Elementary Particle Physics: theory and experiments

Interactions

Akcelerators for high energy physics

Some slides from M. A. Thomson lectures at Cambridge University

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Preliminaries: Natural Units

- S.I. UNITS: **kg m s** are a natural choice for "everyday" objects

- not very natural in particle physics
- instead use Natural Units based on the language of particle physics
  - **From Quantum Mechanics** - the unit of action : $\hbar$
  - **From relativity** - the speed of light: c
  - **From Particle Physics** - unit of energy: GeV (1 GeV ~ proton rest mass energy)

★ **Units become (i.e. with the correct dimensions):**

Energy	GeV	Time	$(\mathrm{GeV}/\hbar)^{-1}$
Momentum	GeV/c	Length	$(\mathrm{GeV}/\hbar c)^{-1}$
Mass	GeV/c^2	Area	$(\mathrm{GeV}/\hbar c)^{-2}$

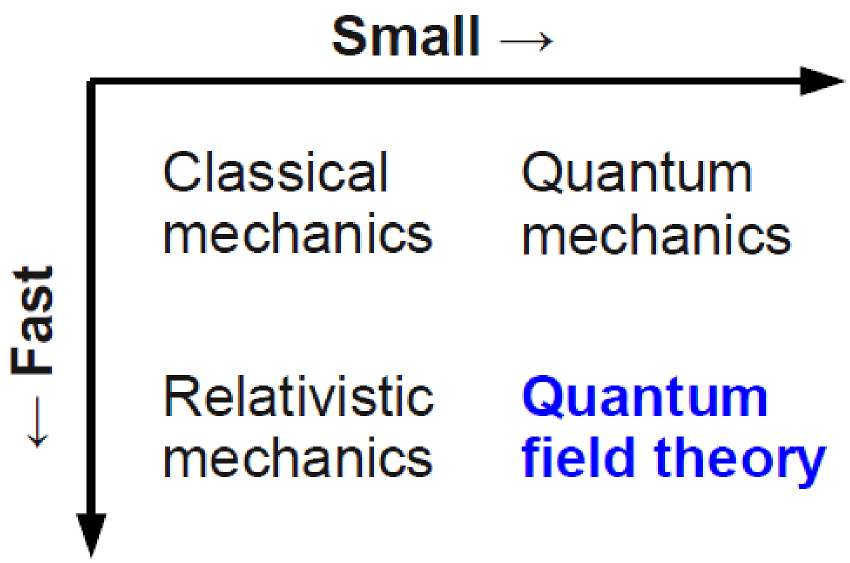
★ **Simplify algebra by setting:** $\hbar = c = 1$

- Now all quantities expressed in powers of GeV

Energy	GeV	Time	GeV^{-1}
Momentum	GeV	Length	GeV^{-1}
Mass	GeV	Area	GeV^{-2}

To convert back to S.I. units, need to restore missing factors of $\hbar$ and c

Quantum field theory



First major achievement: Dirac's equation for free electrons (and positrons)

$$E^2 - \mathbf{p}^2 c^2 = m^2 c^4$$

$$E = \pm\sqrt{\mathbf{p}^2 c^2 + m^2 c^4}$$

Interpretation of negative energies: sea of electrons → holes in sea act as positively charged electrons → confirmed by Anderson 1932

Paul Dirac
(NP 1933)

Carl Anderson
(NP 1936)

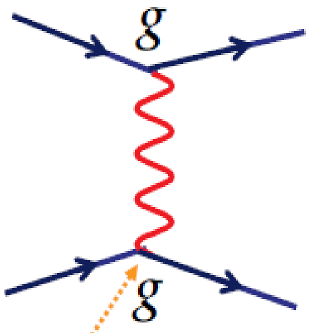
Interactions

- **In particle physics high energies are needed to create new particles and to explore the structure of hadrons. Energies must be at least of several hundred MeV.**
- **Any theory of elementary particles must combine the requirements of both special relativity and quantum theory.**
- **For every charged particle of nature, whether elementary or a hadron, there is an associated particle of the same mass, but opposite charge, called antiparticle. This result is a necessary consequence of combining special relativity with quantum mechanics.**
- **This important theoretical prediction was made by Dirac and follows from the solution of the equation he first wrote down to describe relativistic electrons.**

Forces in the Standard Model

★ Forces mediated by the exchange of spin-1 Gauge Bosons

Force	Boson(s)	J^P	m/GeV
EM (QED)	Photon γ	1^-	0
Weak	$W^\pm$ / Z	1^-	80 / 91
Strong (QCD)	8 Gluons g	1^-	0
Gravity (?)	Graviton?	2^+	0



- Fundamental interaction strength is given by charge g.
- Related to the **dimensionless** coupling "constant" α

e.g. QED $$g_{em} = e = \sqrt{4\pi\alpha\varepsilon_0\hbar c}$$

★ In Natural Units $$g = \sqrt{4\pi\alpha}$$

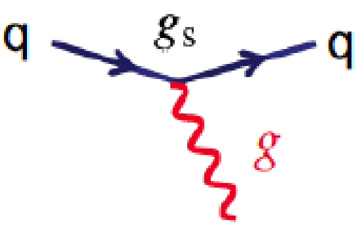
(both g and α are dimensionless, but g contains a "hidden" $\hbar c$)

★ Convenient to express couplings in terms of α which, being genuinely dimensionless does not depend on the system of units (this is not true for the numerical value for e)

Standard Model vertices

The interaction of gauge bosons with fermions is described by the Standard Model

STRONG



Only quarks

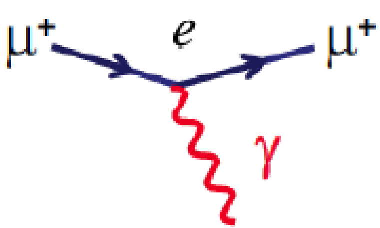
Never changes flavour

$\alpha_S \sim 1$

Gluons

massless

EM



All charged fermions

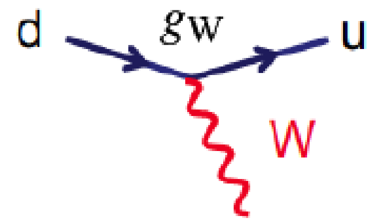
Never changes flavour

$\alpha \simeq 1/137$

Photon

massless

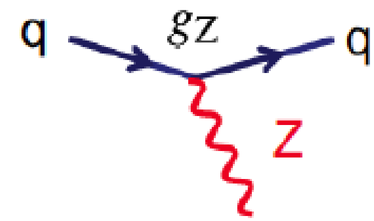
WEAK CC



All fermions

<u>Always</u> changes flavour

WEAK NC



All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

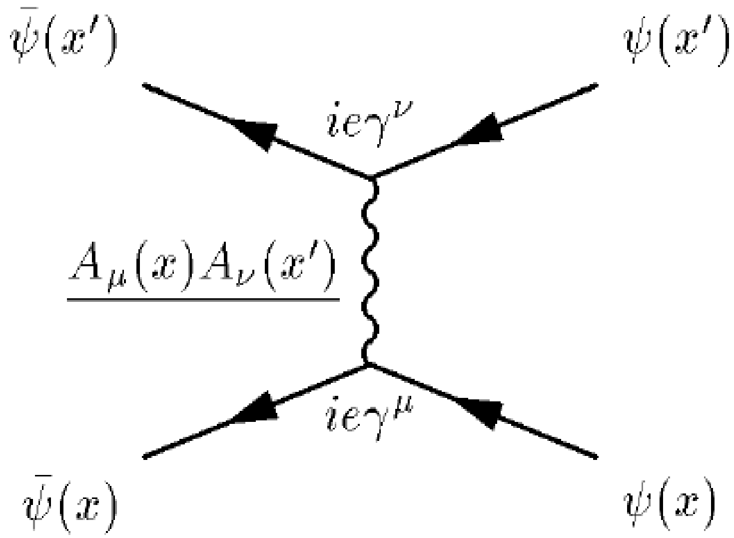
W+, W-

very massive

Z^0

very massive

Feynman diagrams



Feynman diagrams:

Powerful tool to write down scattering amplitudes (also for higher order perturbations)

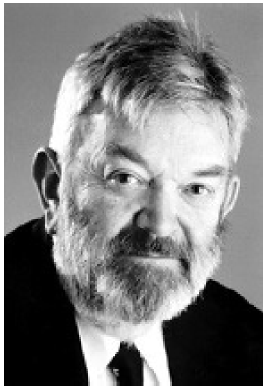
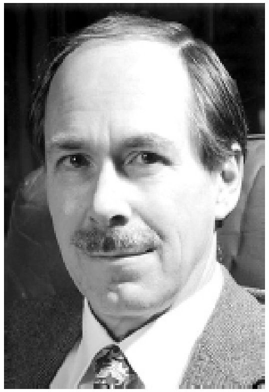
Feynman rules:

Set of rules to get from a Feynman diagram to the mathematical expression

R. Feynman
(NP 1965)

In QFTs perturbation theory is only **valid for finite energy range** → **divergences in calculation of scattering amplitudes**

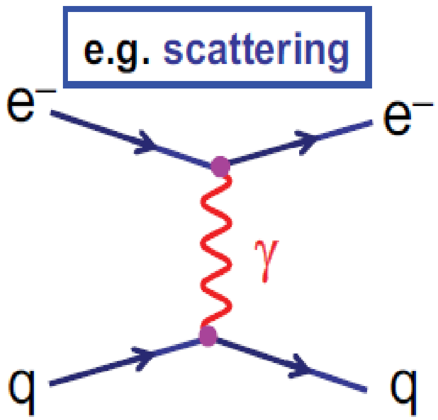
Renormalization is a technique to remove these divergences

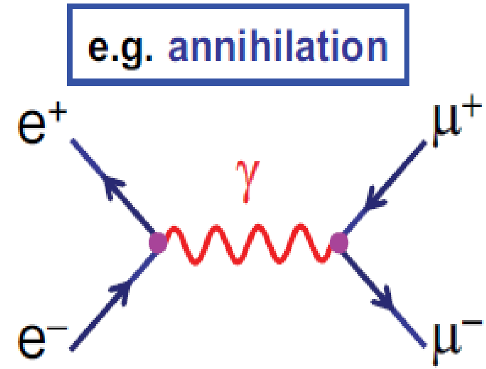



M. Veltman and G. 't Hooft
(NP 1999)

Feynman diagrams

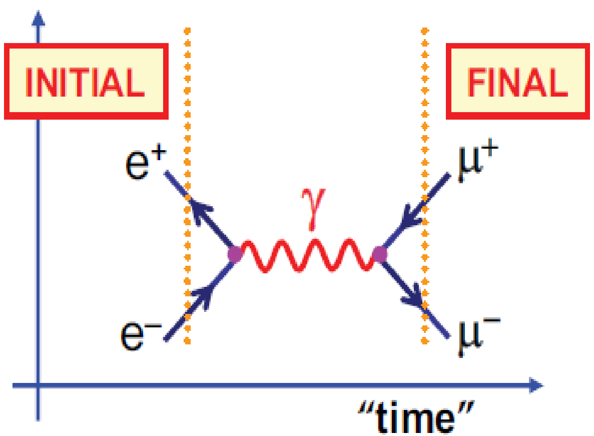
★ Particle interactions described in terms of Feynman diagrams





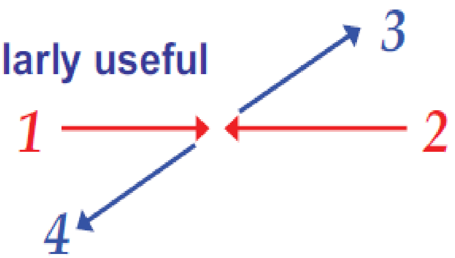
★ **IMPORTANT POINTS TO REMEMBER:**

- "time" runs from left – right, only in sense that:
  - LHS of diagram is initial state
  - RHS of diagram is final state
  - Middle is "how it happened"
- anti-particle arrows in –ve "time" direction
- Energy, momentum, angular momentum, etc. conserved at all interaction vertices
- All intermediate particles are "virtual" i.e. $E^2 \neq |\vec{p}|^2 + m^2$

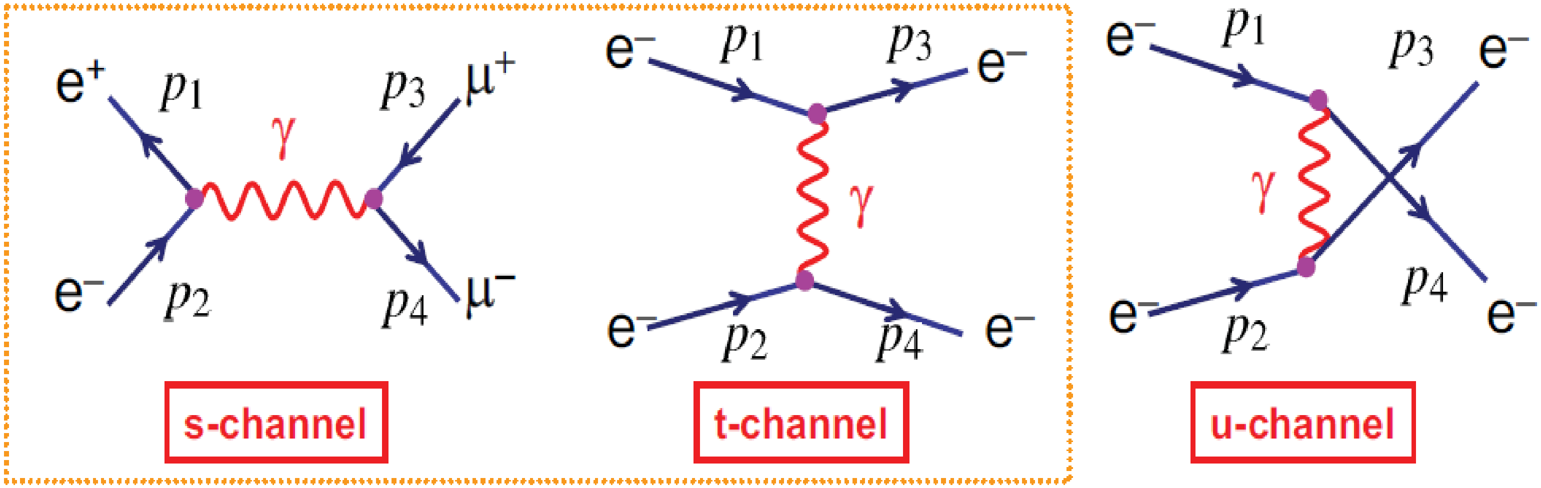


Mandelstam s, t and u

- In particle scattering/annihilation there are three particularly useful **Lorentz Invariant quantities: s, t and u**
- Consider the scattering process $1 + 2 \rightarrow 3 + 4$



- (Simple) Feynman diagrams can be categorised according to the four-momentum of the exchanged particle

