

The Large Hadron Collider LHC

European Masterclasses 2008
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Large Hadron Collider

- Perche' lo facciamo
- Cos'e'
- Cosa guardiamo
- Cosa speriamo di vedere

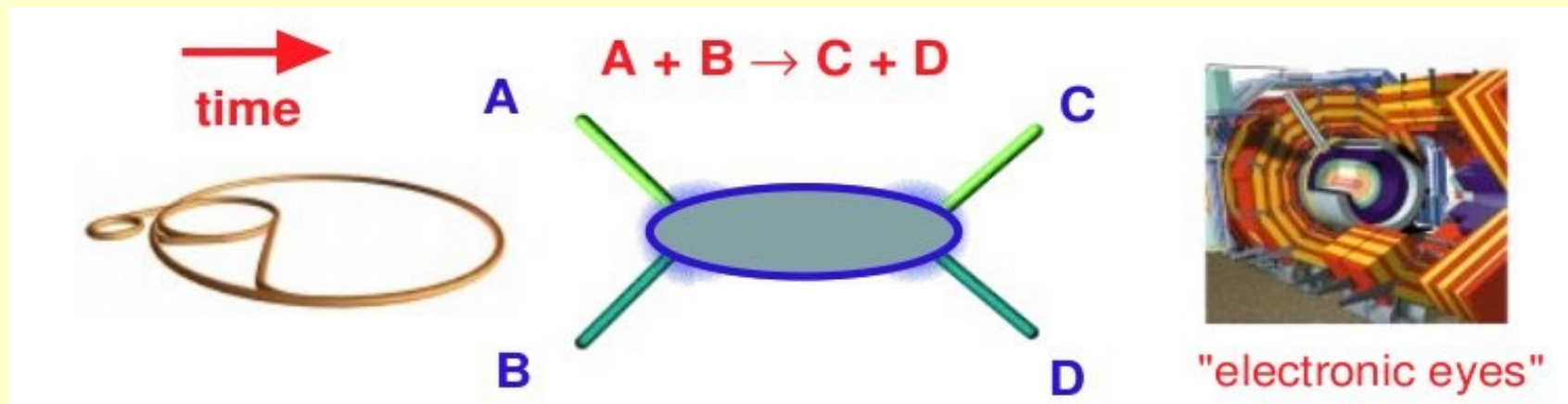
Come sono fatte le cose?

- Bisogna guardare: con lo strumento giusto
- La lunghezza d'onda λ della sonda deve essere più piccola dell'oggetto da vedere
- $\lambda \propto 1/E$
 - Cellula ($d \sim 10 \mu\text{m} = 10^{-5} \text{ m}$): luce visibile $E \sim \text{eV}$
 - Virus: ($d \sim 10 \text{ nm} = 10^{-8} \text{ m}$): microscopio elettronico $E \sim \text{keV}$
 - Protone: ($d \sim 1 \text{ fm} = 10^{-15} \text{ m}$): acceleratore di particelle $E \sim \text{GeV}$
 - Quark: ($d < 10^{-18} \text{ m}$): LHC $E \sim 10 \text{ TeV}$ $d \sim 0.0002 \text{ fm}$

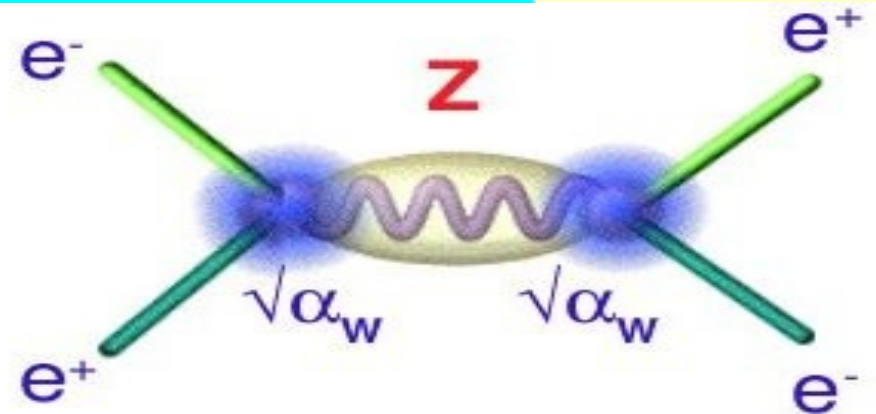
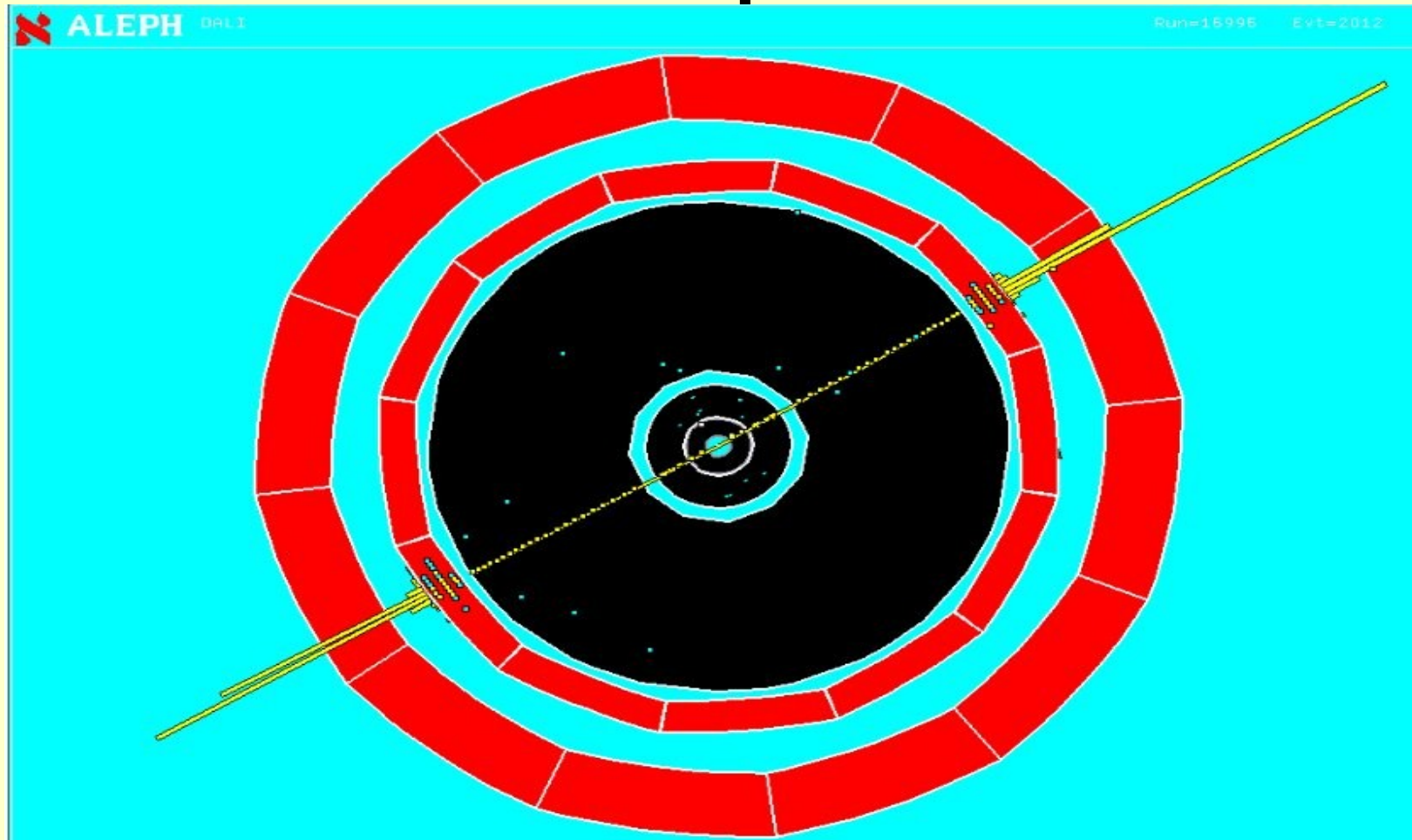


“Vedere” con gli acceleratori

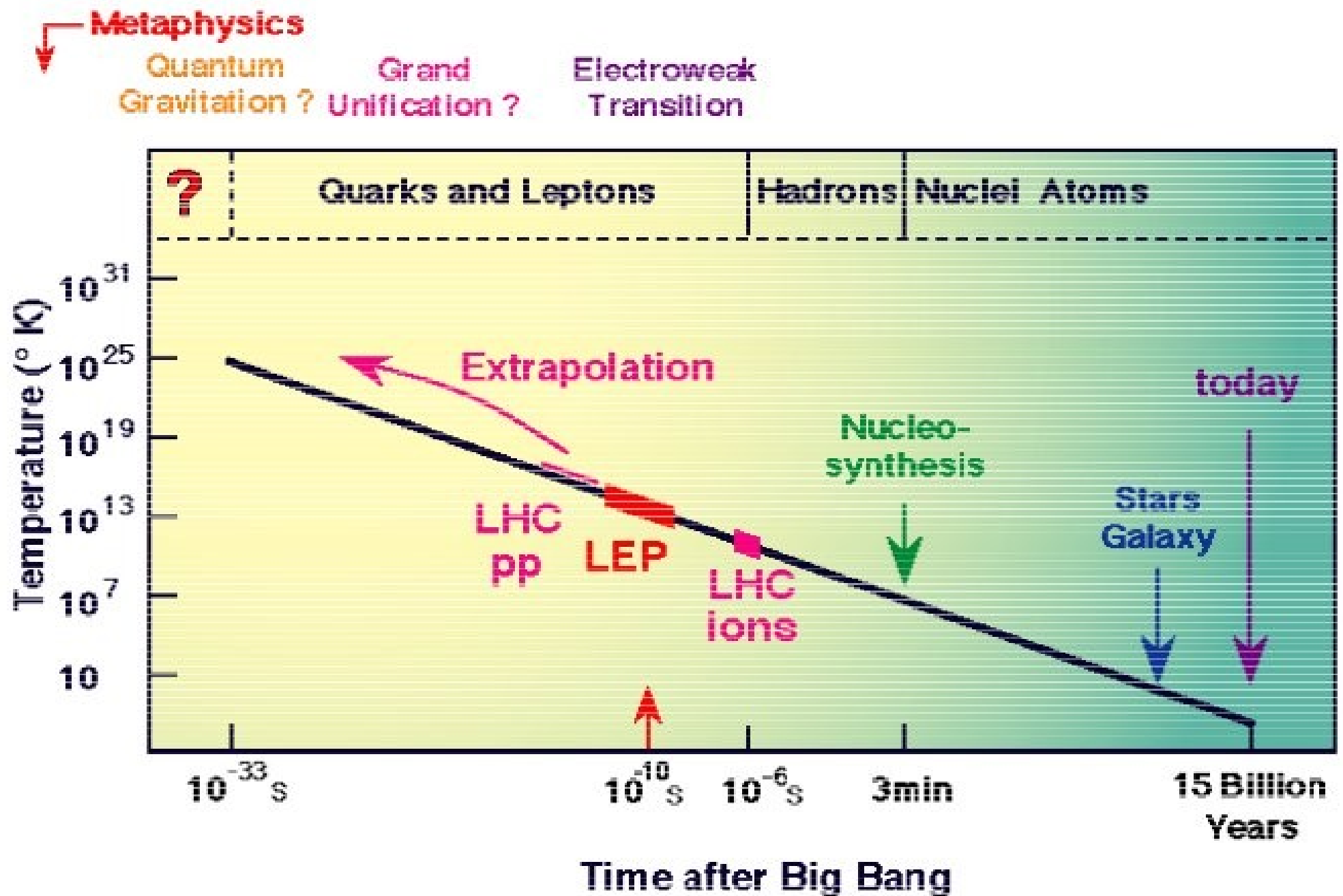
- Non possiamo vedere davvero quello che succede a scale così piccole
- Prendiamo due particelle note (A e B) e le facciamo scontrare e vediamo cosa esce fuori (C e D)
- Da quello che vediamo cerchiamo di capire cosa è successo nel “blob”



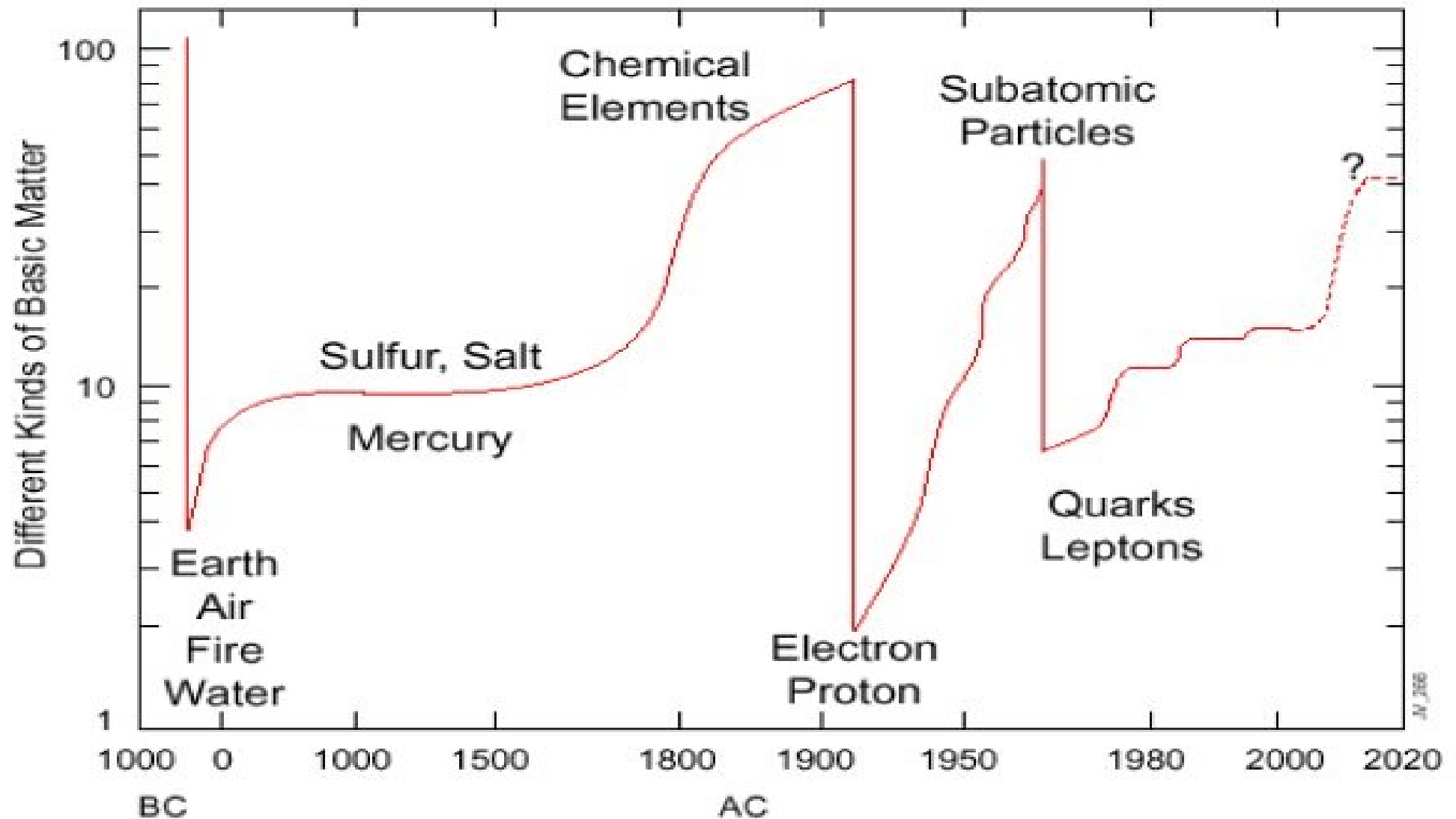
Esempio: Z a LEP

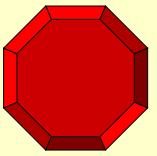


Energia e tempo

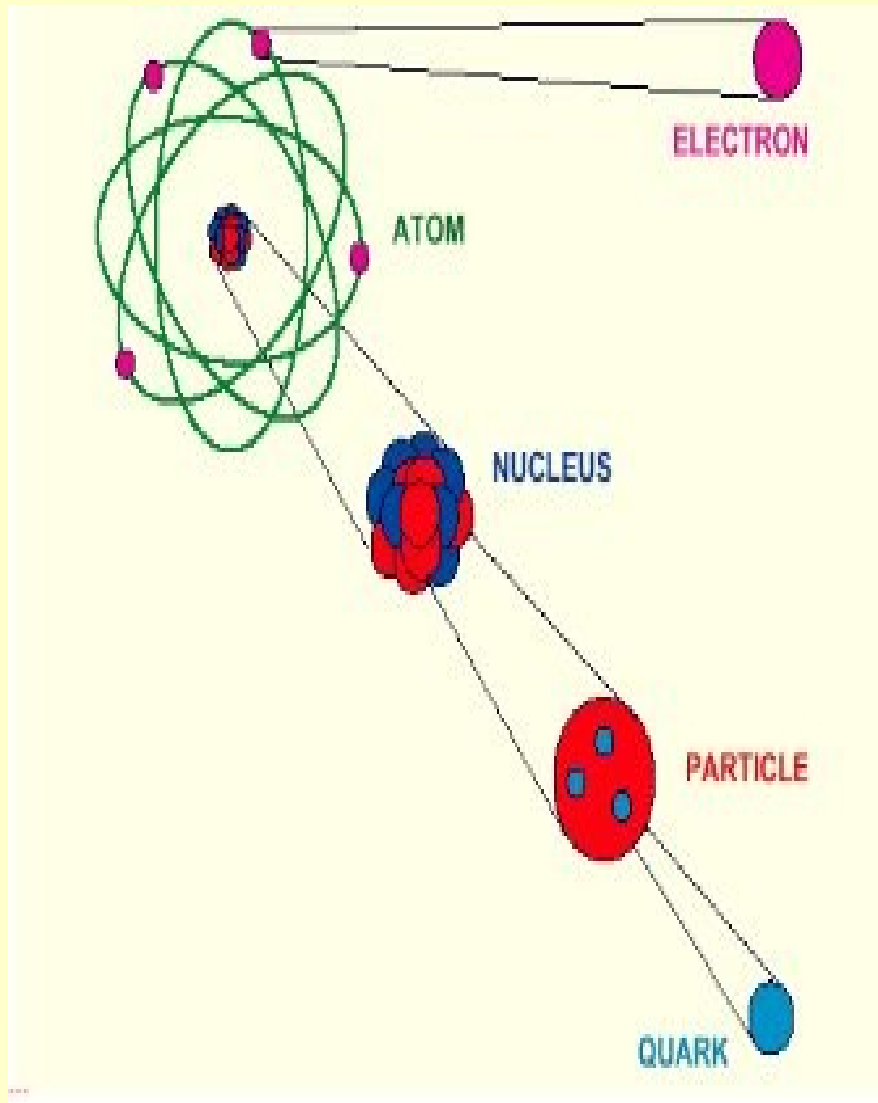


Quanti costituenti?





