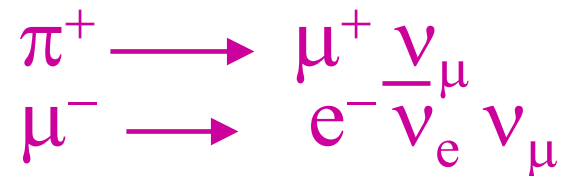


Particelle elementari:

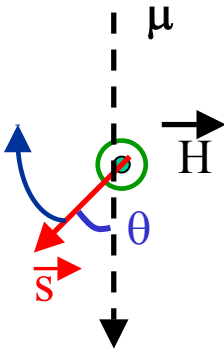
quali sono i metodi sperimentali
per studiarne le caratteristiche?

misure:

- di scattering ex. $eN \longrightarrow eN$ (struttura nucleone);
- stati legati ex. (e^+e^-) (livelli energetici, parita'...);
- vite medie di particelle instabili ex.



- Studio interazione con i campi elettromagnetici ex.



$$\frac{d\vec{s}}{dt} = \frac{g \cdot e}{2m} (\vec{s} \times \vec{H}) = \vec{\mu} \times \vec{H}$$

velocità di precession e, $\omega = \frac{ge}{2m} H \text{ rad / s}$

$$\theta = \theta(t) \propto \frac{ge}{2m} H \cdot t$$

Vita media

Particella instabile $P \longrightarrow a+b$ con una probabilita' di decadere per unita' di tempo ω , costante nel tempo. La variazione dn di popolazione n di P sara':

$$dn = -n \cdot \omega \cdot dt \rightarrow n = n_0 \cdot e^{-\omega \cdot t}; \quad \frac{1}{\omega} \equiv \tau \equiv \text{vita media della particella}$$

L'incertezza sul tempo di decadimento implica anche un'incertezza sull'energia dello stato (particella): $\Delta E = \Gamma$:

$$\Delta E \equiv \Gamma = \frac{1}{\tau} \quad \Gamma \equiv \text{larghezza della particella}$$

$$\text{ex. } \tau_{\pi^\pm} = 2.6 \cdot 10^{-8} \text{ s} \Rightarrow$$

$$\Gamma_{\pi^\pm} = \frac{1}{2.6 \cdot 10^{-8} \text{ s}} = \frac{6.5 \cdot 10^{-25}}{2.6 \cdot 10^{-8}} \text{ GeV} \approx 2.5 \cdot 10^{-17} \text{ GeV}$$

In termini di decadimento dello stato $\psi(\vec{r}, t)$

$$|\psi(\vec{r}, t)|^2 = |\psi(\vec{r}, t = 0)|^2 e^{-\Gamma t} \text{ e la funzione d'onda } \psi:$$

$$\psi(\vec{r}, t) = \psi(\vec{r}, t = 0) \cdot e^{-\frac{\Gamma t}{2}} \cdot e^{-im_0 t} (*)$$

Dove $e^{im_0 t}$ descrive l'evoluzione di uno stato stazionario ($\omega=0$) di massa m_0 :

$$\psi(\vec{r}, t) = \psi(\vec{r}, t = 0) \cdot e^{-im_0 t} \text{ (soluz. eq. di Schroedinger con } H = m_0 : \frac{\partial \psi}{\partial t} = -iH\psi)$$

Facciamo la trasformata di Fourier della (*):

$$\psi(m) = \frac{1}{2\pi} \int_0^\infty dt \cdot e^{imt} \psi(\vec{r}, t) = \frac{1}{\sqrt{2\pi}} \frac{\psi(\vec{r}, t = 0)}{-\frac{\Gamma}{2} + i(m - m_0)};$$

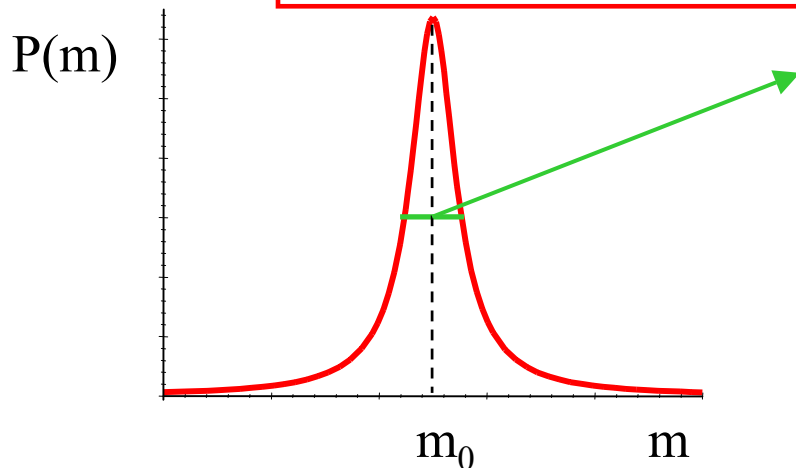
Facendo il modulo quadro e integrando sulla parte spaziale (normalizzata a 1)

$$|\psi|^2 = \frac{1}{2\pi} \frac{1}{\Gamma^2 / 4 + (m - m_0)^2}$$

Quindi la probabilita' di osservare lo stato a una massa m vale:

$$P(m)dm = \frac{1}{2\pi} \frac{\Gamma}{\Gamma^2/4 + (m - m_0)^2} dm$$

(con la normalizzazione: $\int_0^\infty P(m)dm = 1$)



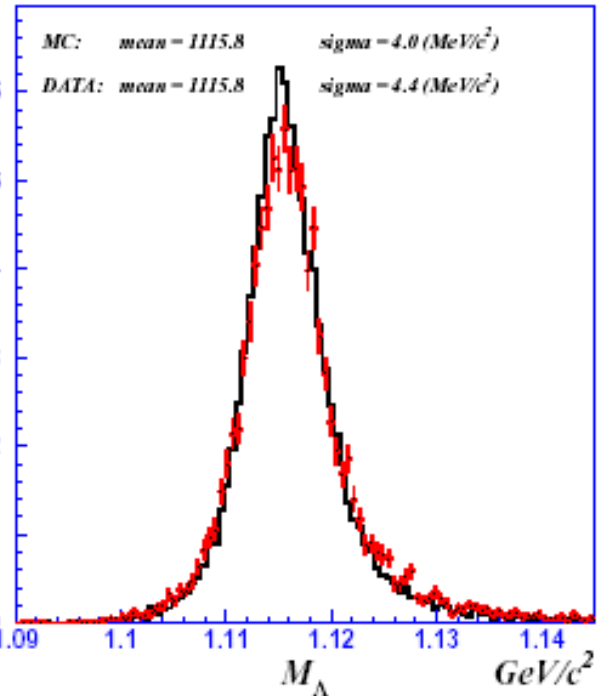
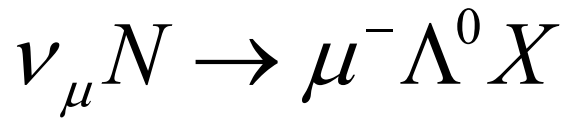
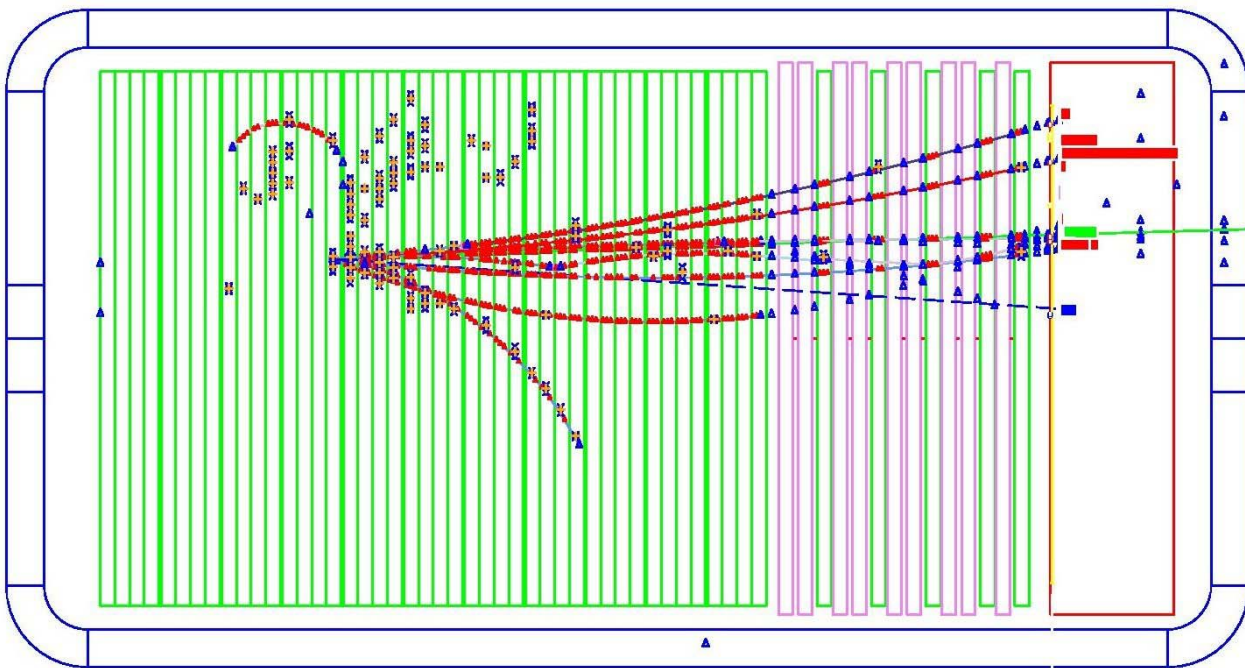
La larghezza a meta' altezza Γ e' una misura dell'intensita' della interazione che ha prodotto il decadimento

ex. $\Gamma(\rho^\pm \rightarrow \pi^\pm \pi^0) = 150 \text{ MeV}$ (interazioni forti)

