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Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Energy Frontier Working Group

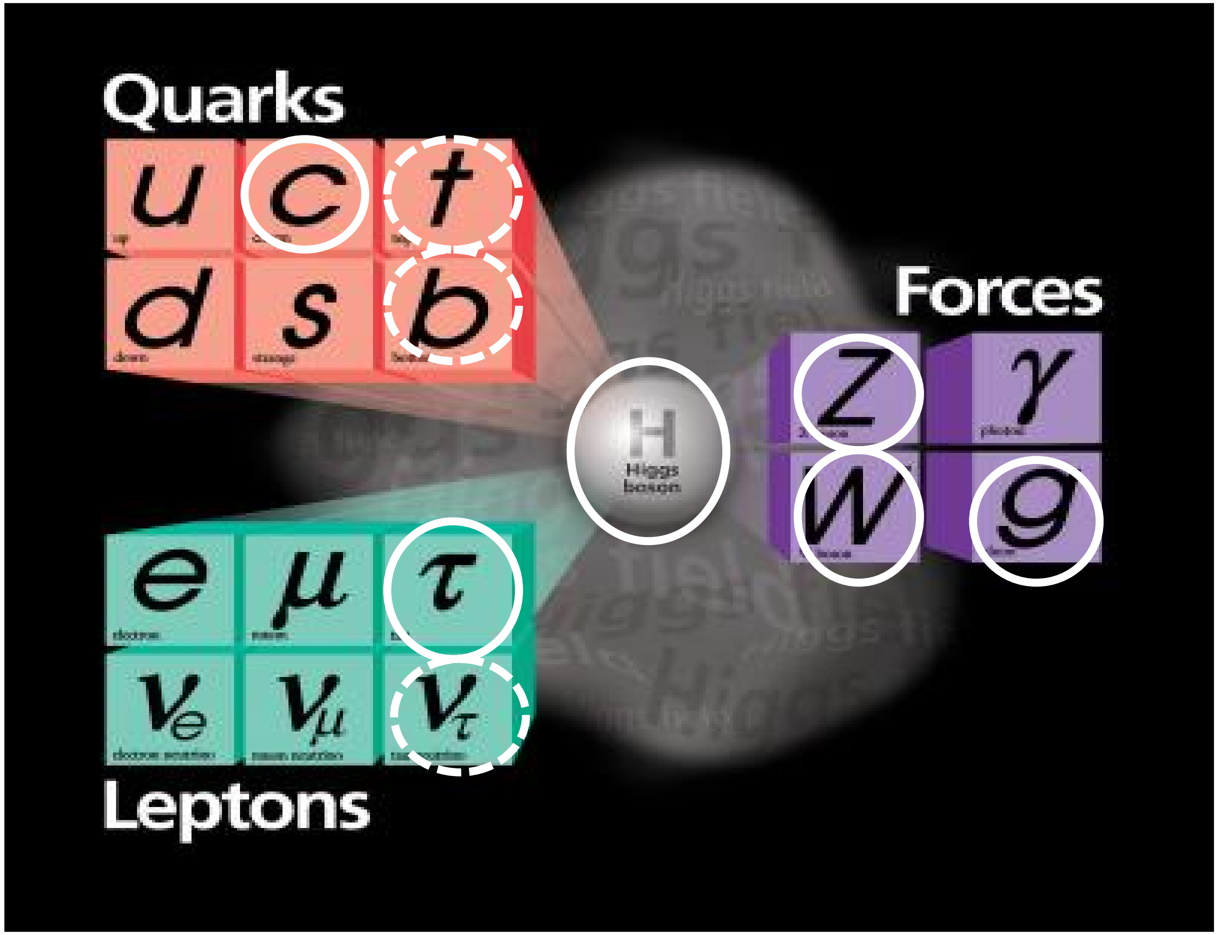
(what to consider for the next Snowmass)

Two very productive meetings with agendas at
https://indico.fnal.gov/conferenceDisplay.py?confId=14207
https://indico.fnal.gov/conferenceDisplay.py?confId=14208

Conveners: John Campbell, Anadi Canepa, Dmitri Denisov, Bogdan Dobrescu, Sergo Jindariani, Vladimir Shiltsev

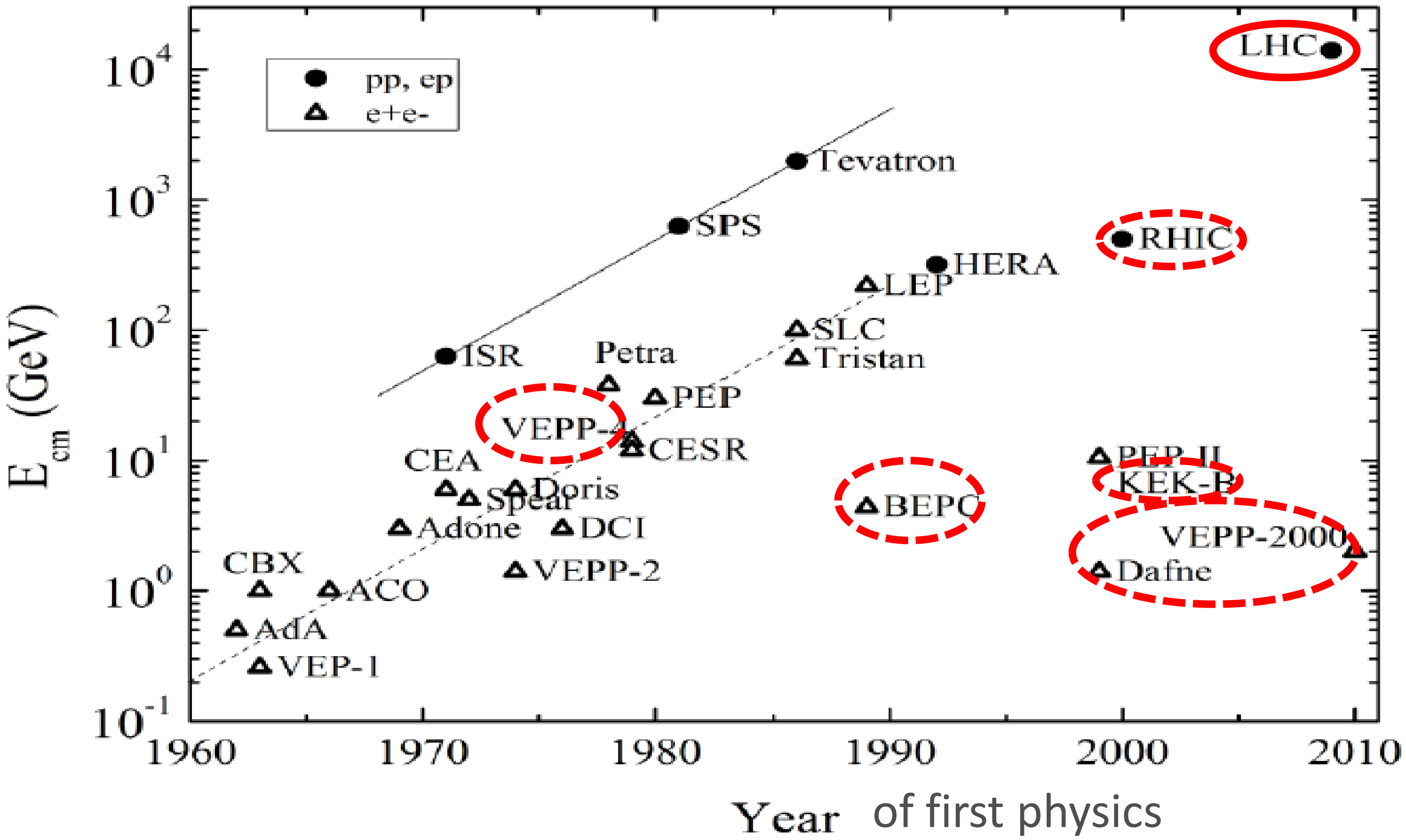
Fermilab Scientists Retreat, May 4, 2017

