Panel

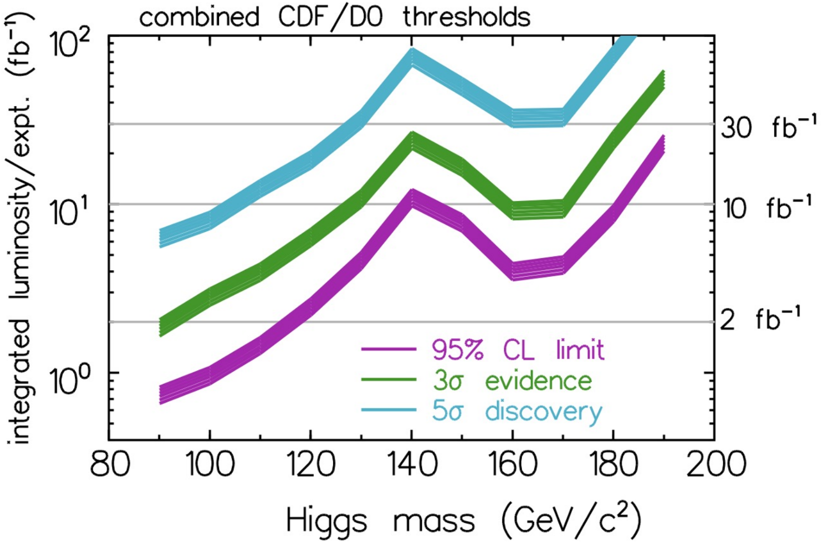
Future of Particle Physics

Prediction is difficult, especially about the future.

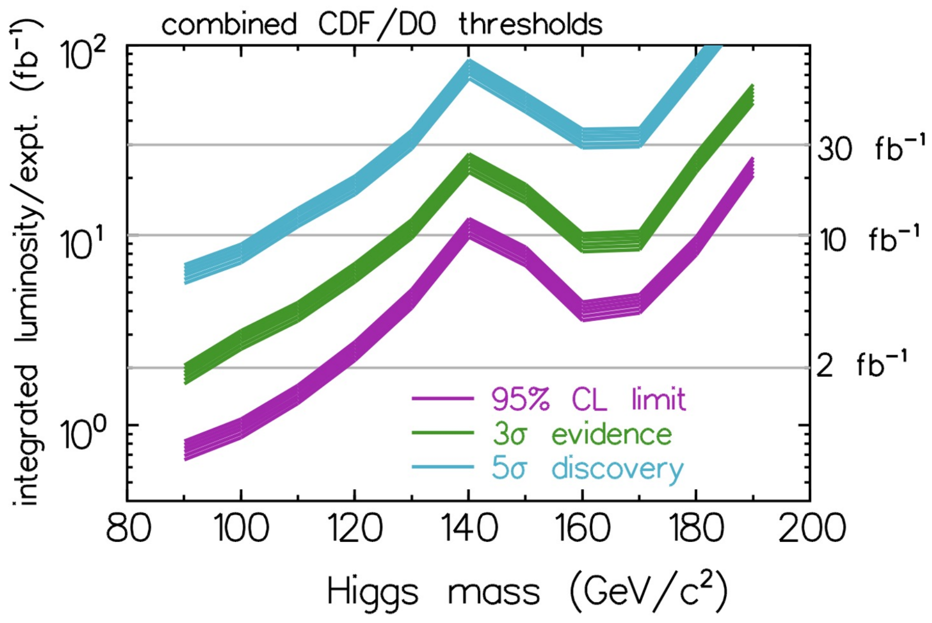
- Hans Bethe

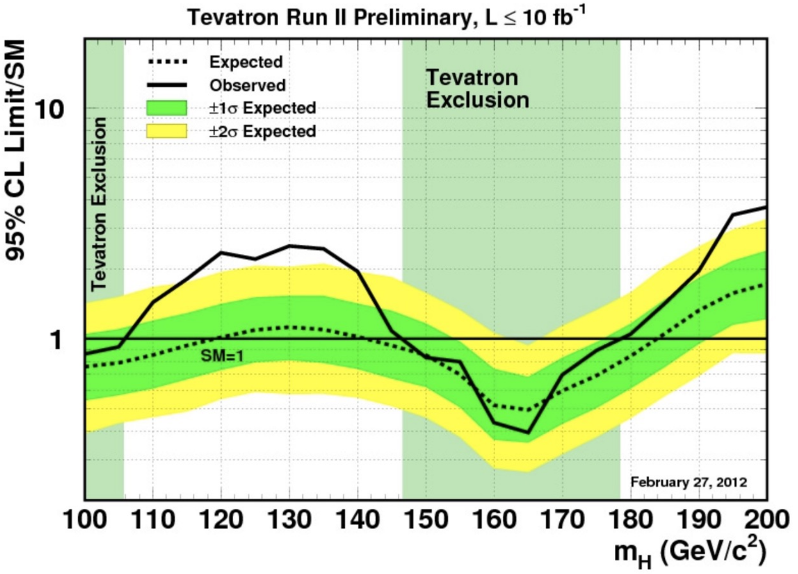
We did predict the future!