$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8 \cdot 10^{-6} \text{ MeV}$ (interazioni elettromagnetiche)

$\Gamma(\pi^\pm \rightarrow \mu^\pm \nu) = 2 \cdot 10^{-14} \text{ MeV}$ (interazioni deboli)

Attenzione: Γ e' determinata anche dal numero di stati finali disponibili (spazio delle fasi). Ex: $\Gamma(Z) \sim 2.5 \text{ GeV}$ (interazione debole), ma lo $Z(m=91 \text{ GeV})$ decade in coppie di quark o leptoni (ex $Z \rightarrow \mu^+ \mu^-$) che hanno $m \ll m_Z$ con un grande spazio delle fasi e quindi grande probabilita' di decadimento (larghezza).



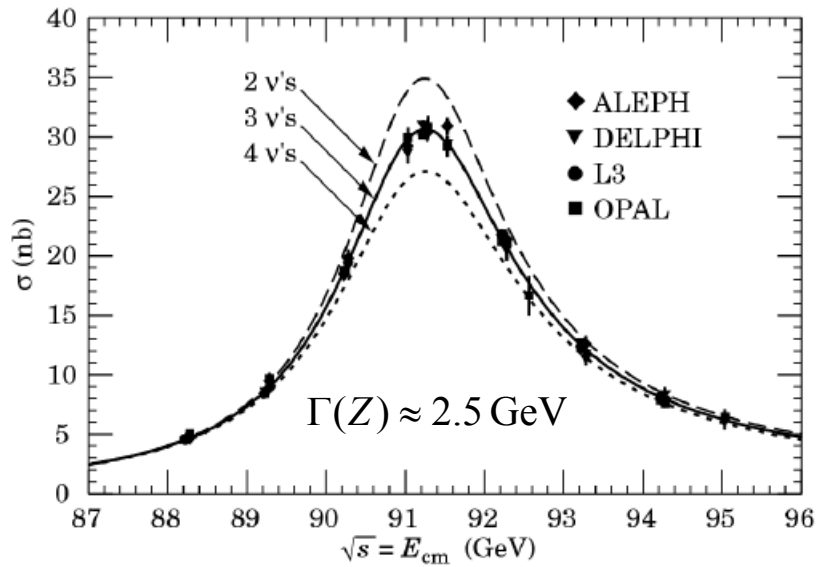
$$\Lambda^0 \rightarrow p\pi^{-} (63.9\%),$$

$$n\pi^0 (35.8\%),$$

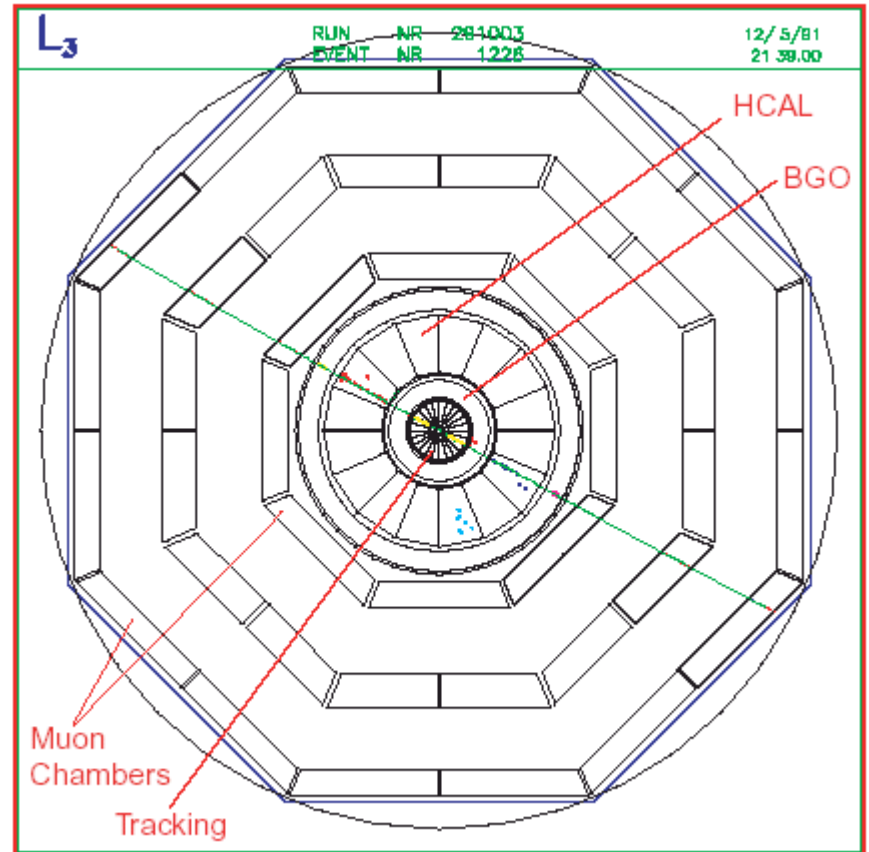
$$pe^{-}\bar{\nu} (8.3 \cdot 10^{-4})$$

$$\tau(\Lambda^0) = 2.6 \cdot 10^{-10} s$$

$$e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$$



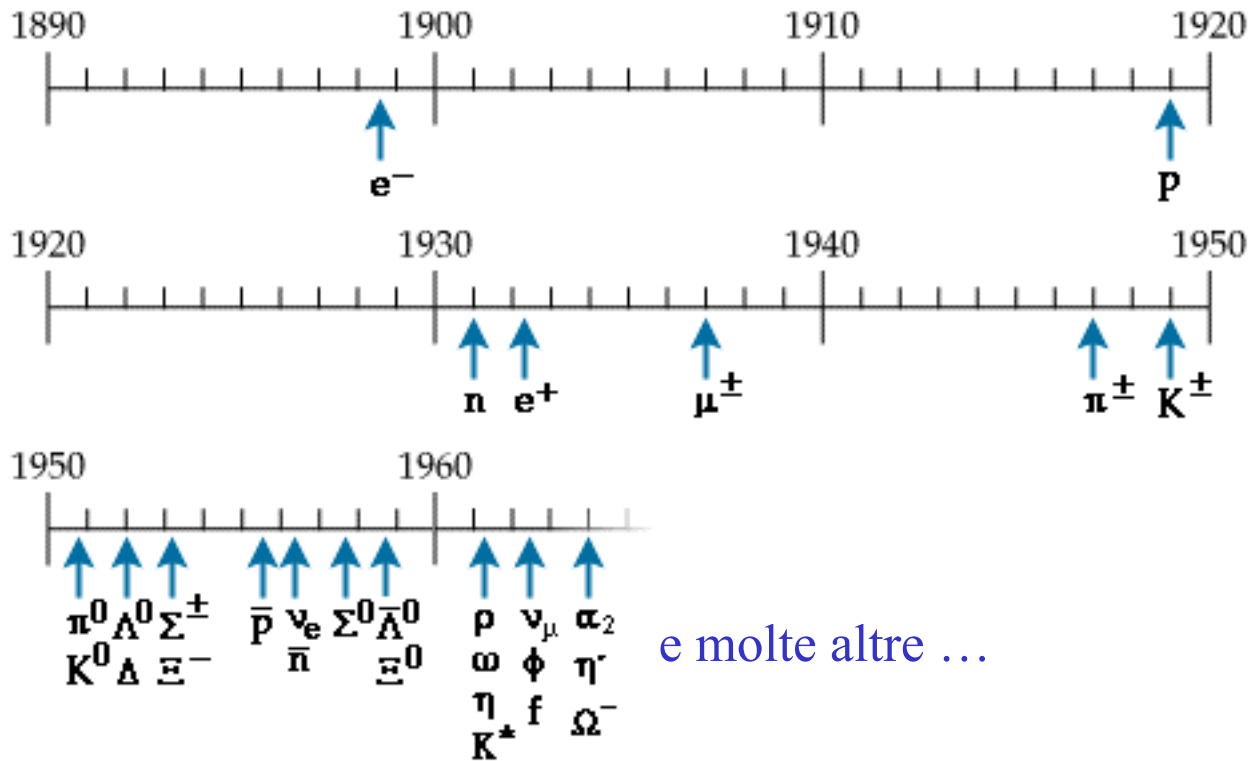
La larghezza della BW
 dipende dalla larghezza
 totale della risonanza ed e'
 quindi sensibile anche a
 canali "invisibili" come:



$$e^+e^- \rightarrow Z \rightarrow \nu_i \bar{\nu}_i$$

Le prime particelle elementari

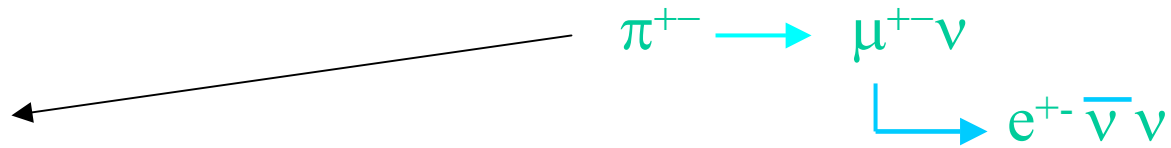
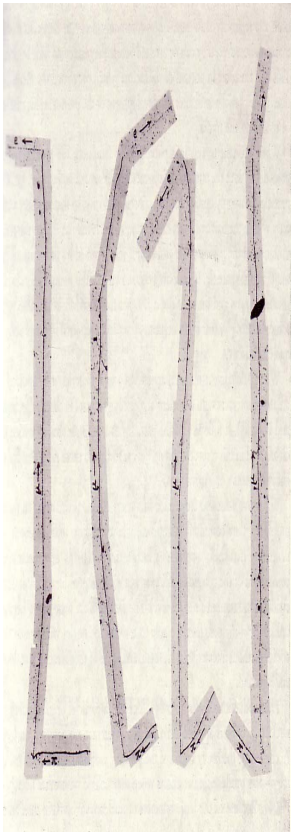
- Le particelle prima del modello standard: uno zoo crescente:



Le prime particelle elementari

- **Anni 30:** p, e⁻, n, γ, e⁺ (antiparticella dell'elettrone predetta teoricamente da Dirac nel 1931). **Stabili eccetto il neutrone.**
- **Anni 40:** π^{+/-}, π⁰, μ^{+/-}, con la corretta sequenza di decadimento:

4 eventi



Instabili: $\tau_{\pi^{\pm}} = 2.6 \cdot 10^{-8} s$; $\tau_{\mu^{\pm}} = 2.2 \cdot 10^{-6} s$; $\tau_{\pi^0} = 8.7 \cdot 10^{-17} s$

$$\text{spin } \pi^{\pm}, \pi^0 = 0; \text{ spin } \mu^{\pm}, e^{\pm} = \frac{1}{2}$$

Anni 50-60: altre particelle a vita media breve (10^{-23} - 10^{-25} s) e spin 1: ω, ρ che decadono in π: $\rho \longrightarrow \pi\pi$, $\omega \longrightarrow \pi^+\pi^-\pi^0$

Ma anche particelle che decadono in π ma con vita media lunga (10^{-8} - 10^{-10} s) e per questo **chiamate strane**:



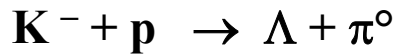
Ma sono tuttavia prodotte in coppia nelle interazioni forti ex:



Idea: associare a queste particelle strane un nuovo numero quantico additivo: “la stranezza” S che si conserva in produzione (forte) ed e’ violato nel decadimento (debole).

$S = +1$: K^+ , K^0 ; $S = -1$: Λ , Σ^\pm , Σ^0 ; $S = -2$: Ξ^0 , Ξ^- ; $S = 0$: tutte le altre particelle (e opposta stranezza $-S$ per le antiparticelle corrispondenti)

Esempio di K^- che si ferma in idrogeno liquido:

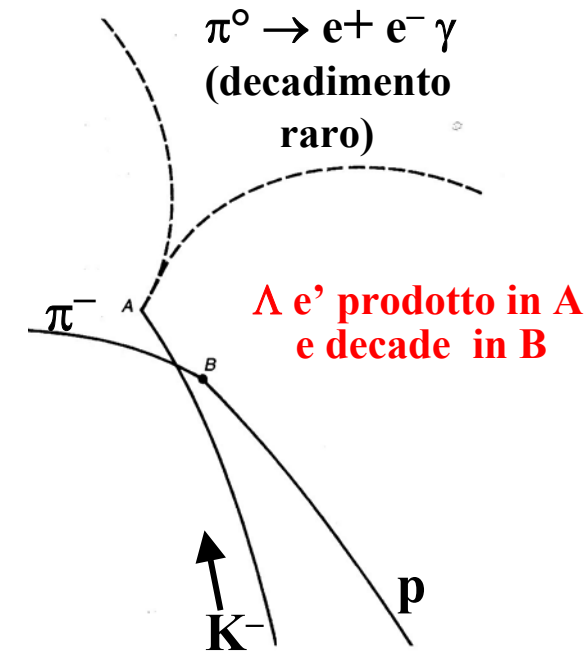
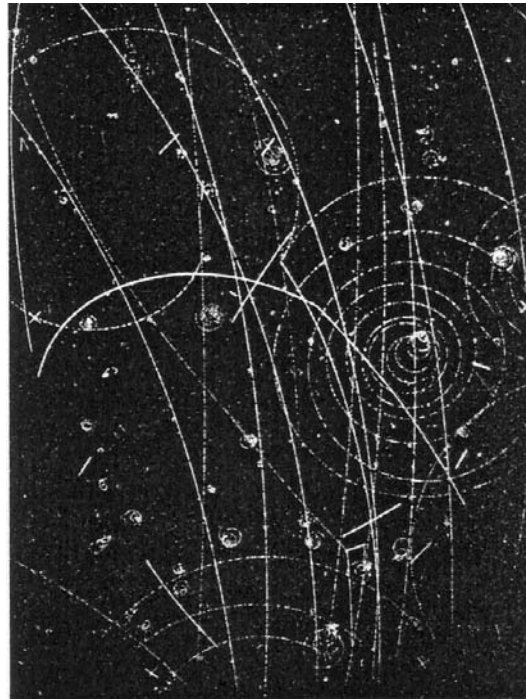


(che conserva la stranezza)

Seguito dal decadimento



(che viola la stranezza)



. Anni 70-80. Il fenomeno delle particelle “strane” si replica con altri adroni ancora piu’ pesanti: ex: D^{+-}, D^0 ($m \sim 2 \text{ GeV}$), Λ_c ; B^{+-}, B^0 ($m \sim 5 \text{ GeV}$), Λ_b

Introduzione di altre “qualita’” che caratterizzano la materia adronica: e che si conserva nelle interazioni forti: charm (c), beauty (b)

Anni 90: scoperto l’ultimo stato degli adroni: **top (t)** ($m \sim 175 \text{ GeV}$),
ma non ha stati legati!!

Questi numeri quantici sono **manifestazioni di gradi di liberta’ interni** degli adroni (i costituenti): **i quark. Modello:**

