Large Hadron Collider

Lecture 2

The accelerator and its physics implications

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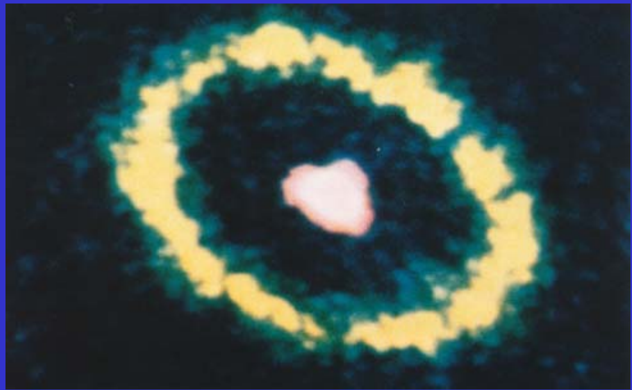
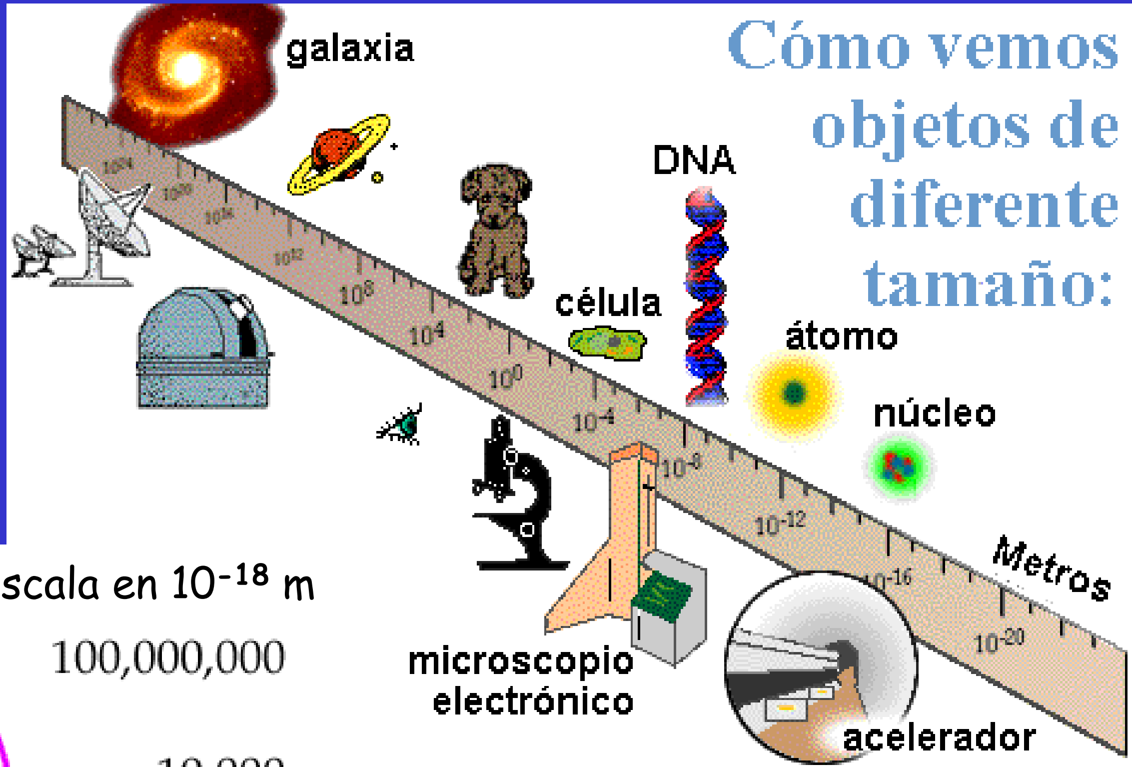
Taller de Altas Energías

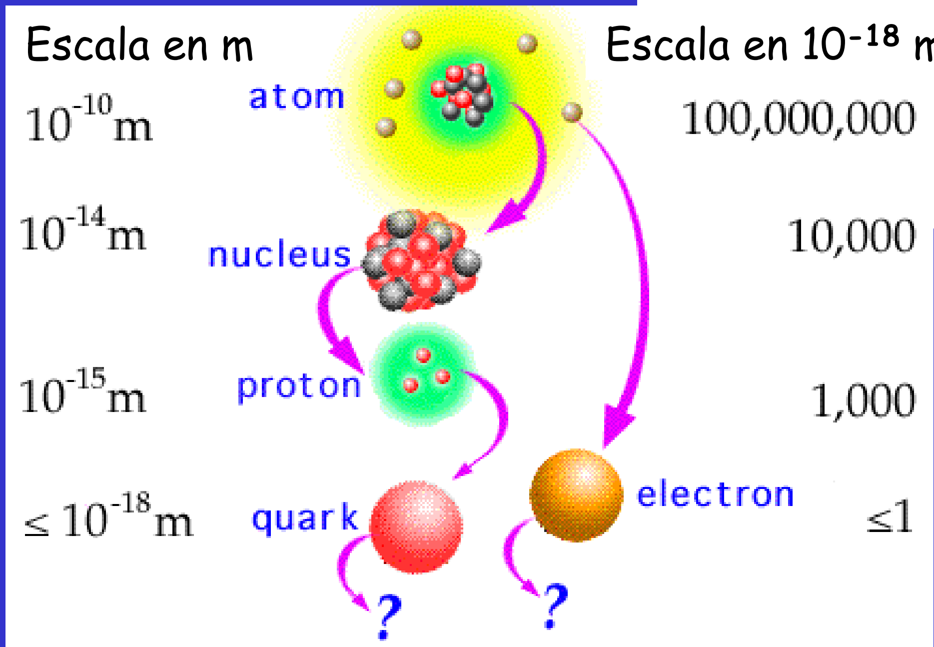
Jaca, 16-18 May 2007

" Las escalas de nuestro mundo "

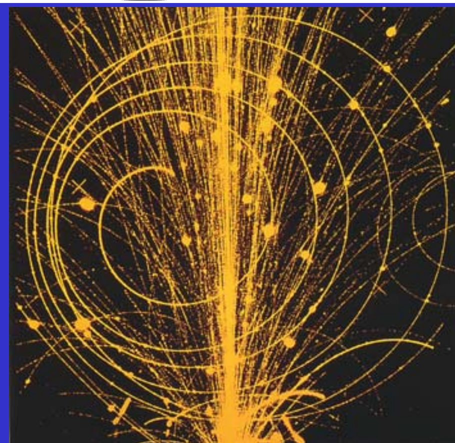


Lo "grande": 10^{22} m"

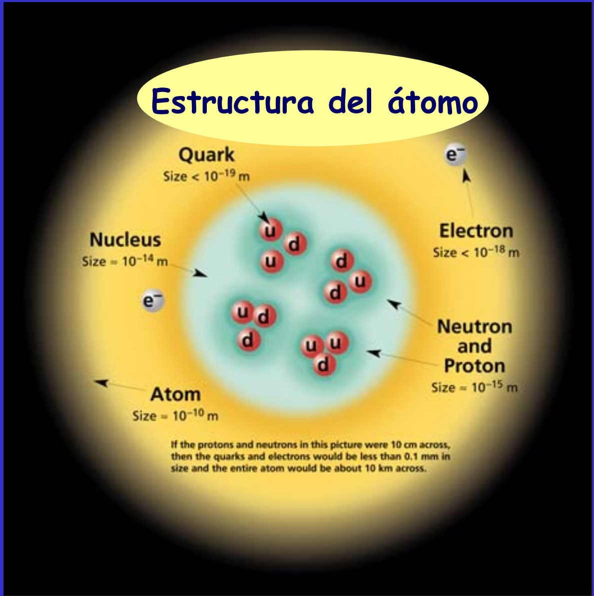




Lo "pequeño": 10^{-18} m"



" El mundo subatómico "



FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

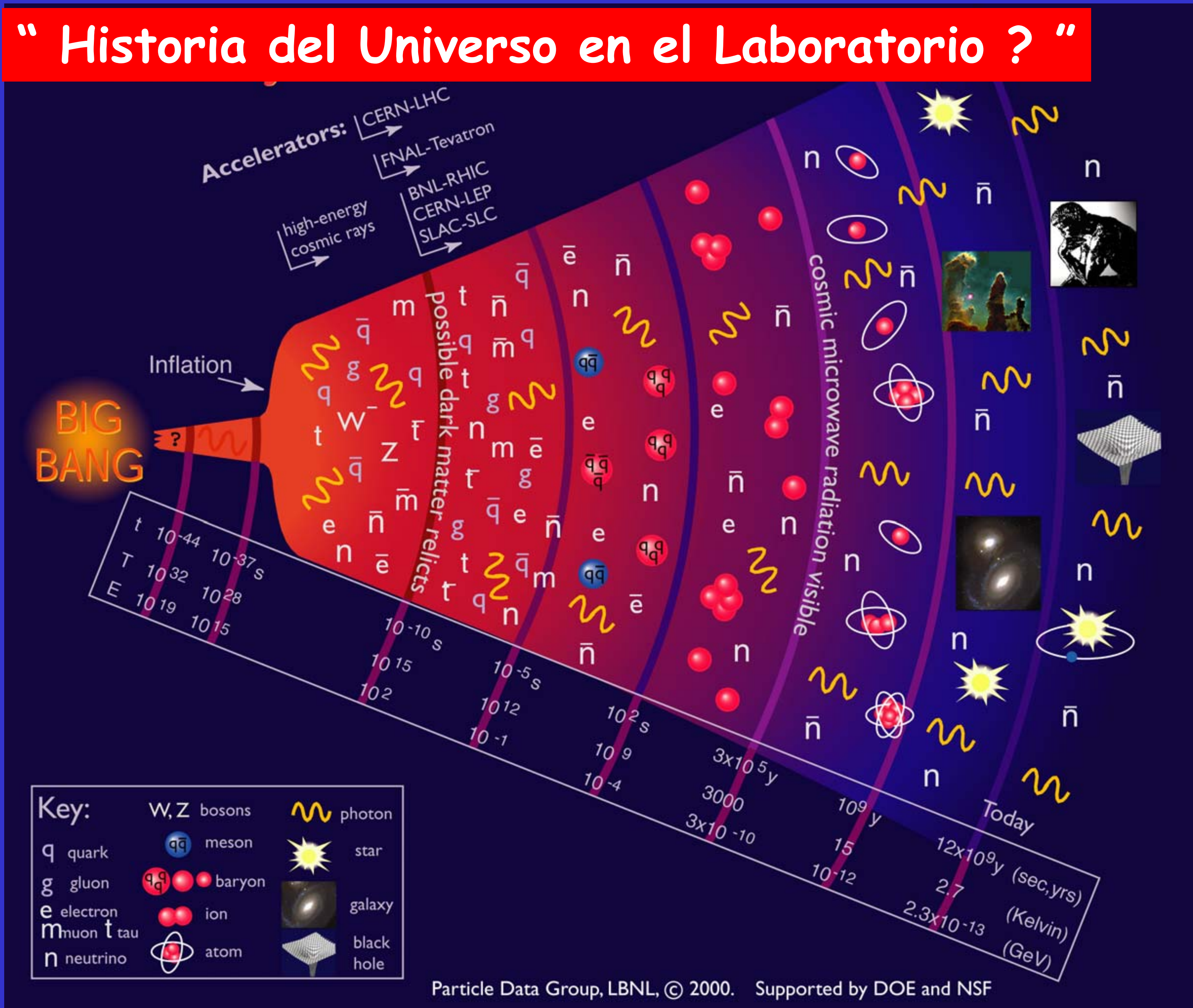
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Solo combinaciones de quarks sin «color» dan a lugar a partículas reales,
Mesones: Quark-Antiquark
Bariones : Tres Quarks (o Tres Anti-Quarks)

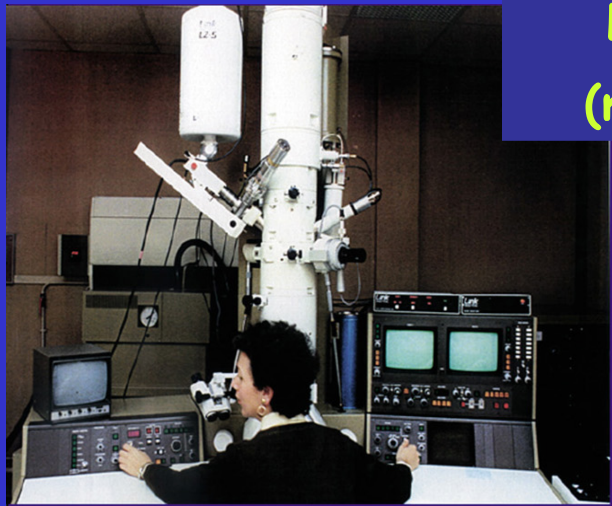
Solo las partículas de la Primera Generación forman materia estable: e^-, p(uud) …
El resto de partículas solo somos capaces de observarlas en los laboratorios (aceleradores o rayos cósmicos) recreando procesos de producción a Altas Energías … condiciones que de manera natural existieron en los primeros instantes de nuestro Universo.

Entonces, podemos recrear las condiciones del Big Bang en el laboratorio ? Es decir remontarnos en el tiempo hasta el origen del universo ?

