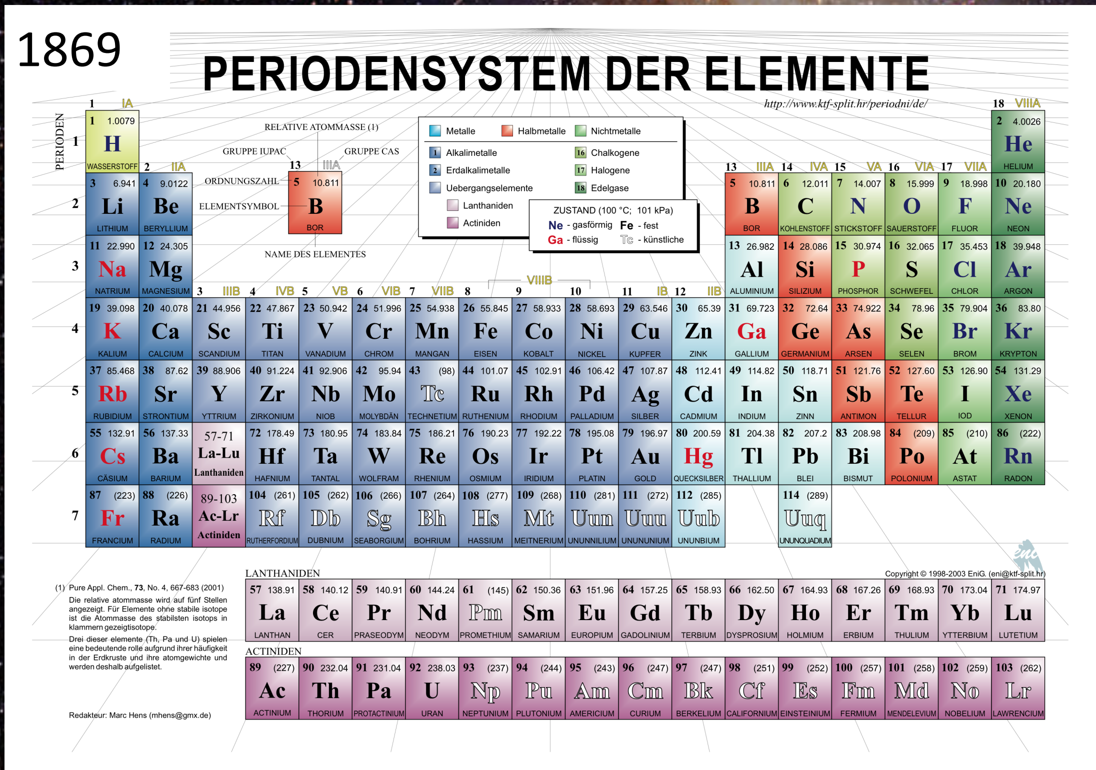
Future Accelerator Projects

Bernhard Holzer
CERN

A Short Introduction ... LOL

In the end and after all ... : We try to explain the structure of the "hadronic matter" in the Universe. In other words: What is going on up there ???

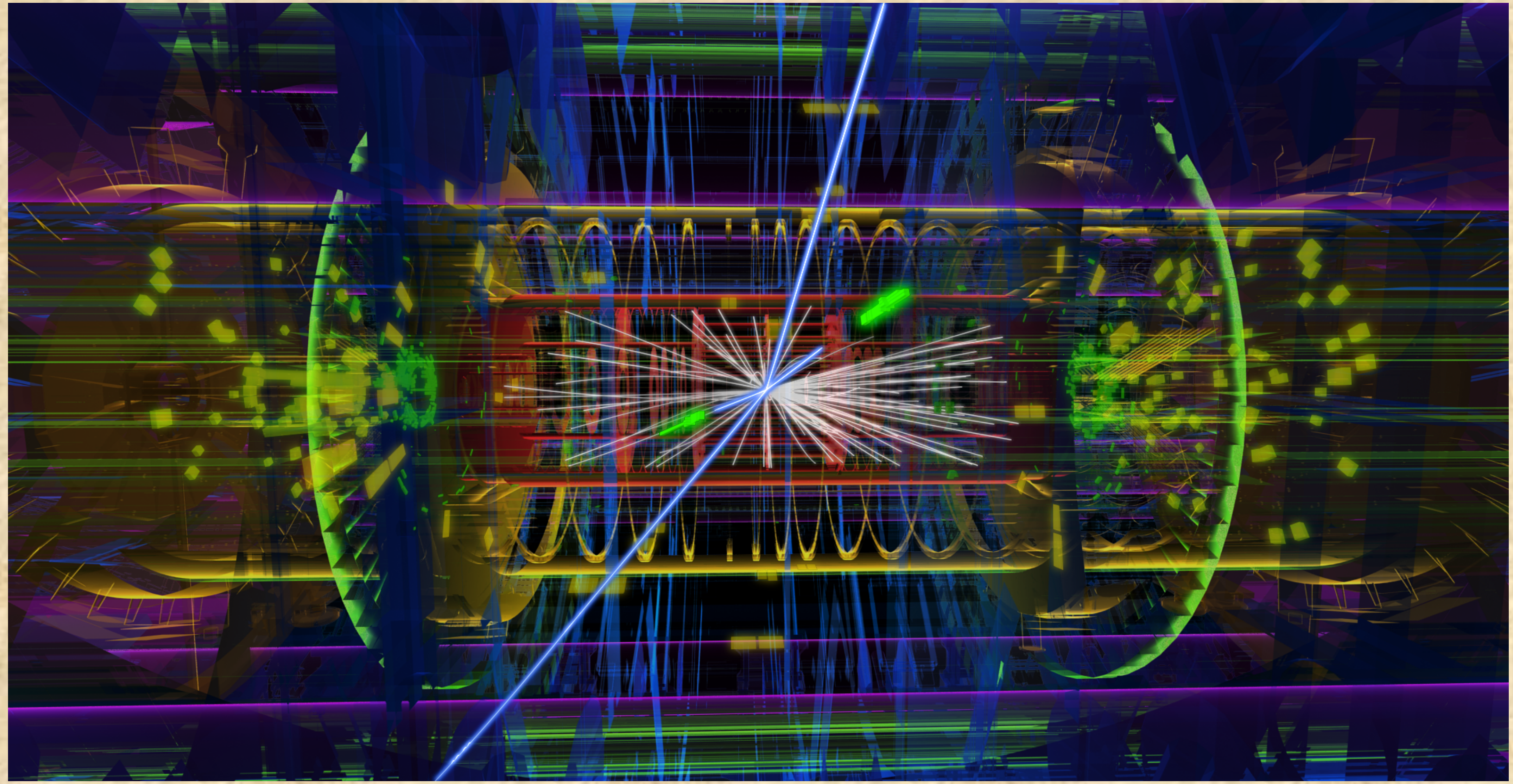


$E=mc^2$, $\lambda=h/p$

1.) Where are we ?

**** Standard Model of HEP***

**** Higgs discovery***



ATLAS event display: Higgs => two electrons & two muons

$$E = m_0c^2 = (m_{e1} + m_{e2} + m_{\mu 1} + m_{\mu 2})*c^2 = 125.4\ GeV$$

European Strategy Group
Future High Energy Frontier Colliders

Luminosity Upgrade of LHC:
HL-LHC

Circular colliders:
FCC (Future Circular Collider)
- **FCC-hh: 100 TeV proton-proton cm energy**
- **FCC-ee: 90-350 GeV lepton collider**

Linear colliders
- **ILC (International Linear Collider): e^+e^-, 500 GeV cms energy,**
- **CLIC (Compact Linear Collider): e^+e^-, 380GeV - 3TeV cms energy,**

Others
ERLs
Muon collider,
Plasma acceleration

2.) Accelerator Design in 3 Minutes

Particle Dynamics determined by the Lorentz Force

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

$$x'' + x(\frac{1}{\rho^2} + k) = 0$$

1/ρ= dipole field
k = quadrupole gradient

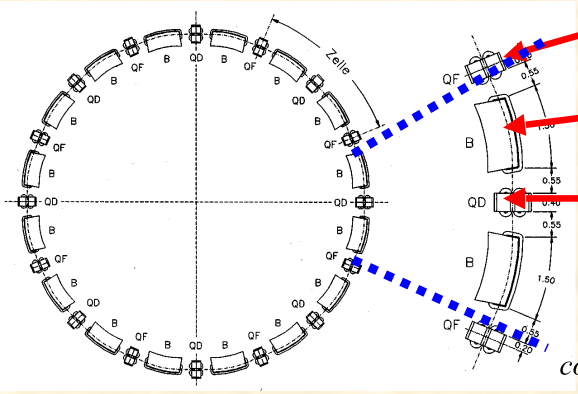
Basic idea:
create linear forces (bending & focusing)
—> harmonic oscillation

$$x(s) = x_0 \cdot \cos(\sqrt{|K|}s) + x_0' \cdot \frac{1}{\sqrt{|K|}} \sin(\sqrt{|K|}s)$$

$$x'(s) = -x_0 \cdot \sqrt{|K|} \cdot \sin(\sqrt{|K|}s) + x_0' \cdot \cos(\sqrt{|K|}s)$$

The movement of a charged particle in the “Lattice” of external magnetic fields can be described analytically.

… and corresponds - in linear fields - to a harmonic transverse oscillation.

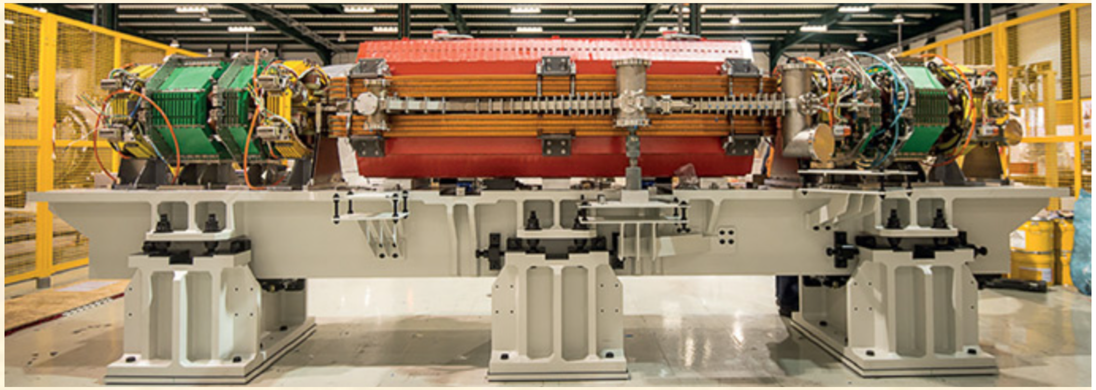


focusing lens

dipole magnet

defocusing lens

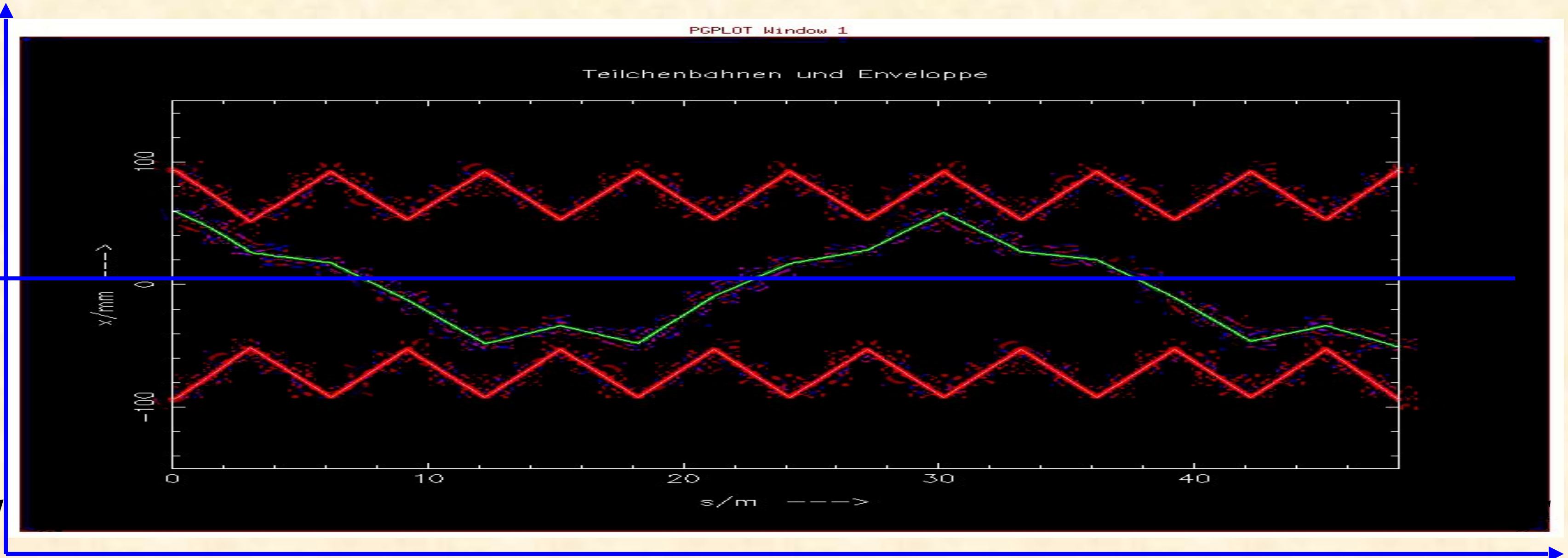
court. K. Wille



We can calculate the single particle trajectories for an arbitrary number of turns.

x(s)

0



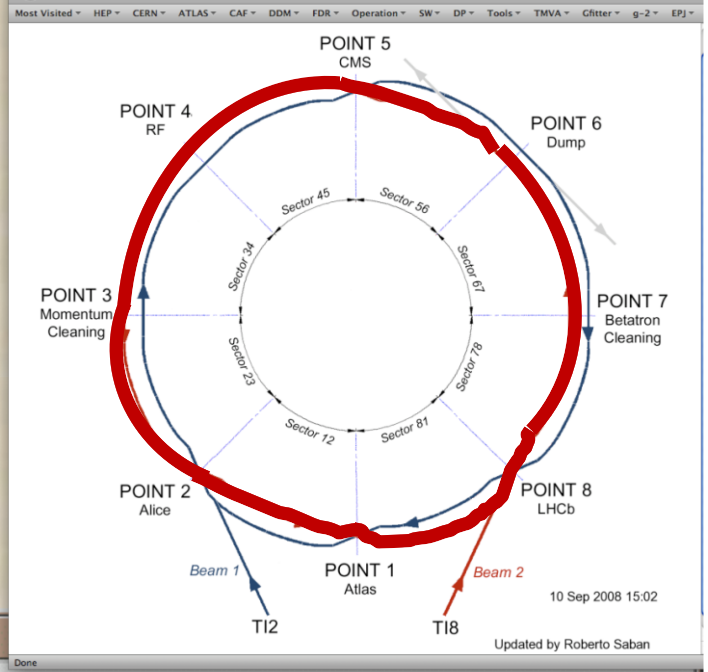
typical values in a strong foc. machine:

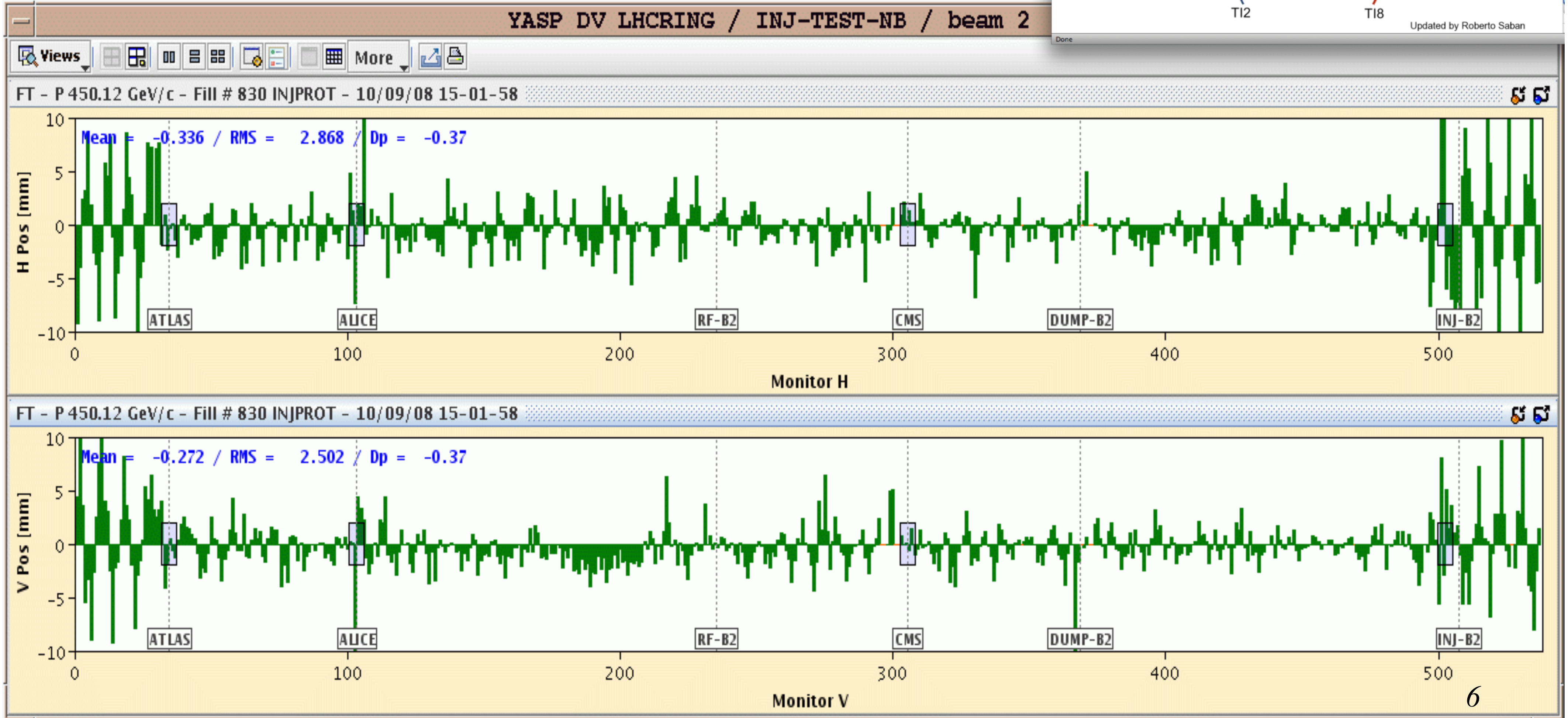
x ≈ mm, x´ ≤ mrad

LHC Operation: Beam Commissioning

First turn steering "by sector:"

- One beam at the time
- Beam through 1 sector (1/8 ring),
correct trajectory, open collimator and move on.