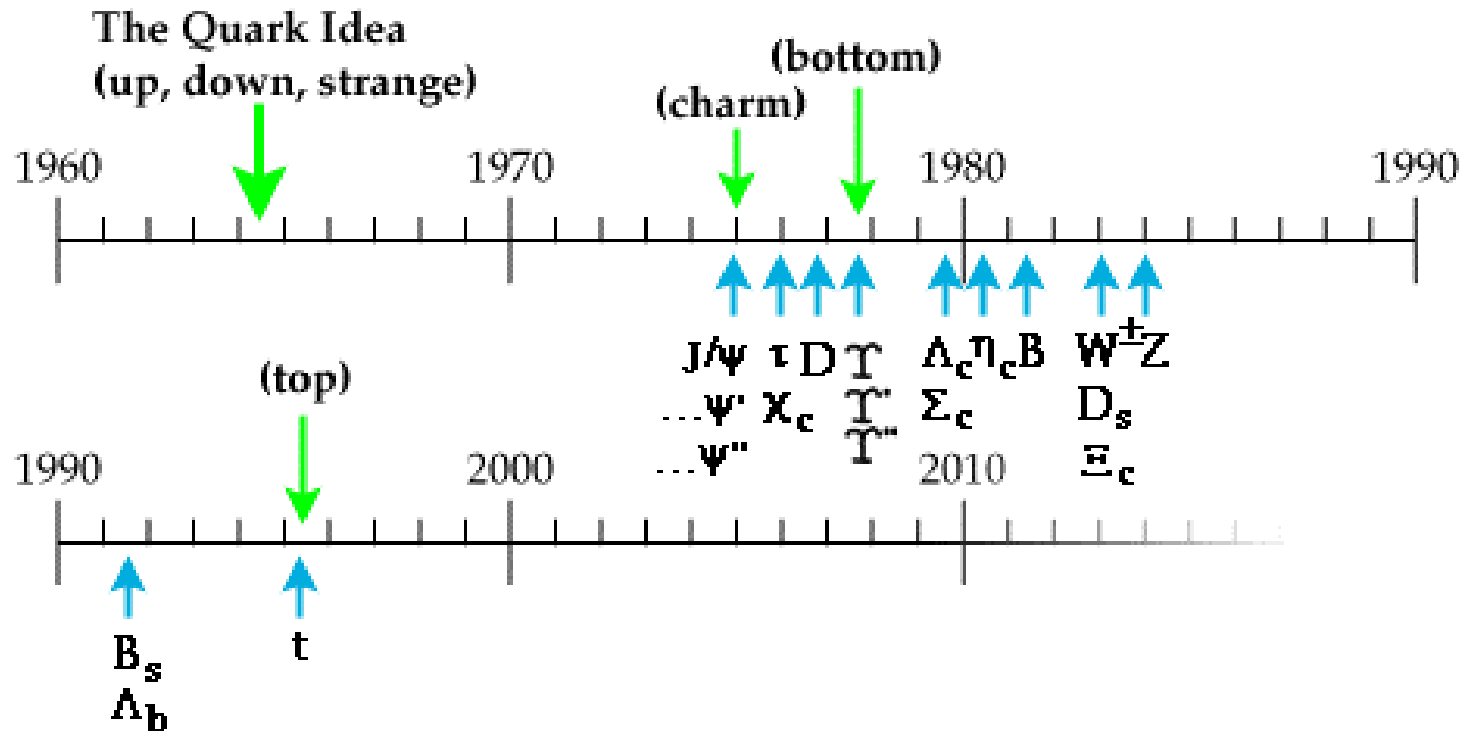
$$\begin{array}{|c|} \hline \begin{array}{c} \left[\begin{array}{c} u \\ d \end{array} \right] \end{array} \\ \hline \end{array} \quad \begin{array}{|c|} \hline \begin{array}{c} \left[\begin{array}{c} c \\ s \end{array} \right] \end{array} \\ \hline \end{array} \quad \begin{array}{|c|} \hline \begin{array}{c} \left[\begin{array}{c} t \\ b \end{array} \right] \end{array} \\ \hline \end{array} \quad \begin{array}{|c|} \hline \begin{array}{c} \left[\begin{array}{c} Q = 2/3 \\ Q = -1/3 \end{array} \right] \end{array} \\ \hline \end{array} + \text{antiquark, tutti a spin} = 1/2$$

Gli adroni misurati **non sono elementari** ma **composti da quark:**

$[q \bar{q}]$: mesoni a spin intero ex. $\pi^+ = [u \bar{d}]$, $\pi^- = [\bar{u} d]$, $\pi^0 = [u \bar{u} + d \bar{d}]$

$[q q q]$: barioni a spin semintero ex. $p = [u u d]$, $n = [u d d]$

Con il modello a quark lo zoo delle particelle adroniche si riduce a 6 particelle fondamentali: i quark con masse da MeV a 175 GeV

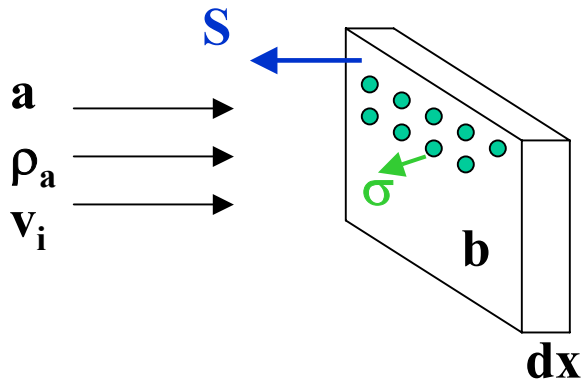


Sezione d'urto

Misura 'l'intensita' della interazione': consideriamo ad es. la reazione:



Flusso di particelle a sulle particelle bersaglio b:



Se la densita' di particelle incidenti e' ρ_a e la velocita' v_i , il flusso incidente (numero di particelle per unita' di tempo e di superficie) sara':

$$\Phi = \rho_a v_i$$

La densita' di bersagli e' ρ_b e ciascuno copre un'area σ , il numero di interazioni per unita' di tempo e di area, R sara':

$$R = \Phi \cdot \sigma \cdot \rho_b \cdot dx = \rho_a \cdot v_i \cdot \sigma \cdot \rho_b \cdot dx$$

Sul volume $dV = S dx$ avro' un numero di interazioni totali al secondo: dN/dt :

$$\frac{dN}{dt dV} = \rho_a \cdot v_i \cdot \rho_b \cdot \sigma$$

Integrando sul tempo e sul volume (su dx) otteniamo il numero N di interazioni:

$$N = n_b \cdot \rho_a \cdot \int v_i dt \cdot \sigma = \frac{n_a \cdot n_b}{S} \sigma;$$

n_a/S = particelle incidenti per unita' di superficie;
 n_b = numero totale di bersagli b

Se N = numero di Avogadro;

$$n_b = \frac{\rho V N}{A}$$

A = peso atomico;

ρ = densita' del bersaglio (gr/cm³)

$$n'_b (\text{nucleoni}) = \frac{\rho V N}{A} A = \rho V N$$

Da cui:

$$N = n_a \frac{\rho V N}{AS} \sigma = n_a \left[\frac{M_b}{AS} \right] N \sigma \quad \text{con } M_b = \text{massa del bersaglio}$$

Riscriviamo N:

$$N = \left[\frac{n_a}{S} \right] \left[\frac{n_b}{V} \right] \cdot V \cdot \sigma$$

Se T e' il tempo totale di misur e $\Phi_a = n_a/S$

$$N = \frac{\Phi_a}{T} \cdot \rho_b \cdot V \cdot T \cdot \sigma = f \cdot \rho_b \cdot V \cdot T \cdot \sigma \quad \text{con } f = \frac{\Phi_a}{T}$$

Vogliamo passare dal lab a un riferimento qualsiasi; nota che **VT e N sono invarianti di Lorentz**; vogliamo che anche **f ρ_b lo sia.**

Partiamo dall'invariante:

(ρ_a, ρ_b densità a riposo delle particelle a e b)

$$\rho_a \rho_b F = \frac{\rho_a \rho_b}{m_a m_b} \sqrt{(p_a \cdot p_b)^2 - (m_a m_b)^2}$$

Che si riduce a $f \rho_b$ nel lab dove

$$p_a = [E_a, \vec{p}_a], p_b = [m_b, \vec{0}]$$

Nel centro di massa di a e b (cms): $\vec{p}_a = -\vec{p}_b$ e definiamo $|\vec{p}_a| = |\vec{p}_b| \equiv q$

$$F = \frac{q(E_a + E_b)}{m_a m_b} = \frac{q\sqrt{s}}{m_a m_b}, \text{ con } s = (p_a + p_b)^2$$

Occorre definire ρ_a e ρ_b . E' conveniente scegliere la cosiddetta "normalizzazione covariante" della funzione d'onda tale che assicura che la densità di volume sia la stessa in ogni sistema di Lorentz.

$$\int_{V=1} \rho \cdot d^3x = 2E$$

Se ρ_a, ρ_b sono le densità nel sistema di riposo: $\rho_a = 2m_a, \rho_b = 2m_b$, da cui:

$\rho_a \rho_b F = 4m_a m_b \frac{q\sqrt{s}}{m_a m_b} = 4q\sqrt{s}$ e nel cms $N = 4q\sqrt{s} \cdot V \cdot T \cdot \sigma$ E il rate R (eventi/tempo)

$$R = \frac{N}{T} = \left\{ \rho_a \rho_b q \frac{(E_a + E_b)}{m_a m_b} V \right\} \cdot \sigma \equiv L \cdot \sigma$$

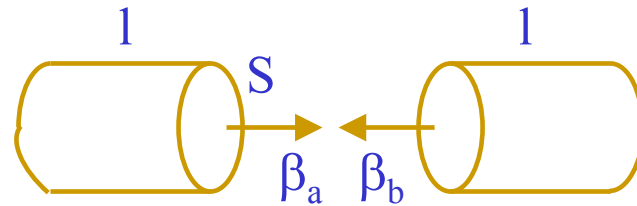
L e' definita come la luminosita' del sistema e ha dimensioni $\text{cm}^{-2}\text{s}^{-1}$

$$L = \left(\rho_a \rho_b q \frac{(E_a + E_b)}{m_a m_b V} V^2 \right) = \rho_a V \rho_b V \frac{1}{V} \left[\gamma_a \frac{q}{m_b} + \gamma_b \frac{q}{m_a} \right] =$$

$$\rho_a V \rho_b V \frac{1}{V} \gamma_a \gamma_b [\beta_a + \beta_b] \quad \text{con } \gamma_{a,b} = \frac{E_{a,b}}{m_{a,b}} \text{ e } \beta_{a,b} = \frac{q}{\gamma_{a,b} m_{a,b}}$$

Se le particelle sono contenute in due pacchetti di sezione S e lunghezza l :

volume del pacchetto
nel suo sistema di
riferimento



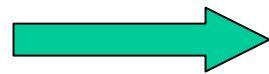
$$L = \rho_a \gamma_a V \rho_b \gamma_b V \frac{\beta_a + \beta_b}{lS} = n_a n_b \frac{\beta_a + \beta_b}{lS}$$

Ex. $n_a = n_b = 10^{10}$

$l = 10 \text{ cm}$

$S = 1 \text{ mm}^2$

$\beta_a = \beta_b = 1$



$L = 2 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

Questa, tuttavia e' una luminosita' istantanea: definisce il rate nel tempo $T=l/(\beta_a+\beta_b)$ di attraversamento dei due pacchetti.

