Foundation of Collider (1)

Circular Collider
Linear Collider
Energy Recovery Collider
Gamma-Gamma Collider
Muon Collider
Plasma Collider

Kaoru Yokoya, KEK

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Limitation of Target Experiments

- By using synchrotrons/linacs we can accelerate particles (proton/electron, etc) up to some tens of GeV, even some 100's of GeV
- However, the center-of-mass energy of a 1000GeV proton and a proton at rest is only some 40GeV (next page)

$$\sqrt{2Mc^2E} = \sqrt{2 \times 1000 \times 0.938} = 43\ \mathrm{GeV}$$

- High energy physics demands higher and higher energies
- How can we reach such energies?

Collider

- Consider a collision of two beams
  - ✓ Either scheme is equivalent if the collision energy is the same

- ✓ Energy of the projectile beam is lower in the right-hand scheme
- ✓ When the particle energy is so high ($E>>mc^2$), the right-hand-side scheme is by far better

$$E_{CM} \approx \sqrt{2mE}$$ target experiment

$$E_{CM} = 2E$$ colliding beam

note: here mc^2 is simplified to m

Derivation:

$$\sqrt{s} = \sqrt{(p_1+p_2)^2} = \sqrt{p_1^2+p_2^2+2p_1p_2} = \sqrt{2m^2+2(E_1E_2-\boldsymbol{p}_1\cdot\boldsymbol{p}_2)}$$

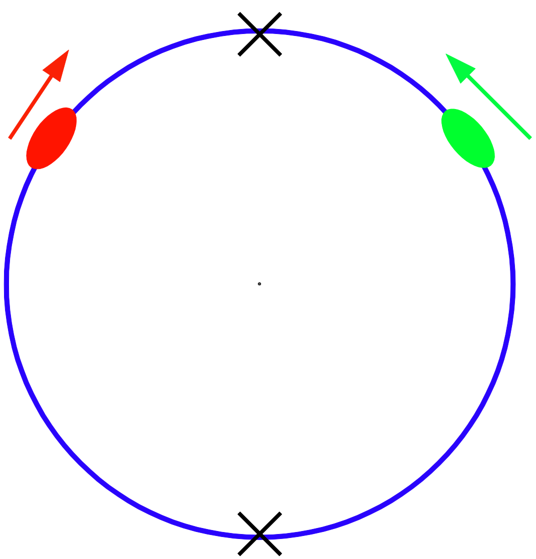
$$= \begin{cases} \sqrt{2mE} & (E_1=E,\ E_2=m,\ \boldsymbol{p}_2=0,\ m\ll E) \\ 2E & (E_1=E_2=E,\ \boldsymbol{p}_2=-\boldsymbol{p}_1,\ \ m\ll E) \end{cases}$$

- For example, a collision of two 0.5GeV electrons is equivalent to collision of 1TeV electron with an electron at rest

How to make particles collide?

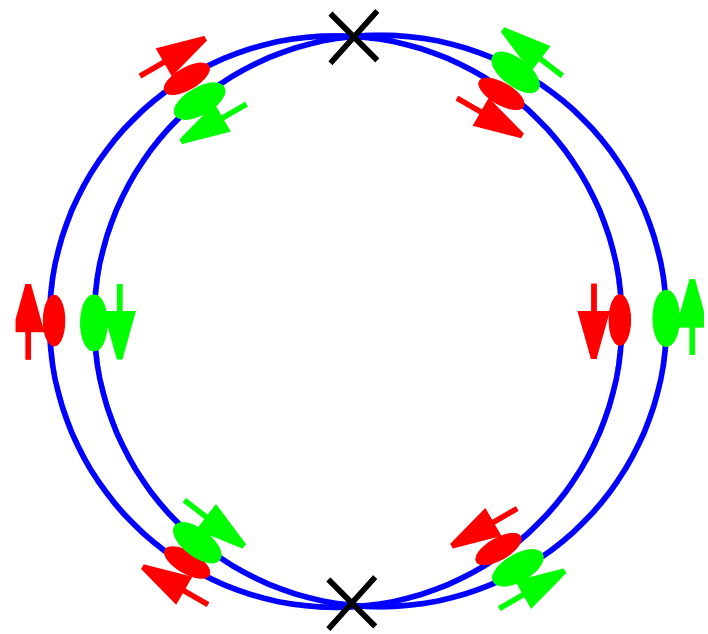
- Beams of same energy and opposite charge
- Can use a single ring
- You need (electro-static) separators to avoid unnecessary collisions

- Much more freedom by using two rings



.... PETRA, TRISTAN, LEP,

..... SppS, Tevatron

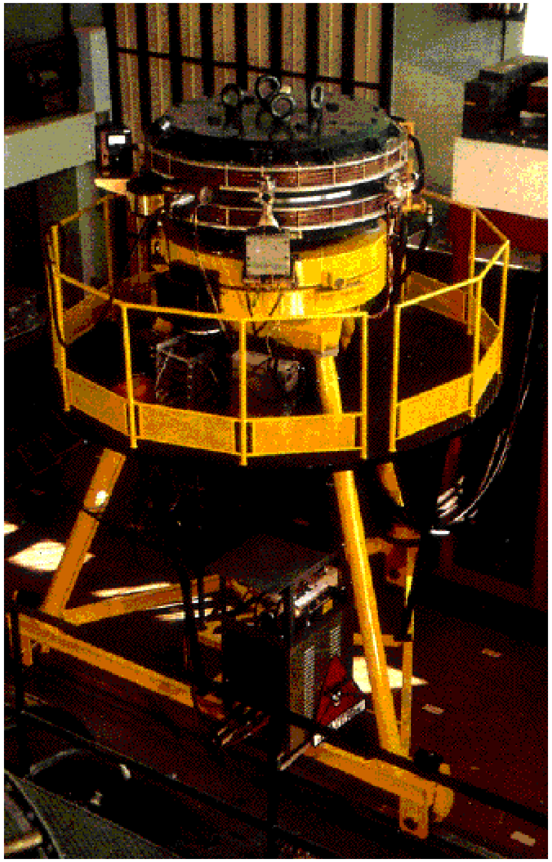


PEPII, KEKB, LHC, ...

First Electron-Positron Collider: AdA

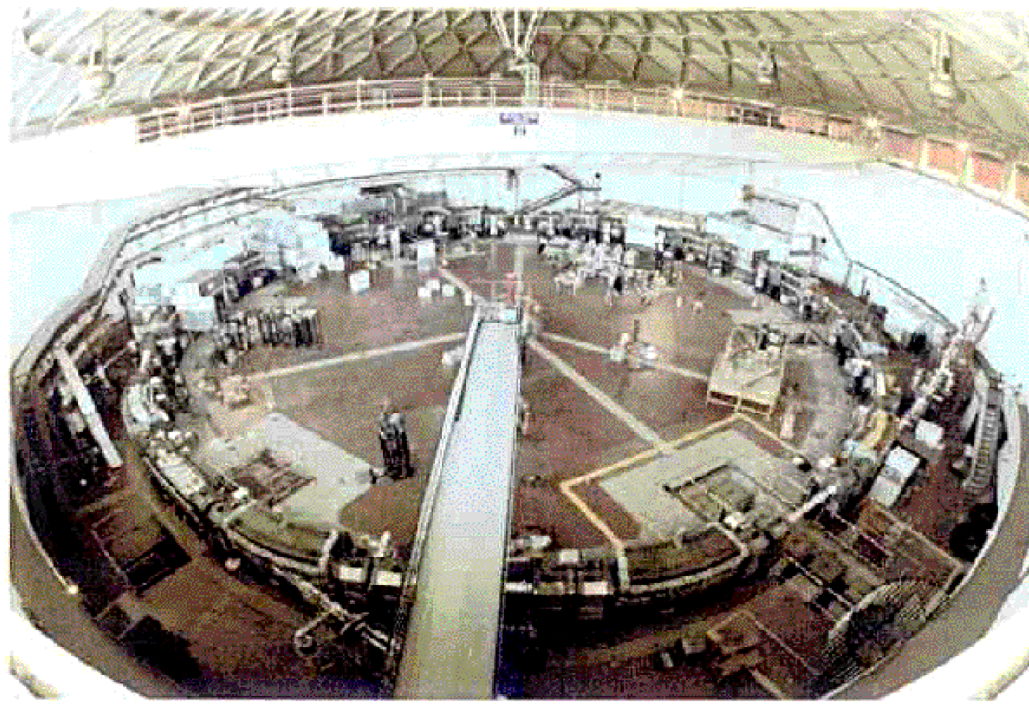
- First beam in Italy in 1961
- Moved to Orsay (France) and the first collision in 1964
- Orbit radius 65cm, collision energy 0.5GeV

