Experimental particle physics

esipap
European School of Instrumentation in Particle & Astroparticle Physics

2. a few things about particle accelerators

why?

a small hint…

$$E = mc^2$$

Aren't natural radioactive processes enough?
What about cosmic rays?

Why accelerating and colliding particles?

Aren't natural radioactive processes enough? What about cosmic rays?

High energy

$$E = mc^2$$

- Probe smaller scale
- Produce heavier particles

Large number of collisions

$$N = \mathcal{L} \cdot \sigma$$

- Detect rare processes
- Precision measurements

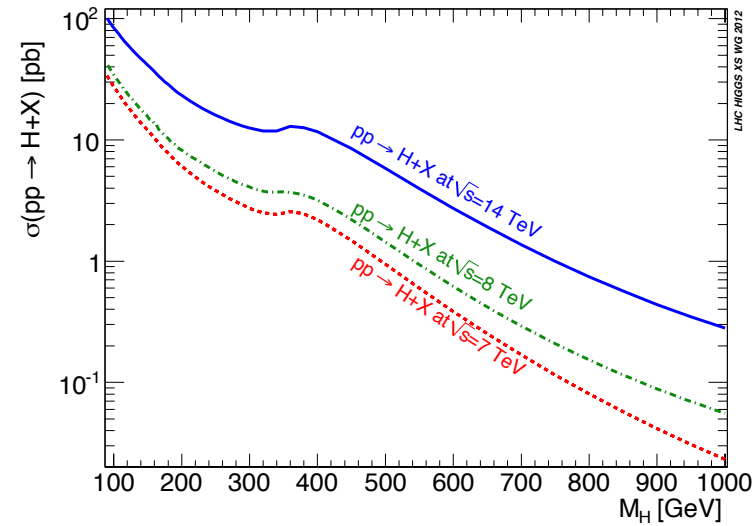
Luminosity

Number of events
in unit of time

$$N = \mathcal{L} \cdot \sigma$$

[t^{-1}] [$L^{-2}\,t^{-1}$] [L^{2}]

? 10^{34} $cm^{-2}\,s^{-1}$ $\sigma(pp \rightarrow H+X) \sim 20$ pb



In a collider ring…

$$\mathcal{L} = \frac{1}{4\pi} \frac{f k N_1 N_2}{\sigma_x \sigma_y}$$

Current

Beam sizes (RMS)

What particle to accelerate and collide?

- **Stable (charged) particle**
  - ✓ Electron/positron
  - ✓ Proton/antiproton

  } *what particle should we use?*

- **Secondary beams of charged or neutral particles**
  - ✓ (Anti)neutrinos
  - ✓ Muons
  - ✓ Photons
  - ✓ Charged pions
  - ✓ Kaons
  - ✓ …

Particle accelerations for dummies

(non-relativistic)
Lorentz Force

$$\vec{F}_L = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

time variation of
kinetic energy

$$\frac{dE_{\mathrm{kin}}}{dt} = \vec{F}_L \cdot \vec{v} = q\vec{v} \cdot \vec{E}$$

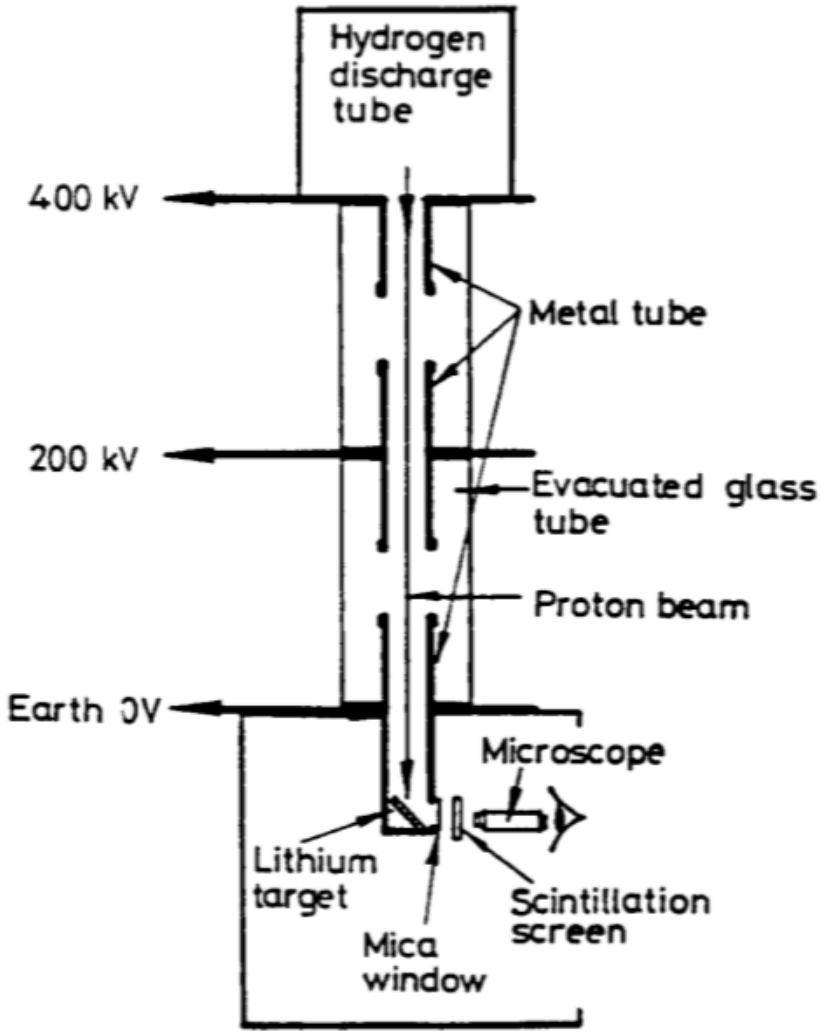
- Only longitudinal component of electrical field matters
- Time-varying electrical field to change energy
- (Static) magnetic field cannot change particle momentum…
- … but can be used to bend its trajectory!

A brief history of particle accelerators – part 1

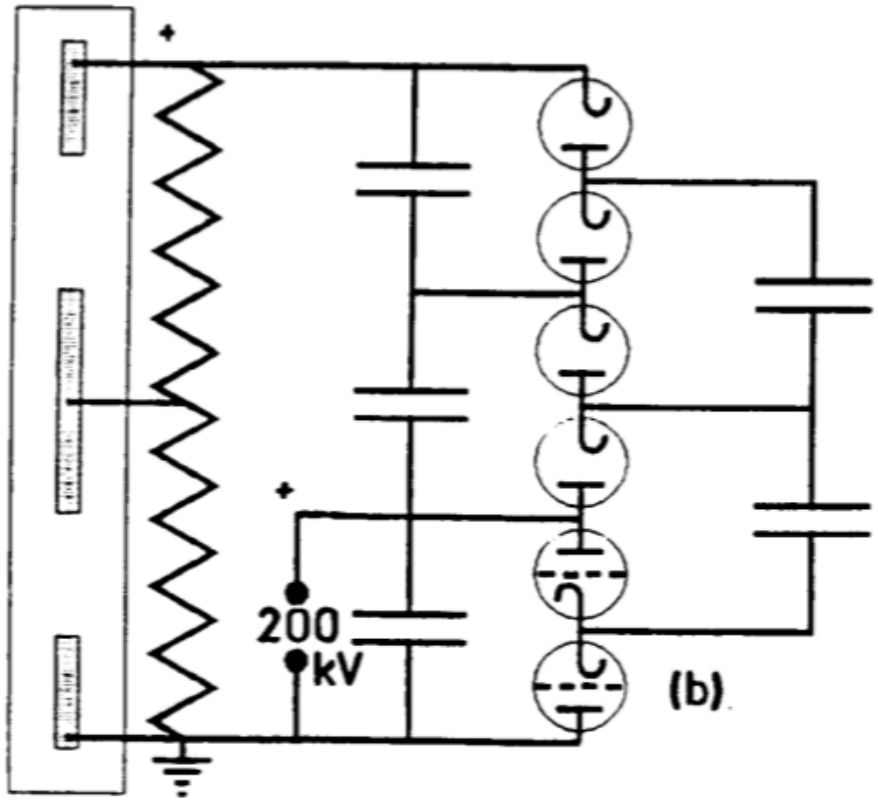
1906	Rutherford bombards mica sheet with natural alphas and develops the theory of atomic scattering.	Natural alpha particles of several MeV
1911	Rutherford publishes theory of atomic structure.	
1919	Rutherford induces a nuclear reaction with natural alphas.	
	... Rutherford believes he needs a source of many MeV to continue research on the nucleus. This is far beyond the electrostatic machines then existing, but ...	
1928	**Gamov predicts tunnelling and** perhaps 500 keV would suffice ...	
1928	Cockcroft & Walton start designing an 800 kV generator encouraged by Rutherford.	
1932	Generator reaches 700 kV and Cockcroft & Walton split lithium atom with only 400 keV protons. They received the Nobel Prize in 1951.	

(inspired by "A brief history and review of accelerators" by P.J Bryant https://cds.cern.ch/record/261062/)

Cockcroft and Walton's apparatus

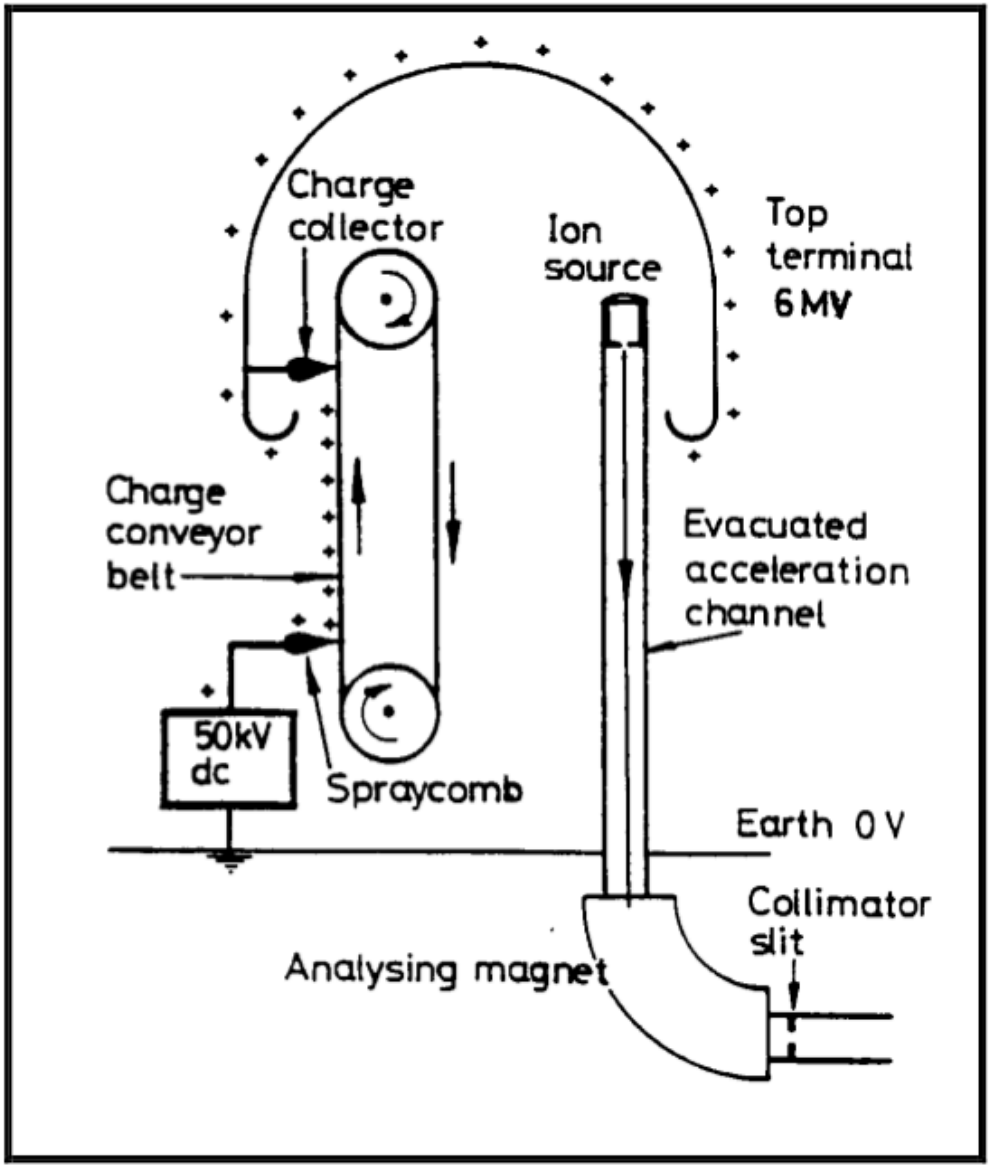


(a) Accelerating column

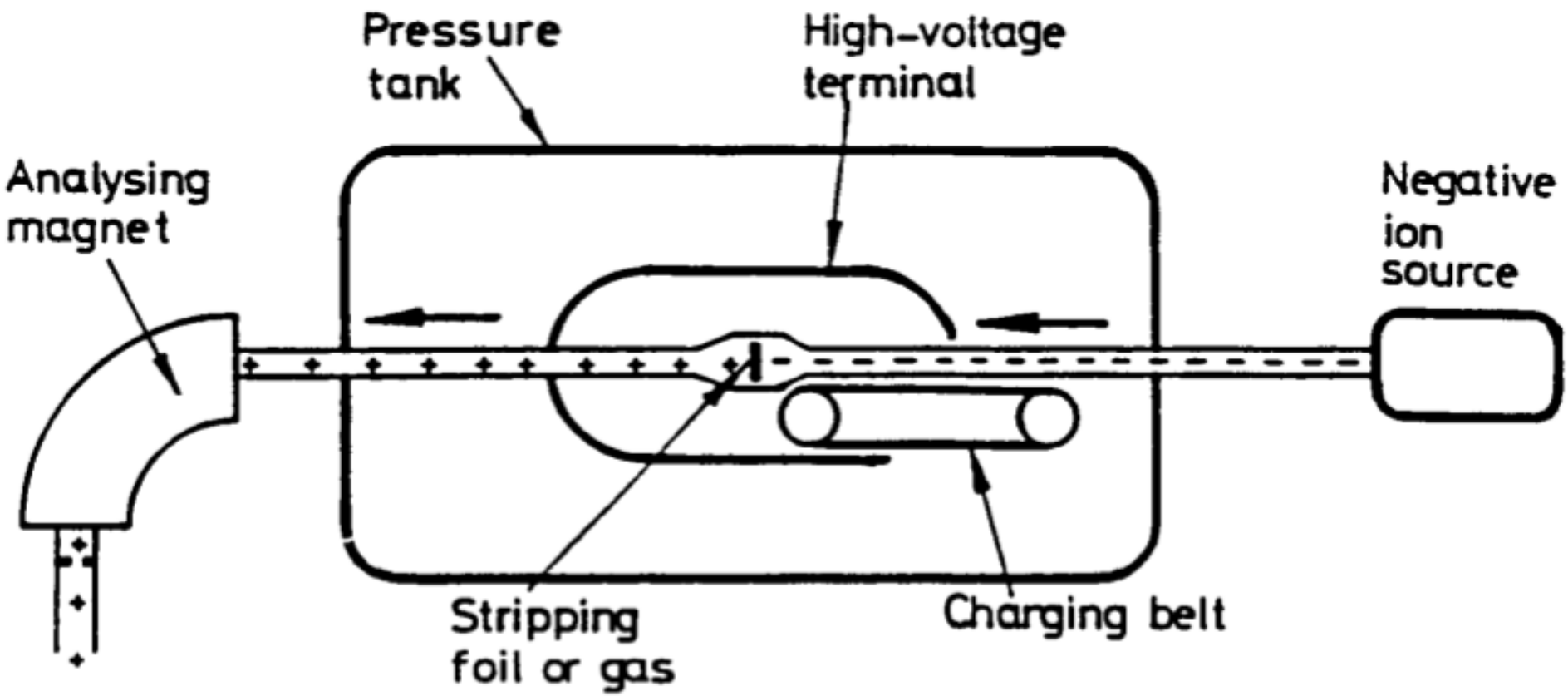


(b) DC generator

Van de Graaff electrostatic generator



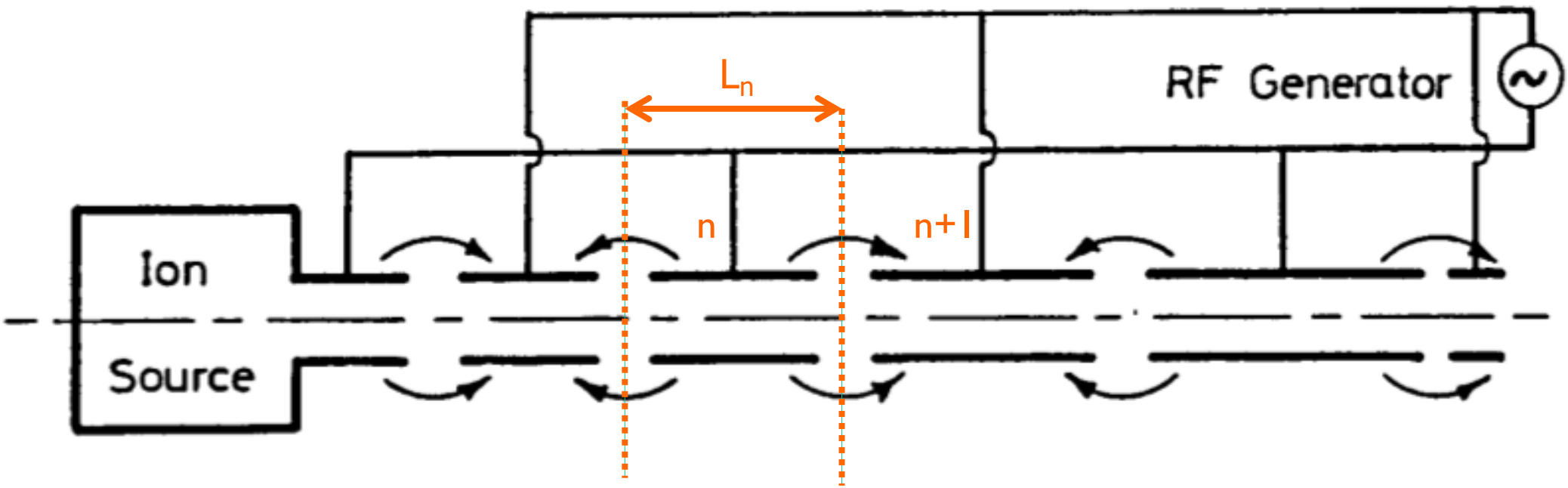
Two-stage Tandem accelerator



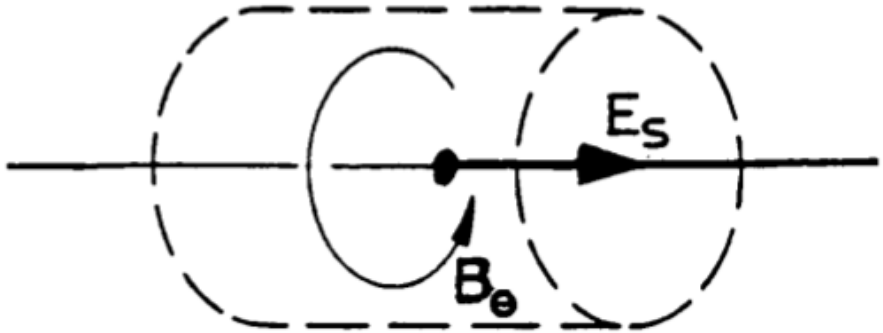
A brief history of particle accelerators – part 2

1924	Ising proposes time-varying fields across drift tubes. This is "resonant acceleration", which can achieve energies above that given by the highest voltage in the system.
1928	Wideröe demonstrates Ising's principle with a 1 MHz, 25 kV oscillator to make 50 keV potassium ions.
1929	Lawrence, inspired by Wideröe and Ising, conceives the cyclotron.
1931	Livingston demonstrates the cyclotron by accelerating hydrogen ions to 80 keV.
1932	Lawrence's cyclotron produces 1.25 MeV protons and he also splits the atom just a few weeks after Cockcroft and Walton (Lawrence received the Nobel Prize in 1939).