1998 Run 2 SUSY/Higgs Workshop at FNAL:
What can Tevatron Run 2 say about discovering the Higgs boson and supersymmetry?



The final result in July 2012 agreed perfectly!





Snowmass 2021

https://www.slac.stanford.edu/econf/C210711/

Snowmass 2021

Proceedings of the 2021 US Community Study on the Future of Particle Physics

(Snowmass 2021)

organized by the APS Division of Particles and Fields

Summary & Frontmatter

Cosmic Frontier

Rare Processes Frontier

Accelerator Frontier

Energy Frontier

Theory Frontier

Community Engagement Frontier

Instrumentation Frontier

Underground Facilities Frontier

Computational Frontier

Neutrino Frontier

Snowmass Early Career

Snowmass 2021 Succinct Summary:

Lead the exploration of the fundamental nature of matter, energy, space and time, by using ground-breaking theoretical, observational, and experimental methods; developing state-of-the-art technology for fundamental science and for the benefit of society; training and employing a diverse and world-class workforce of physicists, engineers, technicians, and computer scientists from universities and laboratories across the nation; collaborating closely with our global partners and with colleagues in adjacent areas of science; and probing the boundaries of the Standard Model of particle physics to illuminate the exciting terrain beyond, and to address the deepest mysteries in the Universe.

Opportunities in HEP for the decade & beyond

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4	Next Gen. Grav. Wave Observatory*
	Spectroscopic Survey - S5*	Line Intensity Mapping*
	Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility

Medium- and Small-Scale Future Experiments and Projects:

(see the full frontier reports)

Medium- and small-size experiments and projects are an important component of the current and proposed program. In the past, experiments with these scales have made significant measurements and important discoveries, opening up new areas of scientific exploration. Furthermore, because of their timescale and size, these experiments offer unique leadership and training opportunities for younger physicists and allow for greater diversity in the experimental particle physics ecosystem.

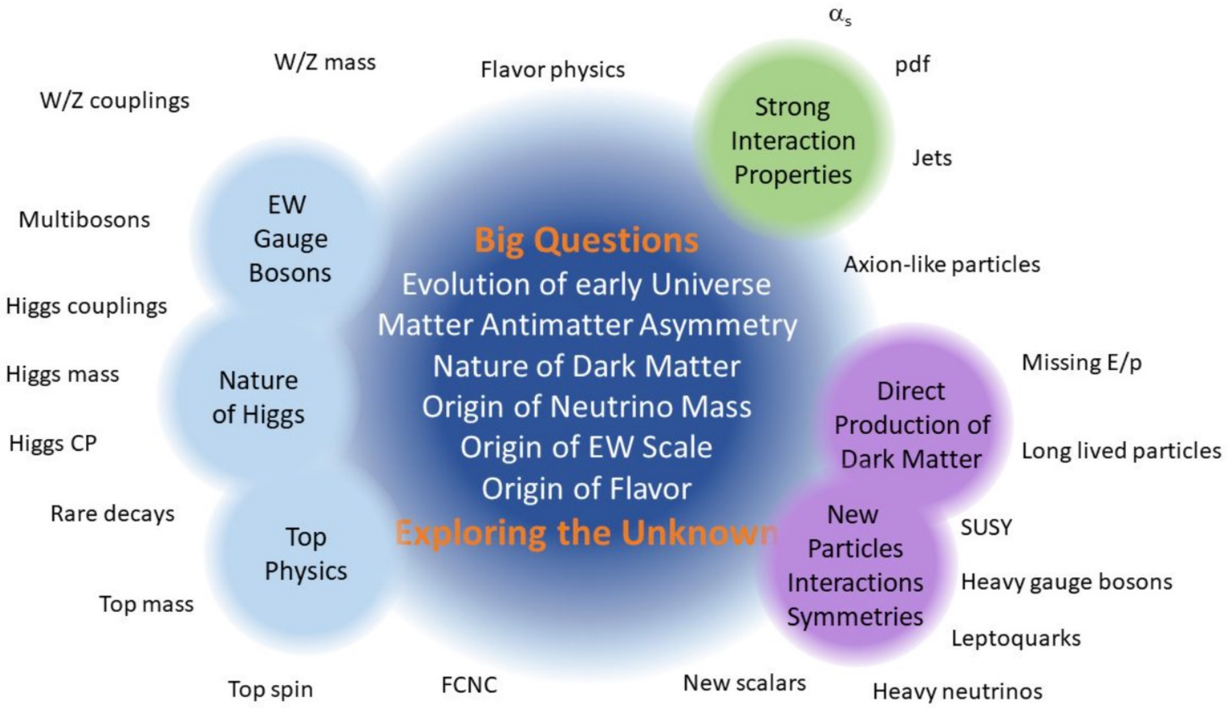
Such as SBND, CEνNS; g-2, Mu2e, 0$\nu\beta\beta$, AMF, Belle II; DM …

The field of HEP is vibrant, dynamic & exciting!