Now exhibited in a garden in Frascati, Italy



The second：Adone

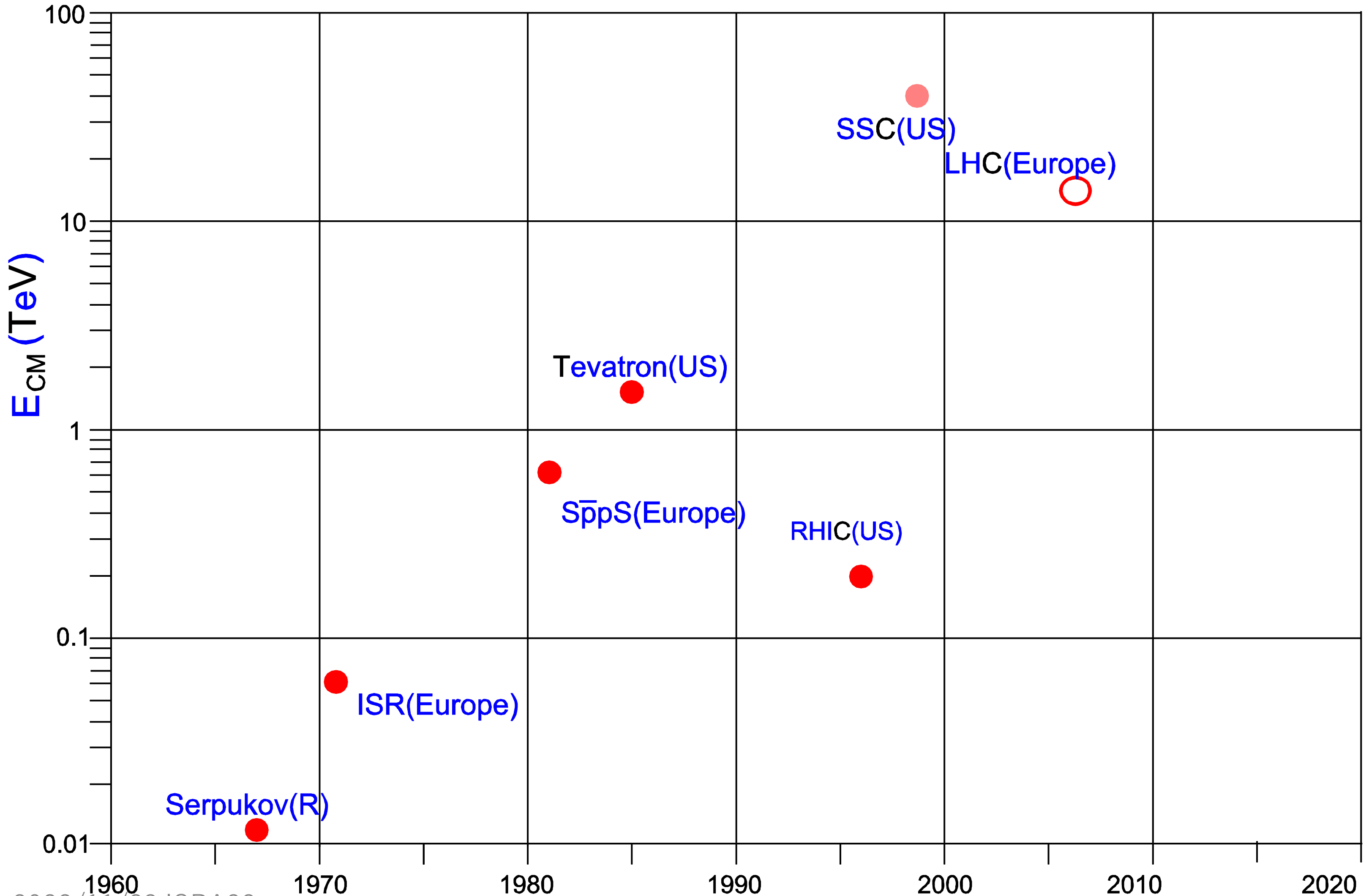
- The first beam in 1967
- Circumference 105m
- Collision energy < 3GeV (Did not reach J/ψ at 3.1GeV)
- Luminosity $3x10^{29}$ /cm^2/s