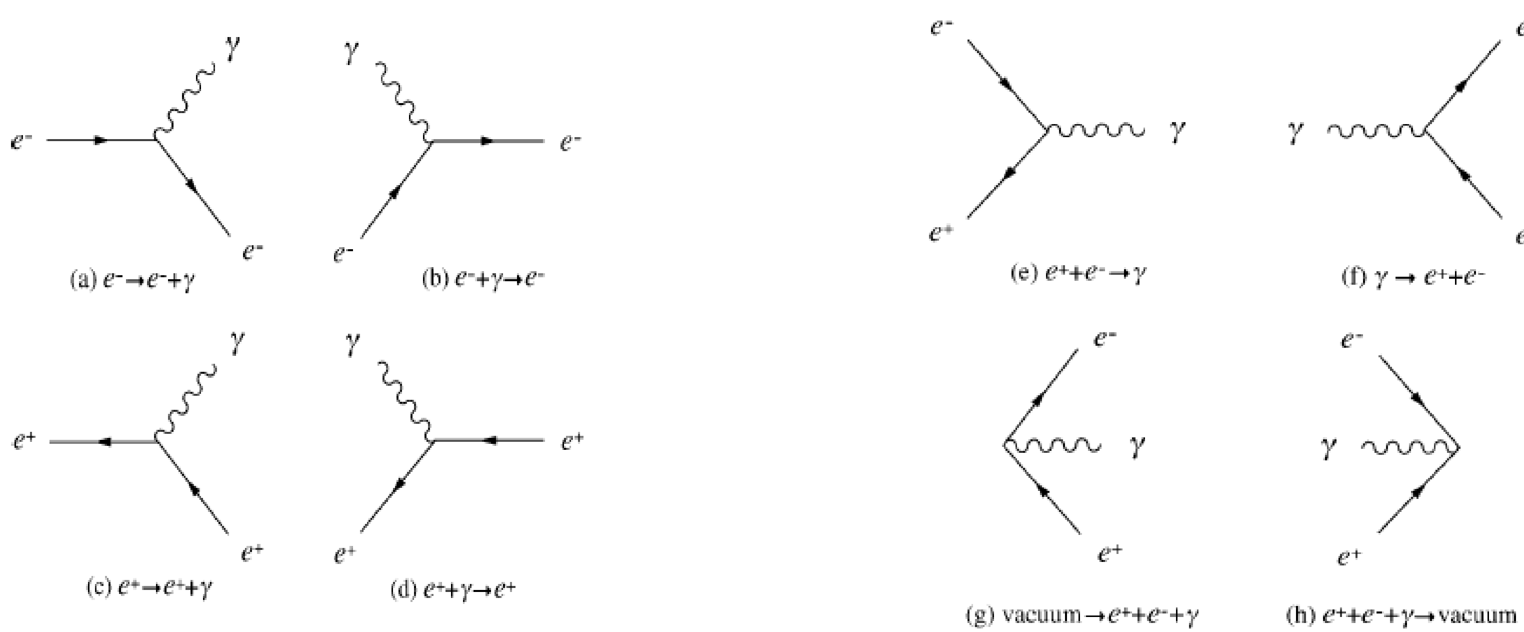


- Can define three kinematic variables: s, t and u from the following four vector scalar products (squared four-momentum of exchanged particle)

$$s = (p_1 + p_2)^2, \quad t = (p_1 - p_3)^2, \quad u = (p_1 - p_4)^2$$

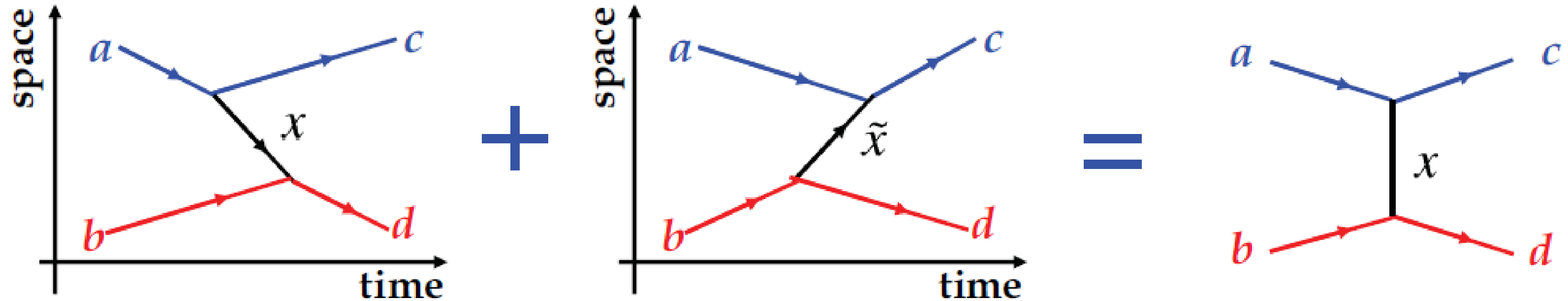
Quantum Electrodynamics (QED)

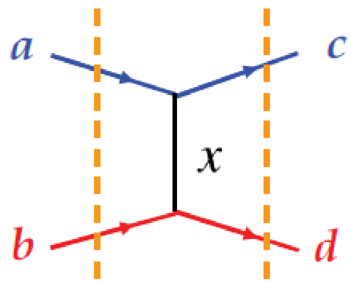
- **The oldest, the simplest and the most successful of the dynamical theories**
- **All electromagnetic phenomena are ultimately reducible to the following elementary process, where electron either emits or absorbs a photon.**



Feynman Rules for QED

- The sum over all possible time-orderings is represented by a **FEYNMAN diagram**





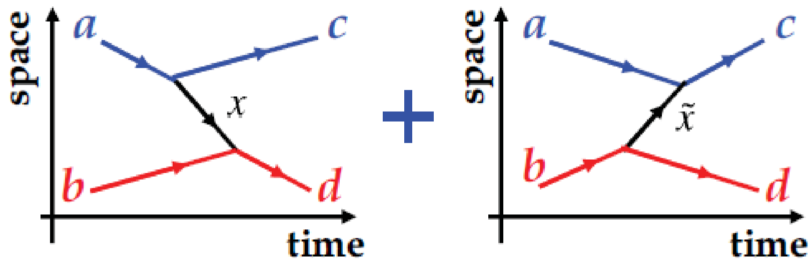
In a Feynman diagram:

- the LHS represents the initial state
- the RHS is the final state
- everything in between is "how the interaction happened"

- It is important to remember that energy and momentum are conserved at each interaction vertex in the diagram.
- The factor $1/(q^2 - m_x^2)$ is the propagator; it arises naturally from the above discussion of interaction by particle exchange

Virtual Particles

"Time-ordered QM"

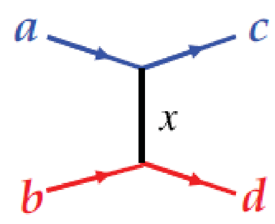


- **Momentum conserved at vertices**
- **Energy not conserved at vertices**
- **Exchanged particle "on mass shell"**

$$E_x^2 - |\vec{p}_x|^2 = m_x^2$$

=

Feynman diagram



$$M_{fi} = \frac{g_a g_b}{q^2 - m_x^2}$$

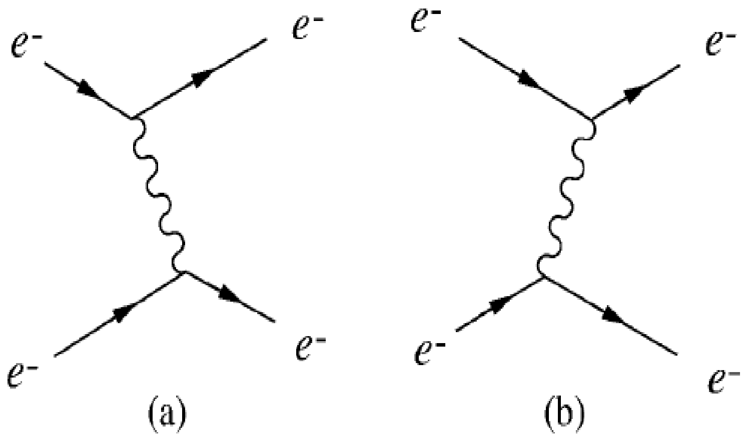
- **Momentum AND energy conserved at interaction vertices**
- **Exchanged particle "off mass shell"**

$$E_x^2 - |\vec{p}_x|^2 = q^2 \neq m_x^2$$

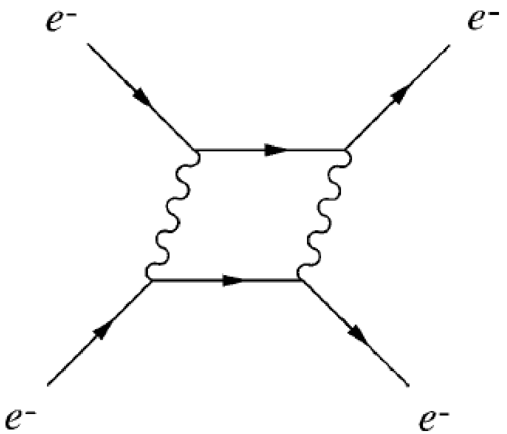
VIRTUAL PARTICLE

- **Can think of observable "on mass shell" particles as propagating waves and unobservable virtual particles as normal modes between the source particles:**

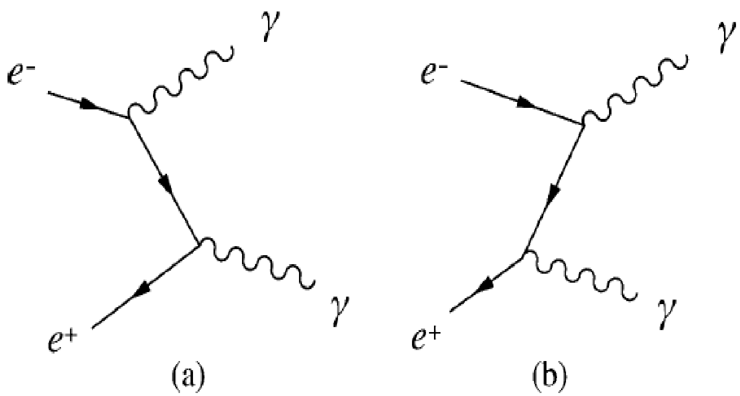
Quantum Electrodynamics (QED)

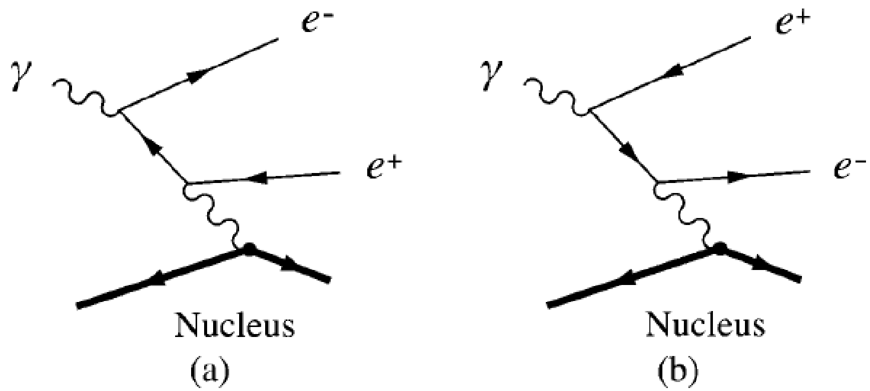


Single photon exchange



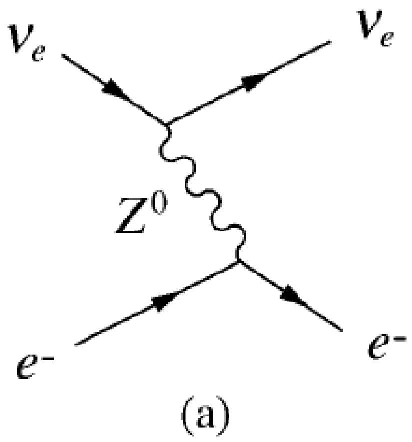
Double photon exchange



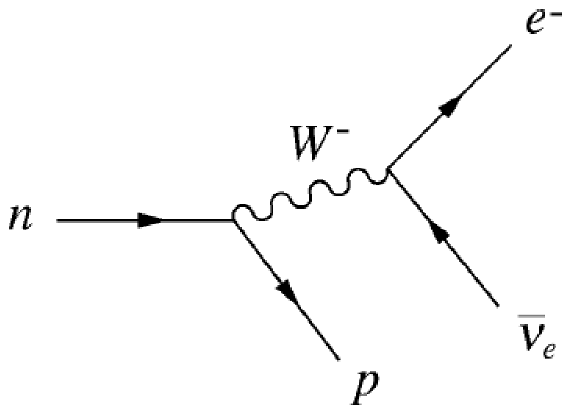


Pair annihilation

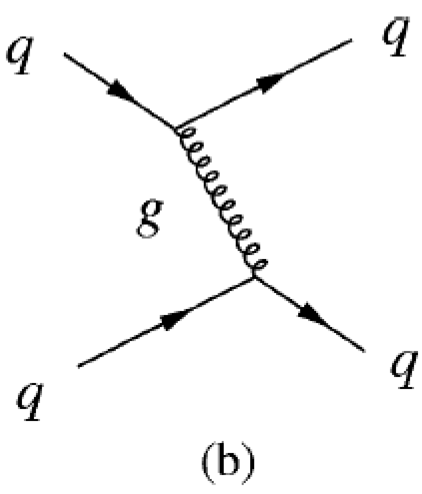
Weak and Strong interactions



Elastic weak scattering



Decay on neutron
via intermediate vector boson



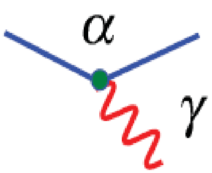
Strong interactions

Colour in QCD

★ The theory of the strong interaction, Quantum Chromodynamics (QCD), is very similar to QED but with 3 conserved "colour" charges

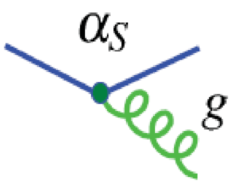
In QED:

- the electron carries one unit of charge $-e$
- the anti-electron carries one unit of anti-charge $+e$
- the force is mediated by a massless "gauge boson" – the photon



In QCD:

- quarks carry colour charge: r, g, b
- anti-quarks carry anti-charge: $\bar{r}, \bar{g}, \bar{b}$
- The force is mediated by massless gluons



★ In QCD, the strong interaction is invariant under rotations in colour space

$$r \leftrightarrow b;\ r \leftrightarrow g;\ b \leftrightarrow g$$

i.e. the same for all three colours

➡ **SU(3) colour symmetry**

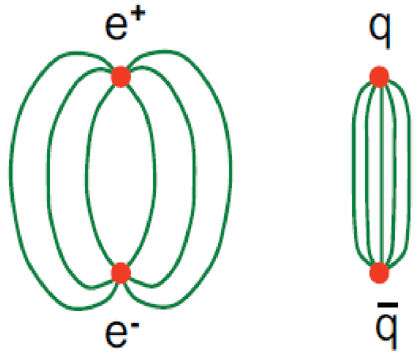
- This is an exact symmetry, unlike the approximate uds flavour symmetry discussed previously.

