High PT physics at LHC – Lecture I (Introduction and LHC accelerator)

Juraj Bracinik, Miriam Watson
(University of Birmingham)

Warwick week, April 2012

- Introduction
- LHC machine
- High P_T experiments – Atlas and CMS
- Standard Model physics
- Searches

Introduction

What are these lectures going to be?

- An introduction to the topics
- Rather an overview, the topic is too broad to go into details
- Different people need to know different details, but an overview can be useful to everyone...
- Not too much maths, most of it just to give us feeling for orders of magnitude
- (hope) a lot of discussion! (at least some...)

Four lectures ...

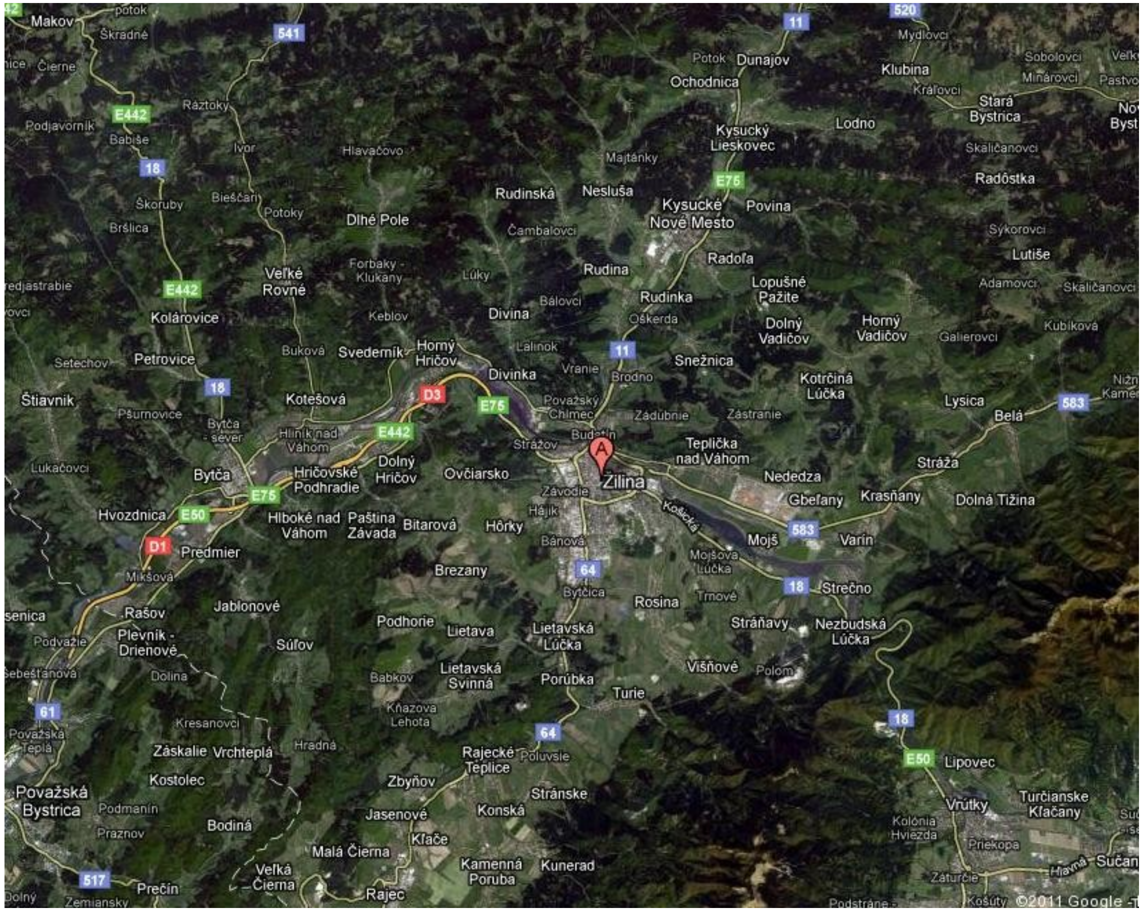
Lecture 1 : Introduction to LHC physics, LHC accelerator

Lecture 2: General purpose experiments (ATLAS and CMS)

Lecture 3: "Bread and butter" physics at LHC

Lecture 4: Overview of expected exciting discoveries!

Please allow me to introduce myself ...



I work for ATLAS trigger, so naturally biased ...

Lecture 1 - Introduction and LHC

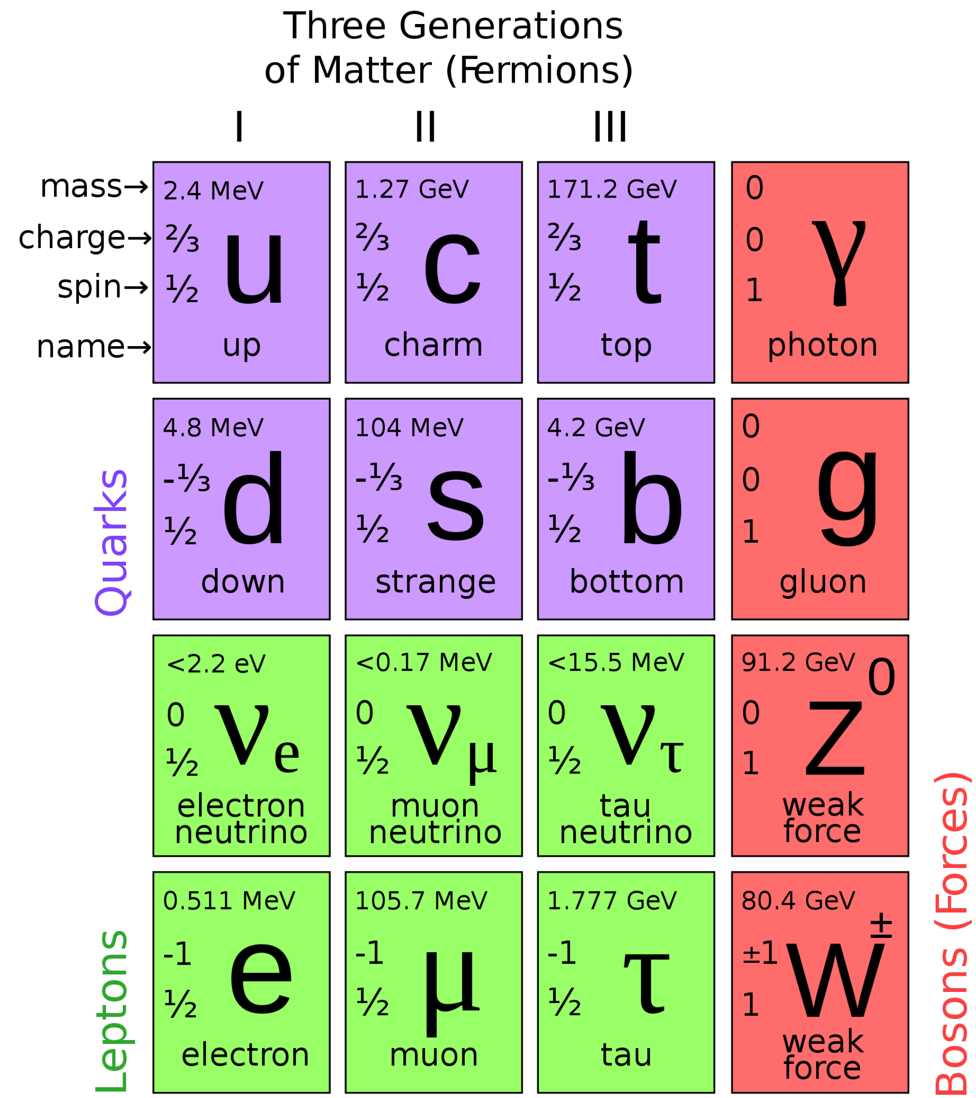
- Standard model of elementary particle physics and its Big Open Questions
- Physics of hadronic collisions:
  - Initial state and parton density functions
  - Final state, kinematic variables used to characterize it
- LHC machine:
  - General parameters
  - How are particles accelerated: RF
  - What keeps them running around?
  - Interaction points, that is where it all happens!

Standard model and its (standard) troubles

Standard model and standard (model) troubles

Standard Model describes all observed phenomena in Elementary particle physics

- 2 x 6 fundamental fermions - “particles of matter”
- 4 fundamental, spin 1 bosons - “particles of interaction”

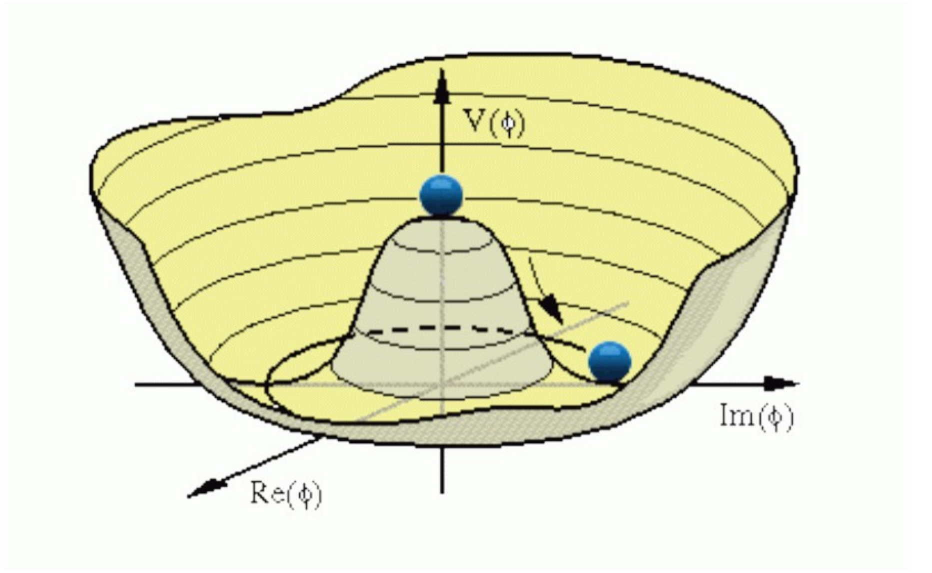


Language (mathematical) of SM:

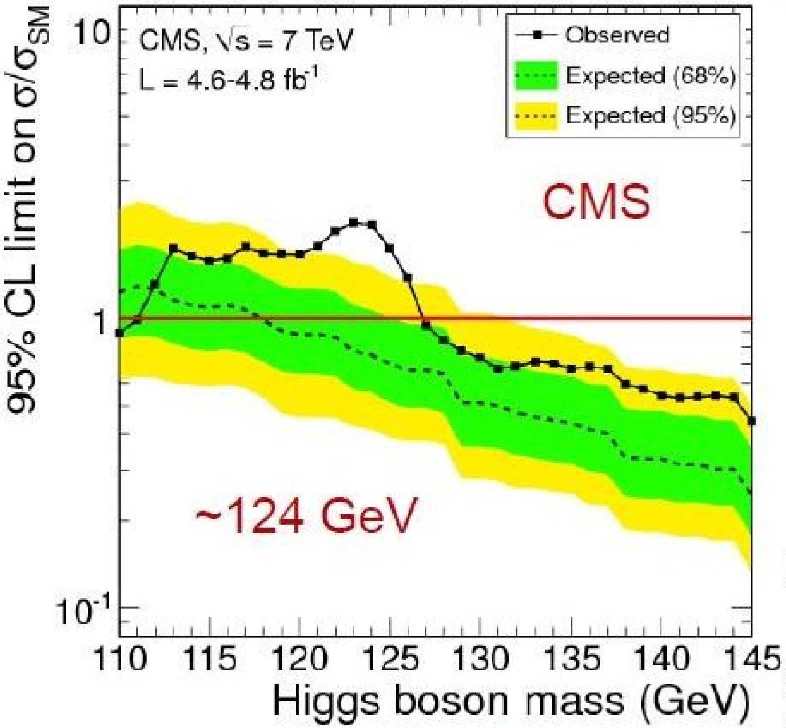
- Local renormalizable Quantum Field Theory

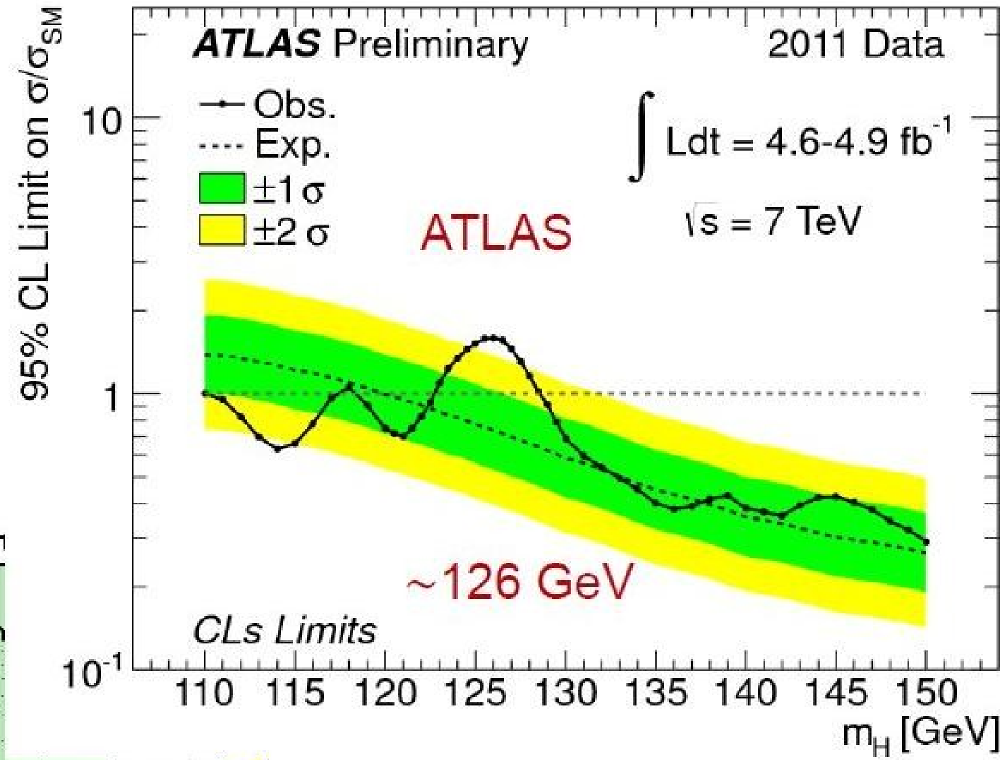
Standard model and its problems

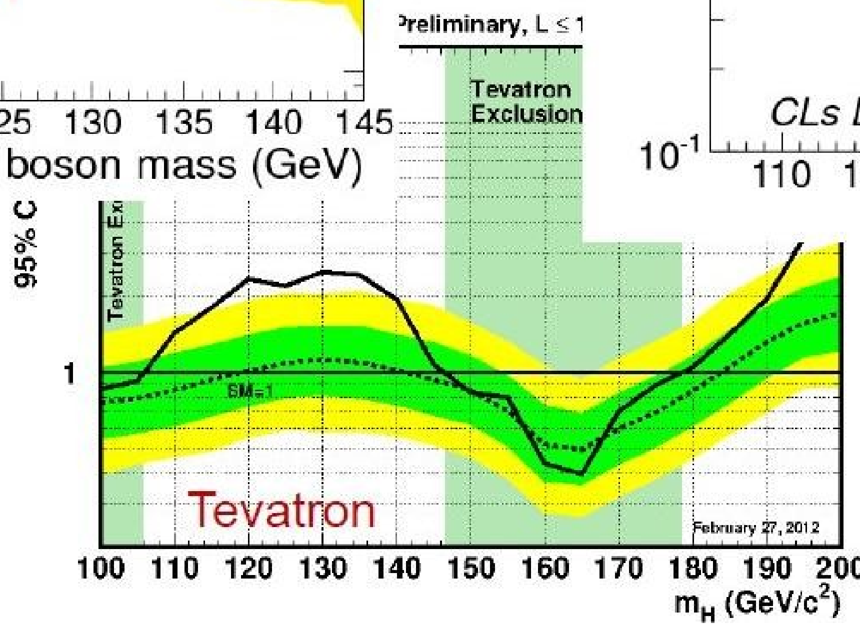
- Quantum field theory with massive spin-1 boson is not renormalizable
- W and Z are very massive!
- The main problem of Elementary Particle Physics today



- The simplest (and most popular) model:
- Postulate additional scalar field – Higgs particle
- It has nonzero vacuum expectation value
- W and Z acquire mass in interaction with Higgs
- γ remains mass-less
- The only free parameter of the model is Higgs mass
- From indirect evidence expect it is just around the corner!