RF linear accelerator (LINAC)



$$L_n = k \frac{v_n}{c} \frac{\lambda}{2}$$



Wideore: k=1, L<λ

LINAC lenght

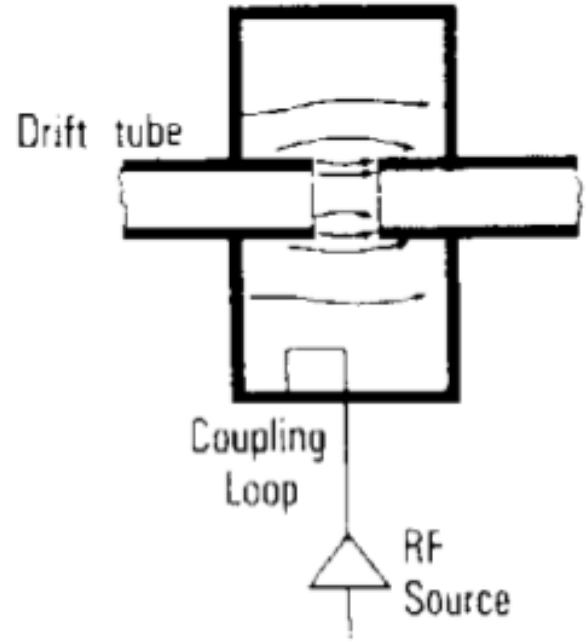
Total LINAC length

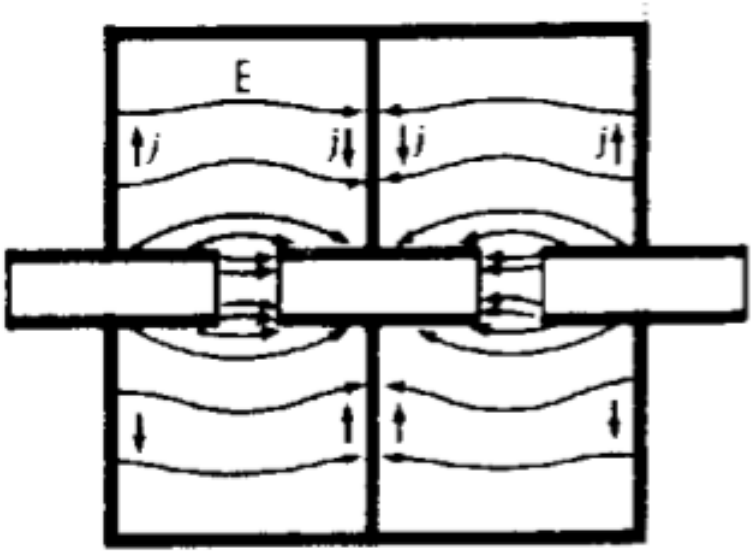
$$L = \frac{k}{\underbrace{\Delta E}_{\text{energy gain per gap}}} \sqrt{\frac{\overbrace{E}^{\text{final particle energy}}{}^{3}}{\underbrace{A}_{\text{ion atomic number}} mc^2}} \frac{\lambda}{2}$$

- Example:
  - ✓ proton (A=1) with E = 1 MeV (β = 4.6 10^{-2})
  - ✓ if ν_{RF} = 7 MHz proton will travel about 1m in half a RF cycle
- **Total LINAC length increases dramatically with speed**
- A possible solution would be to increase ν_{RF}
- … but at very high ν_{RF} open tube structure radiates too much energy!

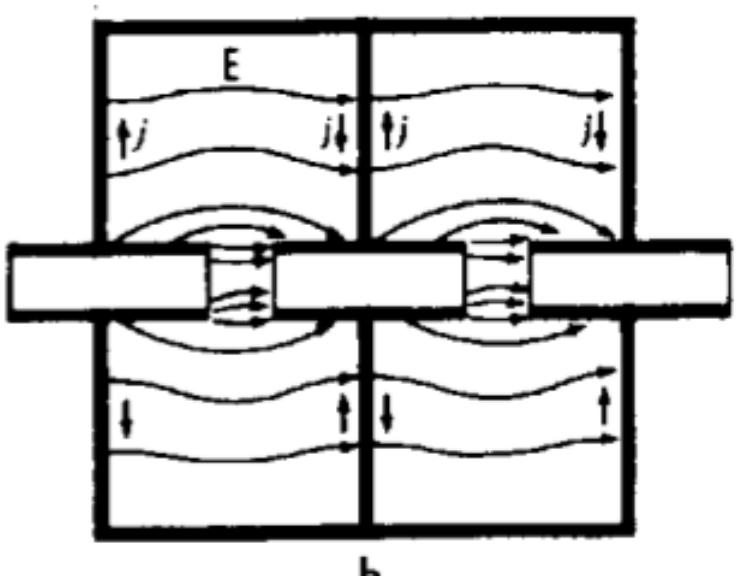
RF cavities

- The problem can be solved by closing the structure as a cavity…
- Cavities can be joined
- Choosing k=2 currents on walls cancel, and walls can be eliminated



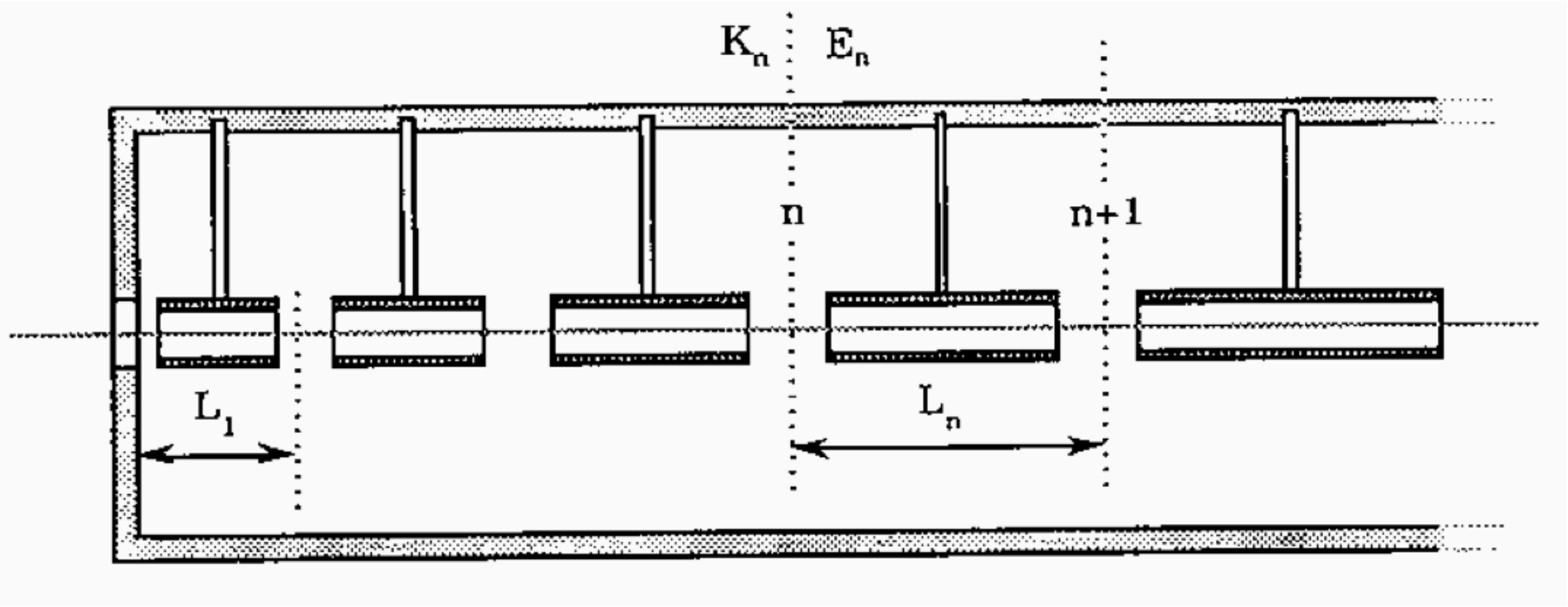


k=1



k=2

Alvarez structure



$k = 2$, $\nu_{RF} \sim 100$ MHz , $\lambda < L$

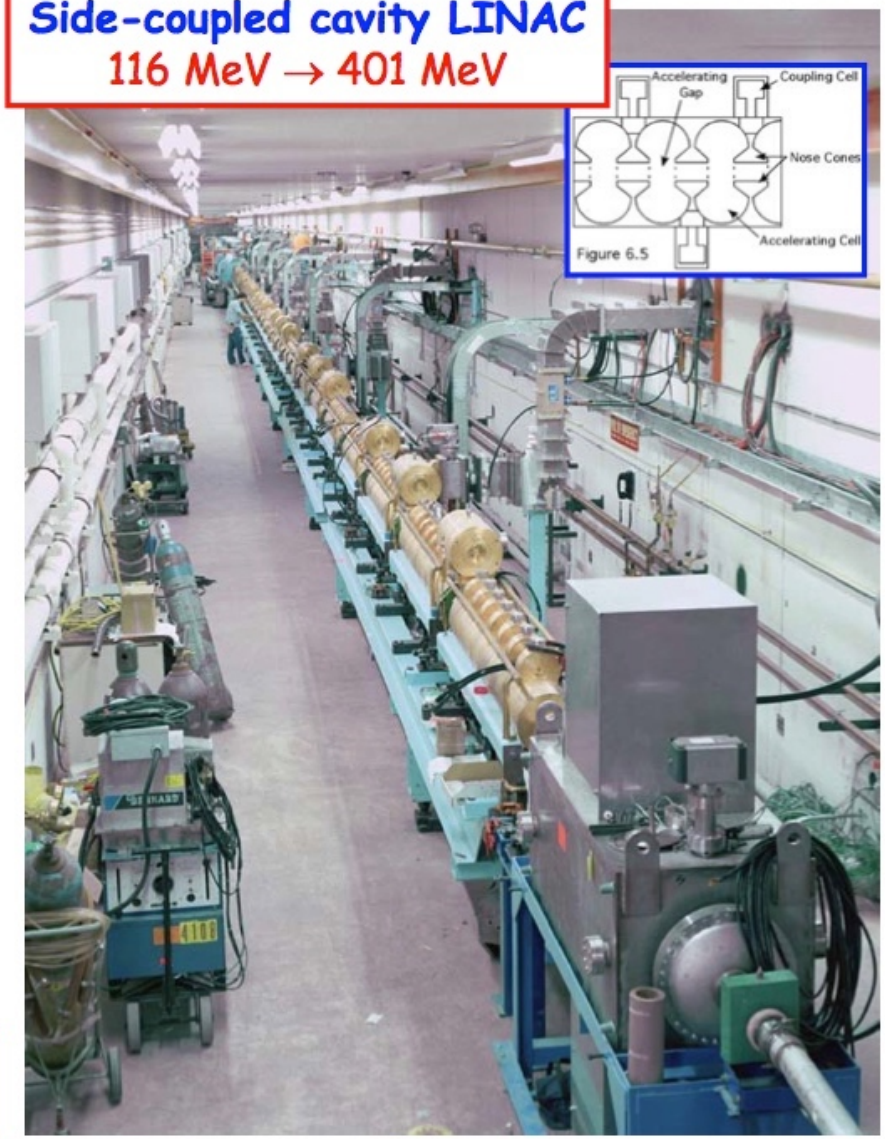
protons $\beta \sim 1$ for $E \sim 10$ GeV electrons $\beta \sim 1$ for $E \sim 10$ MeV

already at those energies v~c → drift tube length can stay constant!

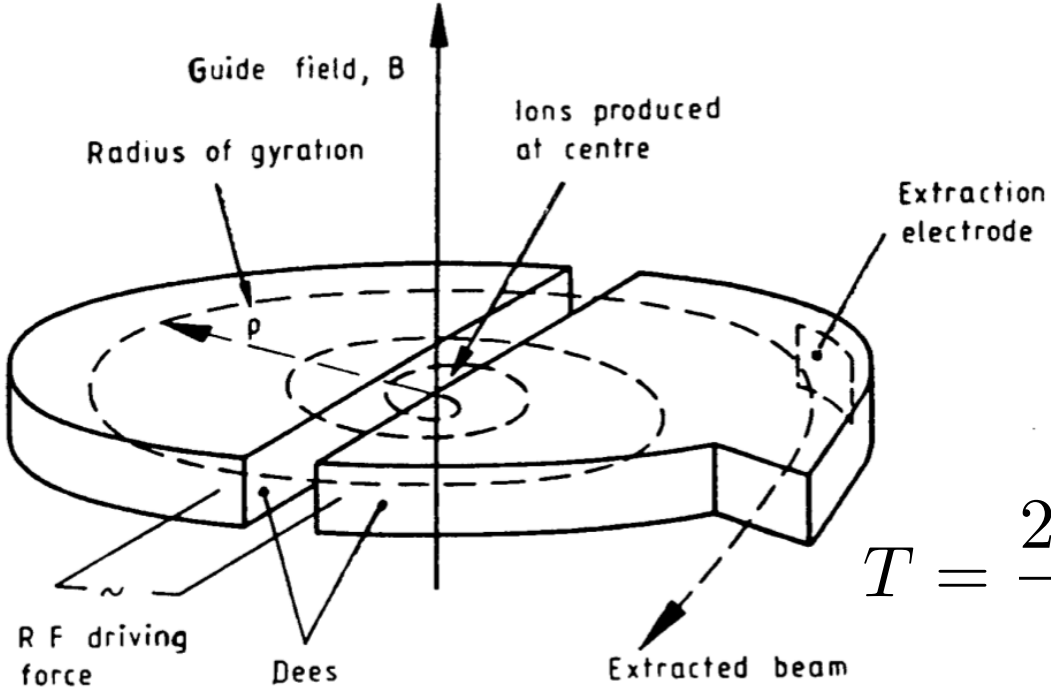
Example: Fermilab LINAC

Drift tube (Alvarez) LINAC
750 keV → 116 MeV

Side-coupled cavity LINAC
116 MeV → 401 MeV



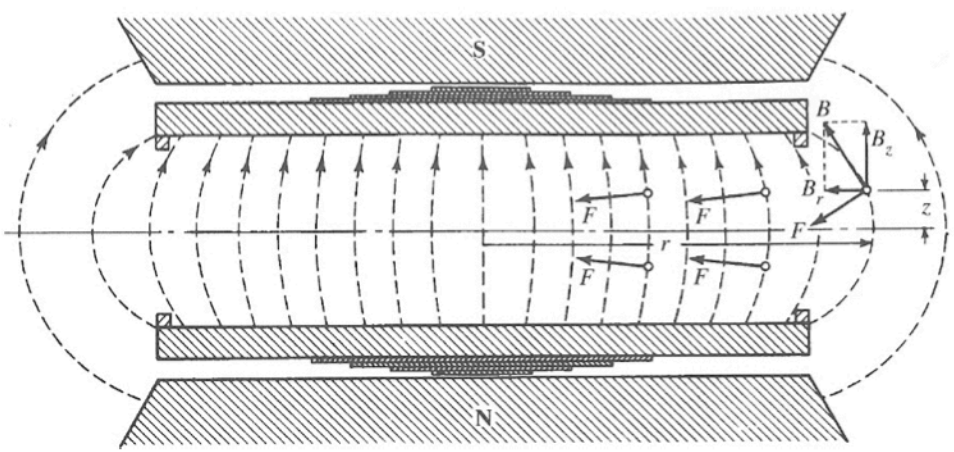
(Syncro) Cyclotron



$$p = m\gamma\beta$$

$$p = eBR$$

$$T = \frac{2\pi R}{v} = \frac{2\pi R}{\beta} = \frac{\pi p}{eB\beta c} = \gamma\frac{\pi m}{eB}$$



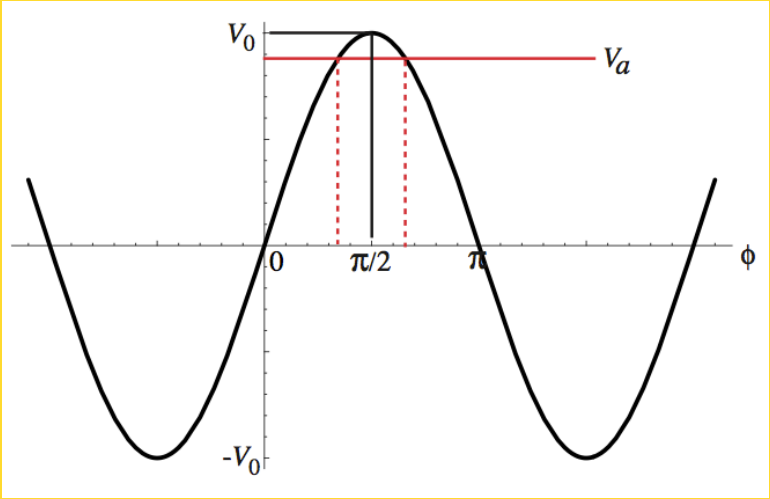
for relativistic particle cyclotron frequency should be adjusted to speed/energy (syncro-cyclotron)

weak focusing

Berkeley syncro-cyclotron (p, E = 340 MeV)

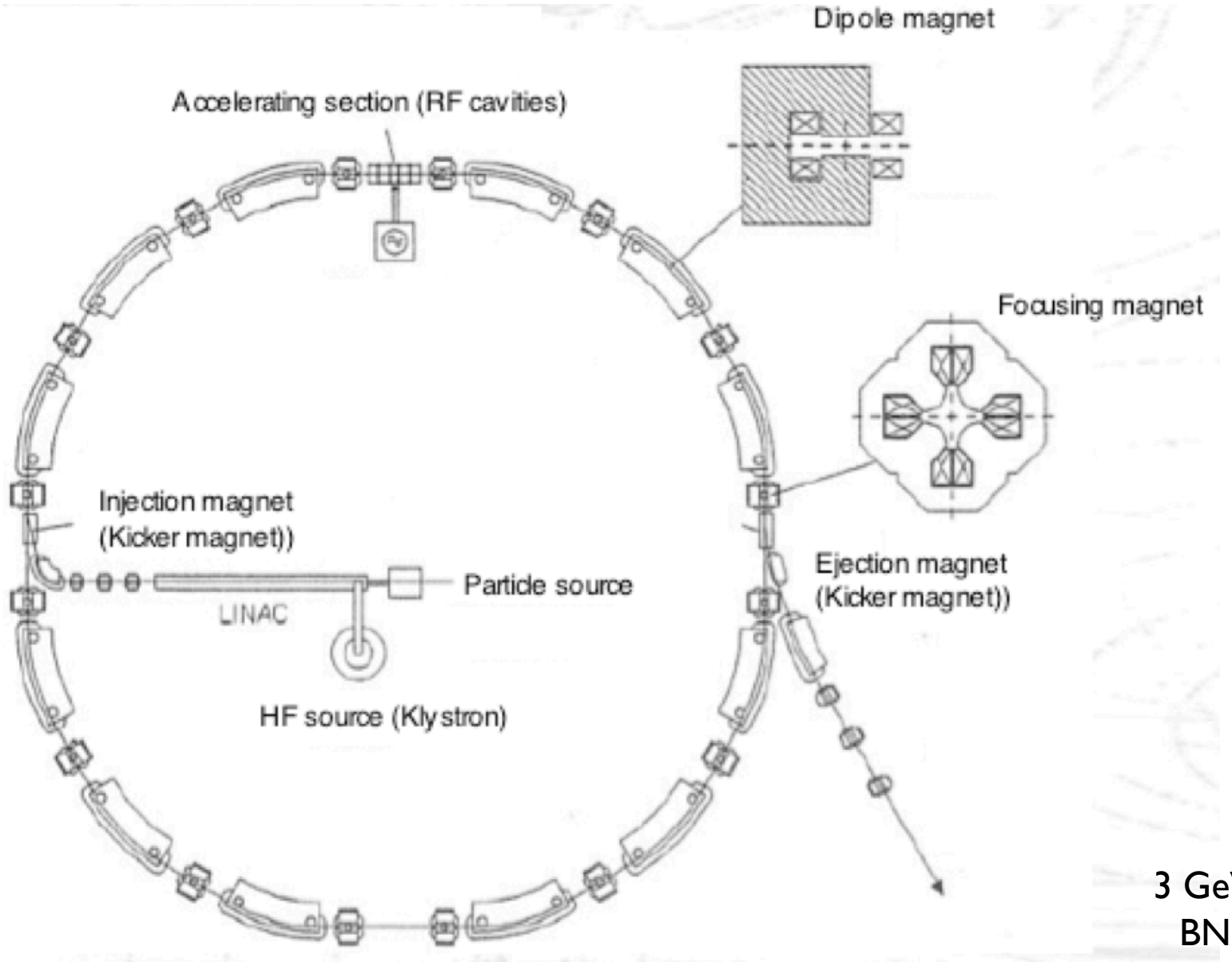
The road toward syncrotrons

- Problems in RF acceleration in the 1940s…
  - ✓ Linacs
    - Poor RF sources; electron tube technology was yet in its infancy
  - ✓ Cyclotrons
    - Relativistic effects → asynchronous RF
- Advancements during WW2
  - ✓ High power microwave tubes for the radars were put to practical use
    - Magnetrons and klystrons
  - ✓ Discovery of the phase stability principle in RF acceleration
    - Veksler (1944) and McMillan (1945)
  - ✓ **Cyclotron → synchrocyclotron → synchrotron**



