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

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Warwick week, 12 April 2023

- Introduction
- LHC machine
- High P_T experiments – Atlas and CMS
- Standard Model physics and BSM searches
- Higgs data analysis

Introduction

What are these lectures going to be?

- Introduction to the topics
- 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
- (maybe) a discussion ???!

Four lectures ...

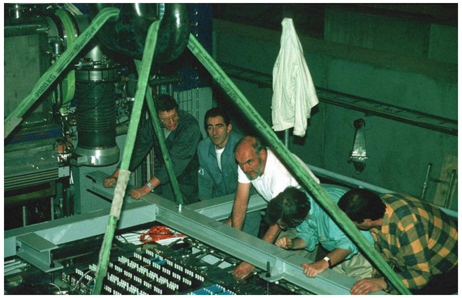
Lecture 1 : Introduction to LHC physics, the LHC accelerator

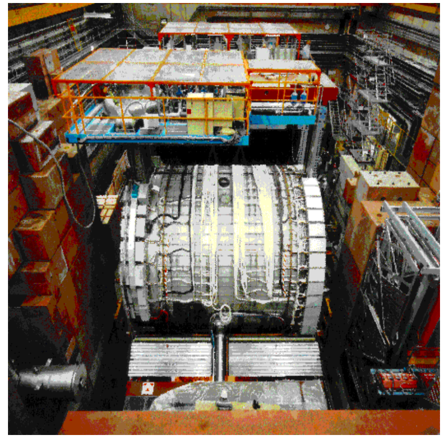
Lecture 2: General purpose experiments (ATLAS and CMS)

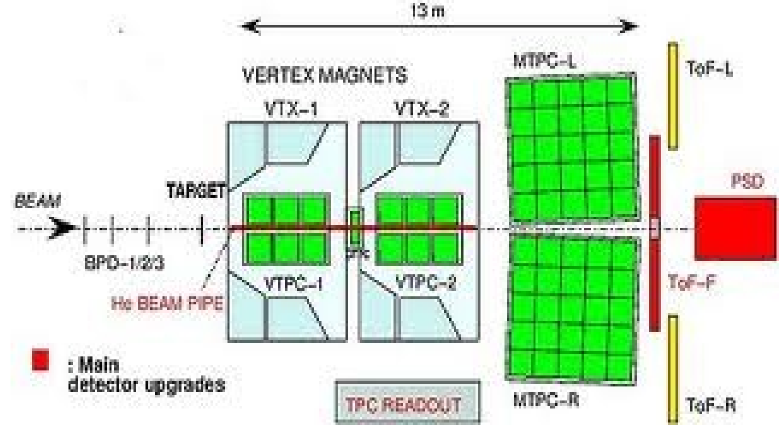
Lecture 3: SM physics and searches

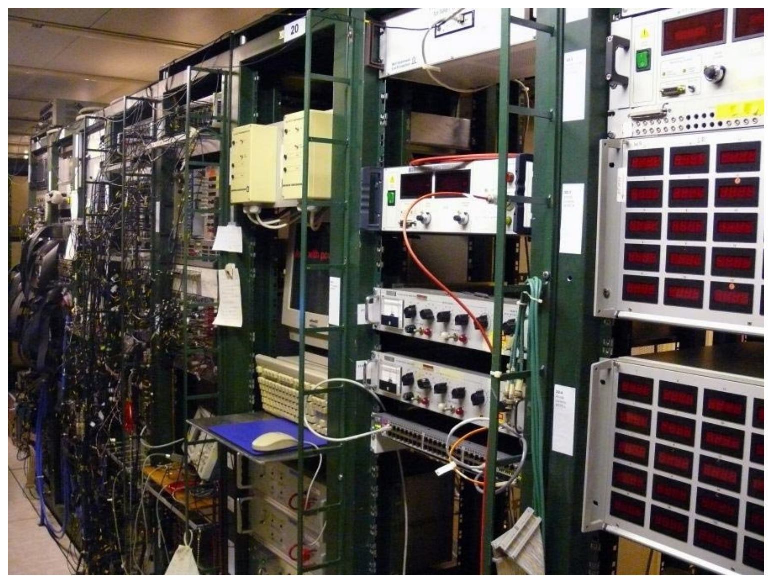
Lecture 4: Higgs physics

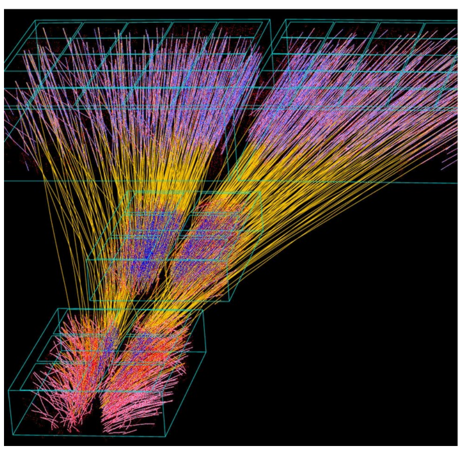
Please allow me to introduce myself ...











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

Lecture 1 - Introduction and the LHC

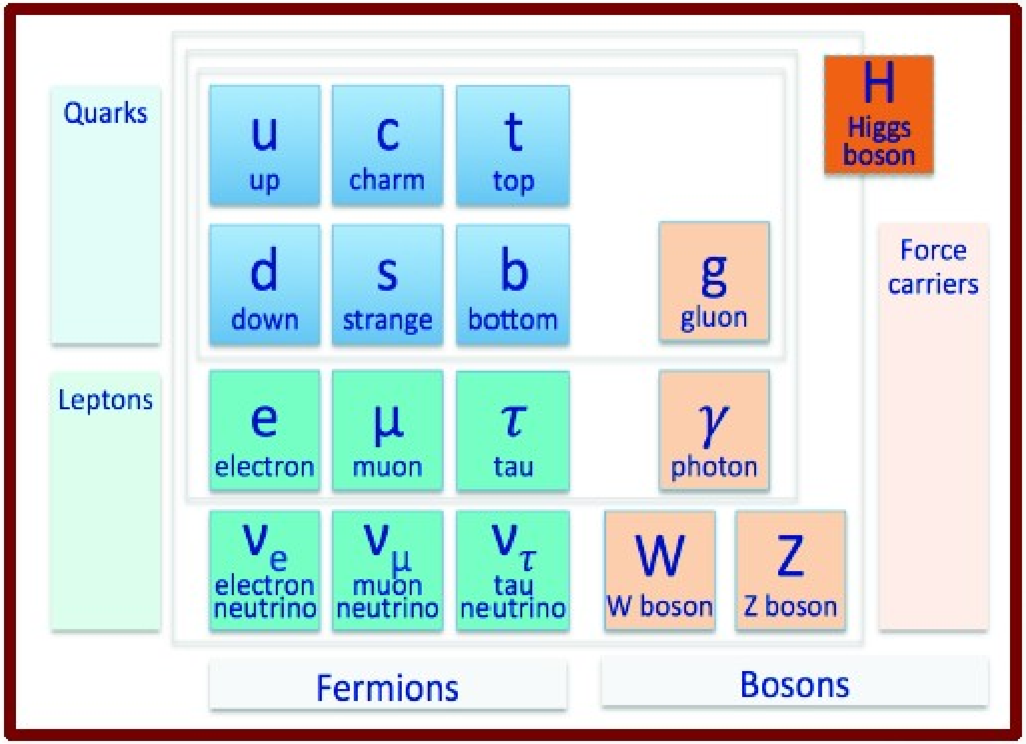
- Standard model of elementary particle physics and its Big Open Questions
- LHC machine:
  - General parameters
  - How are particles accelerated: RF
  - What keeps them running around?
  - Interaction points, that is where it all happens!
- The future of the LHC and beyond

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"

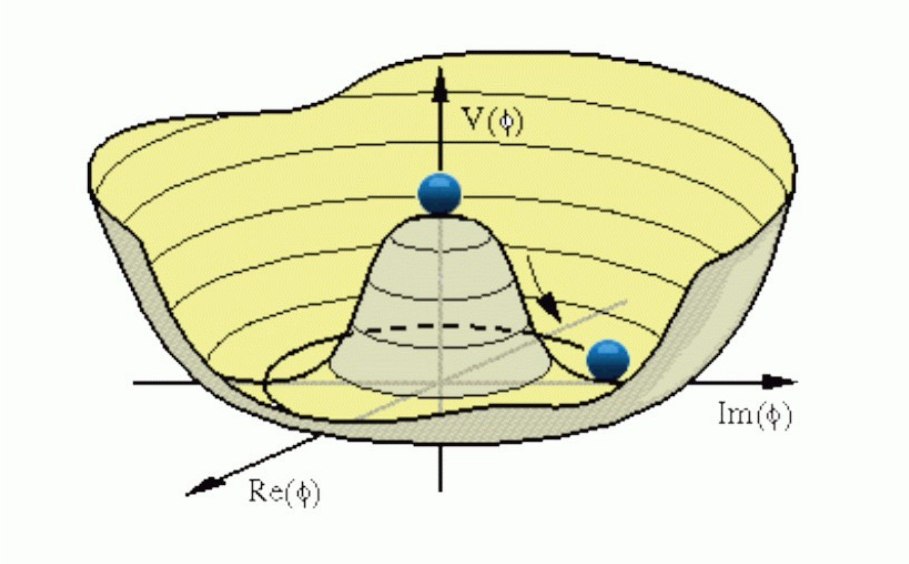


Language (mathematical) of SM:

- Local renormalizable Quantum Field Theory

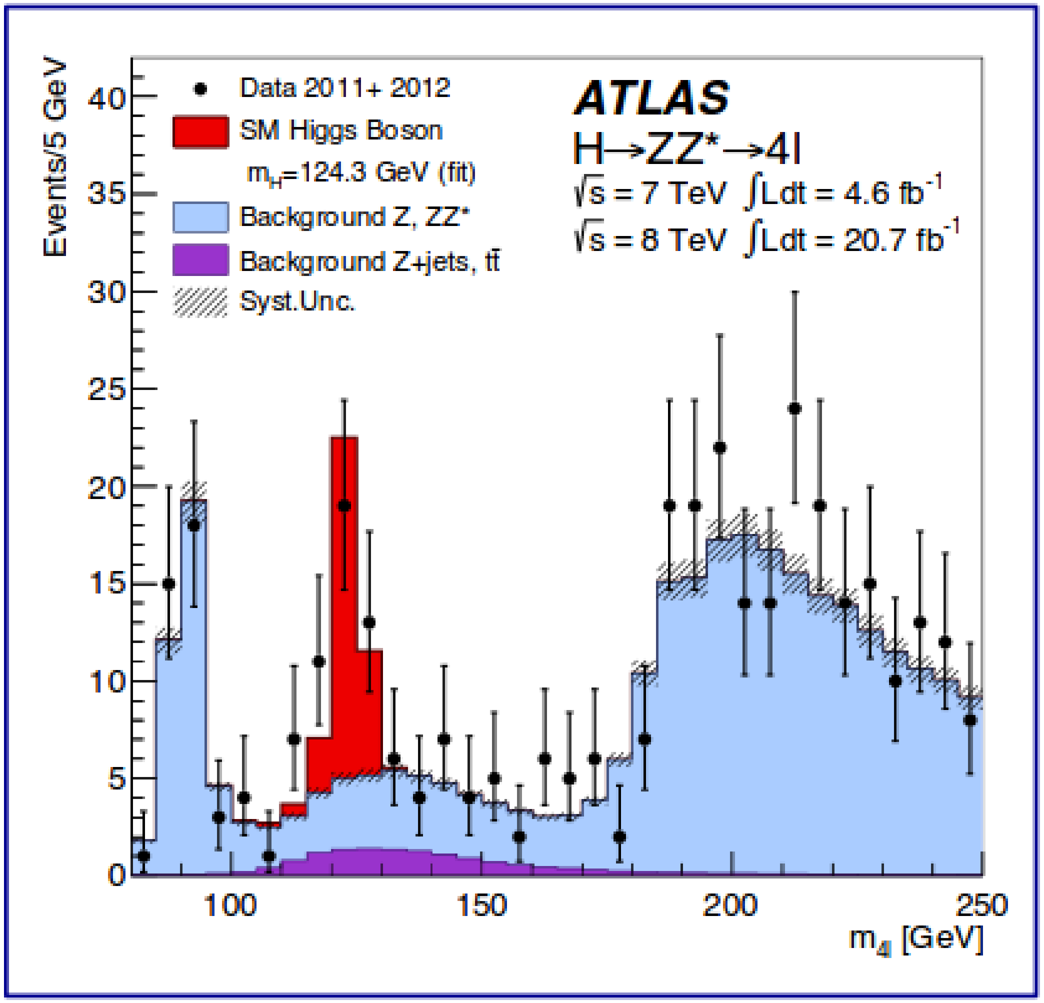
Standard model and its problems

- Quantum field theory with massive spin-1 boson is not renormalisable
- W and Z are very massive!
- Several attempts to solve this problem ...

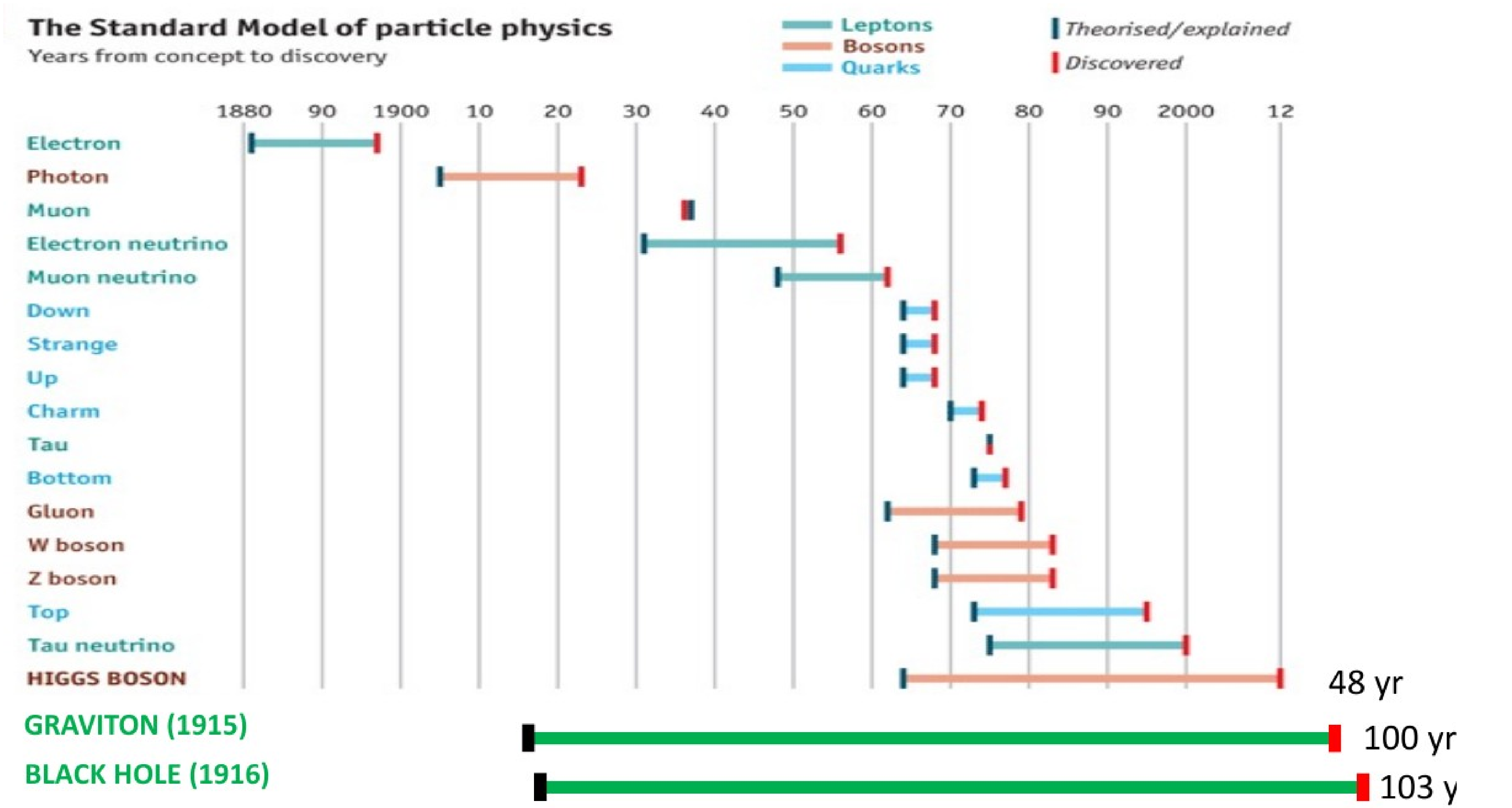


- The simplest model:
  - Postulate additional scalar field – Higgs particle
  - It has nonzero vacuum expectation value
  - W and Z acquire mass in interaction with Higgs
  - γ remains mass-less
- Build LHC to check if this is the case (or not)
- Looks like this simple model is correct (or close ...) !

Standard model and its problems

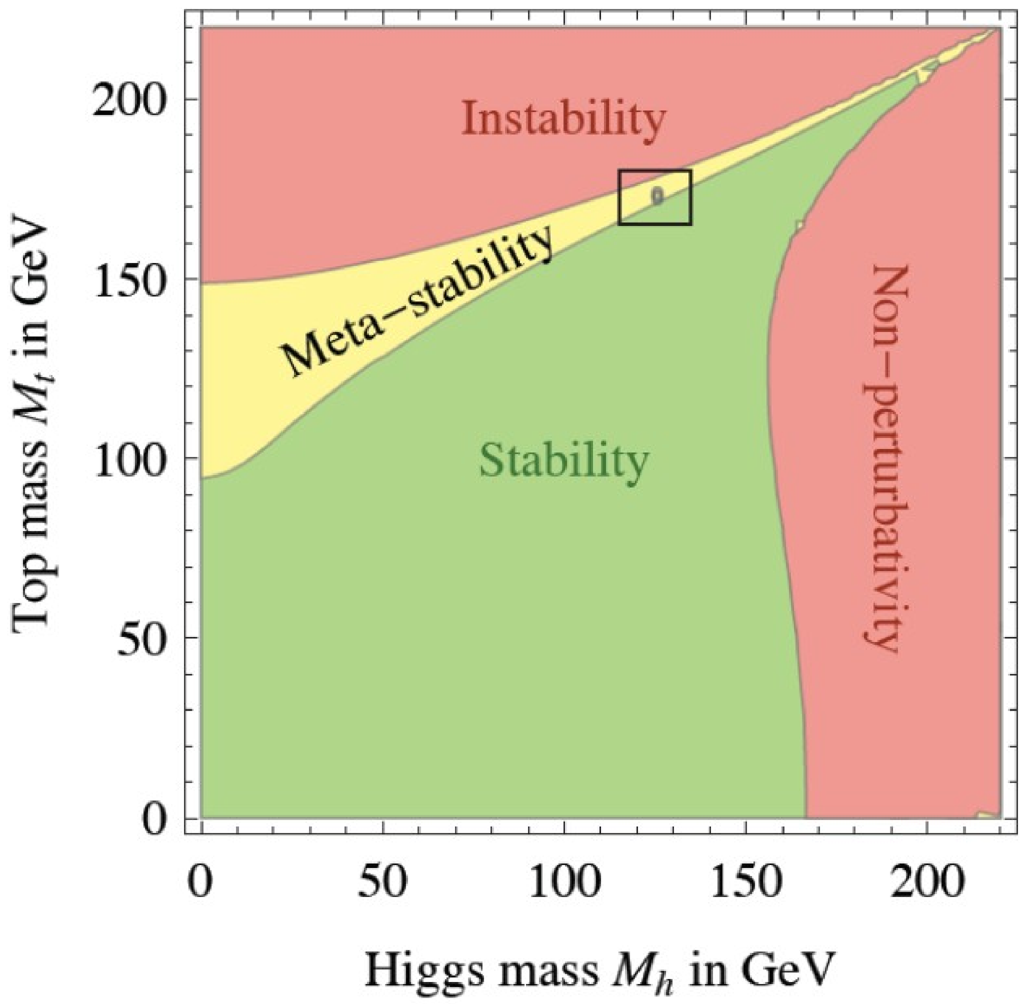


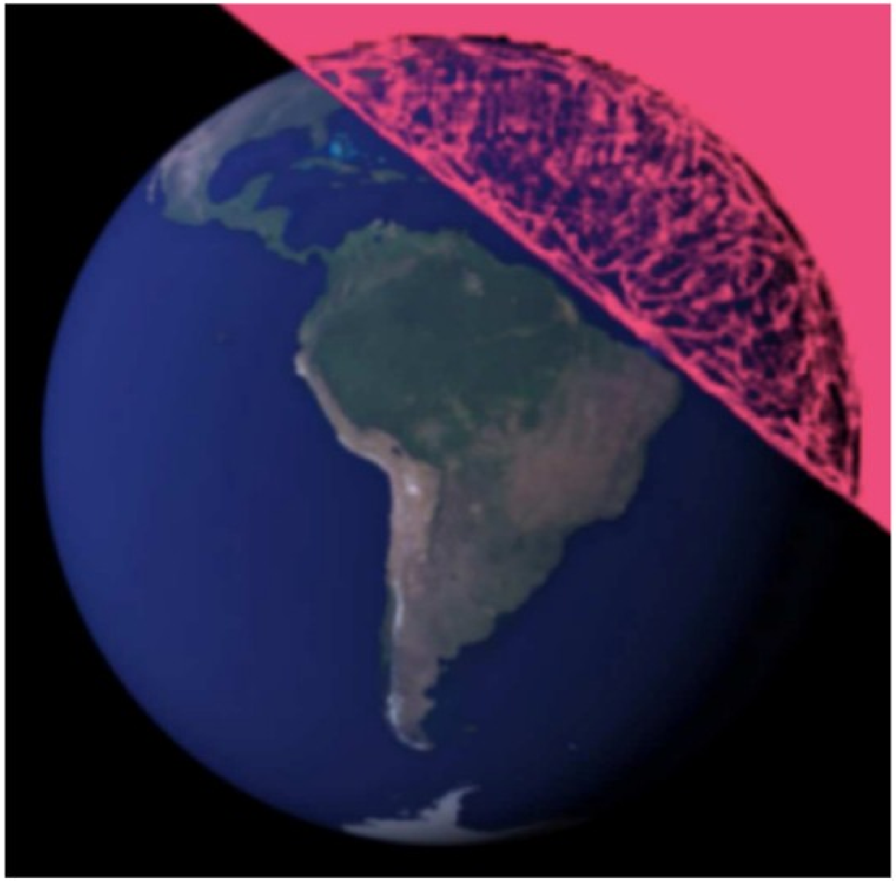
More details in Andy's lectures...



The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON
48 yr
GRAVITON (1915)
100 yr
BLACK HOLE (1916)
103 y

Standard model and its problems





Standard model and its problems

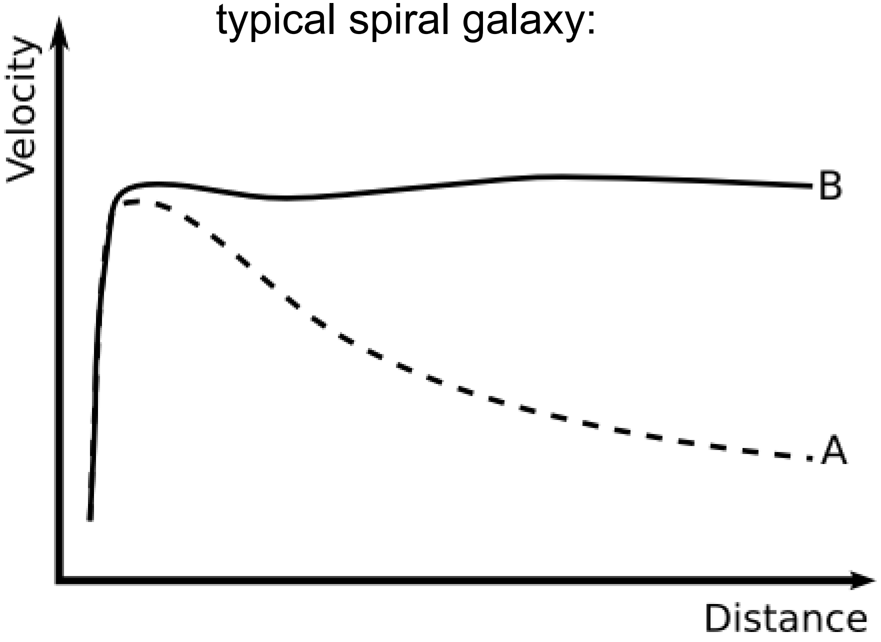
Parameters of the Standard Model [hide]

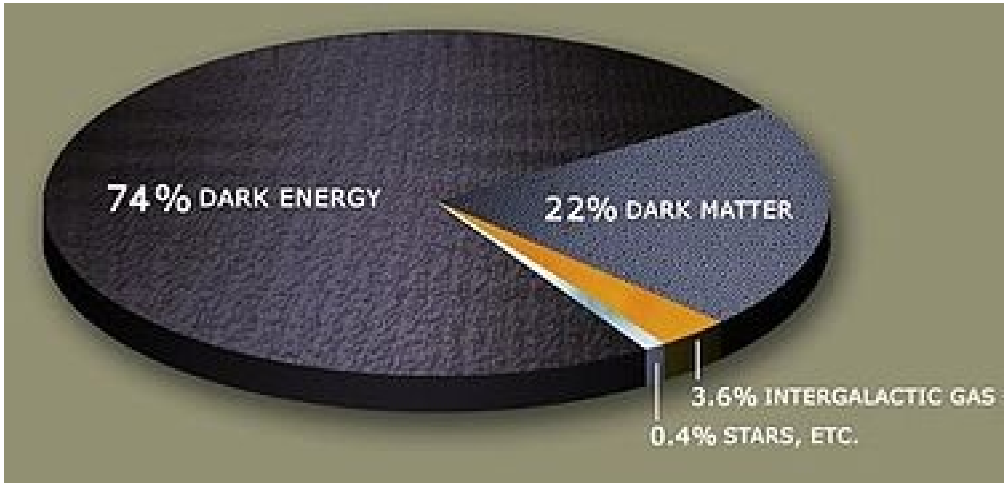
Symbol	Description	Renormalization scheme (point)	Value
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}} = 2$ GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}} = 2$ GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}} = 2$ GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On shell scheme	173.5 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP violation Phase		0.995
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		125.09 ± 0.24 GeV

- Nineteen free parameters that need to be determined from the experiment!

