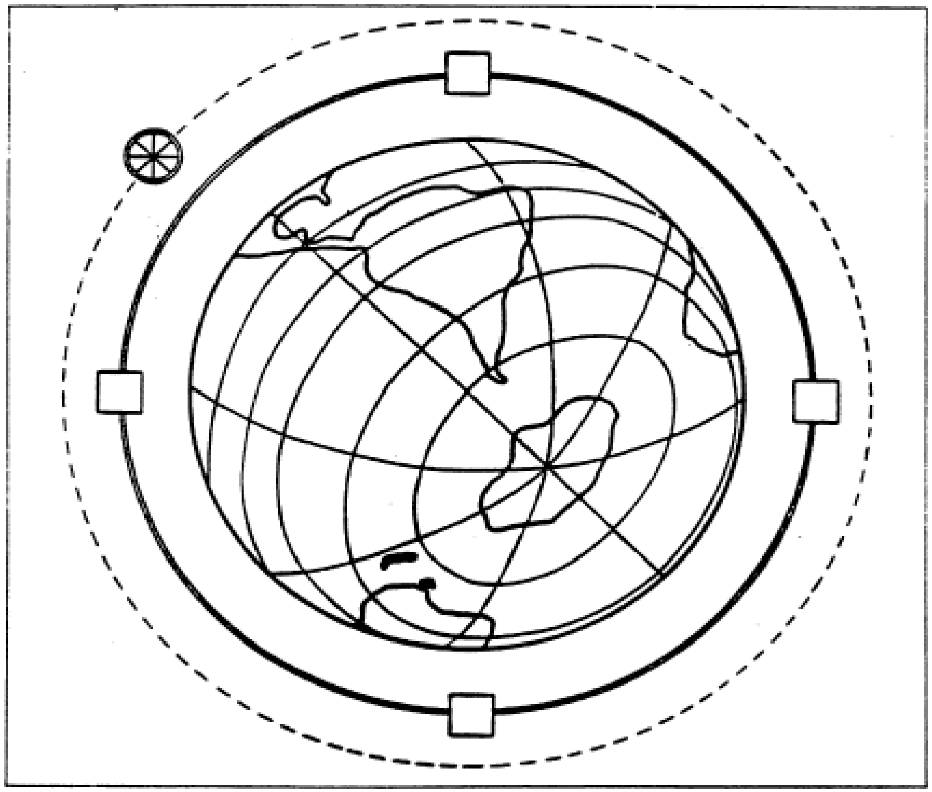
Future Colliders and European Strategy Update



From a 1954 Slide by Enrico Fermi, University of Chicago Special Collections.

Dmitri Denisov, Fermilab

Fermilab Users Meeting, June 21 2018

Outline

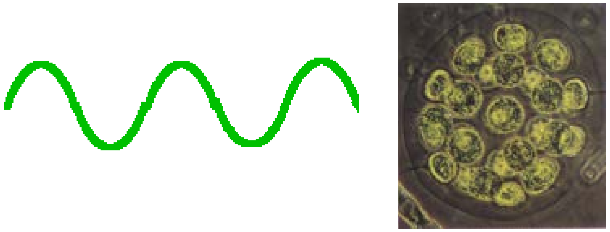
- Why high energy colliders?
- Overview of past and present colliders
- Future colliders challenges
- Medium term future colliders options
  - ILC, CepC, CLIC, FCC
- European Strategy update
- Summary

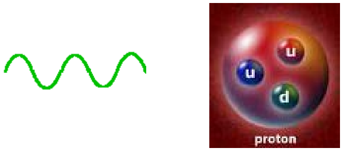
Why High Energy and Why Colliders

- Accelerators are built to study the Nature smallest objects

Wavelength = h/E

~2 ·10^{-18} cm for LHC



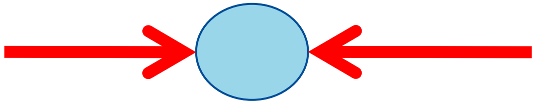


- Accelerators convert energy into mass

$E = mc^2$

Objects with masses up to

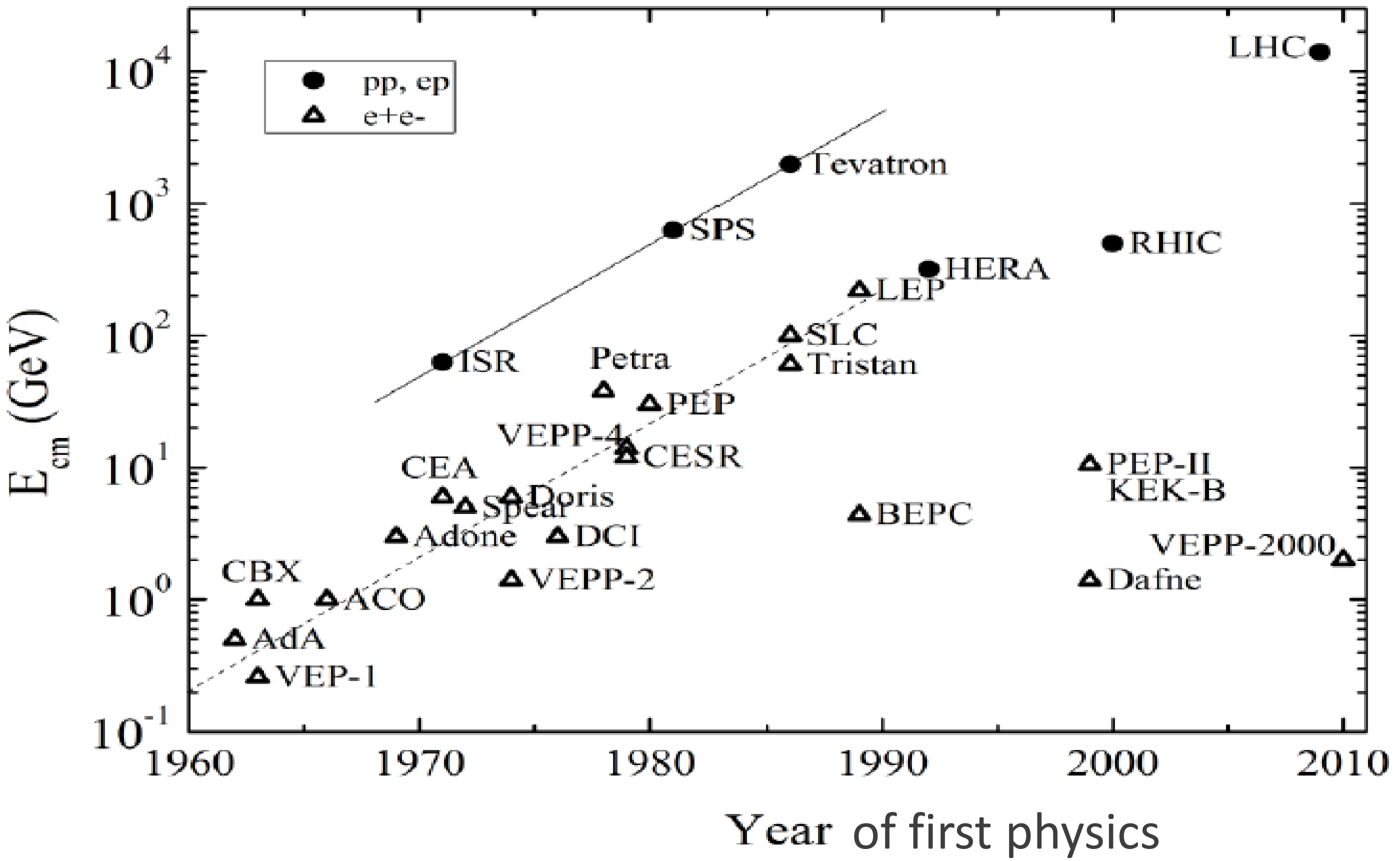
Mass = $2E_{beam}$ could be created



Collider center of mass energy is $2E_{beam}$ instead of $\sqrt{(2mE_{beam})}$ for fixed target

