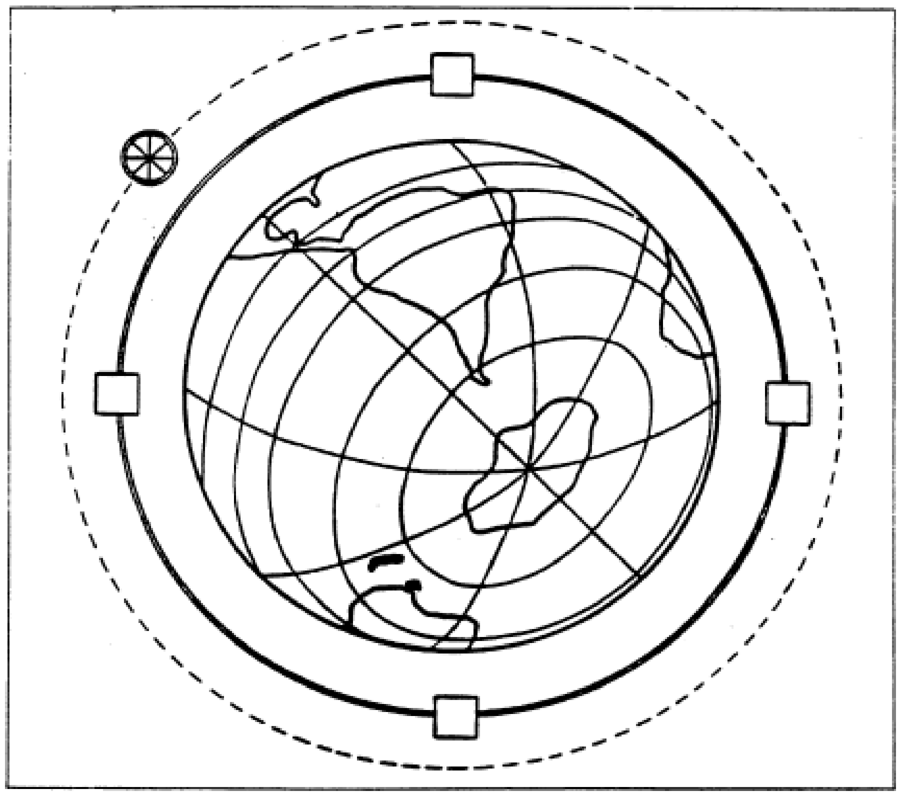
Colliders: Past, Present and Future



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

Dmitri Denisov, Brookhaven National Laboratory

International School on High Energy Physics and Accelerator Technology, Almaty

October 12, 2023

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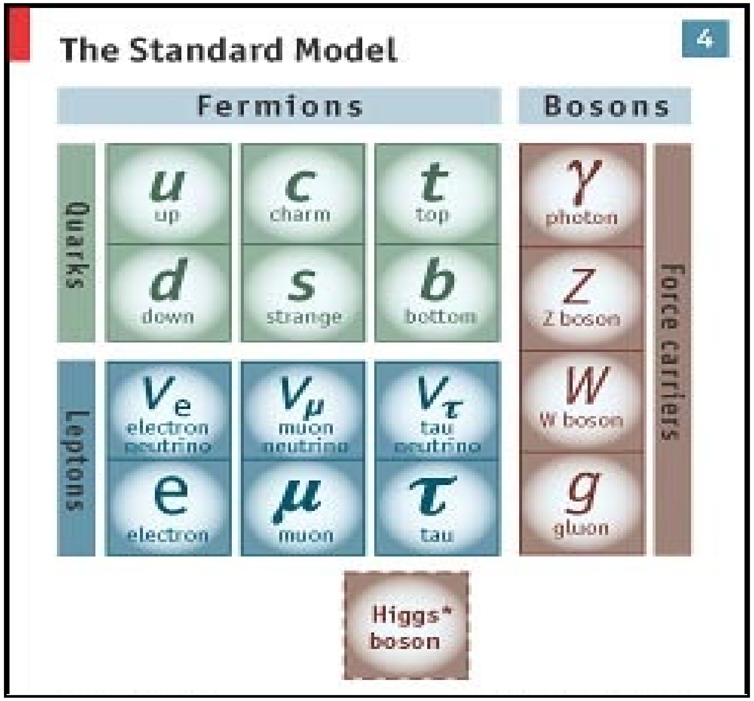
Particle Physics

- 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



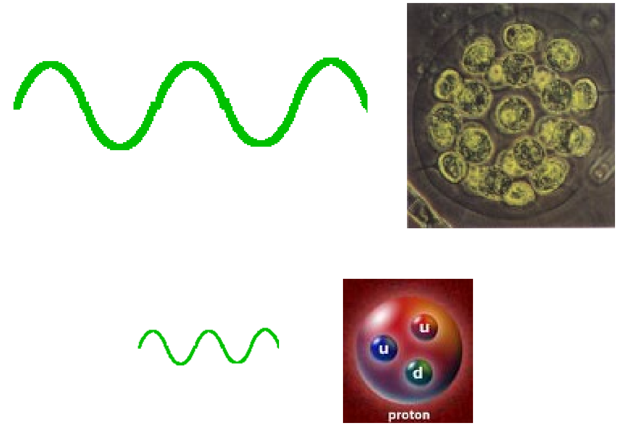
- But our current understanding is incomplete
  - Can't explain the observed number of quarks/leptons
  - Model parameters can't be predicted
- Nothing is "wrong" with the Standard Model
  - The goal is to define the limits of applicability and find what lies beyond

Why High Energy and Why Colliders

- Accelerators are built to study the Nature smallest objects

Wavelength = h/E

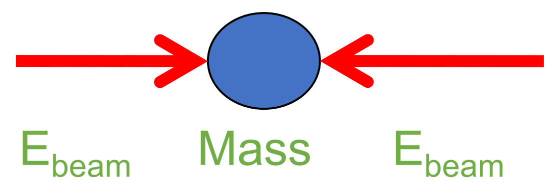
~2 ·10^{-18} cm for LHC



- Accelerators convert energy into mass

$E = mc^2$

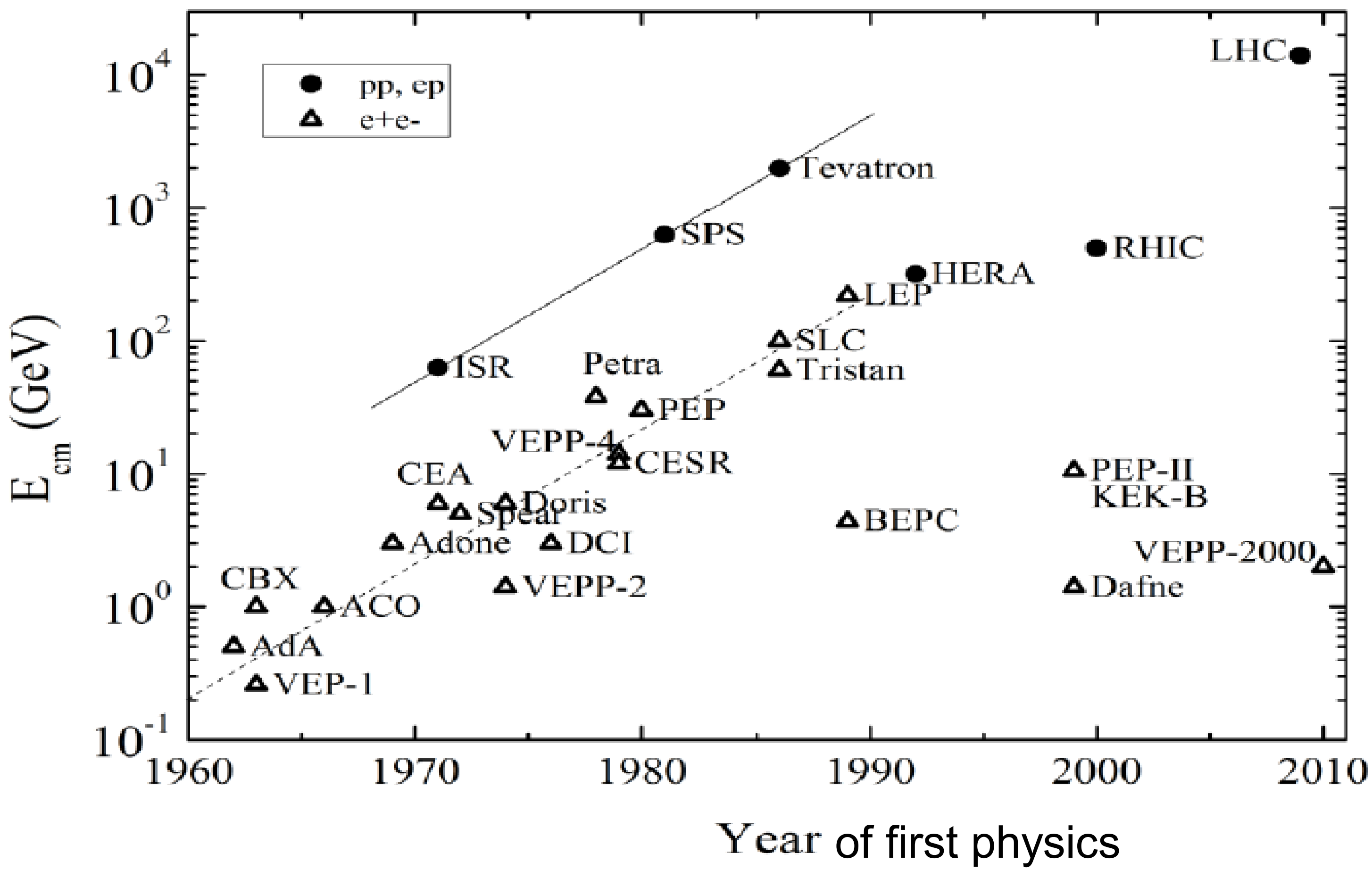
Objects with masses up to
Mass = $2E_{beam}$ could be created



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

To get to the next step in understanding of Nature - at both smaller distances and higher elementary particles masses - higher energy is the only way to succeed