Modello attuale



- Atomo: nucleo + **elettrone**
- Nucleo: protoni + neutroni (nucleoni)
- Nucleoni: **quark**
- Quark: ???

Particelle

Quarks



up



down



charm



strange



top



beauty

Leptons



electron



neutrino e



muon



neutrino μ



tau



neutrino τ

Bosons



photon



gluon



Z^0 $W^\pm$

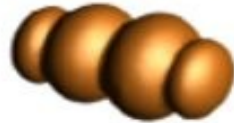


Higgs

Forze

Strong

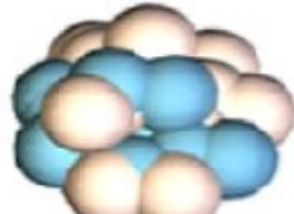
Gluons (8)



Quarks



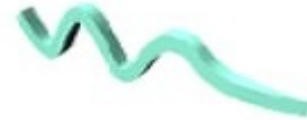
Mesons
Baryons



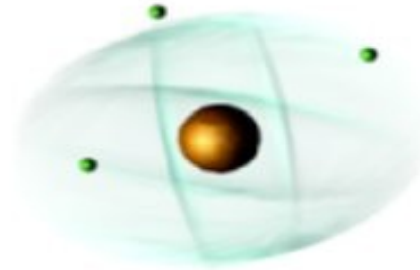
Nuclei

Electromagnetic

Photon



Atoms
Light
Chemistry
Electronics



Gravitational

Graviton ?

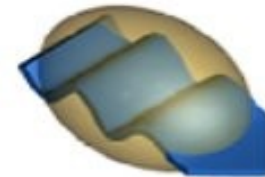


Solar system
Galaxies
Black holes

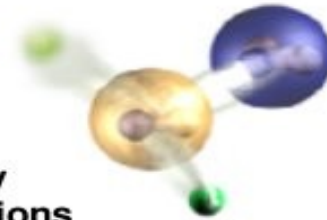


Weak

Bosons (W,Z)

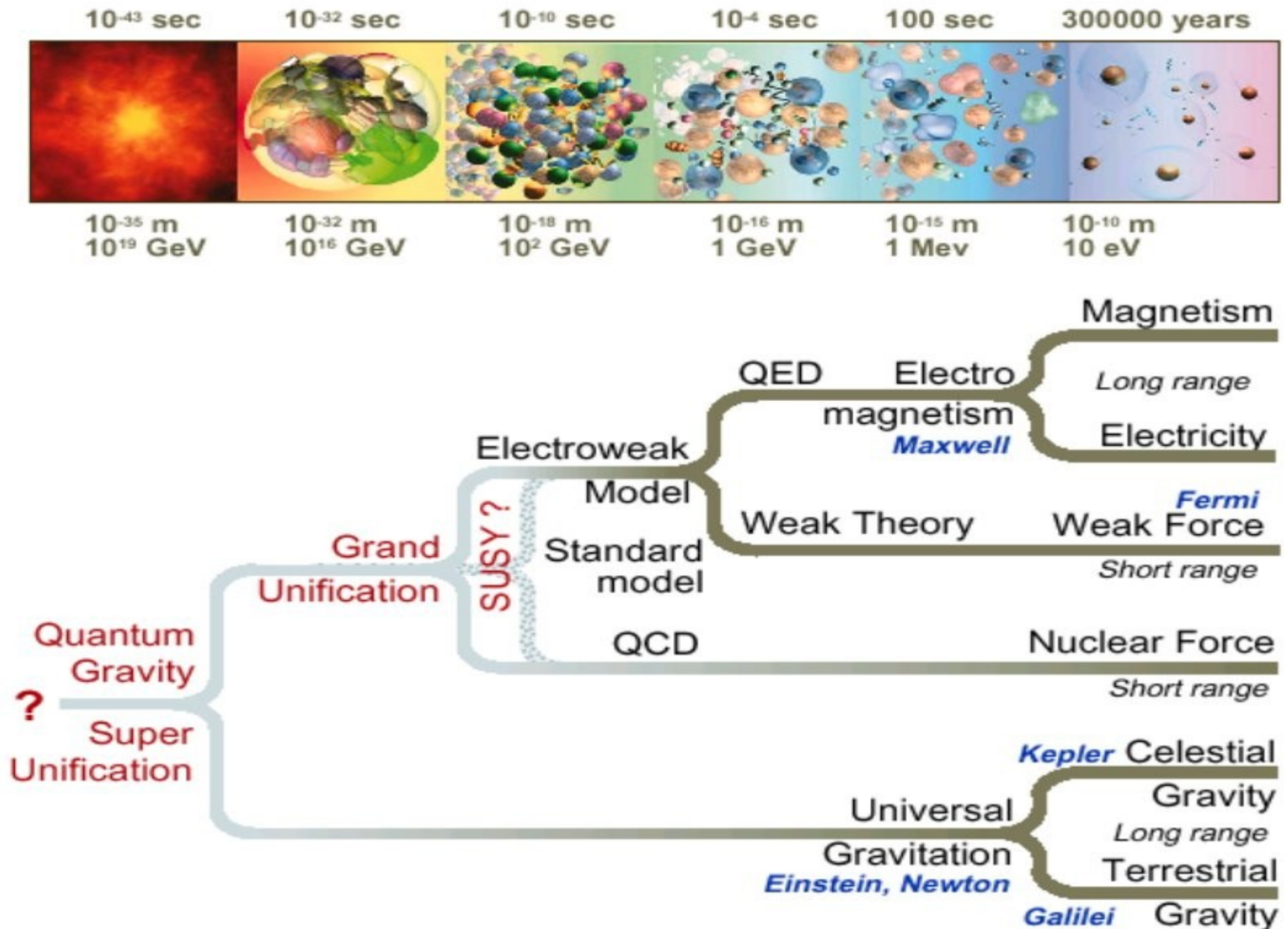


Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun



The particle drawings are simple artistic representations

Unificazione Forze



L'equazione dello SM

$$\begin{aligned}
 \mathcal{L}_{\text{SM}} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c \\
 & -\partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2}M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- \\
 & -M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2}M\phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2}\alpha_h \\
 & -igc_w \left[\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+) \right] \\
 & -igs_w \left[\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+) \right] \\
 & -\frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) \\
 & + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] \\
 & -\frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H \\
 & -\frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] \\
 & + \frac{1}{2}g \frac{1}{c_w} Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + igs_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- \\
 & - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 \\
 & + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) \\
 & + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda \\
 & - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] \\
 & + \frac{ig}{4c_w} Z_\mu^0 \left[(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda) \right] \\
 & + \frac{ig}{2\sqrt{2}} W_\mu^+ \left[(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa) \right] + \frac{ig}{2\sqrt{2}} W_\mu^- \left[(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda) \right] \\
 & + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} \left[-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda) \right] - \frac{g}{2} \frac{m_e^\lambda}{M} \left[H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) \right] \\
 & + \frac{ig}{2M\sqrt{2}} \phi^+ \left[-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) \right] + \frac{ig}{2M\sqrt{2}} \phi^- \left[m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) \right] \\
 & - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- \\
 & + \bar{X}^0 \left(\partial^2 - \frac{M^2}{c_w^2} \right) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) \\
 & + igs_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H \\
 & + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igMs_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] \\
 & + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Ma allora...

- Abbiamo le particelle, abbiamo le forze, abbiamo l'equazione: sappiamo già tutto!
- NO!
- ci manca il bosone di Higgs;
 - Ha un ruolo speciale nello SM: da massa a tutte le altre particelle
- SM non funziona ad alte energie;
- Manca la gravita'.

Altre questioni aperte

- Molte caratteristiche sono apparentemente arbitrarie:
 - Perche' 3 famiglie di particelle (e non 4 o 5 o 87?)
 - Sono davvero solo 3?
- Quale e' l'origine delle masse delle particelle
 - Perche' sono cosi' diverse?
- Le particelle elementari (quark, elettroni) hanno una struttura?
- Ci sono altre particelle che non abbiamo ancora visto?
 - Materia oscura?
 - Altro?
- Perche' l'universo e' fatto di materia e non di antimateria?
- ...

Cosa serve

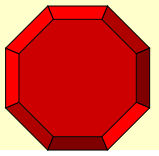
Un acceleratore per avere collisioni alla piu' alta energia possibile [LHC @ CERN](#)

Un rivelatore (meglio di piu') in grado di vedere quello che viene fuori dalle collisioni
[CMS](#) [ATLAS](#) [ALICE](#) [LHCb](#)

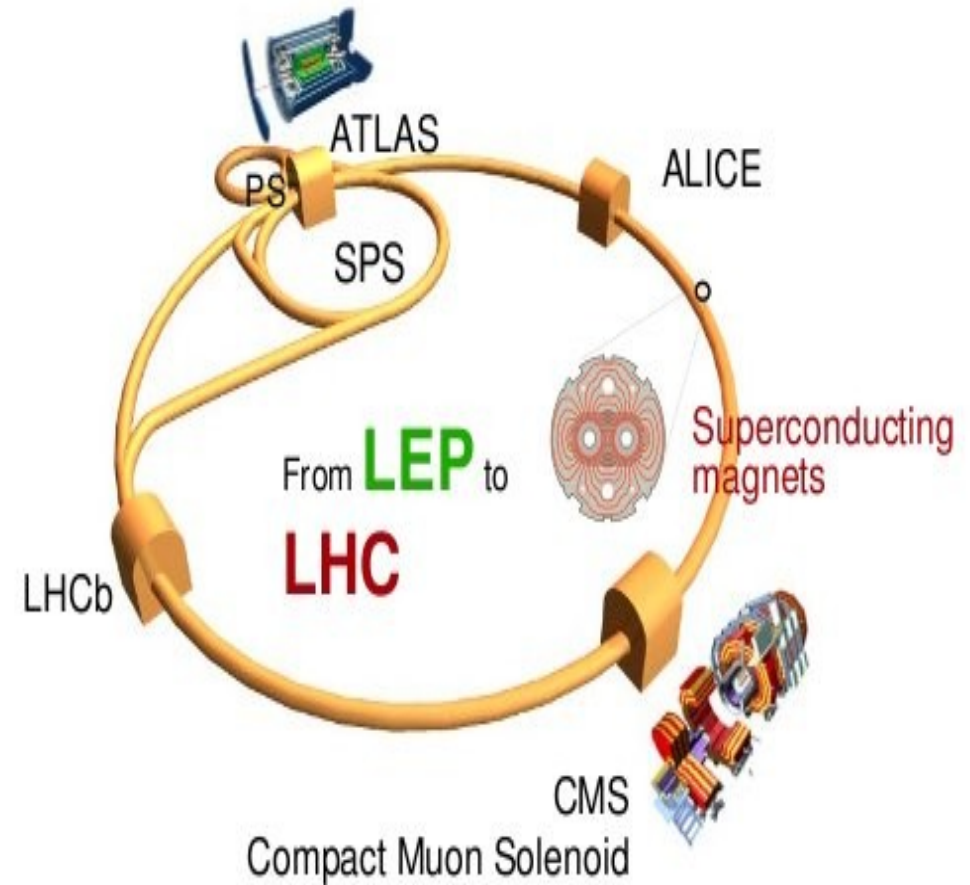
CERN

- **C**entro **E**uropeo per la **R**icerca **N**ucleare
- Organizzazione internazionale fondata nel 1954 (Italia e' un membro fondatore)
- Vicino a Ginevra (Svizzera) sul confine con la Francia
- 19 stati membri (+ osservatori)
- Dedicato a ricerca di base su elementi costitutivi della materia e le loro interazioni fondamentali
- www.cern.ch (WWW inventato al CERN!)

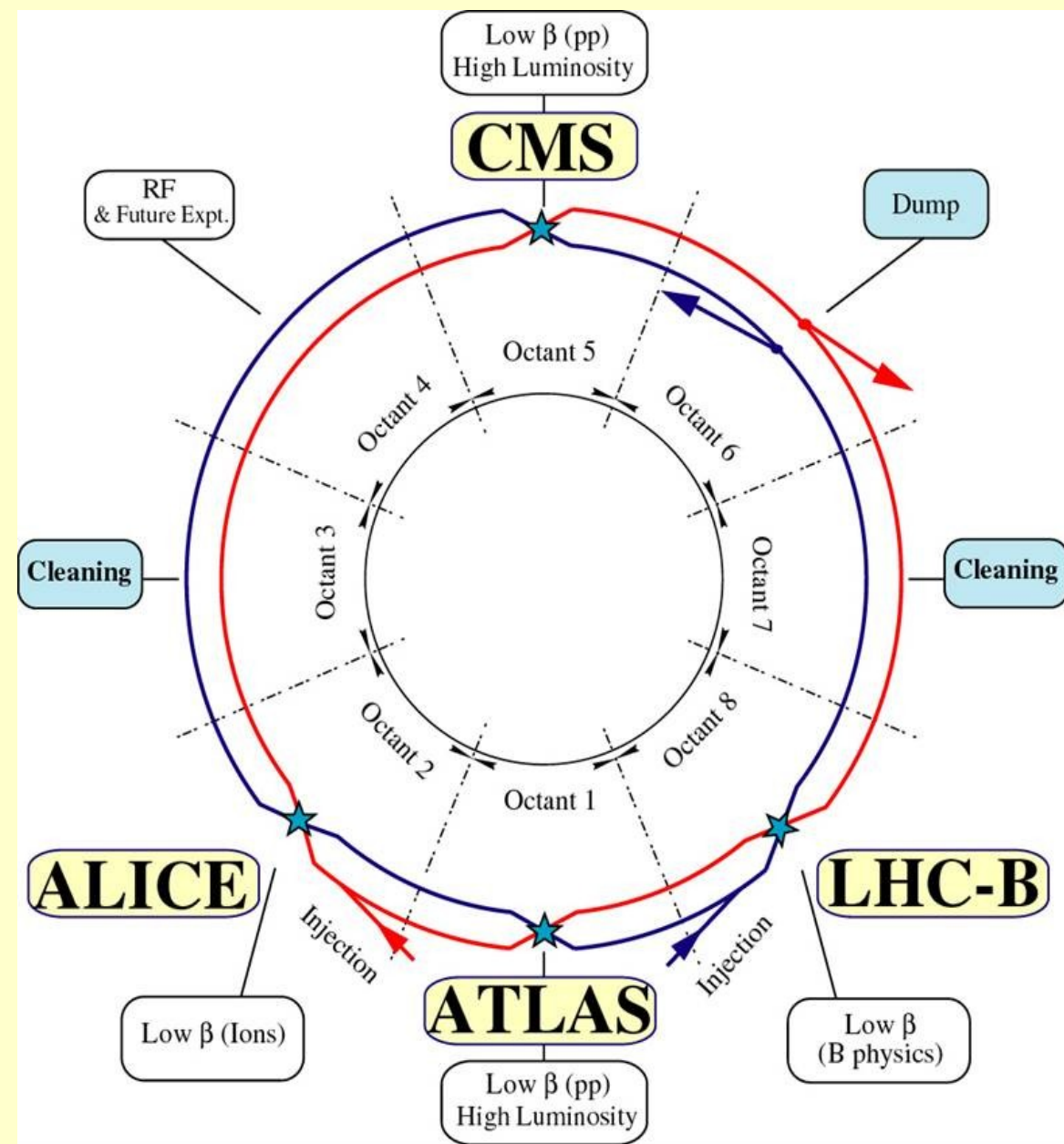
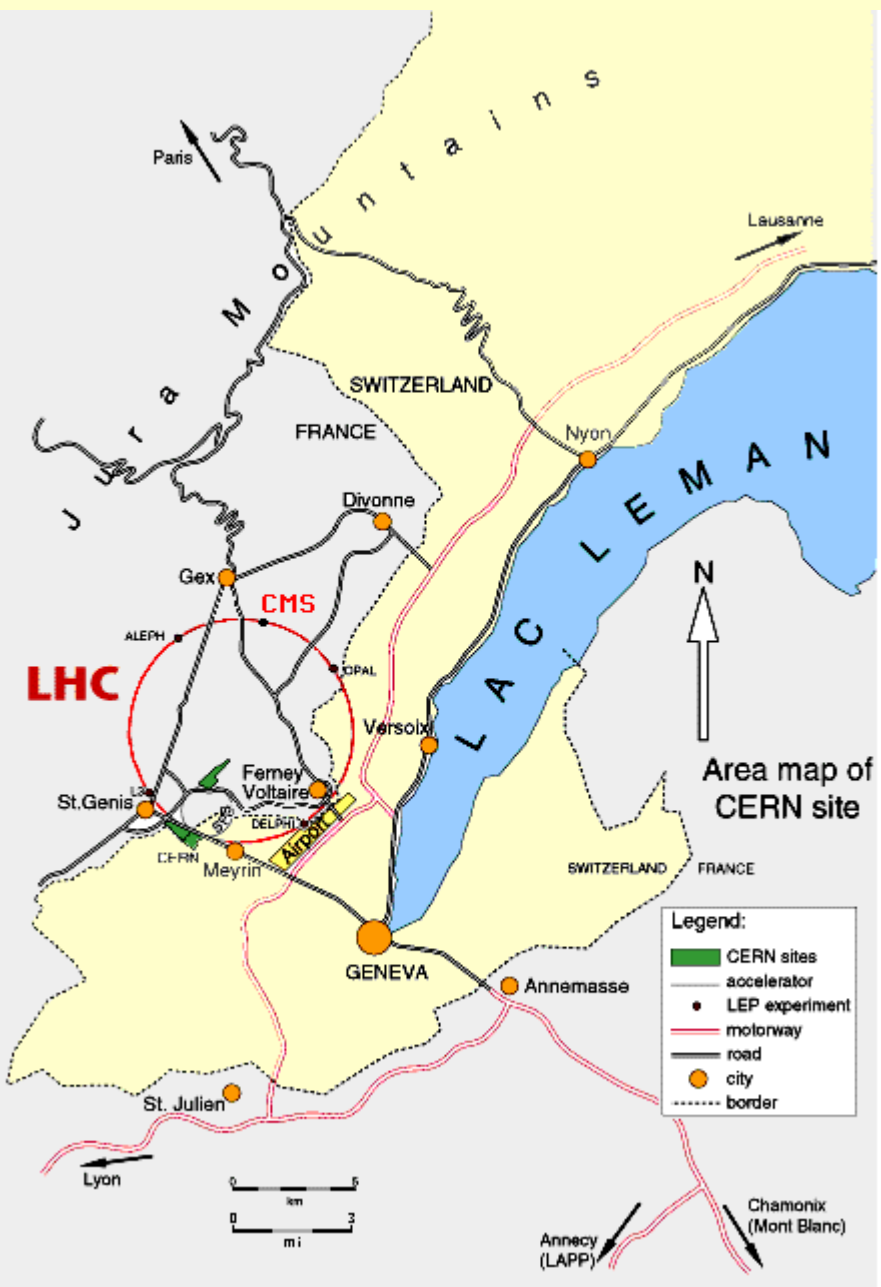
Acceleratore