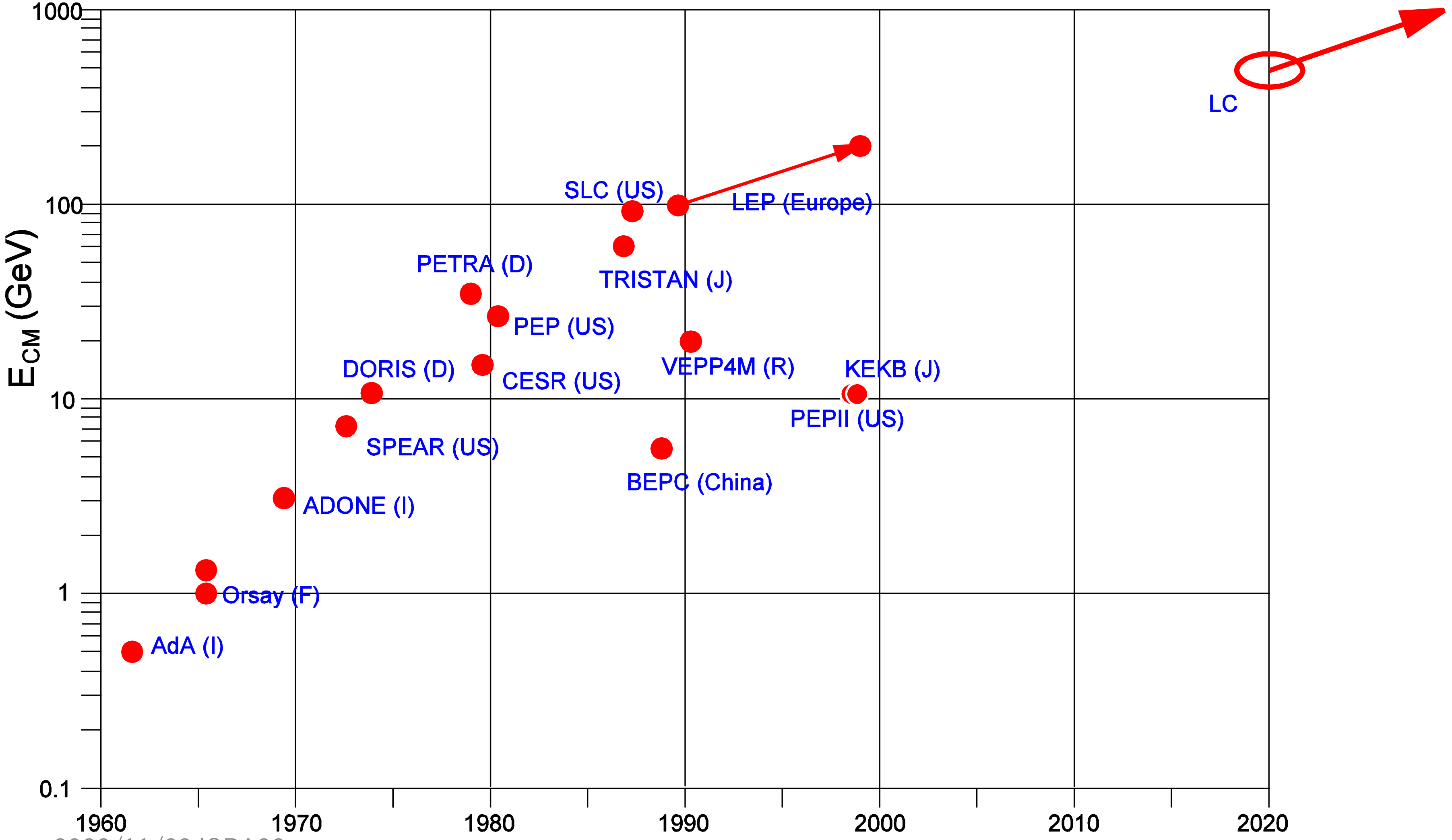
Many Colliders Built Since Then

- e+e-
- pp
- ppbar
- ions
- ep

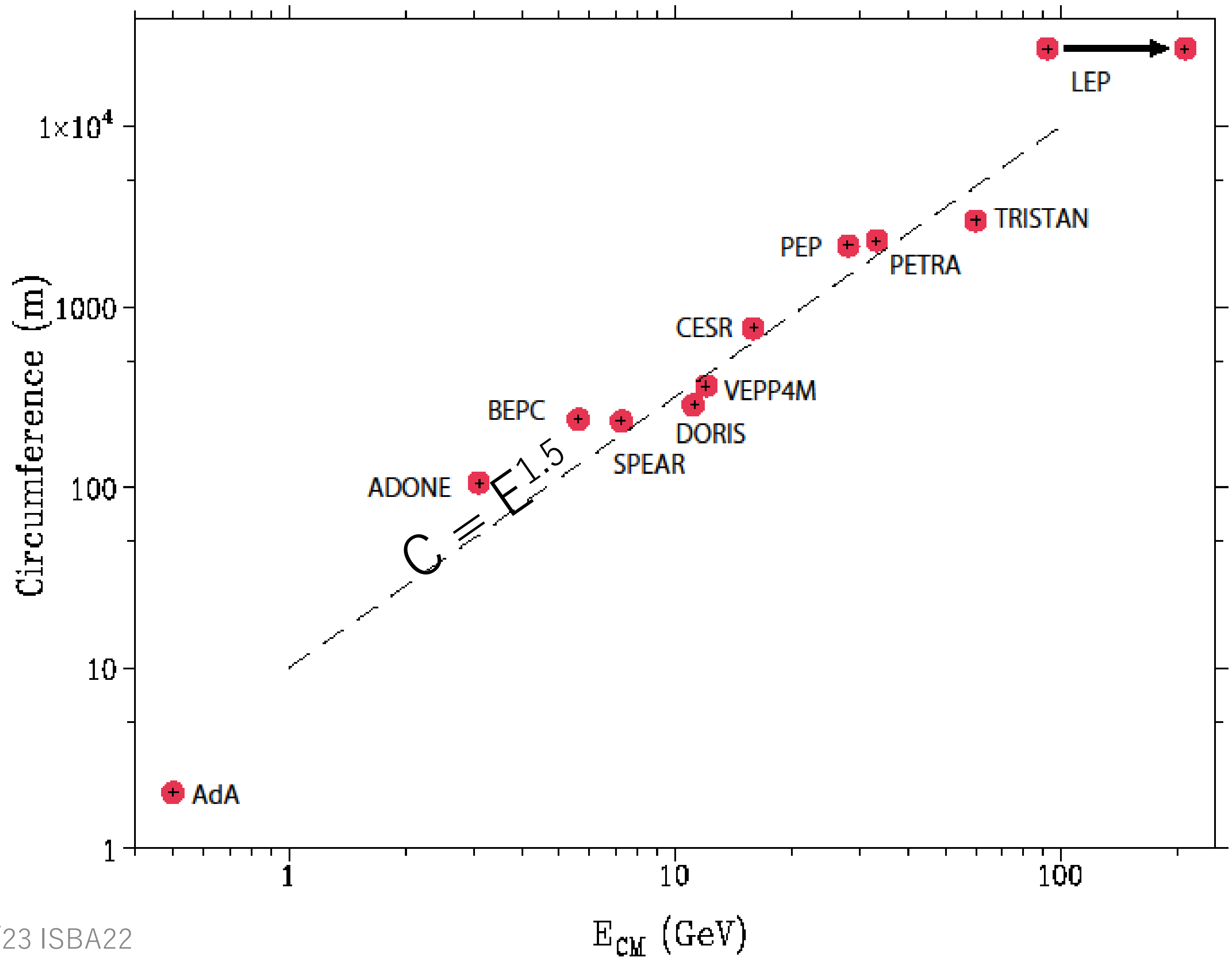
History of Proton/Antiproton Colliders



History of Electron-Positron Colliders



Energy vs. Ring Radius



Difficulty of Colliders

- Number of events per second
  - ✓ Fixed target

    $$F \times n \times d \times \sigma$$

    - F: particle flux (number of particles per second)
    - n: density of target (atoms / m^3) , not the density of projectile
    - d: target thickness
    - σ: event cross-section
  - ✓ Collider

    $$L \times \sigma, \qquad L = fcol \times \frac{N^2}{S} = \frac{FN}{S}$$

    - L: Luminosity
    - f_{col}: bunch collision frequency ($F = f_{col} N$)
    - N: number of particles per bunch
    - S: transverse cross-section of the bunch
- Essential difference: $n \times d \rightarrow N / S$

  i.e., target density vs. beam density
- Need to pack many particles in a small area (firstly, the transverse are)

ABC of Circular Collider Dynamics

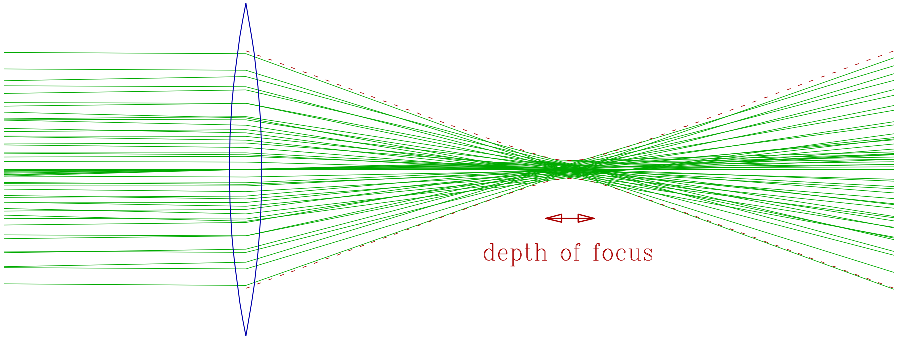
- Beam dynamics in a circular collider is basically similar to that of storage rings except for the conditions coming from the collision point
- Luminosity

$$\mathcal{L} = \frac{f_{col} N^2}{4\pi\sigma_x\sigma_y}, \quad \sigma_x^* = \sqrt{\epsilon_x\beta_x^*}, \quad \sigma_y^* = \sqrt{\epsilon_y\beta_y^*}$$

The asterisk * indicates a quantity at the exact collision point

- Hour-glass Effect

$$\beta_y^* >\approx \sigma_z$$



$$\beta(s) = \beta^*\sqrt{1 + \frac{s^2}{\beta^{*2}}}$$

Beam-beam tune-shift

- The beam is focused (assume oppositely charged beams like e+e-) by the on-coming bunch
- This causes a shift of betatron frequency **as well as its spread**
- Their magnitude can be characterized by the parameter ξ_x, ξ_y . In the simple case of head-on collision of equal size Gaussian bunches

$$\xi_{x(y)} = \frac{r_e}{2\pi} \frac{N\beta^*_{x(y)}}{\gamma} \frac{1}{\sigma^*_{x(y)}(\sigma^*_x + \sigma^*_y)}$$

- There has been a limit of $\xi_{x,y}$ empirically to be around 0.06, but these days we can predict it by computer simulations
- It is larger when the radiation damping is strong (so, it is small for proton collider)
- For e+e- collider it is often assumed $\xi_{x,y} \sim 0.1$ these days.