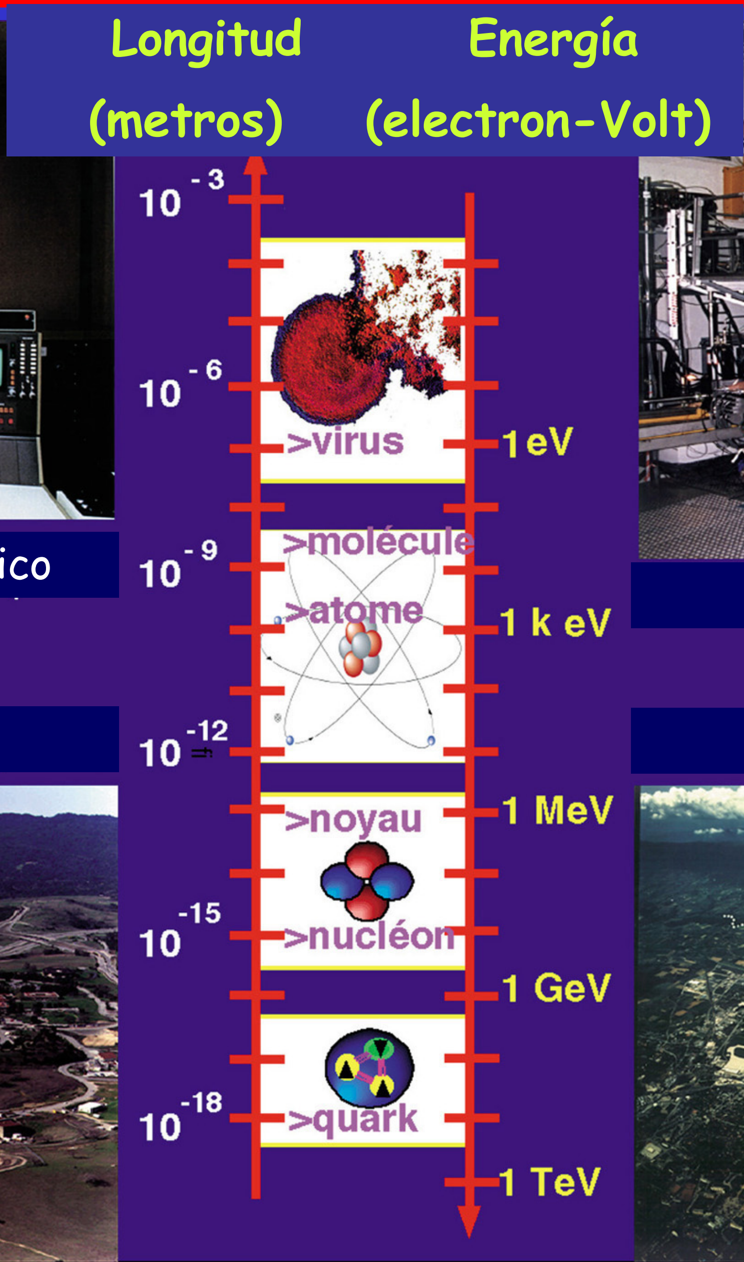
" Historia del Universo en el Laboratorio ? "

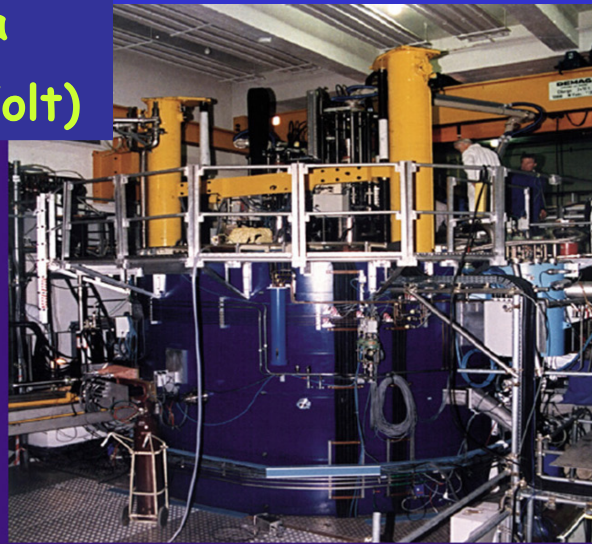


Cómo acceder a estas energías ?
Una manera: Experimentos en Aceleradores



Microscopio Electrónico



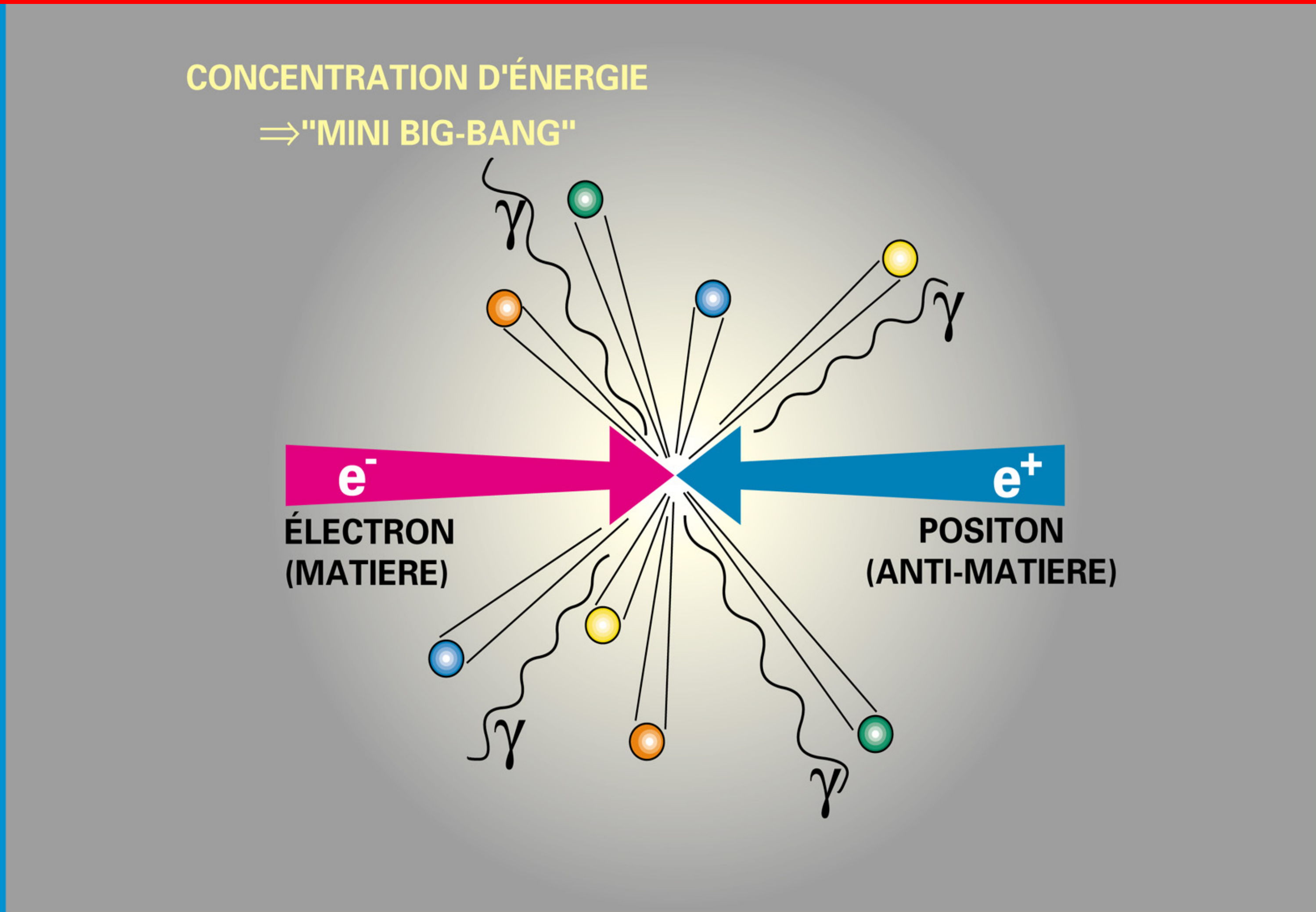


Ciclotrón

Acelerador Lineal

Sincrotrón

$E=mc^2$: aniquilación → El secreto para la accesibilidad y creación de nuevas partículas



T7

Aceleradores

$N_{sucesos} = L \times \sigma$

L = Luminosidad

σ = sección eficáz

Condiciones del Experimento (la energía del proceso, el estado incial..)

$L \propto N_{part} f/A$

f ~ μsec-nsec

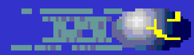
$A \sim 20 \times 200\ \mu m^2$

$N_{part} \sim 10^{10-12}$ part.

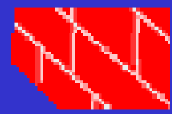
Blanco Fijo

$E \sim (2 m_b E_0)^{1/2}$

E_0 →



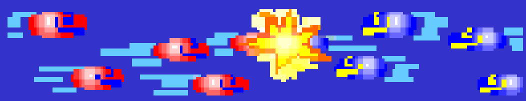
m_b



L **

E *

E_0 → ← E_0

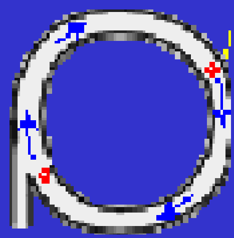


Colisionadores

$E = 2E_0$

$\Delta E_{perdida} \propto E^4/R$

$\Delta E_{perdida} \propto 1/m^4$



Circular

L ***

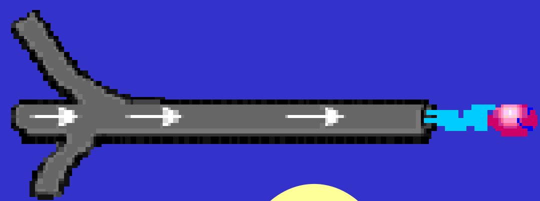
E ***

e^+e^-

pp

$p\bar{p}$

ep



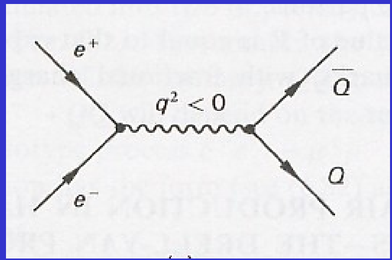
Lineal

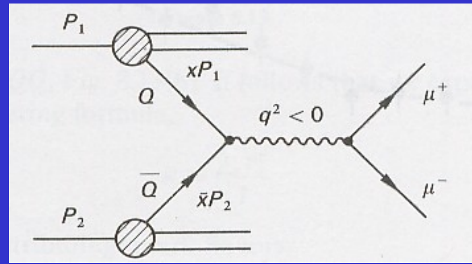
L **

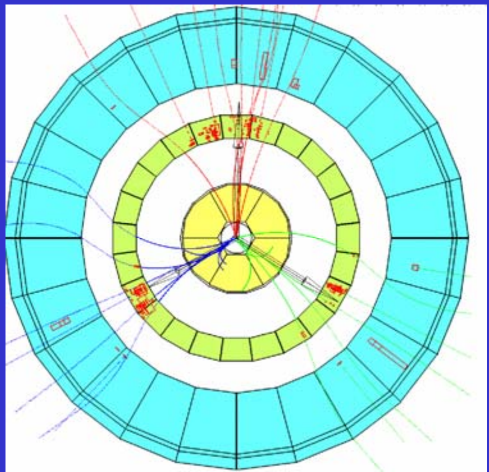
E ***

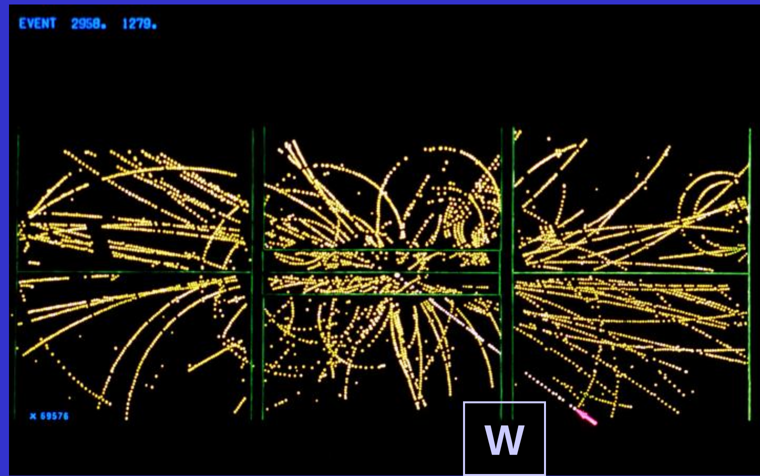
e^+e^-

Aceleradores: e^+e^- versus pp









Los haces son de partículas elementales (e^+e^-)

Energía de la interacción conocida

Todo el estado final es producto de la interacción

Especialidad: Física de Precisión + Alta energía

LEP, $\Delta E_{perdida}$=2.3 GeV para E=100 GeV

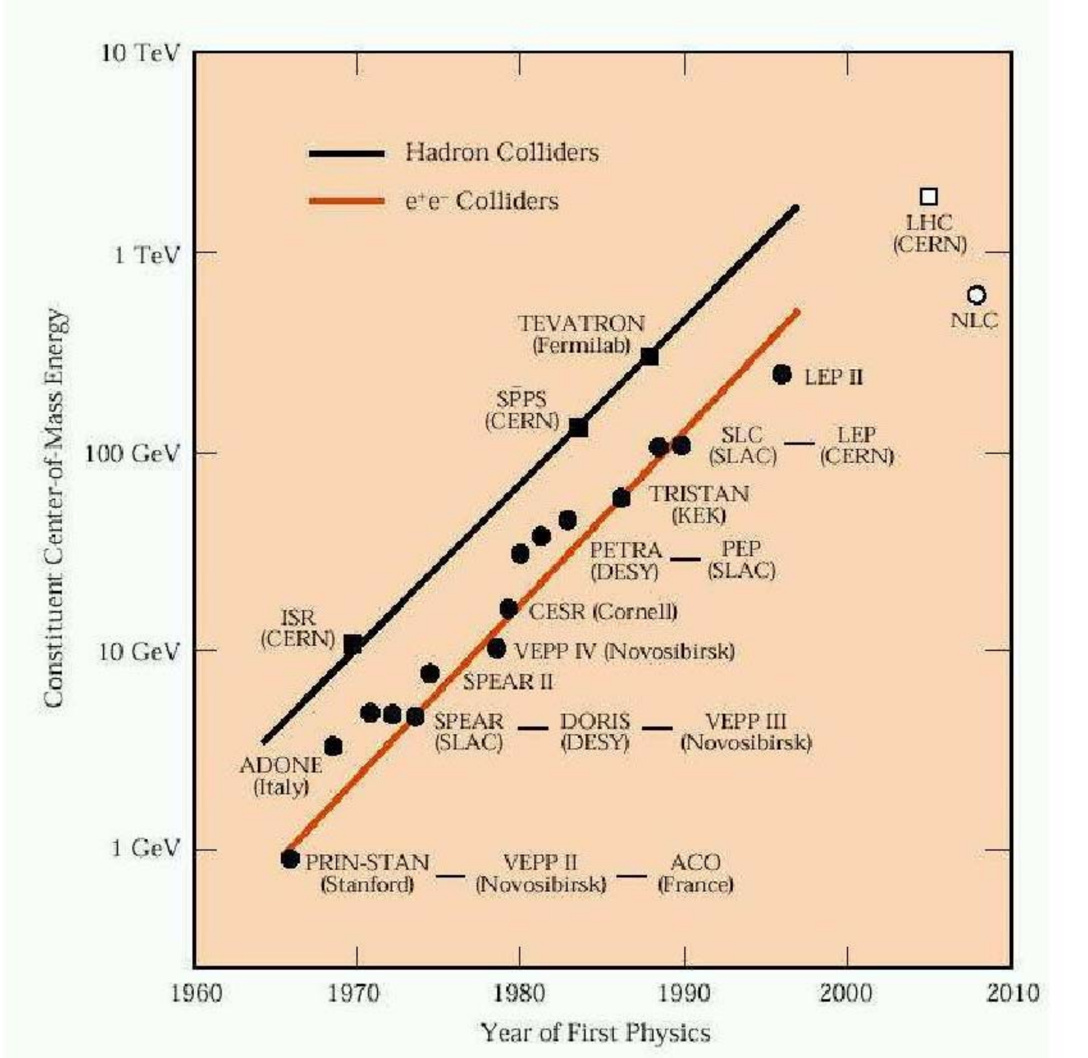
Los haces son partículas compuestas (pp)

Energía de la interacción desconocida

Parte del estado final es producto de la interacción

Especialidad: Alta energía: exploración de regiones cinemáticas nuevas (Descubrimientos).

