

LHC, il potenziale di scoperta e CMS



LHC is the most powerful instrument for particle investigation with accelerators.

It is expected to provide some answers on the EW sector and, possibly, new challenges

CMS is an extremely sophisticated detector.

The local CMS group is involved since 1995 in the project and actively participate to construction and now in data analysis

Key Questions of Particle Physics

1. Mass: What is the origin of mass?

- How is the electroweak symmetry broken ?
- Does the Higgs boson exist ?

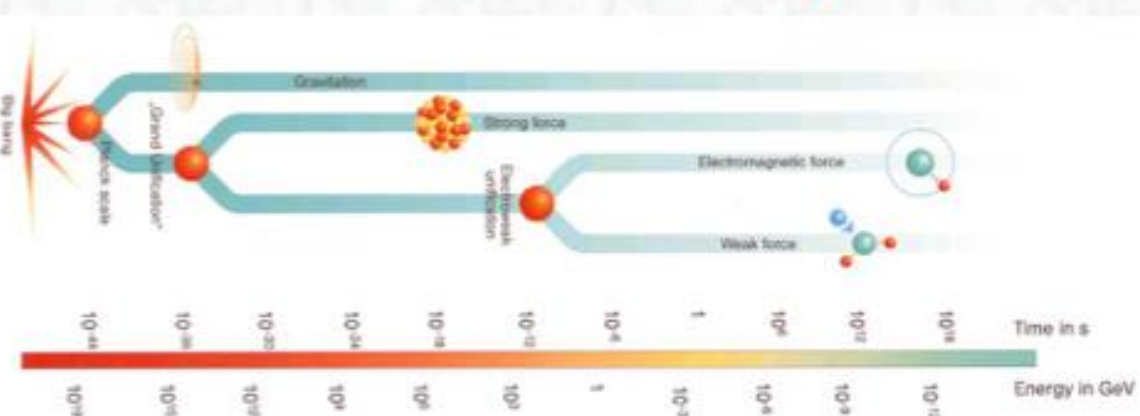
2. Unification: What is the underlying fundamental theory ?

- Can the interactions be unified at larger energy?
- How can gravity be incorporated ?
- Is our world supersymmetric ?
-

3. Flavour: or the generation problem

- Why are there three families of matter?
- Neutrino masses and mixing?
- What is the origin of CP violation?

Answers to some of these questions are expected on the TeV mass scale → LHC



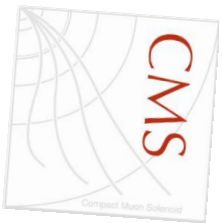
Standard Model - pre 2012

Actually our knowledge, based on the interpretation of natural phenomena, is the **Standard Model** - a relativistic quantum field theory

The symmetry principle is the local gauge invariance, where the generators are described by an $SU(3) \times SU(2) \times U(1)$ algebra; from a phenomenological point of view the model is composed of 3 elements:

- 1) 3 fermion generations (quarks and leptons)
 - ++ huge mass interval $10^{-10} \rightarrow 10^2$ GeV
 - ++ CP violated in transitions among quarks of different generations
- 2) Vector bosons, responsible for the interactions
- 3) Higgs mechanism (which provide mass to fermions and bosons) expected within a mass range [90, 1000] GeV

The model is able to well describe (very well) main part of known phenomena



Standard Model ?

A key element, a “Higgs-like” particle
discovered in 2012 by LHC

Experimentally: **neutrino mass, the dark matter, the barionic asymmetry** cannot be taken into account considering the Standard Model

Gravity is formally excluded

The **hierarchy** problem

...the standard model seems not complete, new theoretical structures needed. Experimentally accessible at the TeV scale

How can we access to the $\sim\text{TeV}$ scale with enough luminosity to see the Higgs ?

The idea is to build a hadronic collider using the old e^+e^- infrastructure (LEP) at CERN

Why hadronic? Is simpler and less expensive than an e^+e^- at the same C.o.M. energy

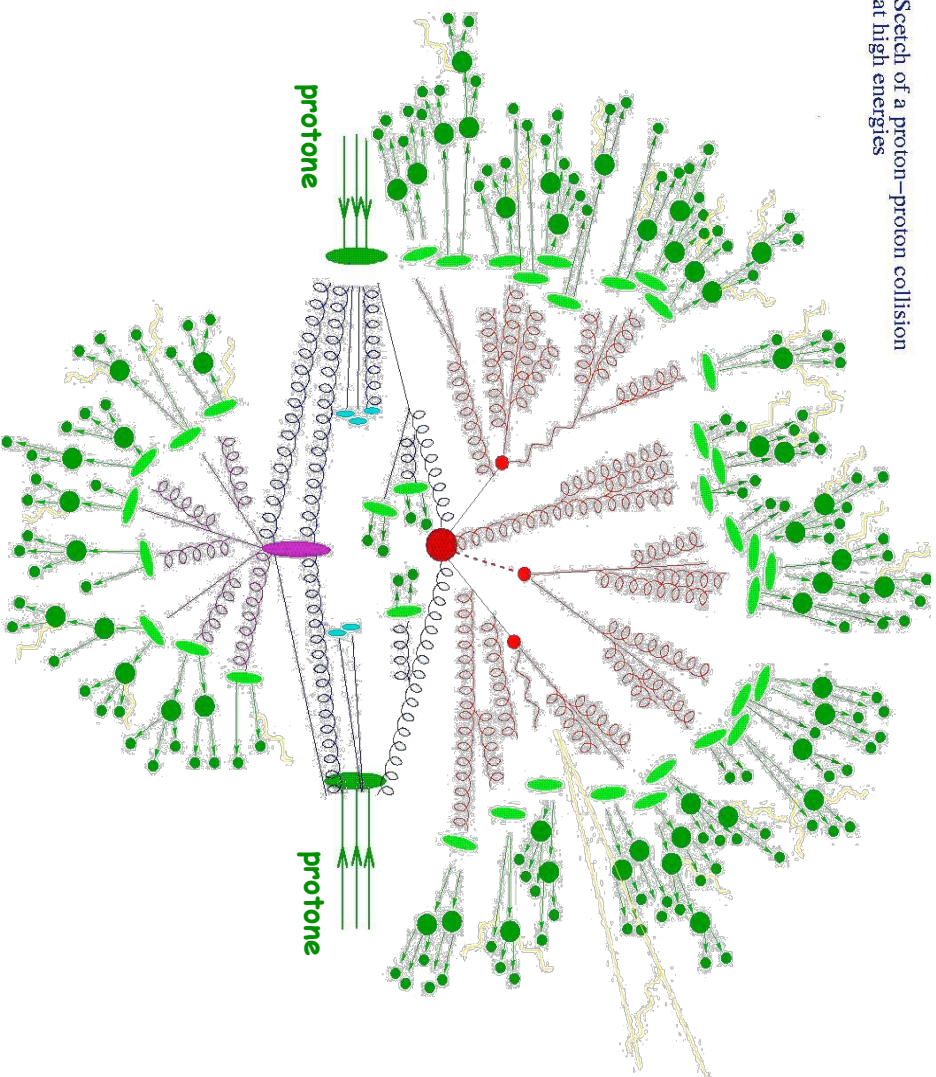
...but the final state is more complex.

We set-up a Large Hadron Collider (LHC), a proton-proton collider with several TeV available in the collisions

We need to understand how the interaction works to properly identify any new signal

Structure of the p-p interaction

Sketch of a proton–proton collision
at high energies



Main Interaction

Radiation (ISR/FSR)

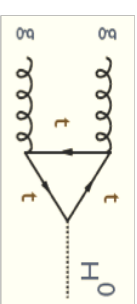
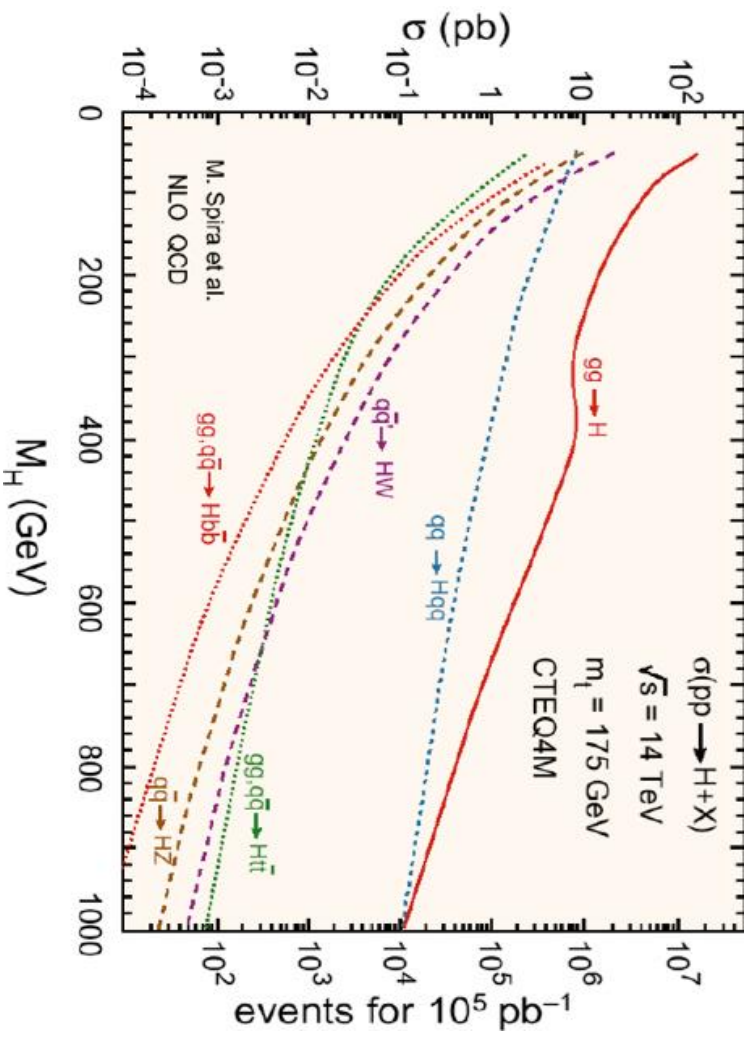
Jet

**Fragmentation/
Hadronization**

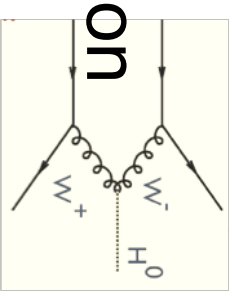
**Multiple Interactions
(MPI)**

Beam Remnant

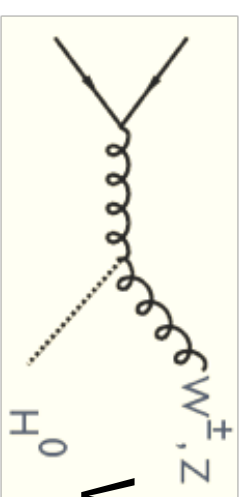
Higgs Production rates



g-g fusion

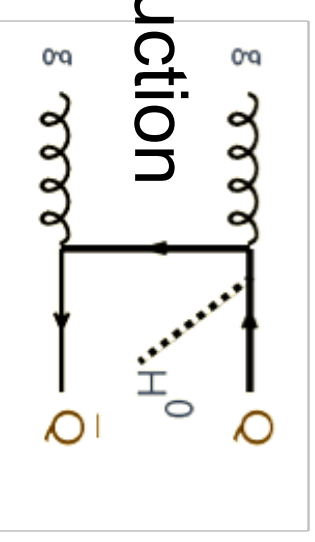


vector bosons fusion

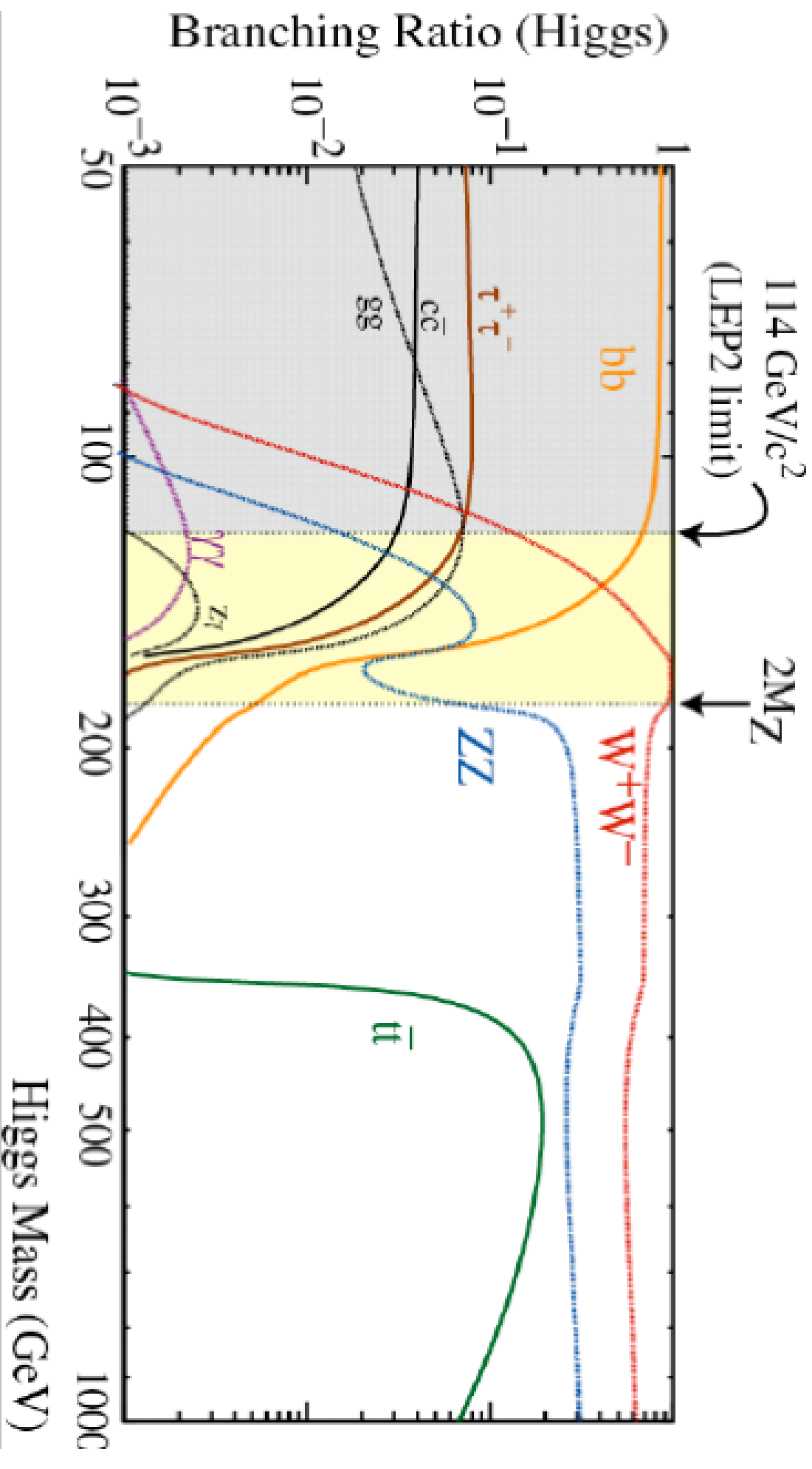


W/Z strahlung

associate production



Decay rates



Our “Master” equation - How detect signals?

The goal is to test SM (in)consistency

For each process expected at LHC:

Event rates (absolute, relative, differential)
Stat vs syst errors, backgrounds from data or MC?
Resolution, Energy Scale, Signal Significance

$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{E} L}$$

Proton-Proton Luminosity
uncertainty $\sim 5\%$? Do better?

