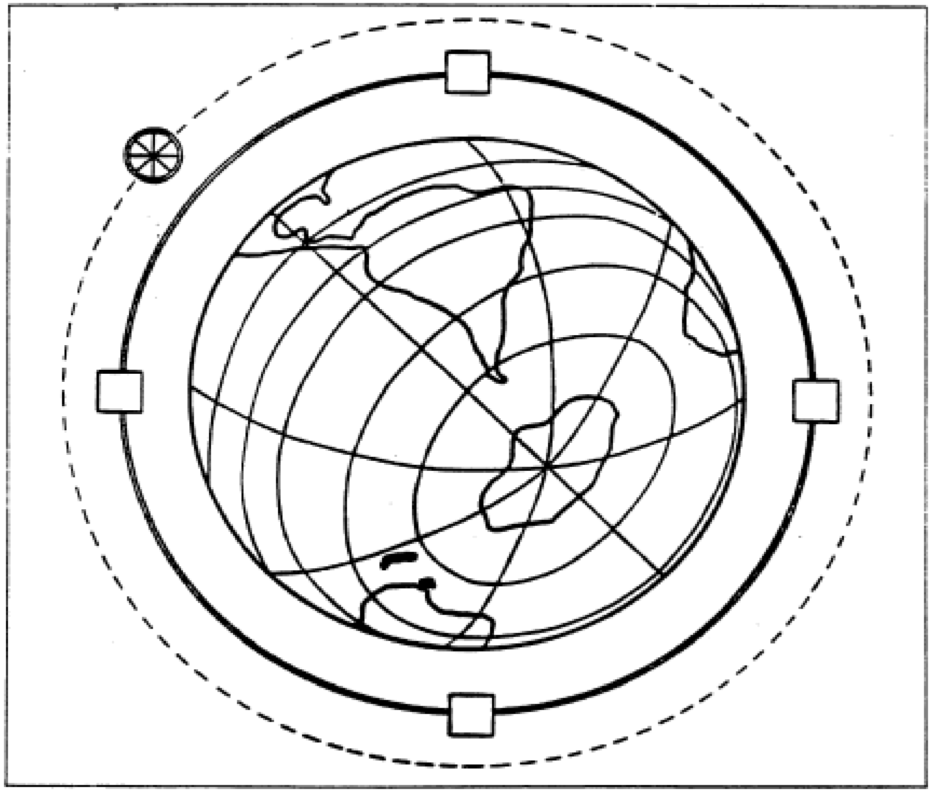
Colliders: Past, Present and Future



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

Dmitri Denisov, BNL

US ATLAS Meeting, University of Massachusetts Amherst,

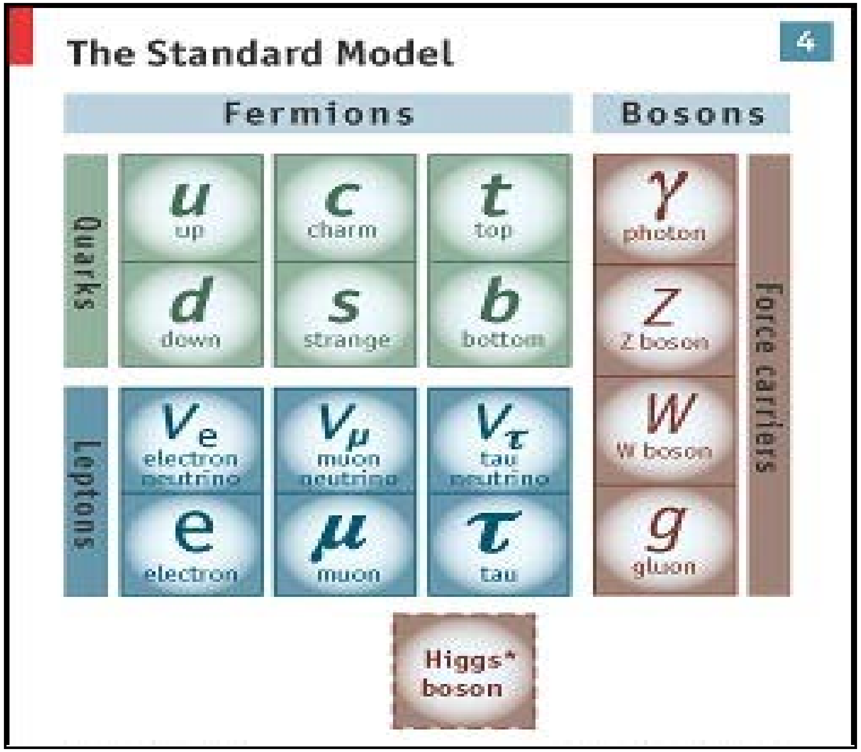
August 6, 2019

Outline

- Why colliders?
- Overview of colliders
- Future colliders options and challenges
  - e^+e^-, $\mu^+\mu^-$, pp colliders
- Medium term future colliders options
  - ILC, CepC, FCC, CLIC
- Next steps

Particle Physics

- Standard Model is the theory of elementary particles and interactions
    - Describes majority of phenomena in Nature
    - Makes everything of a small number of objects
        - Quarks and leptons
    - Forces are carried by
        - photon - electromagnetic
        - gluons - strong
        - W/Z bosons - weak
    - Higgs boson provides mass
    - Accurate to a very high precision
        - Better than 10^{-10}
- Addresses 1000’s of years hunt of mankind to understand
    - What everything around us is made of



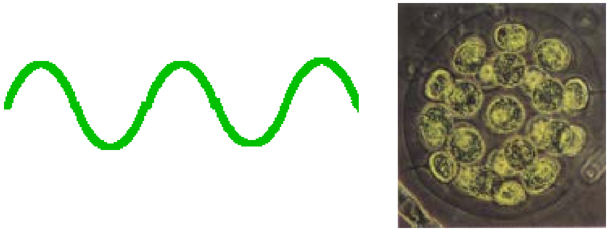
- But our current understanding is incomplete
    - Can’t explain observed number of quarks/leptons
    - Model parameters can’t be predicted
- Nothing is “wrong” with the Standard Model
    - The goal is to define the limits of applicability and find what lies beyond

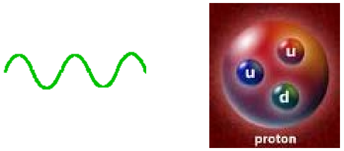
Why High Energy and Why Colliders

- Accelerators are built to study the Nature smallest objects

Wavelength = h/E

$\sim 2 \cdot 10^{-18}$ cm for LHC



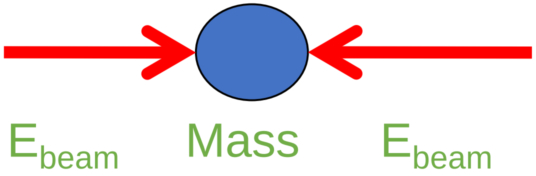


- Accelerators convert energy into mass

$E = mc^2$

Objects with masses up to

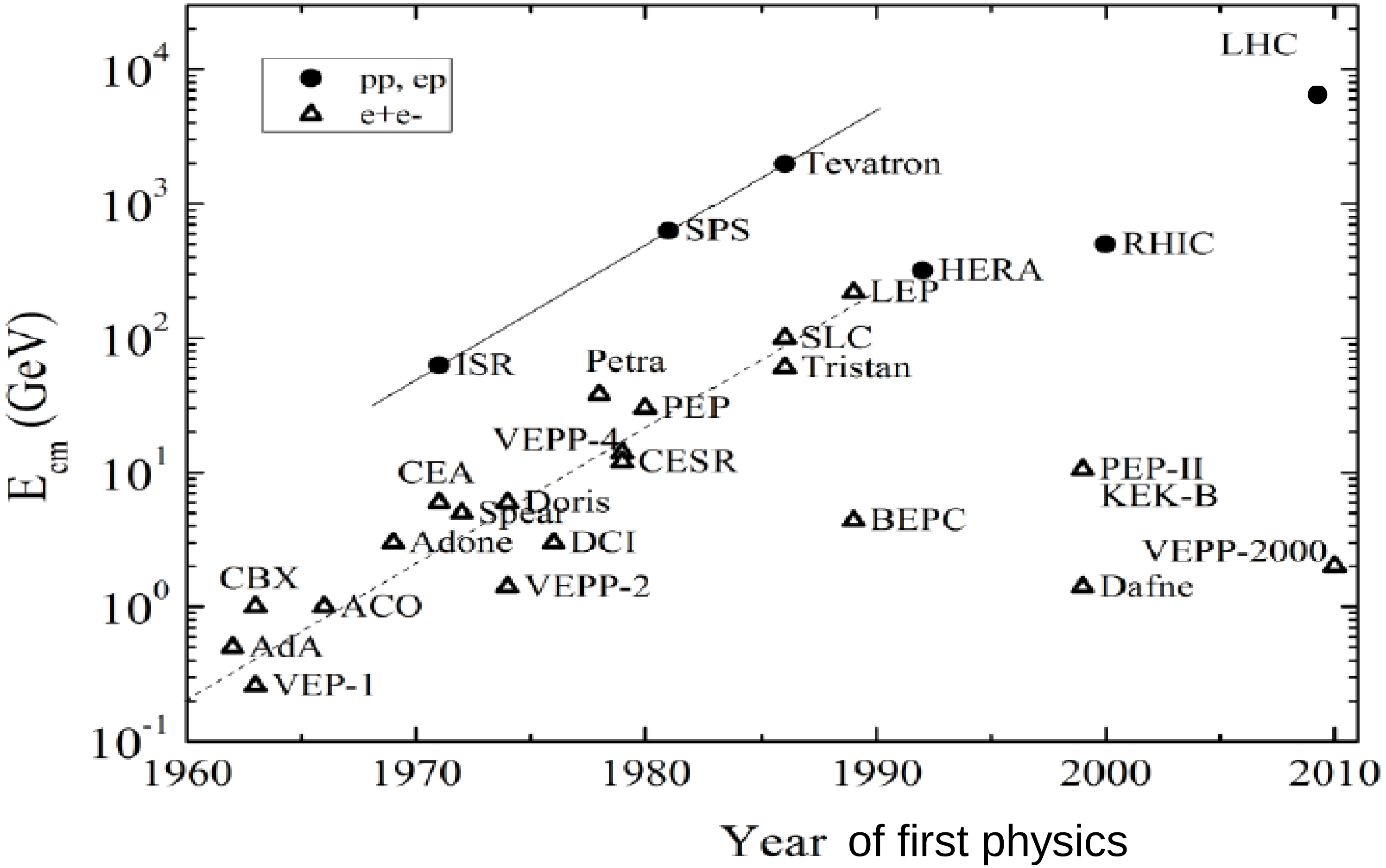
Mass = $2E_{beam}$ could be created



Collider center of mass energy is $2xE_{beam}$ 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 - higher energy is the only way to succeed

