June 20, 2025

FUTURE ACCELERATORS

Jim Brau,
University of Oregon

UNIVERSITY OF
OREGON

Research partially supported
by the U.S. Department of Energy

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FUTURE ~~ACCELERATORS~~ COLLIDERS

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The first "high energy" accelerator

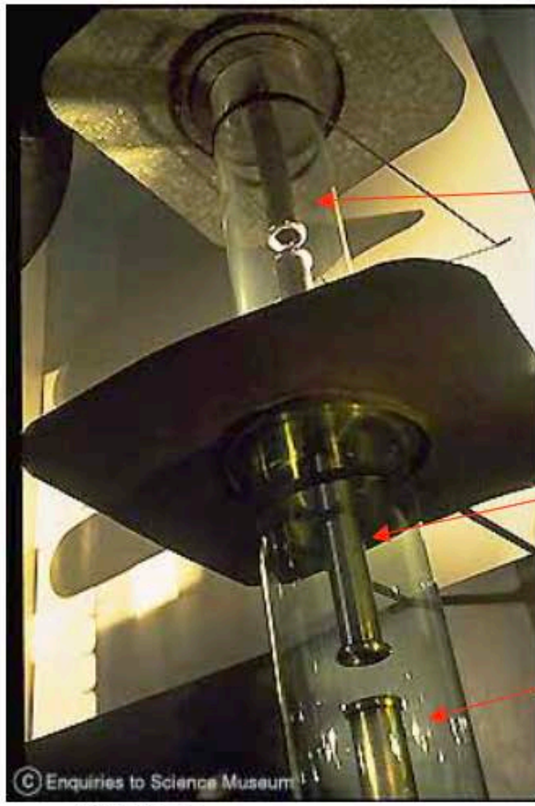
Using this device to accelerate protons produced by a discharge in H gas ,

G. Cockroft and E. Walton obtained the first nuclear transmutation via the reaction :

$$_3Li^7 + {}_1H^1 \ (p) = 2 \ {}_2He^4 \ (2\ \alpha)$$

This earned them the Nobel Prize.

400 KV



1932

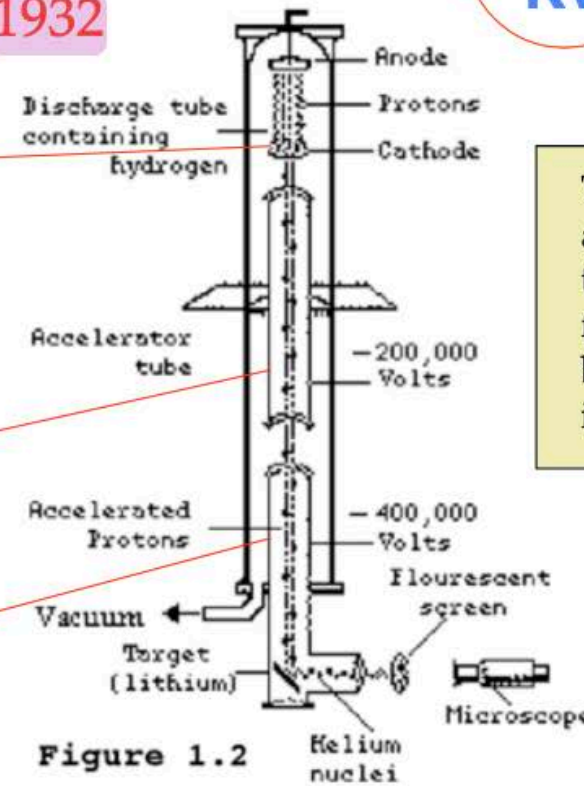


Figure 1.2

This type of accelerator takes its name from that of both its inventors

CAS - IC-2006

13

https://cas.web.cern.ch/sites/default/files/lectures/zakopane-2006/tazzari-history.pdf

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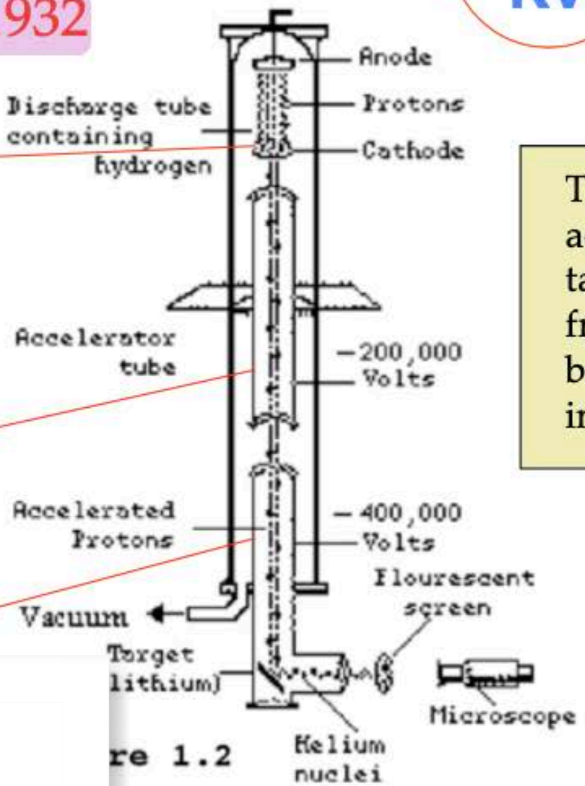

400 KV

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Cockcroft and Walton shared 1951 Physics Nobel Prize

https://cas.web.cern.ch/sites/default/files/lectures/zakopane-2006/tazzari-history.pdf

What is 400 keV?

The electron volt (eV) became a convenient unit to express the energies of particles in accelerators involving electric fields and potentials.

1 eV is energy gained by electron (or proton) accelerated across one volt potential difference.

1 eV = 1.6 x 10^{-19} joules
400 keV = 6.4 x 10^{-17} joules (Cockcroft-Walton)
1 TeV = 1.6 x 10^{-7} joules
14 TeV = 2.2 x 10^{-6} joules

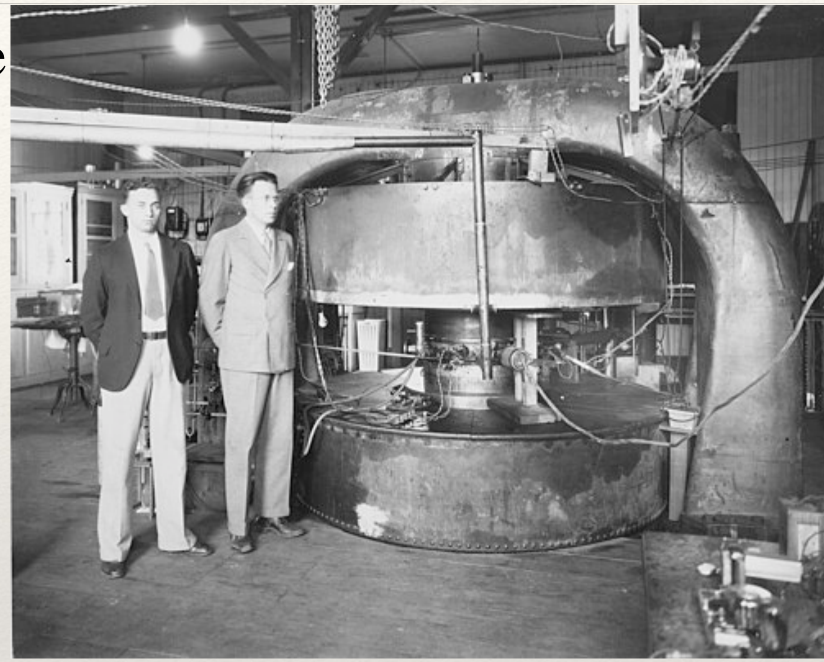
kilo = 10^3
Mega = 10^6
Giga = 10^9
Tera = 10^{12}

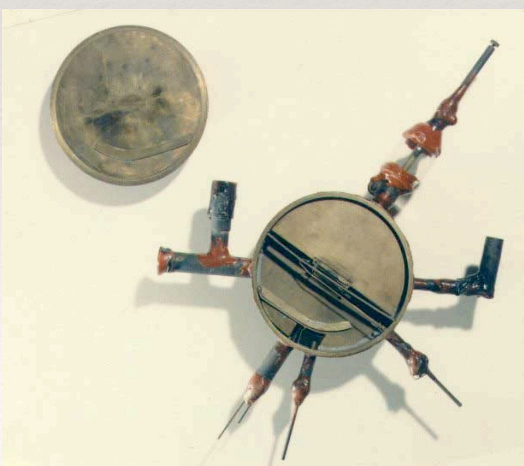
mass of electron = 9.1 x 10^{-31} kg = 0.511 MeV/c^2
mass of proton = 1.67 x 10^{-27} kg = 928 MeV/c^2

Cyclotron

27-inch cyclotron at the Radiation Laboratory in Berkeley (1934).

M. Stanley Livingston (L) and Ernest O. Lawrence.





Original 4.5-inch (11 cm) cyclotron

Cyclotron

27-inch cyclotron at the Radiation Laboratory in Berkeley (1934).

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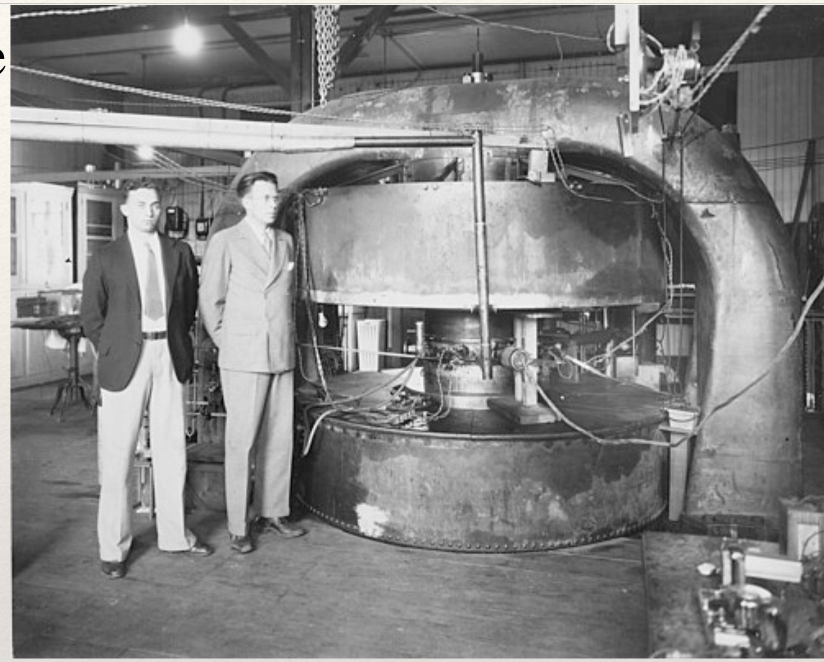
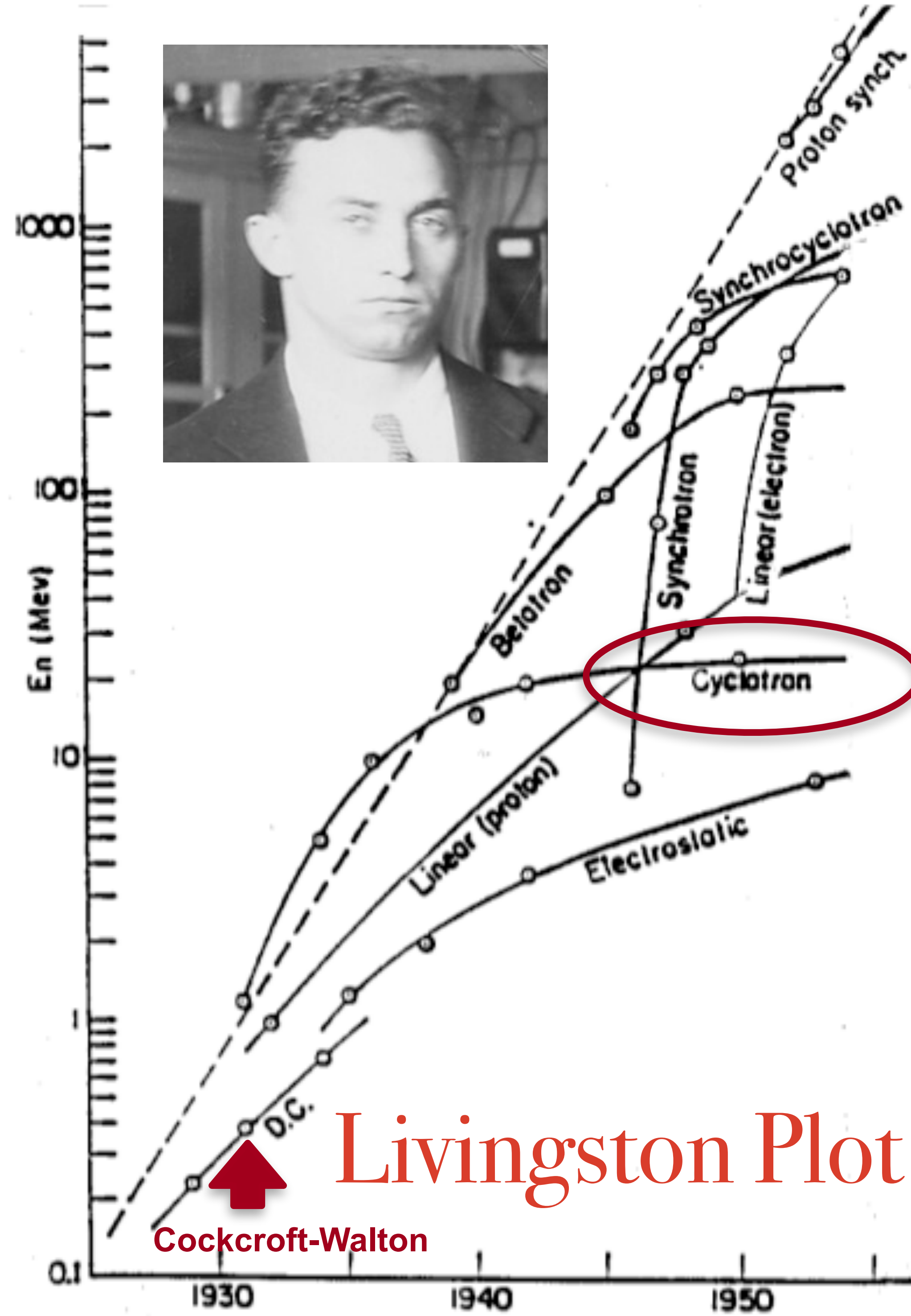




M. Stanley Livingston,
“High Energy Accelerators (1954).
Livingston concluded accelerator energy was doubling every six years (dashed line).