Experimental issues : Triggers, reconstruction, isolation cuts, low-pt jets (jet veto)

Theoretical issues : PT distributions at NLO + resummation;
differential calculations for detectable acceptance.

$$\sigma_{\text{theo}} = PDF(x_1, x_2, Q^2) \otimes \hat{\sigma}_{\text{hard}}$$

constrain, define uncertainties

HO calculations,
implement in MC

Goal : test SM (in)consistency : $\sigma_{\text{exp}} \pm \Delta_{\text{exp}} \stackrel{?}{=} \sigma_{\text{SM}} \pm \Delta_{\text{th}}$

Il collisionatore

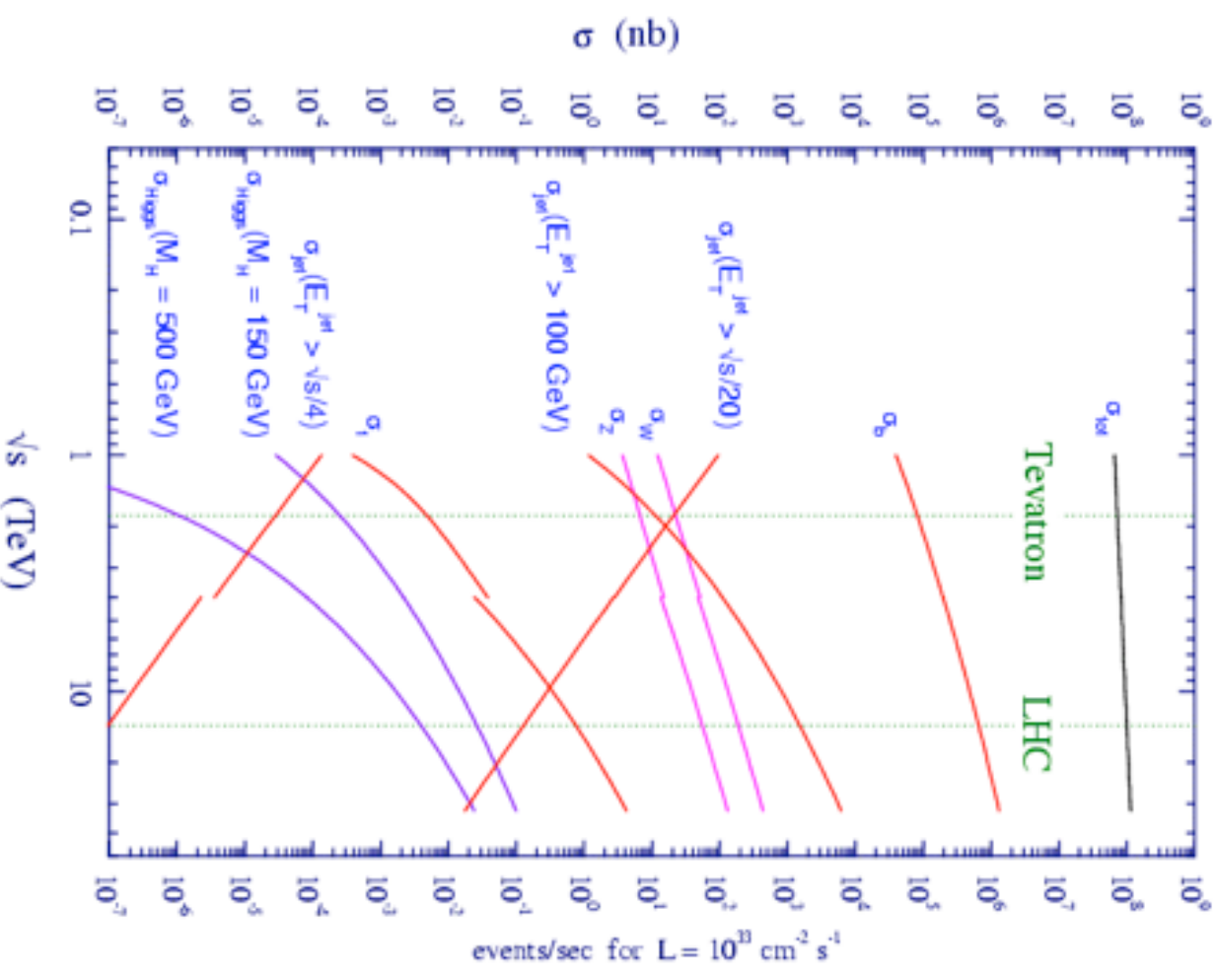
Dobbiamo essere sensibili il più possibile ai processi di fisica che possono realizzarsi

+ **tanta energia**: necessaria per produrre particelle massive (es: il bosone di Higgs)

Altri collisionatori (es e-e) non sarebbero stati altrettanto convenienti energeticamente

+ **alta intensità**:

Spesso i processi che si vorrebbero osservare sono molto rari (es: 10 ordini di grandezza)



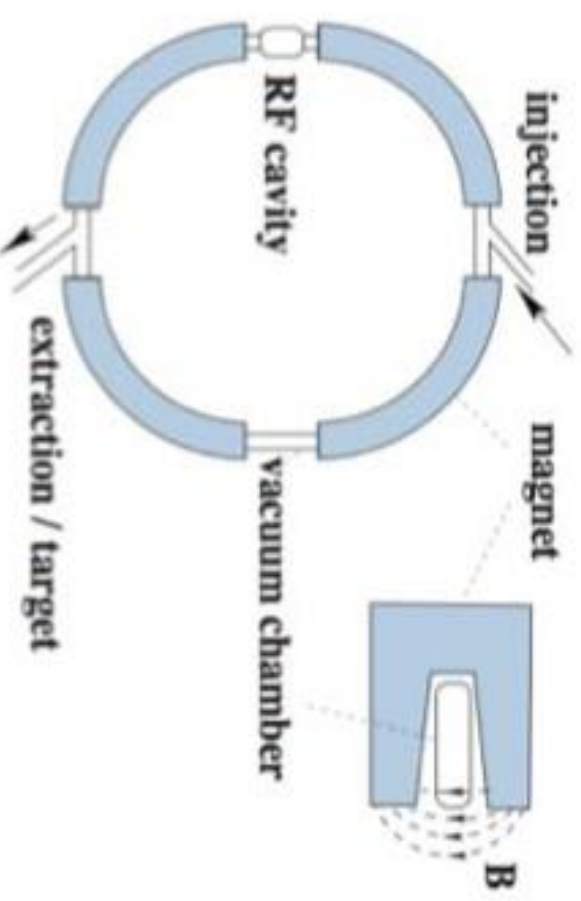
II collisionatore

- **Cyclotron:** constant RF
magnetic field radius ρ increases with energy
used for smaller machines



- **Synchrotron:** $\rho = \text{const}$
 B increases with energy
RF frequency adjusted slightly ($\beta = 0.999 \dots\dots 1.0$)

Most High Energy accelerators and all CERN ring accelerators (PS, SPS, LEP, LHC) are of this type



Basic parameters, Lorentz Force

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

charge q , normally $q = e$; $q = Ze$ for ions

- Electric field \mathbf{E} provides the acceleration or rather energy gain
- The magnetic field \mathbf{B} keeps the particles on their path

ρ is the radius of curvature for motion perpendicular to the static magnetic field. Often called

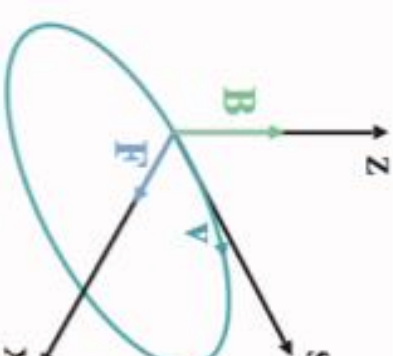
- gyromagnetic or Larmor radius in astroparticle physics
- bending radius for accelerators

$B\rho$ known as magnetic rigidity, units Tm

LHC

- Momentum $p = 7 \text{ TeV}/c$
- LHC bending radius $\rho = 2804 \text{ m}$
- Bending field $B = 8.33 \text{ Tesla}$
- magnets at **1.9 K**, super-fluid He

Circular
motion for
 $\mathbf{E} = 0$
 $\mathbf{v} \perp \mathbf{B}$



$$B = \frac{p}{q \rho}$$

for $q = e$ numerically
 $B [\text{T}] = p [\text{GeV}/c] \cdot 3.336 \text{ m} / \rho$
 high energy, $v = c$ "p = E"
 $E < E_H = q B \rho$ Hillas criterion

Astroparticle

units $10^{-4} \text{ T} = 1 \text{ Gauss}$; a.u. = $1.5 \times 10^{11} \text{ m}$
 Solar system **$B = 10 \mu\text{G}$** $E = 5 \text{ TeV}$ **$\rho = 11 \text{ a.u.}$**
 Intergalactic **$B = 1 \text{ nG}$** $E = 5 \text{ PeV}$ (knee)
 $\rho = 1.7 \times 10^{19} \text{ m}$ (4 % of galaxy-radius)

Luminosity and collision rates

Event rate for process with cross section σ

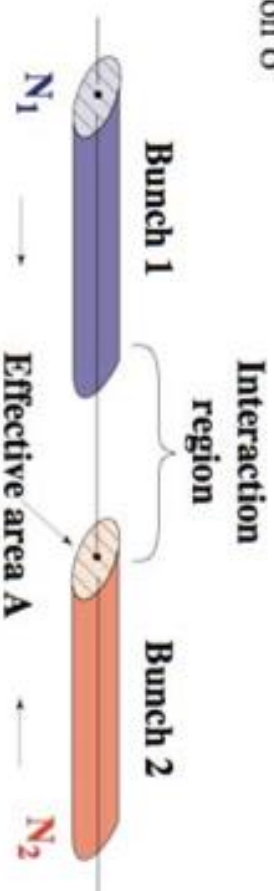
$$\dot{n} = \mathcal{L} \sigma$$

Luminosity from bunch

crossings at frequency $f = f_{\text{rev}} n_b$

$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$

for Gaussian bunches with rms sizes $\sigma_x \sigma_y$ $A = 4 \pi \sigma_x \sigma_y$



High luminosity: Large number of particles (N_1, N_2)

Small beam dimensions (A) in the interaction point

Large f (large number of bunches,

→ small time difference between bunch crossings)

LHC: $N = 1.15 \cdot 10^{11}$, $n_b = 2808$ (number of bunches)

bunch separation: 25 ns (corresponds to 7.5 m)

A: beams squeezed (using strong, large aperture quadrupoles close to the interaction region) from $\sigma = 0.2$ mm to $16 \mu\text{m}$

Alternate gradient focusing

**Quadrupole lens
focusing in x,
defocusing in y
or vice versa**

$$\mathbf{F} = e (\mathbf{v} \times \mathbf{B})$$

here

$$\begin{aligned}\mathbf{F} &= e (0, 0, v) \times (B_x, B_y, 0) \\ &= e (-v B_y, +v B_x, 0)\end{aligned}$$

Combine F D

Defocusing when at

small amplitude

Overall focusing

Normal (light) optics :

Focal length of two lenses

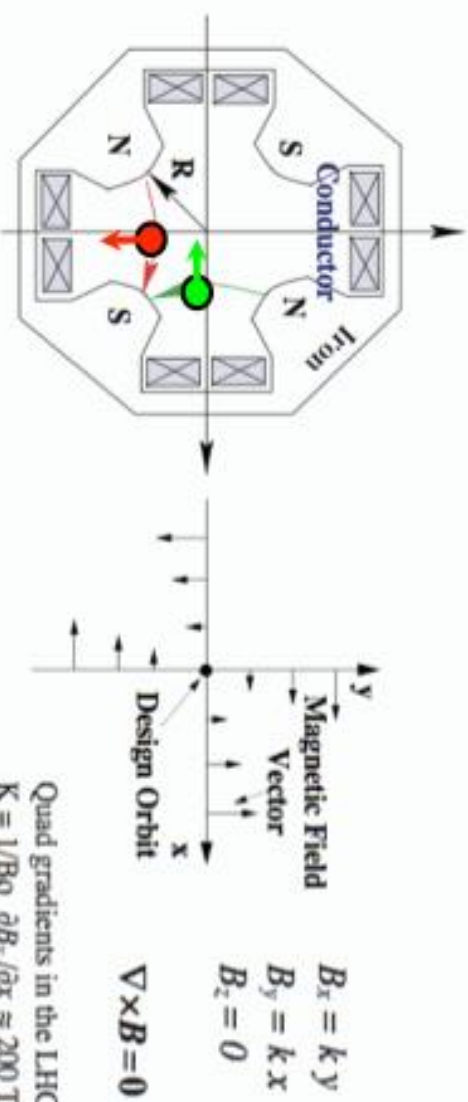
at distance D

$$1/f = 1/f_1 + 1/f_2 = D/f_1 f_2$$

is overall focusing

$$\text{with } 1/f = D/f^2$$

$$\text{for } f = f_1 = -f_2$$



Quad gradients in the LHC
 $K = 1/B_0 \partial B_y / \partial x \approx 200 \text{ T/m}$

**alternate gradient
focusing**

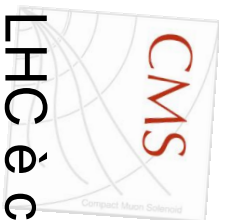


**together with
bending magnets
FODO lattice**



N. C. Christofilos, unpublished manuscript in 1950 and patent
Courant, Snyder in 1952, Phys. Rev. 88, pp 1190 - 1196 + longer review in Annals of Physics 3 (1958)





LHC



LHC è costruito al **CERN**, sfruttando la vecchia infrastruttura del LEP
Un anello di 27km di diametro
in media 80 m sotto terra

Il sistema di iniezione sono i “vecchi” acceleratori PS e SPS (W,Z)

4 esperimenti:

+ **ATLAS**
+ **CMS**

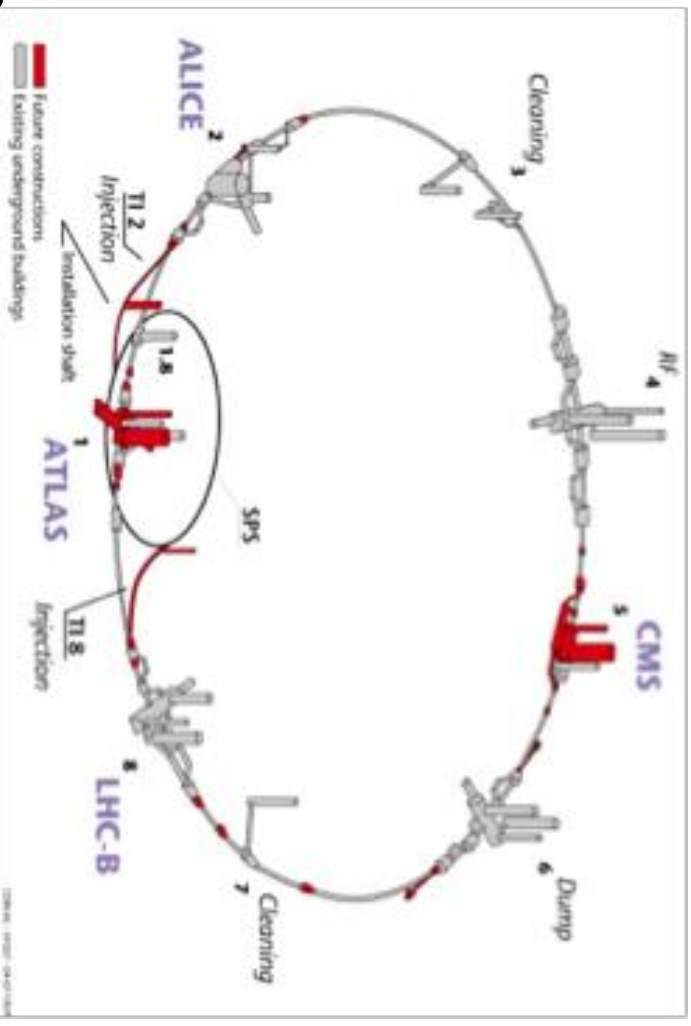
esperimenti “generalisti”, disegnati per assicurare il maggior potenziale di scoperta possibile

+ **LHCb**

ottimizzato per la fisica dei B

+ **ALICE**

ottimizzato per le collisioni tra ioni pesanti



L'energia dei protoni è limitata dal campo magnetico che mantiene i protoni in una traiettoria circolare

Beam energy momentum:

$$p = 0.3 \times B \times r$$

p = momentum [GeV],

B = magnetic field [Tesla],

r = radius [metres]

Dal momento che il raggio è fissato, l'unico modo per incrementare l'energia è aumentare B

Rendere il campo magnetico il più omogeneo possibile
~ 2/3 dell'anello hanno dipoli magnetici

Altri magneti per il focussing

Sono necessarie sezioni rettilinee per posizionare gli esperimenti

Un po' di spazio se lo prendono i sistemi di iniezione ed espulsione

Raffreddati a 1.9 K con elio superfluido

B > 8 Tesla

Magneti “doppi” rispetto a
Tevatron perche' LHC e' p-p
e non p-anti_p

Nota: si usano fasci p-p (e non p-anti_p) perche' non sarebbe conveniente dare le luminosita' che si intendono raggiungere



Il rate di eventi attesi

Energia nel centro di massa

$\sqrt{s} = 14 \text{ TeV}$ per collisioni protone-protone

$\sqrt{s} = 6 \text{ TeV}$ per collisioni Pb-Pb

Luminosità

$L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ per collisioni protone-protone

$L = 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ per Pb-Pb

I protoni circolano in “bunches” (cioè in pacchetti)

La spaziatura temporale è di 25 ns (i.e. 7.5 metri)

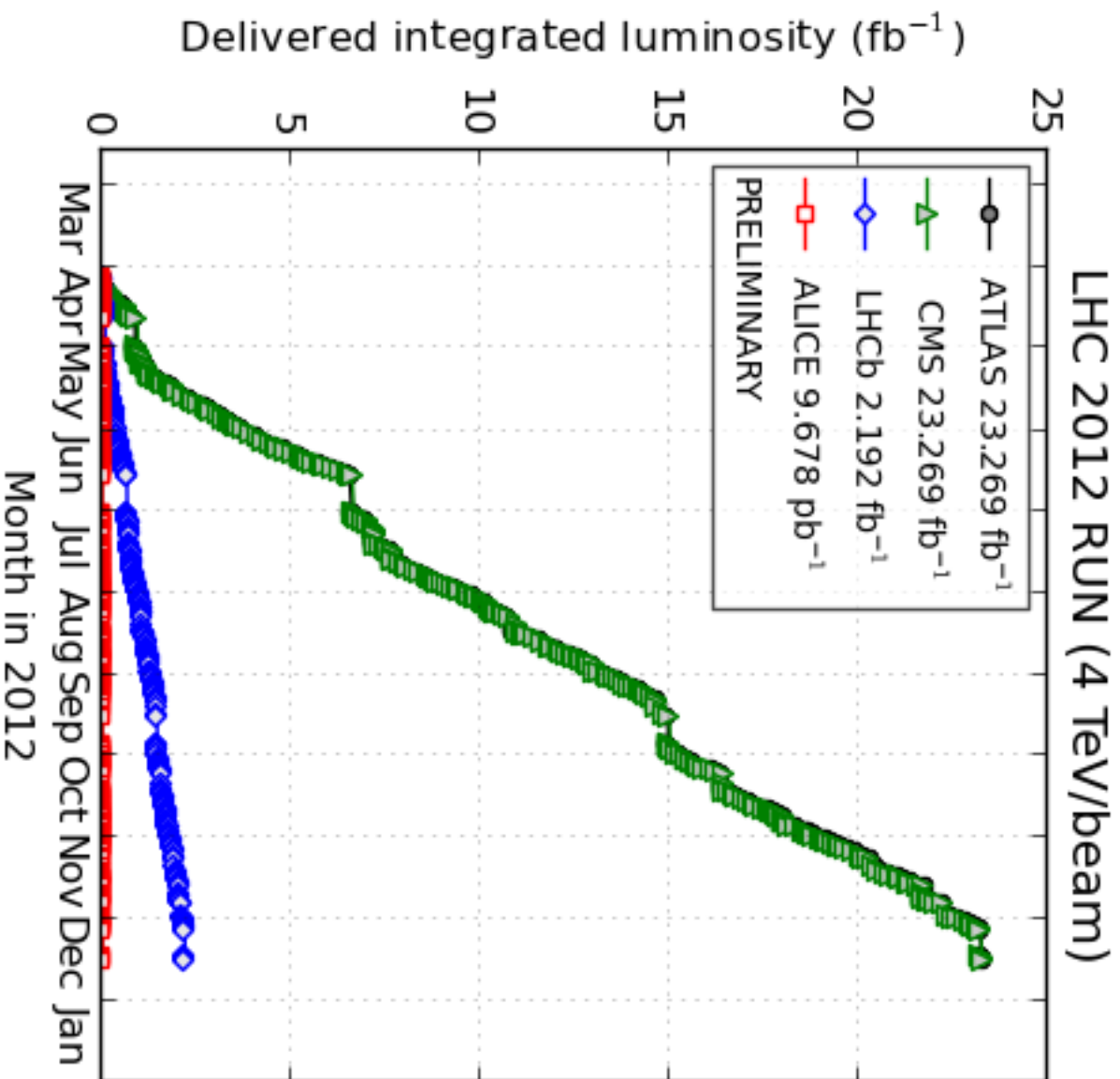
Il rate di Bunch-crossing è 40 MHz

Se consideriamo la sezione d'urto totale p-p $\sim 100 \text{ mb}$

Il rate di eventi a $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ è $R \sim 10^9 \text{ Hz}$