Dark matter

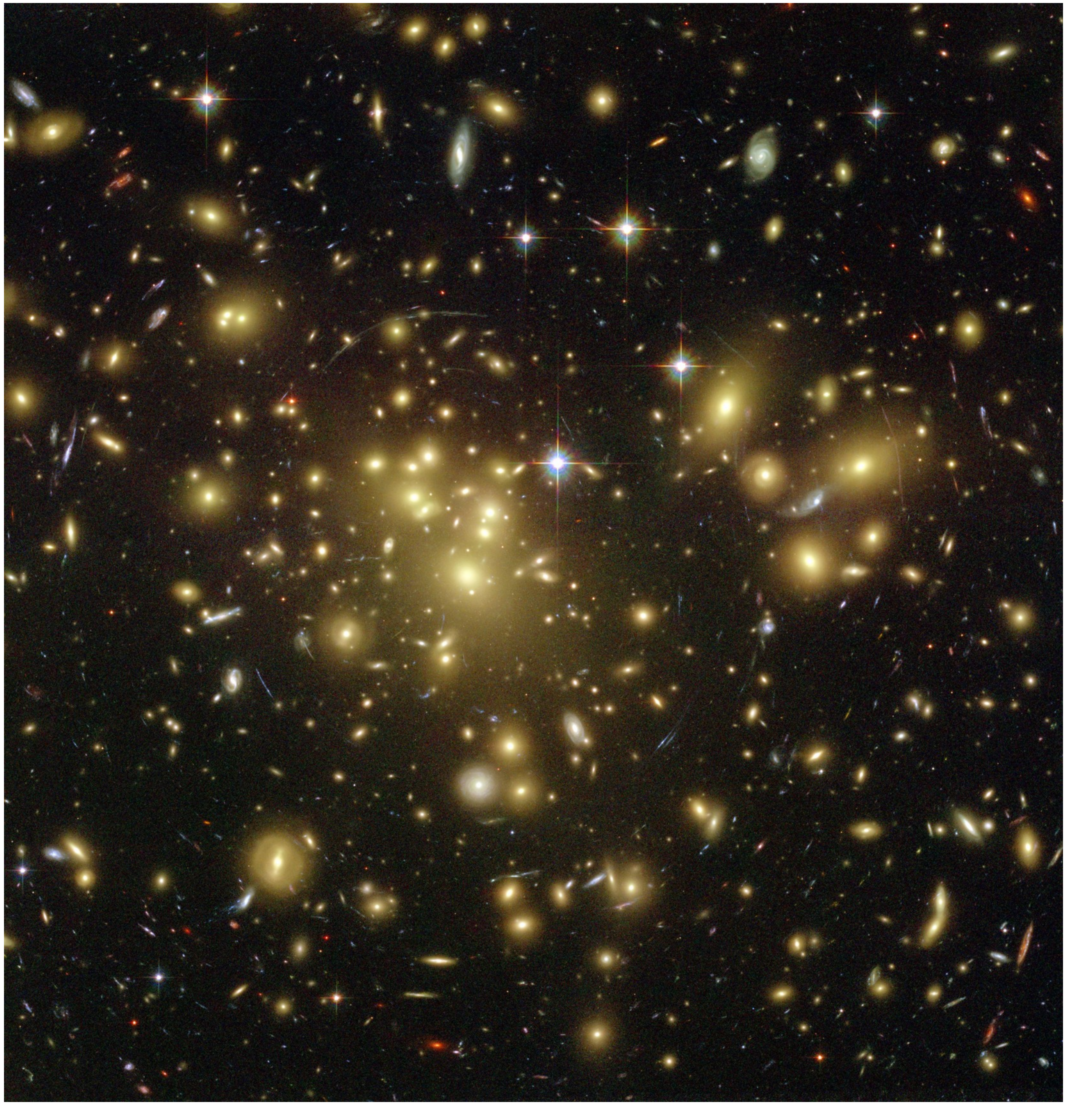
Rotation curve of
typical spiral galaxy:





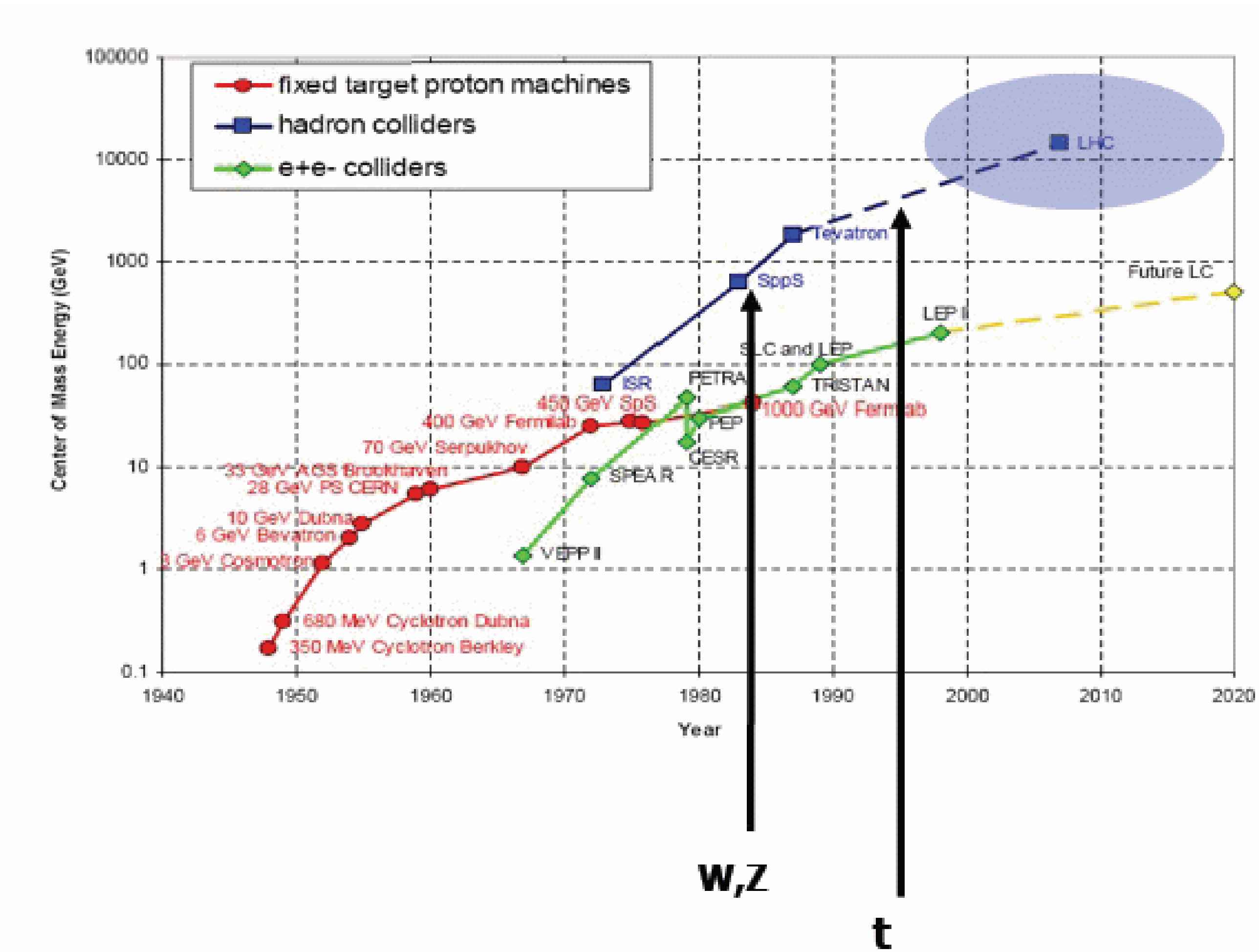
- We know there is a physics beyond Standard model!
- Just need to look at the sky!

Dark matter



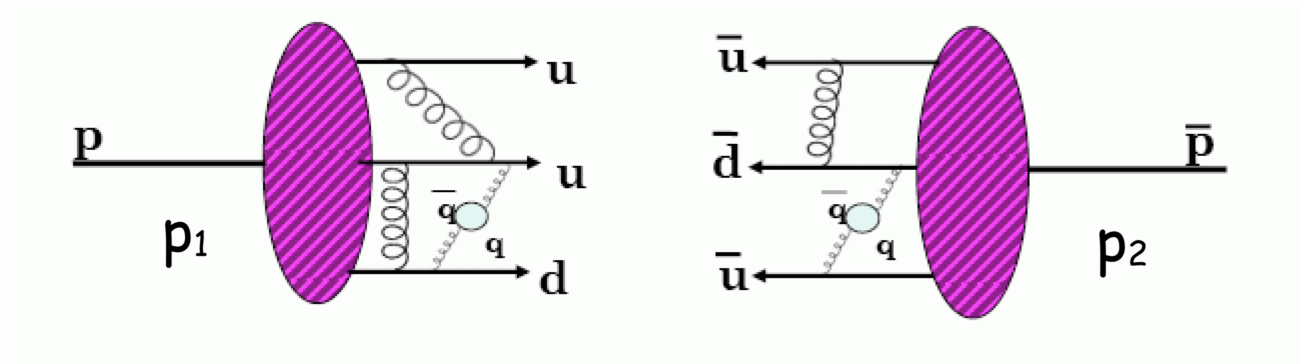
Basic kinematics of high energy hadron collisions

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:

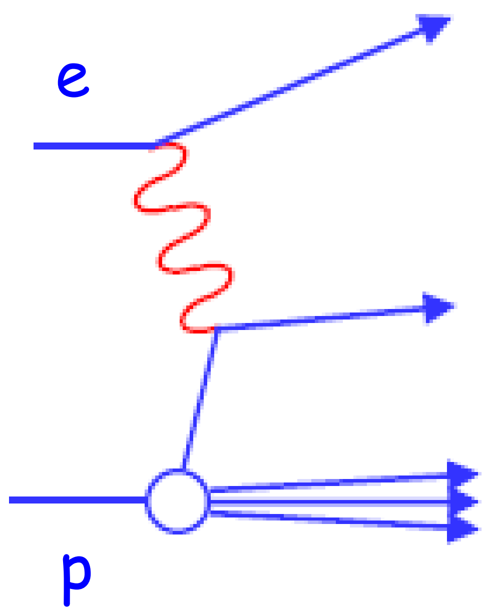
$$\hat{x} = \frac{P_{parton}}{P_{proton}}$$

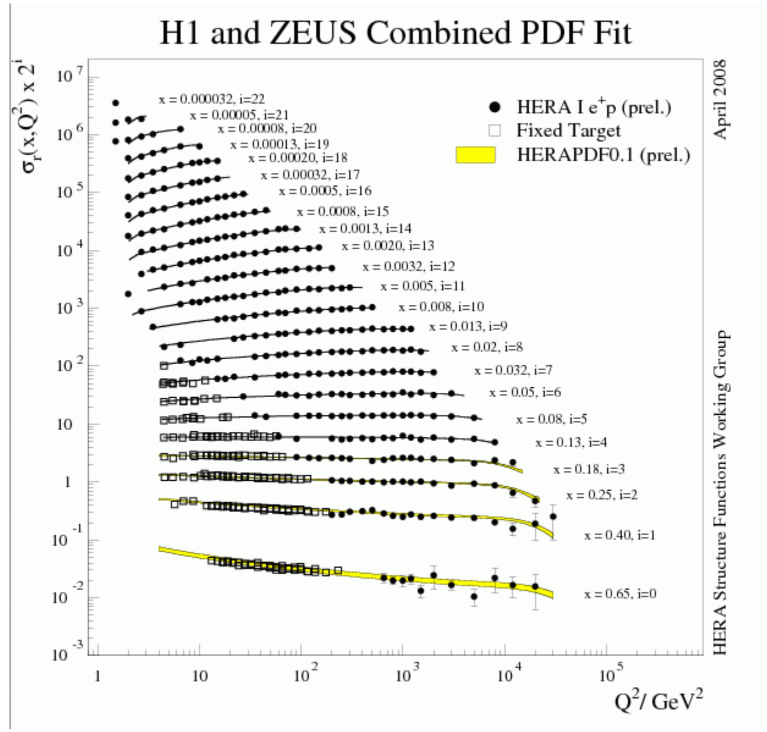
- Energy of (elementary) collision is then

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

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 $\Leftrightarrow$ elastic electron-quark scattering!
- Distribution of scattered electrons is very sensitive to distribution of partons in the proton

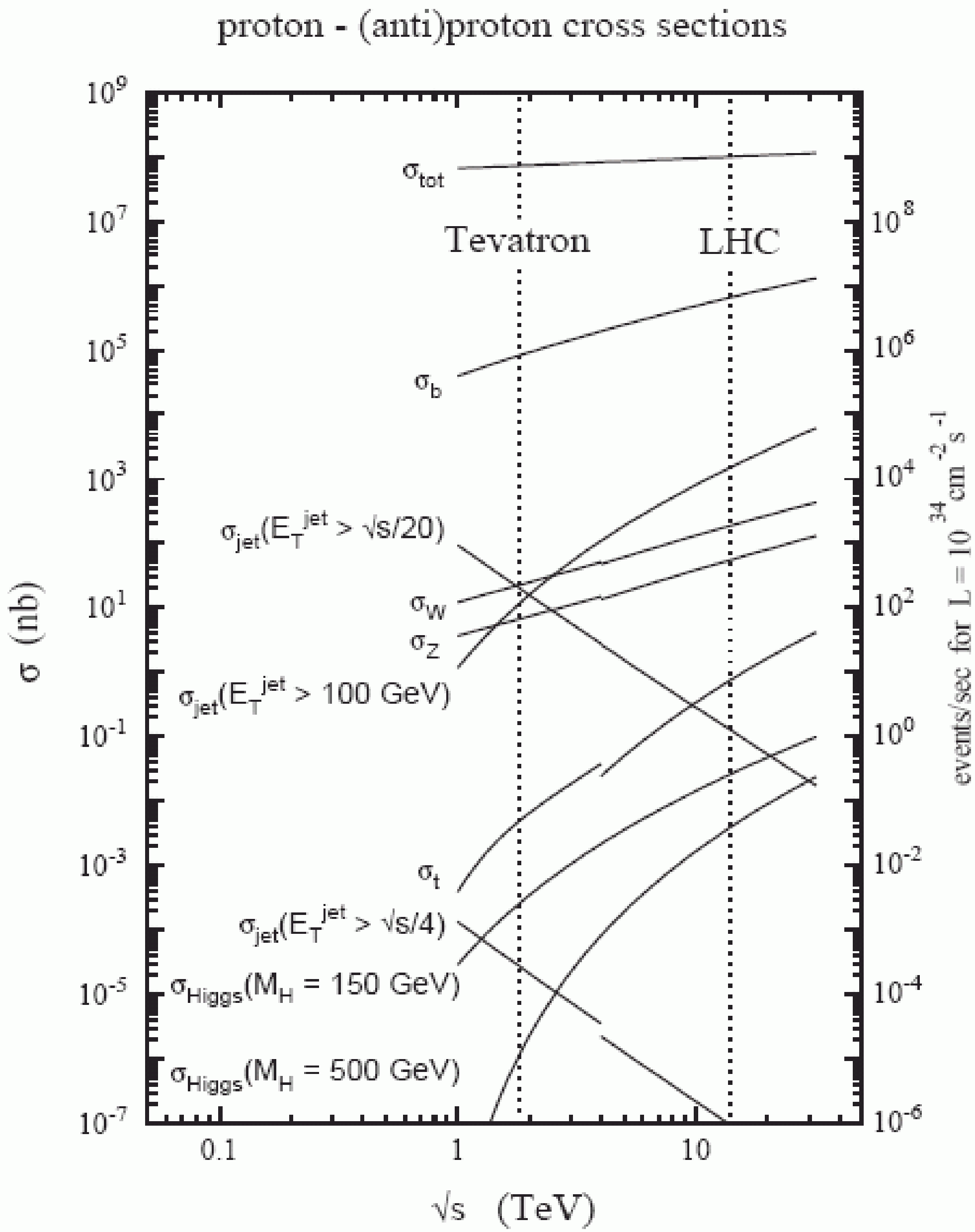
Luminosity

Energy is not enough, one needs luminosity, too...

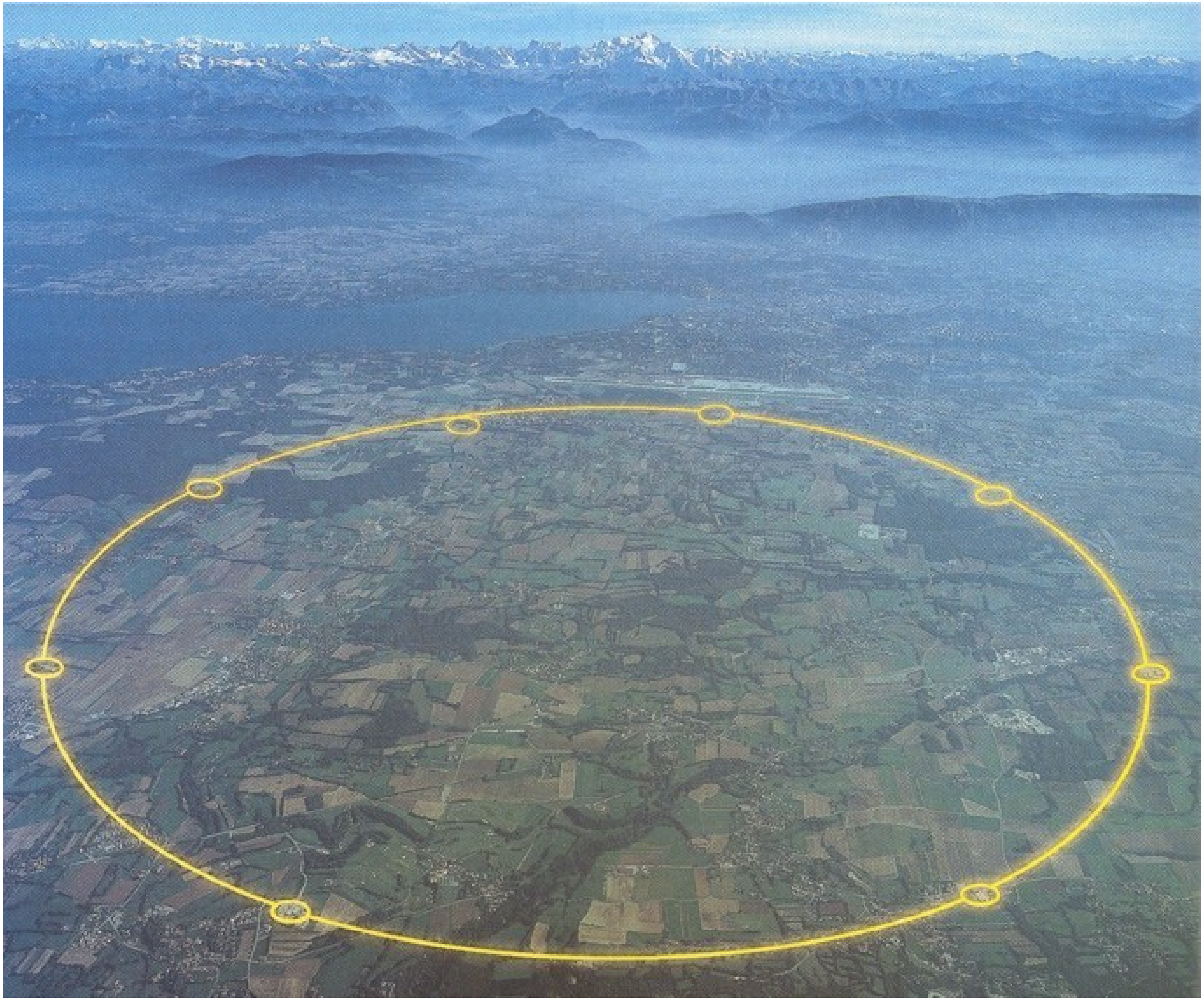
$$N = \sigma \times L$$

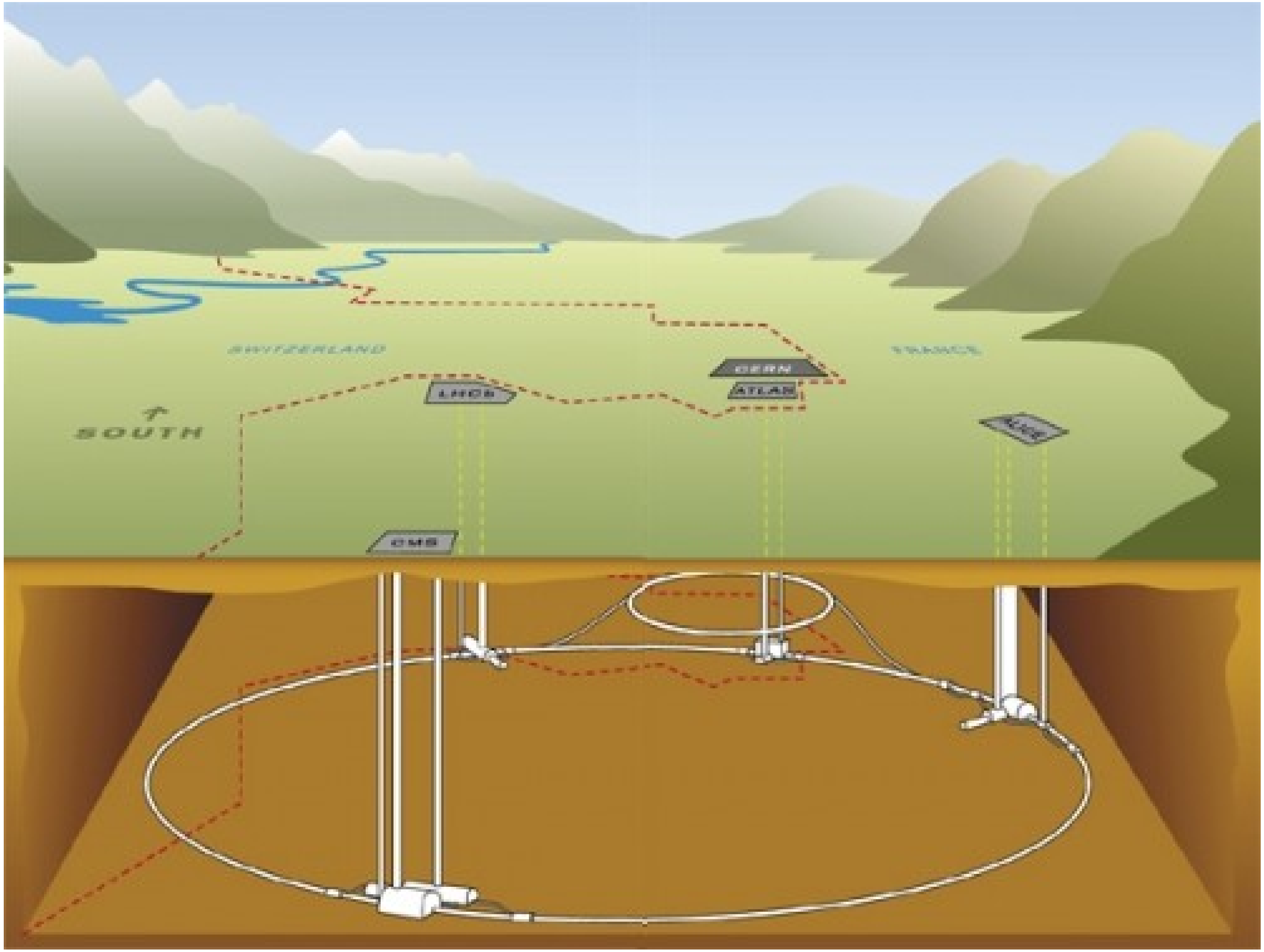
N – number of events (we want)
σ - cross section (given by Nature)
L – luminosity (parameter of an accelerator)

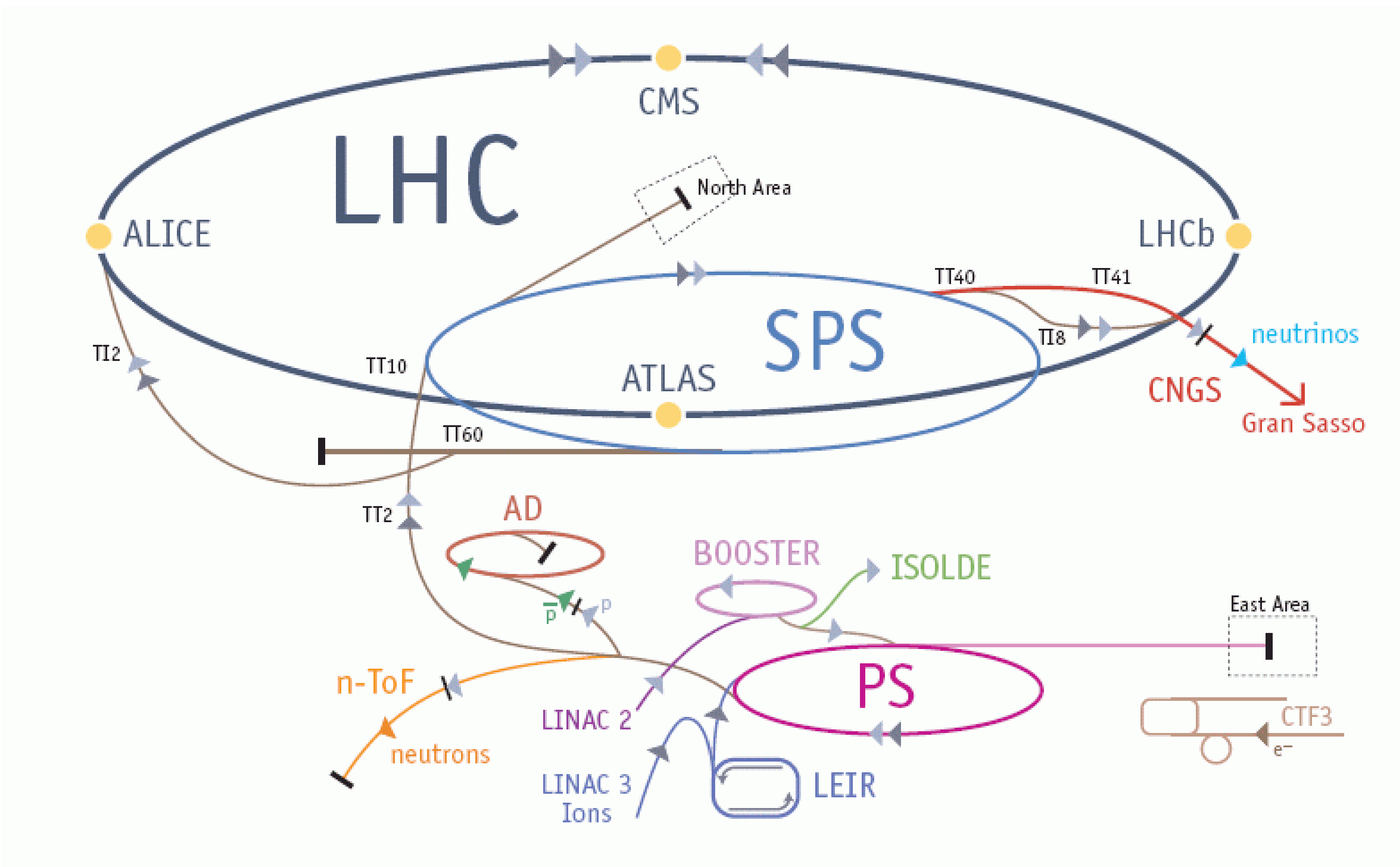
- Higgs couples mainly to particles with high mass, its cross section in pp collisions is rather small
- Need a machine with high luminosity !!!