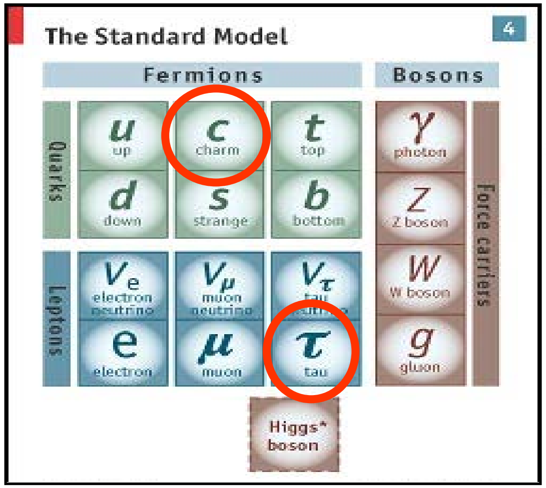
Colliders



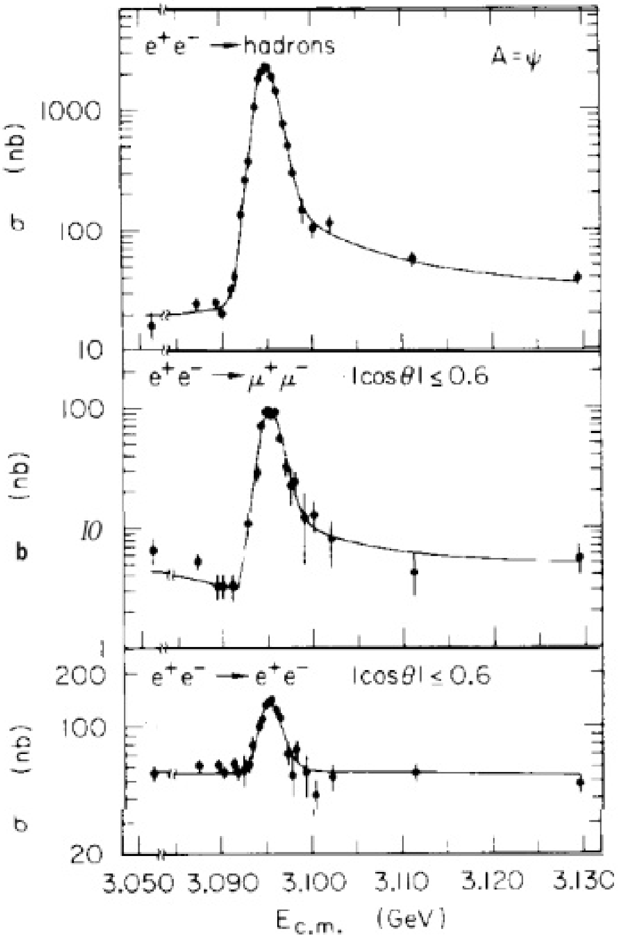
- **First e^+e^- colliders started operation in early 1960's with hadron colliders (storage ring) first collisions in 1971 with the completion of the ISR**
- **Large number of e^+e^- colliders, while few hadron colliders**
- **Hadron colliders provide higher center of mass energy, while colliding "composite"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

SPEAR e^+e^- Collider at SLAC: start 1972

SPEAR construction



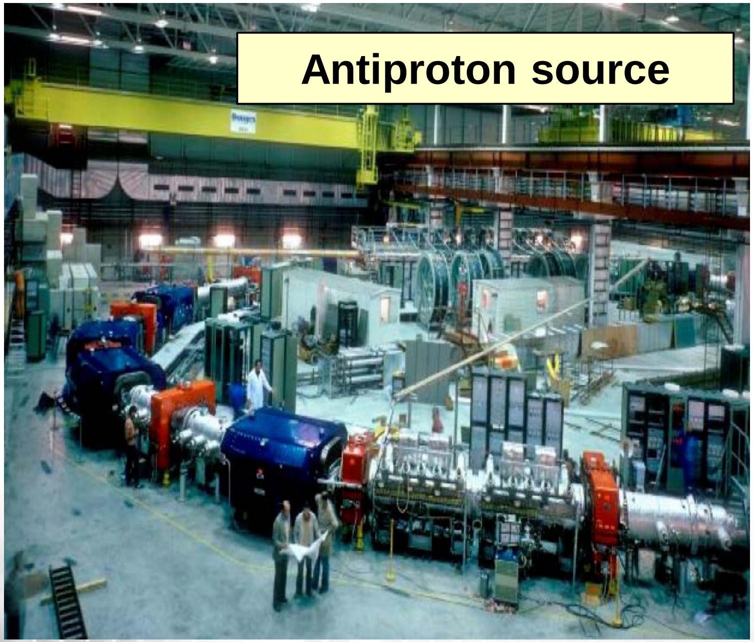
J/Psi discovery



- Started in 1972 with ~3 GeV center of mass energy
- Opened extremely productive energy range
  - Co-discovery of c-quark (J/Psi meson) in 1974
  - Discovery of τ-lepton in 1975
- One of the most productive colliders in the world!

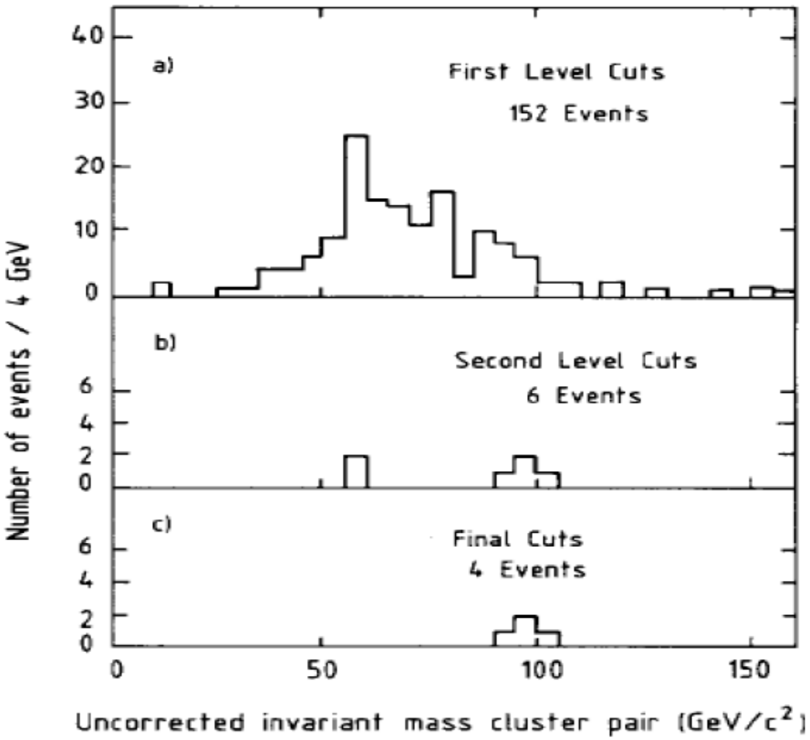
SppS Collider at CERN: start 1981

SppS
630 GeV



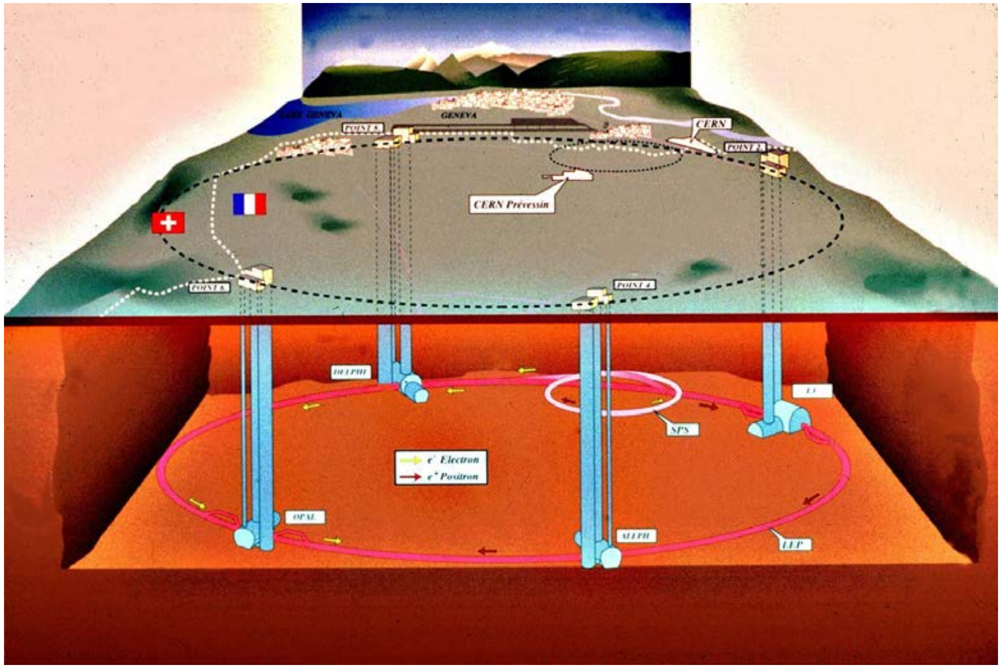
Antiproton source

Z boson discovery

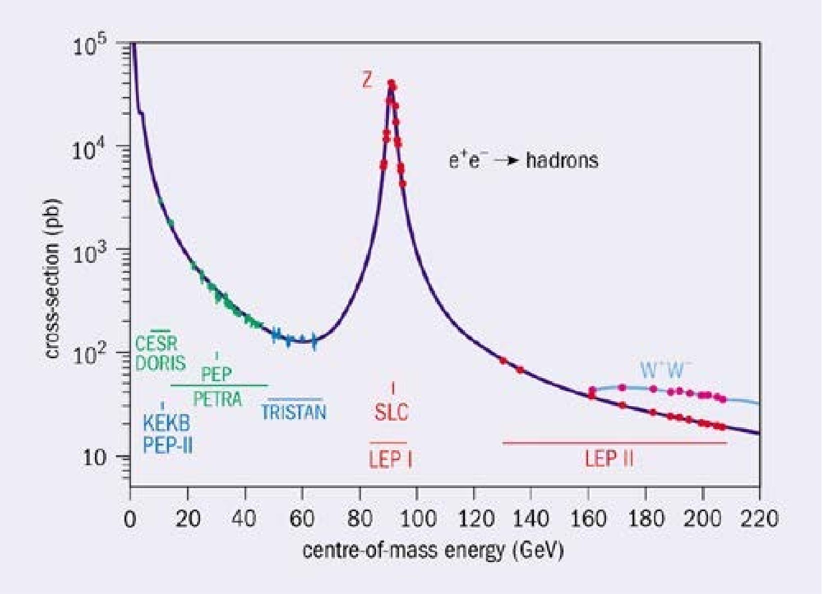


- Use of antiprotons in the existing fixed target accelerator
- Provided next step in the understanding of the standard model
  - W/Z bosons discovery

LEP e^+e^- collider at CERN: start 1989

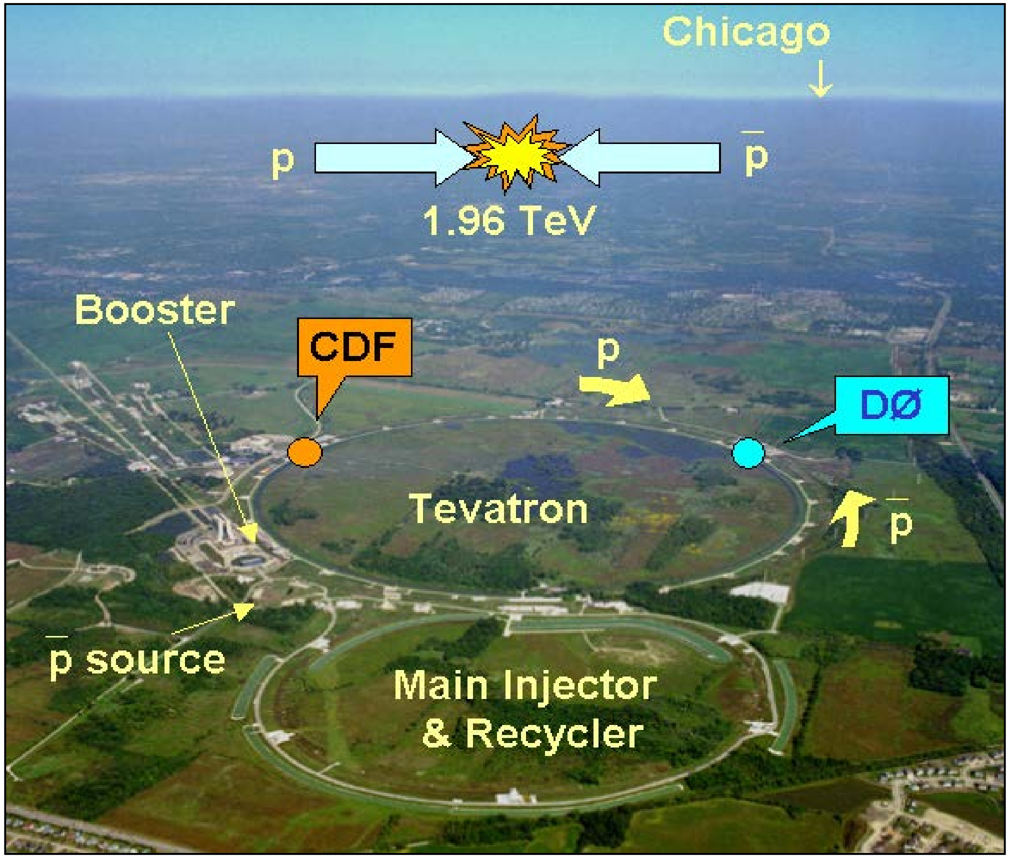


Z boson factory

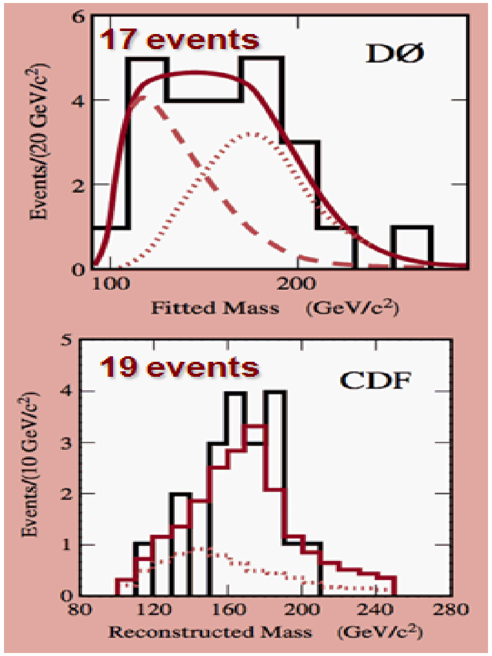


- 27 km long tunnel for up to ~200 GeV center of mass energy
    - Started operation in 1989 as “Z factory”
    - Wide range of extremely precise measurements, including Z boson mass measurement and determination of the number of neutrino generations
- SLC linear collider Z factory at SLAC operated at about the same time
- LEP needed less than 5% extra center of mass energy to discover the Higgs…

