Future Colliders

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Lectures aims

- High energy physics
  - Particle physics reasons for perusing higher energies
  - Relationship between hadron and lepton colliders
- High energy acceleration
  - Luminosity
  - Limits on energy, luminosity, particle production
  - How these limits relate to existing and proposed colliding facilities

Physics of colliders

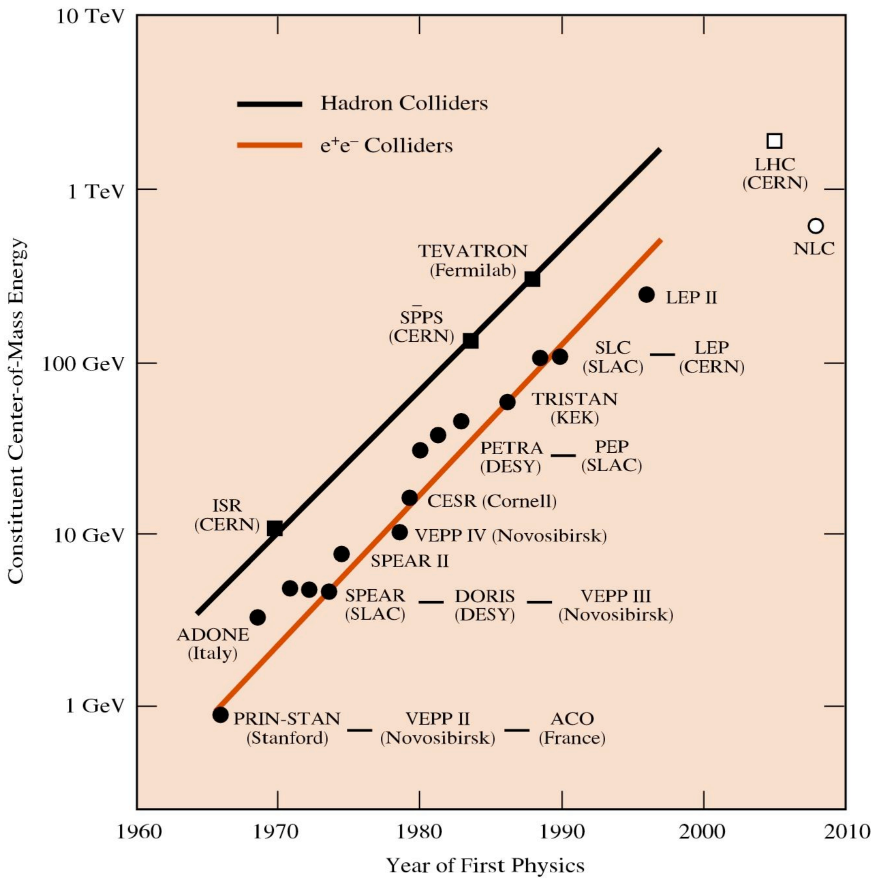
- Particle accelerators immensely powerful tools for understanding the standard model
- Long history of colliding beam experiments
- Review history and future possibilities are examined in this lecture
- Quick review of the particle physics (there is no point building a future facility if there is no physics)
- Technical challenges, limitations
- More sociological and financial challenges

Why accelerators?

- Prepare collisions using accelerator system
- Definite knowledge of particle species, energy and luminosity
- Other considerations
  - Polarisation
  - Lifetime
  - Radiation

Accelerator development

- Long history of high energy acceleration
  - Proton-(anti-)Proton
  - Electron-Positron
  - Electron-hadron
- Exponential increase in beam energy (Moore's law)

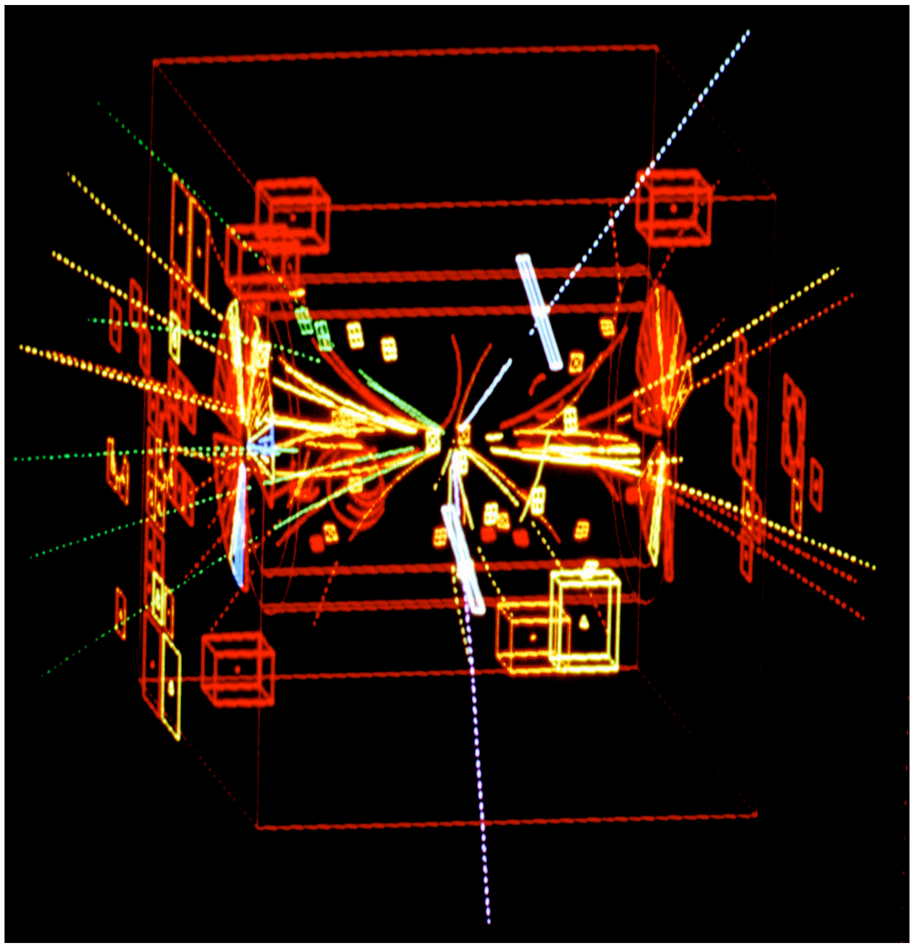


Hadron vs. Lepton colliders

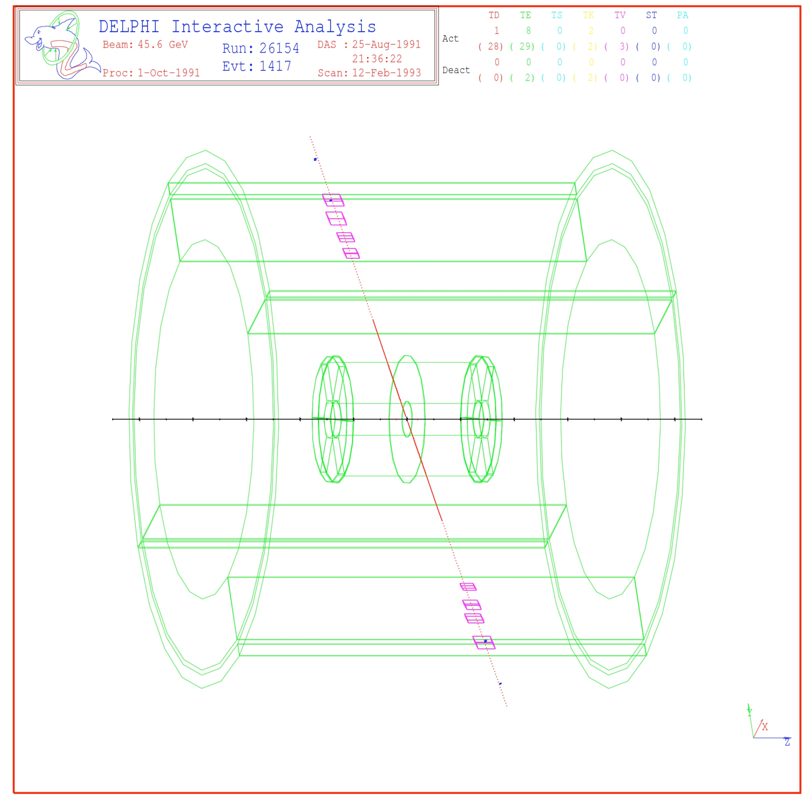
- High energy acceleration has given some of the most powerful insights into constituents of matter and their interactions
  - Strong nuclear force
    - Discovery of gluons at PETRA
  - Electroweak vector bosons
    - Discovery at UA1/2
    - Precision measurement at LEP
  - Top quark and Higgs?