Energy Frontier

Energy Frontier: explore the TeV energy scale and beyond

Through the breadth and multitude of collider physics signatures



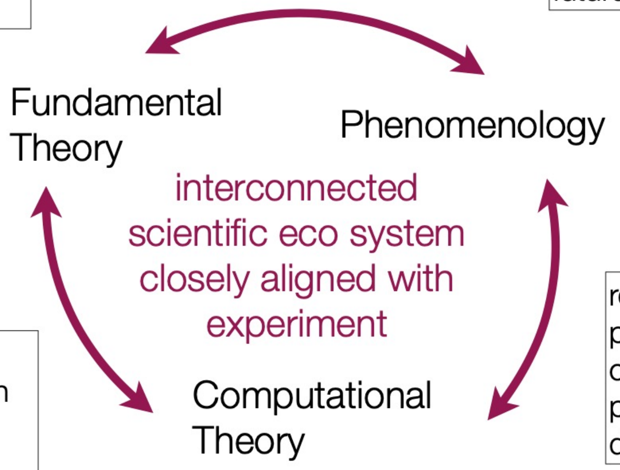
Theory Frontier

HEP Theory

unifies the frontiers of particle physics

lays the foundations for future experiments

connects to gravity, cosmology, astrophysics nuclear physics, condensed matter, AMO, mathematics



central to the motivation, analysis, and interpretation of experiments

responsive:
propose new directions based on data
propose/guide new experiments
develop new analysis tools

advances our understanding of Nature in regimes that experiment cannot (yet) reach

incorporates new perspectives (QI, ML) and technologies to extend the boundaries of our knowledge

FERMILAB-PUB-07-652-T
MADPH–07–1497
ANL-HEP-PR-07-106
EFI-07-39

Higgs Signal for $h \to aa$ at Hadron Colliders

Marcela Carena
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
E-mail: carena@fnal.gov

Tao Han and Gui-Yu Huang
Department of Physics, University of Wisconsin, Madison, WI 53706, USA
E-mail: than@hep.wisc.edu, ghuang@hep.wisc.edu

Carlos E.M. Wagner
HEP Division, Argonne National Laboratory,Argonne, IL 60439, USA
Enrico Fermi Institute and Kavli Institute for Cosmological Physics,
Physics Department, University of Chicago, Chicago, IL 60637, USA
E-mail: cwagner@hep.anl.gov

ABSTRACT: We assess the prospect of observing a neutral Higgs boson at hadron colliders in its decay to two spin-zero states, a, for a Higgs mass of $90-130$ GeV, when produced in association with a W or Z boson. Such a decay is allowed in extensions of the MSSM with CP-violating interactions and in the NMSSM, and can dominate Higgs boson final states, thereby evading the LEP constraints on standard Higgs boson production. The light spin-zero state decays primarily via $a \to b\bar{b}$ and $\tau^+\tau^-$, so this signal channel retains features distinct from the main backgrounds. Our study shows that at the Tevatron, there may be potential to observe a few events in the $b\bar{b}\tau^+\tau^-$ or $b\bar{b}b\bar{b}$ channels with relatively small background, although this observation would be statistically limited. At the LHC, the background problem is more severe, but with cross sections and integrated luminosities orders of magnitude larger than at the Tevatron, the observation of a Higgs boson in this decay mode would be possible. The channel $h \to aa \to b\bar{b}b\bar{b}$ would provide a large statistical significance, with a signal-to-background ratio on the order of $1:2$. In these searches, the main challenge would be to retain the adequate tagging efficiency of b's and τ's in the low p_T region.

KEYWORDS: Higgs, NMSSM, Tevatron, LHC.

FERMILAB-PUB-08–098-T
MADPH-08-1511
NSF-KITP-08-64
arXiv: 0806.3966 [hep-ph]

Heavy Quarks Above the Top at the Tevatron

Anupama Atre[1,2], Marcela Carena[1,2,3], Tao Han[2,4] and José Santiago[2,5] *

[1] *Fermi National Accelerator Laboratory, MS106, P.O.Box 500, IL 60510, U.S.A.*
[2] *Kavli Institute of Theoretical Physics, University of California, Santa Barbara, CA 93107, U.S.A.*
[3] *Department of Physics and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, U.S.A.*
[4] *Department of Physics, University of Wisconsin, 1150 University Avenue, Madison, WI 53706, U.S.A.*
[5] *Institute for Theoretical Physics, ETH, CH-8093, Zürich, Switzerland.*