History

Cathode Ray Tubes
Late 1800s

Multipole Gaps
Cockcroft Walton (1920)

Van Der Graff (1930)

Electrostatic Field Based

Time Varying Field Based

Time Varying Fields linear accelerators
Ising (1924) and Wideroe (1928)

Cyclotron
Lawrence (1930)

Synchrotron
Oliphant (1943)

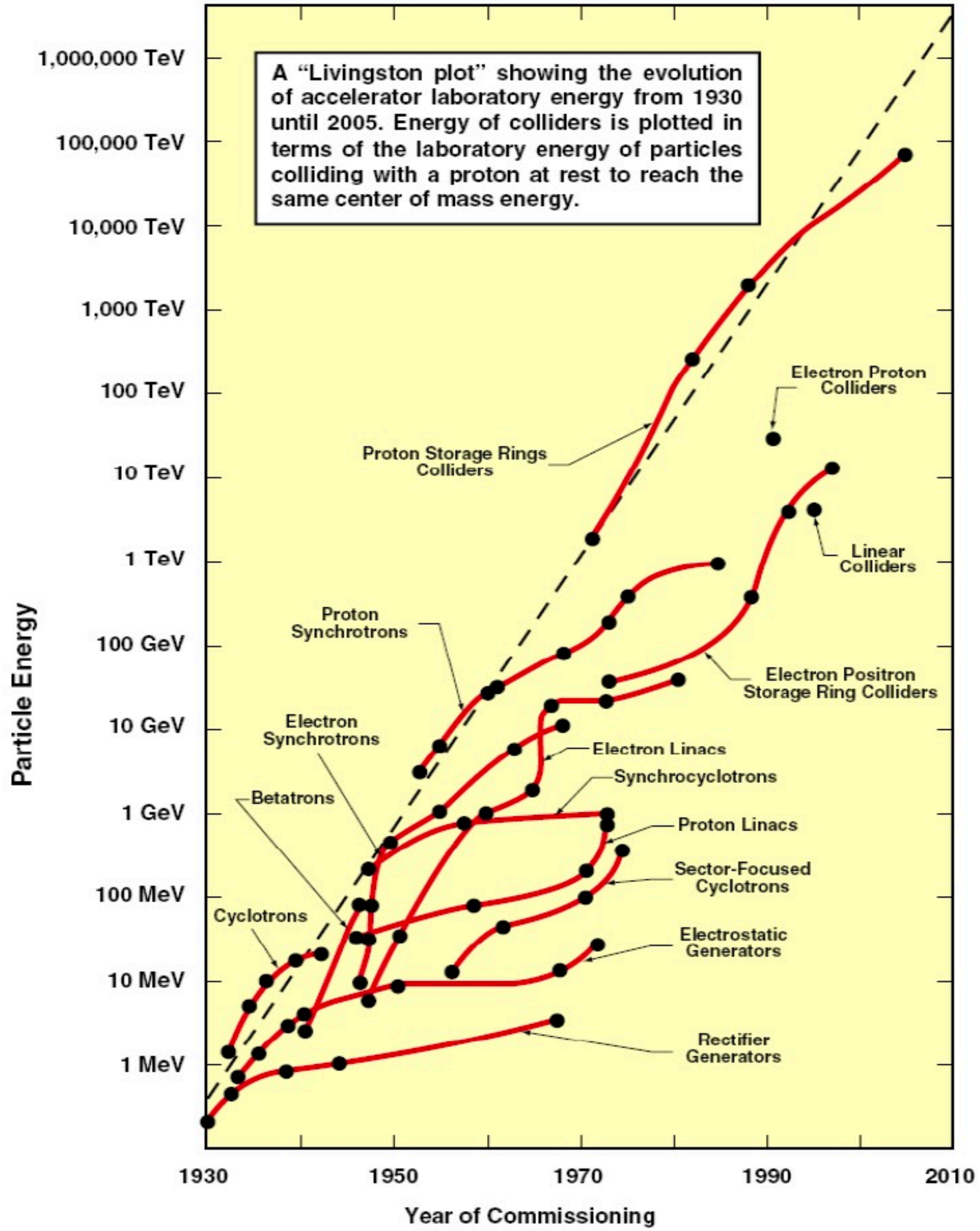
Synchrocyclotron and Betatron
McMillan and Veksler (1944)

Alvarez Linac
McMillan (1946)

Strong Focusing
Courant and Snyder (1952)

Non RF high gradient
accelerators (20??)

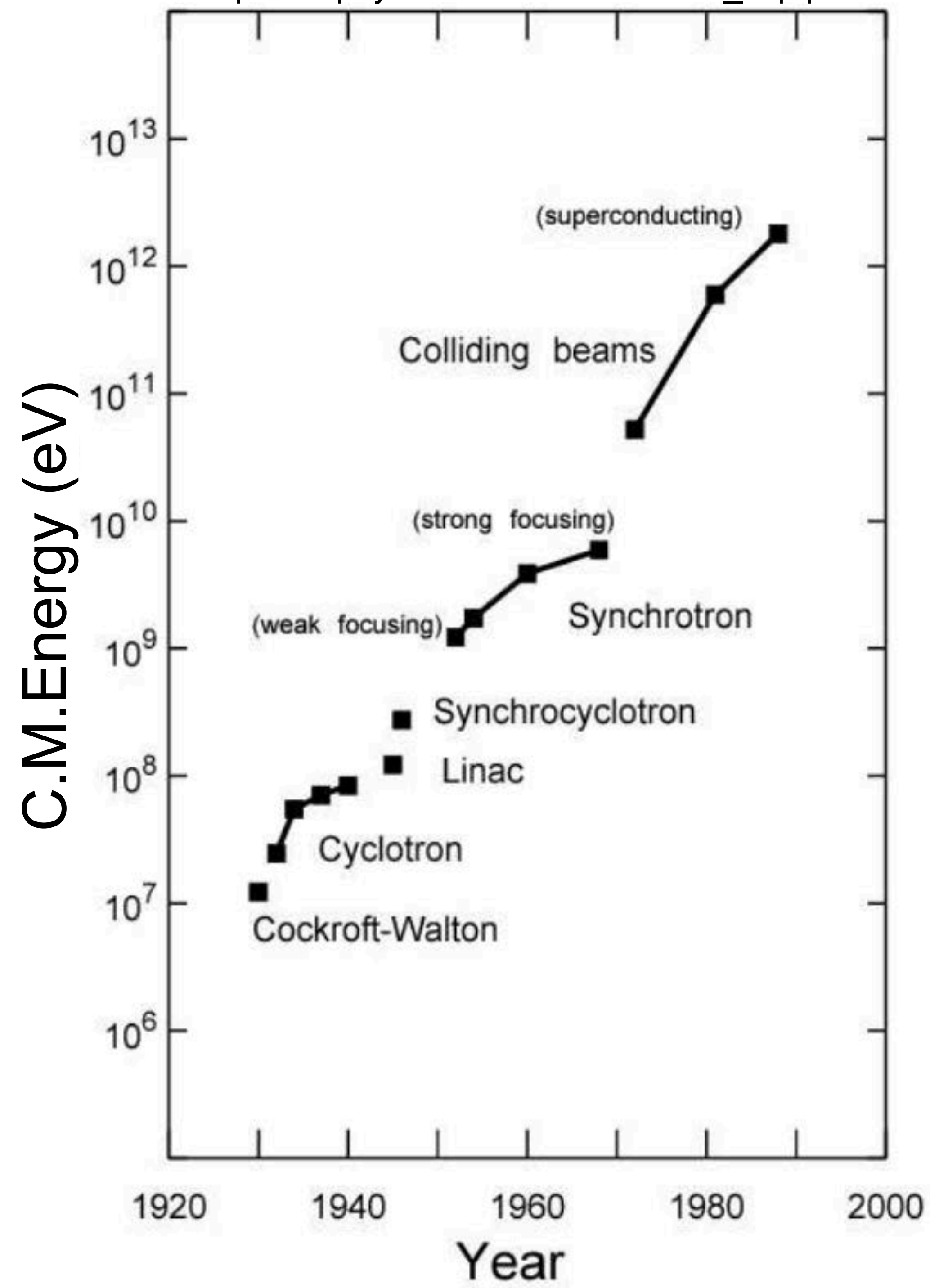
Energy Evolution



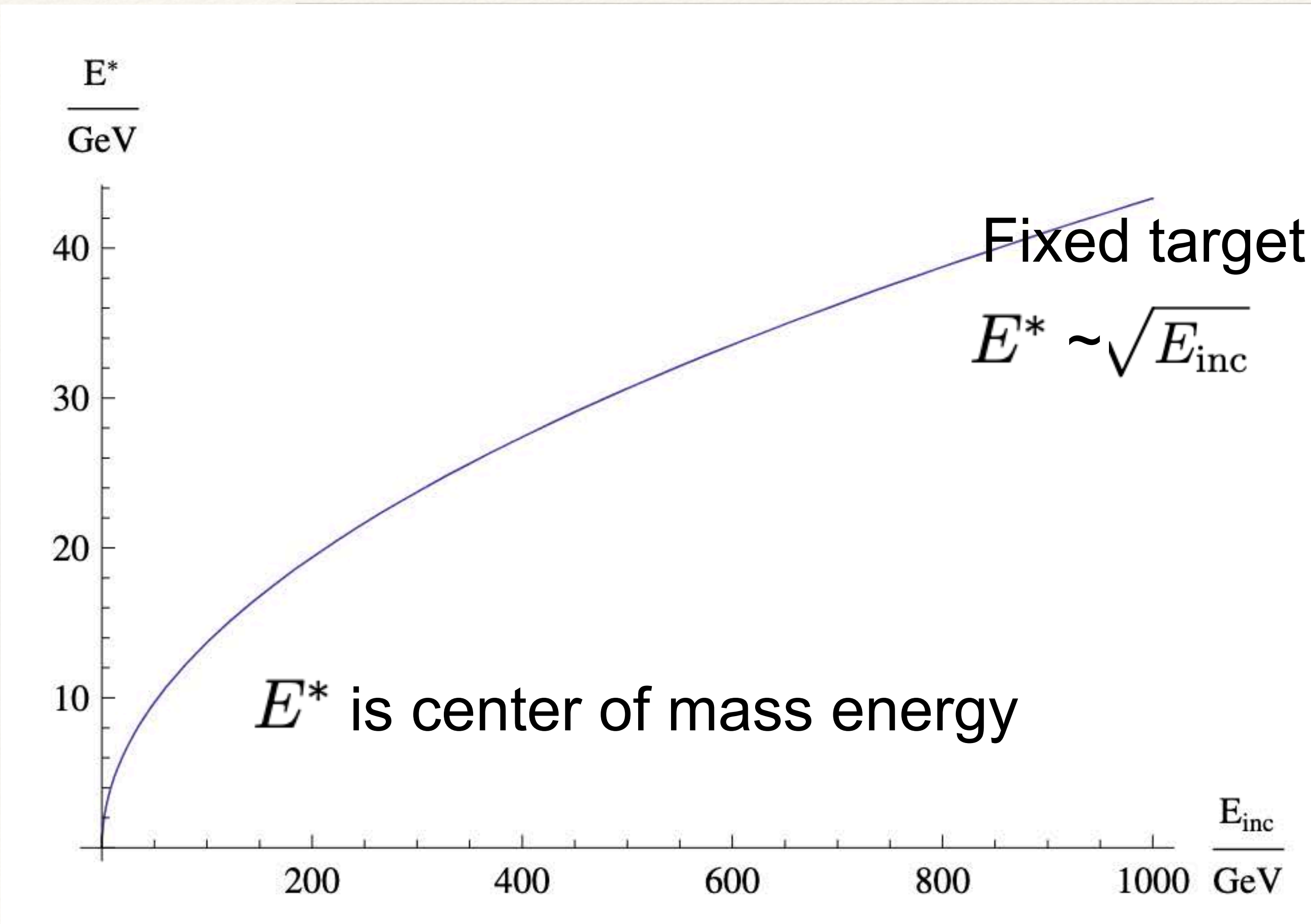
- Exponential growth of energy with time
- Increase of the energy by an order of magnitude every 6-10 years
- Each generation replaces previous one to get even higher energies
- The process continues…
- Energy is not the only interesting parameter
  - Intensity
  - Size of the beam