High Energy Accelerators and the Particle Physics



- Energy frontier accelerators were critical for the developments of our understanding of sub-atomic world over last fifty years
  - Fermilab at the energy frontier: 1972-1981 and 1985-2009

Operating or Soon to be Operating Colliders



- Single energy frontier collider – the LHC, now at 13 TeV
  - RHIC at BNL – nuclear studies

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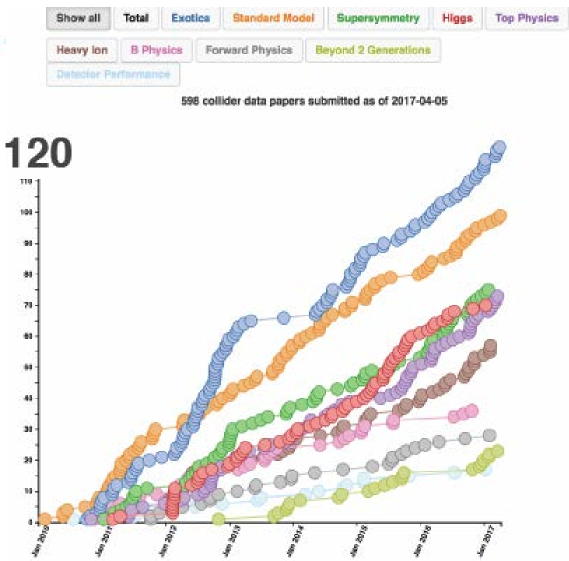
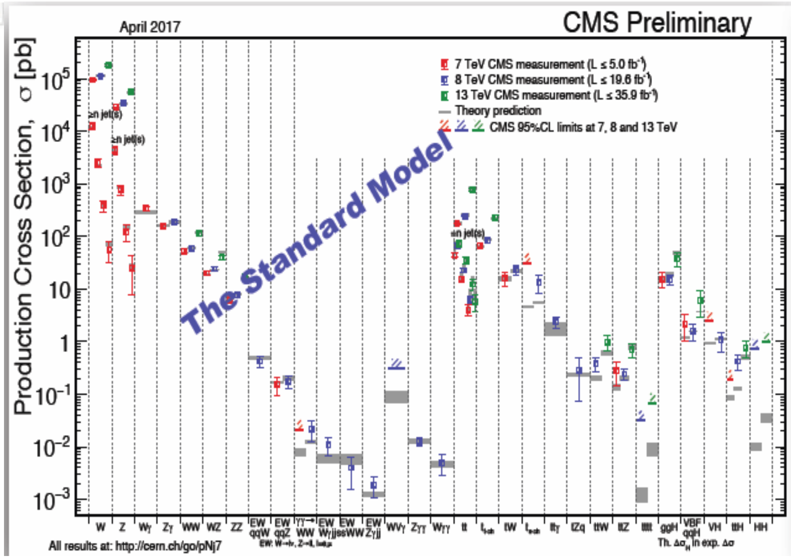
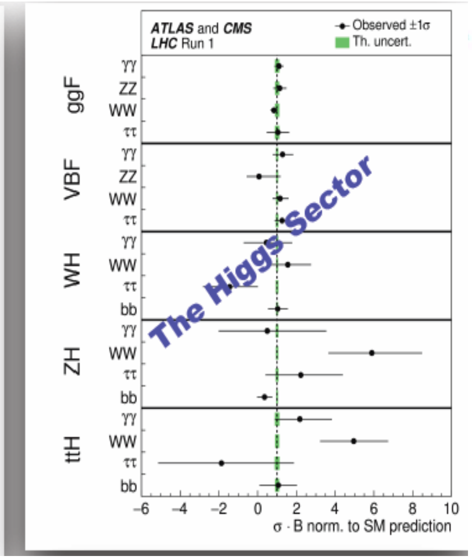
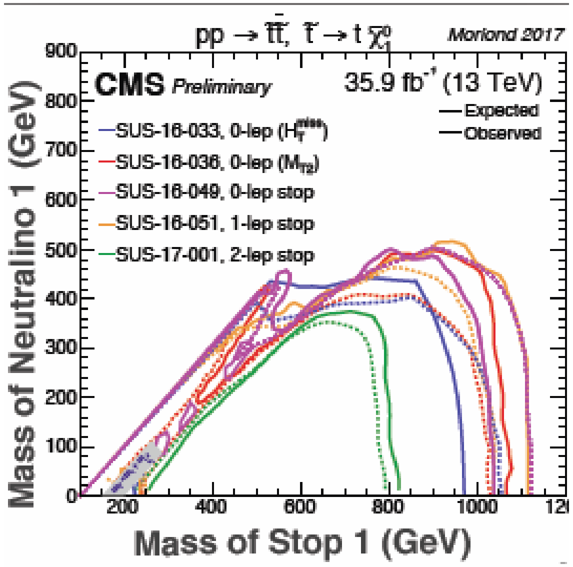
The LHC