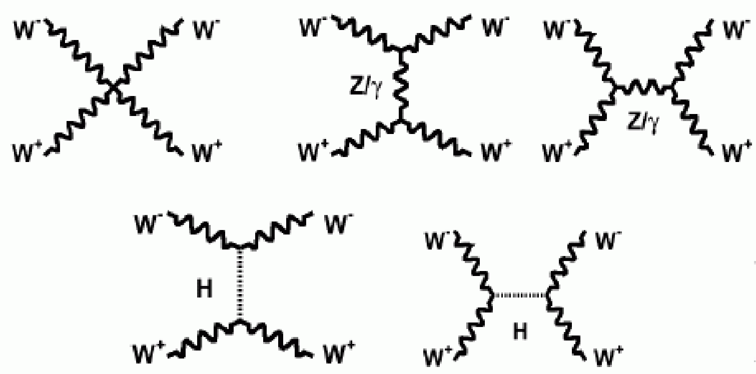


Local excesses in ATLAS and CMS ~2-3 σ

Will be very interesting in 2012!

More details in Miriam's lecture on Friday...

Standard model and its problems



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for E >> M_H

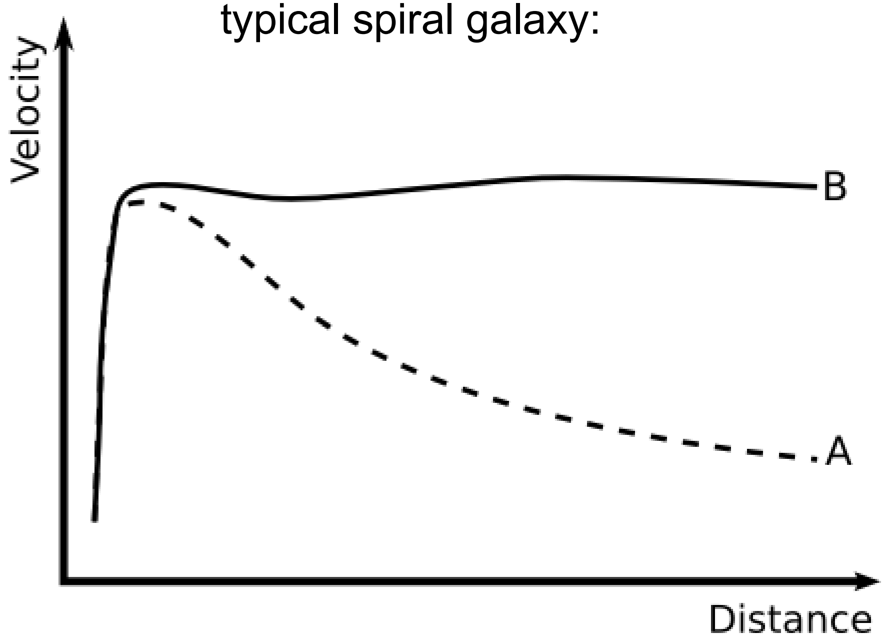
This cancellation requires M_H < 800 GeV

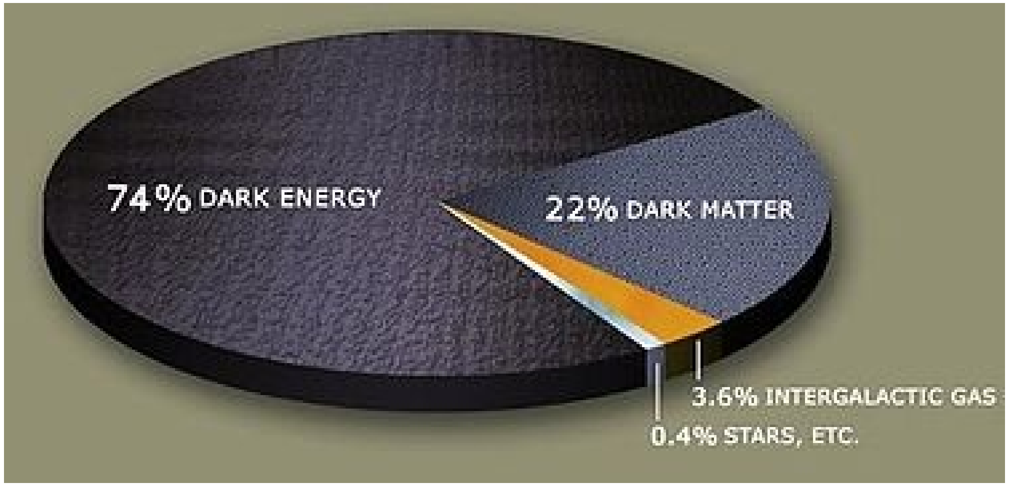
- If there is no Higgs?
- In the SM Higgs boson prevents unitarity violation of WW scattering cross section!
- Without the Higgs σ(pp->WW) > σ(pp->anything)
- At √s = 1.2 TeV!

Something interesting must happen at TeV energies, Higgs or no Higgs...

Dark matter

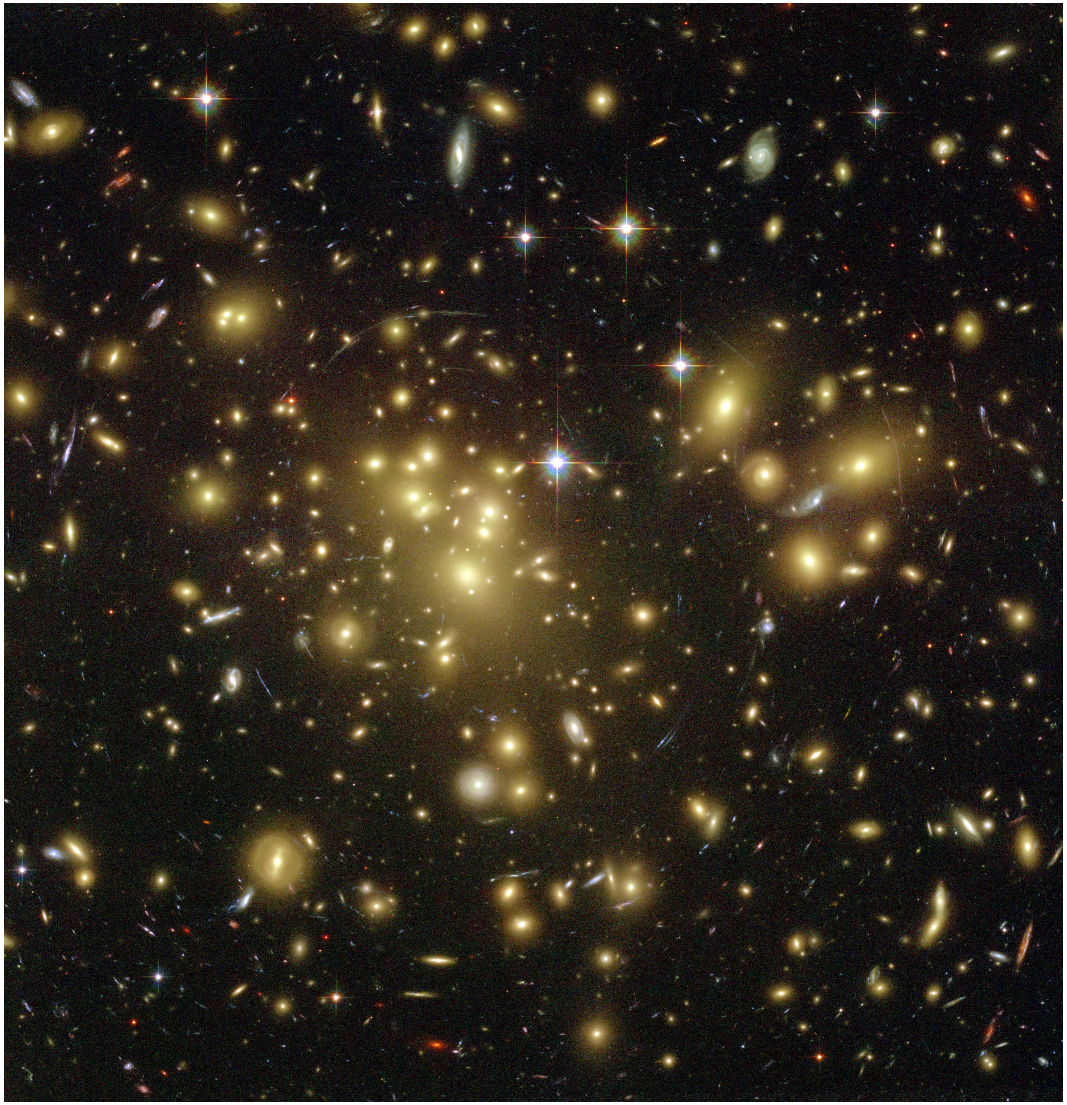
Rotation curve of
typical spiral galaxy:



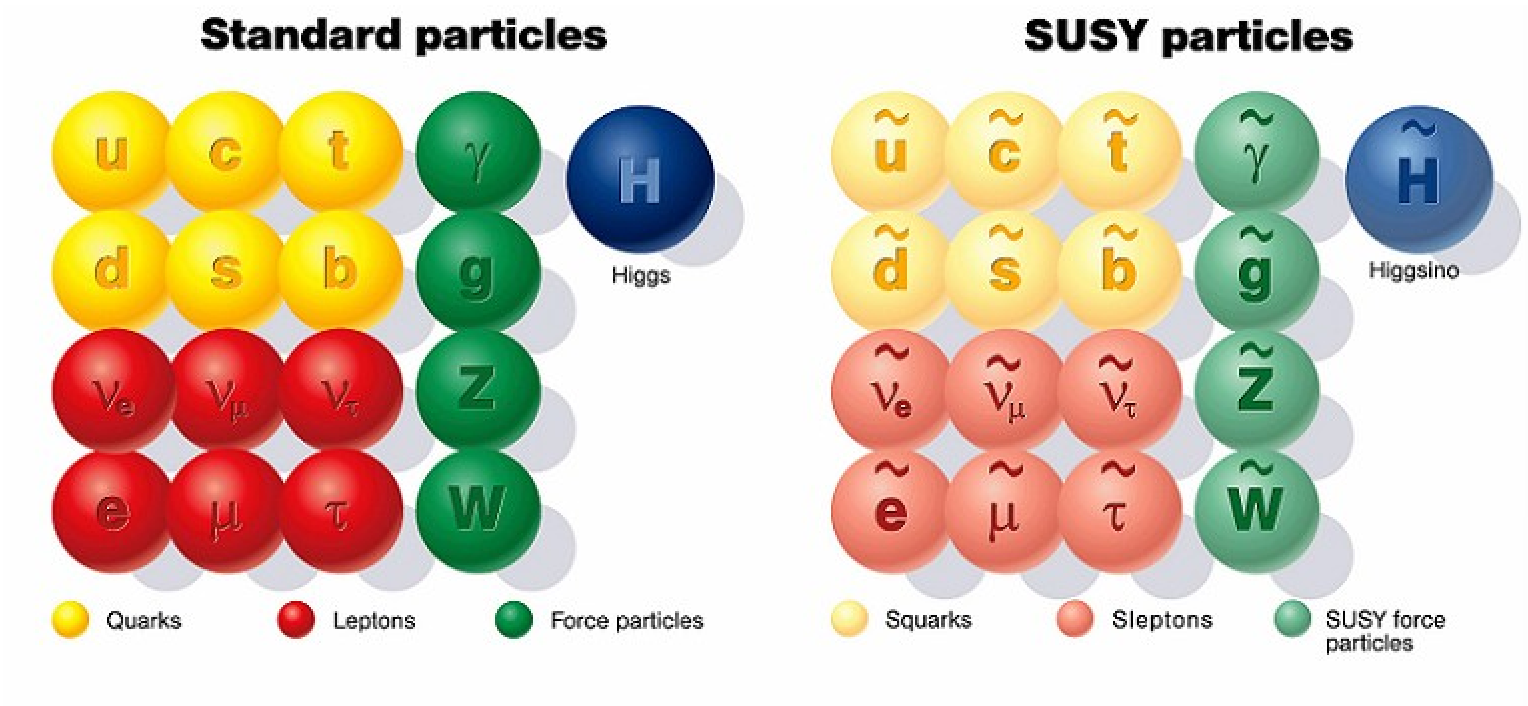


- We know there is a physics beyond Standard model!
- Just need to look at the sky!

Dark matter



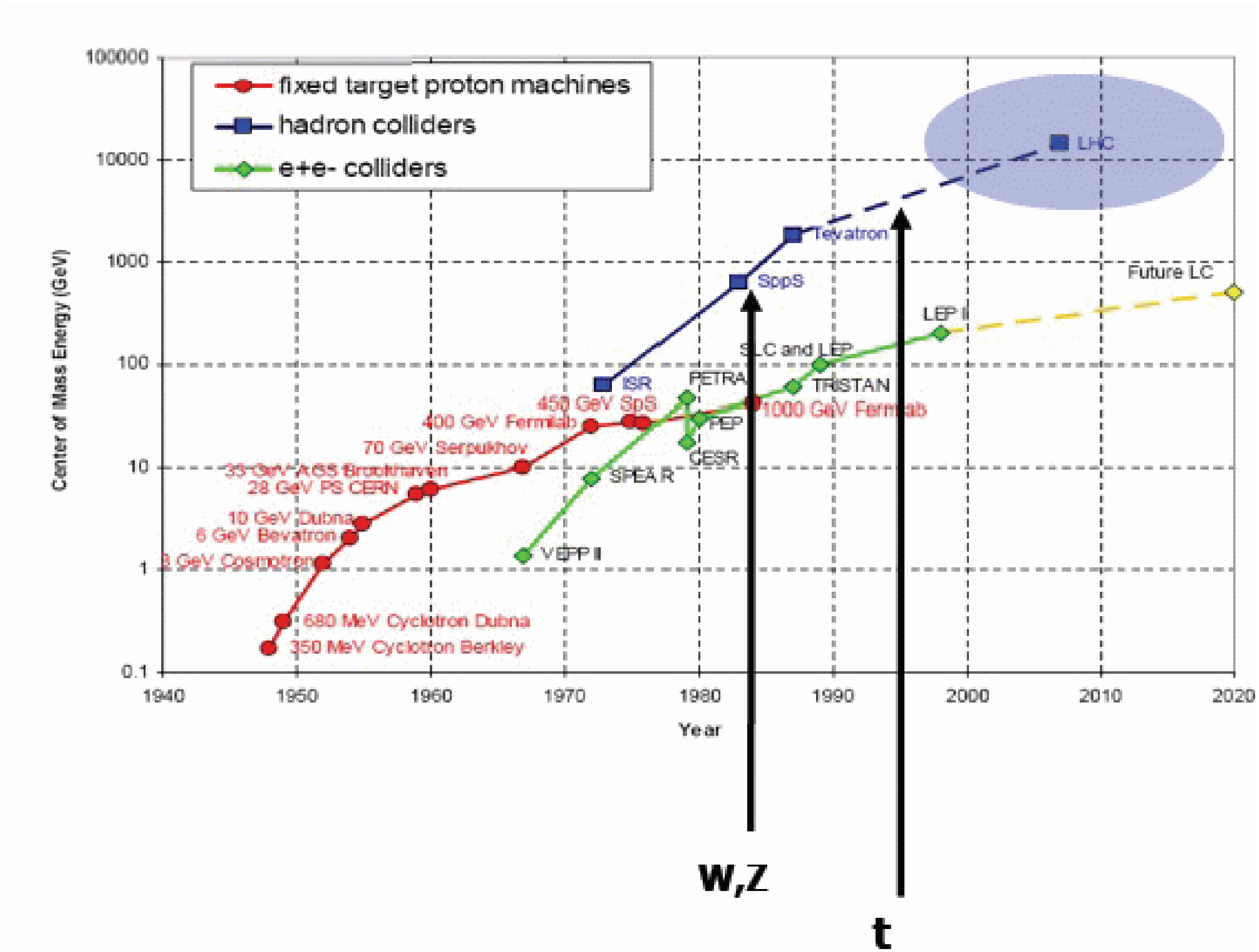
Supersymmetry



- Symmetry between bosons and fermions
- Each SM model particle has it's supersymmetric partner (dream of each experimentalist!)
  - Must be broken, a lot of free parameters
- A lot of nice features
  - Lightest SUSY particle is a dark matter candidate
- Just behind the corner (or not)

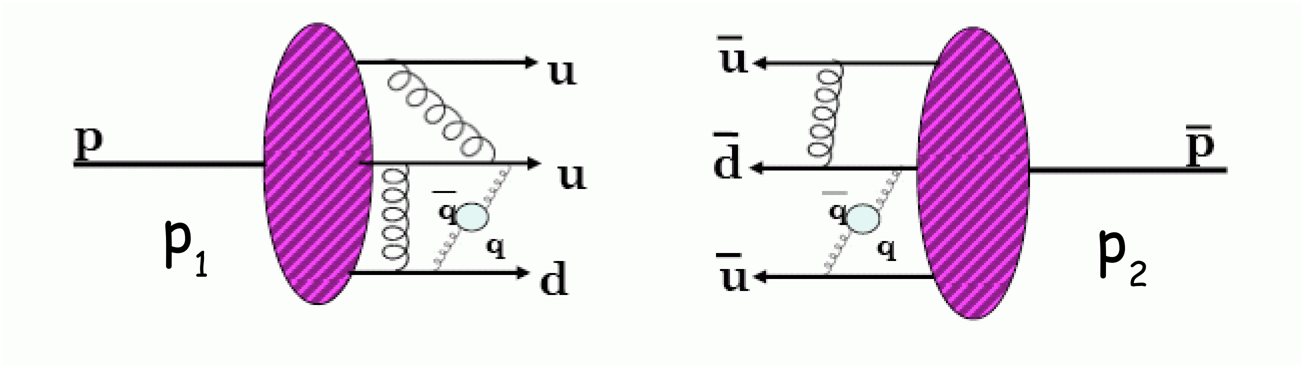
Basic kinematics of high energy hadron collisions

One accelerator with TeV energy, please...