Colliding Beams

https://buphy.bu.edu/cms/talks/rohlf_itep.pdf



Colliding Beams



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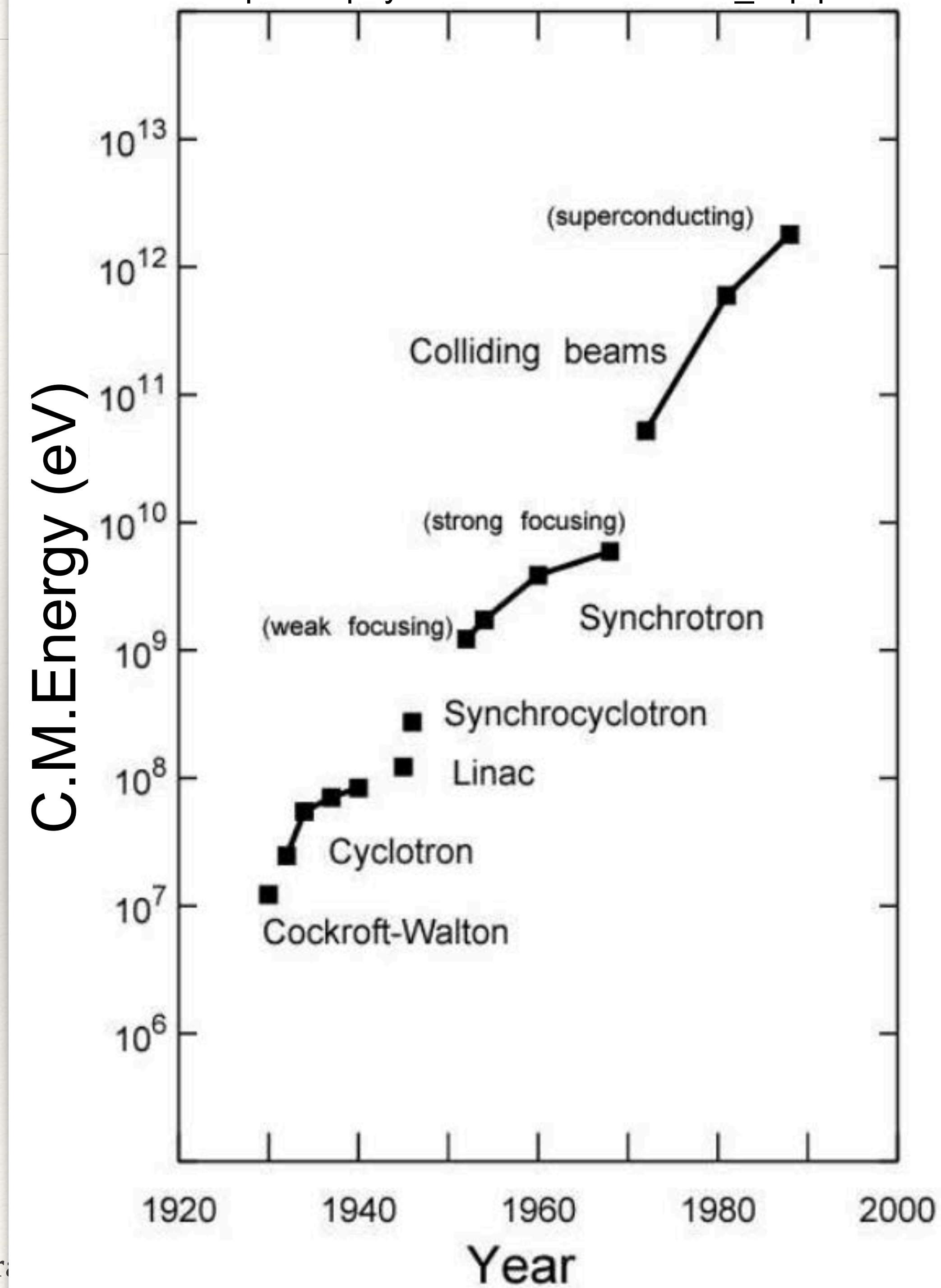
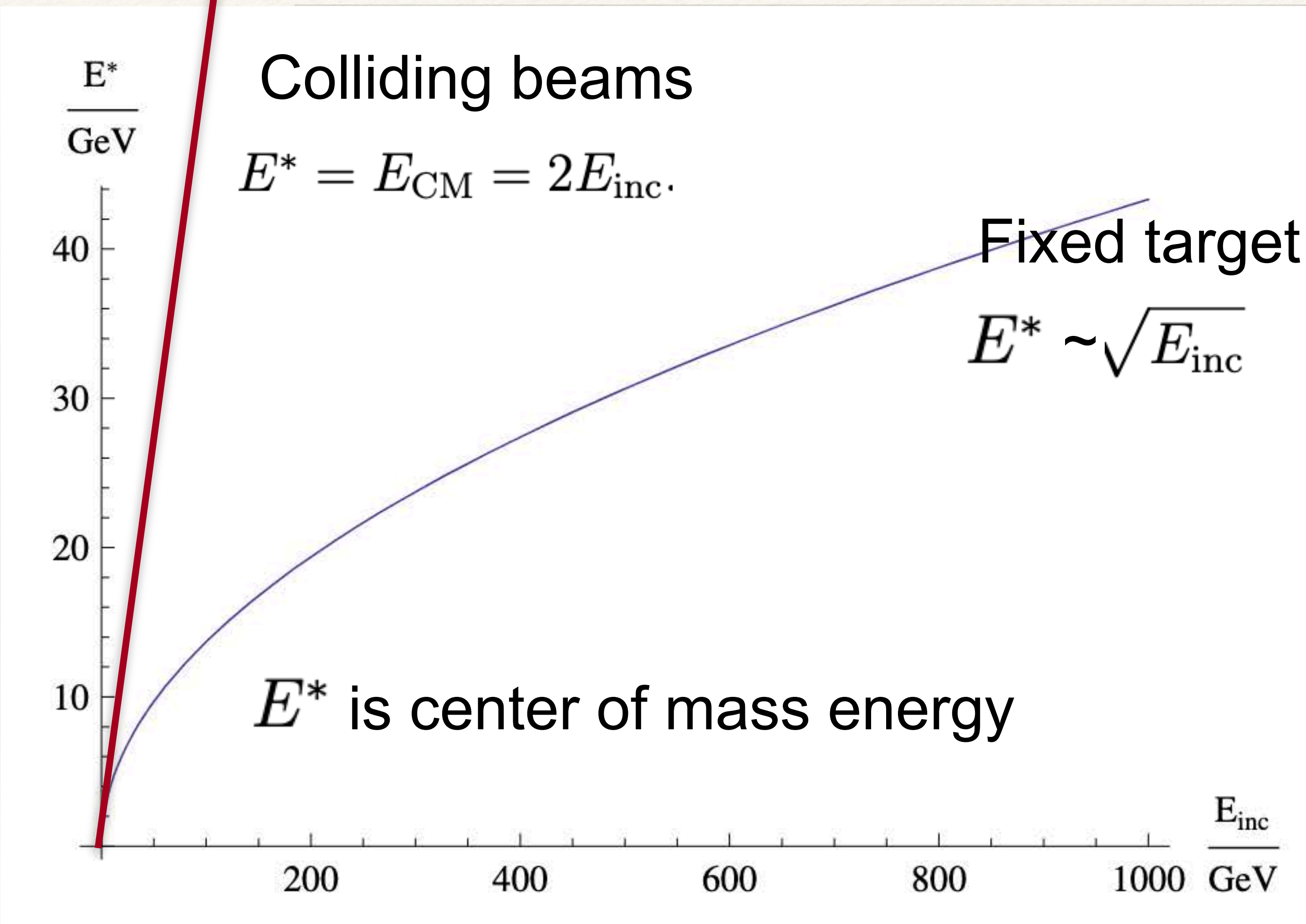
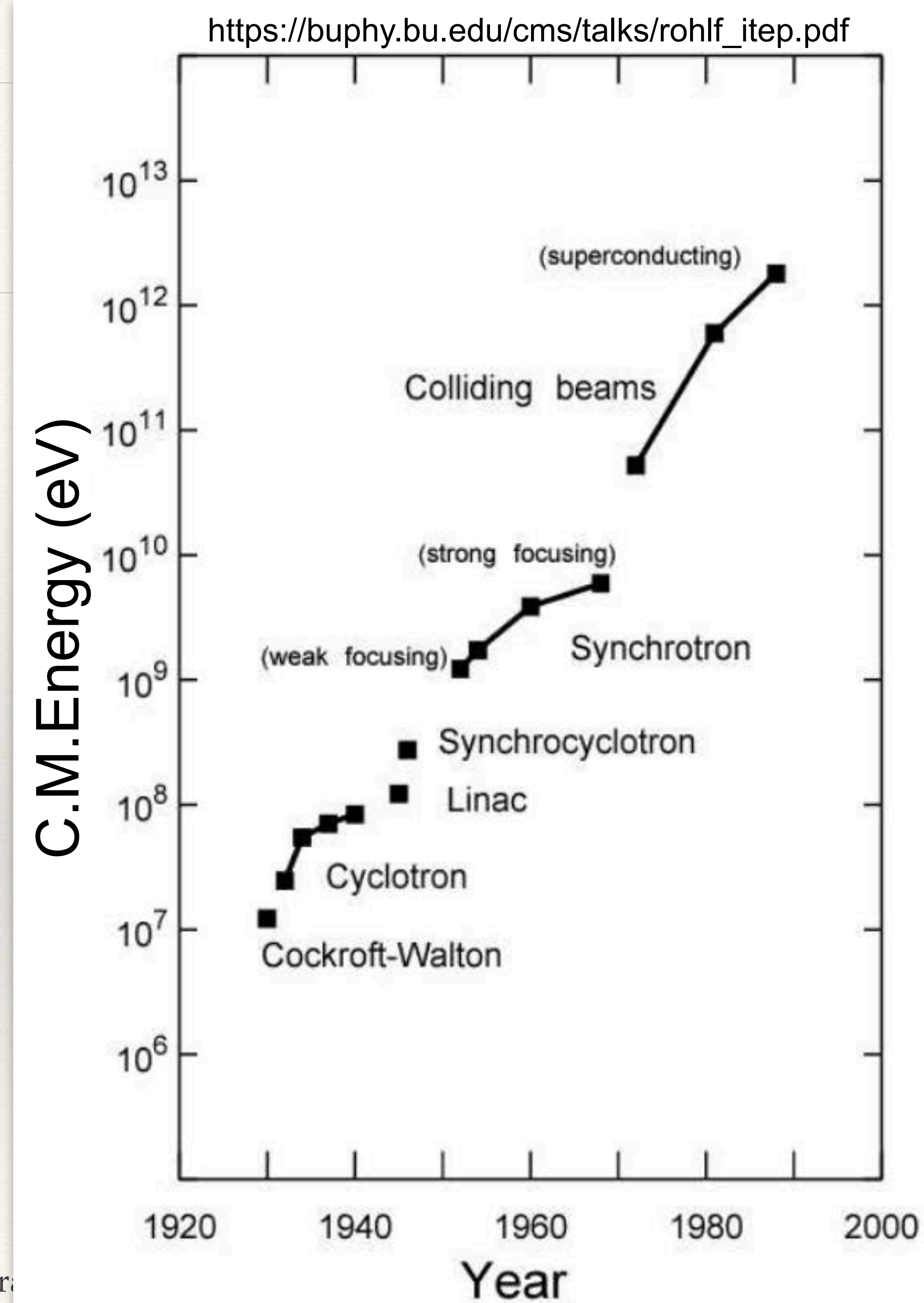


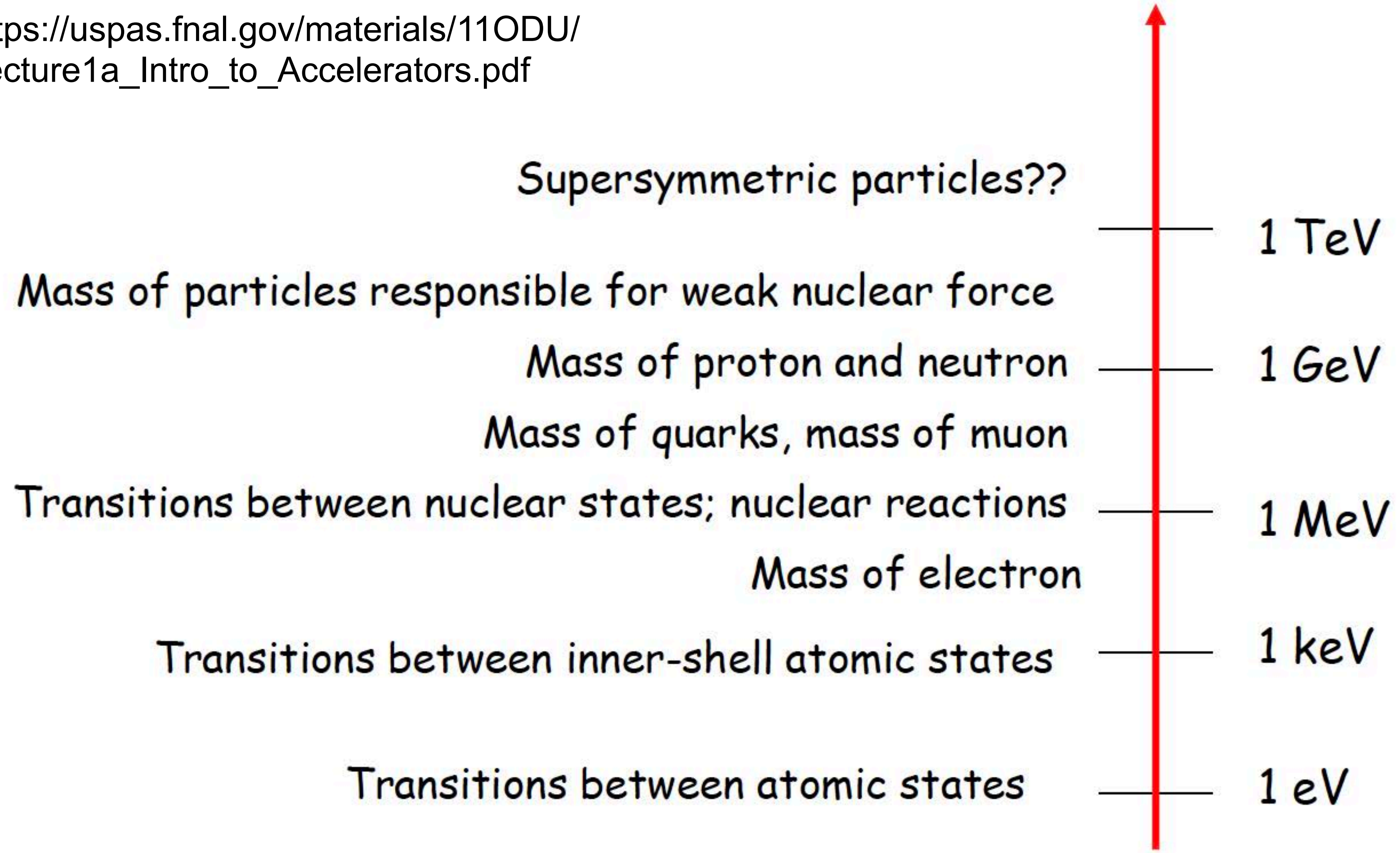
Colliding Beams





Advances in physics reach with increased energy

https://uspas.fnal.gov/materials/11ODU/Lecture1a_Intro_to_Accelerators.pdf



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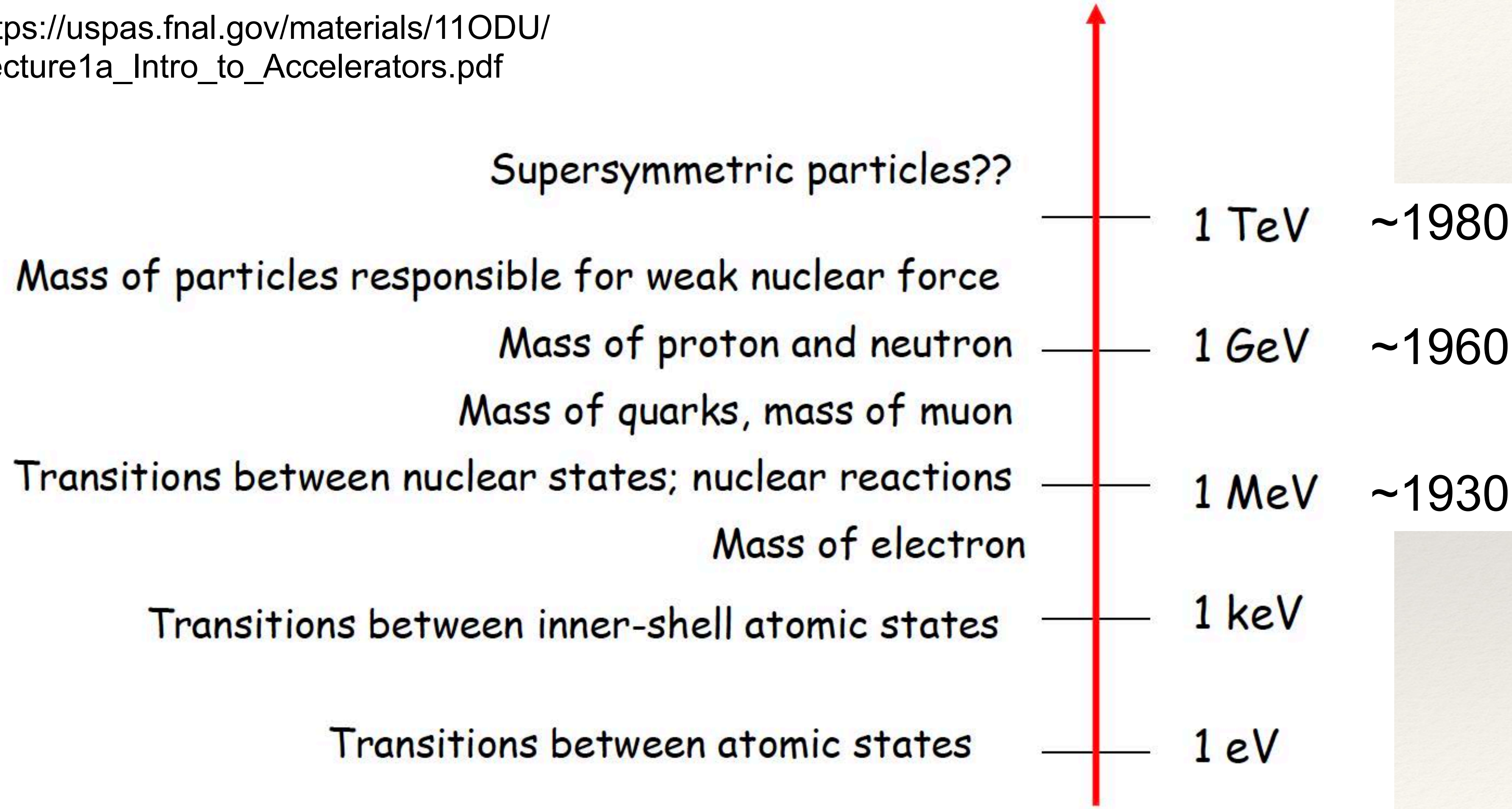