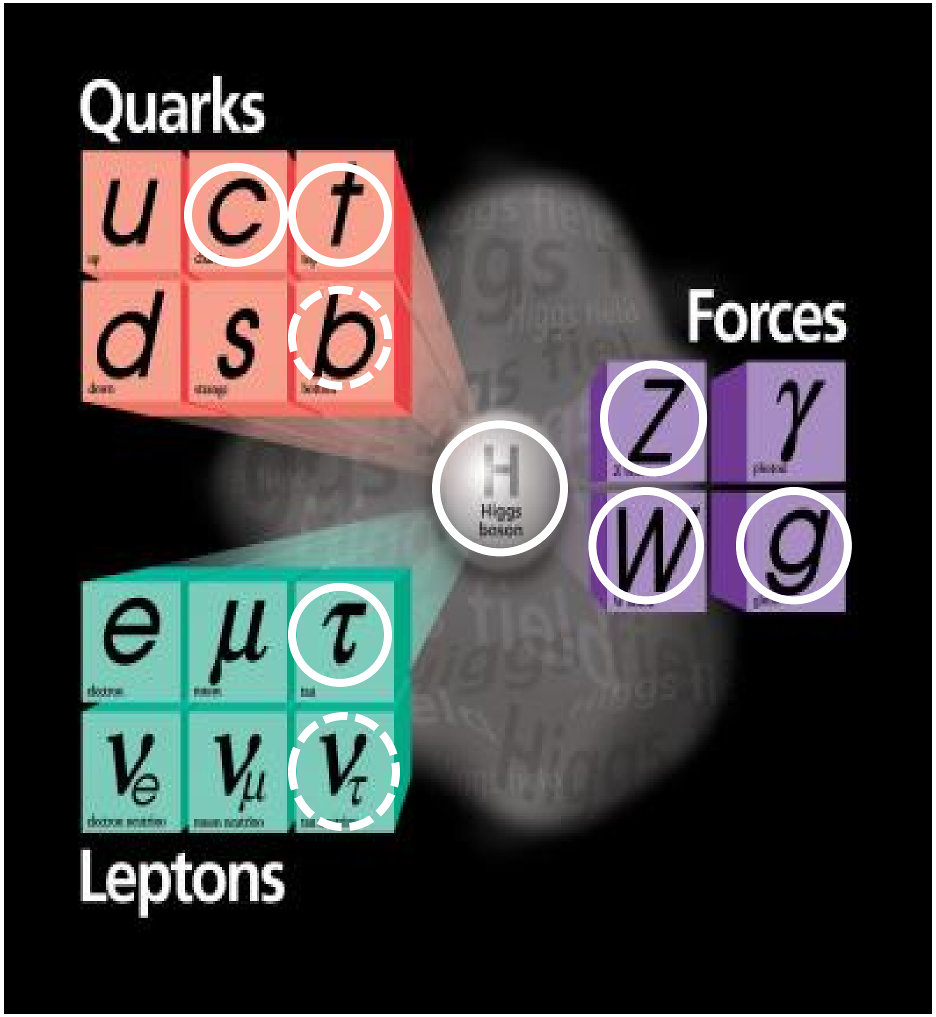
To get to the next step in understanding of Nature - at both smaller distances and higher masses - high energy colliders is the only way to proceed

Colliders



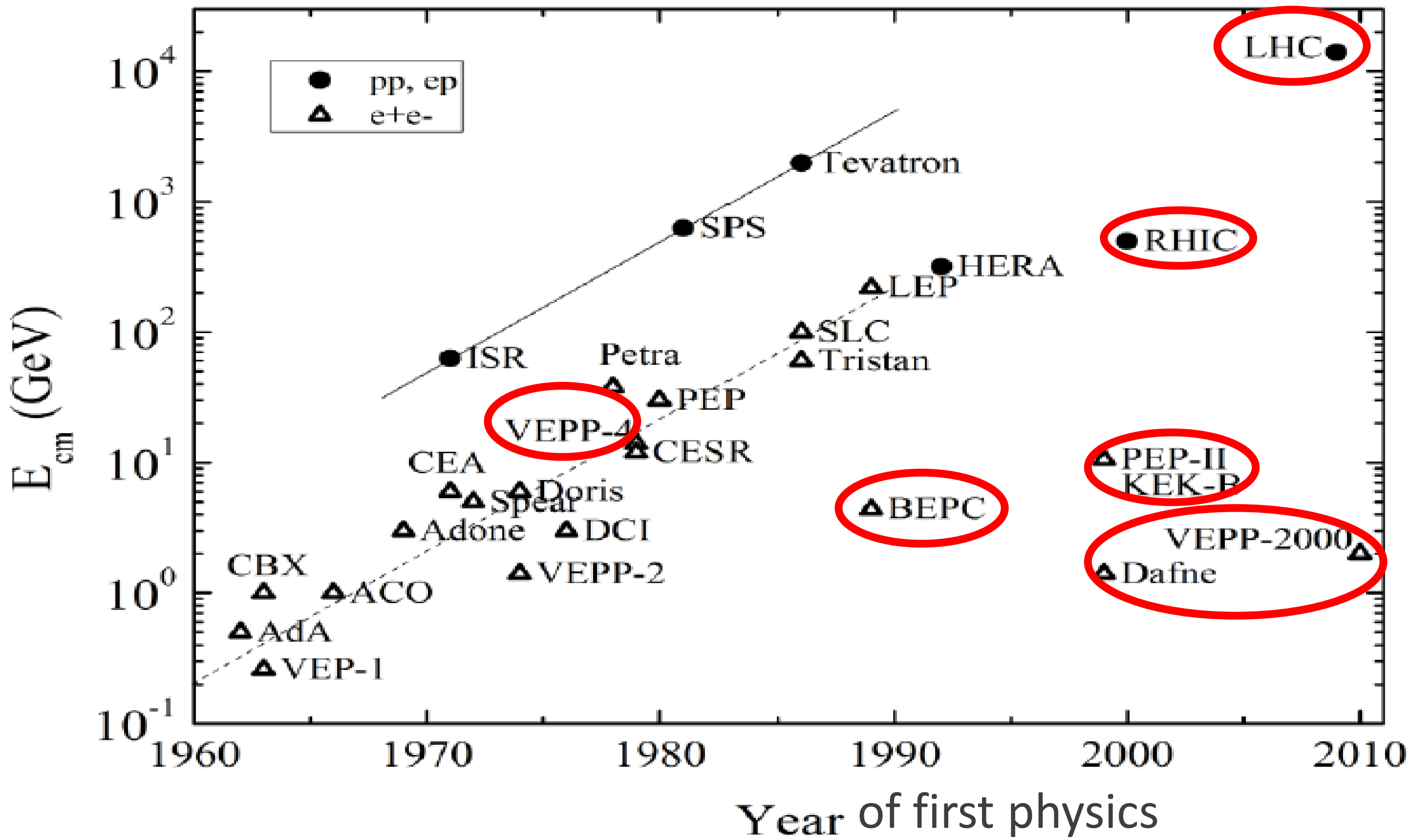
- First e^+e^- colliders started operation in early 1960's with hadron colliders (storage ring) first collisions in 1971 with the completion of the ISR
- Large number of e^+e^- colliders, while few hadron colliders
- Hadron colliders provide higher center of mass energy, while colliding "composite" particles

Colliders and the Standard Model



- Progress in particle physics over past 50 years was closely related to discoveries at ever more powerful colliders
  - e^+e^- colliders
    - c quark, tau lepton, gluon
  - Use of antiprotons in the same ring as protons
    - W and Z bosons
  - Superconducting magnets
    - Top quark and the Higgs boson
- All expected standard model elementary particles have been discovered by now
  - b-quark and tau neutrino in fixed target experiments at Fermilab

Operating Colliders



- Single high energy hadron collider – the LHC, now at 13 TeV
  - RHIC at BNL – nuclear studies
- DAFNE (Frascati), VEPP (Novosibirsk), BEPC (Beijing) – low energy e^+e^- colliders
- SuperKEK-B – b-factory at KEK re-starting physics in 2018 with ~40 times higher luminosity
  - Studies of particle containing b-quarks