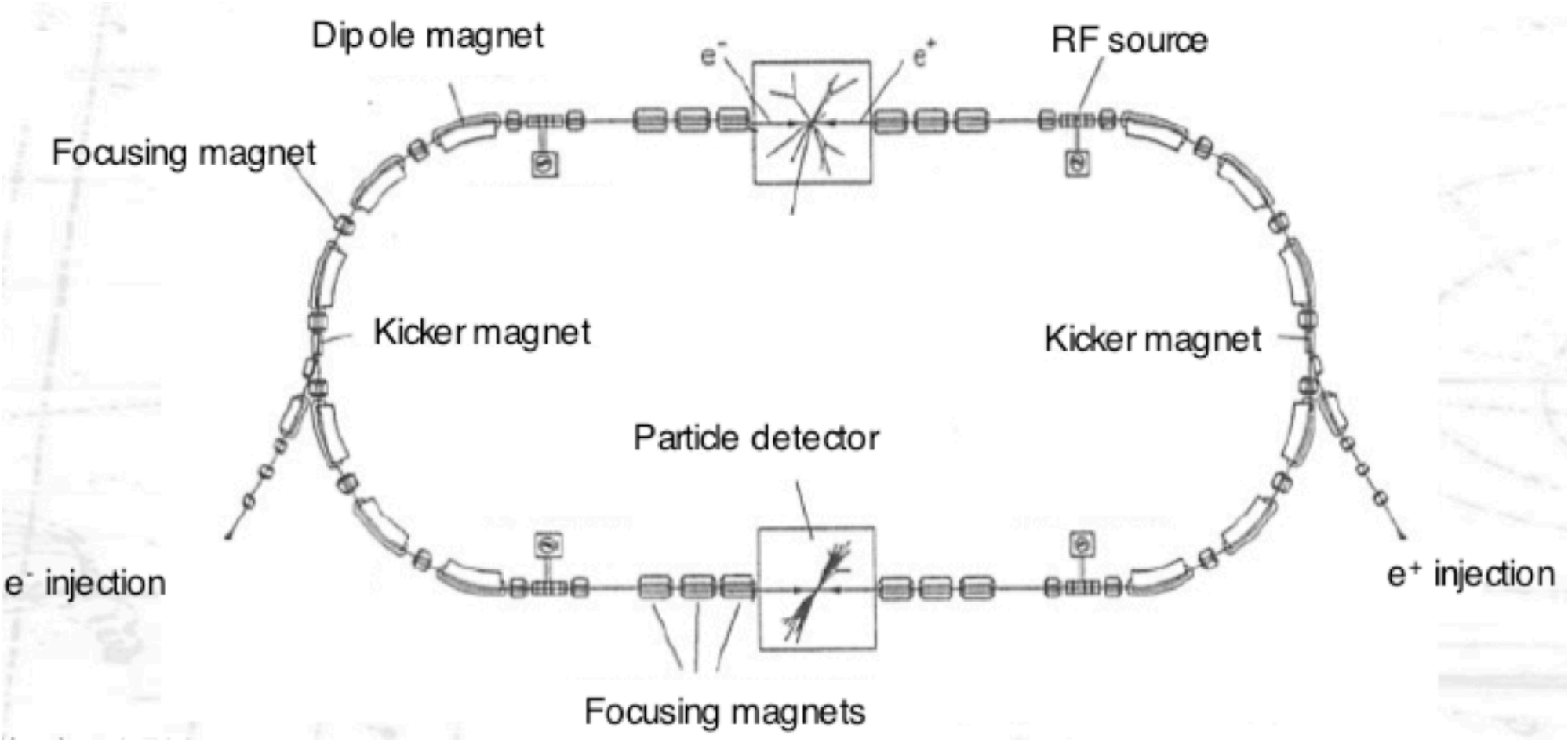
- Particles of different energies have differences in velocity and in orbit length
  - ✓ particles may be asynchronous wrt RF frequency
- RF field have however a restoring force at a certain phase, around which asynchronous particles be captured in bunches

Syncrotron

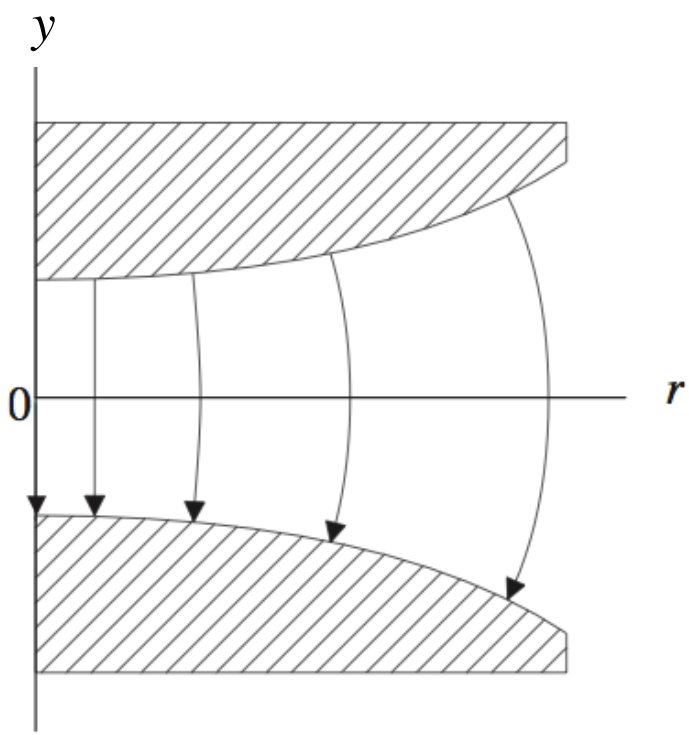


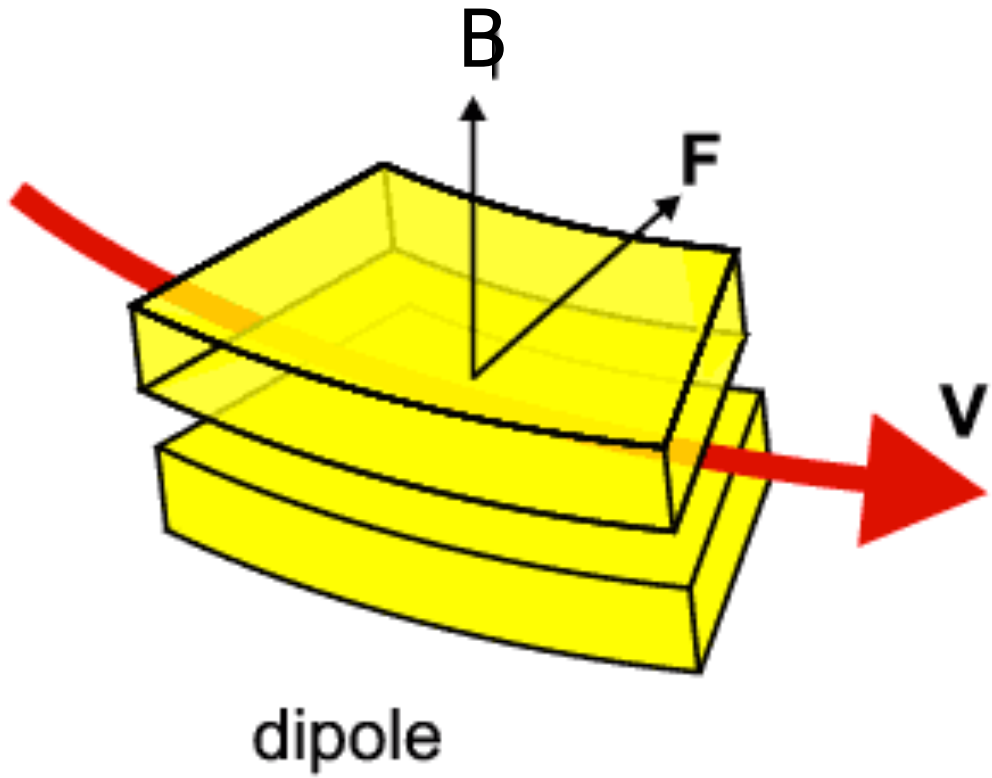
3 GeV protons
BNL ~ 1950

Storage rings



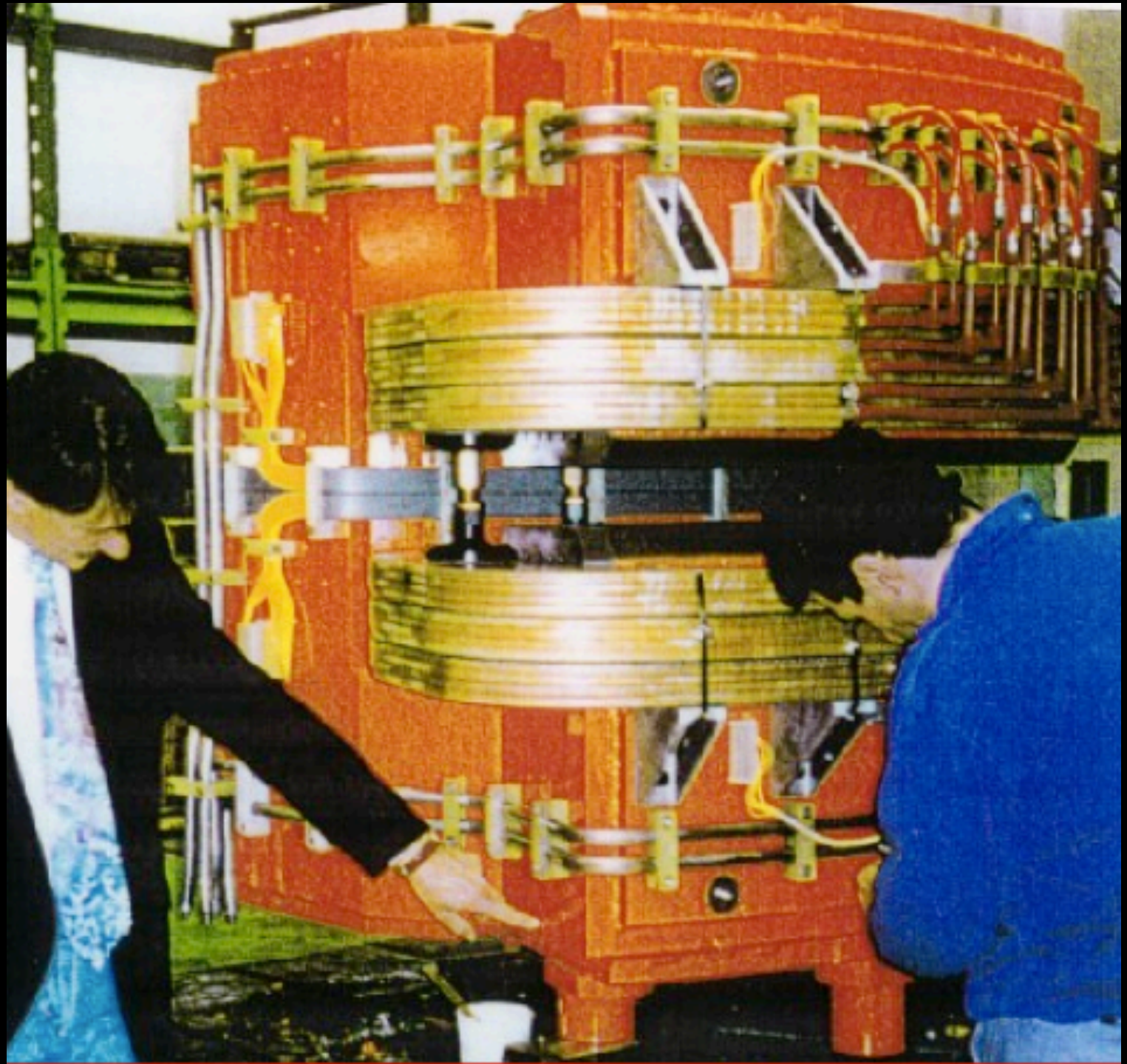
Bending: dipoles



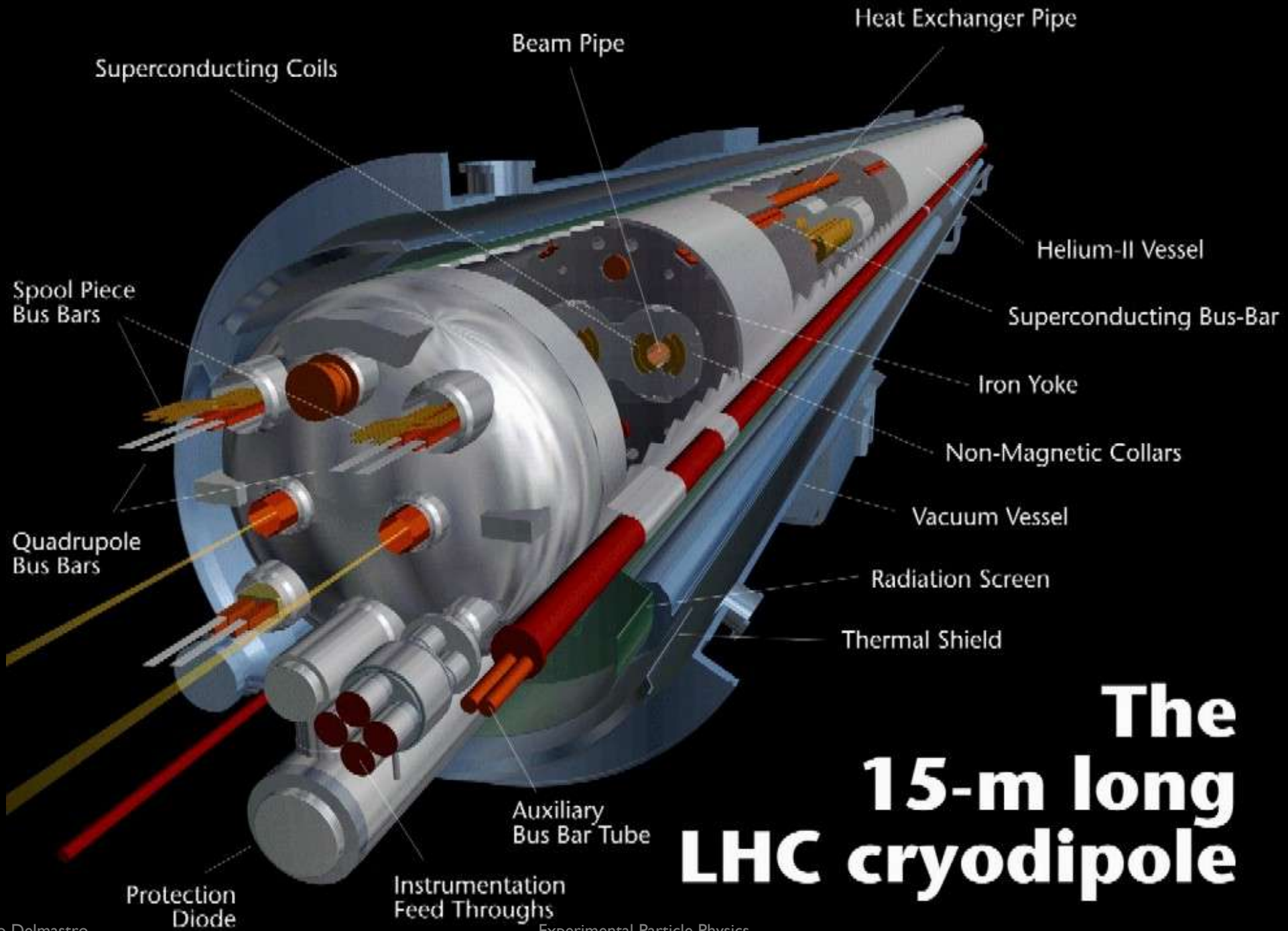


$B_x = 0$
$B_y = B$
$B_z = 0$

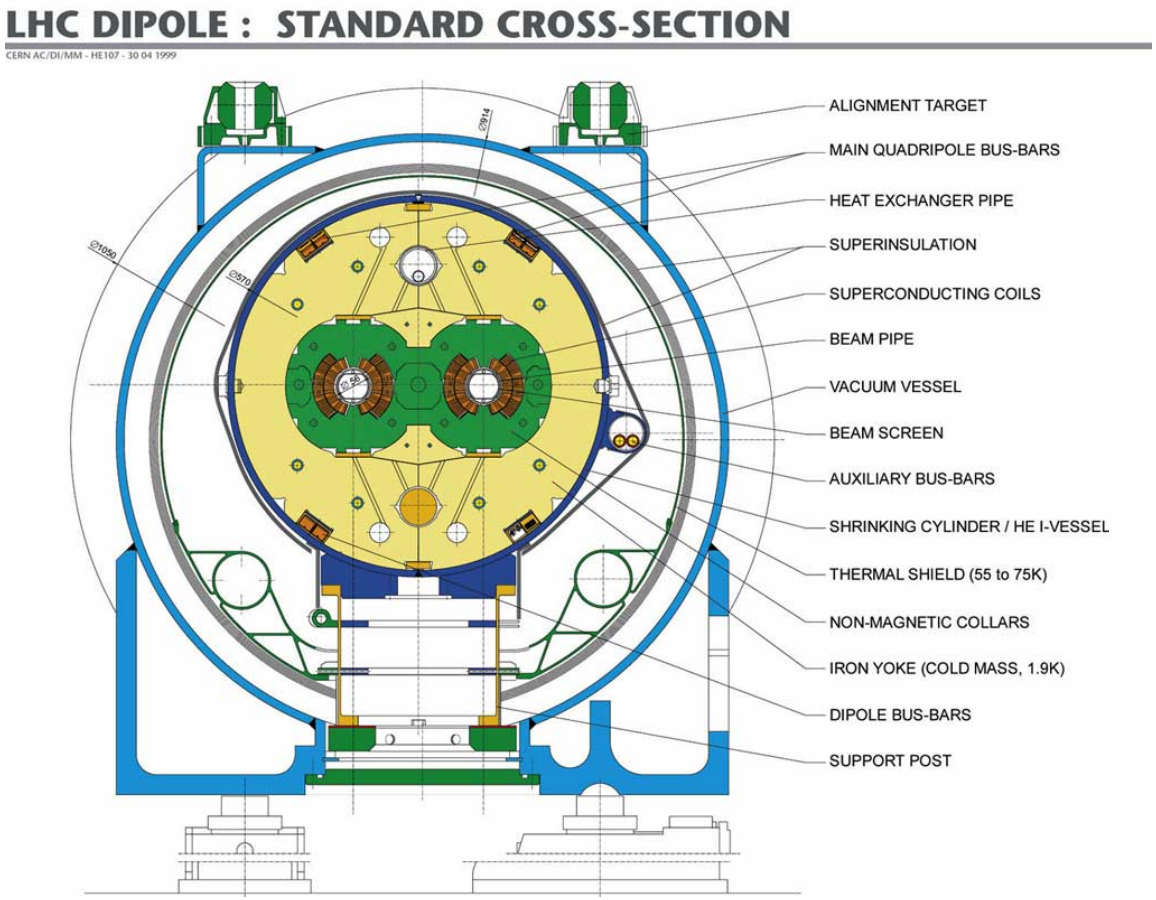
$$\frac{1}{R}[\mathrm{m}^{-1}] = 0.3\frac{B[\mathrm{T}]}{E[\mathrm{GeV}]}$$