CMS Publications



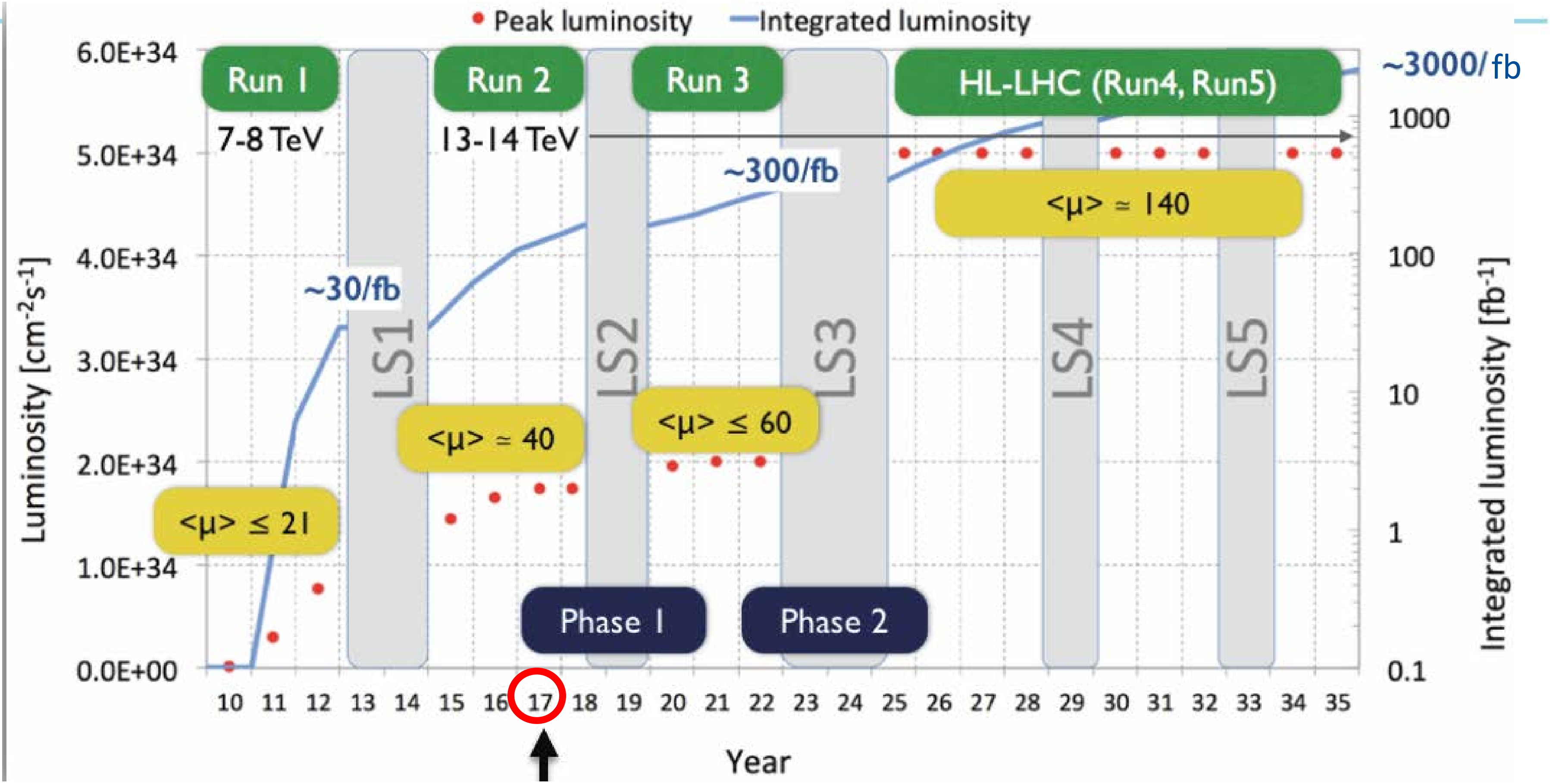






- Rich physics program covering three P5 science drivers
  - Higgs, dark matter and search for unknown
- Large number of studies
  - Excellent accuracy of the standard model measurements
  - High chances of making fundamental discoveries
  - New results will guide particle physics developments

LHC and HL-LHC



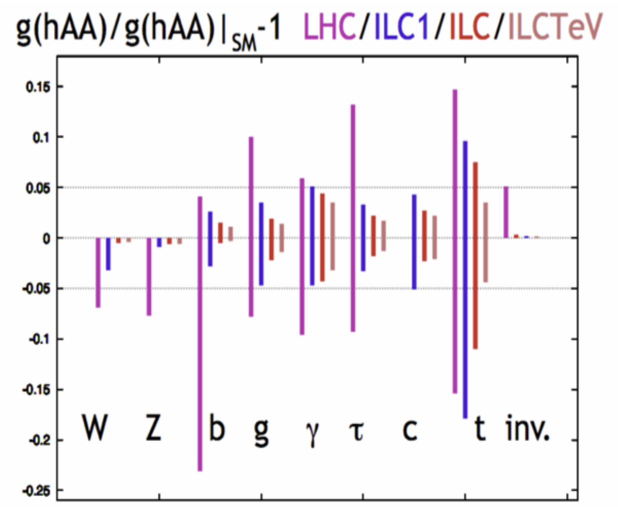
- Currently accumulated only ~1% of the total expected luminosity
- HL-LHC (High Luminosity LHC) will bring luminosity of ~3 ab^{-1}
  - US participation in accelerator and detectors upgrades at HL-LHC is high P5 priority