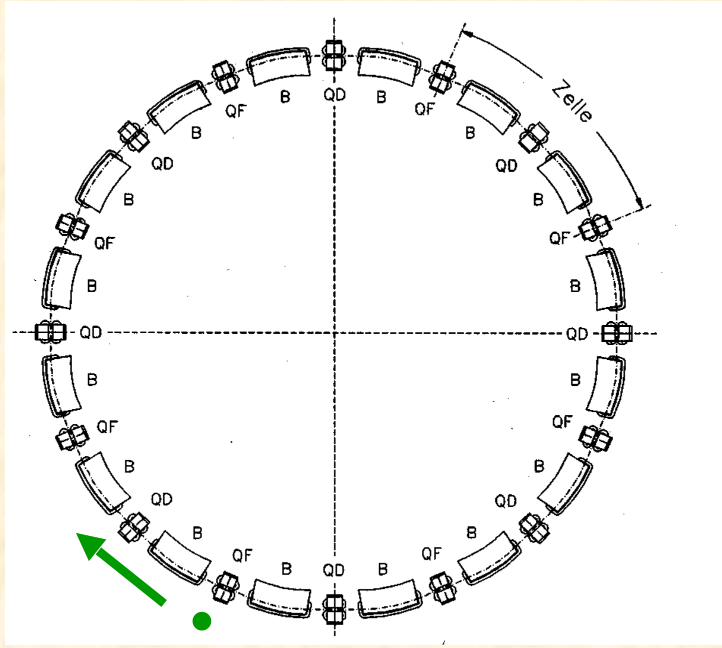
ATTENTION: its classical mechanis

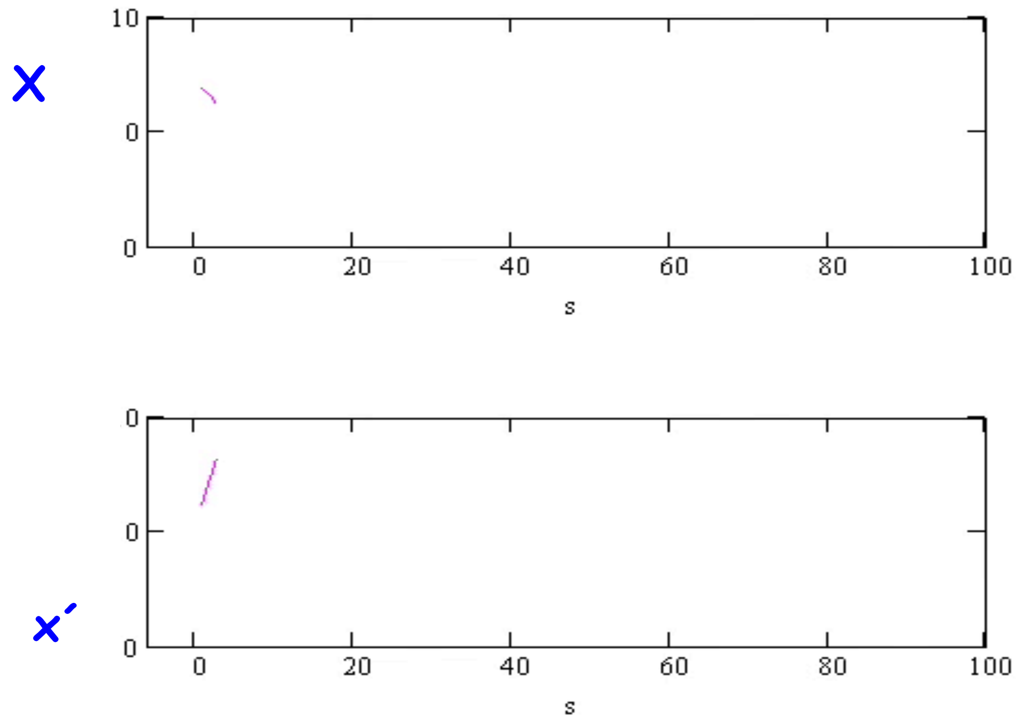
Beam Dynamics in a Storage Ring

The particle movement described in

phase space, x, x'

—> plot x, x´as a function of „s“

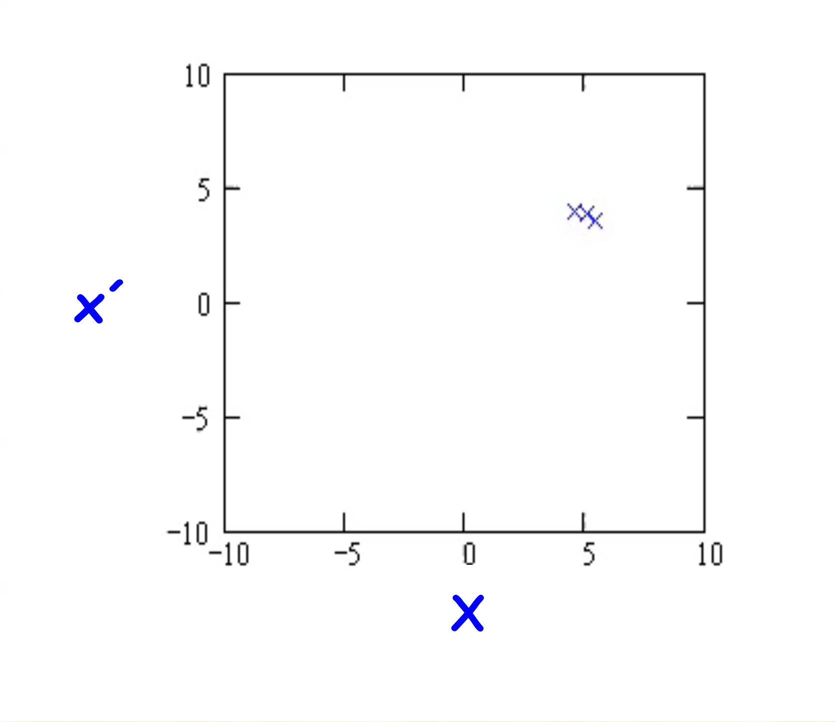




Theorem of Liouville

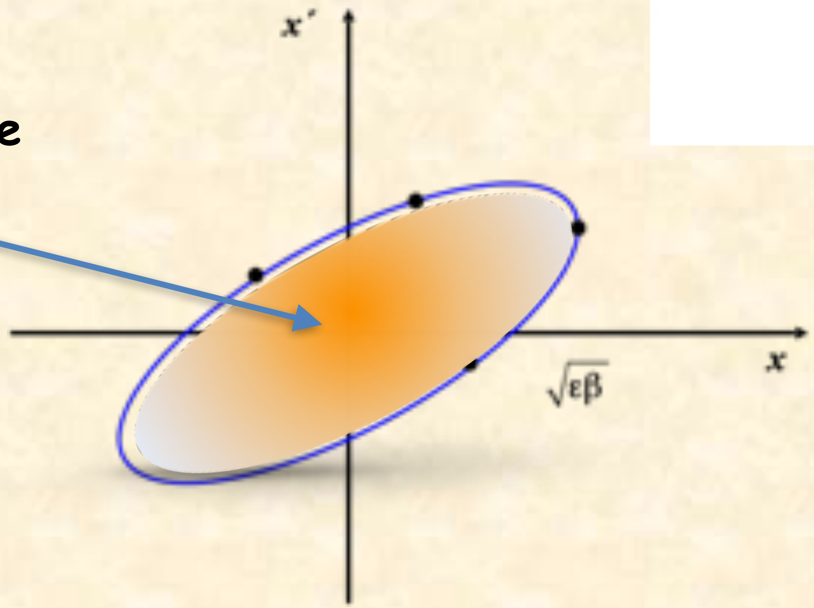
… and now the ellipse:

note for each turn x, x´at a given position „s“ and plot in the phase space diagram



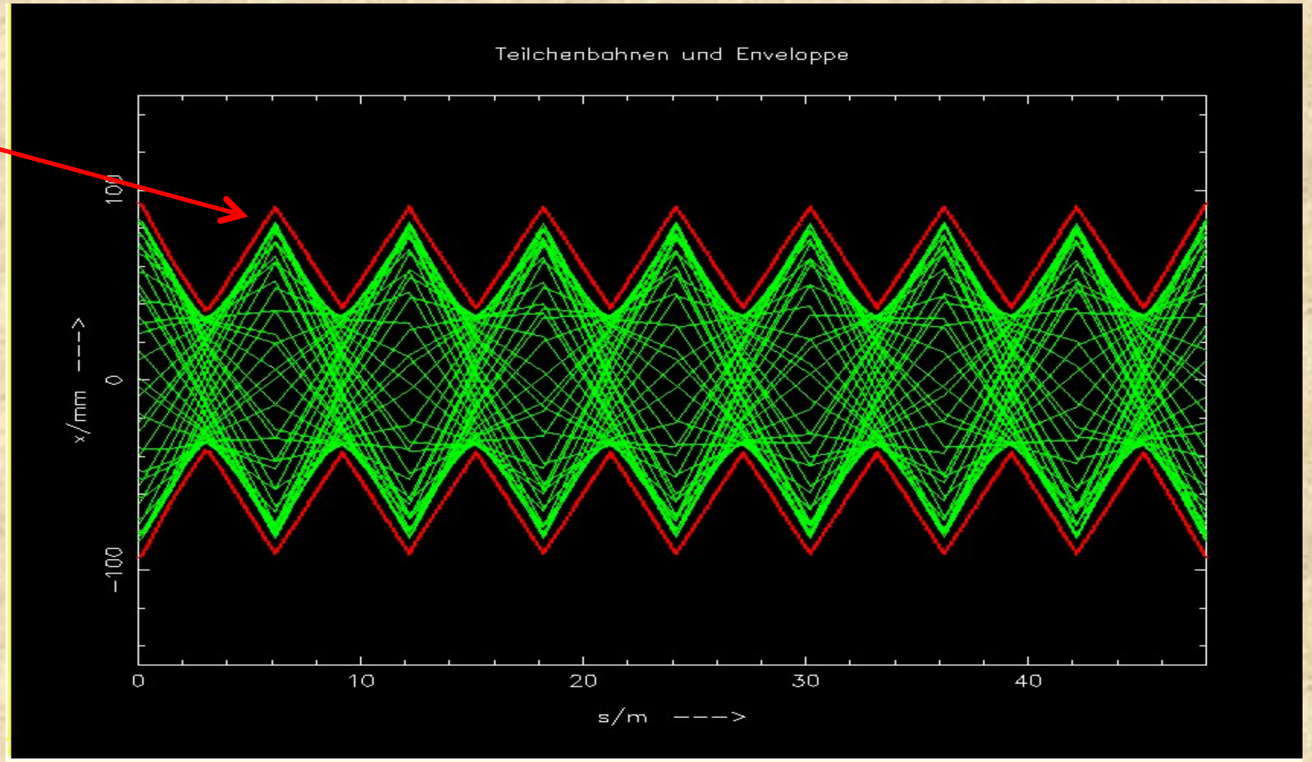
under the influence of conservative forces, the particle kinematics will always follow an ellipse in phase space x, x′phase space volume = constant

We use the area of that beam-ellipse as quality attribute for the particle ensemble: $A = \varepsilon \pi$



Many particles: The Beam

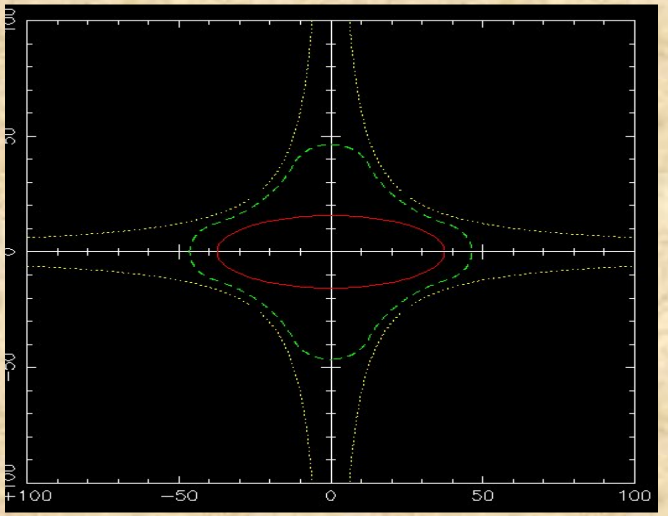
$$\hat{x}(s) = \sqrt{\varepsilon}\,\sqrt{\beta(s)}$$



The trajectories of many (2*10[11]) particles will describe in real space a pattern of harmonic oscillations …
and in phase space a "gaggle" of ellipses

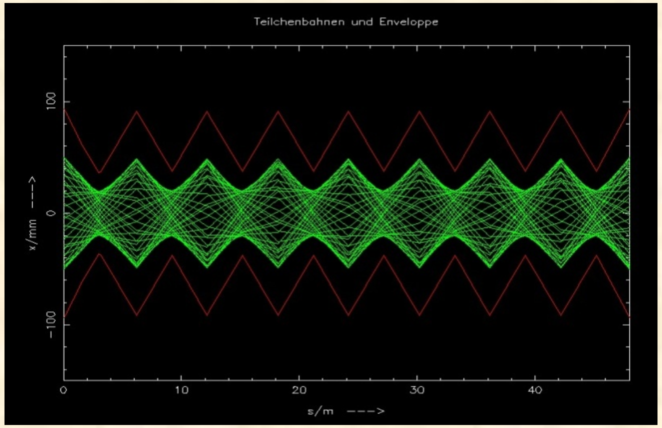
β determines the beam size
… the envelope of all particle trajectories at a given position "s" in the storage ring.
It is determined by the focusing properties in the accelerator

ε describes the beam quality



beam size in a focusing quadrupole

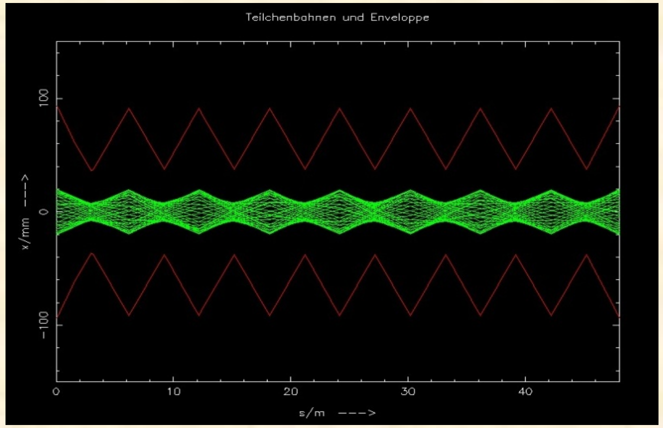
Emittance of the Particle Ensemble:



Beam Emittance:

large ε = bad

small ε = good

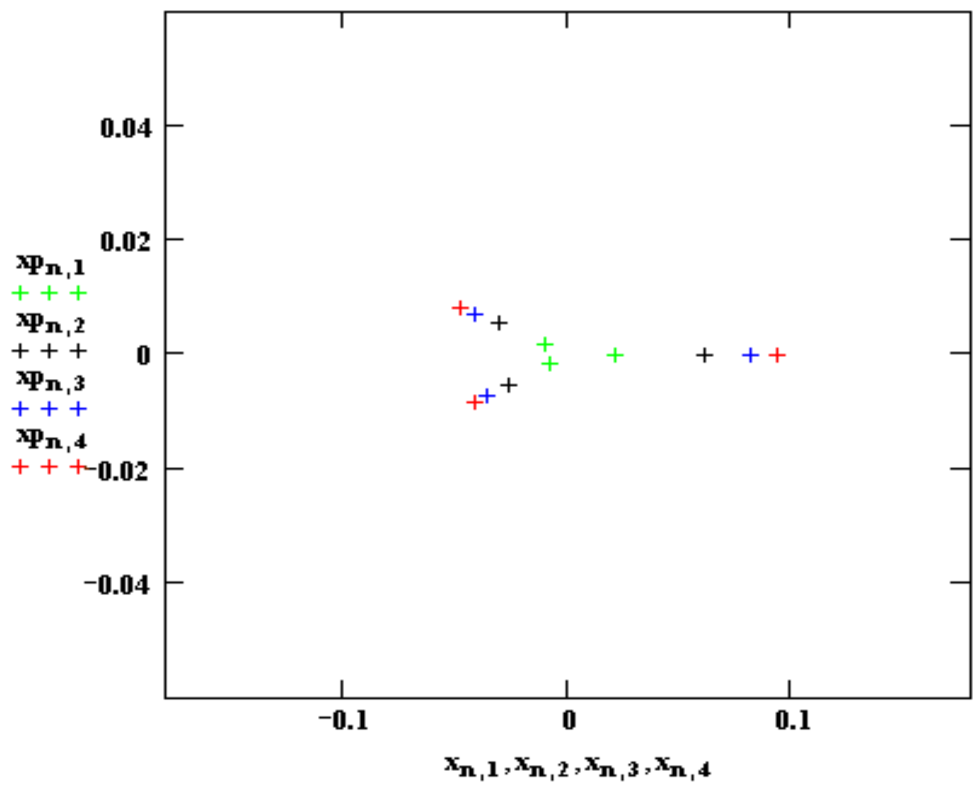


… to be very clear:

—> ***as long as our particle is running on an ellipse in x, x' space ...***

everything is alright, the beam is stable and ***we can sleep well at nights.***

—> ***if however we have scattering at the rest gas, or non-linear fields, or beam collisions (!)*** ***the particle will jump around in x-x'*** ***and ε will increase***



Time for a blue Slide …

Why do we do that ?

—> the beam size is given by two parameters:
β function - focusing properties
ε as intrinsic beam quality

—> beam size: $$\sigma = \sqrt{\varepsilon \cdot \beta}$$

—> the stability of the phase space ellipse, ε,
tells us about the stability
of the particle oscillation, which is …
… "the lifetime" of the beam.

—> the size of the ellipse tells us about the particle density,
… which is the beam quality in collision.

2.) Where do we go ?

* ***Physics beyond the Standard Model***
* ***Dark Matter / Dark Energy***

Physics Beyond the Standard Model (BSM)

Example: Dark Matter

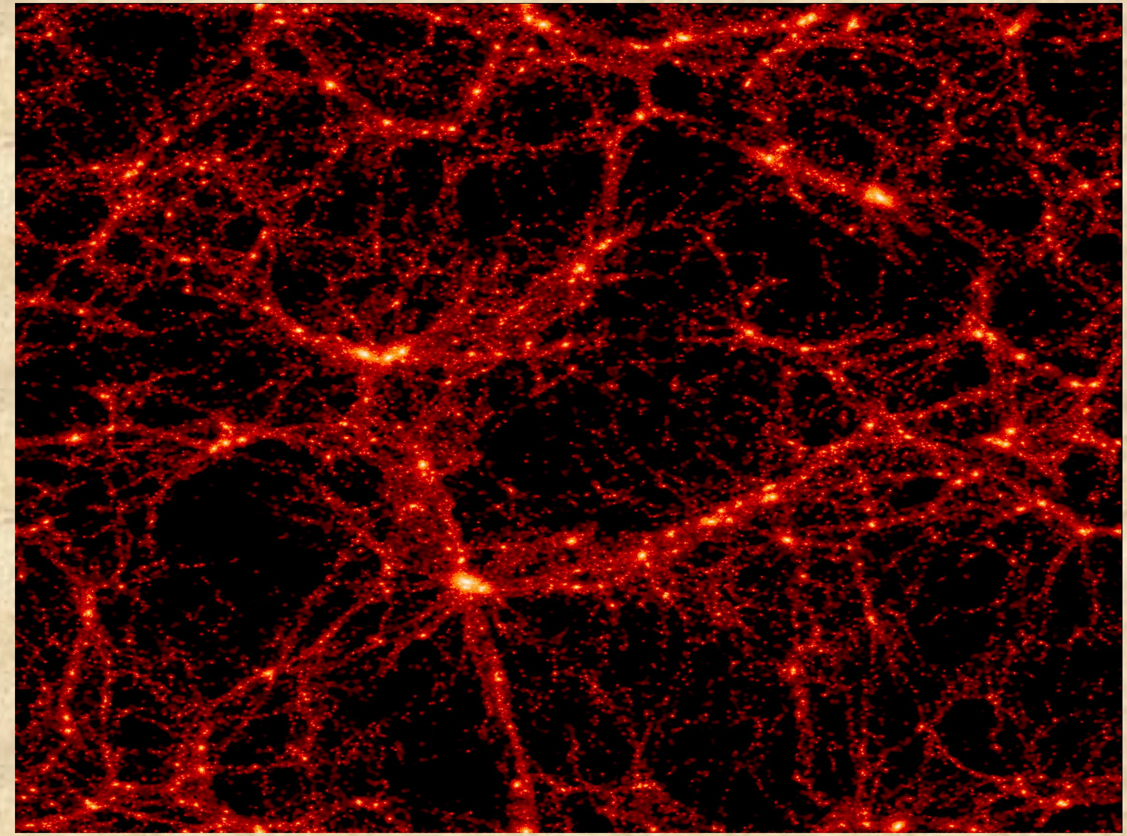
The outer region of galaxies rotate faster than expected from visible matter

Dark matter would explain this

Other observations exist … (grav. lens effects)
but all through gravity

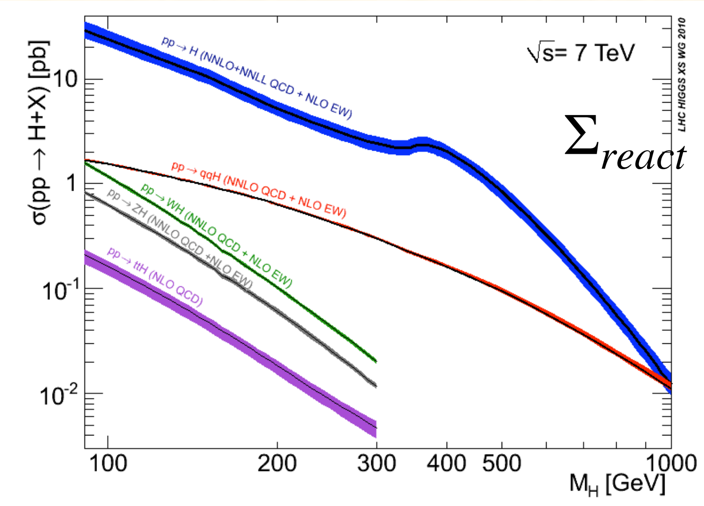
What is it?

Budget: Dark Matter: 26 %
Dark Energy: 70 %
Anything else (including us) 4 %

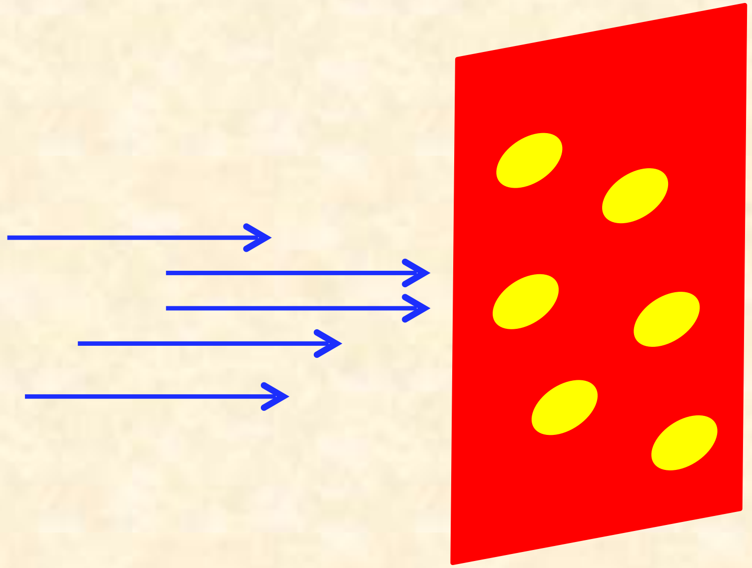


Problem: Our particles are VERY small !!

Overall cross section of the Higgs:



$$\Sigma_{react} \approx 1pb$$

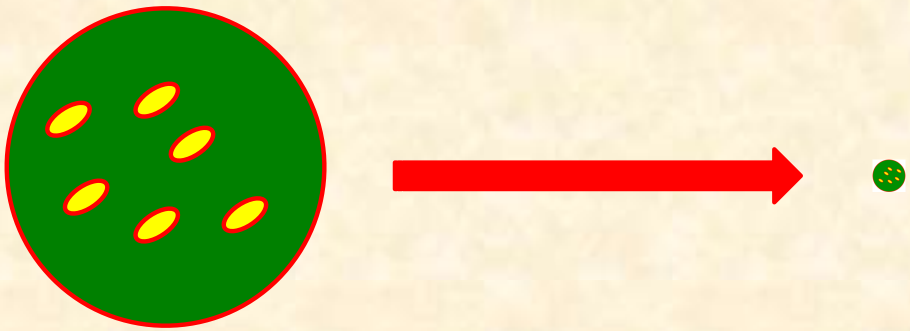


The particles are "very small"

$$1b = 10^{-24}cm^2$$

$$1\ pb = 10^{-12} \cdot 10^{-24}cm^2 = \frac{1}{mio} \cdot \frac{1}{mio} \cdot \frac{1}{mio} \cdot \frac{1}{mio} \cdot \frac{1}{mio} \cdot \frac{1}{10000}\ mm^2$$

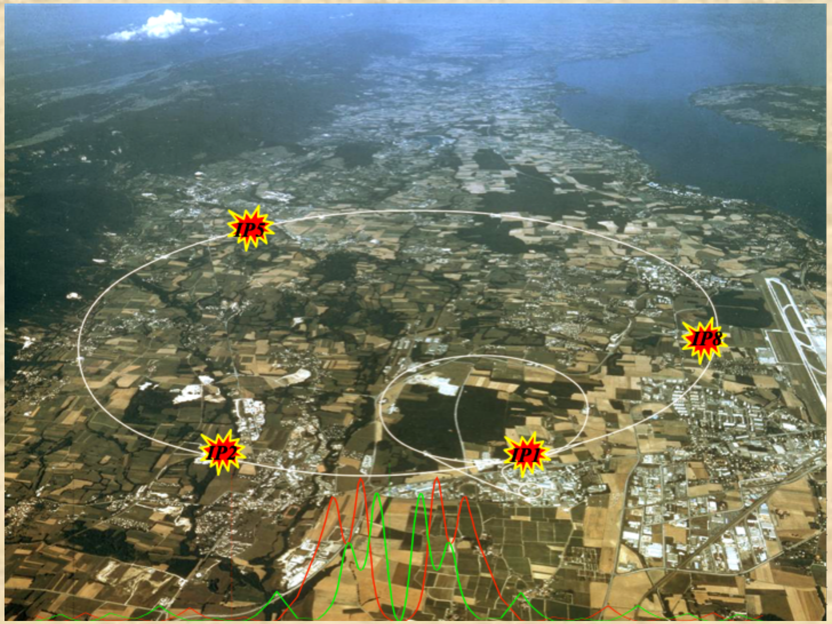
The only chance we have:
compress the transverse beam size … at the IP



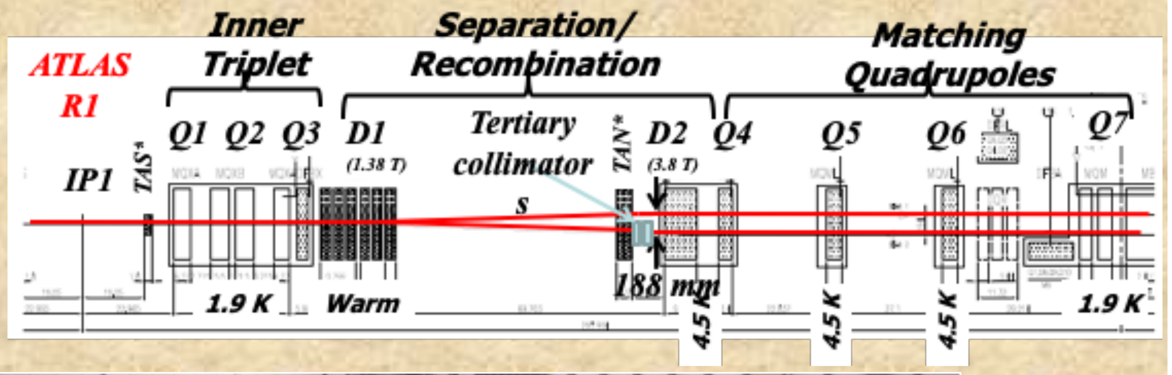
LHC typical:

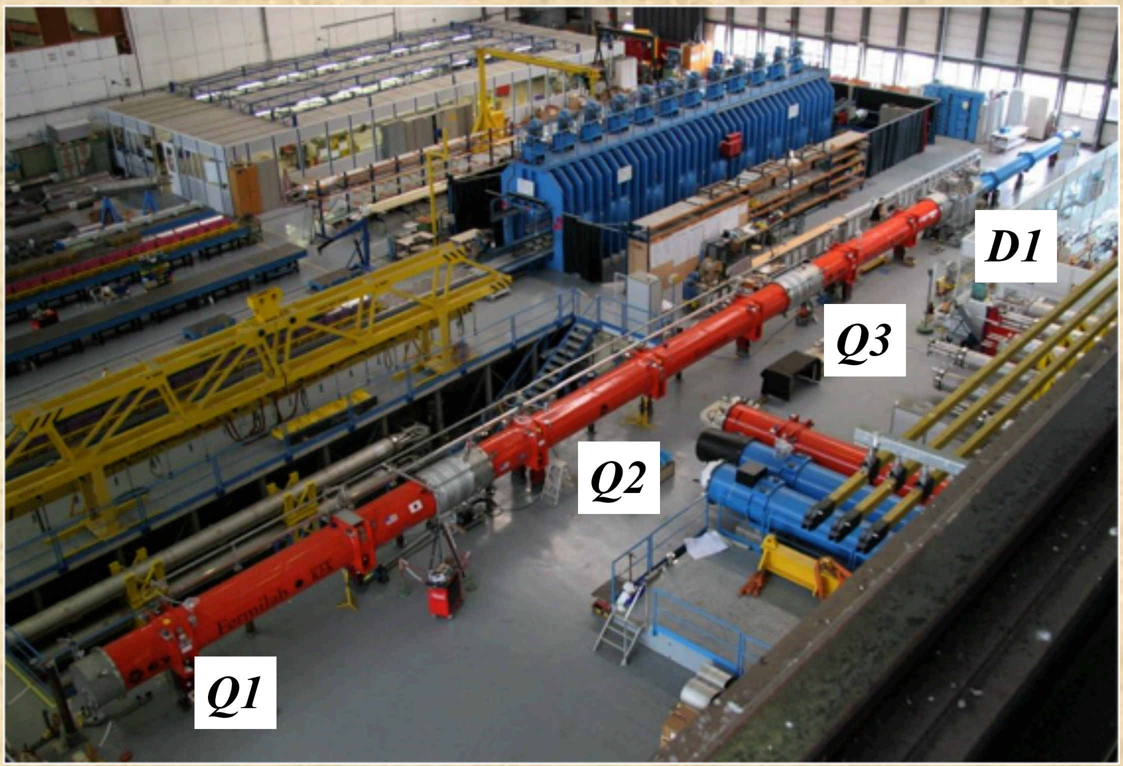
$\sigma = 0.1\ mm \rightarrow 16\ \mu m$