In genere l'acceleratore e' circolare con **K pacchetti** per ciascun fascio e il rate R al secondo e':

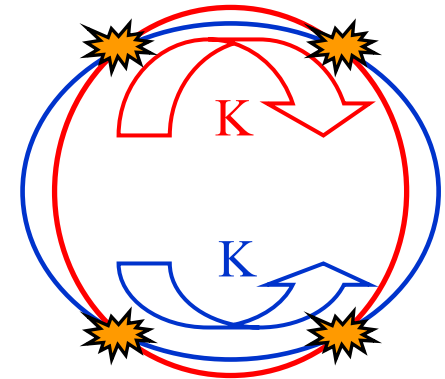
$$R = n_a \cdot n_b \cdot \frac{\beta_a + \beta_b}{lS} \cdot \frac{l}{\beta_a + \beta_b}$$

σ

$K \cdot f$

Luminosita' integrata sul tempo di attraversamento

Frequenza di rivoluzione



Luminosita' al secondo:

$$L = \frac{n_a n_b}{S} K \cdot f$$

se n_a e n_b non sono uniformi ma distribuite gaussianamente con larghezze $\sigma_x \sigma_y$

$$L = \frac{n_a n_b}{4\pi\sigma_x\sigma_y} K \cdot f$$

Ex. LEP : $n_a = n_b (e^+, e^-) = 5 \cdot 10^{11}$, $f = 10^4$, $K = 4$, $\sigma_x \sim 2 \cdot 10^{-2} \text{ cm}$, $\sigma_y \sim 8 \cdot 10^{-4} \text{ cm}$

$$\underline{L \sim 3 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}}$$

$\sigma(e^+ e^- \rightarrow Z) \sim 50 \text{ nb} = 5 \cdot 10^{-32} \text{ cm}^2$ ($\sim 10^{-1}$ Z al secondo)

Ex. LHC : $n_a = n_b (p, p) = 10^{11}$, $f = 10^4$, $\underline{K = 2800}$, $\sigma_x \sim \sigma_y \sim 1.5 \cdot 10^{-3} \text{ cm}$

$$\underline{L \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}}$$

$\sigma(pp \rightarrow H) \sim 1 \text{ pb} = 10^{-36} \text{ cm}^2$ ($\sim 10^{-2}$ H al secondo)

Ma $\sigma_{\text{tot}}(pp) \sim 100 \text{ mb} = 10^{-25} \text{ cm}^2 \longrightarrow R_{\text{tot}} \sim 10^9$ al secondo

Si introduce anche una luminosita' integrata:

$$N = \sigma \int L dt \quad \left(\int L dt \text{ ha dimensioni di } \text{cm}^{-2} \right)$$

La luminosita' integrata si misura in μb^{-1} , nb^{-1} , pb^{-1} , fb^{-1} , ...

Ex. Se $\int L dt = 10^5 \text{ pb}^{-1}$ (1 anno a LHC), per un processo con sezione d'urto
 $\sigma = 1 \text{ pb}$ avro' $N = 10^5 \text{ pb}^{-1} \cdot 1 \text{ pb} = 10^5$ eventi

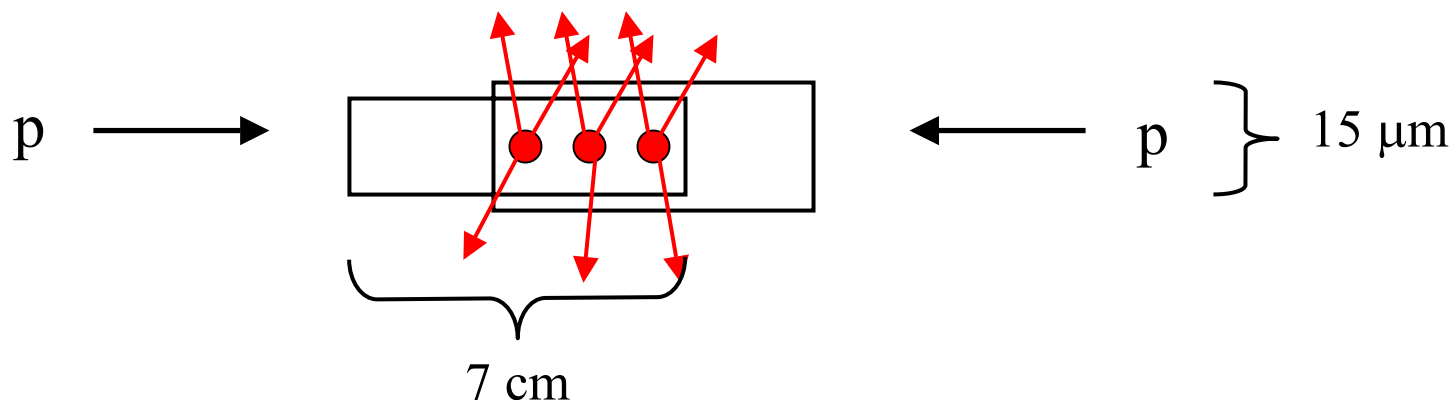
Ulteriore problema a alta luminosita' e alto rate

A LHC $\sigma_T = 100 \text{ mb}$ e se $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, $R = 10^9/\text{s}$

Ci sono ~ 3000 pacchetti per fascio \longrightarrow tempo intercorrente tra due attraversamenti successivi di pacchetti (**bunch crossing**) e' **25 ns** \longrightarrow

\longrightarrow **Numero di eventi medio per bunch crossing N_{BC} :**

$$N_{BC} = 10^9 \cdot 100 \cdot 10^{-9} = 100$$



Risultato: 25 eventi prodotti entro 25 ns (distribuiti poissonianamente) e $\sim 25 \times 30 \sim 1000$ particelle cariche prodotte (+ quelle neutre) ogni 25 ns.

Le interazioni a LHC appariranno così:

A simulated event in ATLAS (CMS)

H ZZ 4

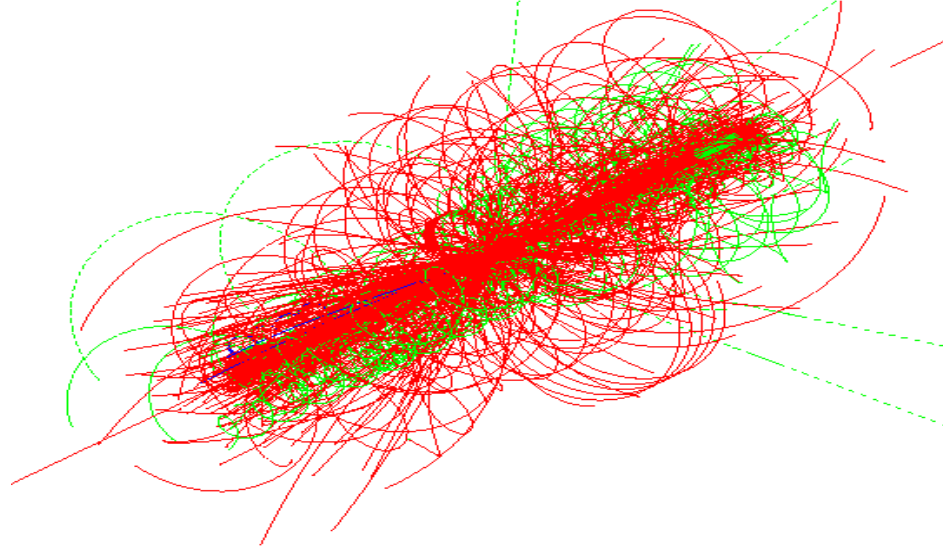
pp collisions at 14 TeV $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, bunch

inel. 70 mb

spacing 25 ns

Interested in processes

with fb



23 overlapping minimum bias events / BC

1900 charged + 1600 neutral particles / BC

HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (I)

The numbers here were received from representatives of the colliders in early 2004 (contact C.G. Wohl, LBNL). Many of the numbers of course change with time, and only the latest values (or estimates) are given here; those in brackets are for coming upgrades. Quantities are, where appropriate, r.m.s. H and V indicate horizontal and vertical directions. Parameters for the defunct SPEAR, DORIS, PETRA, PEP, SLC, TRISTAN, and VEPP-2M colliders may be found in our 1996 edition (Phys. Rev. D54, 1 July 1996, Part I).