Se poi consideriamo che ci sono **circa ~ 25 interazioni pp separate per ogni bunch-crossing** vi renderete conto della difficoltà di separare un evento interessante dal fondo di eventi prodotti

LHC - 2012



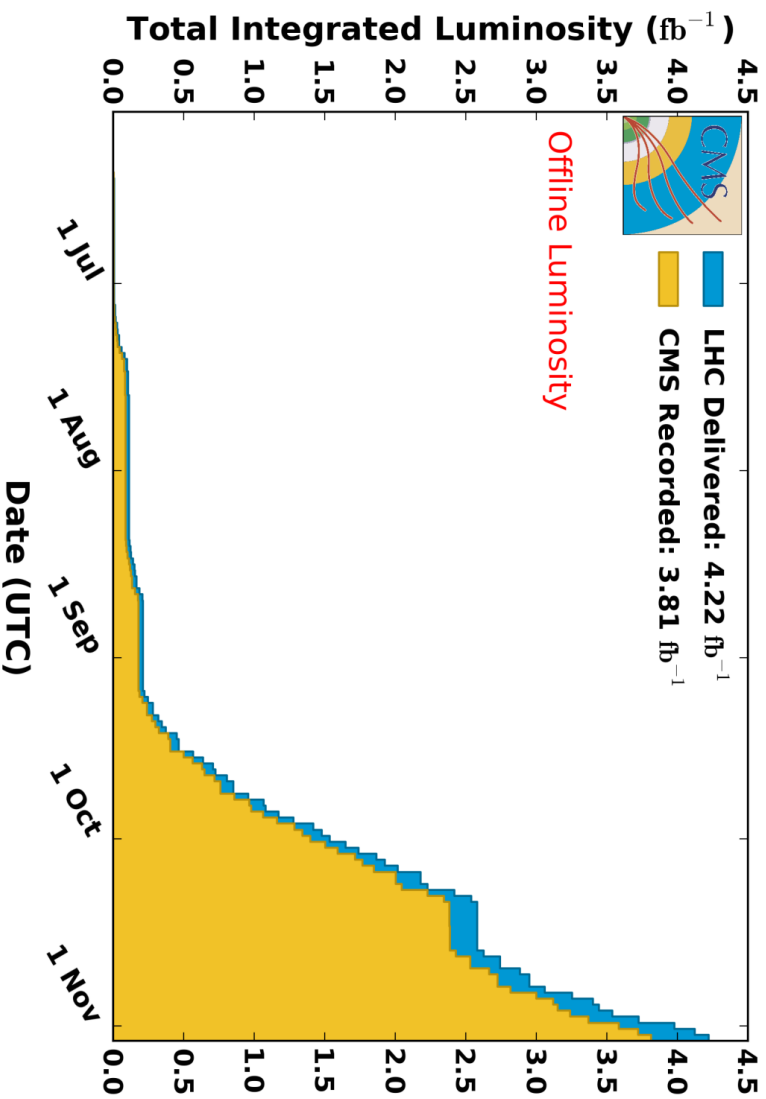
(generated 2013-01-29 18:28 including fill 3453)

From April 2012
8 TeV energy - stable running
with increasing luminosity

~25 fb⁻¹ collected
(L_{inst} up to 10^{32})

CMS Integrated Luminosity, pp, 2015, $\sqrt{s} = 13$ TeV

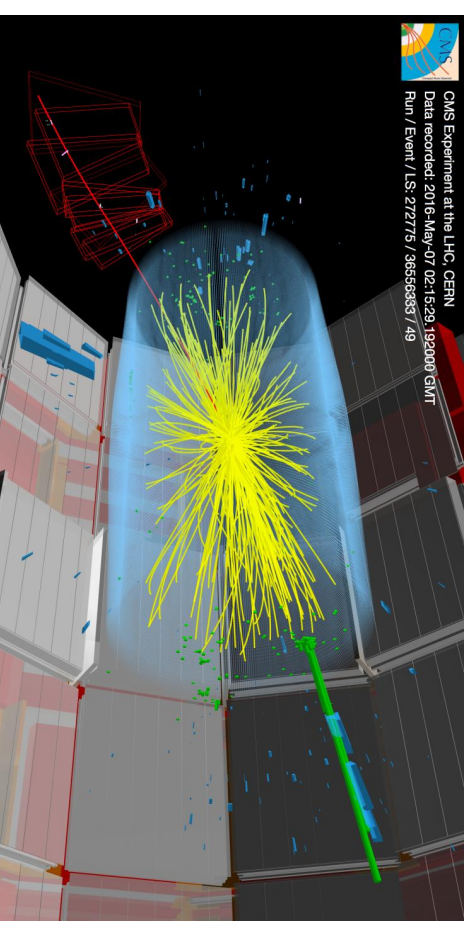
Data included from 2015-06-03 08:41 to 2015-11-03 06:25 UTC



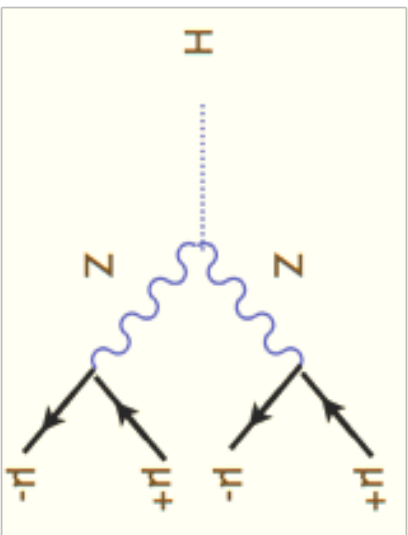
From July 2015
13 TeV energy - stable running
with increasing luminosity

~4 fb^{-1} collected
(L_{int} up to 10^{33})

Now LHC restarted, the first
stable beam last May 7th



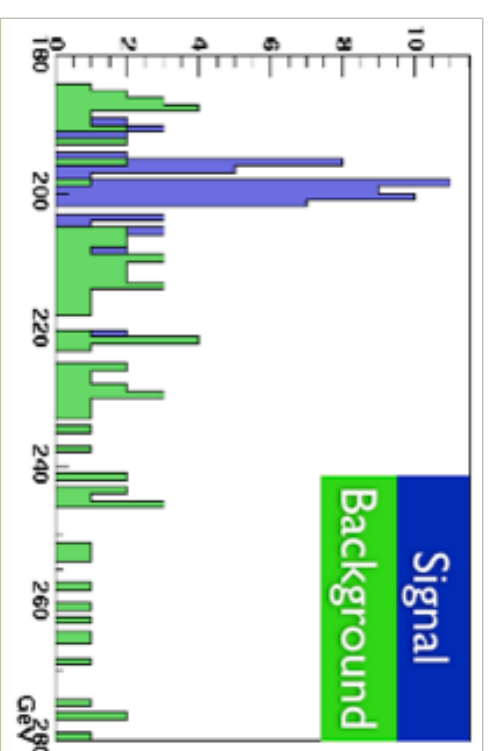
How to “see” the Higgs ?



Particular case: each
Z decays in $\mu\mu$

The idea is:

- + select all the events with:
at least 4 μ (+-,+-) in the final state
- + apply invariant mass condition
best pairing:
 $m_{\text{inv}}(i, j) = m_{\text{inv}}(k, l) = m_Z$
- + at this point:
 $m_{\text{inv}}(i, j, k, l) = m_H$



what is the background ? any other process
with 4 muons in the final state

How to “see” the Higgs ? with a detector

past



present



Il rivelatore deve essere in grado di:

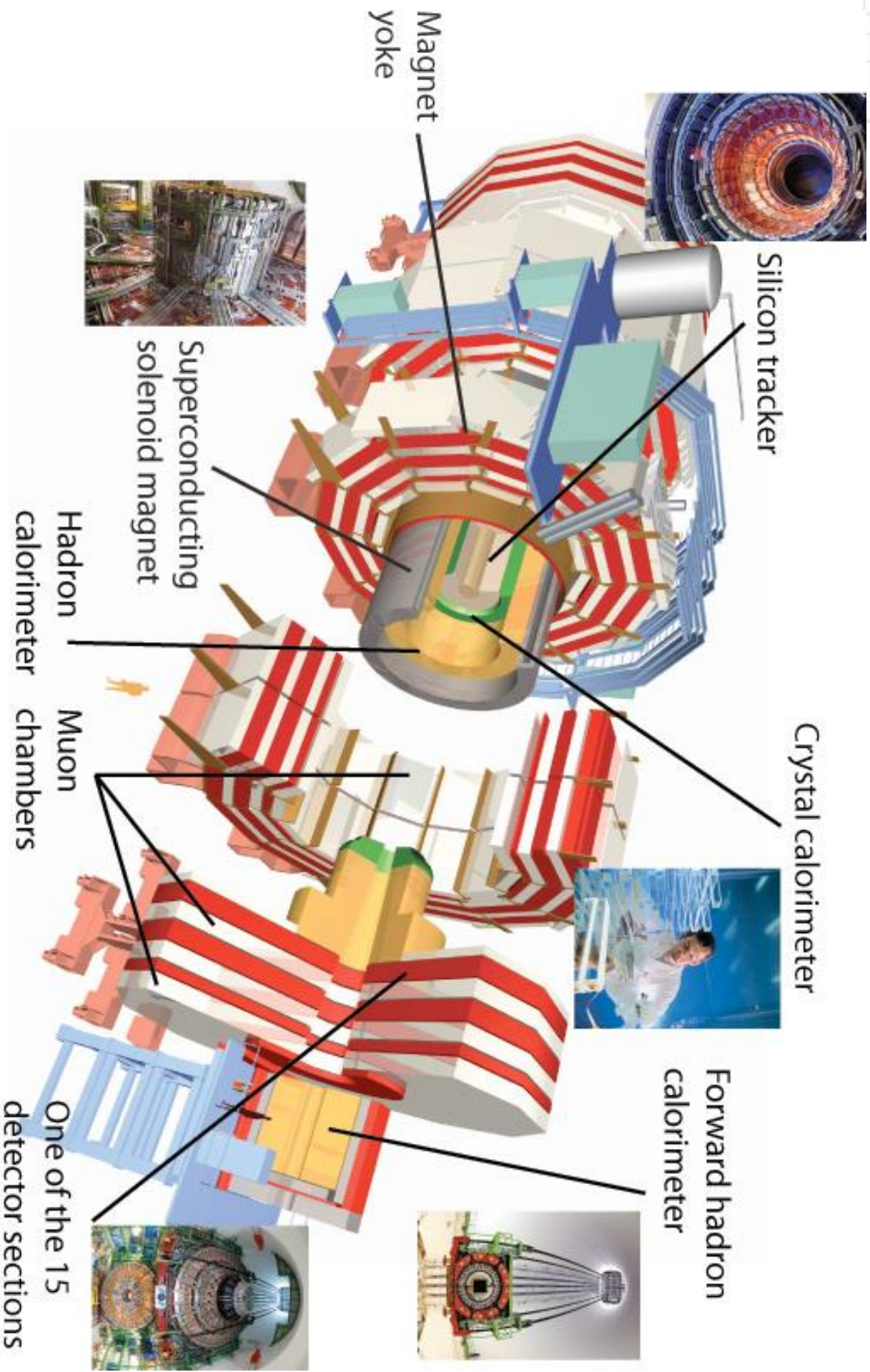
- + **alta efficienza di rilevazione** (es: 1 traccia “interessante” su 1000 - > devo essere in grado di ricostruirle tutte)

- + **alta risoluzione spaziale** (quale delle n interazioni vicine e' quella giusta? Devo ricostruire n vertici primari e secondari alle volte distanti poche decine di micron tra loro)

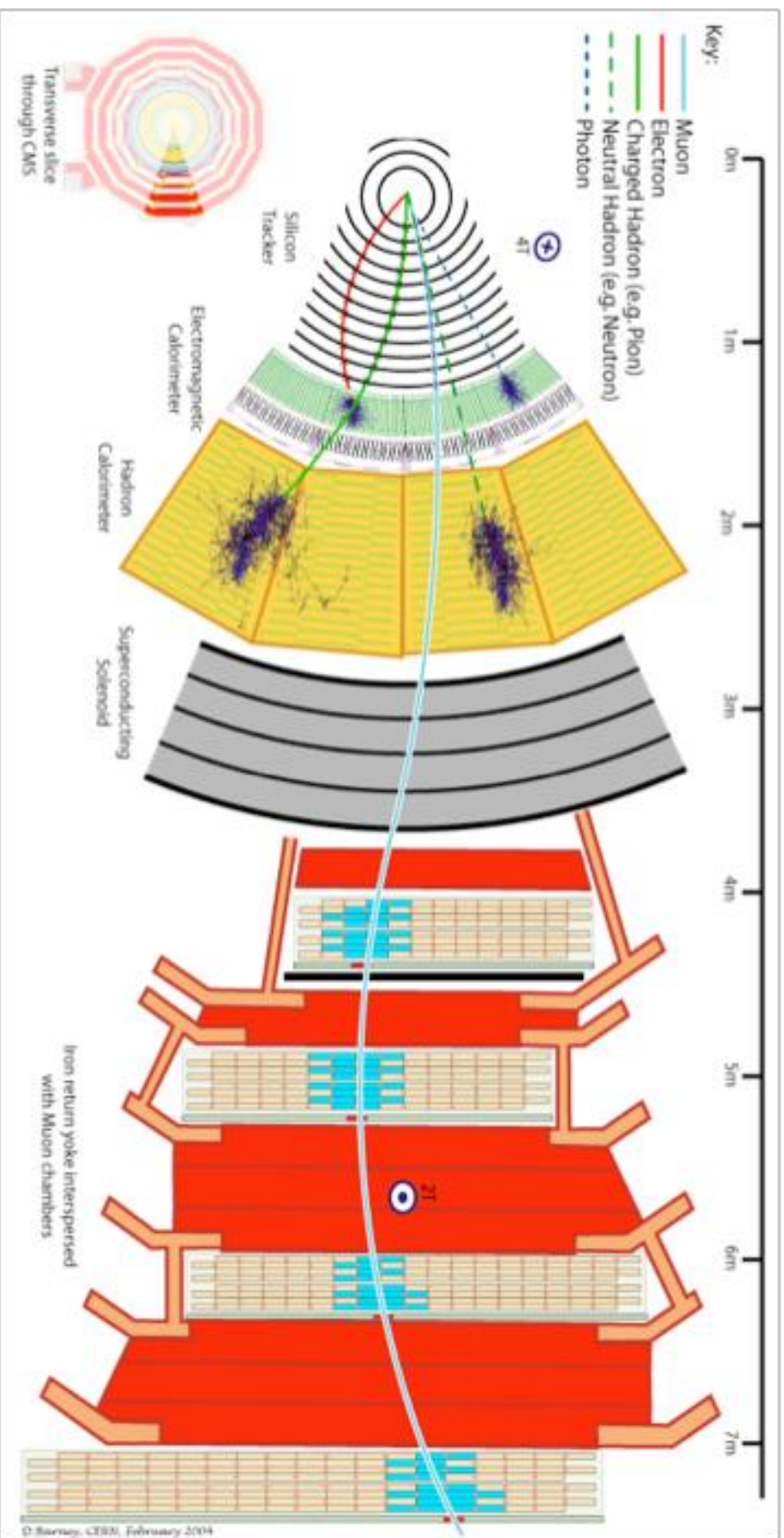
- + **alta velocita' di risposta** (40MHz e' la frequenza di interazione dei bunches ad LHC)

- + inoltre la parte piu' interna deve essere in grado di **resistere al danneggiamento da radiazione**

Il rivelatore CMS



Il ruolo dei sottorivelatori



Il magnete

Un unico solenoide usato sia per i detector interni sia per le camere a μ (usando il campo di ritorno)

Campo intenso (**4 Tesla**) nel volume interno

Grande raggio (~ 3 m)

I calorimetri sono dentro il magnete!