The Tevatron: start 1985

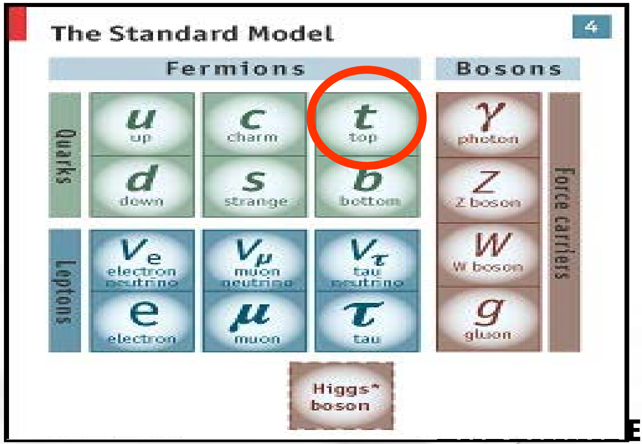


Top quark discovery

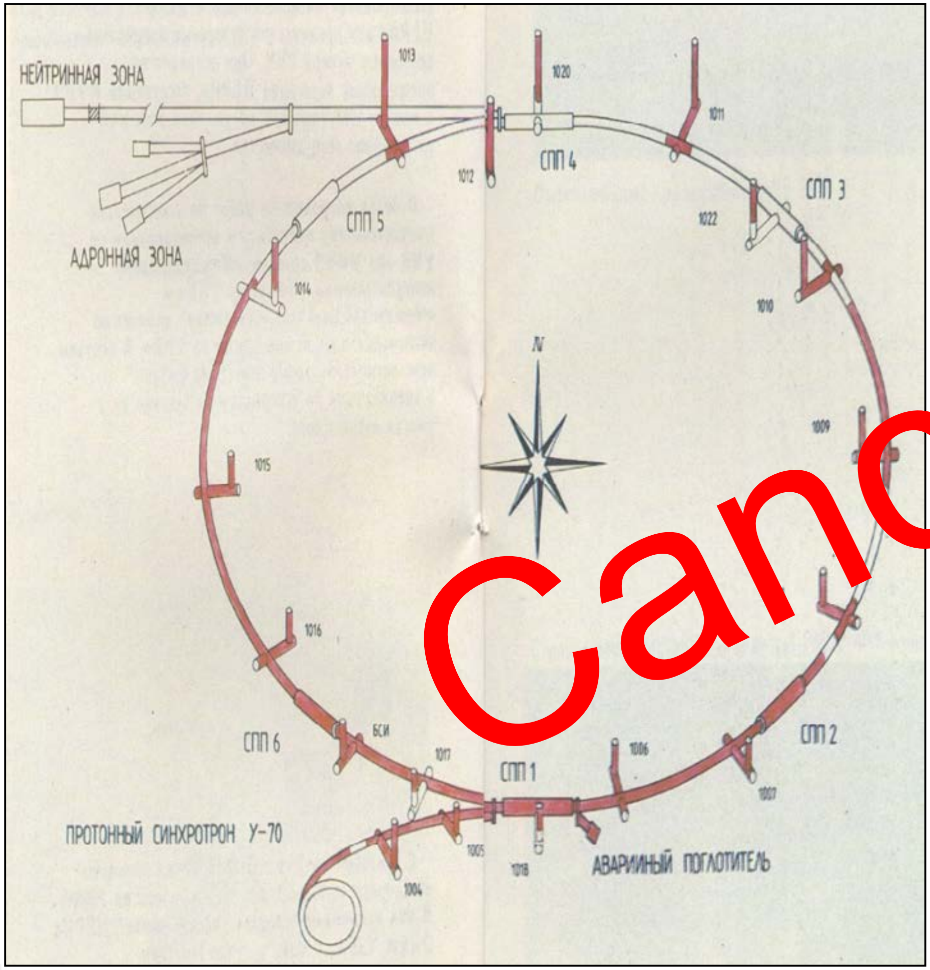


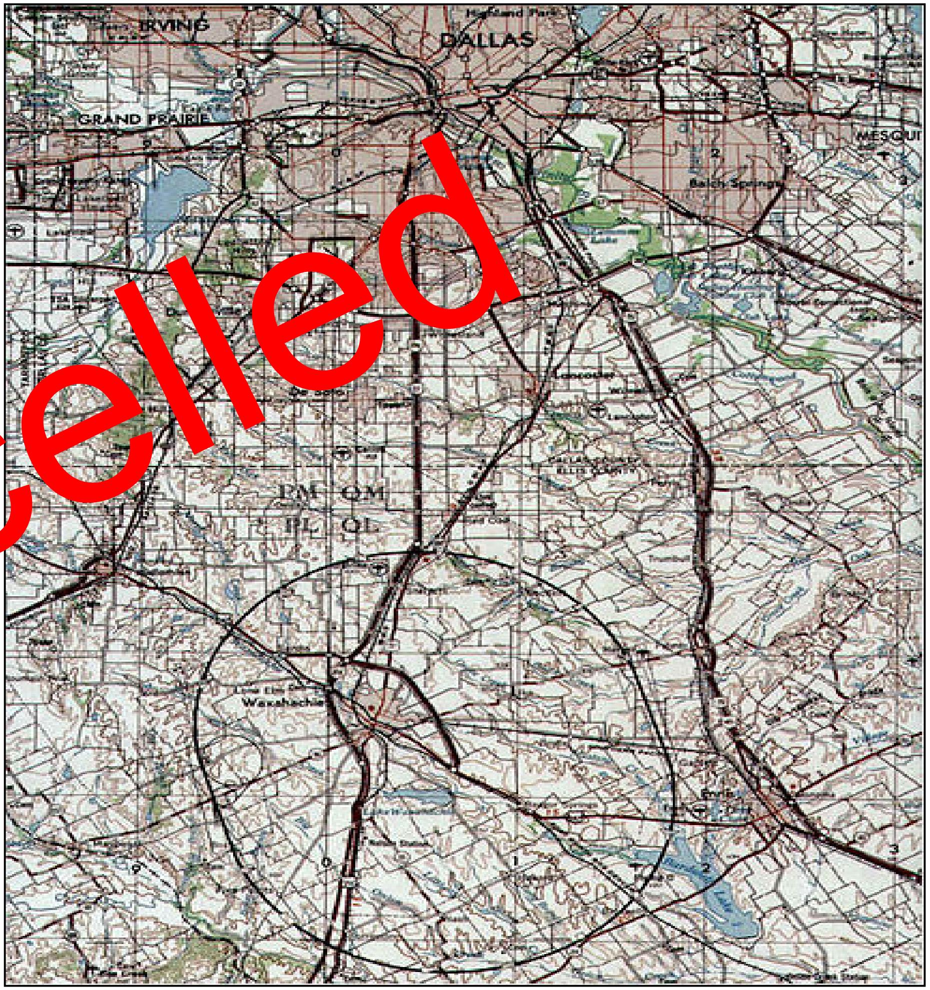
1995, CDF and DØ experiments, Fermilab

- First superconducting accelerator with 2 TeV center of mass energy
- Discovered last standard model quark – the top quark



Attempts to Reach Higher Energies: 90’s



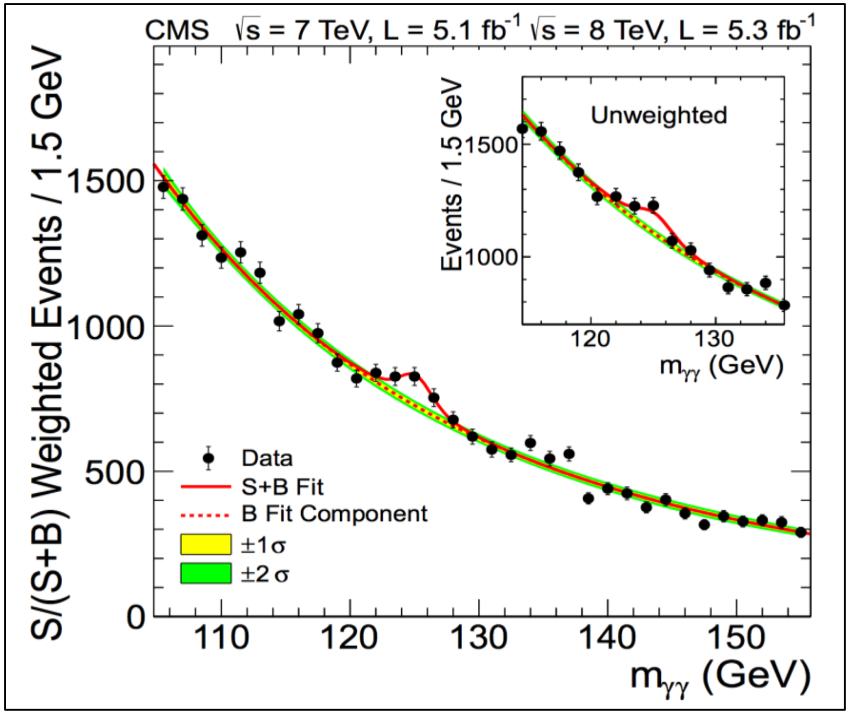


Cancelled

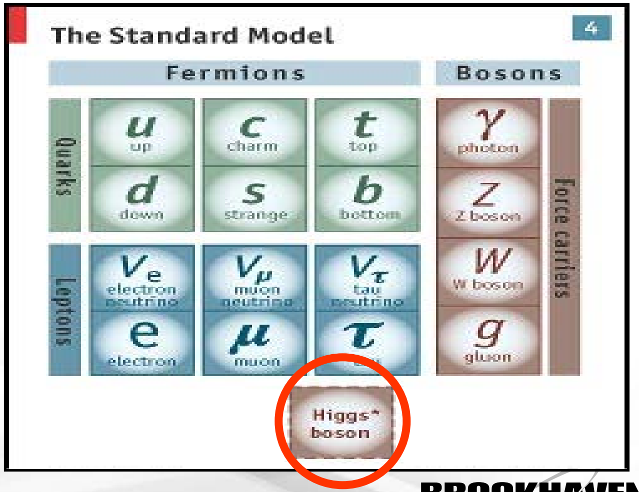
3x3 TeV, UNK, USSR

20x20 TeV, SSC, USA

The LHC – the History in the Making



- Re-use of the LEP tunnel
  - With superconducting magnets
- Discovered last missing piece of the standard model - the Higgs boson
- Extensive searches for physics beyond the standard model
- Many more exciting results expected

