.
Registration	The events will be hosted by the Future Colliders initiative at Fermilab. The plan is to discuss both near and far future collider proposals, in different stages of development, synergistically grouped into five
Participant List	categories:
Fermilab Statement of Community Standards	 Linear e+e- colliders Circular e+e- colliders
APS Code of Conduct	 Muon colliders Circular pp and ep
DPF Core Principles and	Advanced colliders
Community Guidelines (CP&CG)	The events will take place once a month from December 2021 till April 2022, on Wednesdays 3-5 p.m. CST. The detailed agenda will be announced soon. We request you to please save the following dates:
Contact	 Dec. 15, 2021
Conferences@fnal.gov	 Jan. 19, 2022 Feb. 16, 2022
	Mar 16 2022

Mar. 16, 2022

Apr. 13, 2022

A "Collider discussion" will be further organized during the Energy Frontier Meeting planned for the week of March 28.

These events are meant to be focused critical discussions of classes of colliders that share similar concepts, and will have to specifically address both physics and feasibility considering aspects such as:

Active participation and contribution from many theorists

asse Muon Collider Forum

Theorists -> AF: physics studies

- Theorists contribute: first looks, estimates, pheno studies.
- Available studies.
 - European Strategy updates
 - CDR/TDR: <u>ILC/CLIC/CEPC-SppC/FCC(hh, ee, eh)</u>
 - muon collider forum + studies
- Still needed to do more.
 - photon collider, ep...

The rest of my talk

- Review the collider options which have been put forward.

- Briefly summarizes the physics cases have been laid out (so far).

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Name	Details	PO		AF Group
СерС	<u>e+e-</u> , $\sqrt{s} = 0.24$ TeV, L= 3.0 ×10 ³⁴	Jie G	Gao (gaoi@ihep.ac.cn)	AF3
CLIC (Higgs factory)	<u>e+e</u> -, \sqrt{s} = 0.38 TeV, L= 1.5 ×10 ³⁴	Steir	nar Stapnes (Steinar.Stapnes@cern.ch)	AF3
Circular ERL ee collider	e+e-, $\sqrt{s} = 0.24$ TeV, L= 73 ×10 ³⁴	Thor	mas Roser (roser@bnl.gov)	AF3
FCC-ee	e+e-, $\sqrt{s} = 0.24$ TeV, L= 17 ×10 ³⁴	Kats	unobu 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.ip	AF3
LHeC	$ep, \sqrt{s} = 1.3 \text{ TeV}, L= 0.1 \times 10^{34}$	Oliv	er Bruenina (oliver.bruening@cern.ch)	AF3
MC (Higgs factory)	$\mu\mu$, $\sqrt{s} = 0.13$ TeV, L= 0.01 ×10 ³⁴	Mar	k Palmer (mpalmer@bnl.gov)	AF3
Cryo-Cooled Copper (C^3) linac	etter, $\sqrt{s} = 2$ TeV, L= 4.5 ×10 ³⁴		Emilio Nanni (nanni@slac.Stanford.edu)	AF3
High Energy CLIC	<u>e+e</u> -, $\sqrt{s} = 1.5 - 3$ TeV, L= 5.9 ×10 ³⁴		S.Stapnes (steinar.stapnes@cern.ch)	AF4
High Energy ILC	$e+e-$, $\sqrt{s} = 1 - 3 \text{ TeV}$		Hassan Padamsee (hsp3@cornell.edu)	AF4
FCC- <u>hh</u>	pp, $\sqrt{s} = 100 \text{ TeV}$, L= 30 ×10 ³⁴		M.Benedikt (Michael.Benedikt@cern.ch)	AF4
SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10 ×10 ³⁴		J.Tang (tangiy@ihep.ac.cn)	AF4
Collider-in-Sea	pp, $\sqrt{s} = 500 \text{ TeV}$, 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 , $\sqrt{s} = 3.5 \text{ TeV}$, L= 1 ×10 ³⁴		Oliver Bruening (oliver.bruening@cern.ch)	AF4
CEPC-SPPpC-eh	$ep, \sqrt{s} = 6 \text{ TeV}, L = 4.5 \times 10^{33}$		Y.Zhang (vzhang@ilab.org)	AF4
VHE-ep	ep , $\sqrt{s} = 9 \mathrm{TeV}$			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 $\times 10^{34}$		D.Schulte (daniel.schulte@cern.ch)	AF4
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$		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