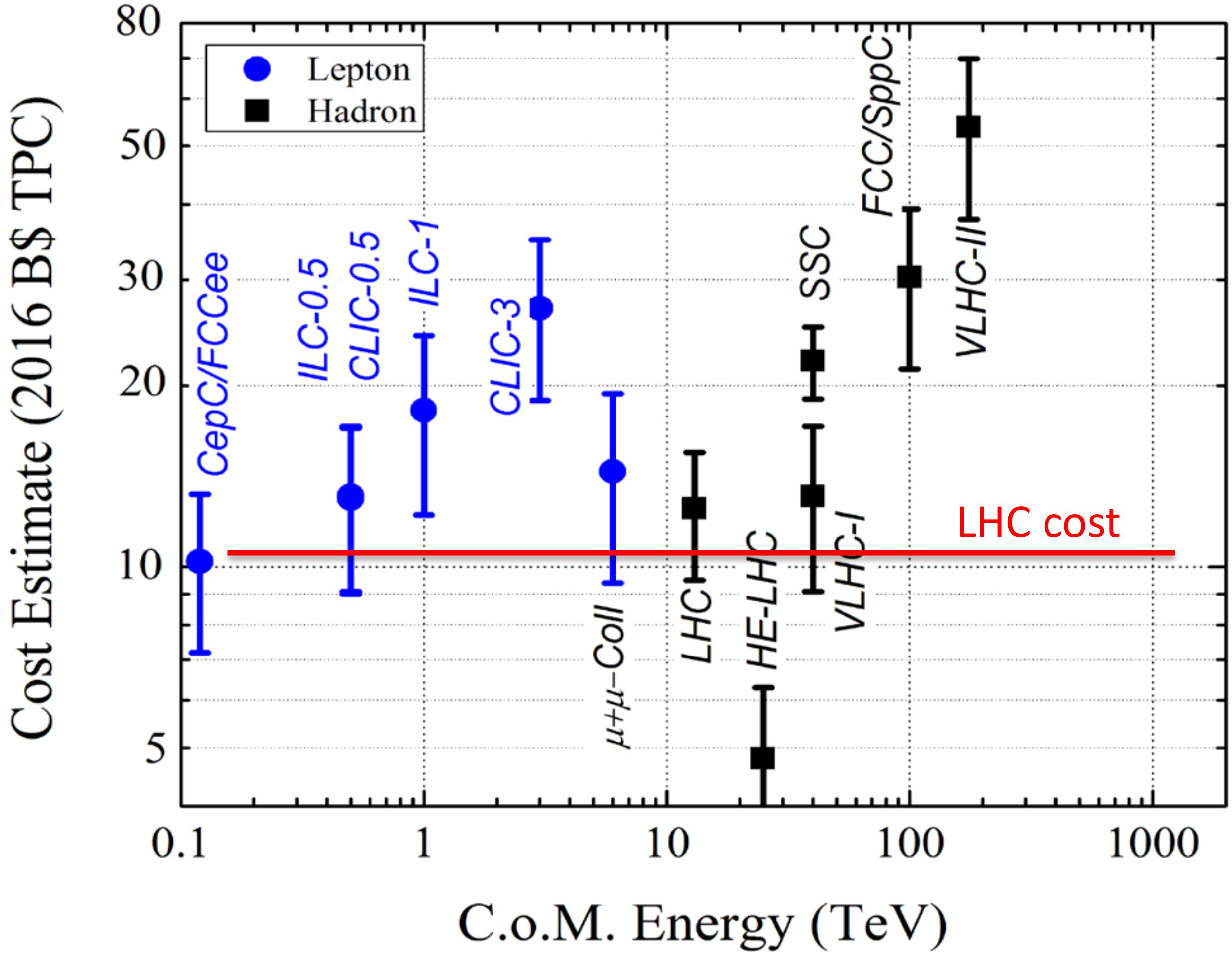
Physics Goals and Challenges of the Future Colliders

- Physics drives accelerators developments
  - Like colliding antiprotons and protons in the already existing ring of SPS at CERN to discover W and Z bosons

- Today there are two areas where new colliders are especially important
  - "Higgs factory" – a collider (most probably e^+e^-) with a center of mass energy 250 GeV and above and high luminosity to study the Higgs boson properties
  - "~100 TeV" pp collider to get to the "next energy frontier" an order of magnitude or so above LHC
    - Study distances up to $\sim 10^{-19}$ cm and particles masses up to ~50 TeV

- What are the challenges in building next generation of colliders
  - Progress in new acceleration methods aimed to reduce the cost of the colliders was relatively slow over past ~20 years

Cost Estimates of LHC and Future Colliders

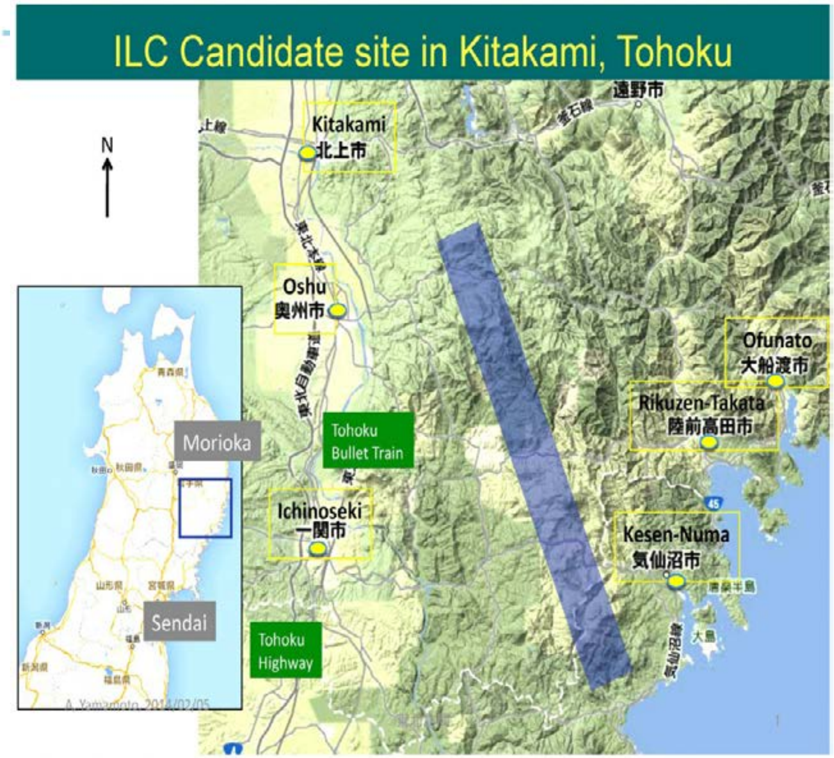


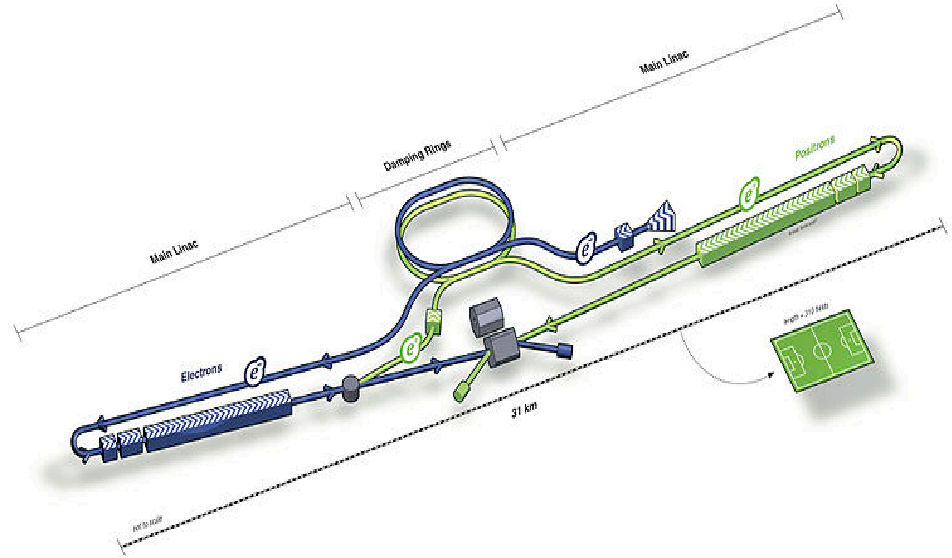
- Shiltsev's parametrized cost model: https://arxiv.org/abs/1511.01934
- Substantial costs based on existing or soon to be reachable technologies