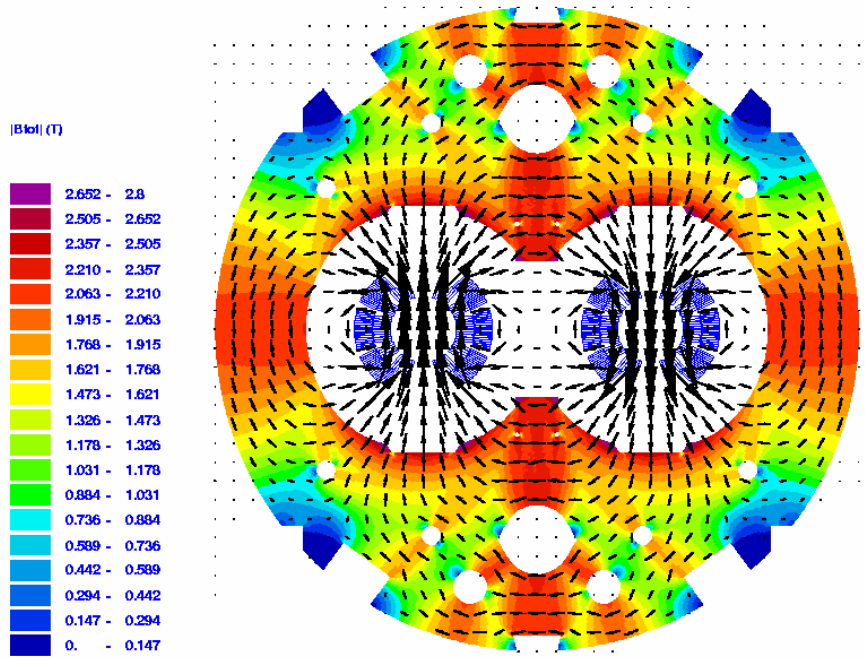


1136


Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Thermal Shield
The
15-m long
LHC cryodipole
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs

LHC dipoles

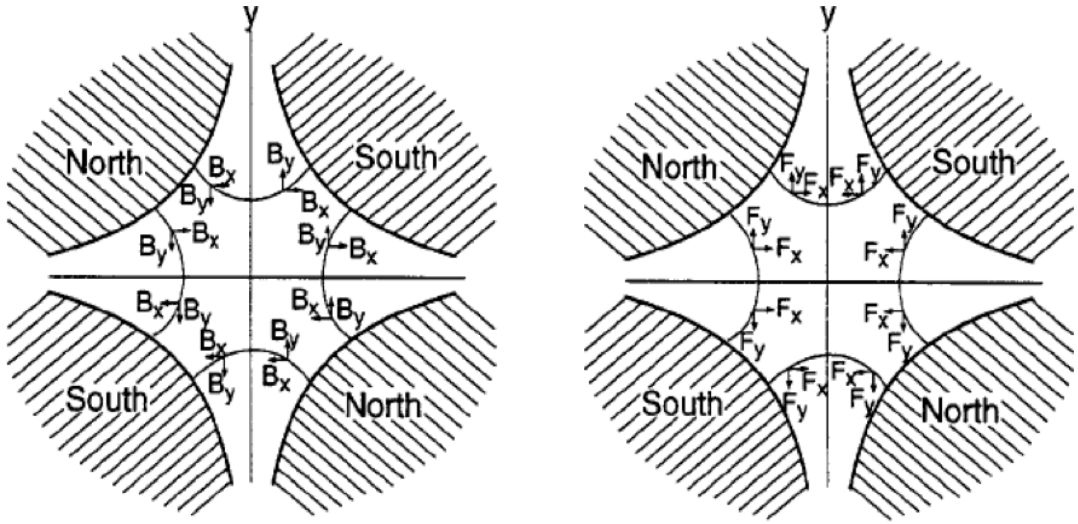

LHC DIPOLE : STANDARD CROSS-SECTION
CERN AC/DI/MM - HE107 - 30 04 1999
ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST


|Btot| (T)
2.652 - 2.8
2.505 - 2.652
2.357 - 2.505
2.210 - 2.357
2.063 - 2.210
1.915 - 2.063
1.768 - 1.915
1.621 - 1.768
1.473 - 1.621
1.326 - 1.473
1.178 - 1.326
1.031 - 1.178
0.884 - 1.031
0.736 - 0.884
0.589 - 0.736
0.442 - 0.589
0.294 - 0.442
0.147 - 0.294
0. - 0.147

Focusing (defocusing): quadrupoles

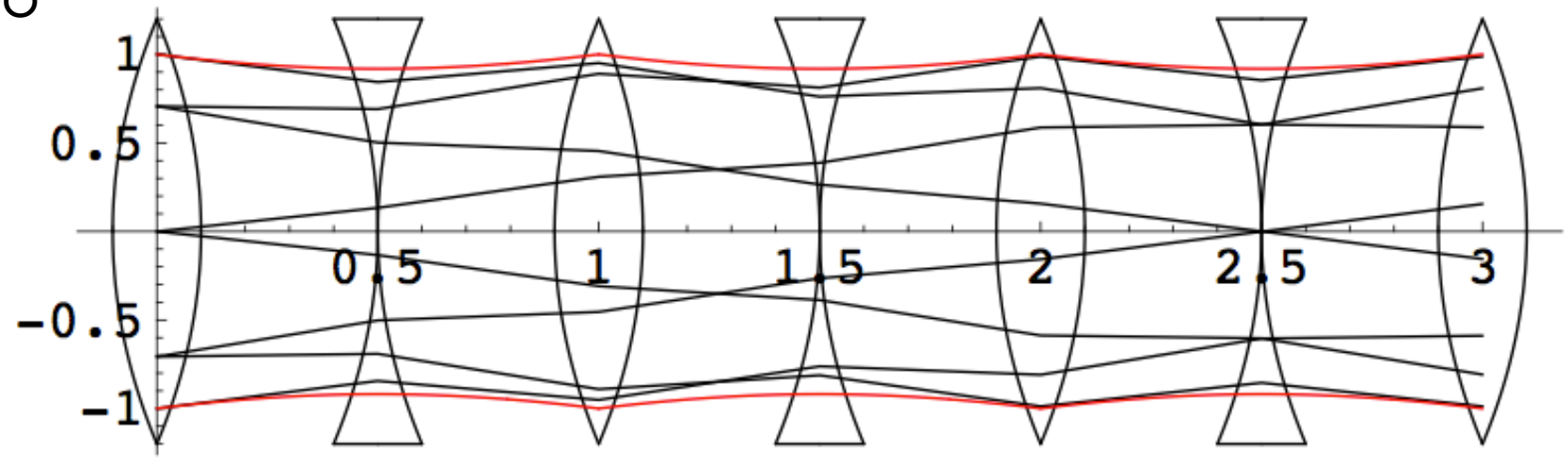
$B_x = -g \times x$
$B_y = -g \times y$
$B_z = 0$

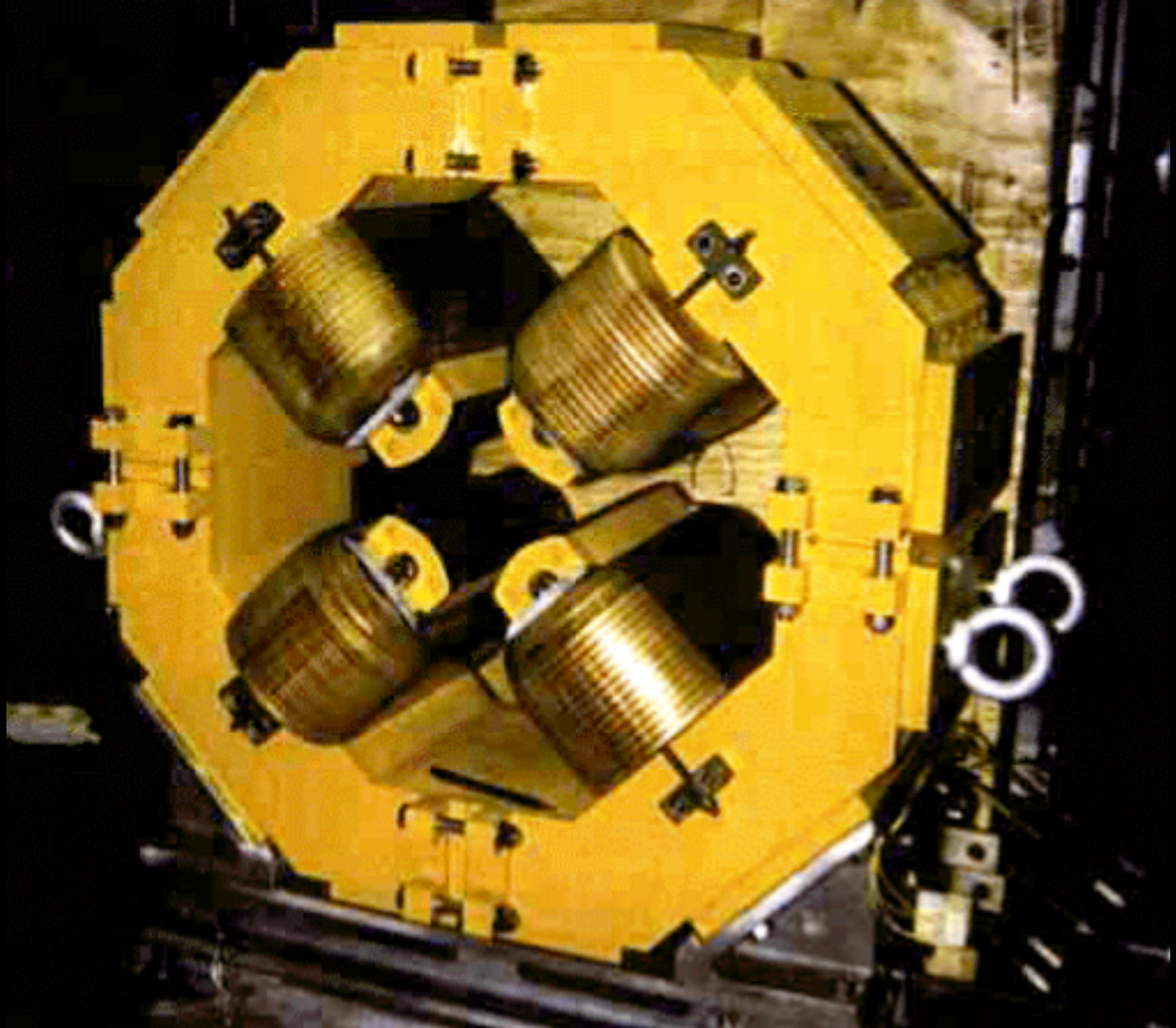
g[T/n] = field gradient



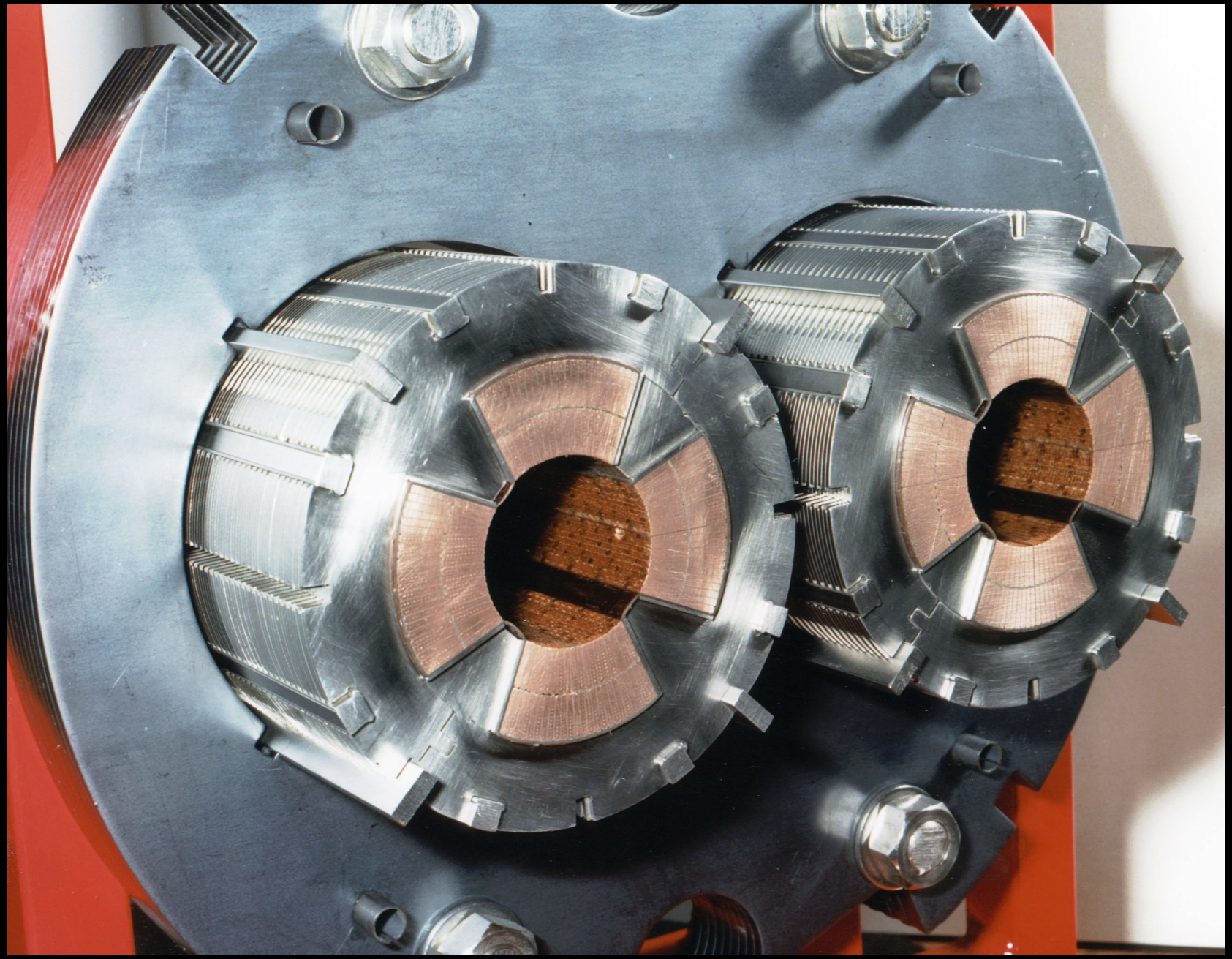
Focusing in one direction, defocusing in the other

FO-DO array

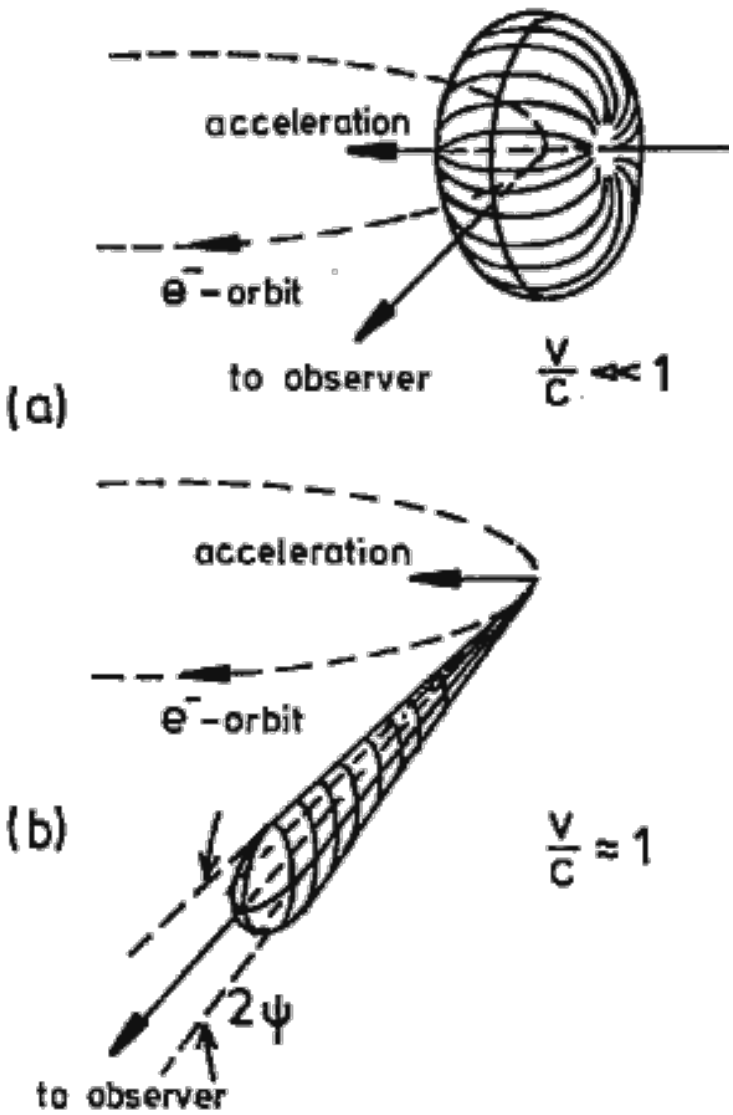




Fermilab



Syncrotron radiation



energy lost per revolution

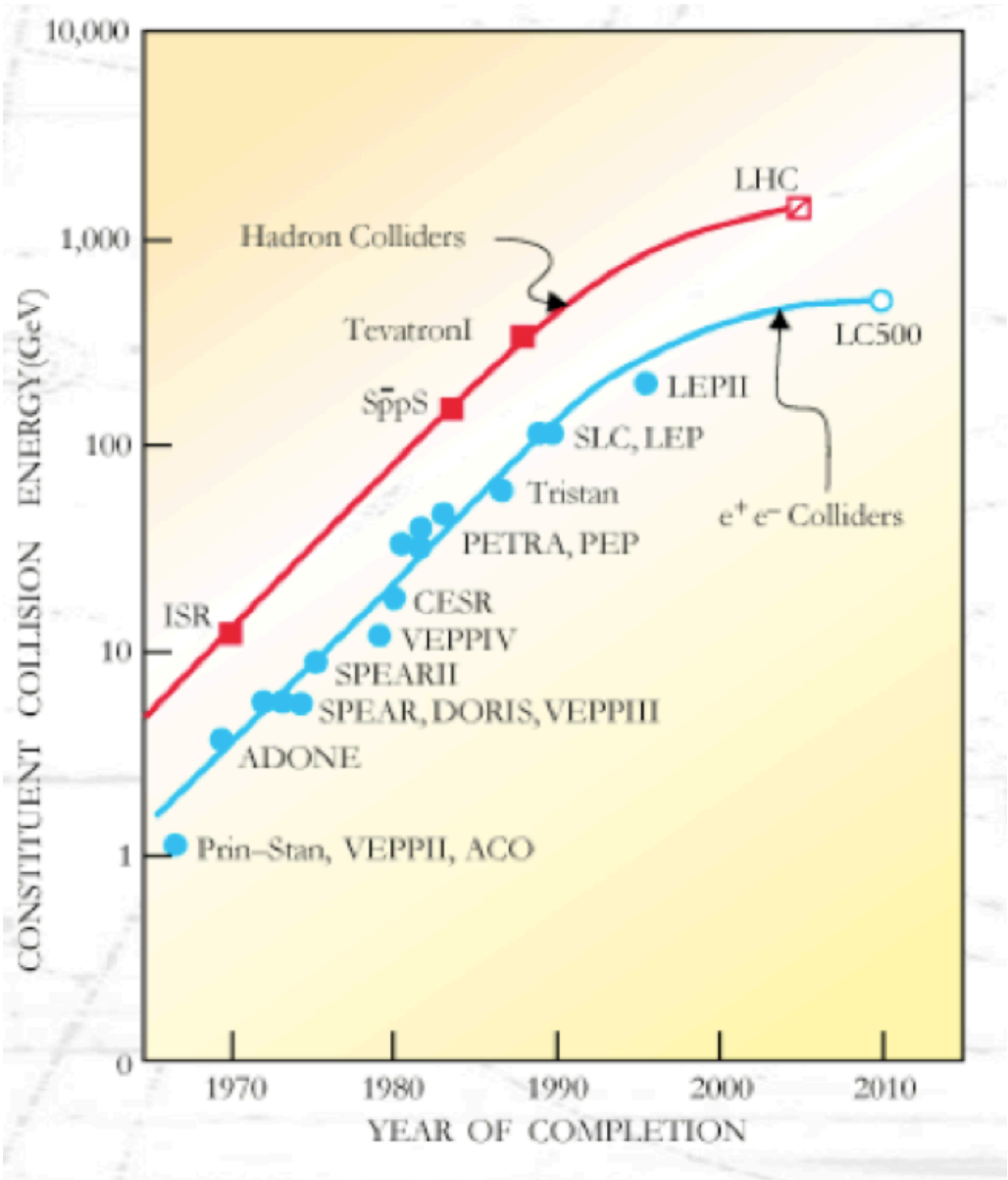
$$\Delta E = \frac{4\pi}{3}\frac{1}{4\pi\epsilon_0}\left(\frac{e^2\beta^3\gamma^4}{R}\right)$$