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HeC	$en \sqrt{s} = 1.3 \text{ TeV} = 0.1 \times 10^{34}$	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 CLIC	$e+e^{-}, \sqrt{s} = 1.5 - 3$			
High Energy ILC	$e+e-, \sqrt{s} = 1 - 3 Te$			
FCC-hh	pp, $\sqrt{s} = 100 \text{TeV}$,	anaray lantan colli	dors	
SPPC	pp, $\sqrt{s} = 75/150 \text{ T}$	$pp, \sqrt{s} = 75/150 T$ Low energy lepton colliders		
Collider-in-Sea	pp, $\sqrt{s} = 500 \text{TeV}$,	pp, $\sqrt{s} = 500 \text{TeV}$, Ligas (7) factories		
Commo gommo		Hinns (7) factorios		
Gamma-gamma	??	Higgs (Z) factories.	,	
LHeC	?? $ep, \sqrt{s} = 1.3 \text{ TeV}, L$	Higgs (Z) factories.	thar	
LHeC FCC-eh	?? $ep, \sqrt{s} = 1.3 \text{ TeV}, L$ $ep, \sqrt{s} = 3.5 \text{ TeV}, L$	Higgs (Z) factories. p physics of WW, th	tbar	
CEPC-SPPpC-eh	?? $ep, \sqrt{s} = 1.3 \text{ TeV}, L$ $ep, \sqrt{s} = 3.5 \text{ TeV}, L$ $ep, \sqrt{s} = 6 \text{ TeV}, L=$	Higgs (Z) factories. p physics of WW, th	tbar	
LHeC FCC-eh CEPC-SPPpC-eh VHE-ep	?? $ep, \sqrt{s} = 1.3 \text{ TeV}, L$ $ep, \sqrt{s} = 3.5 \text{ TeV}, L$ $ep, \sqrt{s} = 6 \text{ TeV}, L =$ $ep, \sqrt{s} = 9 \text{ TeV}$	Higgs (Z) factories. p physics of WW, th	tbar	
LHeC FCC-eh CEPC-SPPpC-eh VHE-ep MC – Proton Driver 1	?? $ep, \sqrt{s} = 1.3 \text{ TeV}, L$ $ep, \sqrt{s} = 3.5 \text{ TeV}, L$ $ep, \sqrt{s} = 6 \text{ TeV}, L =$ $ep, \sqrt{s} = 9 \text{ TeV}$ $\mu\mu, \sqrt{s} = 1.5 \text{ TeV}, L = 1 \times 10^{34}$	Higgs (Z) factories. physics of WW, the physics of WW, the physics of WW, the physics of WW, the physics of the	tbar AF4	
LHeC FCC-eh CEPC-SPPpC-eh VHE-ep MC – Proton Driver 1 MC – Proton Driver 2	?? $ep, \sqrt{s} = 1.3 \text{ TeV}, L$ $ep, \sqrt{s} = 3.5 \text{ TeV}, L$ $ep, \sqrt{s} = 6 \text{ TeV}, L =$ $ep, \sqrt{s} = 9 \text{ TeV}$ $\mu\mu, \sqrt{s} = 1.5 \text{ TeV}, L = 1 \times 10^{34}$ $\mu\mu, \sqrt{s} = 3 \text{ TeV}, L = 2 \times 10^{34}$	Higgs (Z) factories. physics of WW, the physics of WW, the physics of WW, the physics of WW and the physics of	AF4 AF4	
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Name	Details		
CepC	<u>e+e-</u> , $\sqrt{s} = 0.24$ TeV, L= 3.0		
CLIC (Higgs factory)	$e+e-$, $\sqrt{s} = 0.38$ TeV, L= 1.5		
Circular ERL ee collider	$e+e-$, $\sqrt{s} = 0.24$ TeV, L= 73 > High	energy lepton (ph	oton) colliders
FCC-ee	$e+e-, \sqrt{s} = 0.24 \text{ TeV}, L= 17 >$	$M_{\rm H}$ to 10c	
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ILC (Higgs factory)	$e+e-$, $\sqrt{s} = 0.25$ TeV, L= 1.4		
LHeC	$ep, \sqrt{s} = 1.3 \text{ TeV}, L= 0.1 \times 10$		
MC (Higgs factory)	$\mu\mu$, $\sqrt{s} = 0.13$ TeV, L= 0.01 ×10 ³⁺	Mark Palmer (mpalmer@bnl.gov)	AF3
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SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10 ×10 ³⁴	J.Tang (tangiy@ihep.ac.cn)	AF4
Collider-in-Sea	pp, $\sqrt{s} = 500 \text{ TeV}$, L= 50 ×10 ³⁴	P.McIntyre mcintyre@physics.tamu.edu	AF4
Gamma-gamma	??	W.Krasny (mieczyslaw.witold.krasny@cern.ch)	AF4
LHeC	$ep, \sqrt{s} = 1.3 \text{ TeV}, L= 1 \times 10^{34}$	Oliver Bruening (oliver.bruening@cern.ch)	AF4
FCC-eh	$ep, \sqrt{s} = 3.5 \text{ TeV}, L= 1 \times 10^{34}$	Oliver Bruening (oliver.bruening@cern.ch)	AF4
CEPC-SPPpC-eh	$ep, \sqrt{s} = 6 \text{ TeV}, L= 4.5 \times 10^{33}$	Y.Zhang (yzhang@jlab.org)	AF4
VHE-ep	$ep, \sqrt{s} = 9 \text{ TeV}$		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 $\times 10^{34}$	D.Schulte (daniel.schulte@cern.ch)	AF4
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$	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