Hadron colliders versus e+e- circular accelerators



El lugar: CERN
El mayor laboratorio europeo dedicado a la investigación de Partículas

Fundado en 1954 (50 aniversario).

Situado en Ginebra (Suiza)

Una de las primeras aventuras europeas de colaboración internacional.

Actualmente cuenta con 20 estados miembros (entre ellos España). Otros estados participan en calidad de "estados observadores" (EEUU, Japón, Rusia ...) .

Contribución de acuerdo con PIB de cada pais (España contribuye alrededor del 7%).

Mas de 10.000 científicos de todo el mundo participan en experimentos del CERN (Consejo Superior de Investigaciones Científicas –CSIC- son unos 5.000 científicos).

Los principios del CERN

1952

Pierre Auger y Edoardo Amaldi

Genève fut choisie comme siège du CERN à la troisième session du Conseil, à Amsterdam, en octobre 1952. Ce choix fut entériné par un référendum organisé dans le Canton de Genève, en juin 1953, et qui donna 16539 voix pour et 7332 voix contre; en octobre, à l'occasion d'une session du Conseil à Genève, les membres du Conseil du CERN purent visiter un site encore très champêtre.

Votación

1953

Sur le terrain du futur institut nucléaire

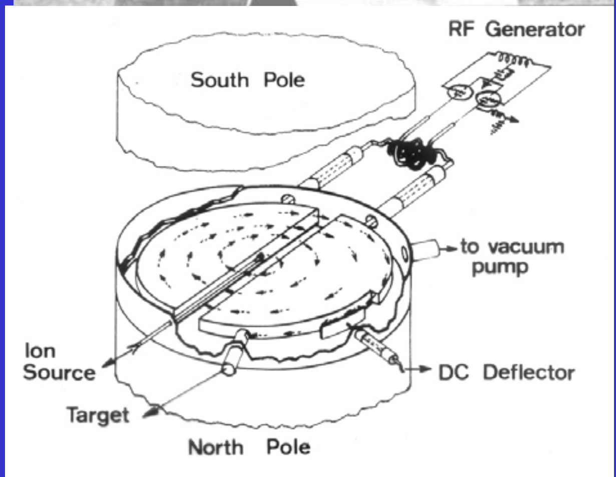
Sous la conduite de M. A. Picot, les membres du Conseil européen pour la recherche nucléaire se sont rendus hier à Meyrin pour reconnaître le terrain où s'élèvera le Centre nucléaire (voir en Dernière heure)

(Photo Freddy Bertrand, Genève)

La Suisse du 30 octobre 1953

17 de Mayo de 1954 en Ginebra hace 50 años

Primeros trabajos de construcción civil incluso antes de ser ratificados por el propio Consejo del CERN, para adelantarse al invierno



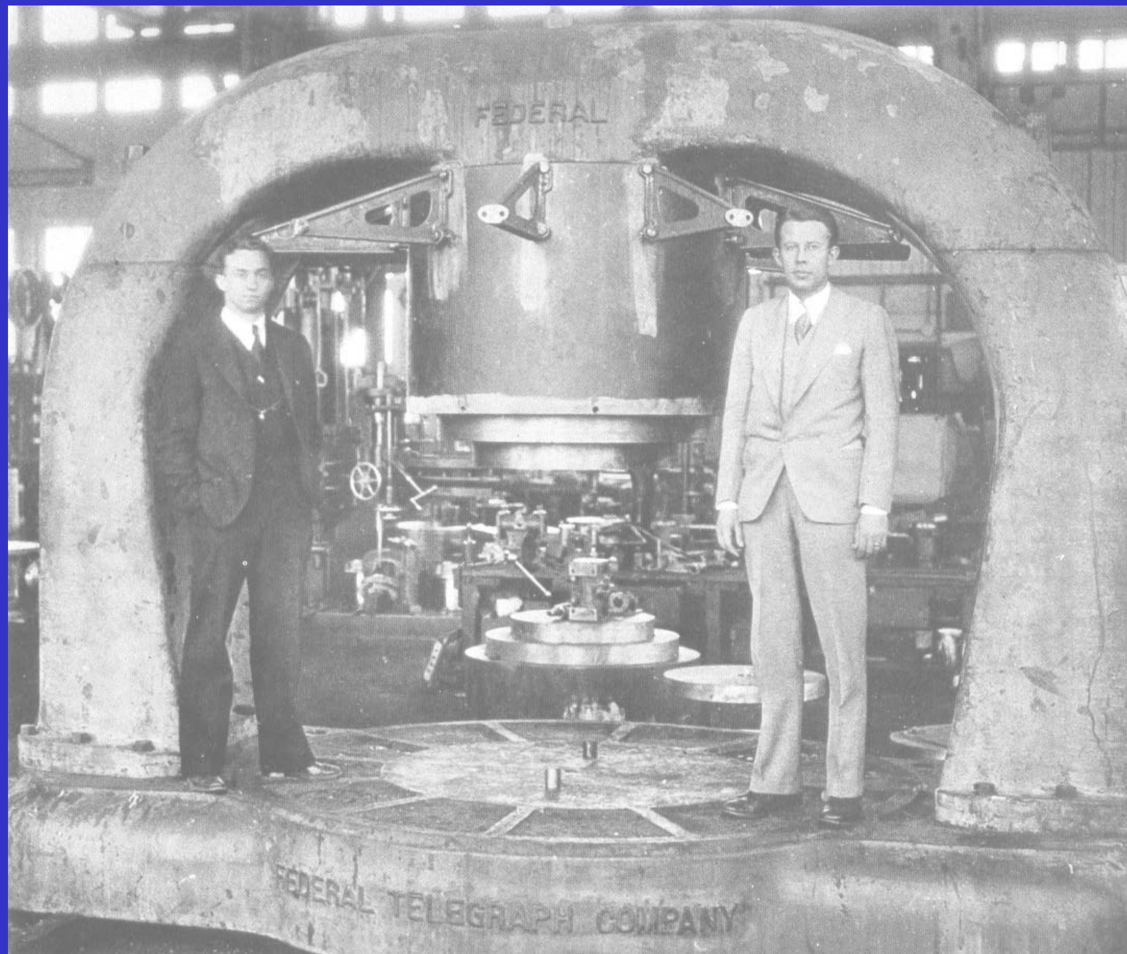
1930

Ernest Lawrence inventa el primer

Acelerador circular: el ciclotrón

M. S. Livingston and E. Lawrence

Con su ciclotrón de 25'



25 de Noviembre de 1959: el SPS funciona !

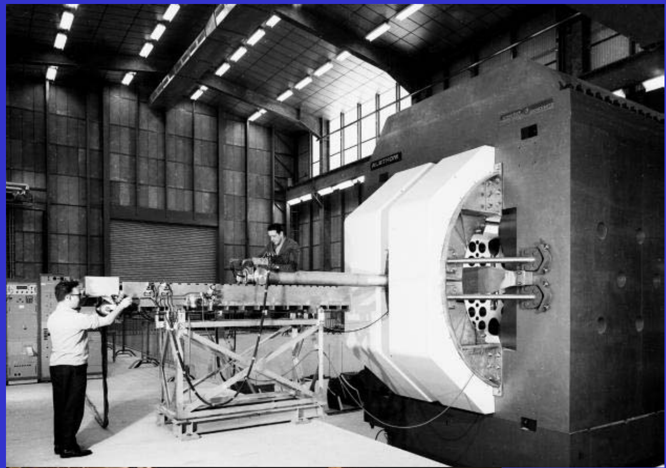
Wolfgang Schnell

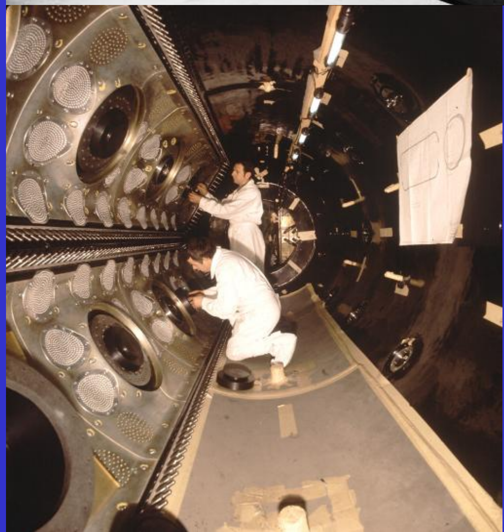
inventor del CLIC

John Adams

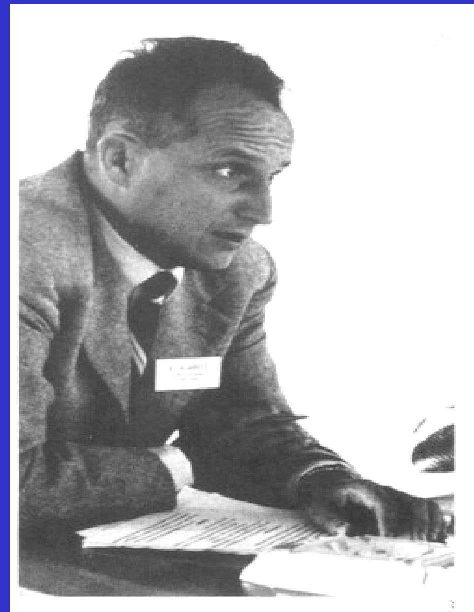
El PS en 1960

1973: Descubrimiento de las corrientes neutras en Gargamelle





GGM 1969-70



André Lagarrique

neutrino

Los principios del CERN

1975

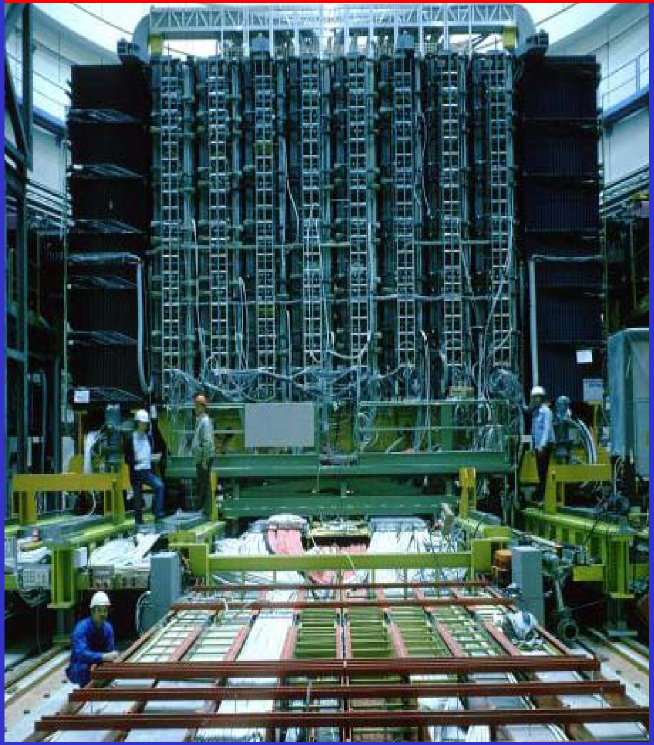
Se consiguen protones a 450 GeV en el SPS

1981: El acumulador de anti-protones

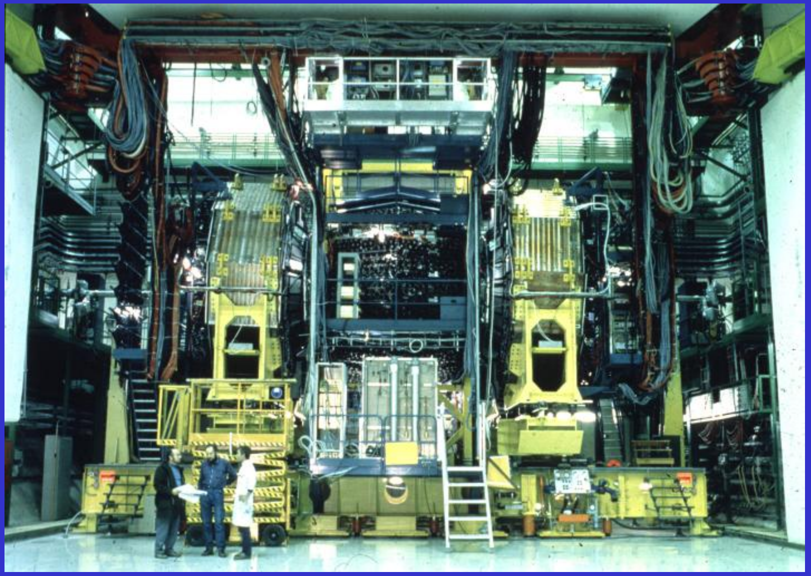
1981: el SPS se transforma en un colisionador proton-antiproton collider utilizando la técnica de Simon van der Meer para el enfriamiento de antiprotones

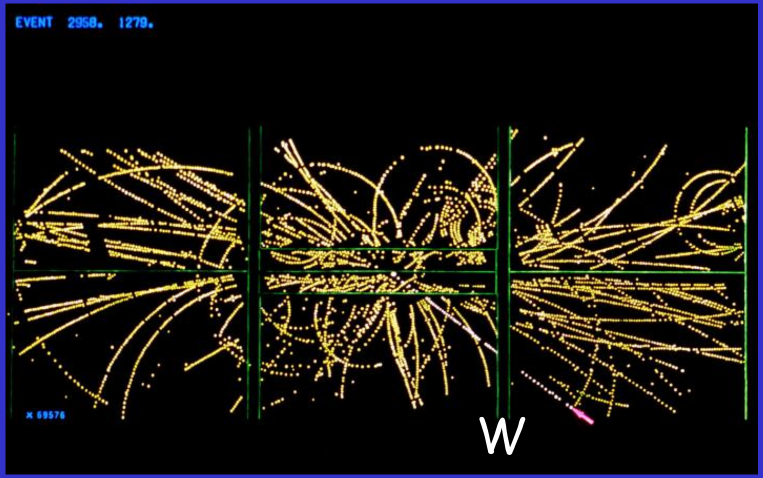
1983: Descubrimiento de los bosones W y Z