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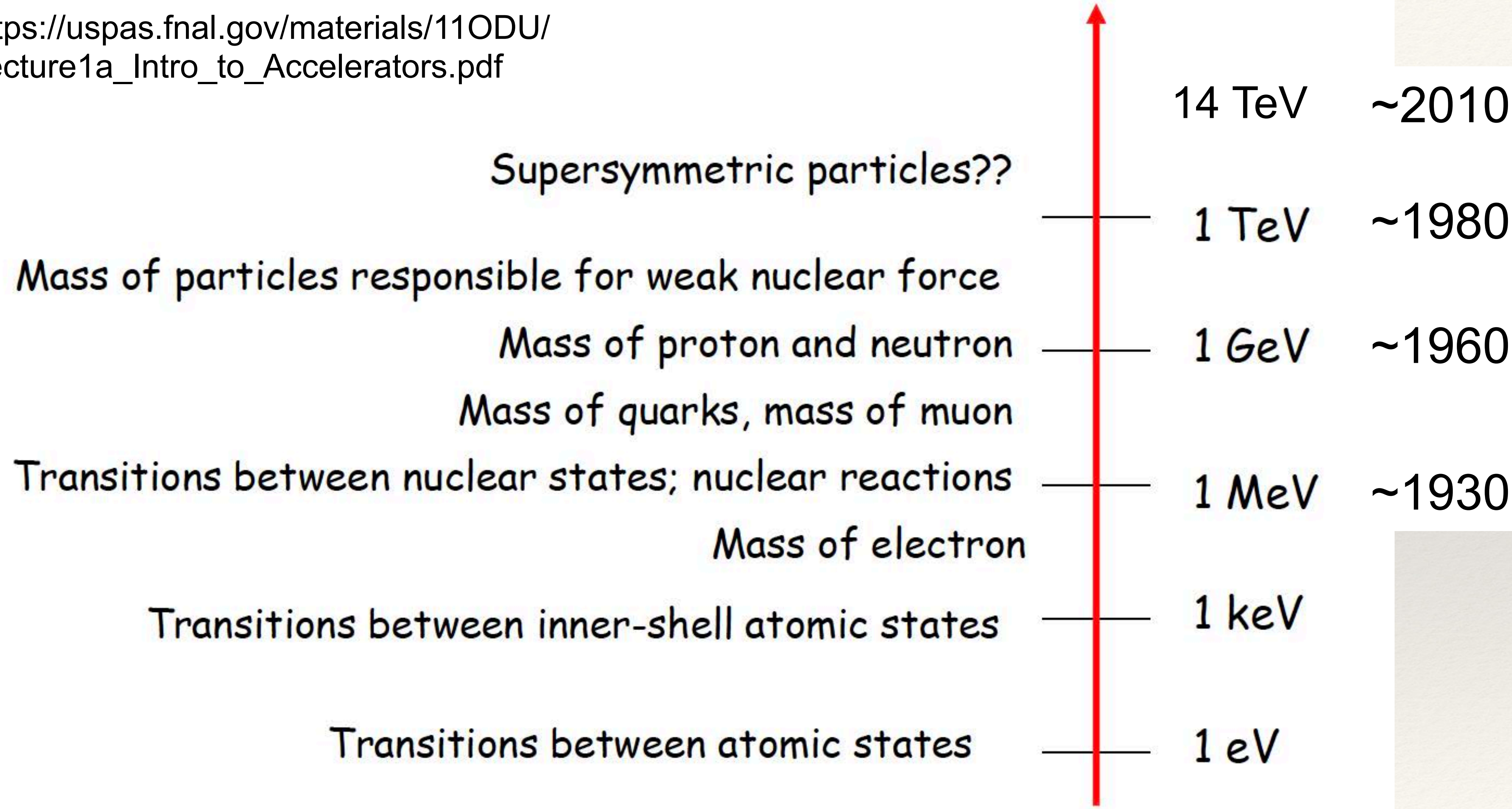
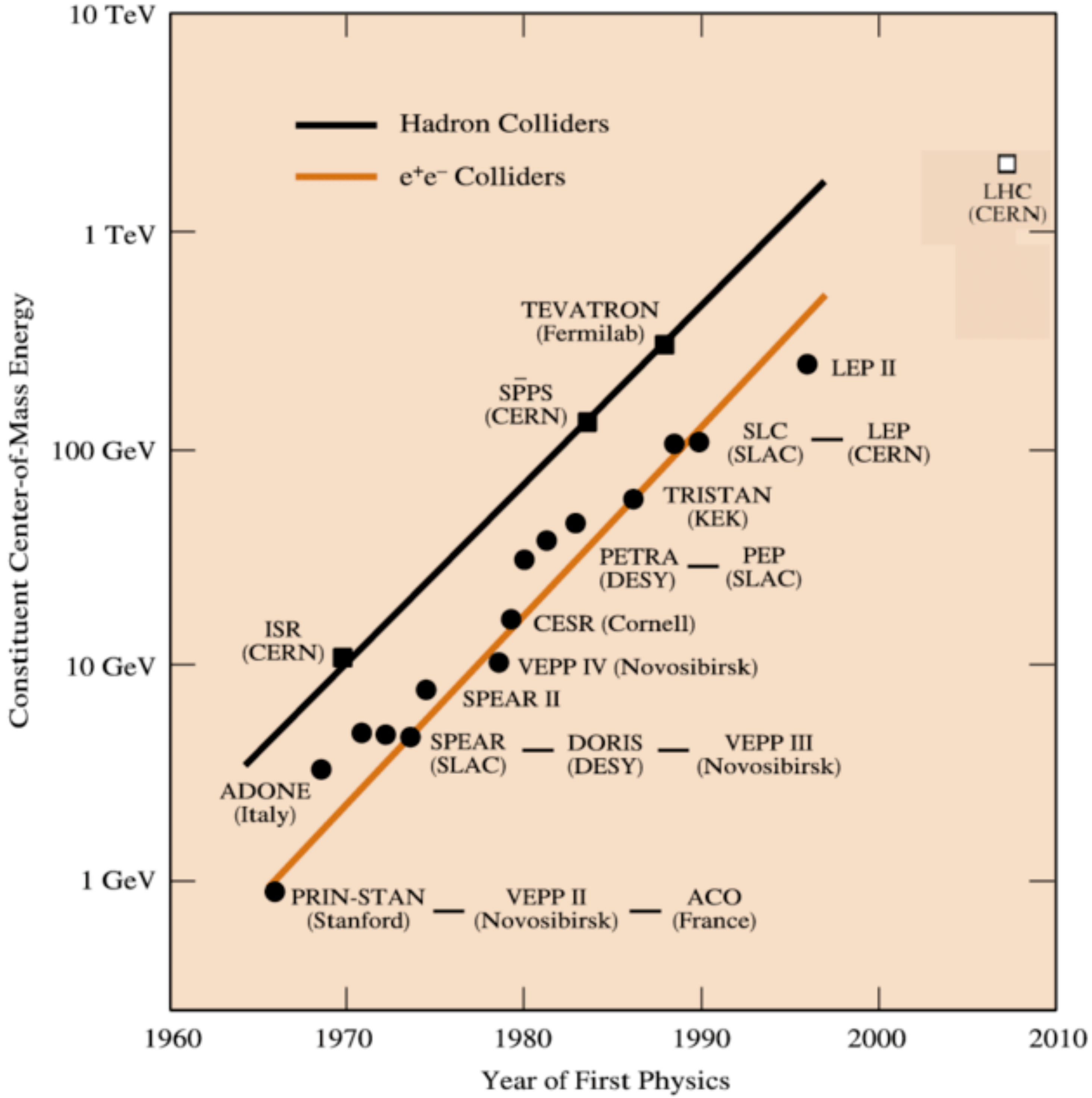
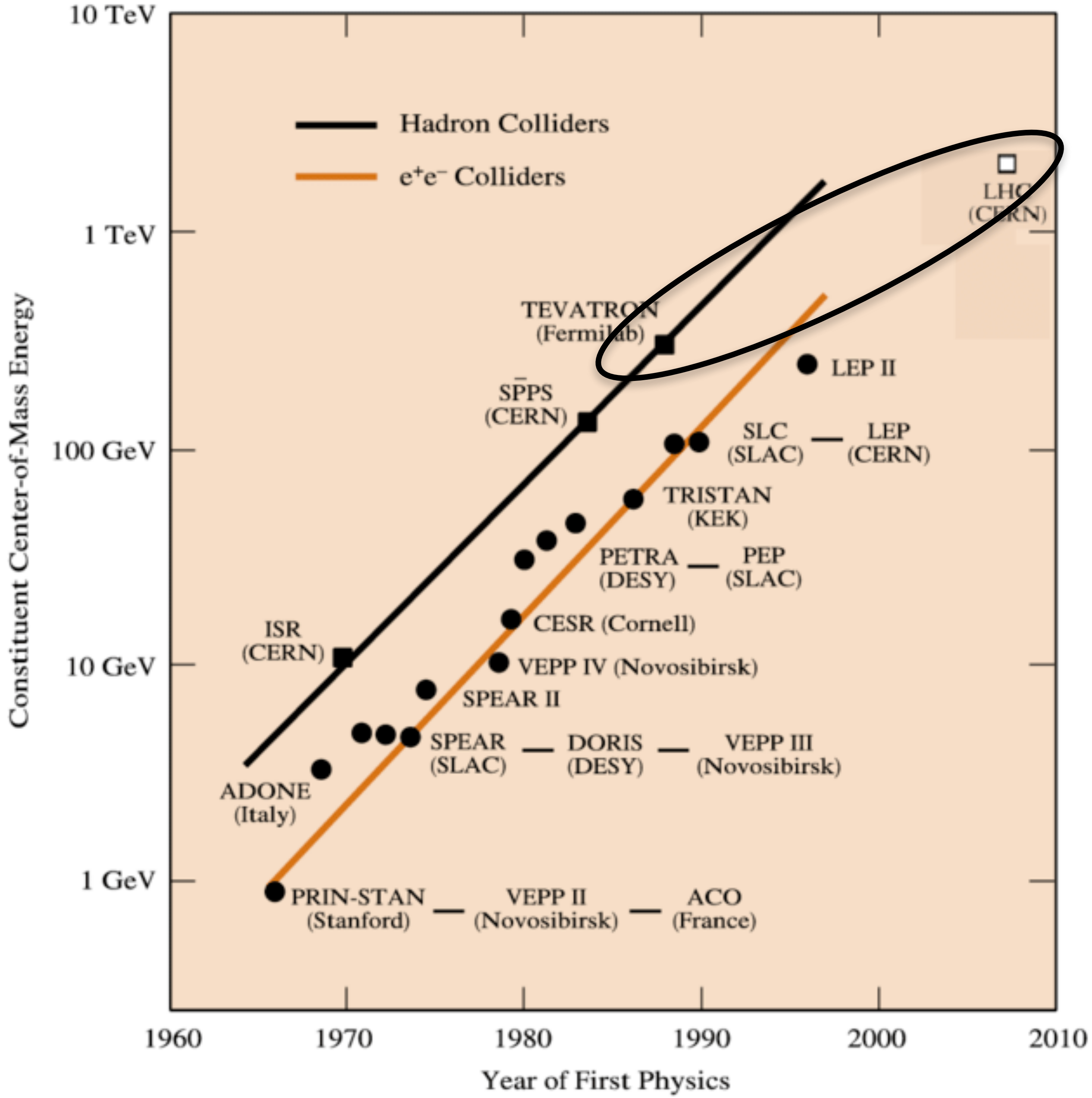




W. K. H. Panofsky, "The evolution of particle accelerators and colliders", Beam Line, Vol. 27, No. 1 (1997) eds. M. Riordan et al. p 36 (LHC start date modified accordingly)



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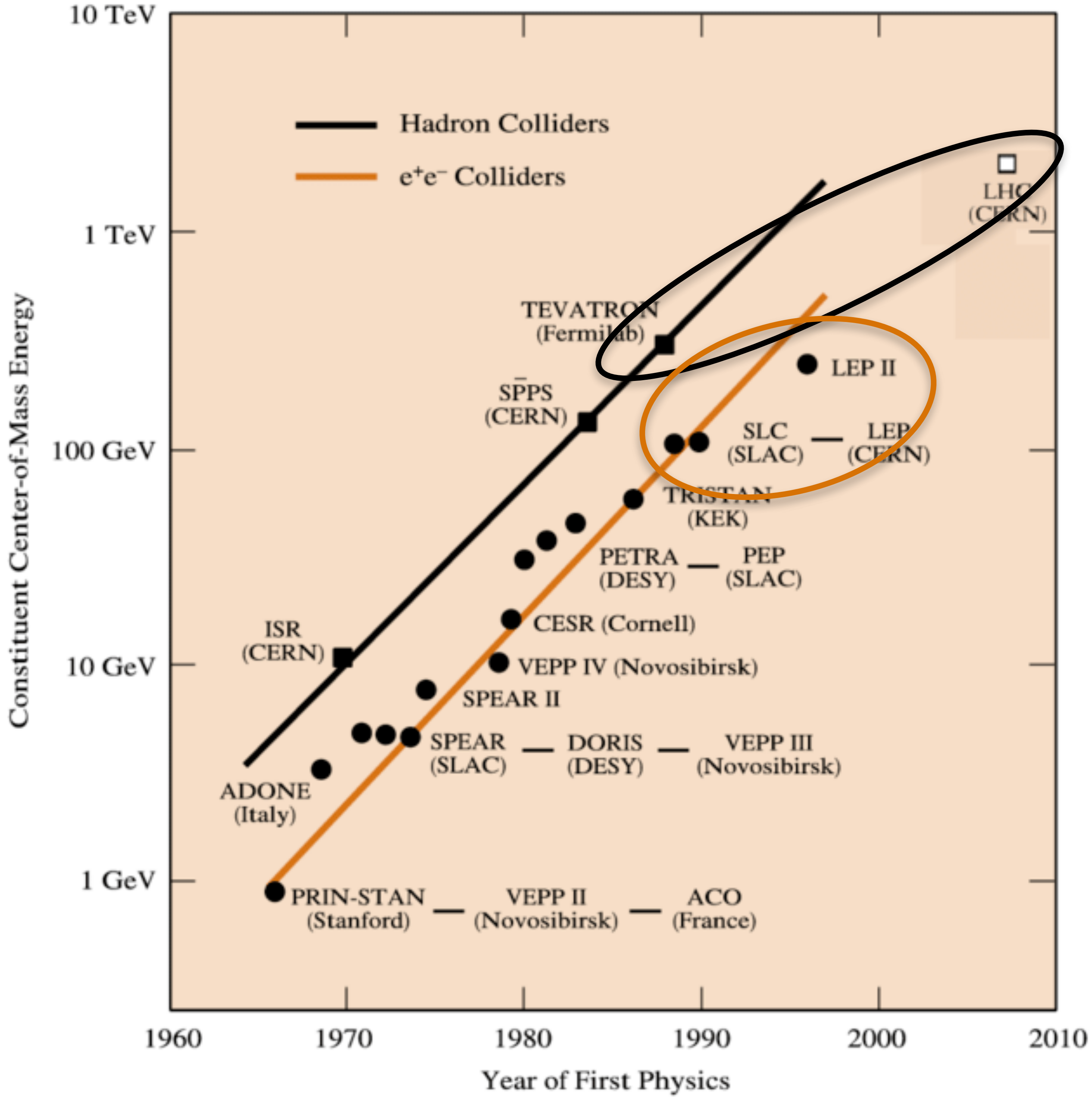