electrons vs. protons

$$\frac{\Delta E_e}{\Delta E_p} \simeq \left(\frac{m_p}{m_e}\right)^4$$

It's easier to accelerate protons to higher energies, but protons are fundamentals…

e^+-e^- vs. hadron collider



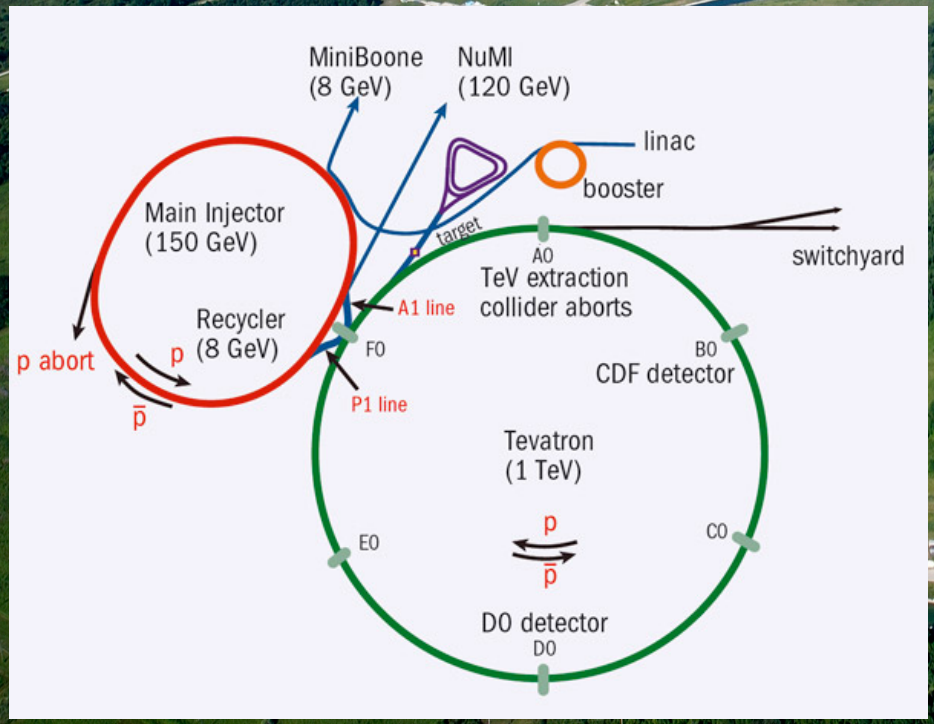
5-10

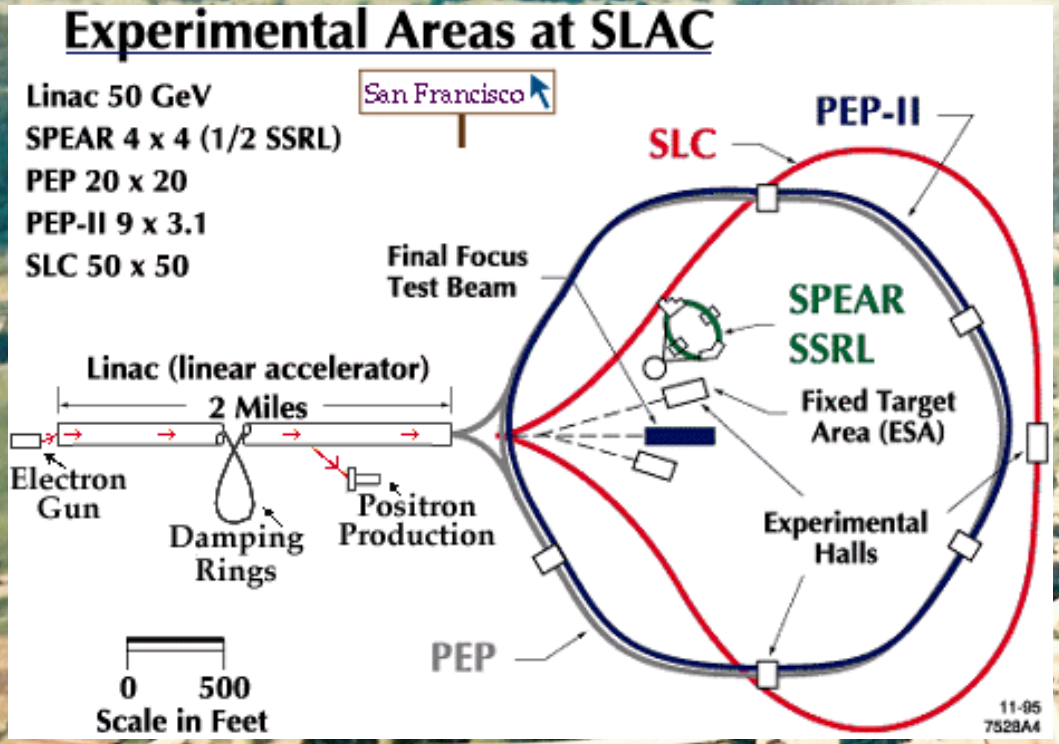
Tevatron

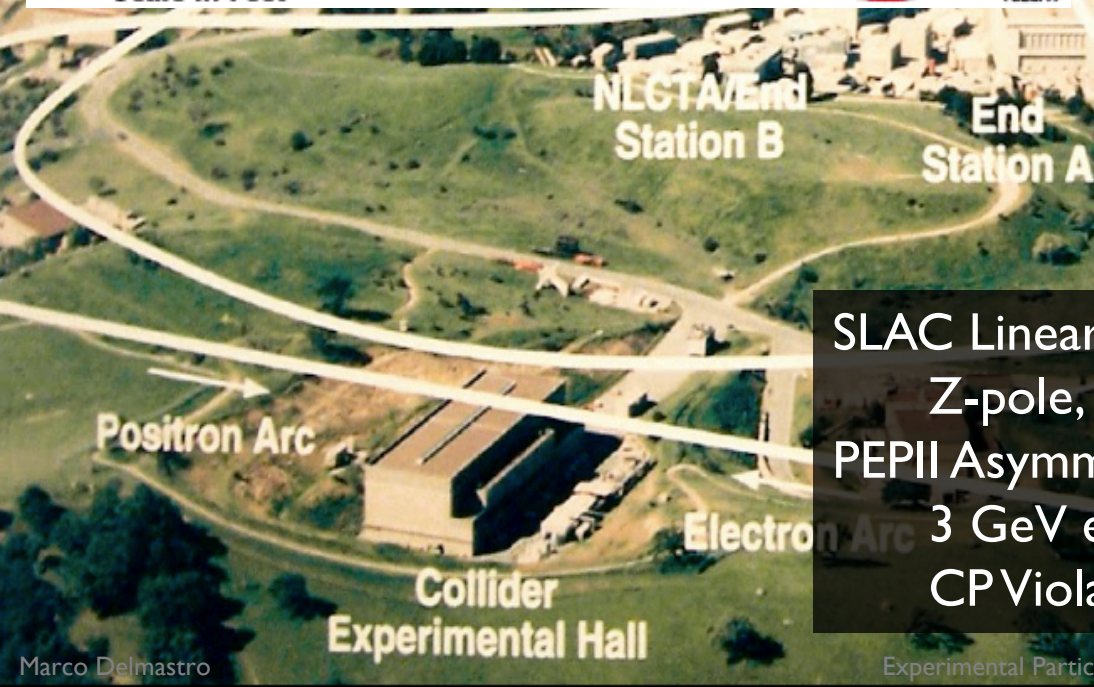
$p\bar{p}$ collider (1983-2011)

$\sqrt{s}$ = 1.96 TeV

CDF-D0
- top quark discovery
- Higgs search
- new physics



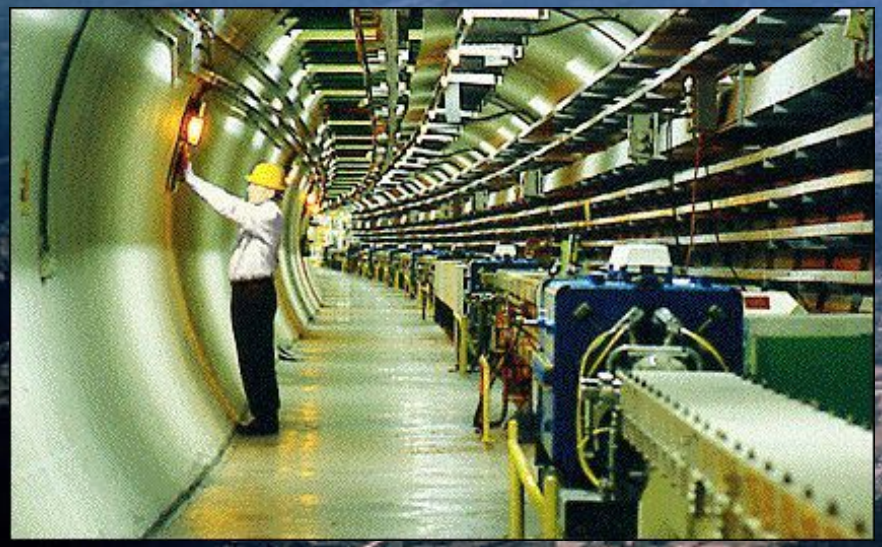


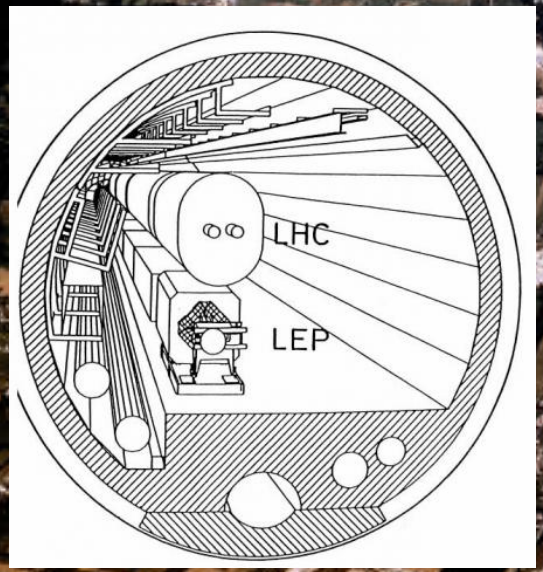


SLAC Linear Collider (1990-1998)
Z-pole, EW physics, B-physics, polarized beams
PEPII Asymmetric Storage Ring (1999-2008)
3 GeV e+ on 9 GeV e- (very high luminosity)
CP Violation, B-physics, rare decays

LEP

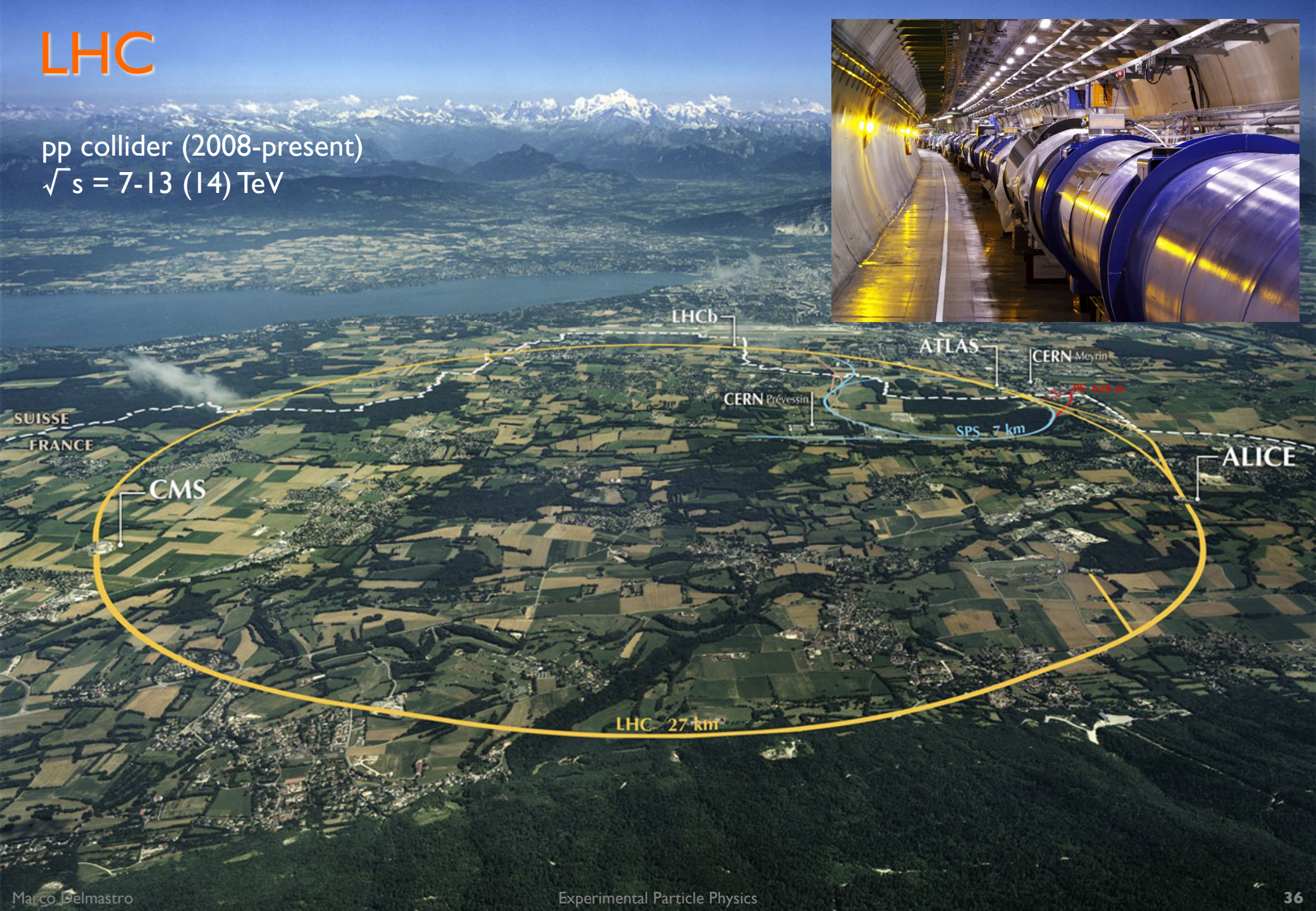
e^+-e^- collider (1998-2000)
$\sqrt{s}$ = 91 GeV (LEP)
$\sqrt{s}$ ~ 200 GeV (LEP2)



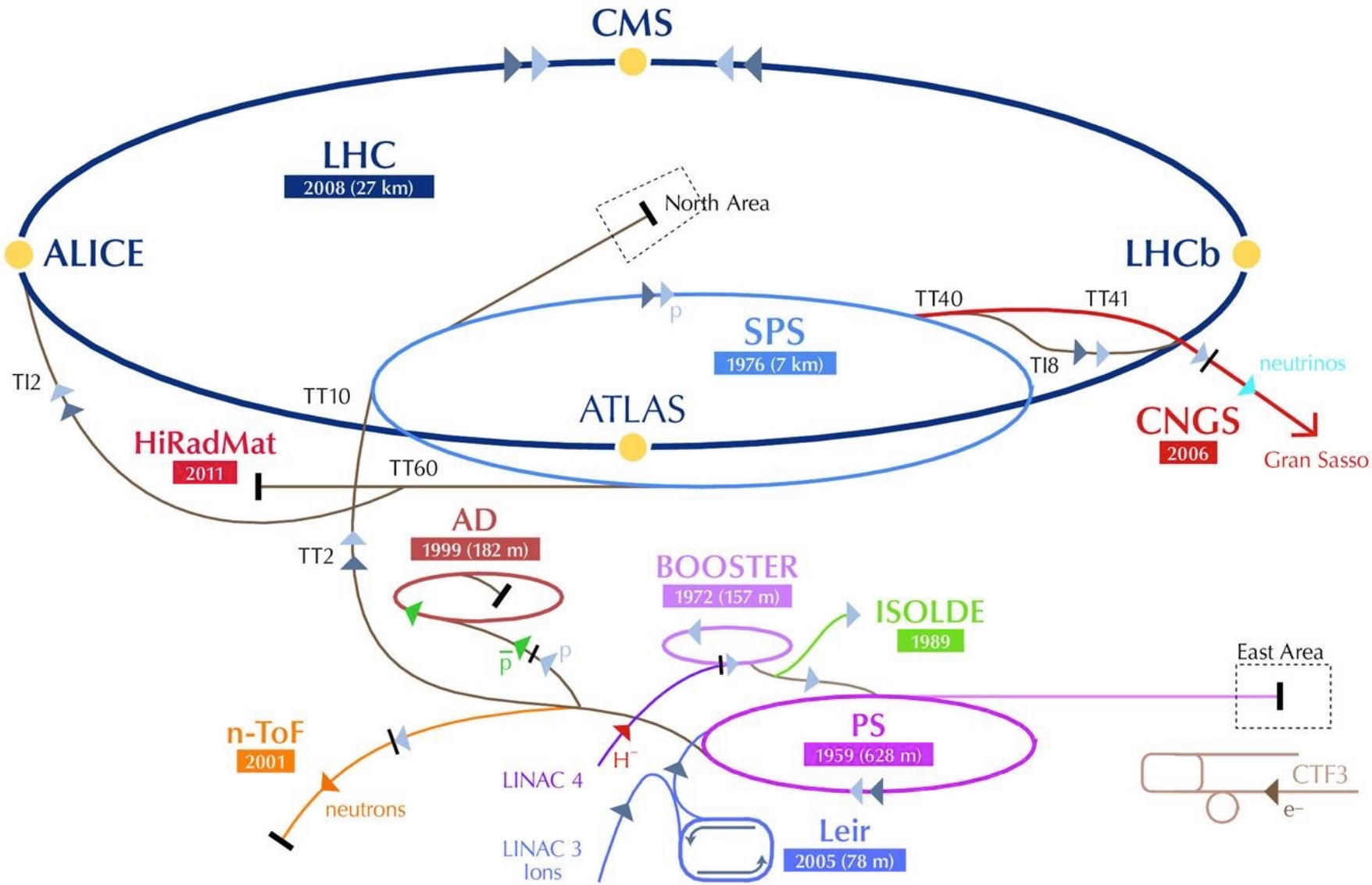


LHC

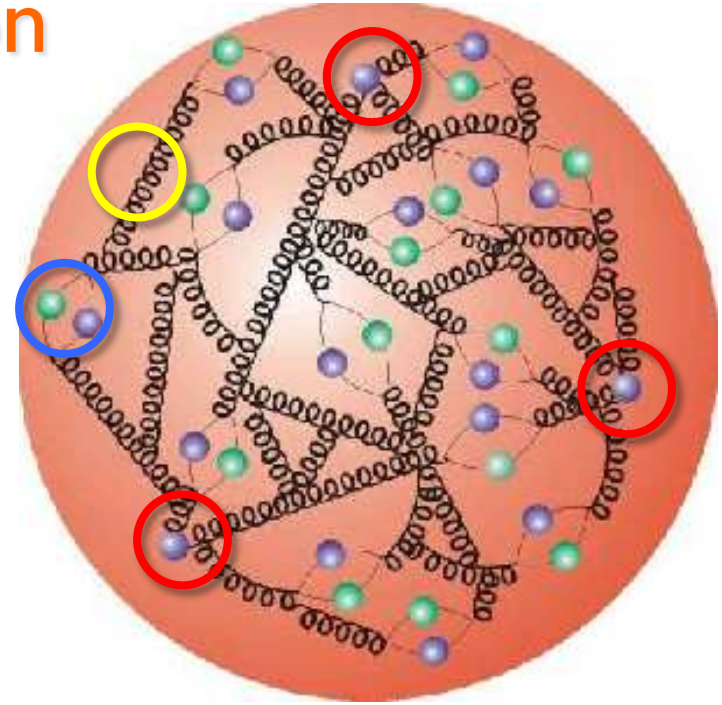
pp collider (2008-present)
$\sqrt{s}$ = 7-13 (14) TeV