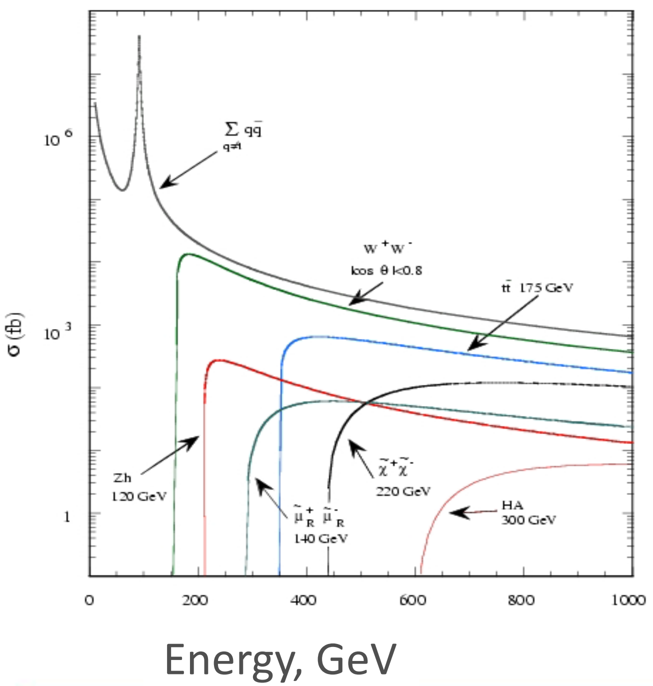
Future Colliders Physics Drivers

- Studies of the Higgs boson and other standard model particles with extremely high precision
  - "Higgs factory" – a lepton collider with a center of mass energy ~250 GeV and above to study the Higgs boson, Z/W bosons and the top quark

- Understanding of the fundamental laws of physics at distances up to $\sim 10^{-19}$ cm and particles masses above LHC reach
  - pp collider at an energy above LHC
  - A multi-TeV muon collider

- Two prong approach
  - Precision measurements of the standard model parameters and search for new physics at higher energies and shorter distances





Lepton colliders

Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry

- Colliding point-like particles
- Extremely high precision standard model measurements
  - Including Higgs couplings to a few % precision
- Search for electroweak coupled new particles
- Studies of any newly discovered particles

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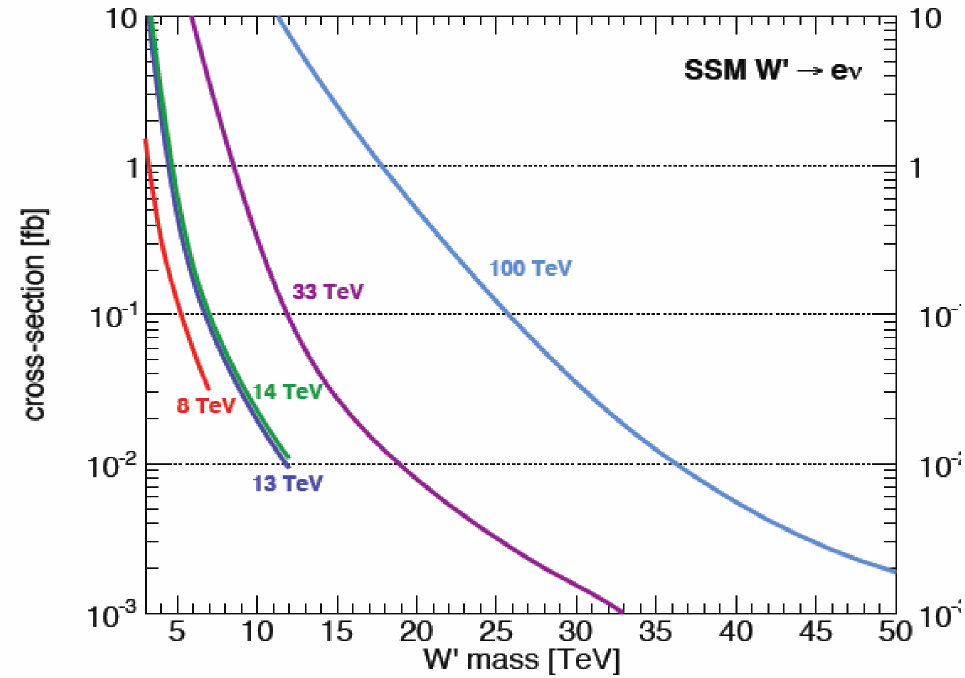
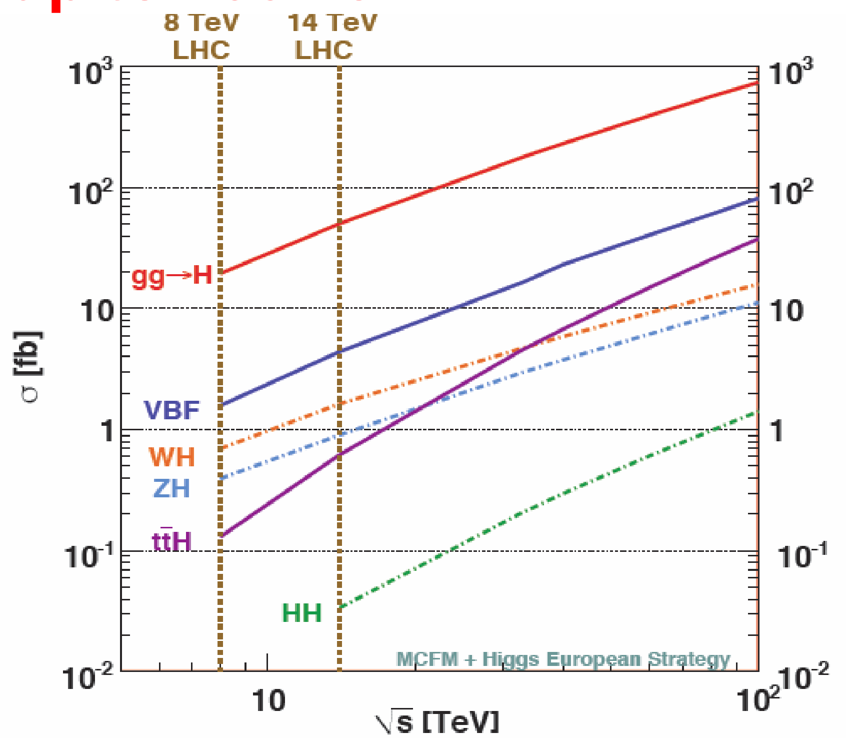
Hadron Colliders up to 100 TeV