Introduction to the LHC




SWITZERLAND
SOUTH
LHCb
CERN
ATLAS
CMS



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


ALICE
CMS
ATLAS
LHCb

LHC nominal parameters

at collision energy

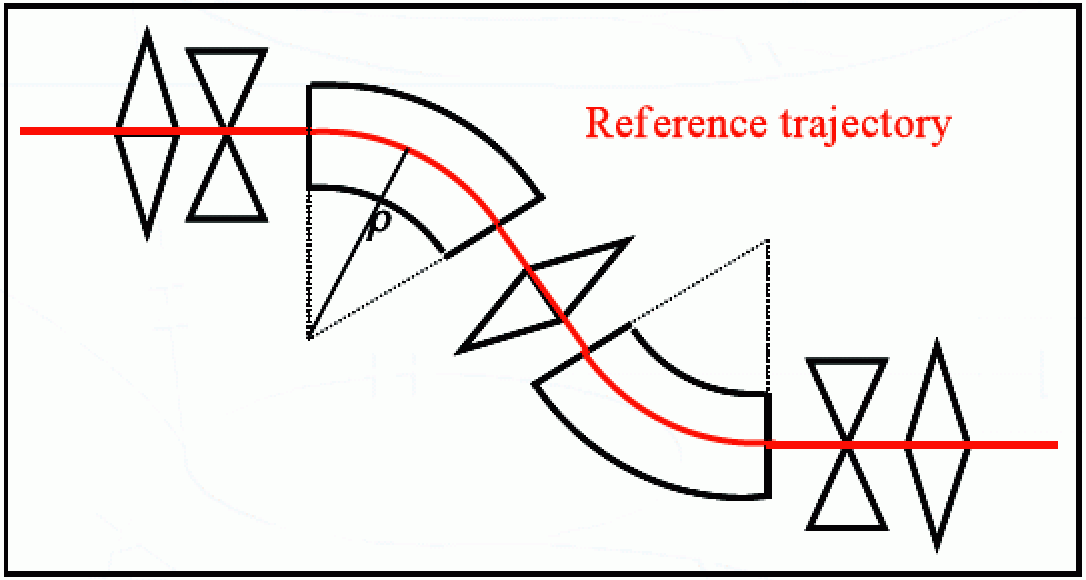
Particle type	p, Pb
Proton energy E_p at collision	7000 GeV
Peak luminosity (ATLAS, CMS)	1×10^{34} cm^{-2}s^{-1}
Circumference C	26 658.9 m
Bending radius ρ	2804.0 m
RF frequency f_{RF}	400.8 MHz
# particles per bunch n_p	1.15×10^{11}
# bunches n_b	2808

Particle accelerators

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

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

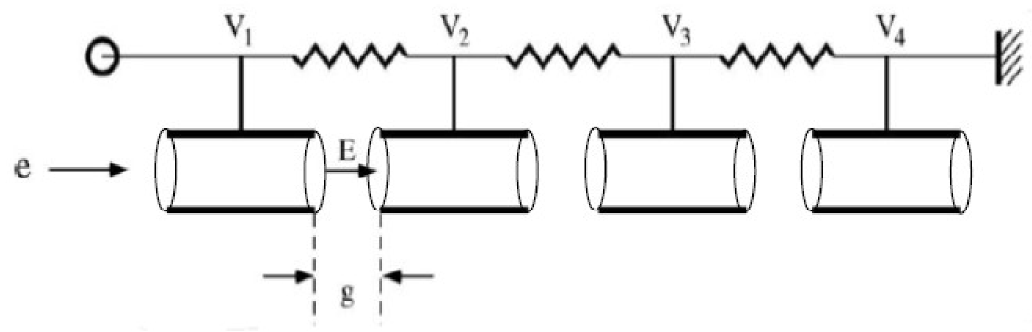
- Both F_E and F_B cause deflection:
- when v~c, 1T~ $3x10^8$ V/m
- Achievable E field ~ few MV/m
- Magnetic field is used in accelerators when possible (beam steering)



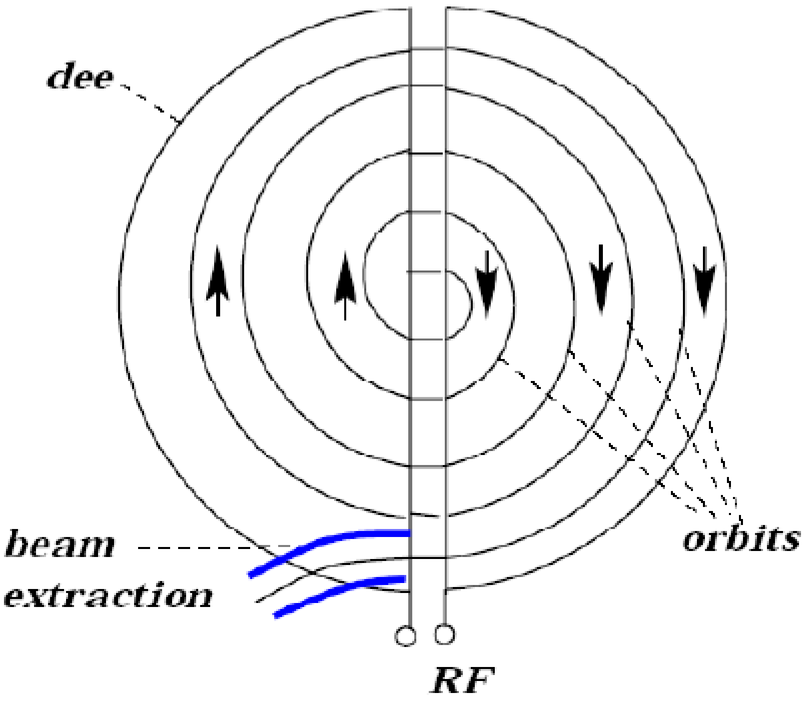
$$\vec{F}_B \perp \vec{v}$$ → Only electric field accelerates!

Accelerating particles

Linear (electrostatic) accelerator

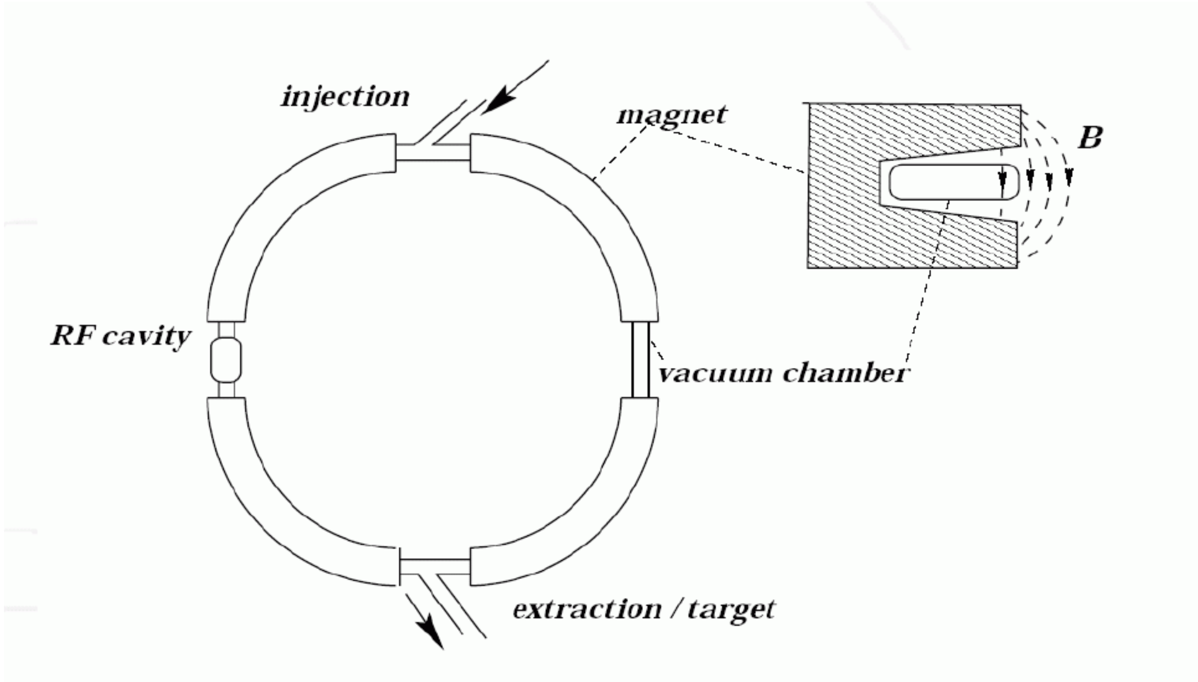


Cyclotron



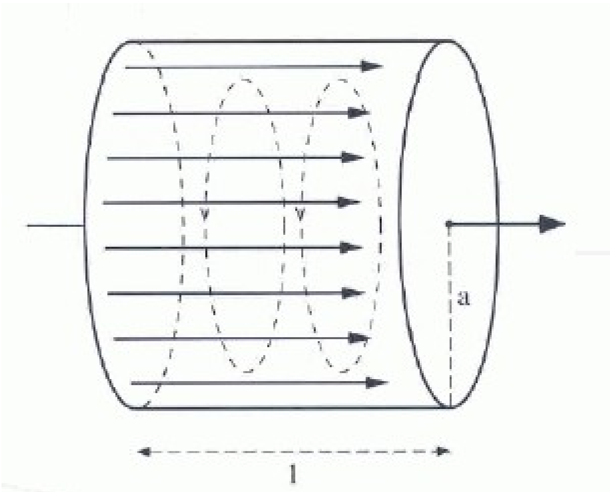
An important function of an accelerator is to accelerate ...

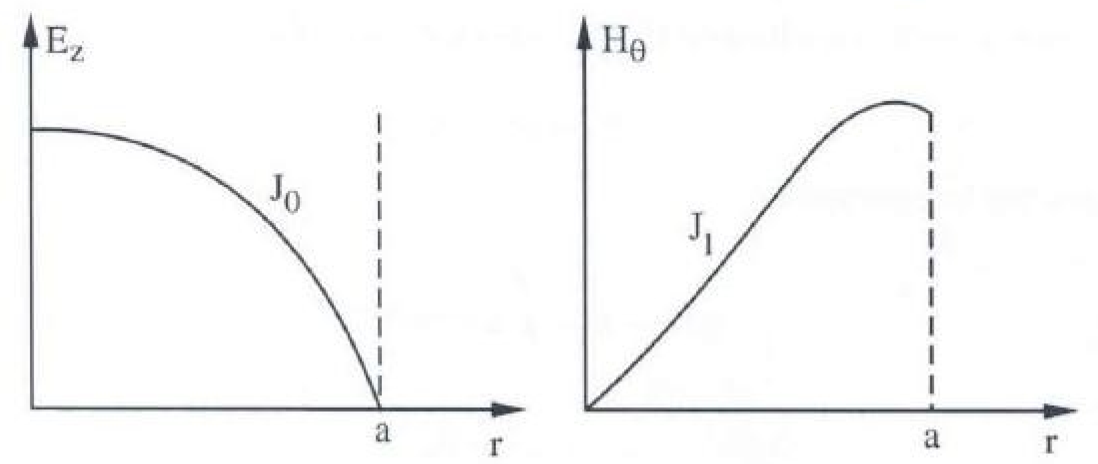
Cyclotron, betatron, synchrotron, oh my ...



- 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
- Acceleration done by RF cavities
- Changing also frequency of accelerating (RF) field

Accelerating particles – RF cavities



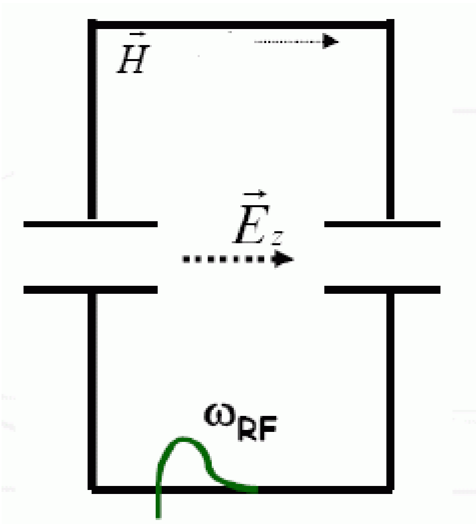


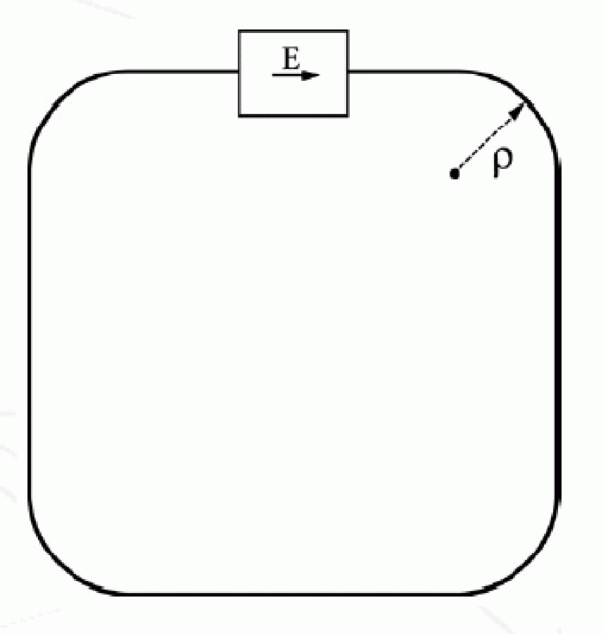
- In any closed metallic box it is possible to generate electromagnetic oscillations
- For example an ideal cylindric cavity
- Many (infinite number) of solutions for E and B – oscillating modes
- The fundamental mode normally used for acceleration is named TM_{010}
- E_z is constant in space along the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



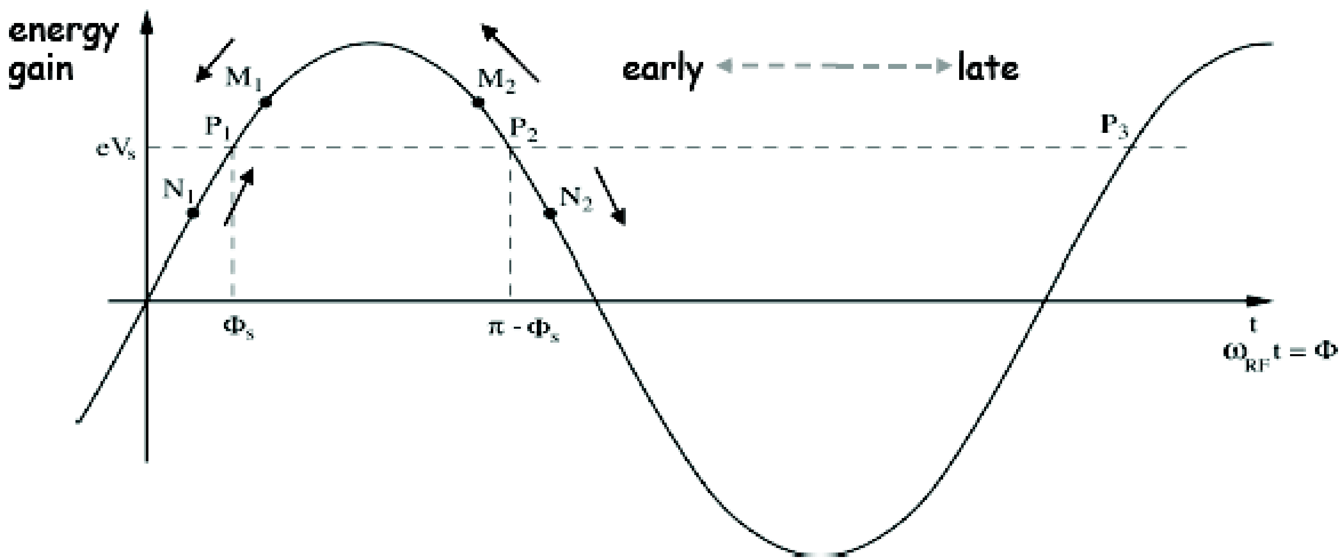


- RF power is fed into the cavity from RF power generators (for example Klystrons)
- RF power oscillates at desired frequency
- Good to have cavity with superconducting walls to minimize losses...
- Particles oscillating in the accelerator pass through the cavity many times, to be accelerated, they need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

Phase stability and bunches I

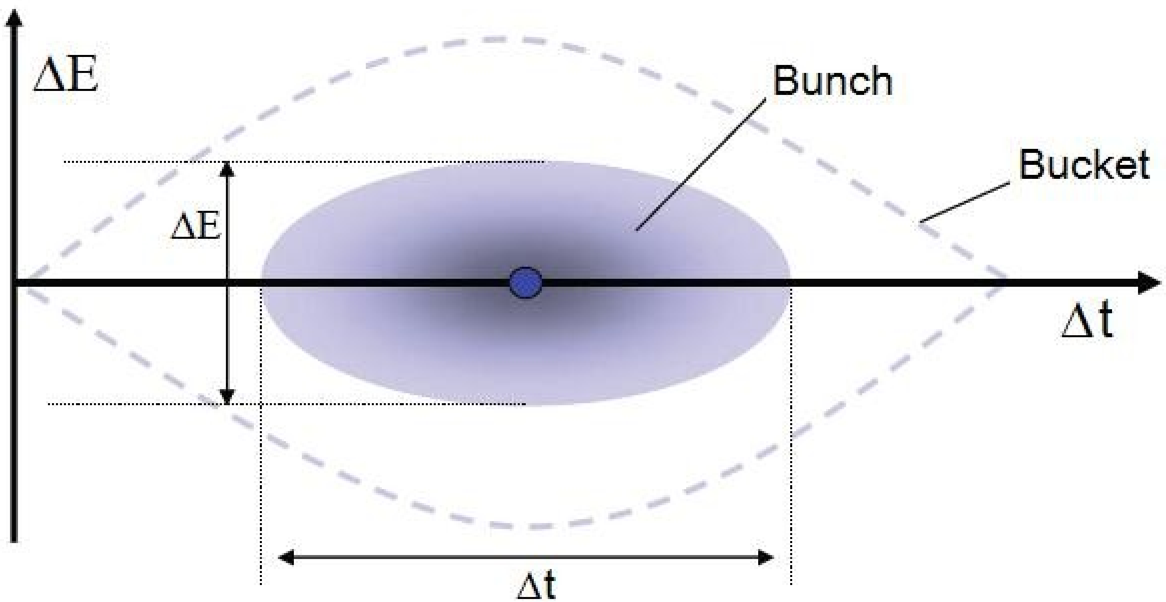
Assume the situation where energy increase is transferred into a velocity increase

Particles P_1, P_2 have the synchronous phase.



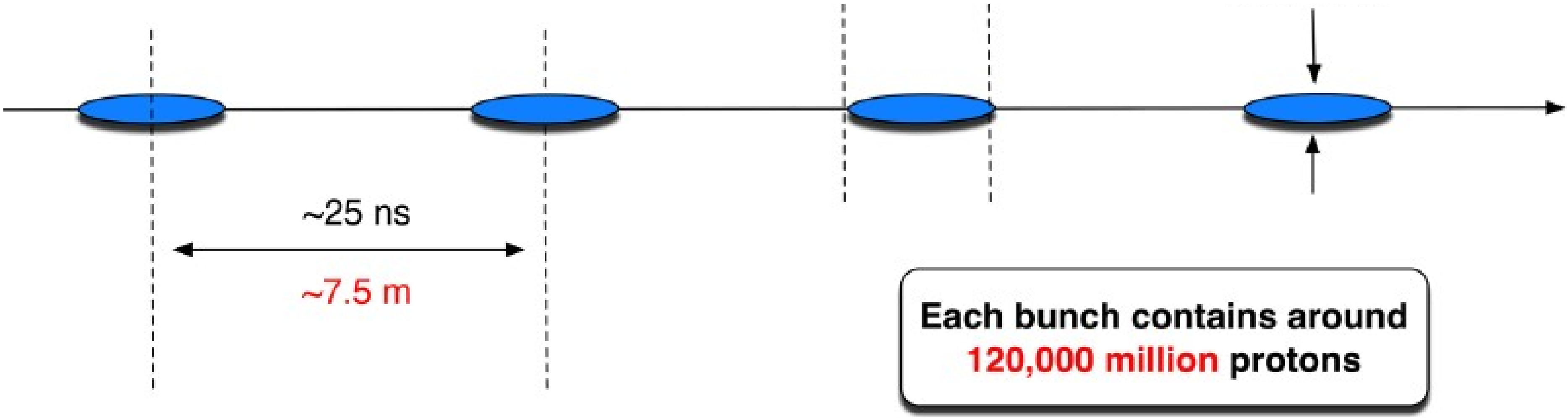
M_1 & N_1 will move towards P_1 => stable
M_2 & N_2 will go away from P_2 => unstable (and finally be lost)

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

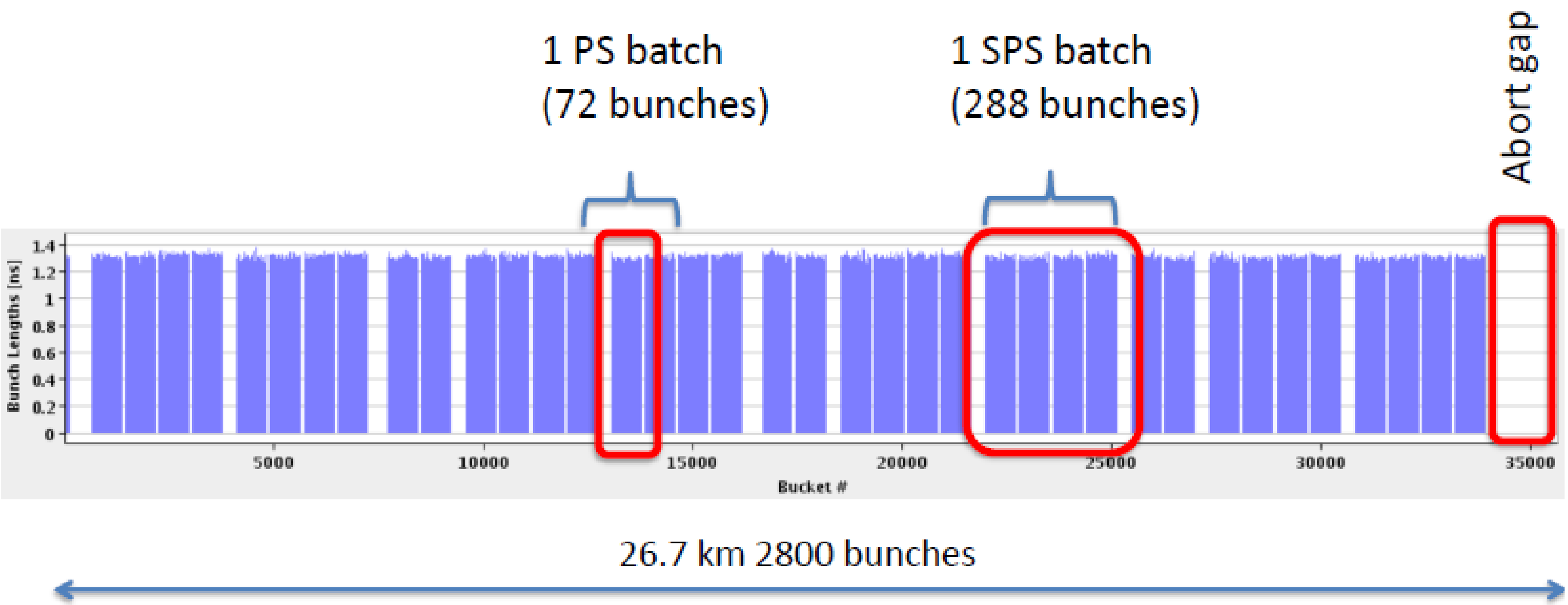
Phase stability and bunches III



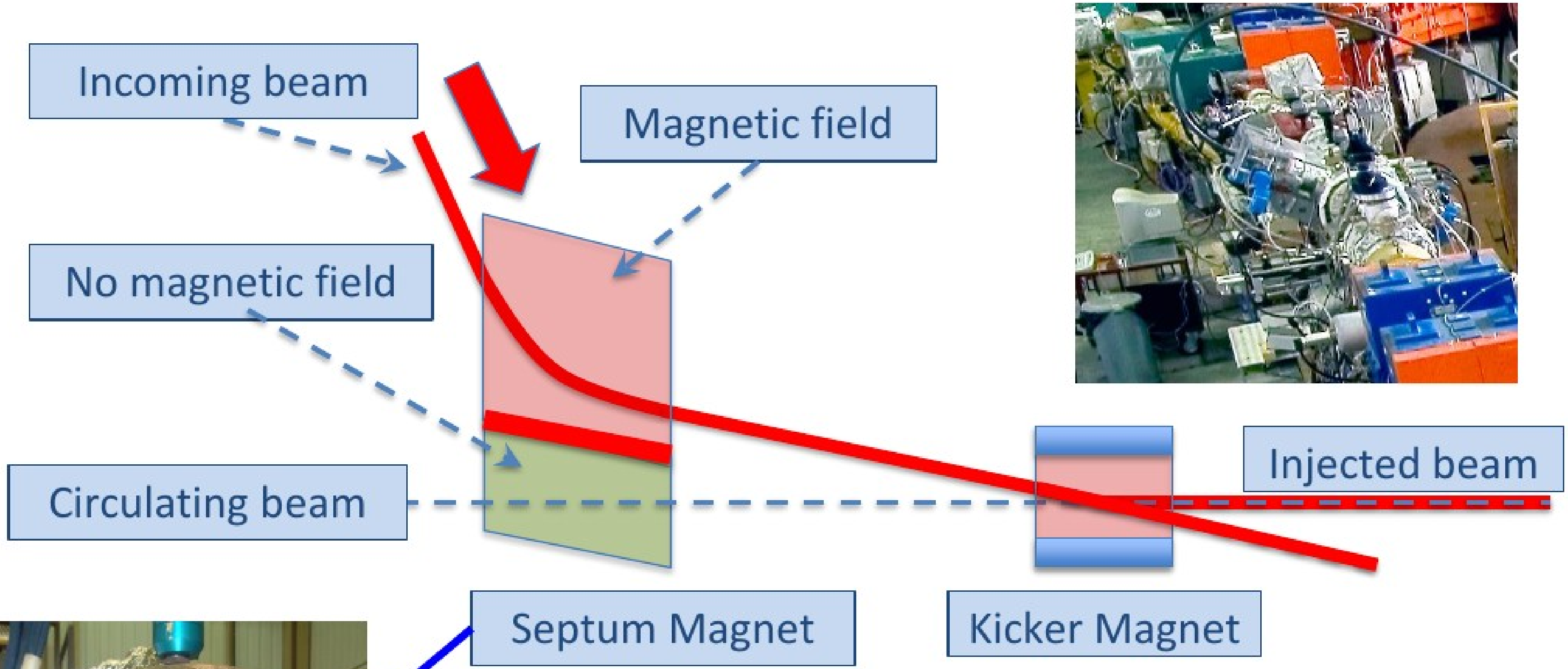
- Around 2800 filled bunches per beam
- Bunch length ~10cm
- Maximum transversal size (far from experimental collision points):
  - ~1mm at injection energy
  - ~0.5 mm at full energy

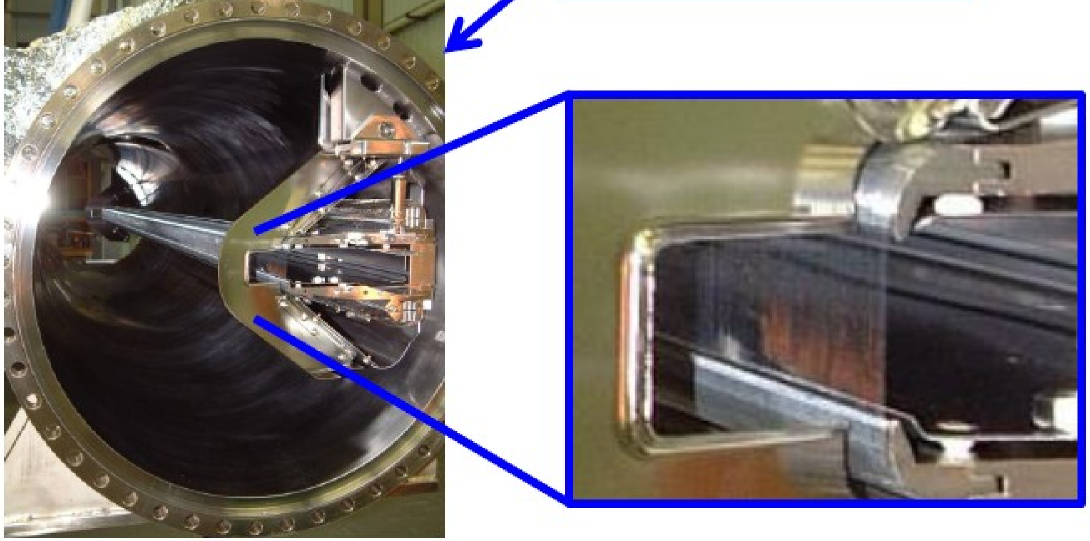
LHC bunch structure - 2016

- 25 ns bunch spacing
- Nominal bunch intensity 1.15 x 10^{11} protons per bunch



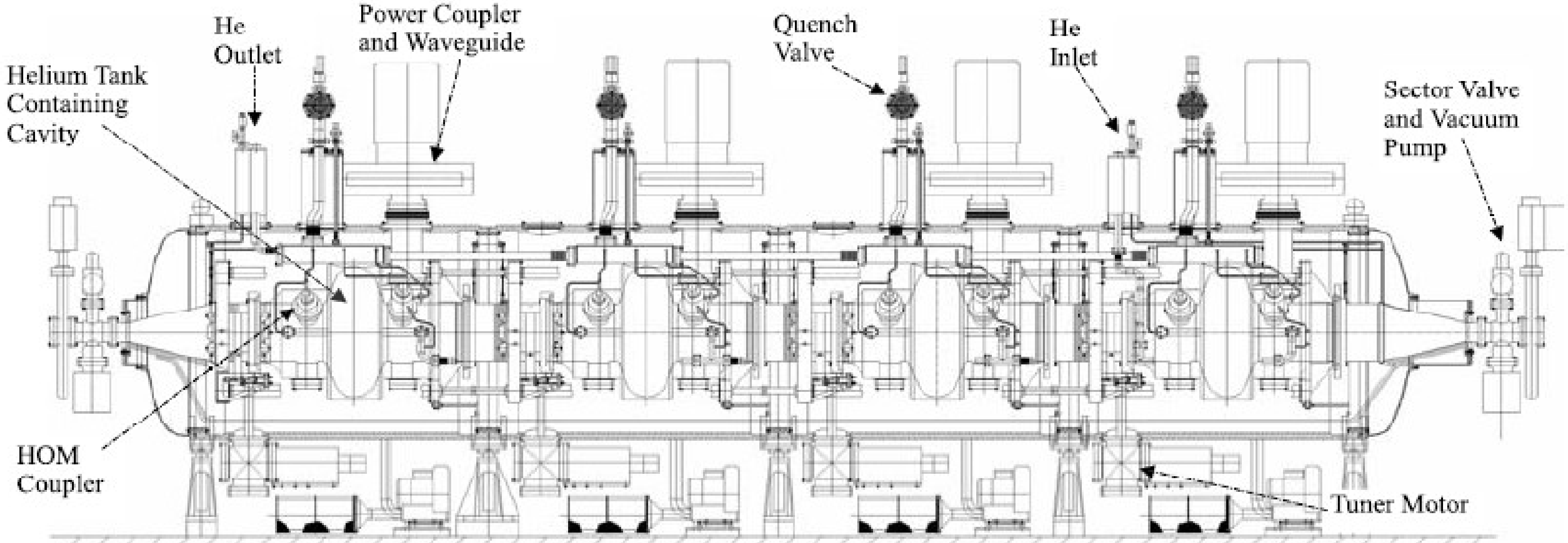
Injection and Extraction





Extraction follows the same principle, but the beam travels in the **opposite direction**.