Z^0 discovery and measurement

$$p\bar{p} \rightarrow Z^0 + X$$

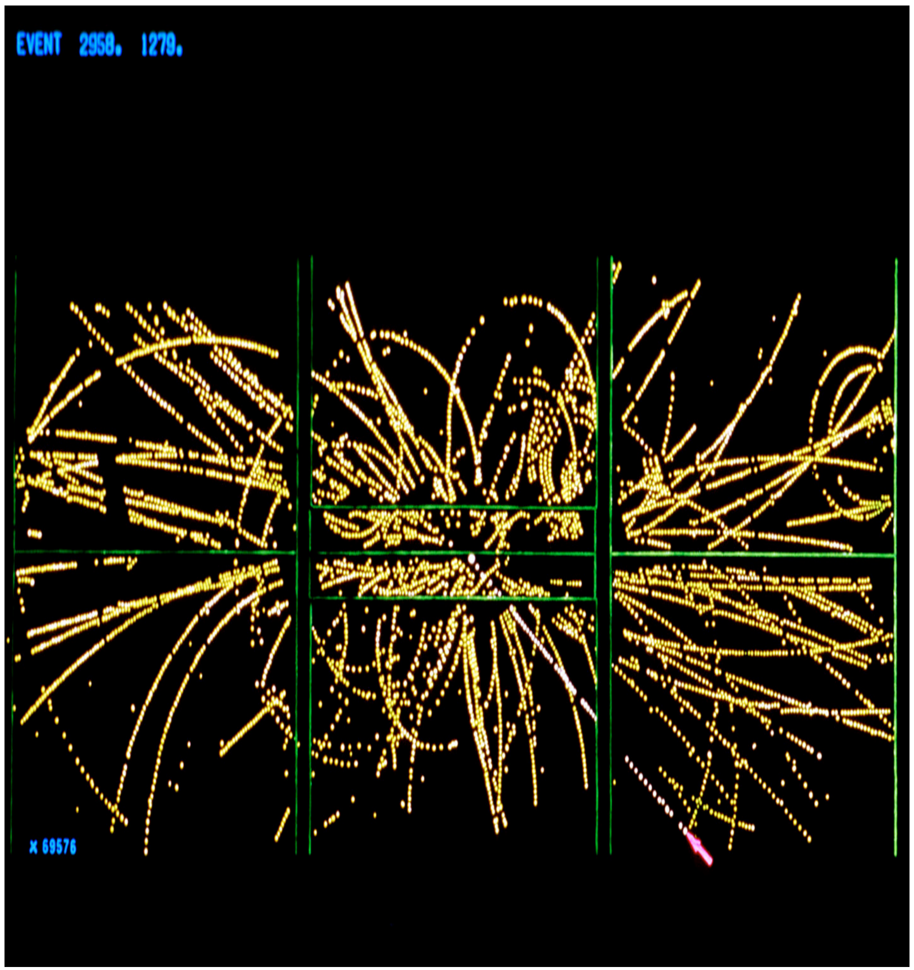


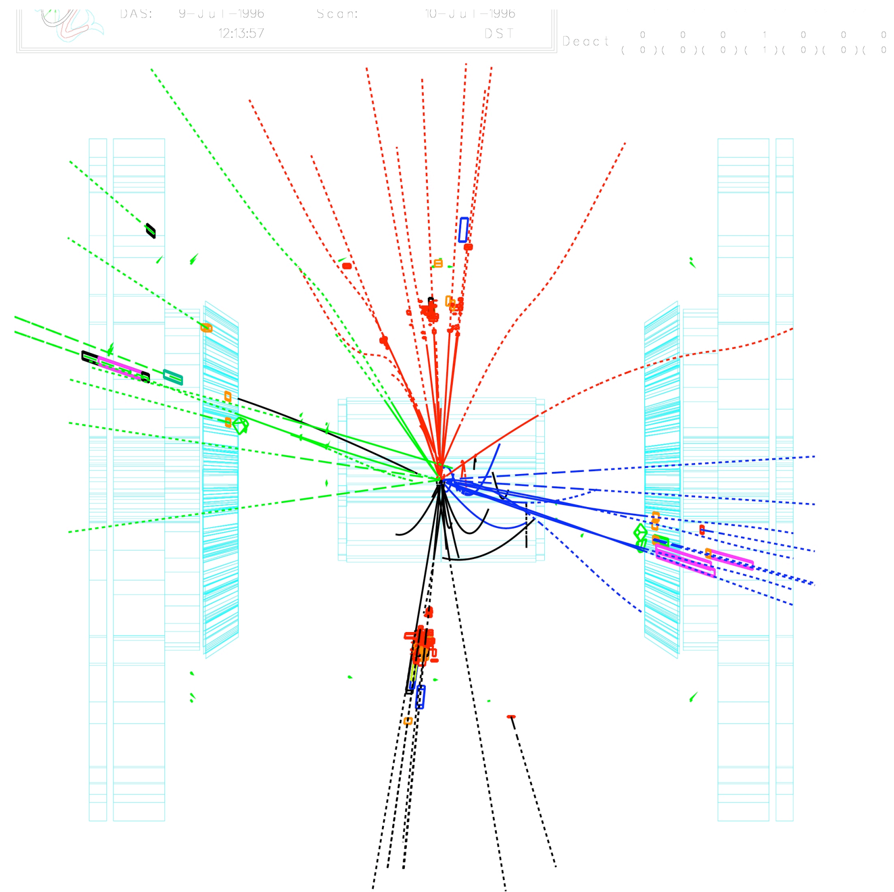
$$e^+e^- \rightarrow Z^*/\gamma \rightarrow \mu^+\mu^-$$



W discovery and measurement

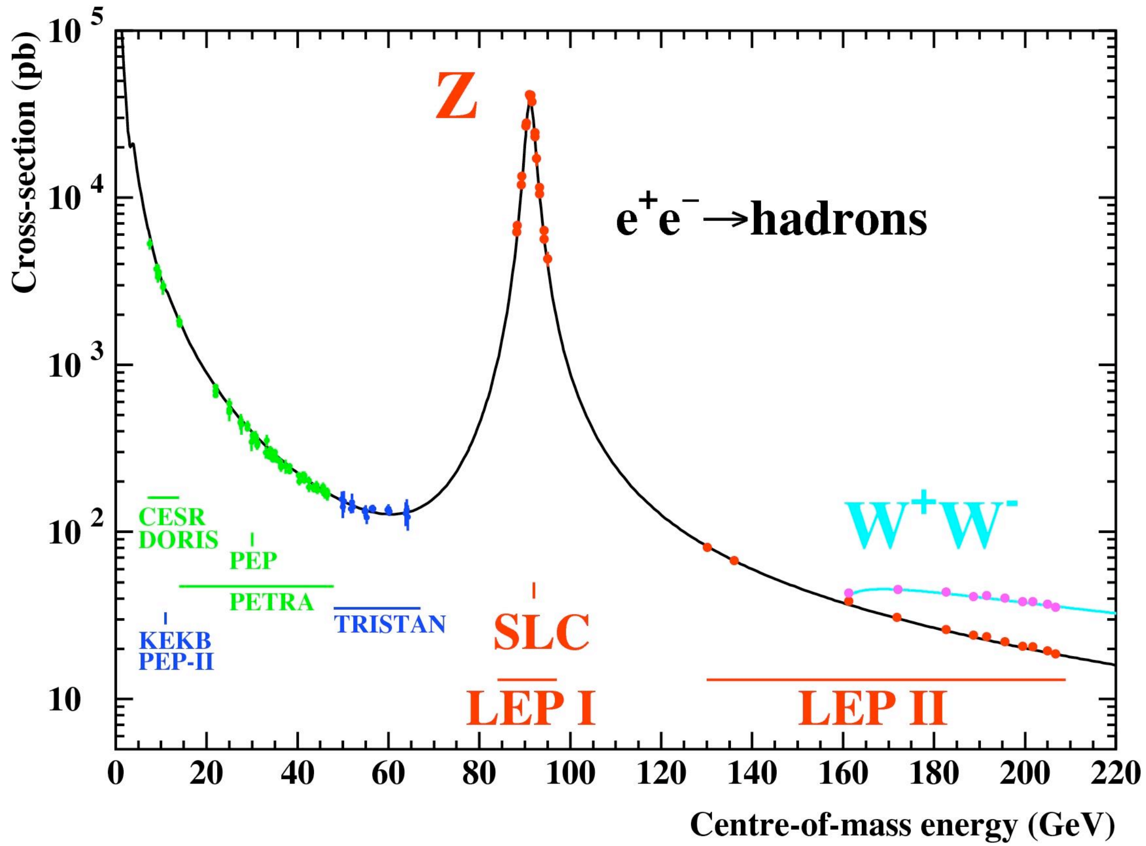
$$p\bar{p} \rightarrow W^{\pm} + X \qquad e^{+}e^{-} \rightarrow W^{+}W^{-} \rightarrow q_1 q_2 + q_3 q_4$$





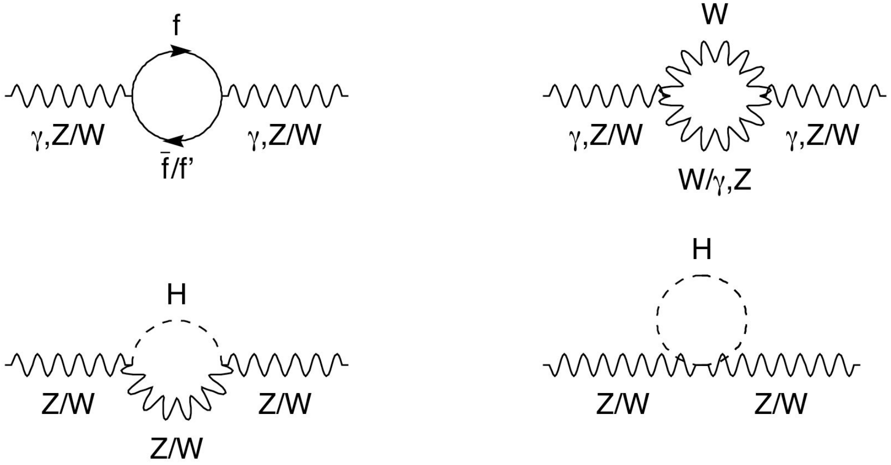
Recent history

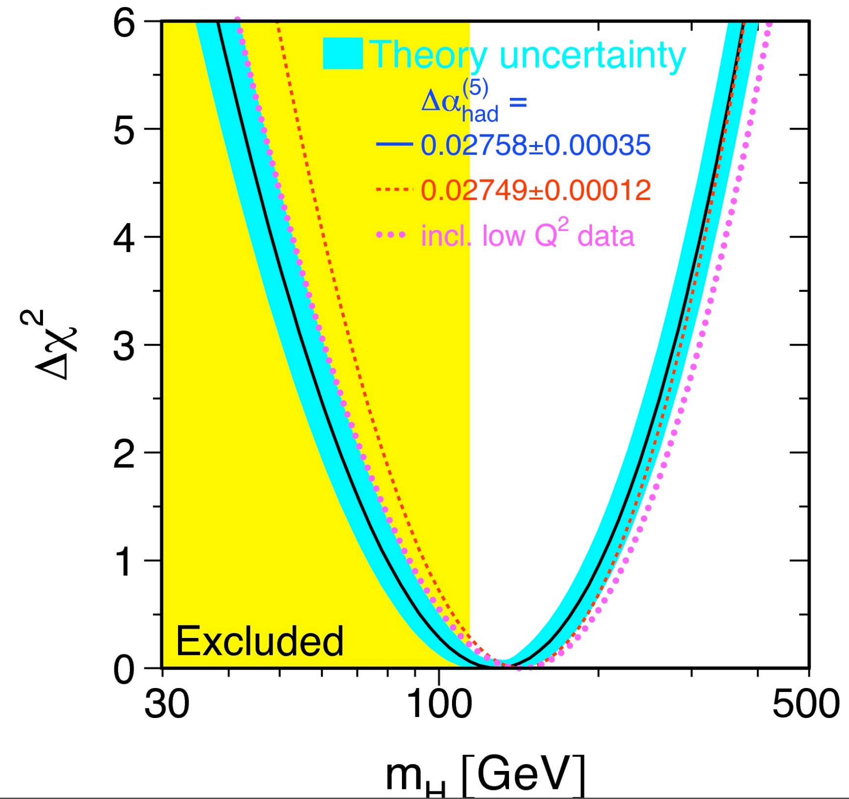
- Pre-LEP
  - Hardronic R-ratio
  - Gluonic jets
- LEP I
  - Z-line shape
- KEP II
  - W threshold



Electro-weak observables

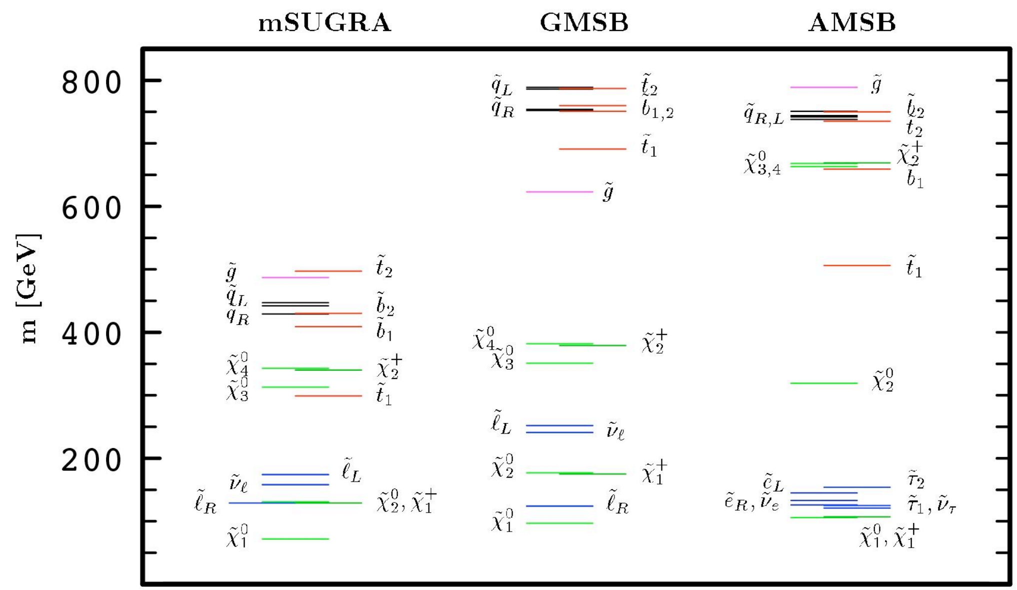
- Higgs not yet observed
  - Precision measurements of the electroweak physics contains a great deal of information
  - Loop corrections to observables
  - Precision electron-positron collisions