	VEPP-2000 (Novosibirsk)	VEPP-4M (Novosibirsk)	BEPC (China)	BEPC-II (China)	DAΦNE (Frascati)
Physics start date	2005	1994	1989	2007	1999
Physics end date	—	—	—	—	~2007
Maximum beam energy (GeV)	1.0	6	2.2	1.89 (2.1 max)	0.700
Luminosity ($10^{30} \text{ cm}^{-2}\text{s}^{-1}$)	100	20	10 at 1.843 GeV/beam 5 at 1.55 GeV/beam	1000	80 present 200 achievable
Time between collisions (μs)	0.04	0.6	0.8	0.008	0.0027
Crossing angle (μ rad)	0	0	0	1.1×10^4	$(2.5 \text{ to } 3.2) \times 10^4$
Energy spread (units 10^{-3})	0.64	1	0.58 at 2.2 GeV	0.52	0.40
Bunch length (cm)	4	5	≈ 5	1.3	1 low current 2 high current
Beam radius (10^{-6} m)	125 (round)	H : 1000 V : 30	H : 890 V : 37	H : 380 V : 5.7	H : 800 V : 4.8
Free space at interaction point (m)	± 1	± 2	± 2.15	± 1.009	± 0.40
Luminosity lifetime (hr)	continuous	2	7–12	1.5	0.7
Filling time (min)	continuous	15	30	26	0.8 (topping up)
Acceleration period (s)	—	150	120	—	on energy
Injection energy (GeV)	0.2–1.0	1.8	1.55	1.89	on energy
Transverse emittance ($10^{-9}\pi$ rad-m)	H : 250 V : 250	H : 200 V : 20	H : 660 V : 28	H : 144 V : 3.1	H : 300 V : 1
β^* , amplitude function at interaction point (m)	H : 0.06 V : 0.06	H : 0.75 V : 0.05	H : 1.2 V : 0.05	H : 1.0 V : 0.015	H : 1.7 V : 0.025
Beam-beam tune shift per crossing (units 10^{-4})	H : 750 V : 750	500	350	400	250
RF frequency (MHz)	172	180	199.53	499.8	356
Particles per bunch (units 10^{10})	16	15	20 at 2 GeV 11 at 1.55 GeV	4.8	
Bunches per ring per species	1	2	1	93	110/120
Average beam current per species (mA)	300	80	40 at 2 GeV 22 at 1.55 GeV	910	1000 (goal 2000)
Circumference or length (km)	0.024	0.366	0.2404	0.23753	0.098
Interaction regions	2	1	2	1	2
Utility insertions	2	1	4	4	2
Magnetic length of dipole (m)	1.2	2	1.6	Outer ring 1.6 Inner ring 1.41	1
Length of standard cell (m)	12	7.2	6.6	Outer ring 6.6 Inner ring 6.2	12
Phase advance per cell (deg)	H : 738 V : 378	65	≈ 60	60–90 no standard cell	360
Dipoles in ring	8	78	40 + 4 weak	84 + 8 weak	8
Quadrupoles in ring	20	150	68	134+2 s.c.	48
Peak magnetic field (T)	2.4	0.6	0.9028 at 2.8 GeV	Outer ring 0.67712 Inner ring 0.76636	1.7

HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (II)

The numbers here were received from representatives of the colliders in early 2004. Many of the numbers of course change with time, and only the latest values (or estimates) are given here. Quantities are, where appropriate, r.m.s. H and V indicate horizontal and vertical directions; s.c. indicates superconducting.

	CESR (Cornell)	CESR-C (Cornell)	KEKB (KEK)	PEP-II (SLAC)	LEP (CERN)
Physics start date	1979	2002	1999	1999	1989
Physics end date	2002	—	—	—	2000
Maximum beam energy (GeV)	6	6	$e^- \times e^+ : 8 \times 3.5$	$e^- : 7-12$ (9.0 nominal) $e^+ : 2.5-4$ (3.1 ") (nominal $E_{cm} = 10.5$ GeV)	101 in 1999 (105=max. foreseen)
Luminosity ($10^{30} \text{ cm}^{-2}\text{s}^{-1}$)	1280 at 5.3 GeV/beam	35 at 1.9 GeV/beam	11305	6777	24 at Z^0 100 at > 90 GeV
Time between collisions (μs)	0.014 to 0.22	0.014 to 0.22	0.008	0.0042	22
Crossing angle (μ rad)	± 2000	± 4000	$\pm 11,000$	0	0
Energy spread (units 10^{-3})	0.6 at 5.3 GeV/beam	0.8 at 1.9 GeV/beam	0.7	$e^-/e^+ : 0.61/0.77$	0.7→1.5
Bunch length (cm)	1.8	1.2	0.65	$e^-/e^+ : 1.1/1.0$	1.0
Beam radius (μm)	$H : 460$ $V : 4$	$H : 300$ $V : 5.7$	$H : 110$ $V : 2.4$	$H : 157$ $V : 4.7$	$H : 200 \rightarrow 300$ $V : 2.5 \rightarrow 8$
Free space at interaction point (m)	± 2.2 (± 0.6 to REC quads)	± 2.2 (± 0.3 to PM quads)	+0.75/-0.58 (+300/-500) mrad cone	± 0.2 , ± 300 mrad cone	± 3.5
Luminosity lifetime (hr)	2-3	2-3	continuous	3.5	20 at Z^0 10 at > 90 GeV
Filling time (min)	5 (topping up)	5 (topping up)	continuous	3 (topping up)	20 to setup 20 to accumulate
Acceleration period (s)	—	—	—	—	600
Injection energy (GeV)	1.8-6	1.5-6	$e^-/e^+ : 8/3.5$	2.5-12	22
Transverse emittance (π rad-nm)	$H : 210$ $V : 1$	$H : 150$ $V : 2.5$	$e^- : 24$ (H), 0.82 (V) $e^+ : 18$ (H), 1.0 (V)	$e^- : 48$ (H), 1.5 (V) $e^+ : 24$ (H), 1.5 (V)	$H : 20-45$ $V : 0.25 \rightarrow 1$
β^* , amplitude function at interaction point (m)	$H : 1.0$ $V : 0.018$	$H : 0.60$ $V : 0.013$	$e^- : 0.63$ (H), 0.0070 (V) $e^+ : 0.59$ (H), 0.0058 (V)	$e^- : 0.50$ (H), 0.012 (V) $e^+ : 0.50$ (H), 0.012 (V)	$H : 1.5$ $V : 0.05$
Beam-beam tune shift per crossing (units 10^{-4})	$H : 250$ $V : 620$	$H : 175$ $V : 200$	$e^- : 710$ (H), 510 (V) $e^+ : 1040$ (H), 680 (V)	$e^- : 400$ (H), 400 (V) $e^+ : 990$ (H), 800 (V)	830
RF frequency (MHz)	500	500	508.887	476	352.2
Particles per bunch (units 10^{10})	1.15	1.15	$e^-/e^+ : 5.5/7.3$	$e^-/e^+ : 4.6/6.7$	45 in collision 60 in single beam
Bunches per ring per species	9 trains of 5 bunches	8 trains of 5 bunches	1281	1230	4 trains of 1 or 2
Average beam current per species (mA)	340	55	$e^-/e^+ : 1130/1500$	$e^-/e^+ : 1200/1800$	4 at Z^0 4→6 at > 90 GeV
Beam polarization (%)	—	—	—	—	55 at 45 GeV 5 at 61 GeV
Circumference or length (km)	0.768	0.768	3.016	2.2	26.66
Interaction regions	1	1	1	1 (2 possible)	4
Utility insertions	3	3	3 per ring	5	4
Magnetic length of dipole (m)	1.6-6.6	1.6-6.6	$e^-/e^+ : 5.86/0.915$	$e^-/e^+ : 5.4/0.45$	11.66/pair
Length of standard cell (m)	16	16	$e^-/e^+ : 75.7/76.1$	15.2	79
Phase advance per cell (deg)	45-90 (no standard cell)	45-90 (no standard cell)	450	$e^-/e^+ : 60/90$	102/90
Dipoles in ring	86	84	$e^-/e^+ : 116/112$	$e^-/e^+ : 192/192$	3280+24 inj. + 64 weak
Quadrupoles in ring	101 + 4 s.c.	101 + 4 s.c.	$e^-/e^+ : 452/452$	$e^-/e^+ : 290/326$	520+288 + 8 s.c.
Peak magnetic field (T)	0.3 normal } at 8 0.8 high field } GeV	0.3 normal } at 8 0.8 high field } GeV 2.1 wigglers at 1.9 GeV	$e^-/e^+ : 0.25/0.72$	$e^-/e^+ : 0.18/0.75$	0.135