Gluon self-Interactions and confinement

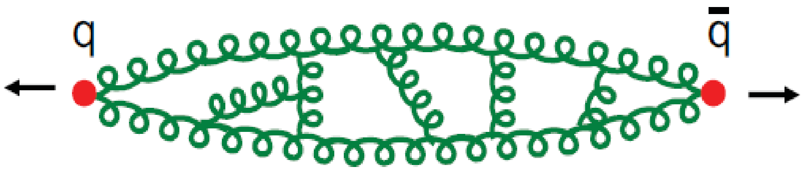
★ Gluon self-interactions are believed to give rise to colour confinement

★ Qualitative picture:

- Compare QED with QCD
- In QCD "gluon self-interactions squeeze lines of force into a flux tube"



★ What happens when try to separate two coloured objects e.g. $q\bar{q}$

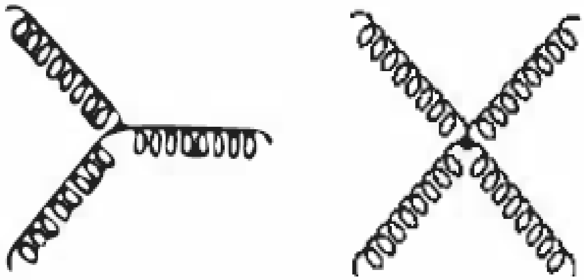


- Form a flux tube of interacting gluons of approximately constant energy density $\sim 1\,\mathrm{GeV/fm}$

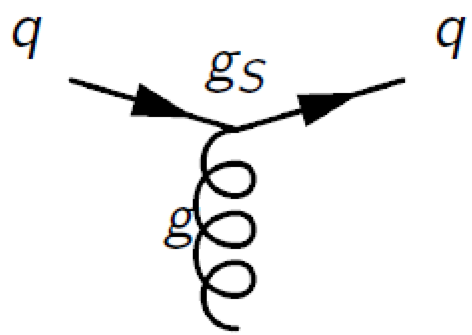
$$\Rightarrow \quad V(r) \sim \lambda r$$

- Require infinite energy to separate coloured objects to infinity
- Coloured quarks and gluons are always confined within colourless states
- In this way QCD provides a plausible explanation of confinement – but not yet proven (although there has been recent progress with Lattice QCD)

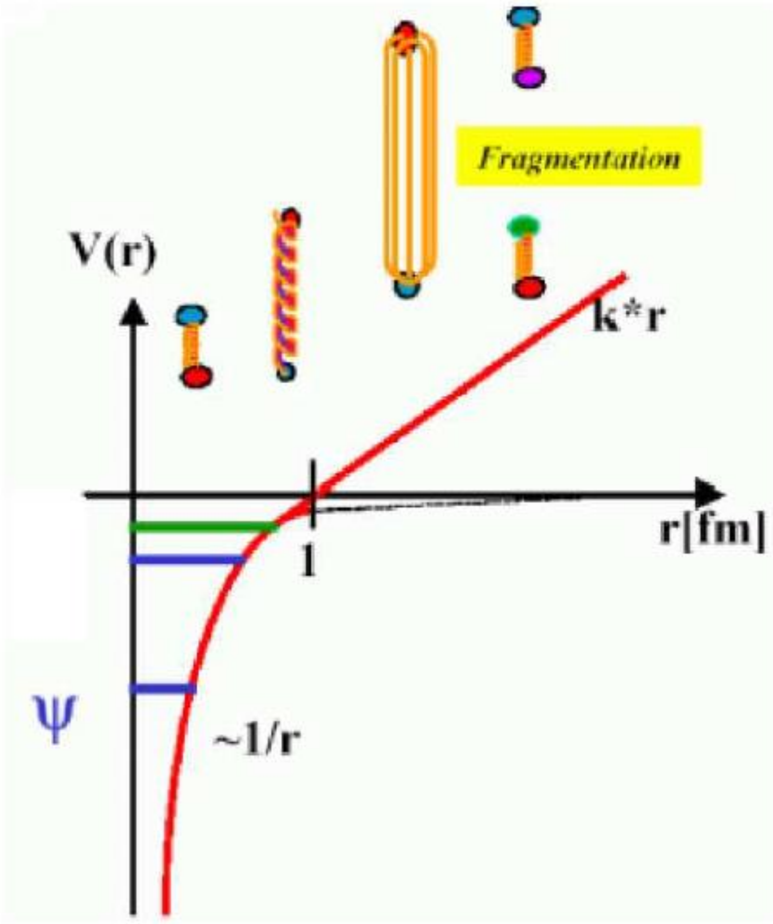
Quantum Chromodynamics



Three-gluon vertices and four-gluon vertices

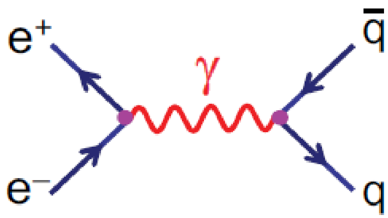


Confinement



QCD and Colour in e^+e^- Collisions

★ e^+e^- colliders are an excellent place to study QCD

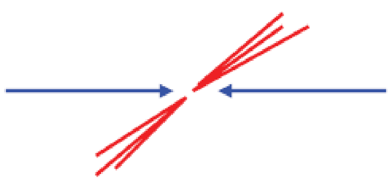


★ Well defined production of quarks
- QED process well-understood
- no need to know parton structure functions
- + experimentally very clean – no proton remnants

★ expressions for the $e^+e^- \to \mu^+\mu^-$ cross-section

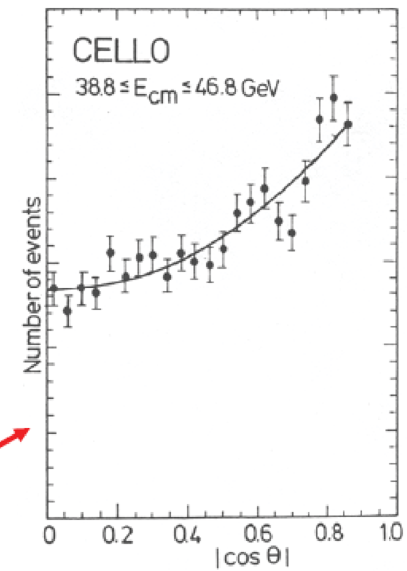
$$\sigma = \frac{4\pi\alpha^2}{3s} \qquad \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1+\cos^2\theta)$$

- In e^+e^- collisions produce all quark flavours for which $\sqrt{s} > 2m_q$
- In general, i.e. unless producing a $q\bar{q}$ bound state, produce jets of hadrons
- Usually can't tell which jet came from the quark and came from anti-quark



★ Angular distribution of jets $\propto (1+\cos^2\theta)$

➡ **Quarks are spin ½**



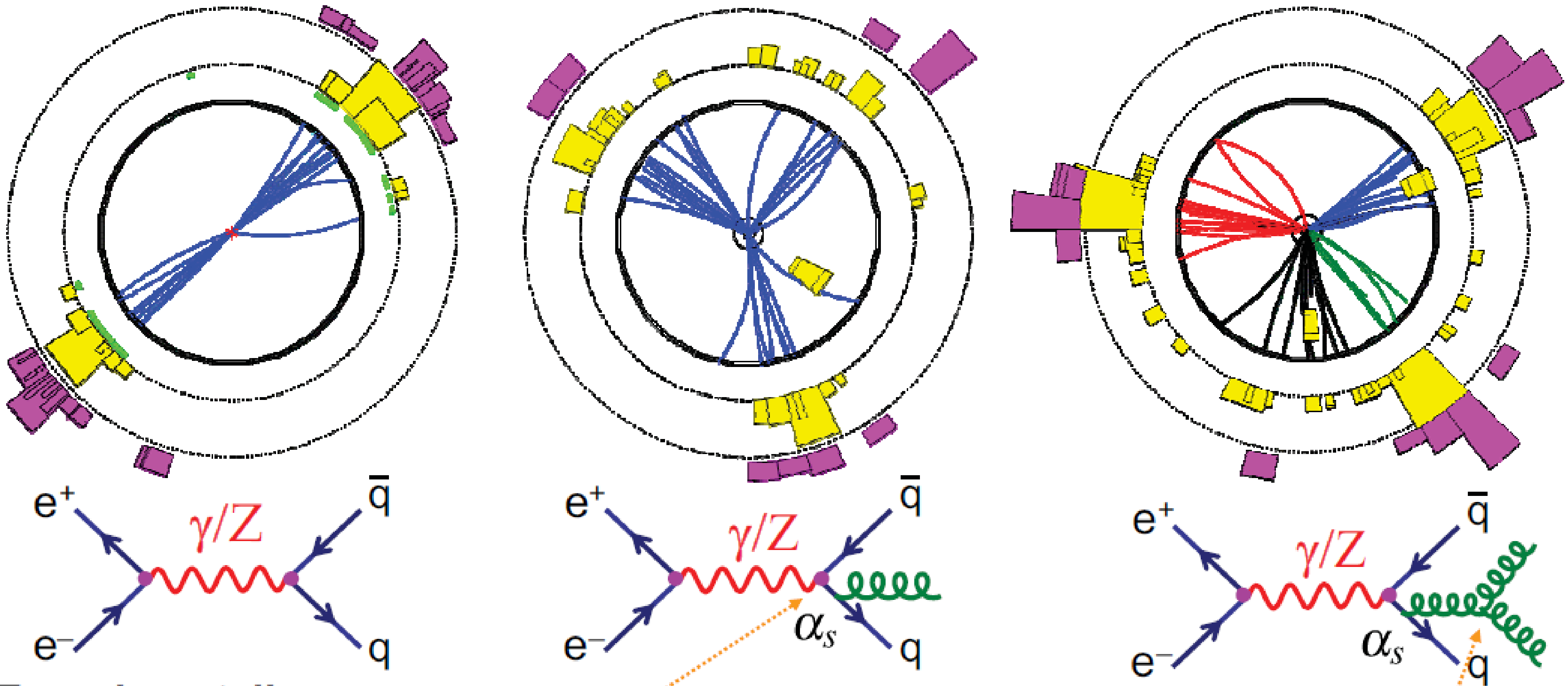
H.J.Behrend et al., Phys Lett 183B (1987) 400

Jet production in e^+e^- collision

★ e^+e^- colliders are also a good place to study gluons

$e^+e^- \rightarrow q\bar{q} \rightarrow$ 2jets $\quad e^+e^- \rightarrow q\bar{q}g \rightarrow$ 3jets $\quad e^+e^- \rightarrow q\bar{q}gg \rightarrow$ 4jets

OPAL at LEP (1989-2000)



Experimentally:

- Three jet rate ➡ measurement of α_s
- Angular distributions ➡ gluons are spin-1
- Four-jet rate and distributions ➡ QCD has an underlying SU(3) symmetry

Weak interaction in quark sector

★ Extend ideas to three quark flavours

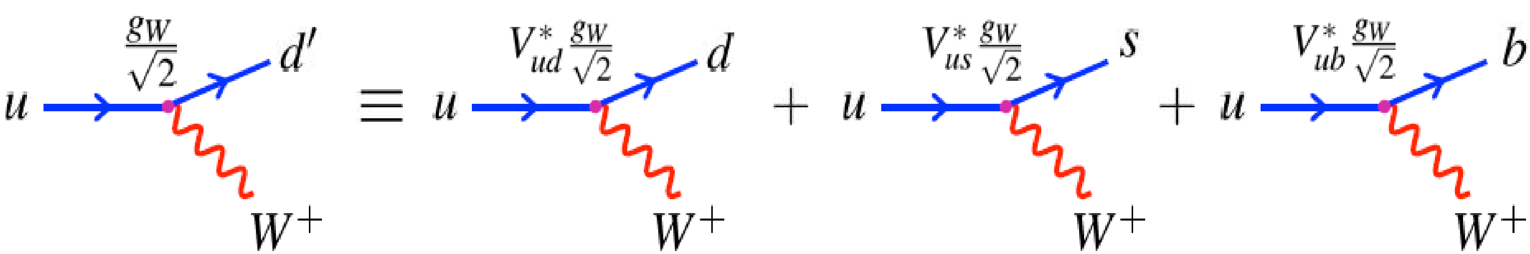
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

By convention CKM matrix defined as acting on quarks with charge $-\frac{1}{3}e$

Weak eigenstates | **CKM Matrix** | **Mass Eigenstates**

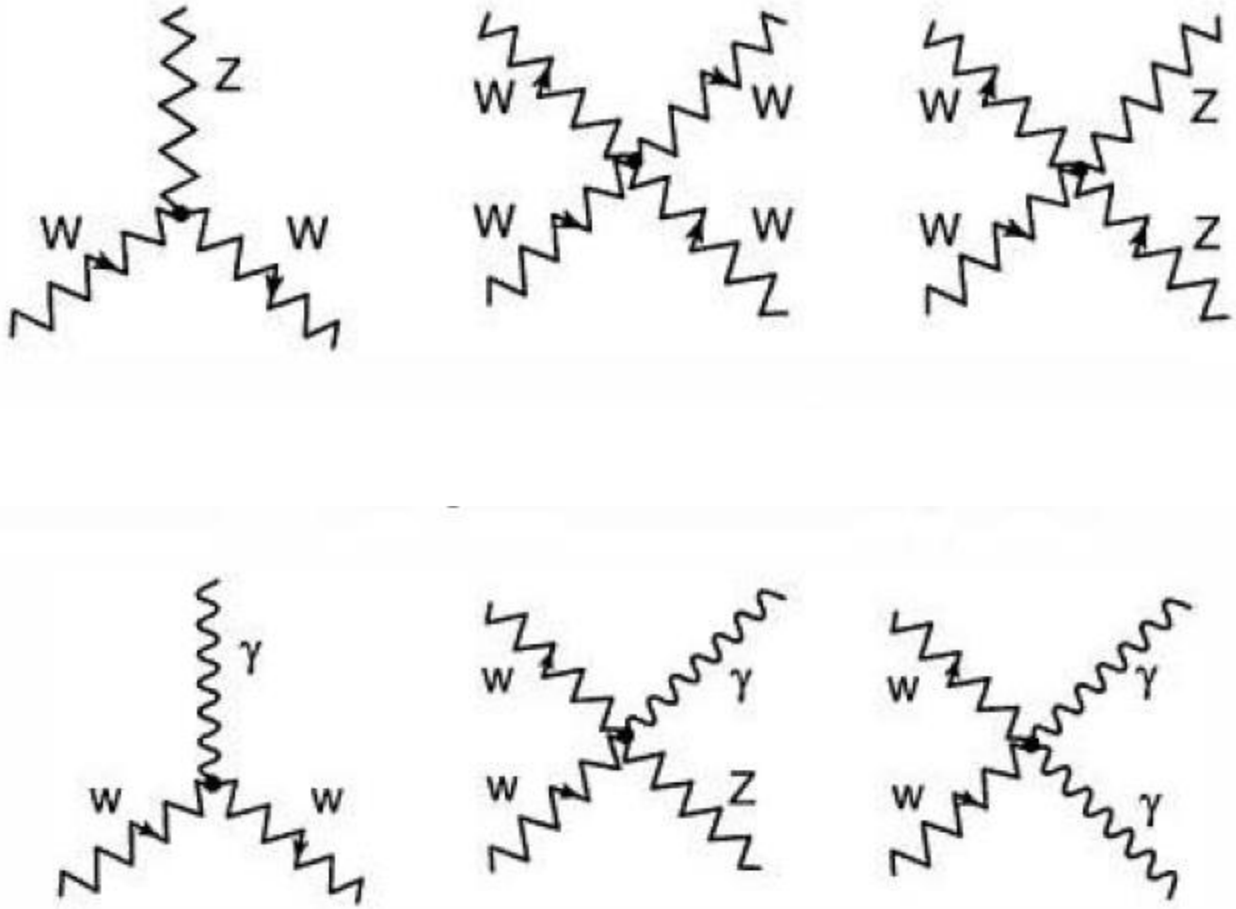
(Cabibbo, Kobayashi, Maskawa)