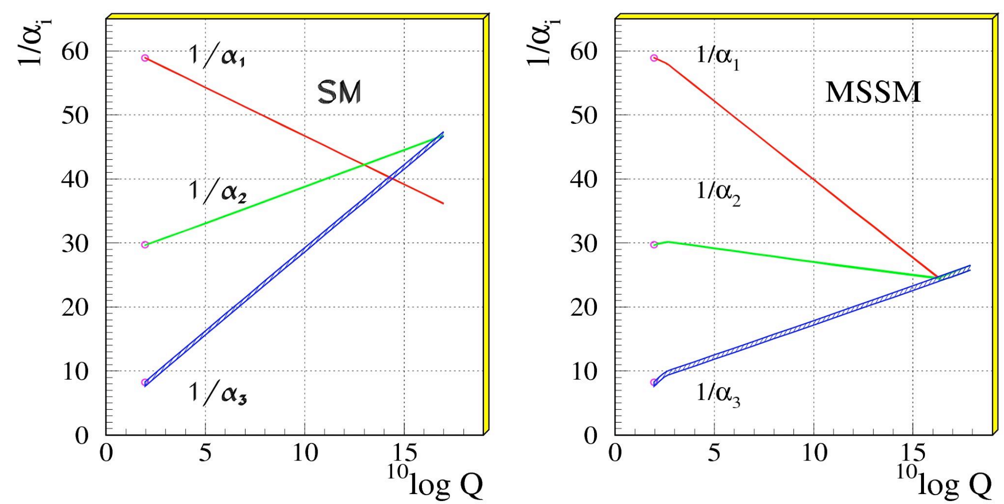




Energy frontier

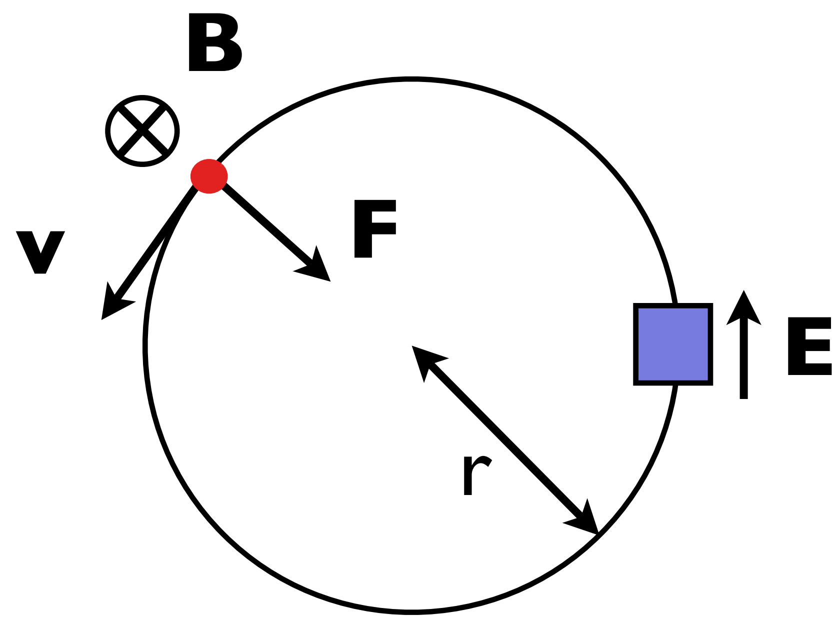
- Why push to higher and higher energies?
  - Standard model is incomplete even with the discovery of Higgs
- Supersymmetry?
- More exotic models
  - Large extra dimensions
  - etc etc...





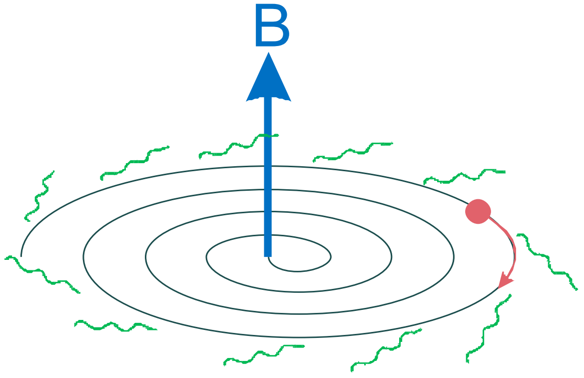
Synchrotrons

- Work horse of modern particle physics
  - Efficient
  - Multiple interaction points
  - Accelerating systems used of each revolution of the accelerator
  - Requires magnetic bending



Limits on synchrotrons

- Why not just build a bigger LEP?
  - Power loss due to synchrotron radiation
  - Energy must be replaced by accelerator
- Higher energies also require higher luminosities



$$P = \frac{1}{4\pi\epsilon_0}\frac{e^2 v^4}{c^3\rho^2}\gamma^4$$

Electron machine

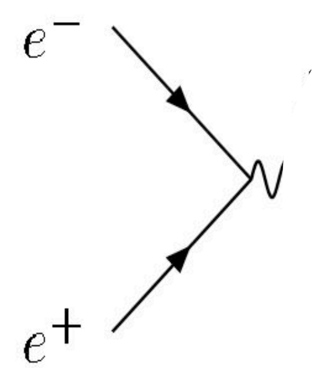
$$W = 8.85 \times 10^{-5} E^4/\rho$$

MeV/turn GeV km

Cross sections (I)

- Standard model course
  - Define the initial state and calculate matrix element then cross section
- More problematic for hadron colliders where the colliding beams are composite objects
  - Parton density functions

Initial state
Species, energy, helicity



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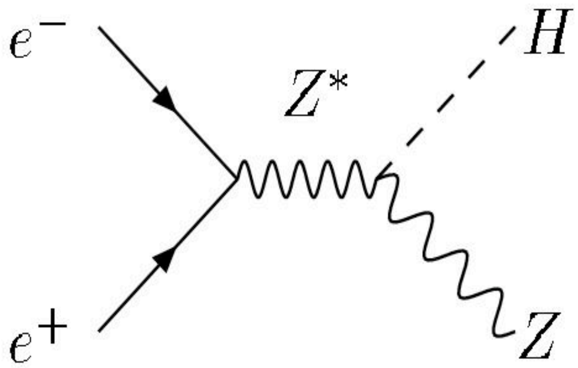


Cross sections (II)

- Consider SM course cross sections
  - In order to probe scales where we need higher energies
  - Higher energies require correspondingly higher luminosity

Cross section

$$\sigma \sim \lambda^2$$

Wavelength

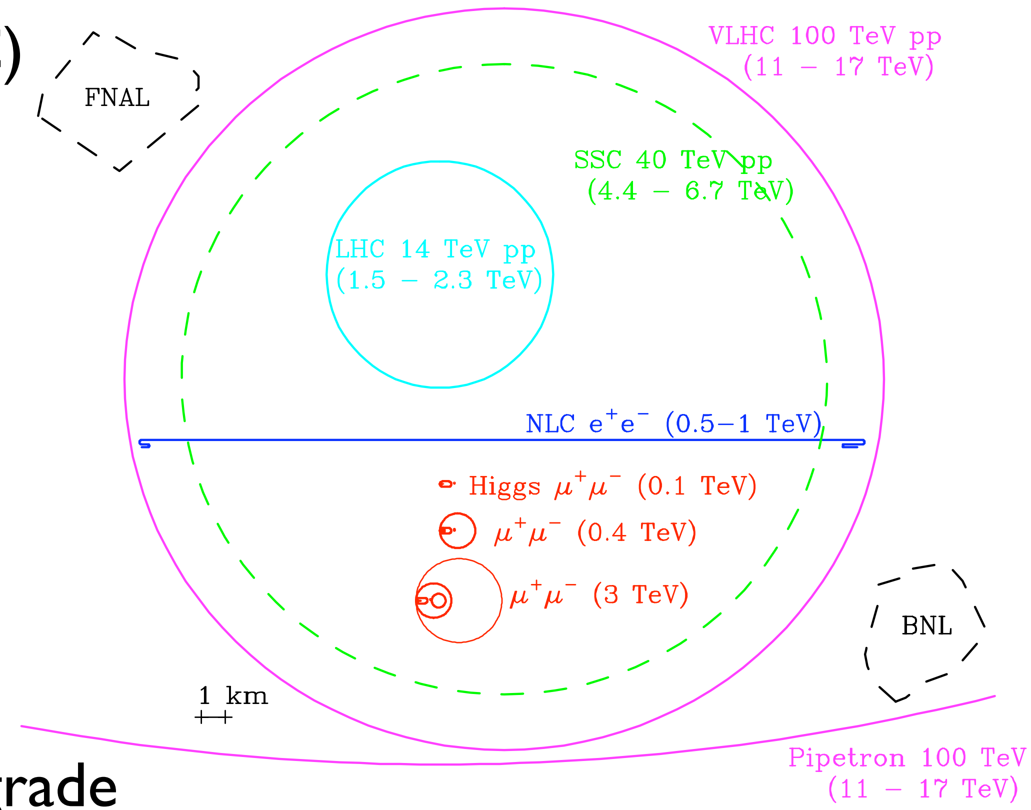
$$E \sim \frac{h}{\lambda}$$

Point-like cross section must scale as

$$\sigma \sim \frac{1}{E^2}$$

Planed facilities

- Linear Collider
  - International Linear Collider (ILC)
  - Compact Linear Collider (CLIC)
- Muon accelerators
  - Muon colliders
  - Neutrino factories
- Hadron colliders
  - Large Hadron collider and its upgrade
  - Very Large Hadron Collider (VLHC)



Designing a machine

- Particle species
  - Electrons/positrons
  - Protons/anti-protons
  - Muons/anti-muons
- Beam energy
- Luminosity

- How does one produce anti-particles?
- Once produced how do you keep them?
- Once you have collided what do you do with the spent beams (ILC), Dumps
- Accelerator and detector protection (LHC)

Luminosity equations

- What luminosity is required for measurement?
  - Require some knowledge of the cross section
  - Integrated luminosity depends on many factors
    - Beam lifetimes

Assuming head on collisions and equal beam sizes

$$\mathcal{L} = f \frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

Rewriting in terms of emittance and beta functions

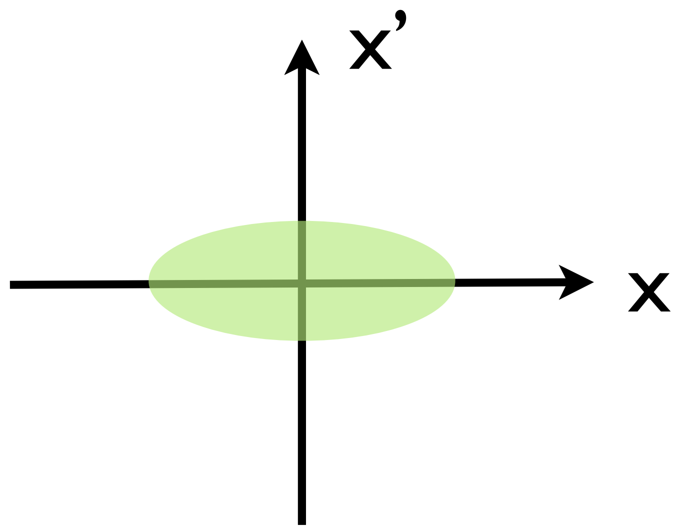
$$\mathcal{L} = f \frac{N_1 N_2}{4\sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

Accelerator aside : Emittance

- Accelerator physics in three slides!
- Emittance is a measure of the spatial properties of a particle beam
  - Essentially the product of the spatial width with the angular width
  - Normalised emittance invariant

position angle

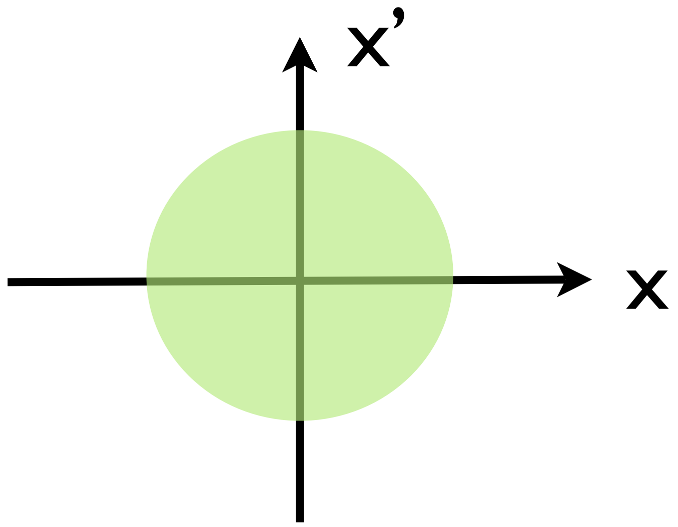
$$\epsilon^2 = \left\langle x^2 \right\rangle \left\langle x'^2 \right\rangle - \left\langle xx' \right\rangle^2$$