Accelerating particles – LHC cavities

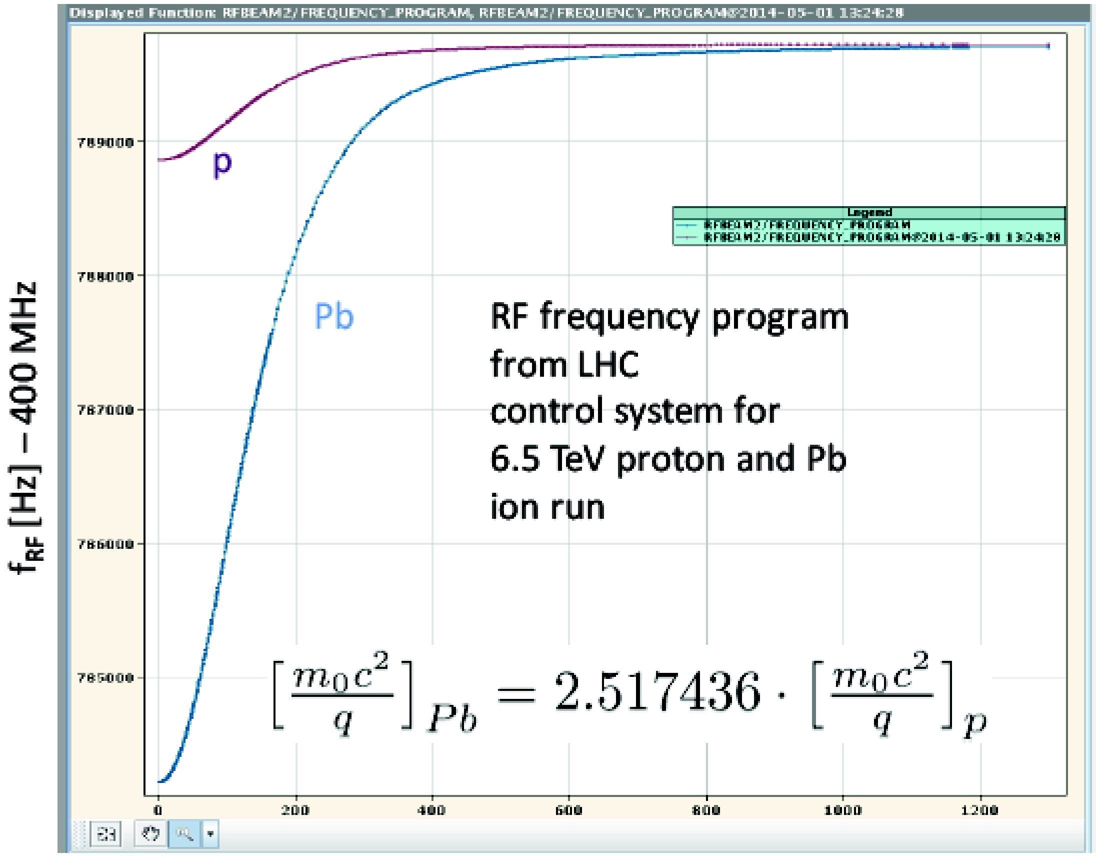


- 400 MHz superconducting cavity system
- 8 single-cell cavities per ring
- 1 klystron per cavity
- 4 cells are in one cryostat (4.5^0 K)

Maximum field 5 MV/m
Energy gain/turn ~0.5 MeV
RF frequency varies from 400.789 MHz (450 GeV) to 400.790 MHz (7 TeV)

Energy ramp

The LHC can accelerate protons and heavier ions.
In the past: runs with p^+ and Pb^{82+}
For the ramp of lead ions larger frequency swing



- Slow ramp (> 15min)
- Small energy gain/turn (~500keV)

Accelerating particles – LHC cavities

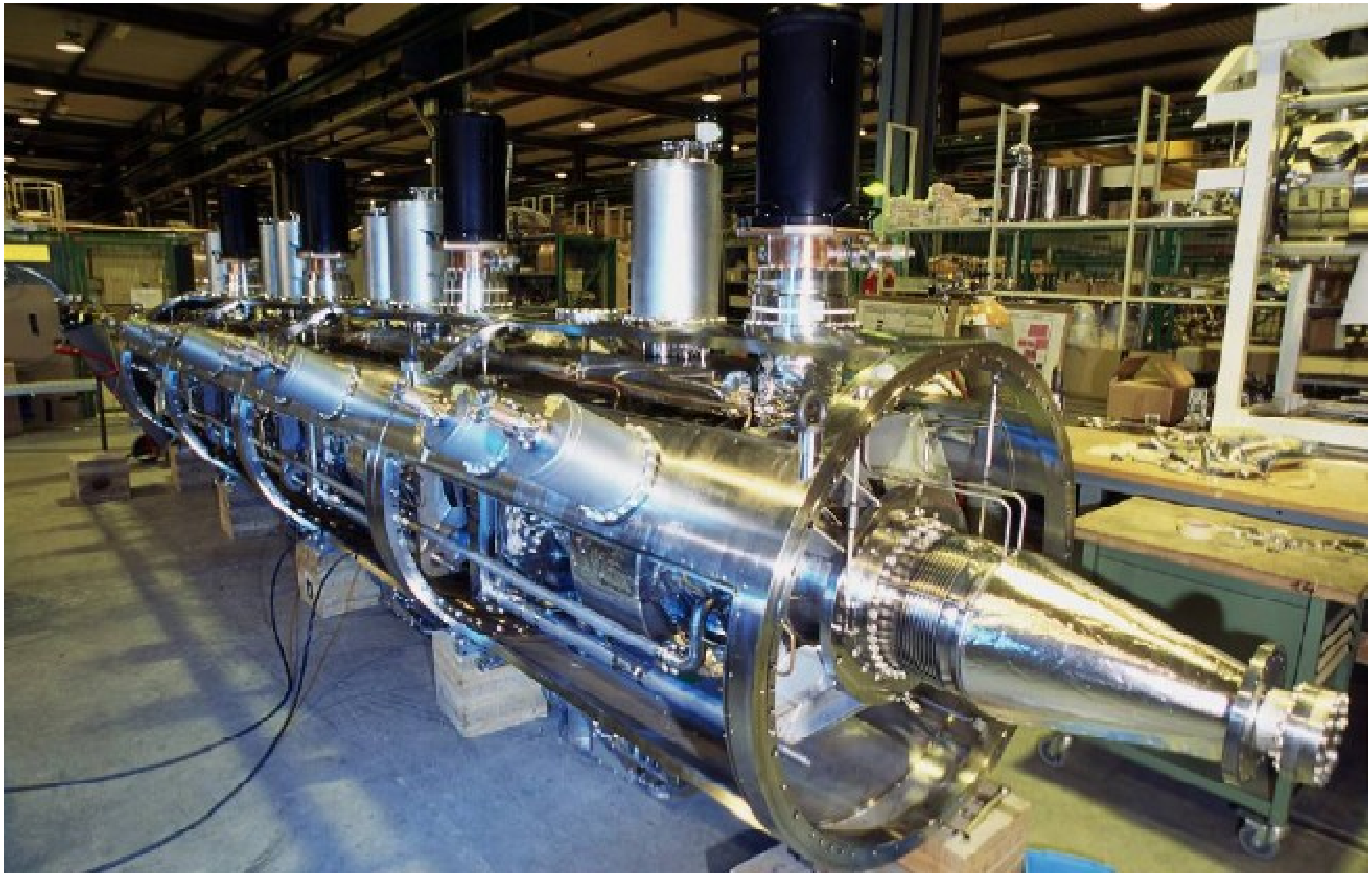


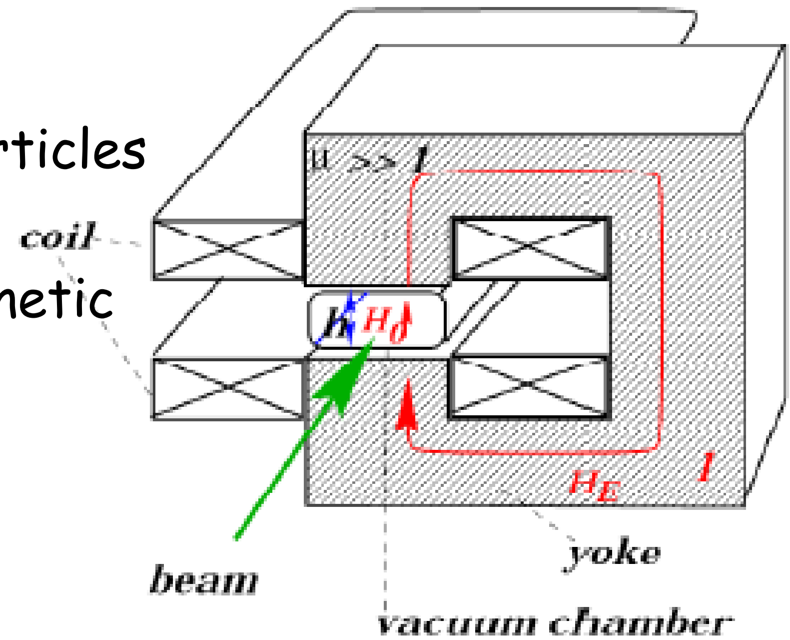
Table 4.1: The Main Beam and RF Parameters.

	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, $\sim$100 ms after each batch injection. The bunch parameters at injection are described in the text.

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 fields
- 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:

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

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

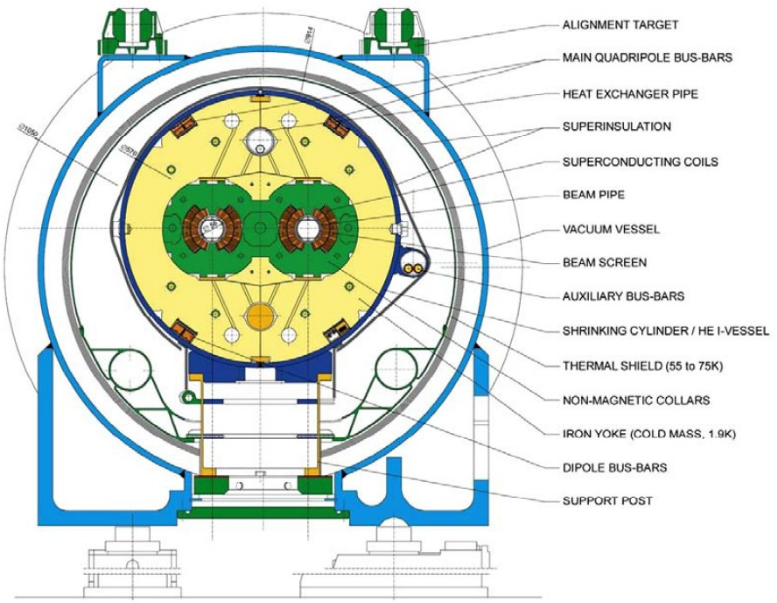
$$\frac{1}{\rho} = 0.333\,\frac{8.3}{7000}\,{1}/{m}$$

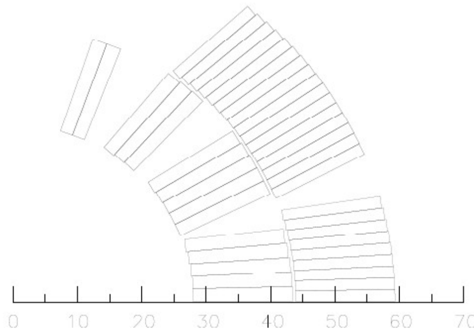
Gives:

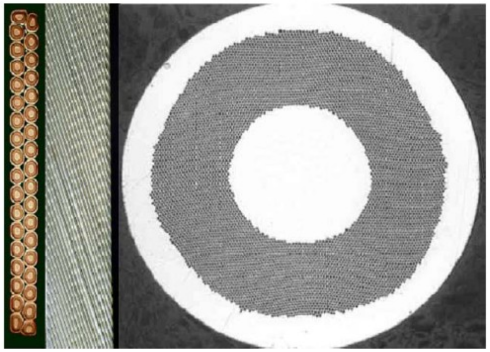
$$\rho = 2.53\,km \longrightarrow \begin{aligned} 2\pi\rho &= 17.6\,km \\ &\approx 66\% \end{aligned}$$

- 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!

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
- 1232 dipole magnets, each 15m long

Keeping particles on circle – dipoles

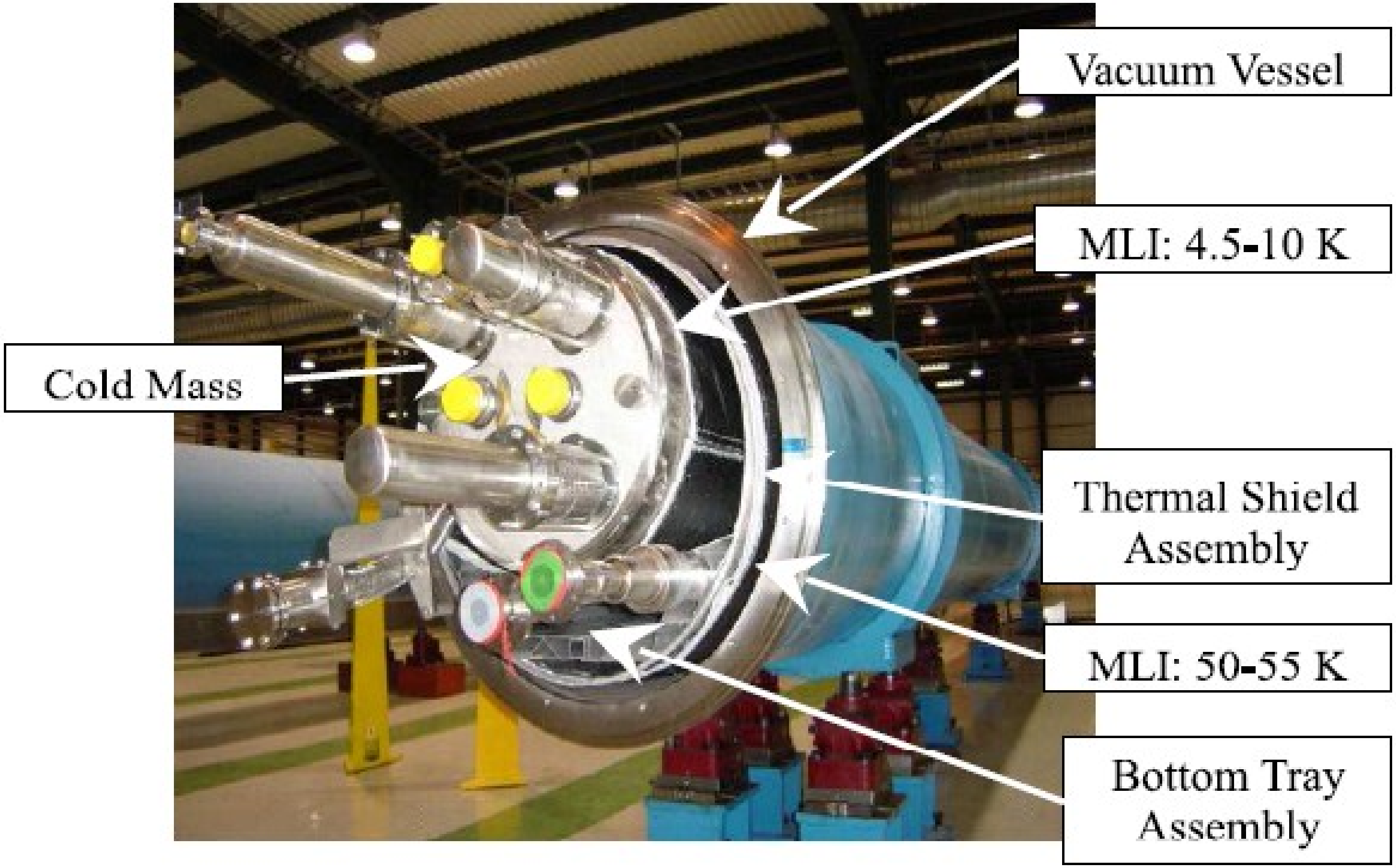
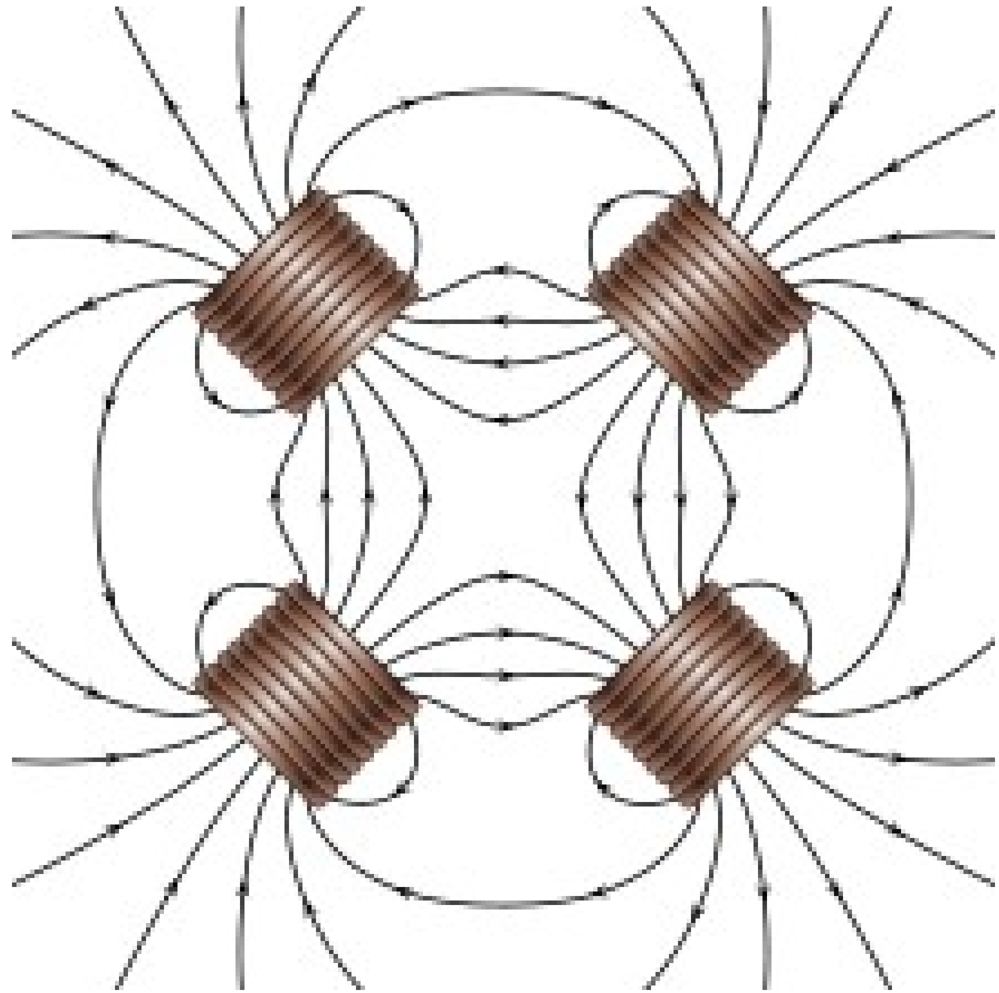


Table 3.4: Main parameters of the dipole cold mass.

	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

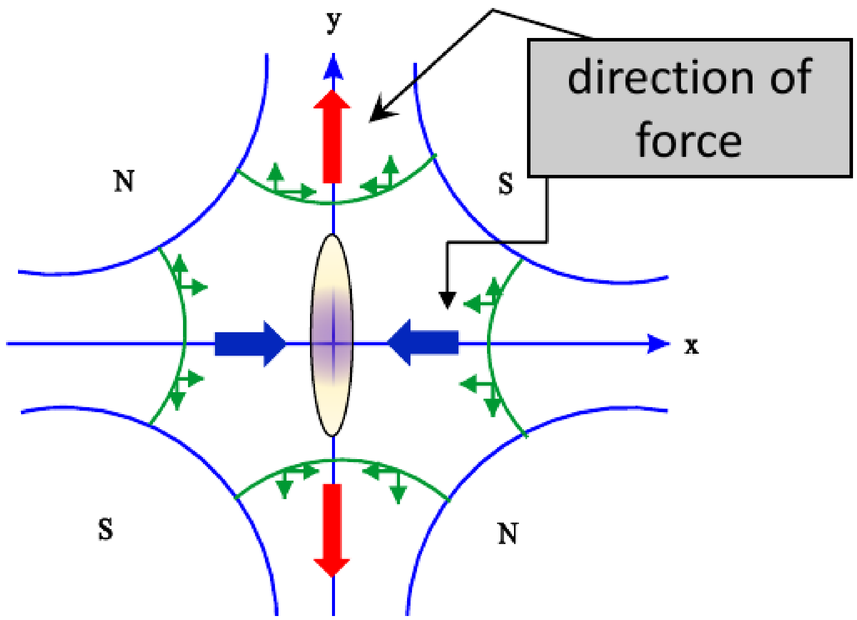
Squeezing the beam - quadrupoles I

- 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!

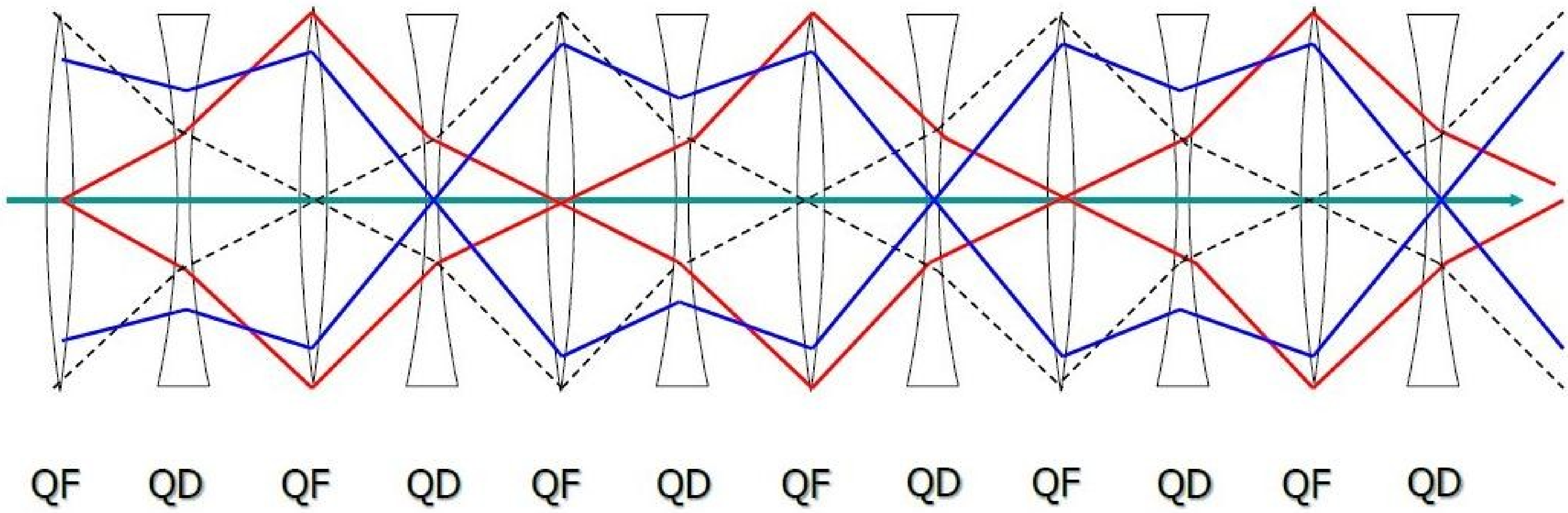


Squeezing the beam - quadrupoles II

- 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°



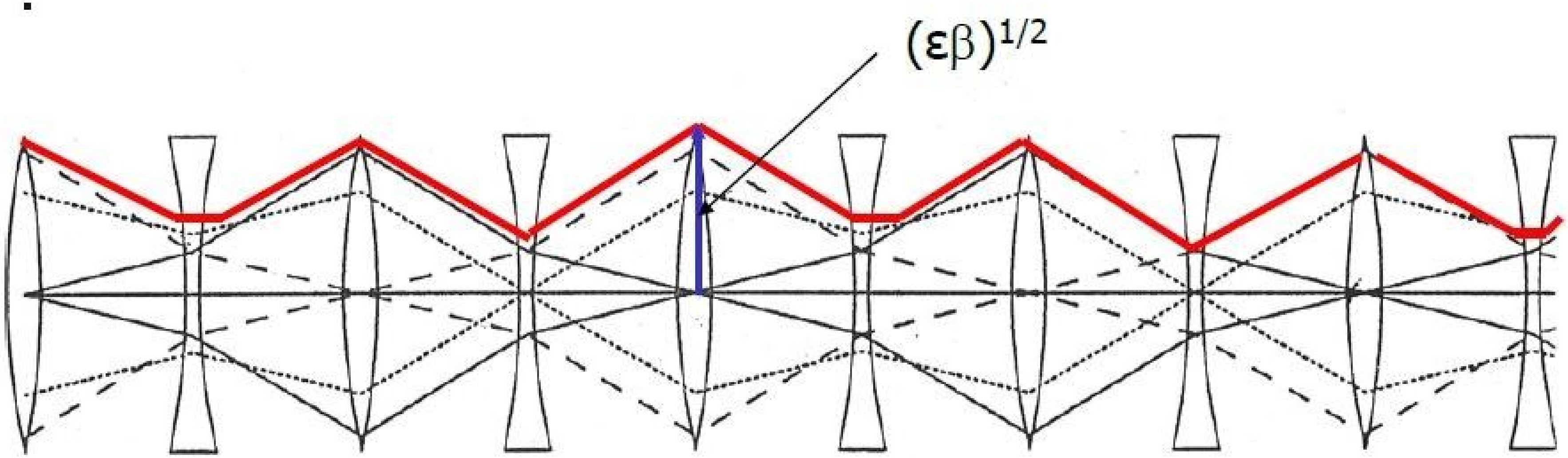
Strong focusing and FODO lattice I



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 circulating 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:

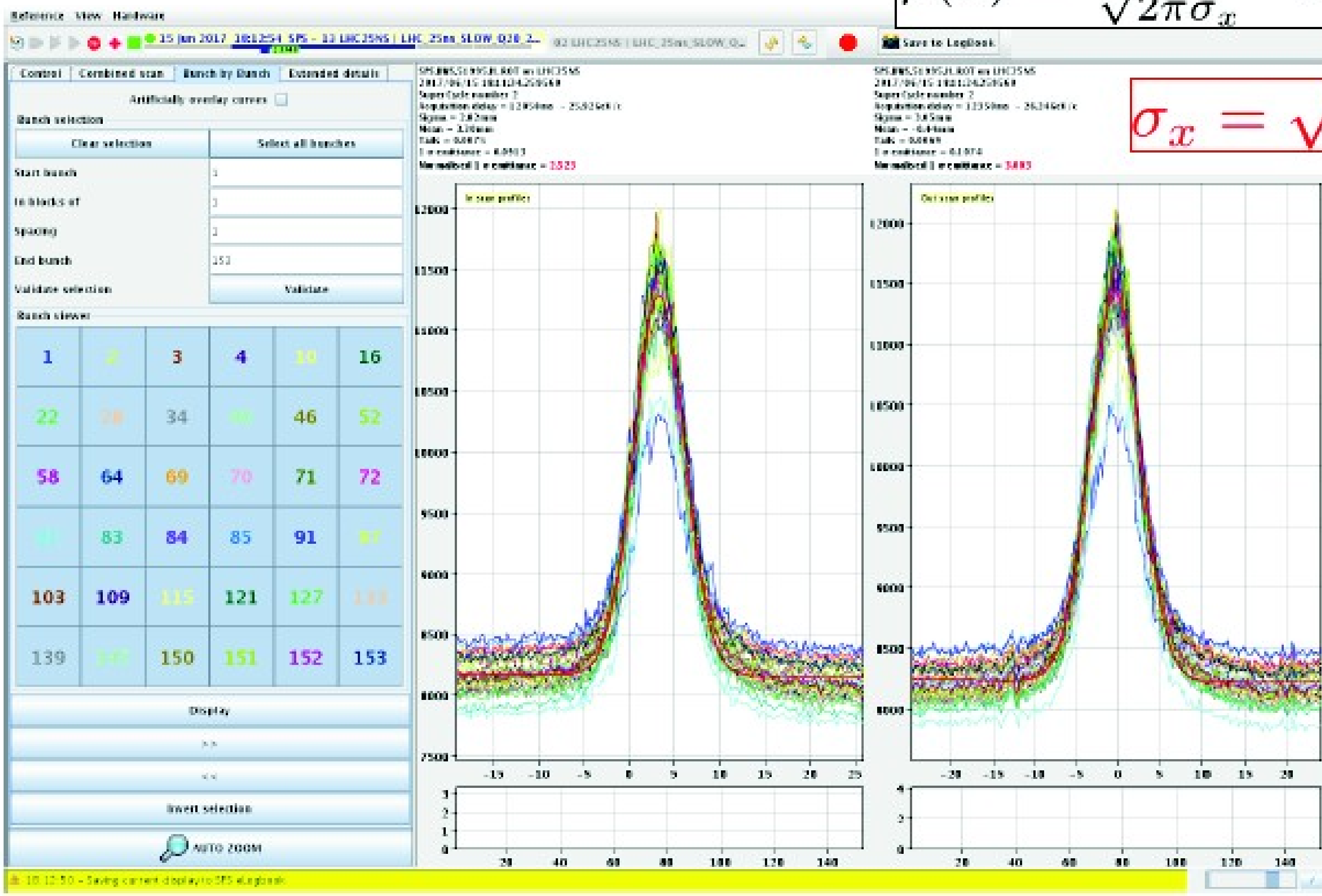
- describes the quality of the beam

Strong focusing and FODO lattice III

Typically particles in accelerator have Gaussian particle distribution in position and angle.

$$\rho(x) = \frac{N}{\sqrt{2\pi}\sigma_x} \cdot e^{-\frac{x^2}{2\sigma_x^2}}$$

$$\sigma_x = \sqrt{\varepsilon\beta_x}$$



LHC quadrupoles

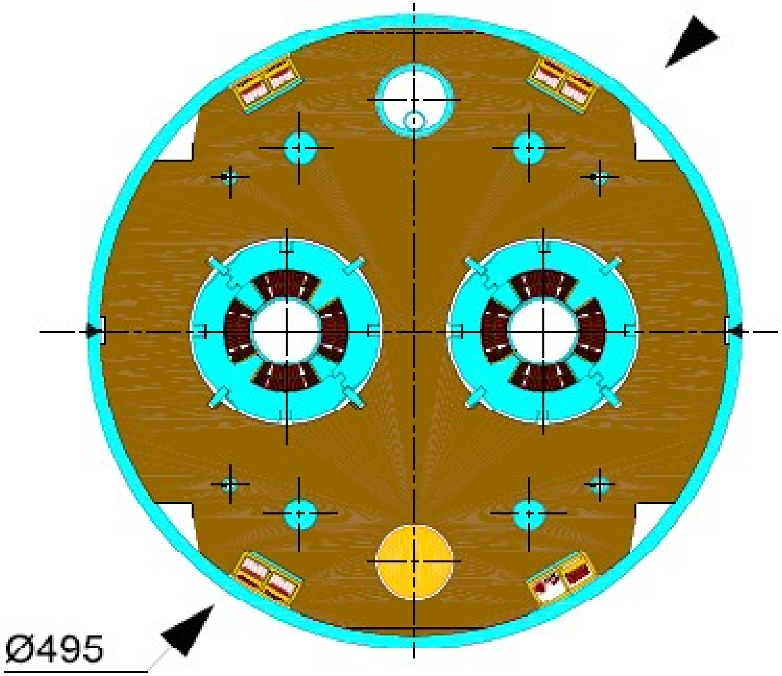
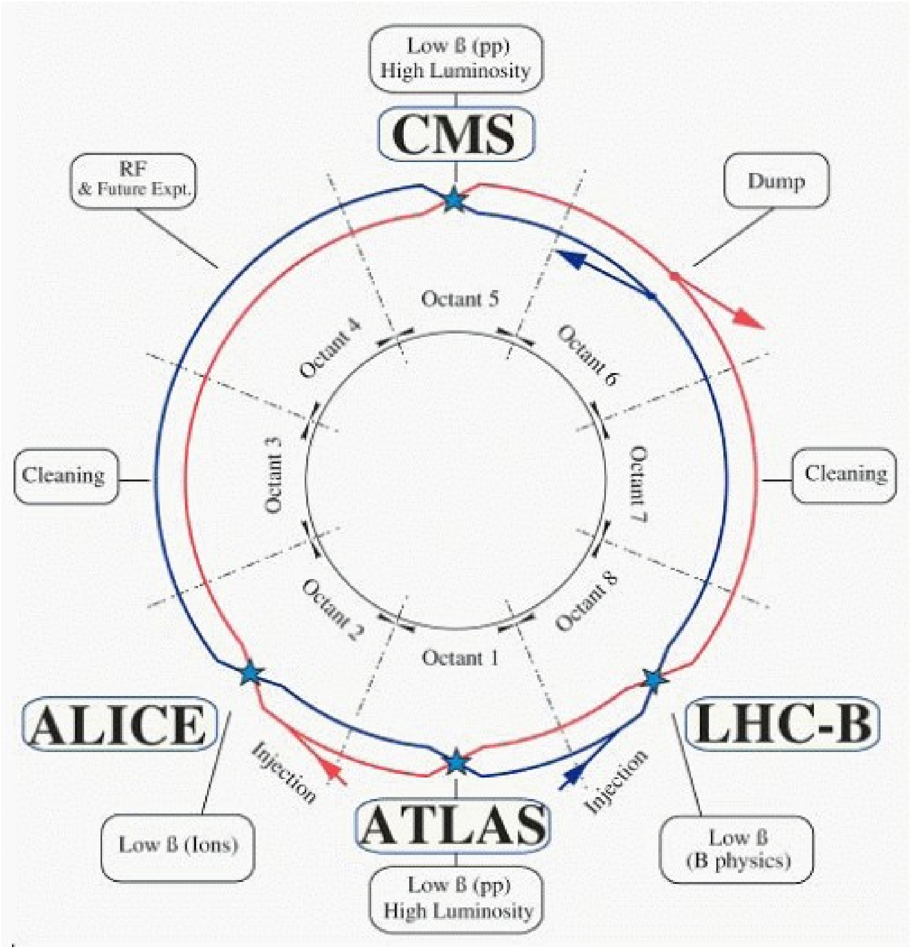


Table 3.5: Parameter list for main quadrupole magnets at 7.0 TeV.

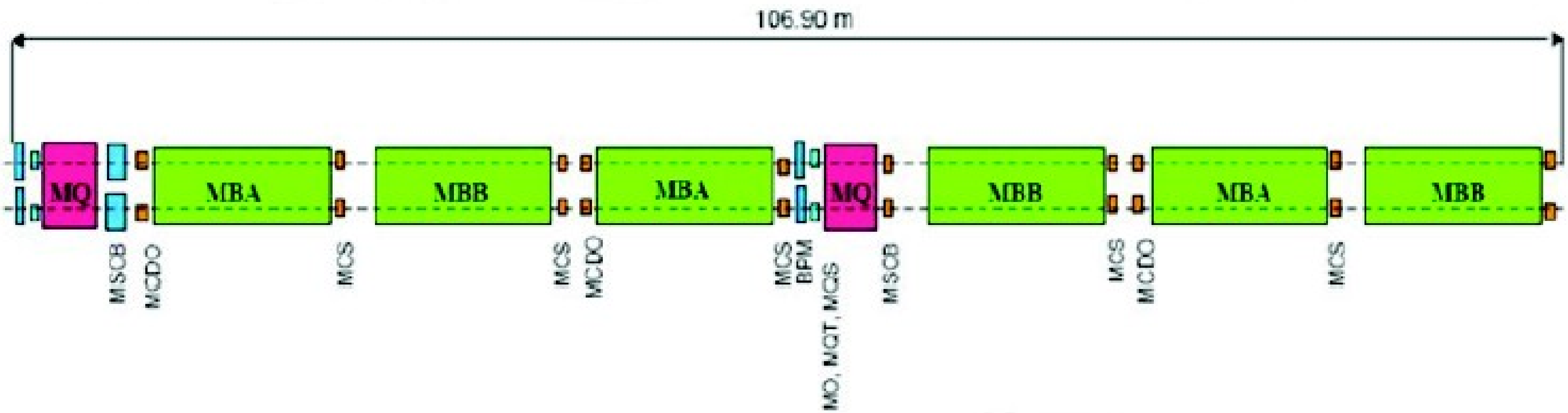
Integrated Gradient	690	T
Nominal Temperature	1.9	K
Nominal Gradient	223	T/m
Peak Field in Conductor	6.85	T
Temperature Margin	2.19	K
Working Point on Load Line	80.3	%
Nominal Current	11870	A
Magnetic Length	3.10	m
Beam Separation distance (cold)	194.0	mm
Inner Coil Aperture Diameter (warm)	56.0	mm
Outer 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

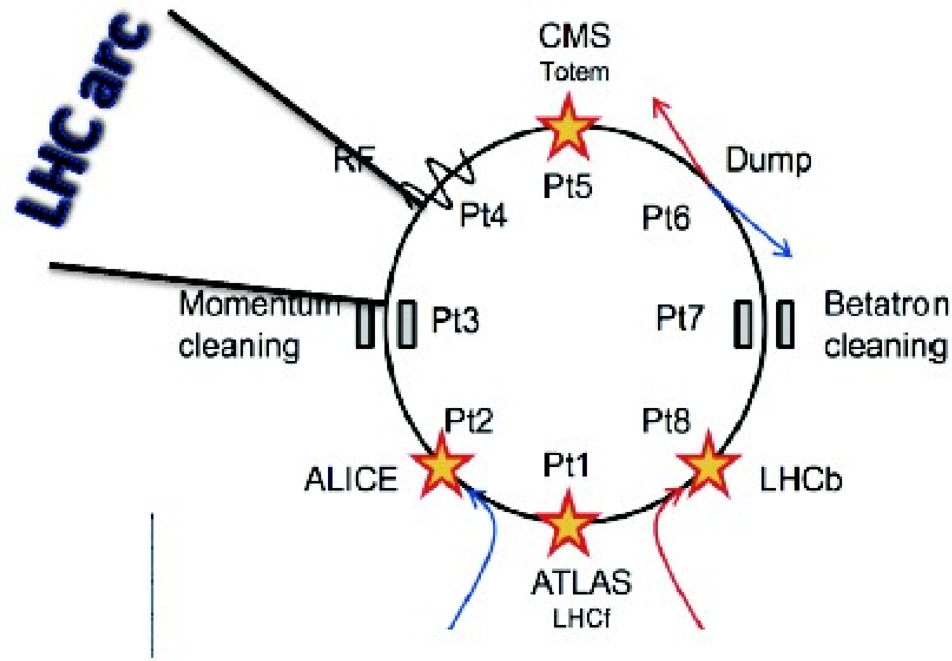
- Circumference = 26658.9 m
- 8 arcs and 8 straight sections
  - Straight sections have either experiment or “utilities”
  - Four used for experiments
  - Arcs contain magnets (LHC lattice)
  - 23 FODO cells in each arc
  - A FODO cell consistes of 2 quadrupoles, 6 dipoles and additional correction magnets



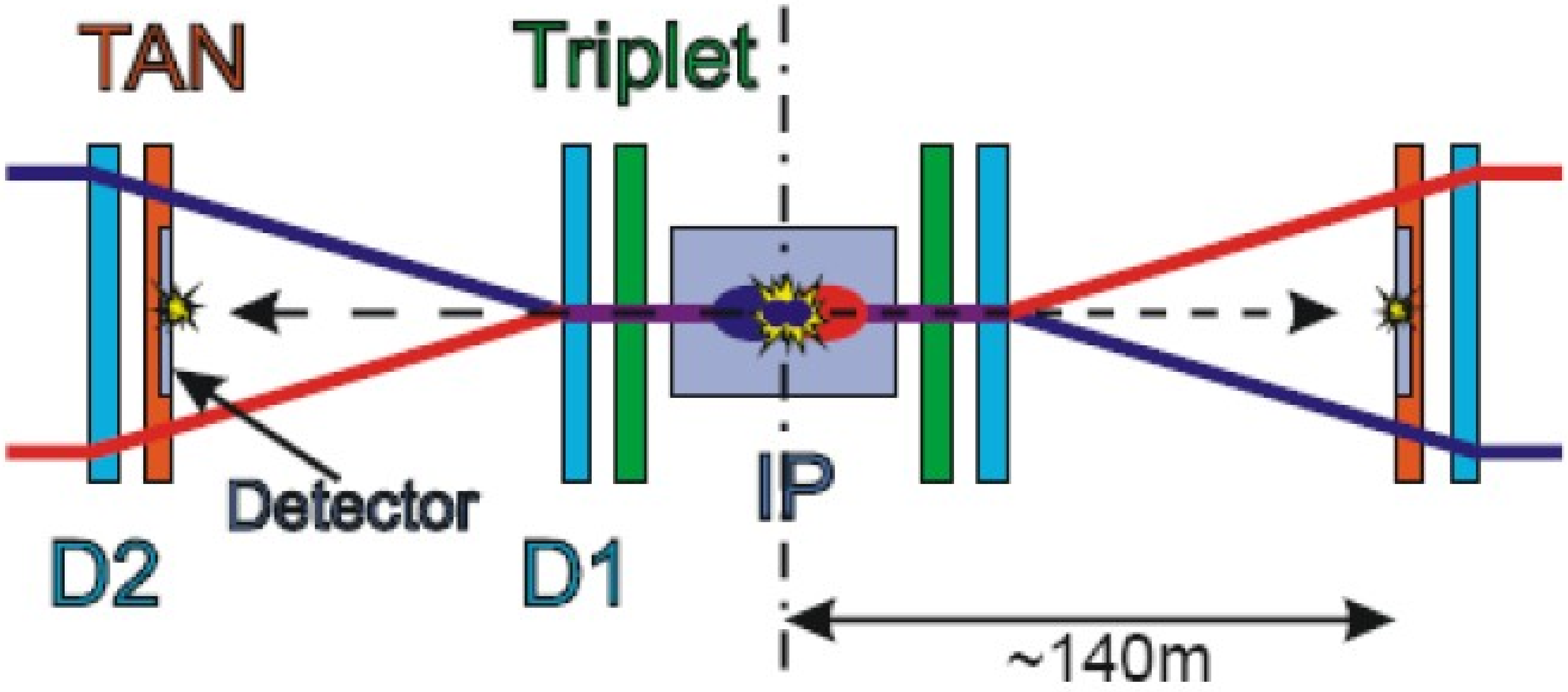
The LHC FODO cell



Each LHC arc consists of 23 FODO cells

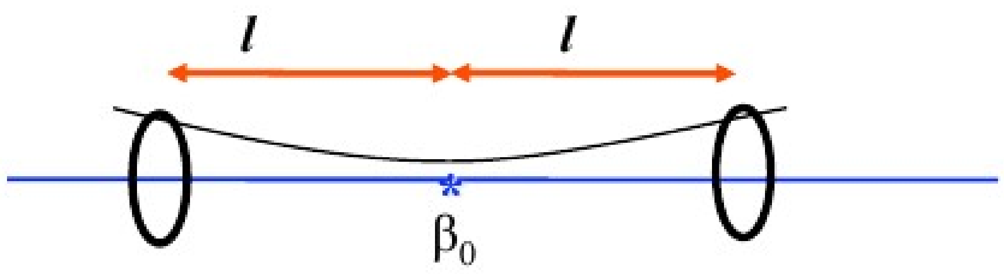


Getting particles to collide – interaction point I



Special drift: Minibeta insertion

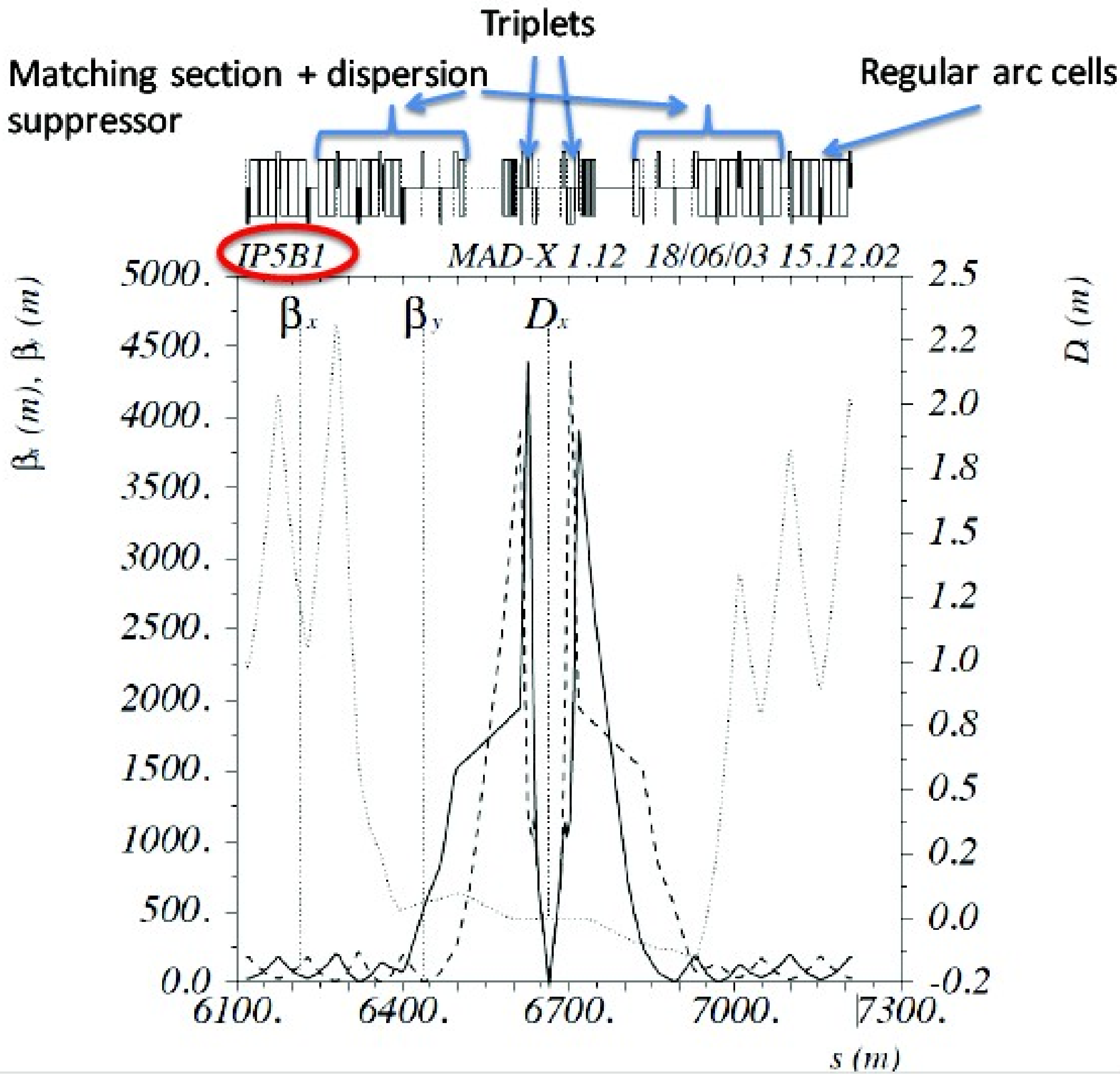
Minibeta insertion is a symmetric drift space with a beta waist in the center of the insertion



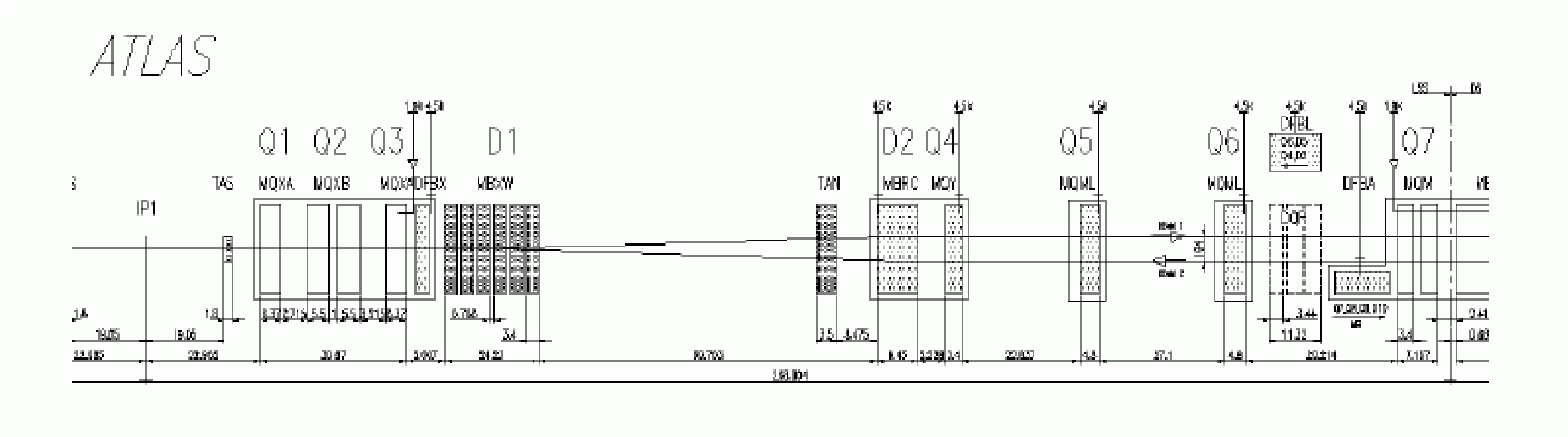
On each side of the symmetry point a quadrupole doublet or triplet are used to generate the waist.
They are not part of the regular lattice.

E.g. collider experiments are located in minibeta insertions: smallest beam size possible for the colliding beam to increase probability of collisions.

Minibeta insertion – Example LHC



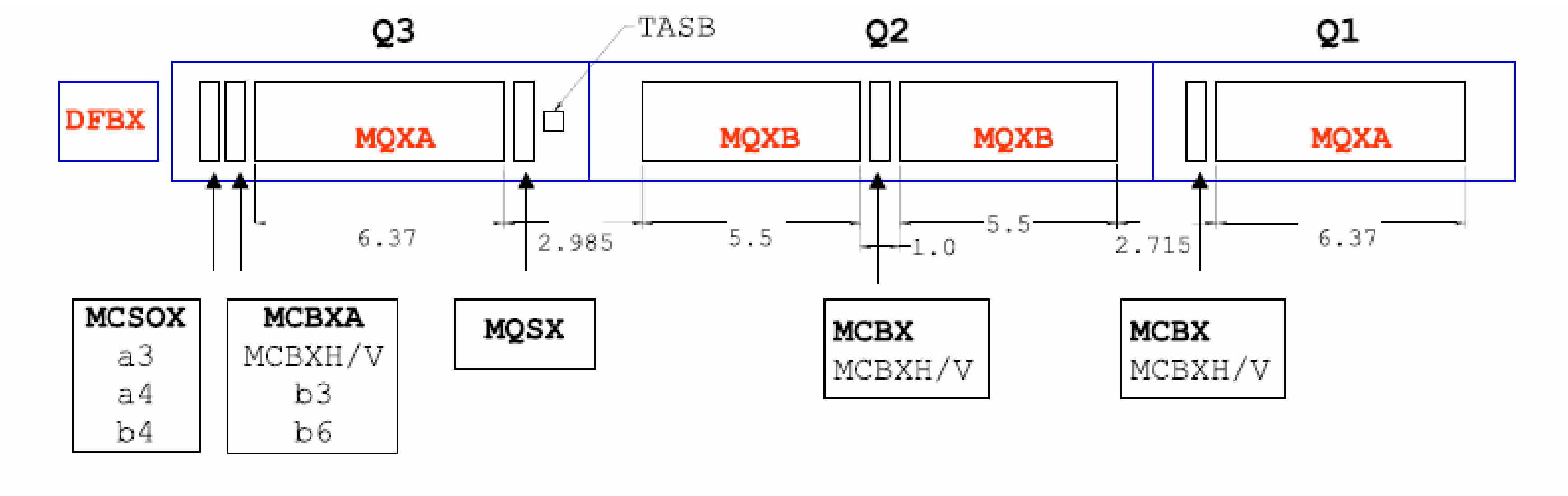
Getting particles to collide – interaction point I



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 III



- Low beta 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
- Pre-accelerators
- Cryogenic system
- Power distribution and protection
- Correction magnets
- Beam monitoring
- Control system
- ...

LHC in the near (and not-so-near) future

The H boson is not just … "yet another particle"

- Profoundly different from all elementary particles discovered so far
- Related to the most obscure sector of SM
- Linked to some of the deepest structural questions (flavour, naturalness, vacuum, …)

Its discovery opens new paths of exploration, and a very broad and challenging experimental programme

Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \underset{\text{flavour}}{\underset{\uparrow}{\lambda}} H \psi \bar{\psi} + \underset{\text{naturalness}}{\underset{\uparrow}{\mu^2}} |H|^2 - \underset{\text{stability}}{\underset{\uparrow}{\lambda}} |H|^4 - \underset{\text{c.c.}}{\underset{\uparrow}{V_0}}$$

G.F. Giudice

- Precision measurements of couplings (as many generations as possible, loops, …)
- Forbidden and rare decays (e.g. H→ τμ) → flavour structure and source of fermion masses
- H potential (HH production, self-couplings):
  → EWSB mechanism (strong dynamics ?)
  → EW phase transition → baryogenesis ?
- Exotic decays (e.g. H→ E_T^{miss}) → new physics ?
- Other H properties (width, CP, …)
- Searches for additional H bosons
- …

F. Gianotti, CERN, 29/10/2015 16

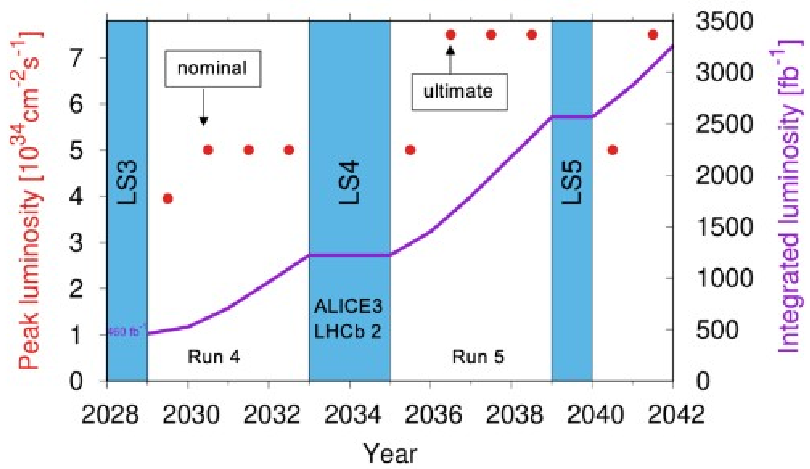
New Year CERN directorate meeting

13 January 2022, Agenda: https://indico.cern.ch/event/1106493/

Fabiola on long-term HL-LHC planning

Note on long-term planning

Preliminary (optimistic) schedule of HL-LHC



Shown integrated luminosities include 1 month/year of HI running and no MD or special runs after 2036

LS4 extended from 1 to 2 years (in view of ALICE and LHCb upgrades)

With proposed shift and extension of LS3, and inclusion of HI runs beyond LS3:
- 2500 fb^{-1} are expected by end 2038 (current end-date of HL-LHC)
- 3000 fb^{-1} (int. luminosity goal) would now be reached in ~ 2041

Note: it should not be assumed that future shifts of LS schedules, or new, ambitious upgrades of the experiments, entail an automatic shift/extension of HL-LHC end date, as this has an impact on the future of the field
(next collider cannot start before ~ 7 years from end of HL-LHC for technical and financial reasons)
→ next European Strategies will need to optimise the overall planning of the field based on HL-LHC performance and physics results, interest of the community, progress with next facility, etc.