★ e.g. Weak eigenstate d' is produced in weak decay of an up quark:

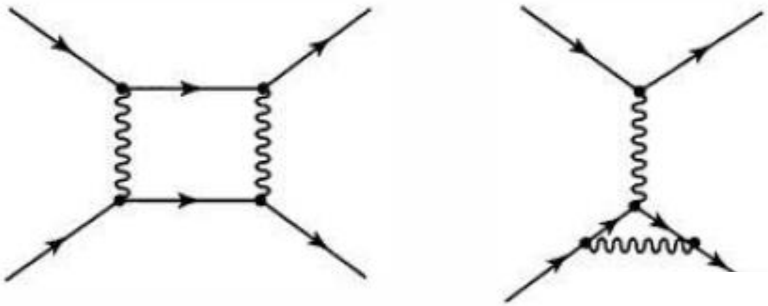


- The CKM matrix elements V_{ij} are complex constants
- The CKM matrix is unitary
- The V_{ij} are not predicted by the SM – have to determined from experiment

Weak and Electromagnetic Couplings

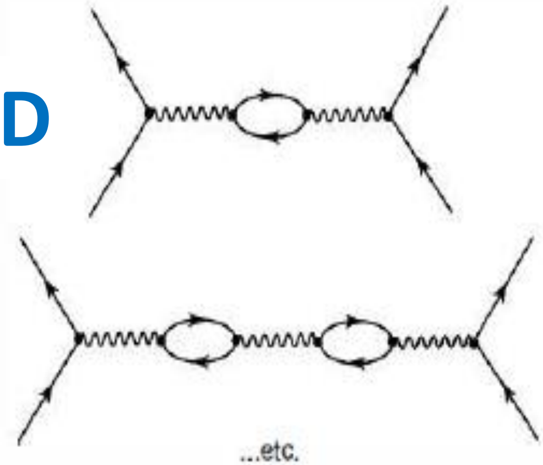


Loops

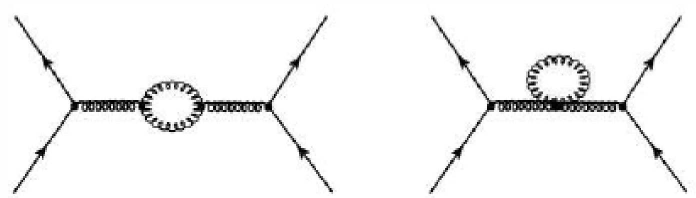


Virtual corrections and box diagrams

QED



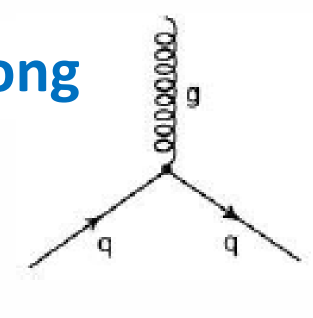
QCD



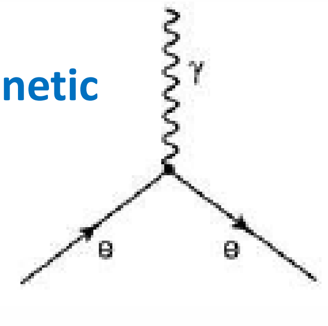
Conservation laws

- **Charge:** all three interactions conserve electric charge
- **Color:** the electromagnetic and weak interactions do not affect color. At strong vertex color change but difference carried by the gluon.
- **Bayron number:** conserved in all simple vertices
- **Lepton number:** is absolutely conserved, cross-generation mixing in neutrino sector (oscilation)
- **Flavour:** conserved at strong and eletromagnetic vertex but not weak vertex

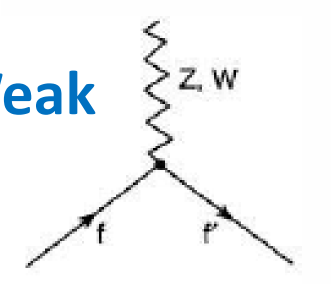
Strong



Electromagnetic



Weak



Grand unification

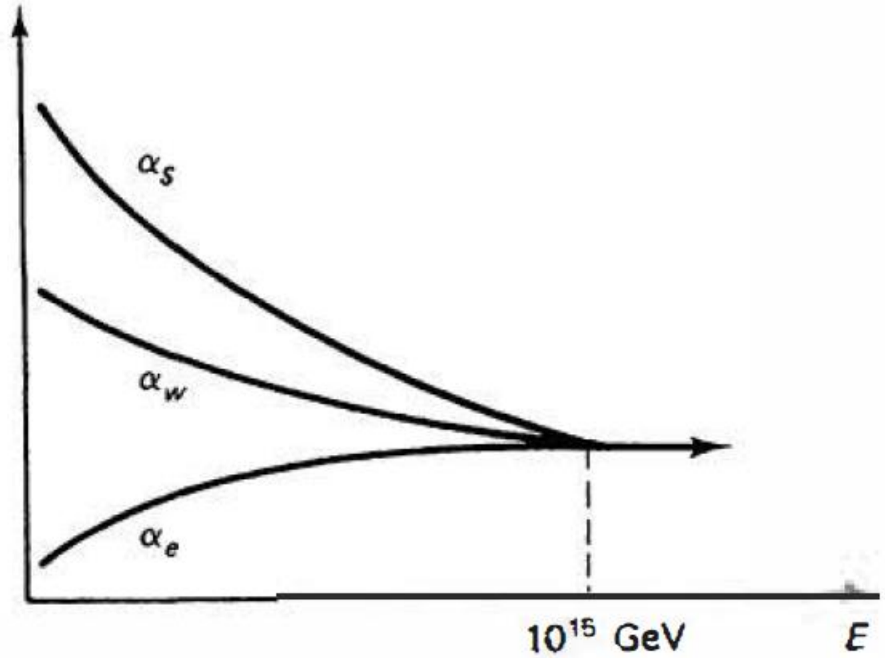
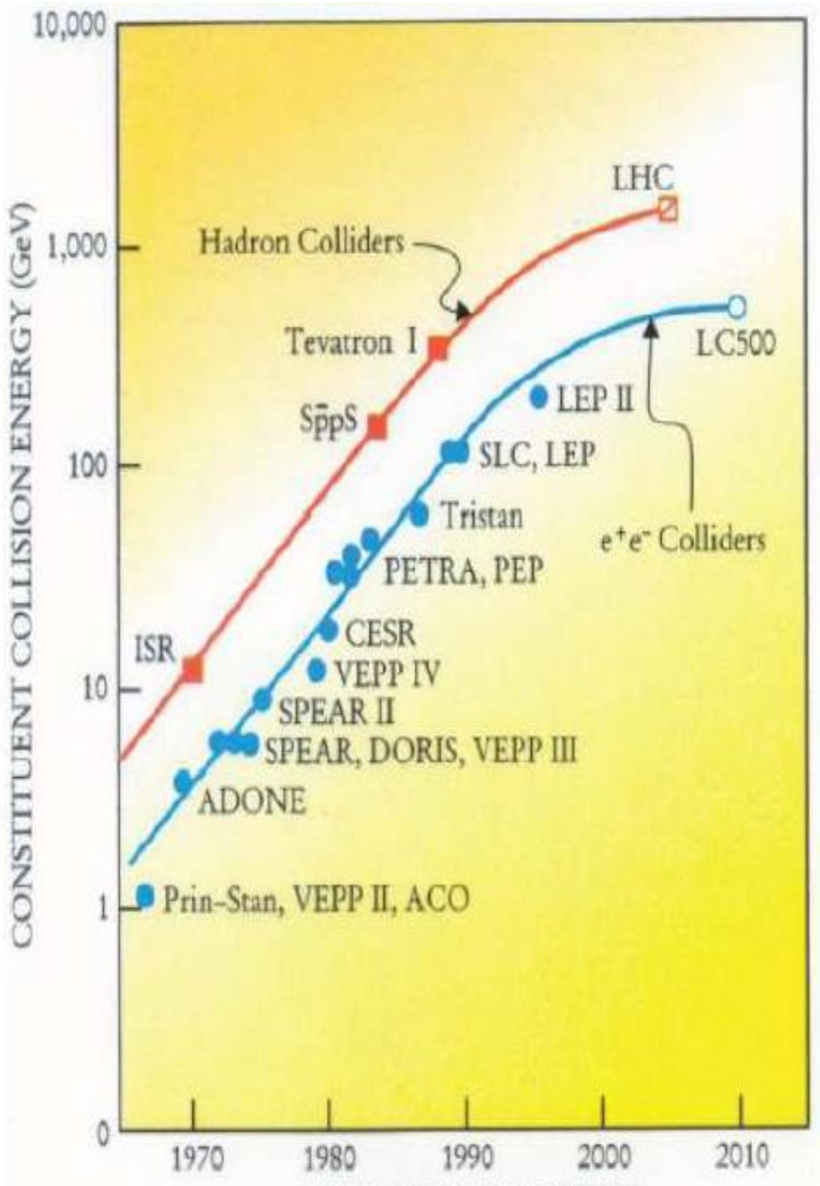


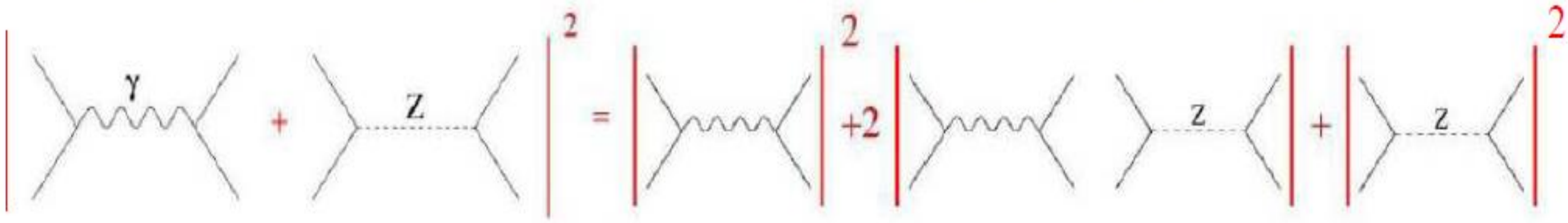
Fig. 2.5 Evolution of the three fundamental coupling constants.

Energy frontier



- The interplay between electron and hadron machines has a long and fruitful tradition
  - J/ψ at SPEAR (e^+e^-) and AGS (proton fixed target)
  - Υ discovery at E288 (p fixed target), precision B studies at the e^+e^- B factories
  - ...
  - top quark at LEP and Tevatron
- To be continued in the form of LHC and ILC

$e^+ e^-$ -> Z cross-section



$$\frac{d\sigma}{d\Omega} = N_C \frac{\alpha_{em}^2}{4s} \{(1+\cos^2\theta)\left[Q_f^2 - 2\chi_1 v_e v_f Q_f - \chi_2 (a_e^2 + v_e^2)(a_f^2 + v_f^2)\right]$$

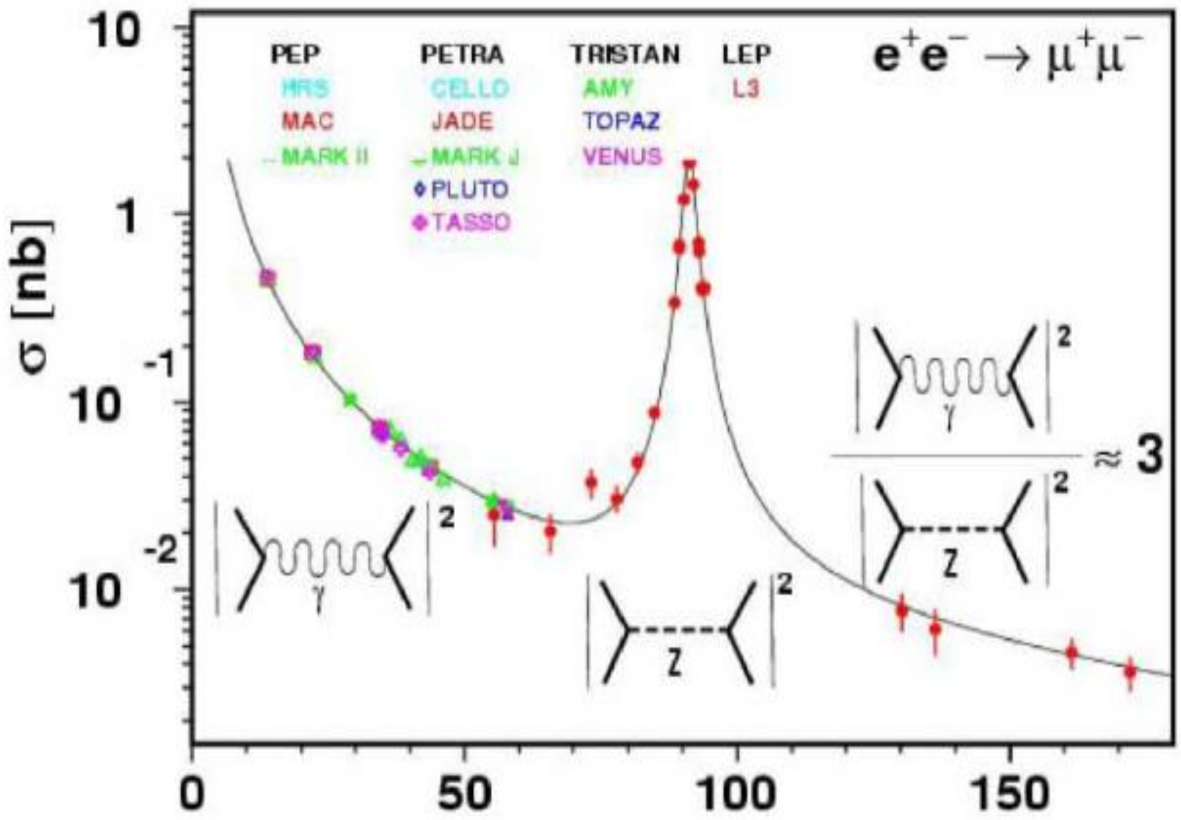
$$+2\cos\theta\left[-2\chi_1 a_e a_f Q_f + 4\chi_2 a_e a_f v_e v_f\right]\}$$

$$\chi_1 = \frac{s(s - M_Z^2)}{16\sin^2\theta_W\cos^2\theta_W\left((s-M_Z^2)^2 + M_Z^2\Gamma_Z^2\right)}$$