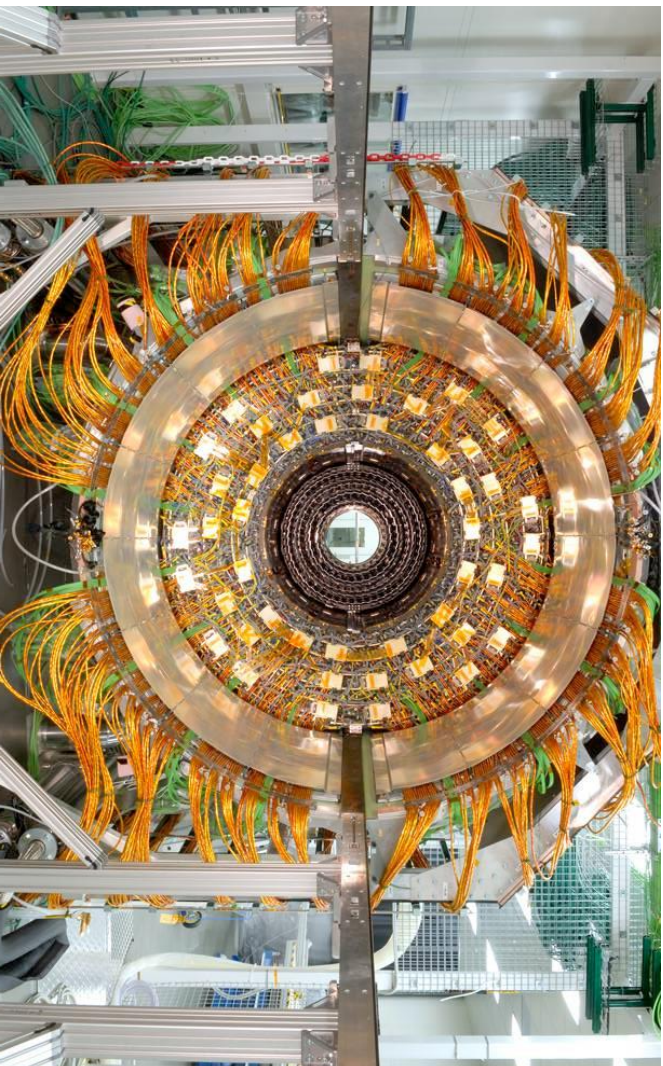
Meno materiale di fronte al calorimetro EM, quindi una risoluzione piu' alta nella determinazione dell'energia di fotoni ed elettroni

Il ferro che contiene il campo di ritorno esterno del solenoide e' equipaggiato con le camere a μ

Pesa 14,500 tonnellate

Tutto questo ferro limita la precisione nella ricostruzione dell'impulso (se ci si basa solo sulla misura esterna!)

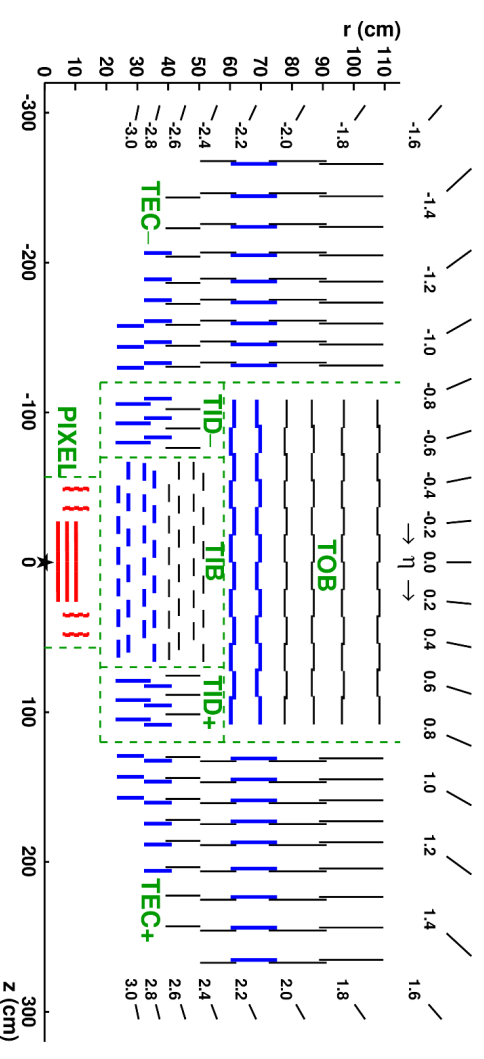
Il tracciatore



L'impulso di una particella carica e' determinato dal raggio di curvatura nel campo magnetico

$$p = 0.3 \times B \times r$$

La risoluzione della misura d'impulso e' determinata dalla precisione nella ricostruzione della traiettoria (es: numero di punti con cui si ricostruisce, risoluzione spaziale del punto)



Per basso impulso e' fondamentale che i rivelatori siano leggeri

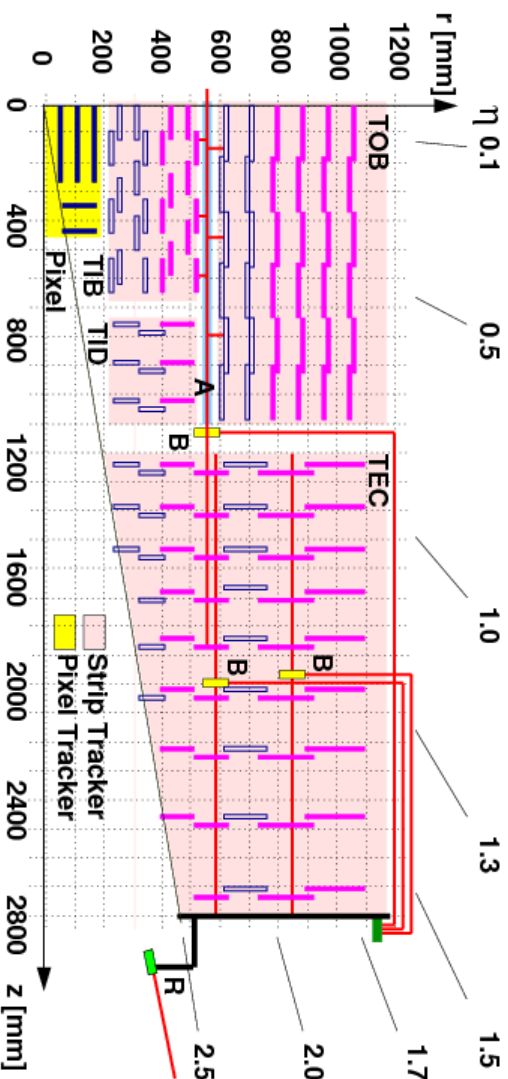
-> meno materiale meno multiple scattering

Il tracciatore

- Silicon detectors with high spatial resolution to measure the coordinates of charged particles with high precision

Basic interaction: ionization energy loss of charged particles

- Pattern recognition (hits / coordinates \rightarrow track candidates)
- Fit of curvature (3 dimensional helix model in a homogeneous magnetic field) \rightarrow momentum



Pixel:

3 layers

2 dischi

Barrel:

4 layer interni

6 esterni

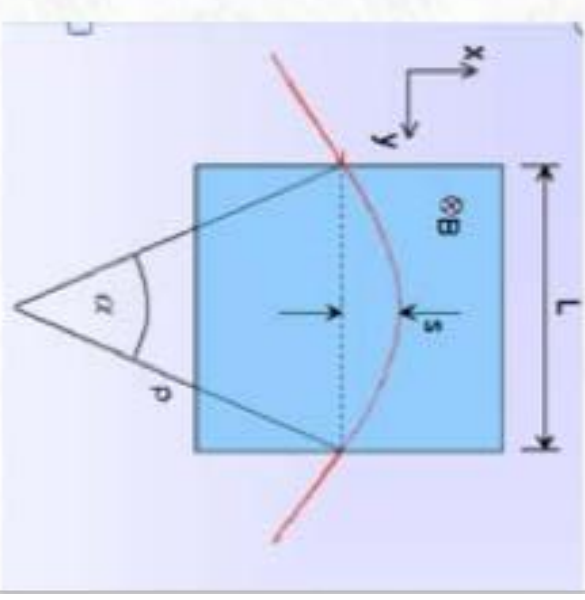
Endcap:

3 dischi interni

9 dischi esterni

Misura dell'impulso

- In general the track of a charged particle is measured using several (N) position-sensitive detectors in the magnetic field volume
- Assume that each detector measures the coordinates of the track with a precision of $\sigma(x)$
- The obtainable momentum resolution depends on:
 - L (length of the measurement volume)
 - B (magnetic field strength)
 - σ (position resolution)



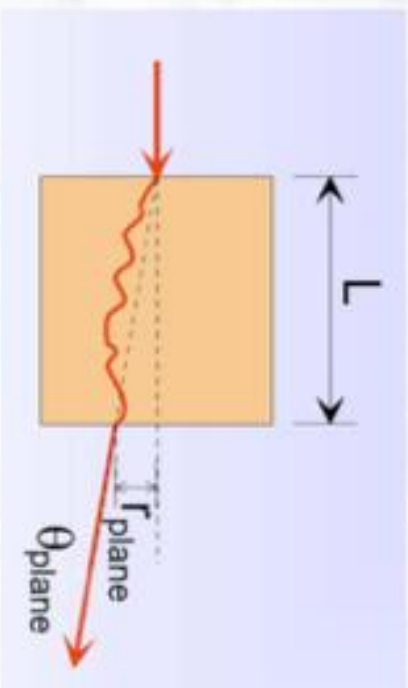
For N equidistant measurements, the momentum resolution is described by the Gluckstern formula (1963):

$$\frac{\sigma(p_T)}{p_T} \Big|^{meas.} = \frac{\sigma(x) \cdot p_T}{0.3 \cdot BL^2} \sqrt{720/(N+4)} \quad (\text{for } N \geq \sim 10)$$

note: $\Delta(p_T) / p_T \sim p_T$ (relative resolution degrades with higher transverse momentum)

Misura dell'impulso

- Degradation of the resolution due to Coulomb multiple scattering (no ionization, elastic scattering on nuclei, change of direction)

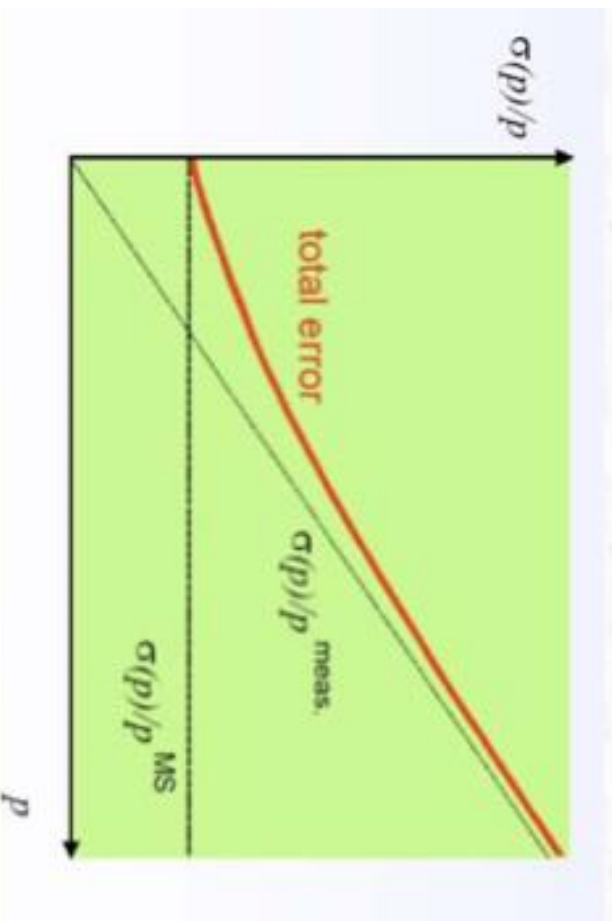


$$\theta_0 = \theta_{plane}^{RMS} = \sqrt{\langle \theta_{plane}^2 \rangle}$$

$$= \frac{1}{\sqrt{2}} \theta_{space}^{RMS}$$

$$\theta_0 \propto \frac{1}{p} \sqrt{\frac{L}{X_0}}$$

where X_0 = radiation length of the material
(characteristic parameter, see
calorimeter section)



$$\left. \frac{\sigma(p)}{p} \right|_{MS} = 0.045 \frac{1}{B \sqrt{L X_0}}$$

Energy loss

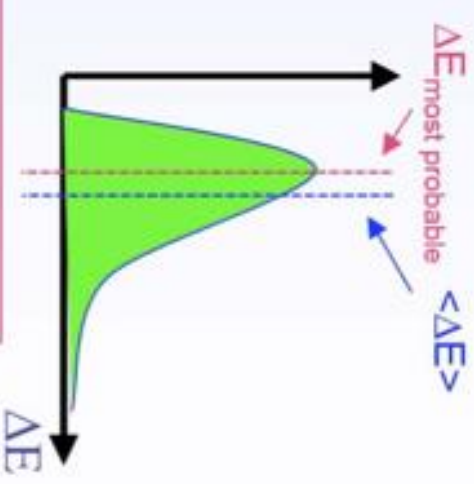
Real detector (limited granularity) can not measure $\langle dE/dx \rangle$!
It measures the energy ΔE deposited in a layer of finite thickness δx .

For thin layers or low density materials:

→ Few collisions, some with high energy transfer.



→ Energy loss distributions show large fluctuations towards high losses: "Landau tails"

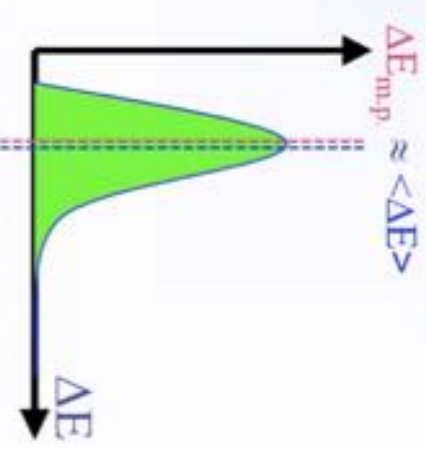


Example: Si sensor: 300 μm thick. $\Delta E_{\text{m.p.}} \sim 82 \text{ keV}$ $\langle \Delta E \rangle \sim 115 \text{ keV}$

For thick layers and high density materials:

→ Many collisions.

→ Central Limit Theorem → **Gaussian shaped distributions.**



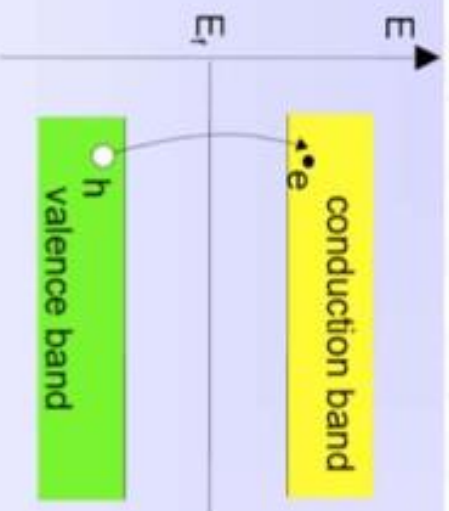
Silicon Detectors

- In all modern particle physics experiments semiconductor detectors are used as tracking devices with a high spatial resolution (15-20 μm)
- Nearly an order of magnitude more precise than detectors based on ionisation in gas (which was standard up to LEP experiments)

■ Some characteristics of Silicon crystals

- **Small band gap** $E_g = 1.12 \text{ eV} \Rightarrow E(e\text{-}h \text{ pair}) = 3.6 \text{ eV}$ ($\approx 30 \text{ eV}$ for gas detectors)
- **High specific density** 2.33 g/cm^3 ; dE/dx (M.I.P.) $\approx 3.8 \text{ MeV/cm} \approx 106 \text{ e-h}/\mu\text{m}$ (average)
- **High carrier mobility** $\mu_e = 1450 \text{ cm}^2/\text{Vs}$, $\mu_h = 450 \text{ cm}^2/\text{Vs} \Rightarrow$ fast charge collection ($< 10 \text{ ns}$)
- **Very pure** $< 1 \text{ ppm}$ impurities and $< 0.1 \text{ ppb}$ electrical active impurities
- **Rigidity** of silicon allows thin self supporting structures
- **Detector production by microelectronic techniques**
 \Rightarrow well known industrial technology, relatively low price, small structures easily possible

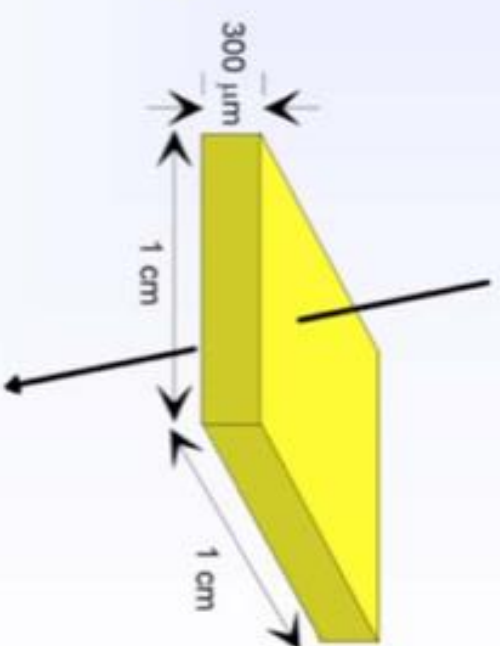
Come ottenere un segnale



In a pure intrinsic (undoped) semiconductor the electron density n and hole density p are equal.

$$n = p = n_i \quad \text{For Silicon: } n_i \approx 1.45 \cdot 10^{10} \text{ cm}^{-3}$$

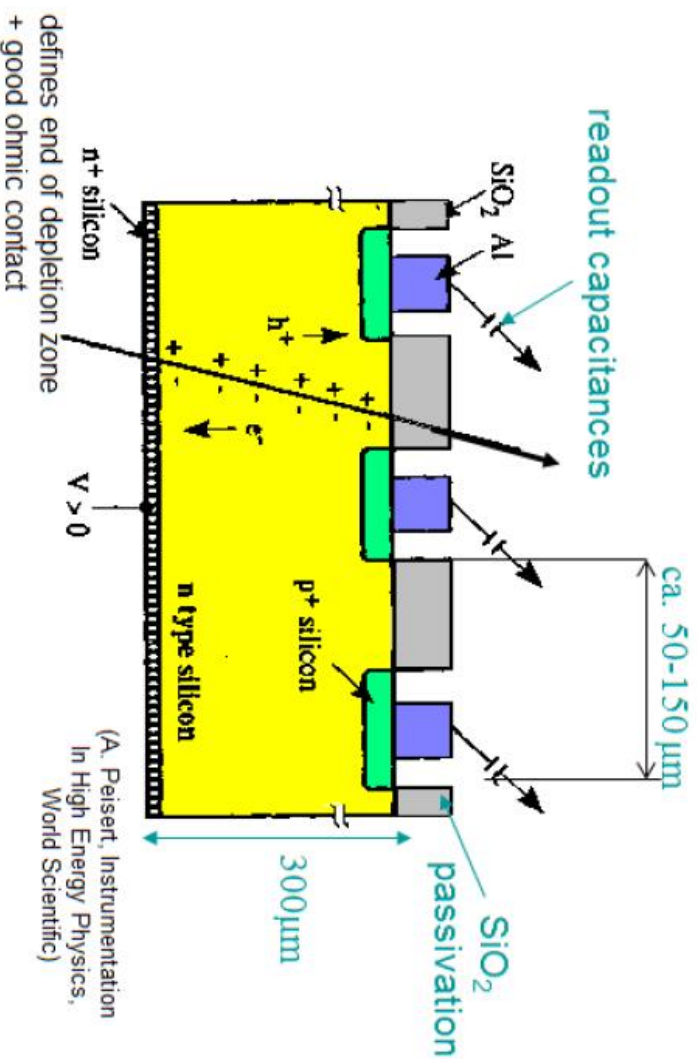
$4.5 \cdot 10^8$ free charge carriers in this volume, but only $3.2 \cdot 10^4$ e-h pairs produced by a M.I.P.