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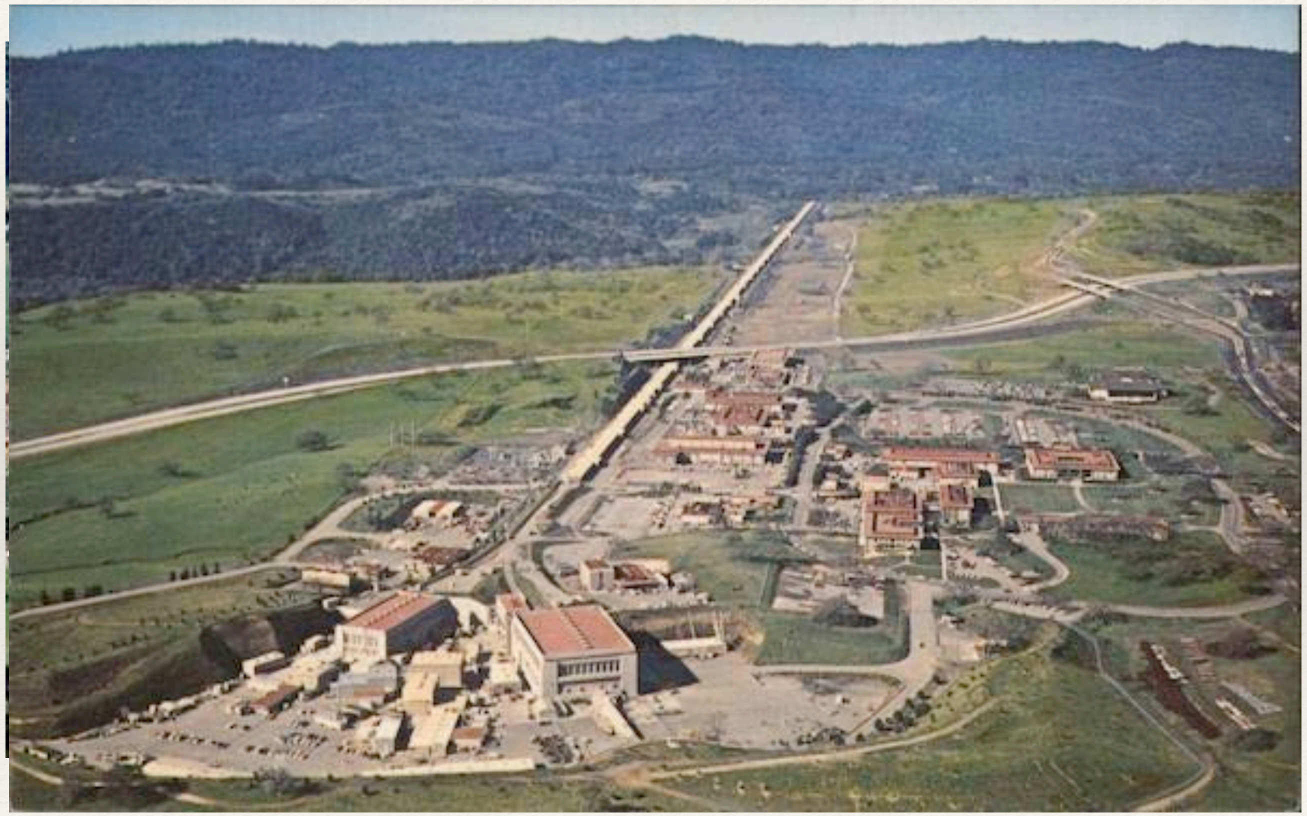
Stanford Linear Accelerator Center (SLAC)

3 km length

- The Stanford Linear Accelerator Center began operation as 20 GeV electron fixed target facility in 1967. (discovered quarks)



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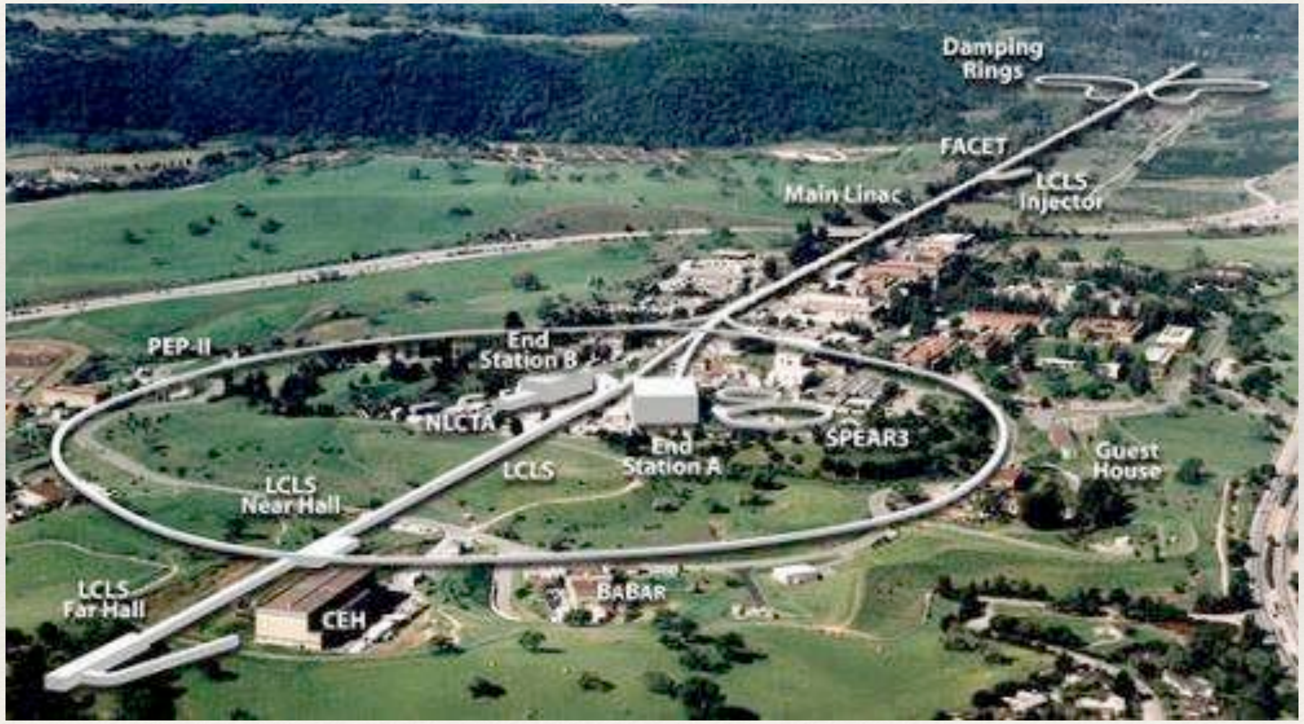

SLAC Linear Collider (SLC)

cms E (e+e-) = 91 GeV   3 km length

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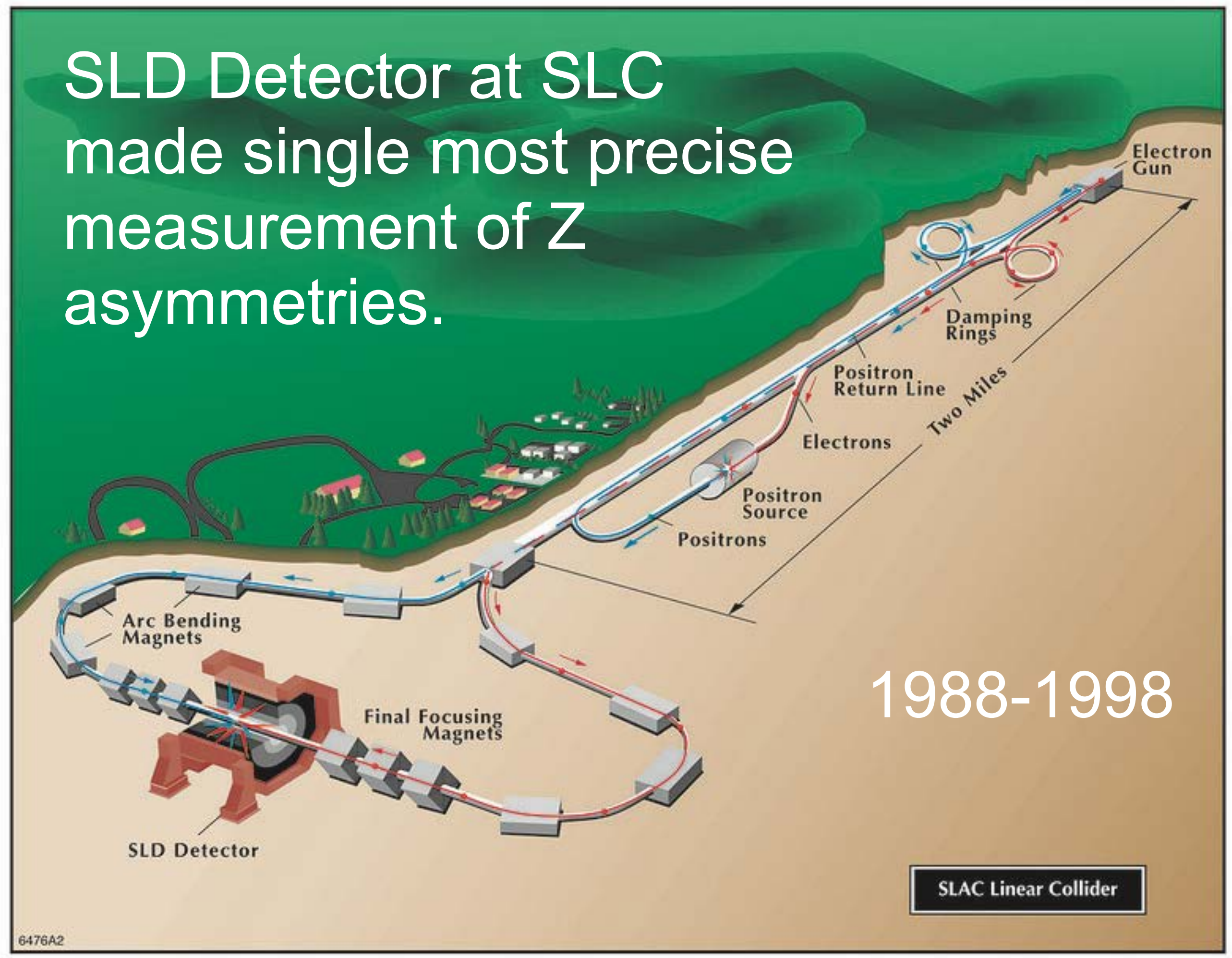
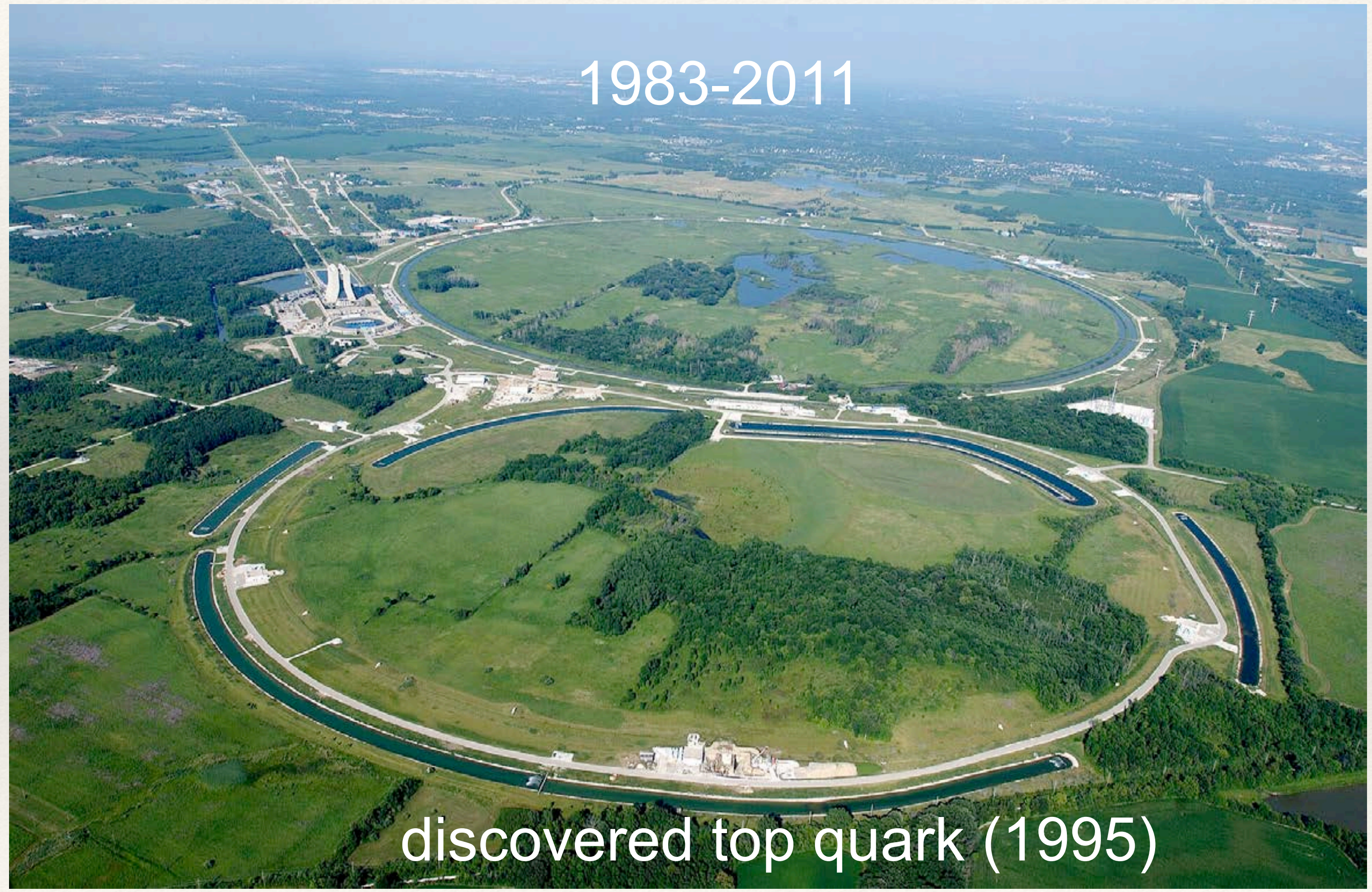


Fermilab collider (Tevatron)

cms E (p anti-p) = 2 TeV   6.2 km circumference

- Fermilab began operation as 200 GeV proton fixed target facility in 1972. (discovered bottom quark)
- Colliding beams in the Tevatron for two experiments, D0 and CDF (1983) (discovered top quark).
- Fixed target experiment DONUT discovered tau neutrino in 2000.