Era of Huge Circular Colliders: Tevatron

- Fermi National Lab
- Proton - antiproton
- Circumference 6.3km
- 1TeV
- Completed in 1983
- Superconducting magnet 4.2Tesla
- 1995 Top Quark
- 2009 shutdown

Tevatron behind and Main Injector front

Era of Huge Circular Colliders: LEP

- LEP (Large Electron-Positron Collider)
  - ✓CERN
  - ✓Construction started in 1983
  - ✓Operation started in 1989
  - ✓Circumference 27km
  - ✓Ultimate beam energy about 100GeV
  - ✓Closed in 2000

- LEP revealed Generation of elementary particles =3

$$n = 2.9841 \pm 0.0083$$

SPS: Super Proton Synchrotron

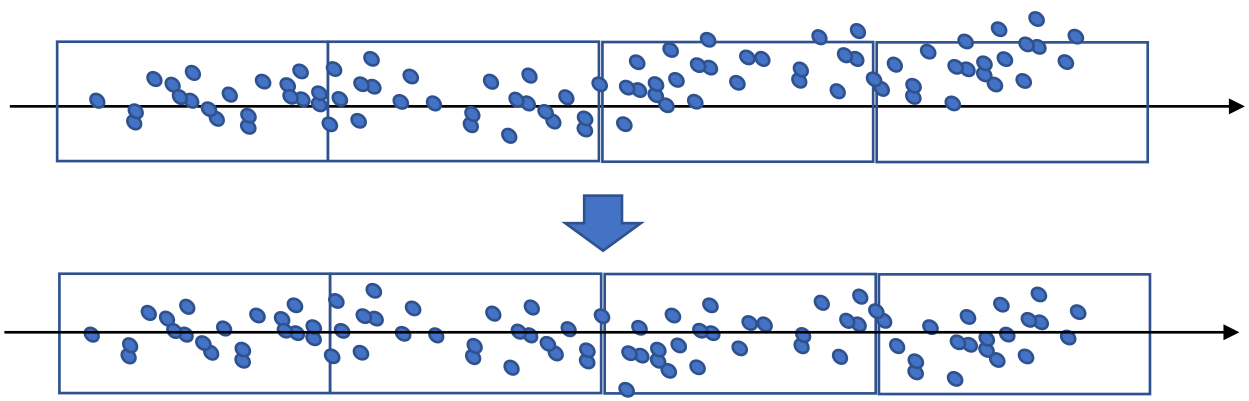
- Large proton synchrotron at CERN
- Operation started in 1976
- Achieved 500GeV in 1978
- Then, converted to the first proton-antiproton collider

Stochastic Cooling

- Is a collider of proton and antiproton possible?
- Antiproton does not naturally exist
- Must be created by accelerator
- Anti-protons can be produced by accelerators >> GeV, but the anti-proton beam is too big (low density)
- “Cooling” is needed for using it in colliders
- Cooling method (stochastic cooling) invented in 1968 by Simon van der Meer
- At CERN
  - ✓ Antiproton beam was cooled and accumulated in AA (Antiproton Accumulator) and transferred to S
  - ✓ SPS → Spp^{bar} S
  - ✓ The first p p^{bar} collision in 1981
  - ✓ Discovery of W^{+-}, Z^0 in 1983

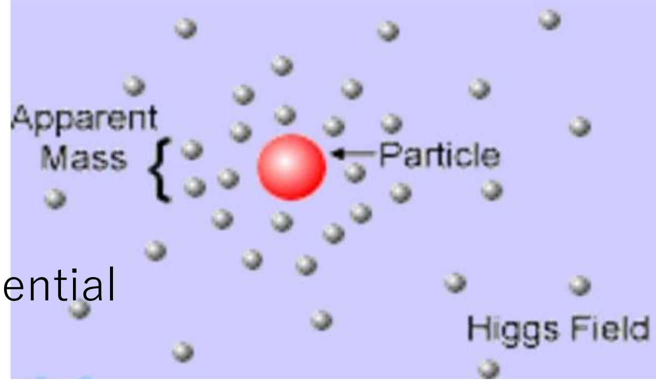
Concept of Stochastic Cooling

- Repeat the following process
  1. Measure the average beam position of the slices
  2. Kick each slice so that the center-of-mass comes to zero
  3. Shuffle the particles (actually, synchrotron oscillation)
- Average position approaches zero
- Speed proportional to $1/N$
  - ✓ N: number of particles in a slice
  - ✓ No cooling if N=infinite

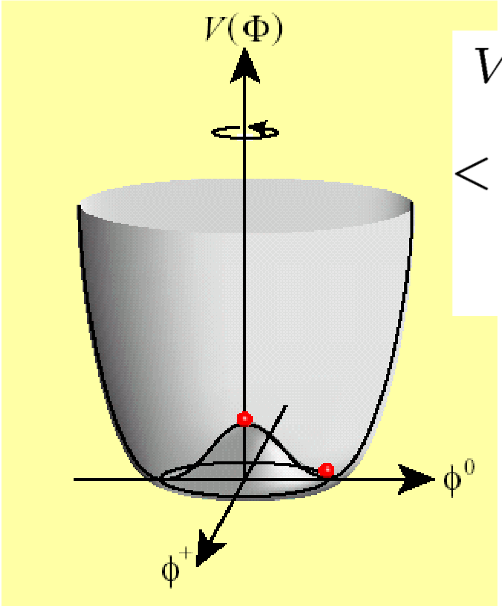


Higgs Particle

- Nambu-Goldstone Model
- Higgs mechanism
  - ✓ Application of Nambu-Goldstone theory
  - ✓ Start with zero-mass particles with symmetry
  - ✓ Spontaneous symmetry breaking due to Higgs potential
  - ✓ All particles coupled to Higgs acquire mass
  - ✓ Applied to Weinberg-Salam theory



- Higgs particle: the only particle that had not been discovered in the Standard Model



$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

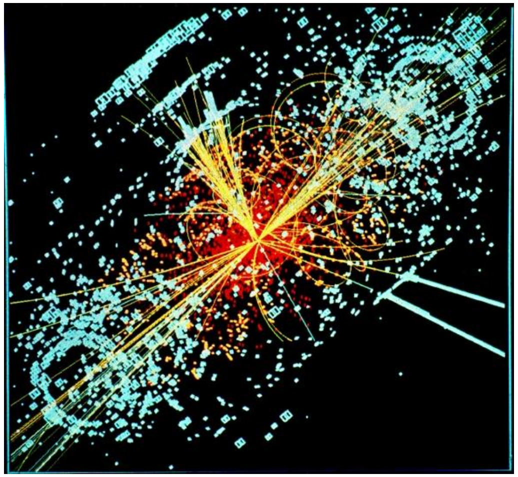
$$<\phi> = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