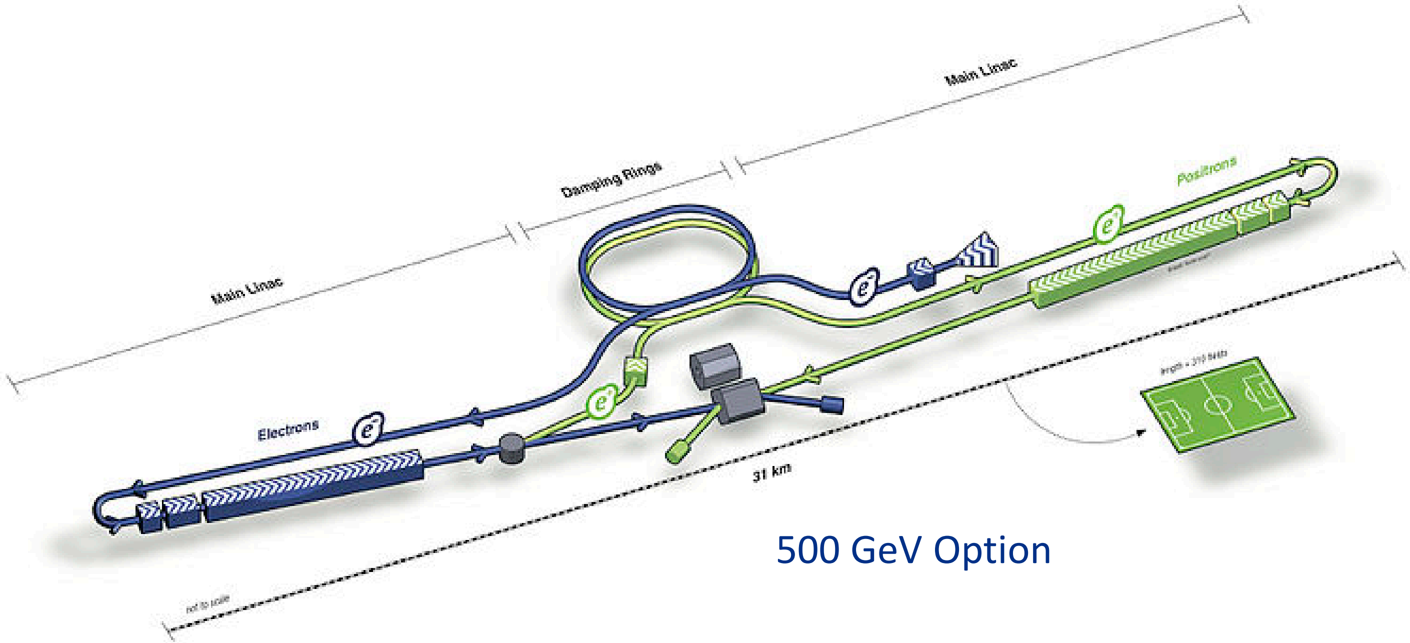
- High-energy collisions directly probe the laws of nature at the shortest accessible distances
- Particles with masses up to ~1/2 of the full energy could be produced
- Large number of standard model particles to be produced
  - Begin precision tests of Higgs potential

process	precision on σ_{SM}	precision on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	2%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$\sim 25\%$	$\lambda_3 \in [\sim 0.6, \sim 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$\sim 15\%$	$\lambda_3 \in [\sim 0.8, \sim 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$\sim 100\%$	$\lambda_4 \in [\sim -4, \sim +16]$

Medium Term Colliders Projects Under Development

- **ILC - International Linear Collider**
  - 250 GeV linear e^+e^- collider (recent option has “staging” with second stage at 500 GeV)
  - Higgs factory (and top quark factory after upgrade)
  - Location – Japan
- **CLIC – Compact LInear Collider**
  - 380 GeV linear e^+e^- collider (with potential upgrade up to ~2 TeV)
  - Higgs factory and top factory
  - Location CERN
- **CepC – Circular Electron Positron Collider**
  - ~380 GeV circular e^+e^- collider (the tunnel could later be used for pp ~100 TeV collider)
  - Higgs factory and top factory
  - Location – China
- **FCC – Future Circular Colliders**
  - 350 GeV e^+e^- and/or ~100 TeV pp and “high energy LHC”
  - Higgs factory and/or next energy frontier
  - Location – CERN