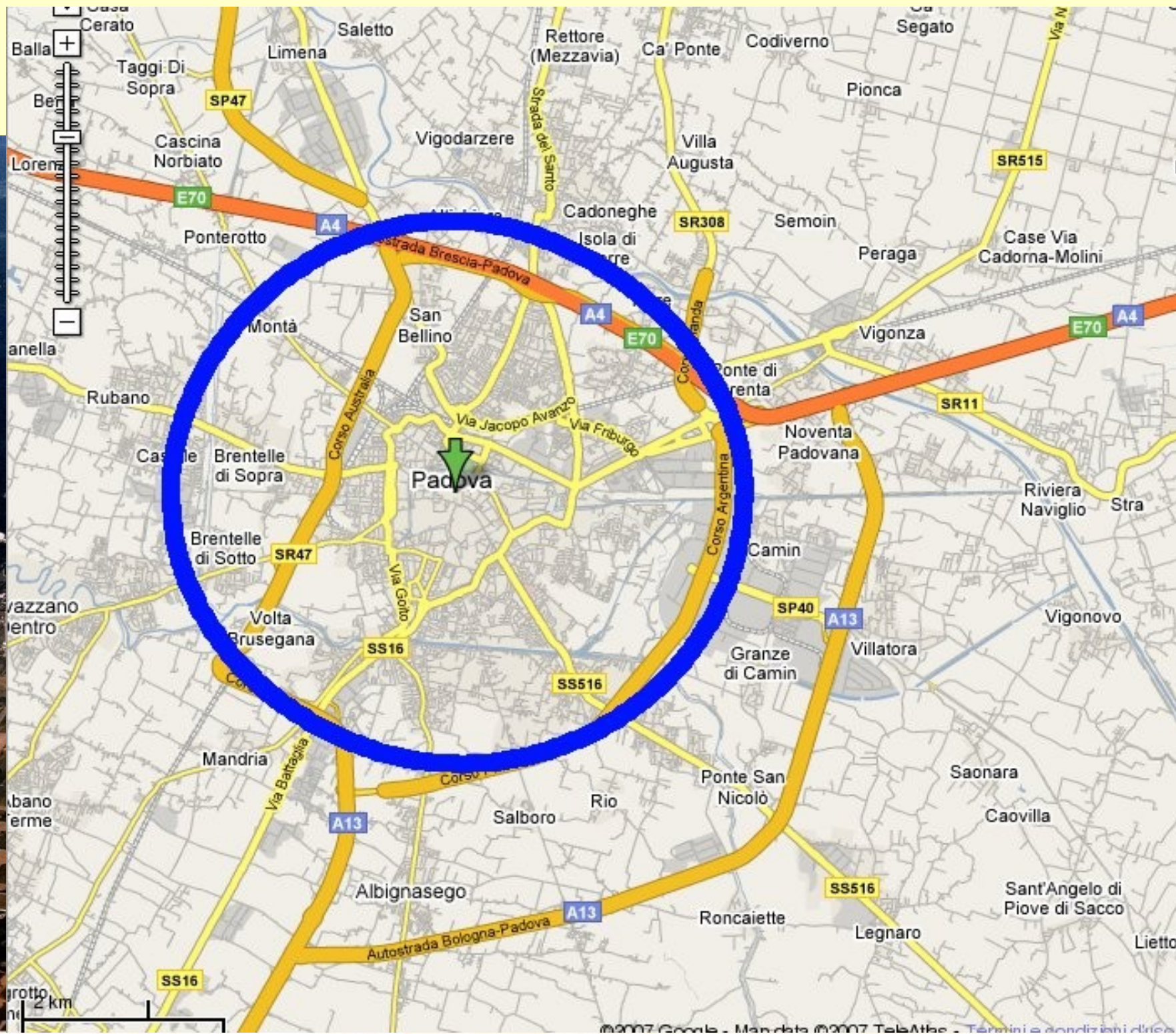


- Energia piu' grande possibile
 - Limite: dimensione tunnel
 - campo magnetico dipoli
- Luminosita' piu' alta possibile

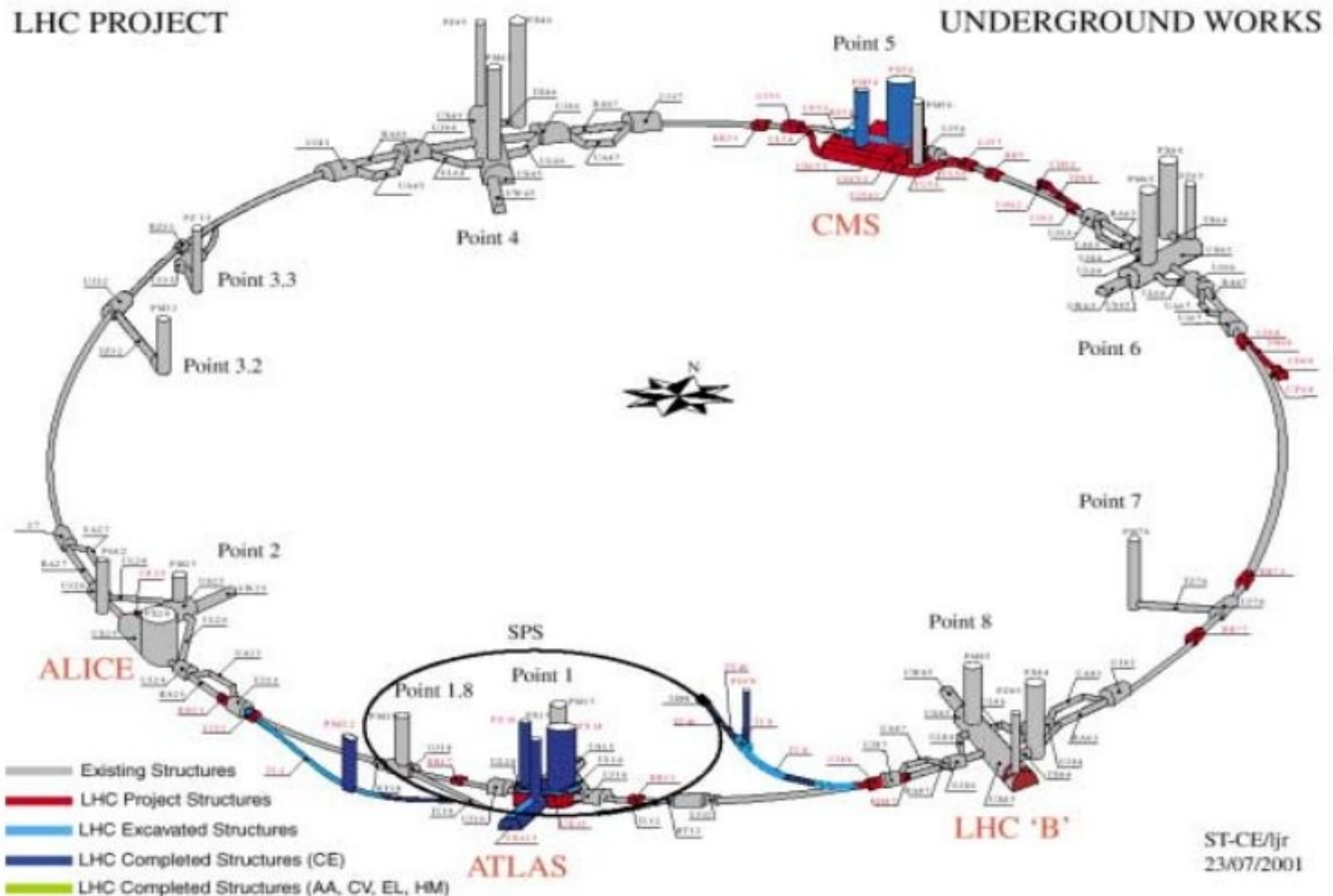


	Beams	Energy GeV	Luminosity
LEP	e+ e-	200	$10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
LHC	p p	14000	10^{34}
	Pb Pb	1,312,000	10^{27}





Il tunnel sotterraneo



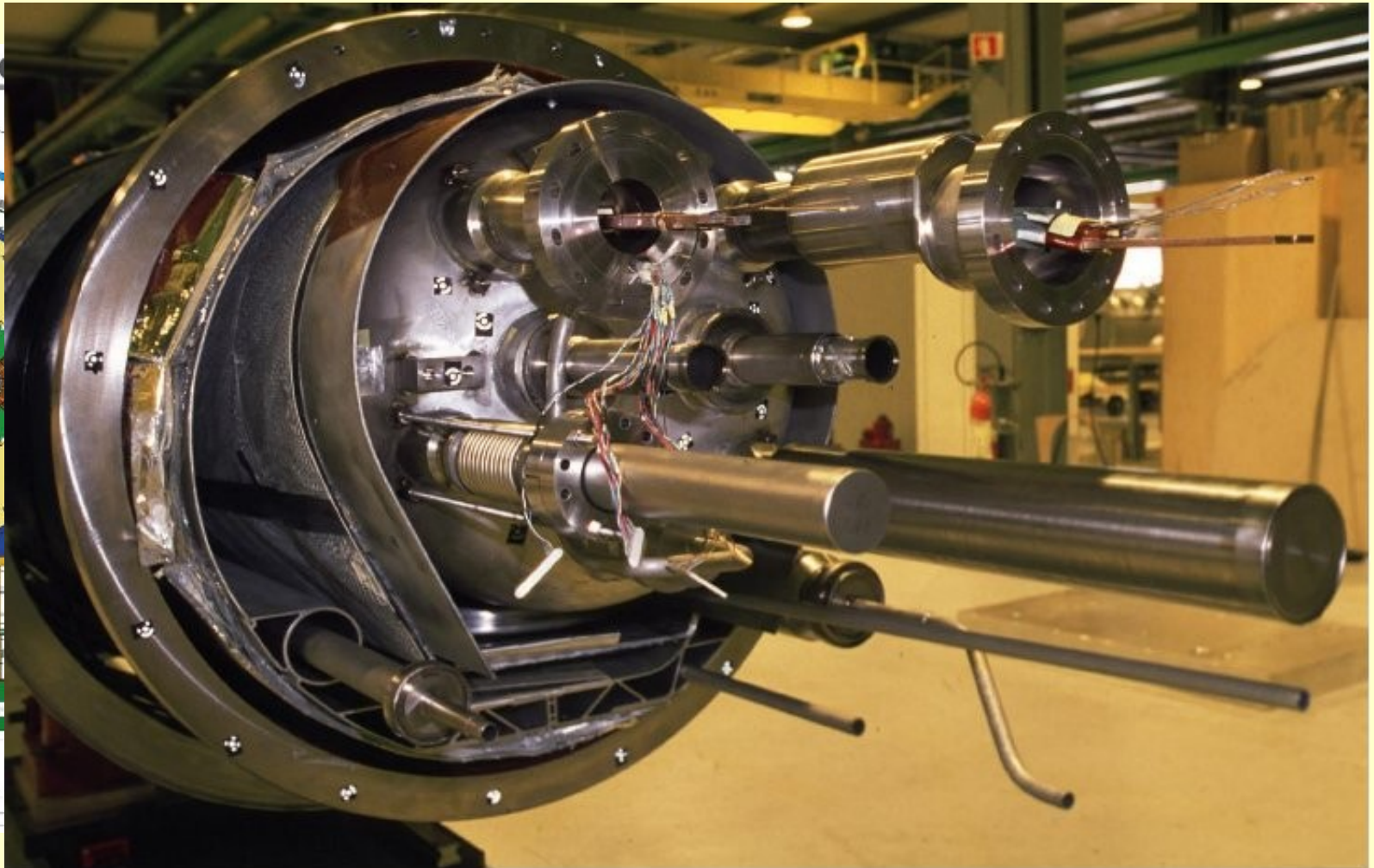
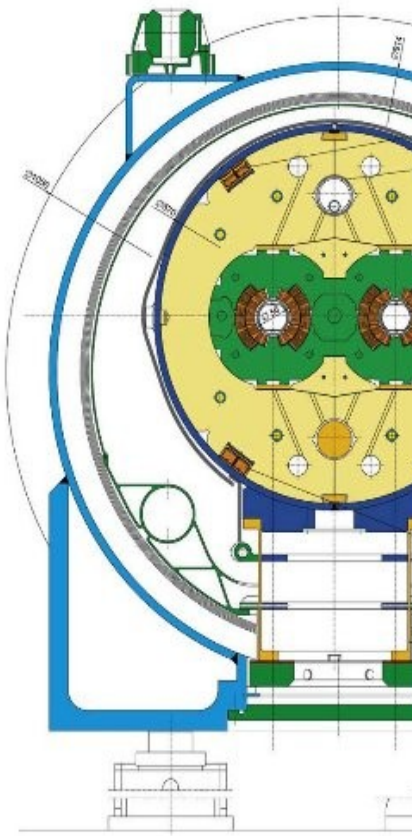


Magneti @ LHC

- Acceleratore circolare: un po' di energia ad ogni giro
- Magneti superconduttori (elio liquido 1.8 K) per curvare i protoni