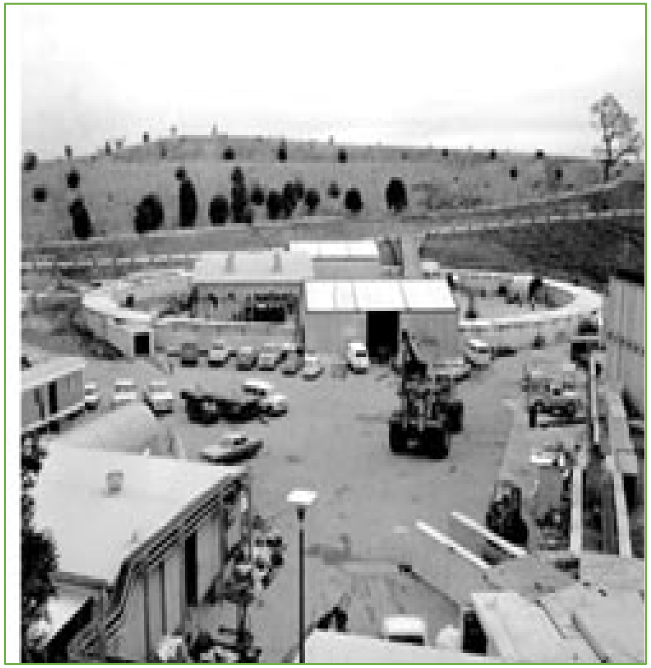
Colliders

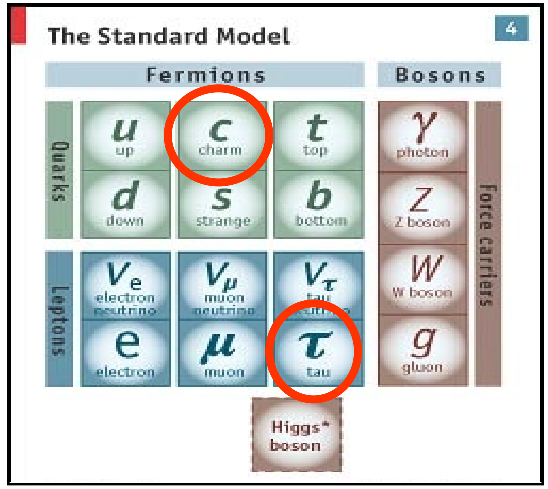


- First e^+e^- colliders started operation in early 1960's with hadron colliders (storage ring) first collisions in 1971 with the completion of the Intersecting Storage Rings (ISR) at CERN
- Large number of e^+e^- colliders, while few hadron colliders
- Hadron colliders provide higher center of mass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

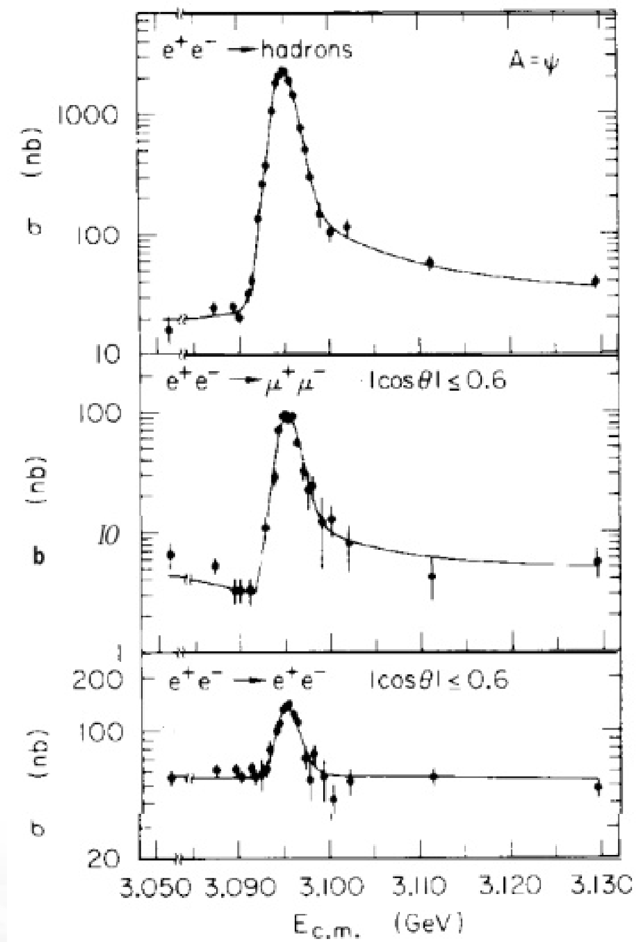
SPEAR e^+e^- Collider at SLAC: start 1972

SPEAR construction



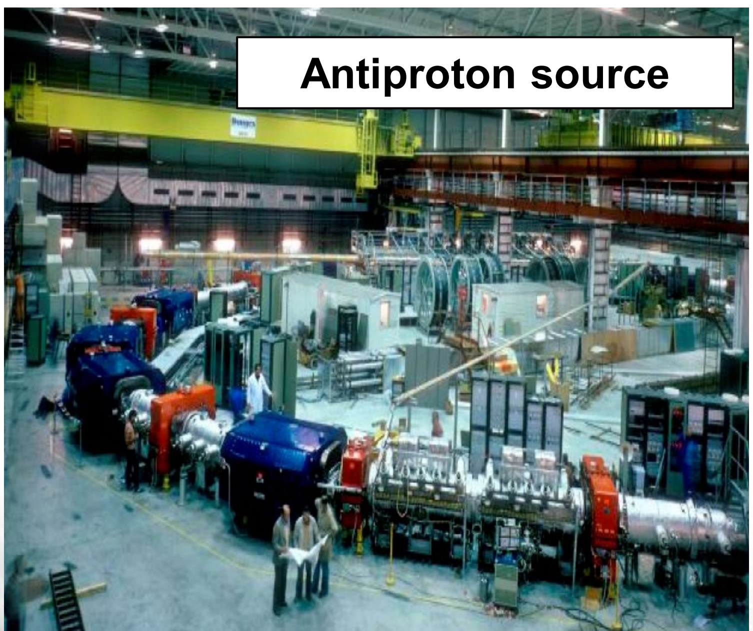


J/Psi discovery

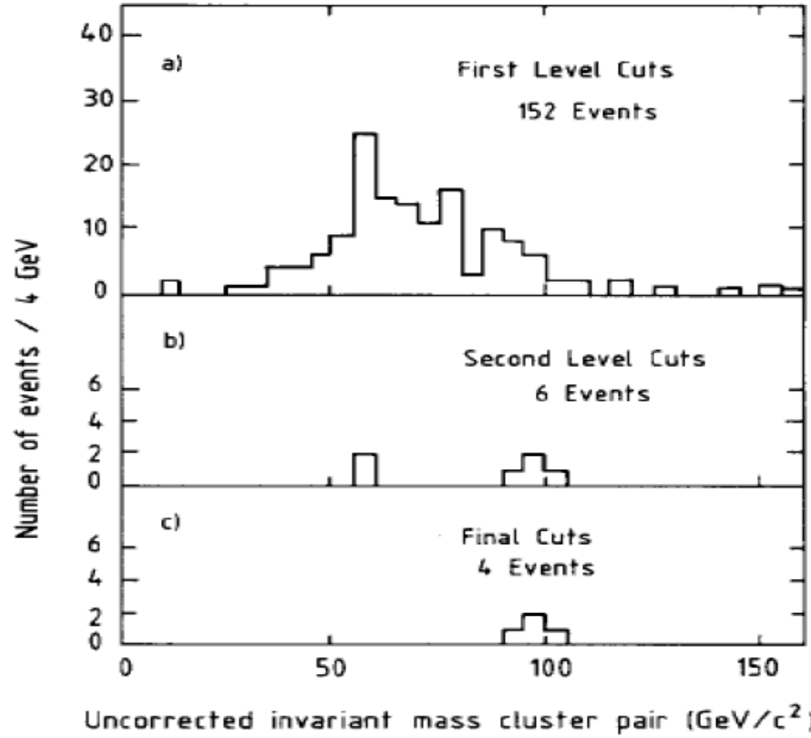


- Started in 1972 with ~3 GeV center of mass energy
- Opened extremely productive energy range
  - Co-discovery of c-quark (J/Psi meson) in 1974
  - Discovery of τ-lepton in 1975
- One of the most productive colliders in the world!

SppS Collider at CERN: start 1981

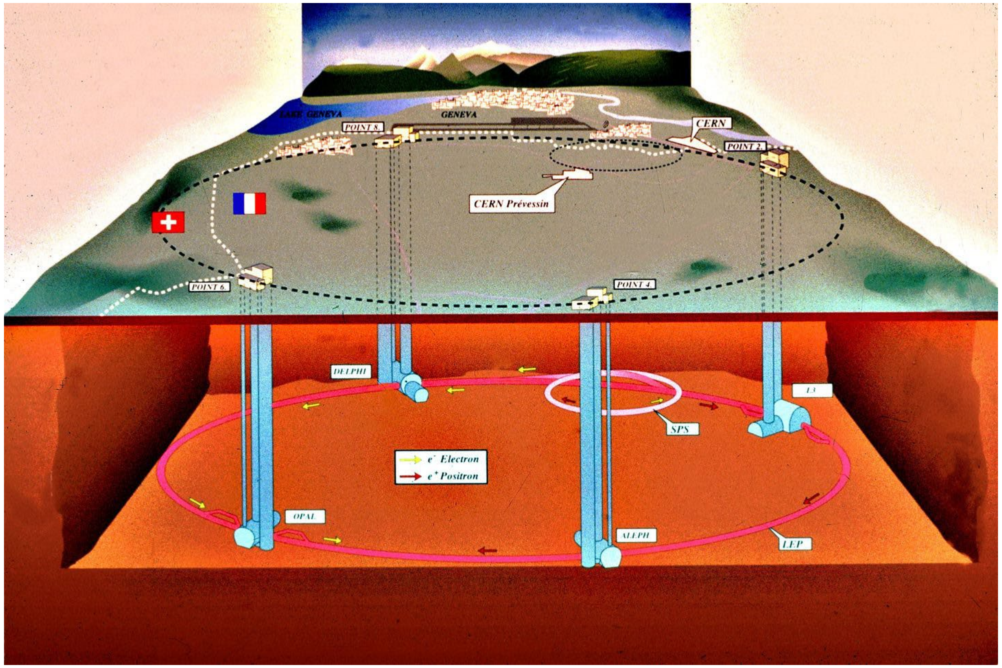


Z boson discovery

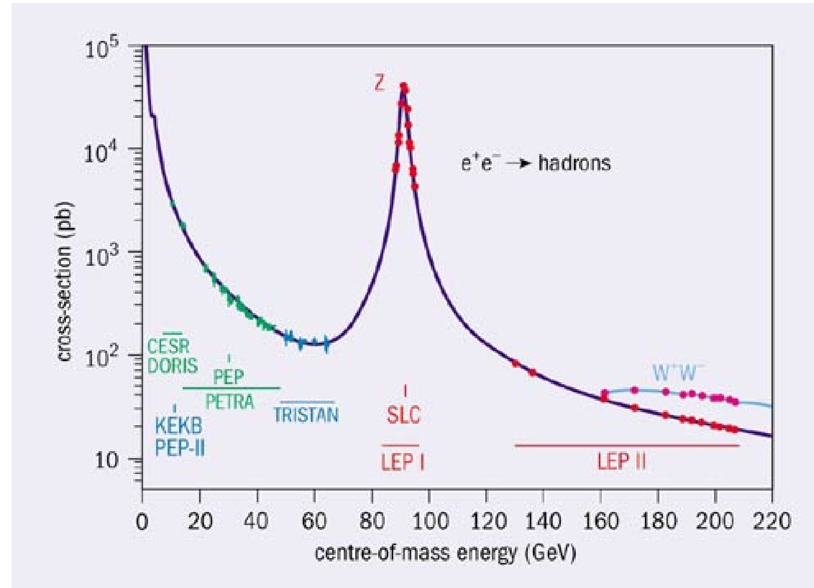


- Use of antiprotons in the existing fixed target accelerator
- Provided next step in the understanding of the Standard Model
  - W/Z bosons discovery