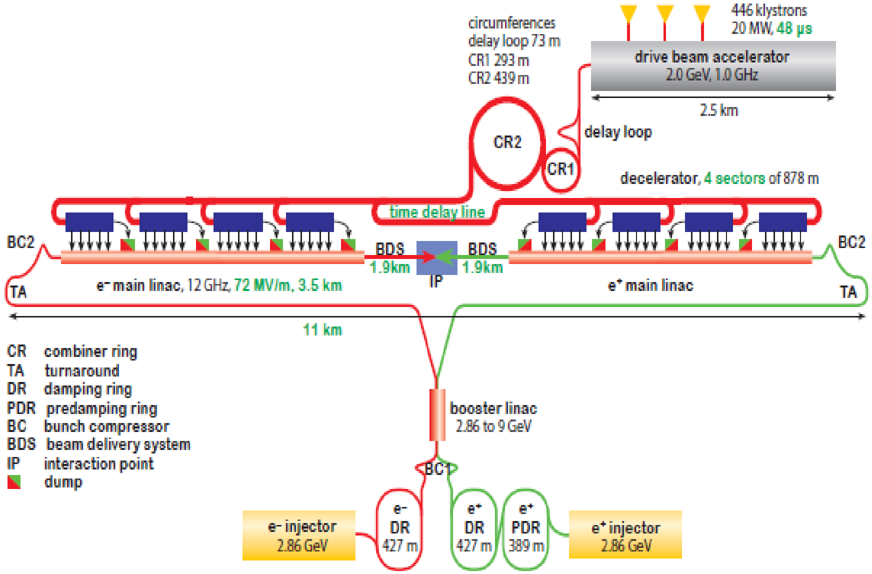
International Linear Collider

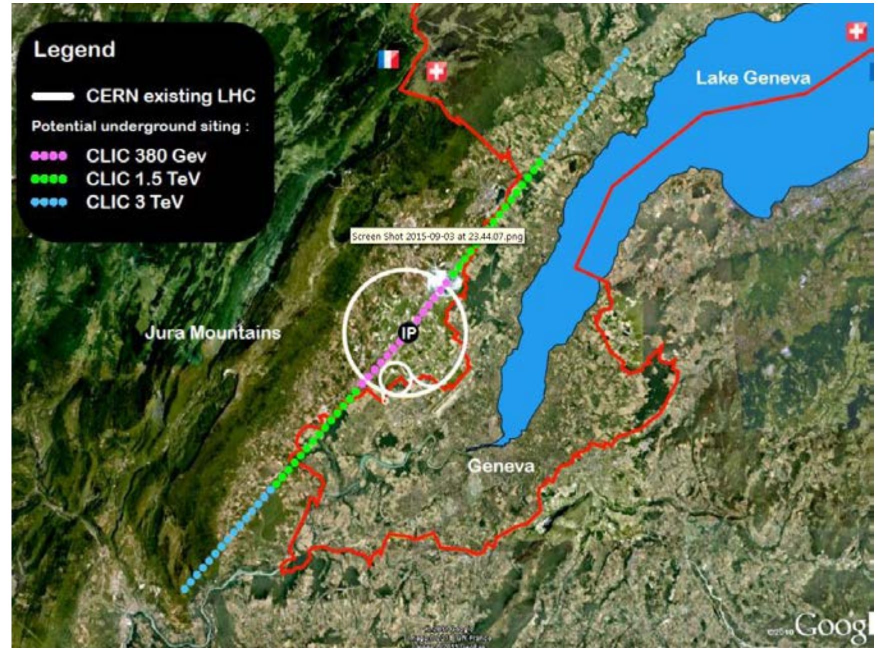


500 GeV Option

- ILC is e^+e^- linear collider based on superconducting RF technology
  - Center of mass energy 250 GeV (enough to produce Higgs in ZH final state)
  - Luminosity $>10^{34}$ $cm^{-2}s^{-1}$
- Long tunnel to accelerate to ~125 GeV/beam with ~31 MV/m acceleration rate
  - Excellent Higgs factory with many Higgs production and decay channels accessible
- Fermilab’s experience in superconducting RF, cryogenic and detectors is critical

CLIC Collider at CERN





- CLIC is linear e^+e^- collider based on “warm” RF technology with 70+ MV/m acceleration
- 11 km long for 380 GeV energy
- Under active design development

Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site length	km	11	50

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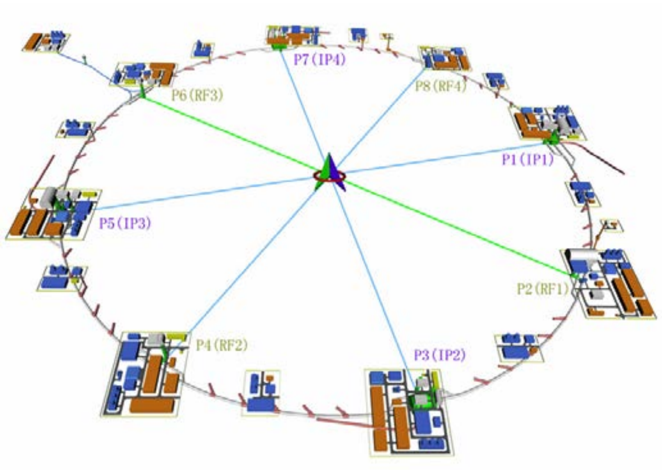
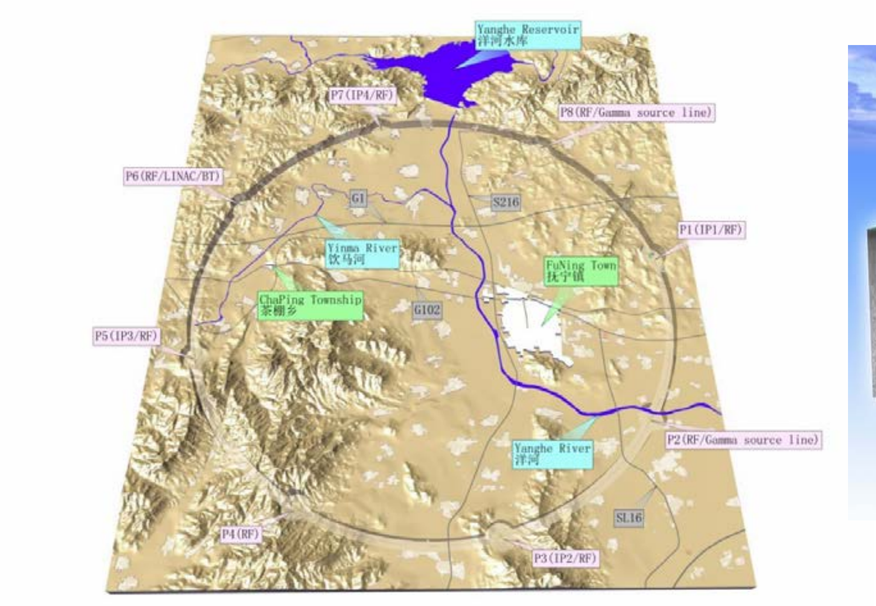
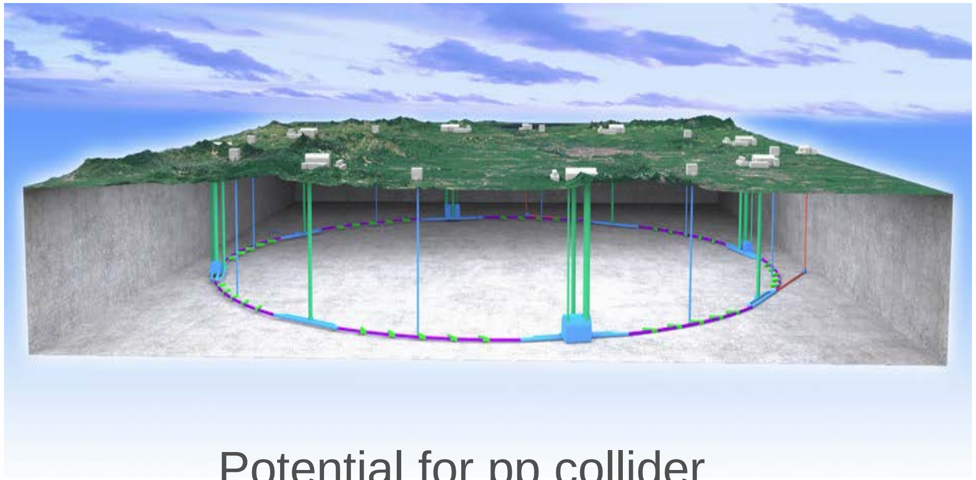
CepC Collider in China