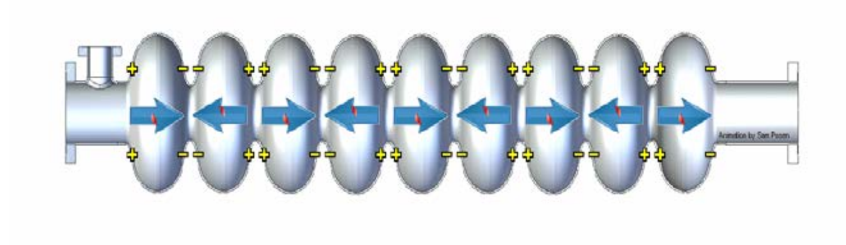
Medium Term Colliders Projects Under Development

- **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. Start of construction ~2024? Estimated cost ~$5B
- **CepC – Circular Electron Positron Collider**
  - ~250 GeV circular e^+e^- collider (the tunnel could be later used for pp collider)
  - Higgs factory
  - Location – China. Start of construction ~2022. Estimated cost ~$5B
- **FCC – Future Circular Colliders**
  - 350 GeV e^+e^- and/or ~100 TeV pp (and HE-LHC)
  - Higgs factory and/or next energy frontier
  - Location – CERN. Start of construction – after 2026. Estimated cost - ?
- **CLIC – Compact LInear Collider**
  - 380 GeV linear e^+e^- collider (with potential upgrade up to 2 TeV)
  - Higgs factory and top factory
  - Location CERN. Start of construction – after 2026. Estimated cost $6B

International Linear Collider



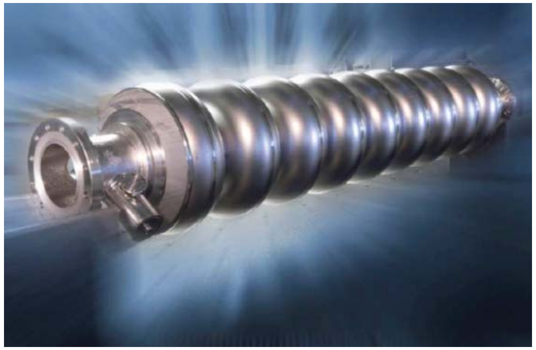




- ILC is e^+e^- linear collider to be constracted in Japan
  - Center of mass energy 250 GeV (upgradeable to higher energies) and ~20 km long
  - Luminosity $>10^{34}$ $cm^{-2}s^{-1}$
- Based on superconducting RF technology (SCRF) with ~30 MV/m acceleration (Fermilab's expertise) to accelerate electrons and positrons to ~ 125 GeV/beam
  - Excellent Higgs factory with many Higgs production and decay channels accessible

ILC Status and Plans

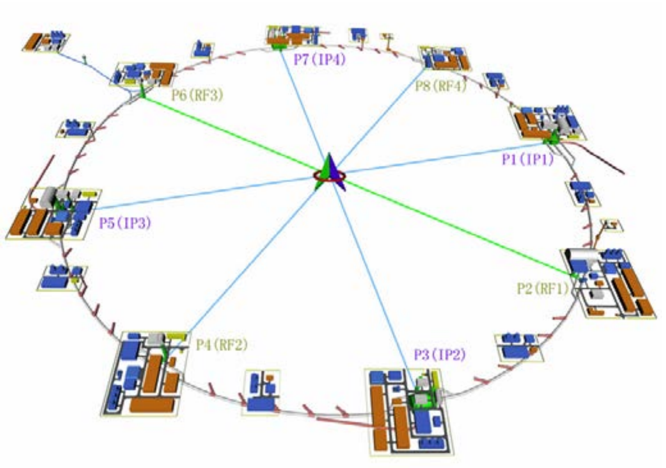
- Starting in 2008 Global Design Effort (GDE) progressed developing
  - Technical design of the ILC
  - Cost estimate and international cooperation plan
- GDE concluded in 2012
  - Including TDRs for the accelerator and detectors
  - Physics case strengthened with the Higgs discovery
- In 2012 Japan expressed strong interest to host the ILC

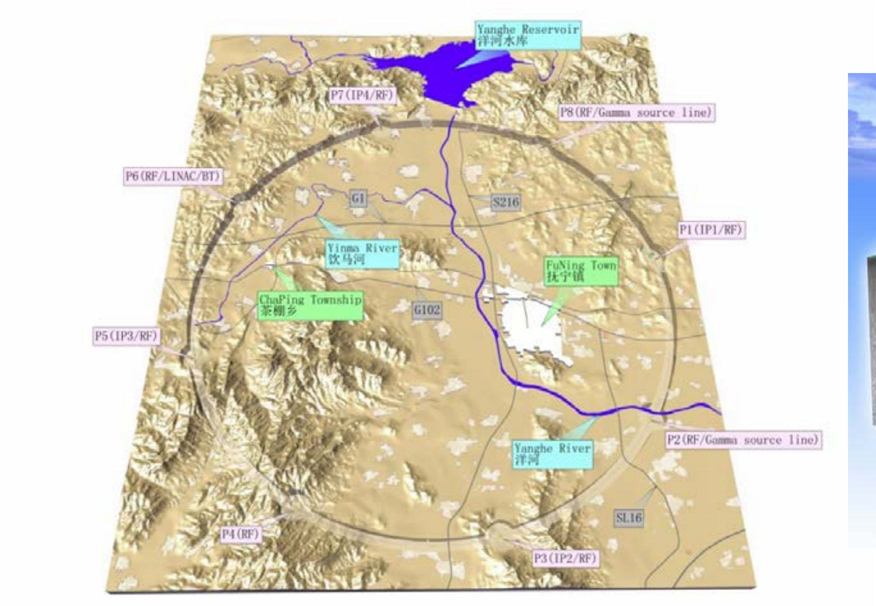


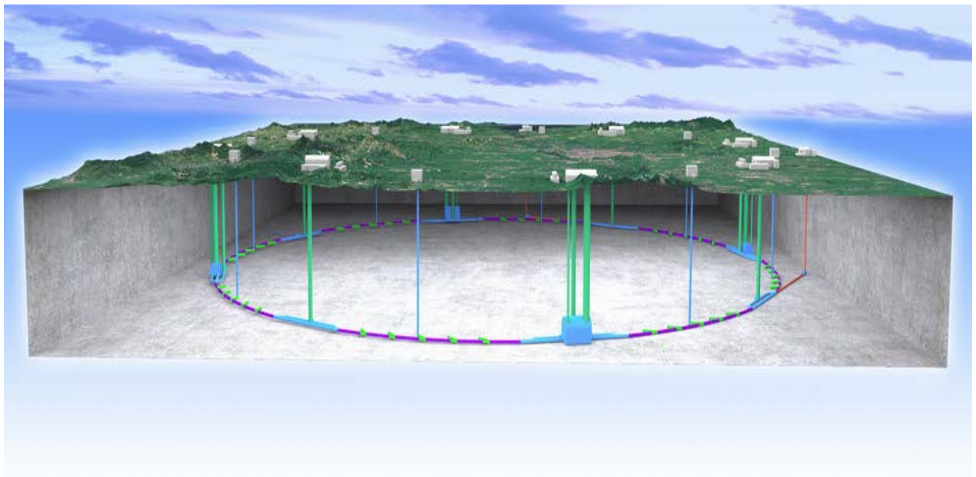
- Recently
  - Substantial progress in technical developments
  - Reduction of initial energy to 250 GeV from 500 GeV to reduce the cost to $5B
- Decision by Japan's government is expected by the end of 2018
  - Chances of positive decision are pretty good
  - Fermilab can participate strongly as the leader in SCRF technology

Proposals for Colliders in China: CepC and SppC

- CepC – Circular Electron Positron Collider
  - ~100 km long ring
  - 90-250 GeV in the center of mass
  - Z and W bosons and Higgs factory
- SppC – Super Proton Proton Collider
  - In the same ring as CepC
  - ~100 TeV with 16 T magnets