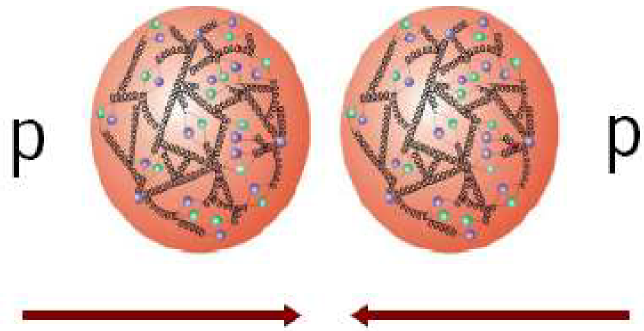
$$\chi_2 = \frac{s^2}{256\sin^4\theta_W\cos^4\theta_W\left((s-M_Z^2)^2 + M_Z^2\Gamma_Z^2\right)}$$

$$a_e = -1; \quad v_e = -1 + 4\sin^2\theta_W; \quad a_f = 2I_f; \quad v_f = 2I_f - 4Q_f\sin^2\theta_W$$

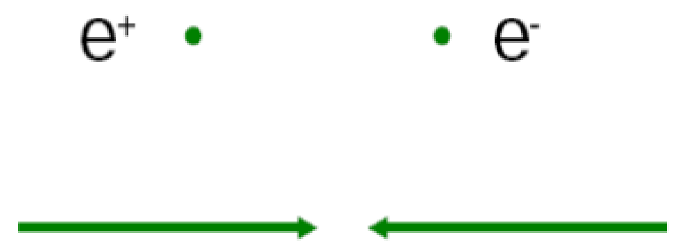
$e^+ e^-$ -> Z cross-section



Complementarity between pp and ee machines

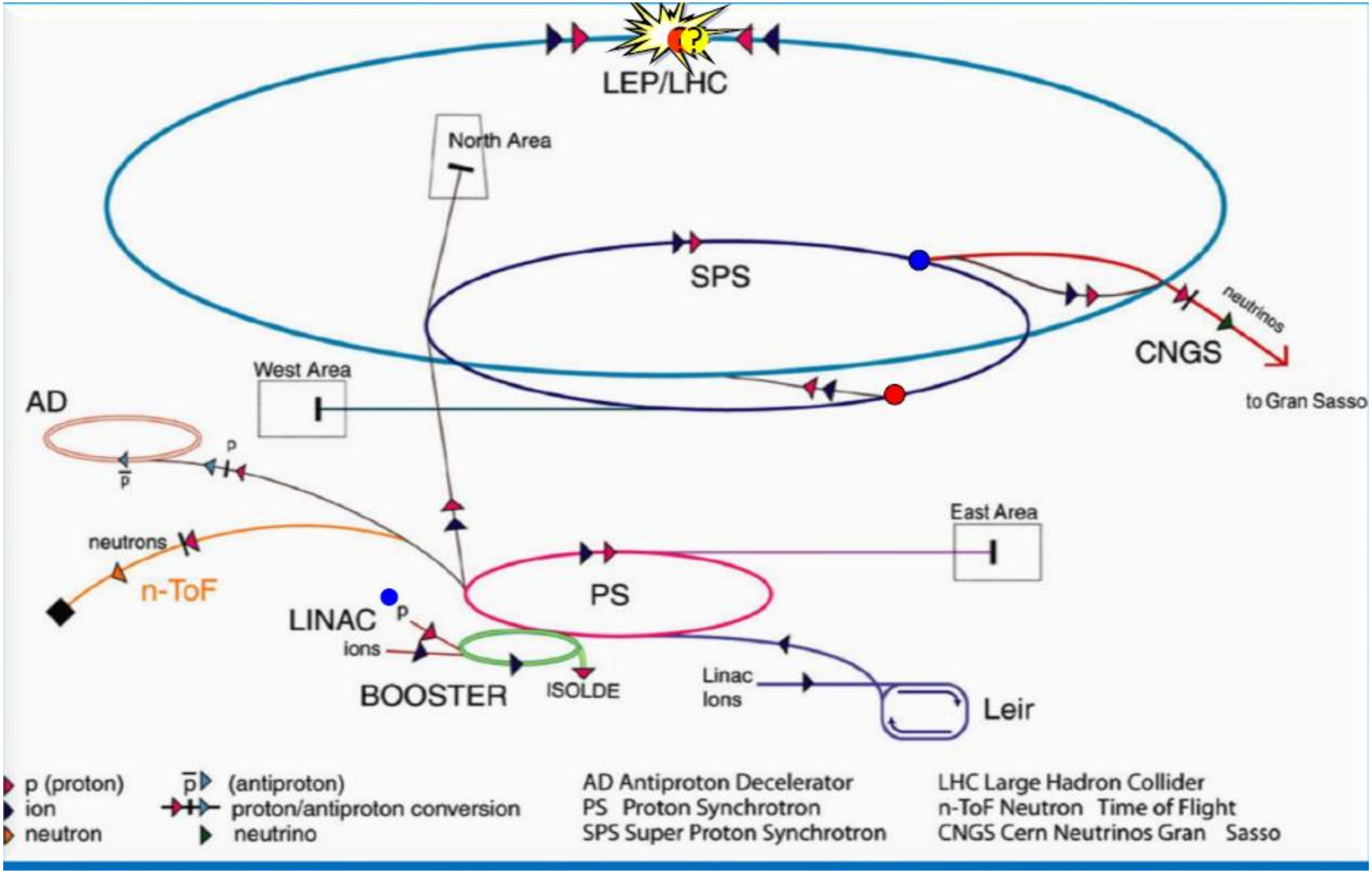


- Proton-(Anti-)Proton Colliders
  - Higher energy reach (limited by magnets)
  - Composite particles: unknown and different colliding constituents, energies in each collision
  - Confusing final states
- Discovery machines (W, Z, t)
- In some cases: precision measurements possible (W mass at the Tevatron)



- Electron-Positron-Colliders
  - Energy reach limited by RF
  - Point like particles, exactly definded initial system, quantum numbers, energy, spin polarisation possible
  - Hadronic final states with clear signatures
- Precision machines
- Discovery potential, but not at the energy frontier

CERN accelerator complex



Luminosity frontier

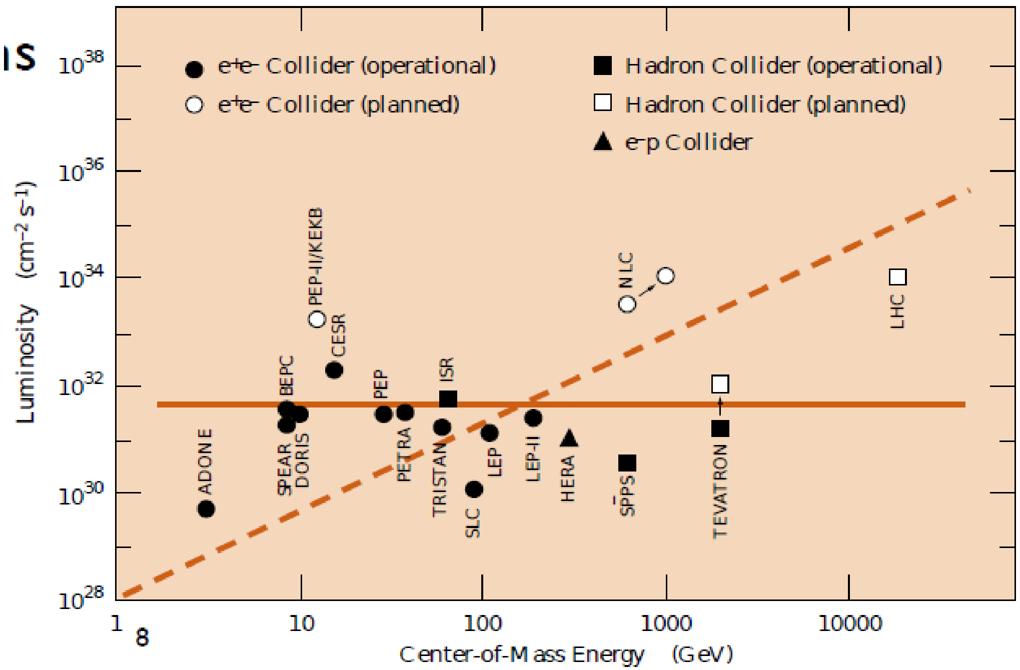
- Need corresponding rise in luminosity (beam intensity)

Number of events Instantaneous luminosity

$$N = \sigma L = \sigma \int \mathcal{L}\, dt$$

Cross section Integrated luminosity

- High luminosity brings all the challenges for the detectors:
  - High event rates
  - Pile up
  - Beam –beam interactions
  - Beamstrahlung



Designing a machine

- Particle species
  - Electron/positrons
  - Protons/antiprotons
  - Muons/antimuons
- Beam energy
- Spin
- Luminosity

- How do you produce antiparticles?
- Ones produced how ones keep them (muon collider)?
- Ones collided what ones does with spent beams?
- Accelerator and detector protection

Accelerator is much more than just….

- Particle production
- Damping, cooling or preparation
- Injection and extraction
- Acceleration
- Collimation (betatron, energy etc.)
- Diagnostics and controls
- Machine (and detector protection)
- Beam delivery and luminosity production
- Technology spin off
  - Lower energy machines, medical applications, applied physics, materials, …..

Acceleration

Lorentz force law

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

Electric field Velocity Magnetic field

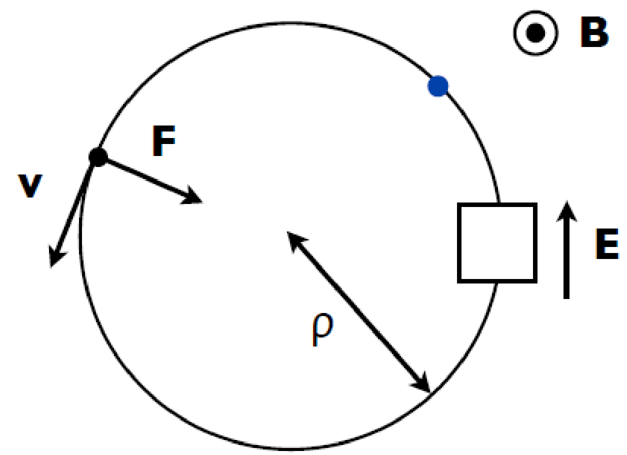
Energy change

$$\Delta E = \int_{\mathbf{r}_1}^{\mathbf{r}_2} \mathbf{F} \cdot d\mathbf{r}$$

- Electric field (either static or more commonly, time varying) to accelerate, or more appropriately, increase energy of beam
- Magnetic part of Lorentz force used to guide and focus
  - Dipole magnets: to bend
  - Quadrupole: to focus or defocus

Synchrotron

- Workhorse of modern particle physics
  - Huge legacy of discovery
  - Increase energy whilst synchronously increasing bending magnet strength
  - Stable storage of high beam current/power
- Magnetic field proportional to momentum