LHC & HL-LHC



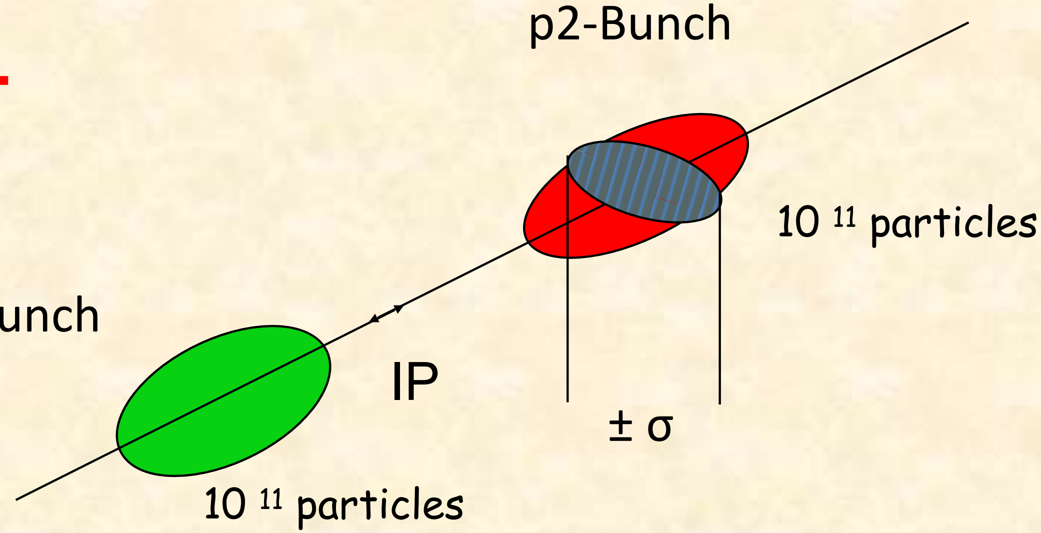
At one (or a very few) points in the accelerator, we make the beams as small as possible, to push for highest particle density.





Mini-Beta Insertion

Luminosity



$$R = L * \Sigma_{react}$$

Example: Luminosity run at LHC

$$\beta_{x,y} = 0.55\ m \qquad f_0 = 11.245\ kHz$$

$$\varepsilon_{x,y} = 5 * 10^{-10}\ rad\ m \qquad n_b = 2808$$

$$\sigma_{x,y} = 16\ \mu m$$

$$I_p = 584\ mA$$

$$L = \frac{1}{4\pi e^2 f_0 n_b} * \frac{I_{p1} I_{p2}}{\sigma_x \sigma_y}$$

$$L = 1.0 * 10^{34}\ \frac{1}{cm^2 s}$$

Every future collider has to push for highest possible luminosity … and energy.

3.) The HL-LHC

- *increasing the luminosity of LHC*
- *higher bunch intensities*
- *smaller β^**

	LHC	HL-LHC
Energy	7 TeV	7 TeV
Particles / bunch	$1.2*10^{11}$	$2.2*10^{11}$
number of bunches	2808	2748
β^*	55 cm	15 cm
ε	$5.0*10^{-10}$ m rad	$3.3*10^{-10}$ m rad
σ	16 µm	7 µm
Luminosity	$1.0*10^{34}$ cm^{-2} s^{-1}	$7.0*10^{34}$ cm^{-2} s^{-1}

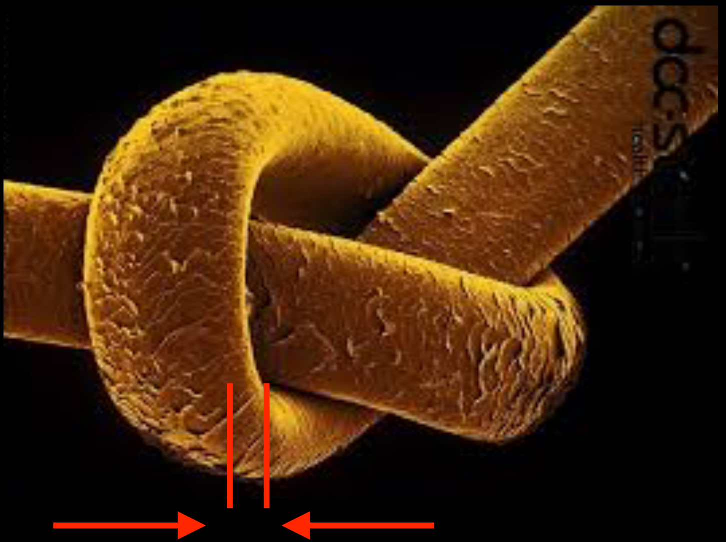
The Luminosity defines the number of "hits". It depends on the particle density at the collision point.

The Beta function at the IP "β*" should be made as small as possible to increase the particle density. In a drift β is growing quadratically and proportional to 1/β*, which sets the ultimate limit to the achievable luminosity.

The distance L* of the focusing magnets from the IP should be as small as possible.
… try to avoid detectors like ATLAS or CMS whenever possible.   LOL.

The beam dimensions at the IP are typically a few μm.

Human hair:
d ≈ 70 μm



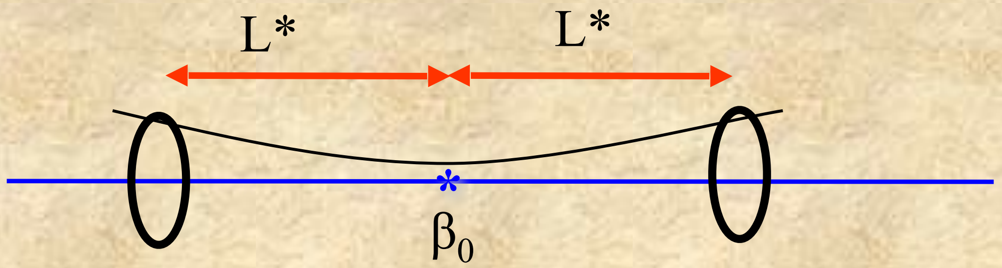
β-Function in a Drift:

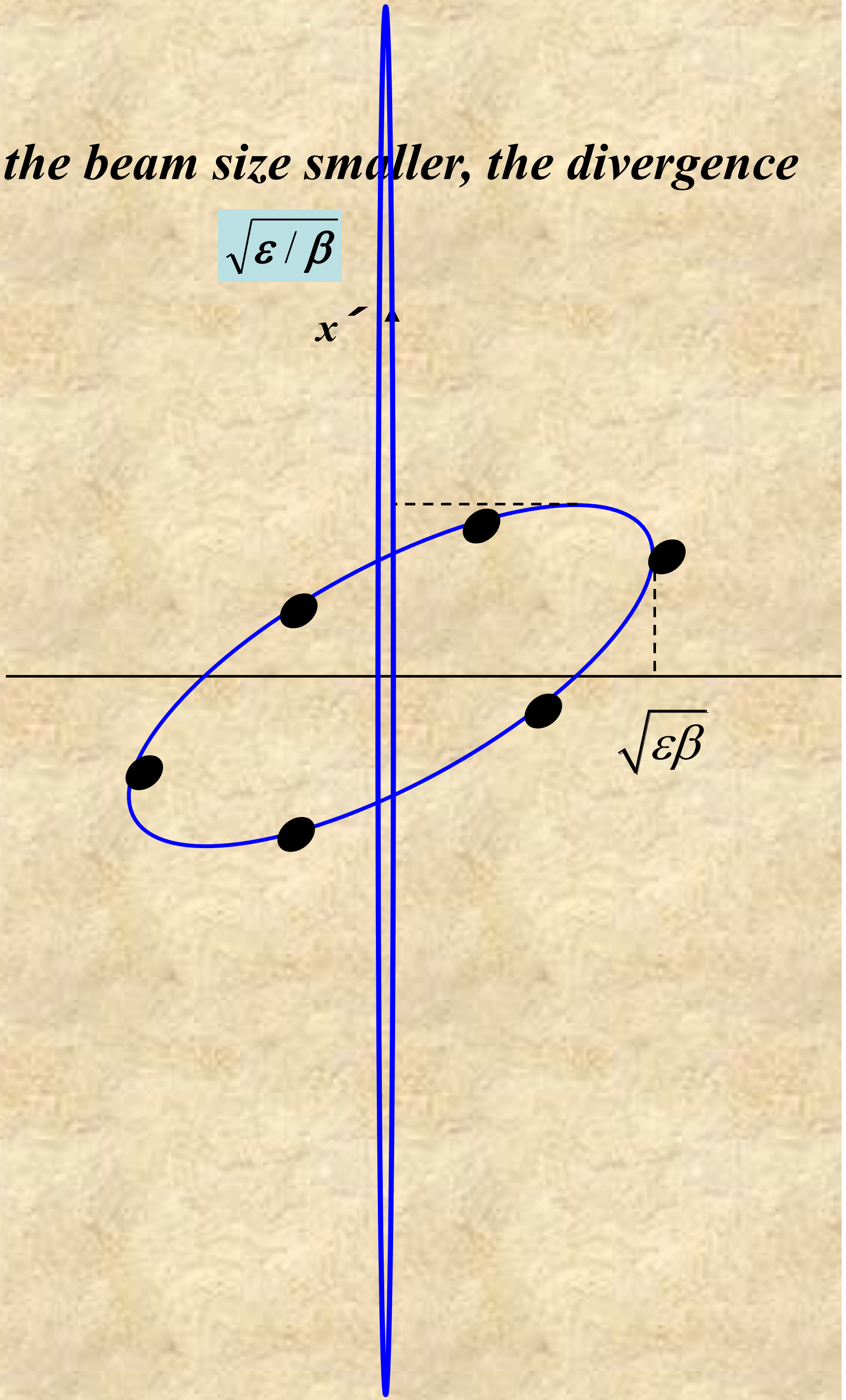
A direct consequence of "Liouville",
i.e. phase sopace conservation, is that … if we make the beam size smaller, the divergence increases.

in our β-language:

$$\beta(s) = \beta_0 + \frac{s^2}{\beta_0}$$

! ! !

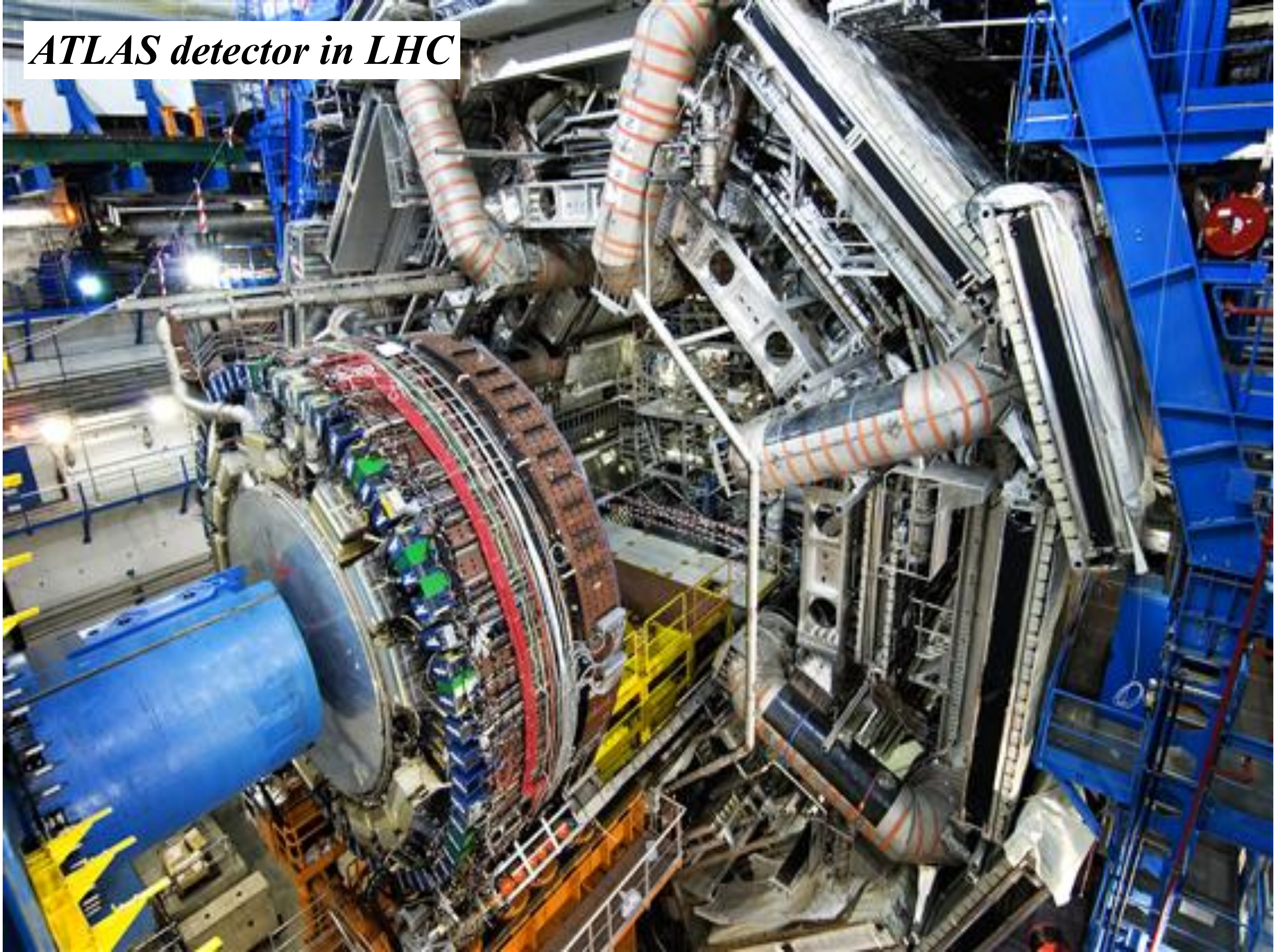




At the end of a long symmetric drift space the beta function reaches its maximum value in the complete lattice.
-> here we get the largest beam dimension.