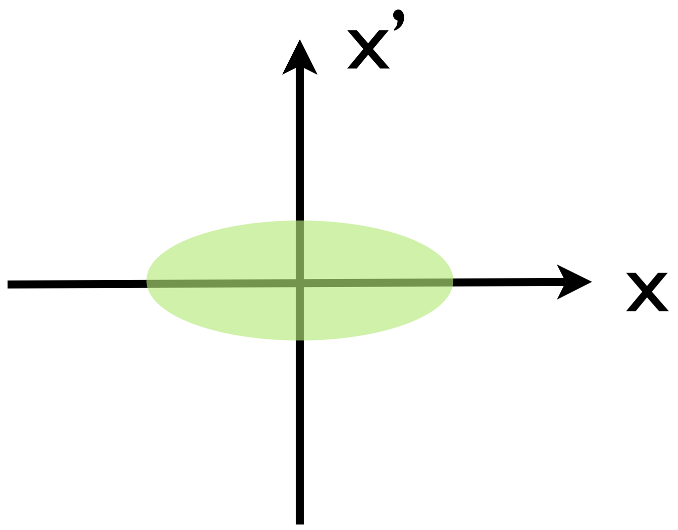


$$\epsilon_N \equiv \epsilon \times \left(\gamma \frac{v}{v} \right)$$

Acceleration

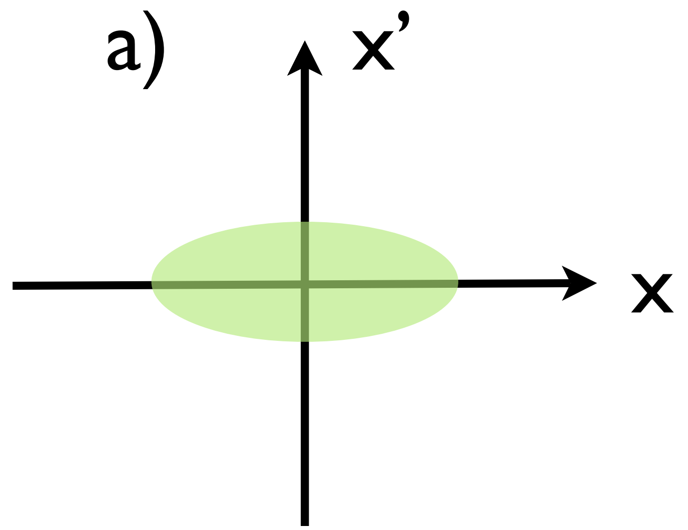
- Accelerating cavities are used to increase the energy of the beam
- The transverse momentum of the particles is not changed but it is increased in the direction of motion
- x’ is reduced

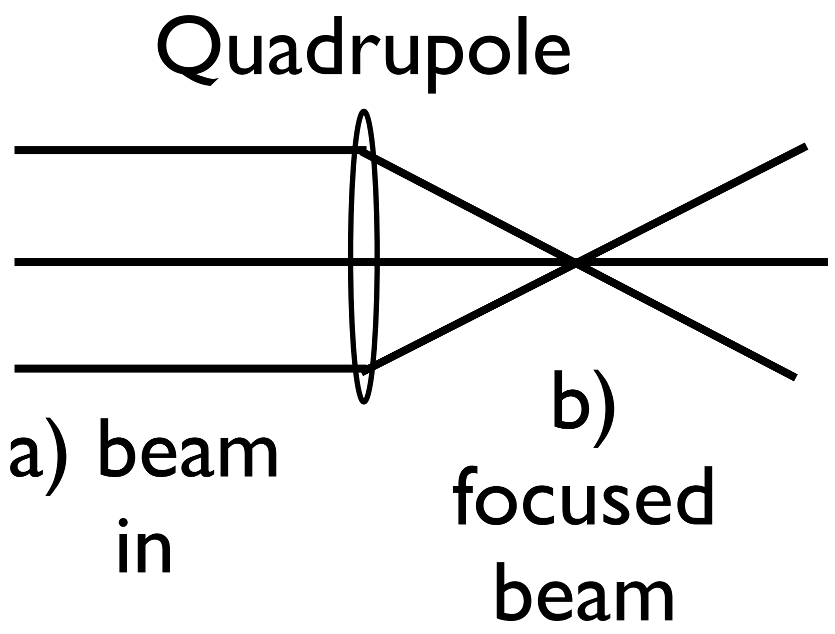


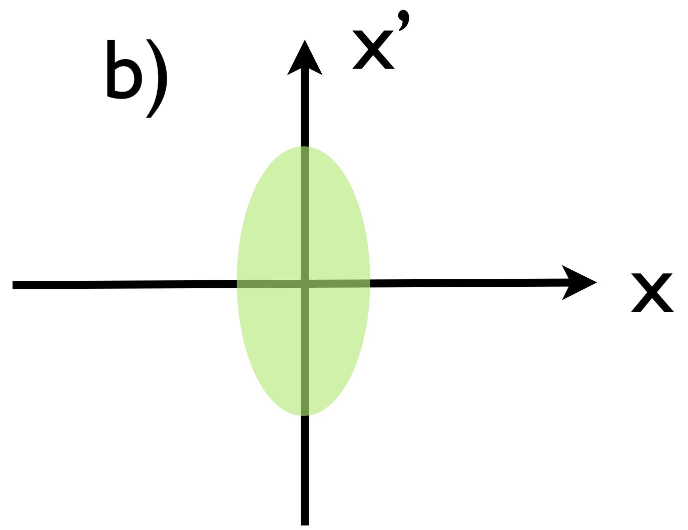


Focusing

- Quadrupole magnets act as lenses
  - Focusing in one axis and defocusing in the other

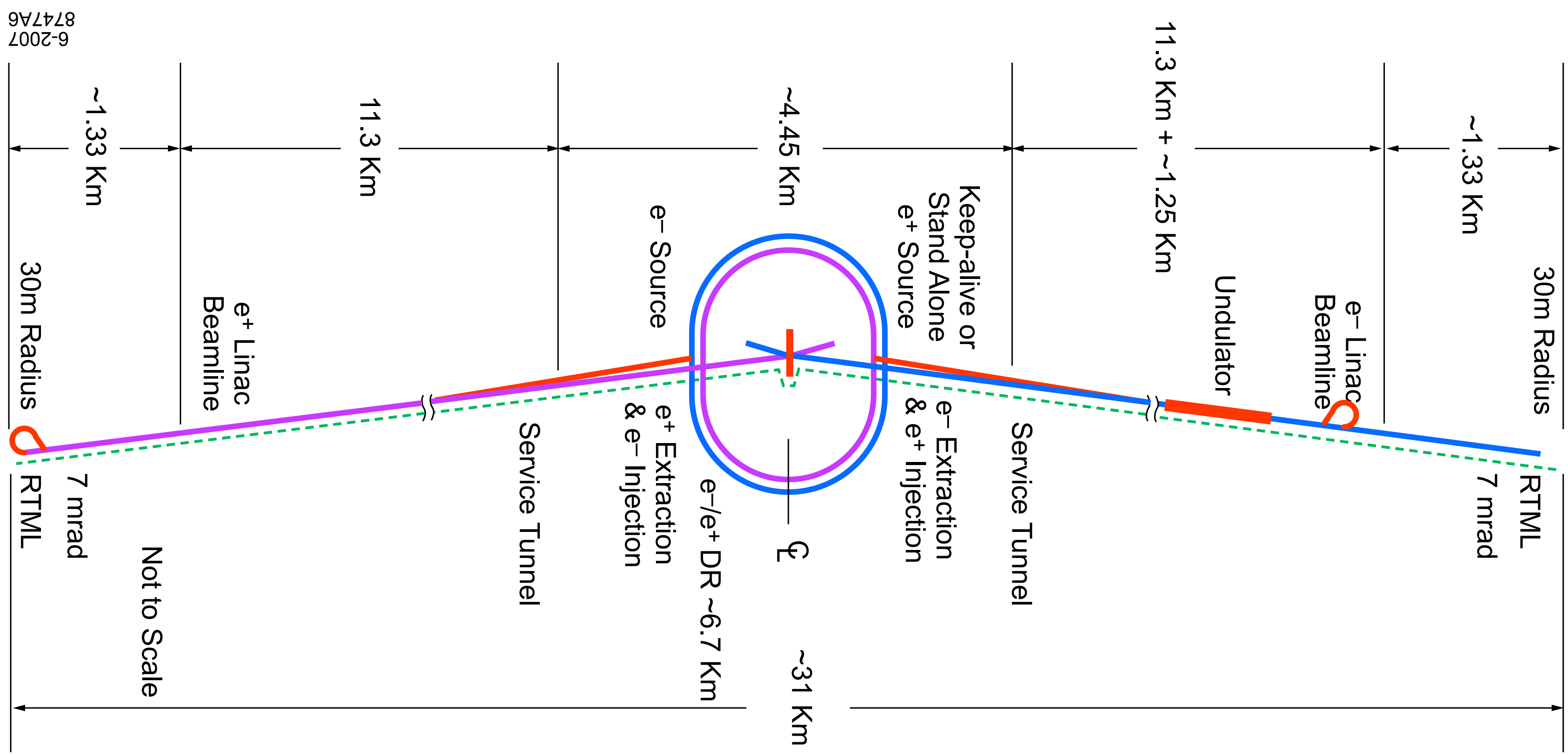






International linear collider ILC

- ILC designed to be a high luminosity e^+e^- collider initially up to 500 GeV then upgradable to 1 TeV
  - Major systems all driven by the requirement for luminosity



International Linear Collider

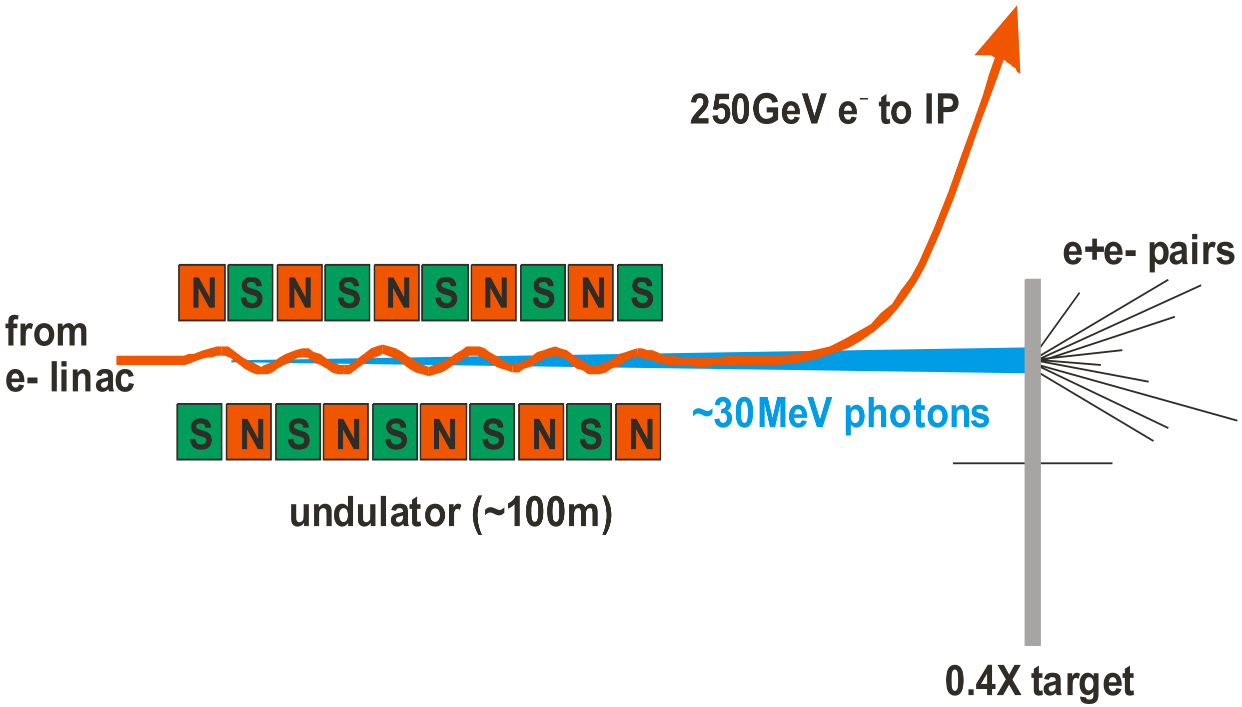
- LEP final energy ~200 GeV
- Note the vertical beam size required
- Not continuous bunches but bunch trains of 2820 bunches at 5 Hz
  - Low emittance beams required
  - High beam powers