Velocity

$$qBv = \frac{m_0 v^2}{\rho}$$

Magnetic field

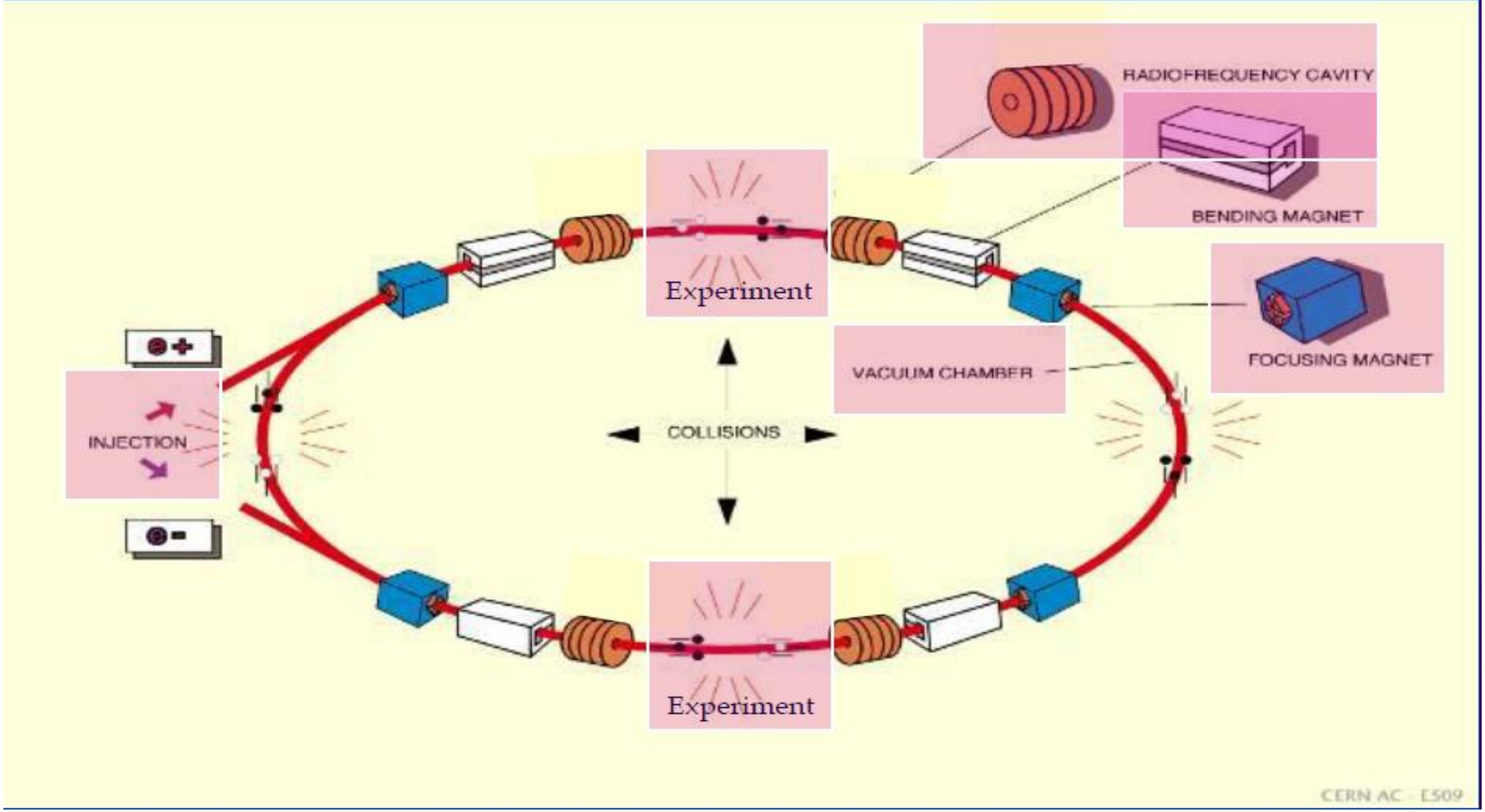
Bending radius

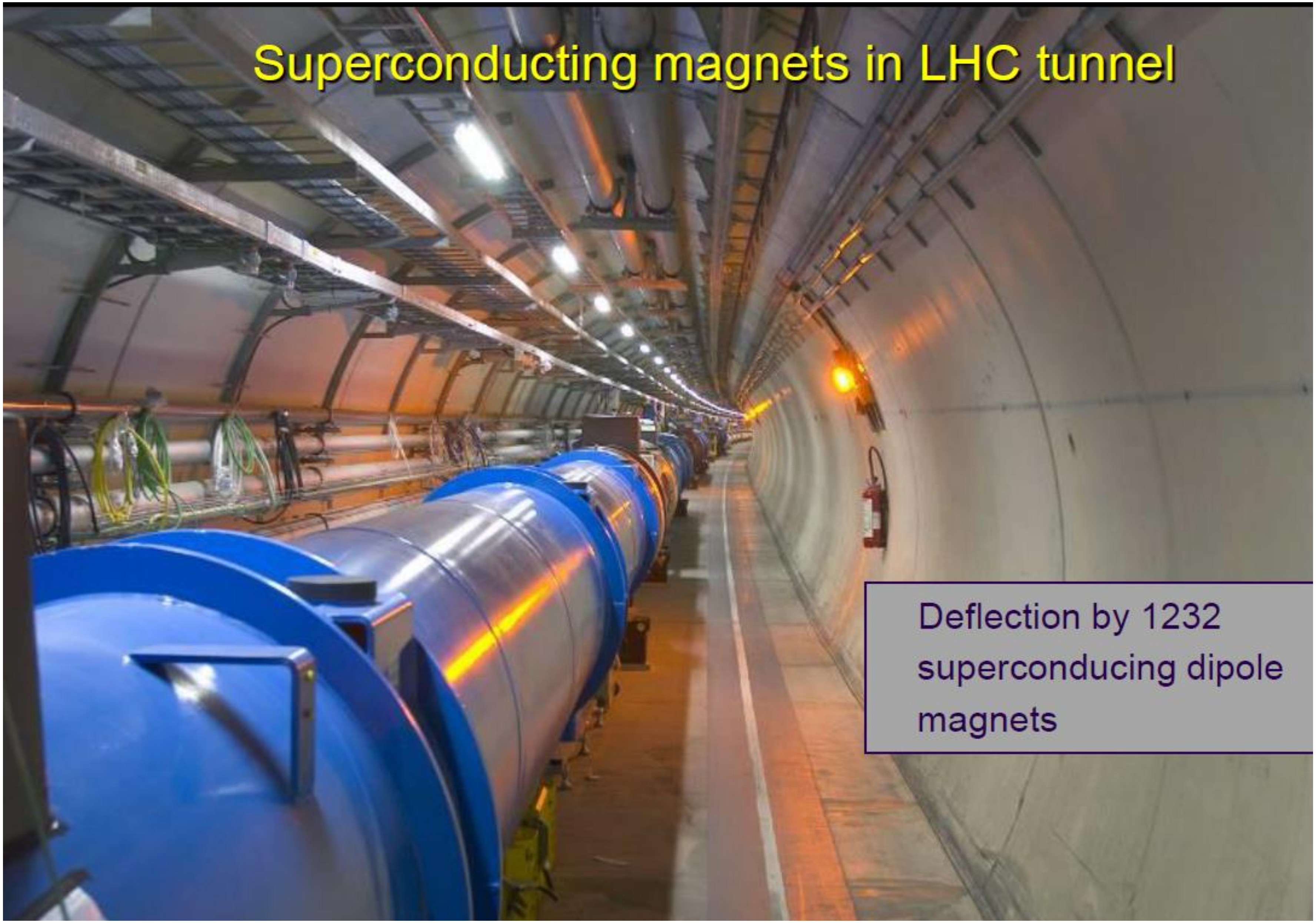
$$B\rho = p/q$$

Momentum

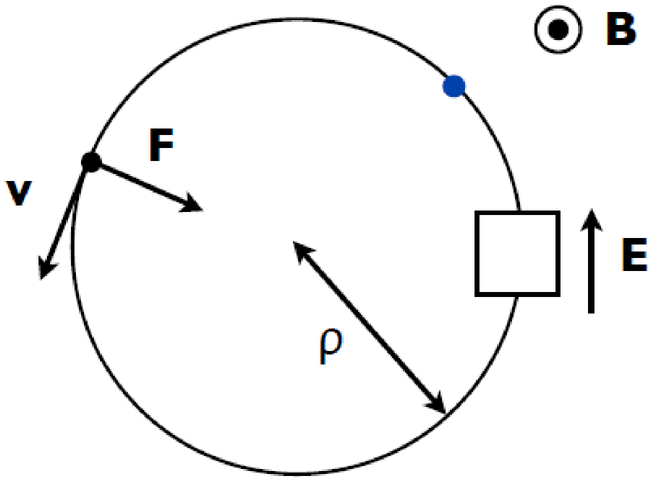
Synchrotron + many passages in RF cavities

LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 7 TeV will take about 20 minutes

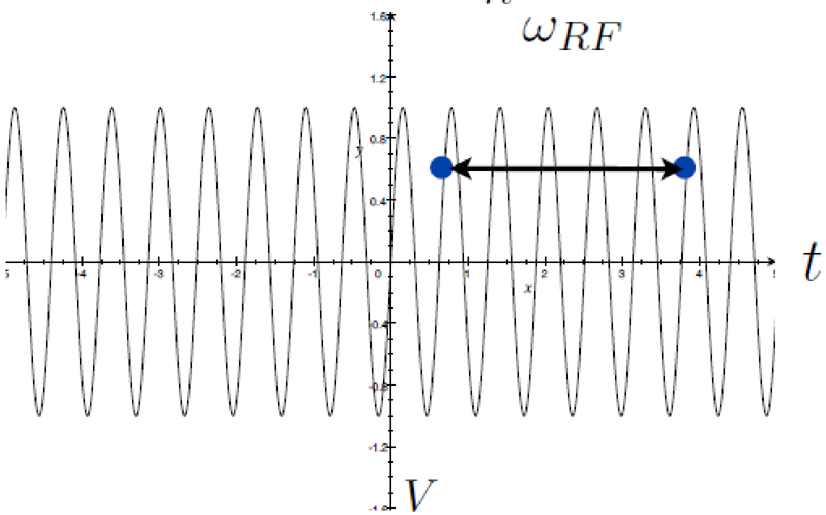



Superconducting magnets in LHC tunnel
Deflection by 1232 superconducing dipole magnets

Synchrotron



$$n\frac{2\pi}{\omega_{RF}}$$



- Time varying electric field:

$$V(t) = V_0 \sin(\omega_{RF} t + \phi)$$

Angular frequency of accelerating field

- Particle gets a kick every revolution

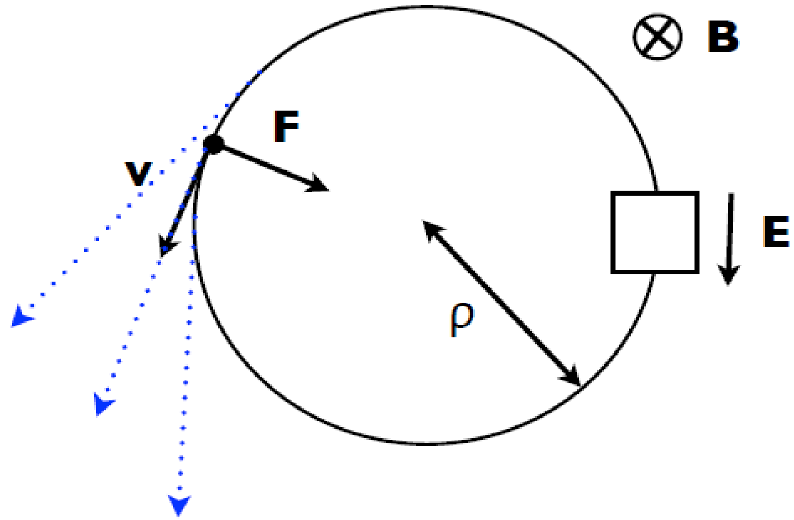
$$\frac{1}{f_{\mathrm{ref}}} = n\frac{2\pi}{\omega_{\mathrm{RF}}}$$

Revolution frequency

Integer

Synchrotron Radiation Limits

- Why not just build bigger LEP?
  - Reuse accelerating section every revolution of particle bunch
  - Power loss due to synchrotron radiation
  - LEP2 was practical limit for electron-positron synchrotron



Power

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

Energy loss per turn

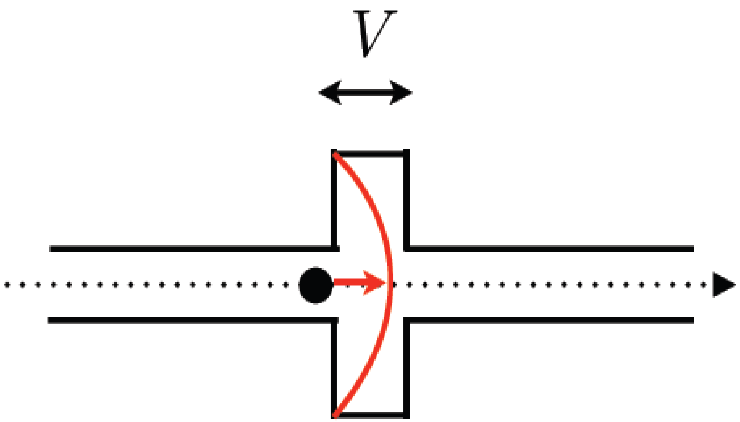
Beam energy

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

Magnetic radius

Absolute Limits on Acceleration

- Need to create large on axis electric fields
  - Accelerating structures:
    - Superconducting (~35 MV/m)
    - Normal conducting (~100 MV/m)
- Beyond these values there is high voltage breakdown



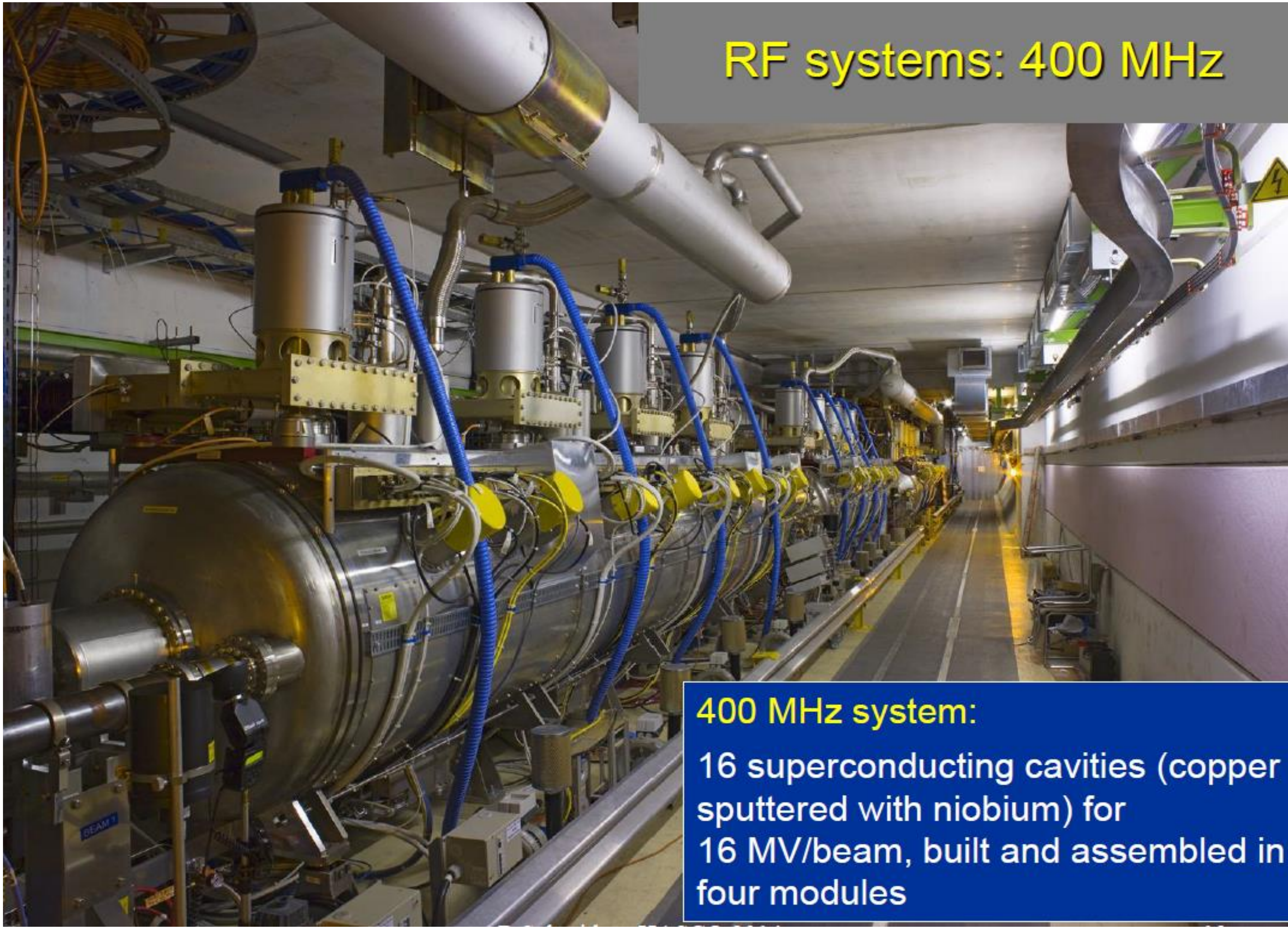
Machine length [m]

Beam energy [MeV]

$$S = \frac{E}{q\, dV/ds}$$

Accelerating gradient [MV/m]