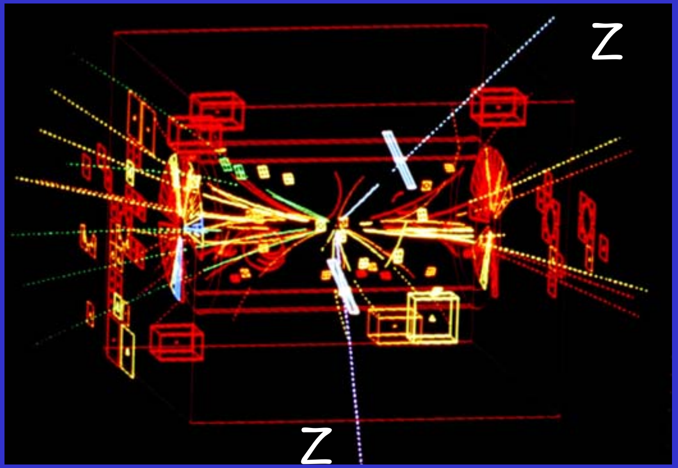
UA1



UA2







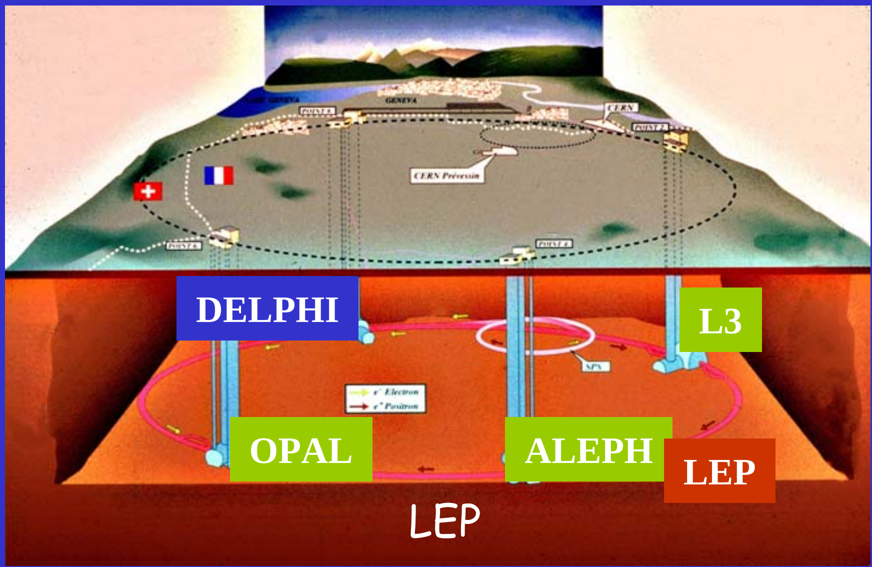
Los que recibieron el Premio Nobel

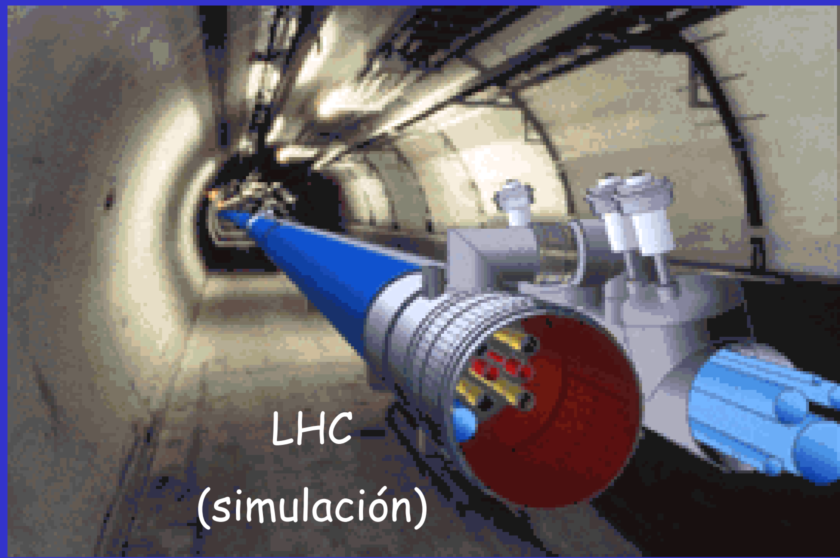
G. Charpak C. Rubbia S. van der Meer

Las Infraestructuras del CERN actuales: LEP (1989-2000) -- LHC(2007-2017 ?)

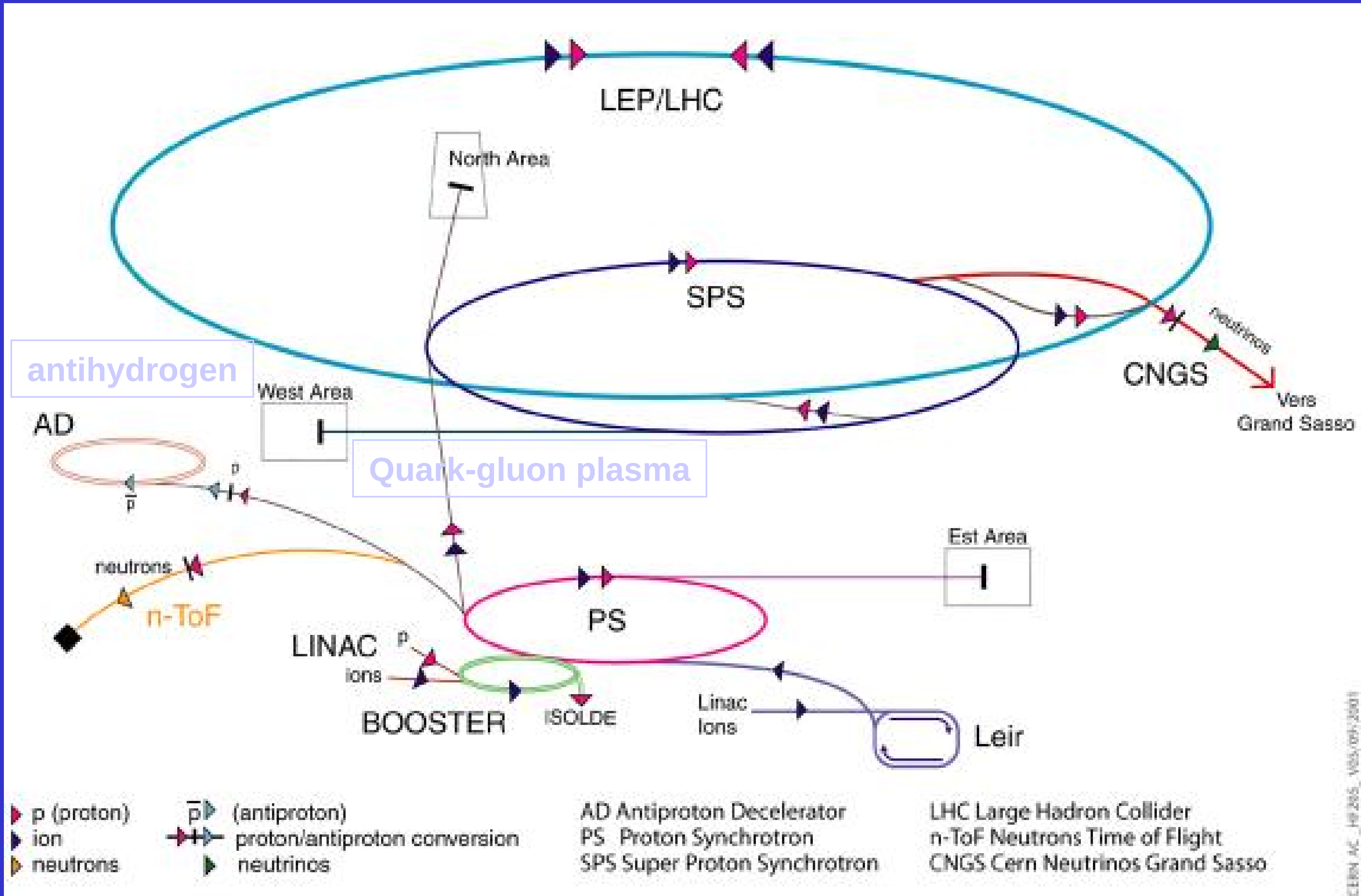
LEP (Large Electron Positron Collider)
E ~ 100-200 GeV
600 millones de euros
27 km (a ~100 m de profundidad)

LHC (Large Hadron Collider)
Imanes superconductores
E ~ 14 TeV
2000 millones de euros
27 km (a ~100 m de profundidad)





Configuración actual del CERN



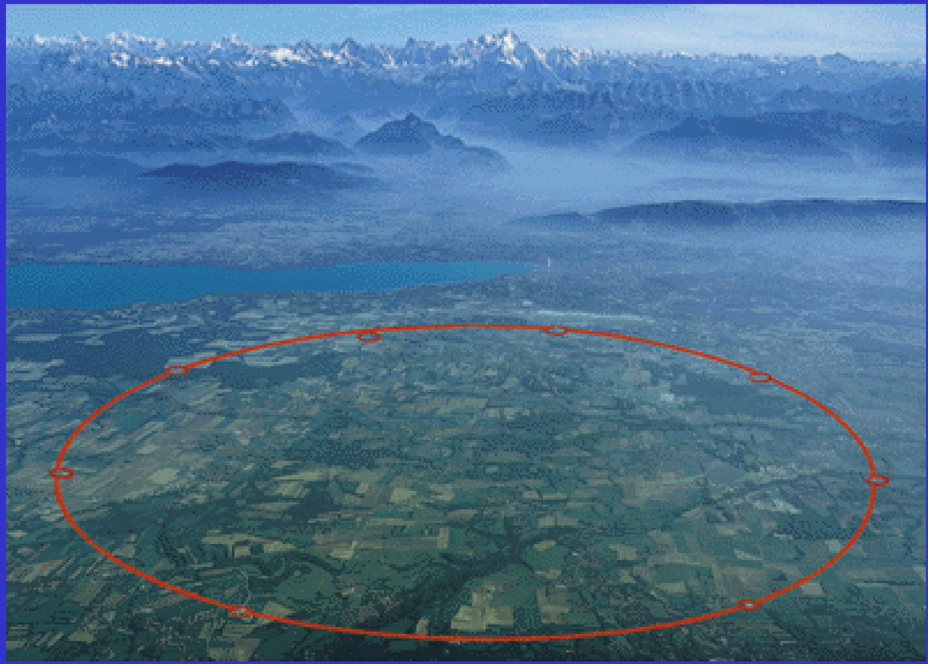
The Large Hadron Collider (LHC)

Proton-proton accelerator in the LEP-tunnel at CERN

p ⇒ ⇐ p

7 TeV 7 TeV

- Four planned experiments:
  - ATLAS, CMS (pp physics)
  - LHC-B (b-quark physics)
  - ALICE (Pb-Pb collisions)
- Constructed as an international collaboration
- Startup planned for 2008



The Large Hadron Collider (LHC): components

- superconducting dipole magnets
  - challenge: magnetic field of 8.33 Tesla
  - in total 1232 magnets, each 15 m long
  - operation temperature of 1.9 K

LHC is the largest cryogenic system in the world

- accelerator structures
  RF cavities with gradient of 5 MV/m

Status of the LHC machine

Beam energy	7 TeV
Luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam

- Key components available
- Installation progressing in parallel and at high speed;

A "likely" startup scenario (one month ago !):

Late 2007: Pilot run, first collisions (at injection energy)

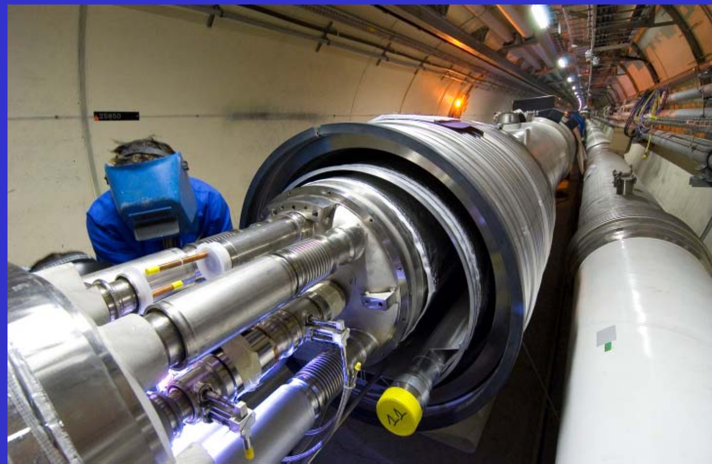
→ detector and trigger commissioning, calibration, early physics

2008: First Physics run at nominal energy

(changed by late accident; impact unknown yet but not dramatic)