Parameter	**Value**
Beam energy	250 to 500 GeV
Bunch density	2×10^{10} e^-
Number of bunches	2820
Bunch spacing	300 ns
Repetition frequency	5 Hz
Beam size y (x)	3.5 (554) nm
Luminosity	2.82 10^{38} $m^{-2}s^{-1}$

Positron production

$$\mathcal{L} = f \frac{N_1 N_2}{4\sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

- Positron production at the ILC will use the high energy electron beam
  - Pass electron beam through undulator
  - 30 MeV photons
  - Thin target generate electron position pairs



Damping of the electron beam

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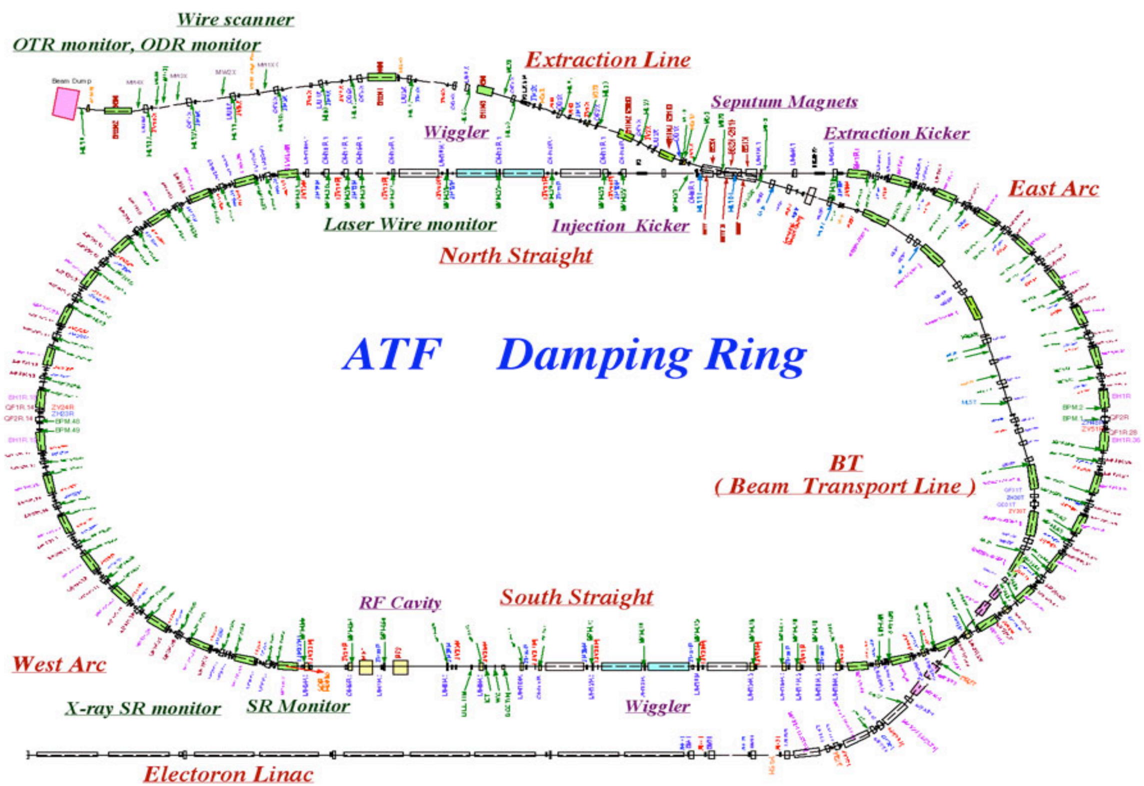
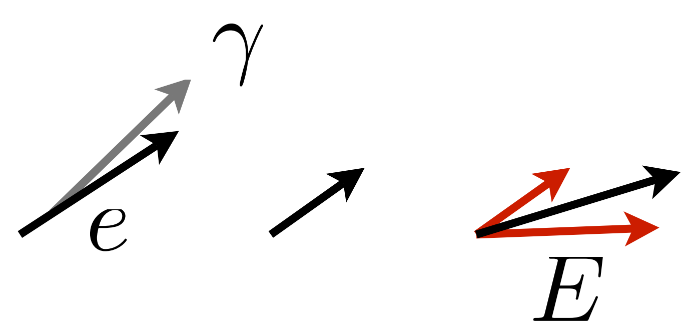


- Ring in which beam is stored for 20 to 200 ms
- To reduce the beam emittance
- Radiation energy loss
  - Longitudinal momentum replaced by accelerator



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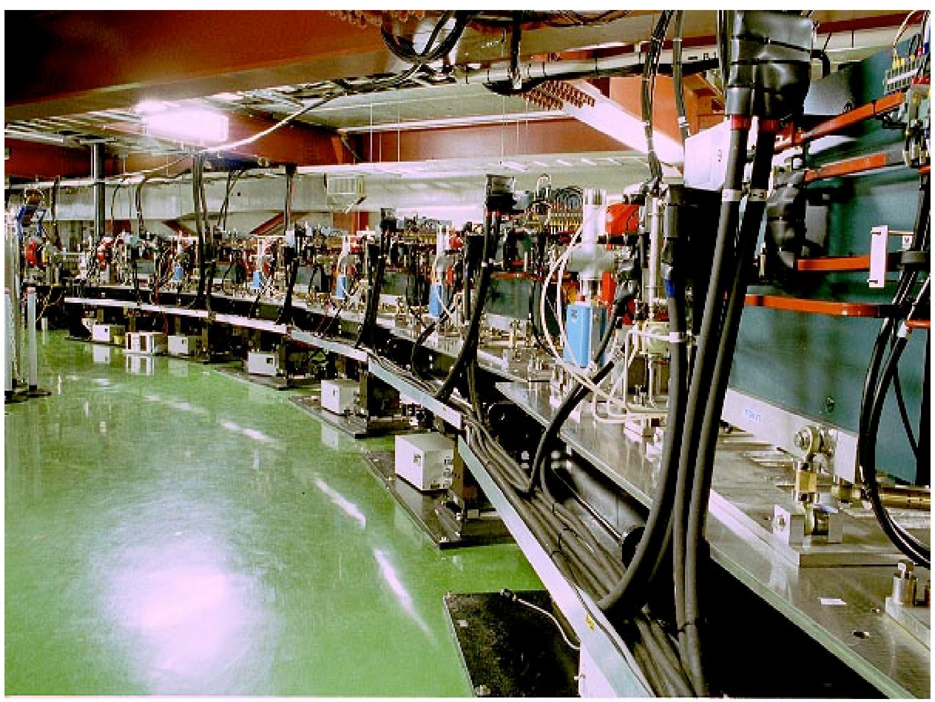

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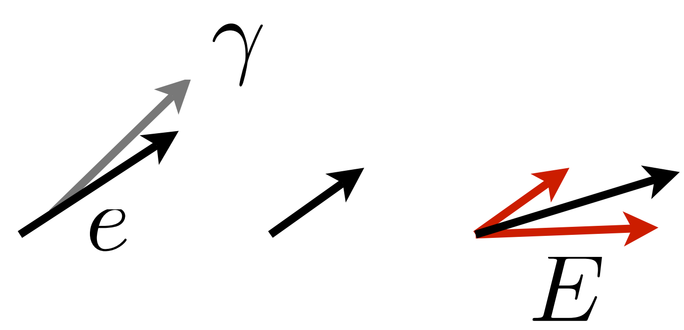
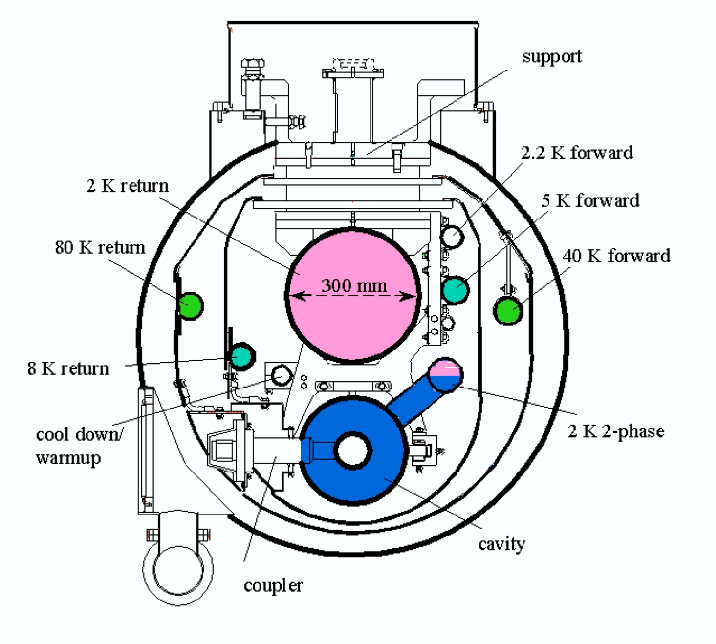


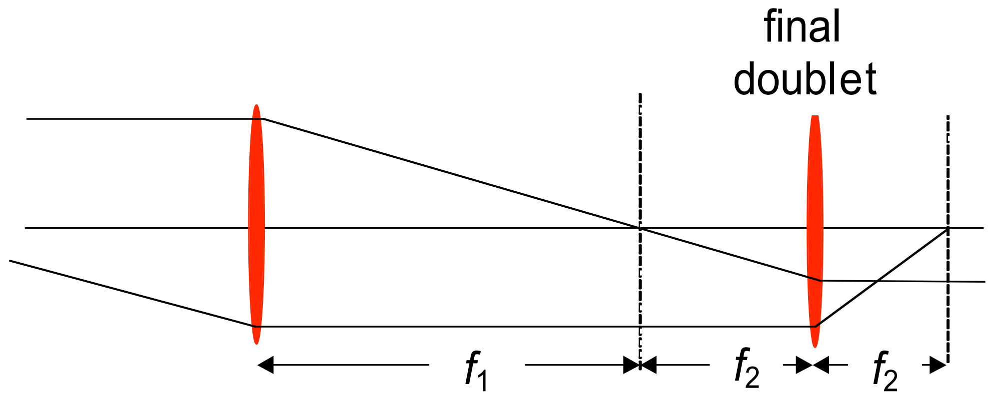
ILC acceleration

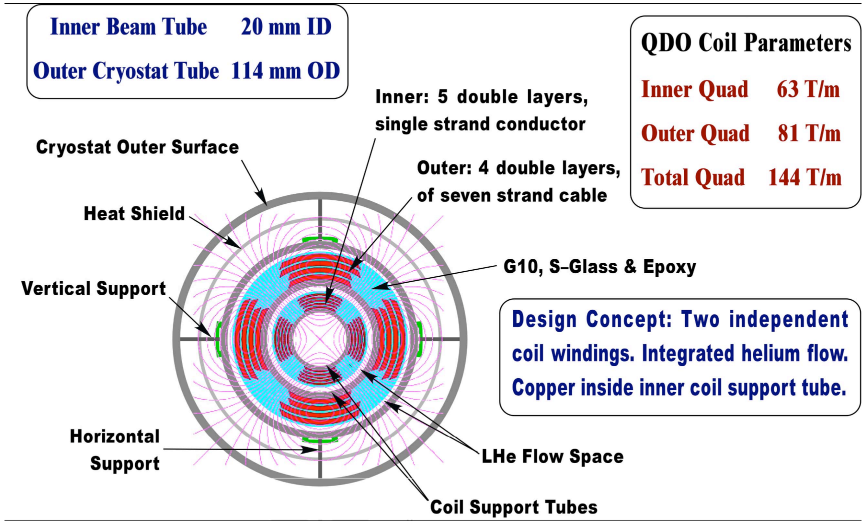


- Pure Niobium cavities
  - 1.2 GHz radio frequency
  - Super conducting at LHe temperatures
  - Require ~35 MeV/m accelerating gradient

Final focus system

- Use telescope to demagnify beam by factor ~300
  - $M = f_1/f_2 = f_1/L^*$
- Set L^*=2 m then f_1=600 m
- Require large magnetic field for final magnet
- Small L^*, magnets inside detector