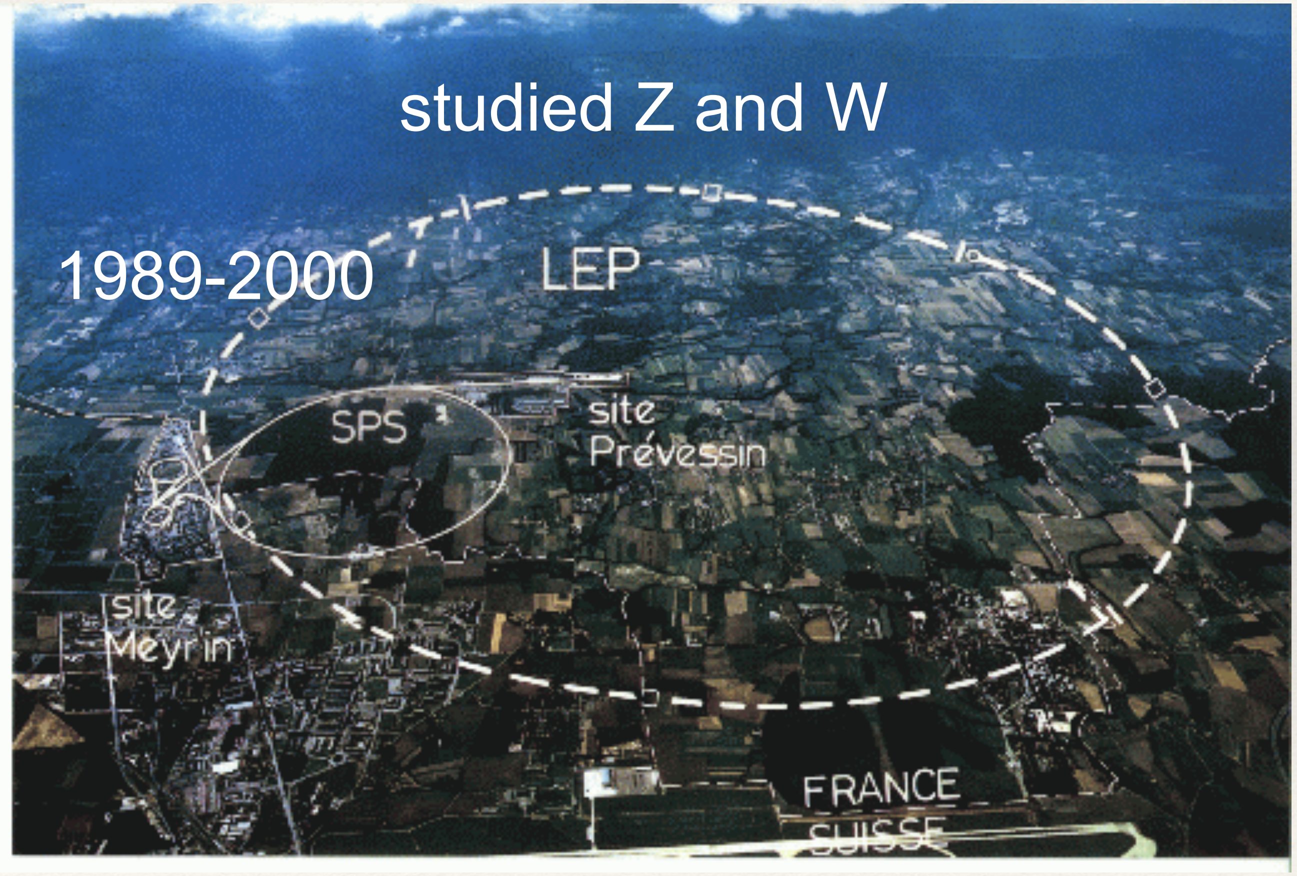


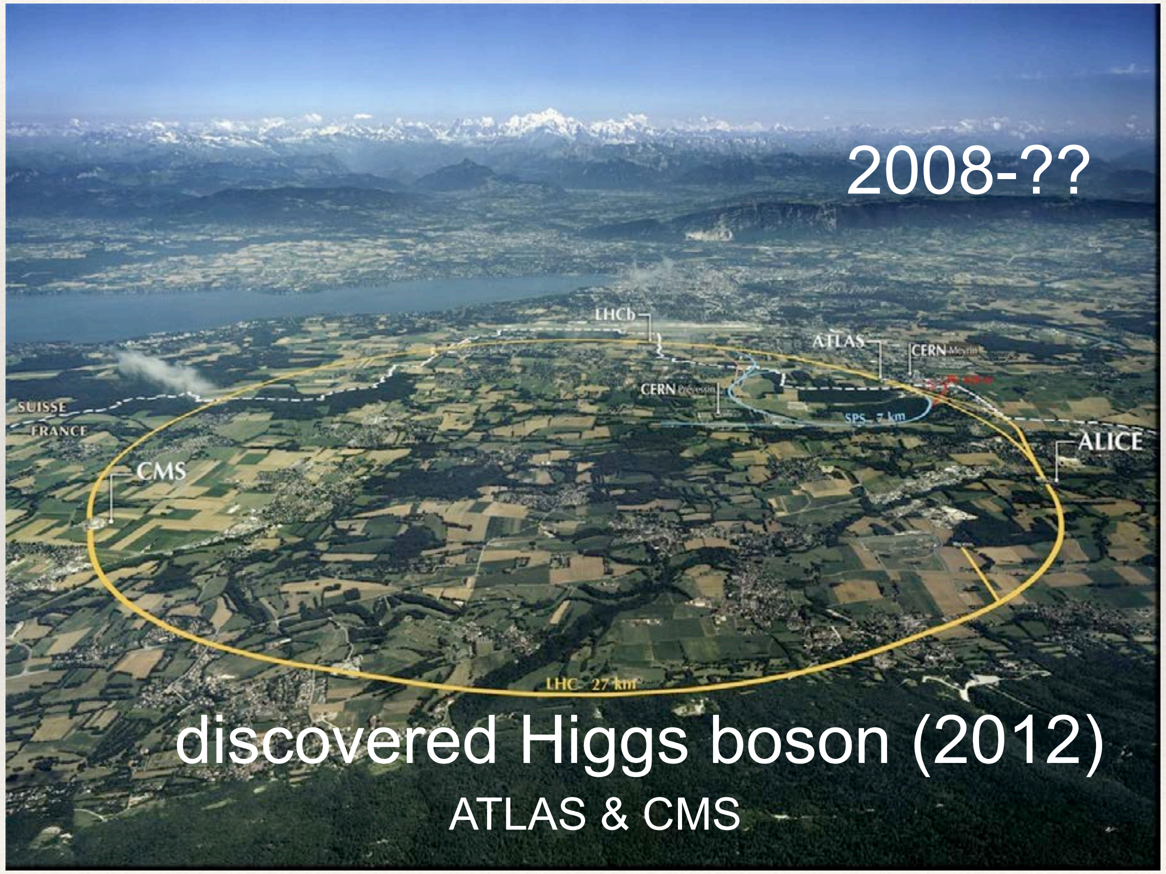
LEP → LEP2 → LHC → HL-LHC

cms E (e+e-) = 91 - 209 GeV

cms E (pp) = 14 TeV

27 km circumference





Physics Motivations for Future Colliders

- Precise understanding of Higgs boson
  - branching ratios (compared to Standard Model)
  - invisible Higgs decays
  - Higgs self coupling (h → h h)
  - Higgs boson mass (what is it exactly and why so light?)
- Dark matter (it's everywhere but what is it?)
- Matter-antimatter asymmetry
- and more ….

see also, 2024 UO Quarknet, "The Higgs boson as a tool for discovery,' https://pages.uoregon.edu/jimbrau/talks/Higgs-Factory-quarknet.pdf

Global Planning

- **APS DPF Snowmass (US)**
  - 2020-2022
- **DOE P5 (Particle Physics Project Prioritation Panel)**
  - 2023
  - Panel endorsed offshore Higgs factory, located in either Europe (CERN) or Japan, to advance studies of the Higgs boson following the HL - LHC.

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- **European Strategy Update**
  - 2024-2026
  - Open Symposium will be hosted in Italy, at Lido di Venezia, 23-27 June.
  - Many white papers by physicists world-wide advocating future colliders, notably the Higgs factory.

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- Other planning exercises in Canada, Asia,…

Future Colliders

- FCC-ee (Future Circular Collider - e+e-) - CERN
- CEPC (Circular Electron-positron Collider) - China
- LCF (Linear Collider Facility) - CERN
    - ILC (International Linear Collider) -CERN or Japan
    - CLIC (Compact Linear Collider)
    - C^3 (Cool Copper Collider)
- FCC-hh (Future Circular Collider - hadron-hadron)
- Muon Collider
- Laser-driven Plasma-wakefield Collider

Future Colliders

Higgs Factories:

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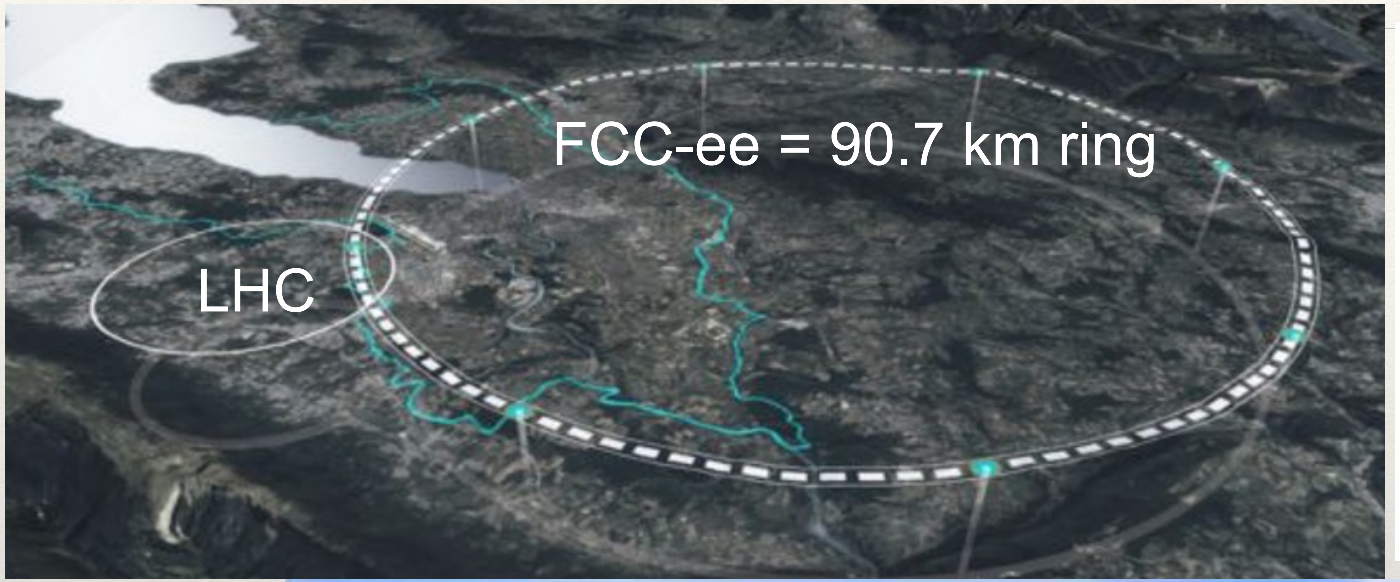
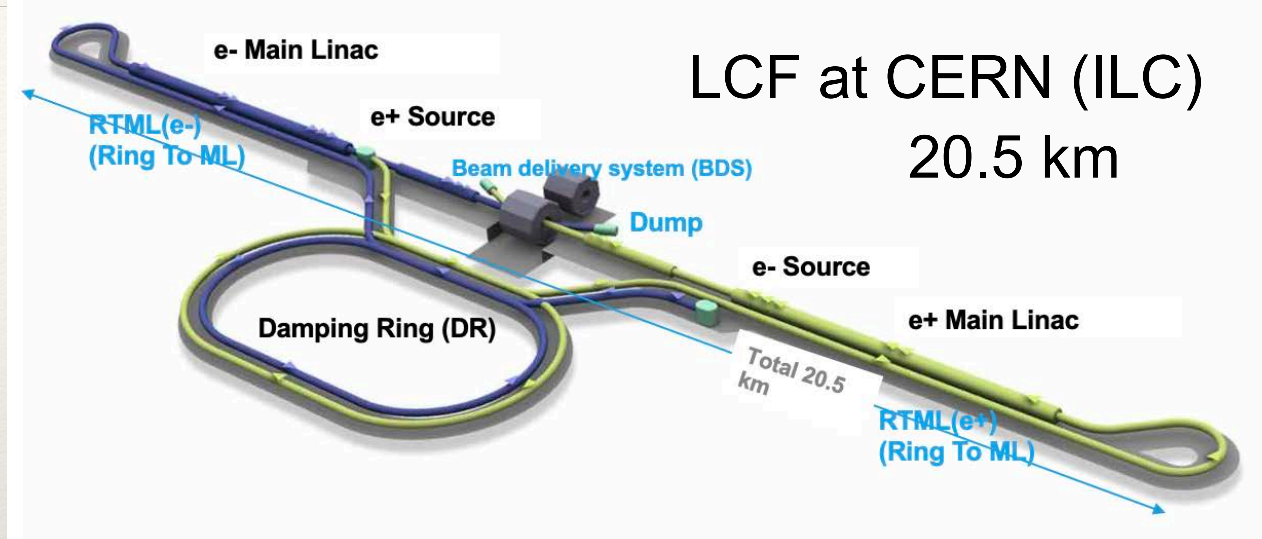
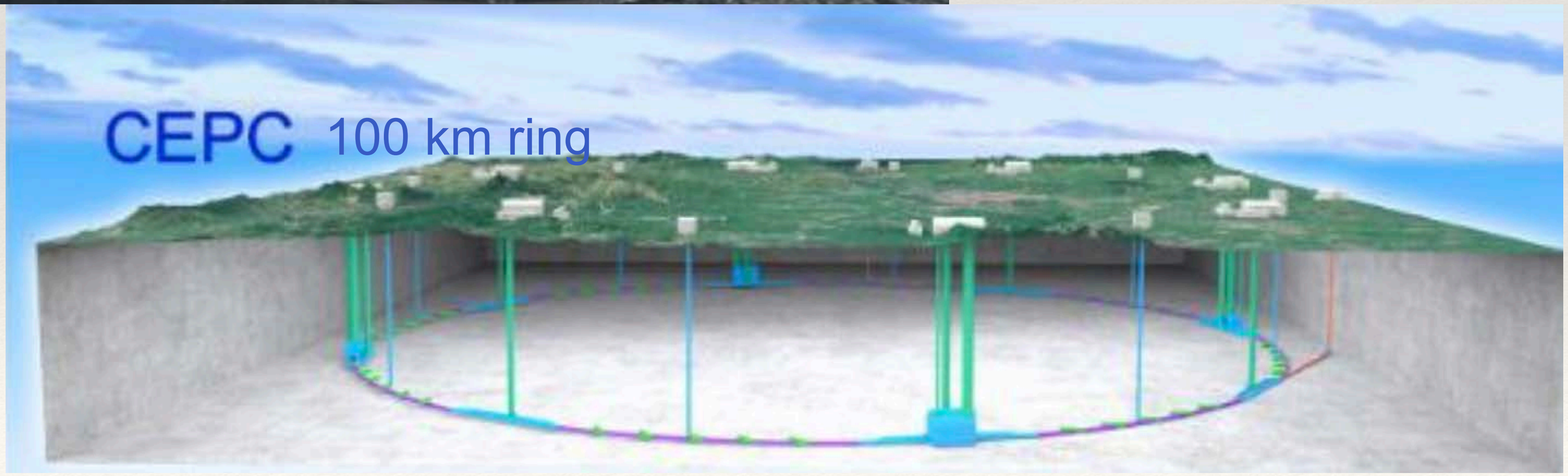
Far Future options

- FCC-hh (Future Circular Collider - hadron-hadron)
- Muon Collider
- Laser-driven Plasma-wakefield Collider