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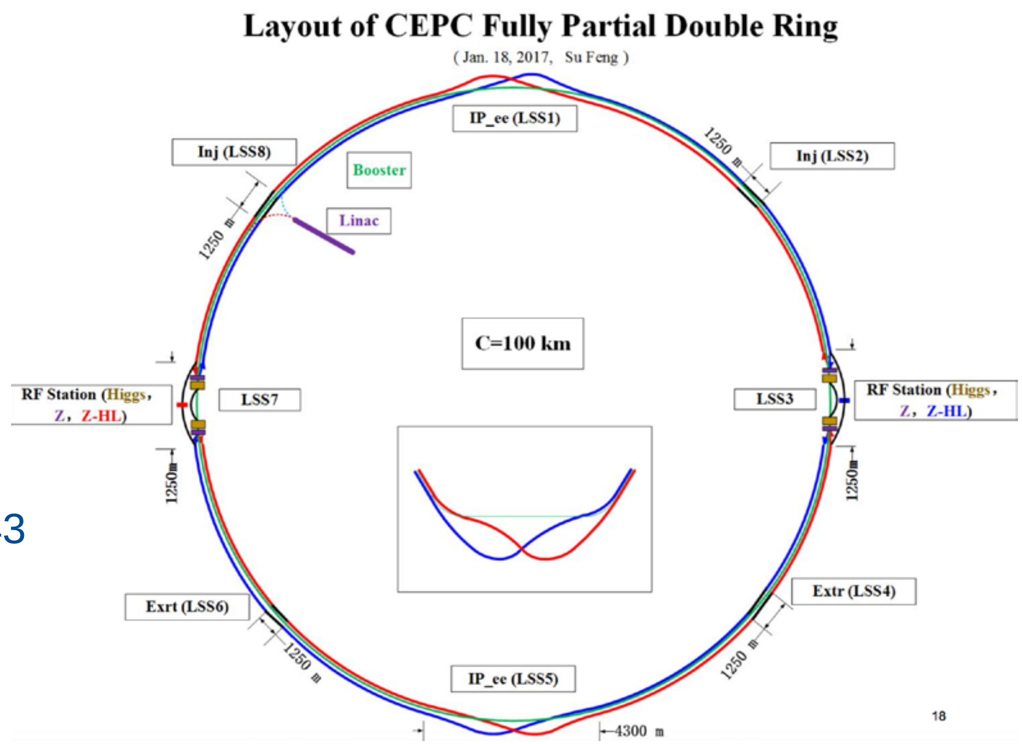
Future Colliders in China

- Active progress with the CepC and SppC design recently

- Plan is to get funding for detailed technical design report
  - Completed by early 2020s

- Construction of CepC to start in ~2021
  - Completed in 2027
  - Data collection 2028-2035



- SppC timeline
  - Design 2020-2030
  - Construction 2035-2042
  - Physics at ~100 TeV starting in 2043

- The proposal is based on
  - Experience with BEPC e^+e^- collider
  - Relatively inexpensive tunneling in China
  - Strong government interest in scientific leadership – both CepC and SppC are “national projects with international participation”

FCC – Future Circular Colliders (CERN)

- FCC activity follows 2013 European particle physics strategy recommendation to develop future energy frontier colliders at CERN

- There are three options in ~100 km long tunnel
  - pp collider with energy of ~100 TeV
  - e^+e^- collider with energy of ~350 GeV
  - ep collider

- High energy HE-LHC (x2 in energy, using higher filed magnets in the LHC tunnel) is also part of the FCC program

FCC 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

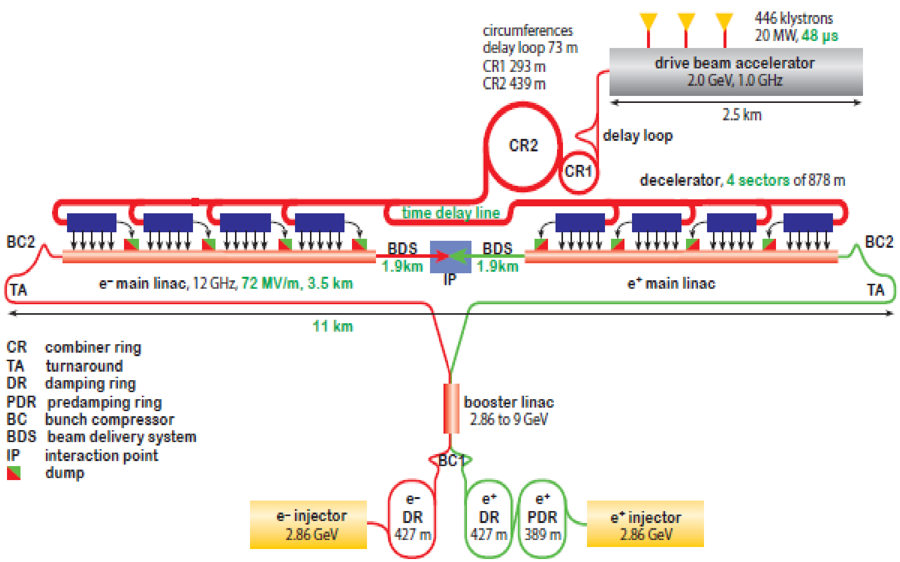
- Circular e^+e^- collider has substantially higher luminosity at lower energies vs linear collider
  - Z, W, Higgs and top quark factory
- Main challenges: 100 km long tunnel and high synchrotron losses require demanding superconducting accelerating system and high electricity consumption

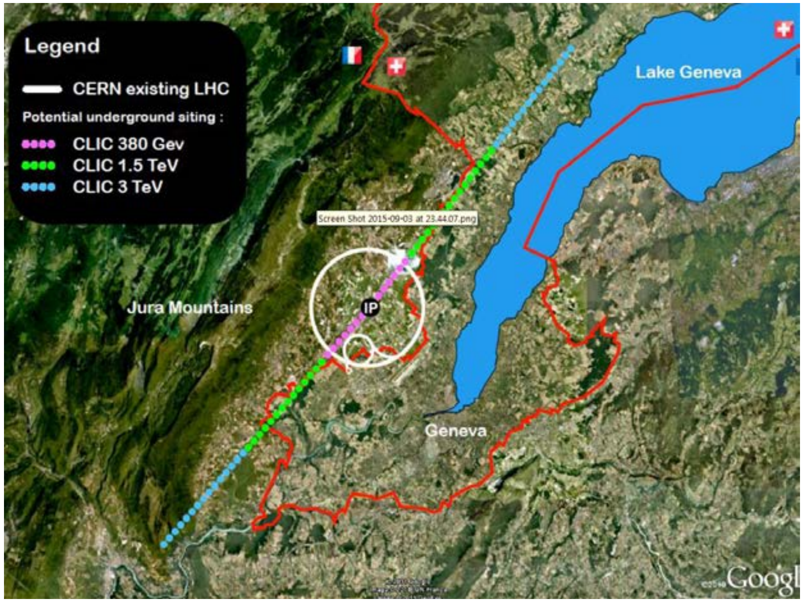
FCC pp 100 TeV collider

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

- 100 TeV pp collider with 16 T magnets in 100km long tunnel will become next energy frontier increasing collider energy by an order of magnitude in comparison with the LHC
- Main challenges: long tunnel, high field magnets, high synchrotron radiation load
  - Fermilab has leading expertise in high field magnets

CLIC Collider at CERN





- CLIC is a linear e^+e^- collider based on "warm" RF technology with 70+ MV/m acceleration
  - The only way to get to multi-TeV e^+e^-
- 11km long for 380 GeV in the center of mass
- 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