Hadron colliders have their advantages when it comes to exploration of unknown territory (discovery physics)

Detailed look at high energy pp collision



- Protons at high energy behave as beams of pointlike particles – partons
- Proton beam offers wide range of (elementary) collision energies
- Variable x (Bjorken x) gives fraction of proton energy carried by a parton:

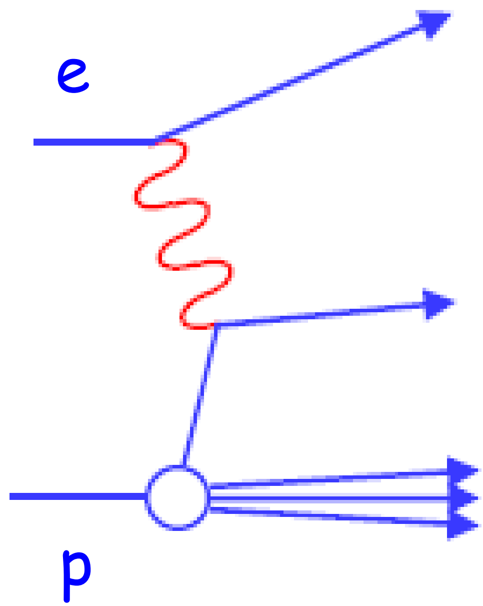
$$\hat{x} = \frac{P_{parton}}{P_{proton}}$$

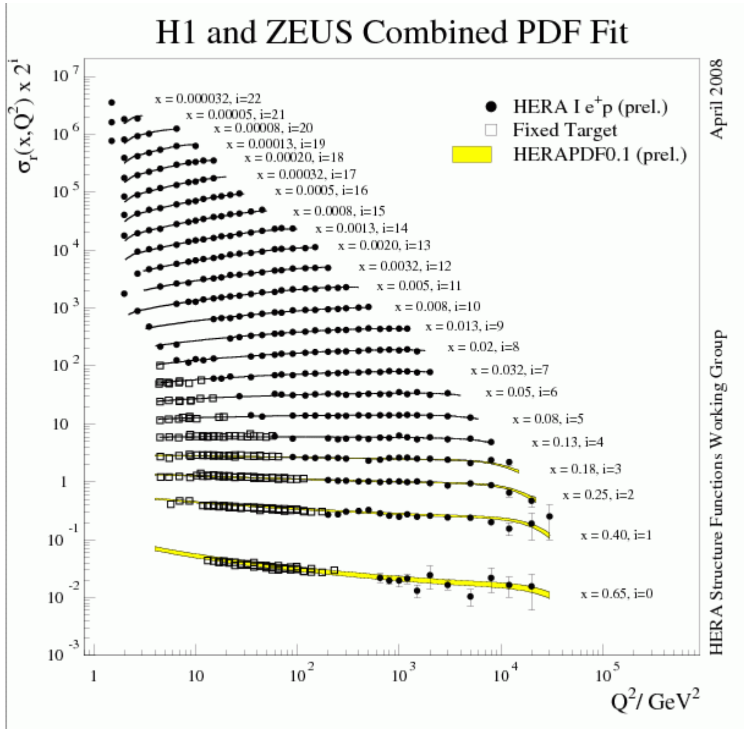
- Energy of (elementary) collision is then

$$\sqrt{s_{elementary}} = \hat{x}_1 \hat{x}_2 \sqrt{s} \qquad s = (p_1 + p_2)^2$$

Proton colliders offer wide range of available center-of-mass energy for elementary collisions :-)

Structure of the proton I





- Distribution of partons in the proton is well known!
- measured (mainly) in Deep Inelastic ep Scattering (DIS)
- DIS ⇔ elastic electron-quark scattering!
- Distribution of scattered electrons is very sensitive to distribution of partons in the proton

Structure of the proton II

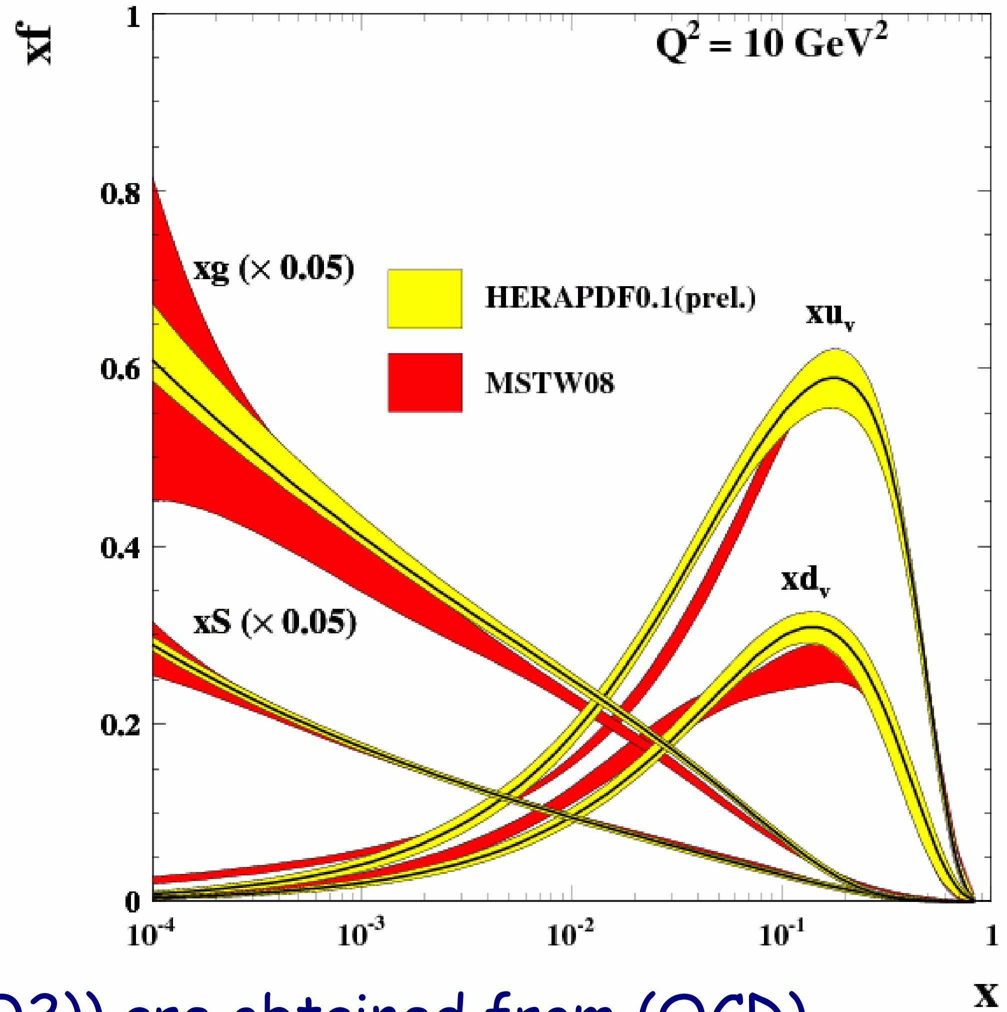
Inclusive DIS cross section:

$$\frac{d^2\sigma_{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left(y^2 xF_1(x,Q^2) + (1-y)F_2(x,Q^2)\right)$$

- Q – virtuality of exchanged photon
- x – Bjorken x

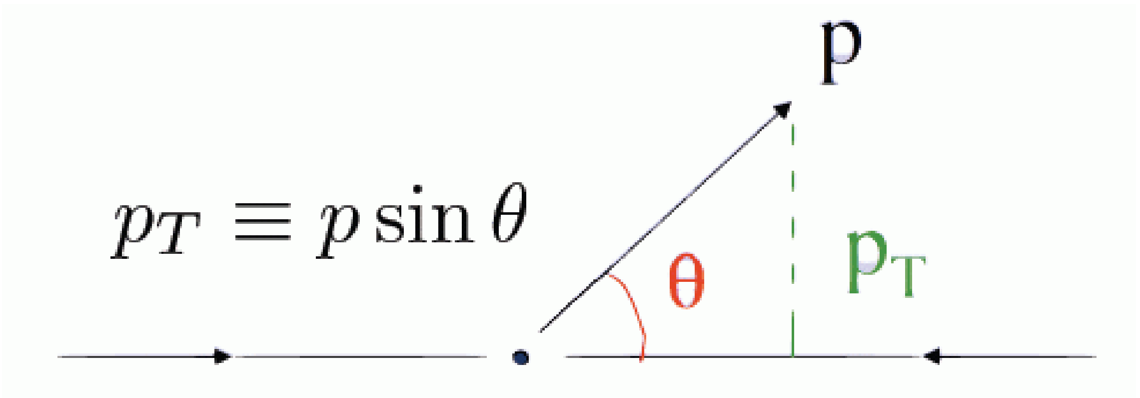
In Leading Order:

$$\begin{aligned} F_2(x,Q^2) &= 2xF_1(x,Q^2) \\ &= x\sum_q e_q^{\,2}\left(q(x,Q^2) + \bar{q}(x,Q^2)\right) \end{aligned}$$



Parton distributions (q(x,Q2)) are obtained from (QCD) fits to cross section of various processes (ep NC, CC, high P_T jet production, ...)

Kinematics of produced particles I



We are interested in momentum of produced particles:

- Could use px,py,pz …
- Geometry of collision is cylindrical, can use cylindrical coordinates
  - P, θ, ϕ
- Physics is symmetric in phi
- The fact that collisions are not collisions between pointlike particles complicates kinematic analysis
  - Total longitudinal momentum of elementary collision is not known
  - Transversal momentum(P_T) is conserved (and used very often)

Produced particles – kinematics II

- Usually do not use P and θ, but rapidity:

$$y=\frac{1}{2}\ln\left(\frac{E+p_Z}{E-p_Z}\right)$$

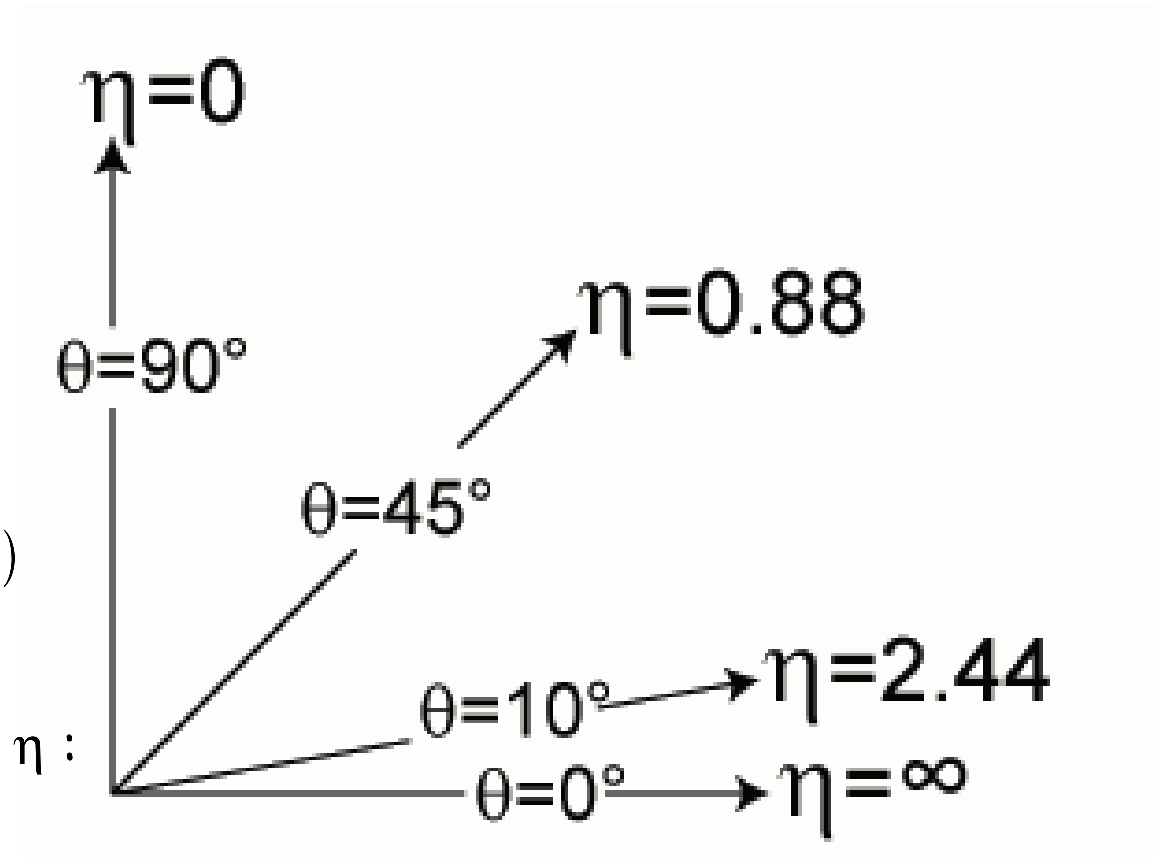
- Rapidity (Δy) and P_T are invariant with respect to Lorentz boosts along beam direction!

$$m_T^2=m^2+p_T^2$$

$$E=m_T\cosh(y) \qquad p_z=m_T\sinh(y)$$

- For zero mass particles (or high p) rapidity is equal to pseudorapidity η :

$$\eta=-\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$



Production of massive particles

- Two partons (with x1, x2) inside of two protons (with $p_{proton\ A}$, $p_{proton\ B}$) collide, create a heavy (new!) particle with mass M and rapidity y_M

$$M^2 = (x_1 p_{proton\,A} + x_2 p_{proton\,B})^2 \longrightarrow x_1 x_2 = \frac{M^2}{s}$$

- Higher x means higher M
- To produce mass of 100 GeV with accelerator running at 7 TeV requires x=0.007
- To produce mass of 5 TeV requires x = 0.36

$$p_{z\,M} = m_T\, sh(y_M) \rightarrow M\, sh(y_M)$$

$$p_{z\,M} = p_{z\,parton\,1} - p_{z\,parton} = (x_1 - x_2)\frac{\sqrt{s}}{2}$$

$$\longrightarrow$$

$$x_1 = \left[\frac{M}{\sqrt{s}}\right]\exp(y_M)$$

$$x_2 = \left[\frac{M}{\sqrt{s}}\right]\exp(-y_M)$$

- To produce M at zero rapidity we need partons with same x, going to higher rapidities of particle M means one parton at higher x, the other one at smaller x