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HL-LHC, luminosity upgrade

Higher intensity

Increase bunch intensity

$$\mathcal{L} = \frac{N_1 N_2 f_{\mathrm{rev}} k_B}{4\pi\beta^* \epsilon_{xy}} F$$

Increase F: shorter bunches, smaller crossing angle, crabs

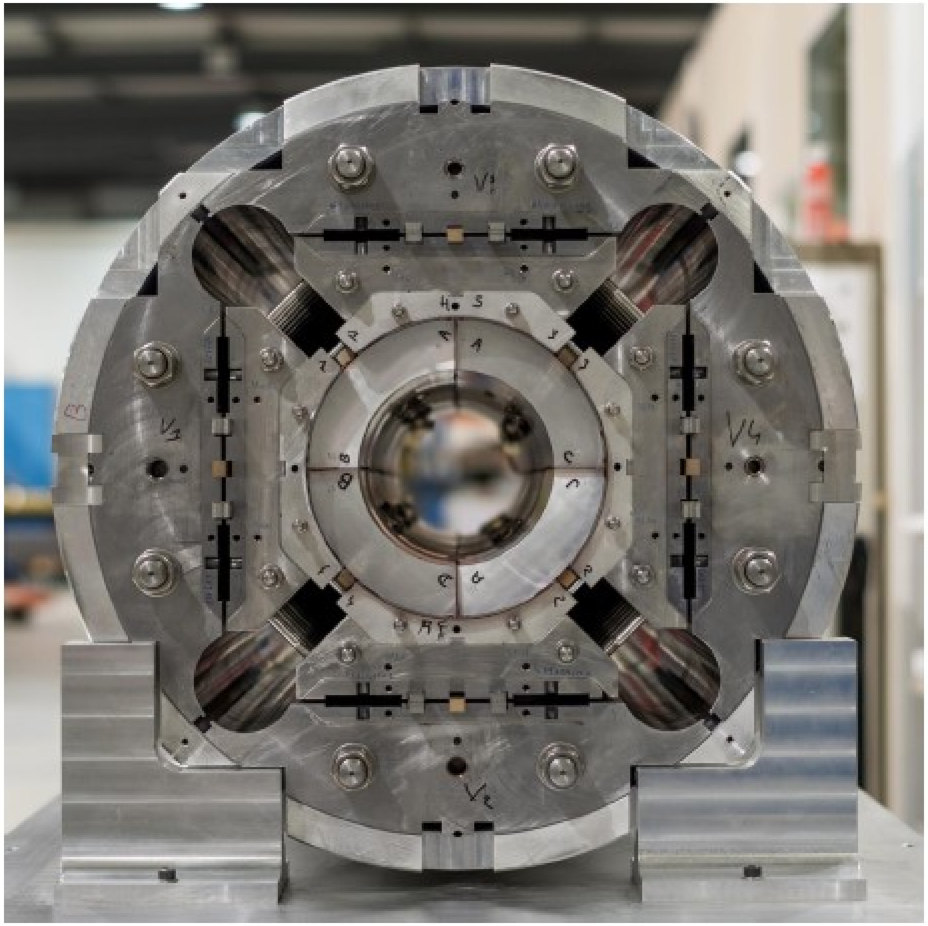
$$\frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

Smaller β*

Smaller emittance

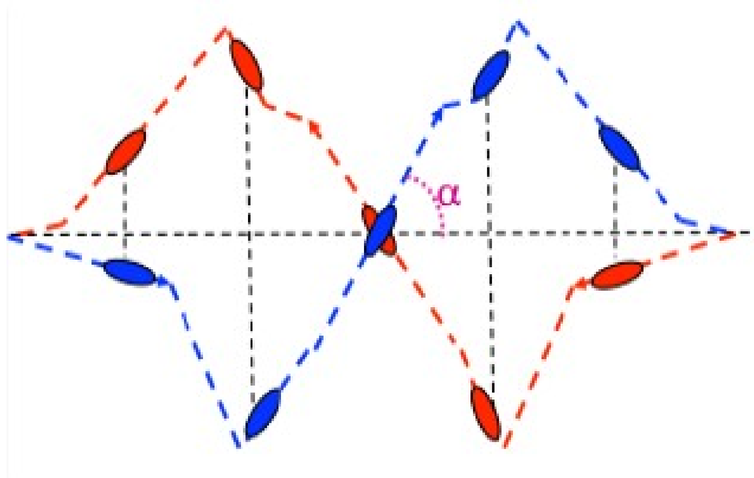
Smaller beam size

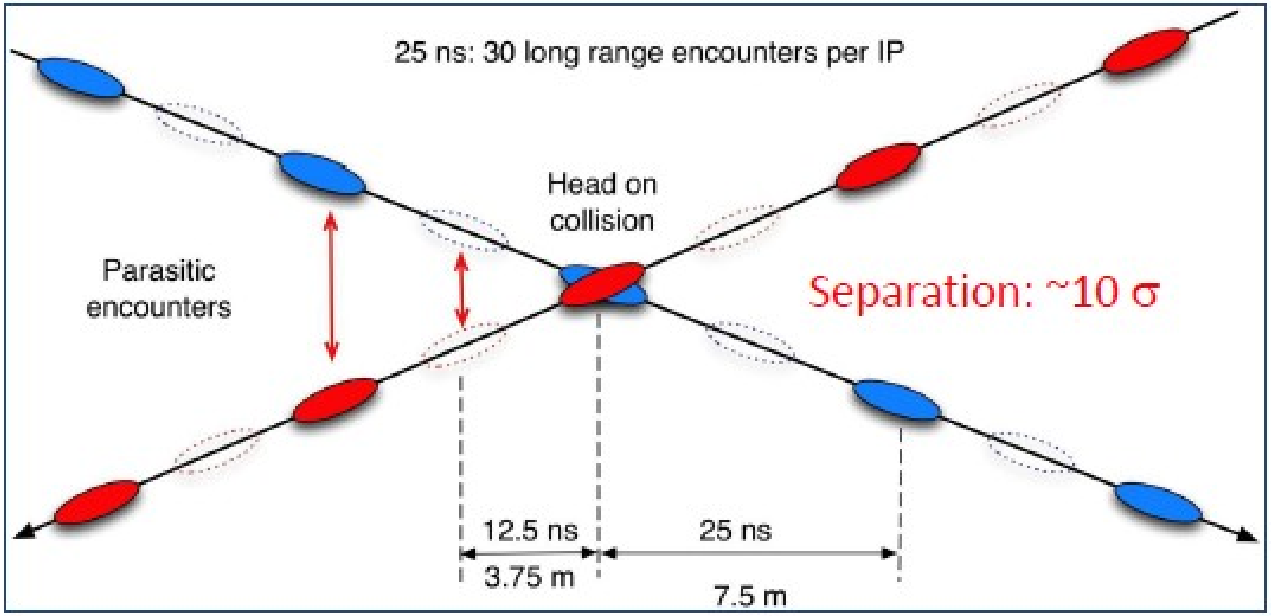
New, wide-aperture quadrupoles



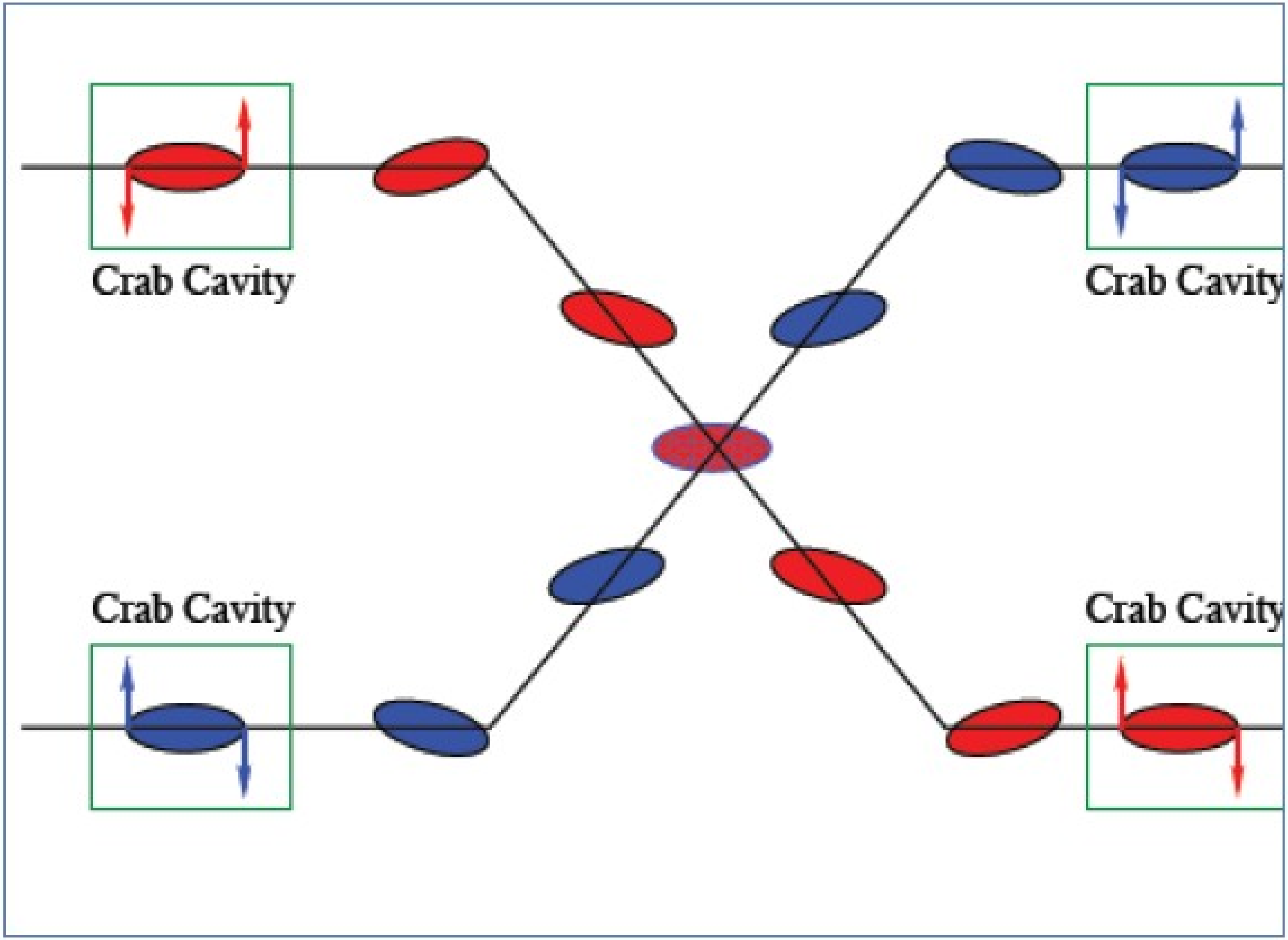
- Requires new, Nb_3Sn technology

Current LHC, operation with crossing angle





HL-LHC, crossing angle compensation using crab cavities



Crab Cavity

- Create a oscillating transverse electric field
- Kick head and tail of the bunch in opposite directions
- Serving to mitigate the effect of the crossing angle at the IP

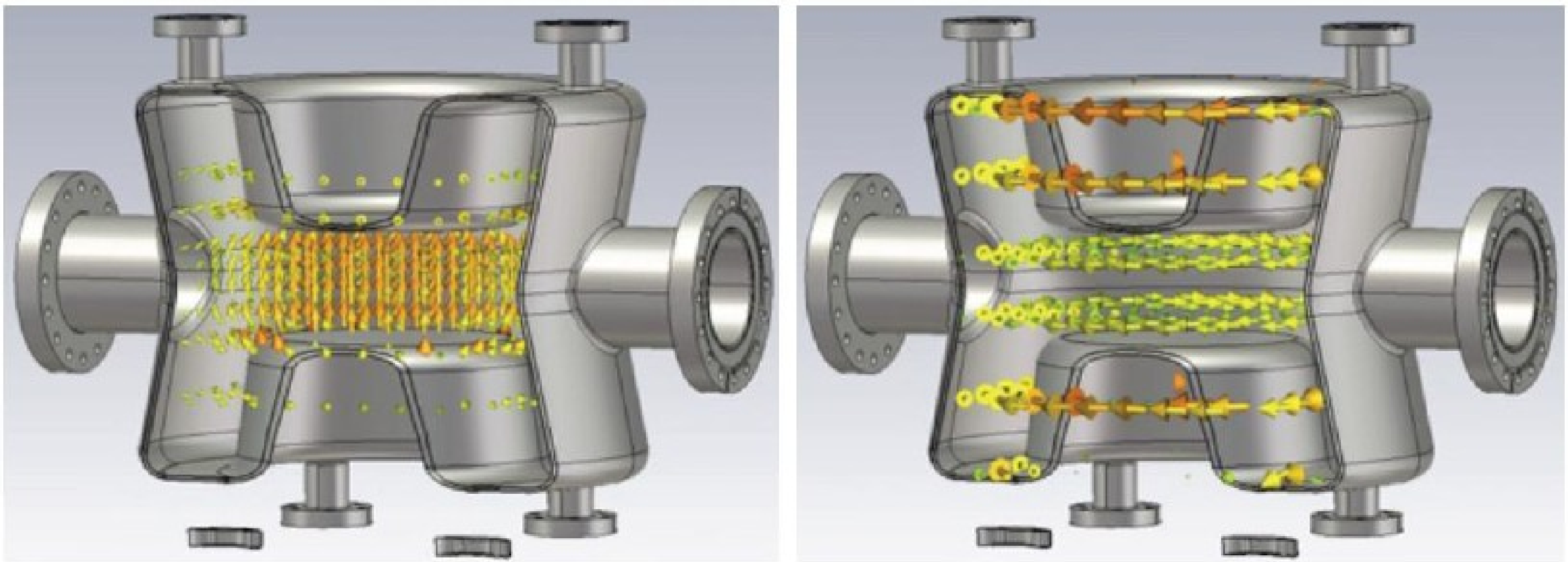
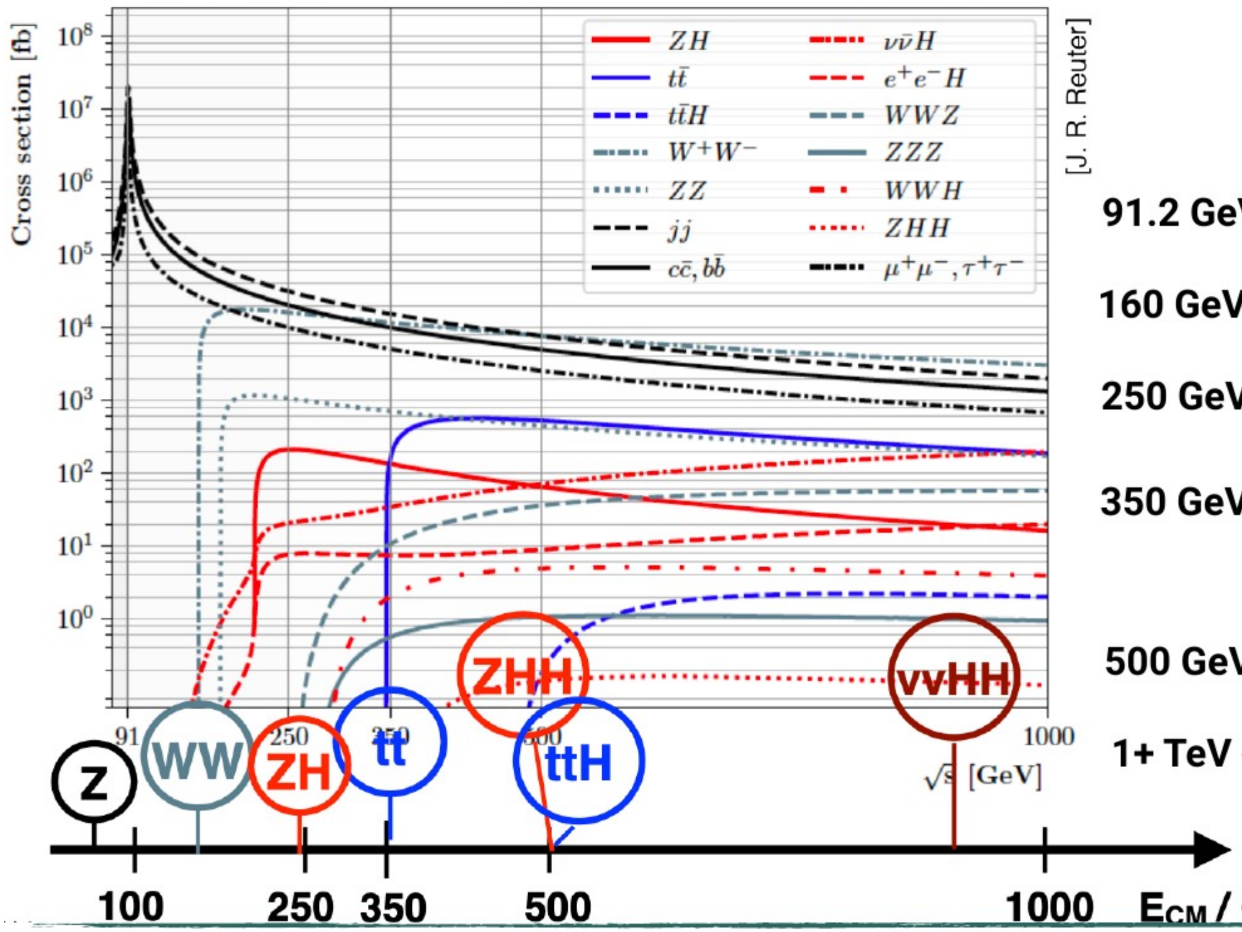


Figure 4. Electric (left) and magnetic (right) field distributions inside the DQWCC.

Perspectives of Energy

Bringing together physics goals and collider energy



Thresholds and cross sections set collider energy targets:

91.2 GeV - The Z pole

160 GeV - The WW threshold

Precision electroweak, Flavour, QCD, ...

250 GeV - The ZH maximum

Higgs properties & couplings

350 GeV - The top threshold, VBF Higgs production

Top properties, Top as probe

500 GeV - ttH, ZHH

Direct top Yukawa Higgs selfcoupling

1+ TeV - VBF double Higgs

Search at the energy frontier

The International Linear Collider

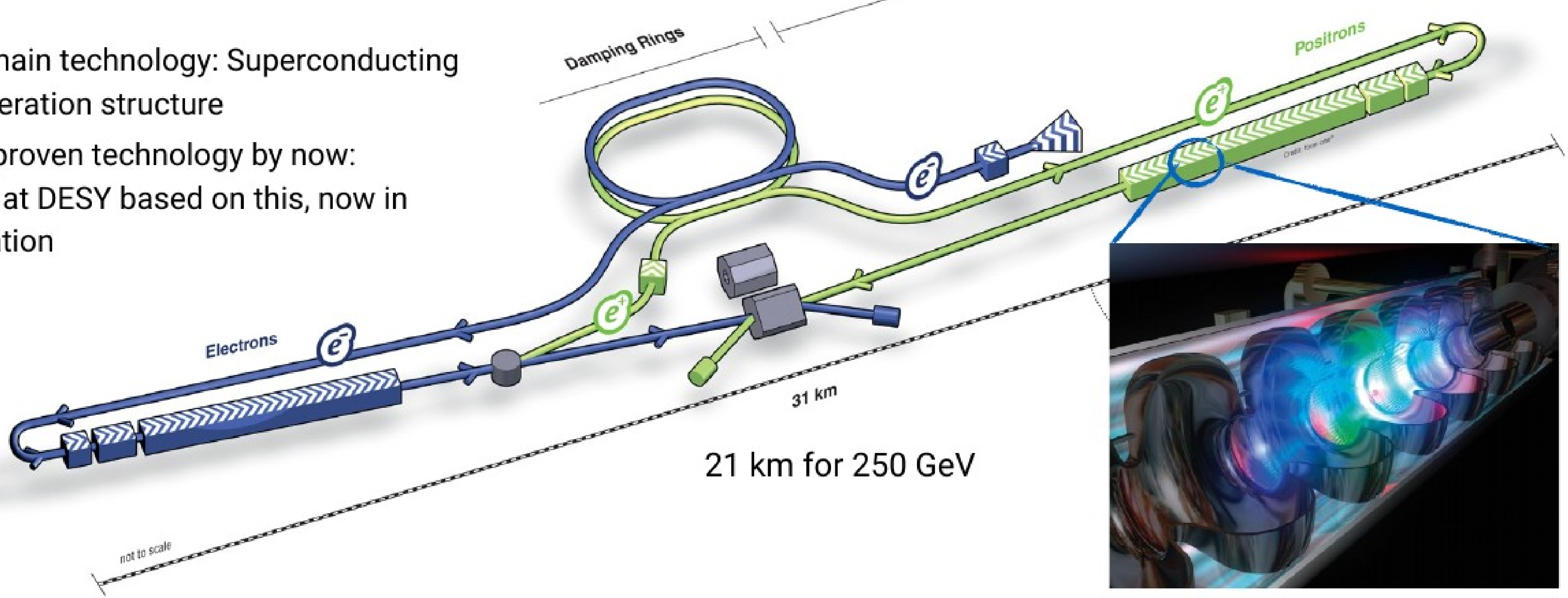
e^+e^- Collider - Construction in Japan?

MAX-PLANCK-INSTITUT FÜR PHYSIK

ILC in Japan: A linear e^+e^- collider at 250 GeV, upgradeable to 500 GeV - perspectives to 1+ TeV

- Established technology - but no decision (yet)

- The main technology: Superconducting acceleration structure
- Well-proven technology by now: XFEL at DESY based on this, now in operation



FUTURE CIRCULAR COLLIDERS

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

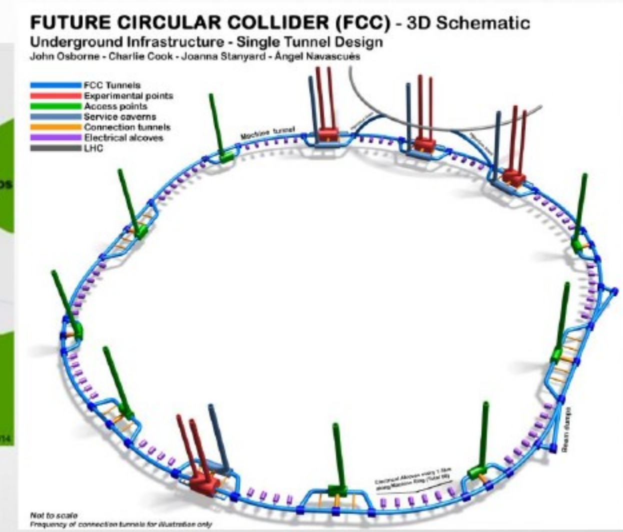
- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements
- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e^- from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

CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

Summary documents provided to EPPSU SG

- **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
- Accessible on http://fcc-cdr.web.cern.ch/

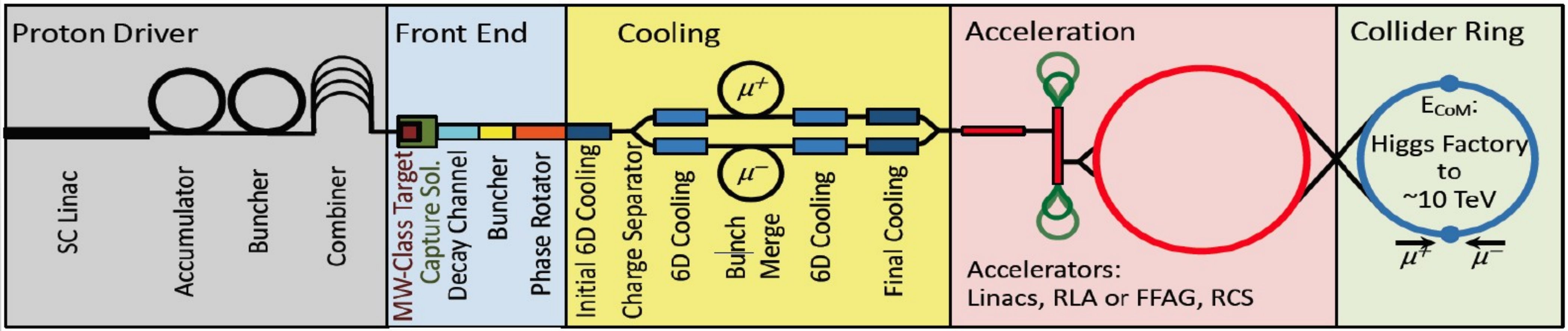
Cost: ~28.6 BCHF
Power: ~580 MW (hh) ≤ 340 MW (ee)



	LHC	HL-LHC	FCC-hh Initial	FCC-hh Ultimate
c.m. Energy [TeV]	14		100	
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	< 30.0
Optimum integrated lumi / day [fb^{-1}]	0.47	2.8	2.2	8
Circumference [km]	26.7		97.75	
Arc filling factor	0.79		0.8	
Straight sections	8×528		6×1400 m $+ 2 \times 2800$ m	
Number of IPs	$2+2$		$2+2$	
Injection energy [TeV]	0.45		3.3	

MOUNS COLLIDER SCHEME

Would be easy if the muons did not decay: lifetime is $\tau = \gamma \times 2.2\ \mu s$



Short, intense proton bunch

Protons produce pions which decay into muons
muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Barbara Dalena CERN Summer Students Lectures 28/7/2022 27

Conclusions and outlook

- Elementary particle physics is in very exciting period indeed !
  - LHC Runs 1 and w were very successful !!
  - At the moment preparing for Run 3, hopefully early 2022
  - Long-term future of particle physics at CERN is bright !!!!

Slides that were not good enough to make it in to the talk

LHC - 2015

- Target energy: 6.5 TeV
  - to be confirmed at end of powering tests!!!
- Bunch spacing: 25 ns
  - strongly favored by experiments (pile-up limit around 50)
- Beta* in ATLAS and CMS: 80 to 40 cm

Energy

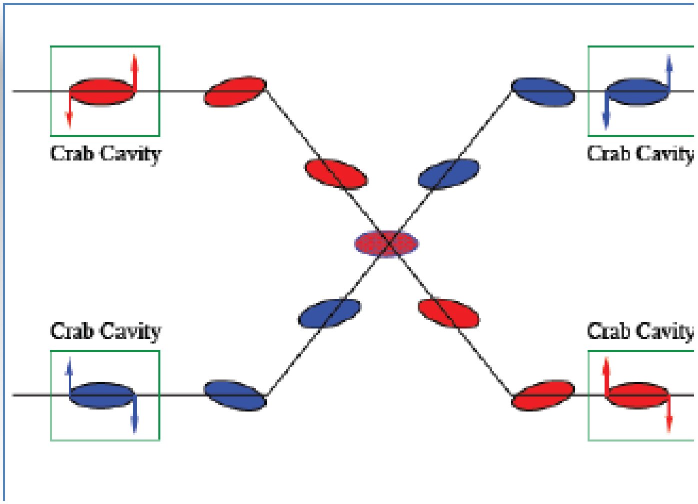
- Lower quench margins
- Lower tolerance to beam loss
- Lower intensity set-up beams
- Hardware closer to maximum (beam dumps, power converters etc.)

25 ns

- Electron-cloud
- UFOs
- More long range collisions
- Larger crossing angle, higher beta*
- Higher total beam current
- Higher intensity per injection

How?

- Beam from injectors
  - High bunch population, low emittance, 25 ns beam
- Lower beta* (~15 cm)
  - New inner triplet magnets - wide aperture Nb_3Sn
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- Crossing angle compensation
  - Crab cavities
- Dealing with the regime
  - Collision debris, high radiation
  - High machine availability
  - Beam stability, losses etc.