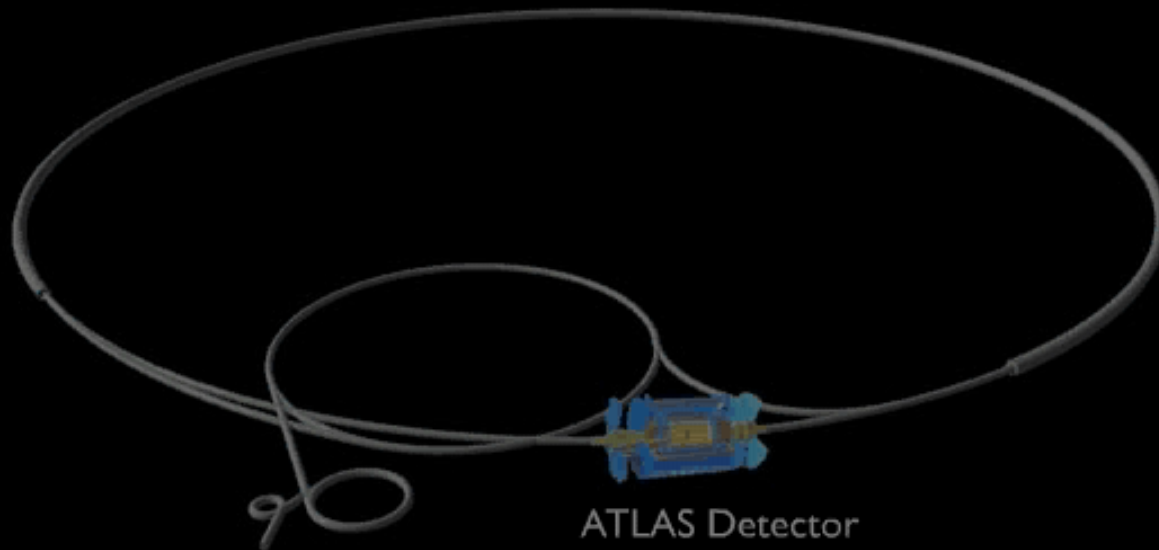
HIGH-ENERGY COLLIDER PARAMETERS: $e\bar{p}$, $p\bar{p}$, and pp Colliders

The numbers here were received from representatives of the colliders in early 2004. Many of the numbers of course change with time, and only the latest values (or estimates) are given here. Quantities are, where appropriate, r.m.s. H , V , and, s.c. indicate horizontal and vertical directions, and superconducting. For existing colliders, the table shows achieved parameters.

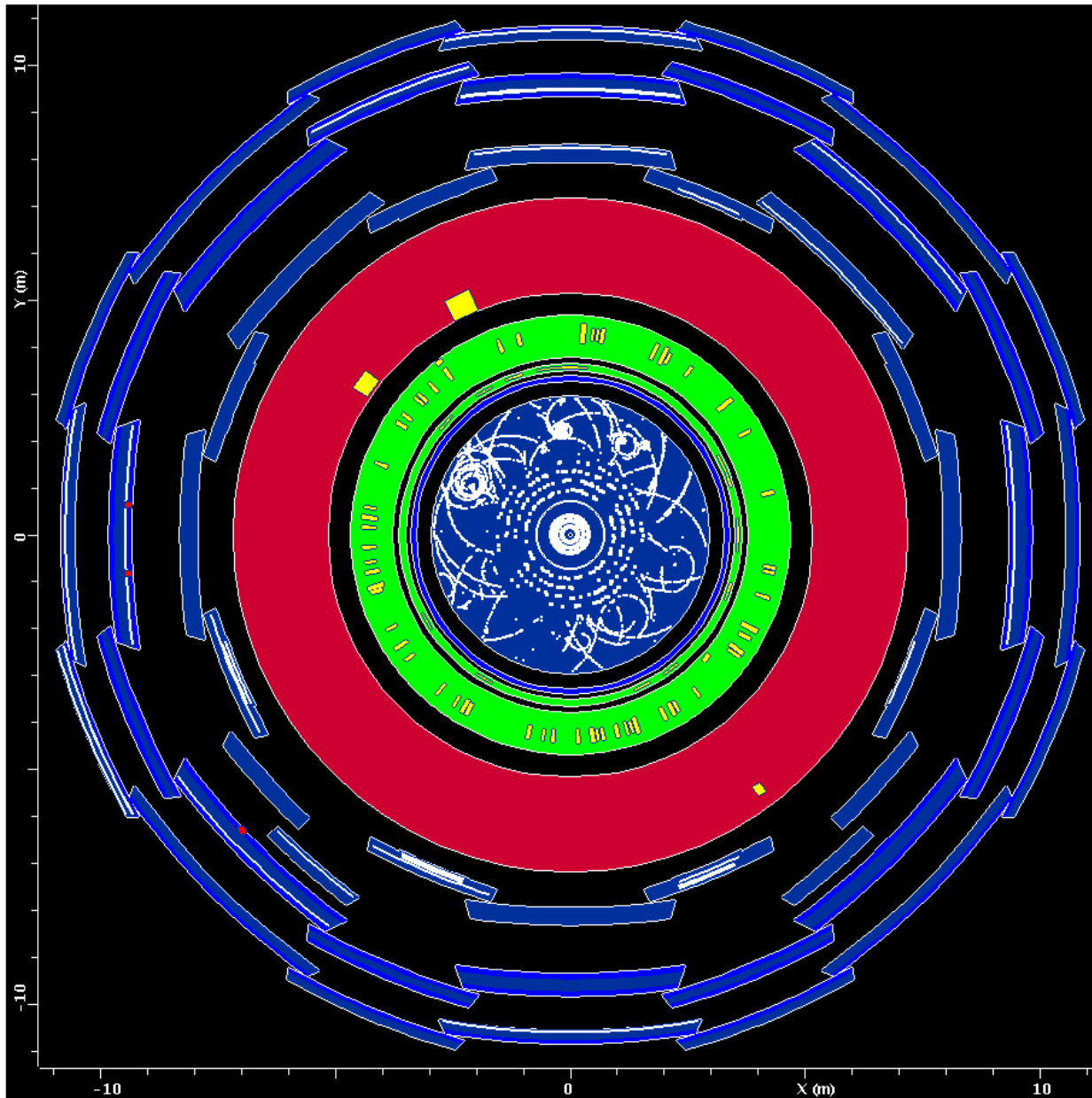
	HERA (DESY)	TEVATRON (Fermilab)	RHIC (Brookhaven)			LHC (CERN)	
						2007	2008
Physics start date	1992	1987	2000				
Physics end date	—		—				
Particles collided	$e\bar{p}$	$p\bar{p}$	$p\bar{p}$ (pol.)	Au Au	d Au	pp	Pb Pb
Maximum beam energy (TeV)	e : 0.030 p : 0.92	0.980	0.1 40% pol	0.1 TeV/u	0.1 TeV/u	7.0	2.76 TeV/u
Luminosity ($10^{30} \text{ cm}^{-2} \text{ s}^{-1}$)	75	50	6	0.0004	0.07	1.0×10^4	0.001
Time between collisions (μs)	0.096	0.396	0.213			0.025	0.100
Crossing angle ($\mu\text{ rad}$)	0	0	0			300	≤ 100
Energy spread (units 10^{-3})	e : 0.91 p : 0.2	0.14	0.2	0.5	0.5	0.11	0.11
Bunch length (cm)	e : 0.83 p : 8.5	57	40	20	20	7.7	7.94
Beam radius (10^{-6} m)	e : 280(H), 50(V) p : 265(H), 50(V)	p : 39 \bar{p} : 31	175 ($\beta^*=1 \text{ m}$)	150 (215 $\beta^*=1 \text{ m}$)	($\beta^*=2 \text{ m}$)	16.7	15.9
Free space at interaction point (m)	± 2	± 6.5	16			38	38
Luminosity lifetime (hr)	10	11–13	10	3	6	14.9	7.3
Filling time (min)	e : 60 p : 120	30	15			7.5 (both beams)	20 (both beams)
Acceleration period (s)	e : 200 p : 1500	86	140	230	230	1200	
Injection energy (TeV)	e : 0.012 p : 0.040	0.15	0.023	0.011 TeV/u	0.012 TeV/u	0.450	0.1774 TeV/u
Transverse emittance ($10^{-9} \pi \text{ rad-m}$)	e : 20(H), 3.5(V) p : 5(H), 5(V)	p : 4.3 \bar{p} : 2.7	31	23	23	0.5	0.5
β^* , ampl. function at interaction point (m)	e : 0.6 (H), 0.26(V) p : 2.45(H), 0.18(V)	0.35	1–10	1–5	2–5	0.55	0.5
Beam-beam tune shift per crossing (units 10^{-4})	e : 190(H), 450(V) p : 12(H), 9(V)	p : 14 \bar{p} : 70	26	9	11	34	—
RF frequency (MHz)	e : 499.7 p : 208.2/52.05	53	accel: 28 store: 28	accel: 28 store: 197	accel: 28 store: 197	400.8	400.8
Particles per bunch (units 10^{10})	e : 3 p : 7	p : 24 \bar{p} : 3	7	0.06	d: 1.1 Au: 0.07	11.5	0.007
Bunches per ring per species	e : 189 p : 180	36	55			2808	592
Average beam current per species (mA)	e : 40 p : 90	p : 66 \bar{p} : 8.2	48	33	d: 7.7 Au: 38	584	6.12
Circumference (km)	6.336	6.28	3.834			26.659	
Interaction regions	2 colliding beam 1 fixed target (e beam)	2 high \mathcal{L}	6			2 high \mathcal{L} +1	1
Utility insertions	4	4	13/ring			4	
Magnetic length of dipole (m)	e : 9.185 p : 8.82	6.12	9.45			14.3	
Length of standard cell (m)	e : 23.5 p : 47	59.5	29.7			106.90	
Phase advance per cell (deg)	e : 60 p : 90	67.8	84			90	
Dipoles in ring	e : 396 p : 416	774	192 per ring + 12 common			1232 main dipoles	
Quadrupoles in ring	e : 580 p : 280	216	246 per ring			482 2-in-1 24 1-in-1	
Magnet type	e : C-shaped p : s.c., collared, cold iron	s.c. $\cos \theta$ warm iron	s.c. $\cos \theta$ cold iron			s.c. 2 in 1 cold iron	
Peak magnetic field (T)	e : 0.274 p : 5	4.4	3.5			8.3	
\bar{p} source accum. rate (hr^{-1})	—	13.5×10^{10}	—			—	
Max. no. \bar{p} in accum. ring	—	2.4×10^{12}	—			—	