RF systems: 400 MHz

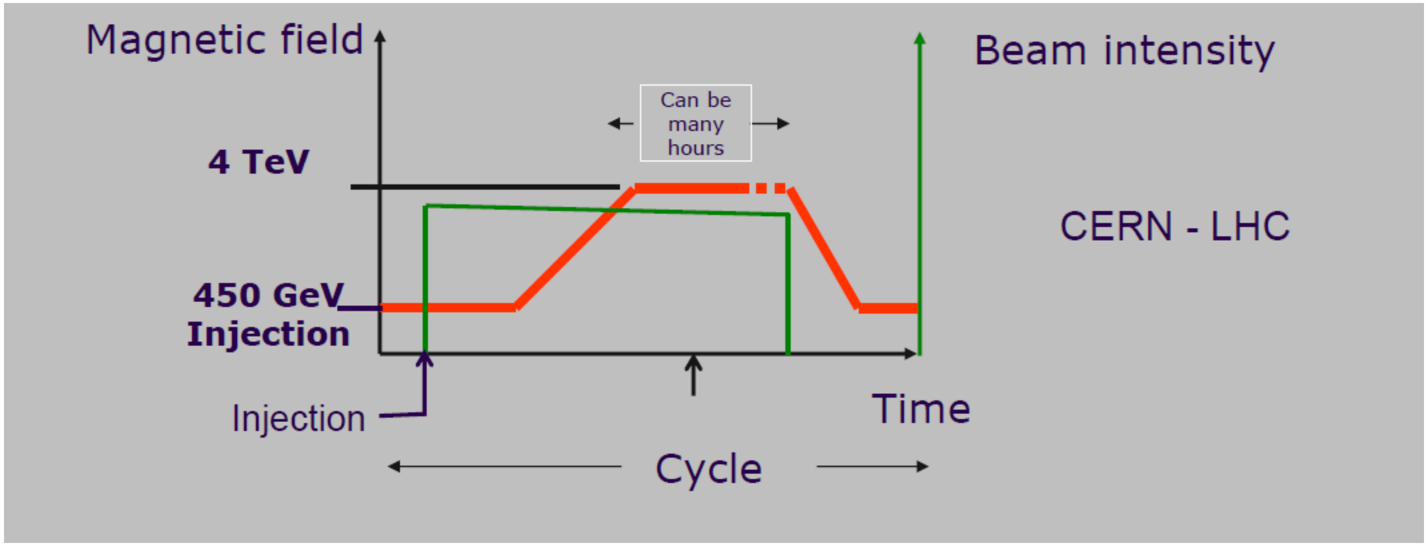


400 MHz system:

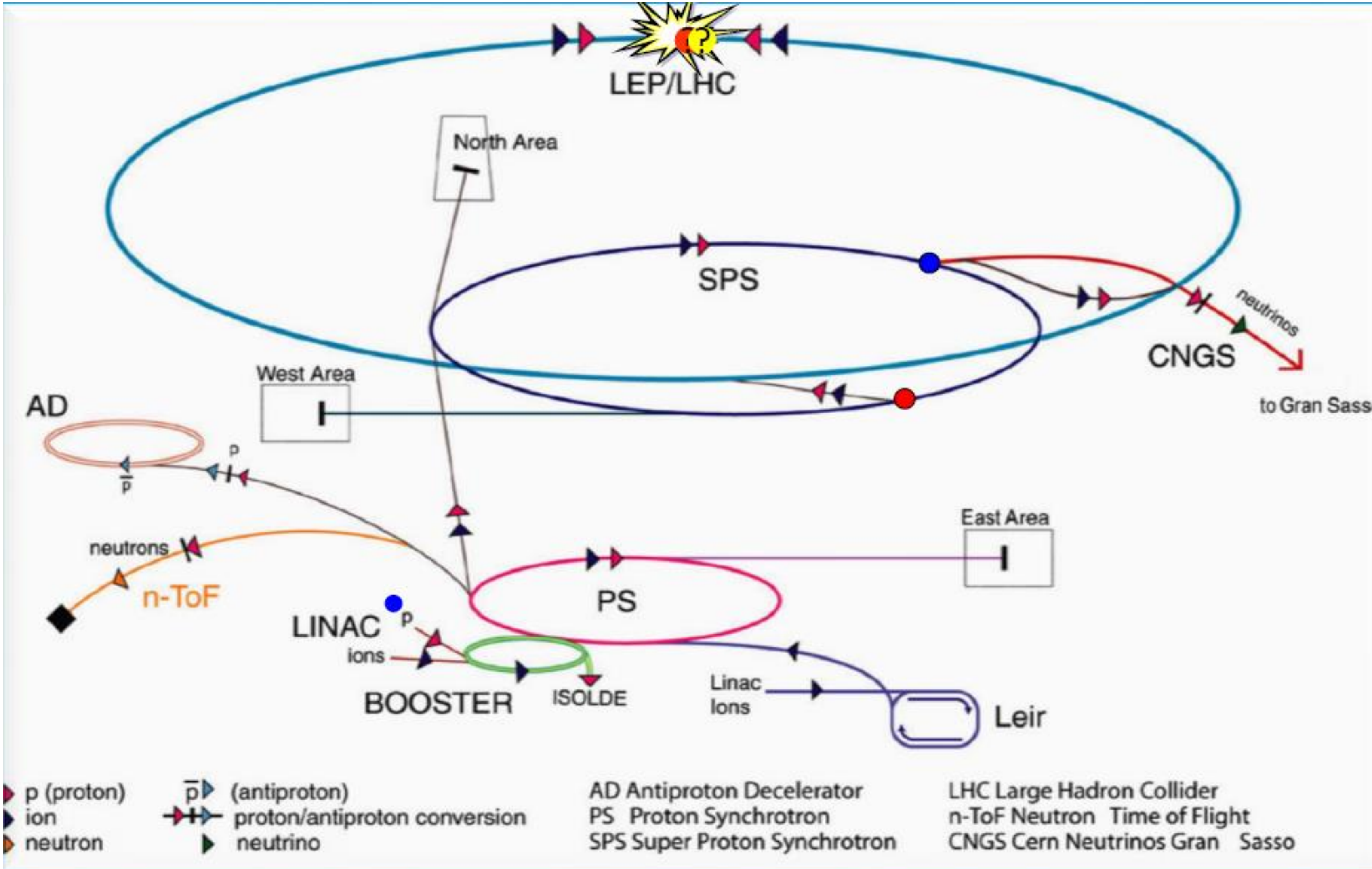
16 superconducting cavities (copper sputtered with niobium) for
16 MV/beam, built and assembled in four modules

Principle of a synchrotron

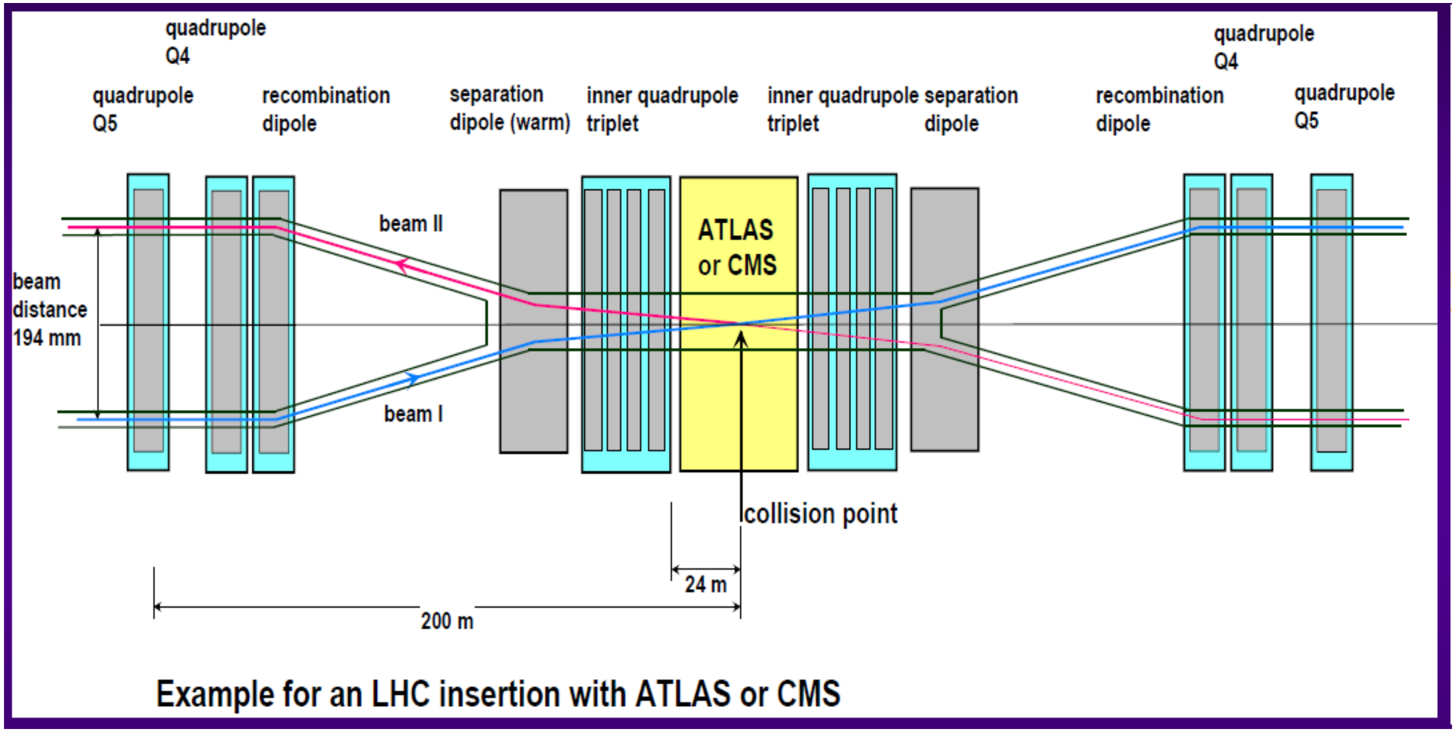
- Injection at low energy
- Ramping of magnetic field and acceleration by RF field. Beams are accelerated in bunches
- Operation (collisions) at top energy



CERN accelerator complex



Experimental long straight section



The 2 LHC beams are brought together to collide in common region. Over ~260m the beams circulate in one vacum chamber with „parasitic" encounters.

The crossing angle of about 300μrad

Luminosity

- What luminosity is required for measurement?
    - Need some knowledge of x-section
- Simple relationship between number of particles, frequency of collision and beam sizes

Luminosity [s^{-1} m^{-2}]

Bunch populations

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

Frequency of collisions [Hz]

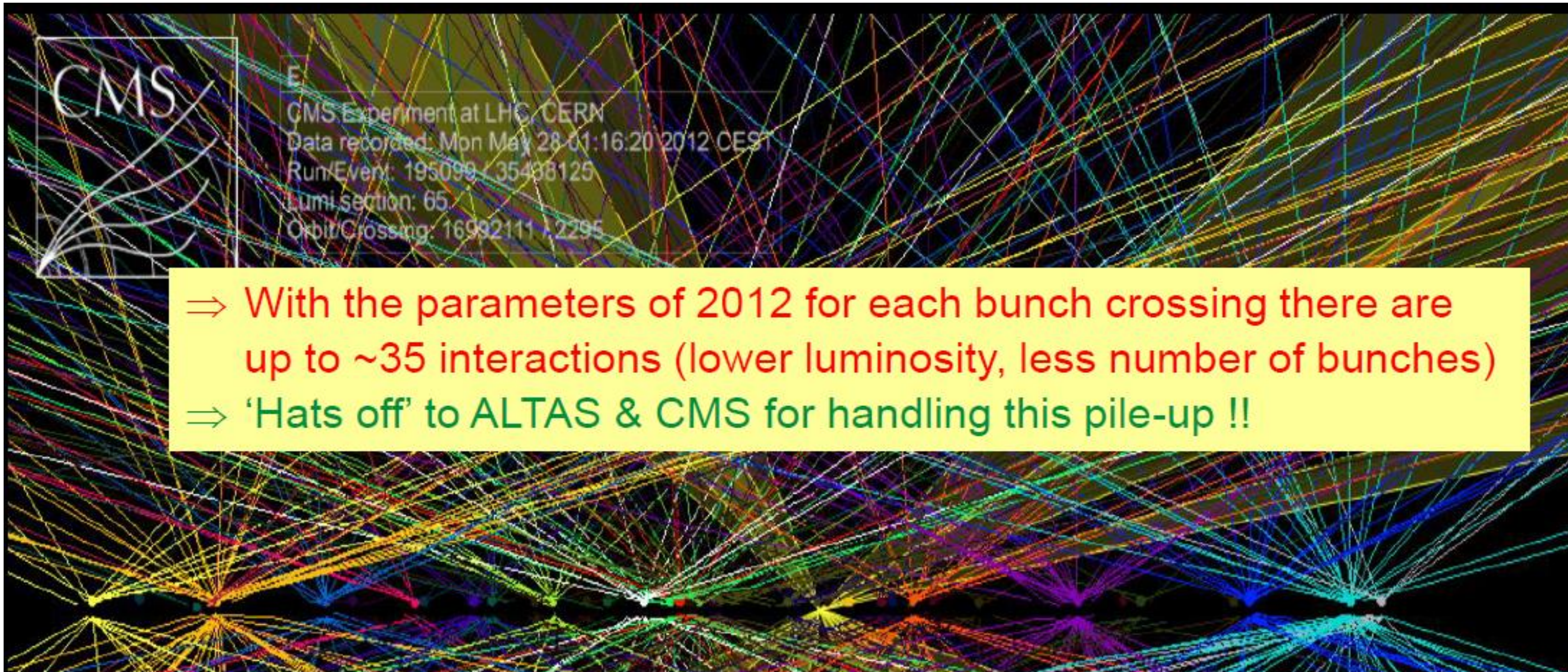
Beam r.m.s. sizes [m]

$$\sigma = \sqrt{\epsilon\beta}$$

Emittance [m]

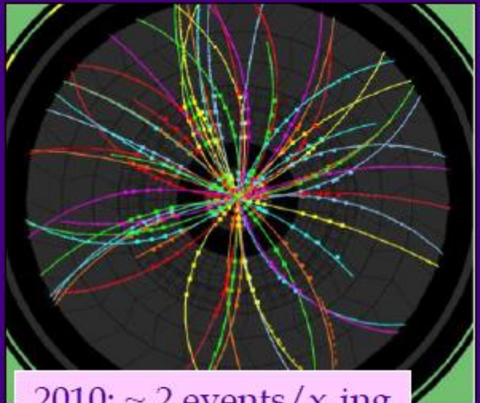
Beta function [m]

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



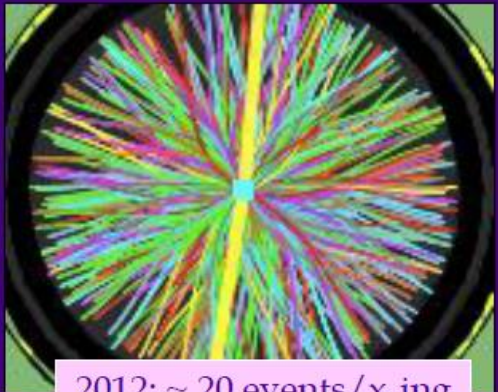
⇒ With the parameters of 2012 for each bunch crossing there are up to ~35 interactions (lower luminosity, less number of bunches)

⇒ 'Hats off' to ALTAS & CMS for handling this pile-up !!