HL-LHC: key 25 ns parameters

Protons per bunch	2.2×10^{11}
Number of bunches	2750
Normalized emittance	2.5 micron
Beta*	15 cm
Crossing angle	590 microrad
Geometric reduction factor	0.305
Virtual luminosity	2.4×10^{35} cm^{-2}s^{-1}
Levelled luminosity	5×10^{34} cm^{-2}s^{-1}
Levelled <pile-up>	140

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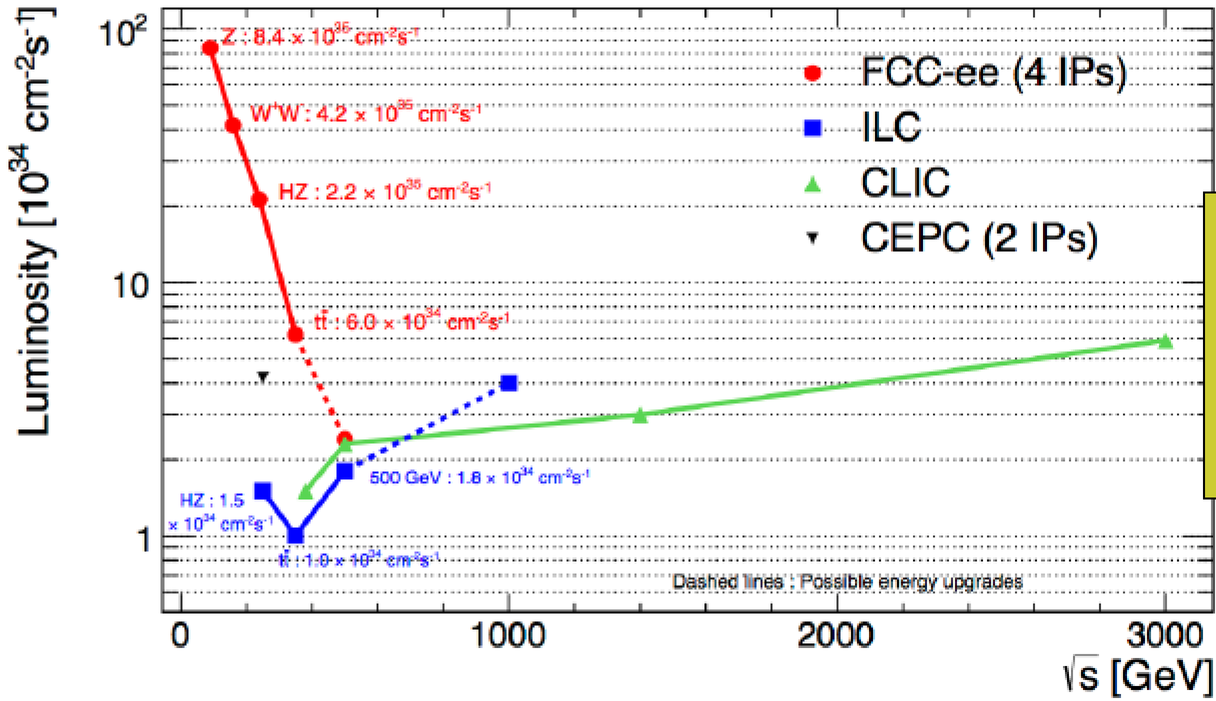
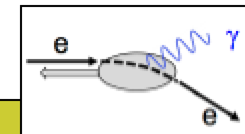
Future e^+e^- colliders

$\sqrt{s}$ (GeV)	Main physics goals
90	Z-pole precision EW measurements beyond LEP, SLC
160	WW precision physics (mass at threshold)
250	H precision physics (HZ)
~350	H (HZ, Hνν) and top (mass, couplings) precision physics
500-3000	ttH, HH (self-couplings), direct searches for new physics





Linear:
- Larger $\sqrt{s}$ reach
- Low repetition rate
  - → L from nm size beams
  - → large beamstrahlung
  - → larger E-spread
- Long. polarization easier

Circular:
- $\sqrt{s}$ limited by SR ~ E^4_{beam}/R
- Large number of circulating bunches → high L (increases at lower $\sqrt{s}$ as less SR → spare RF power used to accelerate more bunches). Note: need top-up injection ring to compensate fast L burn-off (lifetime ~ 30′)
- Several interaction regions possible
- Precise E-beam measurement from resonant depolarization

Searches for physics beyond SM

Haven't found anything, but keep searching ...

Structure of the proton II

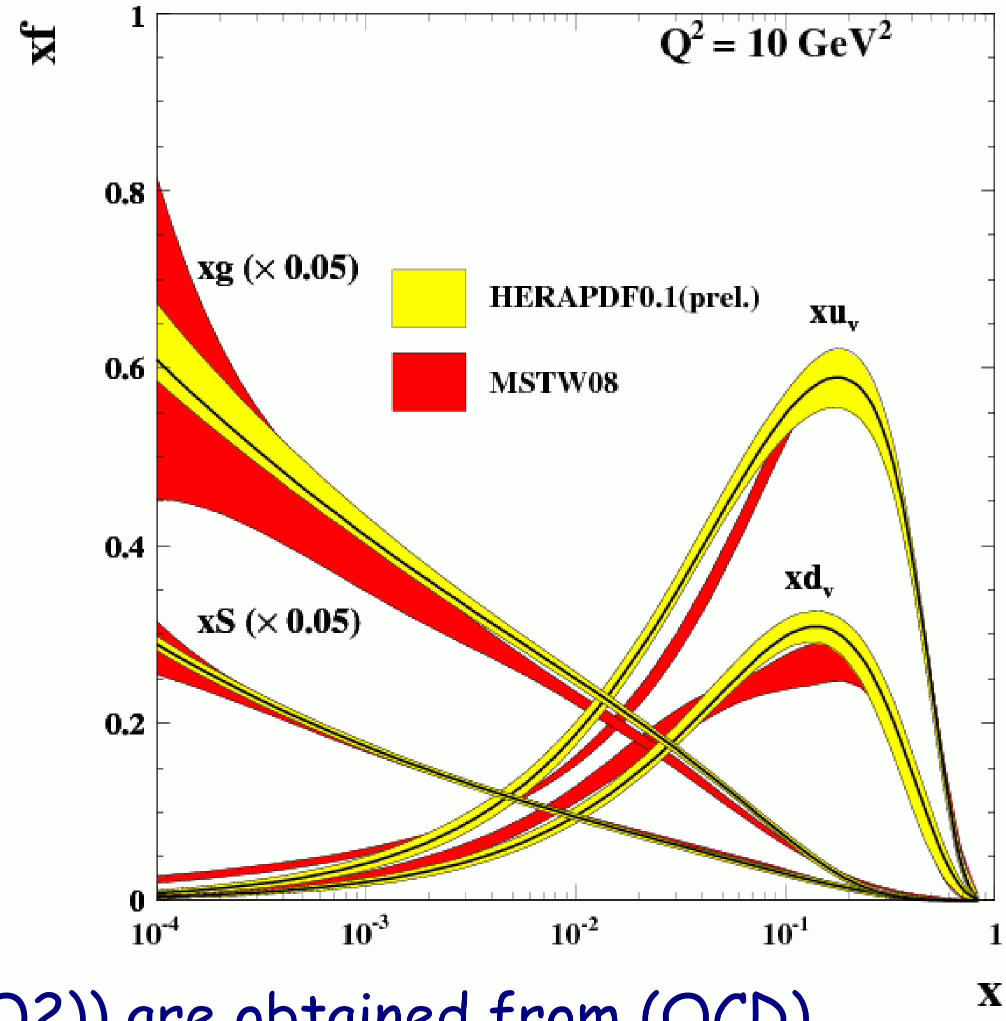
Inclusive DIS cross section:

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

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

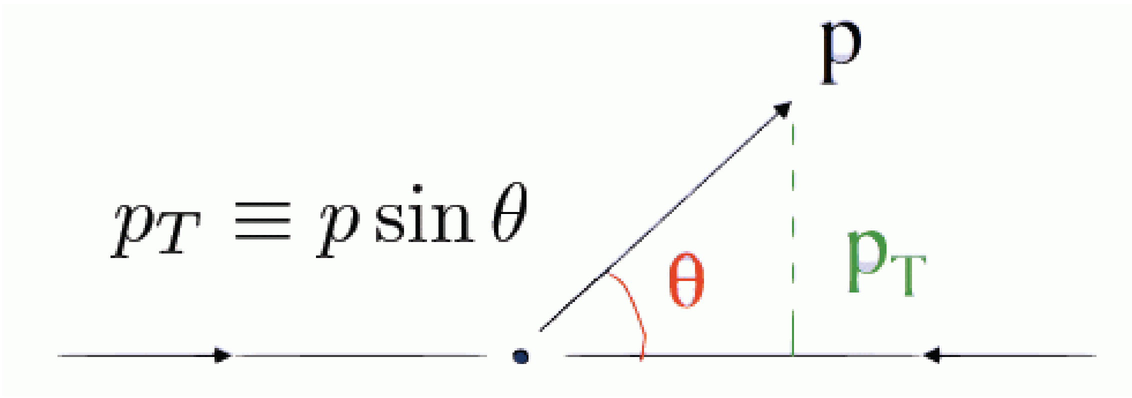
In Leading Order:

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



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:

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

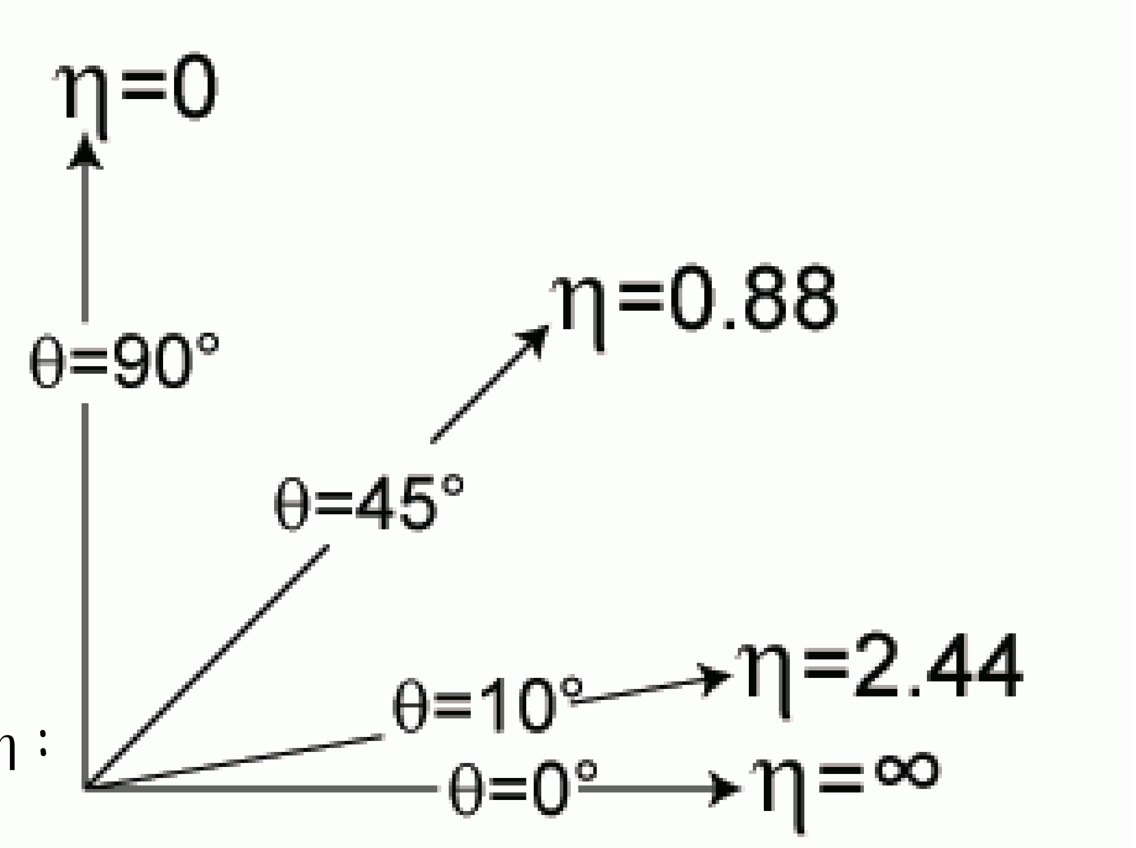
- Rapidity interval Δy and P_T are invariant with respect to Lorentz boosts along beam direction!

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

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

- 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 14 TeV requires x=0.007
- To produce mass of 5 TeV requires x = 0.36

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

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

$$\longrightarrow$$

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

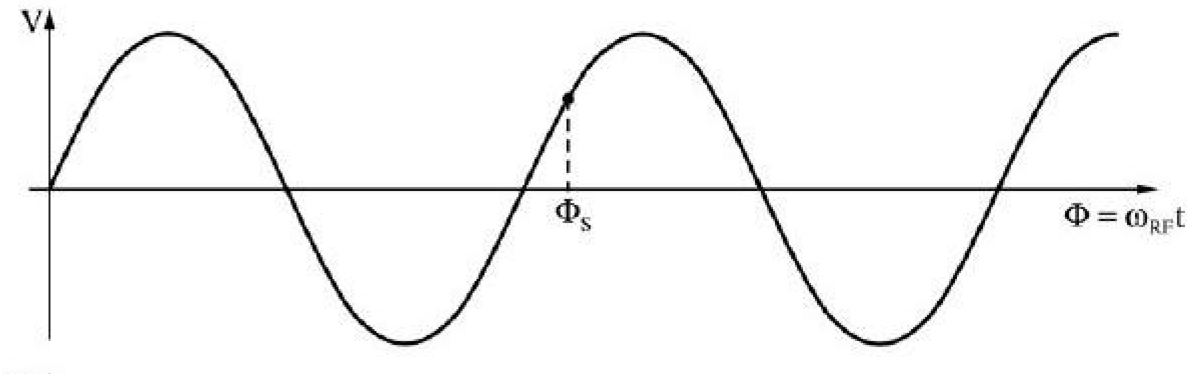
$$x_2 = \left[\frac{M}{\sqrt{s}}\right]\exp(-y_M)$$

- 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

A consequence of phase stability

Longitudinal stability – particle that comes earlier gets accelerated less:

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

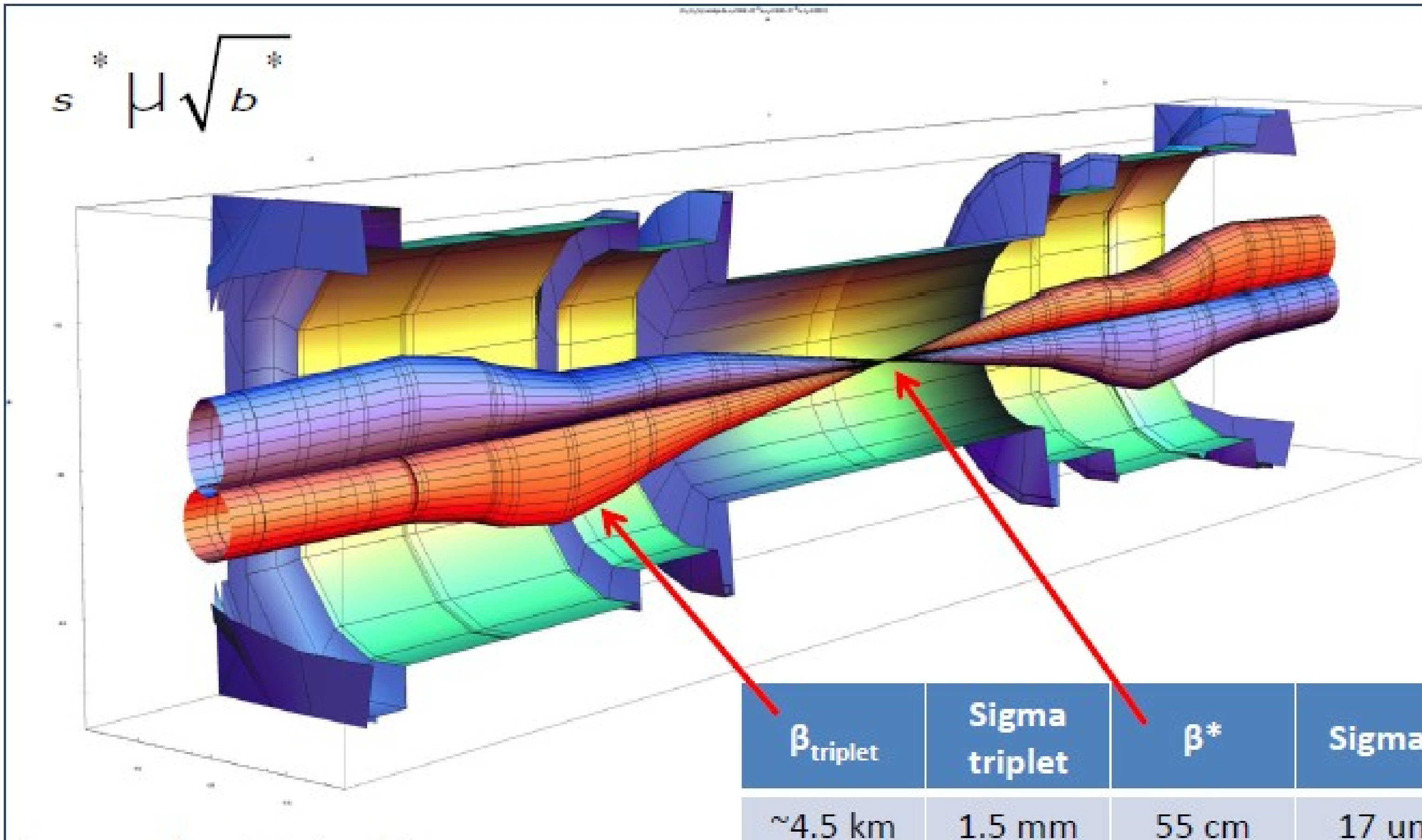


$$\nabla . \vec{E} = 0 \quad \Rightarrow \quad \frac{\partial E_x}{\partial x} + \frac{\partial E_z}{\partial z} = 0 \quad \Rightarrow \quad \frac{\partial E_x}{\partial x} > 0$$

- Maxwell equations show that this leads to de-focusing in transverse direction...
- Want to keep beam profile small, too ...
- Need some magnets ...

Squeeze in ATLAS

- Lower beta* implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- Aperture concerns dictate caution



$\beta_{triplet}$	Sigma triplet	β^*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

Image courtesy John Jowett

Requirement: Lorentz force increases as a function of distance from design trajectory

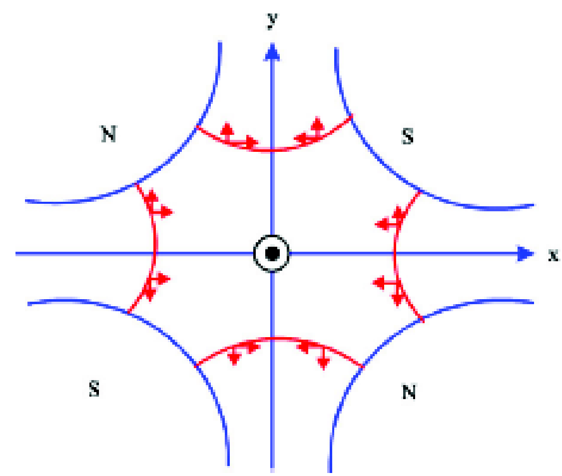
E.g. in the horizontal plane

$$F(x) = q \cdot v \cdot B(x)$$

We want a magnetic field that

$$B_y = g \cdot x \qquad B_x = g \cdot y$$

➔ Quadrupole magnet



The red arrows show the direction of the force on the particle

Gradient of quadrupole

$$g = \frac{2\mu_0 n I}{r^2} \left[\frac{T}{m}\right]$$

Normalized gradient, focusing strength

$$k = \frac{g}{p/q} \left[m^{-2}\right]$$

The emittance at LHC injection energy 450 GeV: ε = 7.3 nm

At 7 TeV: ε = 0.5 nm

$$\varepsilon_{7TeV} = \varepsilon_{450GeV} \frac{\gamma_{450GeV}}{\gamma_{7TeV}}$$

Normalized emittance: ε^* = 3.5 μm

Normalized emittance preserved during acceleration.

And for the beam sizes:

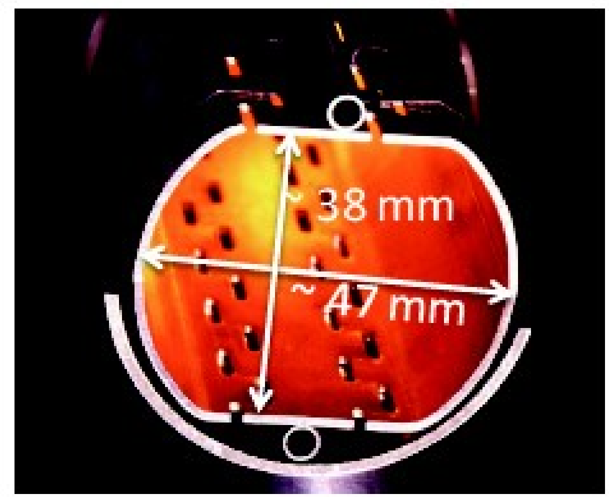
At the location with the maximum beta function (β_{max} = 180 m):

σ_{450GeV} = 1.1 mm

σ_{7TeV} = 300 μm

Aperture requirement: a > 10 σ

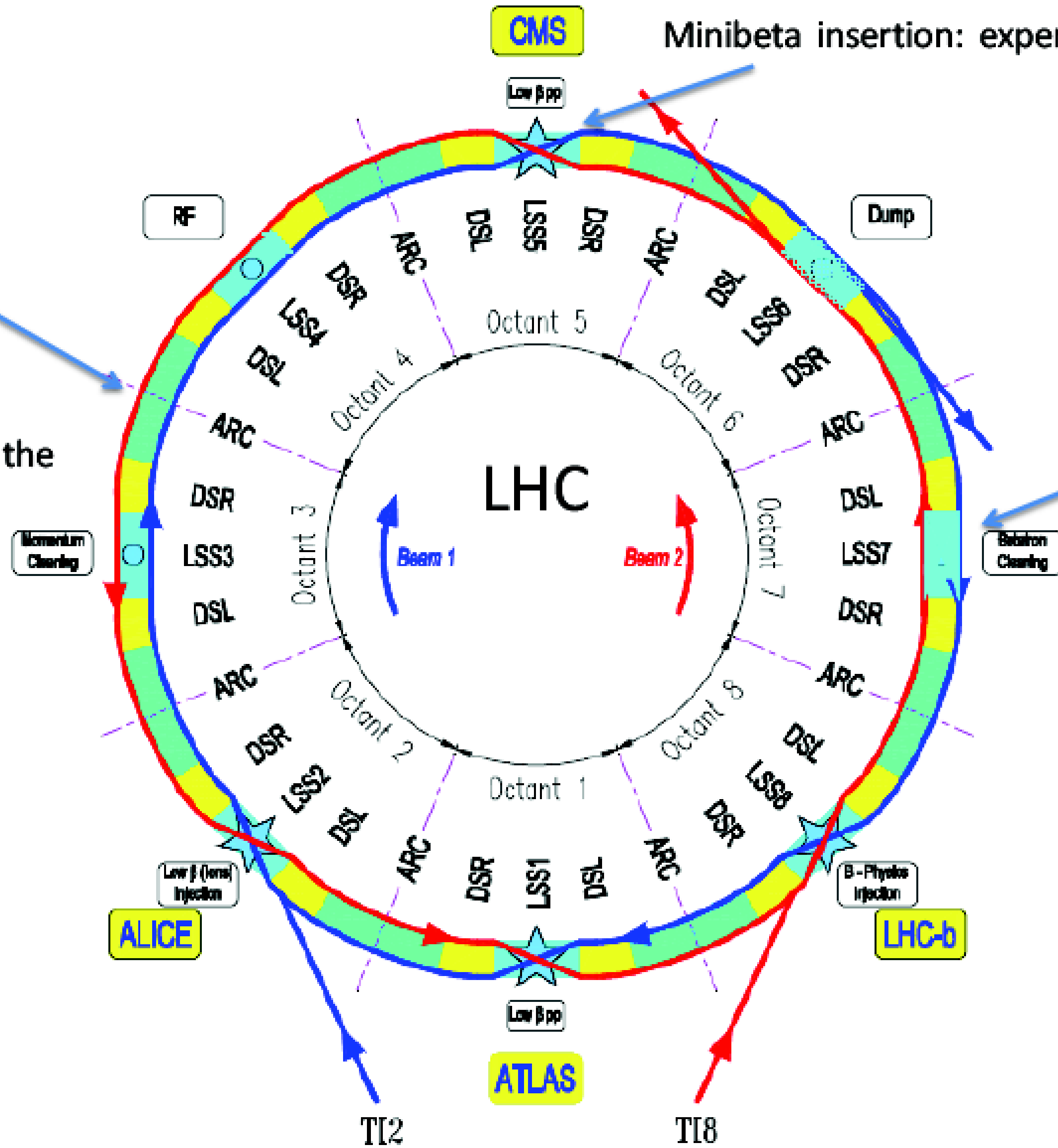
Vertical plane: 19 mm ~ 16 σ @ 450 GeV



Minibeta insertion: experiment insertion

LHC arc:
Regular FODO
structure

All dipoles,
all QF and QD the
same strength

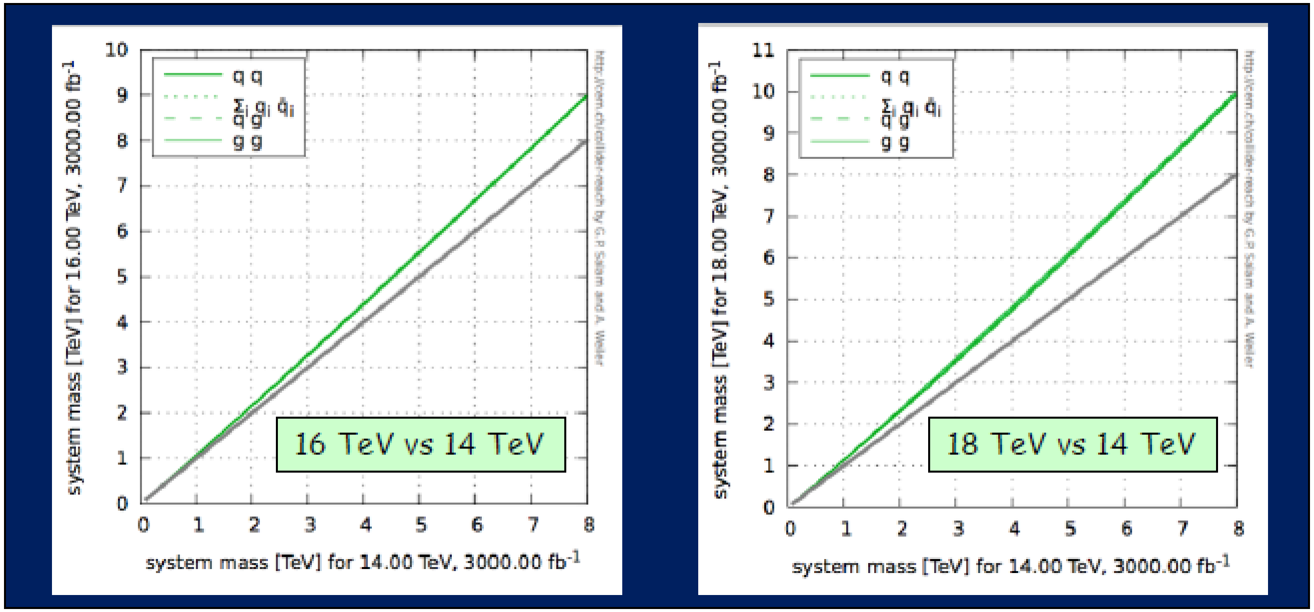


Insertions:
Long straight
sections

Focusing
adjusted for
particular
optics
requirements

High Energy LHC???

Higher √s in the LHC tunnel ?