Name	Details	POC	AF Group
CepC	<u>e+e</u> -, $\sqrt{s} = 0.24$ TeV, L= 3.0 ×10 ³⁴	lie Gao (gaoi@ihen ac on)	ΔΕ3
CLIC (Higgs factory)	$e+e$ -, $\sqrt{s} = 0.38$ TeV, L=		
Circular ERL ee collider	e+e-, $\sqrt{s} = 0.24$ TeV, L=		
FCC-ee	<u>e+e-</u> , $\sqrt{s} = 0.24$ TeV, L=		
gamma gamma	X-ray FEL-based $\gamma\gamma$ colli	nn cellider 100 i	
ILC (Higgs factory)	$\underline{e+e}$ -, $\sqrt{s} = 0.25$ TeV, L=	pp collider, 100-1	sn iev
LHeC	$ep, \sqrt{s} = 1.3 \text{ TeV}, L= 0.1$		
MC (Higgs factory)	$\mu\mu$, \sqrt{s} = 0.13 TeV, L= 0.0		
Cryo-Cooled Copper (C^3) linac	$e+e-$, $\sqrt{s} = 2$ TeV, L= 4.5 ×		
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	$e+e-$, $\sqrt{s} = 1 - 3 \text{ TeV}$	Hassan Padamsee (hsp3@cornell.edu)	AF4
FCC-hh	pp, $\sqrt{s} = 100 \text{ TeV}$, L= 30 ×10 ³⁴	M.Benedikt (Michael.Benedikt@cern.ch)	AF4
SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10 ×10 ³⁴	J.Tang (tangiv@ihep.ac.cn)	AF4
Collider-in-Sea	pp, $\sqrt{s} = 500 \text{ TeV}$, L= 50 ×10 ³⁴	P.McIntyre mcintyre@physics.tamu.edu	AF4
Vannina-gannia	**	W.Masny (Inteczystaw.witold.krasny@cern.cn)	АГЧ
LHeC	$ep, \sqrt{s} = 1.3 \text{ TeV}, L= 1 \times 10^{34}$	Oliver Bruening (oliver.bruening@cern.ch)	AF4
FCC-eh	$ep, \sqrt{s} = 3.5 \text{ TeV}, L= 1 \times 10^{34}$	Oliver Bruening (oliver.bruening@cern.ch)	AF4
CEPC-SPPpC-eh	$ep, \sqrt{s} = 6 \text{ TeV}, L= 4.5 \times 10^{33}$	Y.Zhang (vzhang@ilab.org)	AF4
VHE-ep	$ep, \sqrt{s} = 9 \text{ TeV}$		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	$\mu\mu, \sqrt{s} = 3 \text{ TeV}, L= 2 \times 10^{34}$	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
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Snowmass 2021: EF Benchmark Scenarios

Collider	Type	\sqrt{s}	$\begin{array}{c} \mathrm{P} \ [\%] \\ \mathrm{e}^{-}/e^{+} \end{array}$	$L_{\rm int}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm 80/\pm 30$ $\pm 80/\pm 30$ $\pm 80/\pm 30$ $\pm 80/\pm 20$	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	$\pm 80/0 \\ \pm 80/0 \\ \pm 80/0$	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}	$\frac{P [\%]}{e^{-}/e^{+}}$	$\begin{array}{c} {\rm L_{int}}\\ {\rm ab}^{-1} \end{array}$
FCC-hh	рр	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh	ep	3.5 TeV		2
muon-collider (higgs)	μμ	125 GeV		0.02
High energy muon-collider	μμ	3 TeV		1
		10 TeV		10
		14 TeV		20
		30 TeV		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?)[Need to consolidate g list of c.o.m. energies]
- FCC pp >200 TeV? and ~75 TeV documenting sensitivity loss
- Very high energy e+e- collider
- Other emerging ideas: $\gamma \gamma$ collider, C³ e⁺e⁻ collider [C3=Cool Copper Collider]