CERN accelerator complex

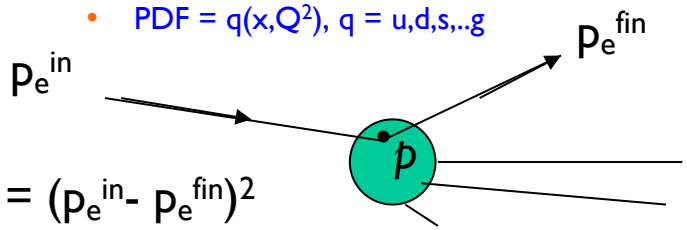


About the inner life of a proton



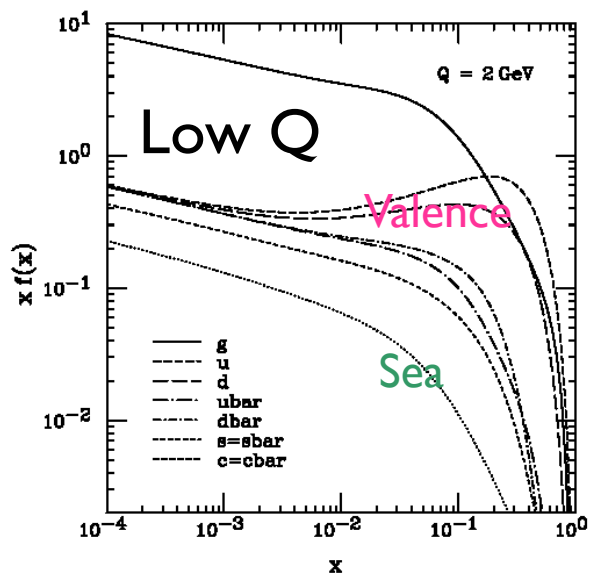
- ***p*rotons have substructures**
  - ✓ partons = quarks & gluons
  - ✓ 3 valence (colored) quarks bound by gluons
  - ✓ Gluons (colored) have self-interactions
  - ✓ Virtual quark pairs can pop-up (sea-quark)
  - ✓ *p* momentum shared among constituents
    - described by *p* structure functions

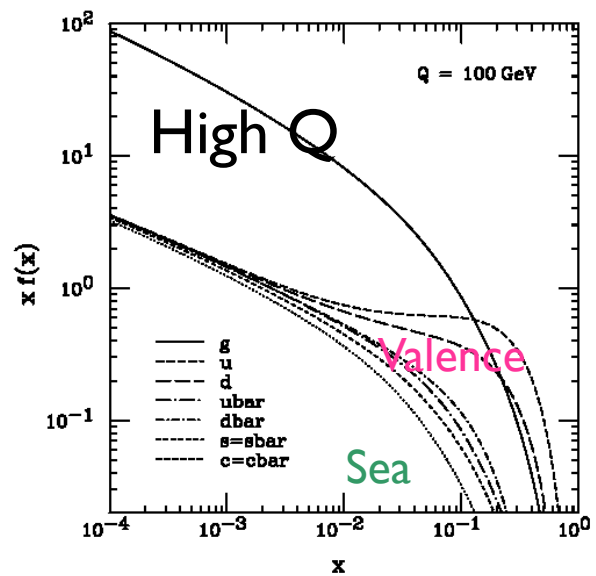
- **Parton energy not 'monochromatic'**
  - ✓ Parton Distribution Function
    - PDF = $q(x,Q^2)$, q = u,d,s,..g



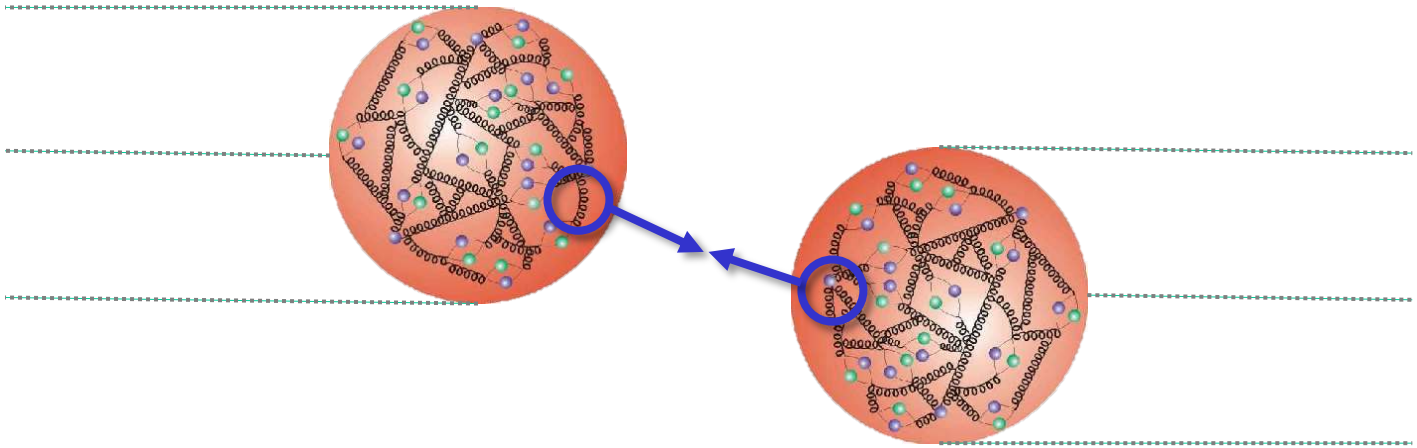
$Q^2 = (p_e^{in} - p_e^{fin})^2$

- **Kinematic variables**
  - ✓ Bjorken-x: fraction of the proton momentum carried by struck parton
    - $x = p_{parton}/p_{proton}$
  - ✓ Q^2 : 4-momentum^2 transfer



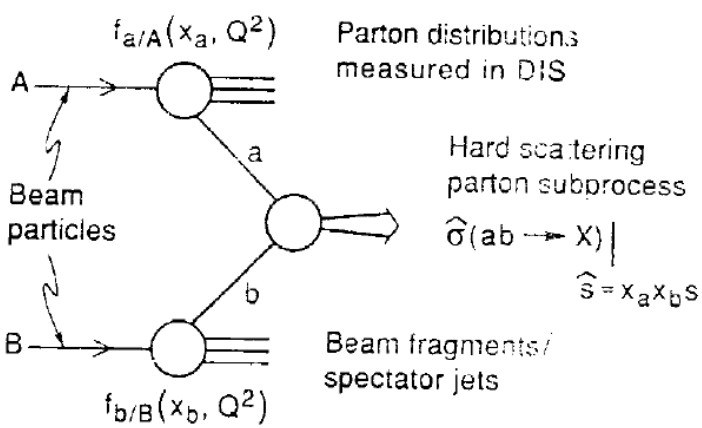


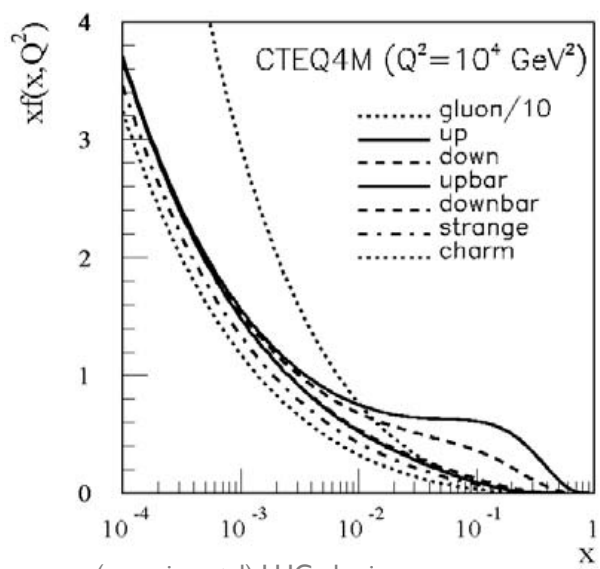
Cross sections at a proton-proton collider



$$\sqrt{\hat{s}} = \sqrt{x_a x_b s}$$

$$\sigma = \sum_{a,b} \int dx_a dx_b f_a(x, Q^2) f_b(x, Q^2) \hat{\sigma}_{ab}(x_a, x_b)$$



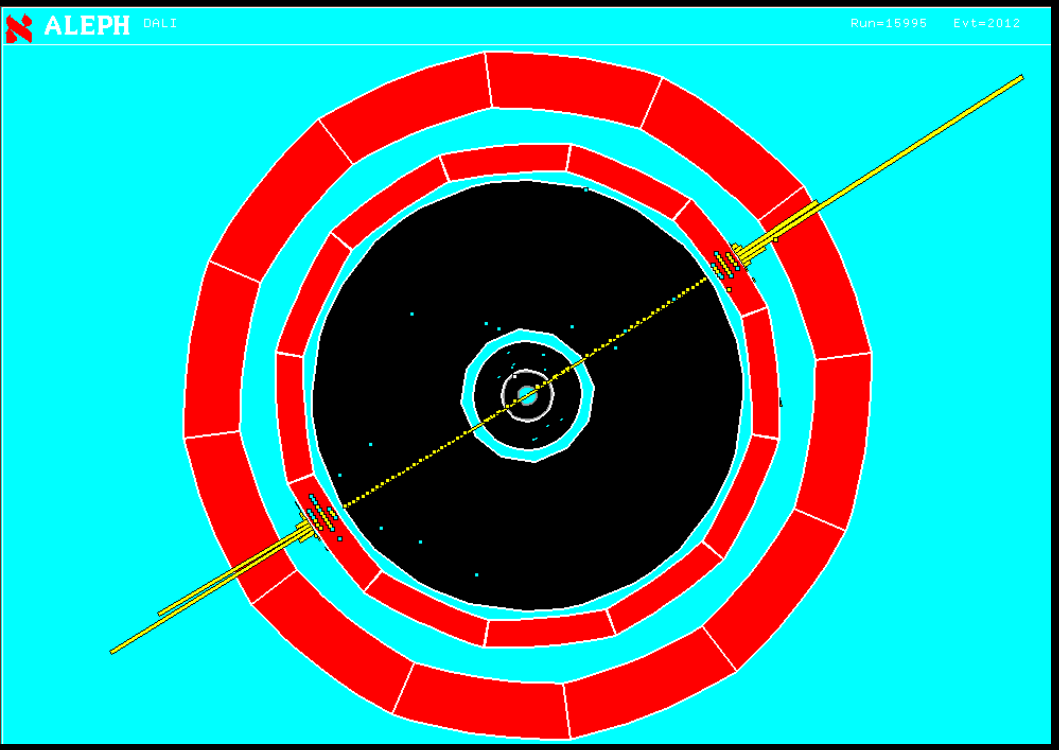


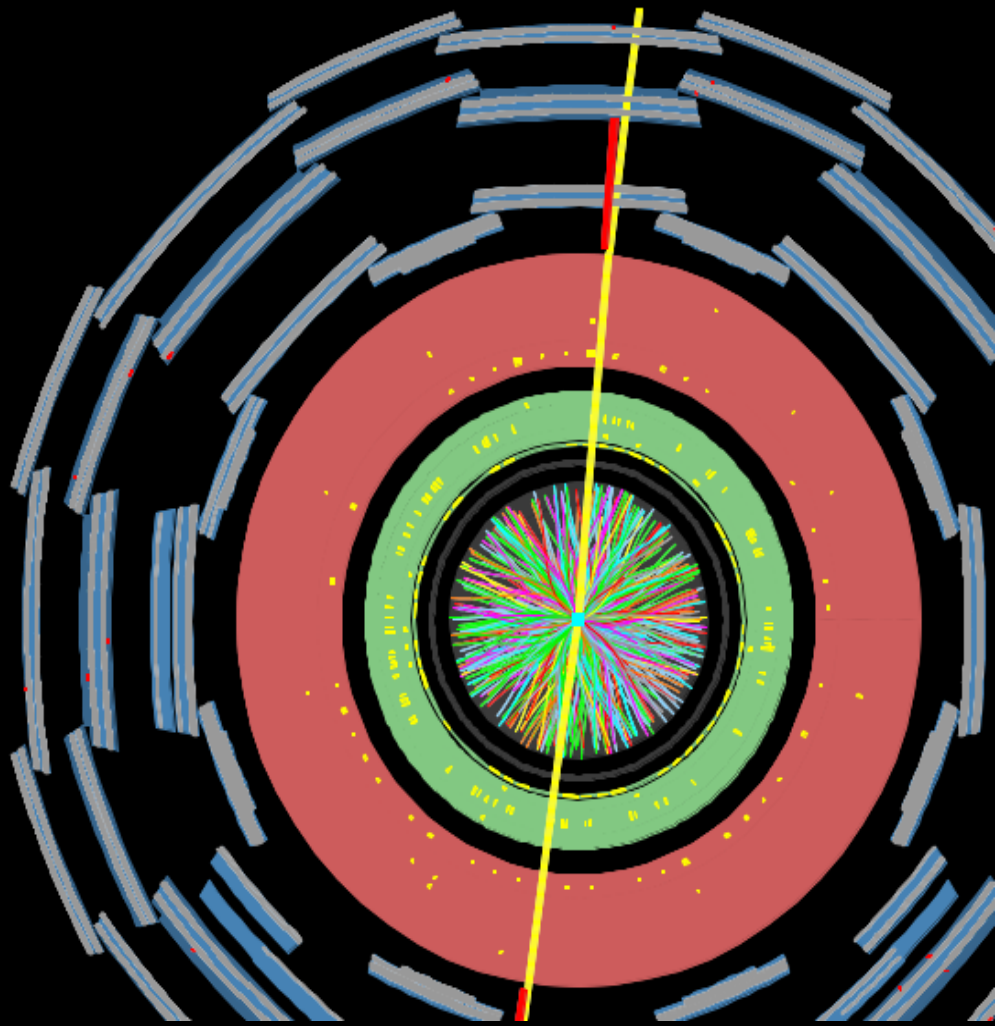
Example: to produce a particle with mass m = 100 GeV

$\sqrt{\hat{s}}$ = 100 GeV

$\sqrt{s}$ = 14 TeV → $x_a x_b$ = 0.007

A $Z \rightarrow e^+e^-$ event at LEP and ad LHC





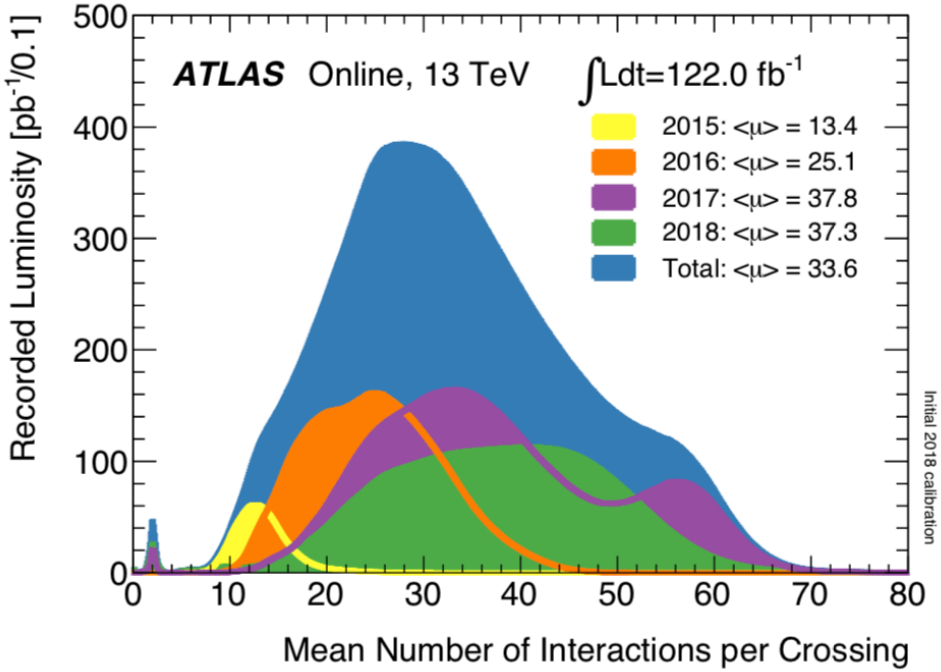
ALEPH @ LEP

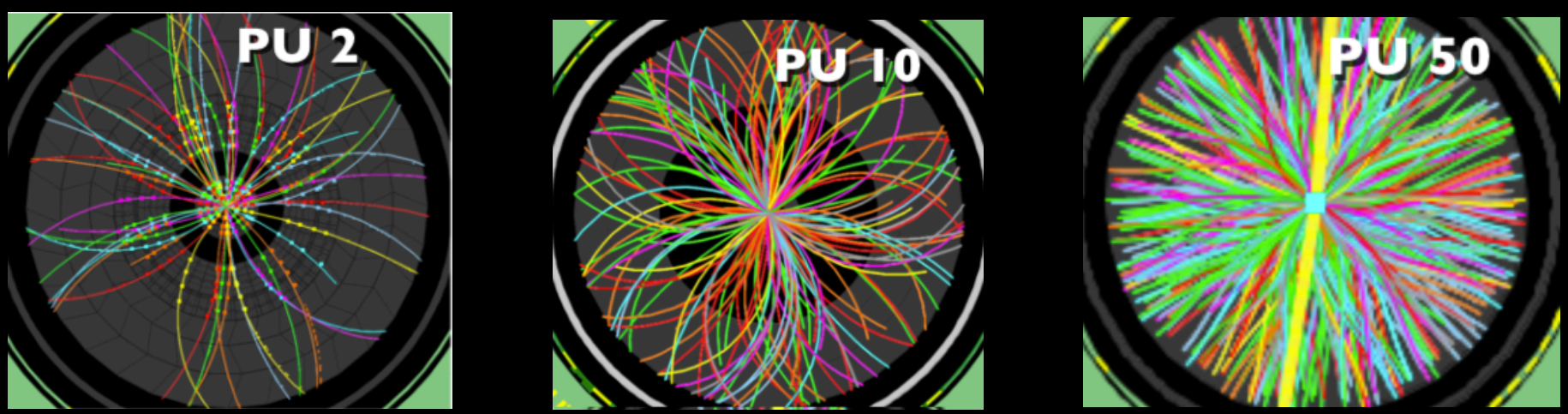
ATLAS @ LHC

Pile-Up

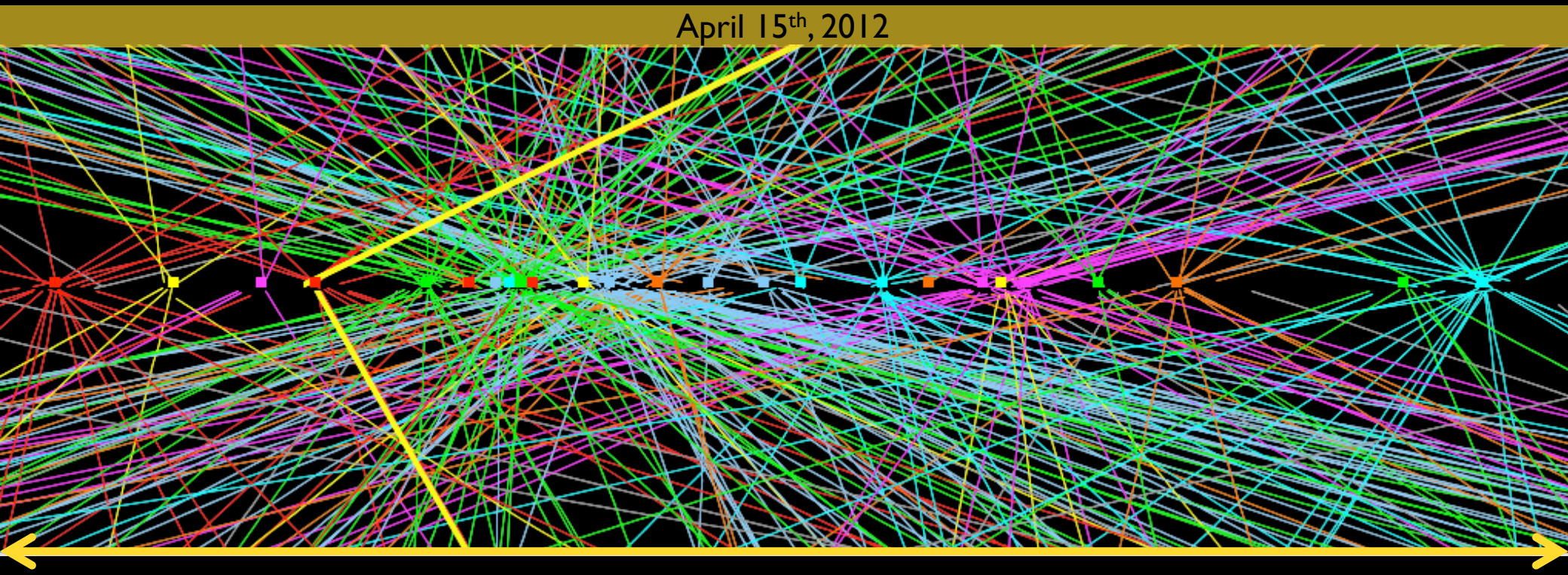
$$\mathcal{L} = \frac{1}{4\pi} \frac{f k N_1 N_2}{\sigma_x \sigma_y}$$