Various options, with increasing amount of HW changes, technical challenges, cost, and physics reach

1) Pushing present dipoles to ultimate performance (→ √s ~15.5 TeV ?)
2) 1) + replacing 30% of present dipoles with higher-field magnets:
   B=11 T → √s ~ 16.5 TeV
   B=14 T → √s ~ 18.5 TeV

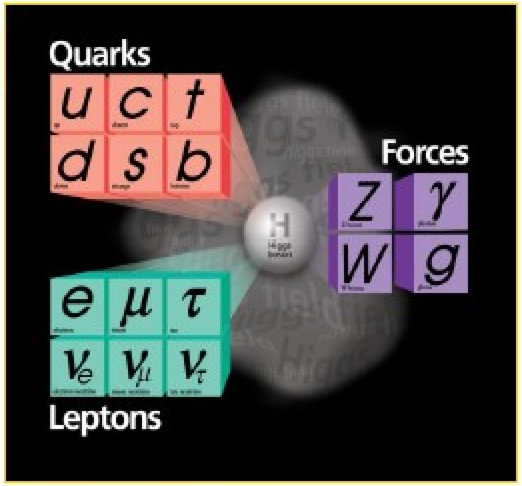
❑ HE-LHC: filling existing 16-20 T magnets → √s = 26-33 TeV
-- strongly motivated if new physics discovered at the LHC/HL-LHC
-- demonstration of technology in view of future higher-E pp colliders
-- would capitalize on existing tunnel and infrastructure
-- magnets might be reused in a bigger tunnel ??

These options are being studied (physics case, technical feasibility, cost, time scale) in time for next round of European Strategy (~2018/2019)

F. Giano

Standard model and its problems

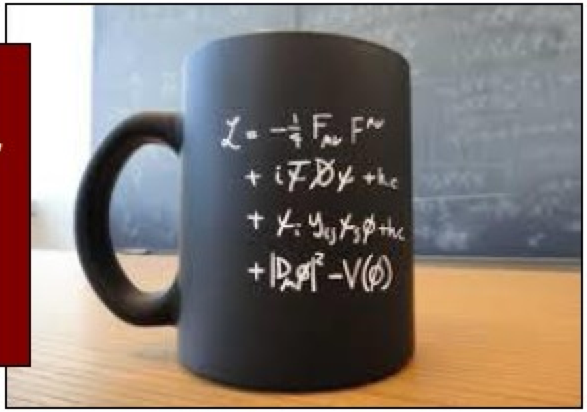
What did we accomplish so far in particle physics ?



With the discovery of the Higgs boson,
we have completed the Standard Model
(> 50 years of theoretical and experimental efforts !)

Note: fermions (c, b, t, τ) discovered at accelerators in the US, bosons (g, W, Z, H) in Europe …

We have tested the Standard Model with very high precision (wealth of measurements since early '60s, in particular at accelerators)
→ it works BEAUTIFULLY (puzzling …)
→ no significant deviations observed (but difficult to accommodate non-zero neutrino masses)



However: SM is not a complete theory of particle physics, as several outstanding questions remain (raised also by precise experimental observations) that cannot be explained within the SM.

These questions require NEW PHYSICS

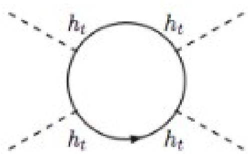
F. Gianotti, CERN,

2

But, can λ become negative? Yes, two main competing effects:

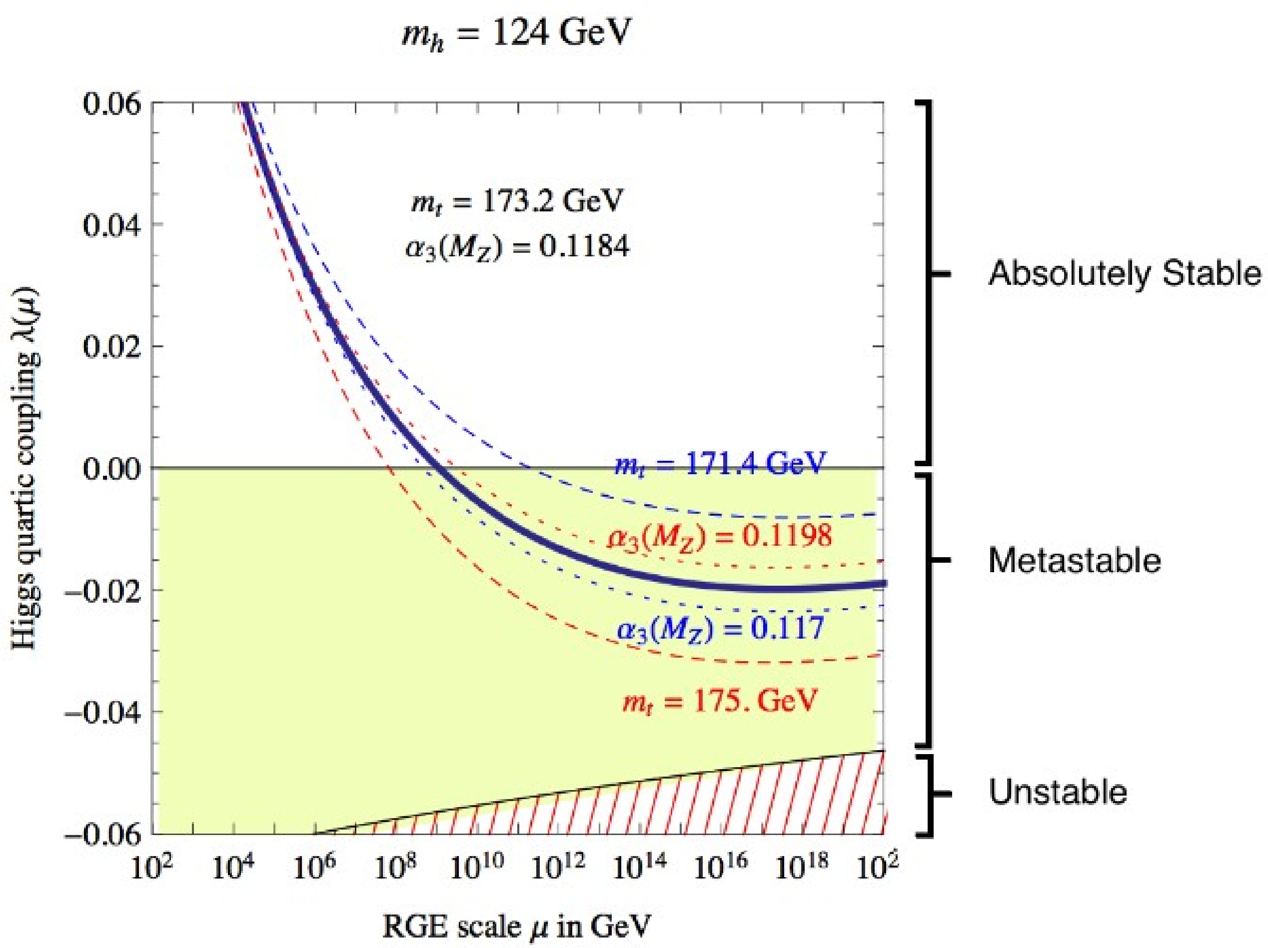
$$\mu \frac{d\lambda(\mu)}{d\log(\mu)} = (\# \lambda^2 + \ldots - \# h_t^4 + \ldots) + \ldots$$

- 

, makes λ grow
- 

, makes λ decrease.

$h_t(v) = \sqrt{2} M_t / v$ and $\lambda(v) = M_h^2/(2v^2)$.



J.EM, J. Espinosa, G.F. Giudice, G. Isidori, A. Riotto, A. Strumia. [hep/1112.3022]

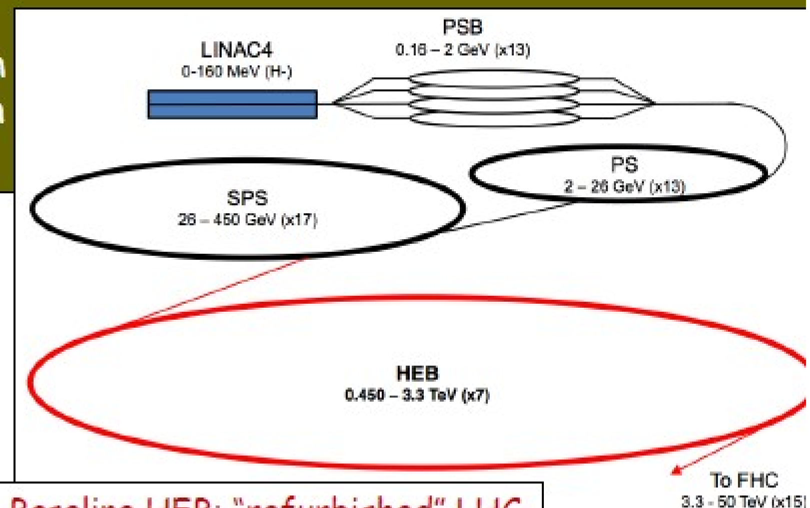
Circular colliders: the CERN FCC project

International conceptual design study for Future Circular Colliders in a ~100 km ring:

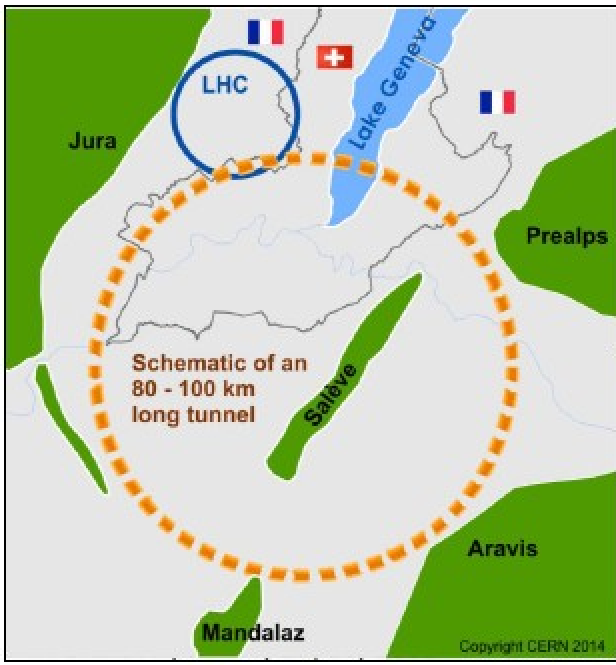
- goal: pp, $\sqrt{s}$ = 100 TeV (FCC-hh), L~2x10^{35}; 4 IP
- possible intermediate step: e^+e^-, $\sqrt{s}$=90-350 GeV (FCC-ee), L=2x10^{36}-2x10^{34}, 2-4 IP
- option: ep, $\sqrt{s}$= 3.5 TeV (FCC-eh), L~10^{34}

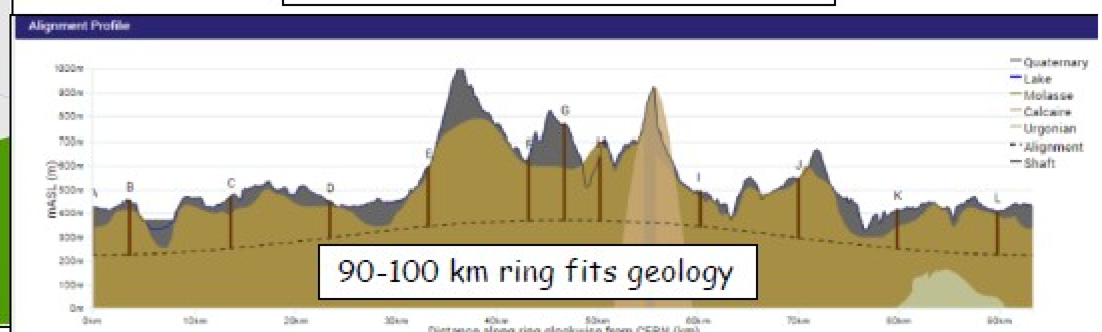
Goal of the study: CDR in ~2018

Machine studies are site-neutral.
However, FCC at CERN would greatly benefit from existing infrastructure (e.g. FCC-hh injector chain would be based on existing accelerator complex)



Baseline HEB: "refurbished" LHC





2020 Strategy Update

European Strategy Update

Preamble

- Many mysteries about the universe remain to be explored: **nature of dark matter, preponderance of matter over antimatter, origin and pattern of neutrino masses**
- Nature hides the secrets of the fundamental physical laws in the **tiniest nooks of space and time**
- Particle Physics develops technologies to probe ever smaller distance scales (higher energies)
- **The Higgs** (discovered at the LHC) is a **unique particle** that raises profound questions about the fundamental laws of nature
  - ✓ Higgs properties study is in itself a powerful experimental tool to look for answers
    → **electron-positron collider as Higgs factory**
  - ✓ Higgs boson pair-production study is key to understanding the fabric of the universe
    → **collider with significantly higher energies than Higgs factory**
- New realm of energies is expected to lead to new discoveries and provide answers to existing mysteries
- **The 2020 Strategy update aims to significantly extend knowledge beyond current limits, to drive innovative technological developments, to maintain Europe's leading role**

The European vision is thus to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges.

The 2020 Strategy presents exciting and ambitious scientific goals that will drive technological and scientific exploration into new and uncharted territory for the benefit of the field and of society.

2020 Strategy Statements

European Strategy Update

Guide through the statements

2 statements on **Major developments from the 2013 Strategy**
a) Focus on successful completion of HL-LHC upgrade remains a priority
b) Continued support for long-baseline experiments in Japan and US and the Neutrino Platform

3 statements on **General considerations for the 2020 update**
a) Preserve the leading role of CERN for success of European PP community
b) Strengthen the European PP ecosystem of research centres
c) Acknowledge the global nature of PP research

2 statements on **High-priority future initiatives**
a) Higgs factory as the highest-priority next collider and investigation of the technical and financial feasibility of a future hadron collider at CERN
b) Vigorous R&D on innovative accelerator technologies

Letters for itemizing the statements are introduced for identification, do not imply prioritization

4 statements on **Other essential scientific activities**
a) Support for high-impact, financially implementable, experimental initiatives world-wide
b) Acknowledge the essential role of theory
c) Support for instrumentation R&D
d) Support for computing and software infrastructure

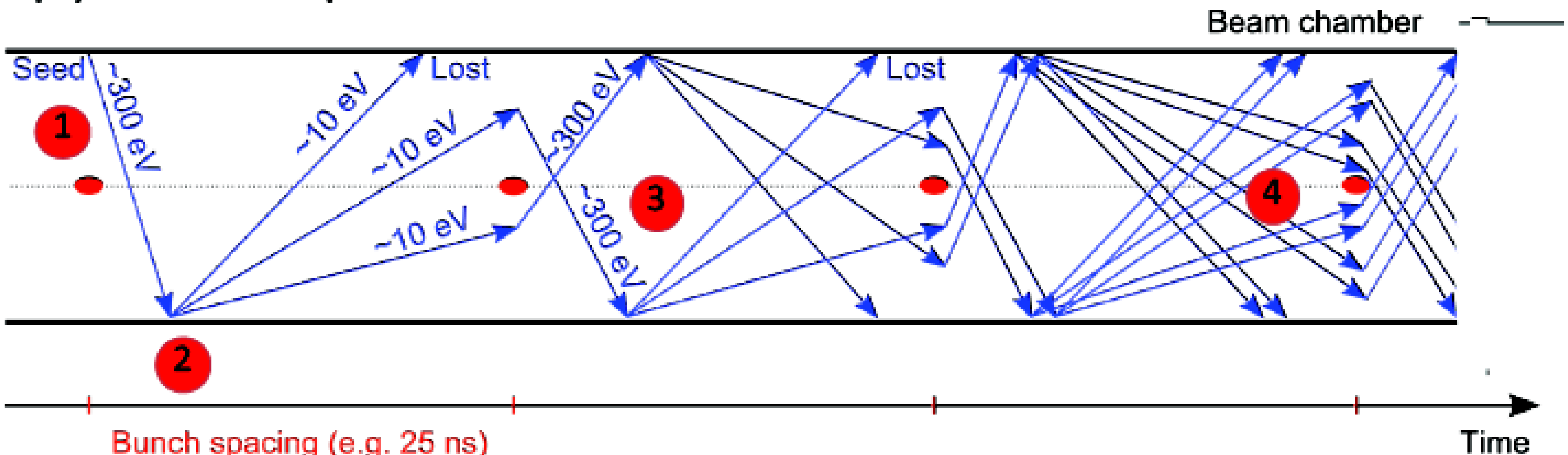
2 statements on **Synergies with neighbouring fields**
a) Nuclear physics – cooperation with NuPECC
b) Astroparticle – cooperation with APPEC

3 statements on **Organisational issues**
a) Global collaboration on projects in and out of Europe
b) Relations with European Commission
c) Open science

4 statements on **Environmental and societal impact**
a) Mitigate environmental impact of particle physics
b) Investment in next generation of researchers
c) Knowledge and technology transfer
d) Cultural heritage: public engagement, education and communication

Electron cloud – One of the LHC Challenges

In high intensity accelerators with positively charged beams and closely spaced bunches electrons liberated from vacuum chamber surface can multiply and build up a cloud of electrons.



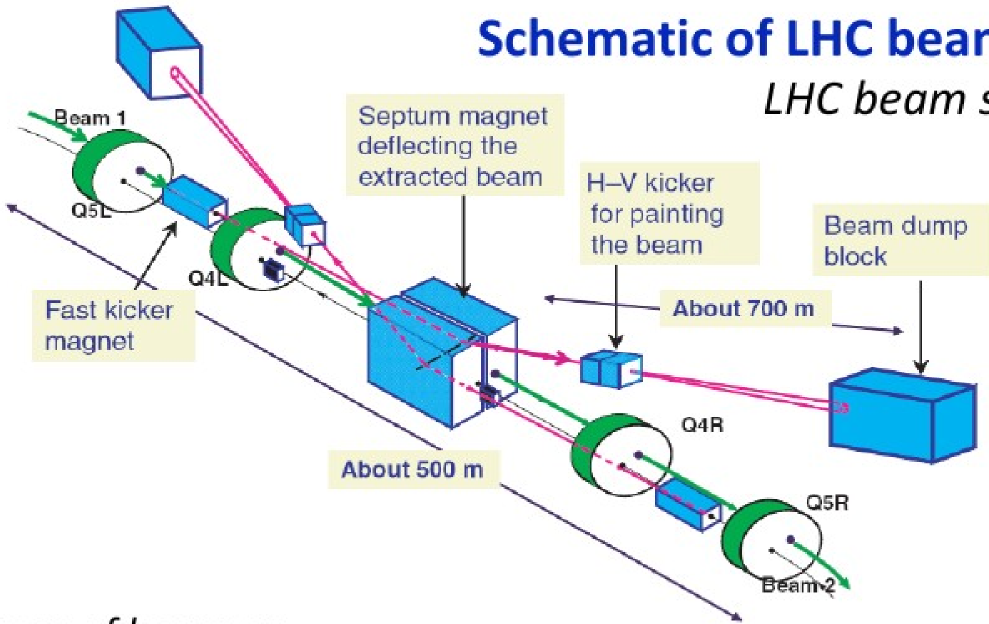
Electrons are generated through:

- Residual gas ionization
- Photo-electrons with synchrotron radiation
- Desorption from the losses on the wall

1) Seed electrons accelerated by beam
2) Produce secondary electrons when hitting chamber
3) Secondary electrons accelerated, producing more electrons on impact
4) May lead to exponential growth of electron density (multipacting)
5) Trailing bunches interact with cloud

Beam Dump – How to safely kill the LHC beam

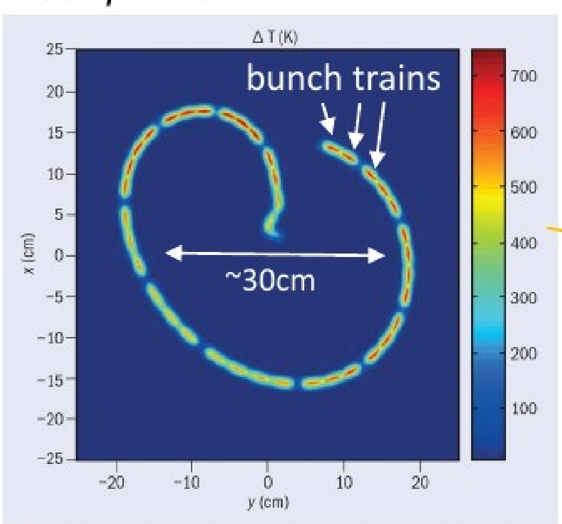
Schematic of LHC beam dump system

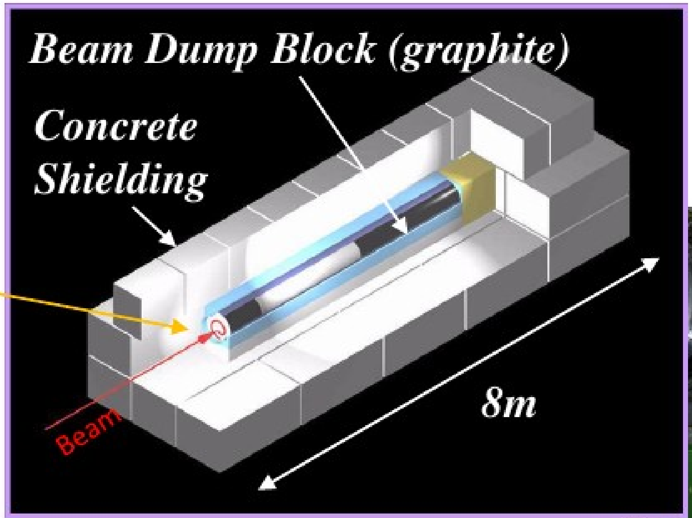


LHC beam stores beam ~360MJ energy.

Lecture on Accelerator Operation and Design Challenges by A. Lechner

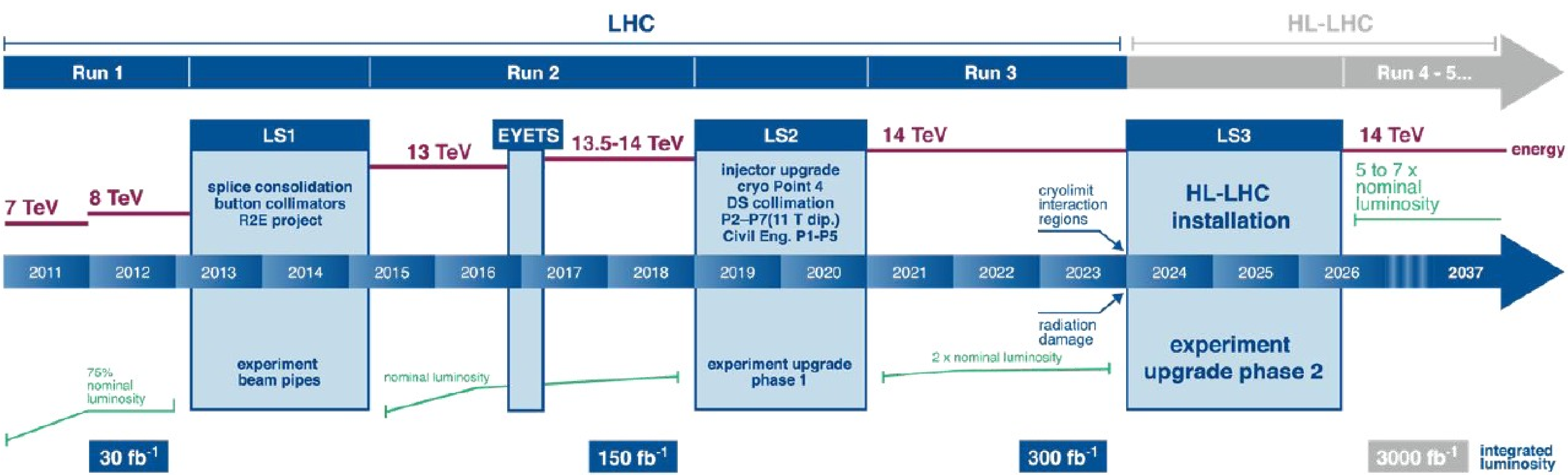
Sweep of beam on beam dump window





Source graphics: http://clipart-library.com

LHC / HL-LHC Plan



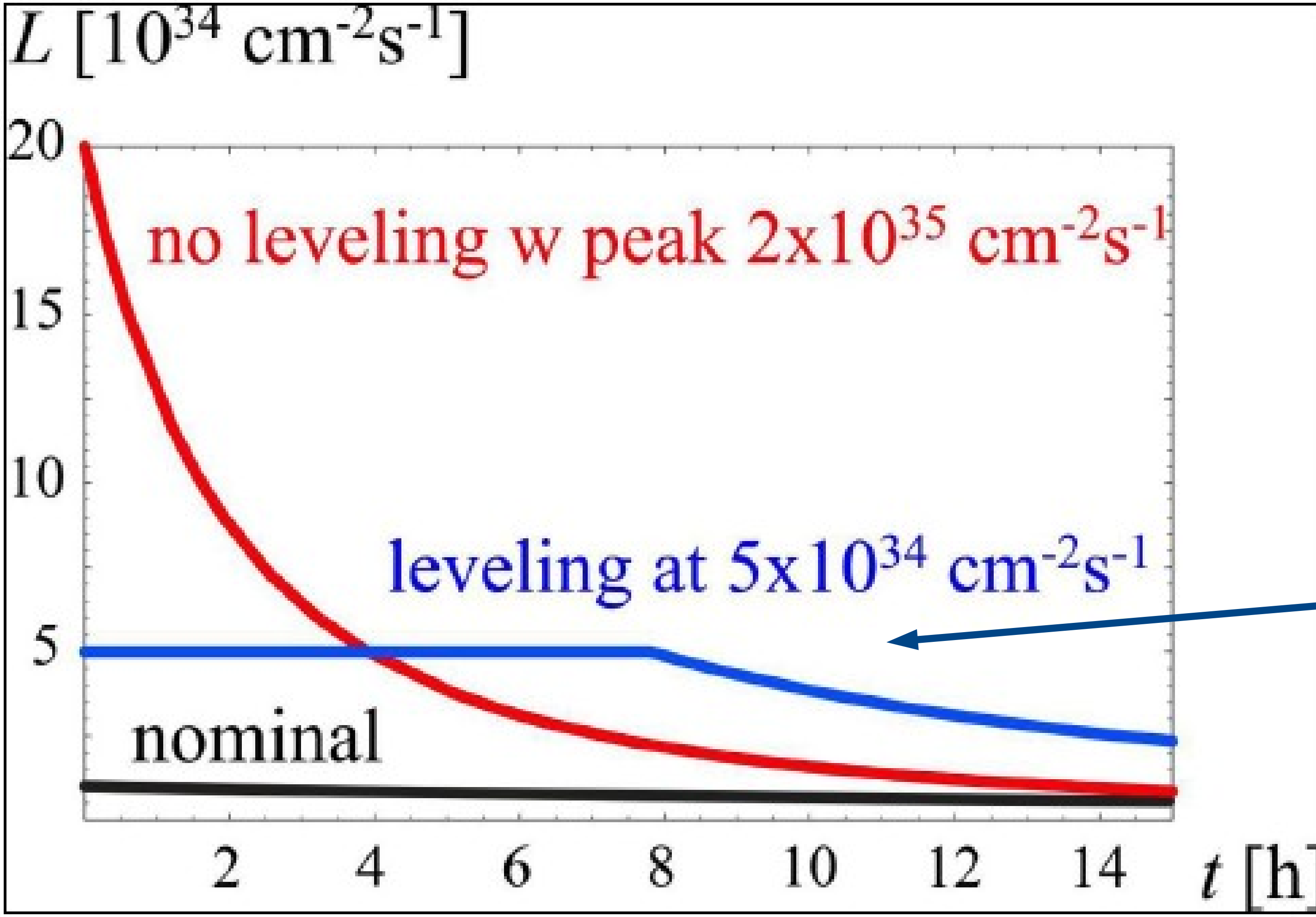
Hard squeeze ...

	2016	HL-LHC
β^*	40 cm	15 cm
Beam size at IP (sigma)	17 um	7 um
β at triplet	~4.5 km	~20 km
Beam size at triplet	1.5 mm	2.6 mm
Crossing angle	370 urad	590 urad

The reduction in beam size buys a factor of 1.6 in luminosity but:

- Bigger beams in inner triplets and so
- Larger crossing angle
- And thus larger aperture in inner triplets is required.

Luminosity leveling



~130 inelastic collisions/BC