$$M_H = 2\lambda v^2$$

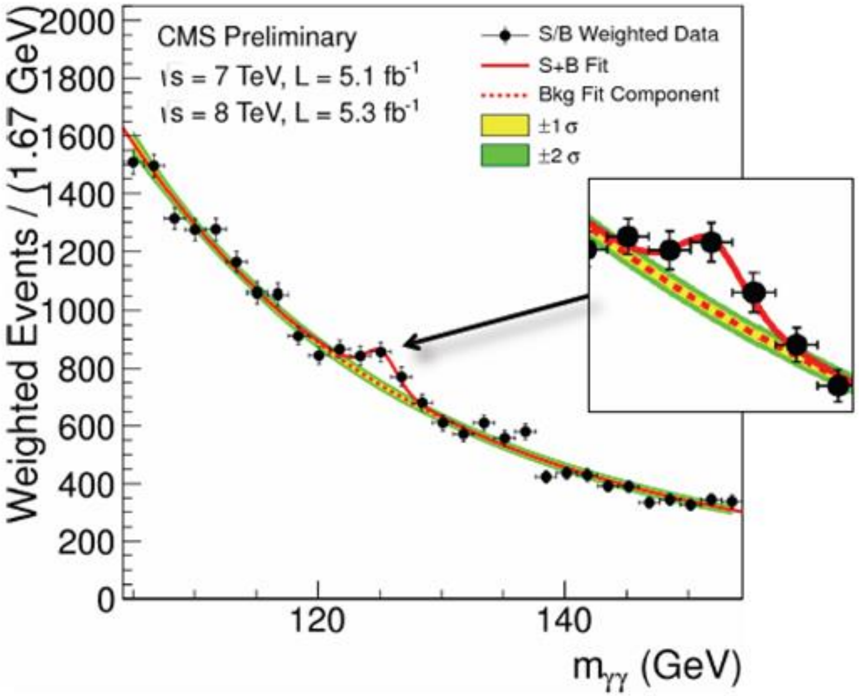
Y. Nambu

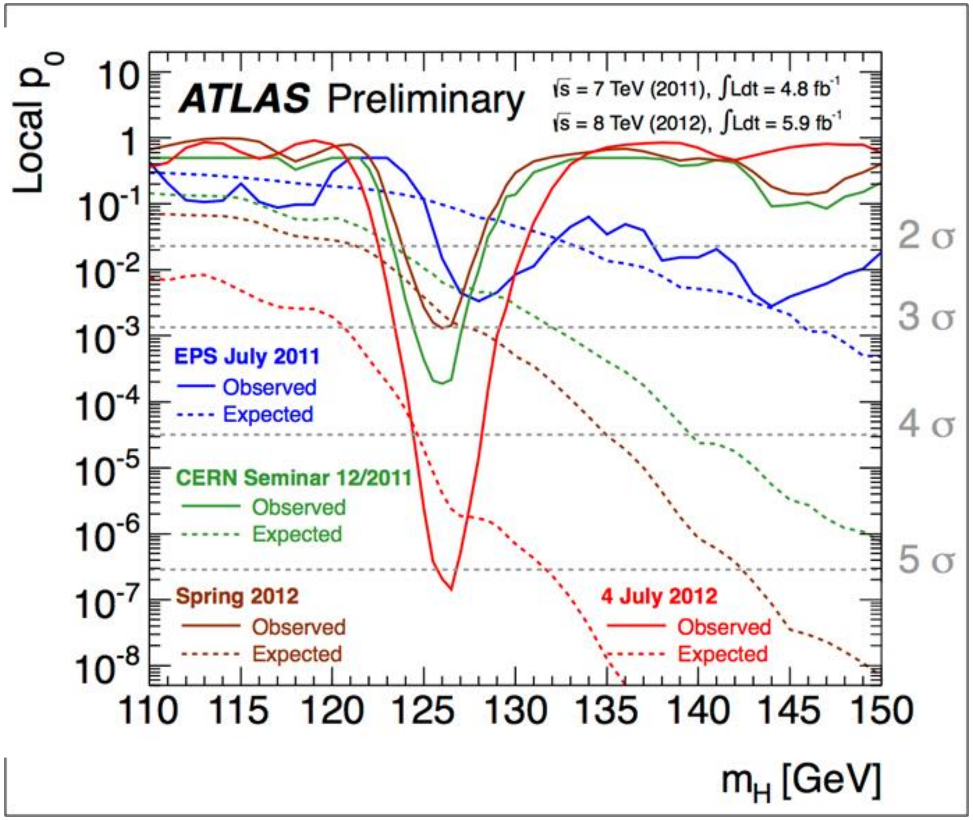
P. Higgs

Discovery of "Higgs"



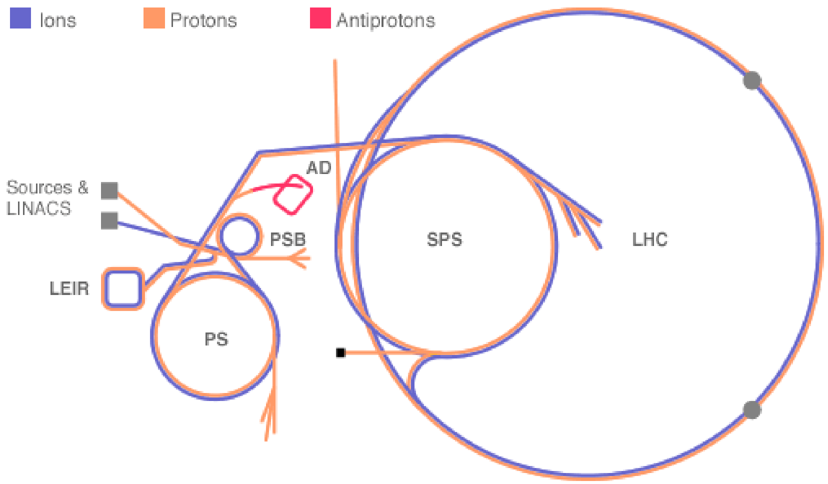
- Announced on Jul.4, 2012
- ~125GeV

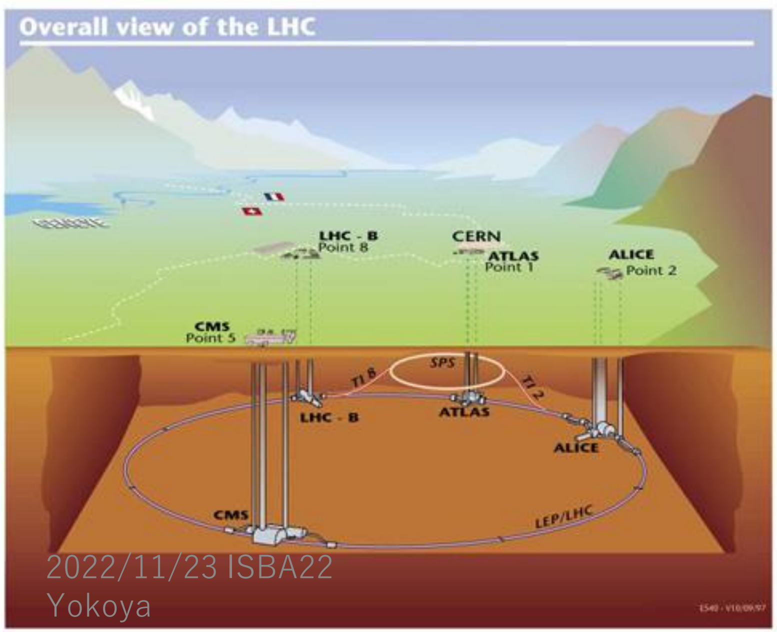


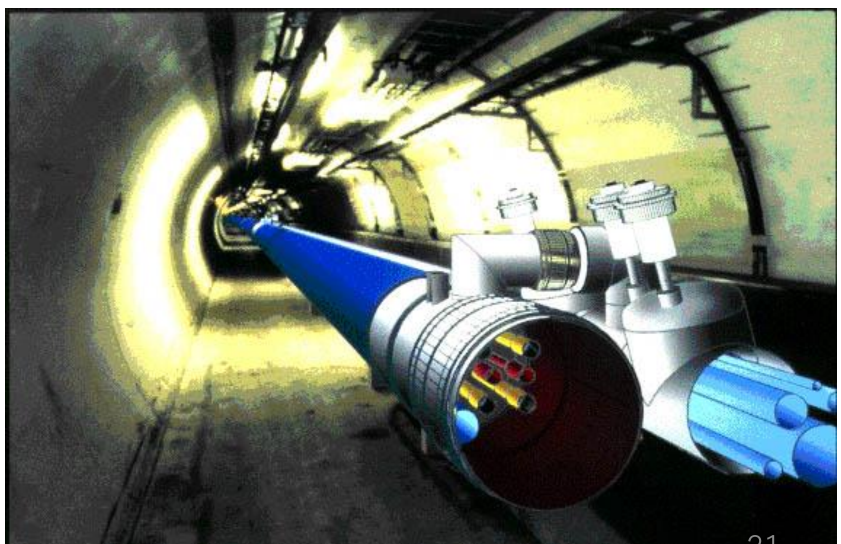


Huge Colliders Era (continued)

- LHC
- Recycle of LEP tunnel
- 14TeV proton-proton
- Discovered Higgs particle in 2012