PU = number of inelastic interactions per beam bunch crossing





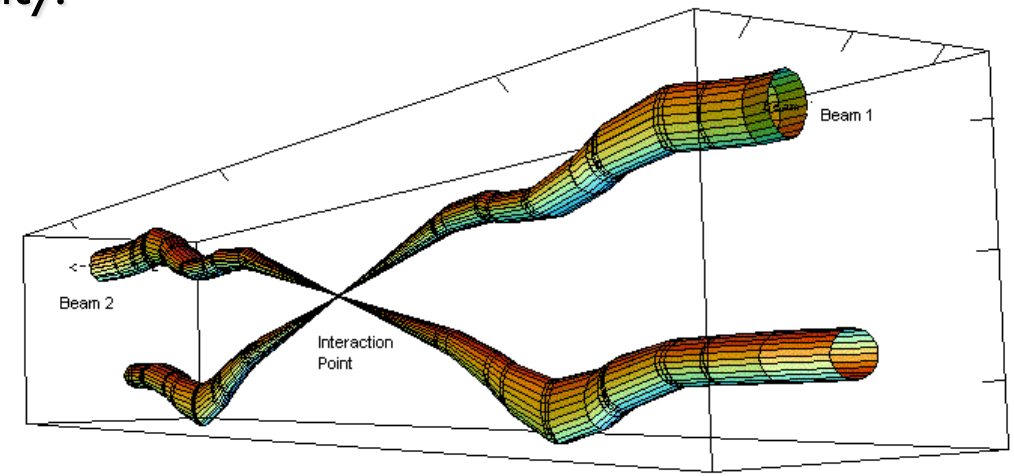
Z→μμ event with 25 reconstructed vertices



Crossing angle

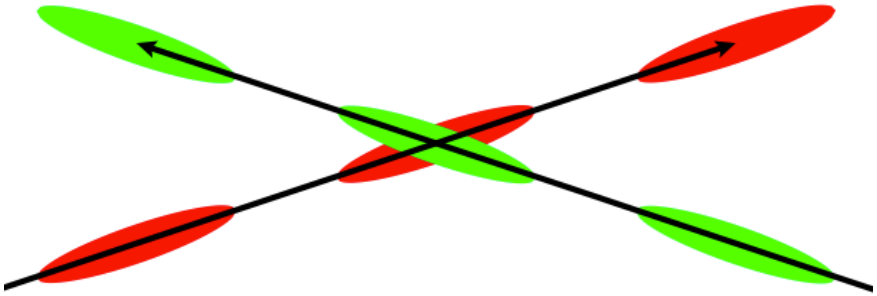
- To avoid parasitic encounters, beams with close bunches often cross at an angle
  - ✓ LHC beams cross at an angle of 300 microradian (bunch spacing 25 ns)
- Crossing angle has an impact on luminosity!

$$\frac{L}{L_0} = \frac{1}{\sqrt{1 + \left(\frac{\sigma_z}{\sigma_x} \tan \frac{\theta_c}{2}\right)^2}}$$