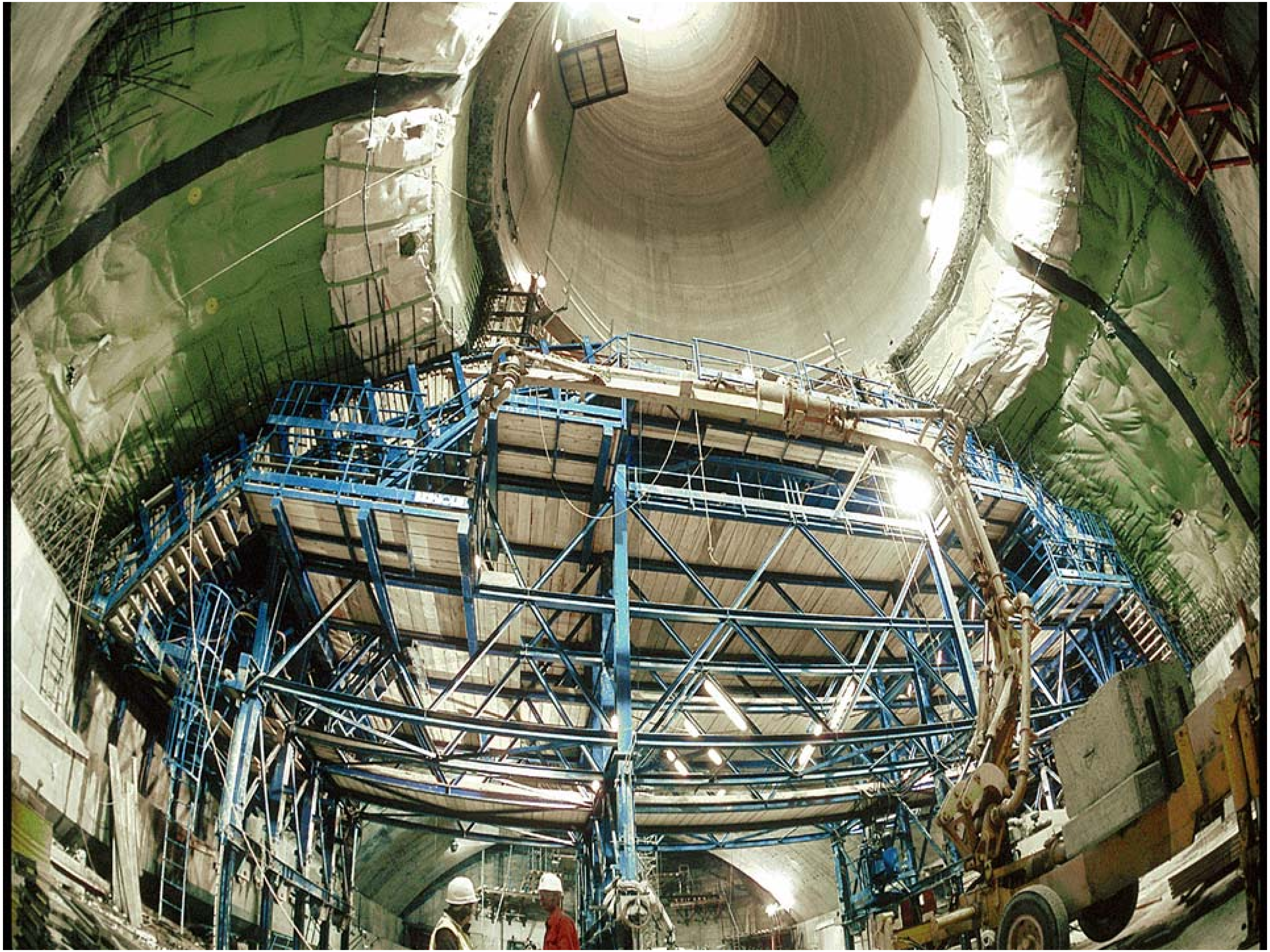
Installation work, underground

Preparation for installation, Hall SMI2

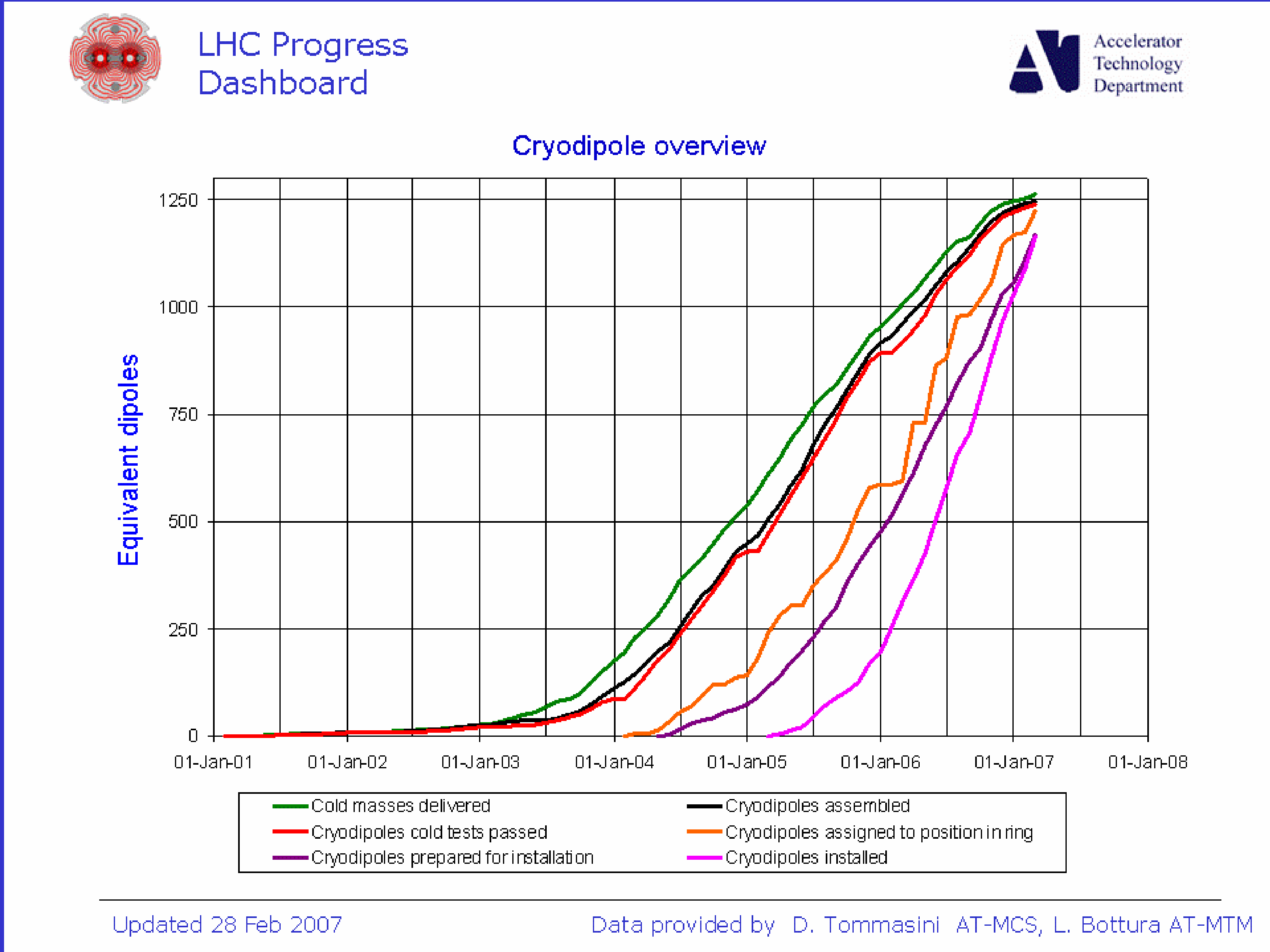


First cryodipole lowered on 7 March 2005

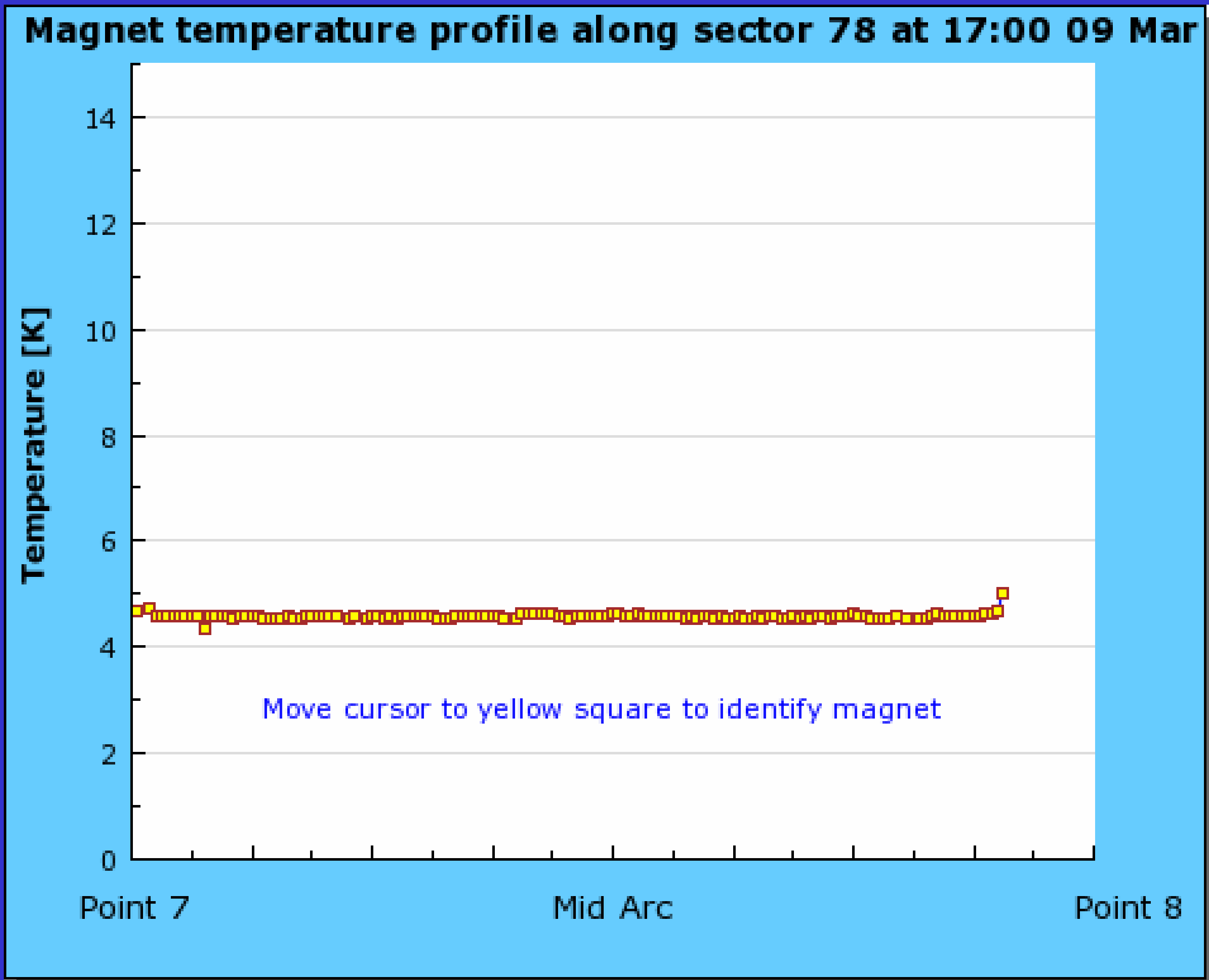

MAFI



Cryodipole overview



Sector 7-8: cool down status



Parámetros del LHC (R. Cid Manzano)

Aceleración: $a \sim c^2/R \sim 2x10^{13}$ m/s, 2 billones de veces la gravedad terrestre

Vueltas por protón: $w \sim c/2\pi R \sim 11245$ v/s, $f \sim 11$ KHz

Paquetes de protones: 10^{11} protones, con dimensiones de ~7cmx20μm^2

Separación paquetes: d~7,5 m, frecuencia de cruce 25 ns, paquetes 3560/2835

Número protones: $3x10^{14}$ p, dos haces: 600 billones de p, m_{Np}~ 0.000000001 gr

Fuerza Centrípeta total: $F_T \sim 157000$ N, ~16 toneladas producidas por un 1 ngr !

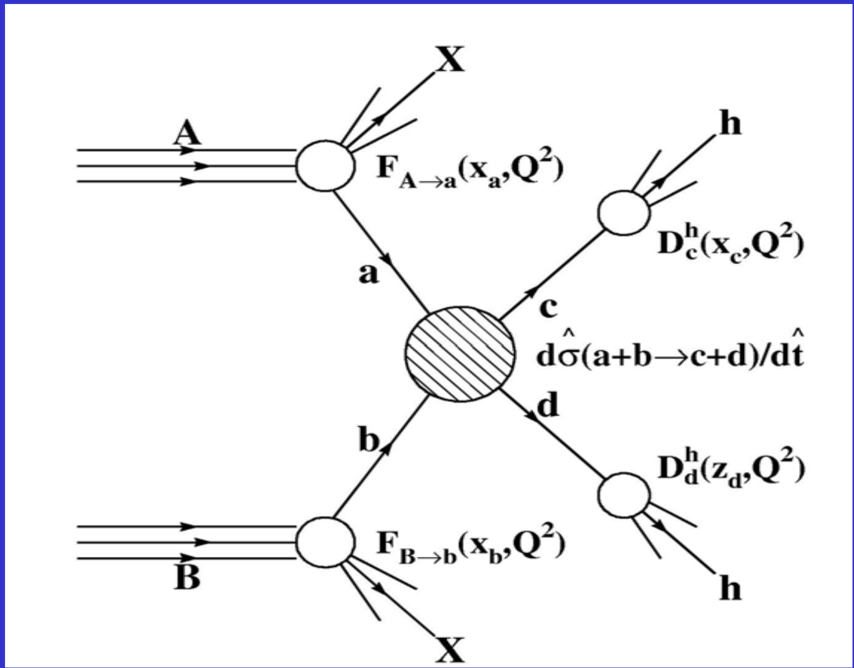
Energía del acelerador: 7 TeV ~ $1{,}12x10^{-6}$ J, densidad energía p: d~$8x10^{38}$ J/m^3
Equivalente a la energía de un insecto 60 mg y volando a 20 cm/s y d~$1x10^3$ J/m^3

Energía cinética paquete: $1{,}2x10^5$ J, equivalente a una moto de 180 Kg a 130Km/h
(el impacto sería equivalente pero ojo al tamaño y peso del paquete !!!)

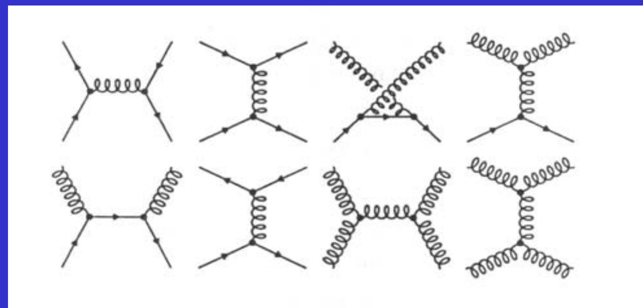
Carga eléctrica y corriente: Q ~ 0.54 Culombios, I ~ 0,54 Amperios

Calor disipado: en LEP era de 2400 Kcal/s ; LHC ~ LEPx30 imanes convencionales (refrigeración: evacuar 30 T/s de agua, necesidad imanes superconductores ~ 3ºK (5000 T de He, la producción mundial anual)

Physics at Hadron Colliders



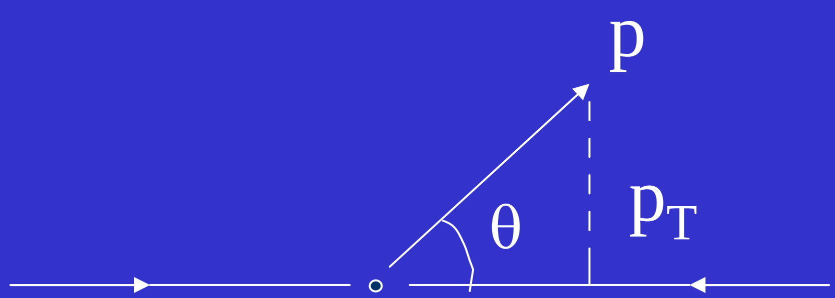
- Protons are complex objects:
  Quarks and Gluons
- Hard scattering processes:
  (large momentum transfer)
  quark-quark, quark-gluon,
  gluon-gluon interactions



However: hard scattering (high P_T processes) represent only a tiny fraction of the total inelastic pp cross section

The total inelastic pp cross section (70 mb) is dominated by events with small momentum transfer

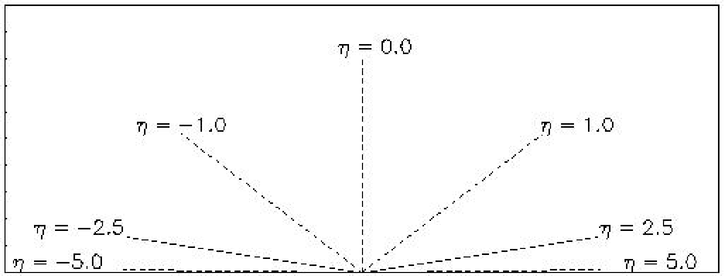
Variables used in the analysis of pp collisions



Transverse momentum
(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

pseudorapidity: $\eta = -\ln \tan \frac{\Theta}{2}$



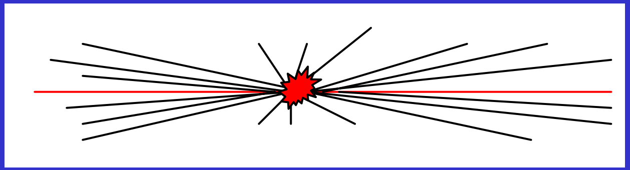
$\theta = 90^o \rightarrow \eta = 0$

$\theta = 10^o \rightarrow \eta \cong 2.4$
$\theta = 170^o \rightarrow \eta \cong -2.4$