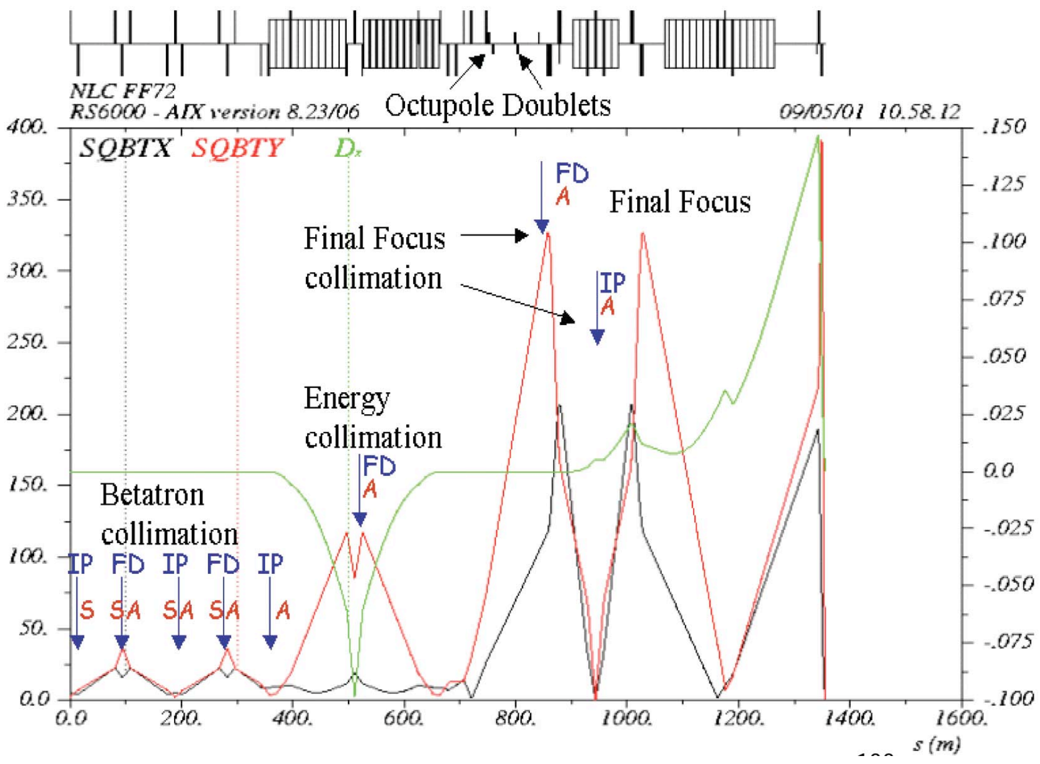




Beam delivery system

$$\mathcal{L} = f \frac{N_1 N_2}{4\sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

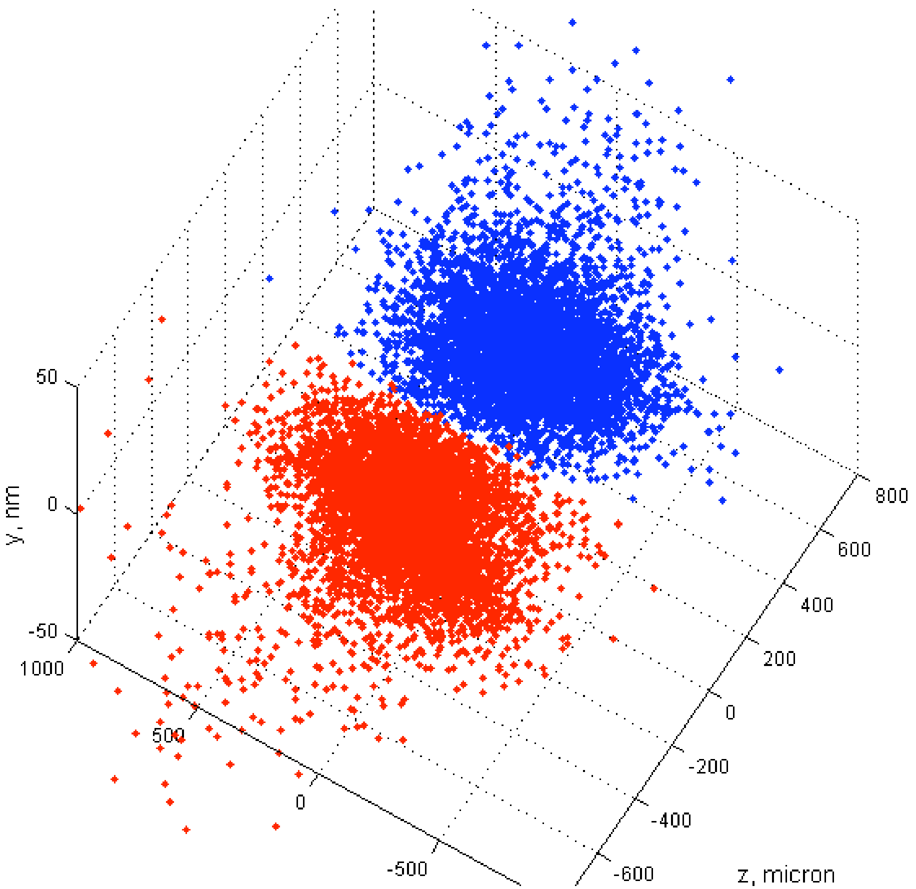
- Beam diagnostics
  - Emittance (transverse and longitudinal)
  - Energy
- Collimation
  - Final focus
- Corrections
  - Chromatic/geometric



Beam-beam interaction

$$\mathcal{L} = N_b f \frac{N_1 N_2}{4\pi\sigma_x\sigma_y} H_D$$

- 5 nm beam size causes some serious problems
  - Strong mutual bunch focusing
  - Radiation from strong opposing bunch fields (beamstrahlung)
  - Pair production, interaction of the radiation with field (pairs)



Luminosity equations

- Can rewrite luminosity equation in many different ways
  - Consider the total beam power
- What is the total beam power given ILC parameters?

Recall equation for luminosity

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$$\begin{aligned} P_{beam} &= f E N_b N_1 \\ &= \eta P_{grid} \end{aligned}$$

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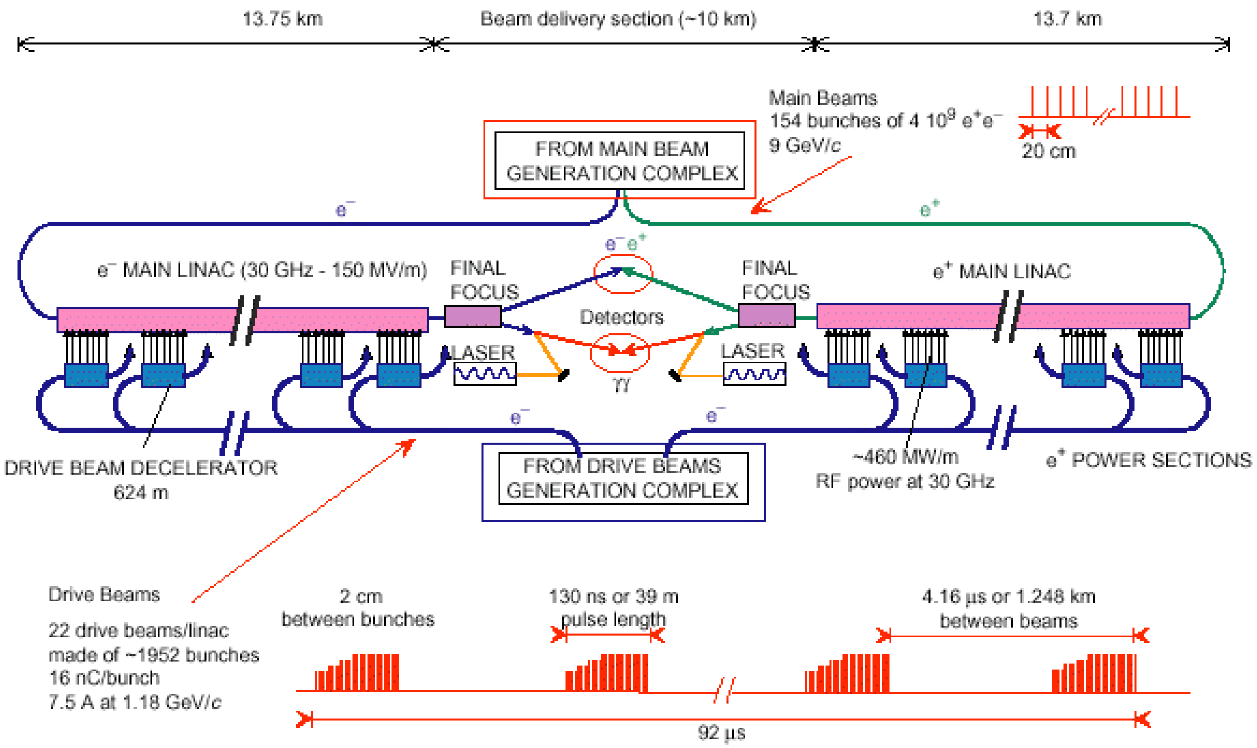
$$\mathcal{L} = \frac{N}{4\pi\sigma_x\sigma_y} H_D \frac{\eta P_{grid}}{E_{CM}}$$

Compact Linear Collider (CLIC)

- Further into the future and higher energies 2-5 TeV
- Power conversion efficiency
  - Use high current low energy beam (drive beam) to generate RF power for probe beam



Linear collider

- Linear collider is a challenging machine
  - Large momentum developed internationally to see the machine built
  - Cost is a important issue $$$
  - Damping rings, accelerator and beam delivery system all push current technologies to the limits
    - 20 km of superconductor fed with high power radio-frequency power, with MW of beam power traveling down the middle.
    - Precision Higgs and top physics.
- Low mass supersymmetry