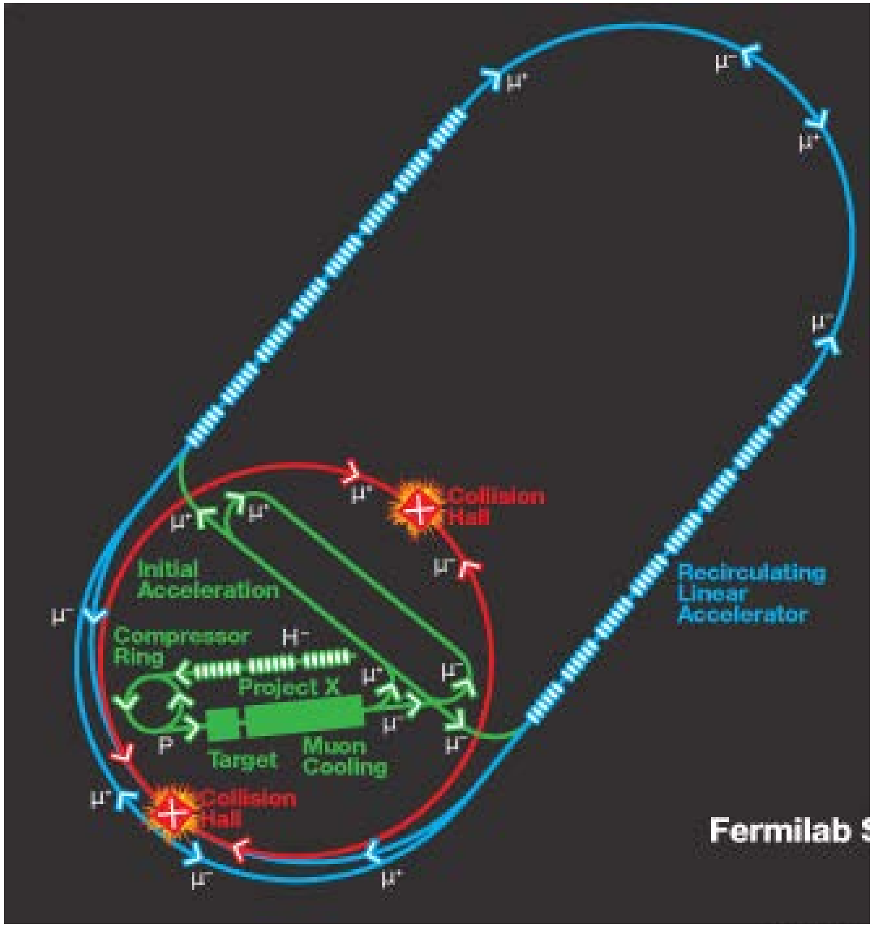
$\mu^+\mu^-$ Colliders

- Muon collider would be an excellent Higgs factory
  - Low synchrotron radiation
  - Higgs production in t-channel
  - 125 GeV collider is only ~100 meters in size

- But… muons are unstable with life-time of 2.2 μs
  - Cooling muons fast is a major challenge
  - High luminosity needed to get reasonable number of Higgs events

- Design work is restarting in Europe based on new ideas of muons production

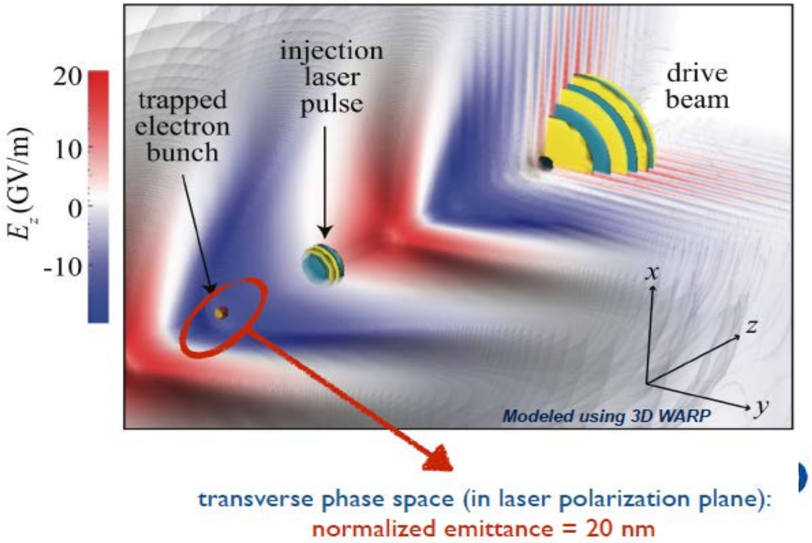
2x2 TeV



Novel Ideas in Very High Gradient Acceleration

- To reduce size/cost develop accelerating gradients in the GV/m range
  - Beam-Driven Wakefield Accelerators
    - In US: FACET/FACET-II
  - Laser-driven Wakefield Accelerators
    - In US: BELLA
  - Dielectric Wakefield Acceleration
    - In US: AWA, ATF
- Major research efforts are also underway in Europe and Asia
  - Some are: AWAKE (CERN), Eupraxia, FLASH Forward (DESY), SPARC Lab (INFN)

- For now these methods are at the initial stages of development
  - At least 10-20 years to practical applications in particle physics, might be longer



How Particle Physicists Will Make the Decisions?

- Driven by planning in various regions
  - Japan plans to decide about hosting ILC by the end of 2018
  - European/CERN future will be developed over next two years – coming slides
  - China is expected to decide by their next five years plan or around 2021
  - US will discuss its plans at Snowmass/P5 process starting in 2021

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European Particle Physics Strategy (EPPS)

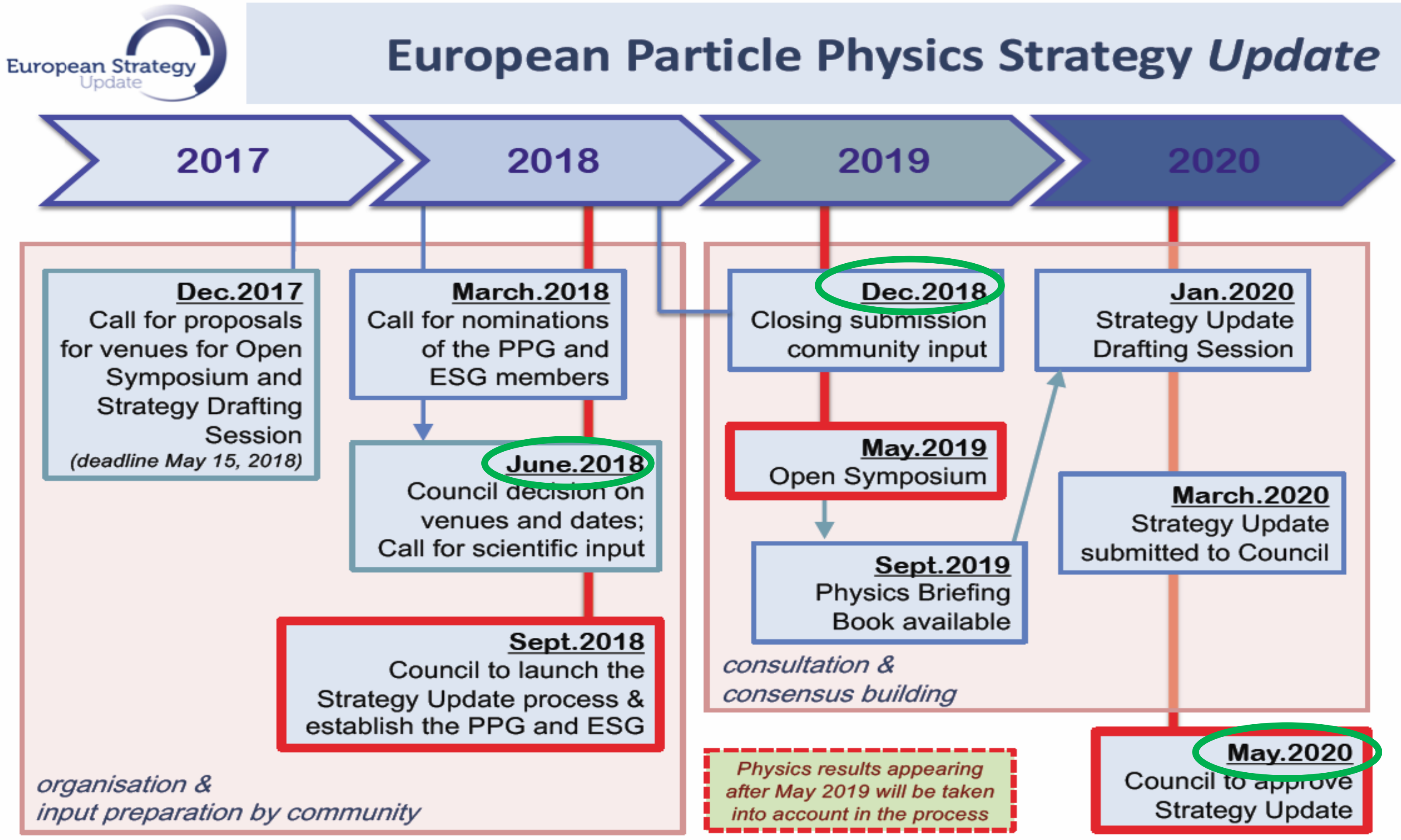
- First EPPS in 2006, latest update in 2013
  - Currently on track to implement 2013 recommendations