-> keep L* as small as possible

ATLAS detector in LHC



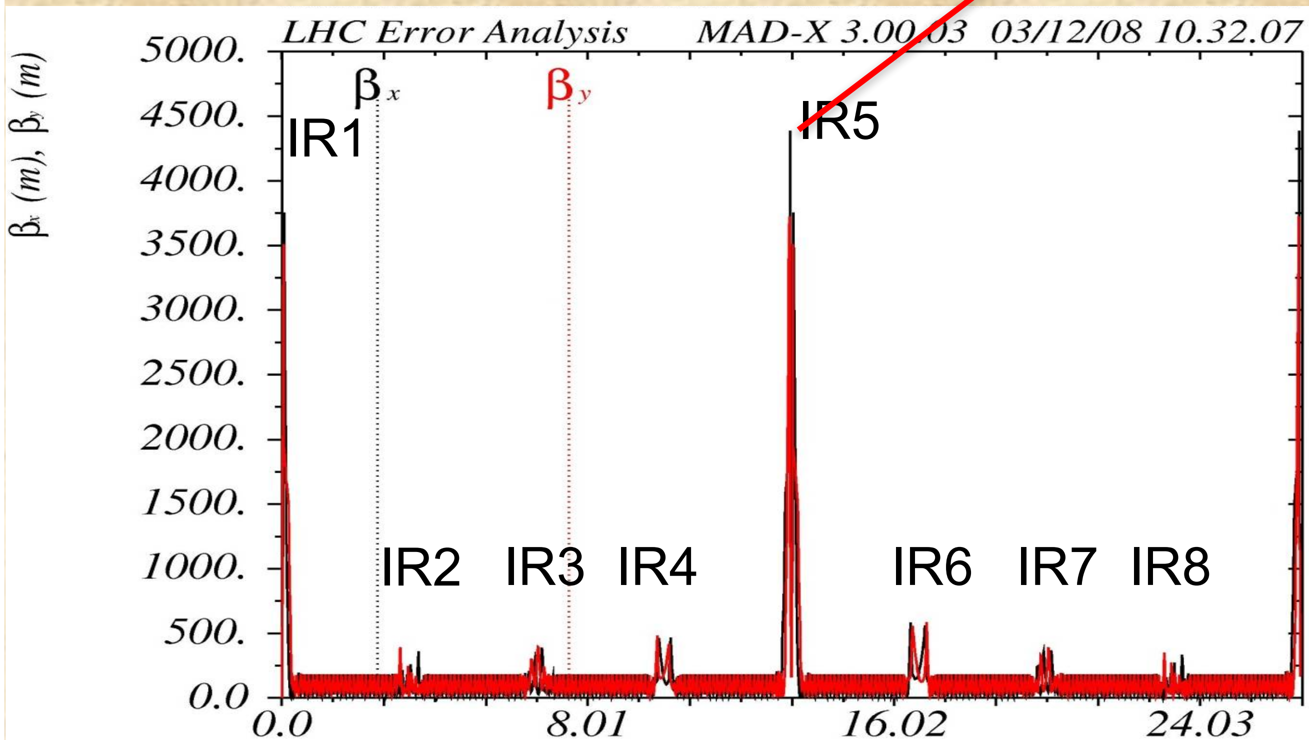
Luminosity Upgrade:

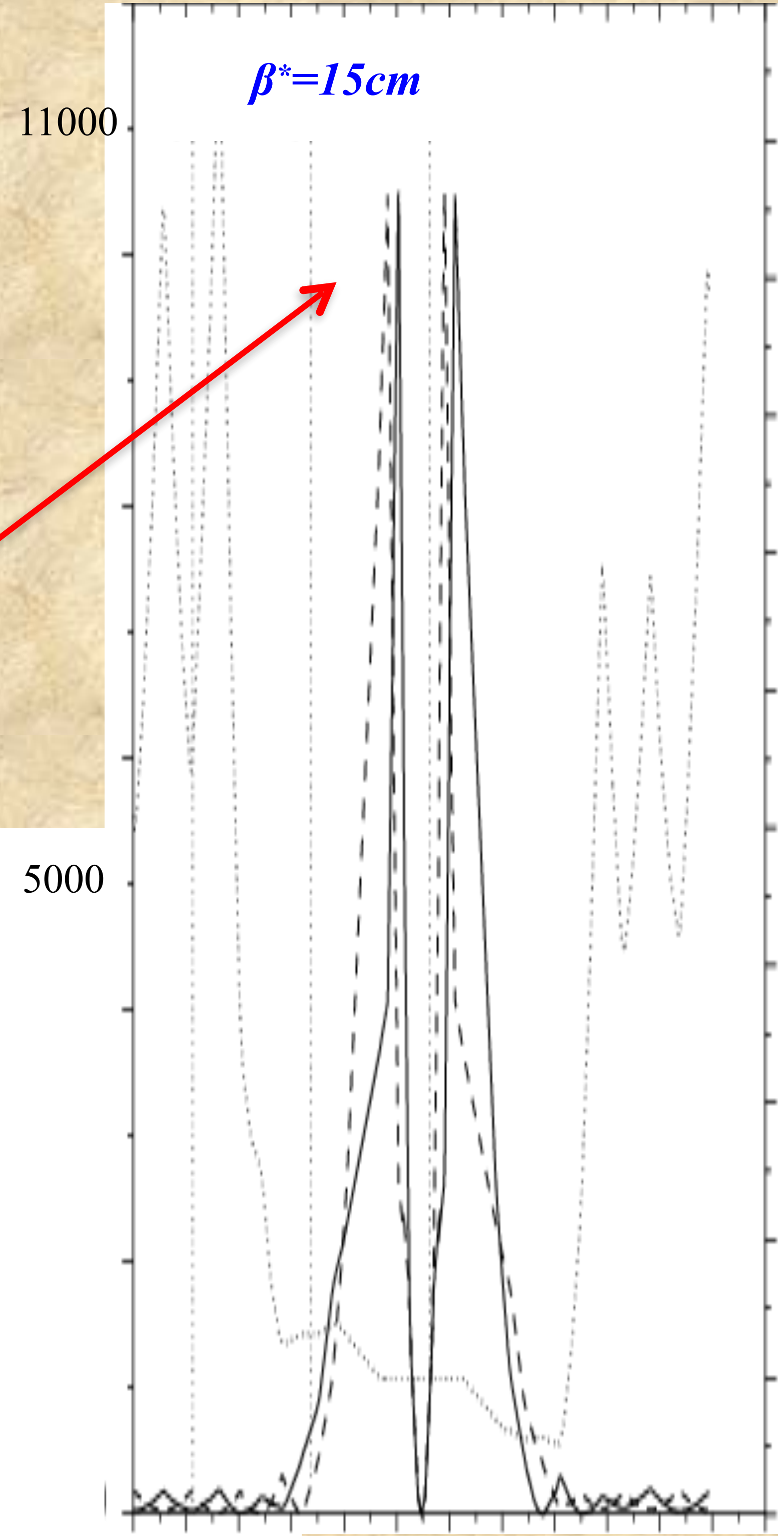
stronger focusing → smaller beam size at the IP

High Gradient / Large Aperture Insertion Quadupole Magnets

l = 8 m, G= 175 T/m, aperture = 120 mm,
(B_{peak}=13 T)

higher gradients & larger aperture
new sc. technology Nb_3Sn

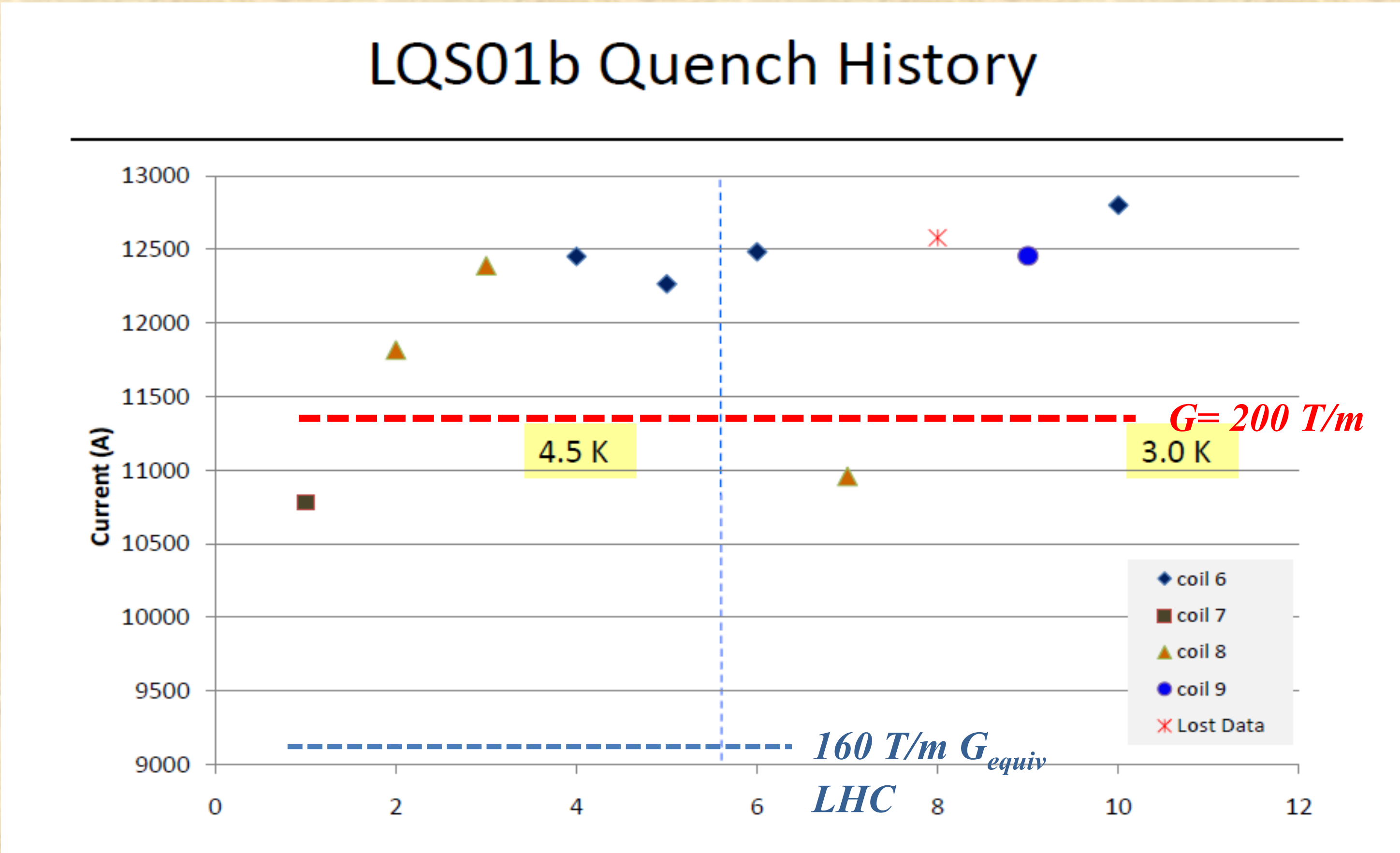




Challenge: High Field Nb_3Sn Quad

Stronger focusing needs stronger magnets

We need a material that can withstand this higher field in its super conducting phase !!! Nb_3Sn



reminder: LHC standard inner triplet NbTi: G=215 T/m, aperture = 66 mm

Future Colliders:
Hadrons or Leptons?

Hadron collisions*: *compound particles

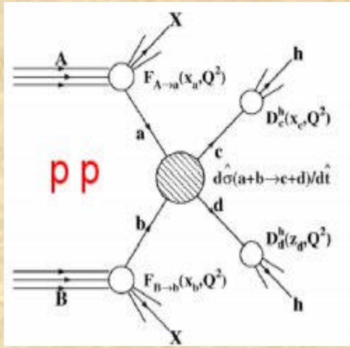
Proton = u+u+d + gluons + sea-quarks

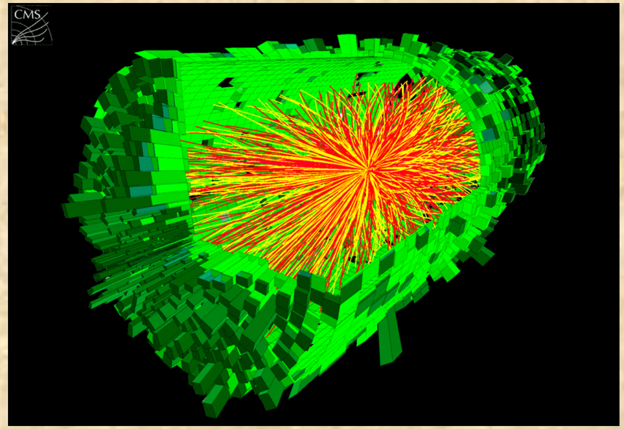
Mix of quarks, anti-quarks and gluons

→ variety of processes

Parton energy spread

Hadron collisions ⇒ large discovery range





LHC Pb-Pb collision (Atlas)

Lepton collisions: Elementary particles / Anti-particles

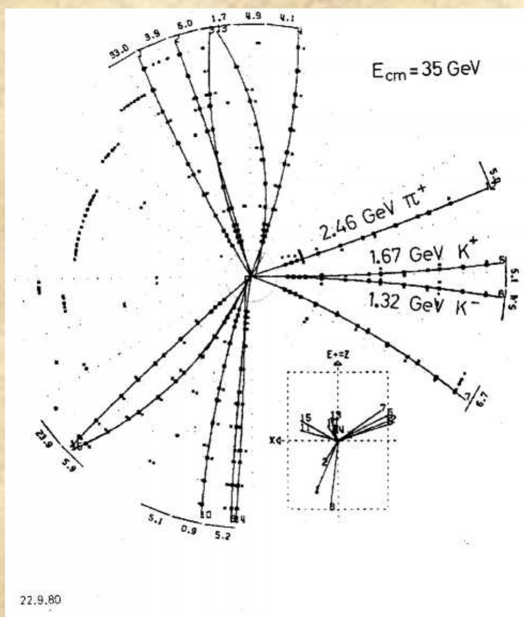
Collision process known

Well defined energy

Other physics background limited

Lepton collisions ⇒ precision measurements

in e+ e- collisions quantum numbers disappear



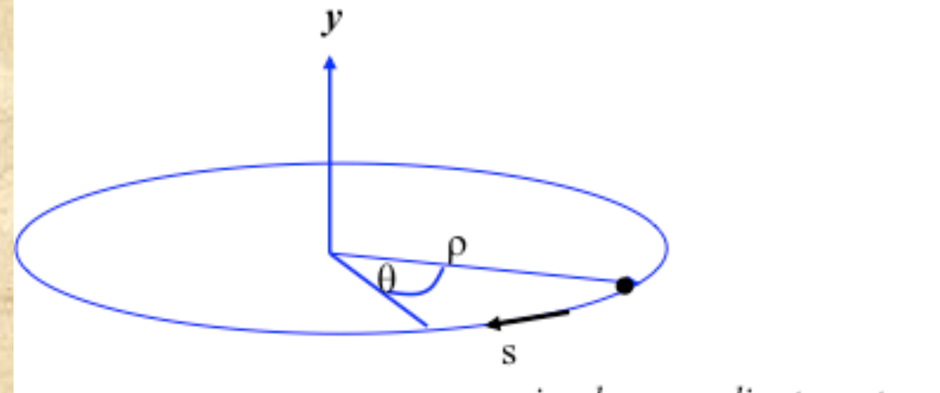
PETRA: gluon discovery

The Next Generation Ring Collider

4.) Push for highest energy:
FCC-pp - Collider

Maximum Beam Energy in a Storage Ring:

For a given magnet technology it is the size of the machine that defines the maximum particle momentum … and so the energy



circular coordinate system

~~$E = mc^2$~~ $$E^2 = (pc)^2 + m^2c^4$$

Condition for an ideal circular orbit:

Lorentz force $$F_L = e\,v\,B$$

centrifugal force $$F_{centr} = \frac{\gamma\, m_0\, v^2}{\rho}$$

$$\frac{\gamma\, m_0\, v^2}{\rho} = e\,v\,B$$

$$\frac{p}{e} = B\,\rho$$

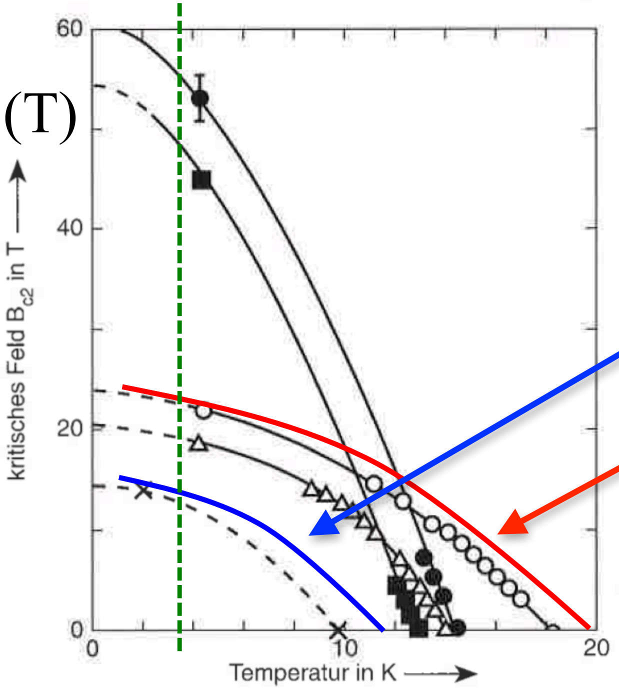
B ρ = "beam rigidity"

The maximum particle momentum is given by the field strength B and the storage ring size 2πρ

Highest B-field technology:
Two key players in sc magnet technology: NbTi and Nb_3Sn

168 5 Supraleiter im Magnetfeld

B(T)



T(K)

Abb. 77 Oberes kritisches Feld einiger Hochfeldsupraleiter.
–○–○–○– Nb_3Sn, Drahtdurchmesser 0,5 mm [127]
–△–△–△– V_3Ga, Sinterprobe [127]
–×–×–×– Nb_{50} Ti_{50} [128]
–■–■–■– $PbMo_{6,35}S_8$ [130]
–●–●–●– $PbGd_{0,3}Mo_6S_8$ [130]
(siehe auch Ø. Fischer: Proceedings LT 14, Otaniemi 1975, Band 5. North-Holland Publ. Comp. 1975).

critical field in
NbTi and Nb_3Sn

FCC -hh
means Nb_3Sn technology
for dipoles & quadrupoles

which is equally true in parts
for HL-LHC

… and we do NOT talk about
$YBa_2Cu_3O_7$ and friends

($j_c\perp$ = 100A/mm², $j_c||$ = 800A/mm²)

FCC-hh Parameter List

	LHC	HL-LHC	FCC-hh	
			Initial	Nominal
Main parameters and geometrical aspects				
c.m. Energy (TeV)	14		100	
Circumference C (km)	26.7		97.75	
Dipole field (T)	8.33		<16	
Physics performance and beam parameters				
Peak luminosity[1] (10^{34} cm^{-2}s^{-1})	1.0	5.0	5.0	<30.0
Beam parameters				
Number of bunches n	2808		10 400	
Bunch spacing (ns)	25	25	25	
Bunch population $N(10^{11})$	1.15	2.2	1.0	
RMS bunch length[2] (cm)	7.55		8	
IP beta function (m)	0.55	0.15 (min)	1.1	0.3
RMS IP spot size (μm)	16.7	7.1 (min)	6.8	3.5
Full crossing angle (μrad)	285	590	104	200[3]
Other beam and machine parameters				
Stored energy per beam (GJ)	0.392	0.694	8.3	
SR power per ring (MW)	0.0036	0.0073	2.4	

Main Issue: Machine Safety
& Quench protection

The Next Generation Ring Collider

5.) Push for highest precision:
FCC e+/e- Collider

Synchrotron Radiation

ca 400 000 v. Chr.: Mankind discovers the Fire

Synchrotron Radiation

In a circular accelerator charged particles loose energy via emission of intense light.