Luminosity

Energy is not enough, one needs luminosity, too…

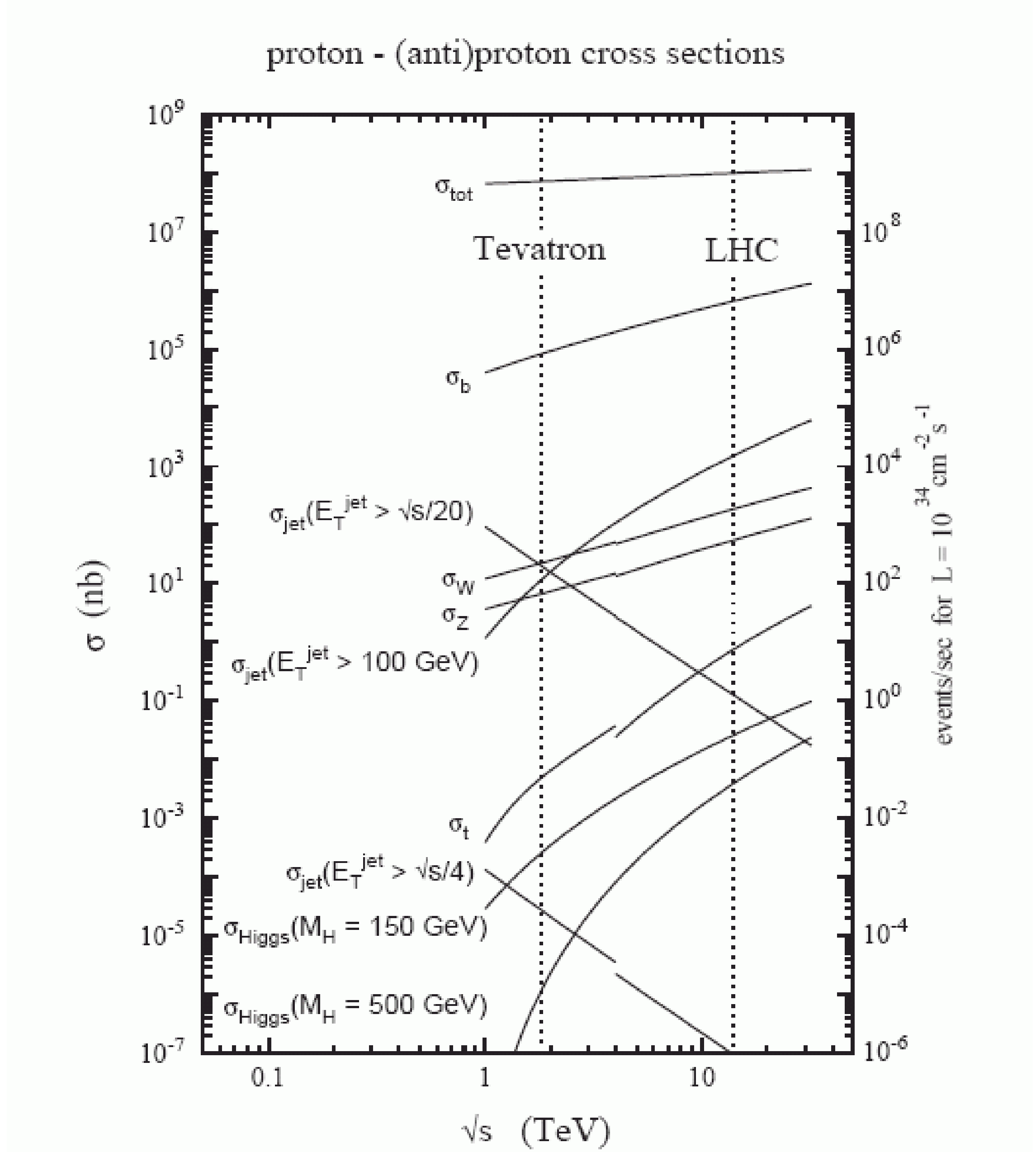
$$N = \sigma \times L$$

N – number of events (we want)

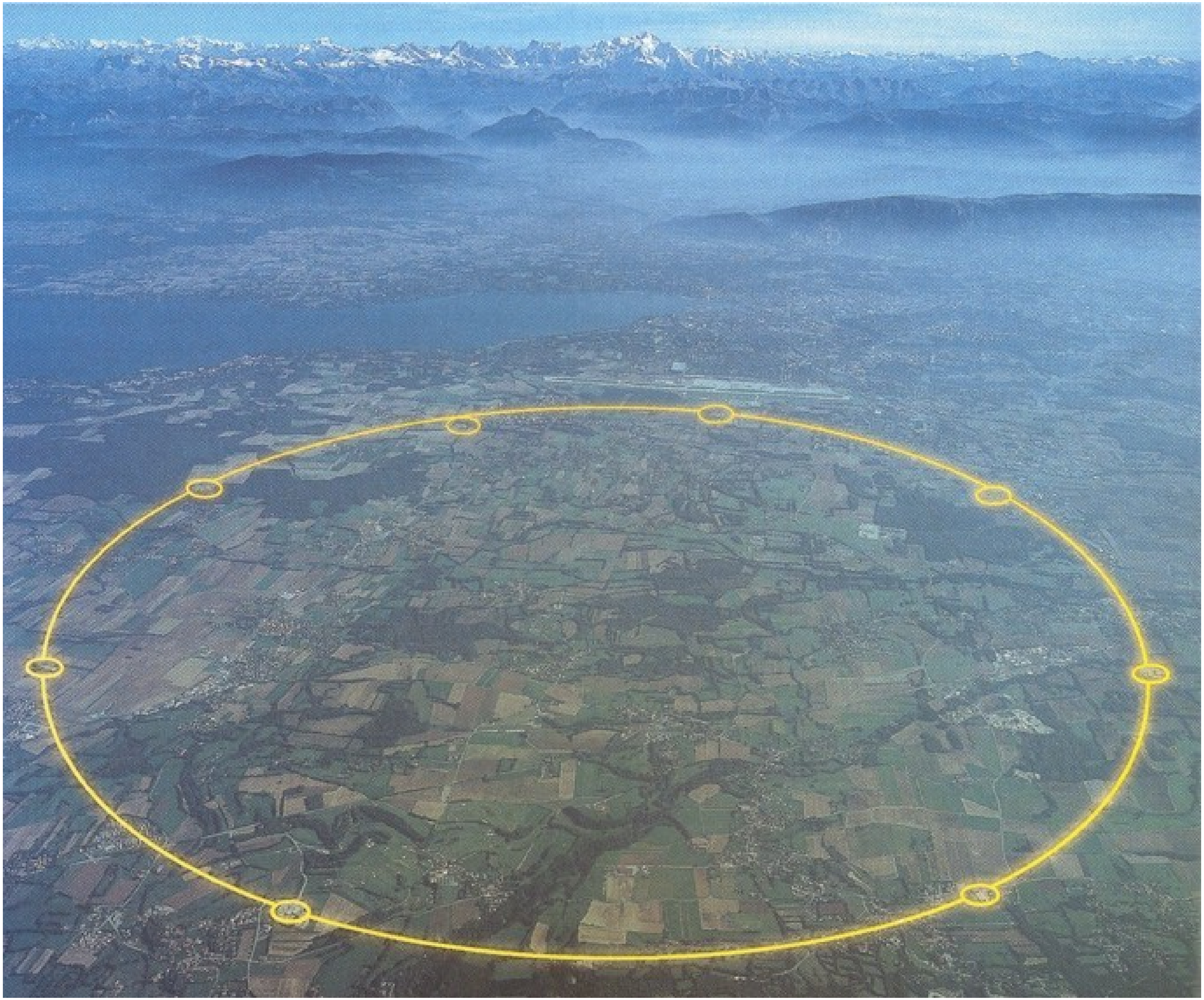
σ - cross section (given by Nature)

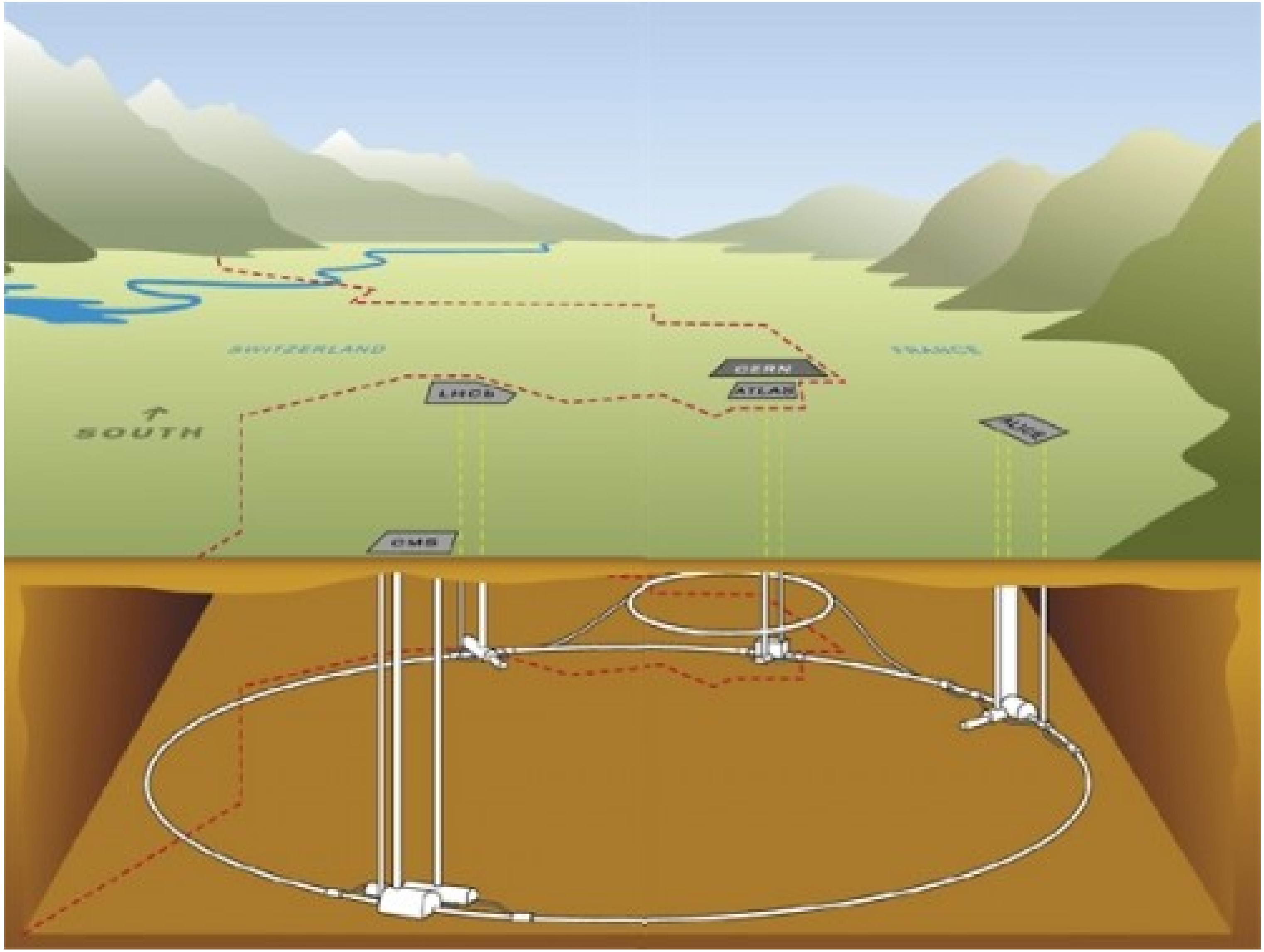
L – luminosity (parameter of an accelerator)

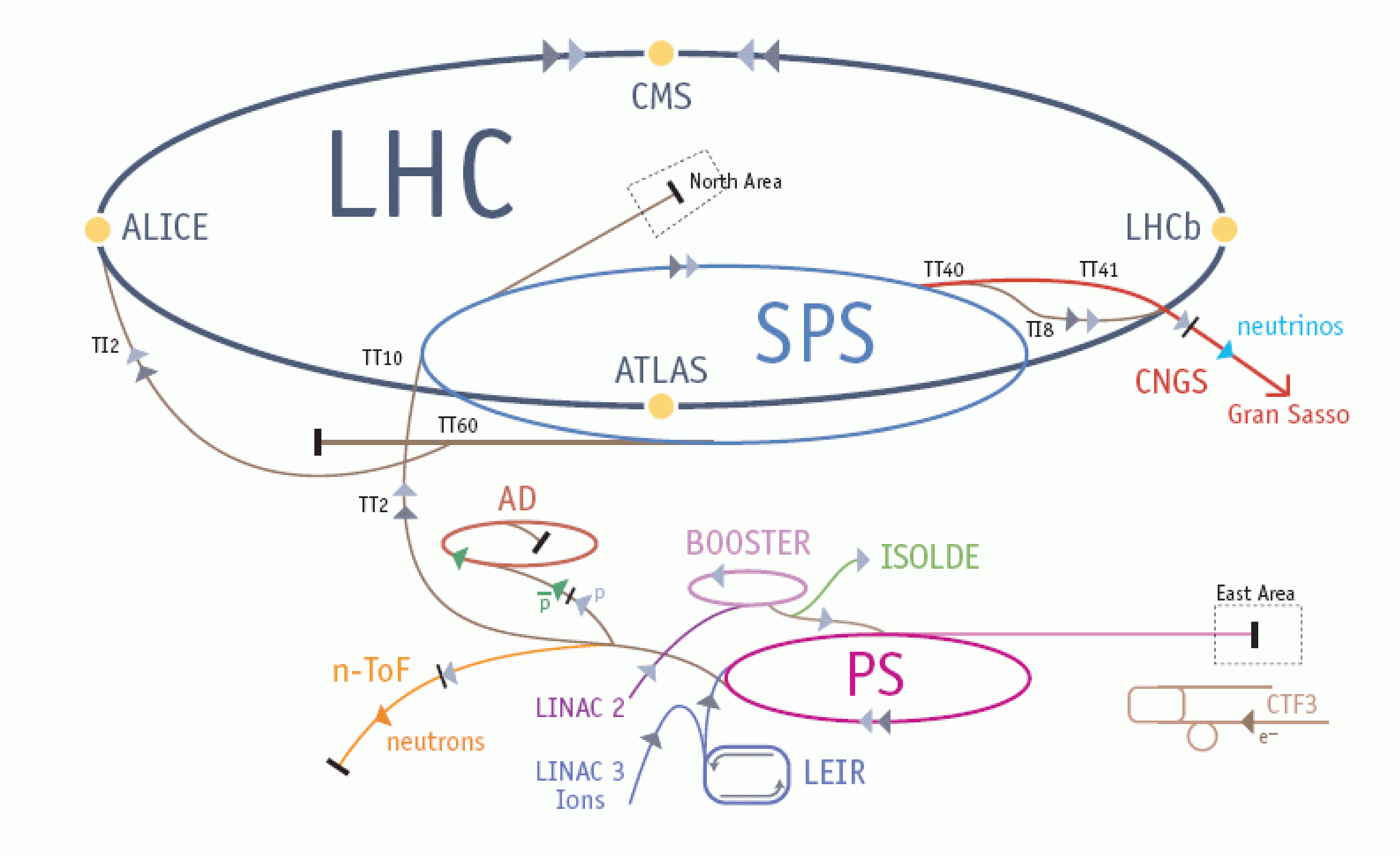
- Higgs couples mainly to particles with high mass, its cross section in pp collisions is rather small
- Need a machine with high luminosity !!!



Introduction to LHC




SWITZERLAND
SOUTH
CERN
ATLAS
CMS


CMS
LHC
North Area
ALICE
LHCb
TT40
TT41
neutrinos
SPS
TI8
TI2
TT10
ATLAS
CNGS
Gran Sasso
TT60
TT2
AD
BOOSTER
ISOLDE
p̄
p
East Area
n-ToF
PS
LINAC 2
CTF3
e⁻
neutrons
LINAC 3
Ions
LEIR


ALICE
CMS
ATLAS
LHCb

LHC nominal parameters

at collision energy

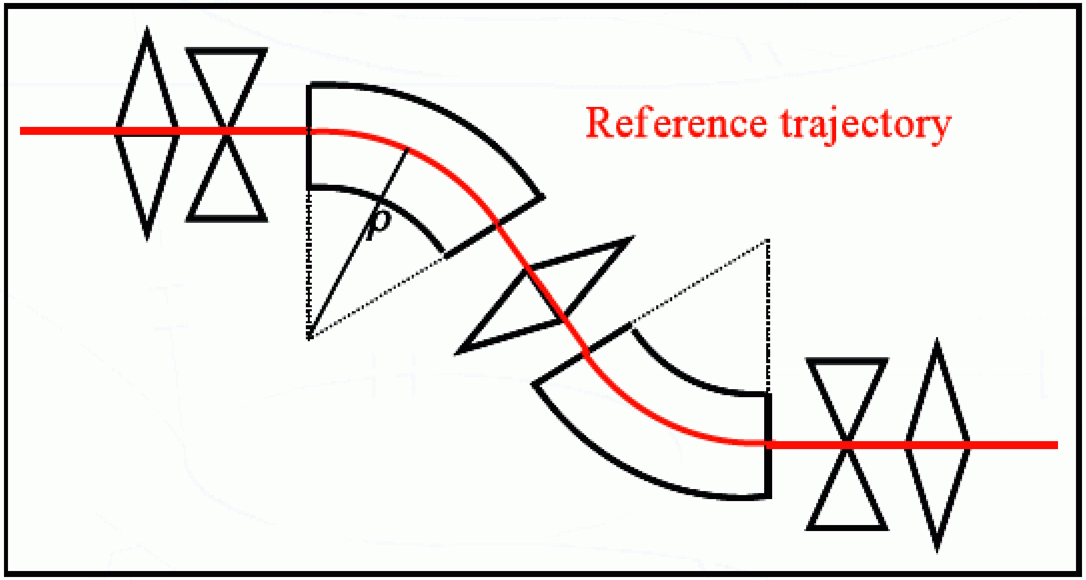
Particle type	p, Pb
Proton energy E_p at collision	7000 GeV
Peak luminosity (ATLAS, CMS)	1×10^{34} cm^{-2}s^{-1}
Circumference C	26 658.9 m
Bending radius ρ	2804.0 m
RF frequency f_{RF}	400.8 MHz
# particles per bunch n_p	1.15×10^{11}
# bunches n_b	2808

Particle accelerators

Accelerator: accelerate and steer particles (and collide them):