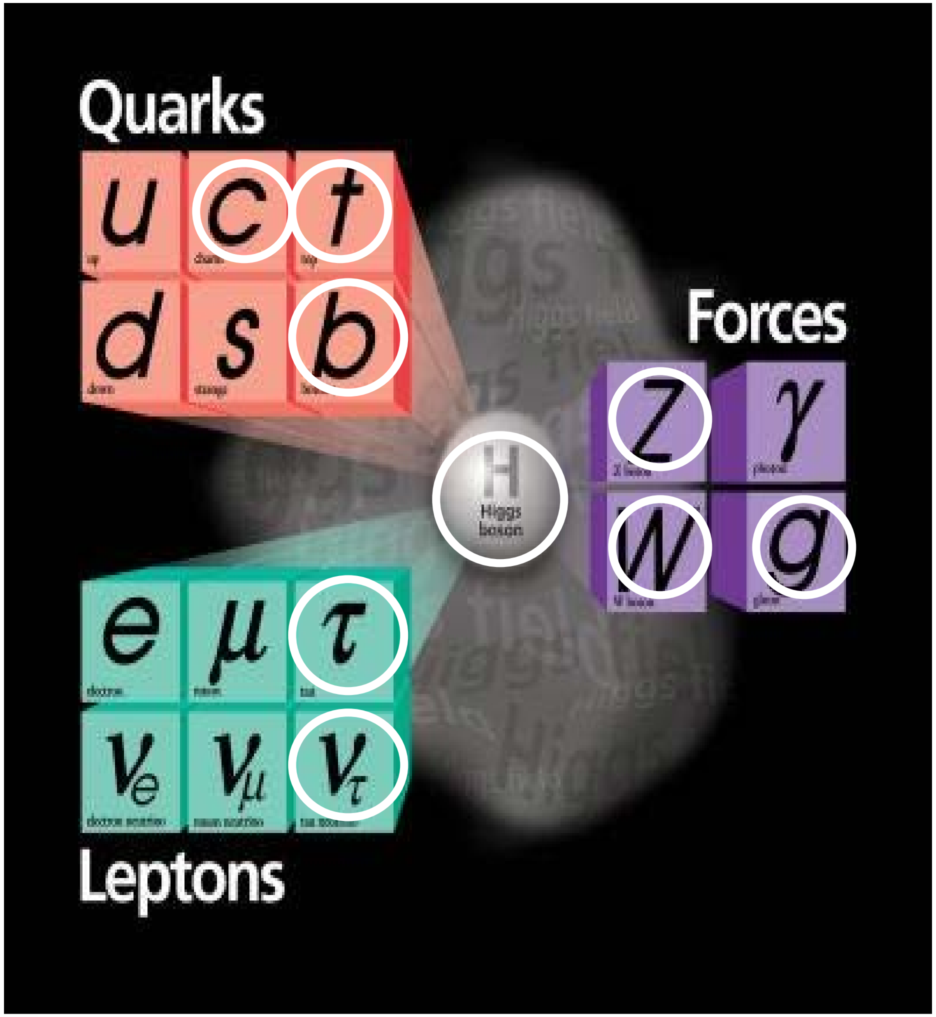


The Standard Model 4

	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	

Higgs* boson

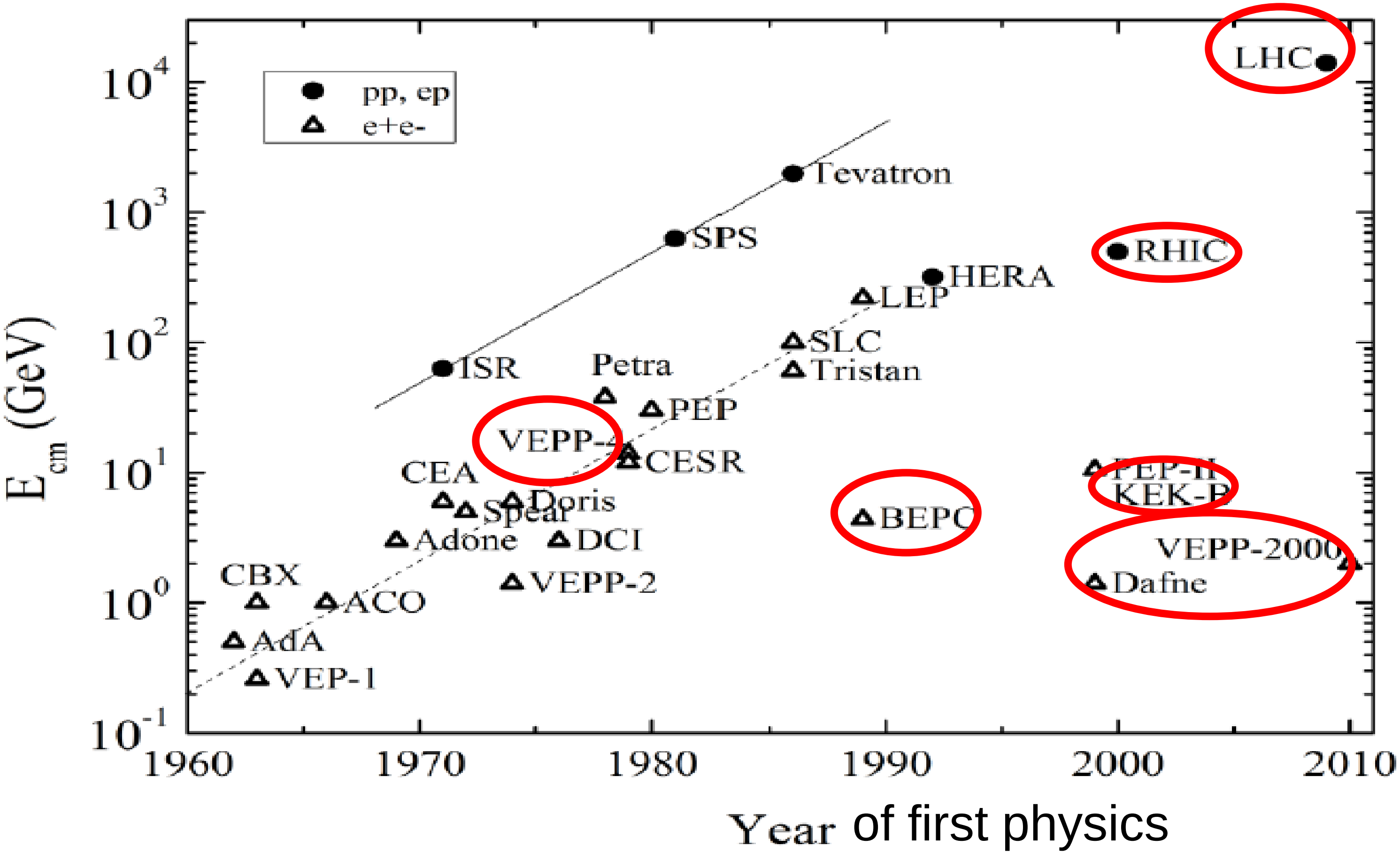
Accelerators and the Standard Model



- 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 at colliders
  - b-quark and tau neutrino in fixed target experiments at Fermilab

At every step new accelerator ideas provided less expensive ways to get to higher beams energies and higher luminosities

Operating or Soon to be Operating Colliders

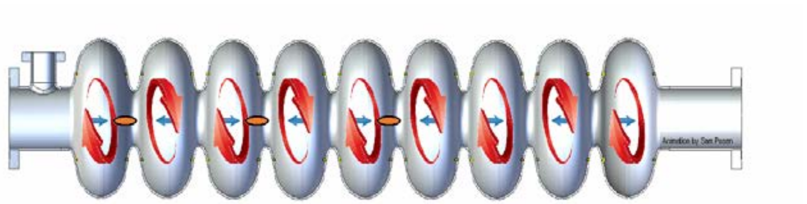


- Single high energy hadron collider – the LHC, now at 13 TeV
  - RHIC at BNL – nuclear studies
- DAFNE (Frascati), VEPP (Novosibirsk), BEPC (Beijing) – low energy e^+e^- colliders
- SuperKEK-B – b-factory at KEK re-stared in 2017 with ~40 times higher luminosity
  - Studies of particle containing b-quarks

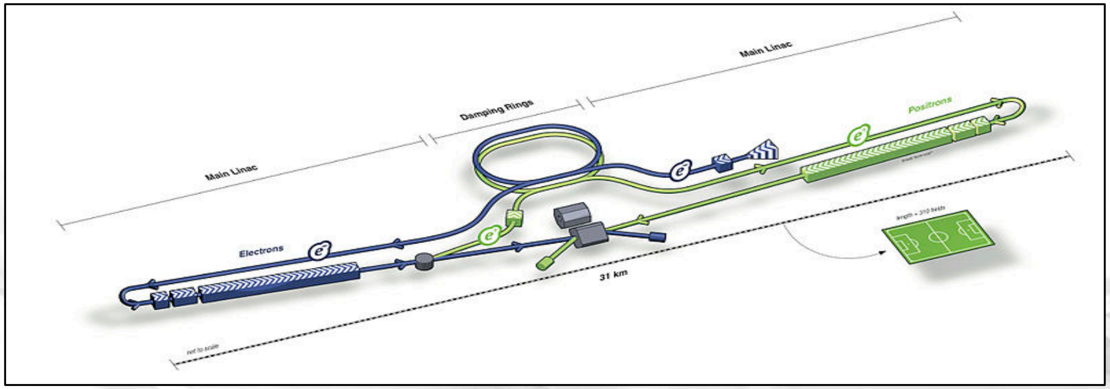
Physics Goals and Challenges of the Future Colliders

- Physics interests drive colliders development
  - Like colliding antiprotons in the already existing ring of SppS 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 ~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 cost of the colliders was relatively slow over last ~20 years
  - Colliders are becoming rather expensive and require long time to build

e^+e^- Colliders



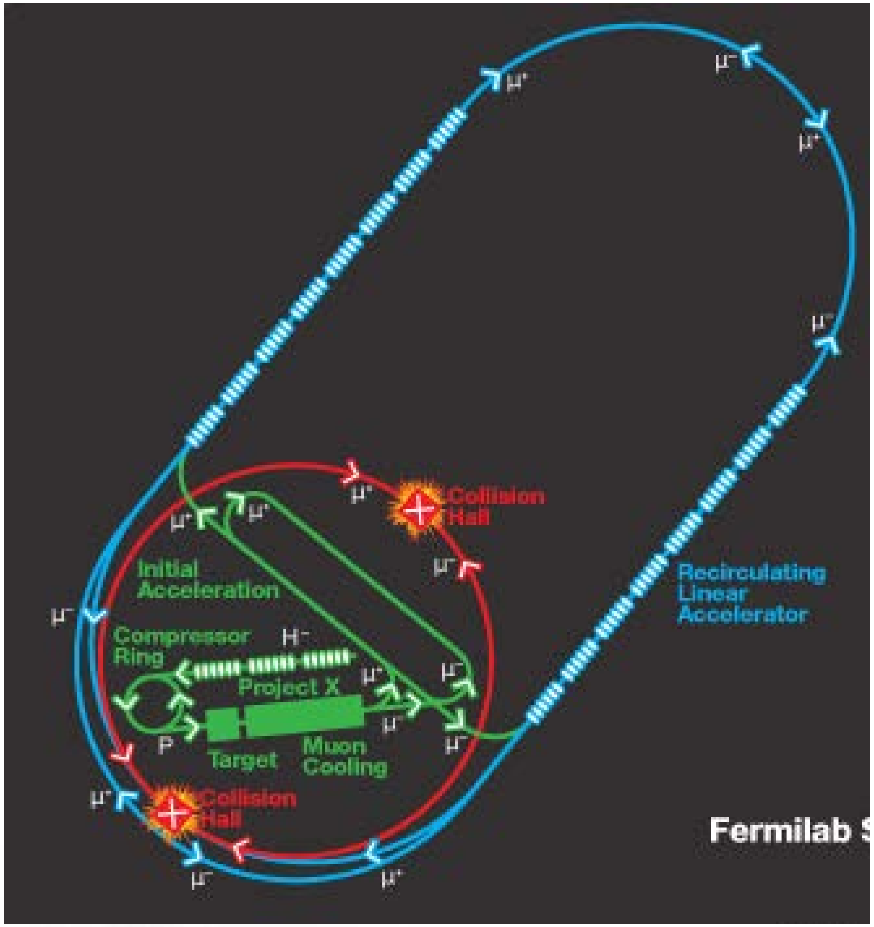
- Circular and linear
  - Large Electron Positron (LEP) collider
  - SLAC linear collider and International Linear Collider (ILC)
- Major limitation of circular e^+e^- colliders
  - Synchrotron radiation causes electrons to constantly loose energy
    - Energy loss is proportional to γ^4
    - Power consumption for such colliders is 100’s MW
    - Limit energy to ~0.5 TeV in the center of mass even for ~100 km long ring
- Major limitation of linear colliders
  - Need to add energy to electron in “one path”
  - Rate of adding energy is limited to ~30 MeV/meter, requires ~30 km long tunnel to reach ~0.5 TeV center of mass energy - ILC



$\mu^+\mu^-$ Colliders

- Muons are “heavy electrons”, they have low synchrotron radiation making circular accelerators viable for multi TeV energies
  - γ factor at the same energy is ~200 times less than for electrons
- Muons are unstable with life-time of 2.2 micro seconds
  - Decay to an electron and a pair of neutrinos
- Main accelerator challenge
  - To make large number of muons quickly and then “cool” them to focus into small diameter beam to collide
- Another issue are decays and irradiation by electrons from muon decays
  - And neutrinos irradiation!