Abstract

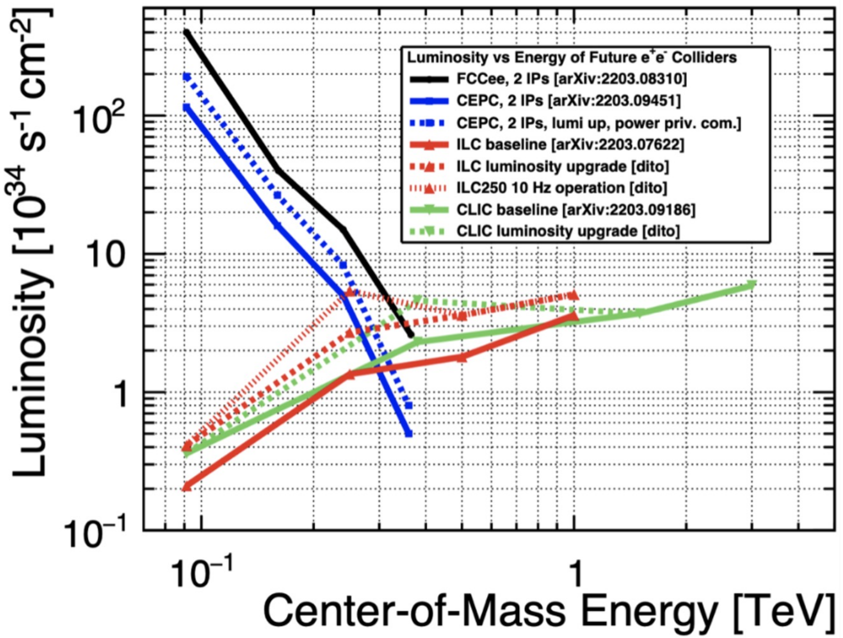
Recent developments in models with warped extra dimensions have opened new possibilities for vector-like quark studies at hadron colliders. These new vector-like quarks can mix sizably with light Standard Model quarks without violating low energy constraints. We perform a model-independent analysis to determine the Tevatron reach in the search for new quarks. We find that the Tevatron has great potential to observe such quarks via their electroweak single production due to their mixing with valence quarks. With 4 (8) fb^{-1} integrated luminosity, one may reach a 5σ statistical significance for a heavy quark of mass 580 (630) GeV if the heavy quark-Standard Model quark mixing parameter is order one.

Happy Birthday Marcela & El Carlos!

After 60, it'll be a recount, you are young again …

Proposed Higgs Factories (1)

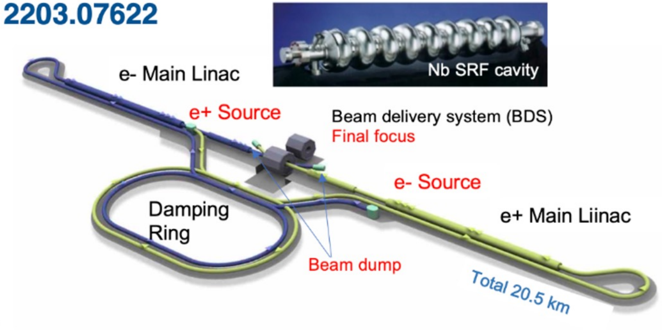
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC and C^3 c.o.m almost similar	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500* GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		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



Other technological solutions (including HELEN) brought forward within the Accelerator Frontier

Proposed Higgs Factories (2)

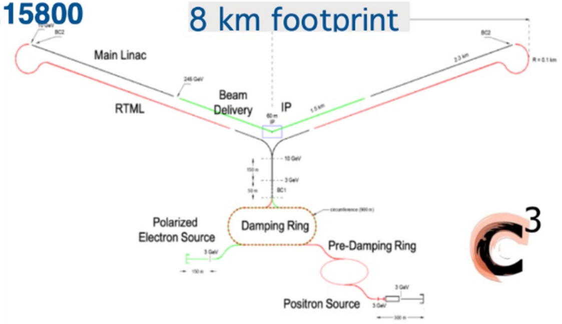
2203.07622



ILC

- SRF cavities, 31.5 to 35 MV/m
- "Shovel ready" (TDR in …), with potential for luminosity and energy upgrades

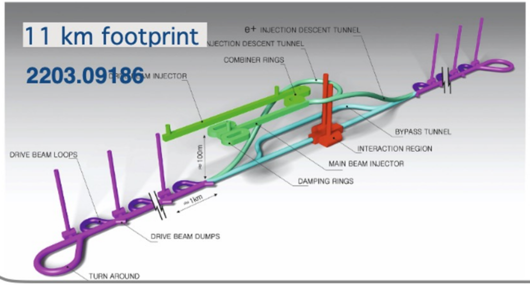
2110.15800



C³

- Normal conducting RF, 70MV/m @ 77K
- R&D (including demonstrator) needed
- Potential for upgrade up to 155MV/m

Proposed Higgs Factories (3)



CLIC

- Two-beam accelerating technique
- Room Temperature RF cavities, 72MV/m
- Potential for energy upgrades (up to 3TeV, 100 MV/m, 50km)
- CDR in 2012

FCC-ee

- Double ring e+e-
- Based on 60 years of experience. Key concepts demonstrated at previous colliders, few remaining challenges.
- Infrastructure will support the FCC-hh
- CDR in 2018, tunnel feasibility report expected in 2025

CEPC

2203.09451

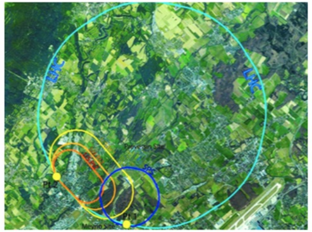
- Double ring e+e-, design very similar to the FCC-ee
- Infrastructure will support SPPC (and possibly ep)
- CDR in 2018, feasibility report expected in 2023