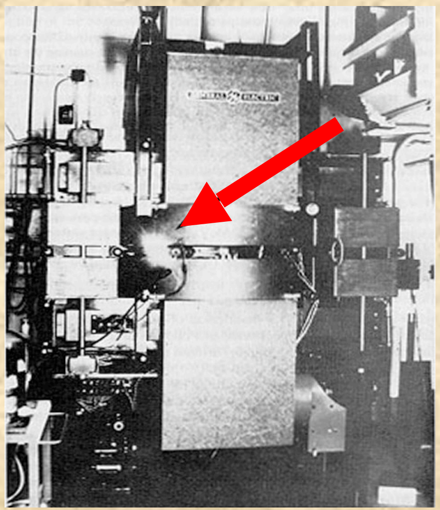
$$P_s = \frac{2}{3}\alpha\hbar c^2 \frac{\gamma^4}{\rho^2}$$ ***radiation power***

$$\Delta E = \frac{4}{3}\pi\alpha\hbar c \frac{\gamma^4}{\rho}$$ ***energy loss***

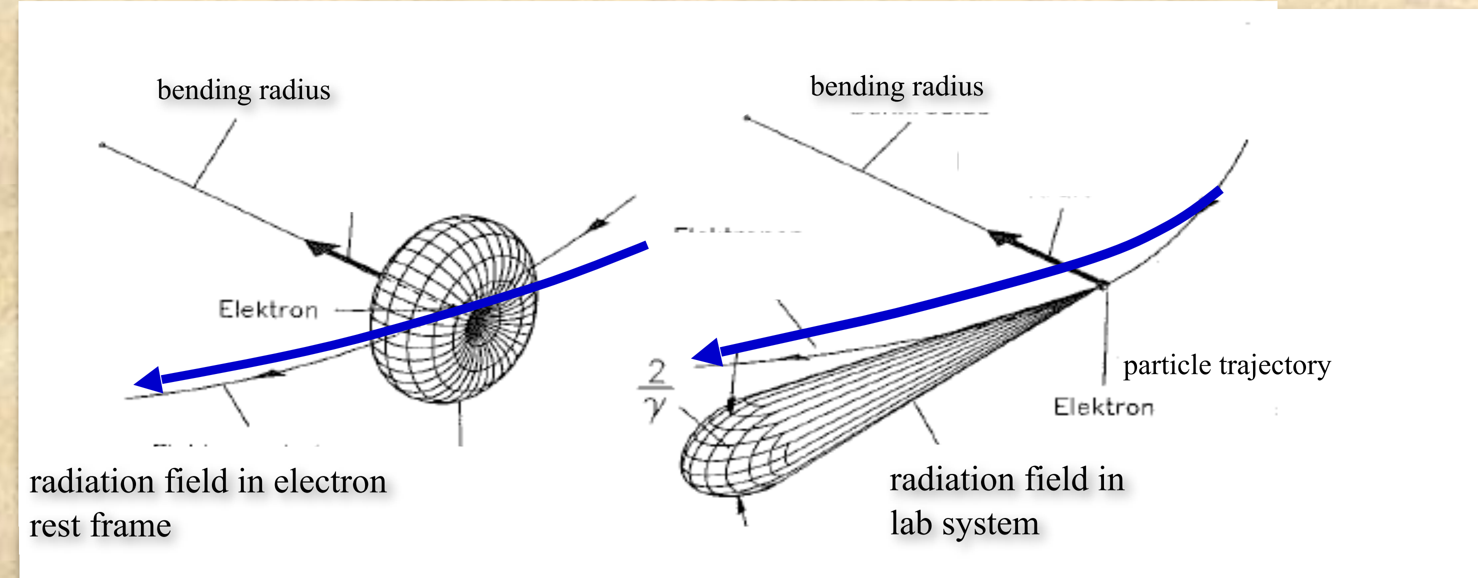
$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}$$ ***critical frequency***

$$\alpha \approx \frac{1}{137}$$

$$\hbar c \approx 197\ MeV\ fm$$



1946 observed for the first time in the General Electric Synchrotron



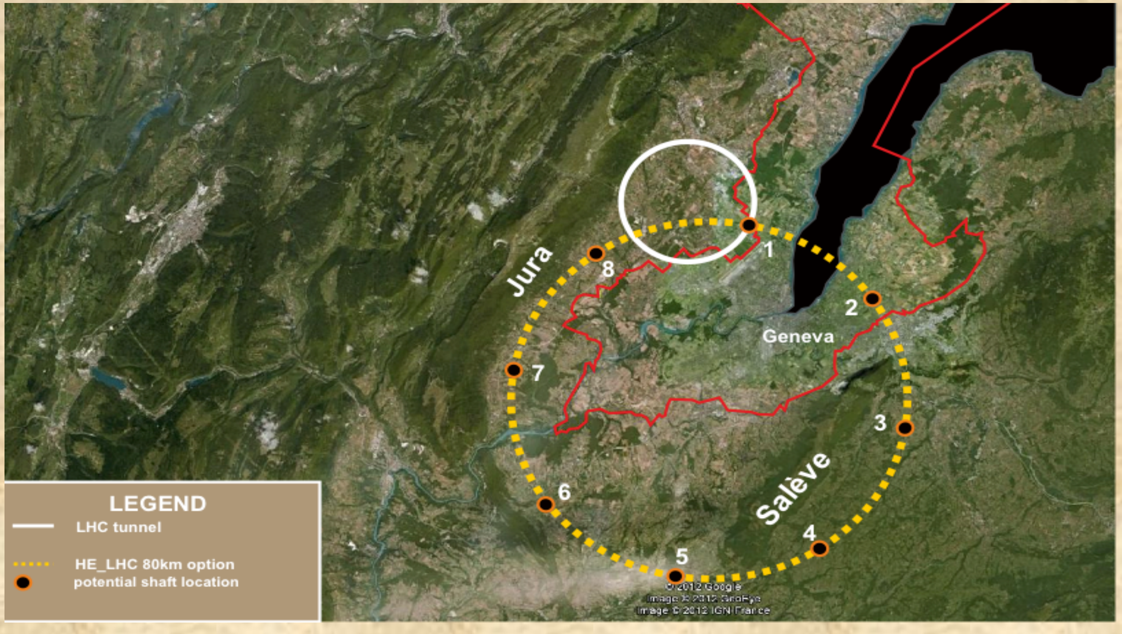
court. K. Wille

FCC-ee: a collider that is dominanted by synchrotron light losses.

→ *Planning the next generation e+ / e- Ring Colliders means build it LARGE.*

Design Parameters FCC-ee

E = 183 GeV / beam
L = 100 km



$$\Delta U_0(keV) \approx \frac{89 * E^4(GeV)}{\rho}$$

$$\Delta U_0 \approx 9\ GeV$$

$$\Delta P_{syn} \approx \frac{\Delta U_0}{T_0} \cdot N_e \cdot n_b \approx \frac{9 \cdot 10^9 V \cdot 1.6 \cdot 10^{-19} Cb \cdot 48 \cdot 2 \cdot 10^{11}}{263 \cdot 10^{-6} s}$$

$$\Delta P_{syn} \approx 50\ MW$$

... per beam

Circular e+ / e- colliders are severely limited by synchrotron radiation losses and have to be replaced for higher energies by linear accelerators

FCC-ee Parameters

	Z	WW	ZH	$t\bar{t}$	
Circumference [km]	97.756				
Bending radius [km]	10.760				
Free length to IP l^* [m]	2.2				
Solenoid field at IP [T]	2.0				
Full crossing angle at IP θ [mrad]	30				
SR power / beam [MW]	50				
Beam energy [GeV]	45.6	80	120	175	182.5
Beam current [mA]	1390	147	29	6.4	5.4
Bunches / beam	16640	2000	328	59	48
Bunch population [10^{11}]	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x [nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y [pm]	1.0	1.7	1.3	2.7	2.9
Horizontal β^*_x [m]	0.15	0.2	0.3	1.0	
Vertical β^*_y [mm]	0.8	1.0	1.0	1.6	
Luminosity / IP [10^{34}/cm^{2}s]	230	28	8.5	1.8	1.55

$$\Delta U(keV) = 89 * \frac{E^4/(mc^2)^4}{\rho}$$

For a given particle energy the beam intensity will be limited by the maximum tolerable Synchrotron radiation power loss

RF Voltage applied depends on the beam energy as $U \propto \gamma^4$

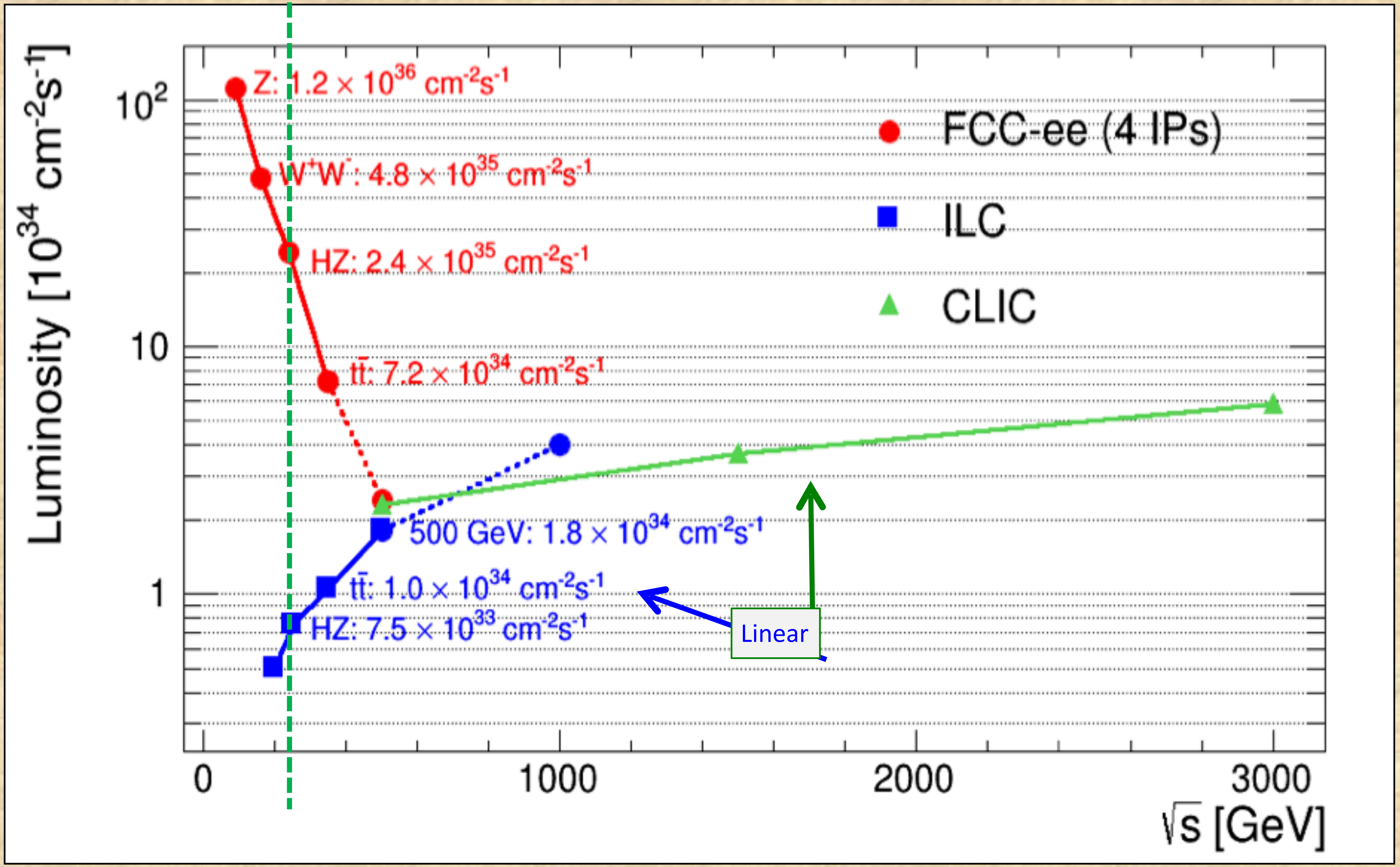
Emittance ratio … in the range of 1-2 per mille !!