LHC DIPOLE : STANDARD

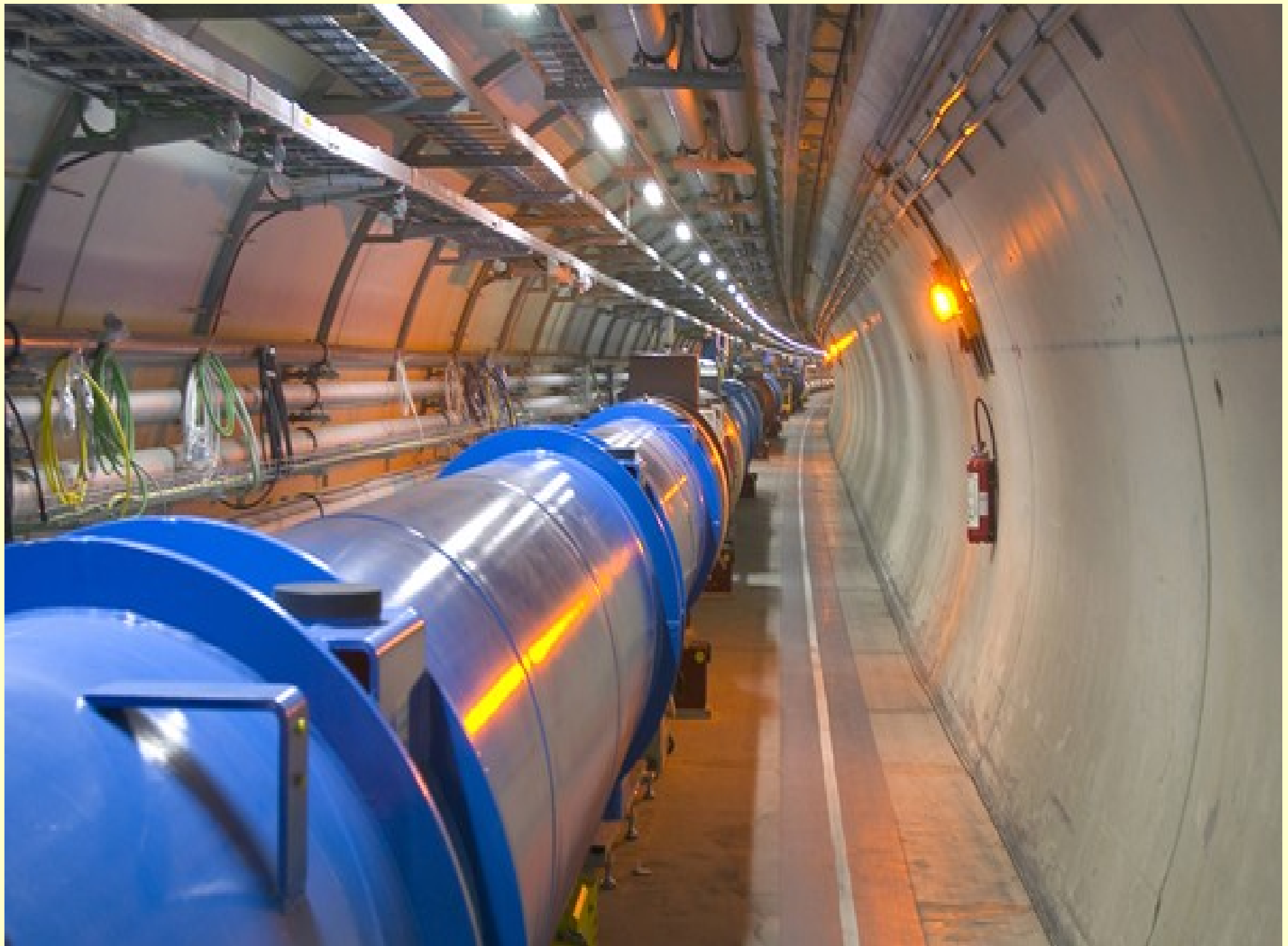
CEBN AC/DIPOLE - HE 107 - 30 04 1999



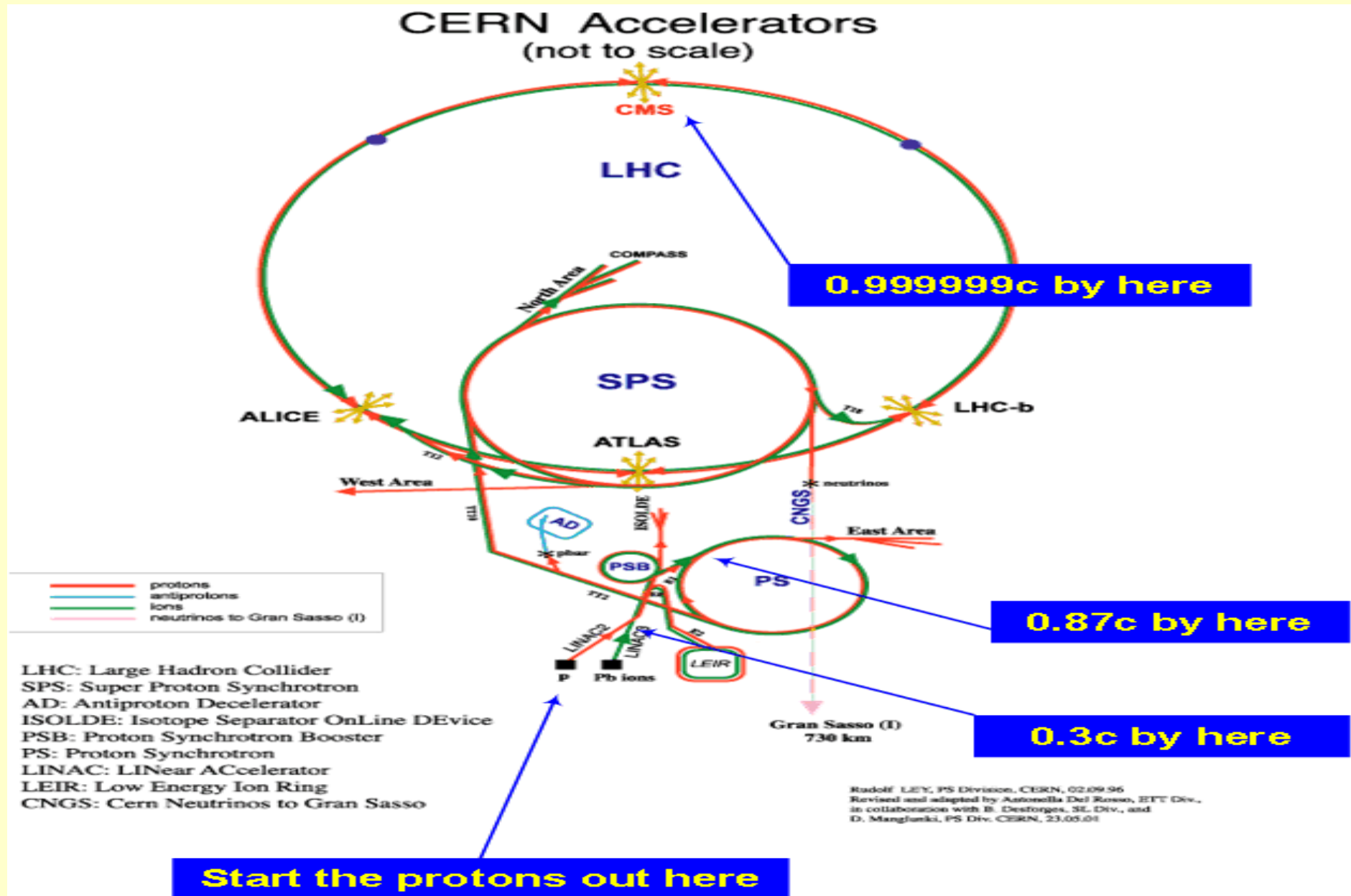
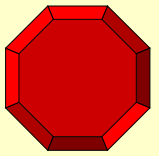


Underground





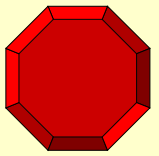
Catena di accelerazione



Cosa vediamo?

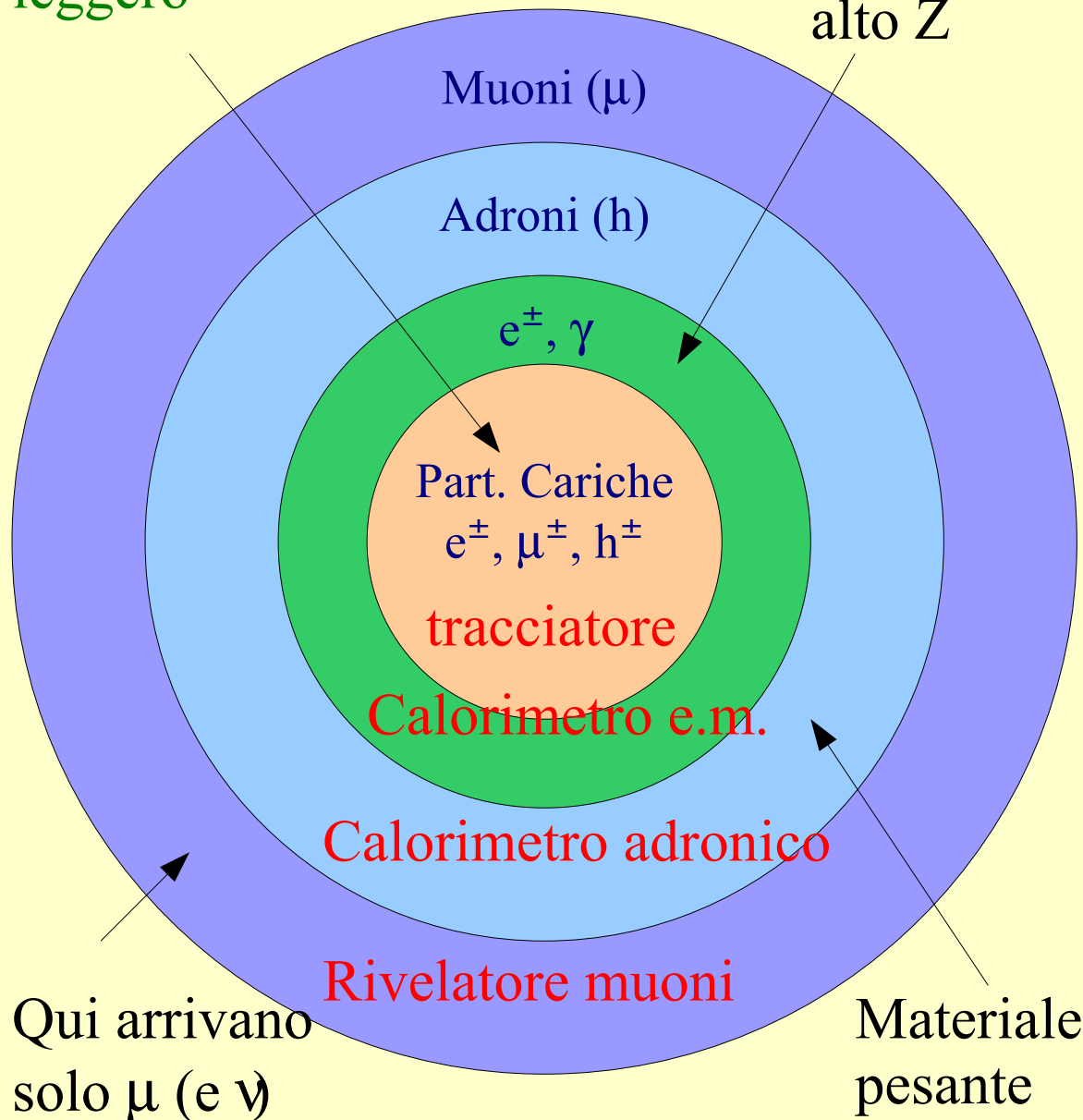
- I prodotti della collisione primaria
- Particelle stabili (o comunque con vita abbastanza lunga)
 - Elettroni e Muoni
 - Fotoni
 - Jets (quark) (particelle cariche e neutre)
 - Energia mancante (neutrini)
- Di tutte vogliamo ricostruire direzione e energia (momento) oltre ad identificarle

Rivelatore a cipolla



Materiale
leggero

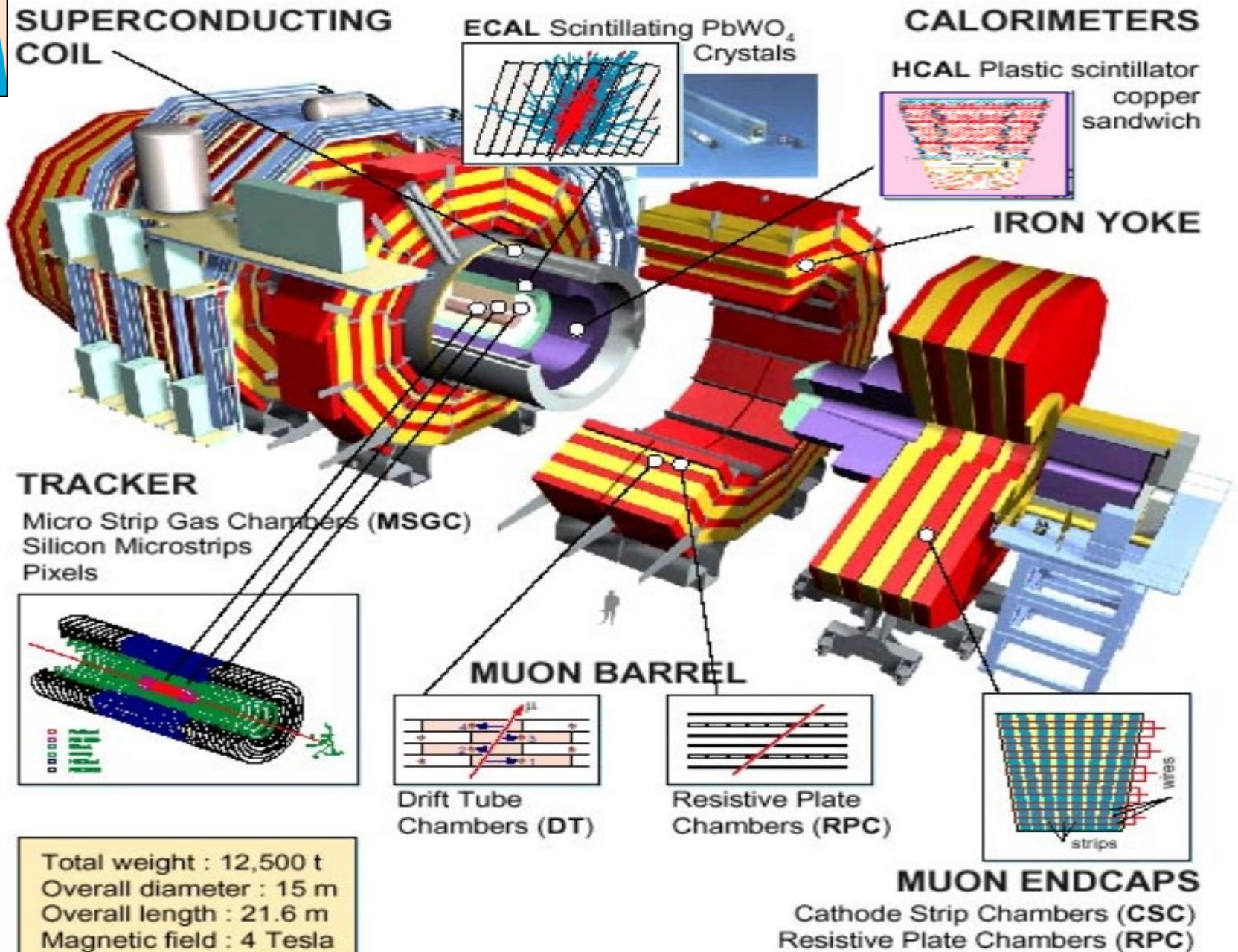
Materiale
alto Z

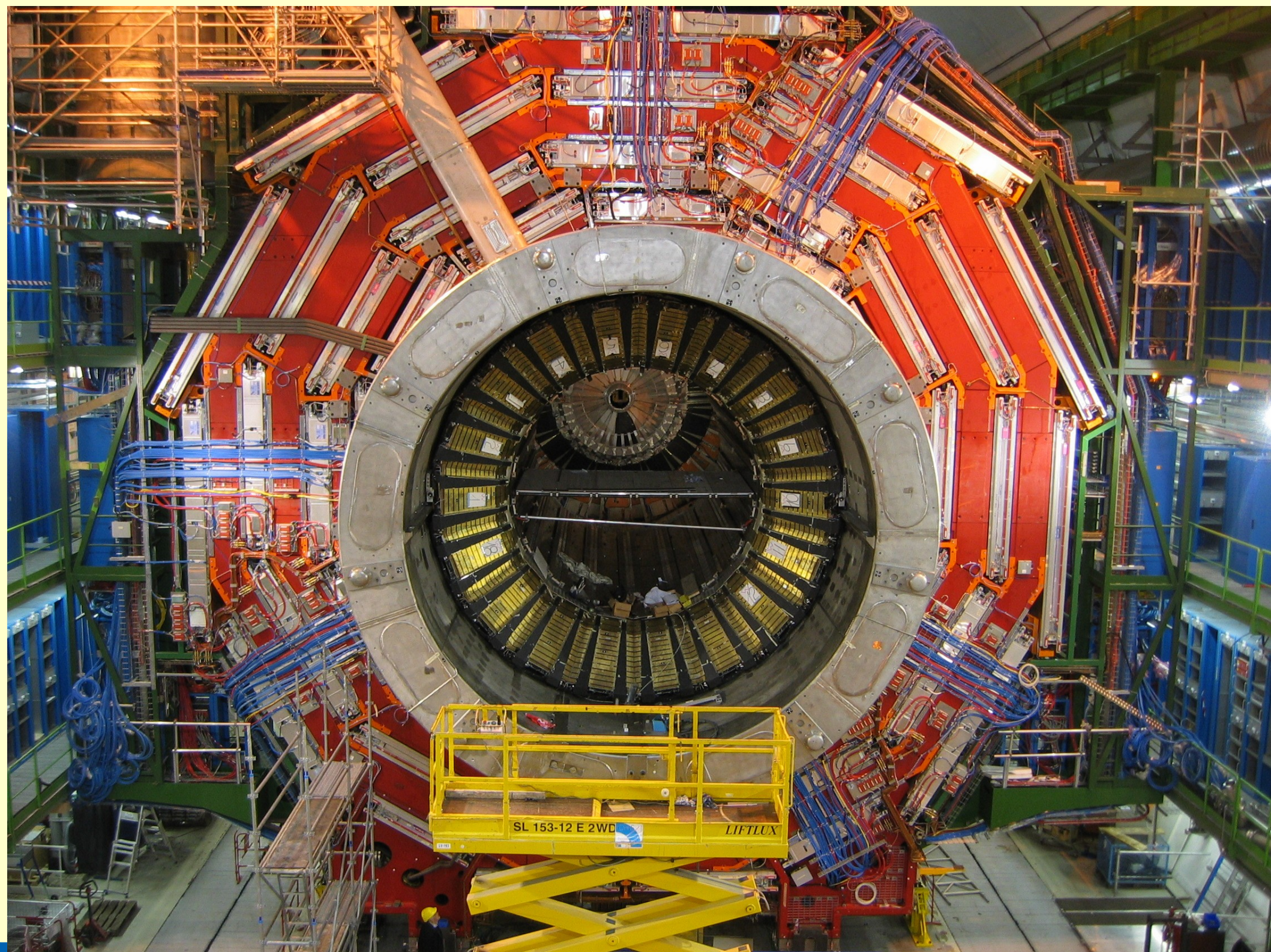


- Non basta un solo rivelatore per vedere tutto
- Ogni strato identifica e misura (o rimisura) l'energia delle particelle non viste dallo strato precedente
- Vedo tutto (tranne i neutrini)
- Mi serve un **magnete** per curvare le tracce cariche e quindi misurarle