2x2 TeV



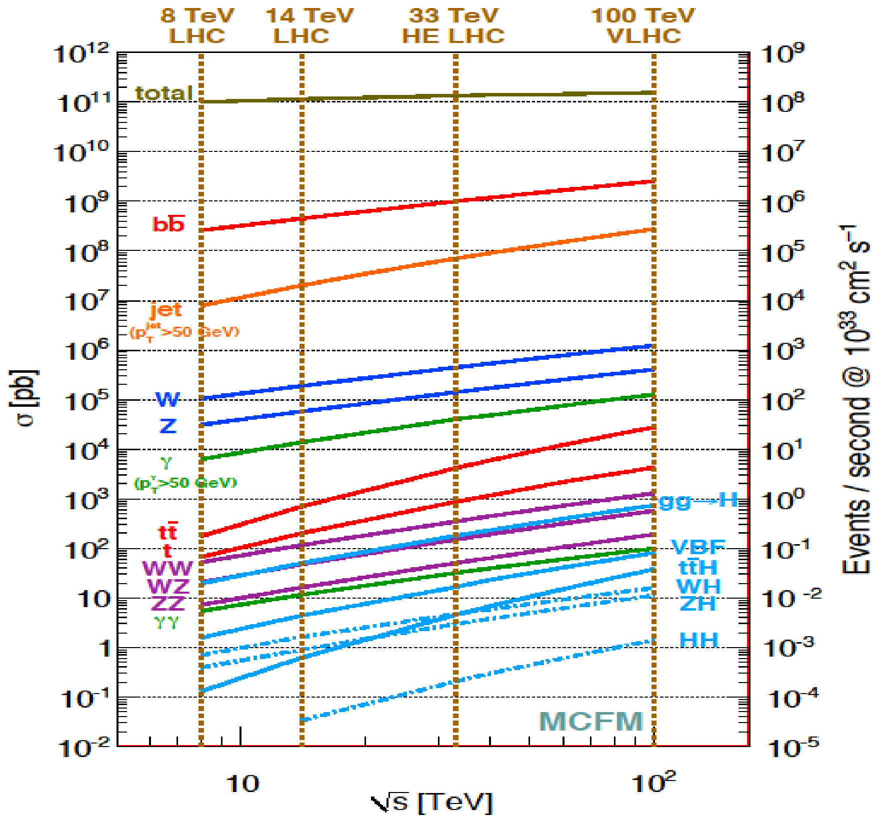
Hadron Colliders

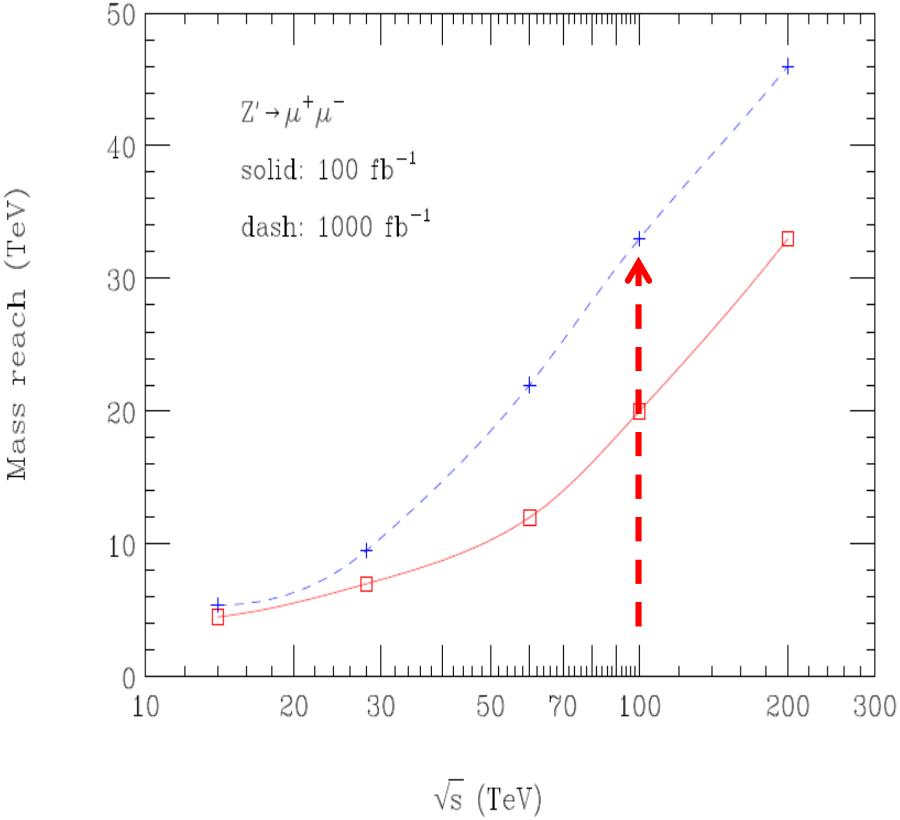
- What particles to collide: pp or ppbar ?
  - Using antiprotons in the first high energy hadron colliders was “quick” way to get to higher center of mass energy by using existing(!) rings designed for fixed target accelerators: SppS (CERN) and Tevatron (Fermilab)
  - If an accelerator complex is designed from the start as a collider, it is better to have proton-proton collisions
    - An order of magnitude or more higher luminosity
    - No complex antiproton source

- All hadron colliders designed since early 1980’s are proton-proton colliders
  - Two separate beam pipes

- Point-like vs not point-like colliding particles
  - Only fraction of the beam energy is utilized in the collision: up to ~50%
  - Lack of precision knowledge about event kinematics is a challenge

Collider Energy and Mass Reach





- Many studies done on the reach of high energy hadron colliders
- With reasonable luminosity mass reach for direct searches of ~1/2 of the full collider energy
  - 20 TeV machine is about twice less expensive than 40 TeV (might save SSC?)
  - But don’t want to miss major discovery due to low energy (LEP lesson)

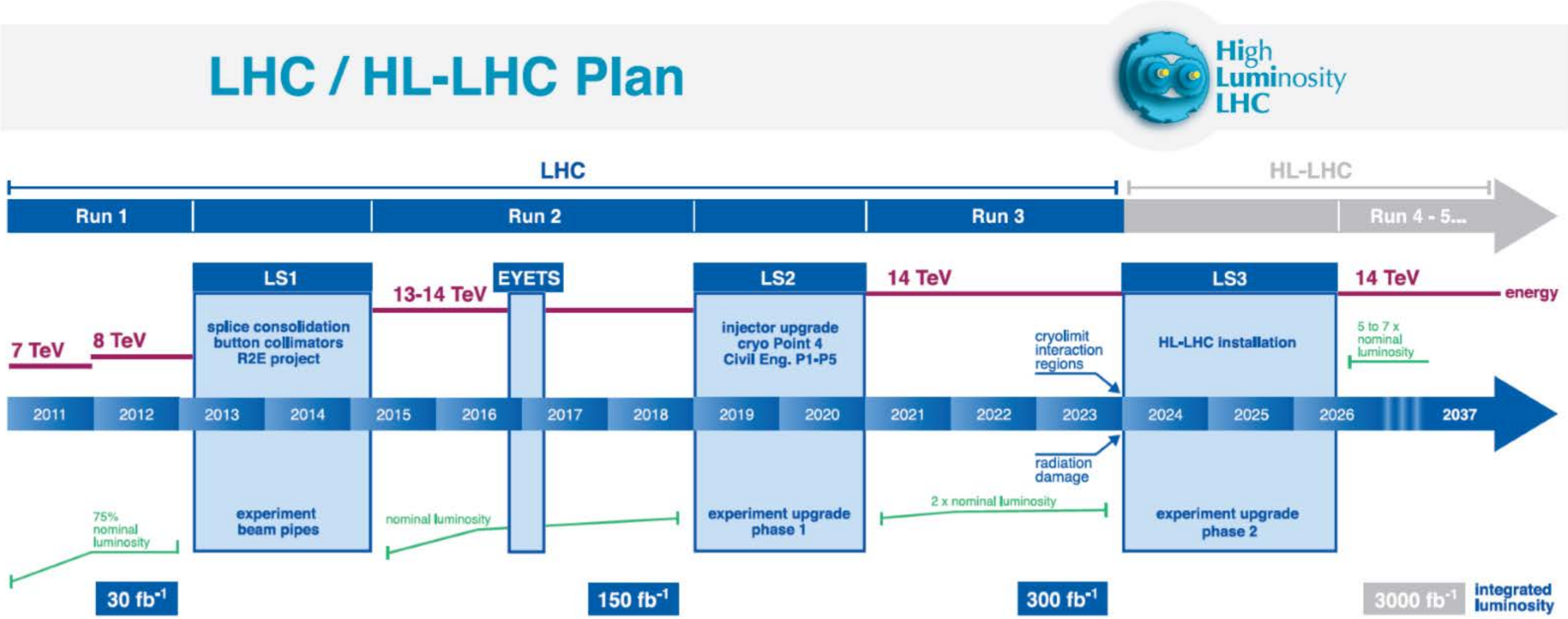
Bending Magnets and Tunnels

- Radius of the accelerator is
  - $R \sim E_{beam} / B$ where B is magnetic field and E_{beam} is beam energy
- First Fermilab accelerator had energy of ~450 GeV with bending field of ~2 Tesla (room temperature iron magnets)
  - Superconducting magnets increased field to ~4.5 Tesla bringing energy of the beam to ~1 TeV – Tevatron
- There are two options to increase energy of a hadron collider
  - Increase magnetic field in the bending magnets
    - Not easy beyond ~10-12 Tesla
  - Increase radius of the tunnel
    - New underground tunneling methods