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

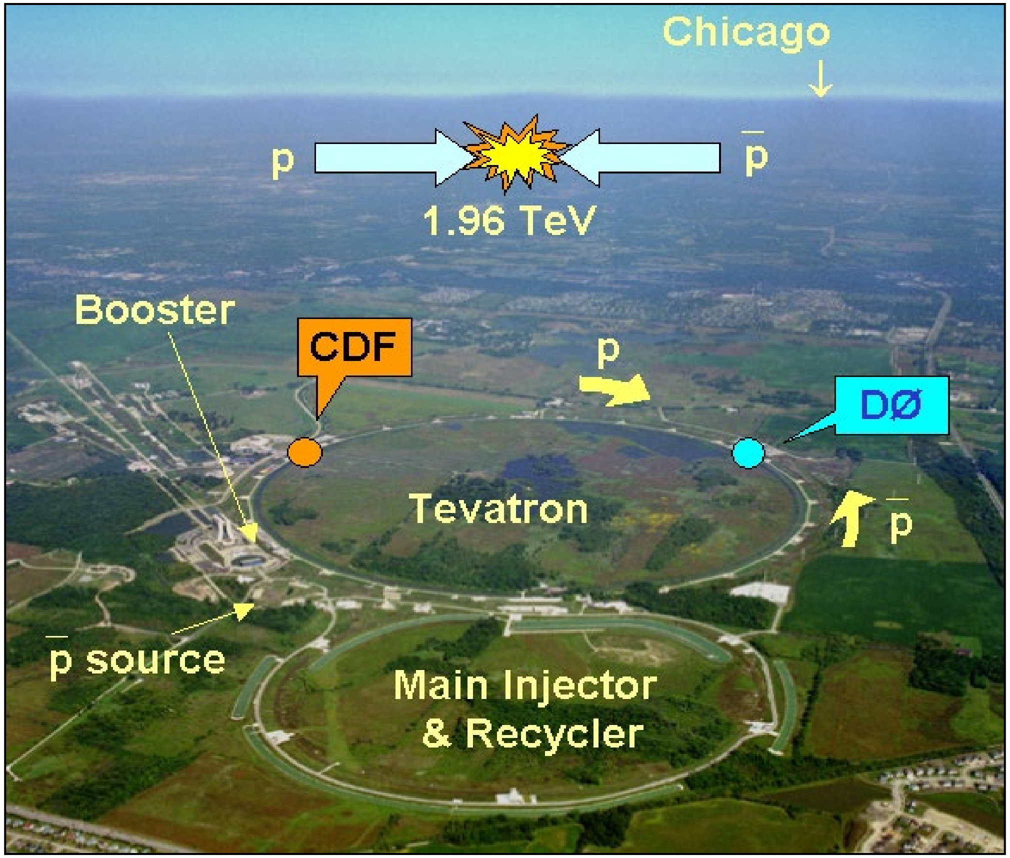


Z boson factory

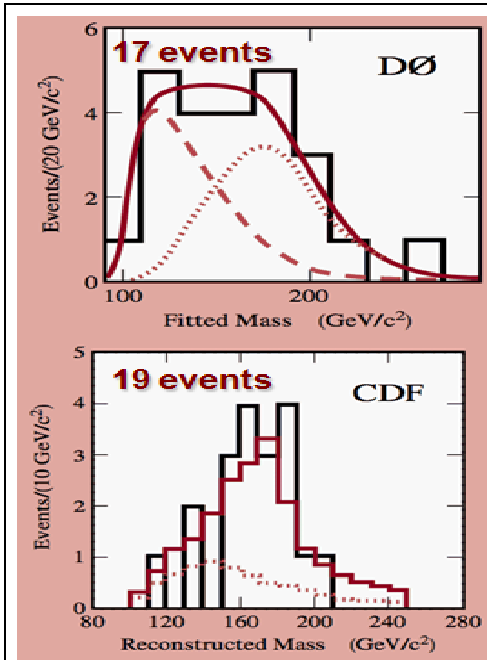


- Large Electron Positron (LEP) collider in 27 km long tunnel with up to ~200 GeV center of mass energy
  - Started operation in 1989 as “Z factory”
  - Wide range of extremely precise measurements, including Z boson mass measurement and determination of the number of neutrino generations
- Stanford Linear Collider (SLC) linear collider Z factory at SLAC operated at about the same time
- LEP needed just 5% extra center of mass energy to discover the Higgs… in the year 2000

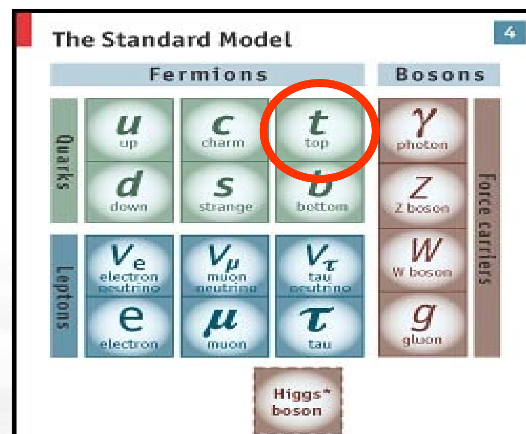
The Tevatron: start 1985



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

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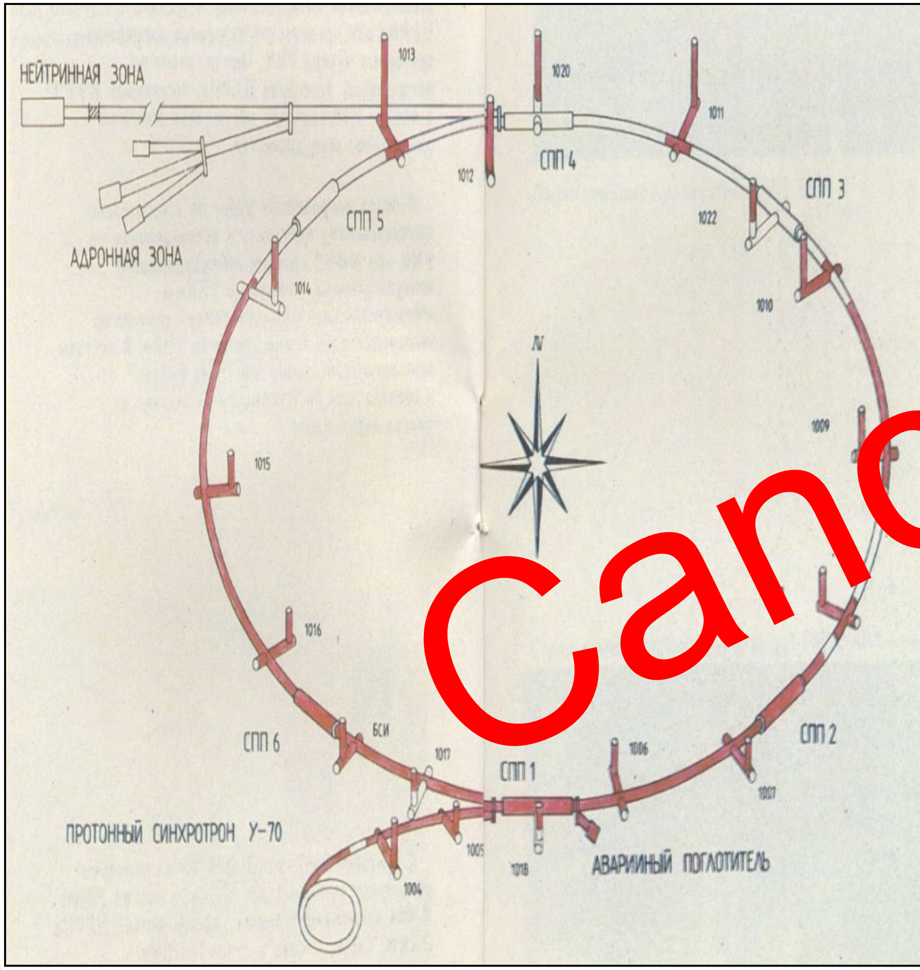
Attempts to Reach Higher Energies: 90’s