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) = \vec{F}_E + \vec{F}_B$$

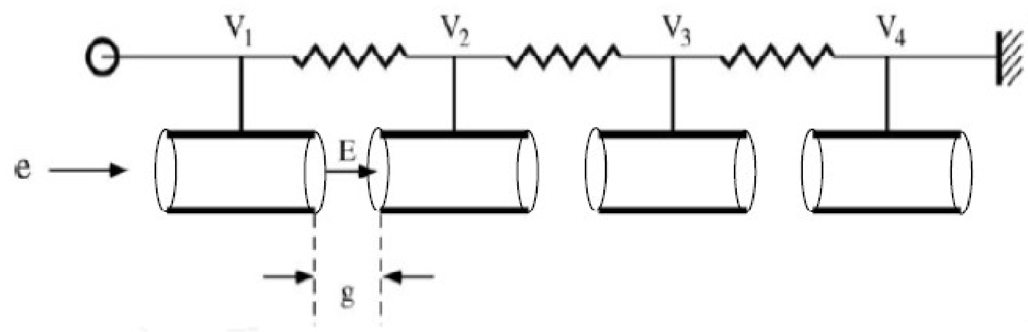
- Both F_E and F_B cause deflection:
- when v~c, 1T~ 3×10^8 V/m
- Achievable E field ~ few MV/m
- Magnetic field is used in accelerators when possible (beam steering)



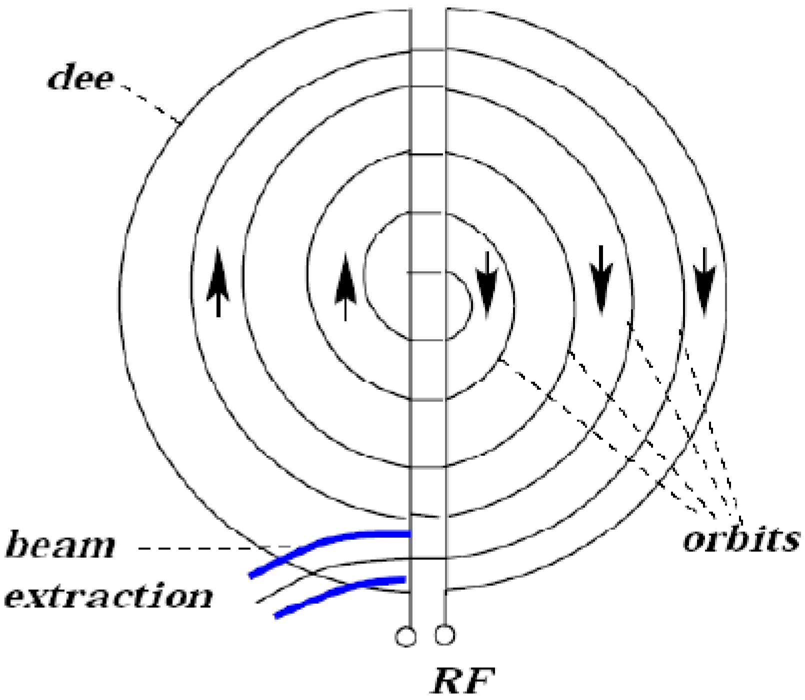
$$\vec{F}_B \perp \vec{v}$$ → Only electric field accelerates!

Accelerating particles

Linear (electrostatic) accelerator

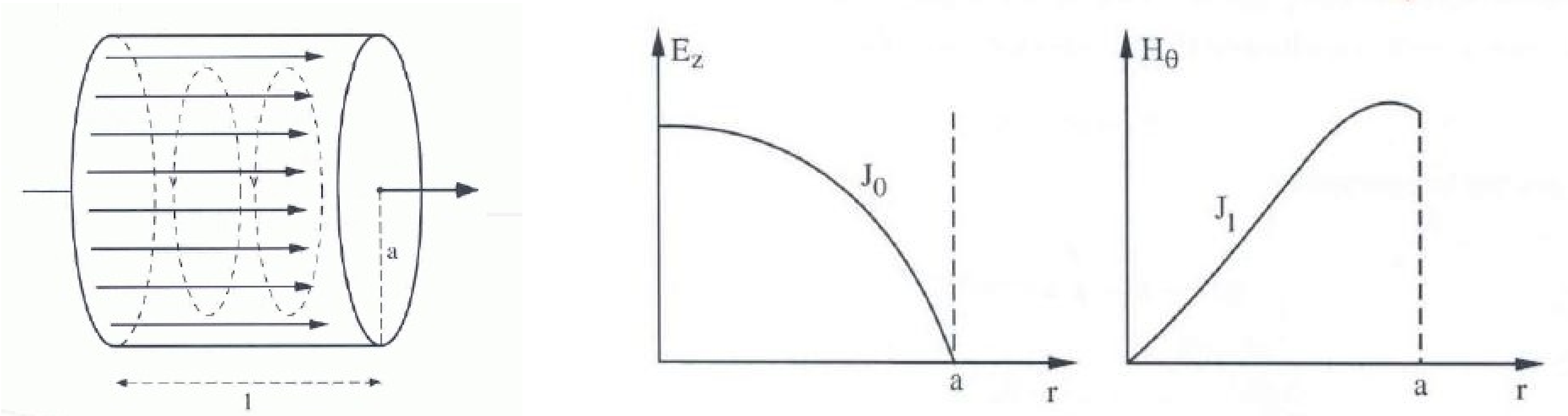


Cyclotron



An important function of an accelerator is to accelerate ...

Accelerating particles – RF cavities

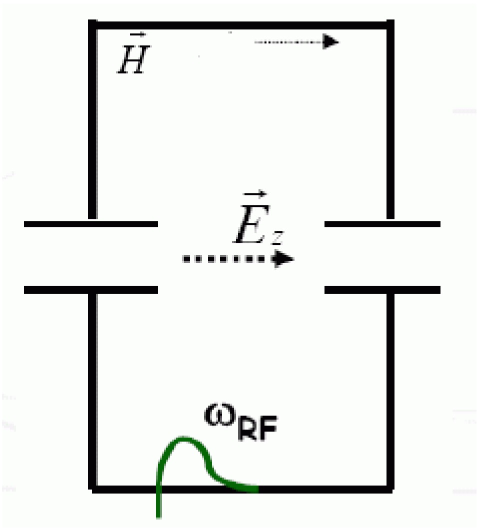


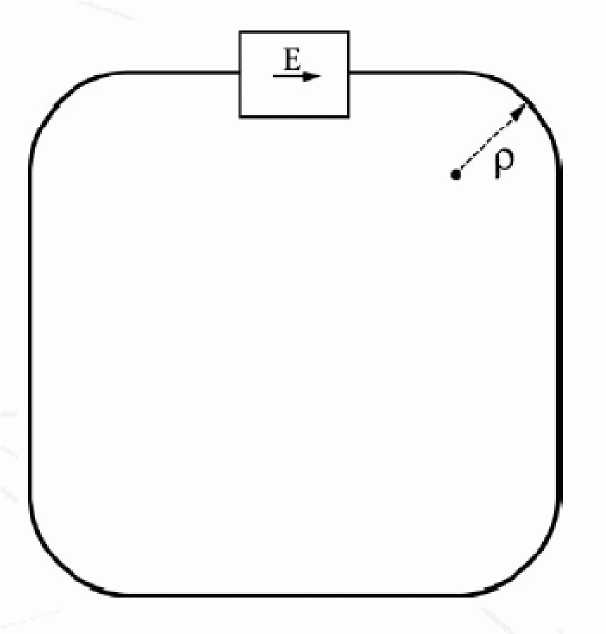
- In any closed metallic box it is possible to generate electromagnetic oscillations
- For example an ideal cylindric cavity
- Many (infinite number) of solutions for E and B – oscillating modes
- The fundamental mode normally used for acceleration is named TM_{010}
- E_z is constant in space along the axis of acceleration, z, at any instant

$$\left.\begin{aligned} E_z &= J_0(kr) \\ H_\theta &= -\frac{j}{Z_0} J_1(kr) \end{aligned}\right\} e^{j\omega t}$$

$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c} \quad \lambda = 2{,}62\,a \quad Z_0 = 377\Omega$$

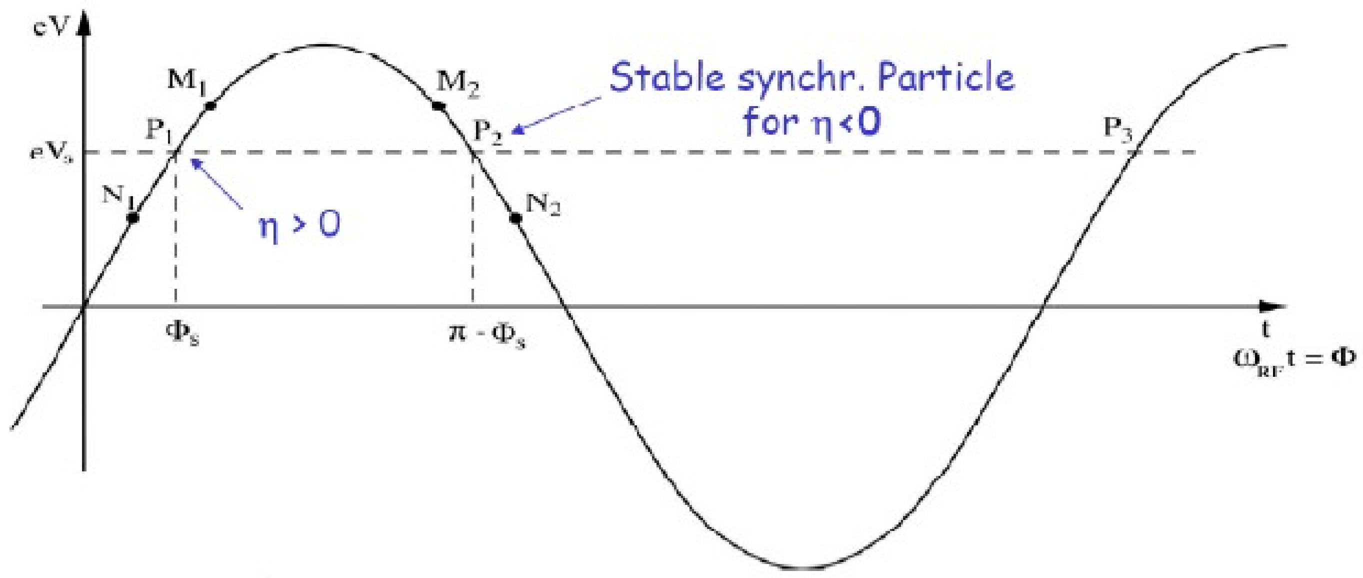
RF cavities





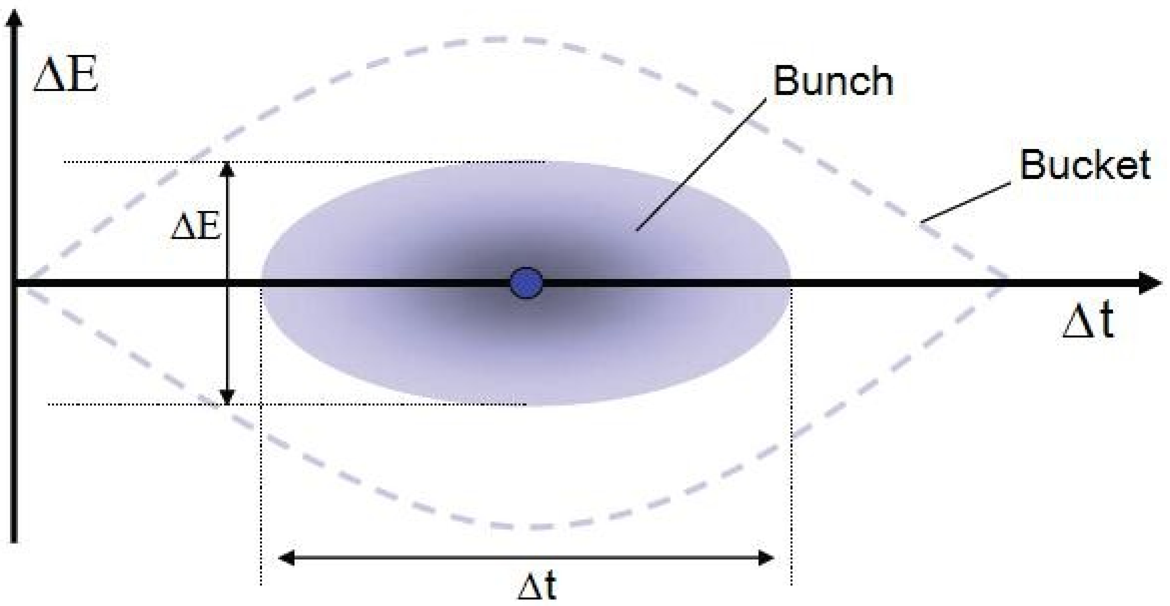
- RF power is fed into the cavity from RF power generators (for example Klystrons)
- RF power oscillates at desired frequency
- Good to have cavity with superconducting walls to minimize losses…
- Particles oscillating in the accelerator pass through the cavity many times, to be accelerated, they need to come at fixed phase
  - Beam is composed of bunches with a large number of particles

Phase stability and bunches I



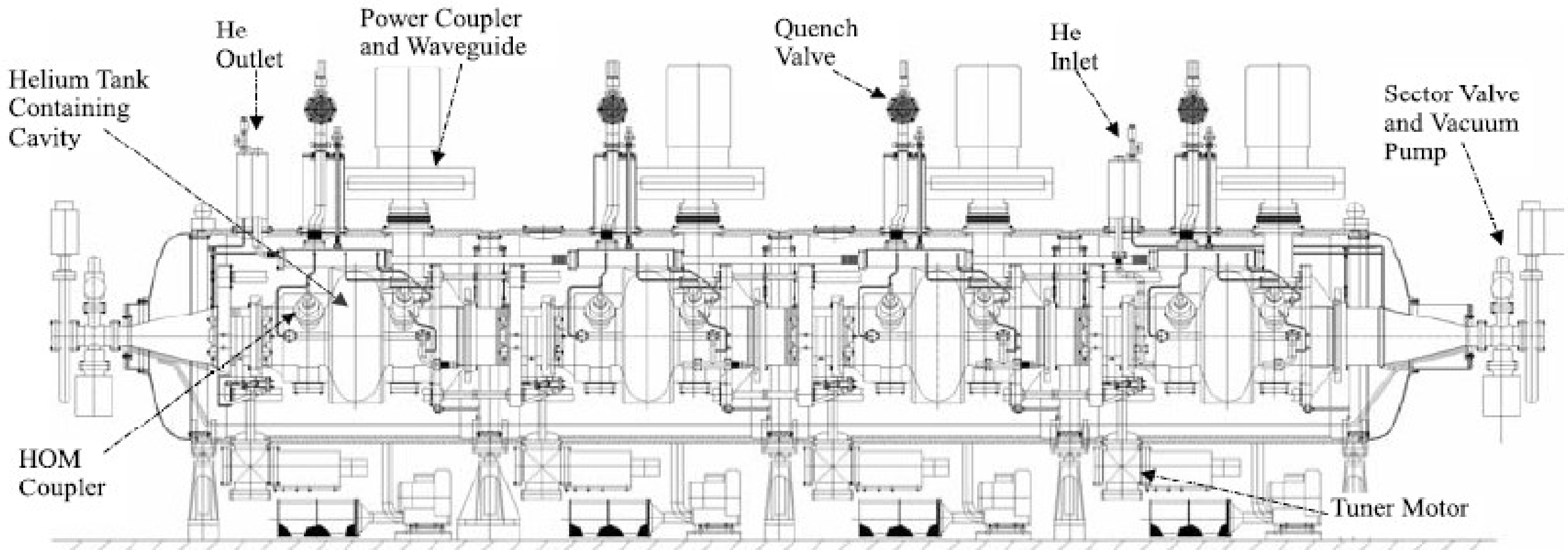
- Particles in a bunch have always certain spread in momentum!
- Phase stability:
- If increase in energy means increase in velocity, M1 and N1 will move toward P1 (stable particle trajectory) while M2 and N2 will move away from P2 (unstable trajectory)

Phase stability and bunches II



- Area of stability in phase space - bunches
- Energy and phase oscillate around nominal values – synchrotron oscillations
- For small amplitudes: Harmonic Oscillator
- Higher amplitudes: non-linearities

Accelerating particles – LHC cavities



- 400 MHz superconducting cavity system
- 8 single-cell cavities per ring
- 1 klystron per cavity
- 4 cells are in one cryostat (4.5^0 K)

Maximum field 5 MV/m

2MV/cavity gives 8MeV/turn "kick"

RF frequency varies from 400.789 MHz (450 GeV) to 400.790 MHz (7 TeV)