6.) Push for higher lepton energy

**** go linear***
**** higher acceleration gradients***

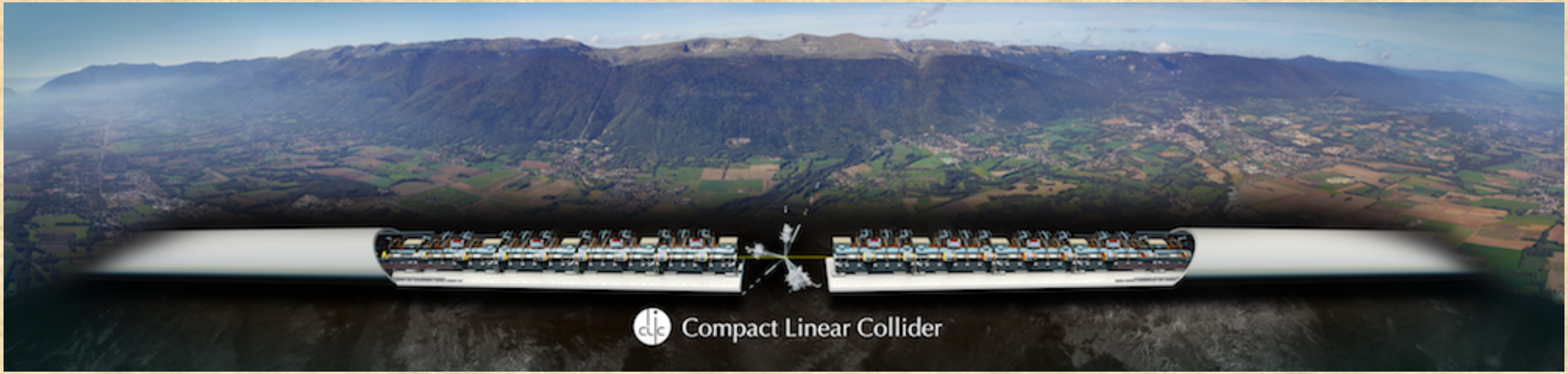
Circular vs. Linear Colliders

… the light problem



CLIC ... a future Linear e+/ e- Accelerator

„C“-LIC ... = CERN ... or „compact“



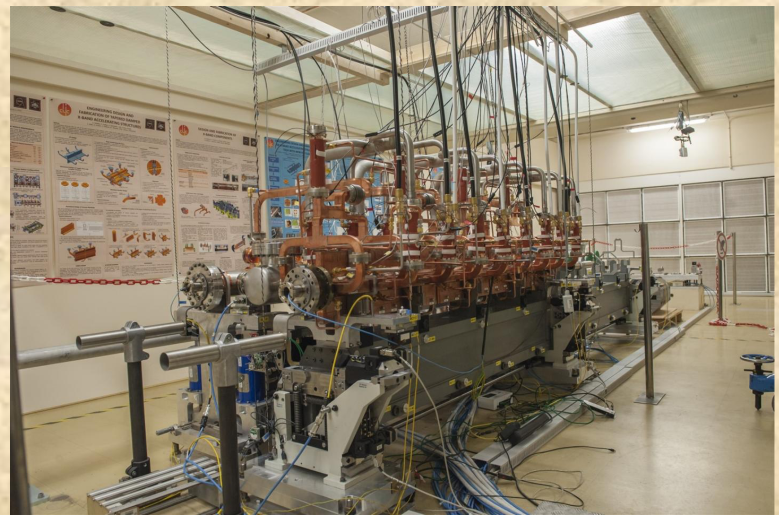
50 km

CLIC parameter list

Description [units]	500 GeV	3 TeV
Total (peak 1%) luminosity	$2.3\ (1.4) \times 10^{34}$	$5.9\ (2.0) \times 10^{34}$
Total site length [km]	13.0	48.4
Loaded accel. gradient [MV/m]	80	100
Main Linac RF frequency [GHz]	12	
Beam power/beam [MW]	4.9	14
Bunch charge [10^9 e^+/e^-]	6.8	3.72
Bunch separation [ns]	0.5	
Bunch length [μm]	72	44
Beam pulse duration [ns]	177	156
Repetition rate [Hz]	50	
Hor./vert. norm. emitt. [$10^{-6}/10^{-9}$m]	2.4/25	0.66/20
Hor./vert. IP beam size [nm]	202/2.3	40/1

CLIC
means pushing
the acc gradient

CLIC: Normal conducting RF system
challenge: running at the break down limit



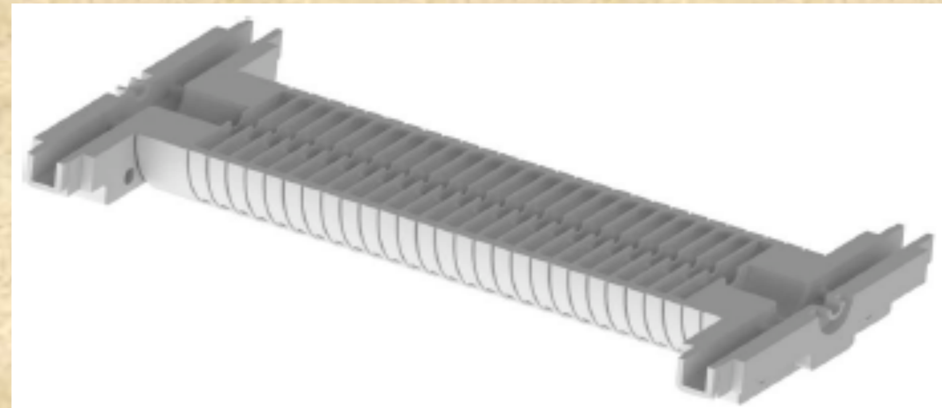
CTF3

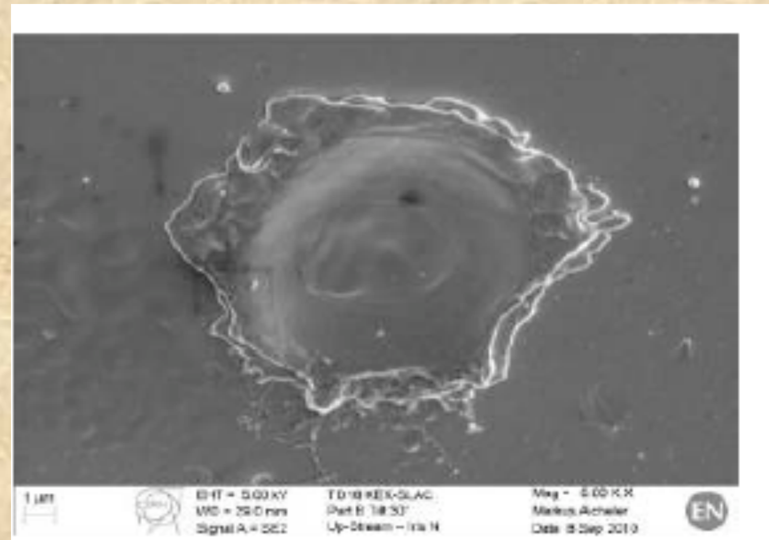
Acceleration Gradient 100MV/m studied & optimised since years

" how far can we go before we reach technical limits and how can we push these limits ? "

They have impact on

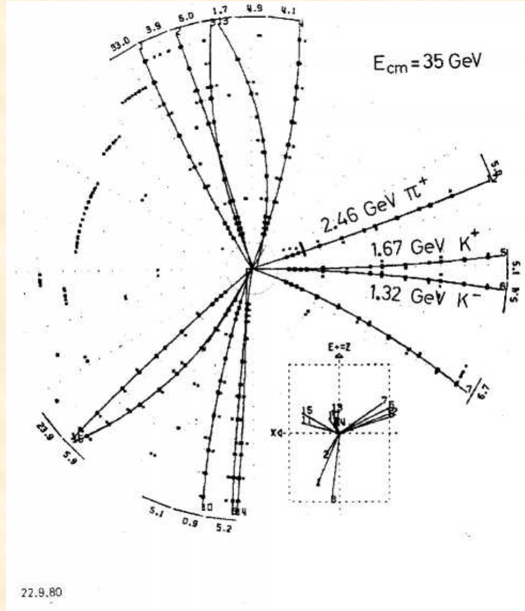
- => *the accelerator performance (luminosity)*
- => *beam quality*
- => *and the accelerating structure itself*





7.) Towards "green" accelerators

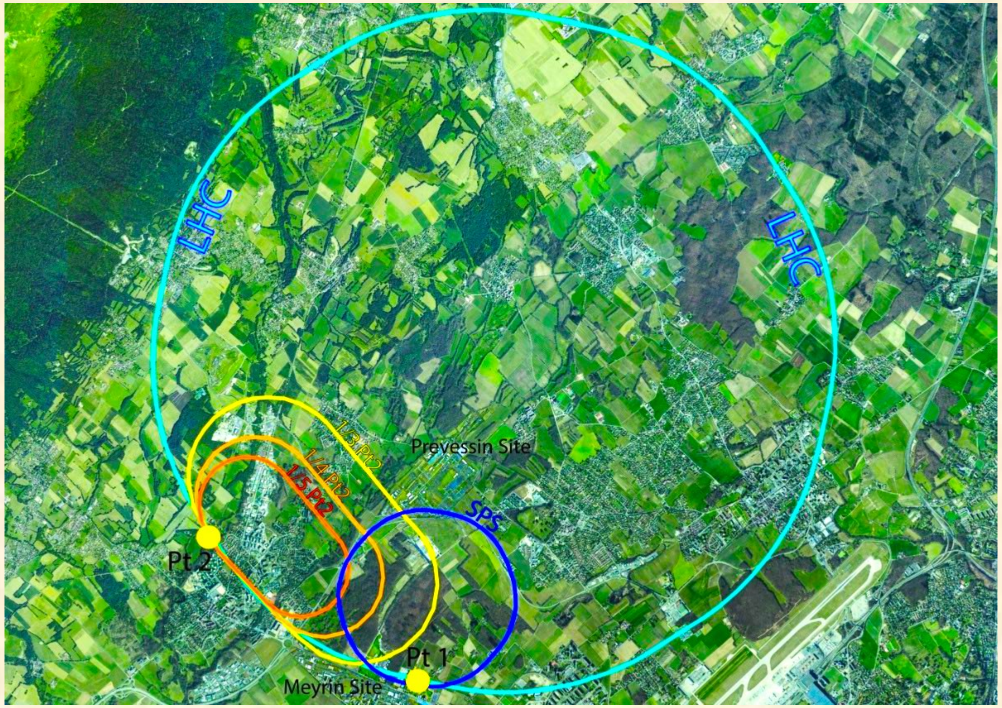
= = > energy recovery



Bunch population ≈ 10 ^{9}

Collisions: … a few (1 … 10)

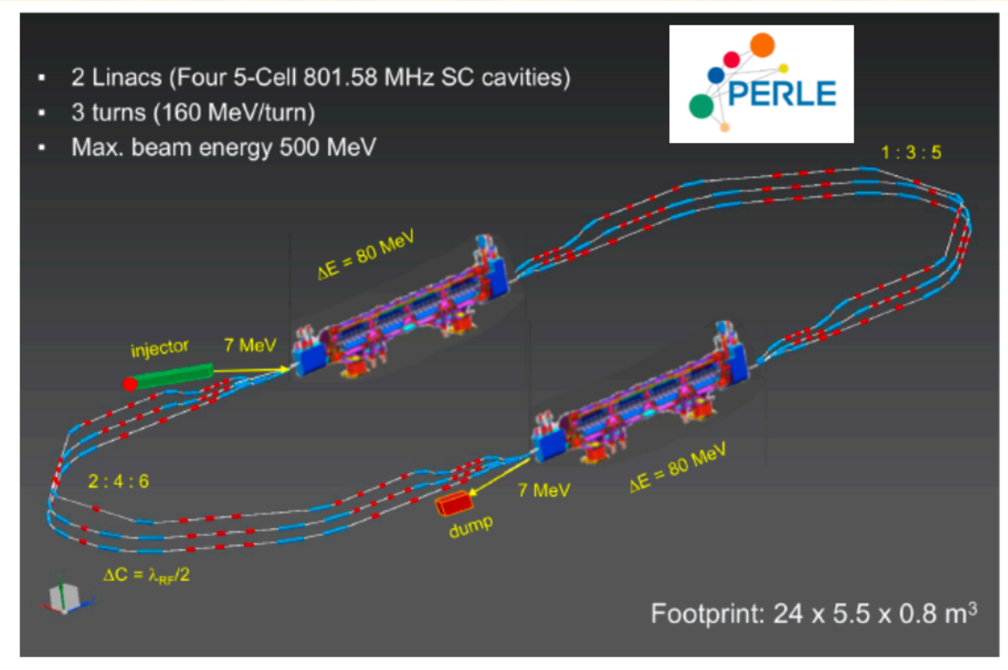
} ***all other particles are lost, and so is their energy.***



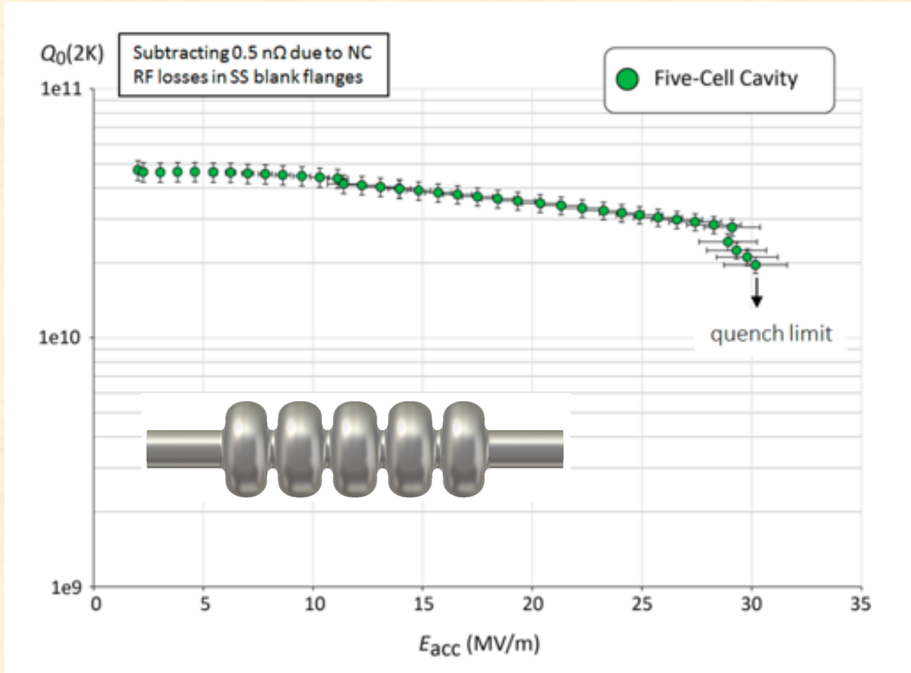
—> ***build a linear accelerator, where after the collision the particle are de-celerated and the energy is stored back to the electro-magnetic field of the (sc.) cavities.***

Energy Recovery Linac, ERL

The LHeC: Electron ERL for ep Collisions



PERLE: prototype ERL at Paris

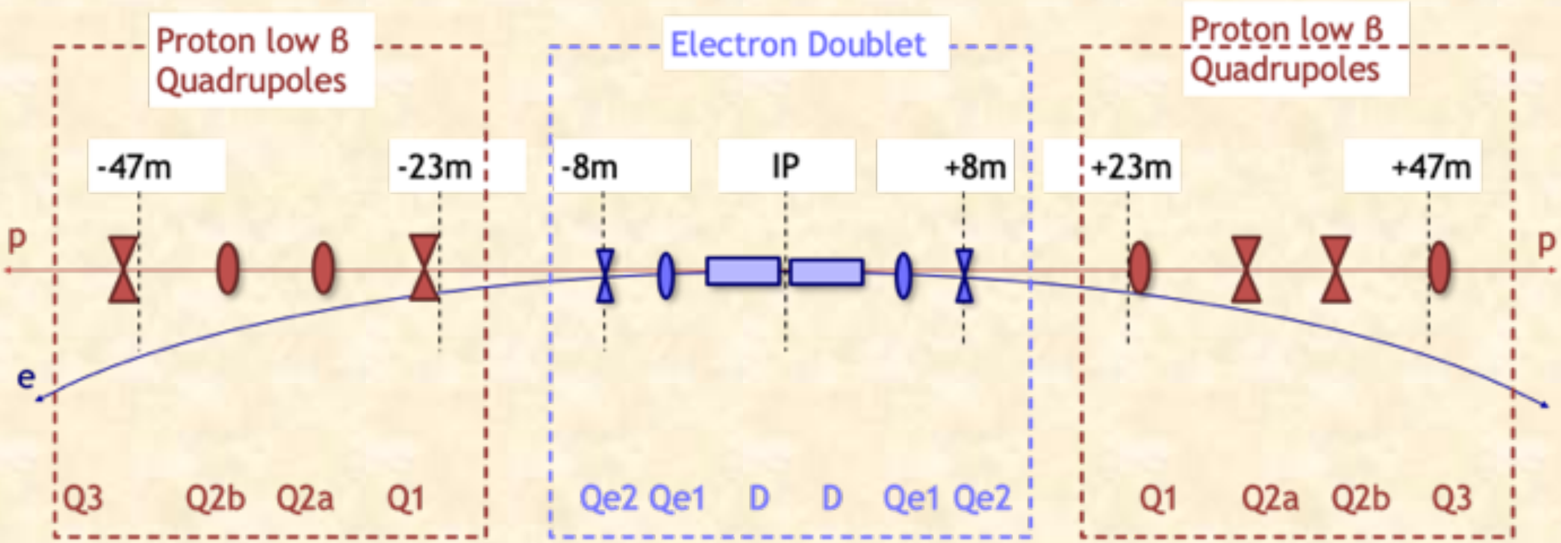


	Electrons
Energy (GeV)	50
N_p /bunch (10^{11})	2.2
N_e /bunch (10^9)	3.1
bunch distance (ns)	25
I_e (mA)	20
Emittance (nm)	0.31
Beam size @ IP (μm)	6 / 6
Luminosity (cm^{-2} s^{-1})	$9*10^{33}$

super conducting cavities required:
store the energy of the
decelerating bunch
to provide it to the next
accelerating bunch.