Cancelled

3x3 TeV, UNK, USSR

20x20 TeV, SSC, USA

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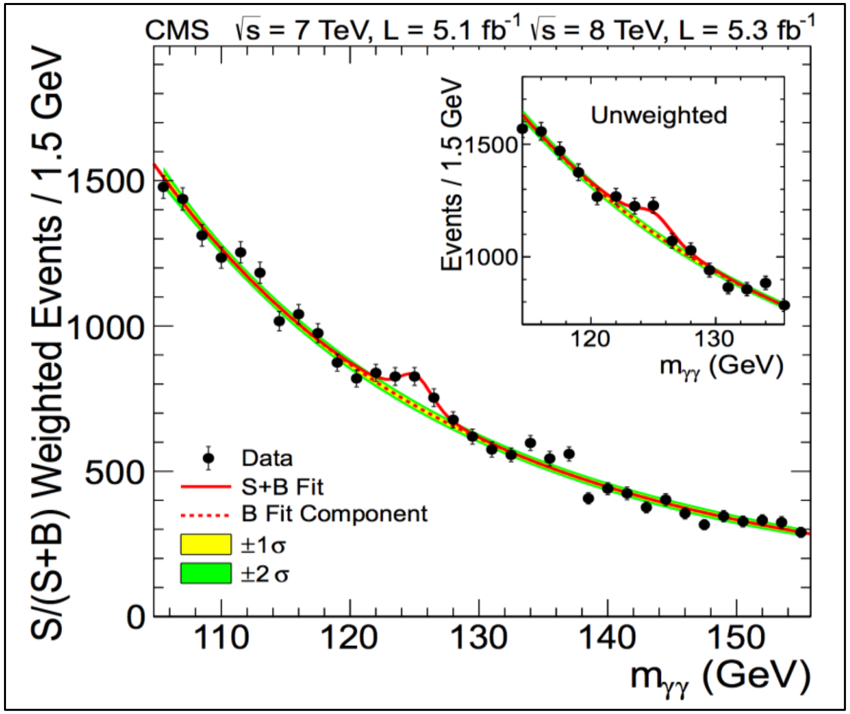
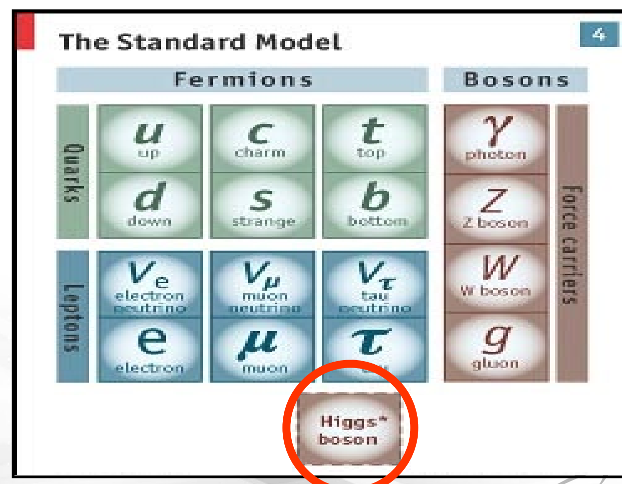
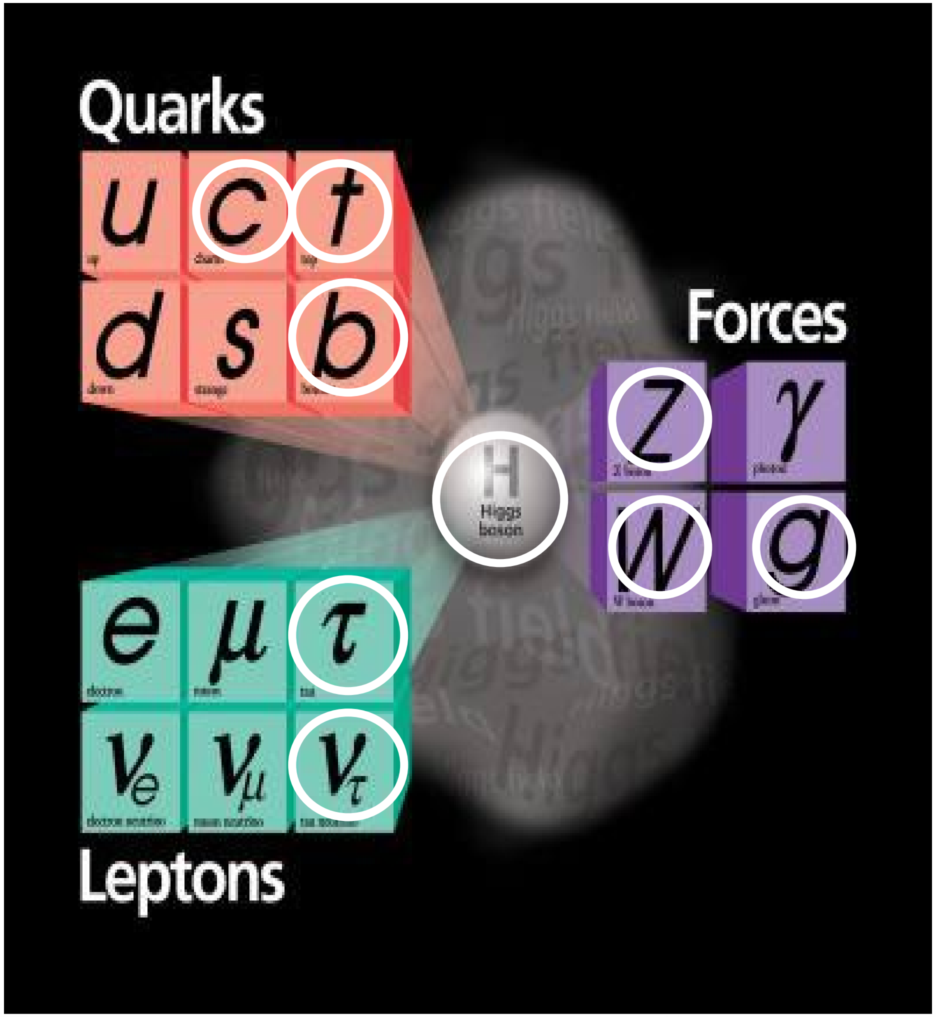
The LHC – the History in the Making



- 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!



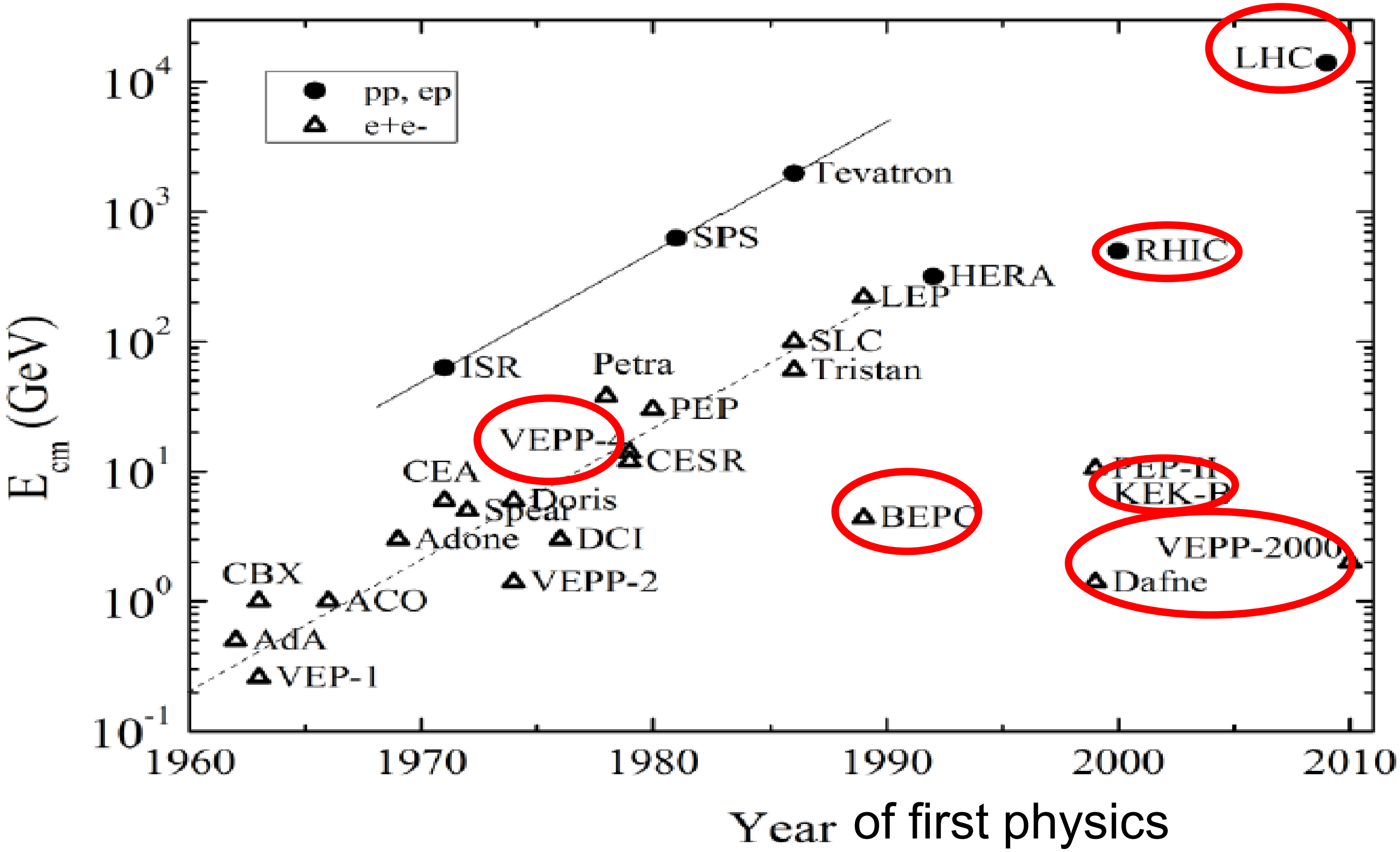
Accelerators and the Standard Model



- 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
  - 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
  - RHIC and in the future EIC at BNL – nuclear studies
  - NICA heavy ion collider at JINR
- DAFNE (Frascati), VEPP (Novosibirsk), BEPC (Beijing) – low energy e^+e^- colliders
- SuperKEK-B – b-factory at KEK re-stared in 2019 with planned 40 times higher luminosity
  - Studies of particle containing b-quarks

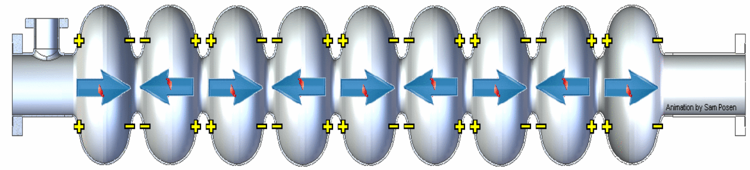
Physics Goals and Challenges of the Future Colliders

- Physics interests drive colliders development
  - Like colliding antiprotons with protons in the already existing proton ring 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

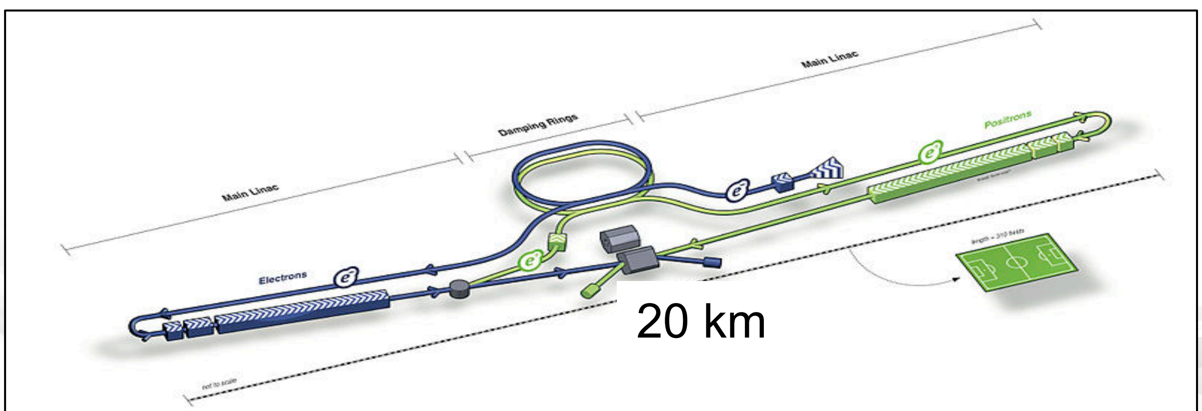
e^+e^- Colliders



- Circular and linear
  - Circular – LEP
  - Linear - SLAC linear collider and future 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
    - Radiation limits energy to ~0.5 TeV in the center of mass even for ~100 km long ring