Higgs Factories

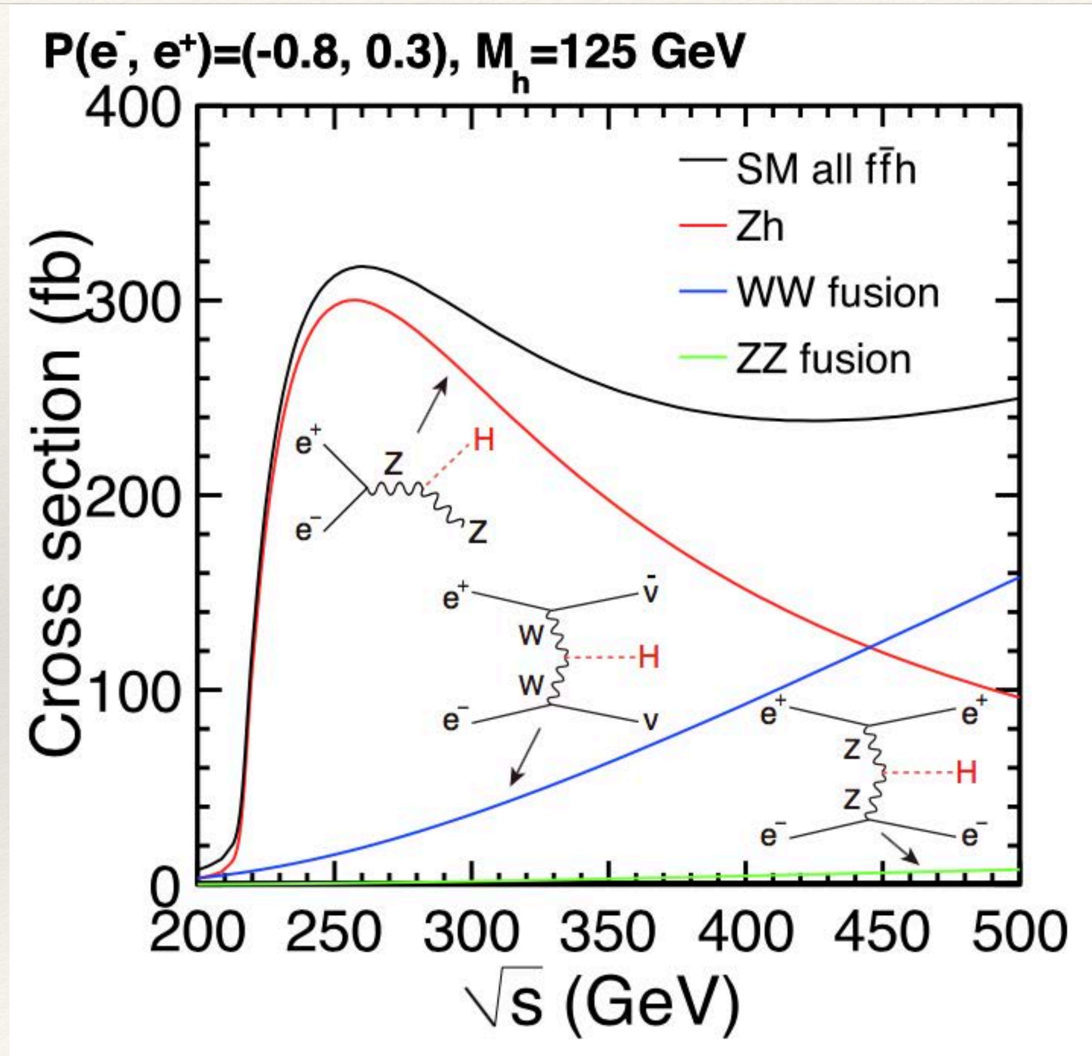


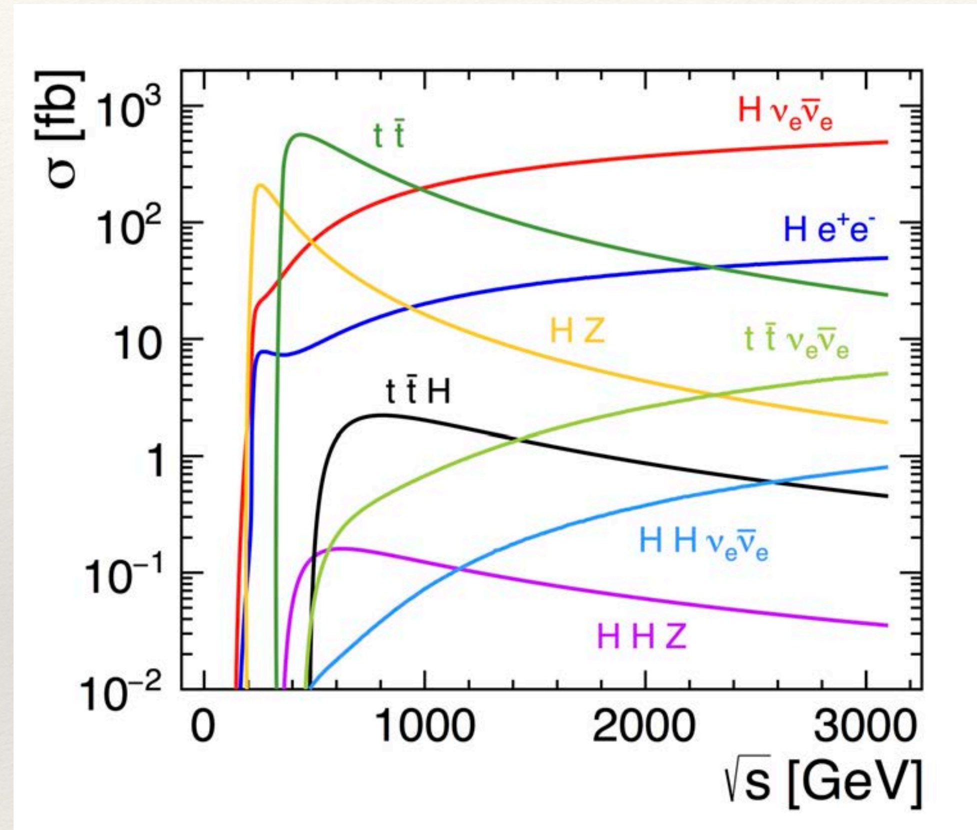




Higgs Factory Cross Sections

- e+e- collisions
- orders of magnitude fewer interactions than for pp
- much, much fewer uninteresting events





fb = 10^{-15} barns = 10^{-39} cm^2

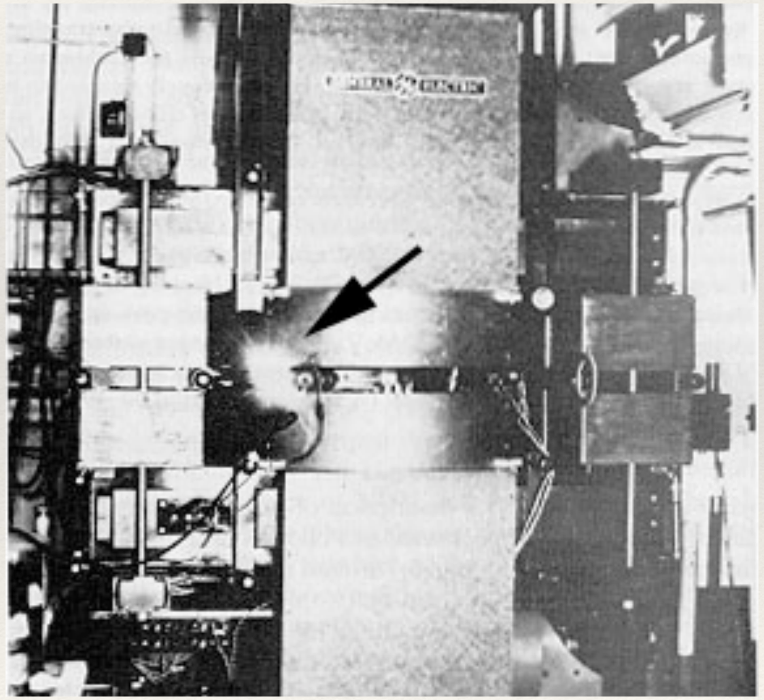
Higgs Factories - Circular vs. Linear

- Circular
  - 👍 Multiple pass
  - 👎 Synchrotron radiation
    - limits Ecm to <400 GeV
  - Potential for lower collision energy
  - Collision energy constrained
  - Larger beam size at collision
  - Transverse beam polarization

- Linear
  - 👎 Single pass
  - 👍 No synchrotron radiation
    - allows increase to Ecm >TeV
  - Potential for higher collision energy
  - Flexible collision energy
  - Small beam size at collision
  - 👍 Longitudinal beam polarization

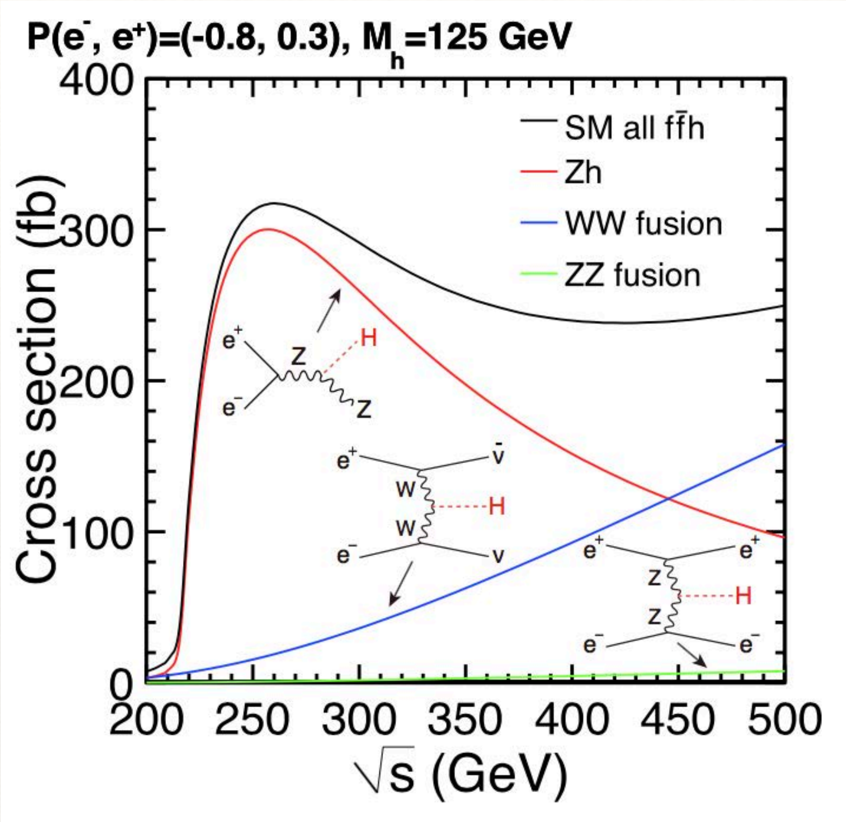
Synchrotron Radiation

- 1897 - Following J.J.Thomson's discovery of the electron, Larmor and Lienard's theory predicted radiation from electron in circular trajectory:
    - $(E/mc^2)^4/R^2$
- 1947 - discovered during operation of 70 MeV synchrotron General Electric Research Laboratory in Schenectady, NY.
- Significantly limits electron energy in circular accelerators.
- Small effect on proton accelerators.
    - The energy lost per turn in LHC (protons)
        - at 7 TeV is about 7 keV;
        - at LEP (electrons) it was 3 GeV.



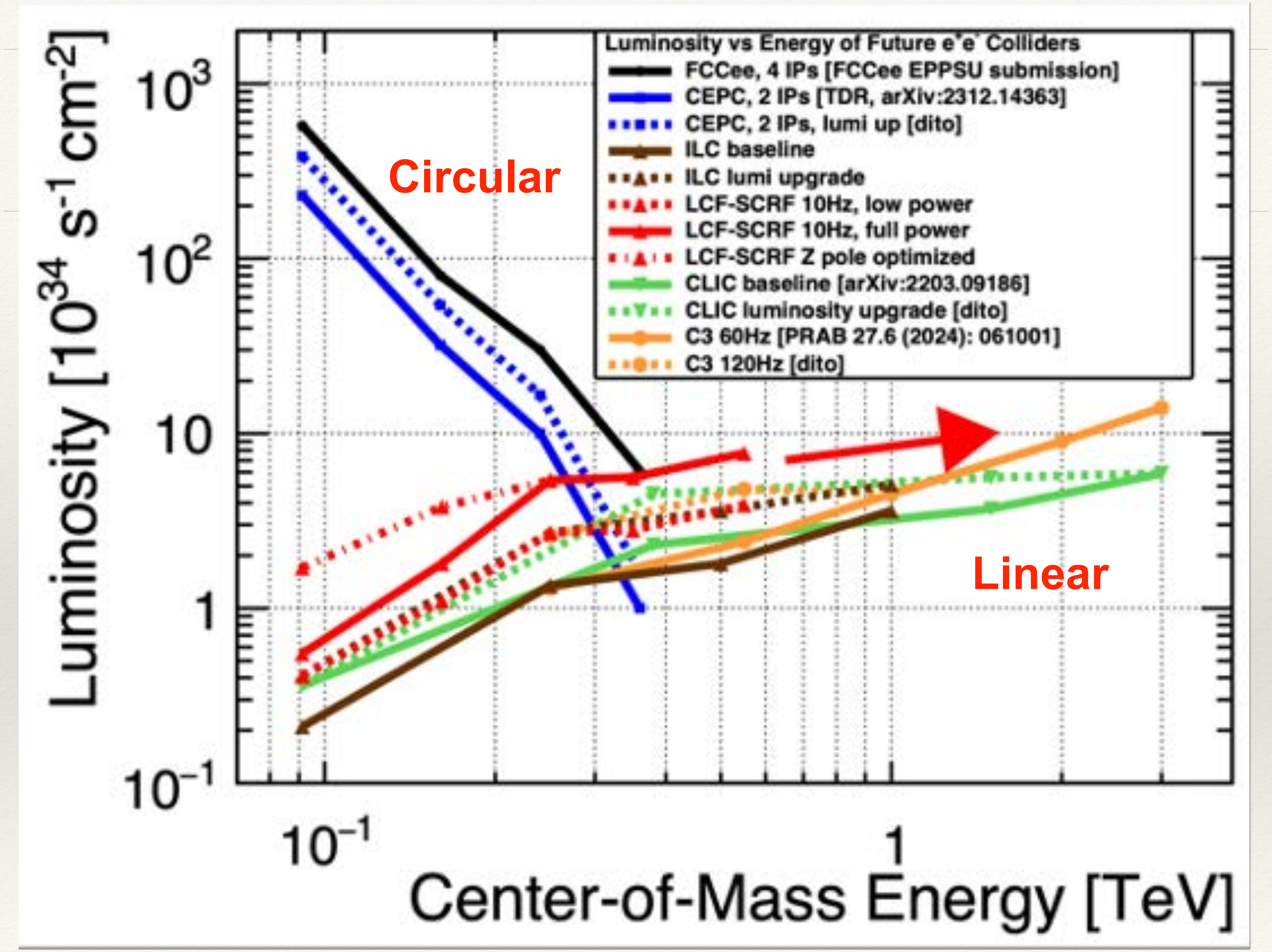
Collider Luminosity

- As center-of-mass energy increases new physics opens up, but how many events will be created?
- Event rate depends on cross section, which is natural measure of process.
- Measure of colliders event rate capability is Luminosity.



$$\frac{dN}{dt} = \sigma \; L$$

Luminosity is in units of $cm^{-2}s^{-1}$


Luminosity vs Energy of Future e⁺e⁻ Colliders
FCCee, 4 IPs [FCCee EPPSU submission]
CEPC, 2 IPs [TDR, arXiv:2312.14363]
CEPC, 2 IPs, lumi up [dito]
ILC baseline
ILC lumi upgrade
LCF-SCRF 10Hz, low power
LCF-SCRF 10Hz, full power
LCF-SCRF Z pole optimized
CLIC baseline [arXiv:2203.09186]
CLIC luminosity upgrade [dito]
C3 60Hz [PRAB 27.6 (2024): 061001]
C3 120Hz [dito]
Circular
Linear
Luminosity [10^{34} s^{-1} cm^{-2}]
10^{3}
10^{2}
10
1
10^{-1}
10^{-1}
1
Center-of-Mass Energy [TeV]

CERN Higgs Factory Costs

FCC-ee at CERN

Domain	FCC-ee – 240 GeV Cost [MCHF]	FCC-ee – 240 GeV Cost class
Booster and collider	4140	3
Pre-injectors and transfer lines	590	3
Civil engineering	6160	3
Technical infrastructures	2840	3
Experiments	1590	4
TOTAL	**15320**	

LCF at CERN

Domain	LCF LP – 250 GeV Cost [MCHF]	LCF LP – 250 GeV Cost class
Collider	3864	3
Injectors and transfer lines	1181	3
Civil Engineering	2338[a]	4
Technical infrastructures	1109	4
Experiments	795	4
TOTAL	**9287**	

[a] The cost for spoil removal (estimated at 200 MCHF) is included here.