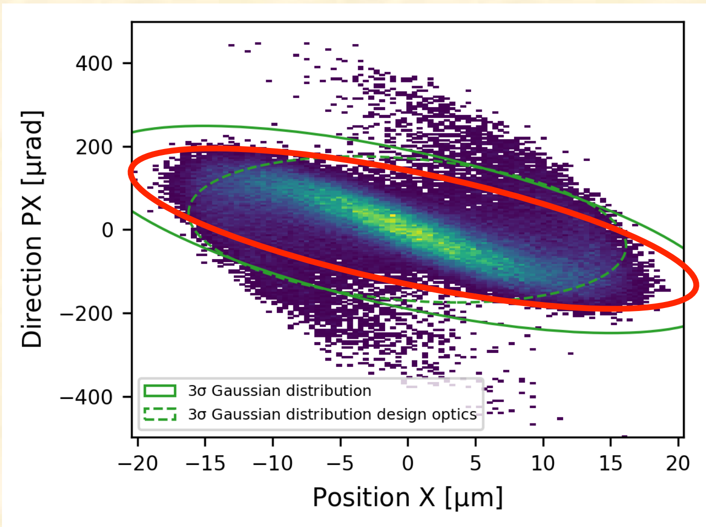
LHeC Interaction Region

Focusing structure for electrons embedded in LHC-proton lattice: Combination of beam focusing & separation



Push for highest luminosity:
—> beam-beam limit,
observed in phase space.

… where is the ε-ellipse ???

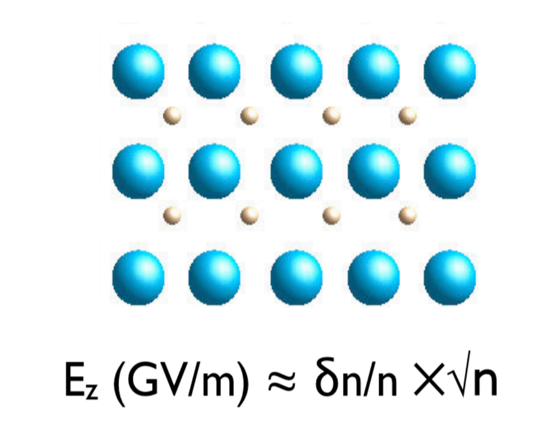


development of tails due to non-linear beam beam force

8.) Push for higher energy

* *highest acceleration gradients*
* *new acceleration techniques*

Plasma Wake Acceleration



separate electrons and ions in a plasma
—> generate extreme E-fields

"AWAKE", and friends

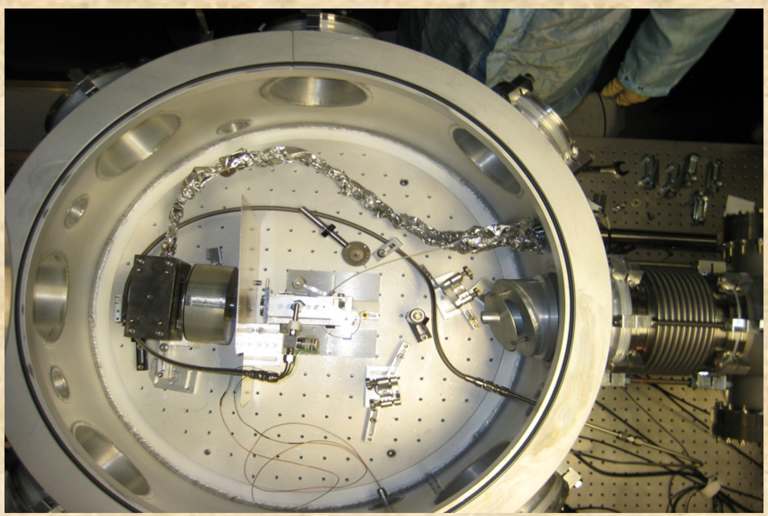
Plasma in a 10 m long Rb Plasma Cell

Study of High Gradient Acceleration Techniques

Plasma Wake Acceleration
particle beam driven / LASER driven

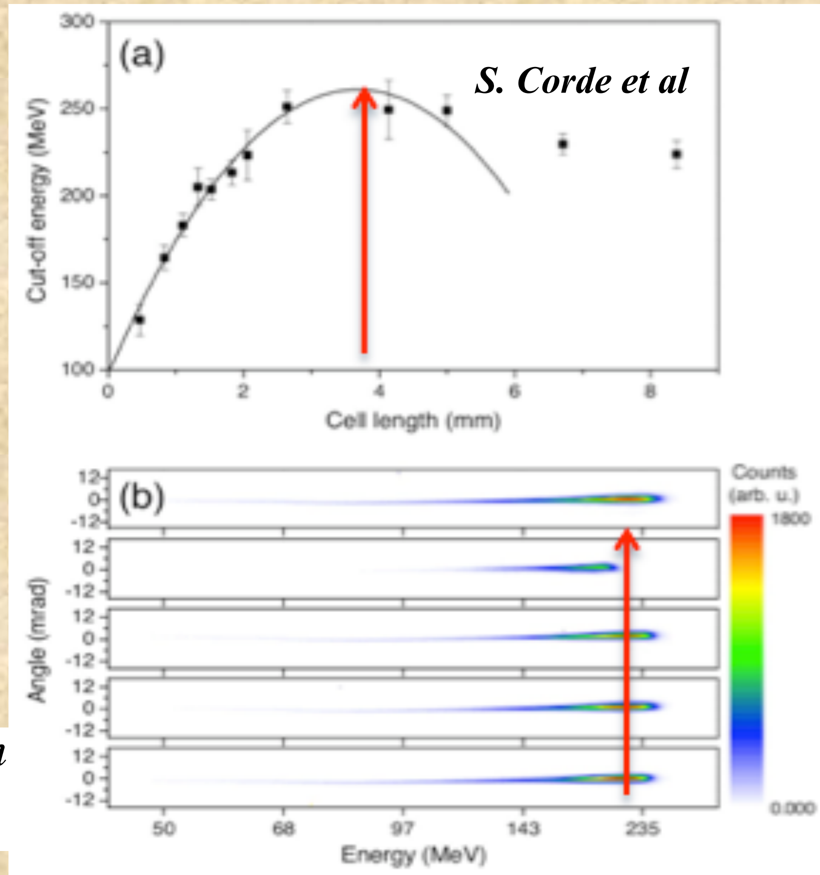
Incoming laser pulse (or pulse of particles) creates a travelling plasma wave in a low-pressure gas
Plasma wake field gradient accelerates electrons that 'surf' on the plasma wave

Field Gradients up to 100 GeV /m observed



Plasma cell Univ. Texas, Austin
E_e =2 GeV

$$\Delta E / \Delta s = 200\, MeV / 4mm = 50\, GeV / m$$



Open questions in particle physics

Dark matter & Energy

… on which energy scale to look for it ?

Physics beyond the standard model

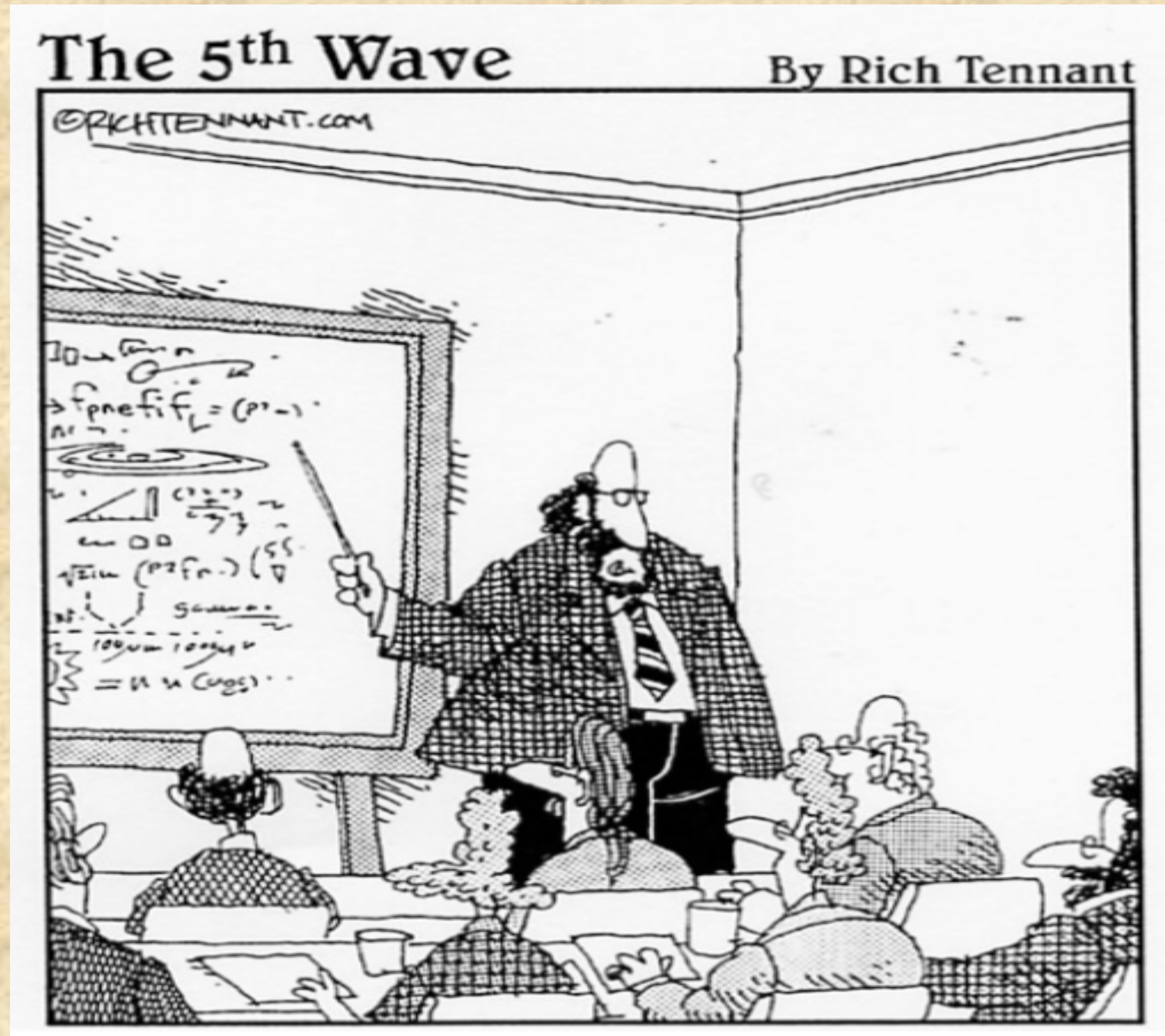
... Lepton or Proton colliders ?

Beam dynamics aspects

... Circular or Linear ?

Technical aspects

... Traditional, sc / nc or PWA ?



"After the discovery of

'Anti Matter'
and
'Dark-Matter'

we have just confirmed the existence of

'Doesn't Matter'

which does not have any influence on the Universe whatsoever".

Merci

Goal for the LHC Upgrade ... and what we have to do

$$L = \frac{1}{4\pi} \cdot f_{rev} n_b \cdot \quad N_1 \cdot \frac{N_2}{\sigma_x \sigma_y} \cdot F$$

... increase number of protons per bunch

$N_1, N_2 = 1.2 \longrightarrow 1.7 \cdot 10^{11}$

... decrease the beam size at IP

stronger gradients, larger aperture

$\beta_x = \beta_y = 0.55$ m $\longrightarrow$ 0.15 m

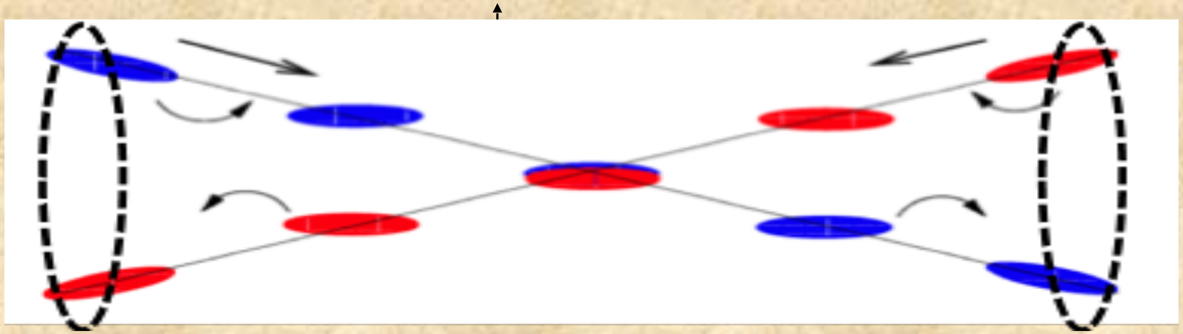
... reduce the geometric loss factor

crab cavities

F is a pure crossing angle (Φ) contribution: $\Phi = 142.5\ \mu rad \longrightarrow 255\ \mu rad$

$$F = \frac{1}{\sqrt{1 + 2\frac{\sigma_s^2}{\sigma_{1x}^2 + \sigma_{2x}^2}\tan^2\frac{\phi}{2}}}$$

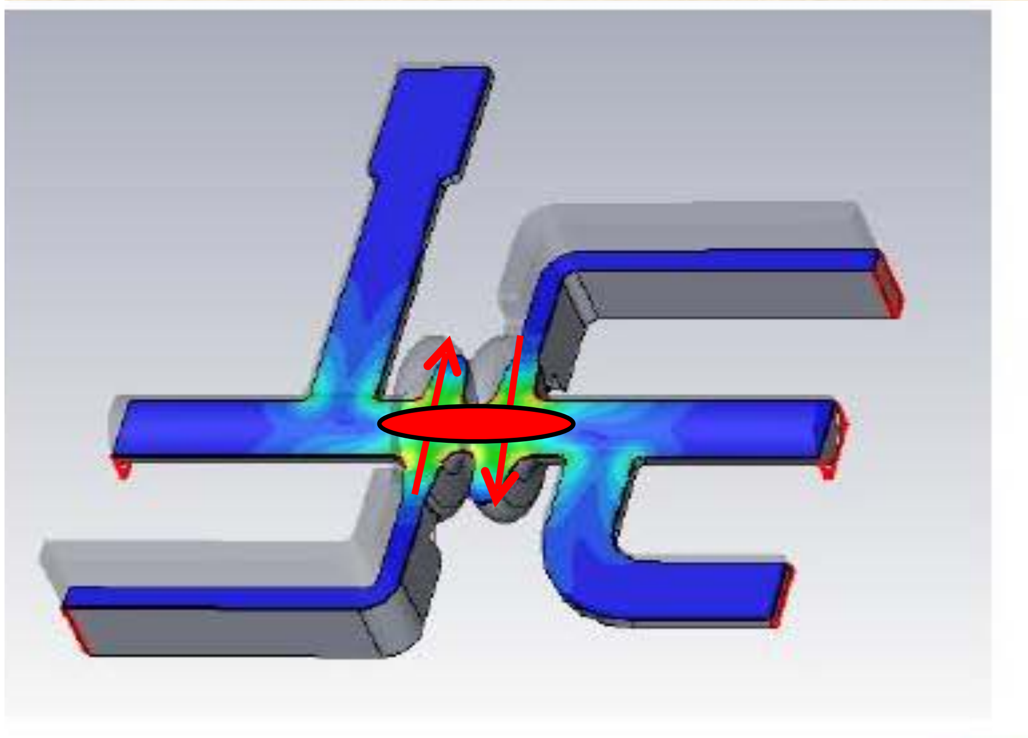
$F_{LHC} = 0.836, \quad F_{HL\text{-}LHC} = 0.31$

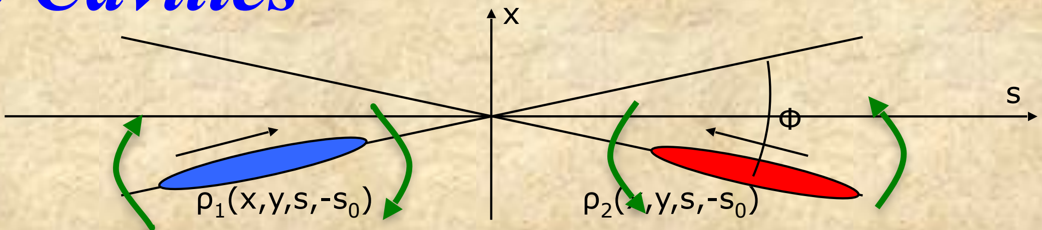


To avoid the geometric luminosity loss …

We have to turn the bunches transversely and allow for head-on collisions

Challenge: HL-LHC Crab Cavities





$$L = L_{ideal} * F$$

$$F = \frac{1}{\sqrt{1 + 2\frac{\sigma_s^2}{\sigma_{1x}^2 + \sigma_{2x}^2}\tan^2\frac{\phi}{2}}}$$

Transverse deflecting cavity at 800 MHz

Prototype tested in SPS.
Technical challenge:
to be fast, precise, compact,
Fail SAFE !!

HL-LHC
means Nb_3Sn technology
for dipoles & quadrupoles

and crab cavities