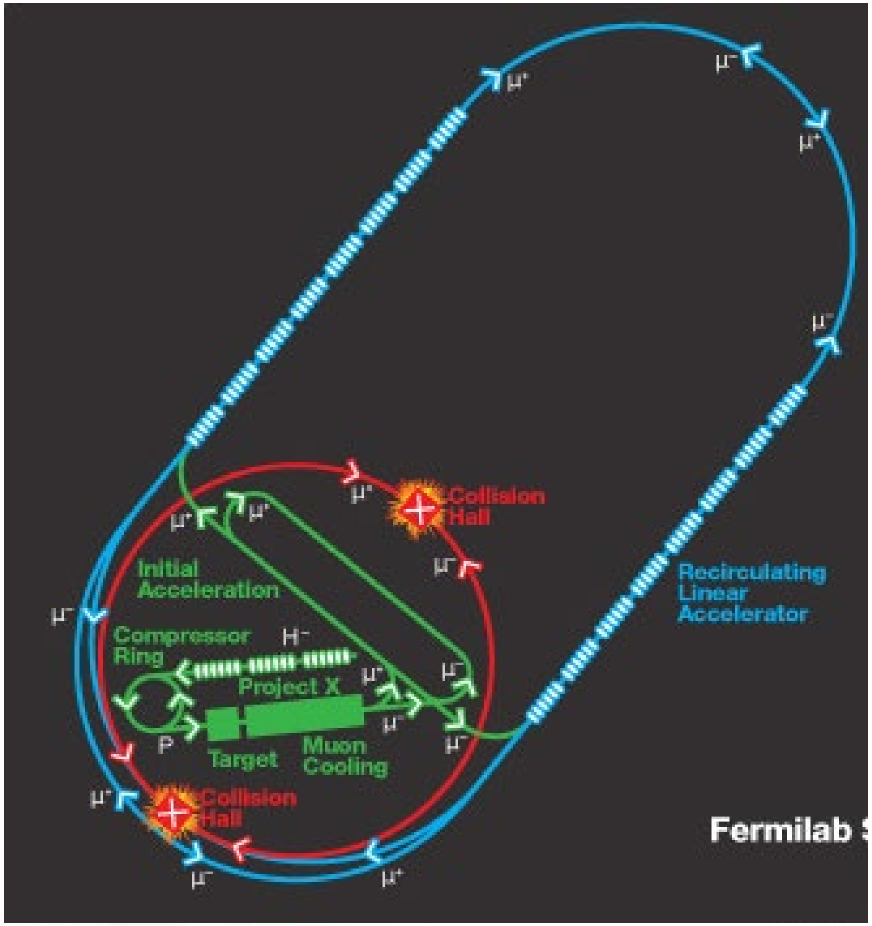
- Major limitation of linear colliders
  - Need to add energy to electron in "one path"
  - Rate of adding energy is limited to ~30 MeV/meter, requires ~30 km long tunnel to reach ~0.5 TeV center of mass energy - ILC



$\mu^+\mu^-$ 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
- But… muons are unstable with life-time of 2.2 μs
  - Decay to an electron and a pair of neutrinos
- Main accelerator challenge
  - Make large number of muons quickly and then "cool" them to focus into a small diameter beam to collide
- Another issue is equipment irradiation by electrons from muon decays
  - And neutrinos radiation!

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
    - Higher luminosity
    - No complex antiproton source

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

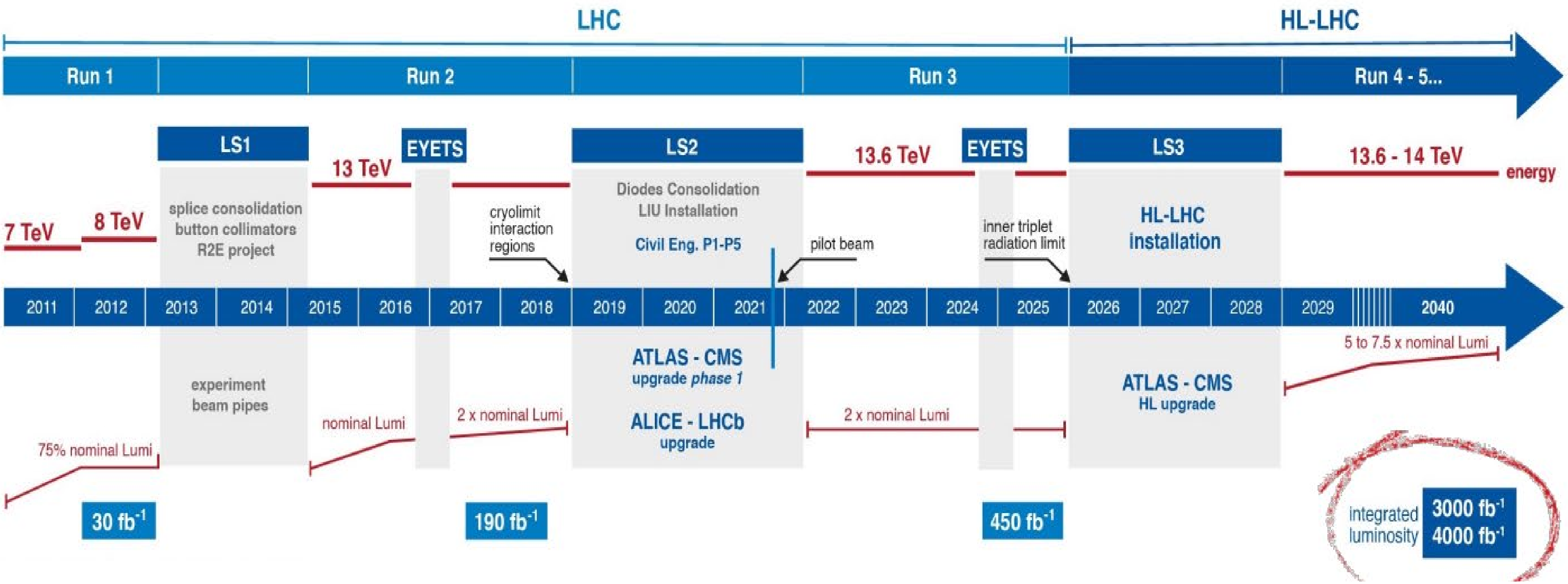
- Point-like vs not point-like colliding particles
  - Only fraction of the beam energy is utilized in the collision: up to ~50%
  - Lack of precision knowledge about event kinematics is a challenge

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 – the 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

CERN High Luminosity LHC Program



- LHC upgrade to ~$5 \cdot 10^{34}$ $cm^{-2}sec^{-1}$ luminosity by ~2027
- Then ~10 years of data collection up to ~3 ab^{-1}

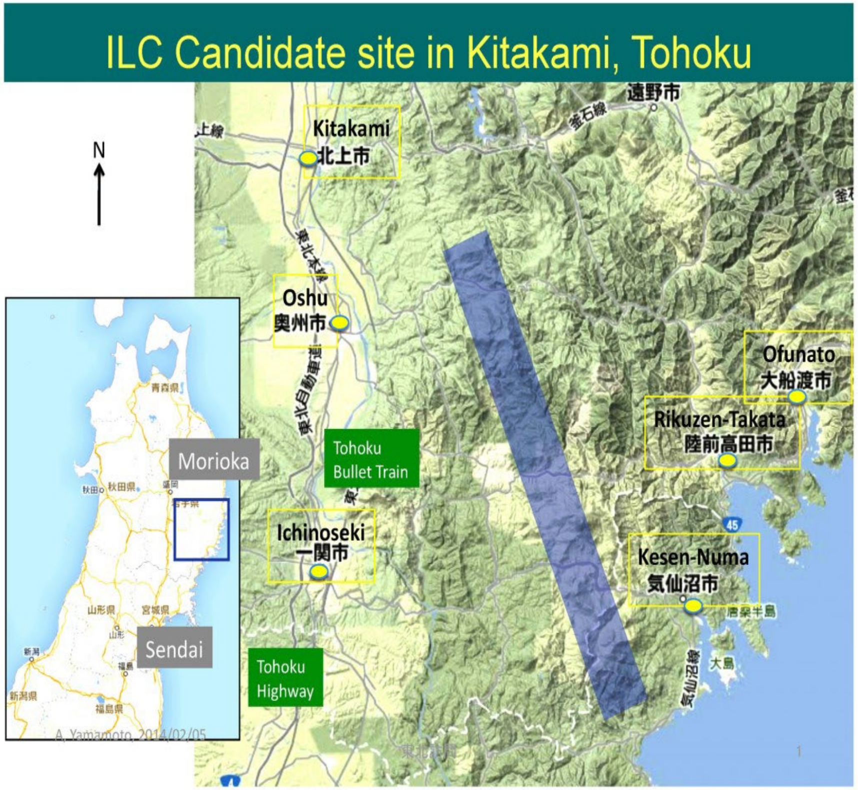
Developed Colliders Proposals

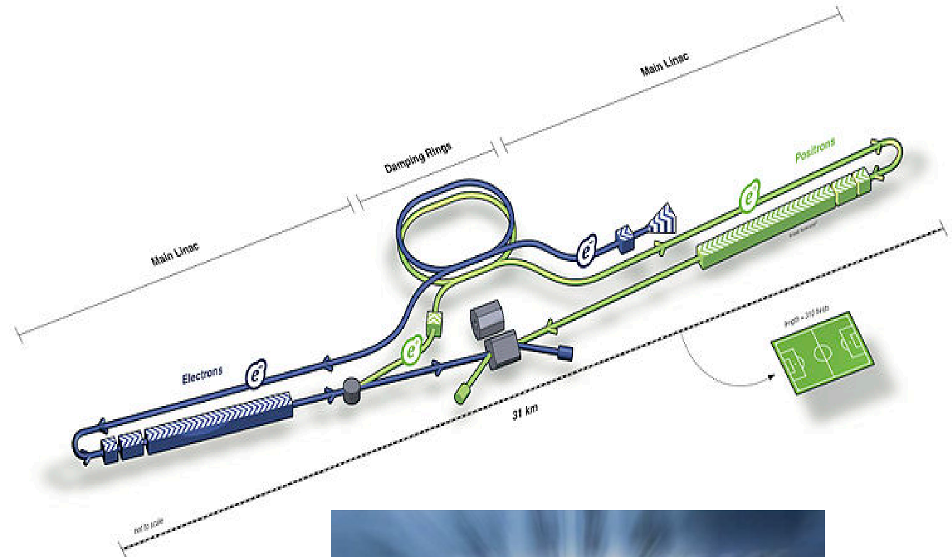
- **ILC - International Linear Collider**
  - 250 GeV linear e^+e^- collider
  - Higgs factory
  - Location – Japan, start of construction 2028(?), estimated cost $8B