- CepC – Circular Electron Positron Collider
  - 100 km long ring
    - Increase in comparison with the original proposal
  - 90-250-380 GeV in the center of mass
  - Z boson, Higgs and top factory
- Main technologies
  - Low field magnets, superconducting RF
- Design is under active development in China







Potential for pp collider
in the same tunnel with 100 TeV

Future Circular Colliders at CERN - e^+e^- Collider

Parameter	FCC-ee			LEP2
Energy/beam [GeV]	45	120	175	105
Bunches/beam	13000-60000	500-1400	51- 98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**21 - 280**	**5 - 11**	**1.5 - 2.6**	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchrotron Power [MW]	100			22
RF Voltage [GV]	0.3-2.5	3.6-5.5	11	3.5

- Circular e^+e^- collider designed on successful LEP experience
- With 350 GeV center of mass – Z, Higgs and top factory
- Main challenges: long tunnel and high synchrotron losses requiring demanding superconducting RF system and high power consumption

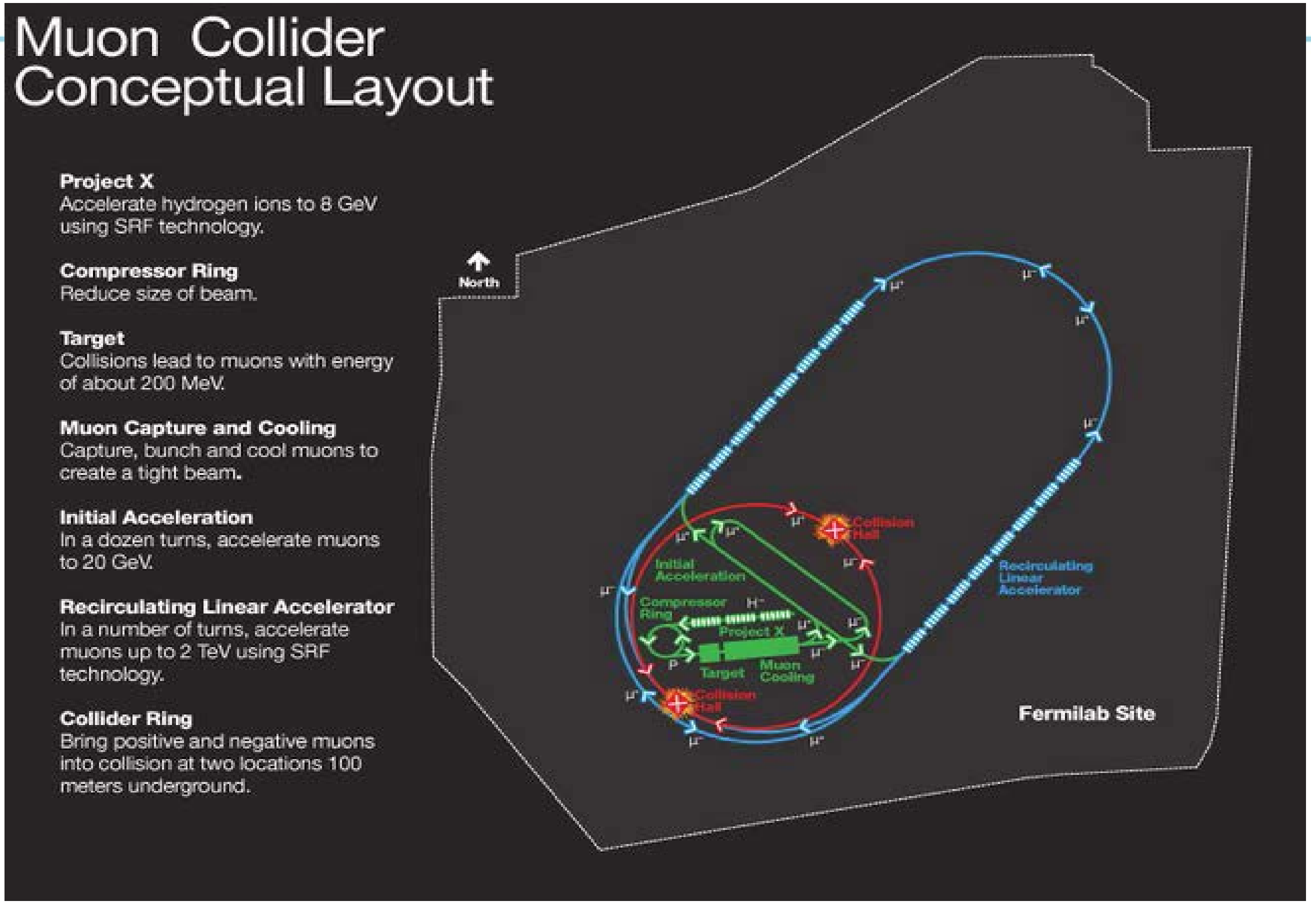
Future Circular Colliders at CERN - pp 100 TeV collider

Parameter	FCC-pp	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5 - 25 x 10^{34}	5 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- Main challenges
  - Long tunnel, high field magnets, high synchrotron radiation load (yes for pp collider…)
- Fermilab has unique capabilities in high field magnets

FCC study is to finish by the end of 2018 as an input to the next European Strategy discussion

Muon Collider



- Main challenge is fast cooling of muons
- Studies (not in US) are progressing and new ideas been developed

- Could be used as Z, Higgs, top factory
  - Such collider will fit in the Main Injector tunnel
    - S-channel Higgs factory can have diameter of less than ~100 meters
- An option if 2-10 TeV lepton collider will be required, based on LHC discoveries