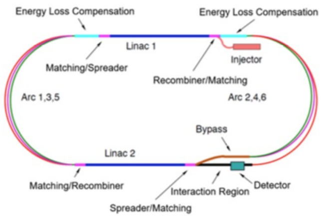
Proposed High Energy Colliders: pp

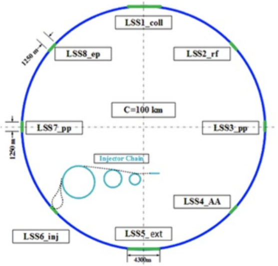
Collider	Type	$\sqrt{s}$ (TeV)	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP
HE-LHC	pp	27		15
FCC-hh	pp	100		30
SPPC	pp	75-125		10-20
LHeC	ep	1.3		1
FCC-eh		3.5		2
CLIC	ee	1.5	±80/0	2.5
		3.0	±80/0	5
μ-collider	$\mu\mu$	3		1
		10		10

FCC-hh
- Re-using FCC-ee infrastructure
- R&D for high field magnets (target 16T)
- CDR in 2019

Electron Recovery Linac based eh machines
- ERL components can be relocated from HL-LHC to FCC-hh - ERL well proven concept
- Electron beam at 50-60 GeV
- CDR in 2012 for LHeC and in 2020 for FCC-eh







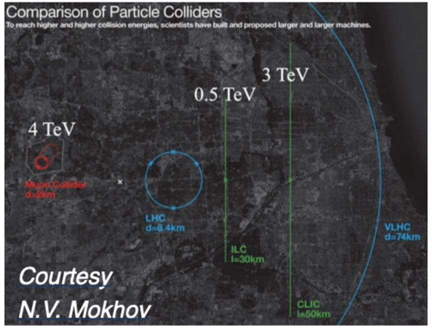
SPPC
- Same collider tunnel as CEPC
- 2-ring collider fed by injector chain of 4 accelerators
- R&D for high field magnets (target 20T)
- CDR in 2019

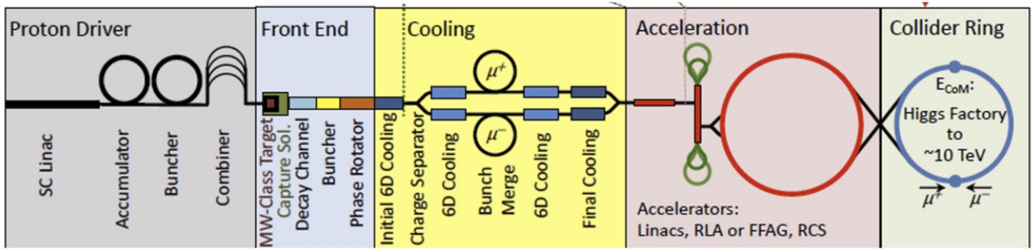
Proposed High Energy Colliders: Muon Collider

2209.01318

Parameter	Symbol	unit			
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Average field	$\langle B \rangle$	T	7	10.5	10.5
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5
Transverse emittance	ϵ	μm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP betafunction	β	mm	5	1.5	1.07
IP beam size	σ	μm	3	0.9	0.63

- **Multi TeV collider conventional production scheme based on proton driver**
- **R&D in proton source, target, cooling, magnets.**



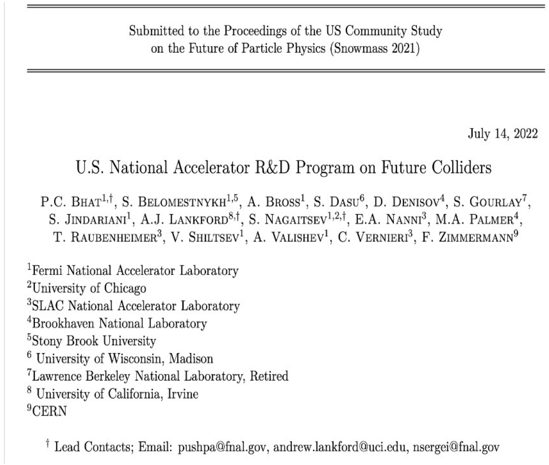


Muon Collider at Fermilab

- **Muon collider emerging as one of the solutions for a FNAL hosted machine**
  - **Aspiration to have a muon collider on site dating back to early 2000'**
- **Synergies with FNAL programs**
  - **Proton driver ↔ ACE**
  - **Target ↔ Mu2e-II target, RaDIATE**
  - **Acceleration ↔ high gradient RF cavities, fast cycling magnets**
  - **Magnets ↔ US-MDP**

Path forward: A few personal notes (1)

- Looking forward to the P5 deliberations, the findings of the FCC feasibility study and the outcome to the next European Strategy
    - Technical feasibility
    - Cost and environmental impact
    - World regions' balance of scientific leadership
- Critical to advancing in collider based HEP
    - Synergistic R&D in accelerators (technologies and machines)
    - Promote enhanced integration of HEP in R&D for accelerator


Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

July 14, 2022

U.S. National Accelerator R&D Program on Future Colliders

P.C. Bhat[1,†], S. Belomestnykh[1,5], A. Bross[1], S. Dasu[6], D. Denisov[4], S. Gourlay[7], S. Jindariani[1], A.J. Lankford[8,†], S. Nagaitsev[1,2,†], E.A. Nanni[3], M.A. Palmer[4], T. Raubenheimer[3], V. Shiltsev[1], A. Valishev[1], C. Vernieri[3], F. Zimmermann[9]

[1]Fermi National Accelerator Laboratory
[2]University of Chicago
[3]SLAC National Accelerator Laboratory
[4]Brookhaven National Laboratory
[5]Stony Brook University
[6] University of Wisconsin, Madison
[7]Lawrence Berkeley National Laboratory, Retired
[8] University of California, Irvine
[9]CERN

[†] Lead Contacts; Email: pushpa@fnal.gov, andrew.lankford@uci.edu, nsergei@fnal.gov

Path forward: A few personal note (2)

- We are in the midst of the exploration of the unknown (more than a crisis?)
  - The LHC has already led to a Nobel Prize!
  - The LHC is one of the most prolific (the most?) scientific instruments in the history: ~3500 PHYSICS PAPERS FROM THE 4 LARGE EXPERIMENTS
  - Run 3 is progressing well, HL-LHC will produce Run2 x 20
- It is key
  - To change the conversation within HEP and within the broader community:
    - We have signs of BSM, but we have no idea about the fundamental theory of Nature: LOTS to explore
    - Colliders ARE very powerful probes of the Universe
    - Revolutionary discoveries are ahead of us
  - Nurture and build stronger and stronger connections among ‘frontiers’ towards a truly comprehensive and integrated approach

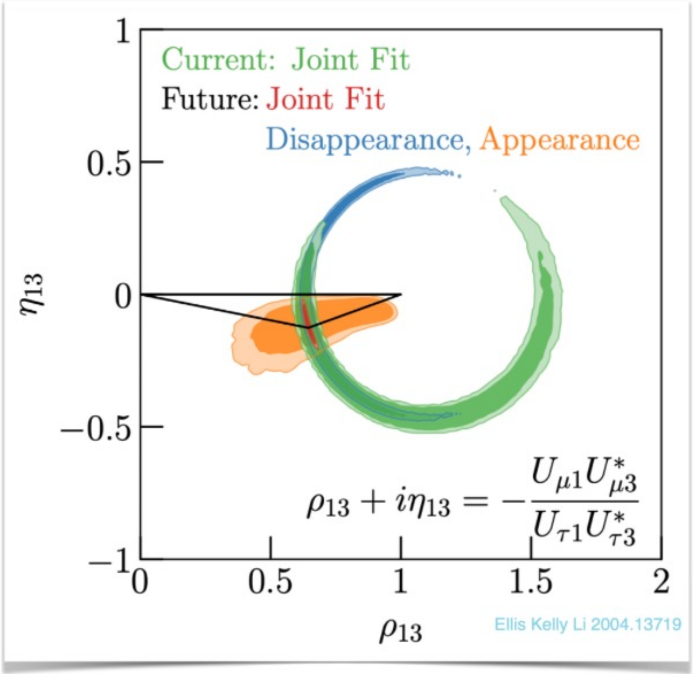
Congratulations

- Leaders who defined and shaped particle physics!
- Inspirational role models!
- Colleagues who instill excitement at every and each opportunity!
- Very kind, present, and warm friends!

Grazie,
Marcela and Carlos!