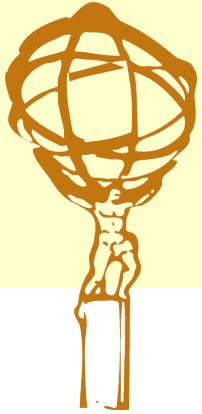
CMS

: Compact Muon Solenoid

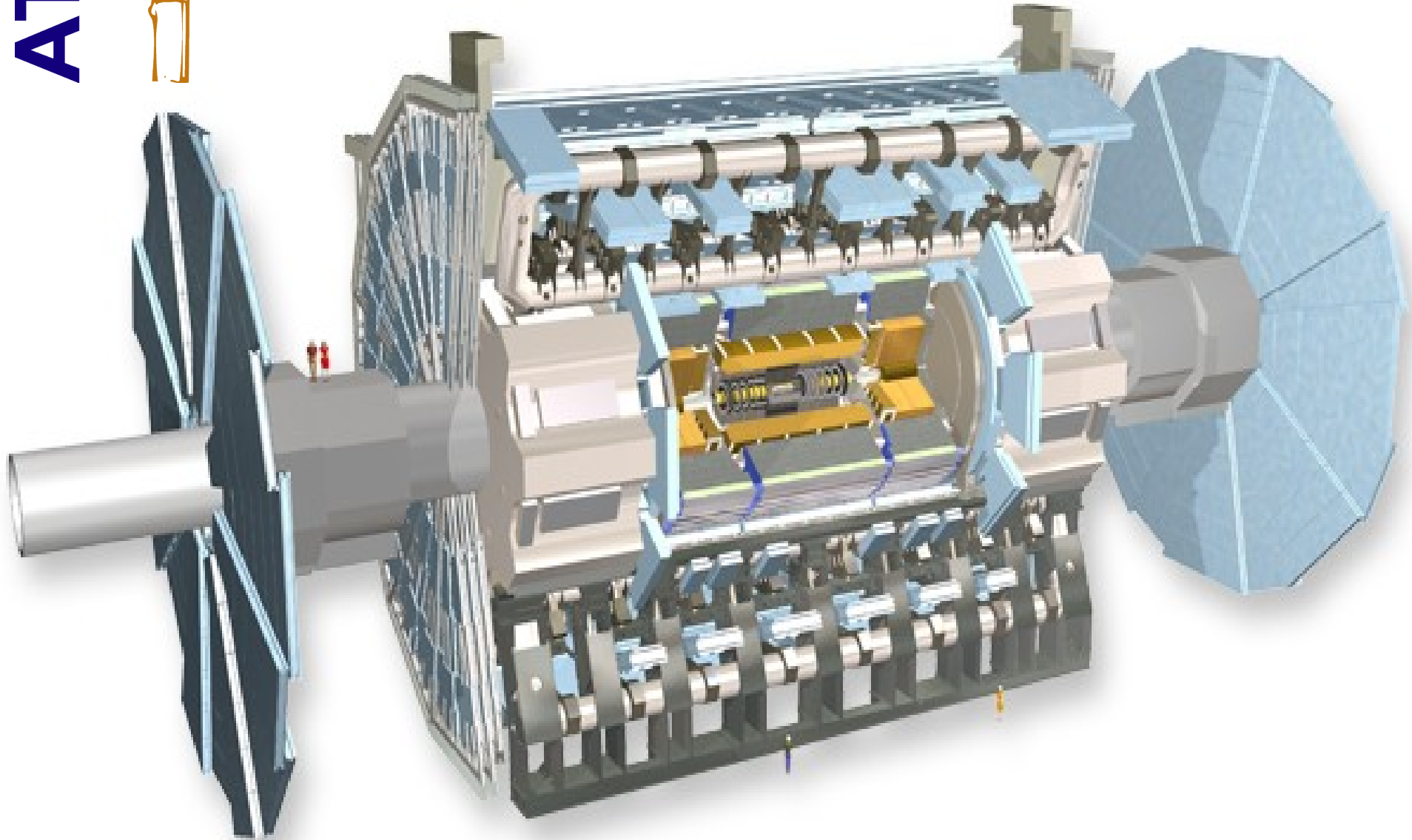


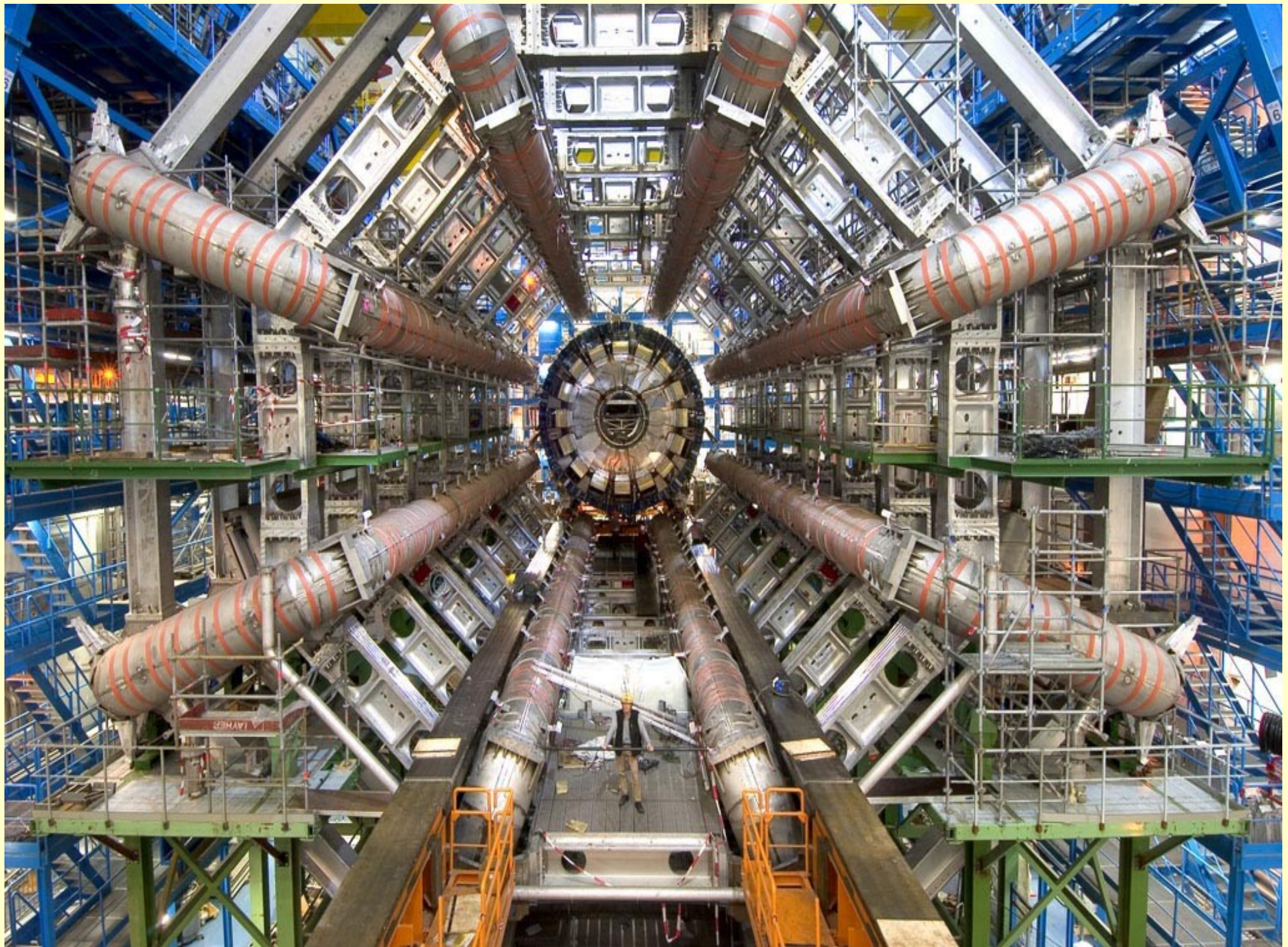


ATLAS



A Toroidal Apparatus





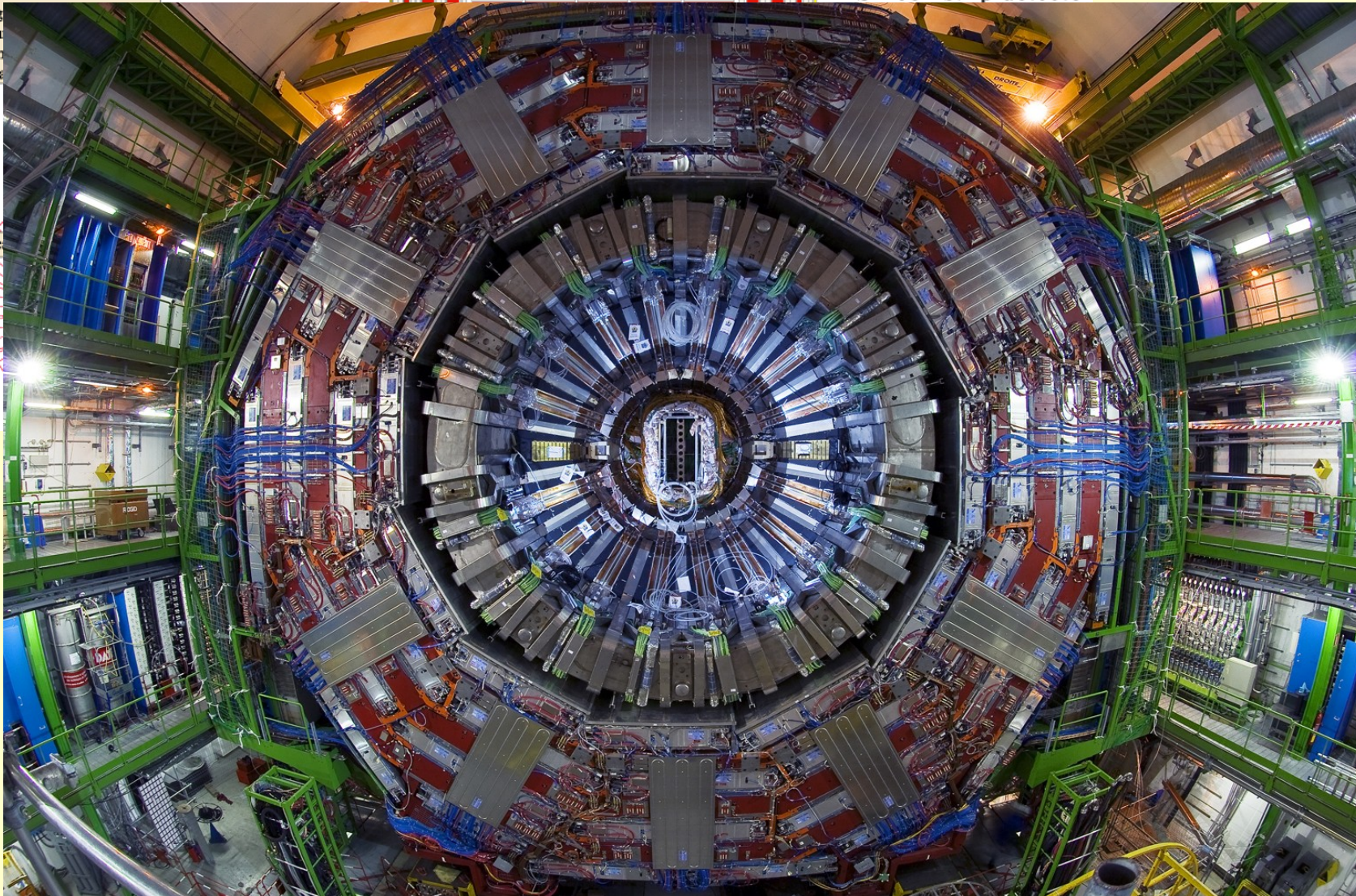
Tracciatore

- Elementi sensibili al passaggio di particelle cariche (silici)
- In campo magnetico: misura traiettoria $\Rightarrow$ curvatura $\Rightarrow$ momento

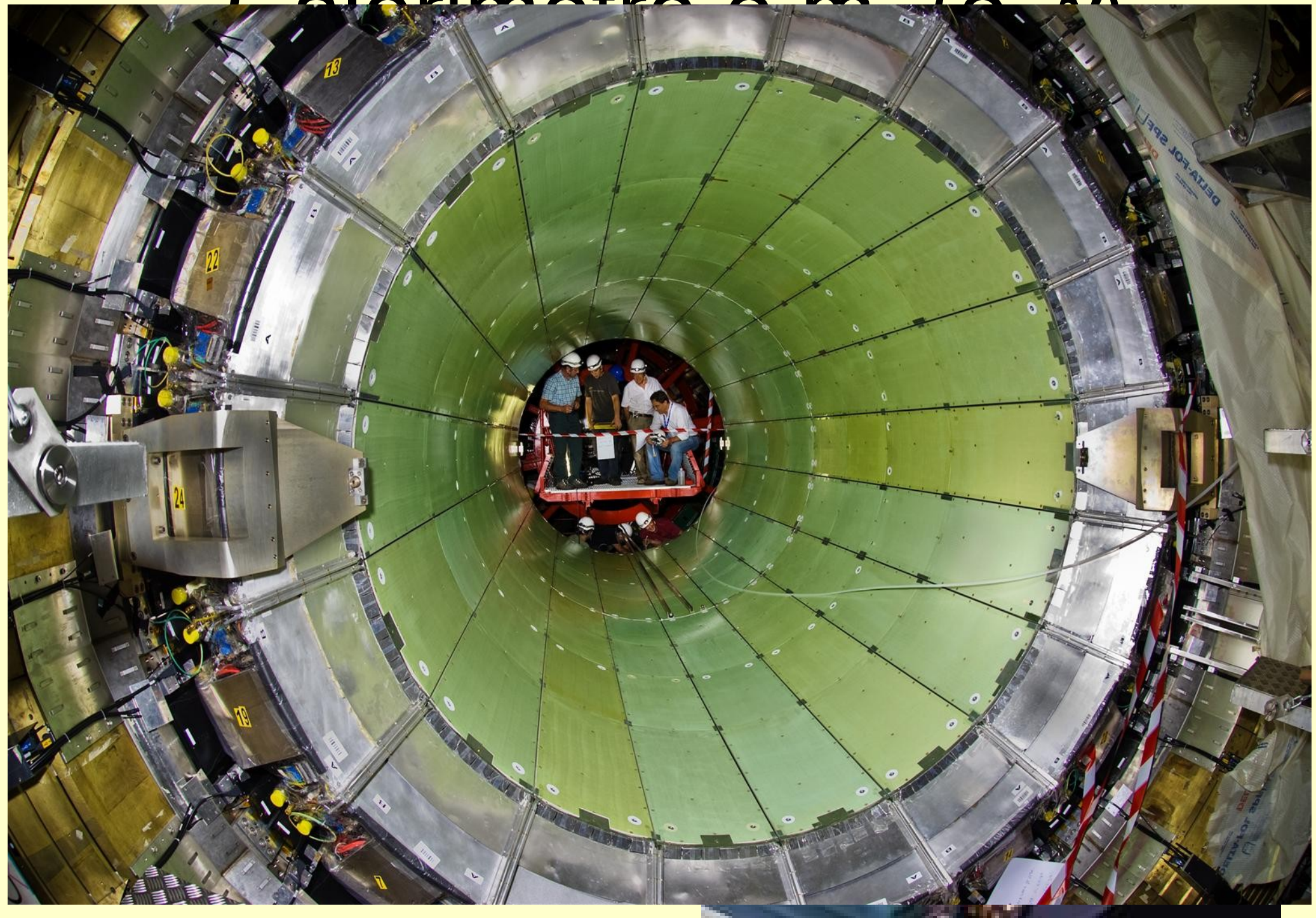
Diameter 2.4m
Length
Volume
Running
Dry s

Endo

Silicon strip detector

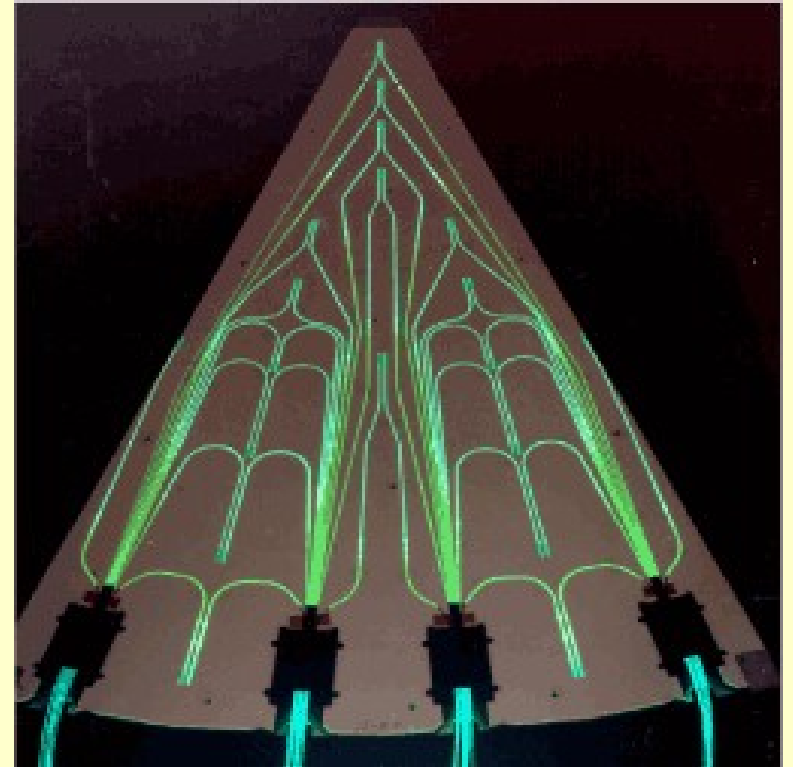
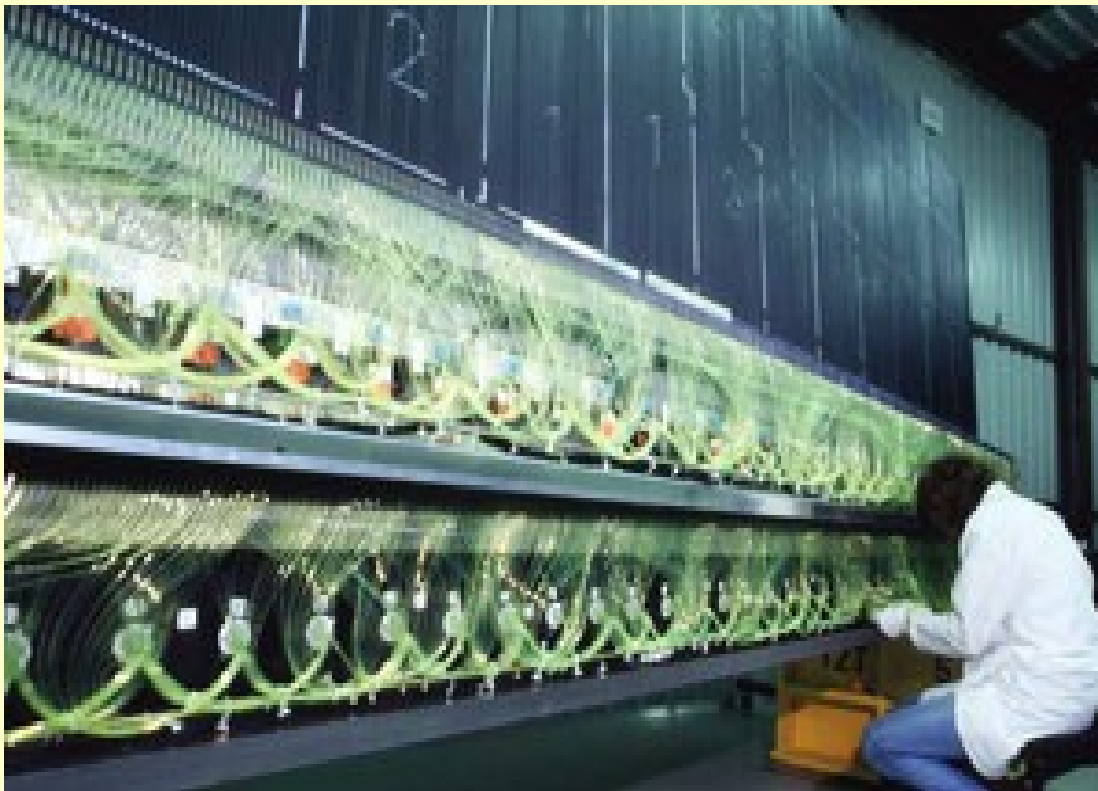