High Energy pp Collider - VLHC

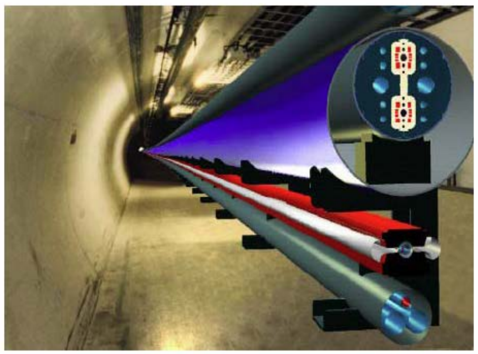
Very Large Hadron Collider

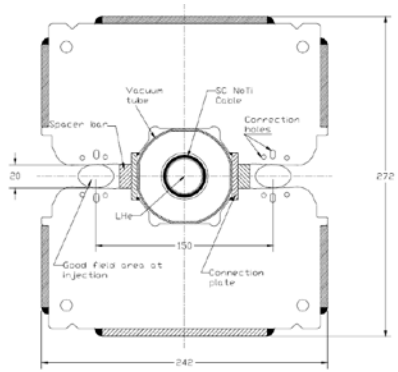
Fermilab-TM-2149

June 4, 2001

Design Study for a Staged Very Large Hadron Collider

Report by the collaborators of
The VLHC Design Study Group:
Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Laboratory of Nuclear Studies, Cornell University
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center





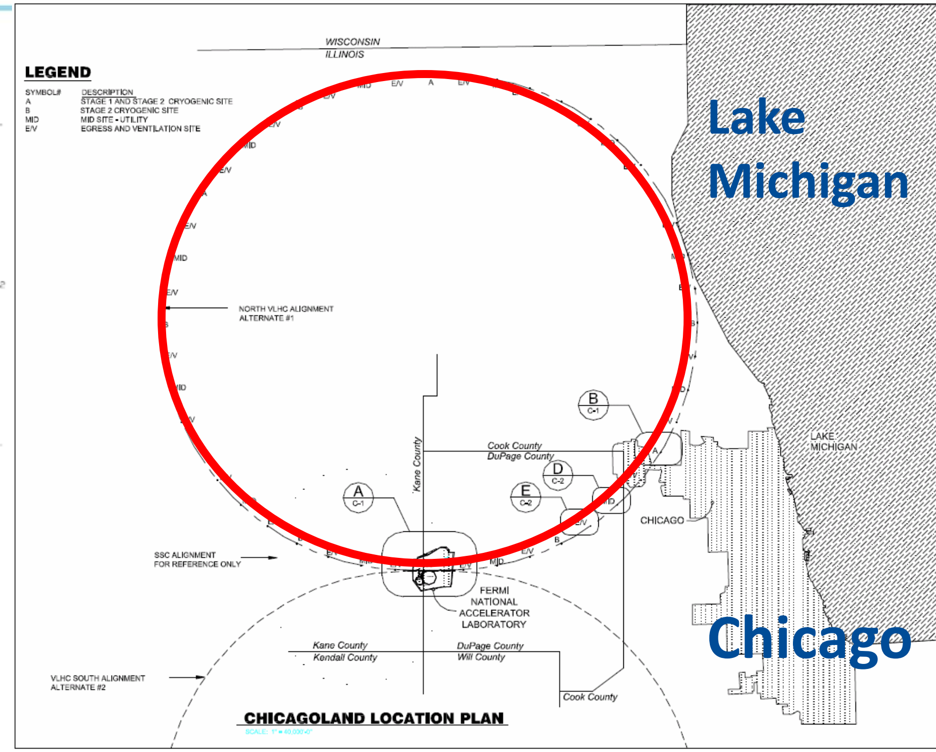


Table 1.1. The high-level parameters of both stages of the VLHC.

	Stage 1	Stage 2
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	175
Number of interaction regions	2	2
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.0×10^{34}
Luminosity lifetime (hrs)	24	8
Injection energy (TeV)	0.9	10.0
Dipole field at collision energy (T)	2	9.8
Average arc bend radius (km)	35.0	35.0
Initial number of protons per bunch	2.6×10^{10}	7.5×10^{9}
Bunch spacing (ns)	18.8	18.8
β^* at collision (m)	0.3	0.71
Free space in the interaction region (m)	± 20	± 30
Inelastic cross section (mb)	100	130
Interactions per bunch crossing at L_{peak}	21	54
Synchrotron radiation power per meter (W/m/beam)	0.03	4.7
Average power use (MW) for collider ring	25	100
Total installed power (MW) for collider ring	35	250

- Main idea of 2001 design
  - Long tunnel vs high field magnets
  - Simple 2 T “single turn” magnet in ~200 km tunnel can provide 40 TeV
  - 175 TeV with 10 Tesla magnet

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News Ideas in Accelerators and Detectors

- Developments in accelerators and detectors were critical for the progress in particle physics
  - Strong focusing, anti-proton production/cooling, superconducting magnets and many others
- To get to the next energy frontier developments in accelerator physics and technology are critical
  - To proceed to even higher energies while keeping *cost* reasonable
  - Superconducting RF, high field magnets, cryogenics are among technologies critical for all machines under consideration
    - New technologies/materials (graphene, high temperature superconductivity, etc.) important to follow closely
  - New ideas in accelerator physics are critical, like new ideas in muon cooling
- New accelerator technologies (plasma, lasers, crystals, etc.)
  - Understand potential and limitations
- Detectors for the proposed machines will be challenging
  - High radiation, extreme coordinate and energy resolution, high data volumes

Proposed Fermilab Activities at the Energy Frontier
(in cooperation with DPF, US and international HEP communities)

- 2017-2021
  - Highest priority is LHC
    - Complete Phase I upgrades, HL-LHC upgrades and LARP, data analysis
  - Participate in activities in Asia and Europe: ILC, CLIC, FCC, CepC
    - To be ready for involvement
  - Develop critical accelerator technologies: SRF and high field magnets
  - Develop proposal(s) for potential energy frontier facility in US for Snowmass
- 2021-2026
  - Participate in HL-LHC detectors upgrades and LARP construction/installation and LHC data analysis
  - Based on Snowmass/P5 outcome develop US energy frontier project
  - Participate in the projects under construction/design in Europe and/or Asia
- 2026 and beyond
  - Participate in HL-LHC data collection and analysis
  - Design/construction of the next energy frontier facility in US
  - Participation in the energy frontier programs in other regions