Medium Term Colliders Projects Under Development

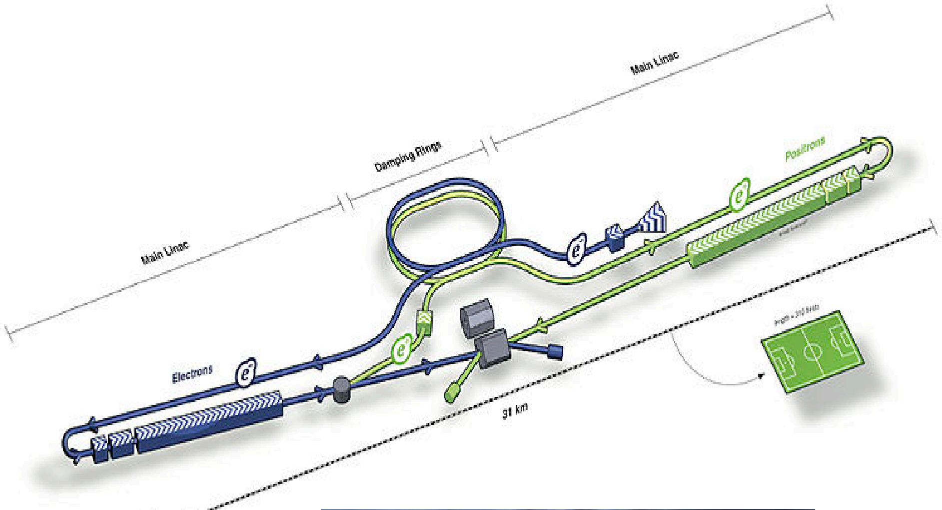
- **ILC - International Linear Collider**
  - 250 GeV linear e^+e^- collider (can be upgraded to ~500 GeV)
  - Higgs factory (and top quark factory after upgrade)
  - Location – Japan. Start of construction ~2023? Estimated cost ~$4B
- **CepC – Circular Electron Positron Collider**
  - ~250 GeV circular e^+e^- collider (the tunnel could be later used for pp collider)
  - Higgs factory
  - Location – China. Start of construction ~2021. Estimated cost ~$5B
- **FCC – Future Circular Colliders**
  - 350 GeV e^+e^- and/or ~100 TeV pp
  - Higgs factory and/or next energy frontier
  - Location – CERN. Start of construction – after 2030. Estimated cost - ~$12B e^+e^- and ~$24B pp
- **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 2030. Estimated cost $6B

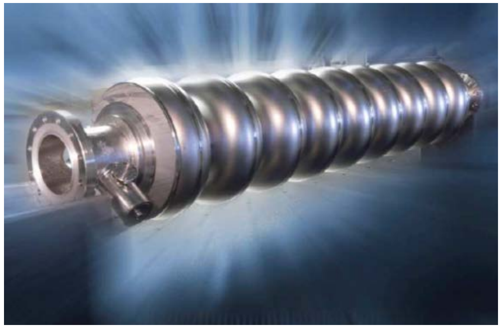
High Luminosity LHC Program



- LHC upgrade to $\sim 5 \cdot 10^{34}$ cm^{-2}sec^{-1} luminosity by 2026
- Then ~10 years of data collection up to ~ 3 ab^{-1}

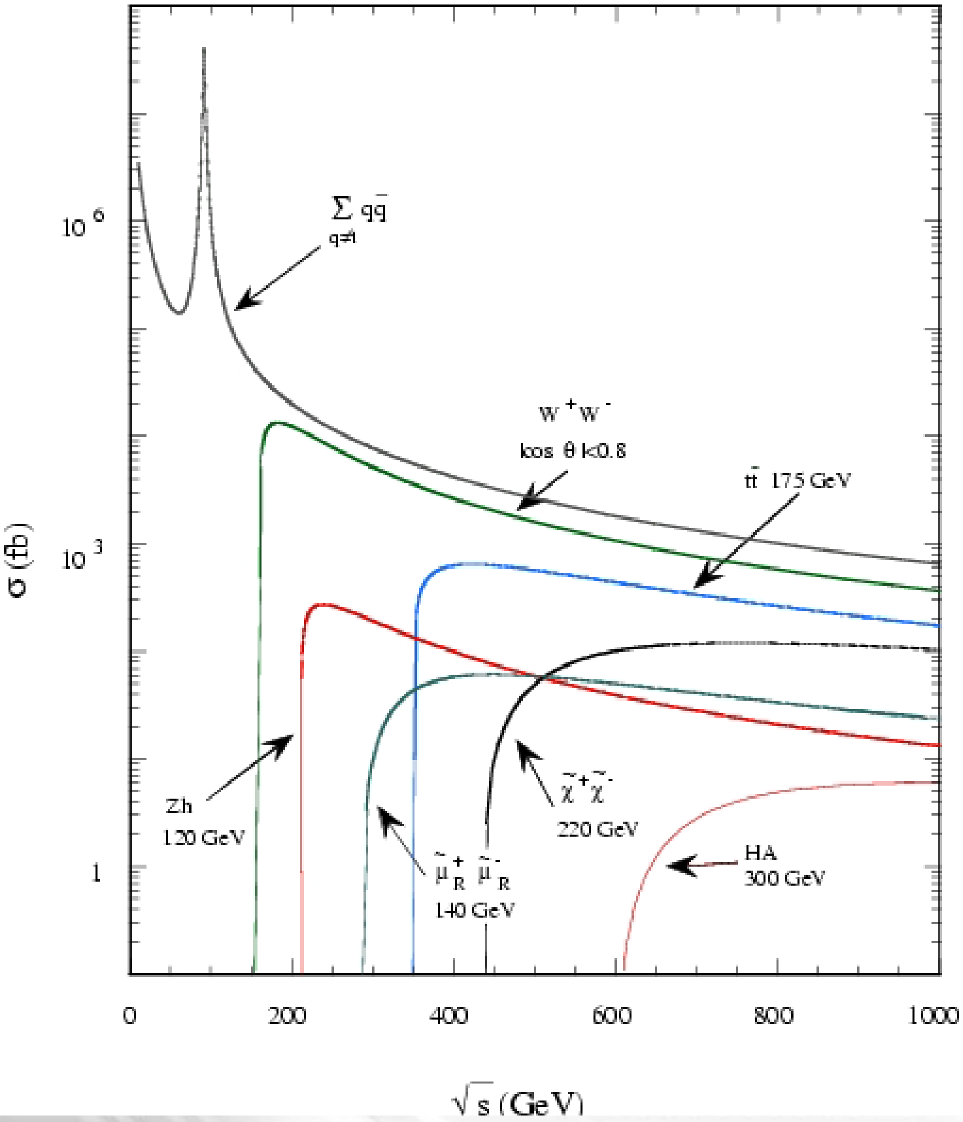
International Linear Collider





- ILC or International Linear Collider is e^+e^- linear collider with the following main parameters
  - Center of mass energy 250 GeV (upgradeable to higher energies)
  - Luminosity $>10^{34}$ $cm^{-2}s^{-1}$
- No synchrotron radiation, but long tunnel to accelerate to ~ 125 GeV/beam
  - Excellent Higgs factory with many Higgs production and decay channels accessible

e^+e^- Colliders Physics and Experiments



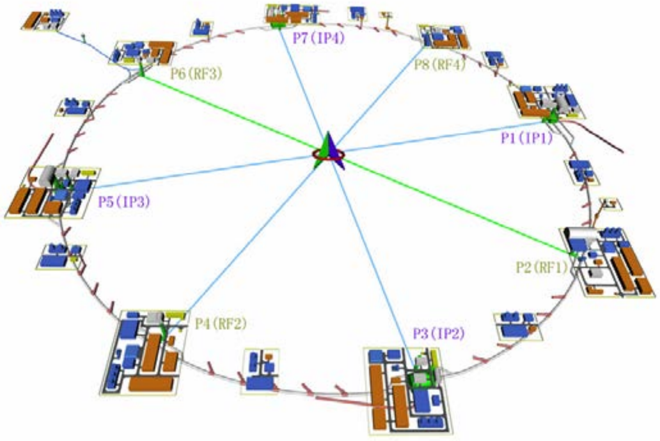
- Low cross sections
  - High luminosity needed
- Low rate of interactions
  - Collect all events
  - High efficiency needed
- Point like particles colliding
  - Sharp thresholds
  - Can be used for precision measurements including top quark mass
- Large number of different production/decay channels
  - Have to detect all “standard objects” well
  - Jets/photons, leptons, charged tracks, missing energy

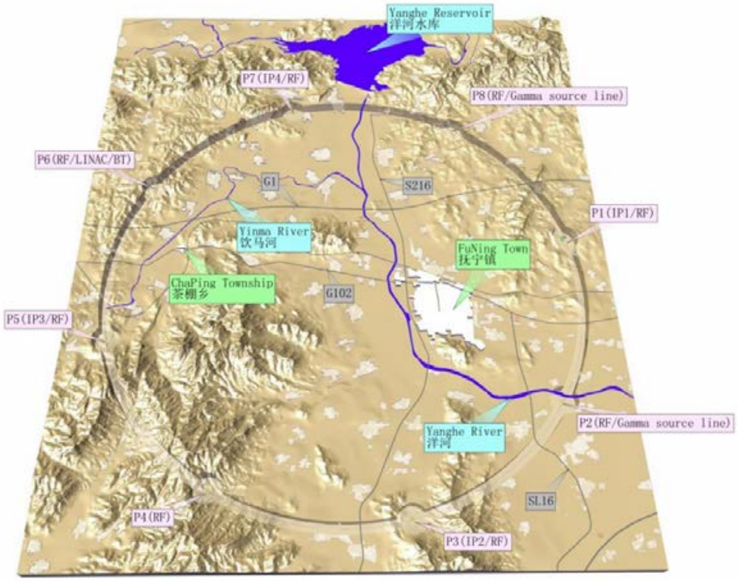
ILC Status and Plans

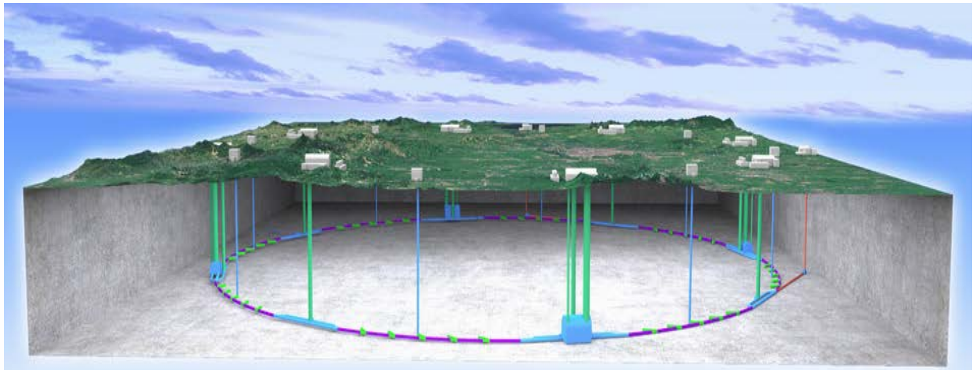
- After success of SLAC's linear e^+e^- collider in 1990's (SLC) various proposals developed to go to even higher colliding energy
  - Among them NLC(SLAC), TESLA(DESY), "ILC at Fermilab"
- Starting in 2008 Global Design Effort (GDE) progressed developing
  - Technical design of the ILC
  - Cost estimate 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
  - Part of Primer Minister Abe election platform
- Recently
  - Substantial progress in technical developments
  - Development of cooperation between participants on "Governments level"
- All involved agree that ILC project should be international project with Japan as the host country
  - Funding for this international project, including in Japan, is expected to be "in addition to the existing particle physics funding"

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 boson and Higgs factory
- SppC – Super Proton Proton Collider
  - In the same ring as CepC
  - ~100 TeV with 16 T magnets

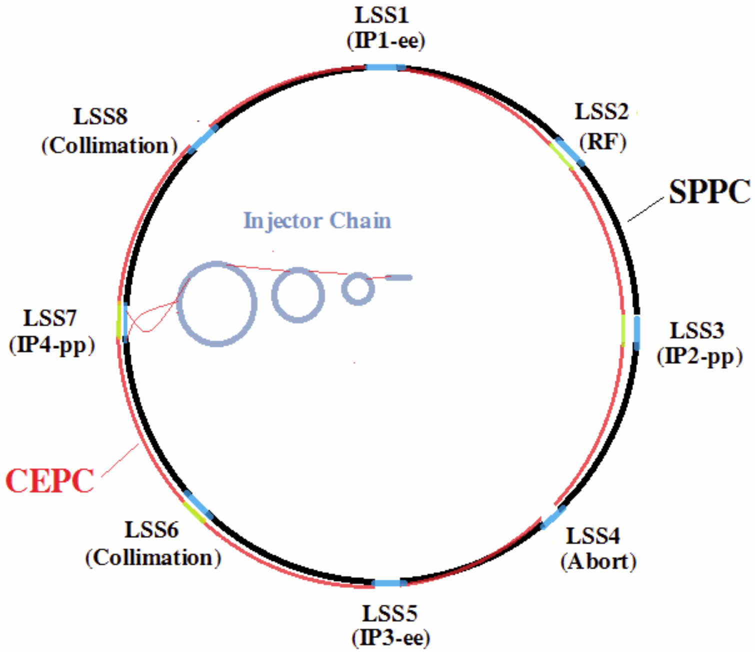






Future Colliders in China

- Active progress with the CepC and SppC design over last two years
  - International reviews (positive) of the conceptual proposals in Spring of 2015
- 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 time line
  - Design 2020-2030
  - Construction 2035-2042
  - Physics at ~100 TeV starting in 2043