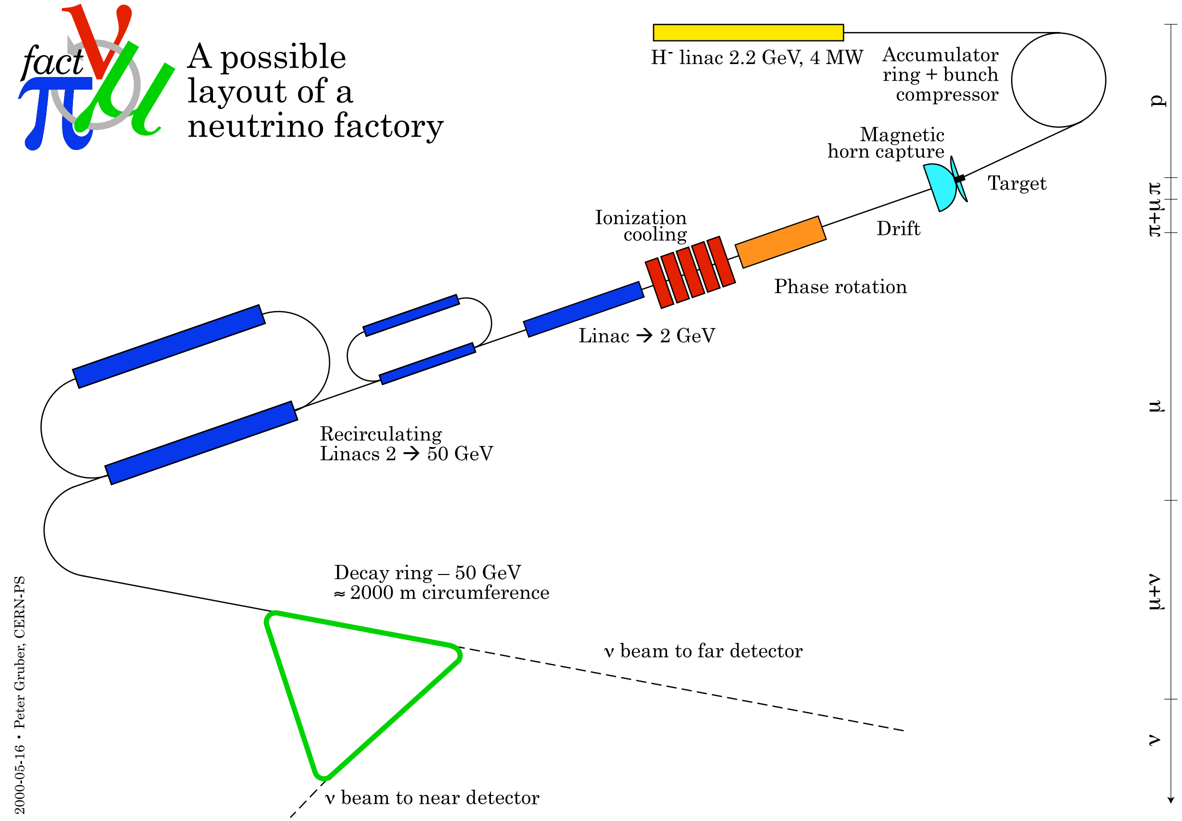
Muon storage and acceleration

- Muon significantly more massive that electron

$$m_\mu \approx 207 m_e$$

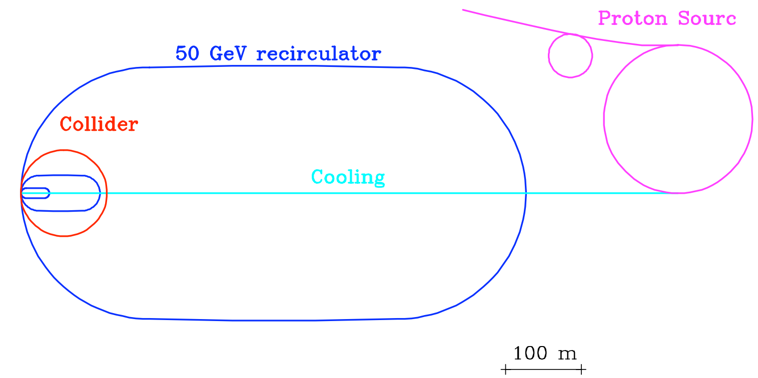
$$P = \frac{1}{4\pi\epsilon_0}\frac{e^2 v^4}{c^3 \rho^2}\gamma^4$$

  - SR losses low
- Production and capture difficult
- Cooling (lowering emittance)
- Quick acceleration before decay

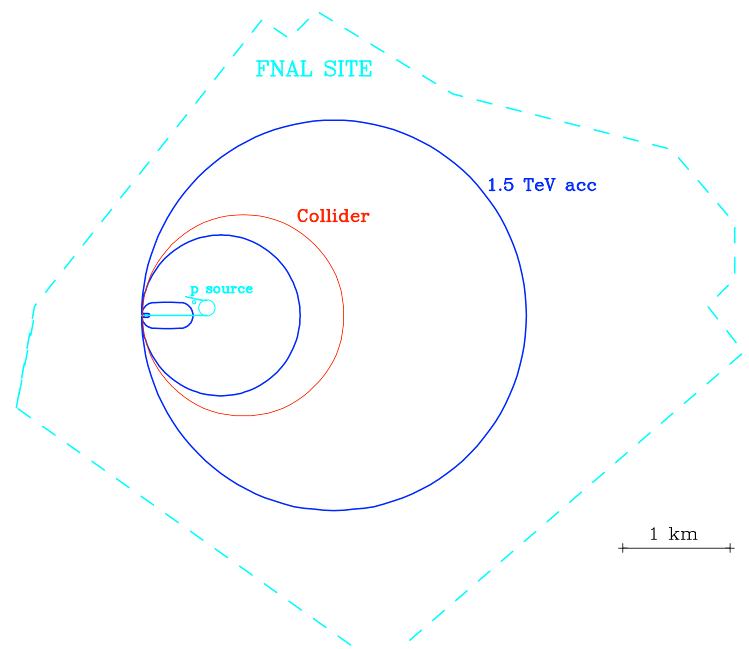


Muon collider

- Muon collider is highly challenging
  - Possible to achieve required luminosity
  - First stage is neutrino factory technology
  - Main accelerator is not so challenging



Plan of a 0.1 TeV COM muon collider.

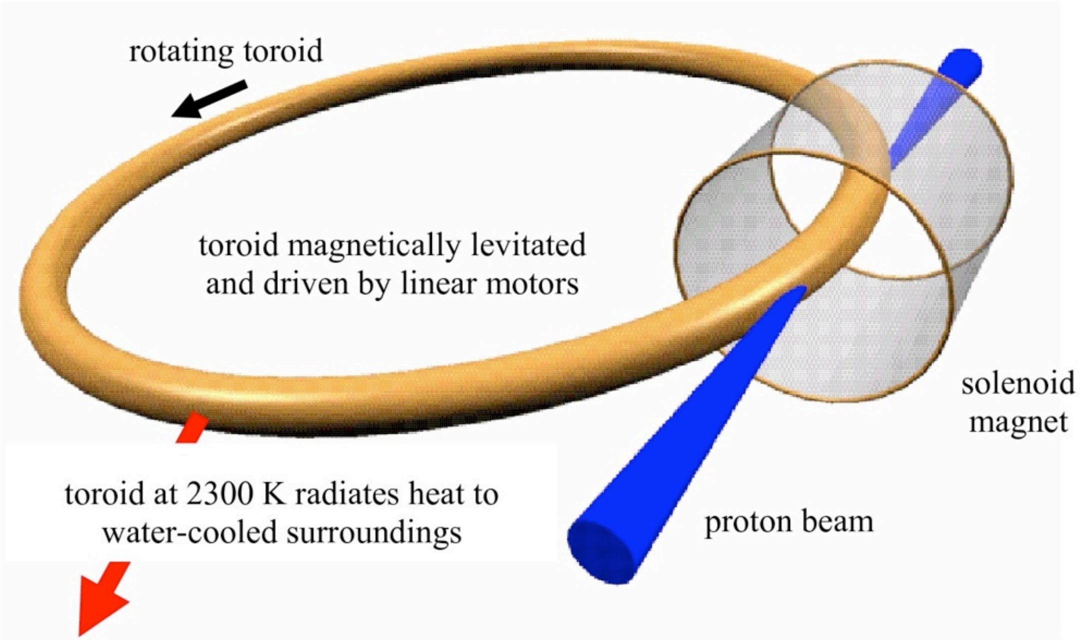


Plan of a 3 TeV COM muon collider shown on the Fermi National Laboratory site as an example.

Muon production

$$\mathcal{L} = f \frac{N_1 N_2}{4\sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

- Muons created from pion decay
  - Pions from proton-solid target collisions
- Problems are numerous
  - Heat dissipation
  - Radiation damage
  - Thermal stress, shock and fatigue



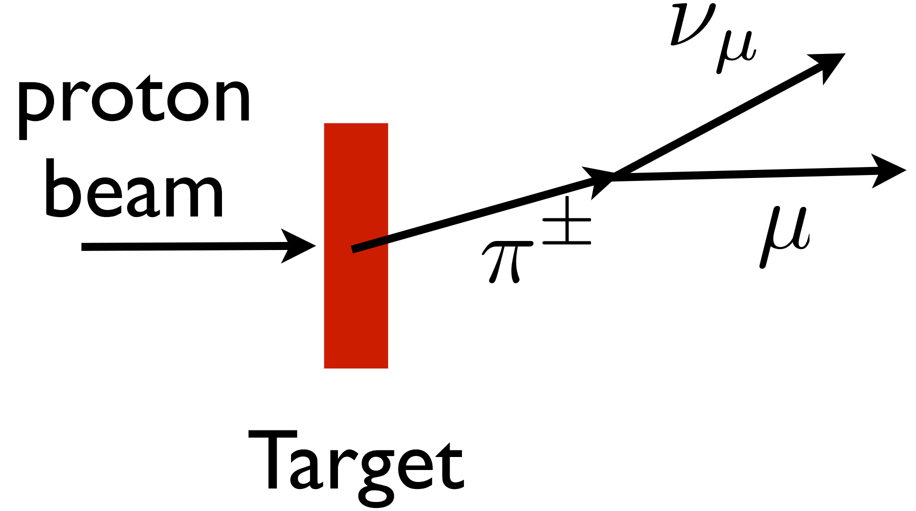
One target idea rotating metal ring

Muon production

- Generate charged pions from proton interaction with target

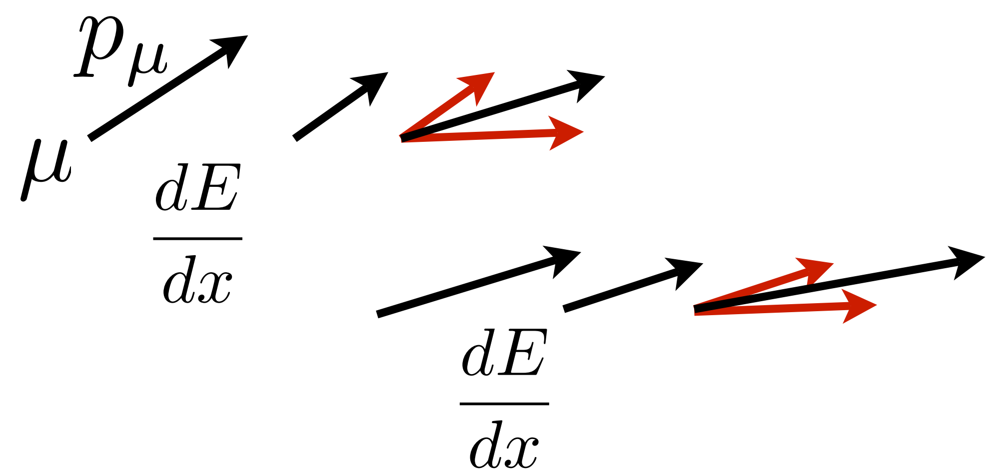
- Allow pions to decay into muons

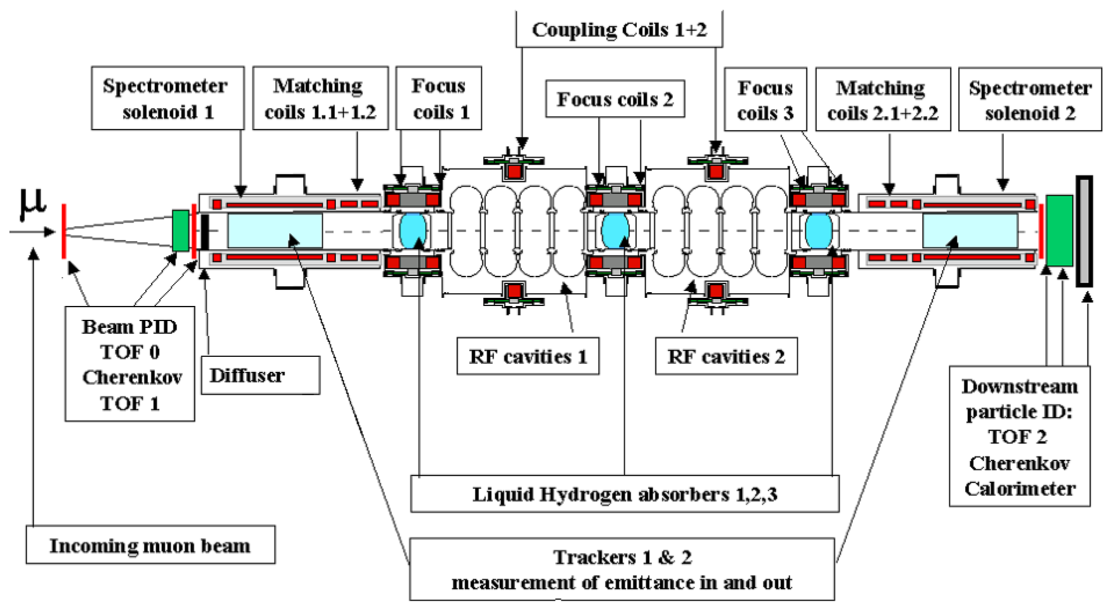
- Angular and momentum distribution of pions and decay products



Ionization cooling

- Reduction of emittance
- Radiation cooling impossible
  - Reduce momentum of muons, accelerate in one direction
  - Energy loss in material
  - Low mass target - Liquid hyrdrogen