⇒ Reduce number of free charge carriers, i.e. deplete the detector

⇒ Most detectors make use of reverse biased p-n junctions

Come ottenere un segnale

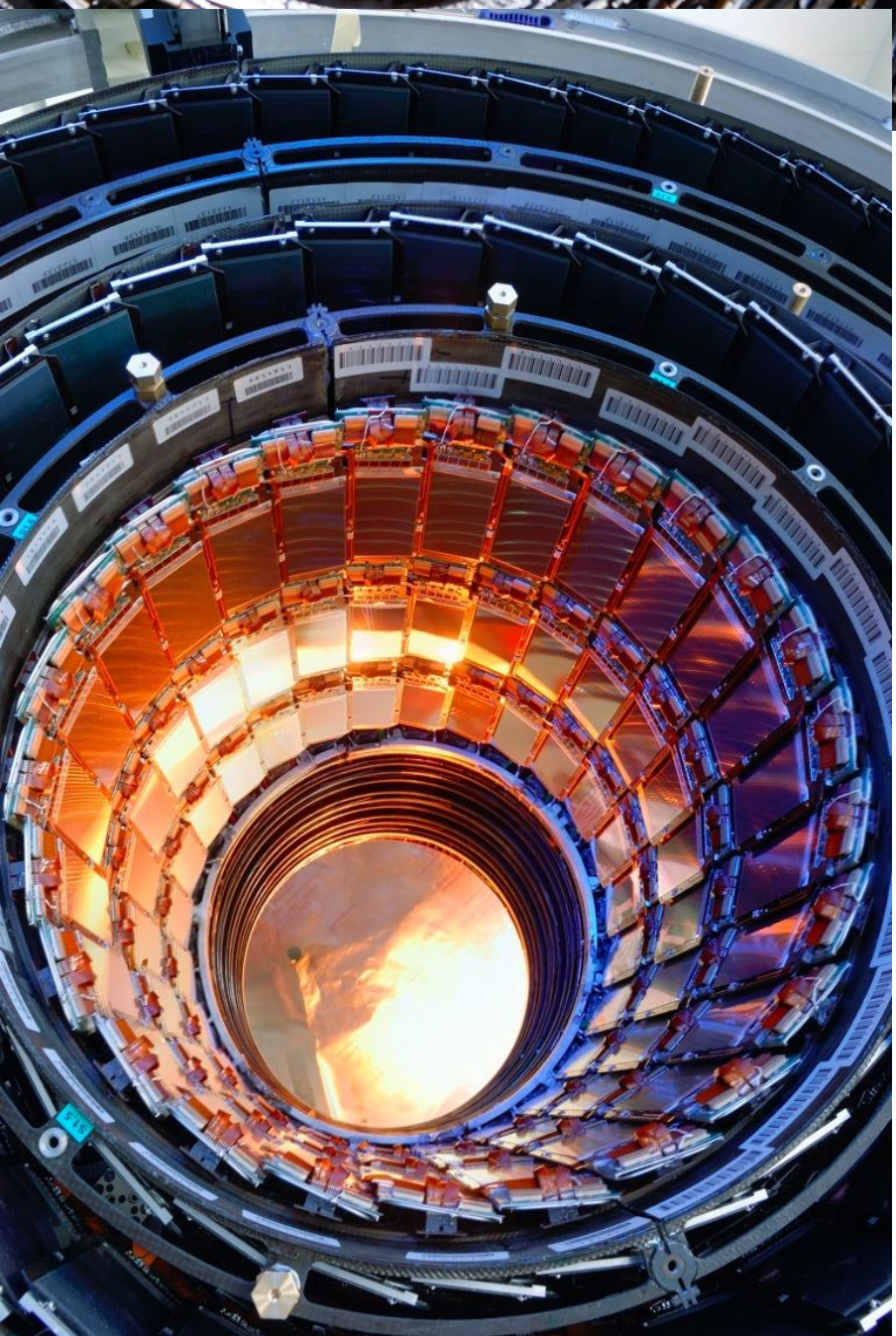
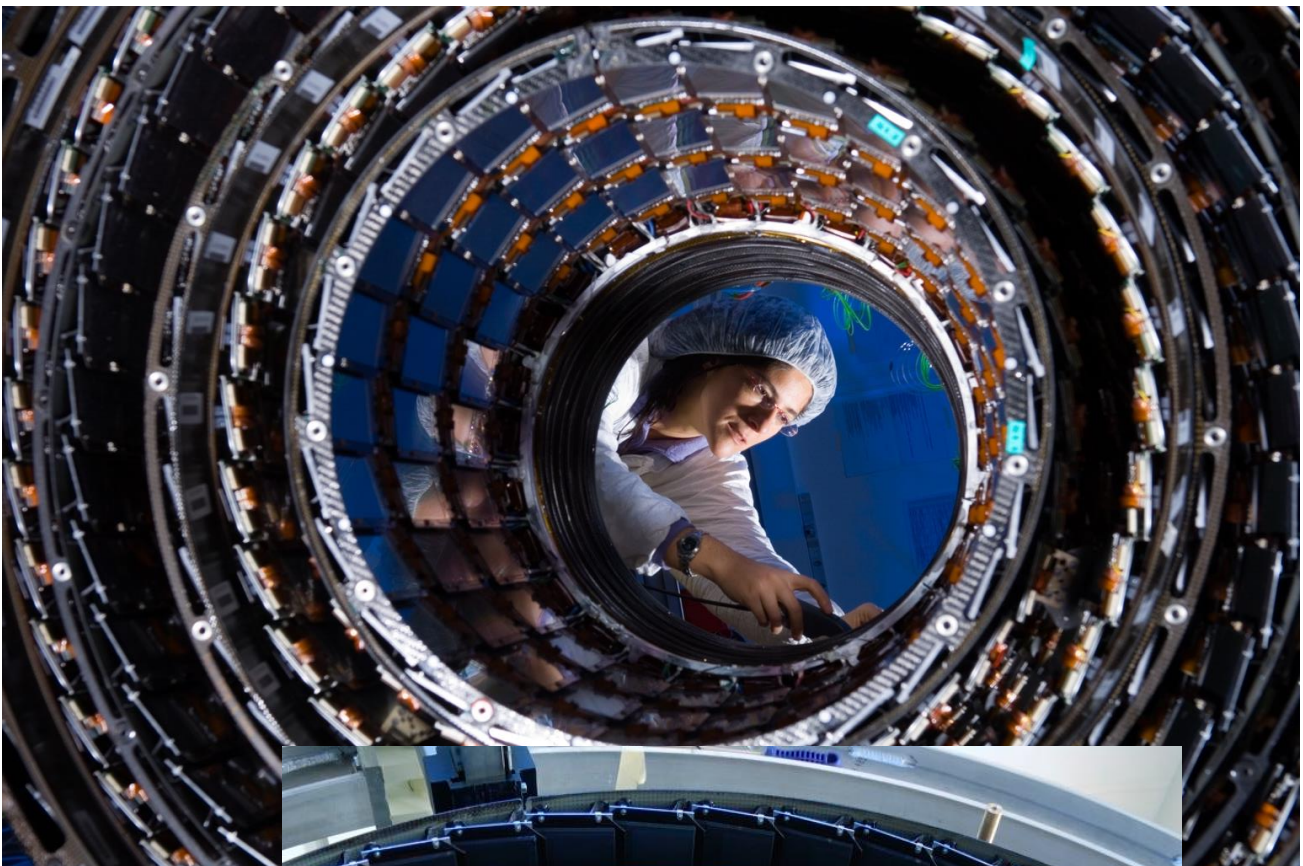


Due silici drogati diversamente vengono uniti per creare un'interfaccia detta giunzione p-n. Se polarizzata inversamente si crea in prossimità della giunzione una regione di svuotamento che minimizza le correnti di fondo.

Il passaggio di una particella carica deposita energia creando coppie elettrone-lacuna. Il campo elettrico fa sì che gli elettroni derivino verso la regione n e le lacune verso la p.

Ogni unità fornisce informazioni bidimensionali e la disposizione su più strati permette di definire una regione di segnale in 3D

The Tracker



CMS

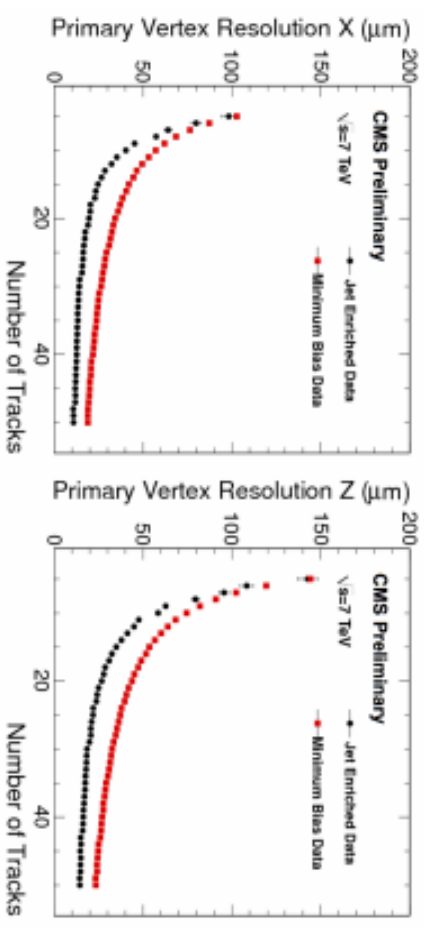
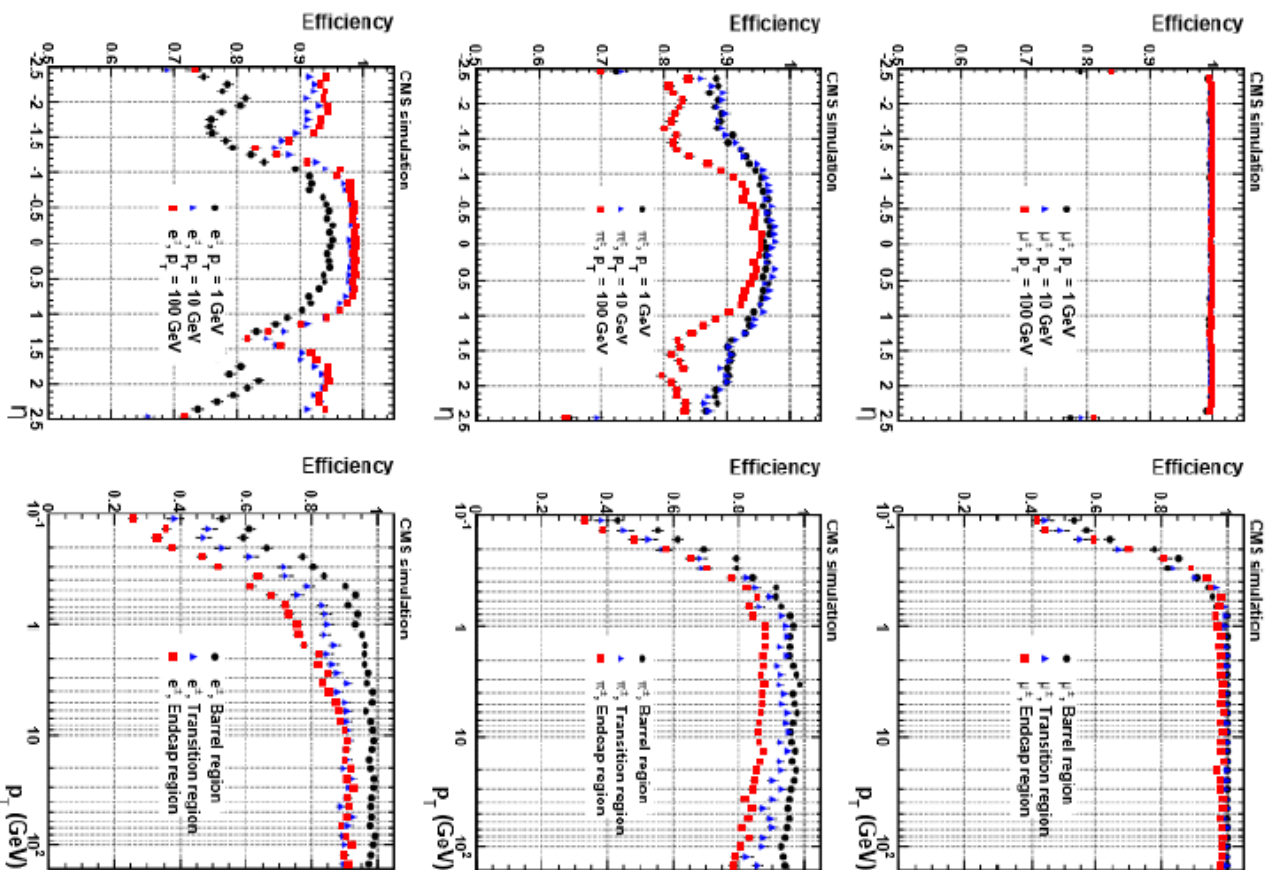
The Tracker

INFN





Il tracciatore - prestazioni



Calorimetria

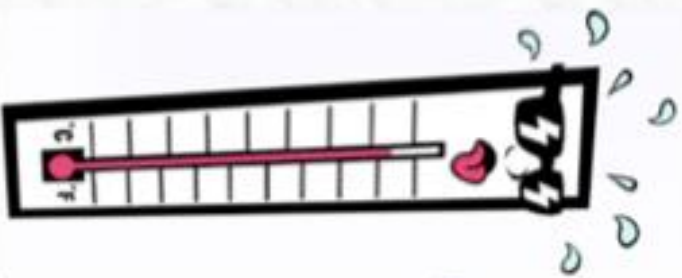
Calorimetry: = Energy measurement by total absorption,
usually combined with spatial information / reconstruction

latin: calor = heat

However: calorimetry in particle physics does not correspond
to measurements of ΔT

- The temperature change of 1 liter water at 20 °C by the energy deposition of a 1 GeV particle is $3.8 \cdot 10^{-14} \text{ K}$!
- LHC: total stored beam energy
 $E = 10^{14} \text{ protons} \cdot 14 \text{ TeV} \sim 10^8 \text{ J}$

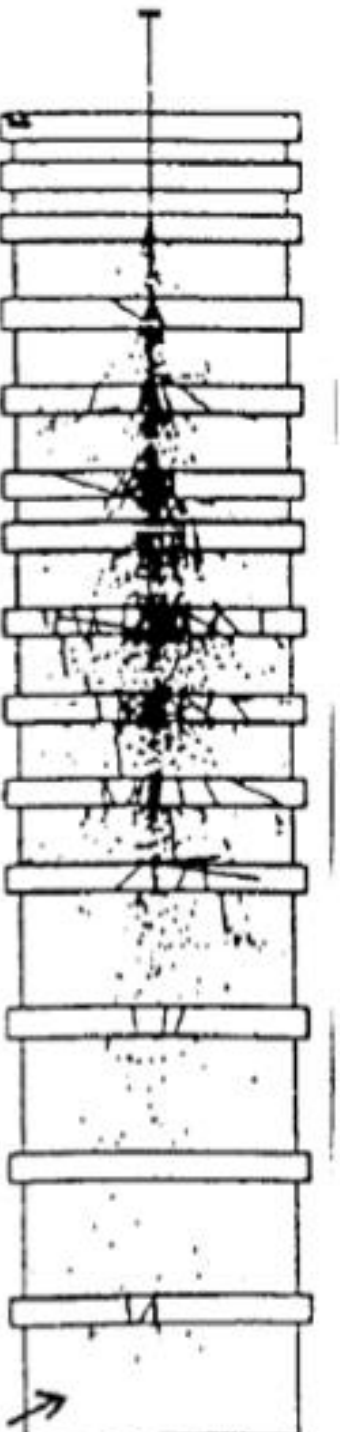
If transferred to heat, this energy would only suffice to heat a mass of 239 kg water from 0° to 100°C
 $[C_{\text{Water}} = 4.18 \text{ J g}^{-1} \text{ K}^{-1}, \quad m = \Delta E / (C_{\text{Water}} \Delta T)]$



- Primary task: measurement of the total **energy** of particles
- Energy is transferred to an **electrical signal** (ionization charge) or to a **light signal** (scintillators, Cherenkov light)
This **signal** should be **proportional to the original energy**: $E = \alpha S$
Calibration procedure $\rightarrow \propto [\text{GeV} / \text{S}]$

Energy of primary particle is transferred to new, particles,
 \rightarrow cascade of new, lower energy particles

- Layout: block of material in which the particle deposits its energy
 (absorber material (Fe, Pb, Cu,...)
 + sensitive medium (Liquid argon, scintillators, gas ionization detectors,...)