2010: ~ 2 events/x-ing

2011: ~ 10 events/x-ing

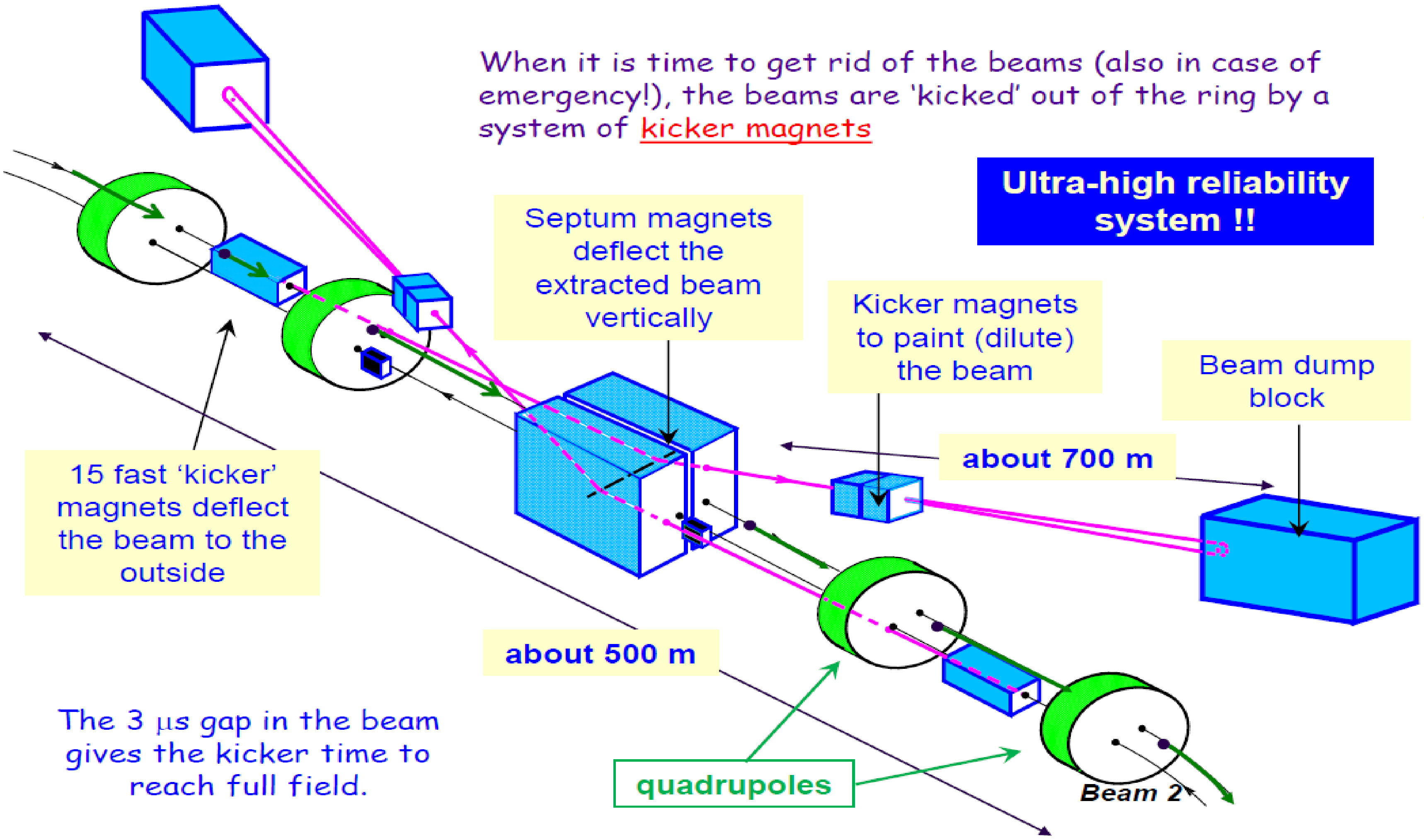


2012: ~ 20 events/x-ing

Layout of beam system dump

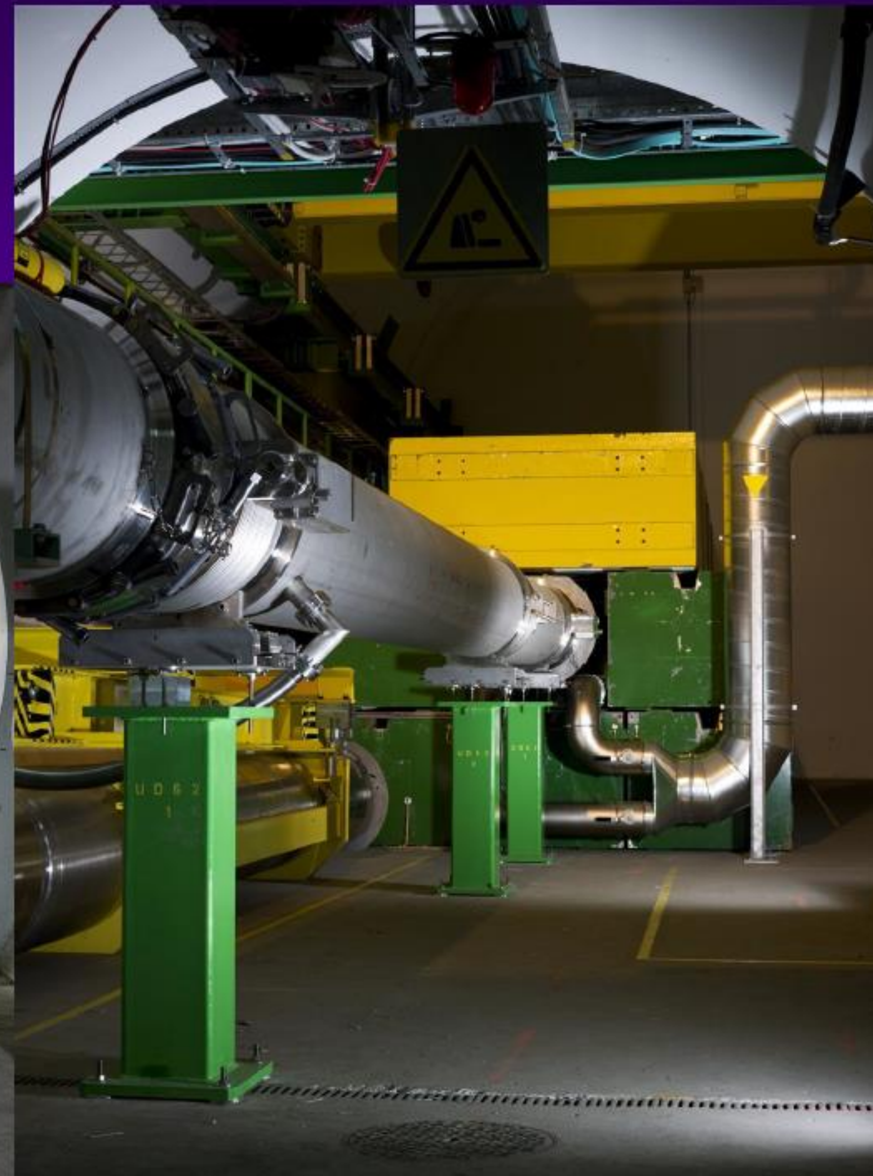
When it is time to get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of kicker magnets

Ultra-high reliability system !!



The 3 μs gap in the beam gives the kicker time to reach full field.

Dump line

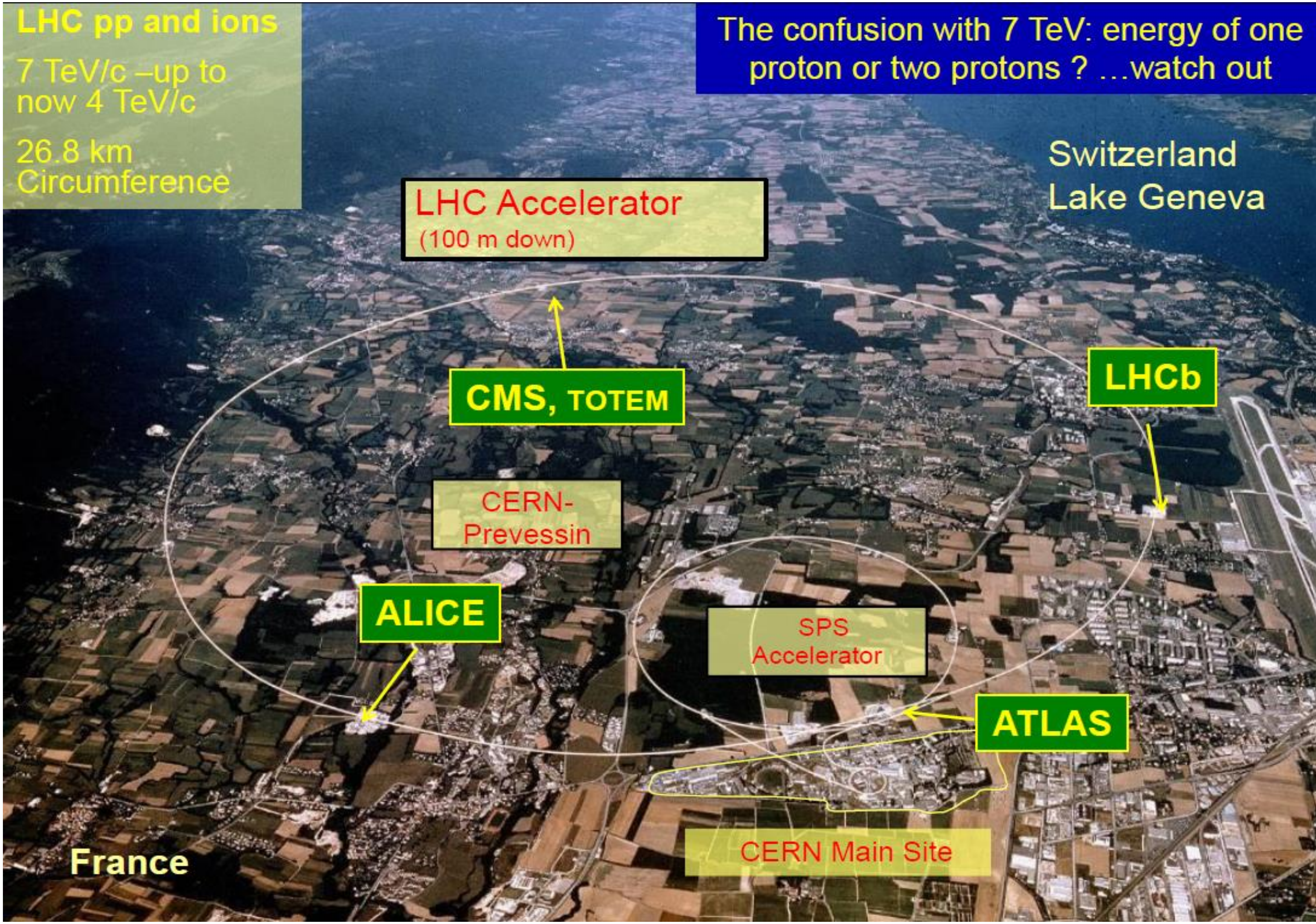


Beam Loss Monitors

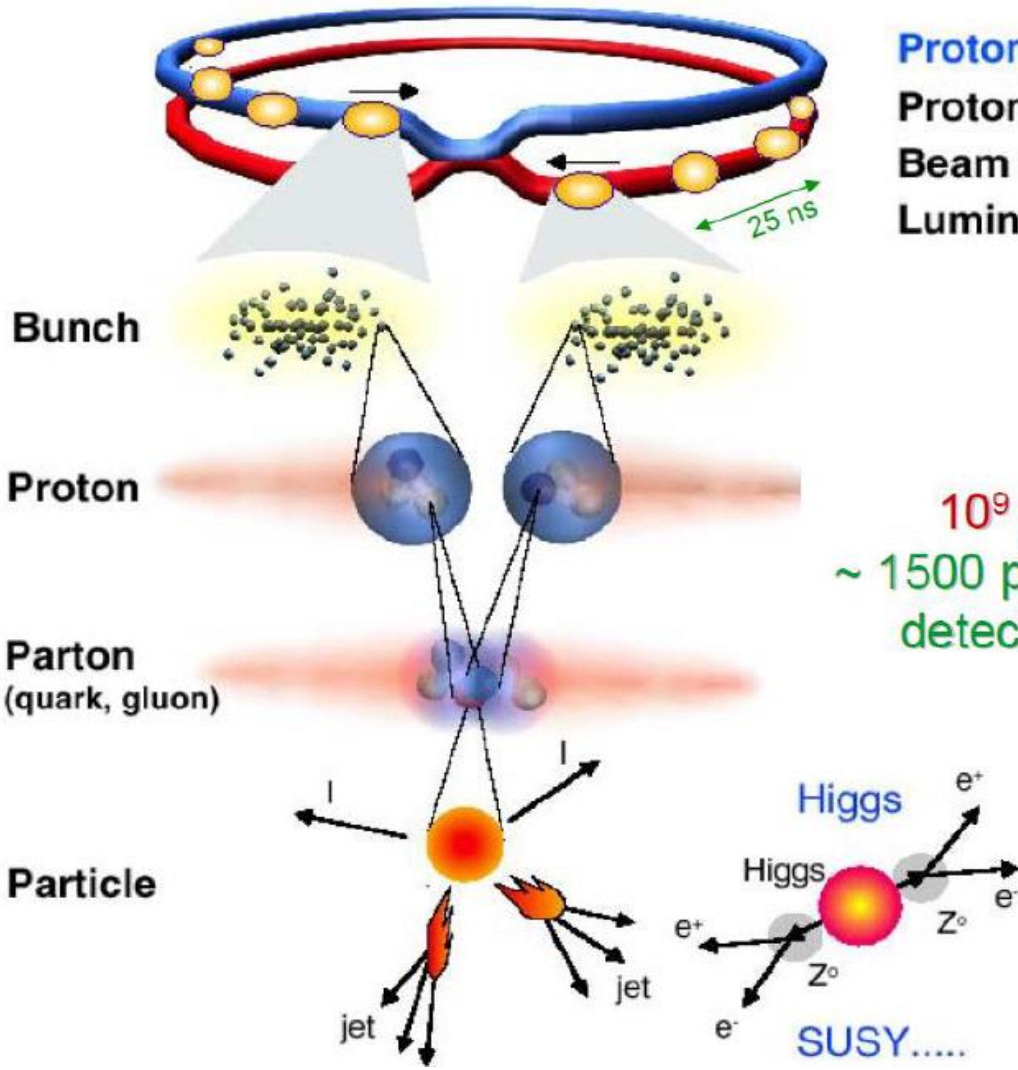
- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- There are **~3600 chambers** distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !
- Very important beam instrumentation!

The LHC: just another collider?

	Start	Type	Max proton energy [GeV]	Length [m]	B Field [Tesla]	Lumi [$cm^{-2}s^{-1}$]	Stored beam energy [MJoule]
TEVATRON Fermilab Illinois USA	1983	p-pbar	980	6300	4.5	4.3 10^{32}	1.6 for protons
HERA DESY Hamburg	1992	p – e+ p – e-	920	6300	5.5	5.1 10^{31}	2.7 for protons
RHIC Brookhaven Long Island	2000	Ion-Ion p-p	250	3834	4.3	1.5 10^{32}	0.9 per proton beam
LHC CERN	2008	Ion-Ion p-p	**7000** Now 4000	26800	8.3	10^{34} Now 7.7× 10^{33}	**362 per beam**
Factor			7	4	2	**50**	**100**


LHC pp and ions
7 TeV/c –up to now 4 TeV/c
26.8 km Circumference
The confusion with 7 TeV: energy of one proton or two protons ? …watch out
Switzerland
Lake Geneva
LHC Accelerator
(100 m down)
CMS, TOTEM
LHCb
CERN-Prevessin
ALICE
SPS Accelerator
ATLAS
CERN Main Site
France

Collisions at LHC



Proton-Proton	**2835 bunch/beam**
Protons/bunch	**10^{11}**
Beam energy	**7 TeV (7×10^{12} eV)**
Luminosity	**10^{34} cm^{-2} s^{-1}**

In the experiments:

10^9 pp interactions per second

~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing

Selection of 1 in 10,000,000,000,000

Summary: 2010 - 2012

$$L = \frac{kN_b^2 f \gamma}{4\pi \beta^* \varepsilon^*} F$$

Parameter	2010	2011	2012	Nominal
Energy [TeV]	3.5	3.5	**4.0**	7.0
N_b [10^{11} p/bunch]	1.2	1.45	**1.6**	1.15
k (no. bunches)	368	1380	**1380**	2808
Bunch spacing [ns]	150	75 / 50	**50**	25
Stored energy [MJ]	25	112	**140**	362
ε^* [μm]	2.4	2.4	**2.5**	3.75
β^* [m]	3.5	1.5 → 1	**0.6**	0.55
Crossing angle [μrad]	200	240	**290**	285
L [10^{34} cm^{-2}s^{-1}]	0.02	0.35	**0.76**	1.0
Beam-beam parameter/IP (ΔQ_{bb})	-0.0054	-0.0065	**-0.0069**	-0.0033
Average Pile-up @ beg. of fill	8	17	**38**	26

The next years