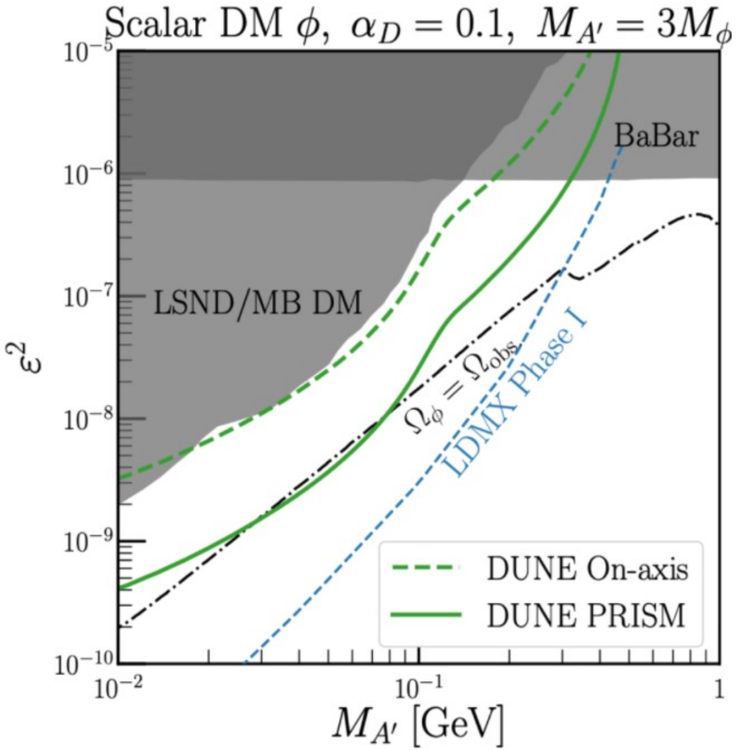
The future of neutrino physics

- Why neutrinos?
  - Mass mechanism is qualitatively different from charged fermions
  - There is no experimental hint of the scale at which neutrino masses are generated
  - Neutrinos are the only fermions which could be Majorana
- In the near future, we will have a precision neutrino physics program
  - DUNE, HK, JUNO: pin down all standard oscillation parameters
  - Measure oscillation probabilities in many channels, at different energies and baselines, to the % or sub-% level
  - Lots of redundancy, which is key to discover new physics:
    - Beam neutrinos: θ_{23}, δ_{cp}, $\Delta m^2_{\mu\mu}$, mass ordering
    - Reactor neutrinos: θ_{12}, Δm^2_{ee}, mass ordering
    - Solar neutrinos: θ_{12}, Δm^2_{21}, matter effects
    - Atmospheric neutrinos: θ_{23}, Δm^2_{31}, mass ordering, δ_{cp}, matter effects

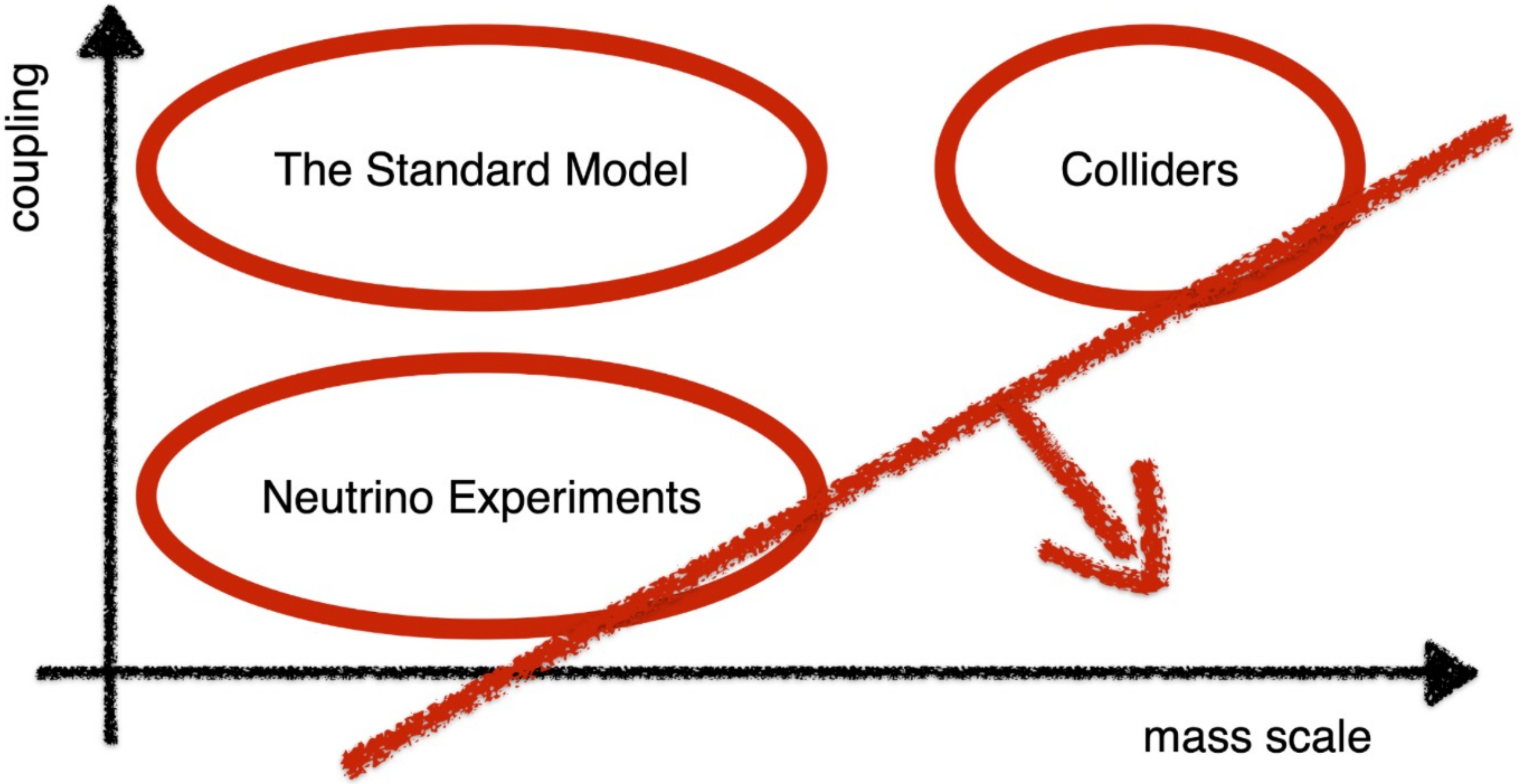


The future of neutrino physics

- But neutrinos >> neutrinos!!
  - Near detectors can probe light, weakly coupled physics: axions, dark matter, HNLs, dark photons
  - While far detectors can probe consequences of unification: proton decay, neutron-antineutron oscillation
  - Oscillation physics can be sensitive to novel particles and interactions, and to astrophysics: ultralight dark matter, extra dimensions, supernova
- From a practical point of view, having an intense neutrino beam requires a versatile, powerful proton beam, which carries synergies with beam dump experiments and other intensity frontier efforts