PLAY ▶

Large Hadron Collider

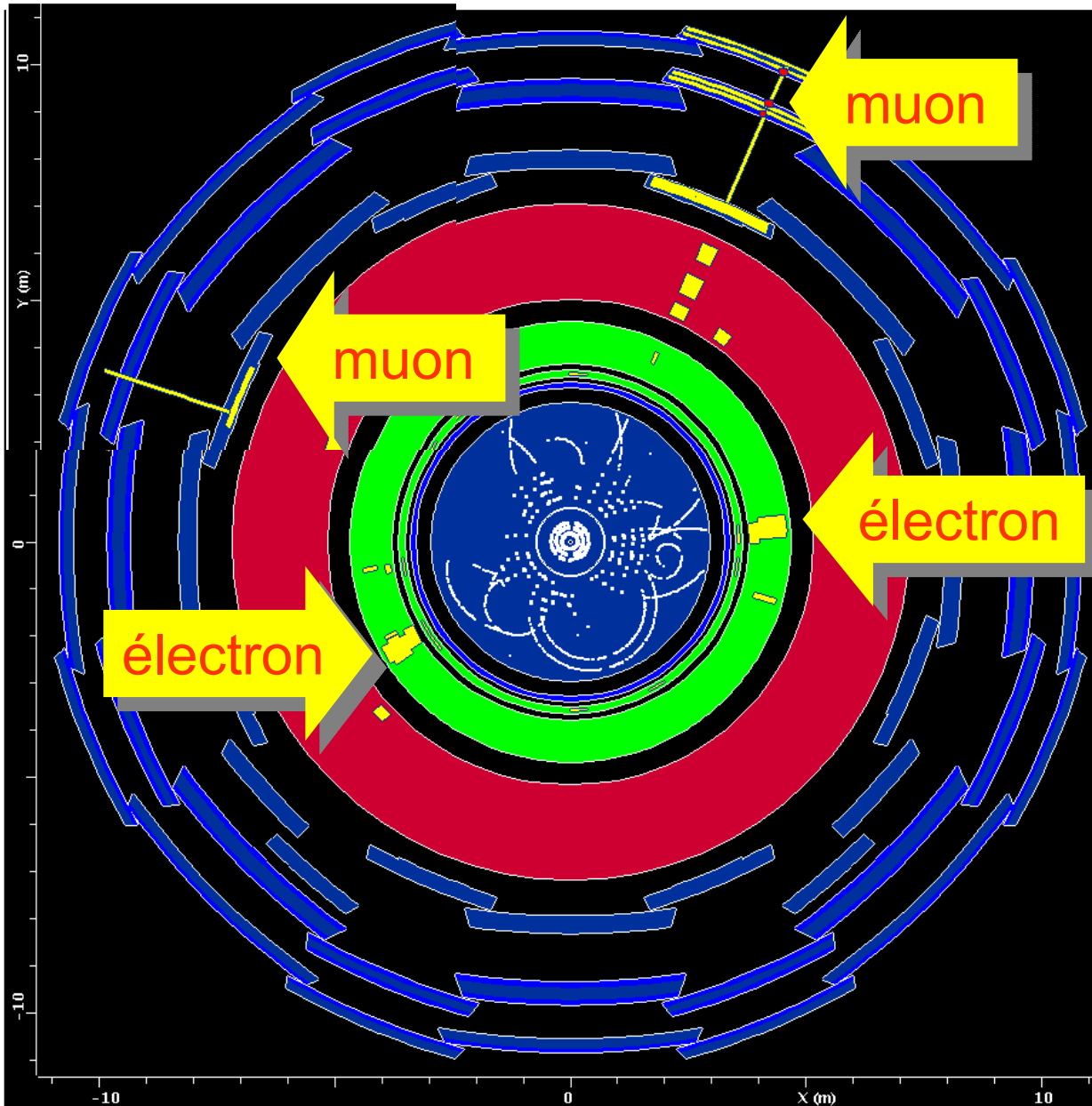


ATLAS Detector



Solo 1 evento
su 5000000
puo' essere
registrato

Evento
rigettato



Solo 1 evento
su 5000000
puo' essere
registrato

Bosone di Higgs

$$H \rightarrow \mu^+ \mu^- e^+ e^-$$

La massa invariante:

$$m = \sqrt{(p_{\mu^+} + p_{\mu^-} + p_{e^+} + p_{e^-})^2}$$

e' la massa della particella H

La "scoperta" del bosone di Higgs

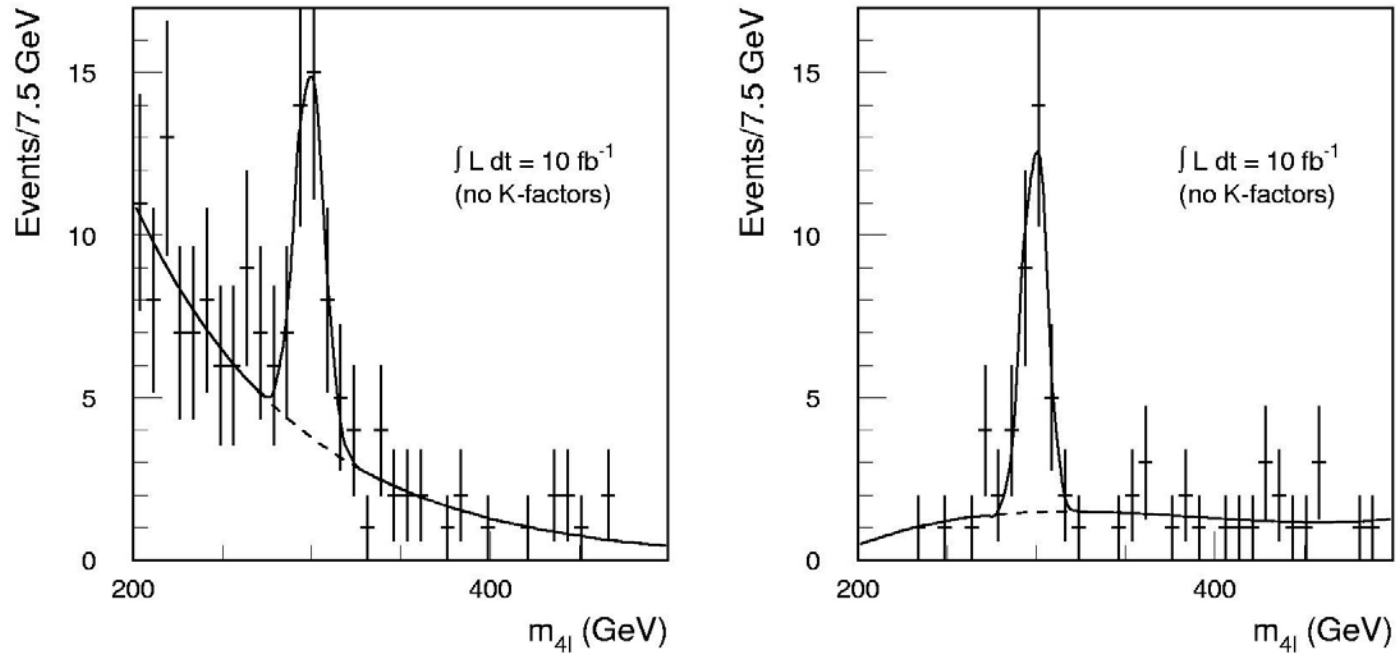


Figure 19-31 Expected $H \rightarrow ZZ \rightarrow 4l$ signal for $m_H = 300$ GeV and for an integrated luminosity of 10 fb^{-1} . The signal is shown on top of the ZZ continuum background before (left) and after (right) the $p_T^{\max}(Z_1, Z_2)$ cut is applied (see text).