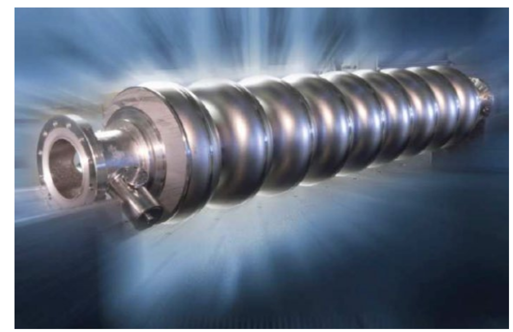
- **CepC – Circular Electron Positron Collider**
  - ~250 GeV circular e^+e^- collider
  - Higgs factory
  - Location – China, start of construction 2026(?), estimated cost $5B

- **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^- or $24B pp

International Linear Collider

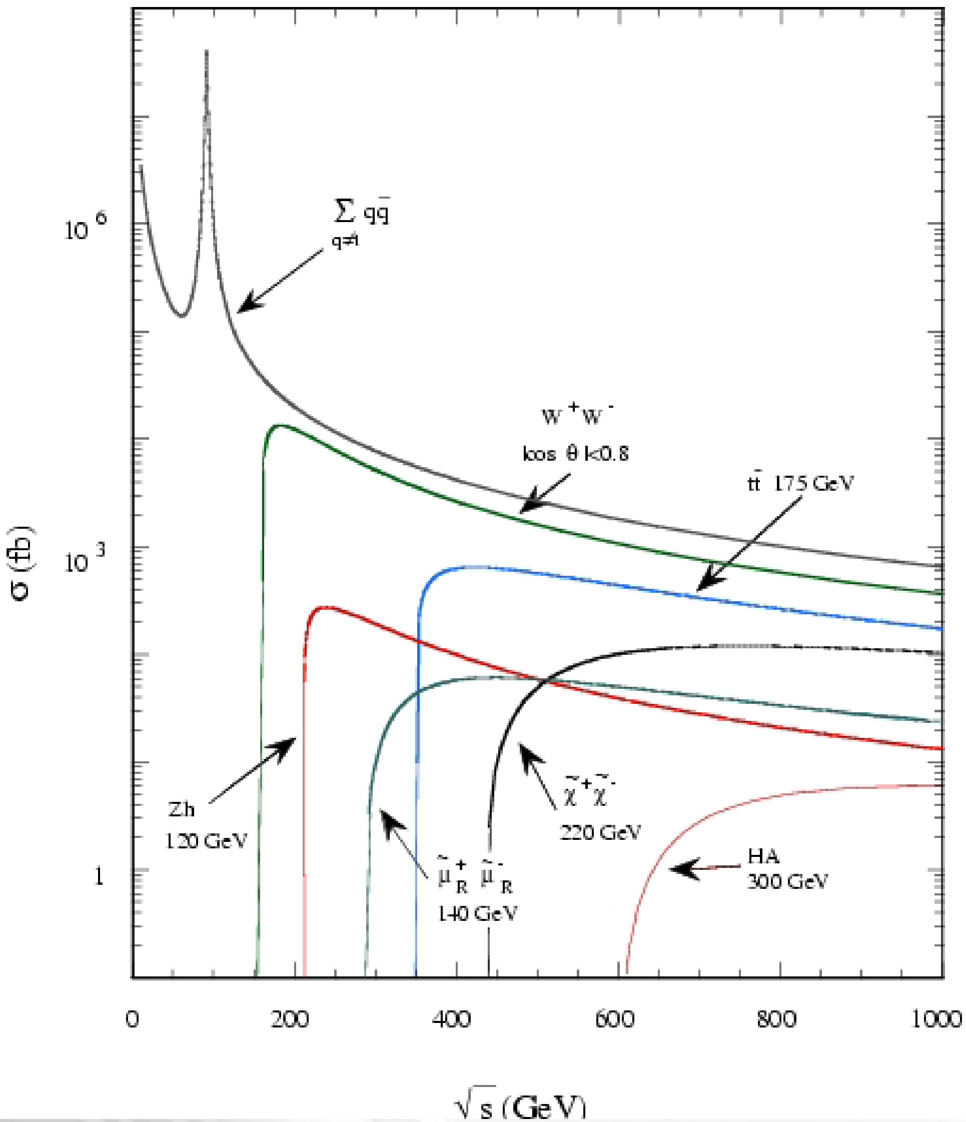






- ILC or International Linear Collider is e^+e^- linear collider
  - Center of mass energy 250 GeV (upgradeable to higher energies)
  - Luminosity ~10^{34} $cm^{-2}s^{-1}$
- No synchrotron radiation, but long tunnel to accelerate to ~ 125 GeV/beam
  - Excellent Higgs factory with many Higgs production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

ILC Status and Plans

- Starting in 2008 Global Design Effort (GDE) progressed developing
  - Technical design of the ILC
  - Cost estimate and international cooperation plan

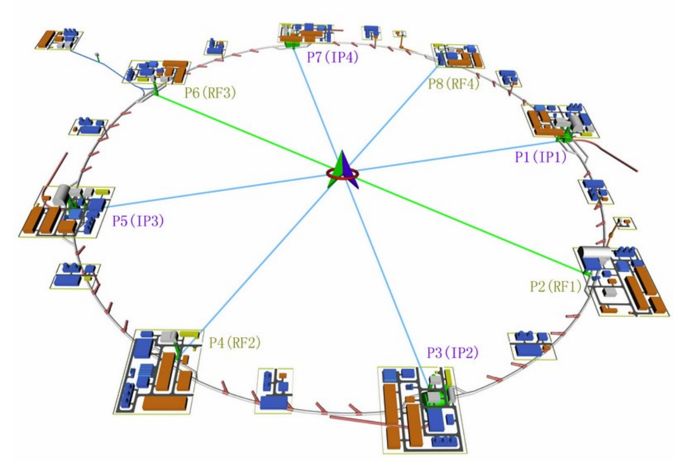
- GDE concluded in 2012
  - Including designs for the accelerator and detectors
  - Physics case strengthened with the Higgs discovery

- In 2012 Japan expressed strong interest to host the ILC

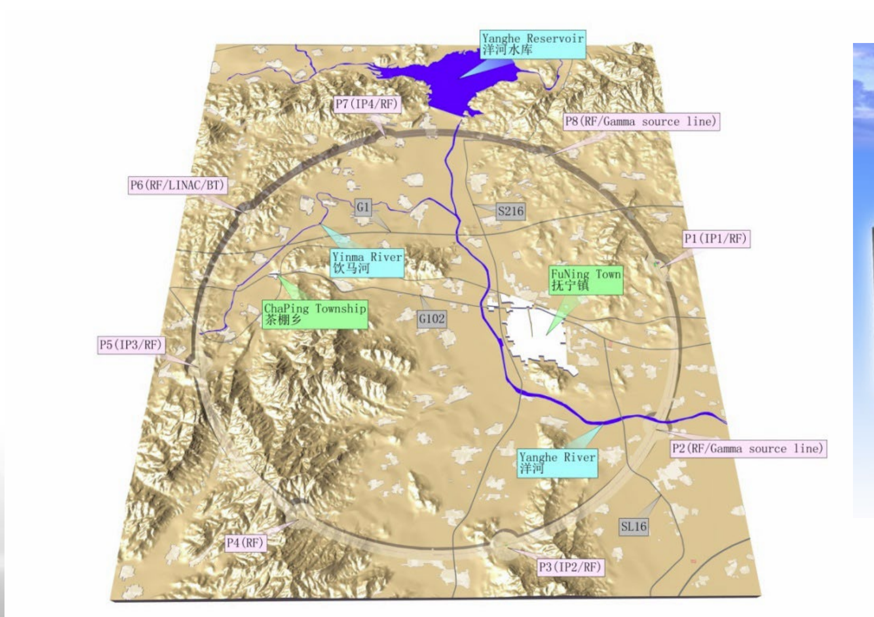
- Recently
  - Development of cooperation between participants on "Governments level"
  - ILC project will be an international project with Japan as the host country
  - Japan is expected to start funding pre ILC laboratory in 2023

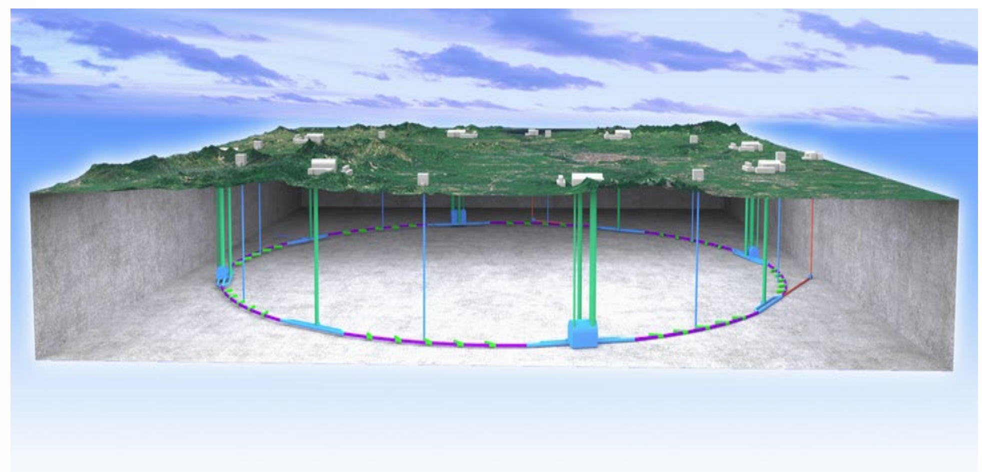
Proposals for Colliders in China: CepC and SppC

- CepC – Circular Electron Positron Collider
  - ~100 km long ring
  - 90-250 GeV in the center of mass
  - Z boson and Higgs factory



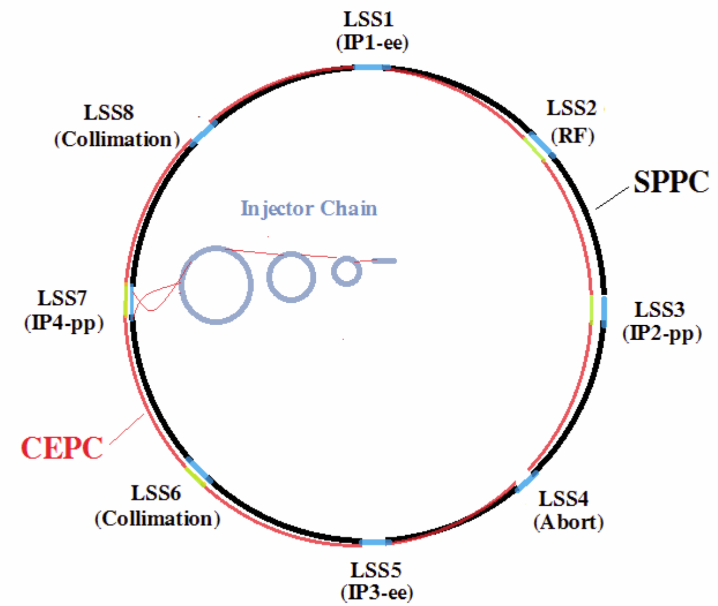
- SppC – Super Proton Proton Collider
  - In the same ring as CepC
  - ~100 TeV with 16 T magnets