- Update to EPPS – why now
  - Europe/CERN has to develop plans beyond HL-LHC
    - CERN expects to have funds available for new project(s) construction in 2026
  - LHC luminosity doubling time is now years, so running into late 2030’s is not productive

European Strategy Update

- EPPS is led by the Strategy Secretariat
  - Halina Abramowicz is the Strategy Secretary
- EPPS includes Physics Preparatory Group ~17 people and European Strategy Group ~ 64 people
  - It will have representatives from all regions, including US

Timeline of the European Strategy Update



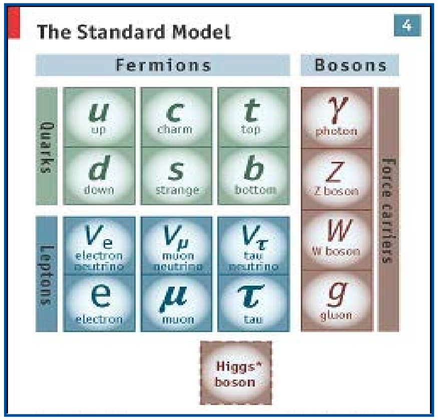
- December 18, 2018 – deadline for “white papers” proposals
- The Open Symposium will take place in Granada, Spain, 13-16 May 2019
- Strategy Drafting Session in Bad Honnef, Germany, 20-24 January 2020

Comments on US Participation in EPPS Update

- It is *European* planning with the goal to develop future for *CERN*
- Preferred way is for the communities involved in specific initiatives to come together with joint white papers, examples
  - HE-LHC is expected to be coordinated by ATLAS/CMS and accelerator experts from FCC
  - CLIC 380 GeV proposal is coordinated by CLIC working group
  - 250 GeV ILC proposal is coordinated by Linear Collider Collaboration
  - Rare muon decays program is proposed to be coordinated by mu2e, COMET and MEG
- Coordination within communities over coming months, in consultation with EPPS secretariat, to develop white papers strategy

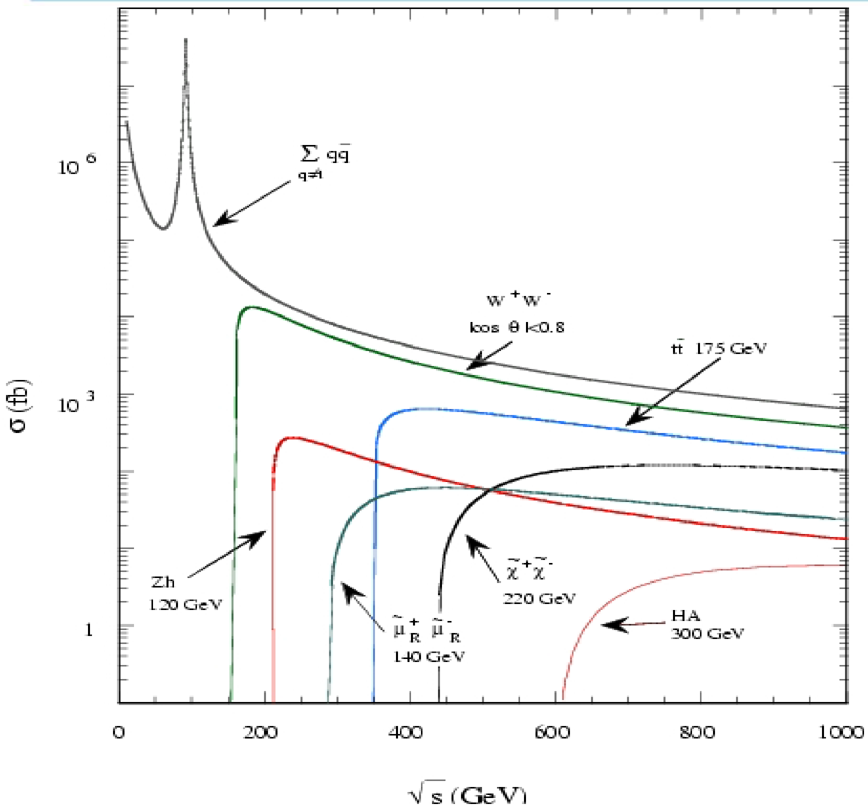
Future Colliders - Summary

- Colliders played major role in establishing and understanding the standard model
  - Discovered all expected standard model particles
- Future proposed colliders are of two types
  - e^+e^- colliders as "Higgs factory"
  - pp colliders as the next energy frontier
- Three proposals are under active discussion
  - ILC (Japan) – decision by Japan's Government is expected this year
  - CepC Higgs factory (China) – decision by 2021
  - FCC (CERN) – European strategy outcome by early 2020



- At Fermilab we have a group engaged in the future colliders activities and preparations for the next Snowmass/P5 process
  - Subscribe at strategicplanning-energyfrontier@listserv.fnal.gov

ILC Physics and Experiments



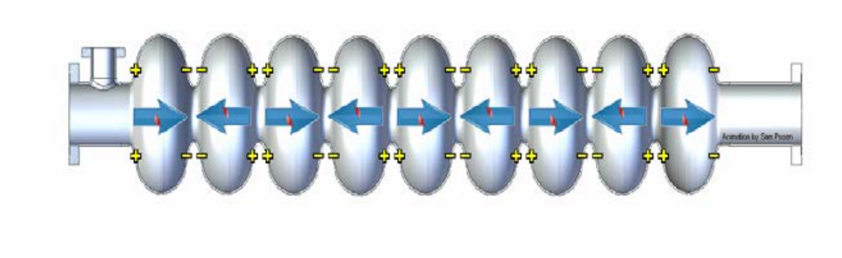
Summary of expected accuracies $\Delta g_i/g_i$ and Γ_T for model independent determinations of the Higgs boson couplings

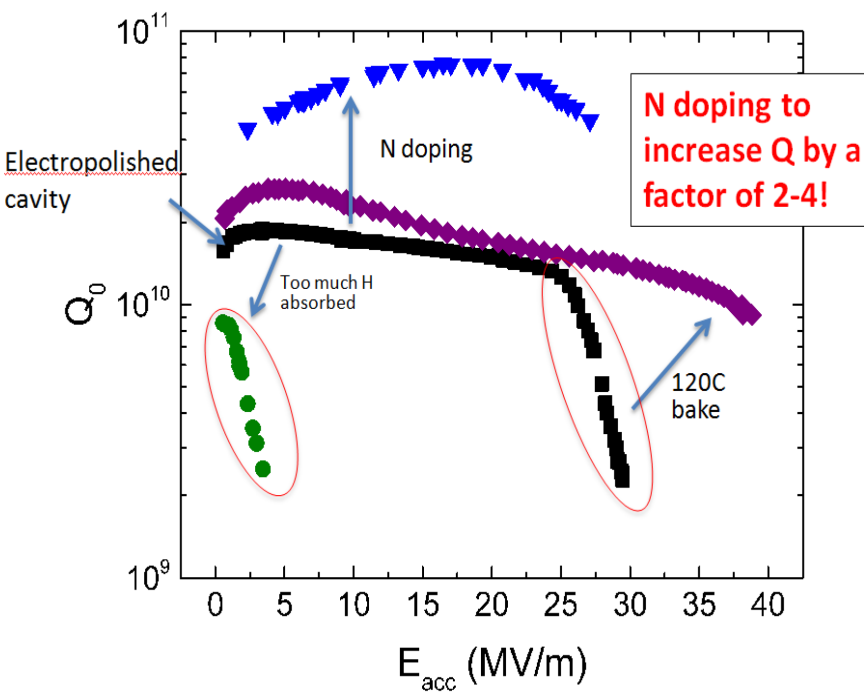
Mode	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.9 %	1.2 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.2 %	2.0 %
$b\bar{b}$	5.3 %	1.7 %	1.3 %	0.8 %
$\tau^+\tau^-$	5.8 %	2.4 %	1.8 %	1.0 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.1 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
Γ_T	12 %	5.0 %	4.6 %	2.5 %
hhh	–	83 %	21 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.9 %	< 0.4 %