Calorimetro em (GeV)



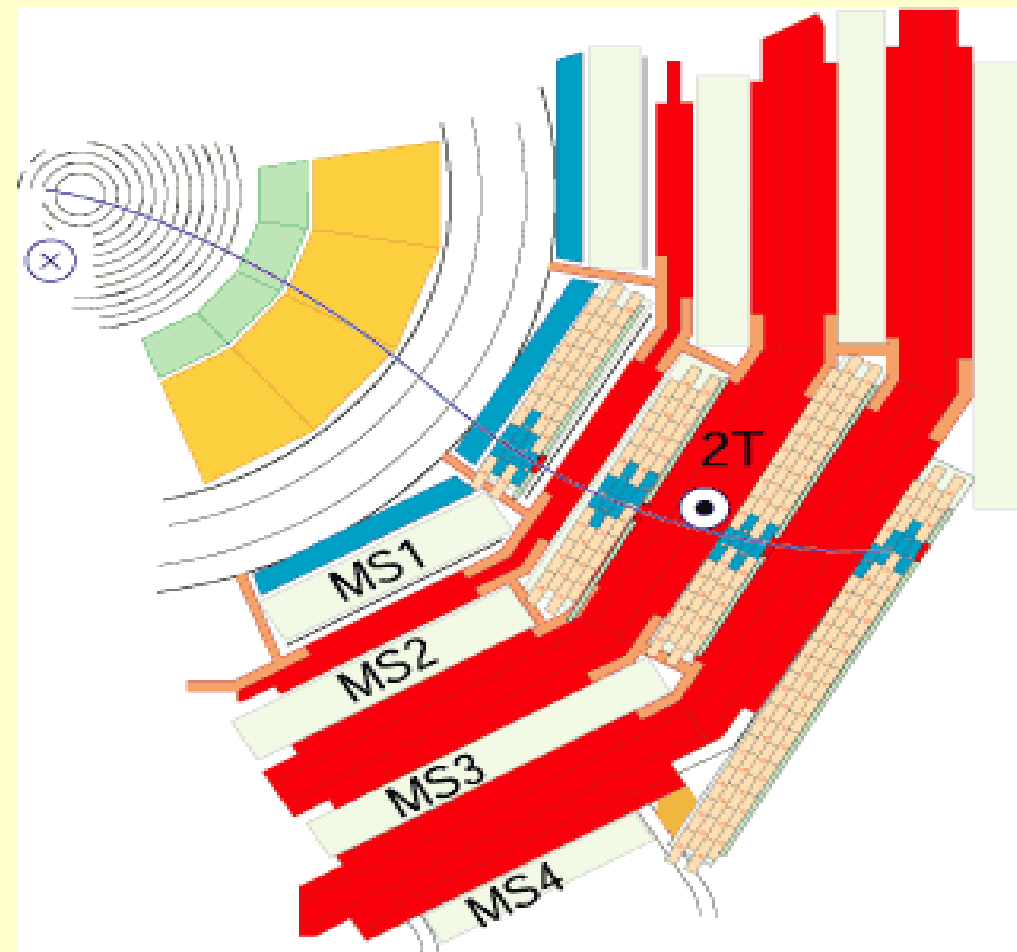
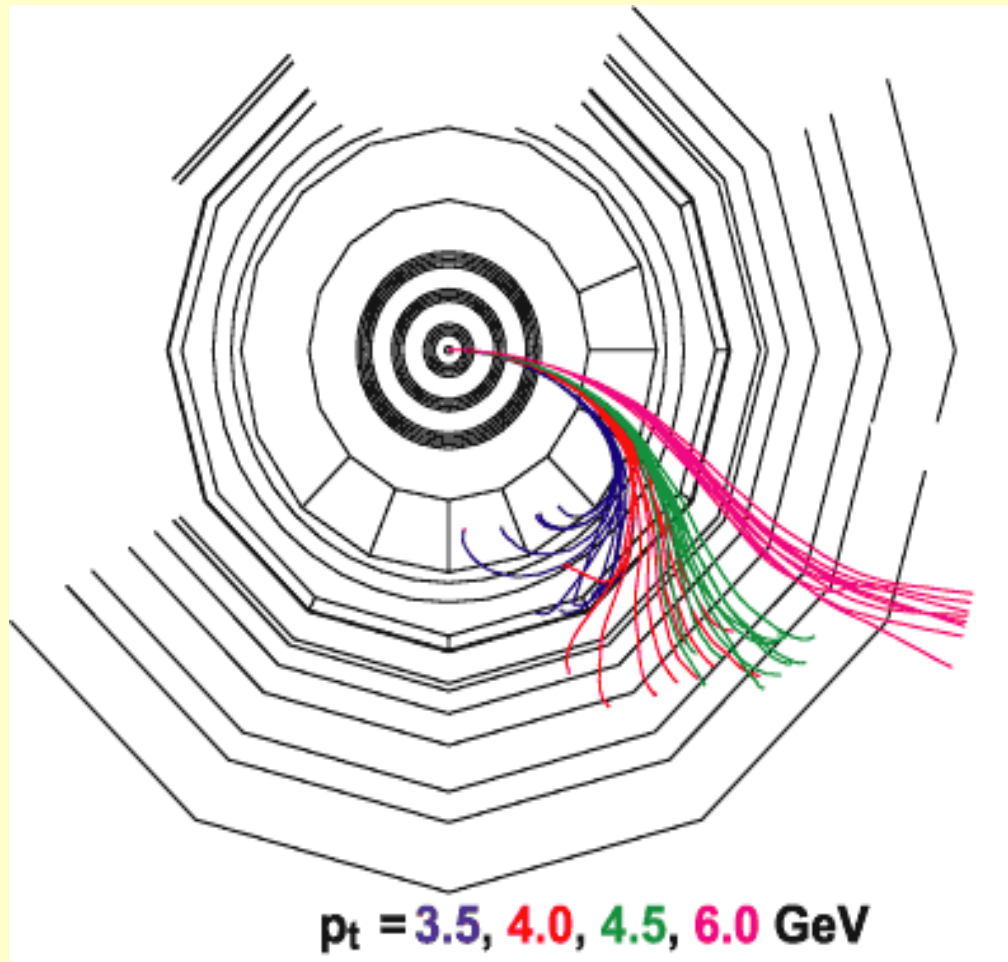
Calorimetro adronico

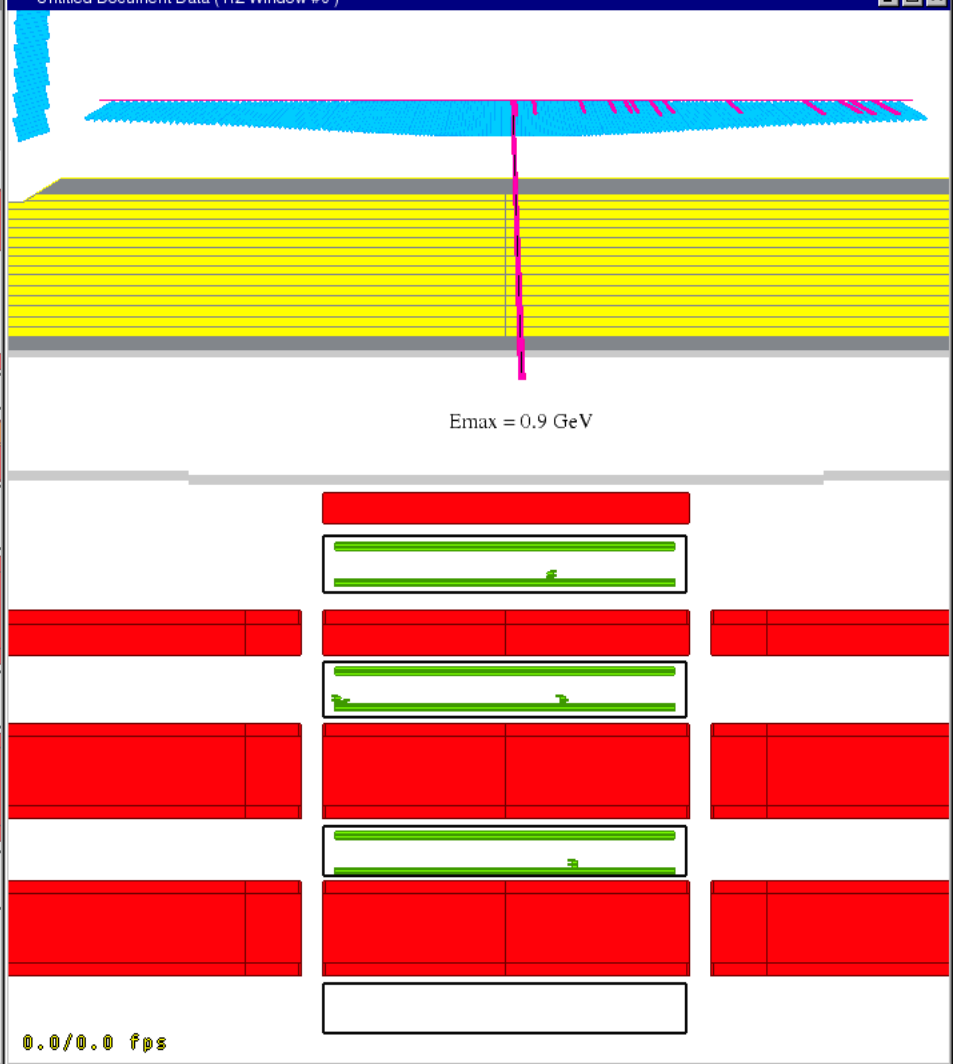
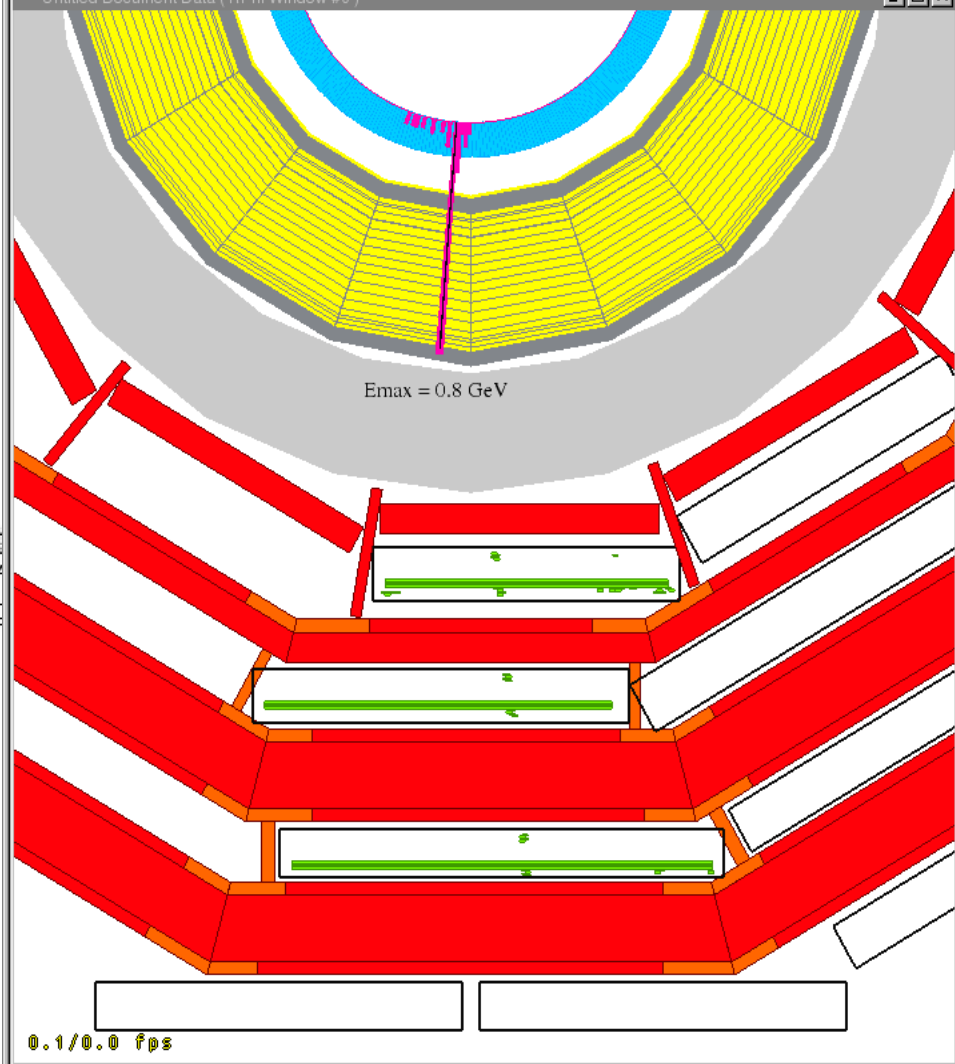
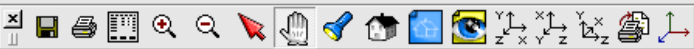
- Concettualmente simile a quello e.m.
- Serve piu' pesante e profondo (sciami adronici sono piu' profondi)
- Materiale assorbitore (Fe Cu) + materiale attivo (produce luce poi raccolta)



Rivelatore di Muoni

- Come il tracciatore: muoni sono particelle cariche
- Metto molto materiale davanti per fermare tutto tranne muoni (e neutrini)
- Sono all'esterno, devono essere molto grandi

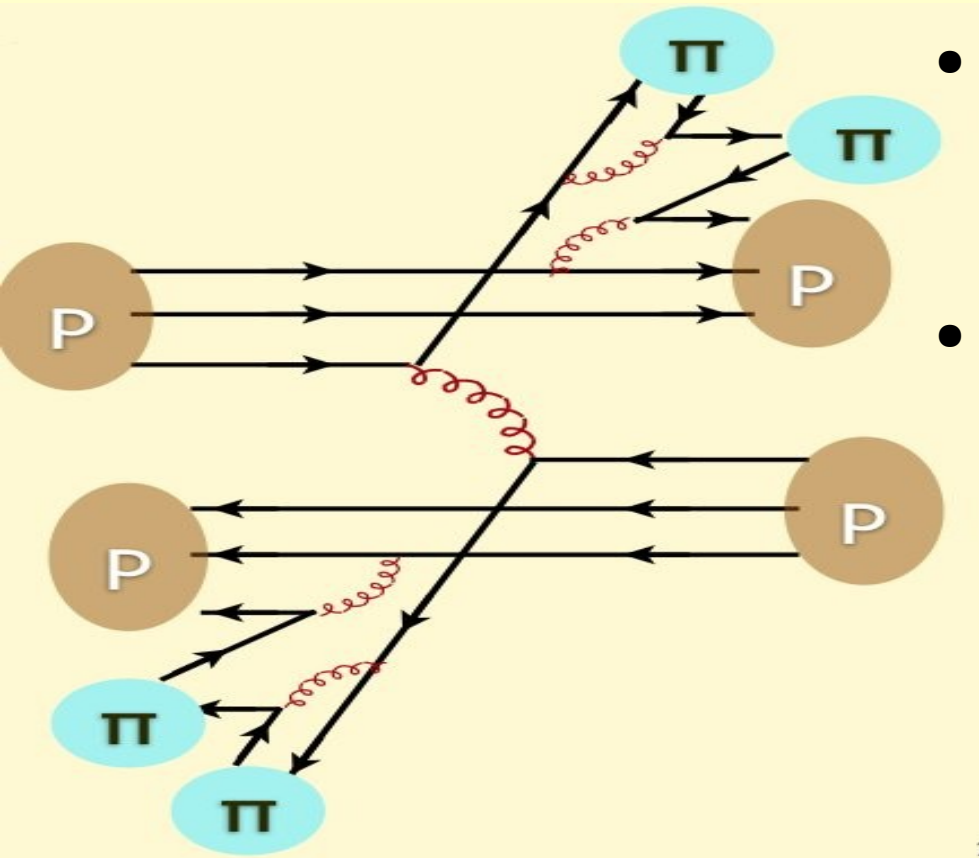






Jet (Getti)

- Le interazioni primarie producono quark
- I quark non vivono da soli
- Si “rivestono” di adroni: ecco un Jet
- I Jet si “ricordano” del quark iniziale che li ha generati