Future Colliders in China

- Active progress with the CepC and SppC designs
  - e^+e^- collider first to follow with proton collider
- Construction of CepC can start in 2026
  - Completed in 2033
  - Data collection 2033-2040
- SppC timeline
  - R&D/design 2020-2035
  - Construction 2035-2045
  - Physics at 100 TeV starting in 2045



- The proposal is based on
  - Experience with e^+e^- collider operating in China
  - 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 at CERN

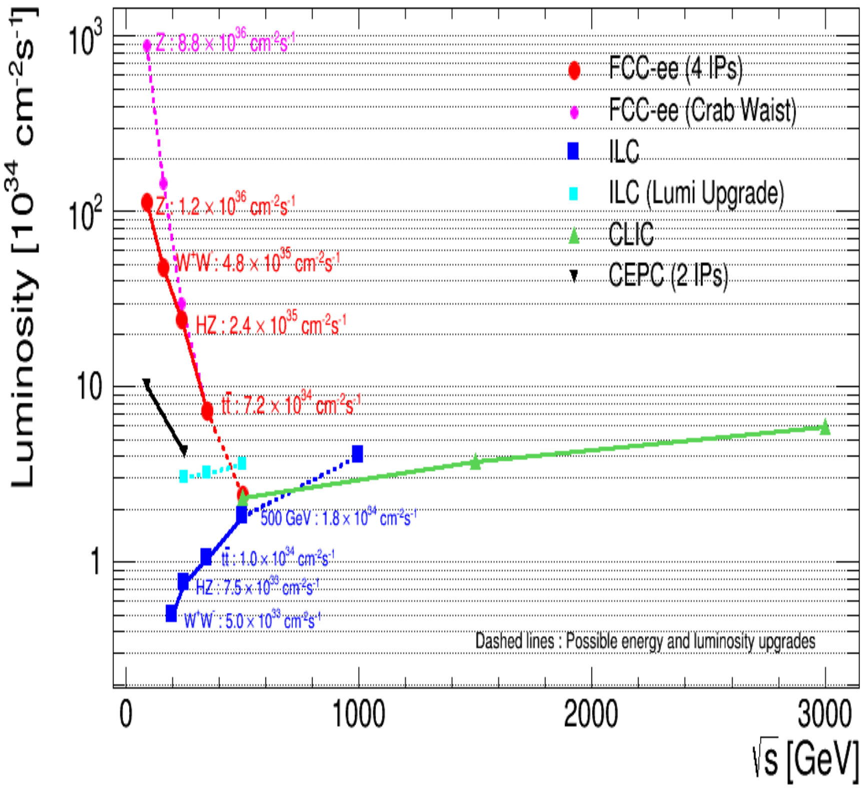
- FCC activity follows 2020 European particle physics strategies recommendation to develop future energy frontier colliders at CERN
  - "…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton 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

FCC
hh ee he

- 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

- FCCee is a 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 radiation 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

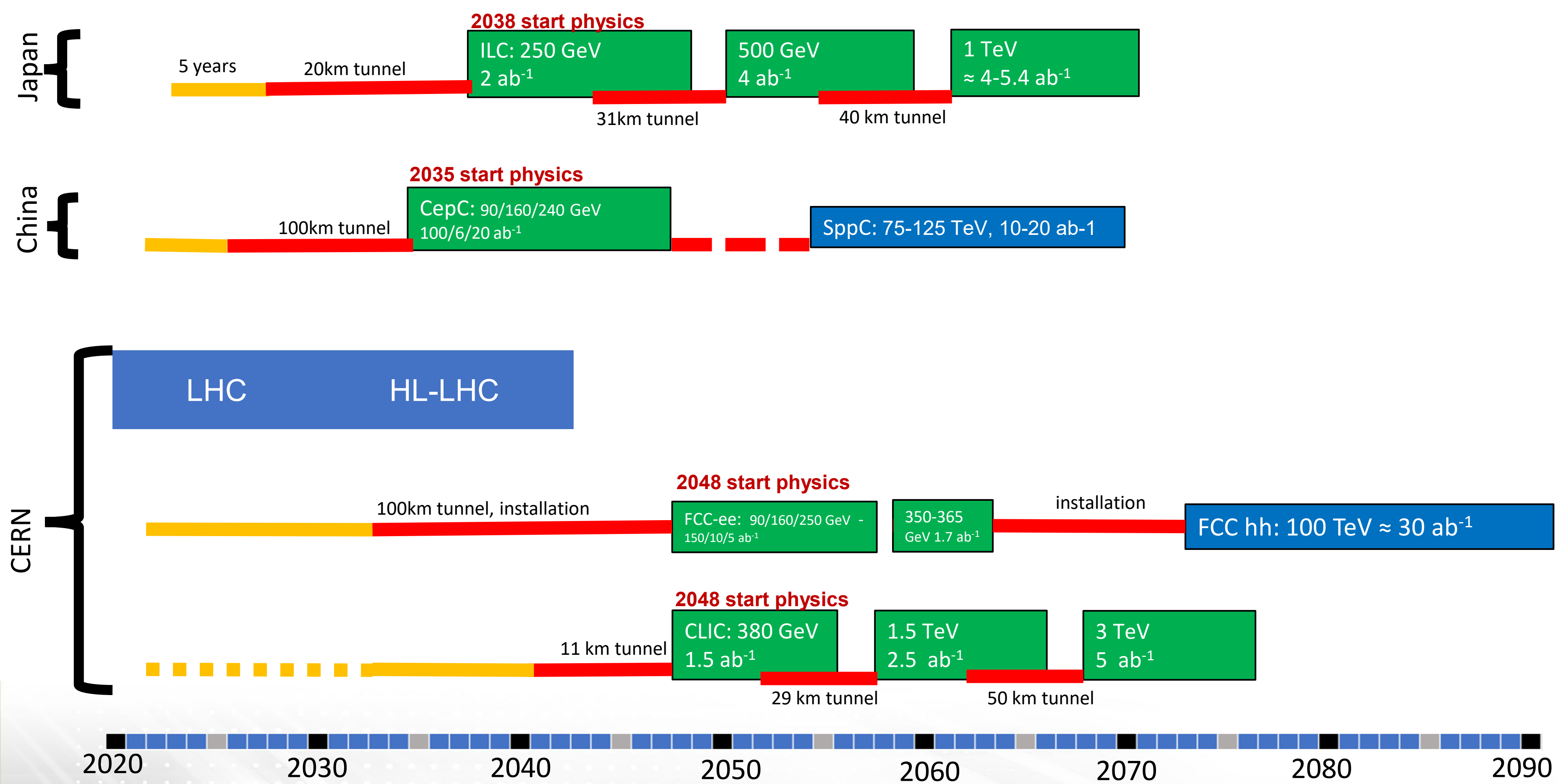
- Main challenges
  - Long tunnel
  - High field magnets
  - High synchrotron radiation load!
- Tevatron and LHC experience demonstrate feasibility of such a collider

Future Colliders Timeline

Indicative scenarios of future colliders [considered by ESG]

Proton collider
Electron collider
Muon collider

Construction/Transformation
Preparation / R&D

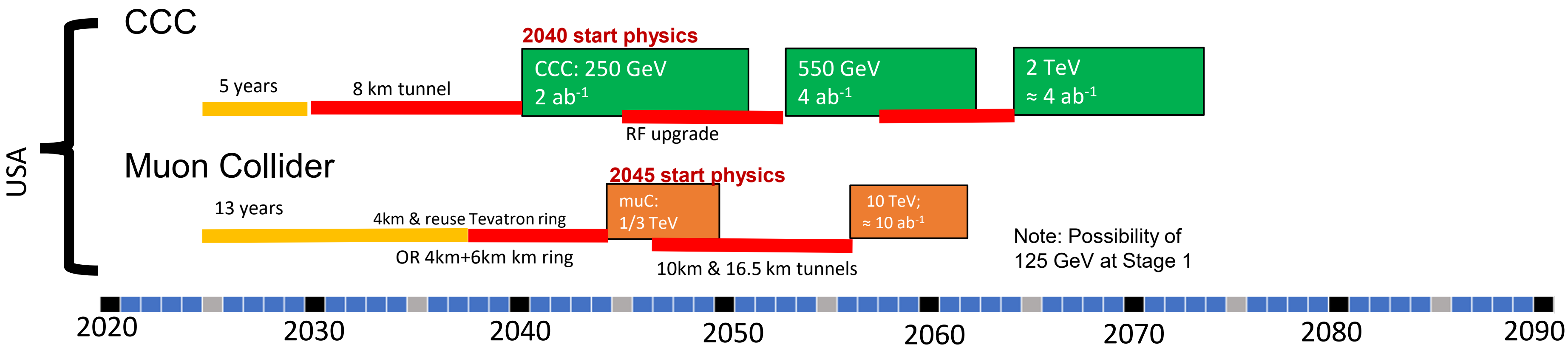


Future Colliders Timeline

Possible scenarios of future colliders

- Proton collider
- Electron collider
- Muon collider
- Preparation / R&D

Proposals emerging from this Snowmass for a US based collider



Timelines technologically limited

Future Colliders - Summary

- Colliders played major role in establishing and understanding the Standard Model
  - Discovered all expected Standard Model particles

- LHC is the main energy frontier collider for ~20 years
  - Great potential for discoveries

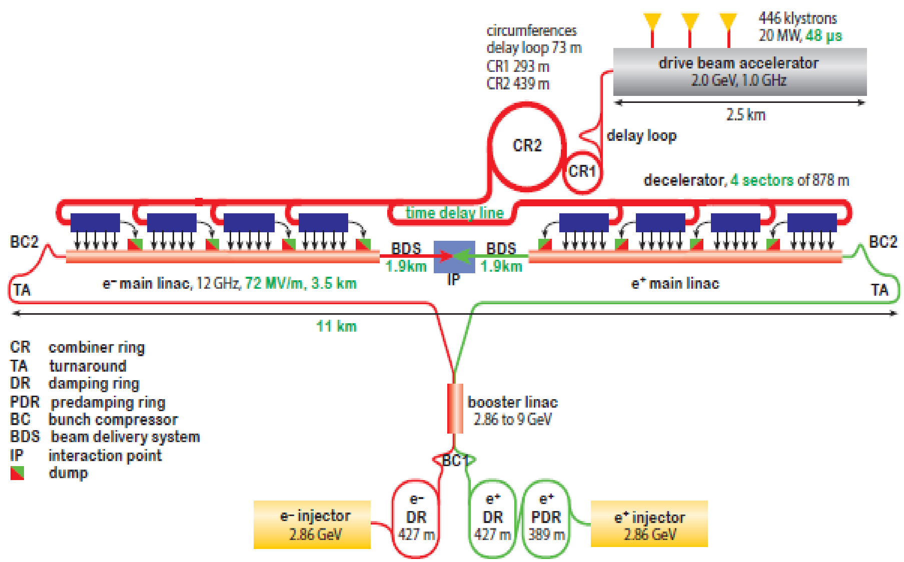
- Future proposed colliders are of two types
  - e^+e^- colliders as “Higgs factory”
  - pp colliders at the next energy frontier or muon collider (if feasible)