Accelerating particles – LHC cavities

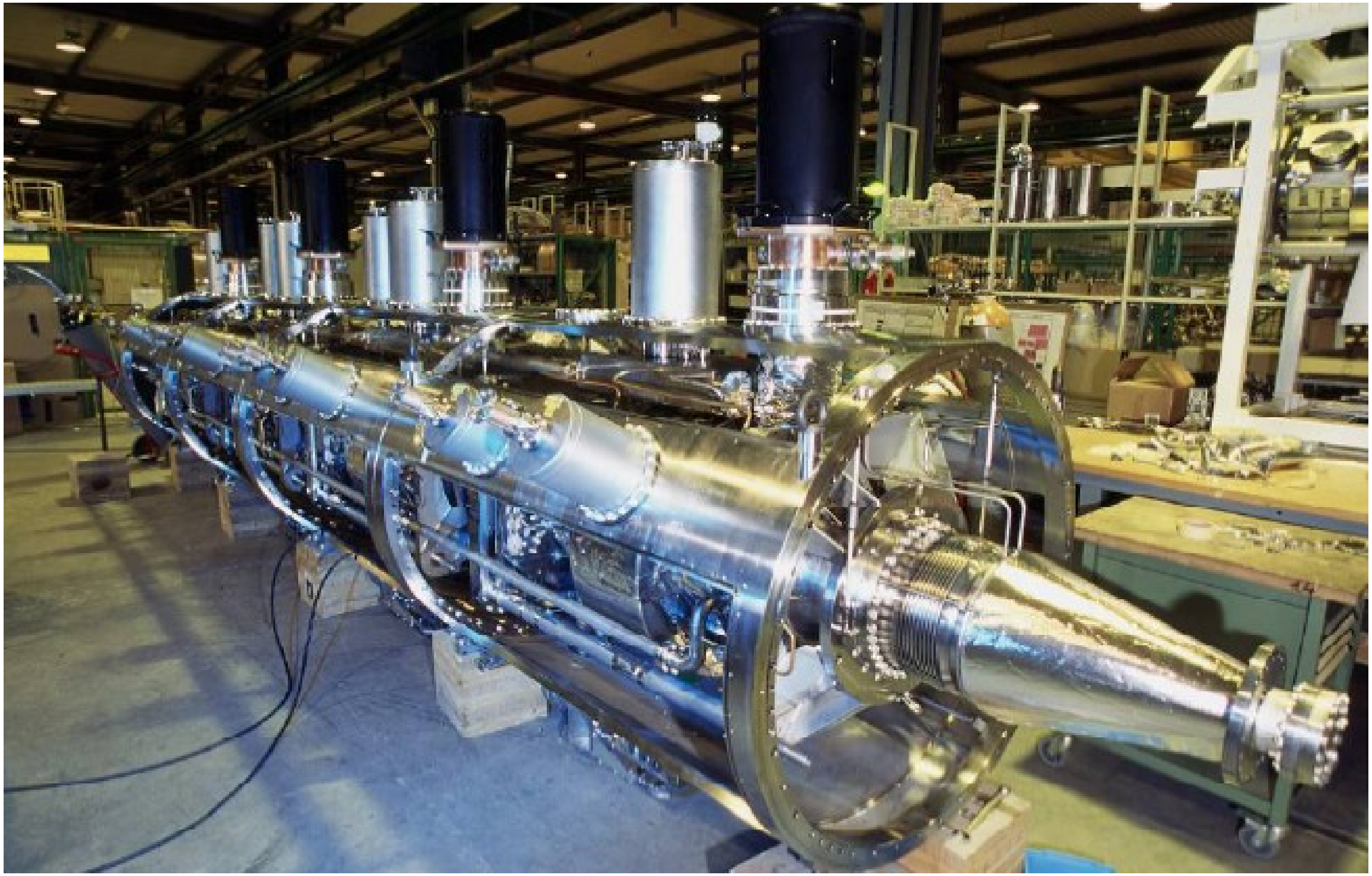


Table 4.1: The Main Beam and RF Parameters.

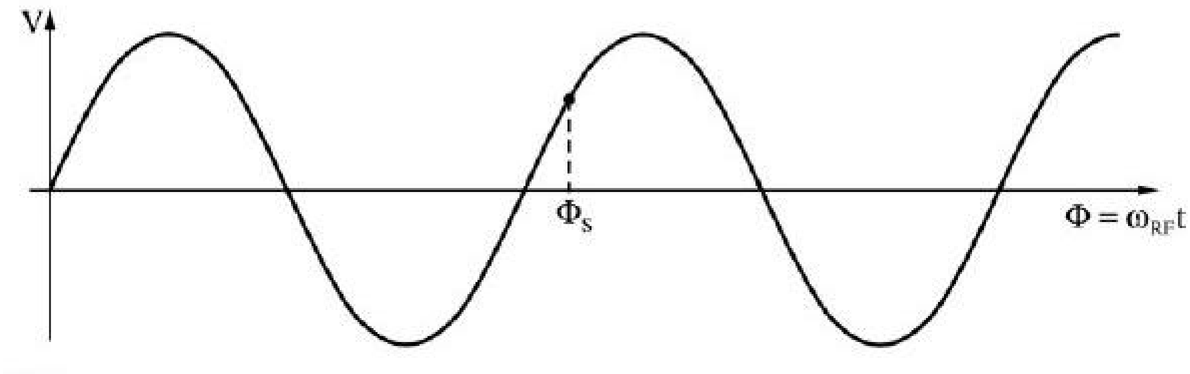
	Unit	Injection 450 GeV	Collision 7 TeV
Bunch area (2σ)*	eVs	1.0	2.5
Bunch length (4σ)*	ns	1.71	1.06
Energy spread (2σ)*	10^{-3}	0.88	0.22
Intensity per bunch	10^{11} p	1.15	1.15
Number of bunches		2808	2808
Normalized rms transverse emittance V/H	μm	3.75	3.75
Intensity per beam	A	0.582	0.582
Synchrotron radiation loss/turn	keV	-	7
Longitudinal damping time	h	-	13
Intrabeam scattering growth time - H	h	38	80
- L	h	30	61
Frequency	MHz	400.789	400.790
Harmonic number		35640	35640
RF voltage/beam	MV	8	16
Energy gain/turn (20 min. ramp)	keV	485	
RF power supplied during acceleration/ beam	kW	~ 275	
Synchrotron frequency	Hz	63.7	23.0
Bucket area	eVs	1.43	7.91
RF (400 MHz) component of beam current	A	0.87	1.05

* The bunch parameters at 450 GeV are an upper limit for the situation after filamentation, ~100 ms after each batch injection. The bunch parameters at injection are described in the text.

A consequence of phase stability

Longitudinal stability – particle that comes earlier gets accelerated less:

$$\frac{\partial V}{\partial t} > 0 \Rightarrow \frac{\partial E_z}{\partial z} < 0$$

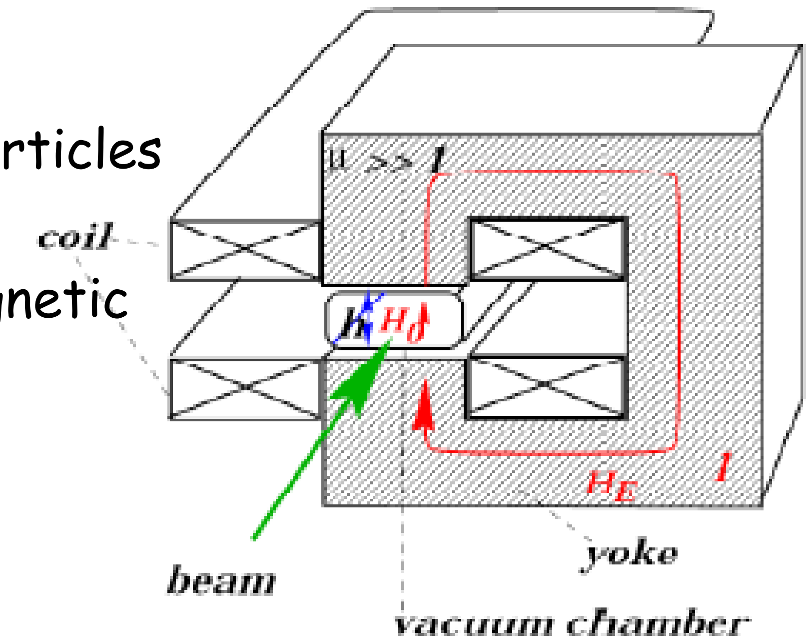


$$\nabla . \vec{E} = 0 \quad \Rightarrow \quad \frac{\partial E_x}{\partial x} + \frac{\partial E_z}{\partial z} = 0 \quad \Rightarrow \quad \frac{\partial E_x}{\partial x} > 0$$

- Maxwell equations show that this leads to defocussing in transversal direction...
- Need some magnets ...

Keeping particles on circle – dipoles I

- Circular accelerator - deflecting forces are needed
  - Usually done with pieces of circular trajectory
  - Straight sections used to accelerate particles (RF) and to collide them (detectors)
  - In circular arc section – bending by magnetic fiels
- Dipole magnets:



$$\frac{1}{\rho} = \frac{eB}{p}$$

$$\frac{1}{\rho}[m^{-1}] = 0.3\frac{B[T]}{p[GeV/c]}$$

Keeping particles on circle - dipoles II

Assuming:

$$\left.\begin{aligned} B &= 8.3\,T \\ p &= 7000\,\frac{GeV}{c} \end{aligned}\right\}$$

$$\frac{1}{\rho} = e\,\frac{8.3\,Vs/m^2}{7000*10^9\,eV/c} = \frac{8.3\,s\,3*10^8\,m/s}{7000*10^9\,m^2}$$

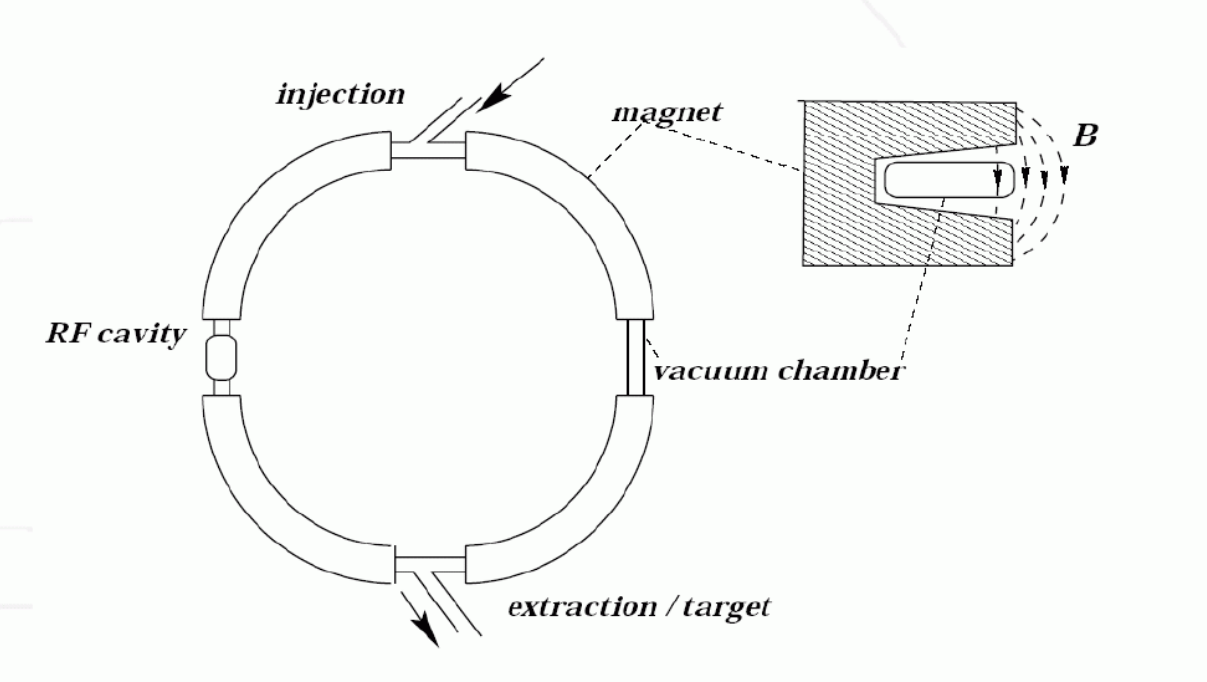
$$\frac{1}{\rho} = 0.333\,\frac{8.3}{7000}\,1/m$$

Gives:

$$\rho = 2.53\,km \longrightarrow 2\pi\rho = 17.6\,km \approx 66\%$$

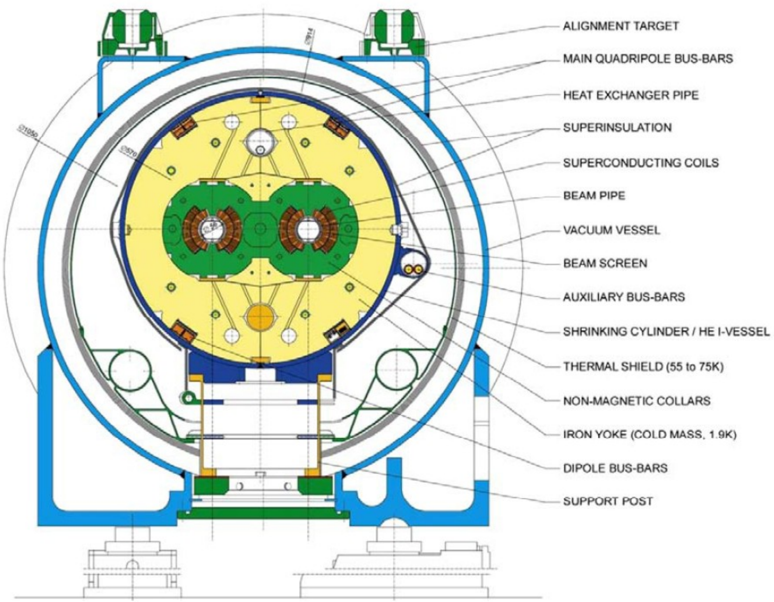
- Need strong magnets to bend high energy beam!
- Most of LHC circumference used by dipole magnets!
- In fact this limits maximum energy of LHC beams!

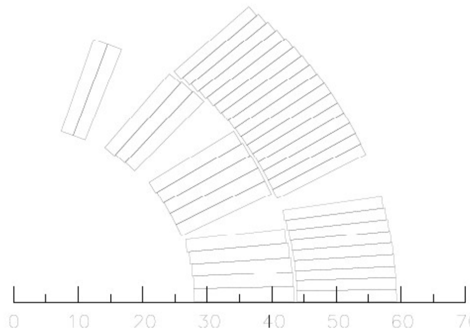
Cyclotron, betatron, synchrotron, oh my ...

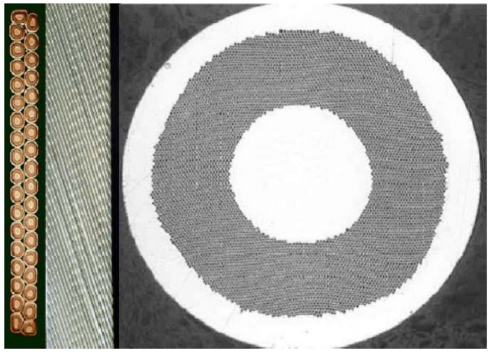


- LHC is a synchrotron!
- (in fact most of high energy accelerators are synchrotrons, for example HERA, Tevatron, LEP, SPS, PS, ...)
- Means that particles follow the same (circular) trajectories, steered by magnets
- When accelerating, changing magnetic field
- Changing also frequency of accelerating (RF) field

LHC dipole magnets







- Edge of present technology
- NbTi superconductors used at 2° K
- Magnetic fields up to 8 T
- Two-in-one (twin bore) design for two beam in common cryostat