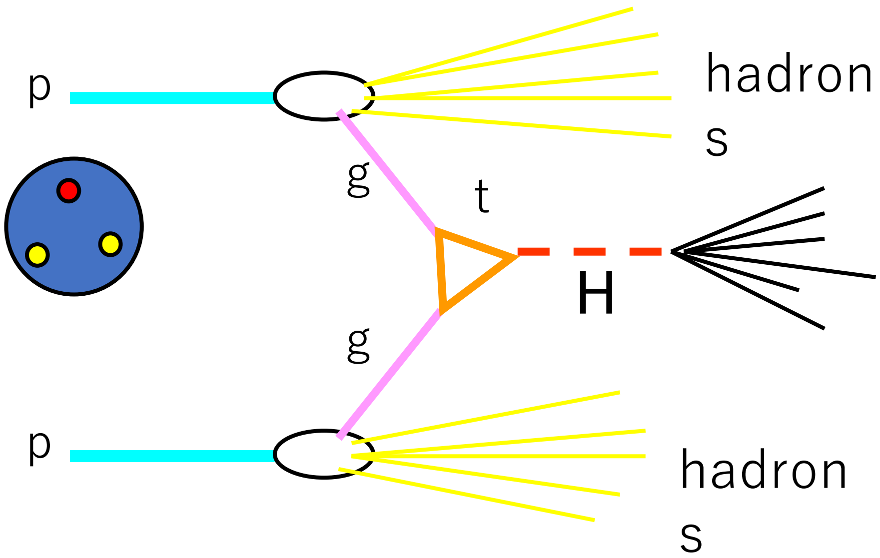


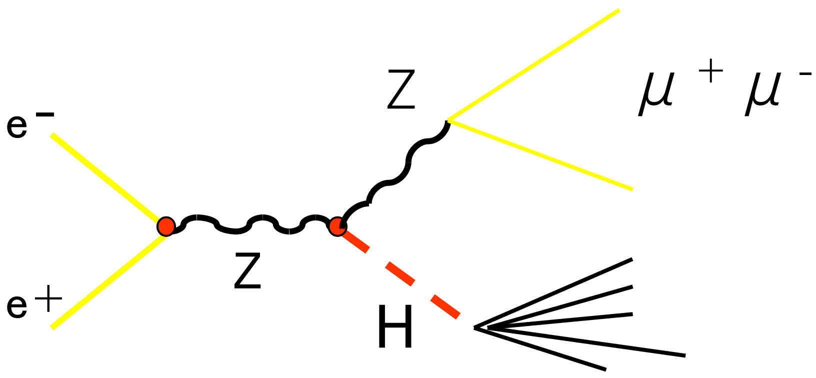


http://athome.web.cern.ch/athome/LHC/lhc.html

LHC is not the End

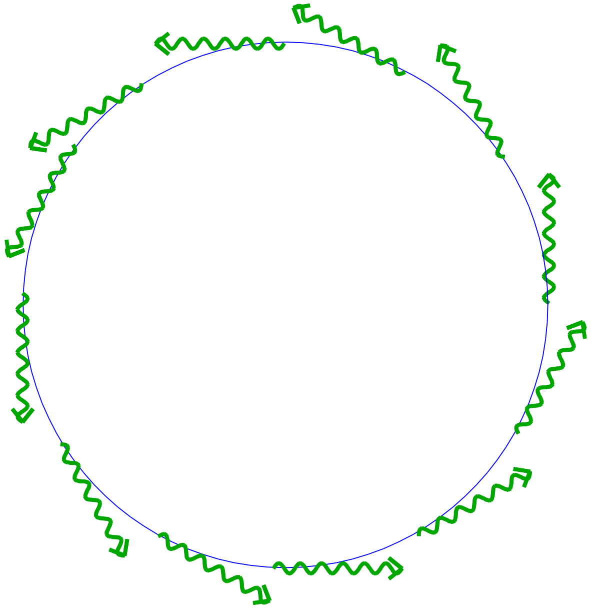
- LHC discovered Higgs
  - ✓LHC is a proton collider
  - ✓Protons are easier to accelerate to high energies
  - ✓But the collision is complex due to the complexity of proton
- On the other hand, e+e- collider is:
  - ✓Particle structure is simple
  - ✓Better for probing particle properties
  - ✓e+e- colliders are useful for precision measurement





Limitation of Circular Accelerator

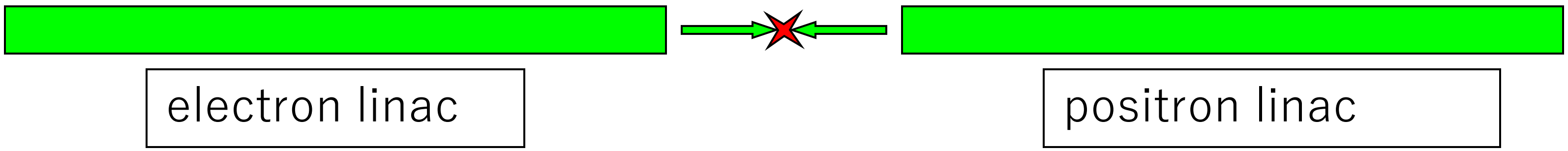
- High energy electron (positron) in a circular orbit emits photons (synchrotron radiation) in forward direction and loses energy
- Energy loss in one second is proportional to E^4 / ρ^2



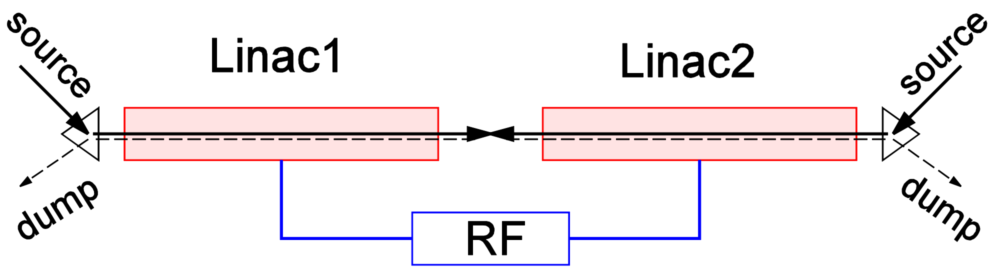
- This is useful for some purposes
  - Use synchrotron light for material physics
- But is a big obstacle for getting high energy electron

Electron-Positron Linear Collider

- To go beyond E_{CM} = 209GeV, linear collider is the natural choice



- Proposal in early 1960's
  - About the same time as the first circular collider AdA
  - Energy recovery was the original concern