Jet in pratica

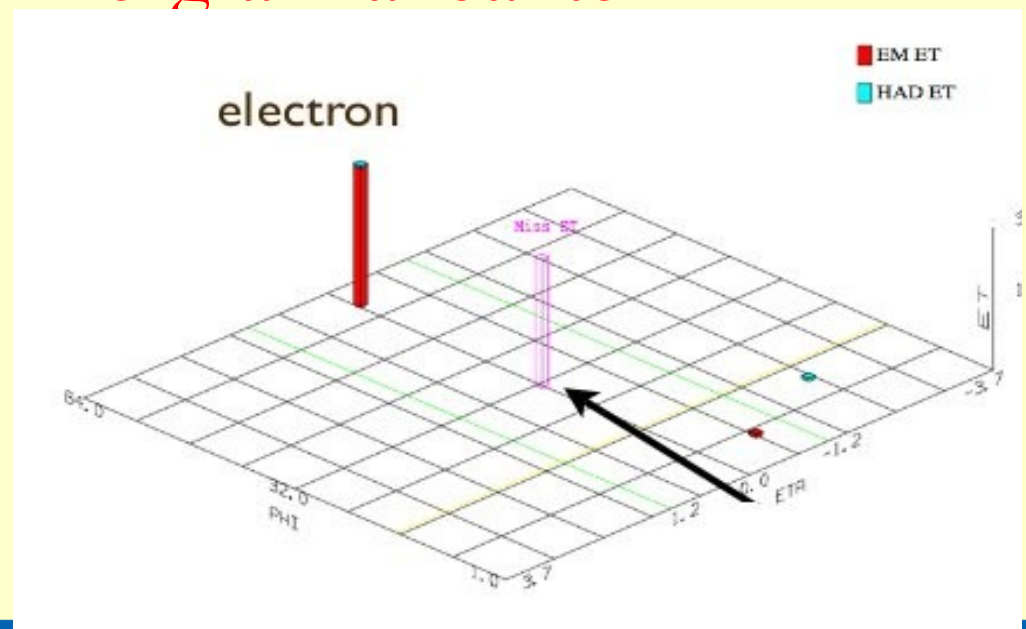
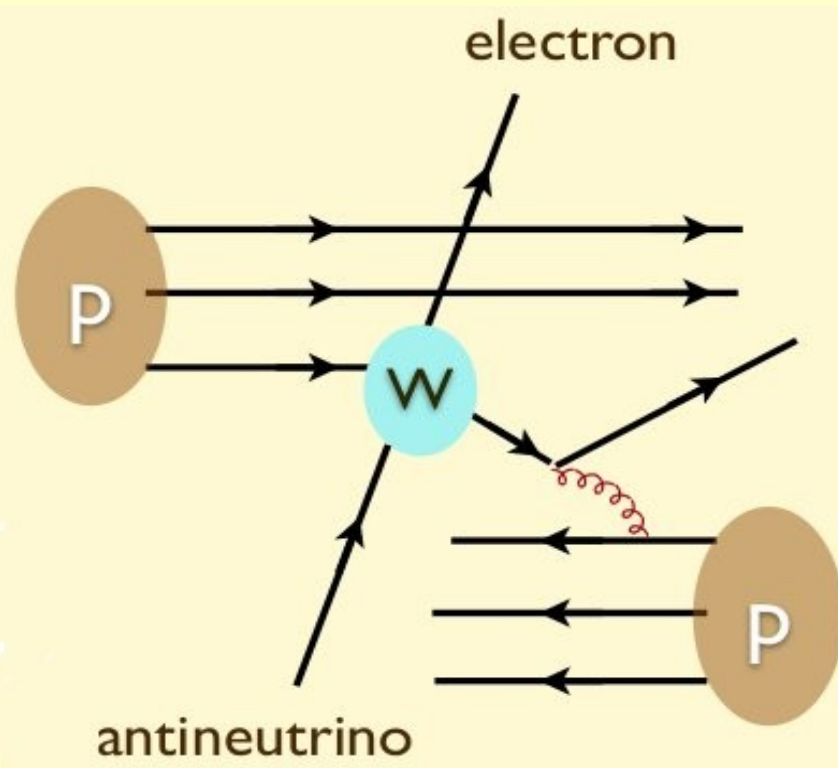


$$e^+e^- \rightarrow Z \rightarrow q \bar{q}$$



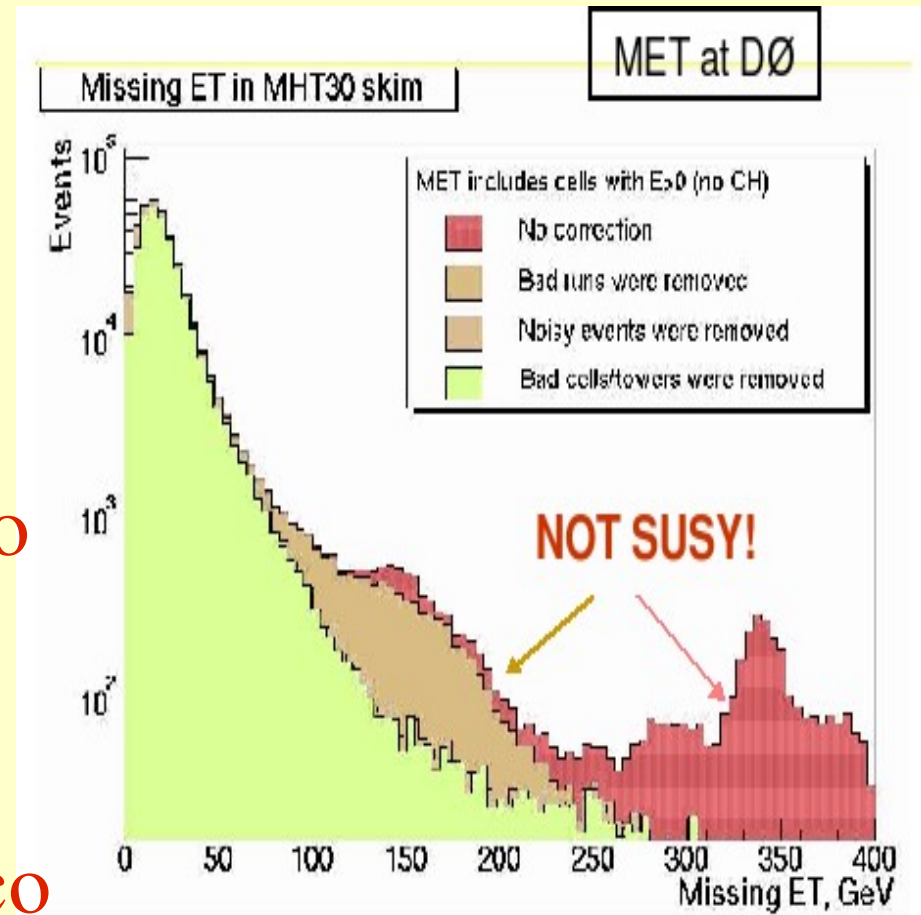
Energia mancante

- Vedere l'invisibile!
- Con i nostri rivelatori vediamo tutto **tranne i neutrini**
- E altre particelle che non interagiscono (vedi dopo)
- **Energia mancante**



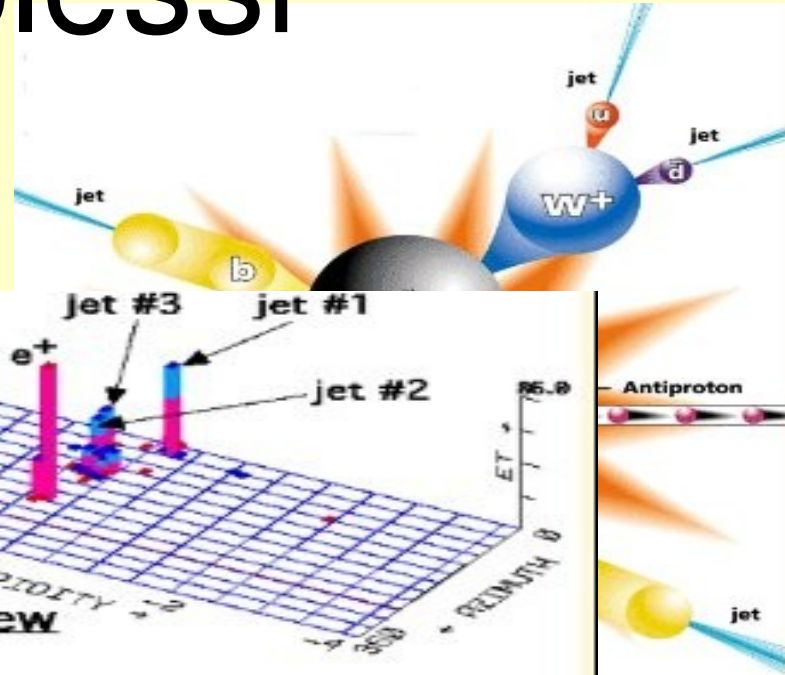
Come si fa?

- Sommo tutto quello che vedo (e , γ , h , μ , ...)
- Nel piano trasverso ai fasci l'energia si deve bilanciare
- Se manca, allora mi sono perso qualcosa in quella direzione (neutrino o altro)
- Rivelatore deve essere ermetico
- E' difficile da fare (cavi, tubi, servizi...): bisogna stare attenti!



Oggetti complessi

Si combinano i vari pezzi
misurati dai vari rivelatori



e + 4 jet event

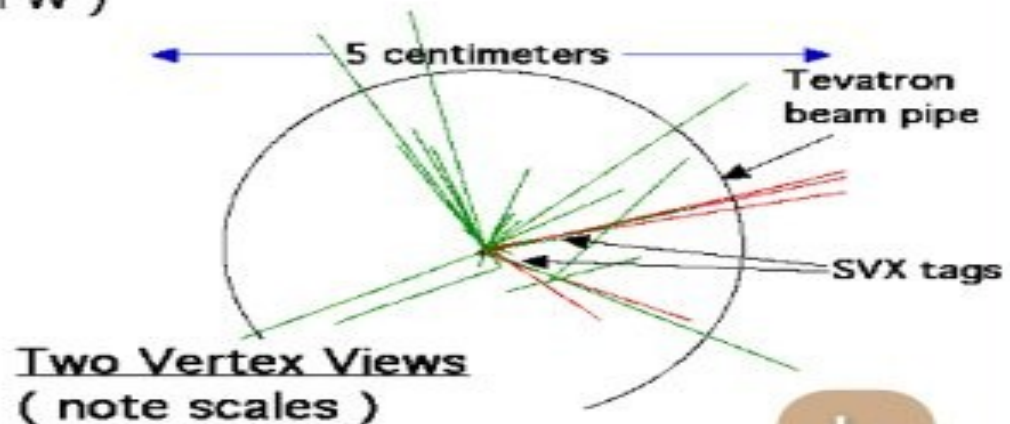
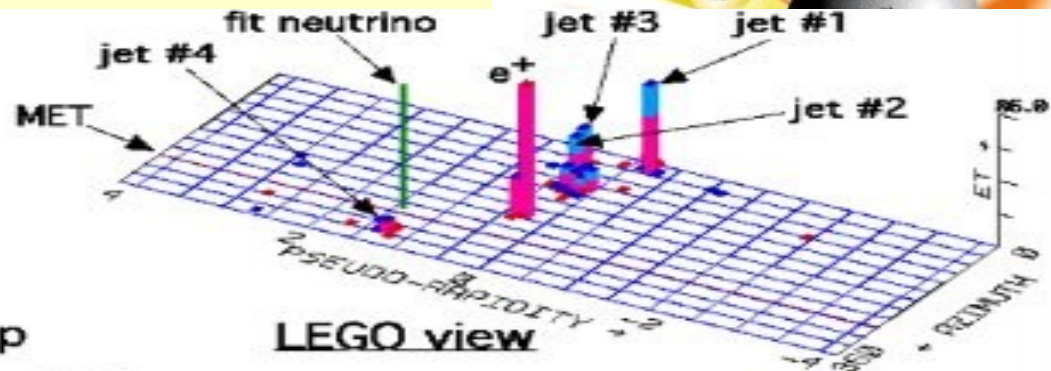
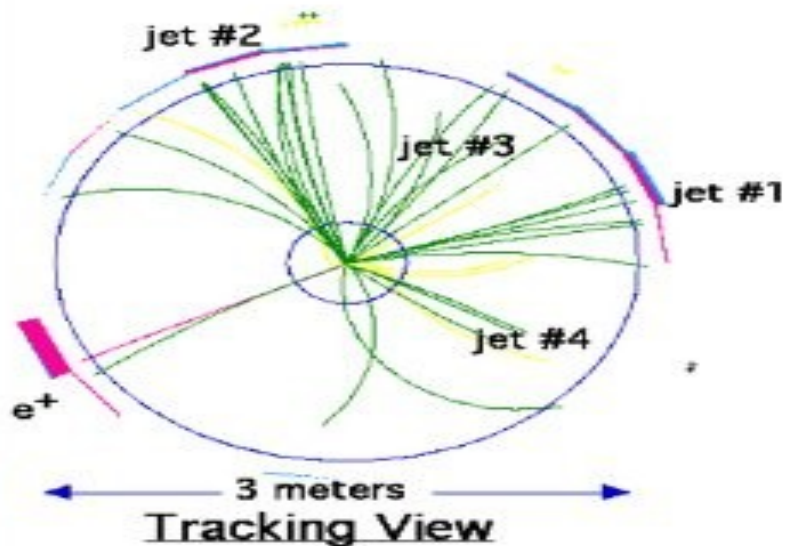
40758_44414

24-September, 1992

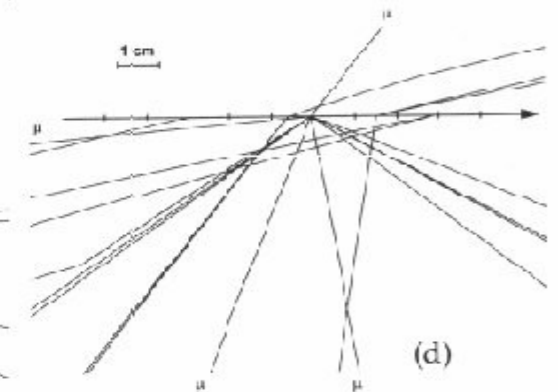
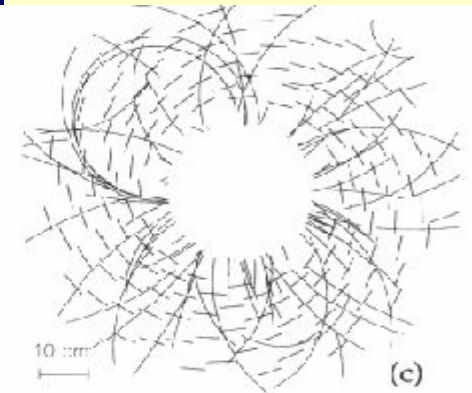
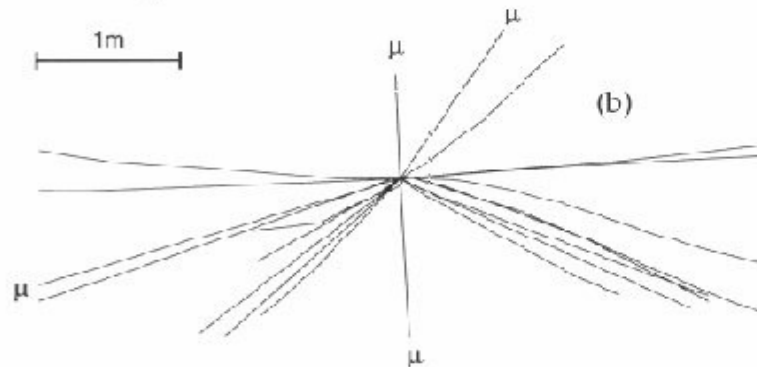
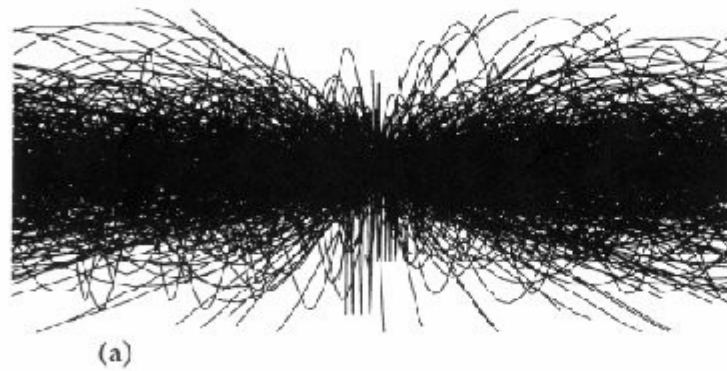
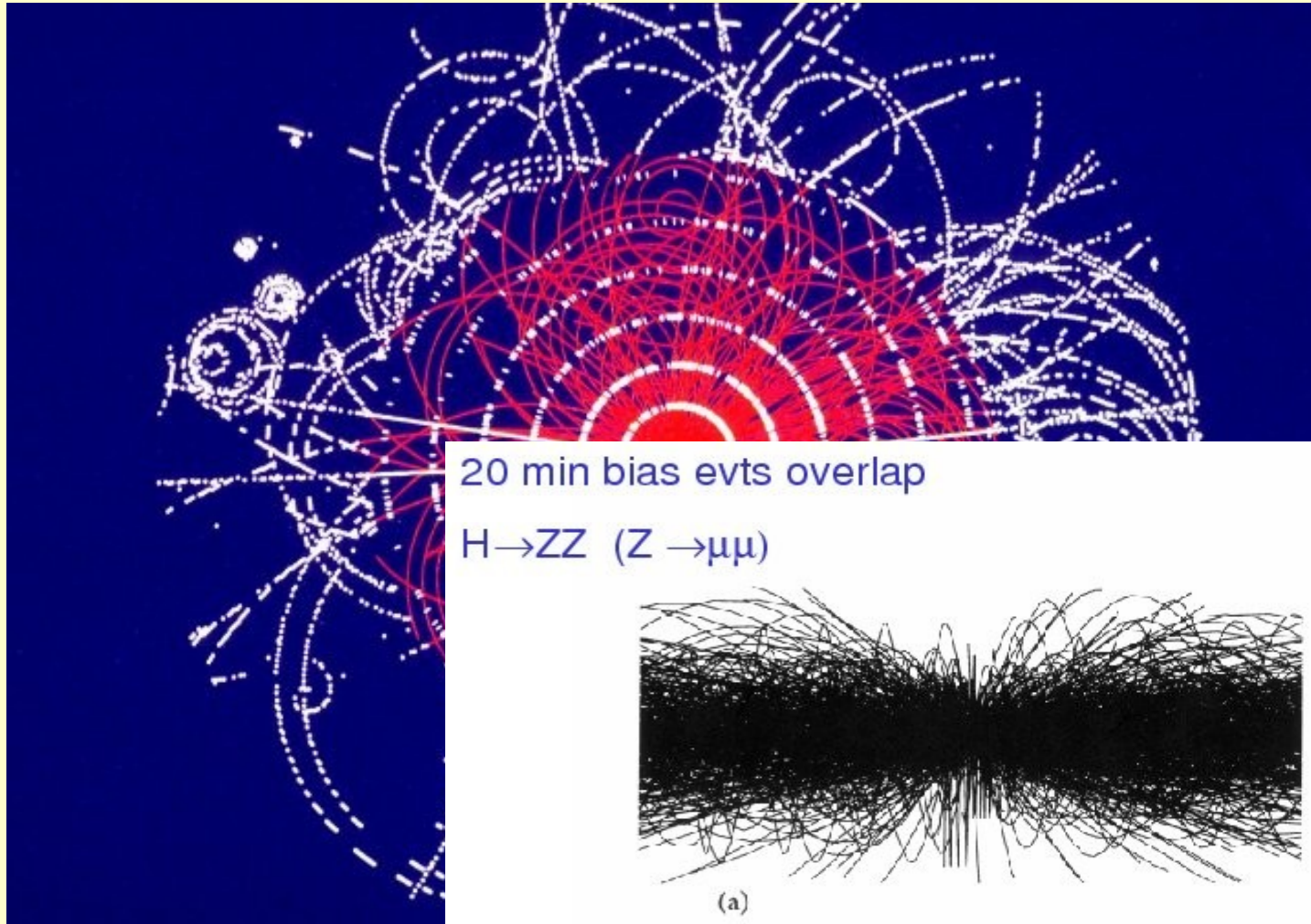
TWO jets tagged by SVX