$\theta = 1^o \rightarrow \eta \cong 5.0$

Inelastic low - PT collisions

Most collisions are due to <u>interactions at large distance</u> between incoming Protons → <u>small momentum transfer</u>, particles in the final state have large longitudinal but small transverse momentum

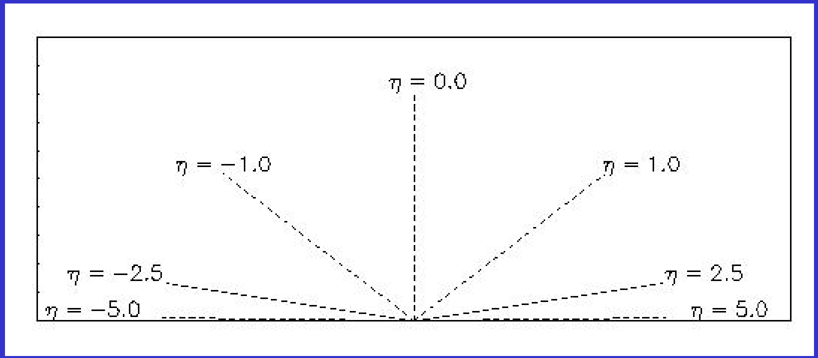


$< p_T > \approx 500$ MeV (of charged particles in the final state)

$$\frac{dN}{d\eta} \approx 7$$

- about 7 charged particles per unit of pseudorapidity in the central region of the detector
- uniformly distributed in Φ

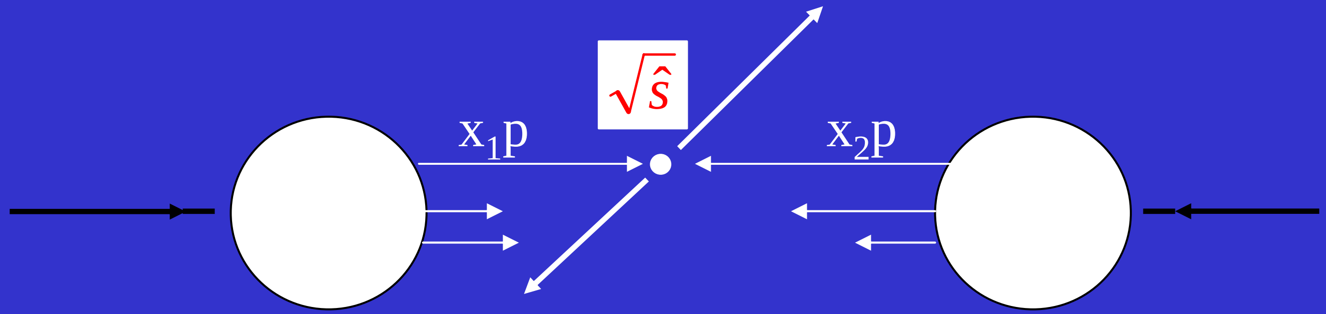
These events are called "Minimum-bias events"



Hard processes

Proton beam can be seen as beam of quarks and gluons with variable energies

The proton constituents (partons) carry only a fraction 0 < x < 1 of the proton momentum



The effective centre-of-mass energy $\sqrt{\hat{s}}$ is smaller than $\sqrt{s}$ of the incoming protons

$$p_1 = x_1 \, p_A$$
$$p_2 = x_2 \, p_B$$
$$p_A = p_B = 7 \text{ TeV}$$

$$\sqrt{\hat{s}} = \sqrt{x_1 \, x_2 \, s} = x \sqrt{s}$$

$$(\text{if } x_1 = x_2 = x)$$

<u>To produce a mass of:</u>

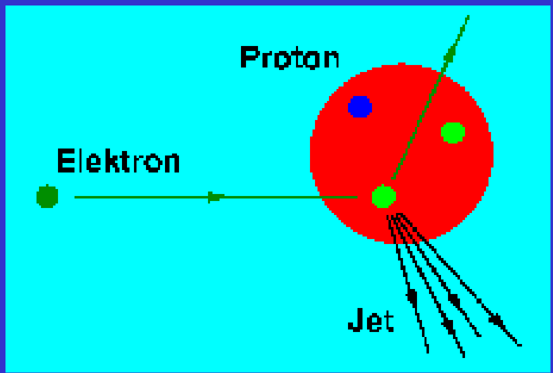
	LHC	Tevatron
100 GeV:	x ~ 0.007	0.05
5 TeV:	x ~ 0.36	--

From where do we get the x-values ?

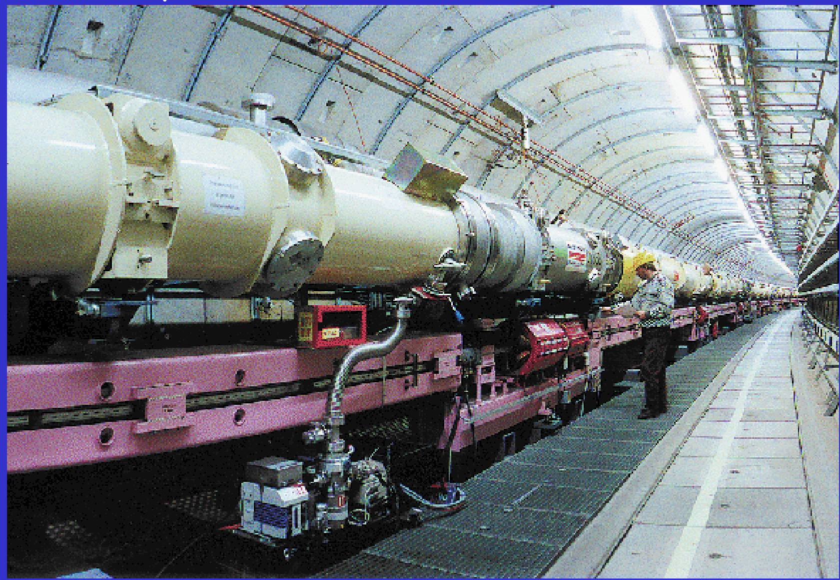
The structure of the proton is investigated in Deep Inelastic Scattering experiments:

Today's highest energy machine: the HERA ep collider at DESY/Hamburg

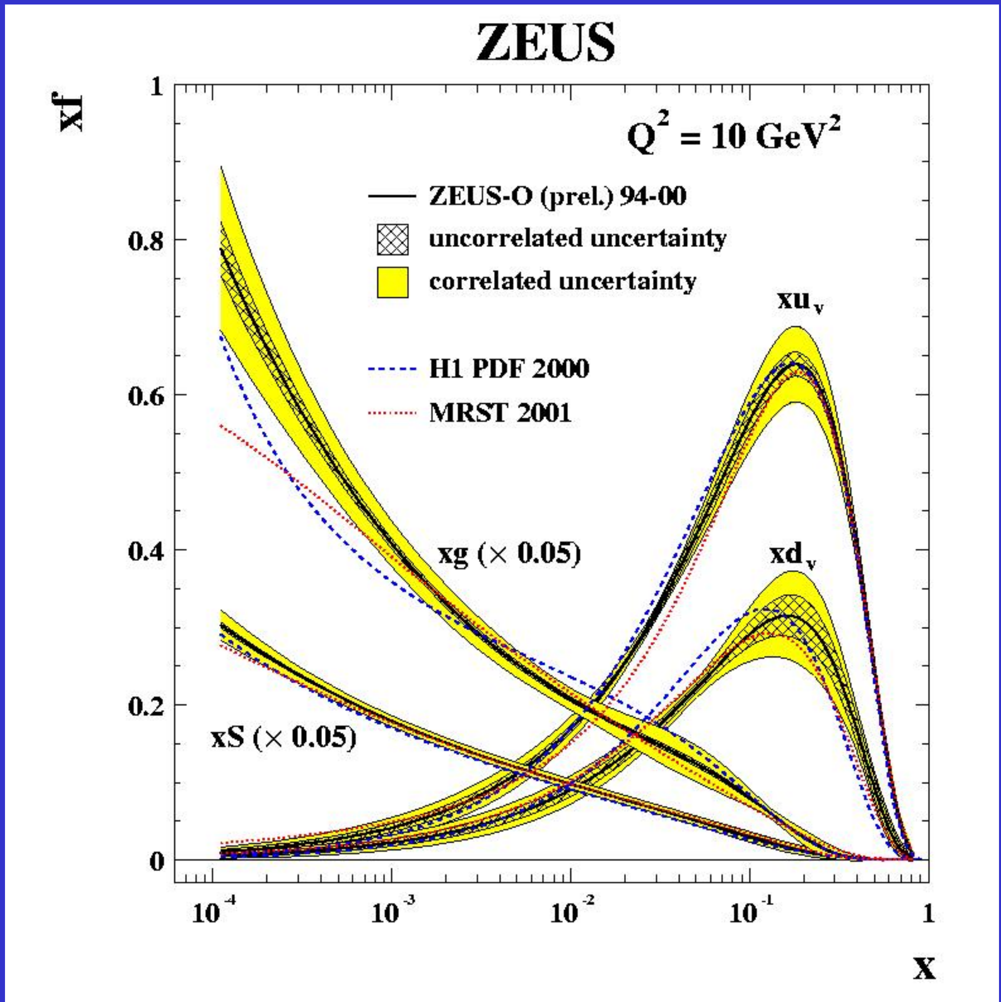
Scattering of 30 GeV electrons on 900 GeV protons



HERA ep accelerator, 6.3 km circumference



How do the x-values of the proton look like?



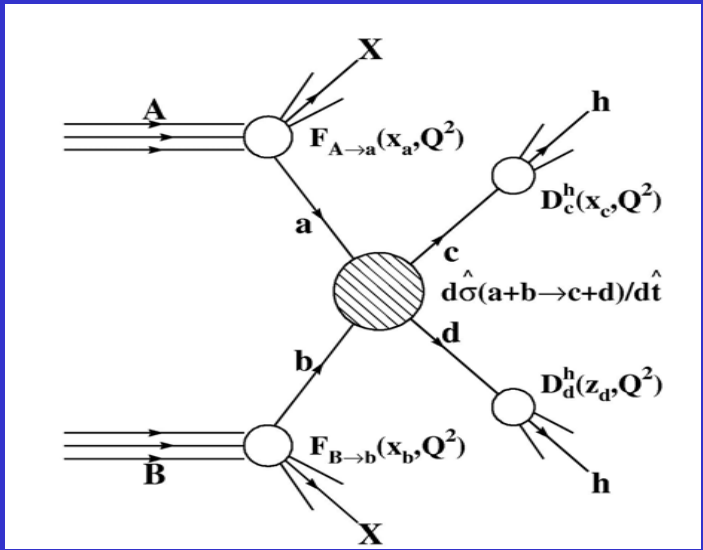
Parton density functions (pdf):

u- and d-quarks dominate
at large x-values

Gluons dominate at small x !!

There are uncertainties in the pdfs, in particular on the gluon distribution at small x

Calculation of cross sections



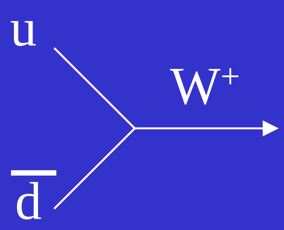
$$\sigma = \sum_{a,b} \int dx_a\, dx_b\, f_a(x_a, Q^2)\, f_b(x_b, Q^2)\, \hat{\sigma}_{ab}(x_a, x_b)$$

Sum over initial partonic states: a,b

$\hat{\sigma}_{ab}$ $\equiv$ hard scattering cross-section

$f_i(x, Q^2) \equiv$ parton density function

Example: W-production: (leading order diagram)



σ (pp $\rightarrow$ W) ~ 150 nb ~ $2 \cdot 10^{-6}\, \sigma_{tot}$ (pp)

… + higher order QCD corrections (perturbation theory)

Luminosity and Event Rate

The rate of produced events for a given physics process is given by:

$$N = L \times \sigma$$

L = Luminosity
σ = cross section

dimensions: $s^{-1} = cm^{-2}\, s^{-1} \cdot cm^{2}$

Luminosity depends on the machine:
important parameters: number of protons stored, beam focus at interaction region,….

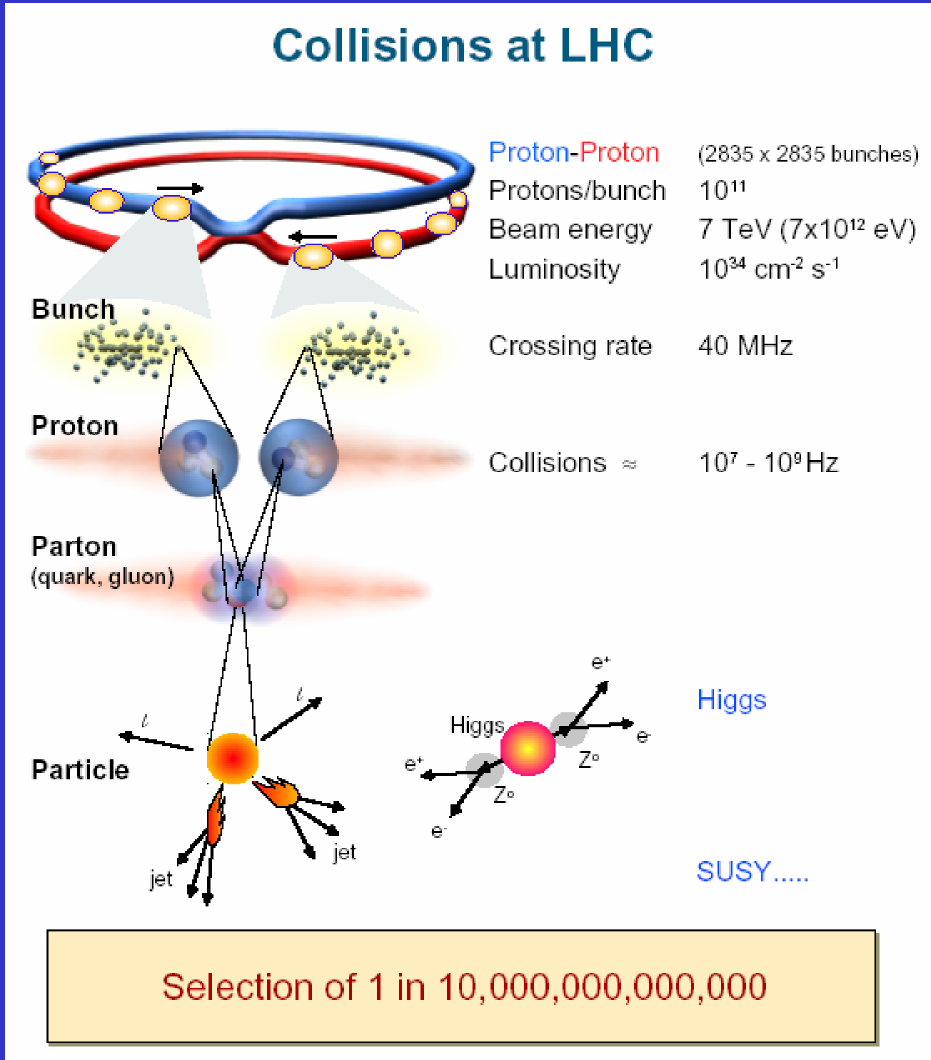
In order to achieve acceptable production rates for the interesting physics processes, the luminosity must be high as possible

$L = 2 \cdot 10^{32}\ cm^{-2}\, s^{-1}$ design value for Tevatron Run II
$L = 10^{33}\ cm^{-2}\, s^{-1}$ planned for the initial phase of the LHC (3 years)
$L = 10^{34}\ cm^{-2}\, s^{-1}$ LHC design luminosity, very large !!