Important parameters of a calorimeter:

- **Linearity** of the energy measurement
- Precision of the energy measurement (**resolution**, $\Delta E / E$) in general limited by fluctuations in the shower process
worse for sampling calorimeters as compared to homogeneous calorimeters
- Uniformity of the energy response to different particles (**e/h response**)
in general: response of calorimeters is different to so called electromagnetic particles (e, γ) and hadrons (h)

e/fotoni - interazioni

Energy loss due to excitation and ionisation

Bethe Bloch formula

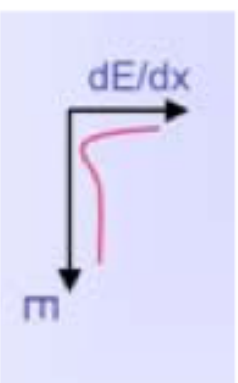
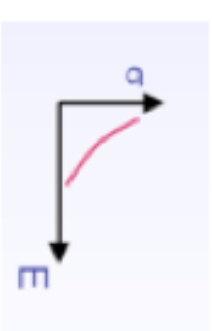
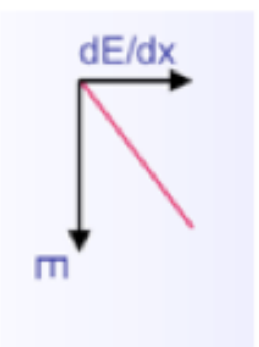


Photo effect

(dominant in \sim keV energy range)

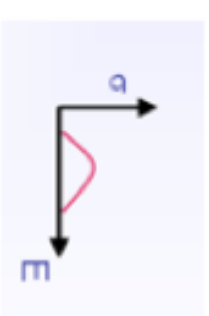


Bremsstrahlung



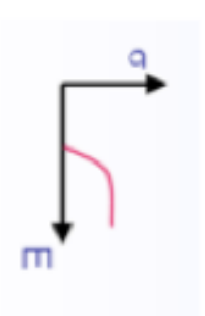
Compton effect

(dominant in MeV energy range)



Cherenkov radiation

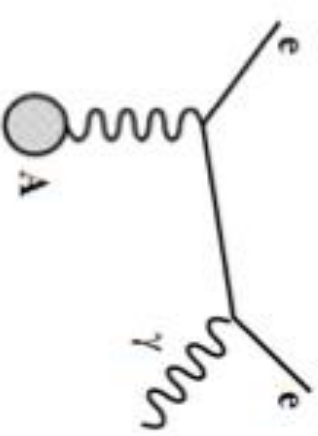
Pair creation
(threshold energy
 $= 2 m_e = 1,022$ MeV)



bremsstrahlung

- Charged high energy particles undergo an additional energy loss (in addition to ionization energy loss) due to bremsstrahlung, i.e. radiation of photons, in the Coulomb field of the atomic nuclei

$$-\frac{dE}{dx}|_{Brems} = 4\alpha N_L \left(\frac{e^2}{mc^2} \right)^2 \ln \frac{183 Z(Z+1)}{A} Q^2 E$$



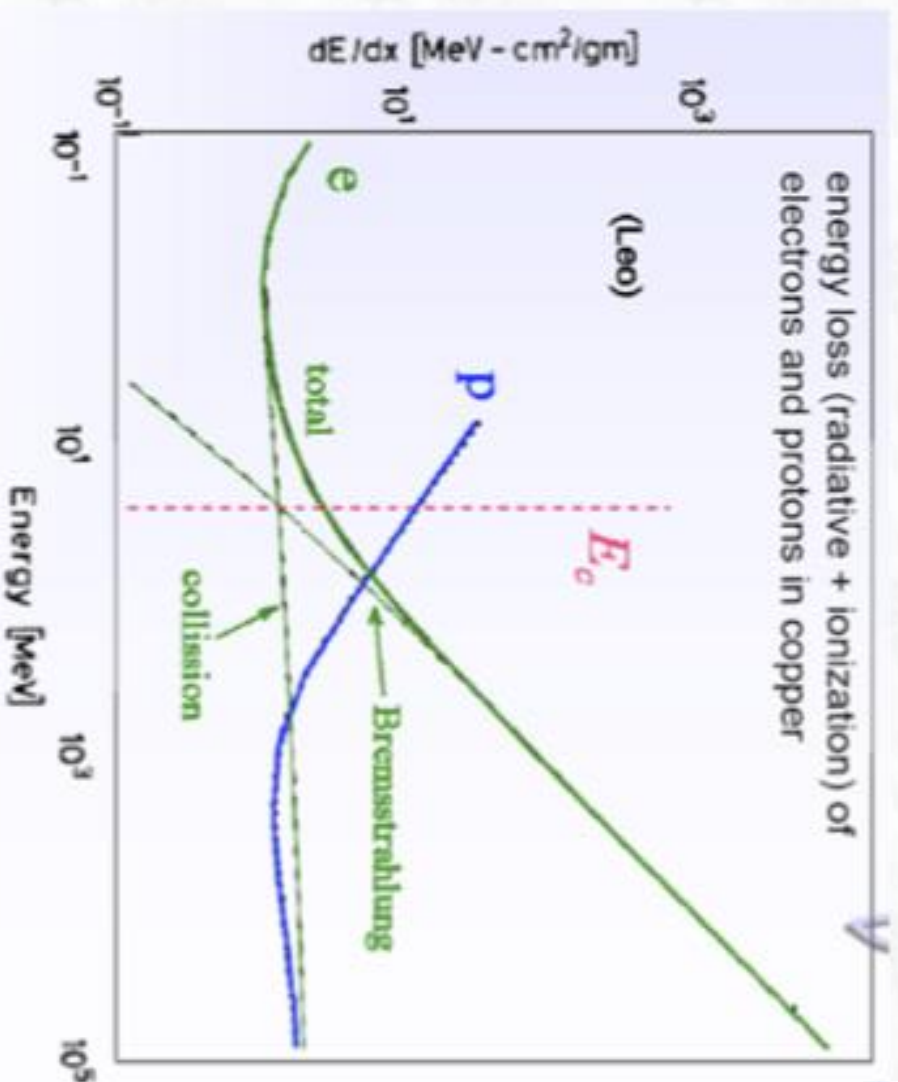
$$-\frac{dE}{dx}|_{Brems} := \frac{1}{X_0} Q^2 E \Rightarrow E(x) = E_0 e^{-x/X_0}$$

where: Q , m = electric charge and mass of the particle, α = fine structure constant
 A, Z = atomic number, number of protons of the material

- Important material constant: X_0 = radiation length
- Energy of the particle decreases exponentially as a function of the thickness x of the traversed material, due to bremsstrahlung;
 (After $x=X_0$: $E(X_0) = E_0 / e = 0.37 E_0$)

$$\begin{aligned} dE/dx &\sim Z(Z+1) \\ dE/dx &\sim 1/m^2 & \rightarrow & \left(\frac{dE}{dx} \right)_\mu / \left(\frac{dE}{dx} \right)_e \sim \frac{1}{40.000} \\ dE/dx &\sim E \end{aligned}$$

ionizzazione/bremsstrahlung



Critical energy is defined as:

$$-\frac{dE}{dx}|_{\text{ion}}(E_c) = -\frac{dE}{dx}|_{\text{brems}}(E_c)$$

For electrons, one roughly finds: $E_c \approx (550 \text{ MeV}) / Z$, $X_0 \approx 180 \text{ A} / Z^2 \text{ (g/cm}^2\text{)}$

Critical energies in copper ($Z = 29$):

$$E_c(e) \approx 20 \text{ MeV}$$

$$E_c(\mu) \approx 1 \text{ TeV}$$

- Muons with energies in the 10 - 100 GeV range are able to penetrate thick layers of matter, e.g. calorimeters;
- Can also be used for **particle / muon identification**

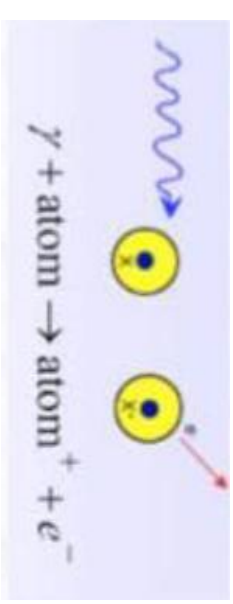
In order to be detected, photon must transfer their energy to charged particles:

Photo electric effect: only possible in the close neighborhood of a third collision partner

$$\sigma_{photo}^K = \left(\frac{32}{e^7}\right)^{\frac{1}{2}} \alpha^4 Z^5 \sigma_{Th}^e \quad \varepsilon = \frac{E_\gamma}{m_e c^2} \quad \sigma_{Th}^e = \frac{8}{3} \pi r_e^2 \quad (\text{Thomson})$$

At high energies ($\varepsilon \gg 1$)

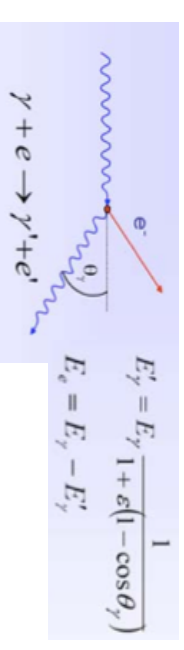
$$\sigma_{photo}^K = 4\pi r_e^2 \alpha^4 Z^5 \frac{1}{\varepsilon} \quad \sigma_{photo} \propto Z^5$$



Compton scattering: only possible in the close neighborhood of a third collision partner

Atomic Compton cross-section:

$$\sigma_c^{atomic} = Z \cdot \sigma_c^e$$



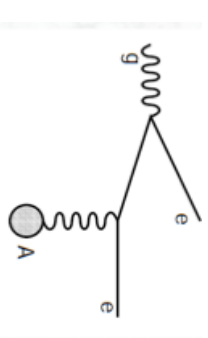
$$E_\gamma' = E_\gamma \frac{1}{1 + \varepsilon(1 - \cos \theta_\gamma)} \quad E_e = E_\gamma - E_\gamma'$$

$$\gamma + e \rightarrow \gamma' + e'$$

Pair production: only possible in the close neighborhood of a third collision partner.

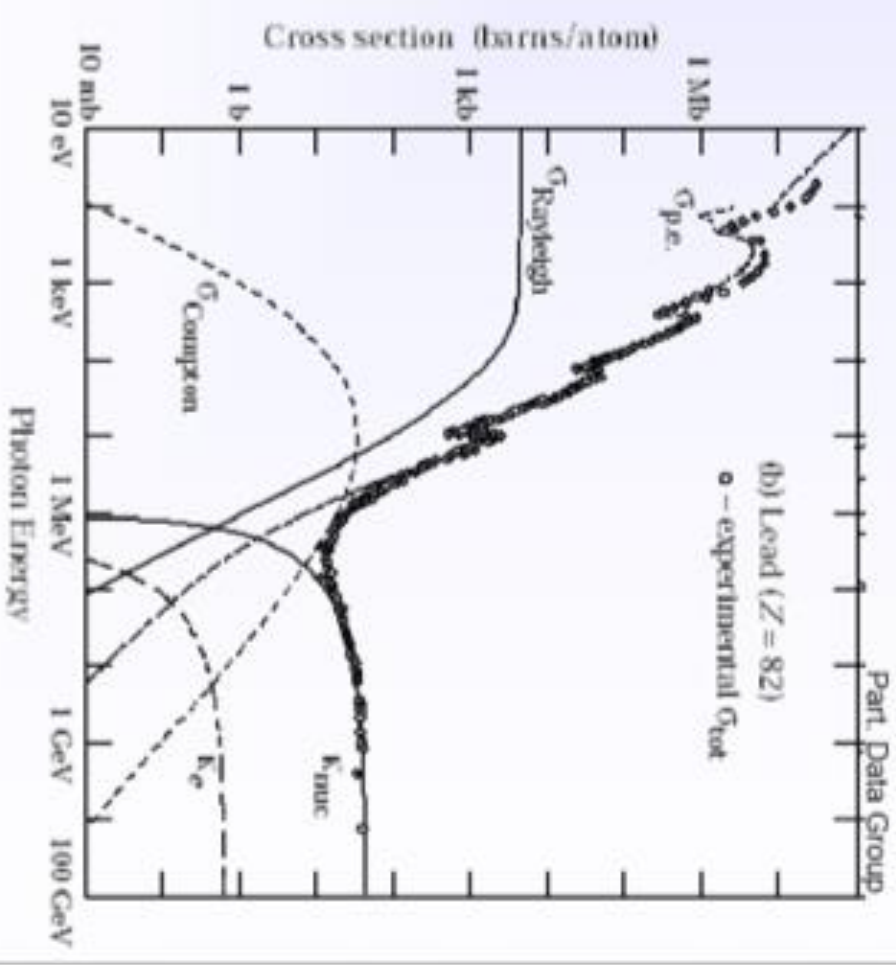
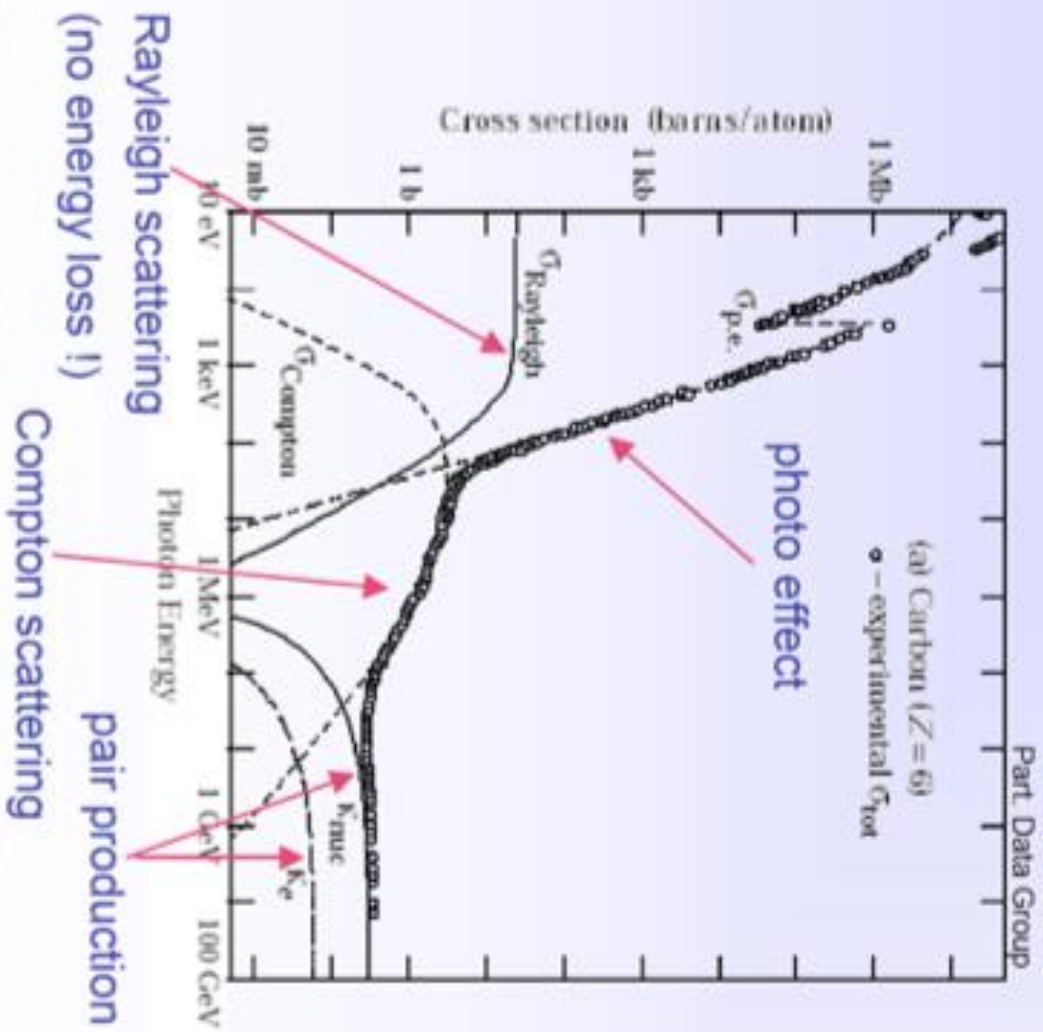
Threshold energy $> 2m_e = 1.022 \text{ MeV}$

$$\sigma_{Pair} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{1/3}} - \frac{1}{54} \right) \approx \frac{7}{9} \cdot \frac{A}{N_L} \cdot \frac{1}{X_0}$$



$$\gamma + (A) \rightarrow e^+ e^- + (A)$$

grand total



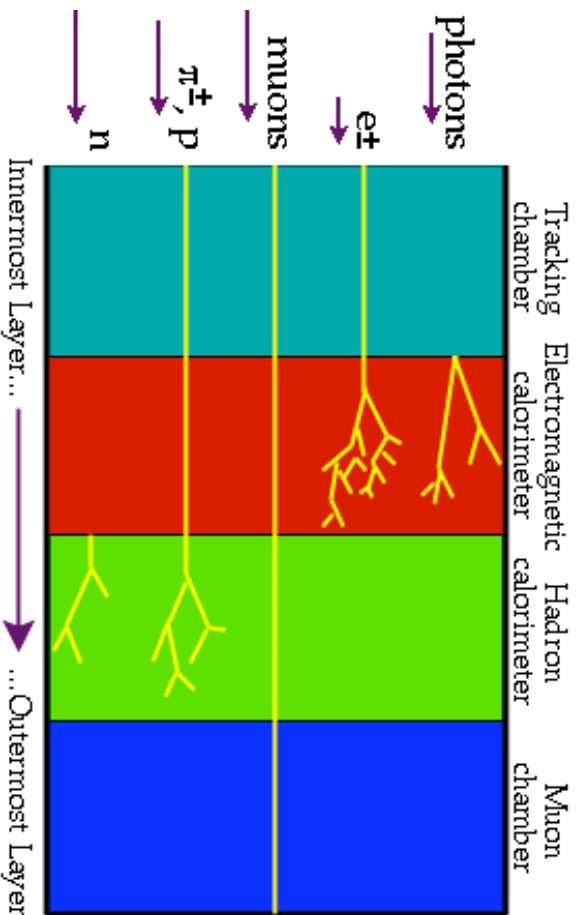
Il principio e' determinare l'energia dello sciame che si sviluppa