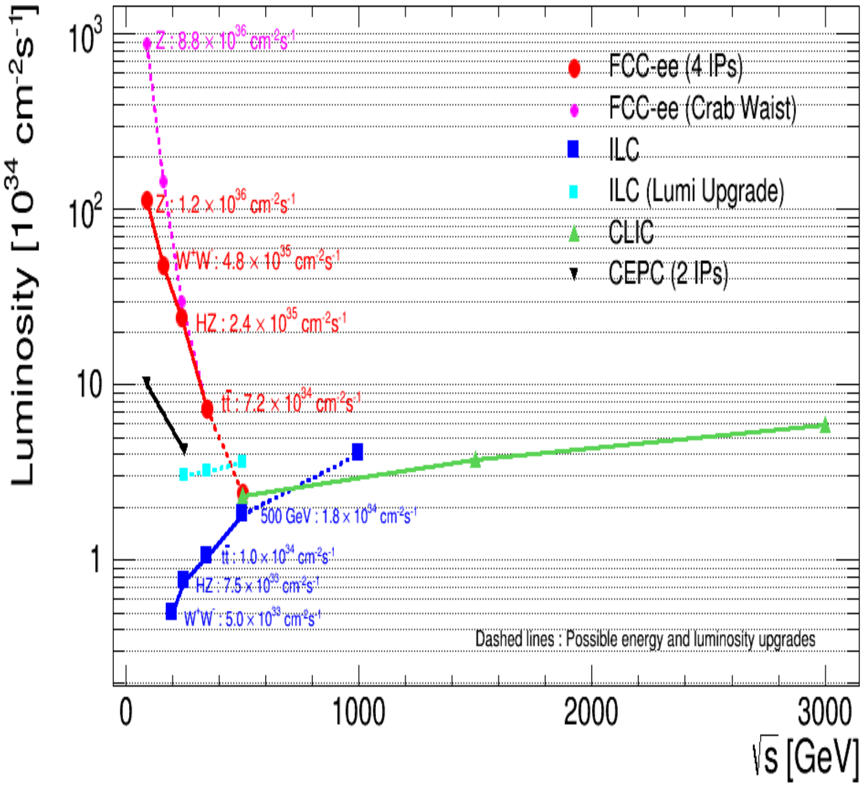


- The proposal is based on
  - Experience with BEPC e^+e^- collider
  - Relatively inexpensive tunneling in Ch
  - Strong Government interest in scientific leadership – both CepC and SppC are “national projects with international participation”
  - Setting realistic goals based on the expected availability of resources

FCC – Future Circular Colliders at CERN

- FCC activity follows 2012 European particle physics strategy recommendation to develop future energy frontier colliders at CERN
  - "…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines…"
- 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
- Similar to "LEP then LHC" option of starting from 350 GeV e^+e^- collider and later going to 100 TeV pp collider is considered
  - But in no way decided

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

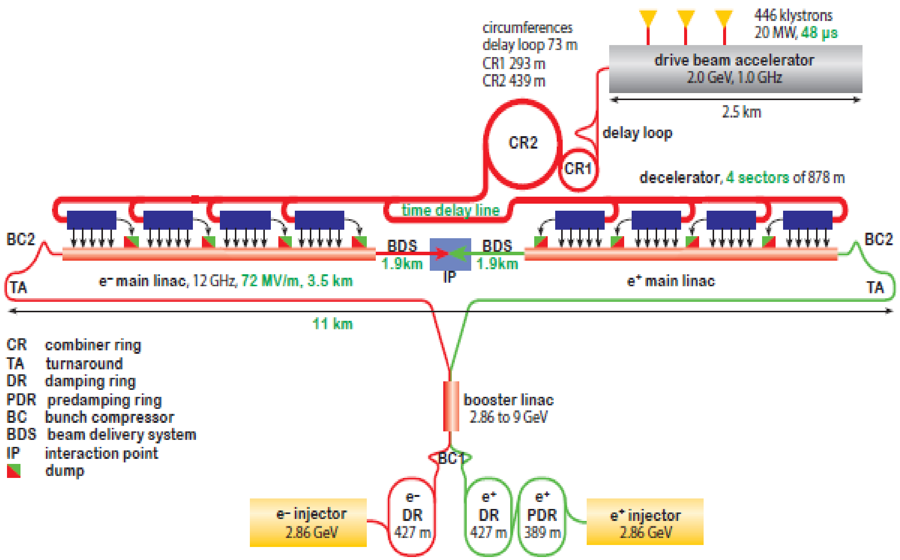
- FCC ee is circular e^+e^- collider in 100km long ring with ~350 GeV maximum energy
- Circular e^+e^- collider has substantially higher luminosity at lower energies vs linear collider
  - Z, W, Higgs and top quark factory
- Main challenges: long tunnel and high synchrotron losses requiring demanding superconducting accelerating system and high electricity consumption

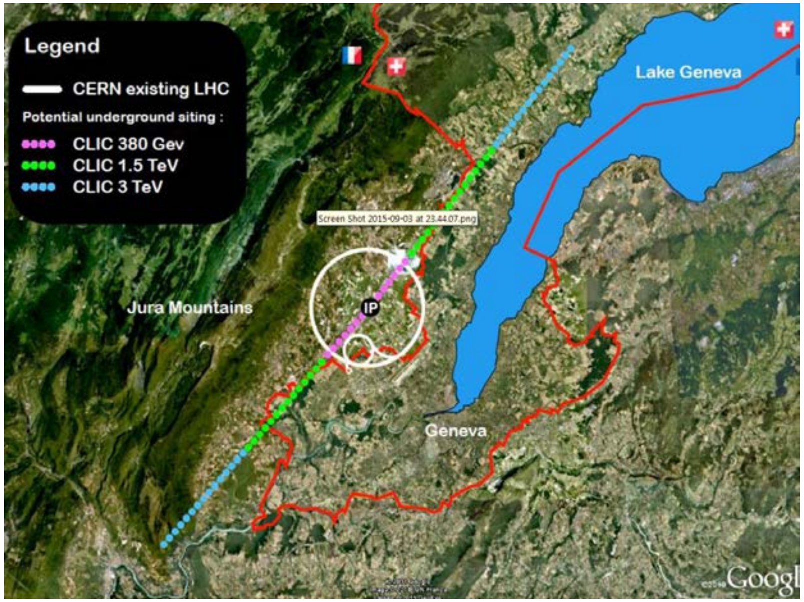
FCC pp 100 TeV collider

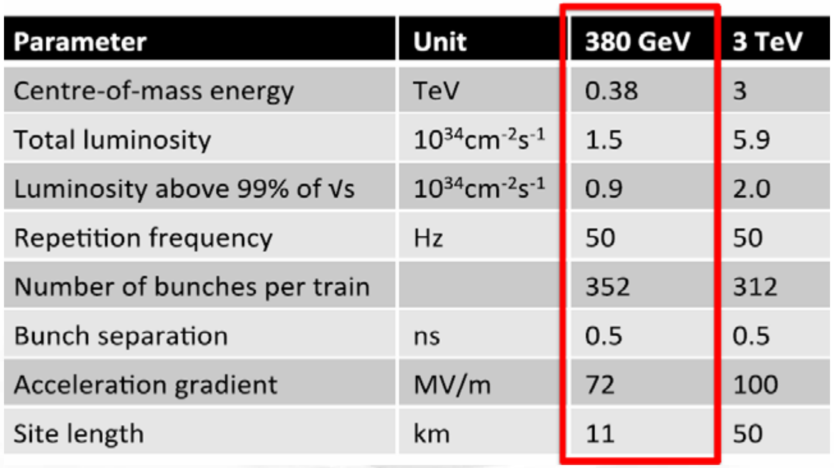
Parameter	FCC-pp	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [cm^{-2}s^{-1}]	5 - 25 x 10^{34}	5 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- Main challenges
  - Long tunnel
  - High field magnets
  - High synchrotron radiation load
- Tevatron and LHC experience demonstrate feasibility of such a collider

CLIC Collider at CERN



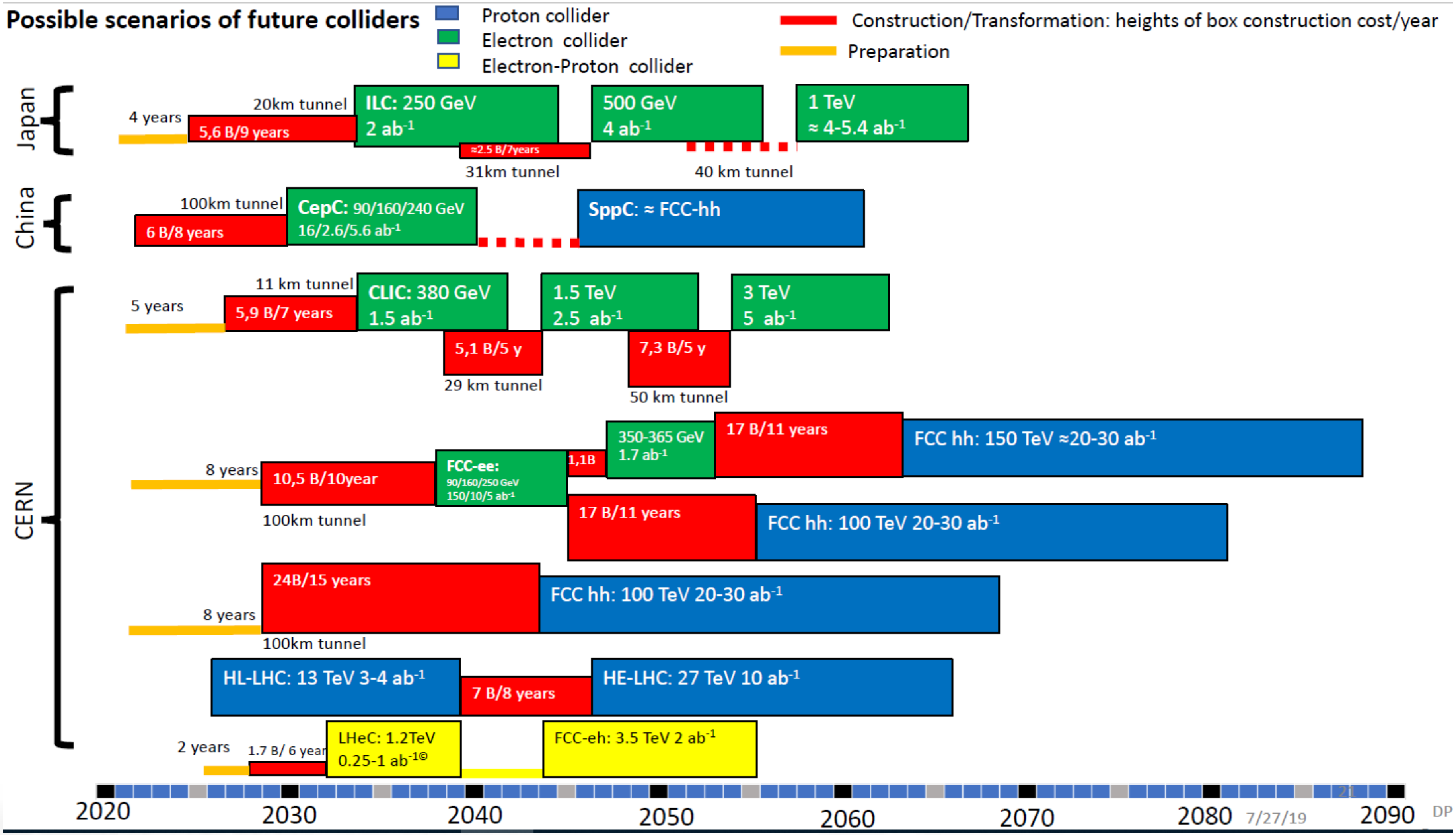




Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site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