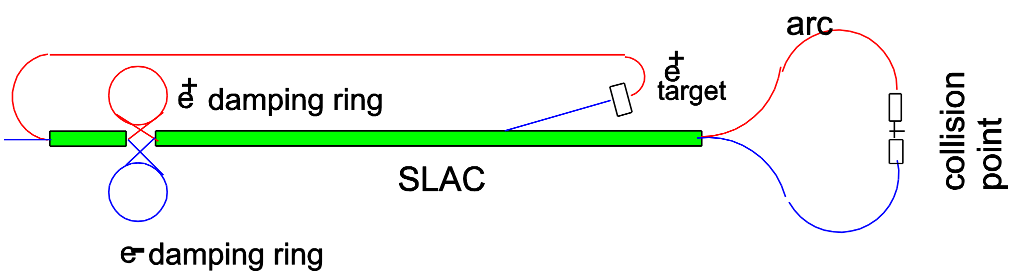


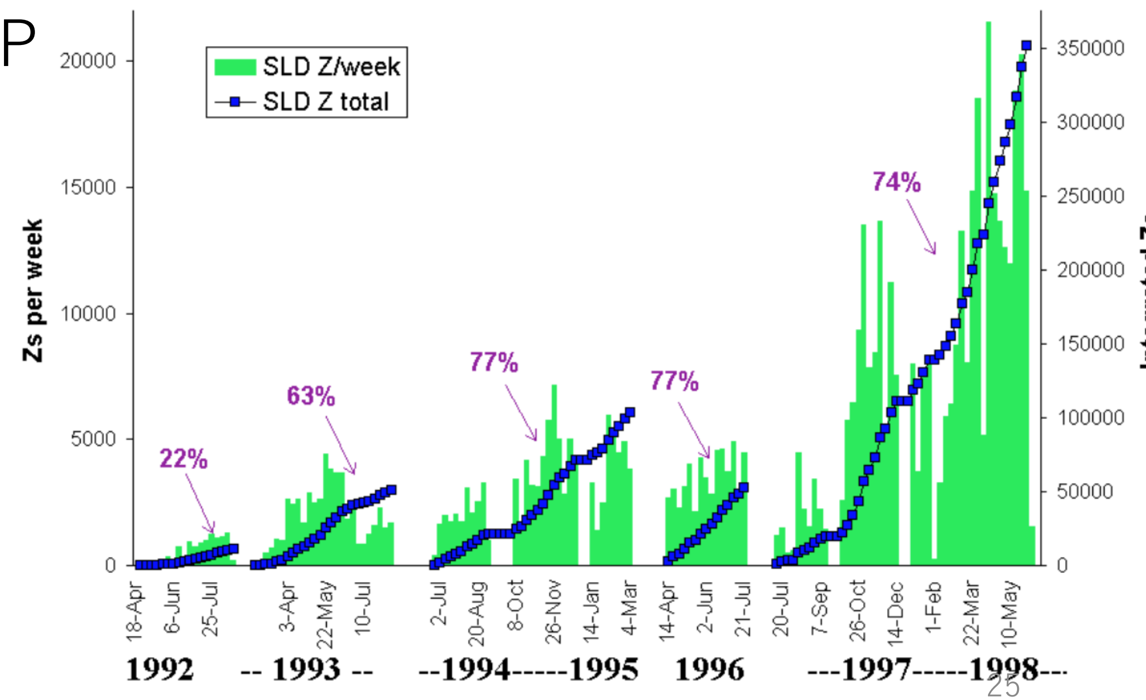
M. Tigner, Nuovo Cimento **37** (1965) 1228

- Note: Linear Collider not needed for proton

SLC : The First Linear Collider

- Single linac
  - ✓ One revolution was possible if up to 46GeV
- Completed in 1987 at SLAC
- First Z^0 event in May 1989
- Competition with LEP
- Polarized electron beam (~80%)
- Finished in 1998
- luminosity 3×10^{30} $/cm^2/s$ (design 6×10^{30})



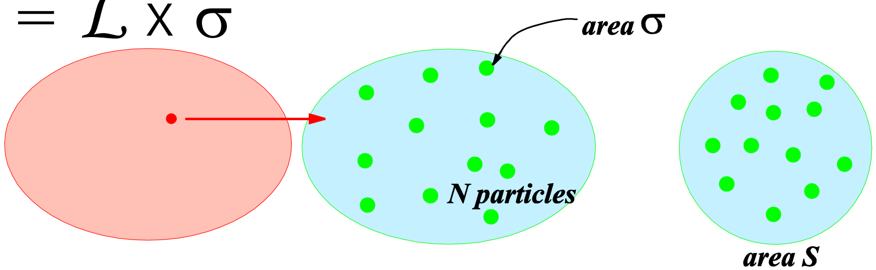


Why LC was not built till 1987 ?

- Difference from Ring collider : single pass
  - ✓Pass accelerating structure only once
  - ✓Beam is thrown away after one collision
- 2 Issues come from this nature of LC
  - ✓High gradient acceleration
    - Total length is decided by the accelerating gradient
  - ✓Fine beam
    - Low collision rate
    - Beam must be focused to a tiny spot at the collision point

Luminosity

- Number of events in unit time = $\mathcal{L}$ x σ
  - ✓ σ comes from physics
  - ✓ $\mathcal{L}$ accelerator parameter



- Luminosity

$$\mathcal{L} = \frac{f_{col} N^2}{\text{beam crosssection}}$$

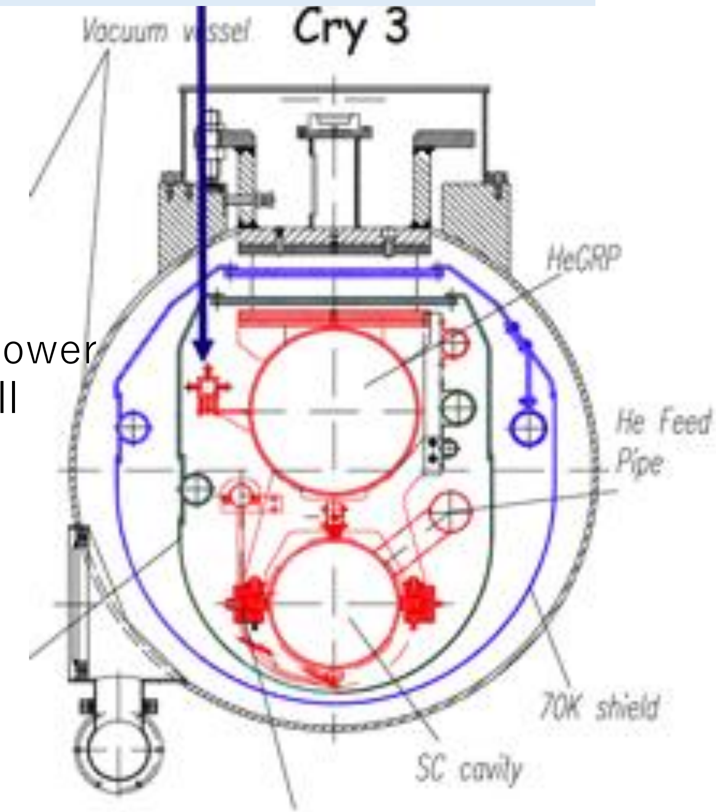
- N: number of particles per bunch
- f_{col} bunch collision frequency
  - ✓ Circular: number of bunches x revolution frequency
  - ✓ Linear: number of bunches x pulse repetition frequency
  - ✓ LC loses factor 100-10000
- To compensate for this difference, LC must squeeze the beam to a tiny spot at the interaction point (IP)

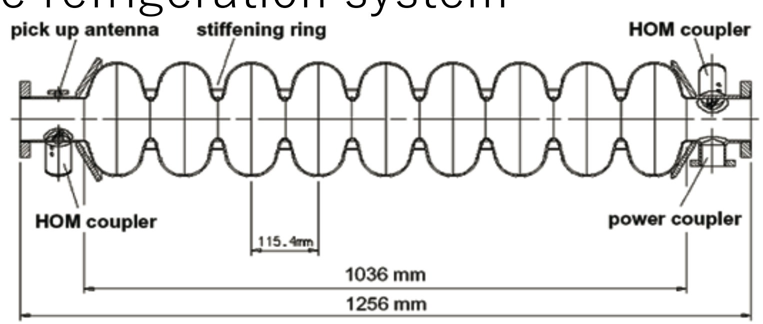
Development of LC Technology

- Serious R&D started in mid 1980's
  - ✓US, Germany, Soviet Union, CERN, Japan
  - ✓Many machine names were born
    NLC, TESLA, VLEPP, CLIC, JLC
- Acceleration method
  - ✓New advanced schemes proposed in early stages
    - Laser grating, inverse FEL, dielectric accelerator, plasma
  - ✓Settled to the conventional microwave method but with improved technologies
  - ✓SCRF, Xband NC, C-band NC, Xband single bunch, two beam
  - ✓R&D's unified to SCRF for the next (after SLC) generation LC in 2004

Advantages of SCRF

- Low loss
  - ✓ The Ohmic energy loss per unit time proportional to $1/Q_0$
  - ✓ $Q_0 \sim 10^{10}$ (SC), 10^4 (NC)
  - ✓ But, keep in mind
    - Pulse length ~ ms (SC), ~μs (NC)
    - To remove 1W of heat, SC required 1kW AC power
    - So, the difference between SC and LC is small (see the next page)
- Long pulse
  - ✓ Easier intra-pulse feedback
  - ✓ Detector deadtime
- Disadvantages of SC
  - ✓ Lower accelerating gradient
    - ~30 MV/m (ILC), ~100 MV/m (CLIC)
  - ✓ Large refrigeration system