M. Narain. Energy frontier restart workshop.

ITF will present

Possible Higgs factory comparison table

Proposal Name	Nominal COM energy (Range) [TeV]	Luminosity per IP at nominal COM energy [10 ³⁴ cm ⁻² s ⁻¹]	Years of pre- construction R&D required	Construction cost range, including explicit labor [2021 MUS\$]	Estimated operating electric power consumption [MW]
FCC-ee	0.24 (0.09 - 0.37)	8.5			
CEPC	0.24 (0.09 - 0.24)	2.9			
ILC (Higgs factory)	0.25 (0.09 - 3)	1.35			
CCC (Cryo Cooled Collider)	0.25 (0.25 - 0.55)	1.3			
CLIC (Higgs factory)	0.38 (0.09 - 0.38)	1.5			
CERC (ERL ee collider)	0.24 (0.09 - 0.6)	78			
ReLiC (Linear ERL Collider)	0.24 (0.09 - 1.0)	115			
ERLC (ERL Linear Collider)	0.25	100			
XCC FEL-based γγ Collider	0.125 (0.125 - 0.14)	0.1			
Circular ee Fermi site filler	0.24	1.2			
TWLC Fermi site filler	0.25	1.4			
MC (Higgs factory)	0.13	0.01			

The rest of my talk

- Review the collider options which have been put forward.

 Briefly summarizes the physics cases have been laid out (so far).

Frontiers: smaller distances



Tao Han: everything has a factory, Higgs needs one too!

Frontiers: smaller distances



Tao Han: everything has a factory, Higgs needs one too!

We all agree.

At the same time, useful to say more about the physics questions we would like these facilities to address.

- Good consensus in the community.
 - Main physics drivers: Higgs, dark matter.
- Higgs.
 - couplings: precision measurement
 - naturalness: direct production (higher energy)
- Dark matter
 - ▷ WIMP: higher energy
 - dark sector: intensity
- Rich physics program: portals, flavor physics, QCD,
 QFT tests, ...

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No guarantee to discover new particles, of course. But, we will learn a lot.

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Higgs coupling

European Strategy Physics Briefing book



Muon smasher's guide

10 TeV Muon Collider with HL-LHC κ_W 0.06 0.06 κ_Z 0.23 0.22 κ_g 0.15 0.15 κ_γ 0.64 0.57 $\kappa_{Z\gamma}$ 1.0 1.0			Fit Result $[\%]$
κ_W 0.06 0.06 κ_Z 0.23 0.22 κ_g 0.15 0.15 κ_γ 0.64 0.57 $\kappa_{Z\gamma}$ 1.0 1.0		10 TeV Muon Collider	with HL-LHC
κ_Z 0.23 0.22 κ_g 0.15 0.15 κ_γ 0.64 0.57 $\kappa_{Z\gamma}$ 1.0 1.0	κ_W	0.06	0.06
κ_g 0.15 0.15 κ_γ 0.64 0.57 $\kappa_{Z\gamma}$ 1.0 1.0	κ_Z	0.23	0.22
κ_{γ} 0.64 0.57 $\kappa_{Z\gamma}$ 1.0 1.0	κ_g	0.15	0.15
$\kappa_{Z\gamma}$ 1.0 1.0	κ_γ	0.64	0.57
0.00 0.00	$\kappa_{Z\gamma}$	1.0	1.0
κ_c 0.89 0.89	κ_c	0.89	0.89
κ_t 6.0 2.8	κ_t	6.0	2.8
κ_b 0.16 0.16	κ_b	0.16	0.16
κ_{μ} 2.0 1.8	κ_{μ}	2.0	1.8
κ_{τ} 0.31 0.30	$\kappa_{ au}$	0.31	0.30

Higgs coupling

European Strategy Physics Briefing book



Muon smasher's guide

		Fit Result $[\%]$	
	10 TeV Muon Collider	with HL-LHC	
κ_W	0.06	0.06	
κ_Z	0.23	0.22	
κ_g	0.15	0.15	
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$\kappa_{Z\gamma}$	1.0	1.0	
κ_c	0.89	0.89	
κ_t	6.0	2.8	
κ_b	0.16	0.16	
κ_{μ}	2.0	1.8	
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10⁻³ or better possible