FCC-ee might lead to FCC-hh as LEP led to LHC, but, very costly

https://indico.cern.ch/event/1439855/contributions/6542430/attachments/3076609/5444588/Future_Colliders_Comparative_Evaluation_WG_report.pdf

Asian Cost Estimates

https://arxiv.org/pdf/2506.00353

CEPC in China

Table 8.1: Cost estimation of the CEPC

Tier I	Tier II	Amount (100 M CNY)
Accelerator	Collider	99.2
	Booster	39.2
	Linac and sources	9.1
	Damping ring	0.44
	Common: Cryogenics	10.6
	Survey & alignment	4
	Radiation protection	1.7
Conventional facilities	-	102
Detectors	-	40
γ-ray beam lines	-	3
Project management (1%)	-	3
Contingency (15%)	-	46
Total	-	358

~ 5B US$

https://indico.global/event/12245/contributions/109165/attachments/50444/96879/2023-HKUST-IAS-CEPC-Overview-Haijun.pdf

ILC in Japan

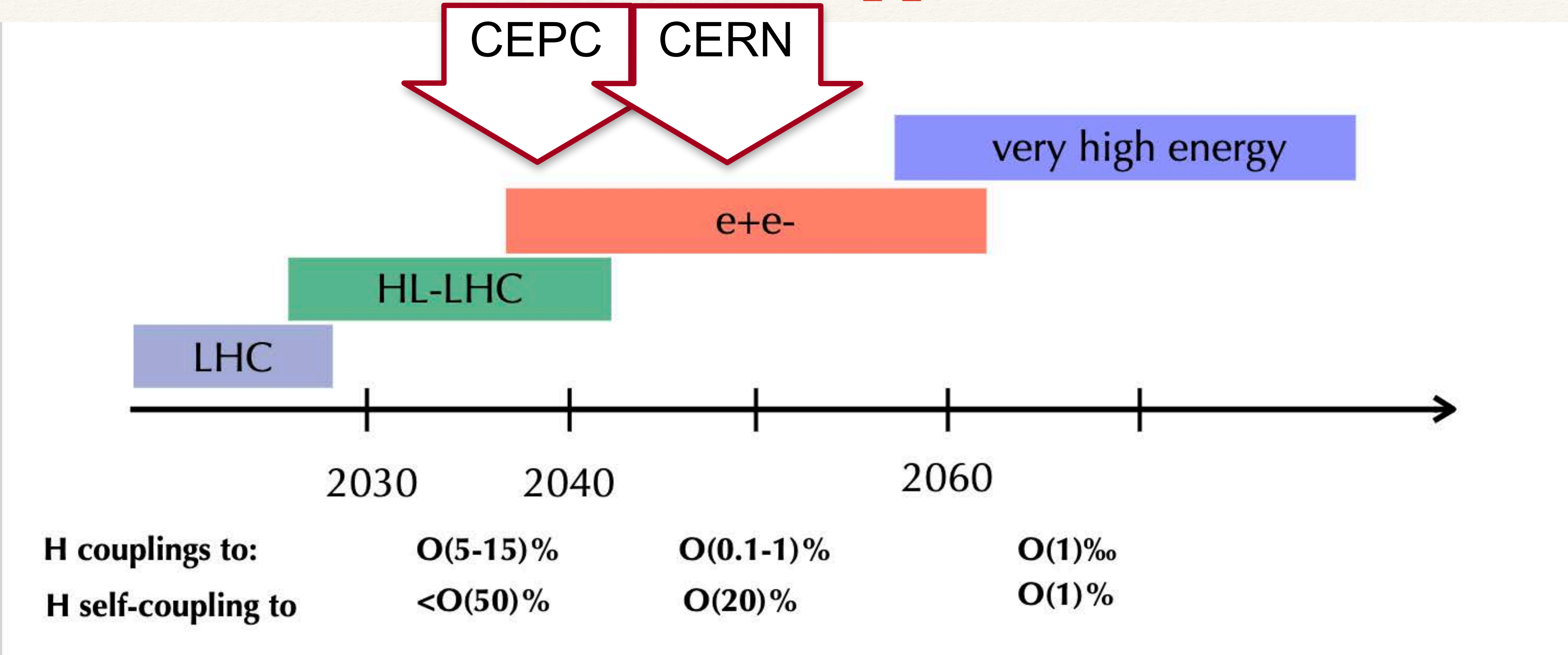
Cost Estimate/Updates (Year)	ILC250 (2024)	
Accelerator Construction (in 9 years)	[B ILCU]	[B JPY]
Value: Acc. + Conv. Facility (CF : global)	6.78	
Civil Engineering (CE : JP specific)		196
Breakdown:	3.69	
Acc-SRF related	1.71	
Conv. Acc. Tech. (mag., vac, and others)	1.38	
CF (utility service): Electric., cooling, ventil.		
Labor (HR): Laboratory staff	7.47	
Installation worker	2.65	
Acc. Operation (/year)		
Value (Electricity, Cooling, etc.)	0.41	
Labor (HR):	638	
Uncertainty (cost premium) [3,4]	29	
Contingency (common fund reserve) [21]	10	
References	[9,11]	

ILCU = purchasing power of 1 USD in the United States, as of January 2024

Summary of Future Higgs Factory Cost Estimates

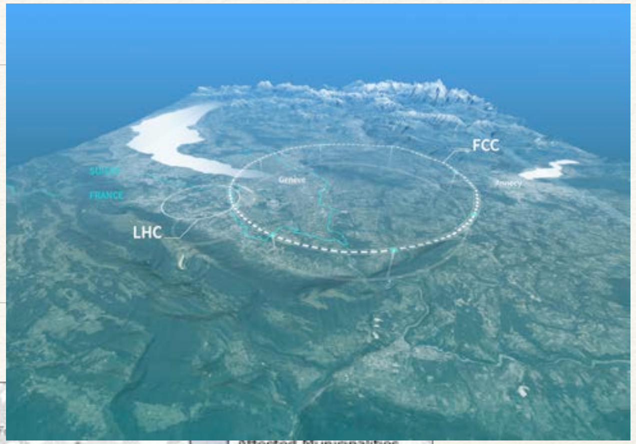
	Cost	Cost in US$ (my est.)
FCC-ee at CERN	15.3 B.CHF	18.7 B
LCF at CERN	9.3 B.CHF	11.4 B
CEPC in China	358 B.CNY	5.2 B
ILC in Japan	6.78 B ILCU +196 B.JPY	8.1 B

When? (approximate)



C. Vernieri – Snowmass21 EF Workshop - Brown U. - March 2022

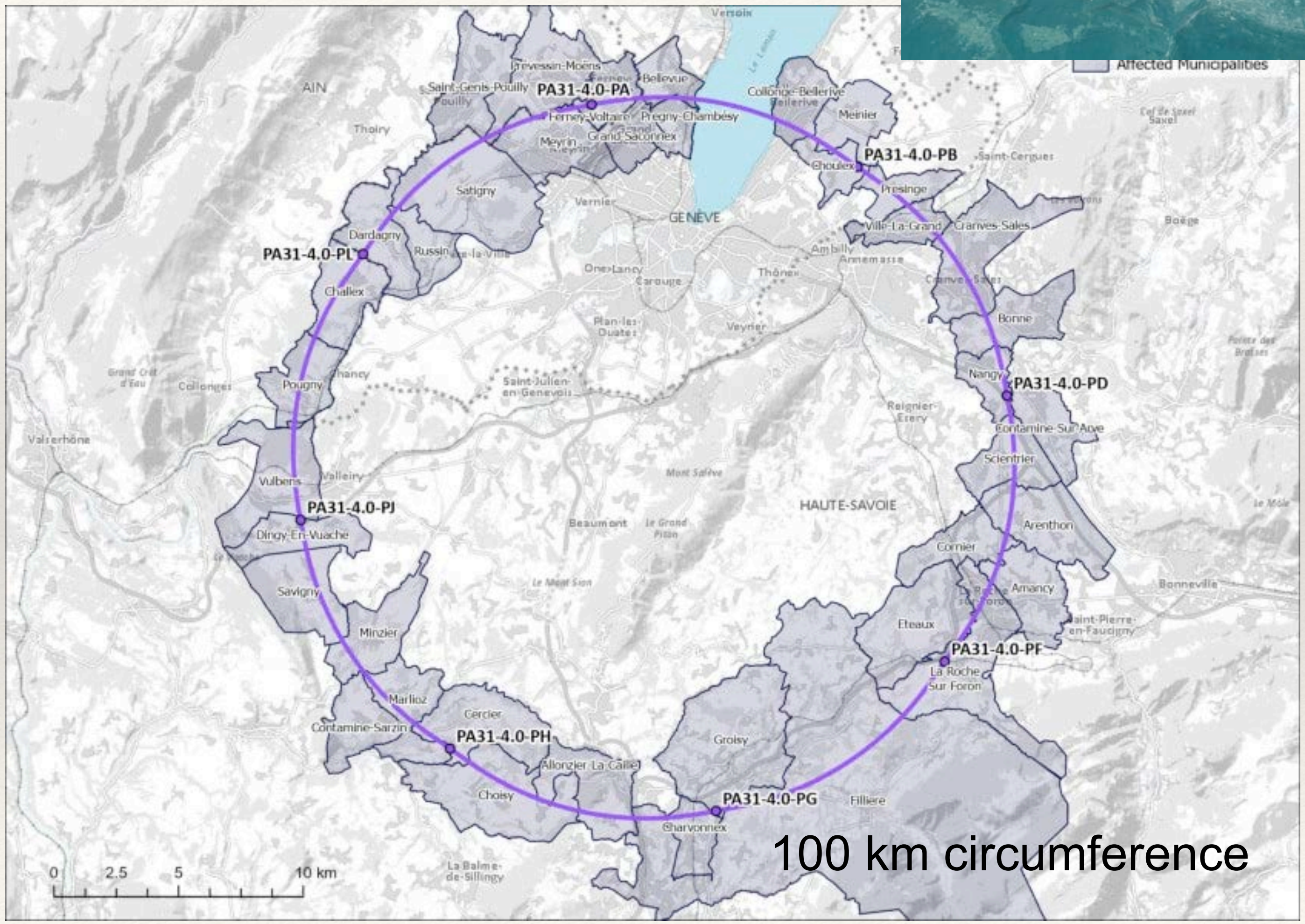
FCC-hh



cms E (pp) = 100 TeV

Reuse FCC-ee tunnel
(as LEP → LHC)

- **2070s**: **FCC-hh** begins operation and runs for approximately 25 years



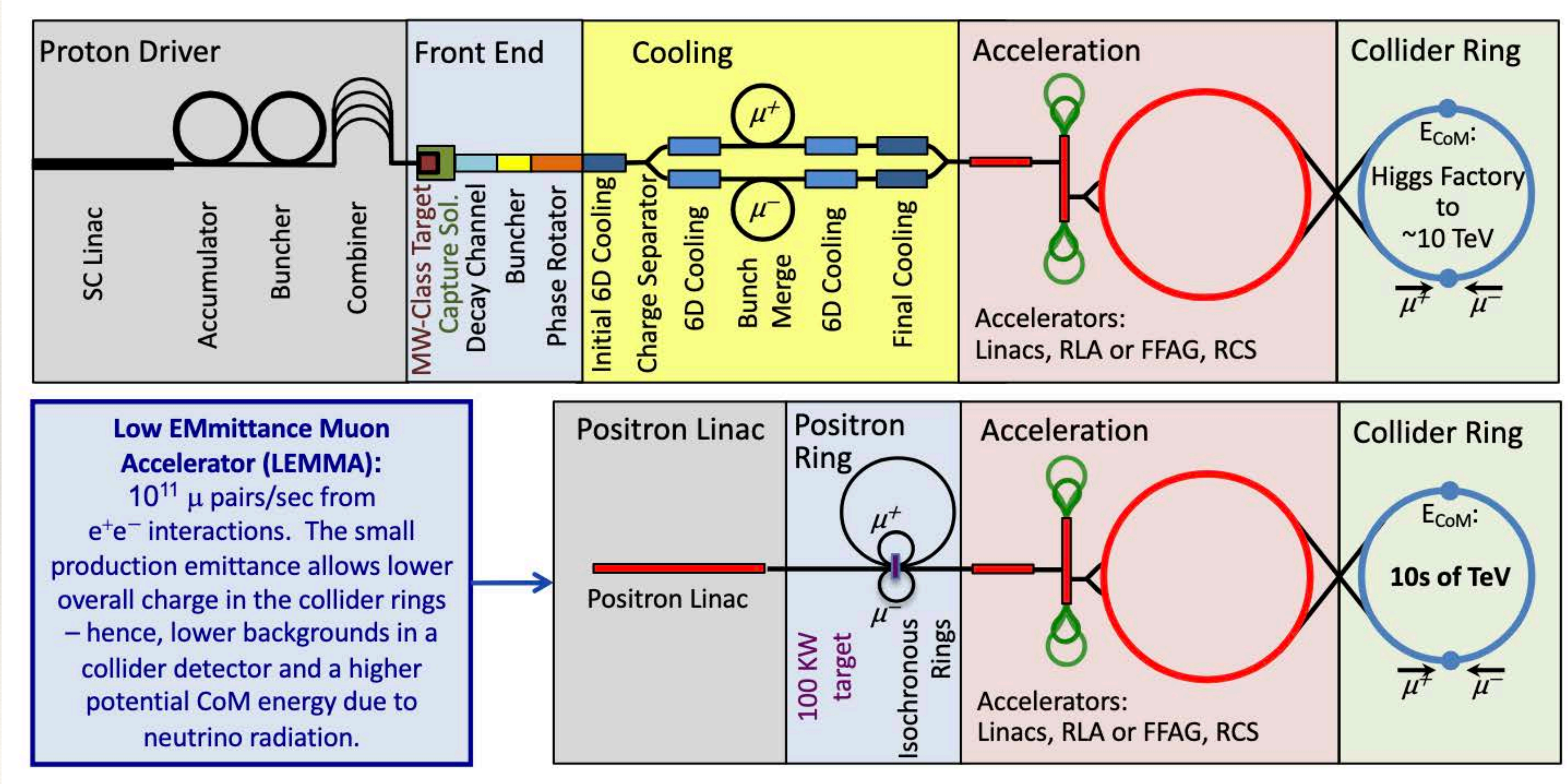
Muon collider - “the muon shot”

- The more massive a particle, the less energy it loses through synchrotron radiation.
- Muon is 200 times heavier than electron, and emits about two billion times less synchrotron radiation.
- Since muons are fundamental particles, unlike protons (made of quarks), muon collider could run using less energy.
  - 10 TeV muon collider competitive with a 100 TeV proton collider.
- Two big challenges
  - Decays after only 2.2 microseconds (lifetime increases with energy).
  - Production of tight beam of muons.

https://indico.cern.ch/event/867138/attachments/1954116/3245303/Muon_Collider_European_Strategy.pdf

Muon collider - two approaches

~10 km circumference



- Biggest question: When will technology mature?
- Needs R&D

Conclusion

- Advances in particle physics depend on the accelerator technology that produces the interactions of interest.
- For a century clever innovations have continued to advance the technology.
- Several Higgs factory designs are ready to play a role in the next round of improvements.
- Beyond the era of the Higgs factory there are other advances being studied.
- Continued discovery will depend on investment to build those concepts.

see also, 2024 UO Quarknet, "The Higgs boson as a tool for discovery,'
https://pages.uoregon.edu/jimbrau/talks/Higgs-Factory-quarknet.pdf