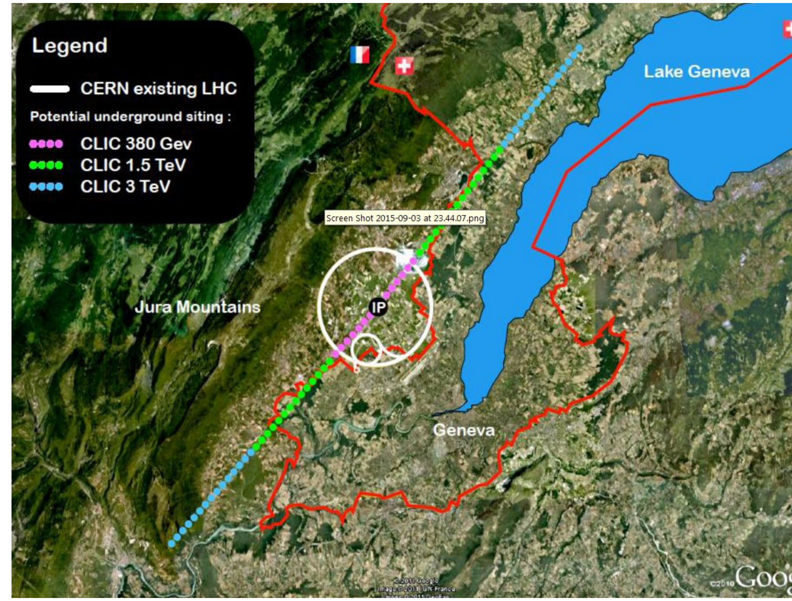
- Three proposals are under active discussion
  - ILC (Japan) – decision by Japan is expected in 2027
  - CepC and SppC (China) – decision around 2026
  - FCC (CERN) – next European strategy update around 2027

- Key for the future colliders is to reduce cost

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

CLIC Collider at CERN





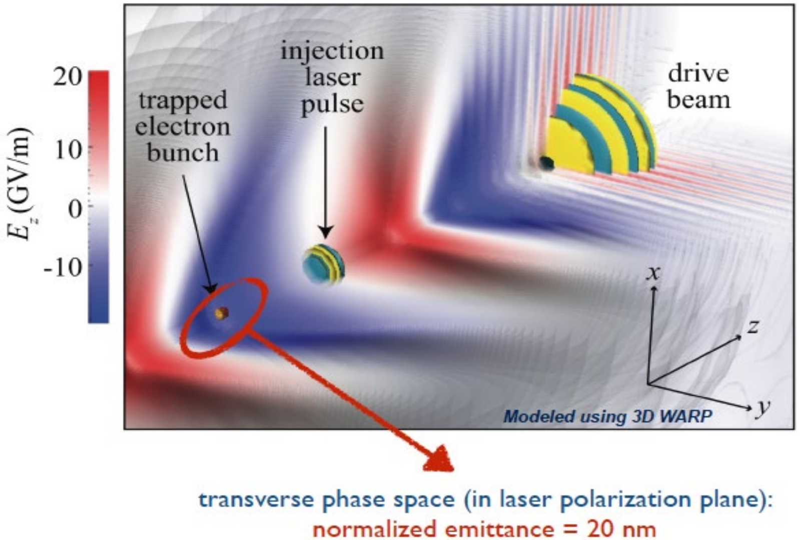
- CLIC is a linear e^+e^- collider based on "warm" RF technology with 70+ MV/m acceleration
  - The only way to get to multi-TeV e^+e^-
- 11km long for 380 GeV in the center of mass
- Under active design development

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

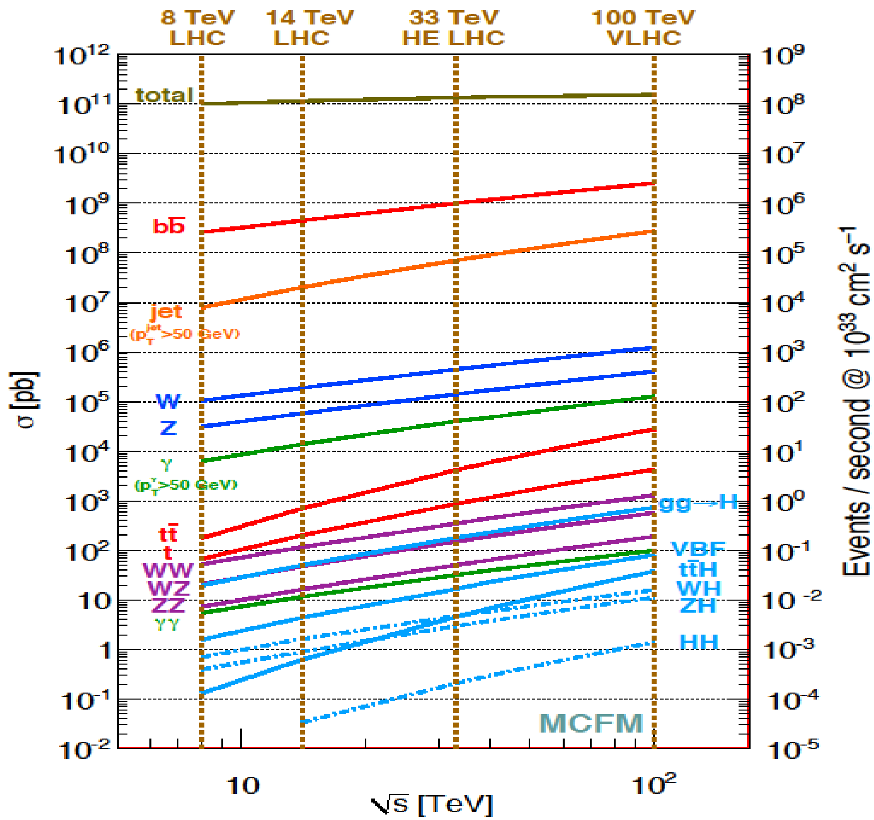
Novel Ideas in Very High Gradient Acceleration

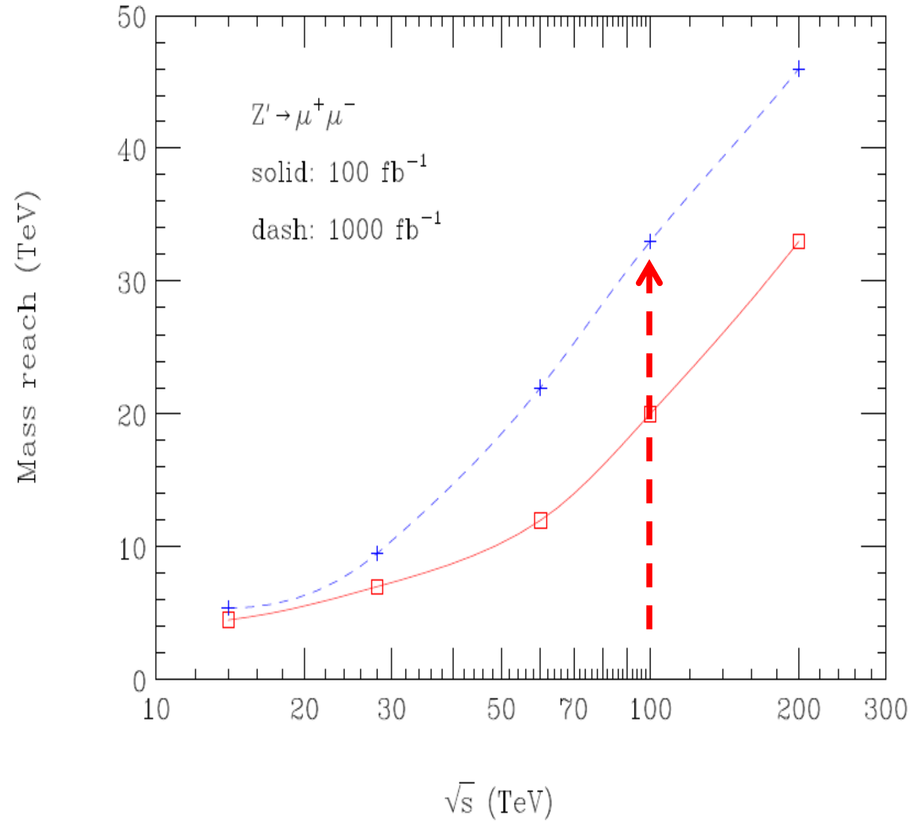
- Potential for accelerating gradients in the GV/m range
- Beam-Driven Wakefield Accelerators
  - In US: FACET/FACET-II
- Laser-driven Wakefield Accelerators
  - In US: BELLA
- Dielectric Wakefield Acceleration
  - In US: AWA, ATF
- Major research efforts are also underway in Europe and Asia
  - Some are: AWAKE (CERN), Eupraxia, FLASH_Forward (DESY), SPARC_Lab (INFN)

- For now these methods are at the initial stages of development
  – At 20+ years to practical applications in particle physics



Collider Energy and Mass Reach





- Mass reach for direct searches is 1/2 of the full collider energy
  - 20 TeV machine is about twice less expensive than 40 TeV (might saved SSC?)
  - But don’t want to miss major discovery due to low energy (LEP lesson)

US High Energy Physics Planning Process - Snowmass

- US High Energy Physics performs planning every 7-10 years
  - For the next ~10 years time frame
- Step 1
  - Groups of scientists develop proposals for future programs/projects/experiments
- Step 2
  - "Snowmass" community wide process develops and discusses proposals, evaluates physics reach and costs and summarizes outcome in a written form
  - Organized by the Division of Particles and Fields (DPF) – professional organization, not laboratories or funding agencies
- Step 3
  - P5 committee (Particle Physics Projects Prioritization Panel) is formed (by NSF/DOE) representing all areas of particle physics
  - The committee, within about a year, recommends priorities based on available funding and on the expected cost of the proposed programs – expect outcome by December 2023
- Step 4
  - HEPAP (High Energy Physics Advisory Panel) appointed by NSF/DOE reviews the proposal and recommends it to be considered by NSF/DOE
- Step 5
  - NSF/DOE fund recommended programs (assuming funds are available)

We are at the end of Step 3 now