Higgs coupling



European Strategy Physics Briefing book

Muon smasher's guide

		Fit Result $[\%]$	
	10 TeV Muon Collider	with HL-LHC	
κ_W	0.06	0.06	
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$\kappa_{Z\gamma}$	1.0	1.0	
κ_c	0.89	0.89	
κ_t	6.0	2.8	
κ_b	0.16	0.16	
κ_{μ}	2.0	1.8	
$\kappa_{ au}$	0.31	0.30	

10-3 or better possible

At Higgs factories: Precision scale (very roughly) with (# of Higgs) $^{-1/2}$

Low energy Higgs factories (Zh) High energy (> 600 GeV) lepton colliders (WW fusion) Sensitive to different couplings.

Measurement at lepton collider more model independent: width, Zh coupling, ... Tera Z (and ttbar threshold) can improve significantly other EW precision measurements.

Higgs self-coupling



A few percent accuracy would cover most of the ground.

Higher energy collider needed: TeV lepton collider, 100 TeV pp collider



Reach of the top partners

Briefing book + my drawings.



All Colliders: Top squark projections

Reach for other top partners similar

Hadron collider reach $\approx 10\%$ of E_{CM} Weaker if new physics without strong int.

Lepton collider reach $\approx 0.5 \times E_{CM}$ Reach for other new physics similar. Photon collider similar but only for

Photon collider similar, but only for produce charged particles.

Motivated by the naturalness puzzle

- Good consensus in the community.
 - Main physics drivers: Higgs, dark matter.
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 - WIMP: higher energy
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- Rich physics program: portals, flavor physics, QCD,
 QFT tests, ...

WIMP Dark matter



Model		Therm.
$(\operatorname{color}, n, Y)$		target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
$(1,3,\epsilon)$	Dirac	$2.0 { m TeV}$
(1,5,0)	Majorana	11 TeV
$(1,5,\epsilon)$	Dirac	6.6 TeV
(1,7,0)	Majorana	$23 { m TeV}$
$(1,7,\epsilon)$	Dirac	$16 { m TeV}$

The simplest WIMP model: DM part of EW multiplet. Interaction: Standard Model gauge interactions.

EW Dark matter reach: pp collider



Higher energy needed to cover higher dimensional multiplets.

Either discovery or exclusion, we can make a clear statement of this very compelling WIMP DM scenario.

High energy muon collider



High energy muon collider can play a decisive role in probing WIMP dark matter!

Another example of th input: luminosity needs and physics goals



Another example of th input: luminosity needs and physics goals



wimp DM: about the muon collider line and E_{CM} > 3 TeV.

Another example of th input: luminosity needs and physics goals



wimp DM: about the muon collider line and E_{CM} > 3 TeV.

Not covered in this talk

Topical groups, Group Conveners, and Liasons

- AF1: Beam Physics and Accelerator Education
- AF2: Accelerators for Neutrinos
- AF3: Accelerators for EW/Higgs
- AF4: Multi-TeV Colliders
- AF5 Accelerators for PBC and Rare Processes
- AF6: Advanced Accelerator Concepts
- AF7: Accelerator Technology R&D
 - AF7-RF : RF Accelerator Technology R&D

More details at <u>AF page</u>

Looking forward

- Theorists have been, and will continue to be, at the forefront of high energy physics.
 - Identifying questions.
 - Suggesting solutions.
 - Proposing ways of testing ideas.
- Laying the foundation of the planning for future accelerator facilities.
- With the future at stake, we need to think harder.
 - Anything big we have missed?



Dark matter reach



briefing book + my drawings for muon (or lepton) colliders.

Simplest WIMP model, very predictive, definitive target mass \approx TeVs. Out of reach for LHC, difficult for direct detection.

Lepton collider reach close to $0.5 \times E_{CM}$ (a little less), need 10(s) TeV and hi lumi Hadron collider \approx a few percent x E_{CM} , need 100 (or more) TeV

Hadron collider scenarios



Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

Hadron collider scenarios



Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

Hadron collider scenarios



Rapid gain in mass reach

10³⁴ cm⁻²s⁻¹ doing a reasonable job for 100 TeV. Need higher luminosity for Higgs self-coupling. 10³⁵-10³⁶ cm⁻²s⁻¹ may be needed for higher energies.

Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

Theorists -> AF: physics goals vs luminosity (polarization...)

- Different physics goals need different machine parameters
 - ▶ For example: at high energy lepton colliders:
 - Discovery of heavy new physics particles and Higgs coupling measurements can require very different luminosities.



Clarifying further such trade-offs can be very beneficial