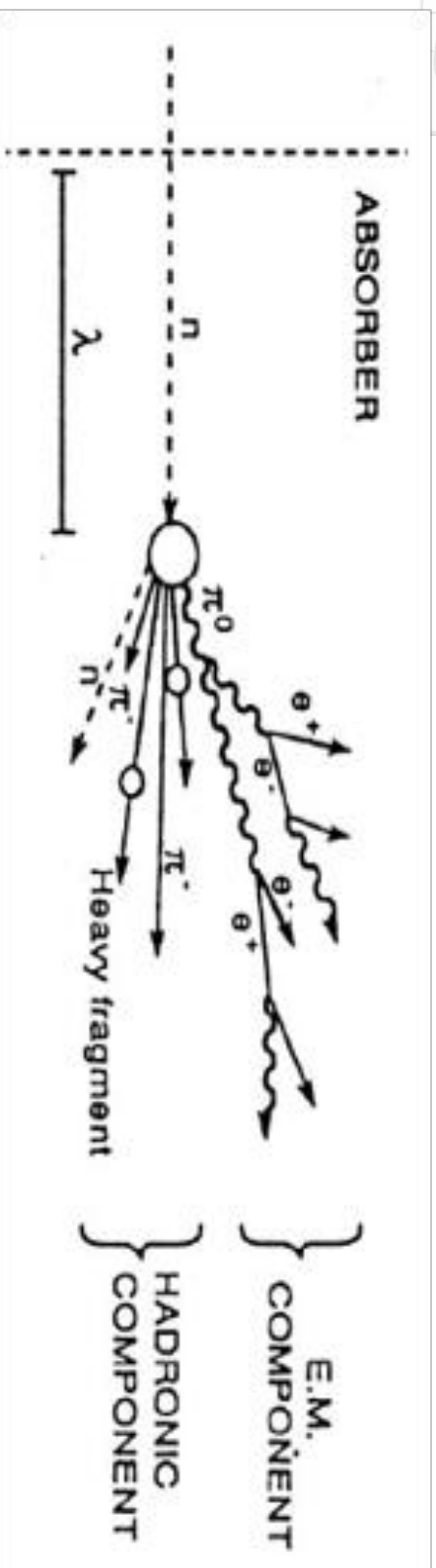
L'energia dell'elettrone o fotone incidente viene misurata per assorbimento totale (una frazione dell'energia viene convertita in luce o carica)

Uno sciame di e e γ si sviluppa a causa dell'interazione con il mezzo assorbente:

+ per energia sopra ~ 1 GeV produzione di coppie e bremsstrahlung sono i processi dominanti (fino a $E > E_c$, dopo ionizzazione)

+ la scala della lunghezza dello sciame e' determinata dalla **lunghezza di radiazione X_0** (la lunghezza sopra cui un elettrone riduce la sua energia di $1/e$ del suo valore iniziale; dipende da $1/Z$ del mezzo (1.76 cm per Fe, 0.56 Pb))





Gli sciami adronici si sviluppano tramite interazione forte con i nuclei

+ molti π^0 : parte dell'energia sviluppa sciami elettromagnetici, si misura solo questa componente (alta fluttuazione -> risoluzione energetica povera)

+ gran parte dell'energia e' usata per eccitare (o rompere) i nuclei, solo una frazione e' EM

+ lo sciame e' definito dalla lunghezza di assorbimento λ , in generale e' piu' largo e profondo di quello elettromagnetico: $\lambda \sim 17$ cm sia nel Pb che nel Fe

Profondita' massima dello sciame (e 95% assorbimento):

$$l_{\max} \approx (0.6 \ln E [\text{GeV}] - 0.2) \lambda$$
$$l_{95\%} (\text{cm}) \approx l_{\max} + 4E^a \lambda \quad \text{con } a = 0.15$$

con sviluppo laterale: $R_{95\%} \approx \lambda$

Tipicamente il rapporto tra
componente em ed adronica e^+ :

$$\frac{e}{h} \approx 1.1 - 1.35$$

layout e readout

I calorimetri si dividono principalmente in **omogenei** e a **campionamento**

Omogenei:

sono fatti di un materiale che è allo stesso tempo pesante e attivo: lo stesso materiale induce gli sciami e ne misura l'energia.

Più precisi ma più voluminosi (e pesanti), costosi e fragili, difficilmente segmentabili

Campionamento:

alternano un materiale passivo, che si occupa di fermare elettroni e fotoni e di indurre gli sciami, e un materiale attivo che ne misura una frazione d'energia.

Meno precisi ma anche meno costosi, compatti, robusti, permettono una segmentazione estremamente fine

risoluzione energetica

- The energy resolution of calorimeters can be parametrized as:

$$\frac{\Delta E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta \oplus \frac{\gamma}{E}$$

- α is the so called **stochastic term** (statistical fluctuations)
- β is **constant term** (determines at high energies)

important contributions to β are:

- stability of the calibration (temperature, radiation,)
- leakage effects (longitudinal and lateral)
- uniformity of the signal
- loss of energy in dead material
-

- γ is the **noise term** (electronic noise,...)

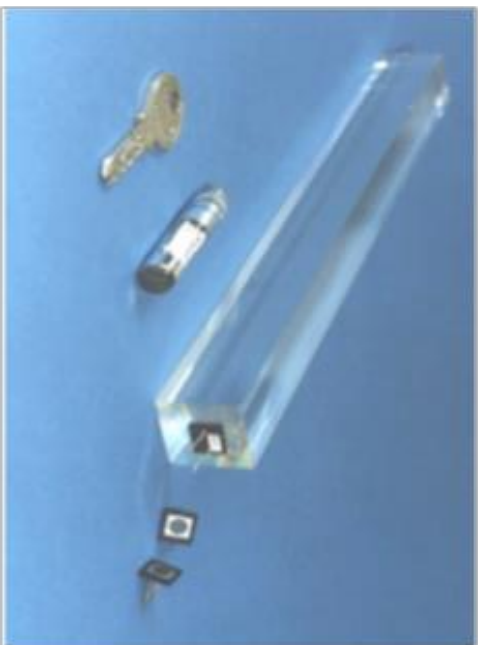
- Also angular and spatial resolutions scale like $1/\sqrt{E}$



il calorimetro EM di CMS

Cristalli di PbWO_4

- + omogeneo, tutta l'energia delle particelle e' depositata nel mezzo
- + l'energia e' convertita principalmente in luce, convertita in segnali elettrici da fotodiodi e fototriodi
- + alta risoluzione energetica
- + intrinsecamente tracciante per l'alta granularita'



$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E(\text{GeV})}} + b + \frac{c}{E},$$

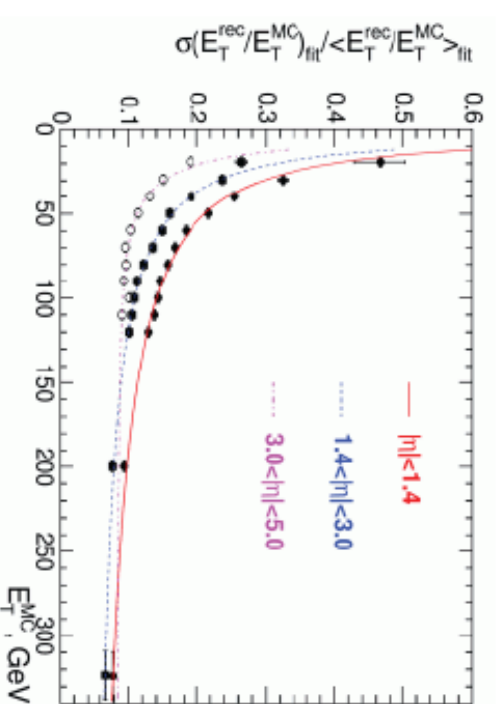
a = 2.7%, fluttuazioni
nello sviluppo dello
sciame
b = 0.55%, sistematiche
da calibrazione
c ~ 0.2 GeV,
sistematiche strumentali

il calorimetro adronico di CMS

E' un calorimetro a campionamento, il mezzo assorbente e' il rame a cui sono interposti dei piatti di materiale plastico scintillante attivo



$$\sigma/E \sim 100\%/\sqrt{E} + \text{few } \%$$



La misura adronica e' piu' complessa di quella elettromagnetica. La risoluzione energetica intrinseca non e' molto alta, **ma la capacita' di integrare la misura con altri sottorilevatori puo' migliorare di molto la risoluzione**

Perche' 3 tipi di camere ?

DT (zona centrale)

+ alta risoluzione spaziale

- lenta

- meno resistente alle radiazioni

CSC

+ buona risoluzione spaziale

- lenta

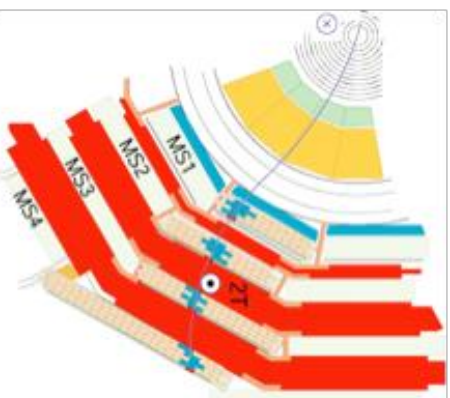
+ alta resistenza alle radiazioni

RPC (in combinazione -
TRIGGER)

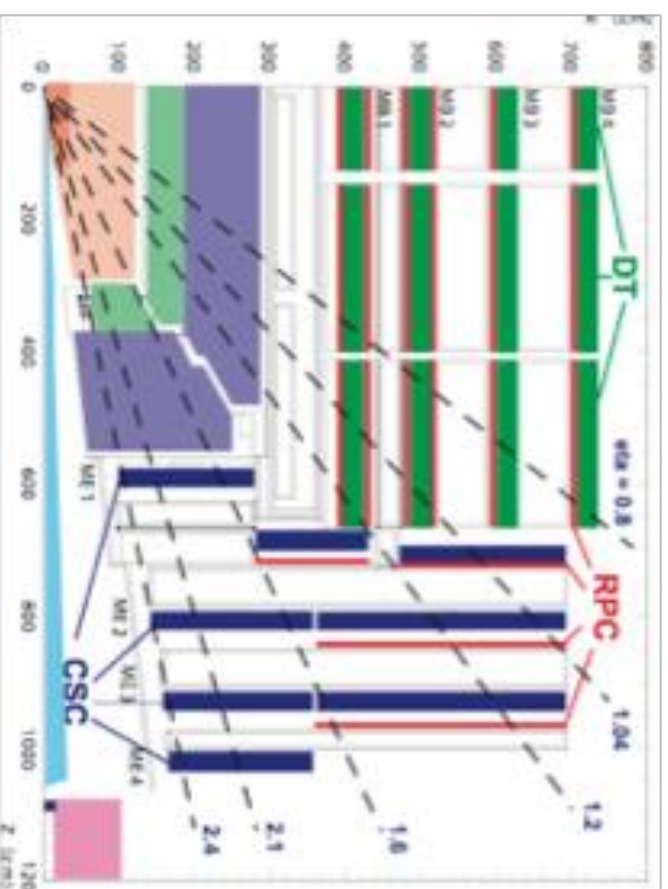
+ scarsa risoluzione spaziale

+ molto veloce

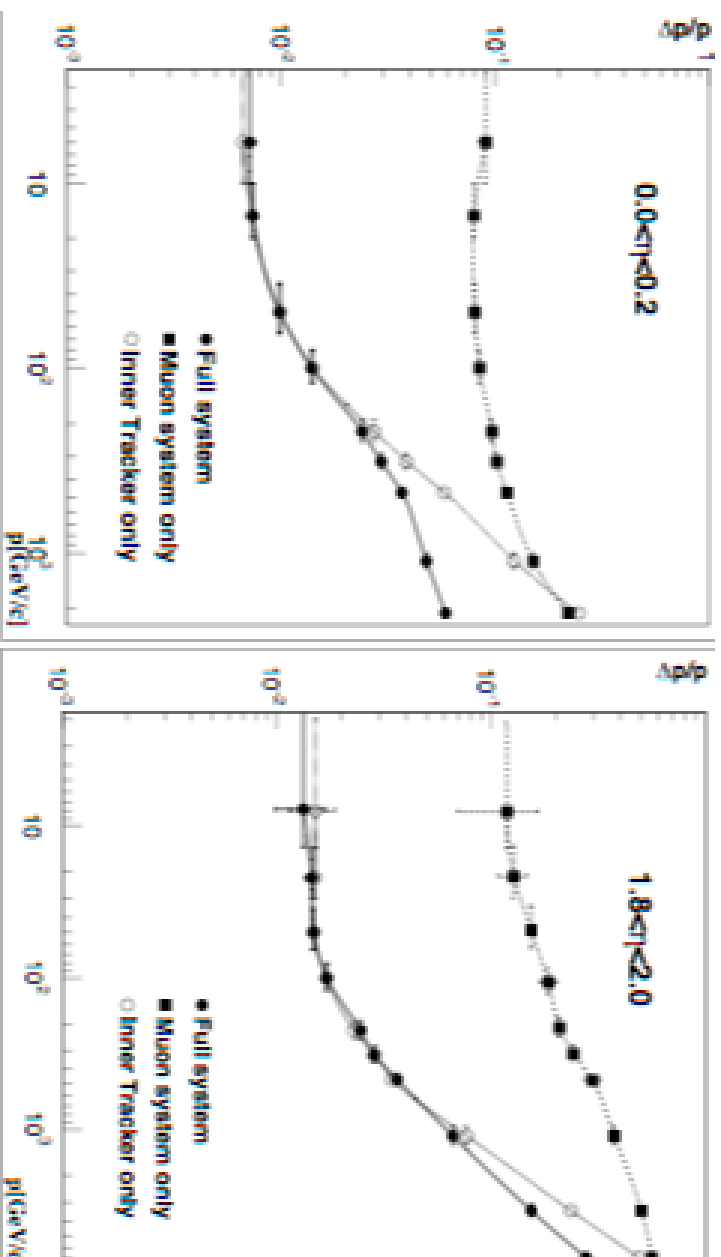
+ buona resistenza alle
radiazioni



Le zone “active” sono
frapposte al ferro che
funge da ritorno per il
campo magnetico



le camere a μ - prestazioni



La bassa risoluzione in impulso del muone, intrinsecamente bassa per le camere a μ da sole (a causa della grande quantita' di ferro) viene compensata dall'uso combinato con il sistema tracciante interno

$$\Delta p_T/p_T \sim 7-10\%$$

per $p_T = 10-100$ GeV

solo camere a μ

$$\longrightarrow \Delta p_T/p_T \sim 0.7-2\%$$

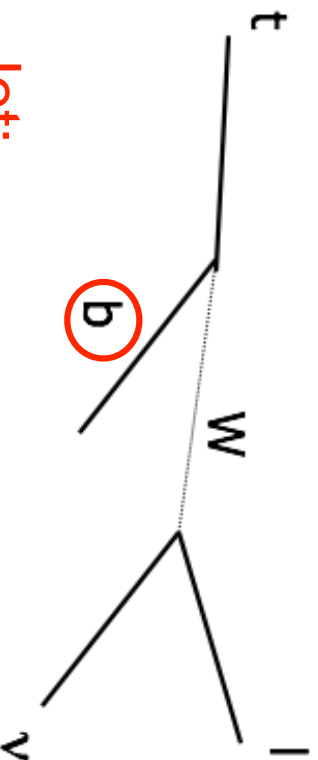
camere a μ + tracciatore

Riassumendo

Con un rivelatore come CMS, siamo in grado di misurare quasi tutto quello che viene prodotto dall'interazione centrale

- + particelle cariche (tracciatore)
- + elettroni/fotoni (calorimetro EM)
- + adroni neutri e carichi (calorimetro adronico)
- + muoni (camere μ)
- + energia mancante (calorimetria)

Tutte quantita' connesse allo stato finale di una reazione



Particella singola

Tracciatore,
camere μ ,
Calorimetro EM

Jet:

Calorimetri,
tracciatore

Energia mancante:

Calorimetri

Rapportiamo tutto alla ricerca dell'Higgs

tracciatore/calorimetri

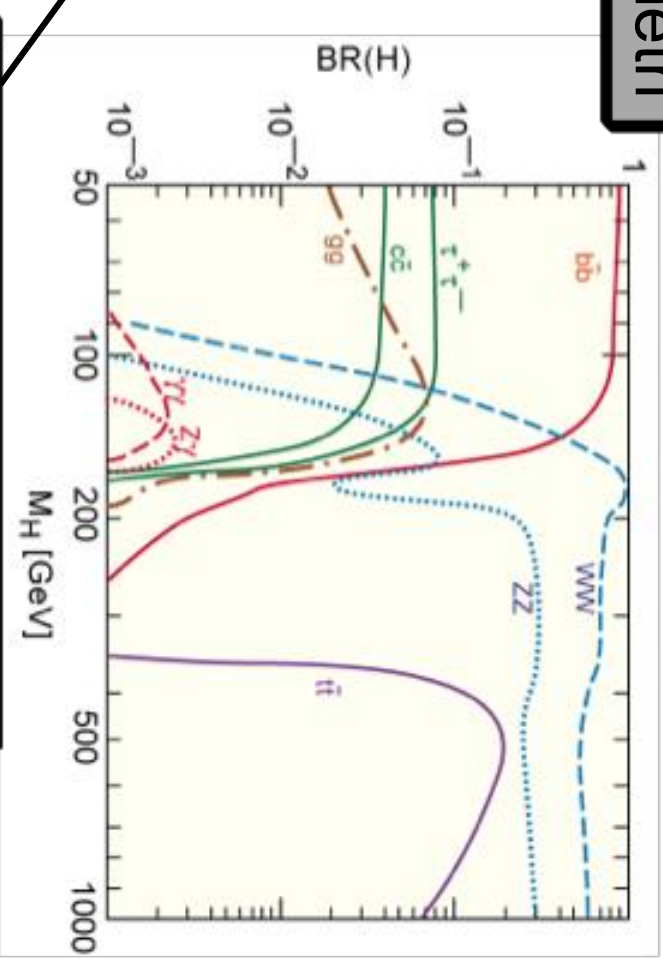
Dipendentemente dalla massa

- 1) $m_H > \sim 2m_W$, le modalita' di decadimento dominante sono $H \rightarrow WW$ o $H \rightarrow ZZ$

ZZ in particolare offre una chiara segnatura sperimentale nello stato finale (leptoni)

- 2) m_H e' piu' bassa i rate di decadimento maggiori si hanno per $b\bar{b}$, $\tau^+\tau^-$, $c\bar{c}$ e $g\bar{g}$

Molto difficile da vedere a causa dell'enorme fondo continuo



camere a μ /tracciatore

In questo caso e' preferibile cercare l'Higgs come $H \rightarrow \gamma\gamma$ (almeno fino a 130 GeV)

calorimetro EM/tracciatore

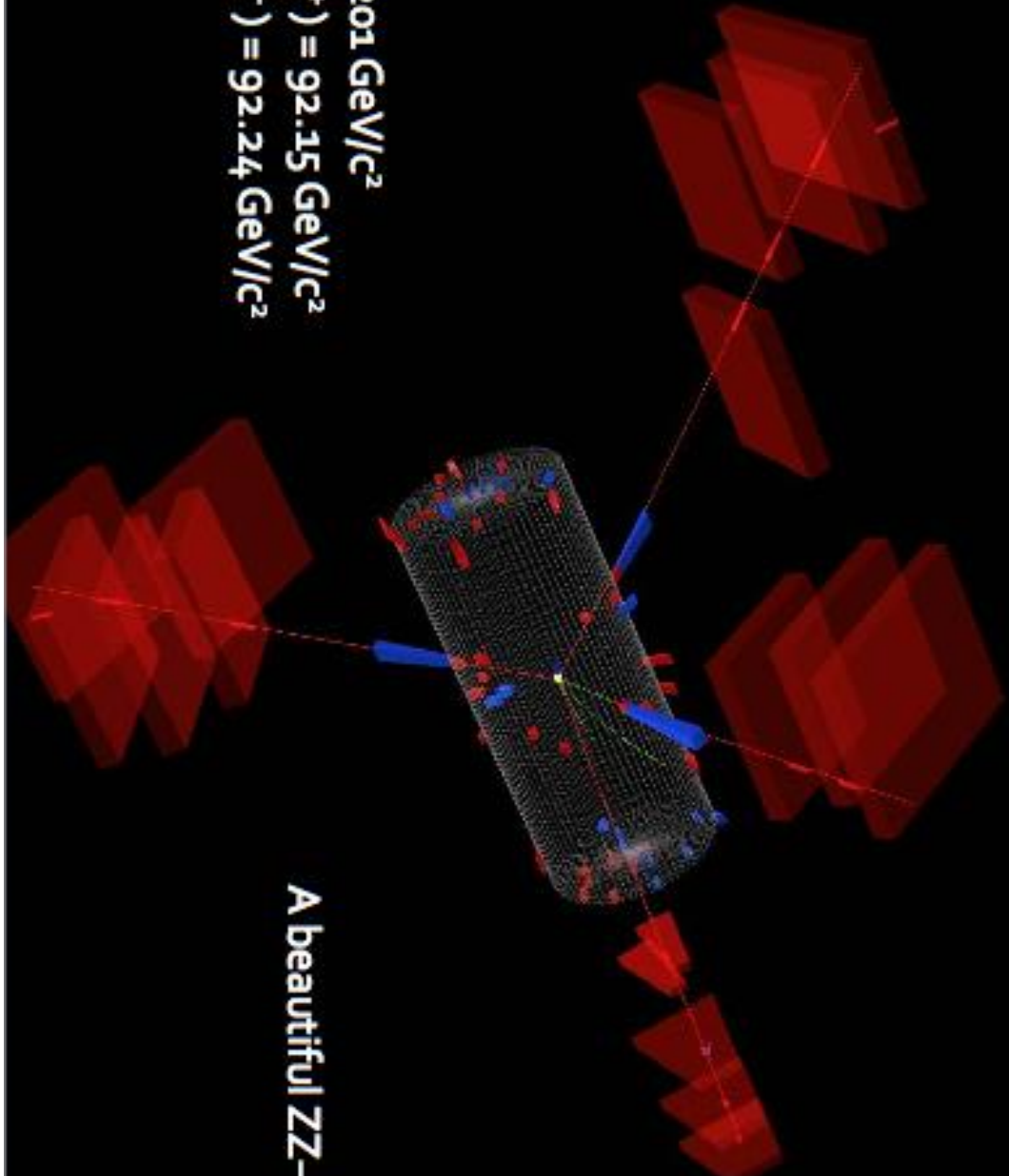
2010 - i primi sospetti...

<http://www.youtube.com/user/CMSExperimentTV>

Recorded September 23, 2010
 $L \approx 7 \text{ pb}^{-1}$

$M(4\mu) = 201 \text{ GeV}/c^2$
 $M(\mu_1^-, \mu_2^+) = 92.15 \text{ GeV}/c^2$
 $M(\mu_3^+, \mu_4^-) = 92.24 \text{ GeV}/c^2$

A beautiful $ZZ \rightarrow 4\mu$ candidate !



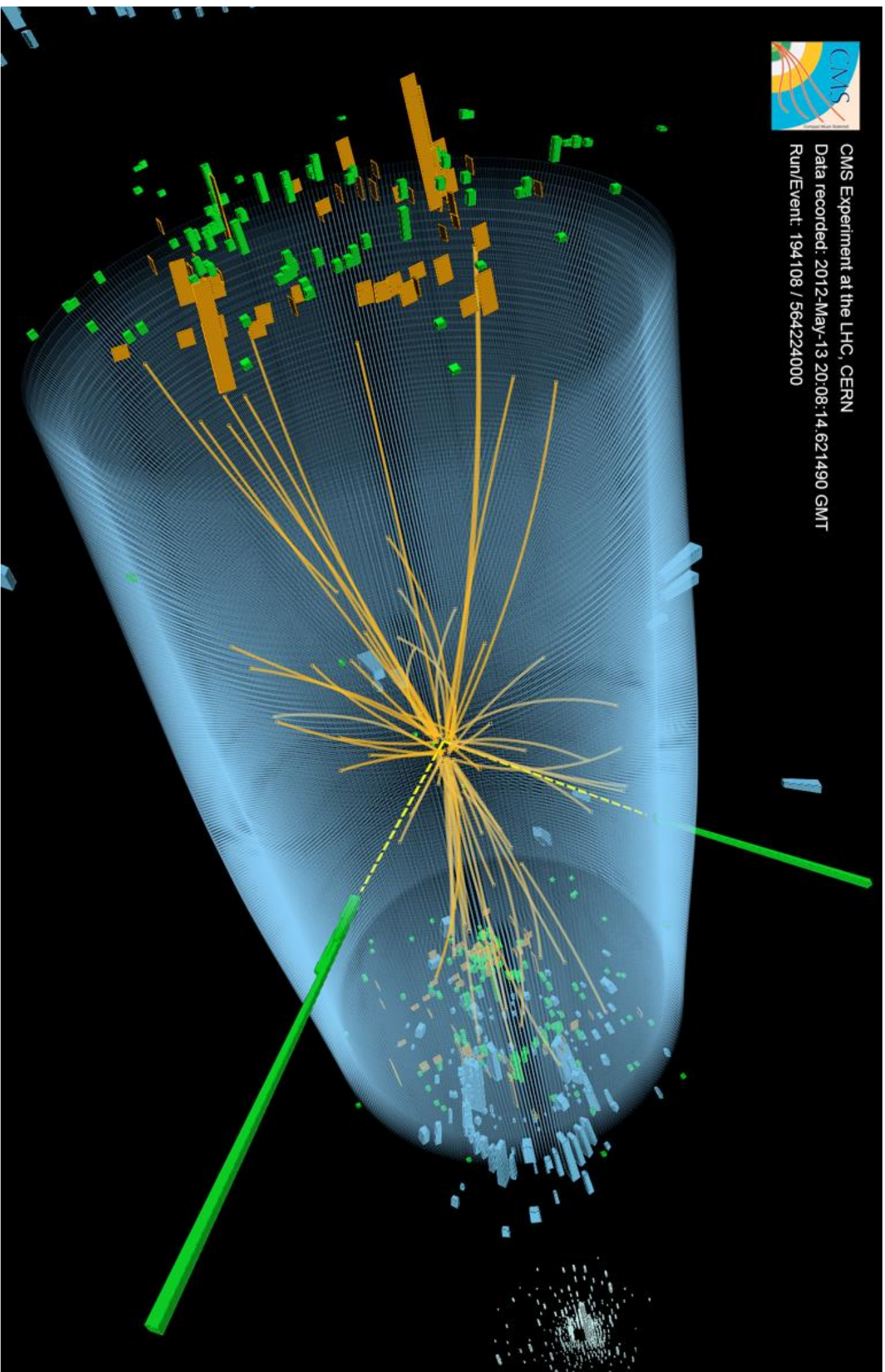
2012



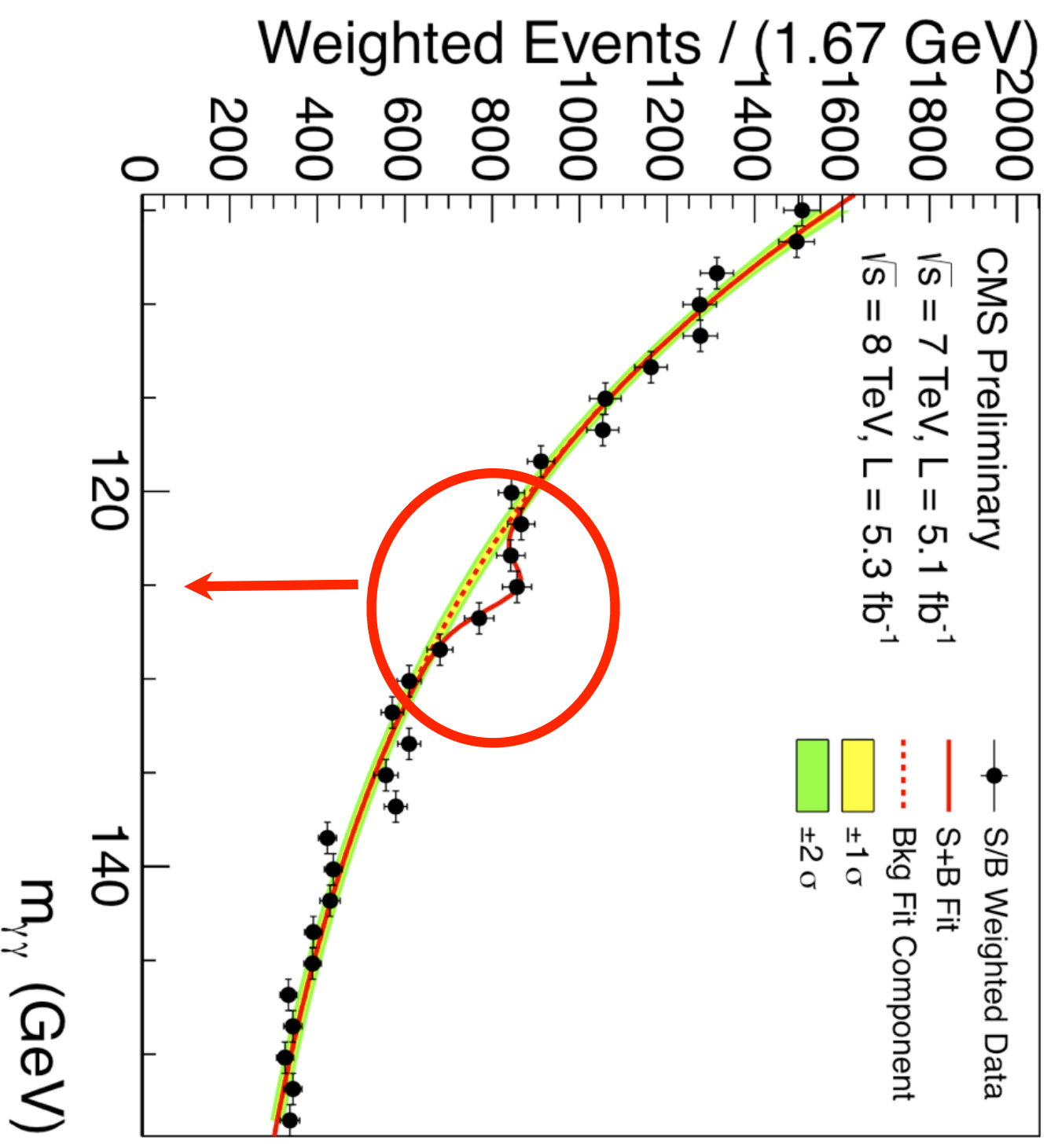
CMS Experiment at the LHC, CERN

Data recorded: 2012-May-13 20:08:14.621490 GMT

Run/Event: 194108 / 564224000

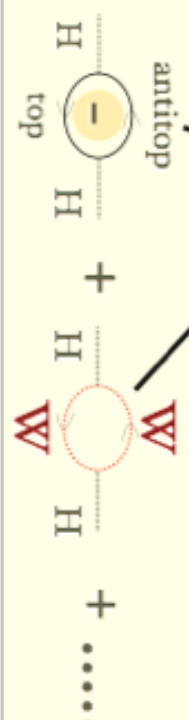


2012/13 - Higgs - La scoperta



The SM Higgs will make me happy ?

radiative correction to the Higgs mass are unstable (Λ^2):

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2} \left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2 \right) \Lambda^2 \sim m_0^2 - (115\text{GeV})^2 \left(\frac{\Lambda}{400\text{GeV}} \right)^2$$


$\Lambda =$ scale up to which the SM is valid

if we want renormalization:

$$m_H^2(v) \sim m_H^2(\Lambda) - (\Lambda^2 - v^2) \quad , \quad v = \langle H \rangle \sim 250\text{GeV}$$

and if we extend up to QG (10^{19} GeV), requiring the Higgs mass < 1

TeV:

$$\frac{m_H^2(\Lambda) - \Lambda^2}{\Lambda^2} \sim \frac{v^2}{\Lambda^2} = \mathcal{O}(10^{-34}) \text{ if } \Lambda \sim M_{Planck}$$

a fine tune of the order of 10^{-34} : unnatural (**Hierarchy problem**)

In analogy to Lorentz invariance to the classical dynamics -> positron (Dirac)

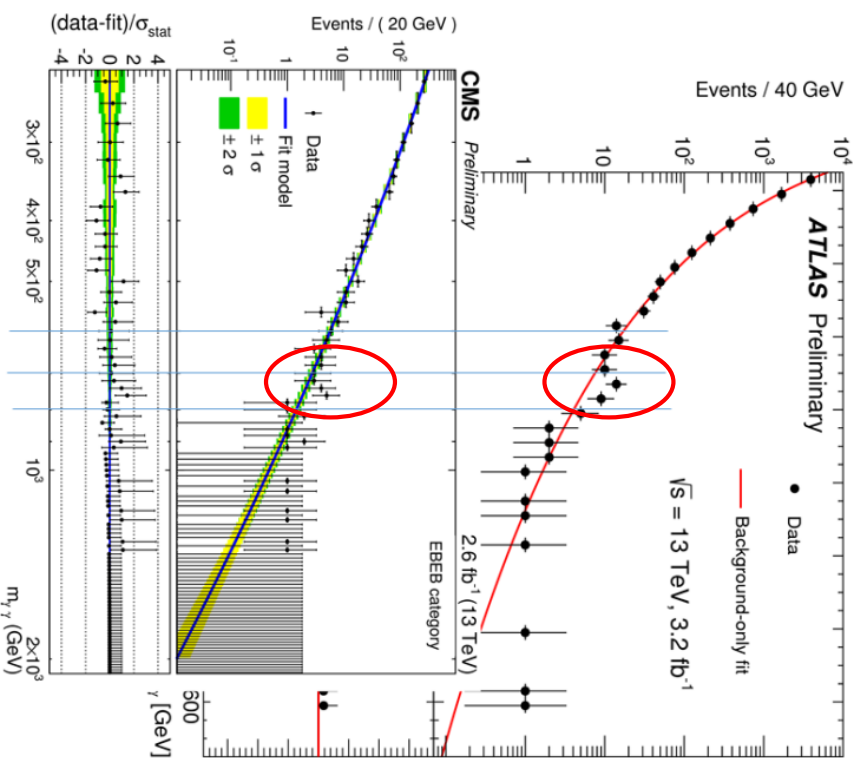
We're looking for new phenomena at the TeV scale: introducing additional terms to the Higgs self-energy in order to cancel the quadratic growth in a natural way

The idea is to introduce a **super**-partner to each Standard Model particle (a **Supersymmetric Model**)

[additional alternative models are based on
Extra-Dimensions, Technicolor, Little Higgs...]



Waiting for Run 2 data



Is there something new?

Stay tuned!