The future of neutrino physics



Backup slides

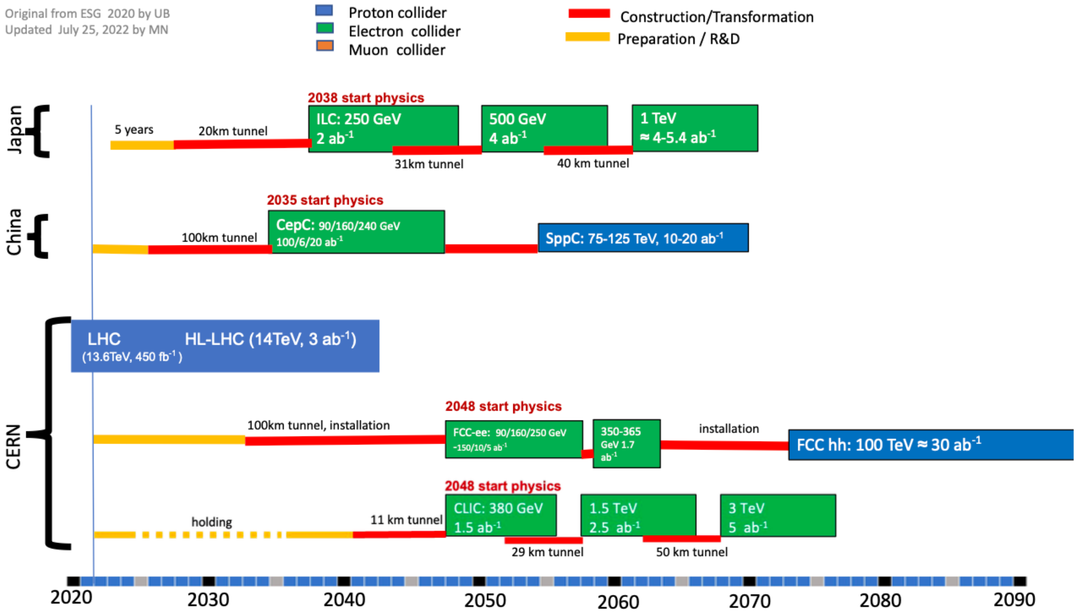


Figure 6-40. *Projected timelines for R&D, construction, and physics operations for some of the leading proposed future collider options.*

The US EF community proposes to develop plans to site an e^+e^- collider in the US. A Muon Collider remains a highly appealing option for the US, and is complementary to a Higgs factory. For example, some options which are considered as attractive opportunities for building a domestic EF collider program are:

- **A US-sited linear e^+e^- (ILC/CCC) Collider**
- **Hosting a 10 TeV range Muon Collider**
- **Exploring other e^+e^- collider options to fully utilize the Fermilab site**

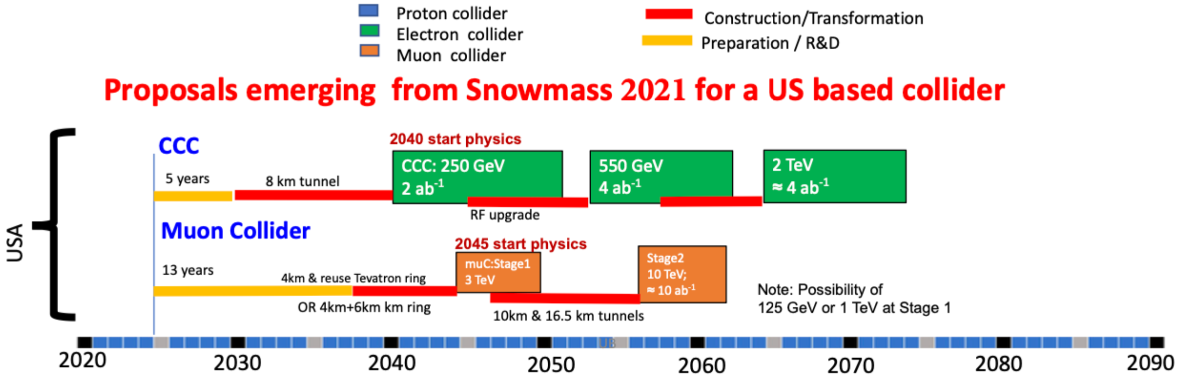


Figure 6-41. *Approximate timelines for proposals for ILC/CCC and Muon Collier emerging from Snowmass 2021 for a US based collider option.*