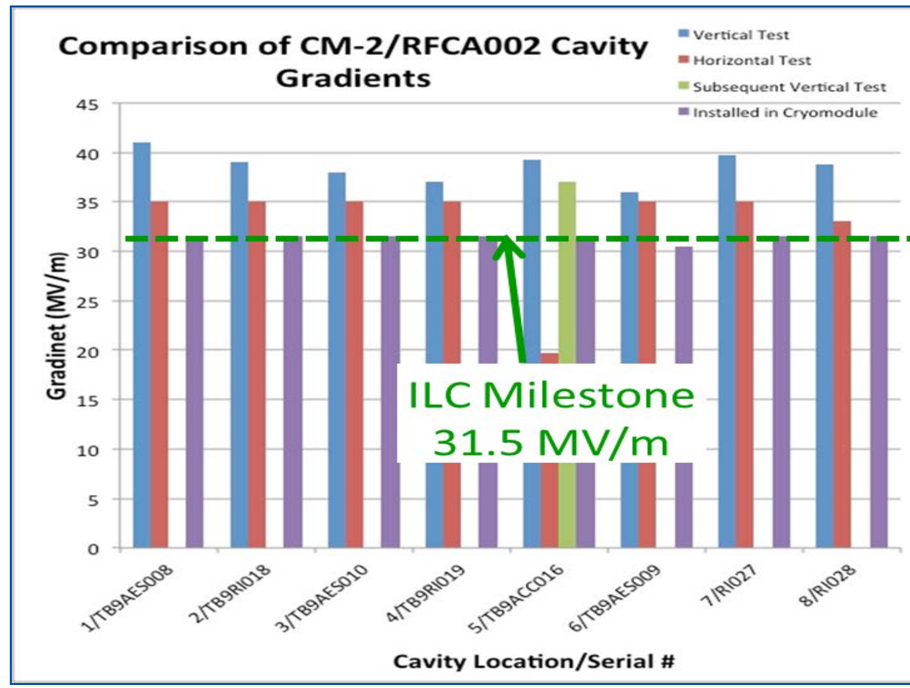
- Low cross sections – high luminosity needed
- Point like particles colliding
  - Can be used for multiple precision measurements of all Standard Model particles
  - Higgs couplings down to ~1% accuracy
- Large number of different production/decay channels

Fermilab's ILC Contributions

- Superconducting accelerating cavities (SCRF)
  - Synergy with SLAC light source accelerating cryomodules
- R&D in accelerator systems, including controls
- Design of the ILC detectors







- Two excellent results for SCRF cavities obtained at Fermilab recently
  - Substantial Q factor increase of the cavities with nitrogen doping
  - Fermilab's cryomodule reached ILC specification of 31.5 MV/m

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CepC Design with 100 km Ring

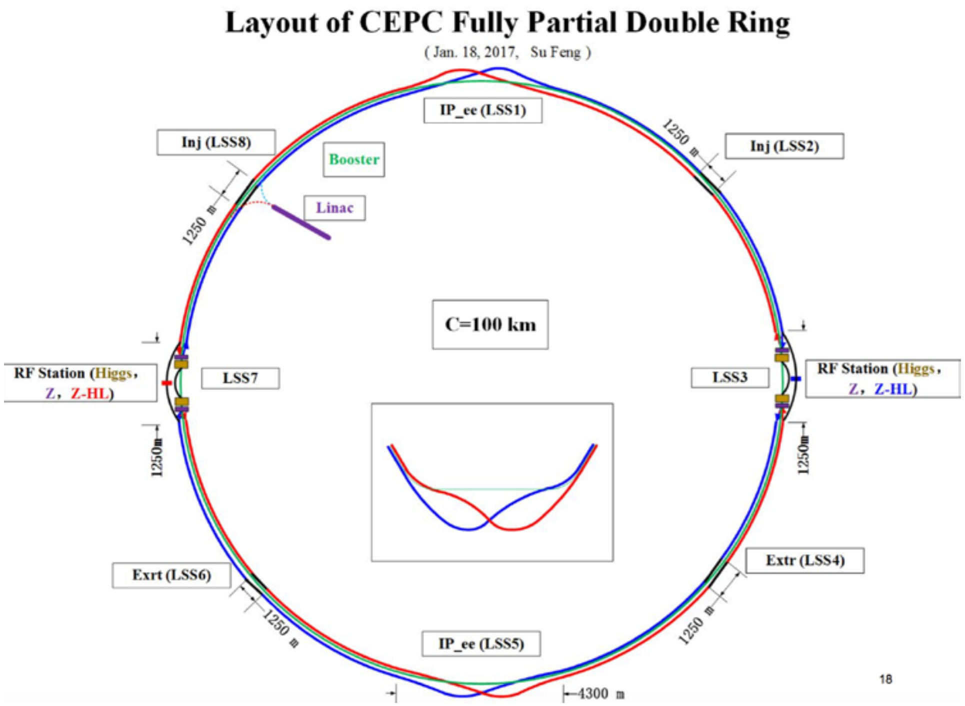

Table 1. Parameters for 100 km CEPC double ring with 2 mm vertical β*.

	Pre-CDR	Higgs	W	Z
Number of IPs	2	2	2	2
Energy (Gev)	120	120	80	45.5
Circumference (km)	54	100	100	100
SR loss/turn (Gev)	3.1	1.67	0.33	0.034
Half crossing angle (mrad)	0	16.5	16.5	16.5
Piwinski angle Φ	0	3.19	5.69	4.29
N_e/bunch (10^{11})	3.79	0.968	0.365	0.455
Bunch number	50	412	5534	21300
Beam current (mA)	16.6	19.2	97.1	465.8
SR power /beam (MW)	51.7	32	32	16.1
Bending radius (km)	6.1	11	11	11
Momentum compaction (10^{-5})	3.4	1.14	1.14	4.49
$\beta_{IP\ x/y}$ (m)	0.8/0.0012	0.171/0.002	0.171 /0.002	0.16/0.002
Emittance x/y (nm)	6.12/0.018	1.31/0.004	0.57/0.0017	1.48/0.0078
Transverse σ_{IP} (um)	69.97/0.15	15.0/0.089	9.9/0.059	15.4/0.125
ξ_x/ξ_y/IP	0.118/0.083	0.013/0.083	0.0055/0.062	0.008/0.054
V_{RF} (GV)	6.87	2.1	0.41	0.14
f_{RF} (MHz)	650	650	650	650
Nature σ_z /Total σ_z (mm)	2.14/2.65	2.72/2.9	3.37/3.4	3.97/4.0
HOM power/cavity (kw)	3.6 (5cell)	0.41(2cell)	0.36(2cell)	1.99(2cell)
Energy spread (%)	0.13	0.098	0.065	0.037
Energy acceptance requirement (%)	2	1.5		
Energy acceptance by RF (%)	6	2.1	1.1	1.1
n_γ	0.23	0.26	0.15	0.12
Life time due to beamstrahlung_cal (minute)	47	52		
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.04	2.0	5.15	11.9

- Over last year China decided to go to 100 km (vs 54km) ring
  - Considerably less challenging design
  - Greater potential for future machines in the same tunnel

Future pp Colliders at CERN

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
beta* [m]	1.1-0.3		0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)		2.5 (0.5)	(2.5) 3.75

HE-LHC is “High Energy” LHC in the LHC tunnel with double field magnets