Keeping particles on circle – dipoles

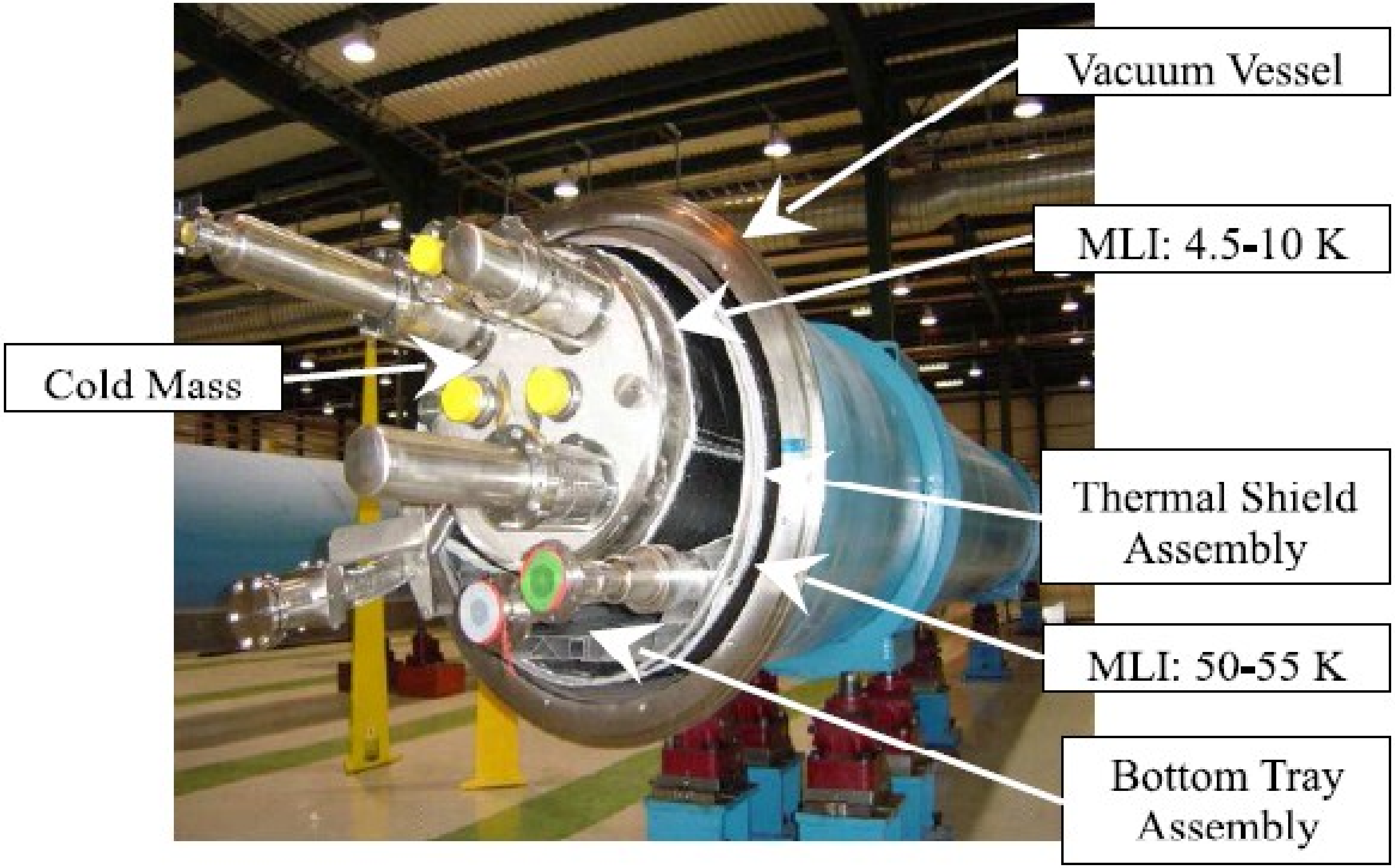
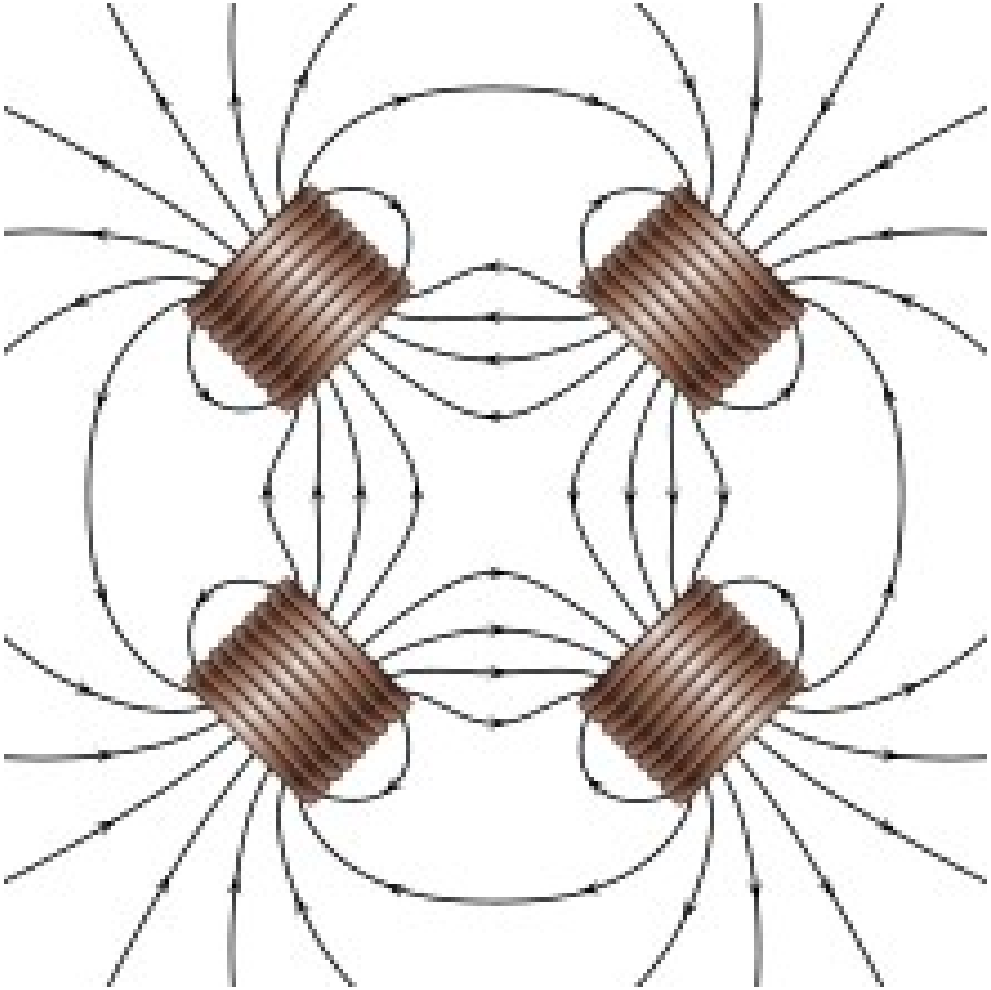


Table 3.4: Main parameters of the dipole cold mass.

	Value	Unit
Injection field (0.45 TeV beam energy)	0.54	T
Current at injection field	763	A
Nominal field (7 TeV beam energy)	8.33	T
Current at nominal field	11850	A
Inductance at nominal field	98.7	mH
Stored energy (both apertures) at nominal field	6.93	MJ
Ultimate field	9.00	T
Current at ultimate field	12840	A
Stored energy (both apertures) at ultimate field	8.11	MJ
Maximum quench limit of the cold mass (from short samples)	9.7	T
Operating temperature	1.9	K
Magnetic length at 1.9 K and at nominal field	14312	mm
Distance between aperture axes at 1.9 K	194.00	mm
Cold mass sagitta at 293 K	9.14	mm
Bending radius at 1.9 K	2803.98	m
Inner coil diameter at 293 K	56.00	mm
Number of conductor blocks / pole	6	
Number of turns / pole, inner layer	15	
Number of turns / pole, outer layer	25	
Electromagnetic forces / coil quadrant at nominal field		
Horizontal force component (inner and outer layer)	1.8	MN/m
Vertical force component (inner and outer layer)	0.81	MN/m
Electromagnetic forces / coil quadrant at ultimate field		
Horizontal force component (inner and outer layer)	2.1	MN/m
Vertical force component (inner and outer layer)	0.94	MN/m
Axial electromagnetic force at each ends at nominal field	0.40	MN
Coil aperture at 293 K	56.00	mm
Cold tube inner diameter at 293 K	50.00	mm
Cold tube outer diameter at 293 K	53.00	mm
Cold mass length at 293 K (active part)	15.18	m
Cold mass diameter at 293 K	570.0	mm
Cold mass overall length with ancillaries	16.5	m
Total mass	$\sim$ 27.5	t

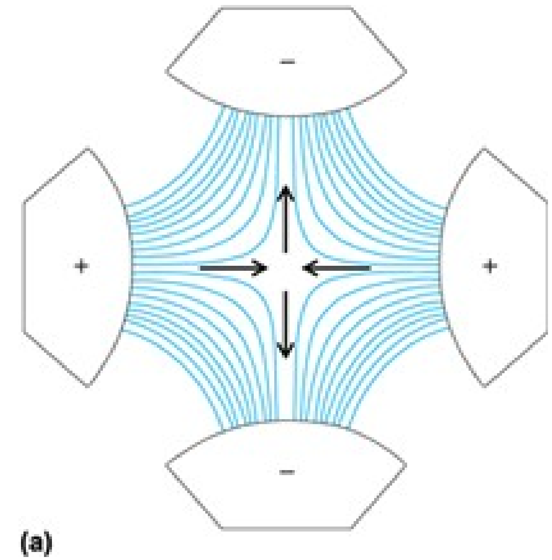
Squeezing the beam – quadrupoles I

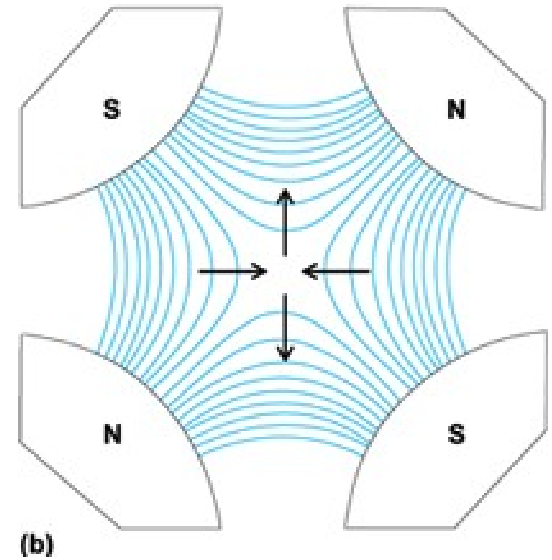
- Want to keep particles rotating on (around) reference trajectories
- Problem to keep the beam together
  - even small disturbances (for example gravity) may lead to lost particles
- restoring force of the type F=-kx , F=-ky would keep the particles close to the ideal orbit!



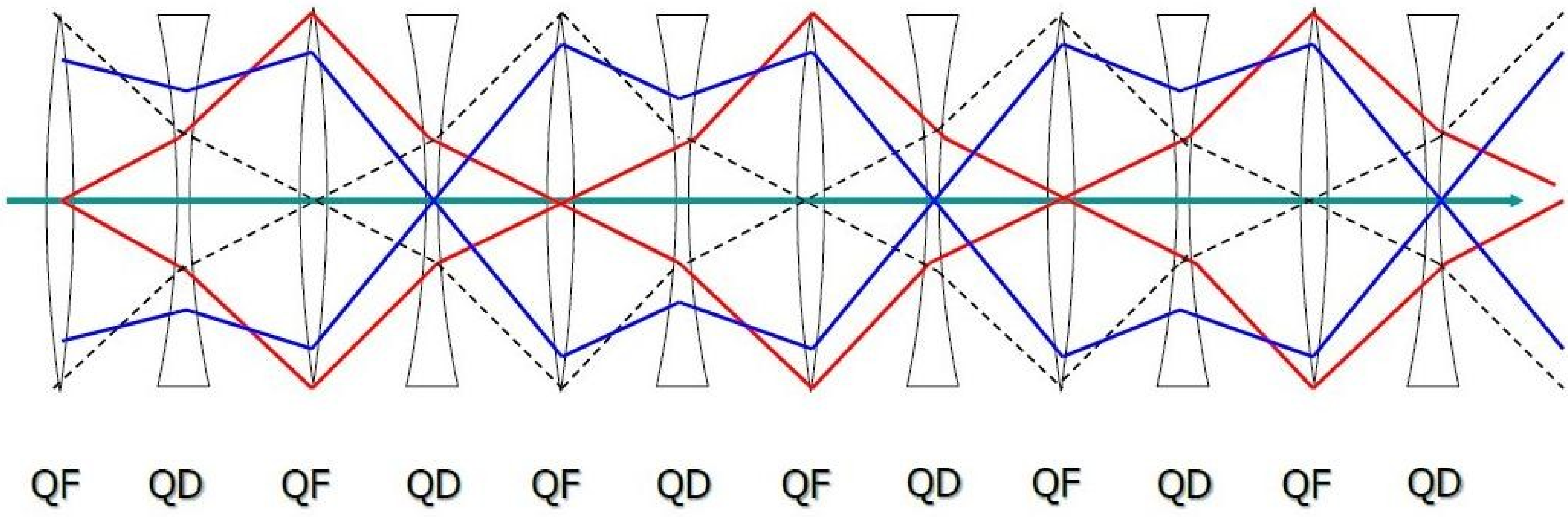
Squeezing the beam - quadrupoles II

- Magnet surfaces shaped as hyperbolas give linear field!
- $B_x = -gy$
- $B_y = -gx$
- Quadrupole magnets!
- Unfortunatelly, forces are focusing in one plane and defocusing in the orthogonal plane
- $F_x = -qvgx$
- $F_y = qvgy$
- Opposite focusing/defocusing is achieved by rotating the magnet by 90°





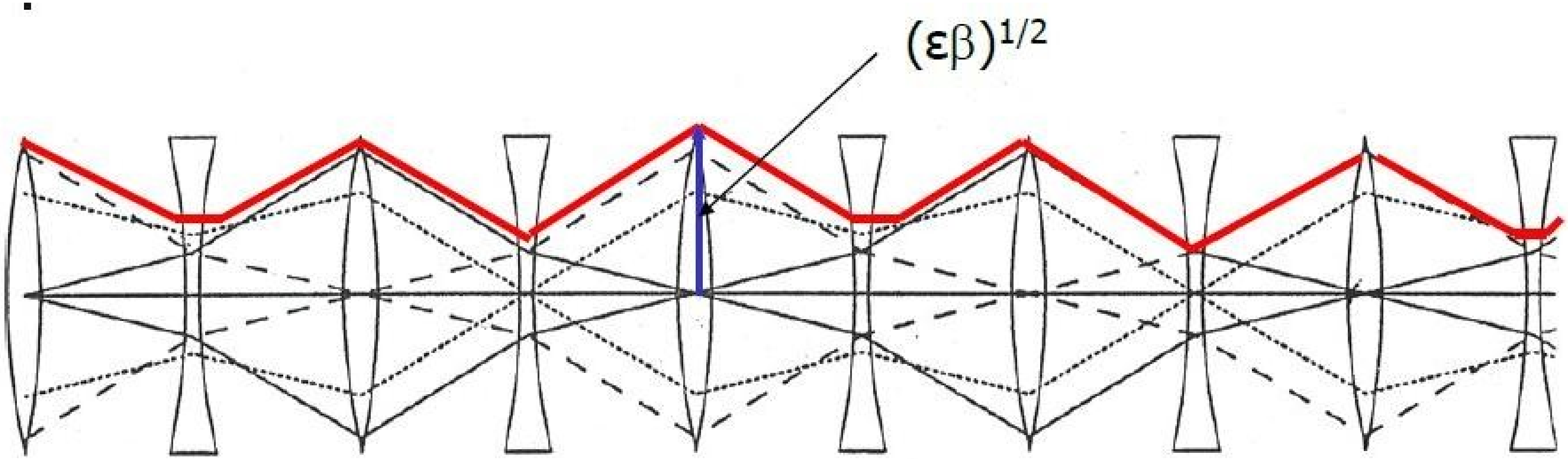
Strong focusing and FODO lattice I



Analogy with optics

- Alternating focusing and defocusing lenses give together total focusing effect in both planes
  - Strong focusing, one of big ideas in accelerator physics
- Modern accelerators – using FODO (FocusingDefOcusing) structures
- Particles oscillate around nominal trajectories – betatron oscillations

Strong focusing and FODO lattice II



The envelope around all the trajectories of the particles circulatin in the machine is called β-function:

- Minimum at QD, maximum at QF
- Property of particular machine (beam optics)

Beam size:

$$\sigma_{x,y} = \sqrt{\varepsilon \beta_{x,y}}$$

ε is the emmitance of the beam:

- describes the quality of the beam

LHC quadrupoles

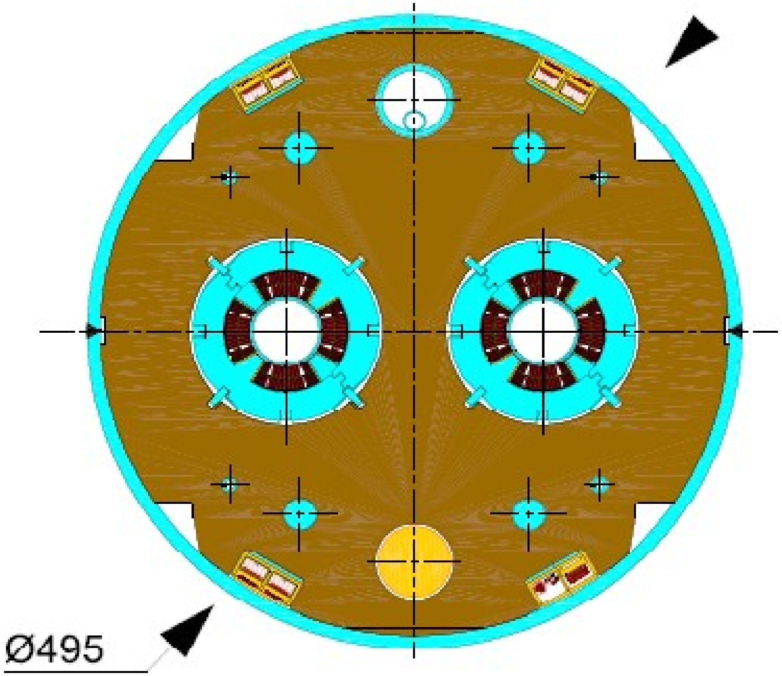
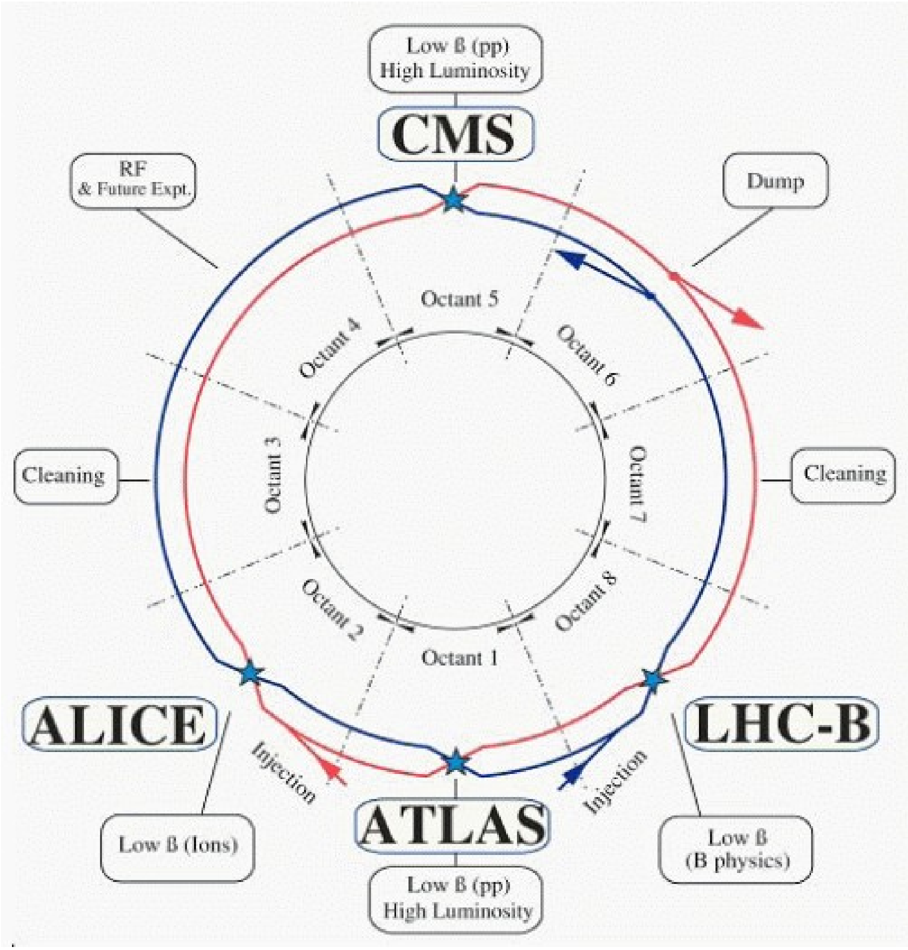


Table 3.5: Parameter list for main quadrupole magnets at 7.0 TeV.

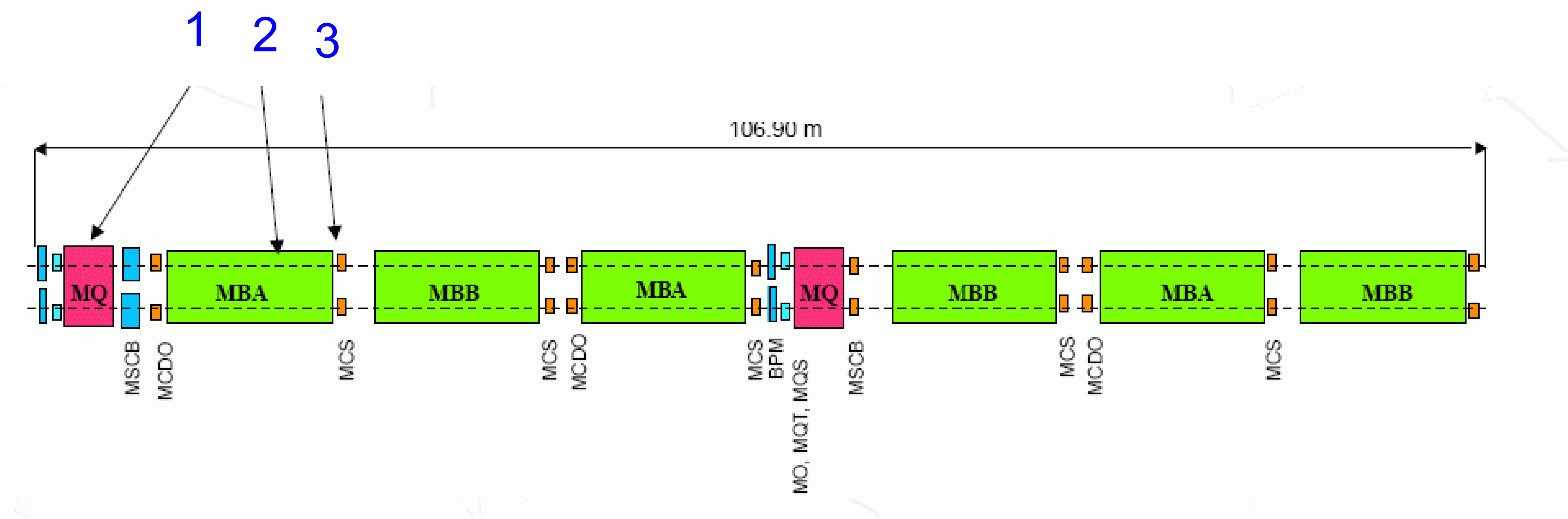
Integrated Gradient	690	T
Nominal Temperature	1.9	K
Nominal Gradient	223	T/m
Peak Field in Conductor	6.85	T
Temperature Margin	2.19	K
Working Point on Load Line	80.3	%
Nominal Current	11870	A
Magnetic Length	3.10	m
Beam Separation distance (cold)	194.0	mm
Inner Coil Aperture Diameter (warm)	56.0	mm
Outer Coils Diameter	118.44	mm
Outer Yoke diameter	452	mm
Collar Material	Austenitic Steel	
Yoke Material	Low Carbon Steel	
Yoke Length including End Plates	3250	mm
Cold Mass Length Between End Covers	5345	mm
Total Mass Including Correctors	6500	kg
Number of turns per Coil (pole)	24	
Number of turns per coil inner layer (2 blocks)	2+8	
Number of turns per coil outer layer (2 blocks)	7+7	
Cable length per coil (pole)	160	m
Cable length per two-in-one quadrupole	1280	m
Bare Cable	Same as dipole outer layer	
Insulation Thickness 1st layer	50	μm
2nd layer	37.5	μm
3rd layer (adhesive)	50+5	μm
Self-inductance, one aperture	5.6	mH
Stored energy, one aperture	395	KJ
Electromagnetic forces: Resultant in x-dir	537	KN
Resultant in y-dir	-732	KN

LHC layout

- Circumference = 26658.9 m
- 8 arcs and 8 straight sections
  - Straight section – 528 m long
  - Either experiment or "utilities"
  - Four used for experiments
  - Arcs are cca 100 m long, contain magnets (LHC lattice)
  - Optimized for maximum bending power
  - Each arc cell has a FODO structure, 106.9 m long

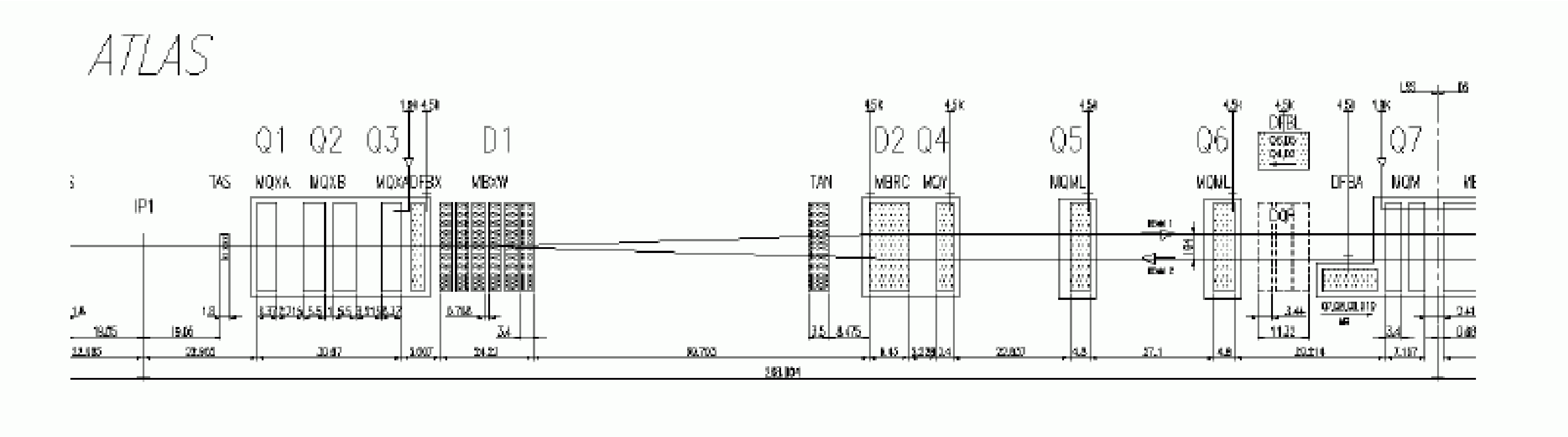


LHC lattice



- LHC FODO structure:
  1. Quadrupoles for focusing (in both planes)
  2. Dipoles for bending the beam
  3. (sextupoles for higher order corrections)

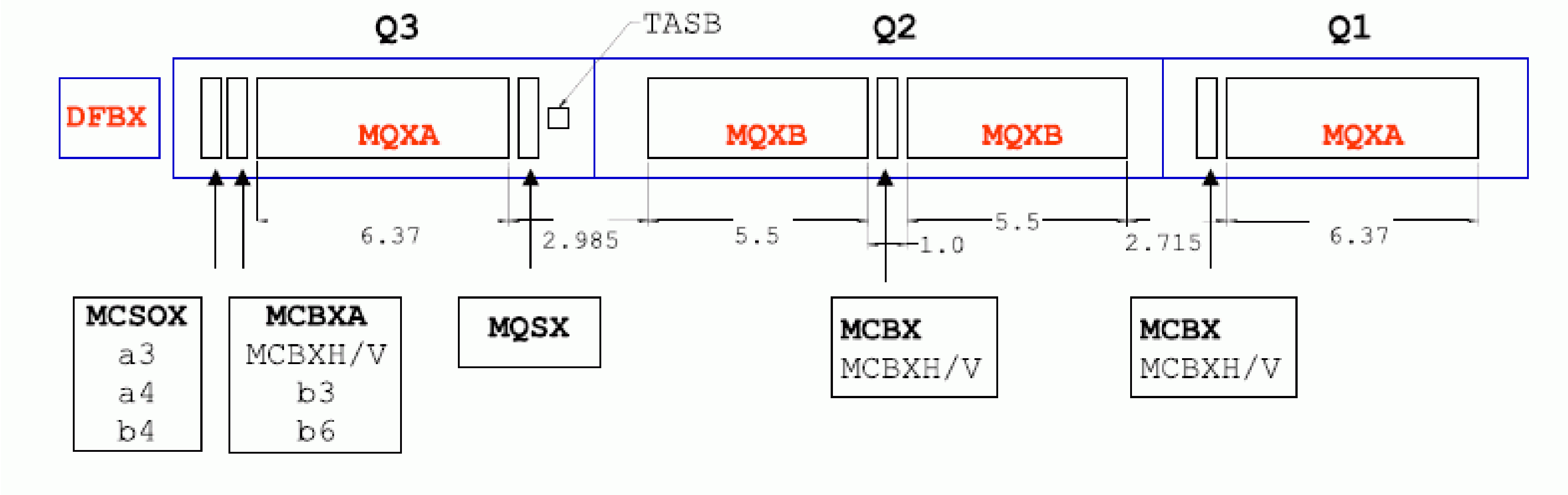
Getting particles to collide – interaction point I



Bringing beams together for collisions:

- Bend them in dedicated dipole magnets (D1, D2 on the figure)
- Then squeeze them as much as possible just before the collision point
  - Low-β triplets

Getting particles to collide – interaction point II



- Low triplets :
  - Set of quadrupole magnets designed to squeeze beam before interaction point

$$L = f \frac{n_1 n_2}{4\pi \sigma_x \sigma_y}$$

- Luminosity depends on:
- Number of particles per bunch (n1, n2)
- Bunch transverse size at the interaction point (σ_x,σ_y)
- Bunch collision rate f

And many others ...

- Vacuum system
- Beam injection system
- Beam dumping
- Preaccelerators
- Cryogenic system
- Power distribution and protection
- Correction magnets
- Beam monitoring
- Control system
- ...

£££ ...

- LHC: the biggest and most expensive physics experiment ever built
- Price (LHC booklet):
  - 3.03 billion Euro – machine
  - 0.71 billion Euro -experiments (CERN contribution), 3.5 billion including other sources (just my guess...)
  - 0.16 billion Euro - computing

Resources
Planning and Control

Member States Contributions to the CERN budget – 2011

	%	MCHF
Austria	2.18%	23.886
Belgium	2.78%	30.486
Bulgaria	0.32%	3.509
Czech Republic	1.13%	12.392
Denmark	1.79%	19.695
Finland	1.26%	13.869
France	15.42%	169.140
Germany	19.44%	213.297
Greece	1.90%	20.860
Hungary	0.67%	7.386
Italy	11.19%	122.772
Netherlands	4.28%	46.959
Norway	2.61%	28.616
Poland	3.15%	34.523
Portugal	1.26%	13.777
Slovak Republic	0.55%	5.987
Spain	8.82%	96.784
Sweden	2.46%	27.041
Switzerland	3.79%	41.617
United Kingdom	15.00%	164.558
	100.00%	1'097.154
Romania (as Candidate for Accession)		4.212

- Price of other projects (coming from google ...) I find reasonable:
  - Hubble space telescope – price at launch 1.5 billion $
  - Project Apollo: 25.4 billion $ (congress in 1973)
  - Wembley stadion (2007) : £ 798 million
  - Space Shuttle Endeavor: 1.7 billion $ (NASA page)
  - Human Genome project: 2.7 billion $ (congress, 1991)

Don't want to talk about money wasted on other things ...

£££ ...

	Baseline 2010-11 £'000	2011-12 £'000	2012-13 £'000	2013-14 £'000	2014-15 £'000	TOTALS £'000	Final Year to Baseline
Research Councils	**2,549,353**	**2,596,196**	**2,573,678**	**2,586,641**	**2,599,812**	**10,356,327**	**101.98%**
AHRC	100,717	99,881	98,370	98,370	98,370	394,993	97.67%
BBSRC	362,341	370,306	359,471	351,471	351,471	1,432,718	97.00%
EPSRC	771,289	759,720	748,150	748,150	748,150	3,004,171	97.00%
ESRC	158,061	155,690	153,319	153,319	153,319	615,648	97.00%
MRC	545,585	536,172	546,243	559,894	574,641	2,216,950	105.33%
NERC	298,071	298,600	297,129	300,129	289,129	1,184,987	97.00%
STFC - Core Programme	177,519	190,060	172,200	172,200	172,190	706,650	97.00%
STFC - Cross-Council facilities[1]	66,800	77,170	79,280	81,410	89,470	327,330	133.94%
STFC - International Subscriptions[2]	68,970	108,598	119,515	121,697	123,071	472,881	178.44%
HEFCE	**1,731,300**	**1,662,112**	**1,699,578**	**1,685,689**	**1,686,321**	**6,733,700**	**97.40%**
QR Research	1,618,300	1,549,112	1,586,578	1,572,689	1,573,321	6,281,700	97.22%
HEIF[3]	113,000	113,000	113,000	113,000	113,000	452,000	100.00%
National Academies	87,832	87,465	86,547	86,547	86,547	347,106	98.54%
Royal Society	48,558	47,830	47,101	47,101	47,101	189,133	97.00%
British Academy	26,448	27,001	27,005	27,005	27,005	108,015	102.10%
Royal Academy of Engineering	12,826	12,634	12,441	12,441	12,441		
Other Programmes	43,616	24,496	24,140	24,165	24,005		
Science & Society	15,441	13,000	13,000	13,000	13,000		
International	5,104	5,095	4,740	4,765	4,605		
Foresight	2,800	2,800	2,800	2,800	2,800		
Evidence & Evaluation	20,271	3,600	3,600	3,600	3,600		
UK Space Agency	163,805	205,637	191,963	192,864	179,221		
Total S&R Resource	**4,575,906**	**4,575,906**	**4,575,906**	**4,575,906**	**4,575,906**		

David Willetts
Minister for Universities and Science

Vince Cable
Secretary of State

Conclusions and outlook

- Elementary particle physics is at its critical point
- SM works very well, masses of Z and W present a puzzle
  - LHC is our chance!