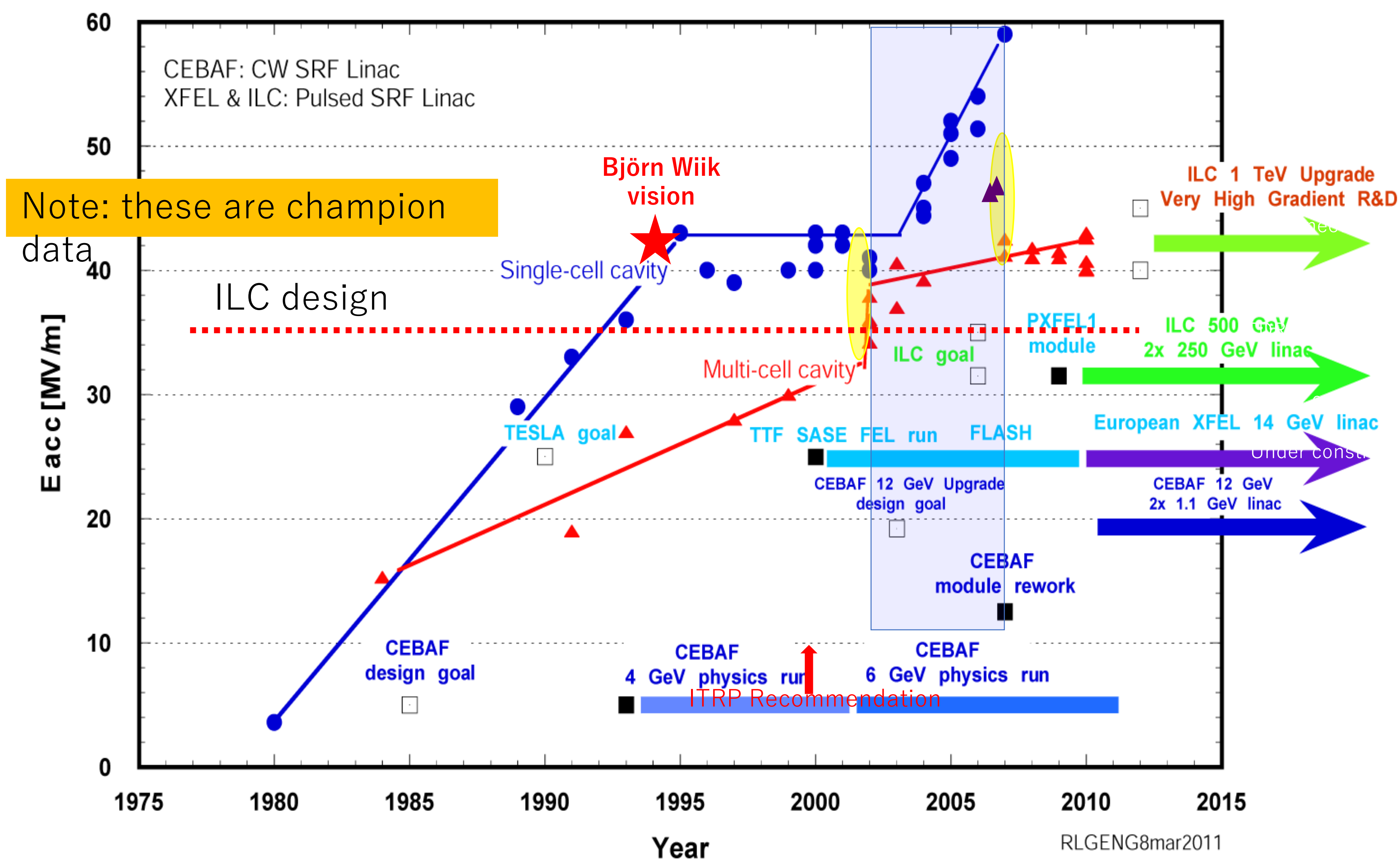


NC vs. SC --- Power Efficifiency

		ILC 500GeV	CLIC 3TeV
Loaded gradient	MV/m	31.5	100
Beam power/beam	MW	5.2	14
Total power consumption	MW	163	582
Beam power/total AC power	%	6.4	4.8
Main linac power efficiency*)	%	12	6

- *) = beam power gain / AC power for main linac
  - Including cryogenics (ILC), drive linac and drive beam manipulation (CLIC), linac magnets,
  - Not including AC high power line

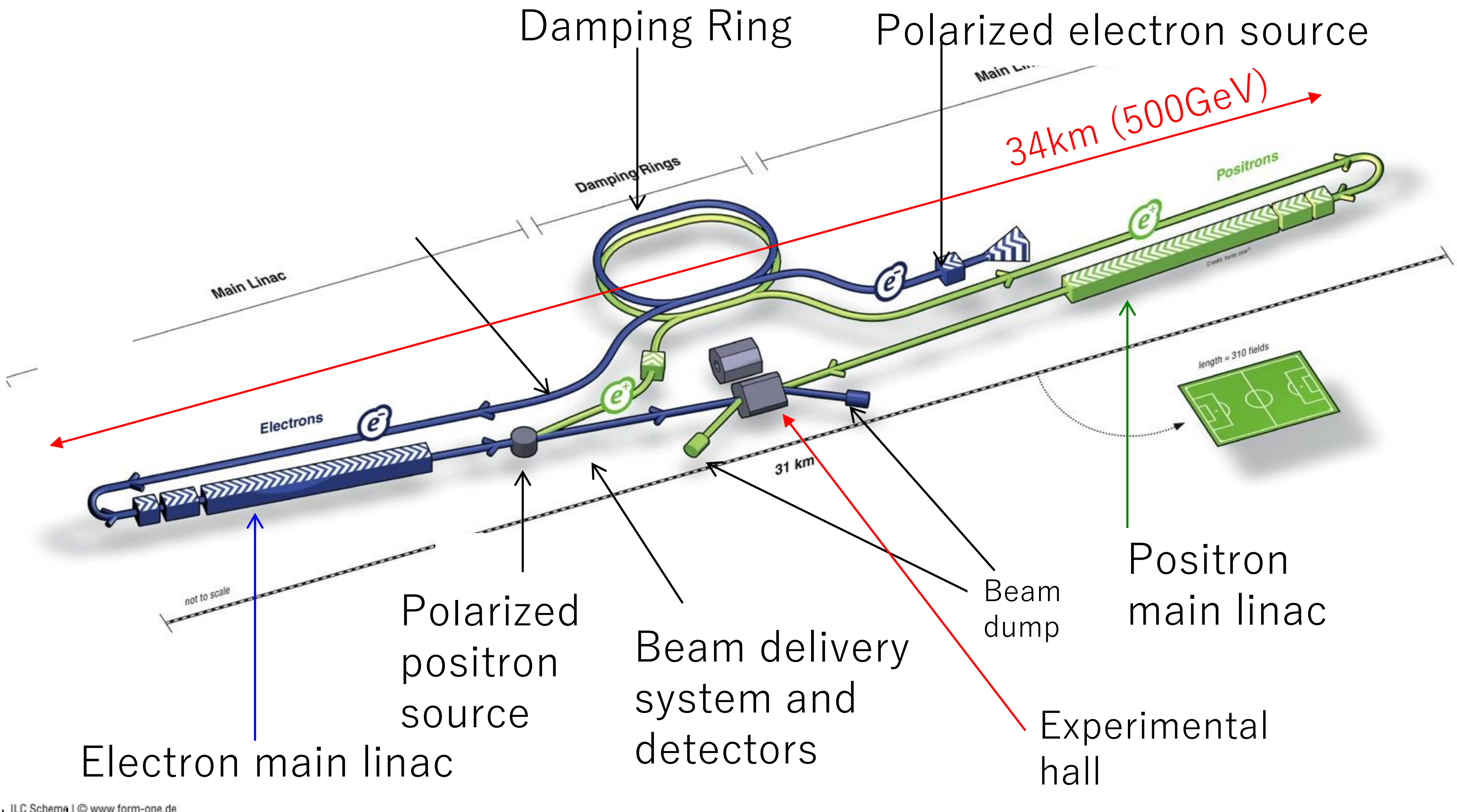
History of Gradient of SCRF Cavities



ILC

- e+e- linear collider using superconducting acceleration technology
- Start with E_{CM}=250GeV, to be later upgraded to 500GeV/1TeV
  - ✓Site length ~20km（~30km for 500GeV, ~50km for 1TeV）
- Average accelerating gradient 31.5MV/m
  - ✓Site length for E_{CM}=500GeV is ~30km
  - ✓Now under R&D for higher gradient
    - Even to 2-3 TeV?
- I will not describe it in detail
  - ✓You will hear many times in this school
  - ✓In particular, Kuriki san’s lecture

ILC Layout



not to scale