- 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

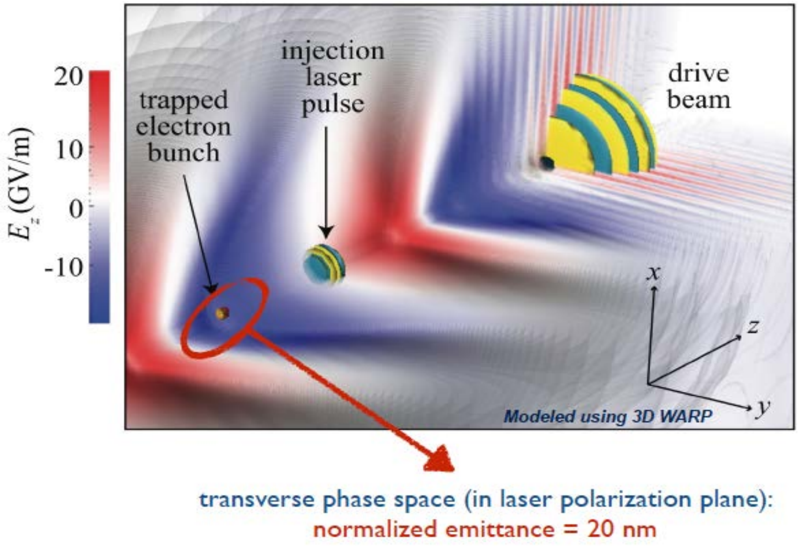
Future Colliders Timeline



Novel Ideas in Very High Gradient Acceleration

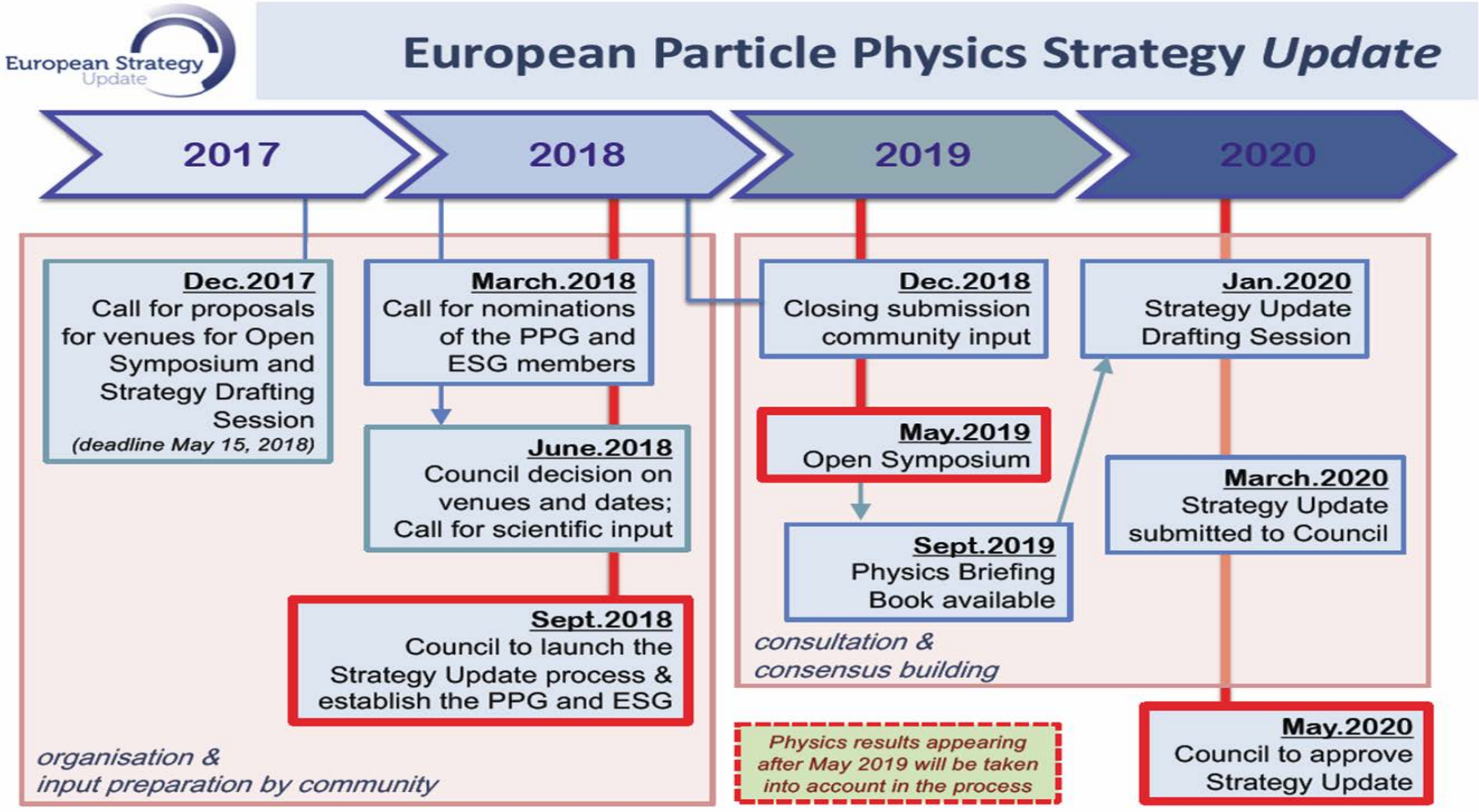
- Leverage the potential for accelerating gradients in the GV/m range
- Beam-Driven Wakefield Accelerators
  - In US: FACET/FACET-II
- Laser-driven Wakefield Accelerators
  - In US: BELLA
- Dielectric Wakefield Acceleration
  - In US: AWA, ATF
- Major research efforts are also underway in Europe and 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 from practical applications in particle physics



transverse phase space (in laser polarization plane):
normalized emittance = 20 nm

How Particle Physics Decides on the Next Project(s)?



European Strategy Update

European Particle Physics Strategy *Update*

2017 | 2018 | 2019 | 2020

Dec.2017
Call for proposals for venues for Open Symposium and Strategy Drafting Session
(deadline May 15, 2018)

March.2018
Call for nominations of the PPG and ESG members

June.2018
Council decision on venues and dates; Call for scientific input

Sept.2018
Council to launch the Strategy Update process & establish the PPG and ESG

organisation & input preparation by community

Dec.2018
Closing submission community input

May.2019
Open Symposium

Sept.2019
Physics Briefing Book available

consultation & consensus building

Physics results appearing after May 2019 will be taken into account in the process

Jan.2020
Strategy Update Drafting Session

March.2020
Strategy Update submitted to Council

May.2020
Council to approve Strategy Update

- It is a mix of cooperation and competition
- Driven by planning in various regions
  - European/CERN future will be discussed over next ~2 years
  - Japan has to decide about ILC by the end of 2019
  - US will discuss its plans (Snowmass-P5 process) starting in 2020
  - China is expected to decide by their next 5 years plan or around 2021

Future Colliders - Summary

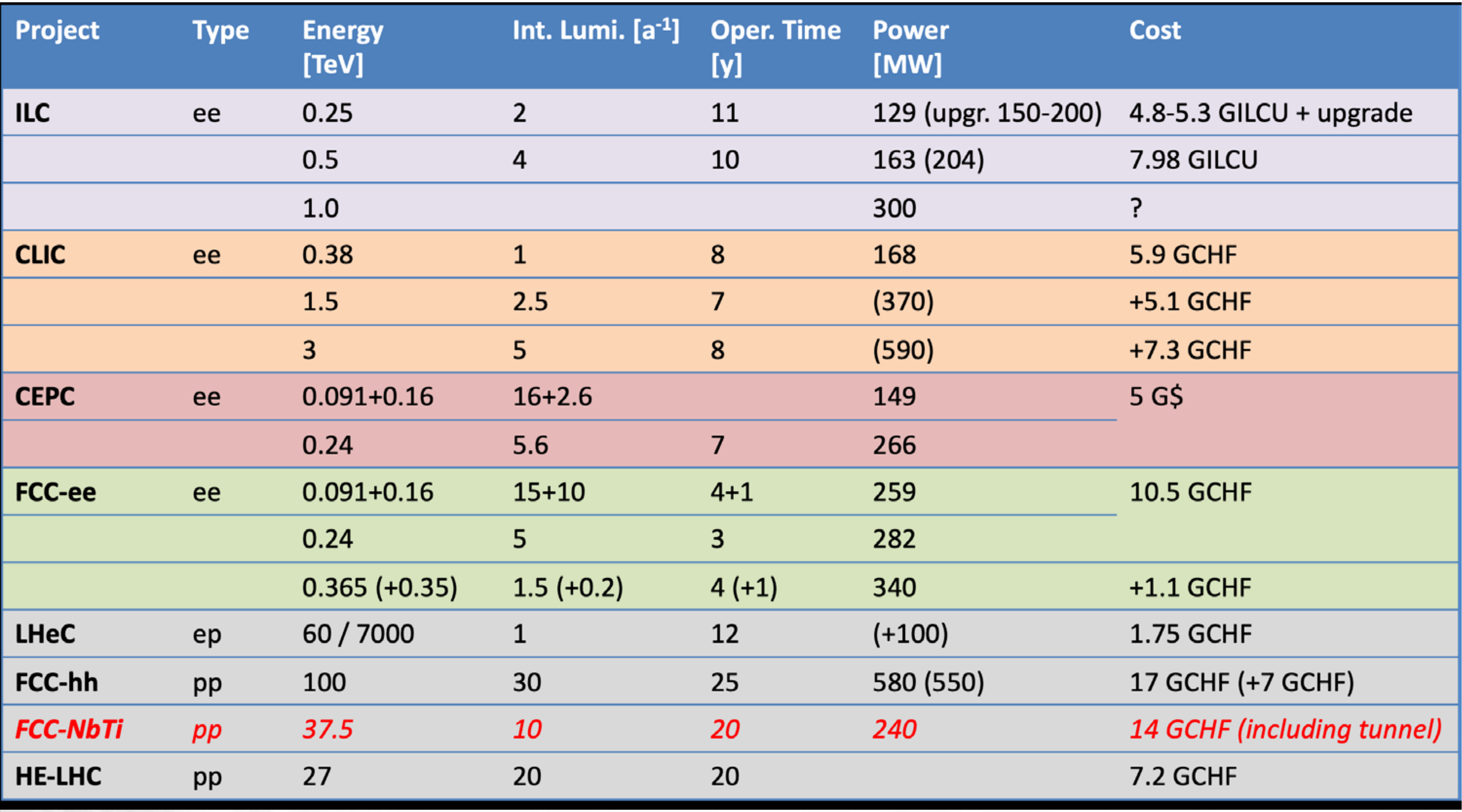
- Colliders played major role in establishing and understanding the standard model
  - Discovered all expected standard model particles!
- Future proposed colliders are of two types
  - e^+e^- colliders as “Higgs factory”
  - pp colliders at the next energy frontier
- Three proposals are under active discussion
  - ILC (Japan) – decision by Japan’s Government is expected this year
  - CepC and SppC (China) – decision around 2021
  - FCC (CERN) – European strategy outcome by early 2020
- Key for the future colliders is to reduce cost dramatically

Progress toward higher colliders energies is the only way to study even smaller distances and create particles with even higher masses than we can today

Detectors for 100 TeV Collider

- We would like to detect all “well know” stable particles including products of short lived objects decays: pions, kaons, muons, etc.
  - Need 4π detector with layers of tracking, calorimetry and muon system
- Central tracker
  - Most challenging is to preserve momentum resolution for ~10 times higher momentum tracks
- Calorimetry
  - Getting better with energy: hadronic energy resolution ~50%/√E, 2% at 1TeV
  - Length of a shower has log(E) dependence – not a major issue
- Muon system
  - Main challenge is momentum resolution and showering of muons as they are becoming “electrons” due to large γ factor
- Occupancies and radiation doses
  - Up to 10^{35} cm^{-2} sec^{-1} looks reasonable, challenging for above both due to pileup and radiation aging

European Strategy - Future Colliders



Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	15+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
FCC-NbTi	*pp*	*37.5*	*10*	*20*	*240*	*14 GCHF (including tunnel)*
HE-LHC	pp	27	20	20		7.2 GCHF