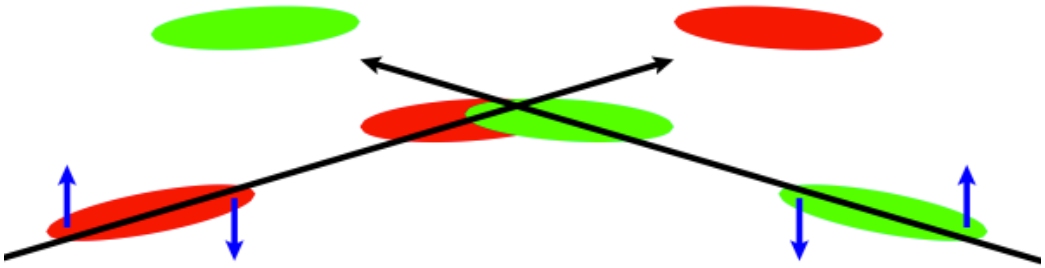


Relative beam sizes around IP1 (Atlas) in collision

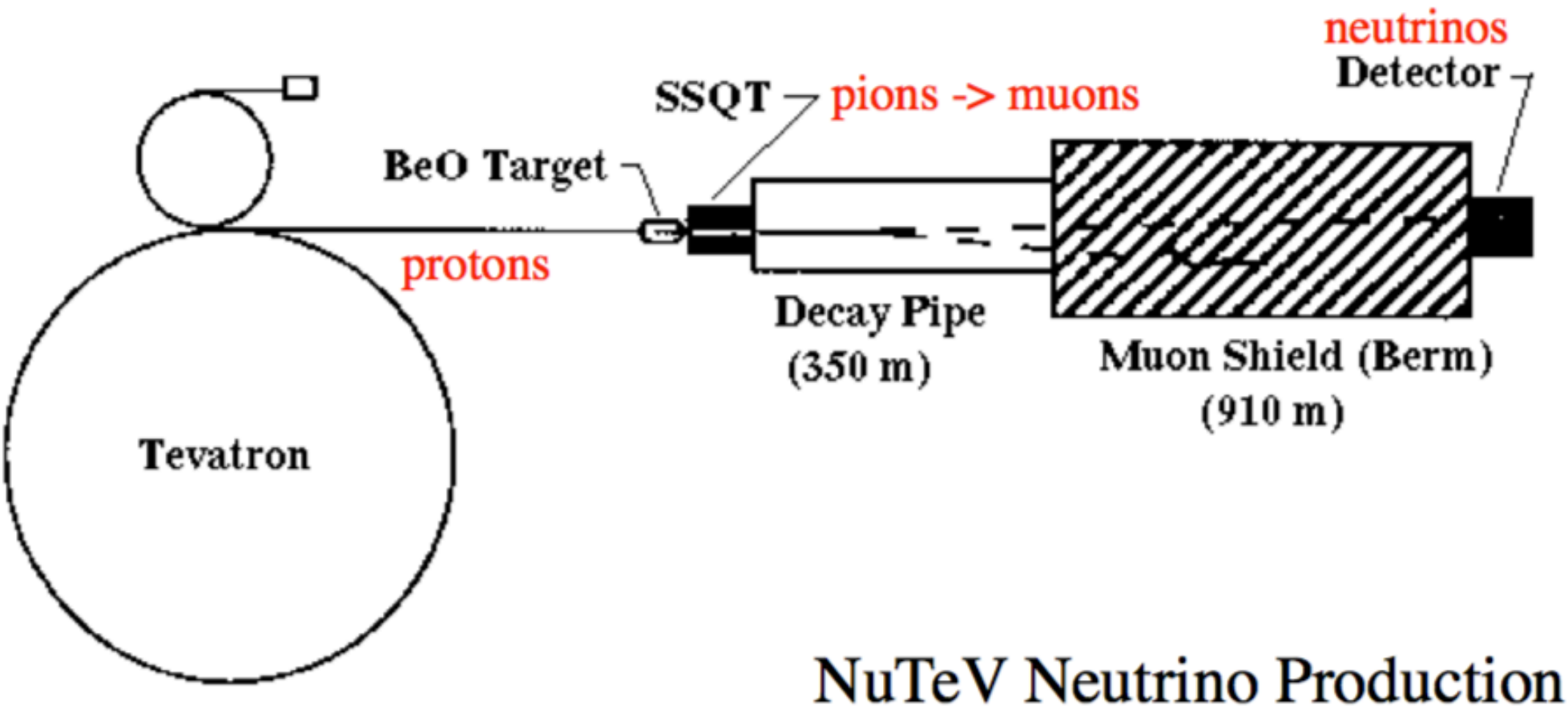
with crossing angle



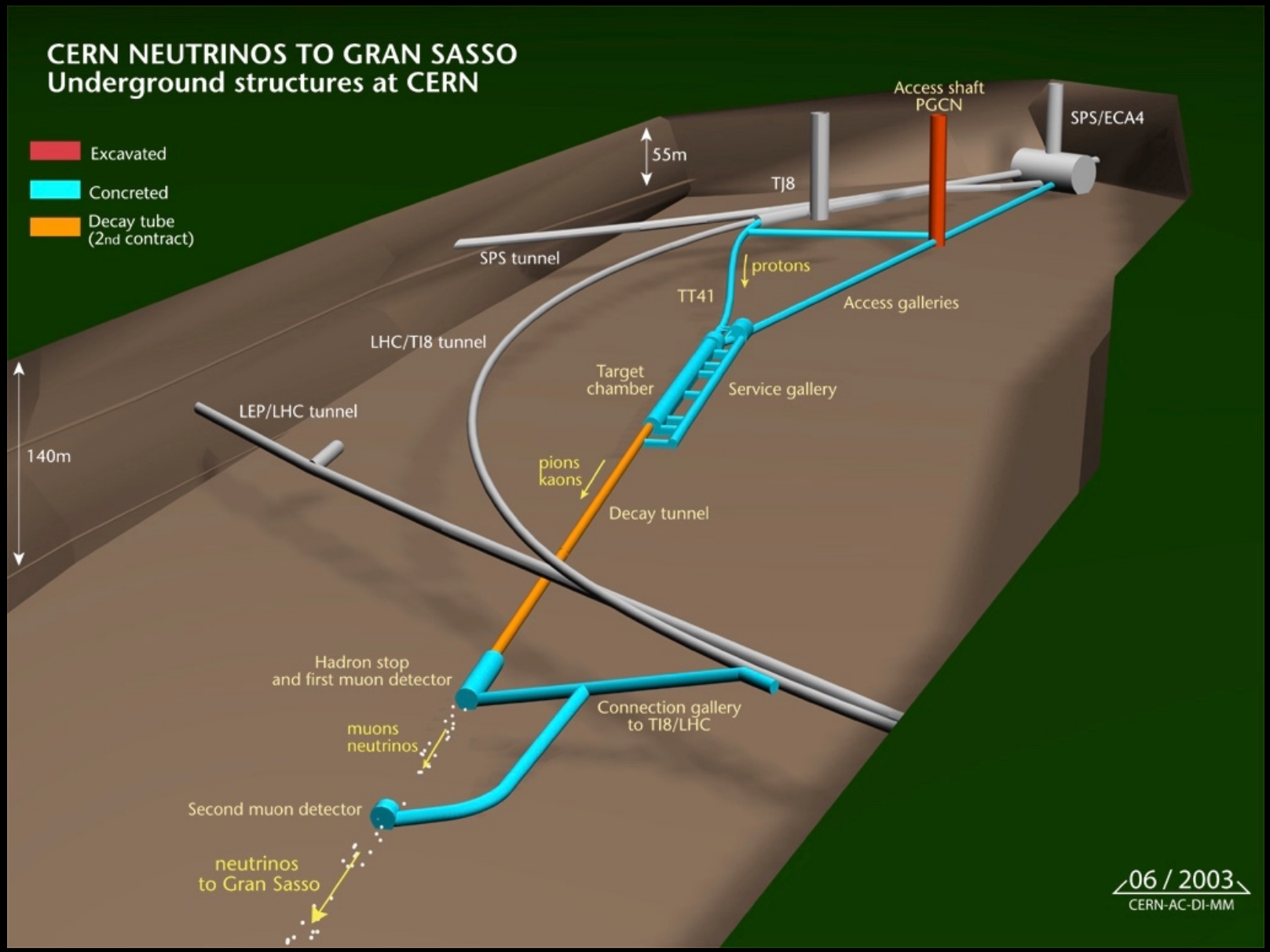
"crab" crossing



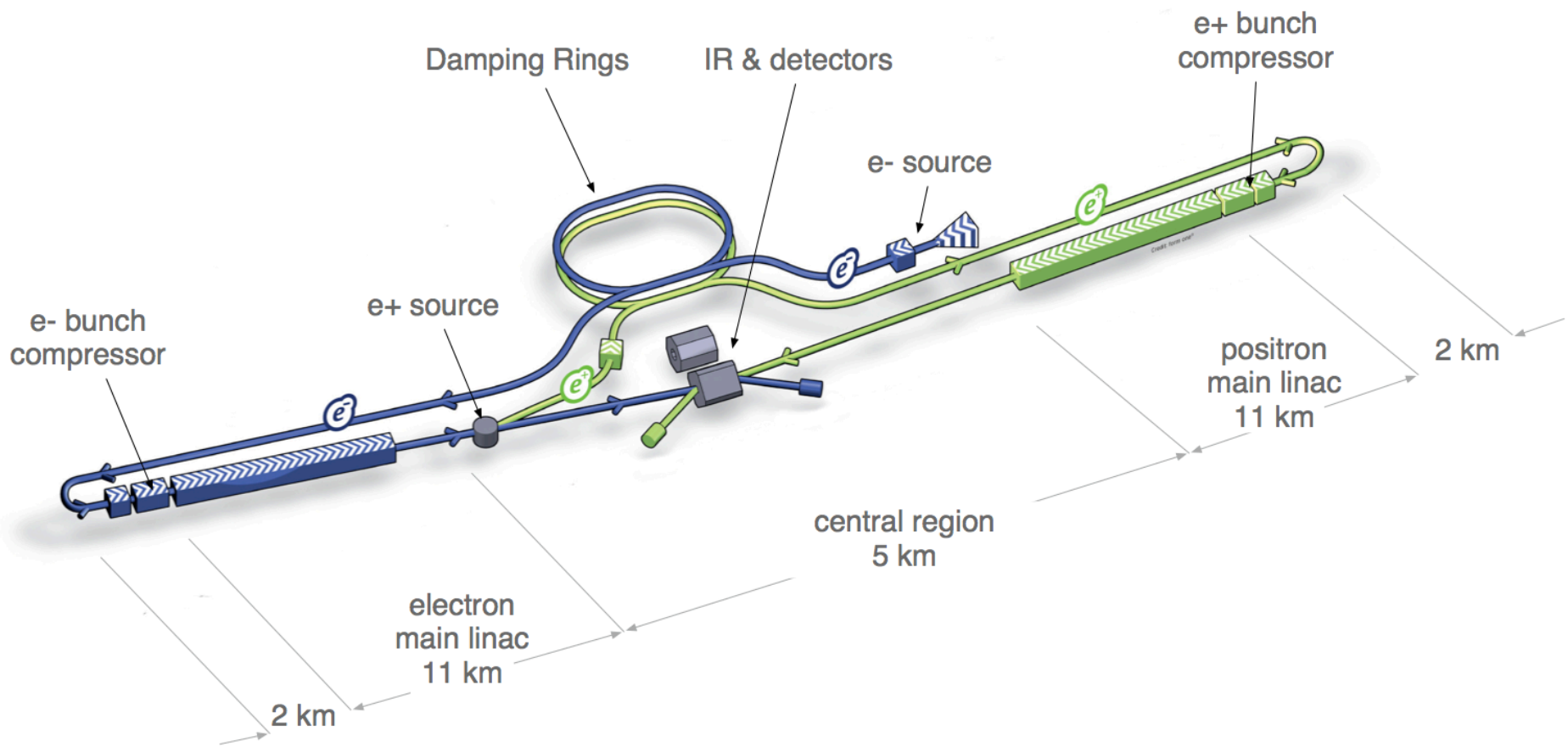
Production of secondary beams



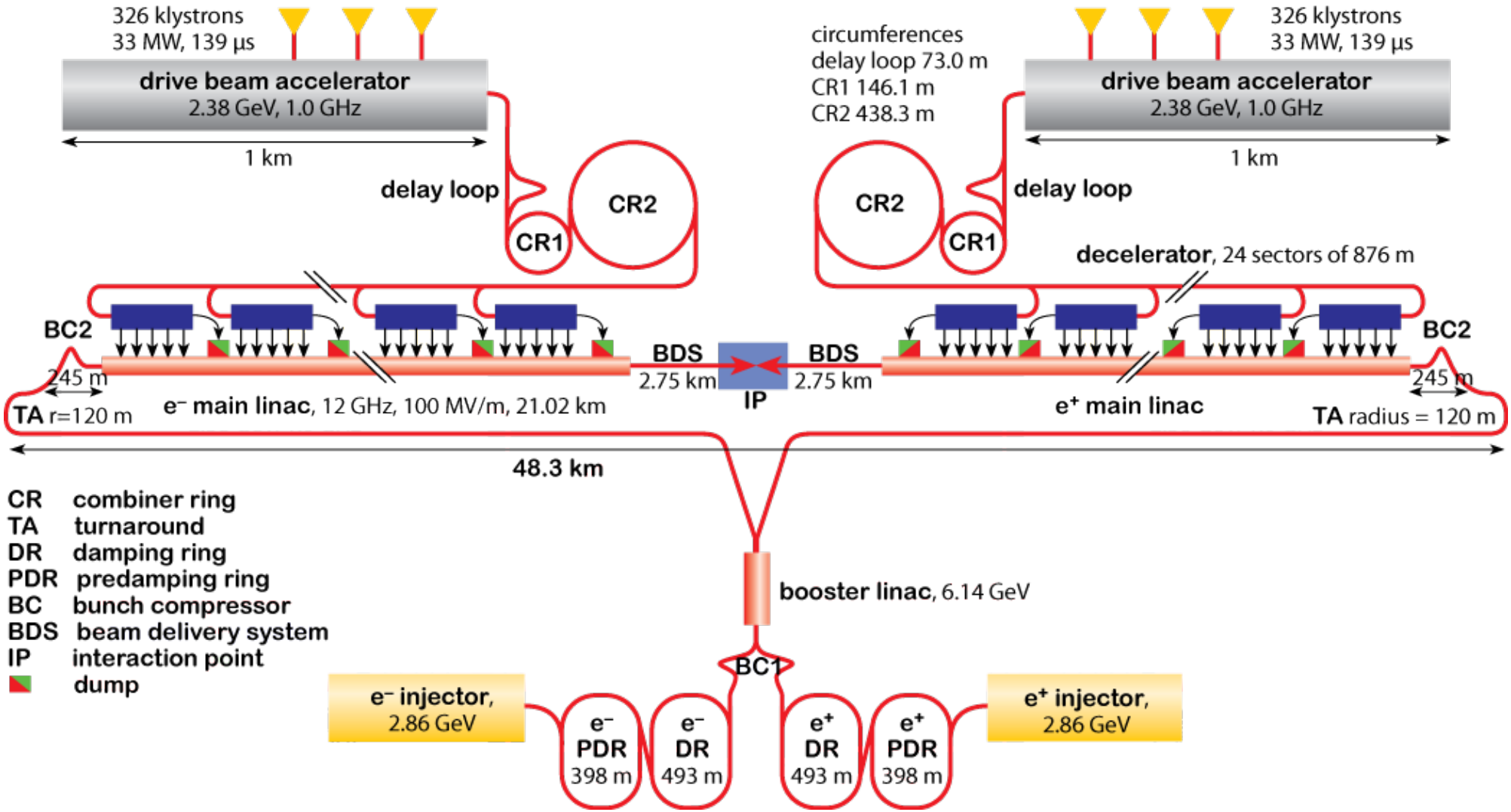
Production of secondary beams



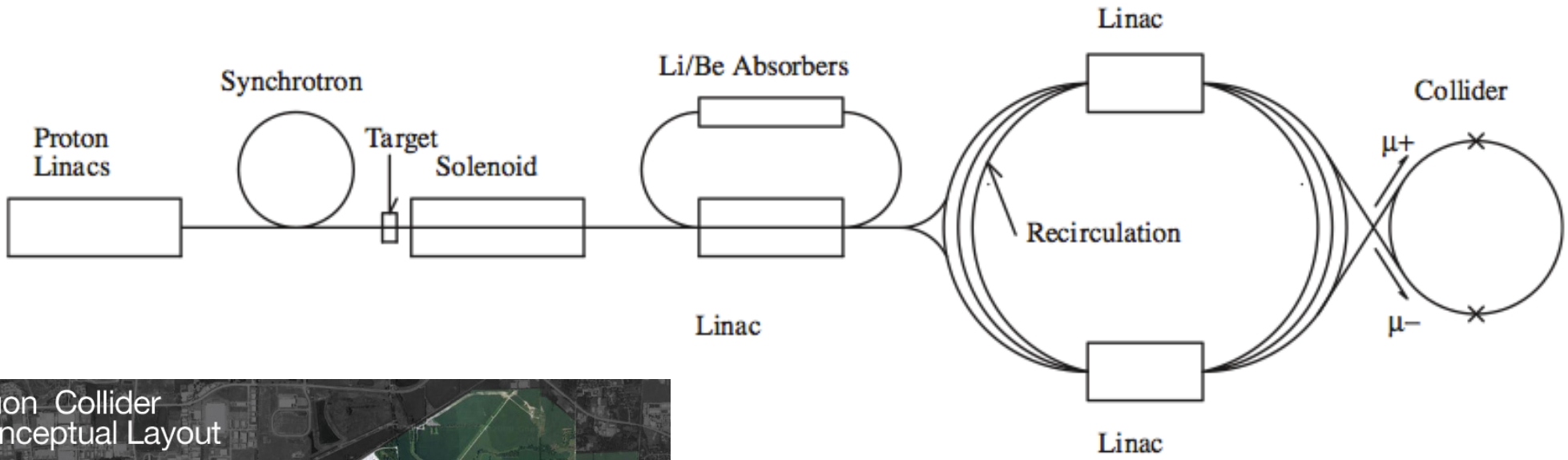
Future colliders? ILC

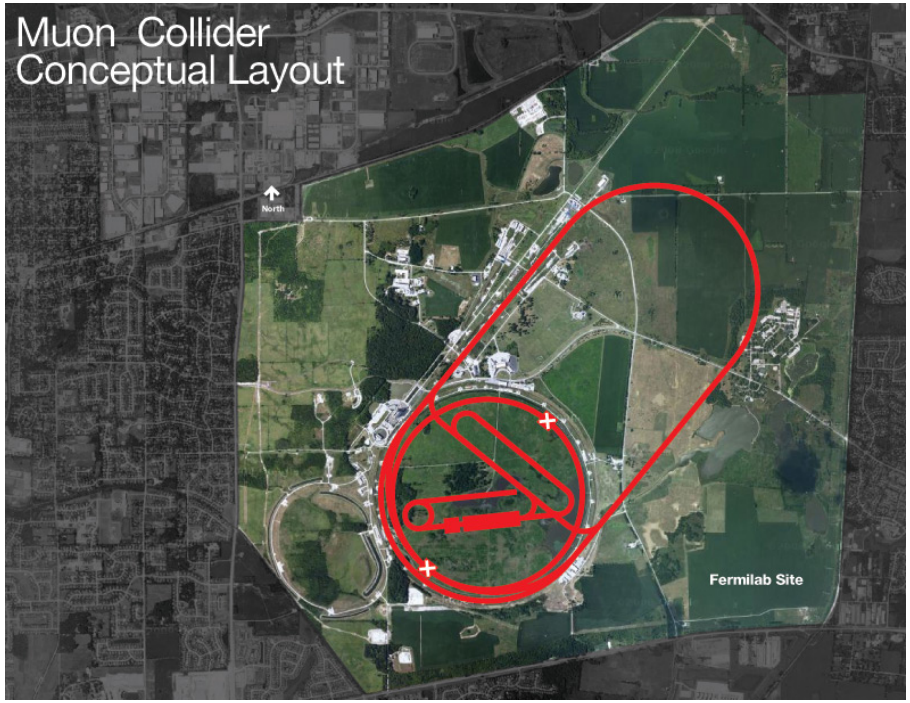


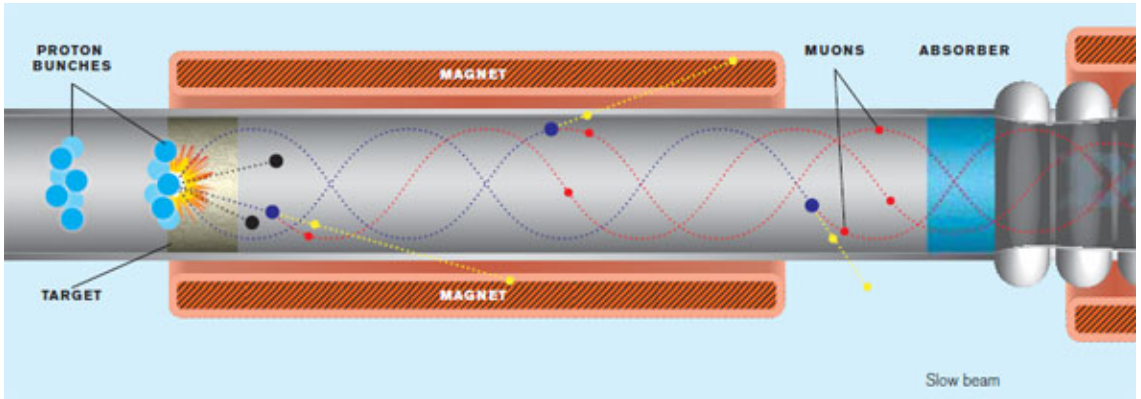
Future colliders? CLIC

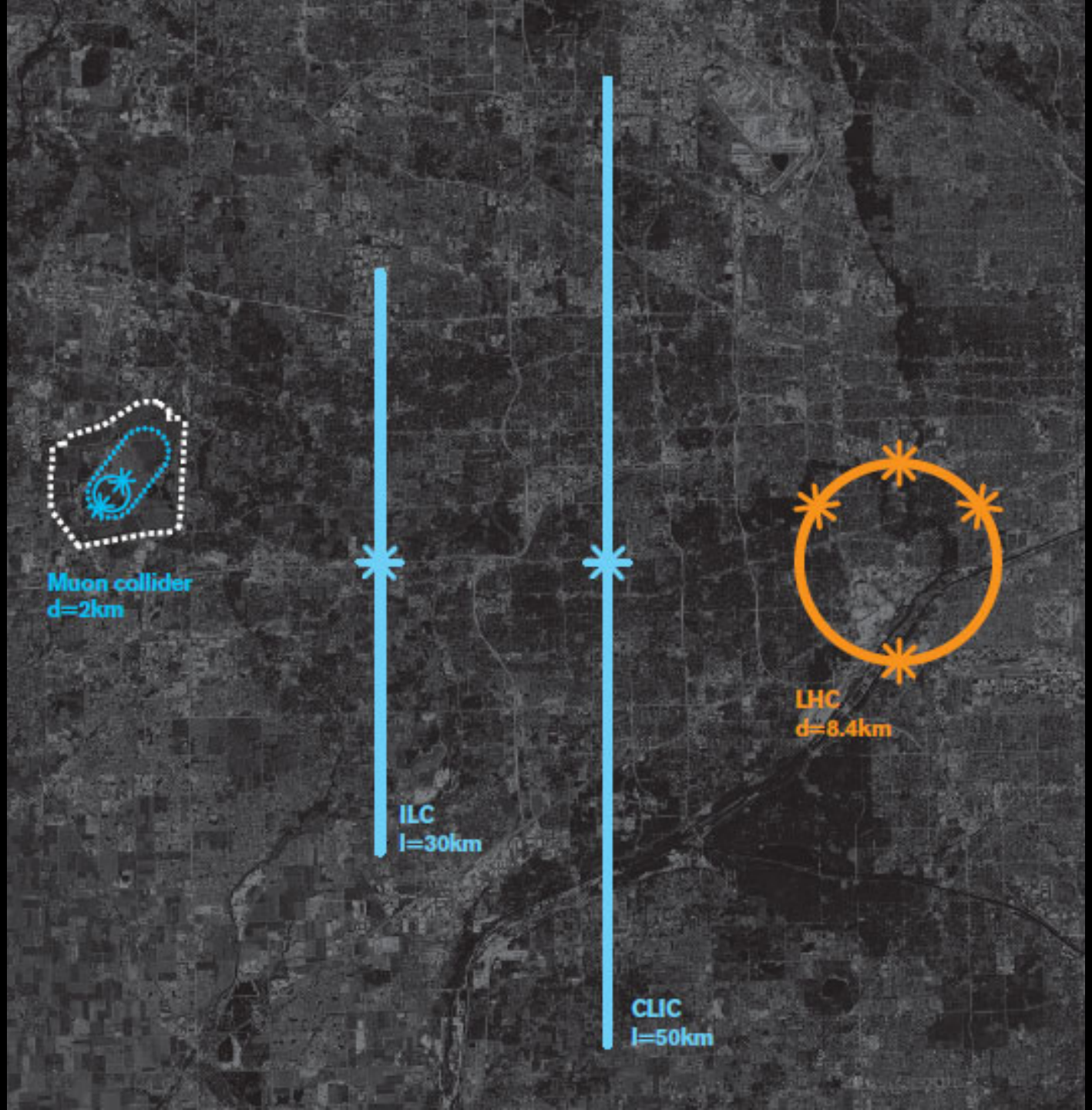


Future colliders? Muon collider

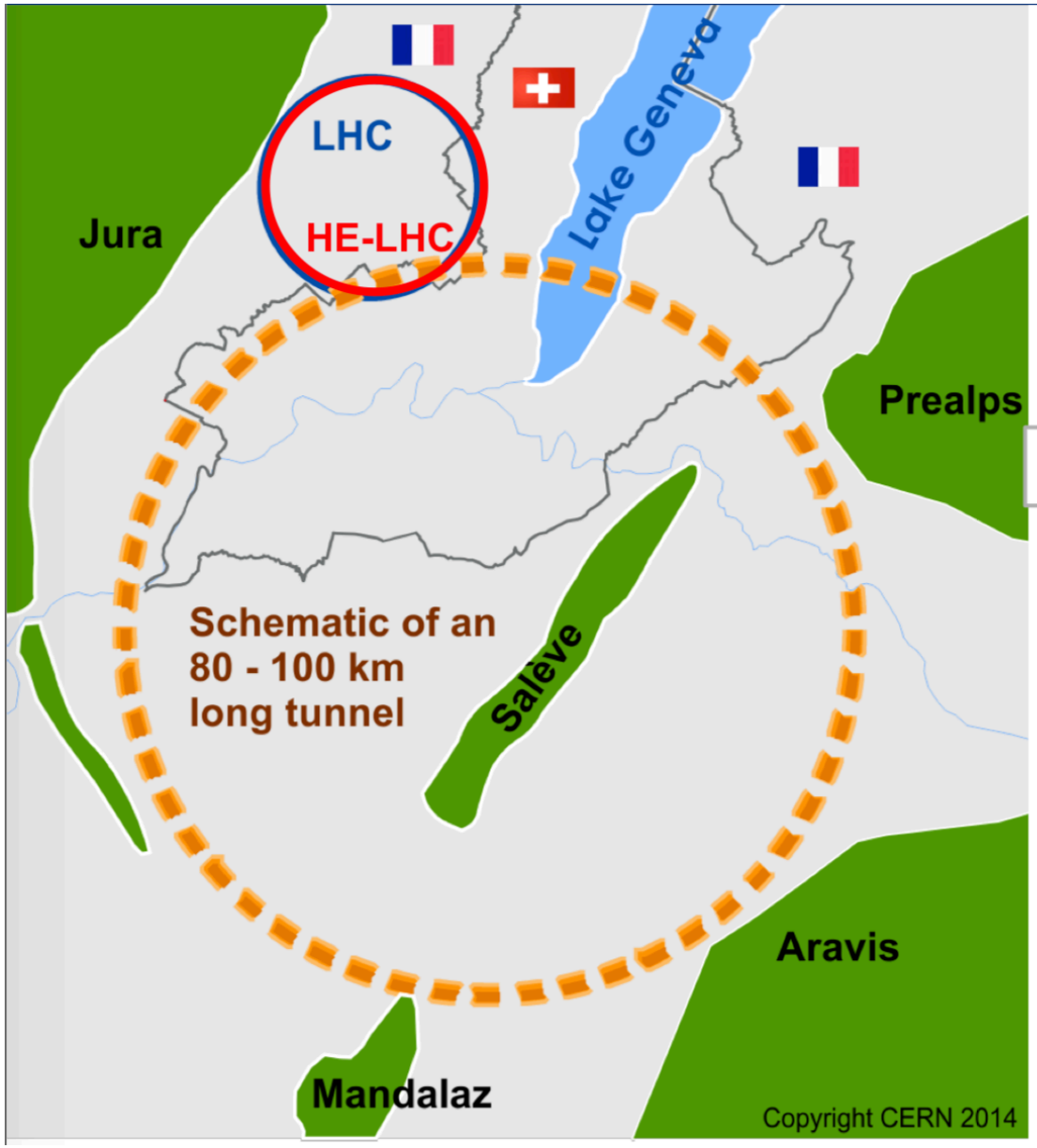







Muon collider
d=2km
ILC
l=30km
CLIC
l=50km
LHC
d=8.4km

Future Circular Collider (FCC)



International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e^- from ERL

Future Circular Collider (FCC)

FCC-ee:

- **Exploration of 10 to 100 TeV energy scale via couplings with precision measurements**
- **~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)**
  (m_Z, m_W, m_{top}, $\sin^2\theta_w^{eff}$, R_b, $\alpha_{QED}(m_z)$ α_s (m_z m_W m_τ), Higgs and top quark couplings)

➢ **Machine design for highest possible luminosities at Z, WW, ZH and ttbar working points**

FCC-hh:

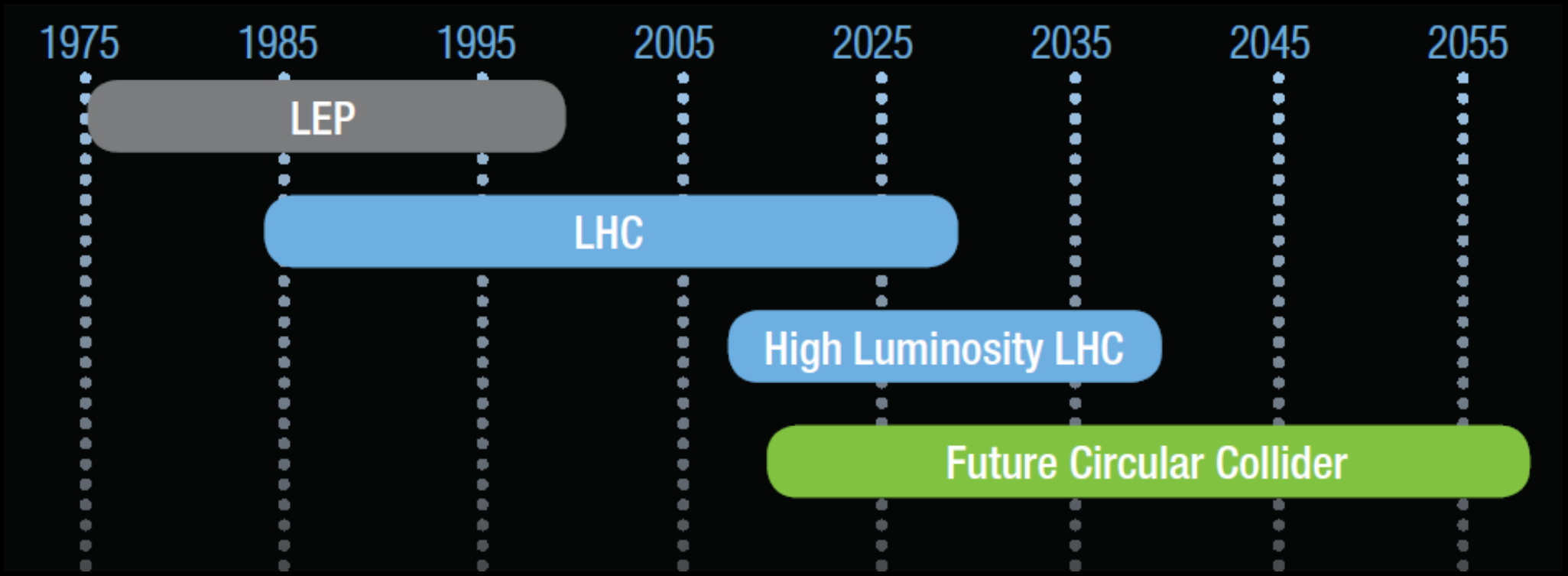
- **Highest center of mass energy for direct production up to 20 - 30 TeV**
- **Huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks**

➢ **Machine design for 100 TeV c.m. energy & integrated luminosity ~ 20ab^{-1} within 25 years**

HE-LHC:

- **Doubling LHC collision energy with FCC-hh 16 T magnet technology**
- **c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC**

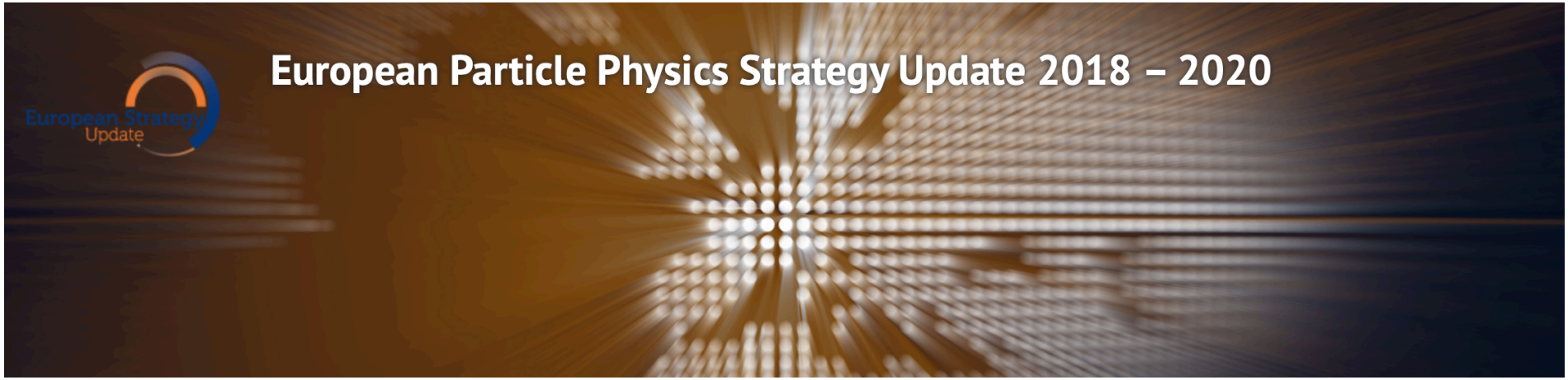
➢ **Machine design within constraints from LHC CE and based on HL-LHC and FCC technologies**



https://fcc-cdr.web.cern.ch

Get curious, inform yourself on the future!

- **European Strategy for Particle Physics**
  - ✓ http://europeanstrategyupdate.web.cern.ch



- **Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020**
  - ✓ https://arxiv.org/abs/1910.11775