One experimental year has ~ 10^{7} s

Integrated luminosity at the LHC: $10\ fb^{-1}$ per year, in the initial phase
$100\ fb^{-1}$ per year, later, design

Proton-proton collisions at LHC

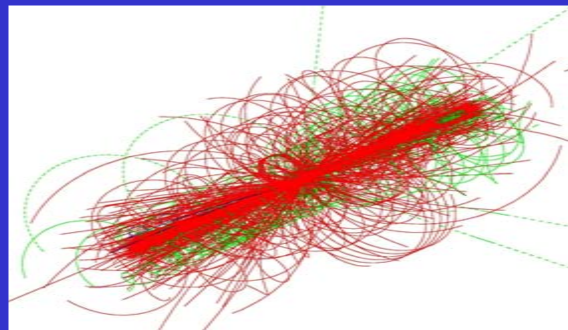


Luminosity:

2835 x 2835 bunches
Separation: 25 ns
10^{11} protons / bunch
Bunch radius: 15 μm
Luminosity: $L = 10^{34}\ cm^{-2}\ s^{-1}$

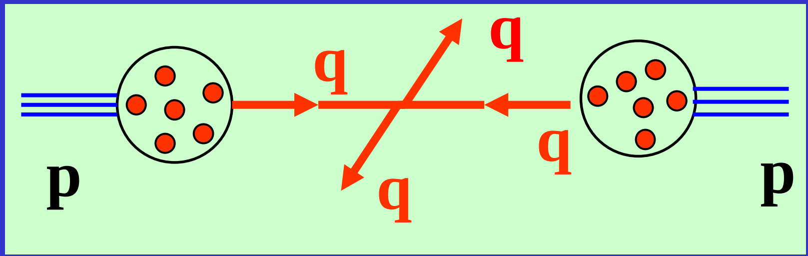
Pile-up:

~10^9 pp collisions / s (σ ~70 mb)
(superposition of 23 pp-interactions per bunch crossing: **pile-up**)
~1600 charges particles in the detector
⇒ high particle densities



What to look for: signatures

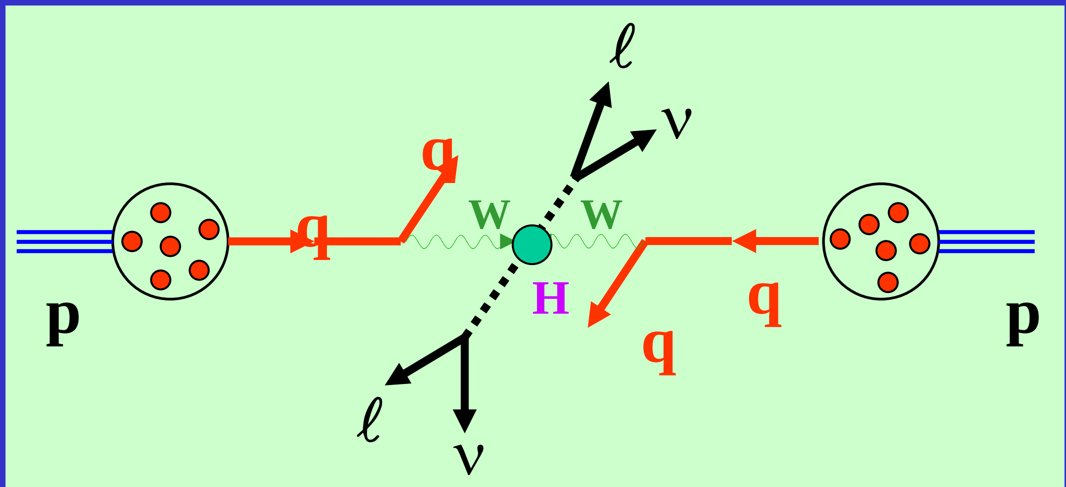
Quark-quark scattering:



No leptons / photons / b-,t-quarks in the initial and final state

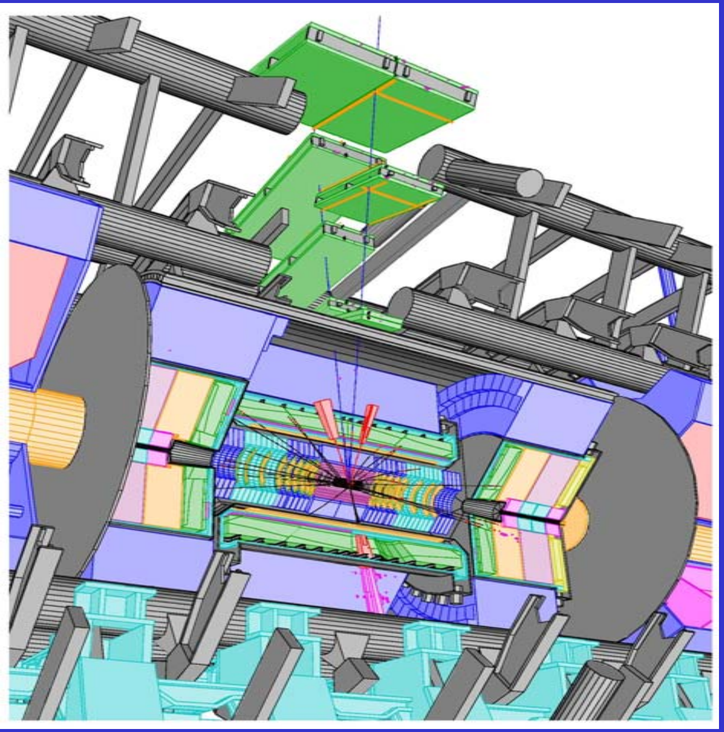
If leptons with large transverse momentum are observed:
⇒ **interesting physics !**

Example: Higgs boson production and decay



Important signatures:
- **Flavour tagging**
- **Leptons und photons**
- **Missing transverse energy**

General detector requirements from physics



- Good measurement of leptons and photons with large transverse momentum P_T

- Good measurement of missing transverse energy (E_T^{miss})

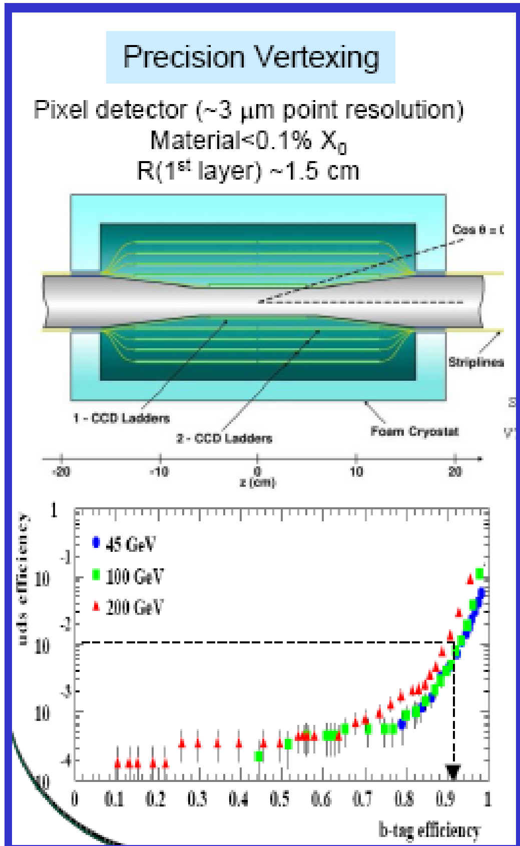
  and

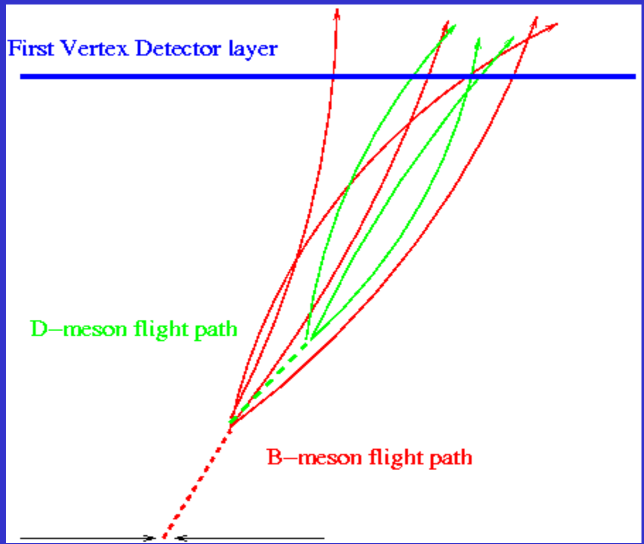
  energy measurements in the forward regions

  $\Rightarrow$ calorimeter coverage down to $\eta \sim 5$

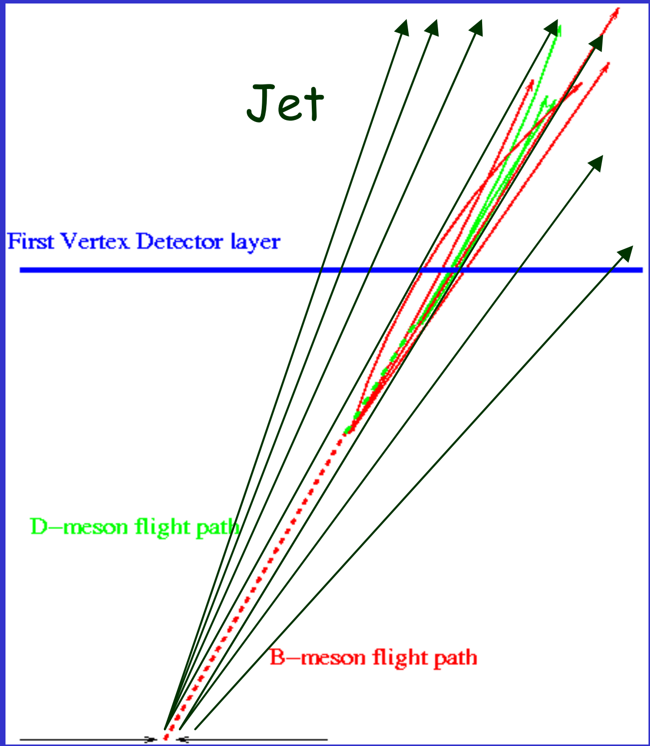
- Efficient b-tagging and τ identification (silicon strip and pixel detectors)

Flavour tagging





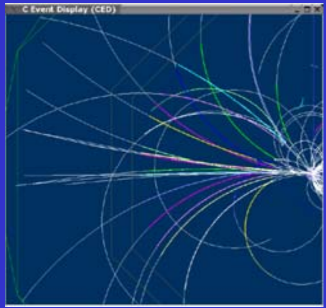
"soft b-jet"



"hard b-jet"

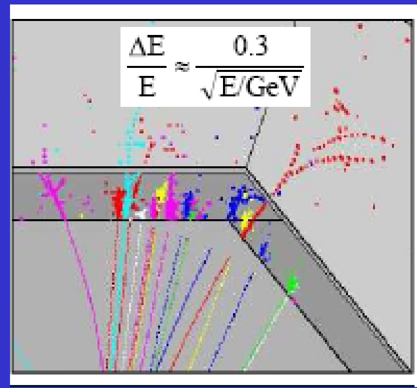
- ✓ Typically b-tagging becomes "easier" for larger jet energy (more and stiffer tracks, boost leads to greater displacement of the vertex for the same lifetime)
- ✓ True only up to the point where a negative effect kicks in: the dense environment in collimated jet, with B/D decay vertex very close to first layer, leads to problems in hit-to-track assignment, merging of hits etc.

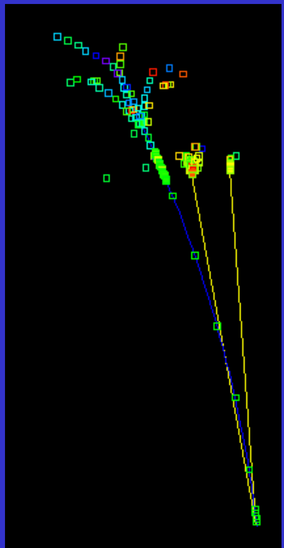
Particle Flow – Jet Energy reconstruction LHC+ILC



Jet Reconstuction:

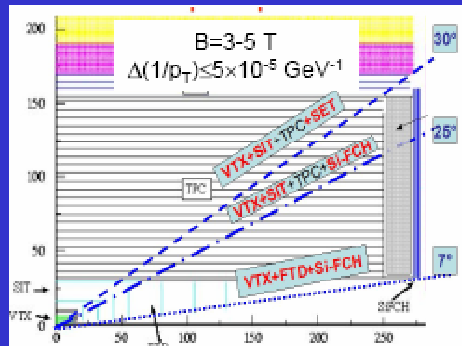
- Track momentum resolution important but not only
- Two track separation essential
- Track association to calorimeters and vertex
- Multi-jet final states require precise forward region

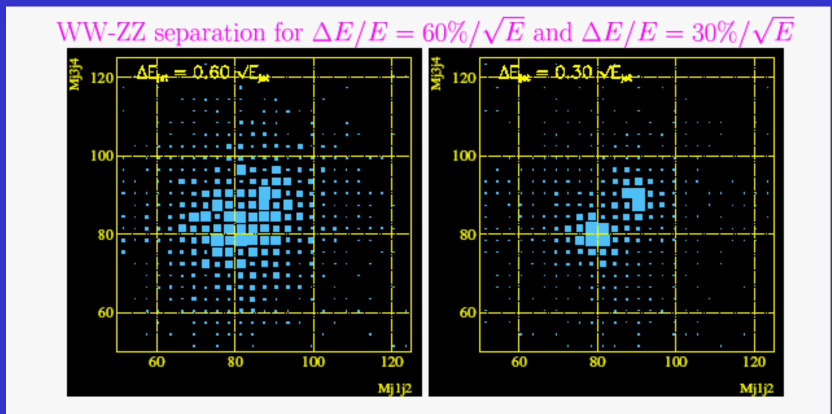




Jets in top topologies:

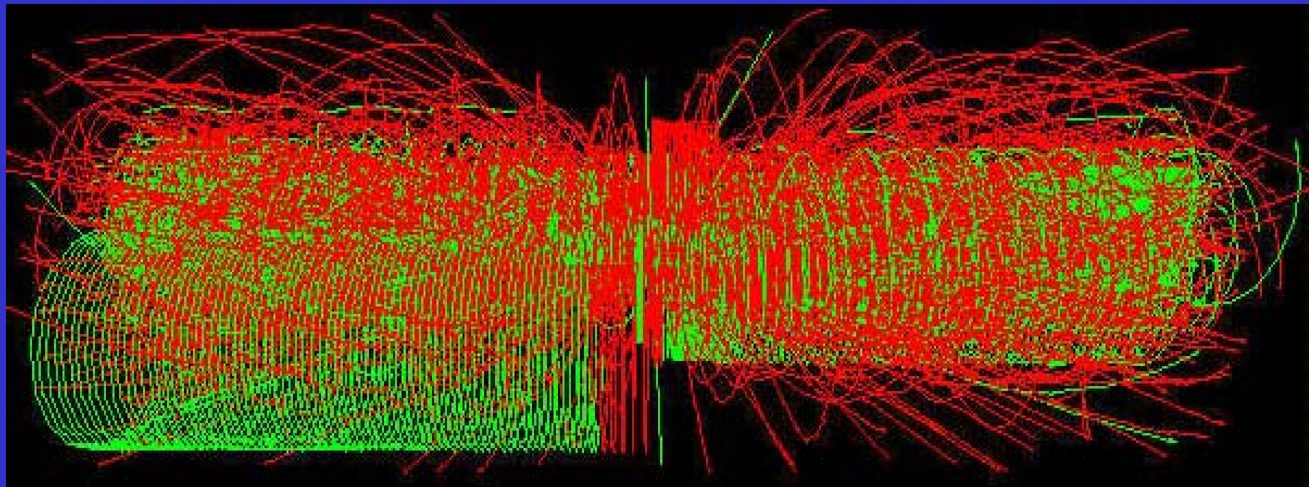
- Essential to have very good jet-jet invariant mass resolution (W-Z separation, etc..)
- Energetic jets imply high collimation requiring granularity

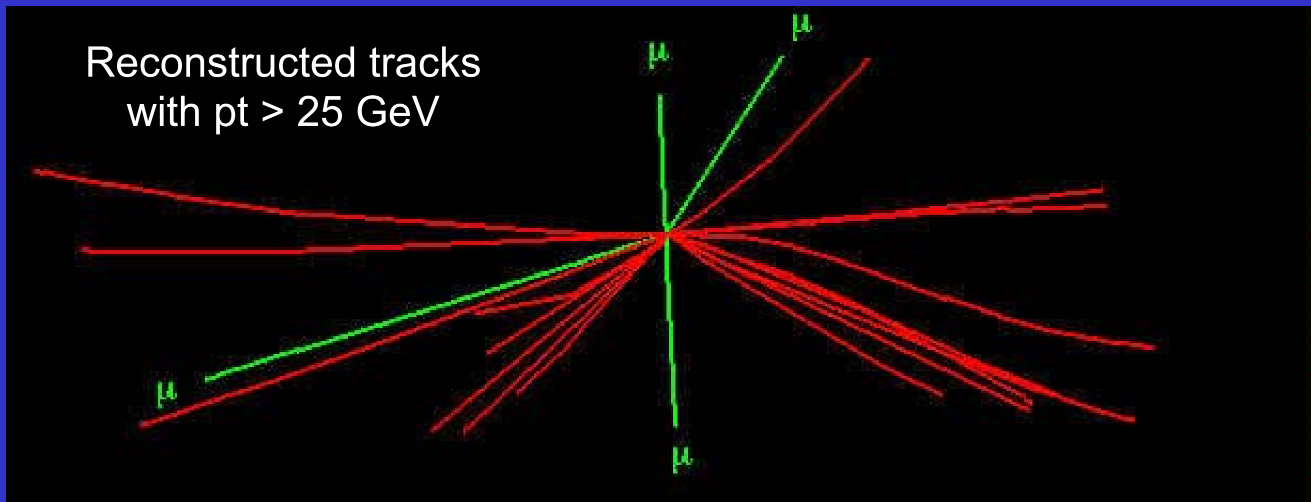




Resolution on the jets δE_{jet}	2-3 better than LHC
Granularity/segmentation of the calorimeter	>250 x LHC

Supression of background: high transverse momentum track selection



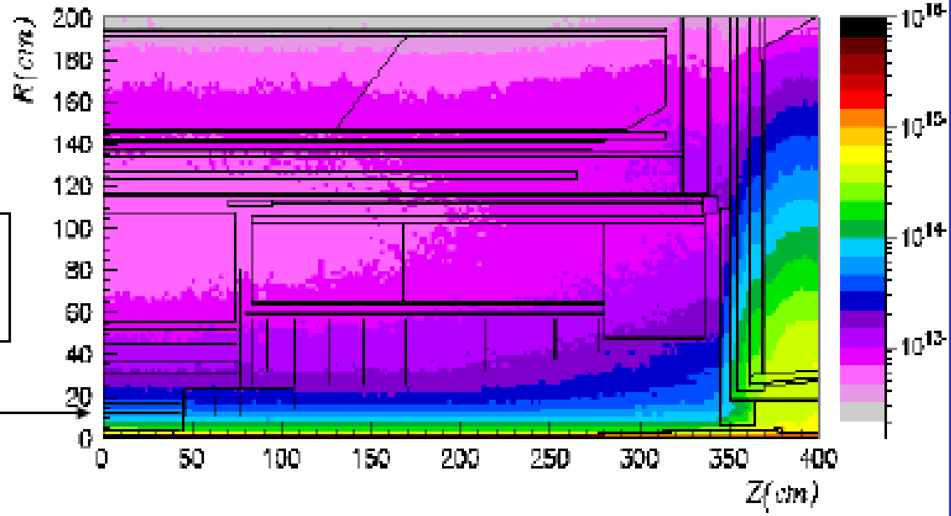


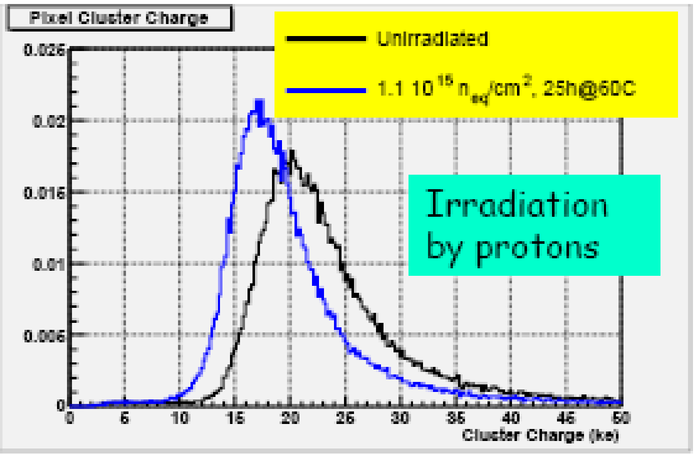
Difficult conditions: High radiation level (detectors & electronics)

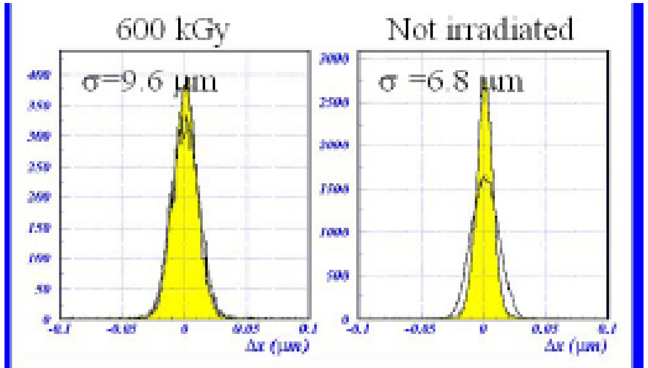
Pixels: radiation damage

Expected neutron fluence per year at high luminosity→

10^{14} n/cm²/year







Spatial Residuals (Rϕ direction) with charge interpolation, B off, 10⁰ incidence
TDR specifications: 13 μm

How are the interesting events selected ?

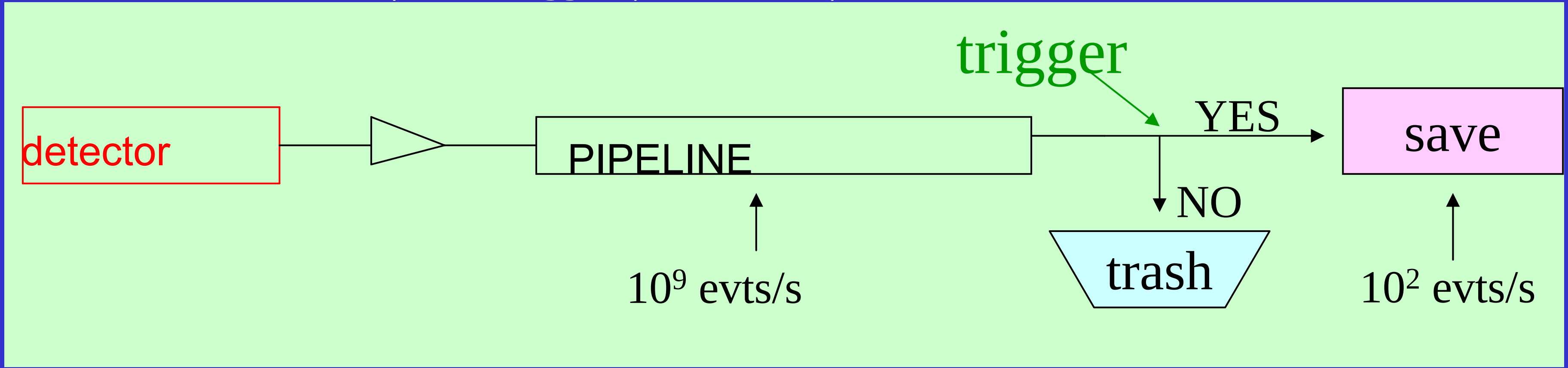
TRIGGER: : much more difficult than at e^+e^- machines

Interaction rate: ~ 10^9 events/s
Can record ~ 200 events/s (event size 1 MB)

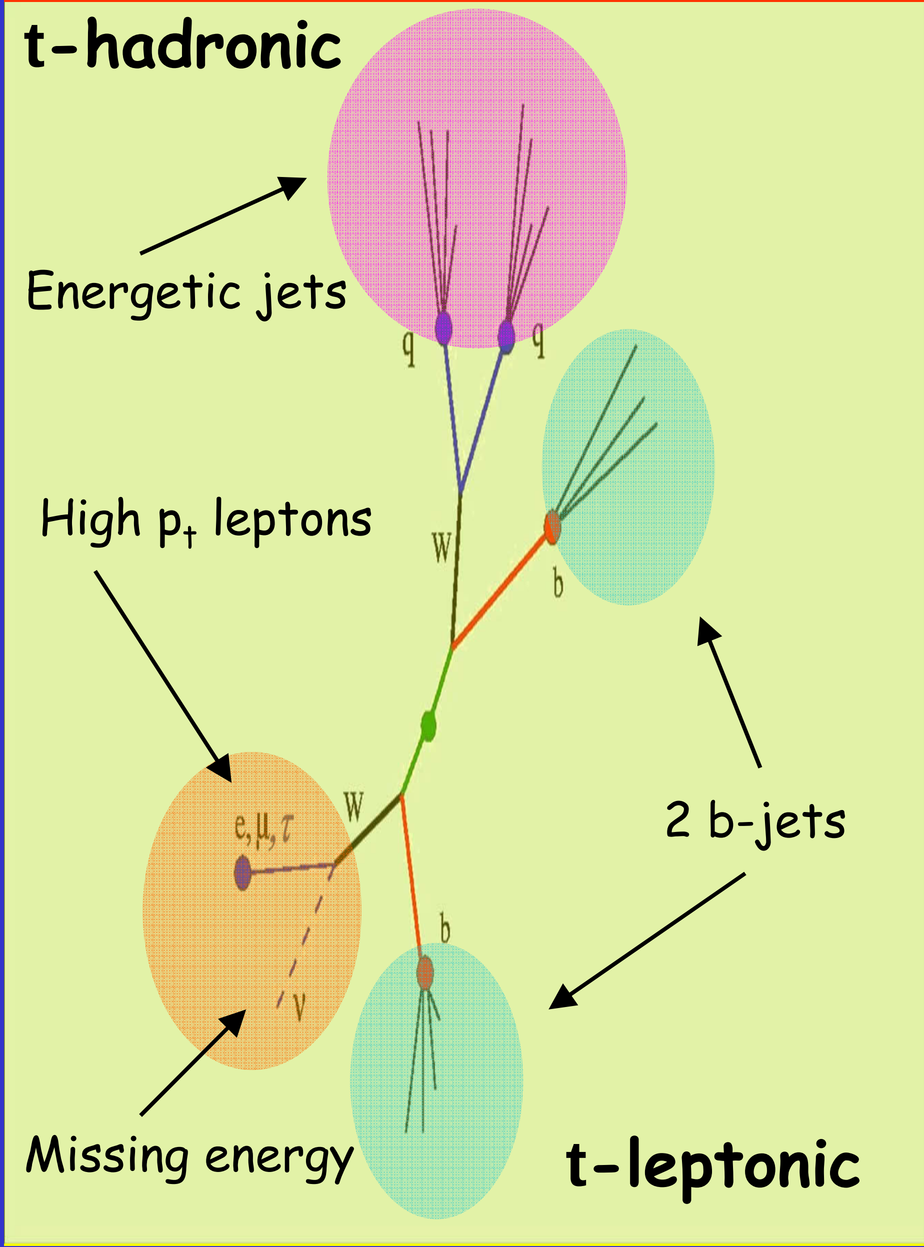
⇒ **trigger rejection ~ 10^7**

Trigger decision ≈ ms → larger than interaction rate of 25 ns

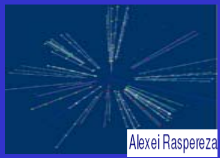
store massive amount of data in **pipelines**
while special trigger processors perform calculations



A demanding process: top production



$t \longrightarrow Wb$ → qq'b (68%), ℓνb (32%)



$t\bar{t}$ final states (standard model):

- ~46% 6 jets (2b)
- ~44% 4jets (2b) + lepton + neutrino
- ~10% 2jets (2b) + leptons + neutrinos
- (complicated topologies !!)

Detector capabilities required (very much demanding):

- b,c,τ-tagging in energetic b,c,τ-jets
- High energetic jet reconstruction
- W mass reconstruction (jets, leptons)
- Missing energy, ie, hermiticity
- Reconstruction of lepton direction
- Precise lepton identification (τ also)

Summary

LHC is really a difficult machine, ie, represents the present highest knowledge (state of the art) in technology of high energy accelerators.

LHC will certainly explore the TeV energy range (up to 5 TeV) in the coming 5-10 years (unique oportunity). Start-up 2008, probably..

Proton-proton collisions are complicated and imply challenging tools both theoretical and experimental.

Sophiticated analyses will be very much demanding in detector capabilities.