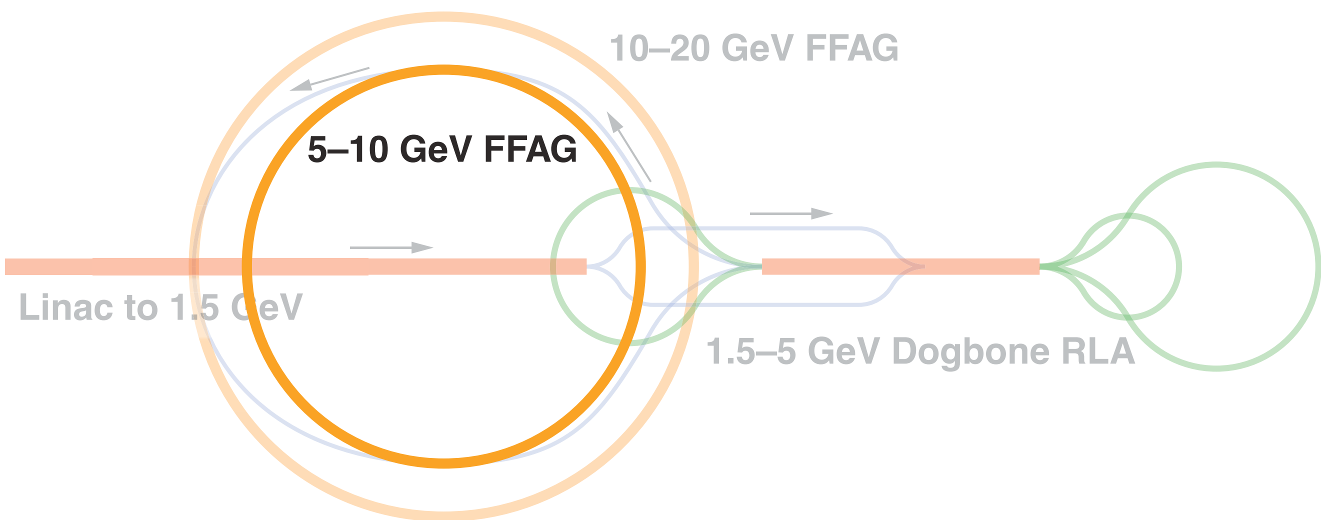


Muon acceleration

- Muon lifetime
  - Proper lifetime 2.2 micro-seconds
  - Time dilation to stop decay in laboratory frame

$$t = \gamma\tau$$

- Quickly accelerate to prevent decay, 10s of turns in each accelerator



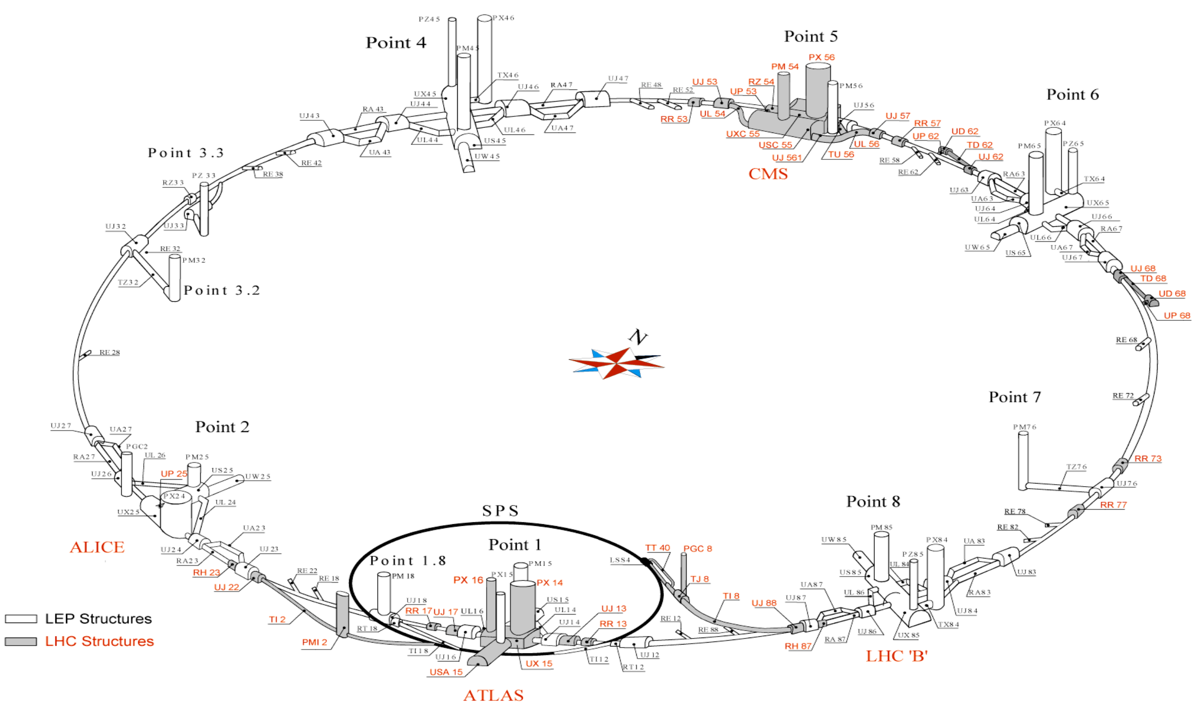
Muon collider

- A muon collider is a very challenging accelerator to design and build
- Neutrino factory might be a more realistic, whilst doing effective R&D towards a collider
- As with the ILC low emittance and beta functions are required to obtain the luminosity
- Problems are mainly at the front end, high power proton driver, proton target, capture of muons, cooling and acceleration
- Still a long way off decades
  - Neutrino factory might be sooner ~decade

Large hadron collider

- LHC is the premier facility for the next decade
  - Proton-proton synchrotron
  - 14 TeV COM collison energy
  - 27 km tunnel
- Luminosity upgrade potential?

Large hadron collider



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Large hadron collider

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	3.56×10^{30}

- LHC is the premier facility for the next decade
    - Proton-proton synchrotron
    - 14 TeV COM collison energy
    - 27 km tunnel
- Luminosity upgrade potential?

LHC Upgrade

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi\epsilon_n \beta^*} F$$

$$F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*} \right)^2}$$

- Reduce beta functions at the IP
- Emittance?
- There is a crossing angle
    - Reduces total luminosity
    - Crab beam crossing

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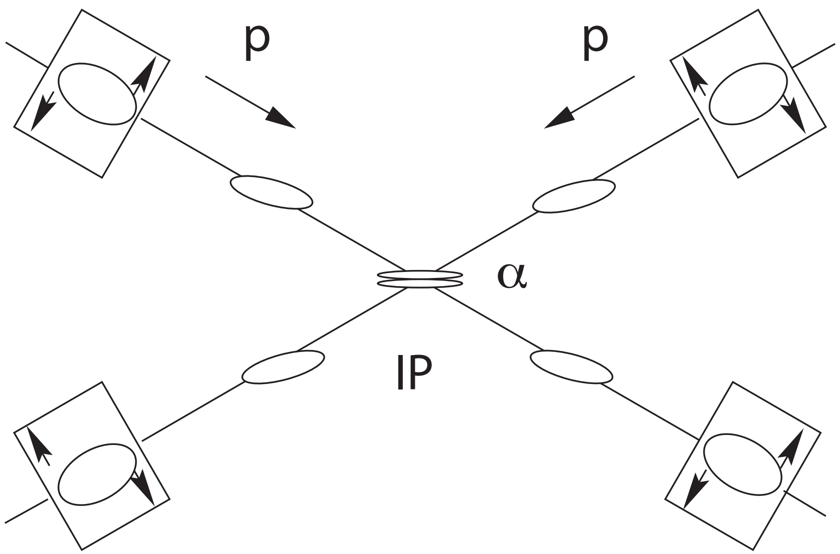
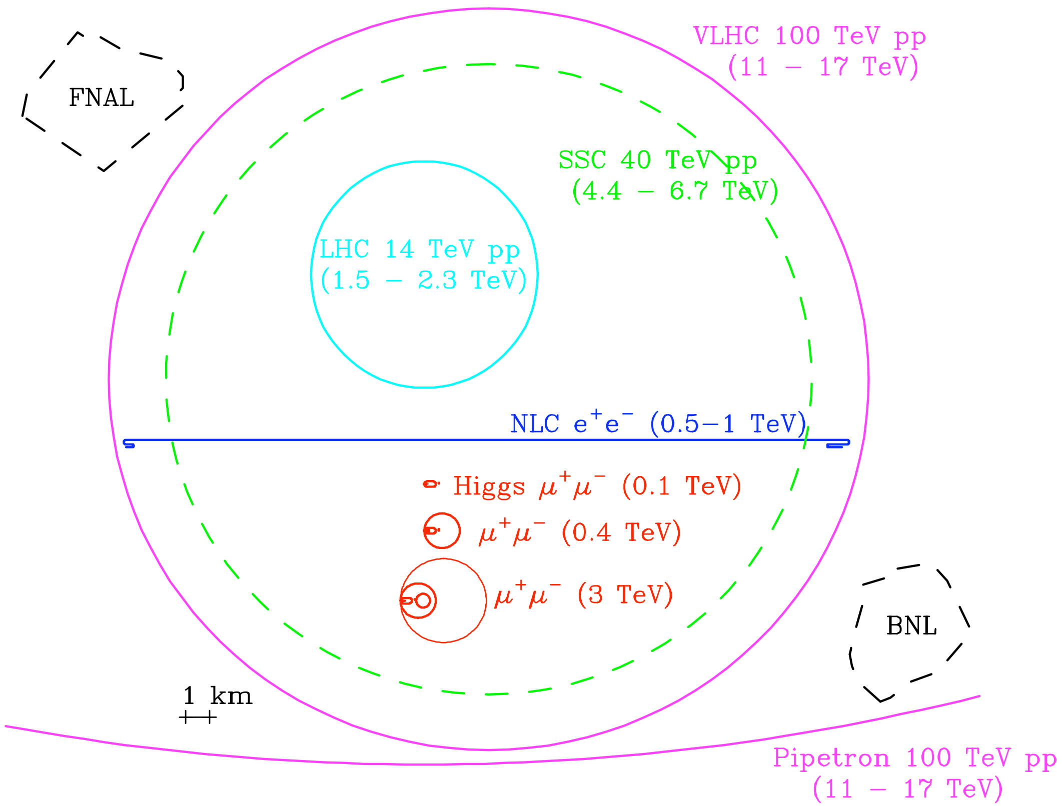


- Reduce beta functions at the IP
- Emittance?
- There is a crossing angle
  - Reduces total luminosity
  - Crab beam crossing

Very Large Hadron Colliders



- Larger radius LHC
  - Significant SR from proton beam
  - Civil engineering
    - Cheaper tunneling required
    - Heating (quenching) of dipole magnets

Very Large Hadron Colliders

Table 1.1. The high-level parameters of both stages of the VLHC.

	Stage 1	Stage 2
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	175
Number of interaction regions	2	2
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.0×10^{34}
Luminosity lifetime (hrs)	24	8
Injection energy (TeV)	0.9	10.0
Dipole field at collision energy (T)	2	9.8
Average arc bend radius (km)	35.0	35.0
Initial number of protons per bunch	2.6×10^{10}	7.5×10^{9}
Bunch spacing (ns)	18.8	18.8
β^* at collision (m)	0.3	0.71
Free space in the interaction region (m)	± 20	± 30
Inelastic cross section (mb)	100	130
Interactions per bunch crossing at L_{peak}	21	54
Synchrotron radiation power per meter (W/m/beam)	0.03	4.7
Average power use (MW) for collider ring	25	100
Total installed power (MW) for collider ring	35	250

US-VLHC study group

- First phase start at 15 to 40 TeV
  - Injection from Tevatron at 900 GeV
- Second phase 85 TeV injection from phase 1
  - Up to 200 TeV machine
  - Proton SR damping
- Can the world afford

Summary

- Discussed new facilities
  - Linear collider (CLIC)
  - Muon factories and colliders
  - Large hadron collider and possible upgrades
  - Very large hadron collider
- Increasing difficult to build these facilities
  - Cost
  - Technical challenges
  - Time scales decades (fortunately you are young)

Resources for further study

- http://www.linearcollider.org/cms/
- http://clic-study.web.cern.ch/clic%2Dstudy/
- http://www.cap.bnl.gov/mumu/
- http://lhc.web.cern.ch/lhc/
- http://vlhc.org/
- http://pdg.lbl.gov/