fit top mass is 170 ± 10 GeV

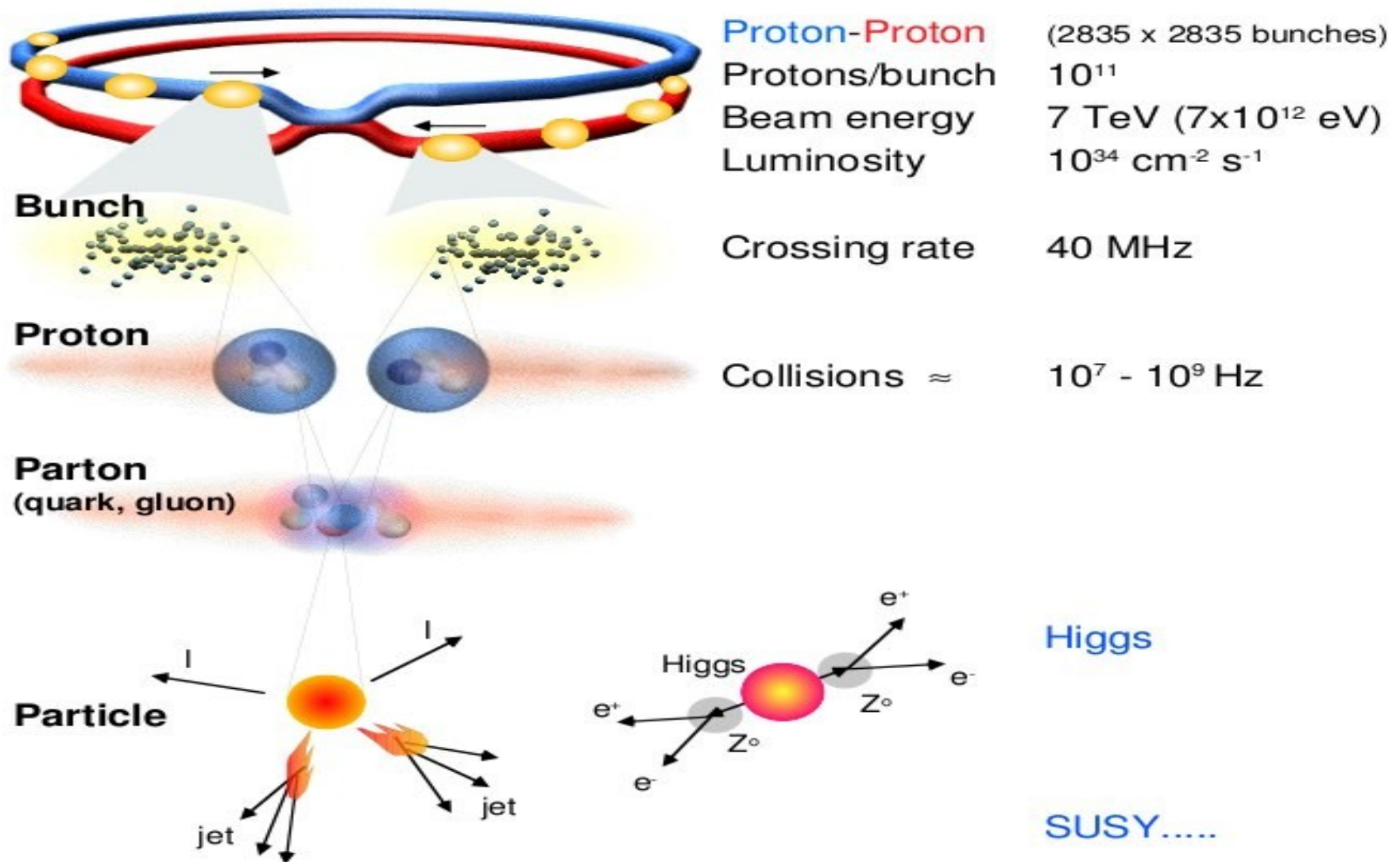
e^+ , Missing E_T , jet #4 from top
jets 1,2,3 from top (2&3 from W)



Evento @ LHC



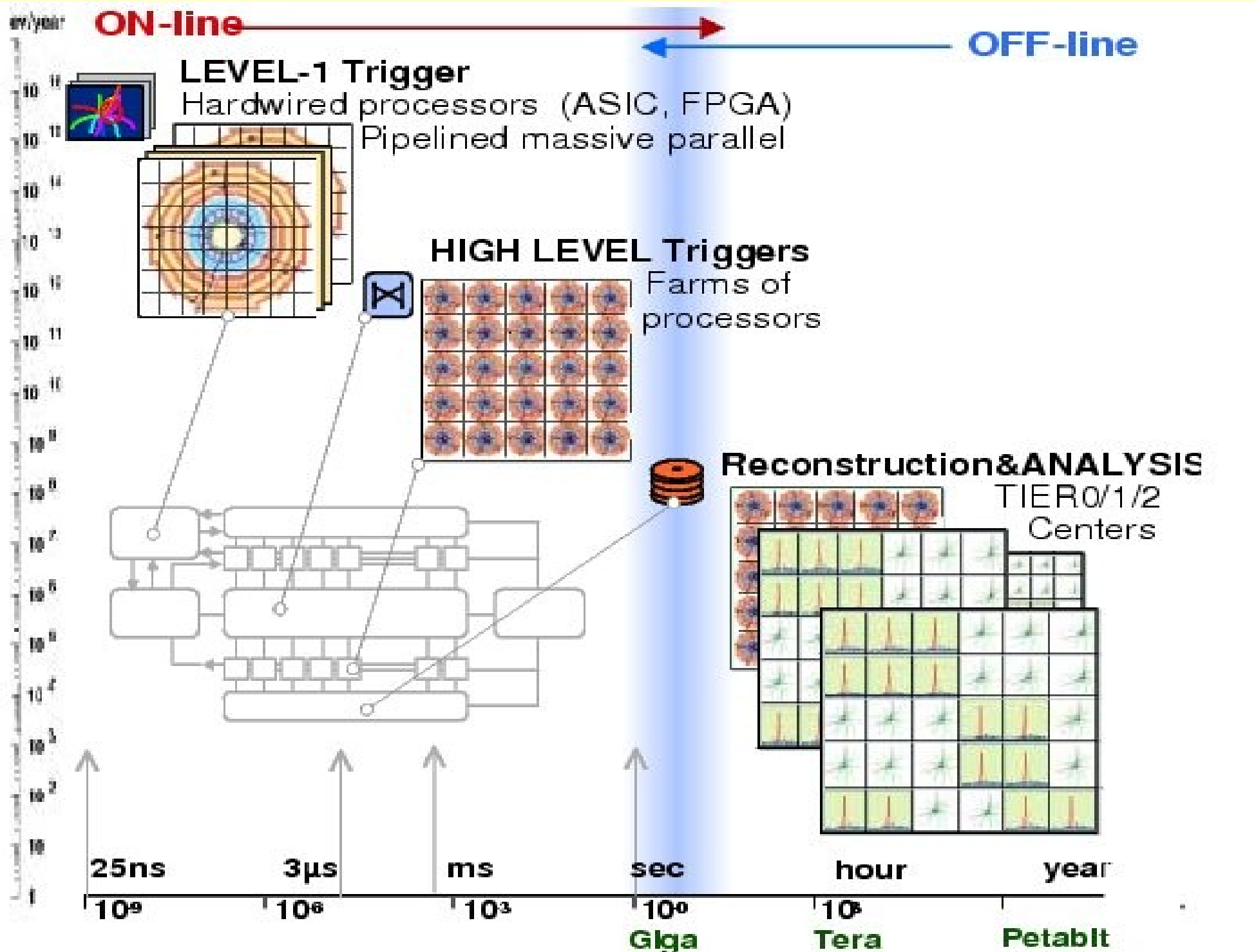
Selezione (Trigger)



Selection of 1 in 10,000,000,000,000

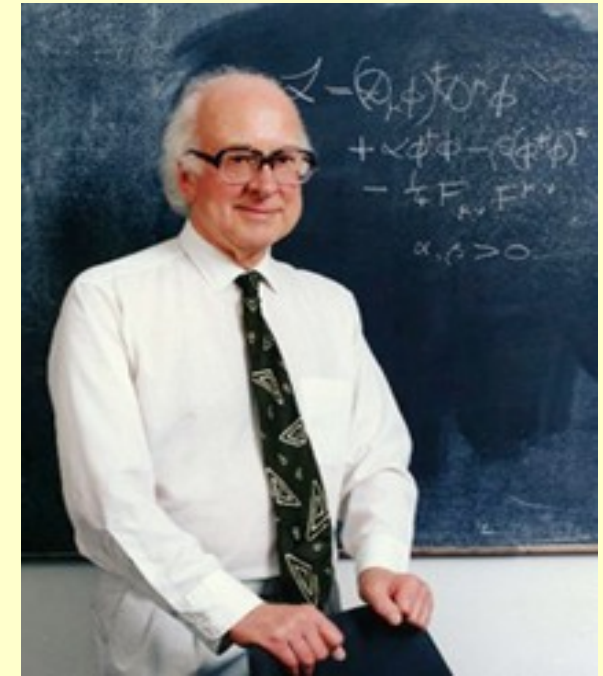
Trigger

- Ogni 25 ns arriva una nuova interazione: 40'000'000 al secondo
- Io ne posso salvare solo 100/200
- e comunque la maggior parte degli altri non sono interessanti...
- Devo capire (velocemente) se un evento e' interessante e vale la pena salvarlo oppure no
- Cerco e , μ , j , MET, ... (o combinazioni) con alta energia
- Se li vedo, allora registro l'evento per l'analisi successiva

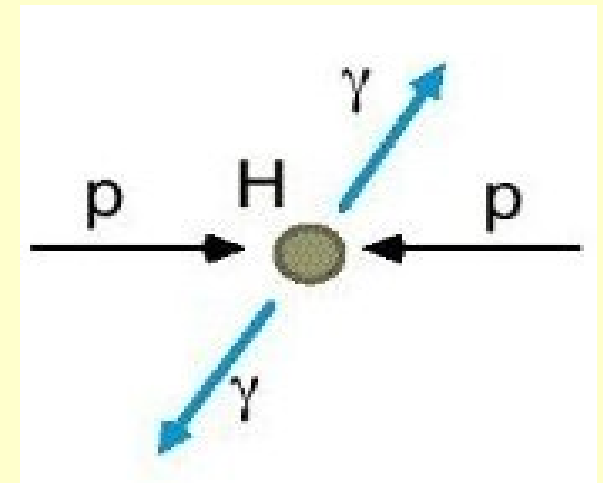
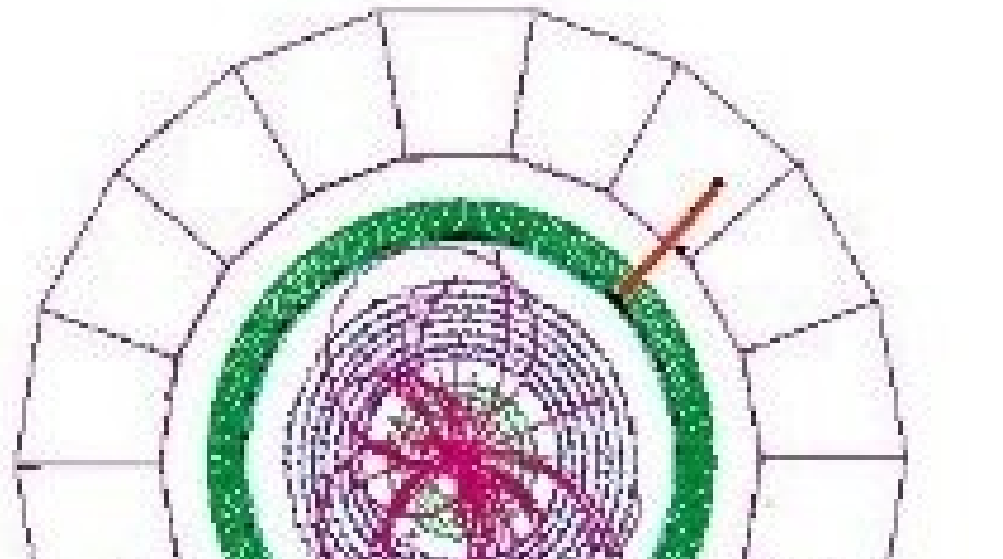


Cosa spero di vedere?

- In primis: l'Higgs!
- Come lo vedo?
- Prodotto da interazione p-p
- Osservo i prodotti del decadimento
- Diversi canali possibili

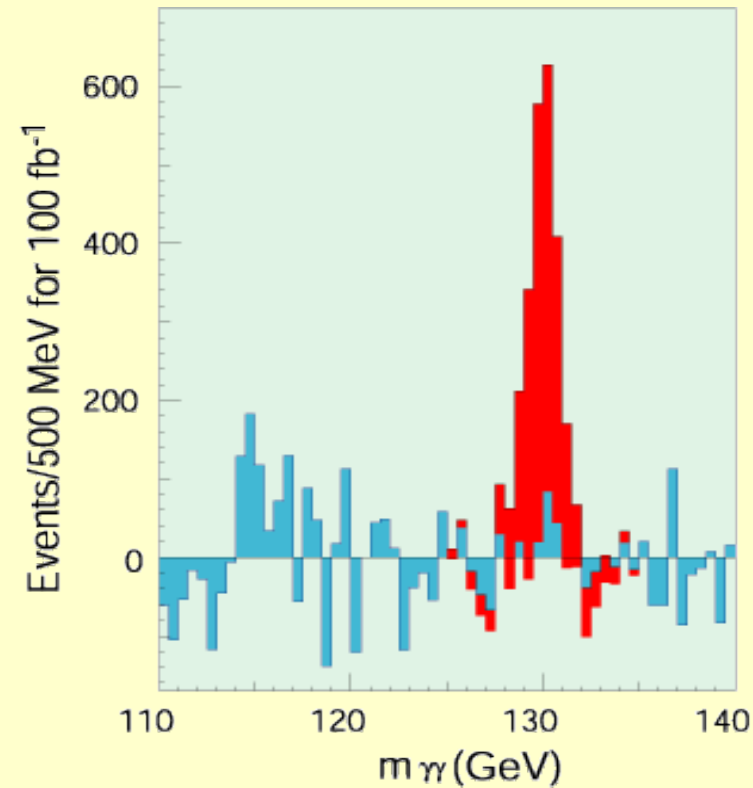
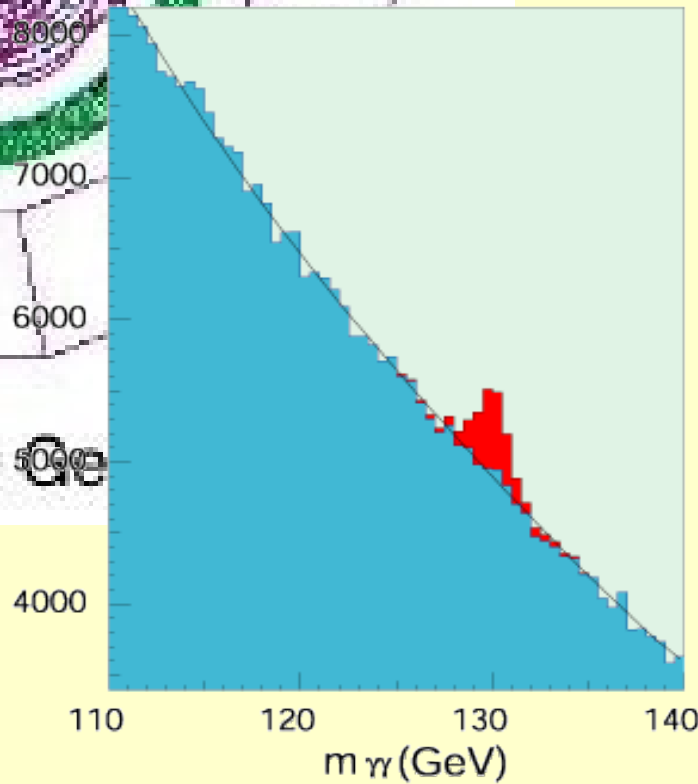


Esempio: $H \rightarrow \gamma\gamma$

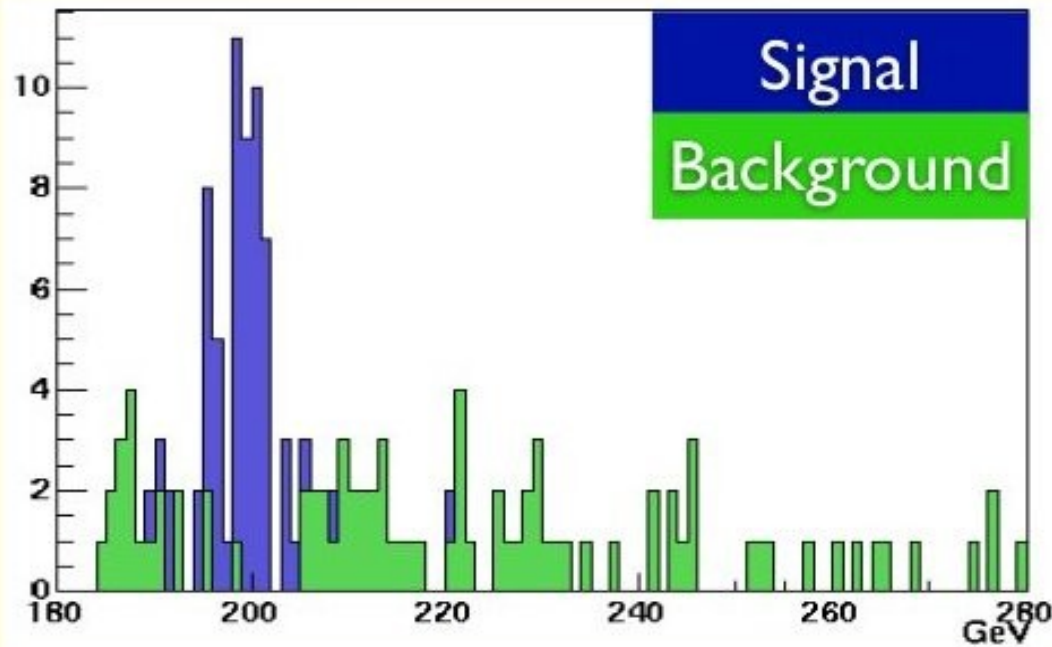
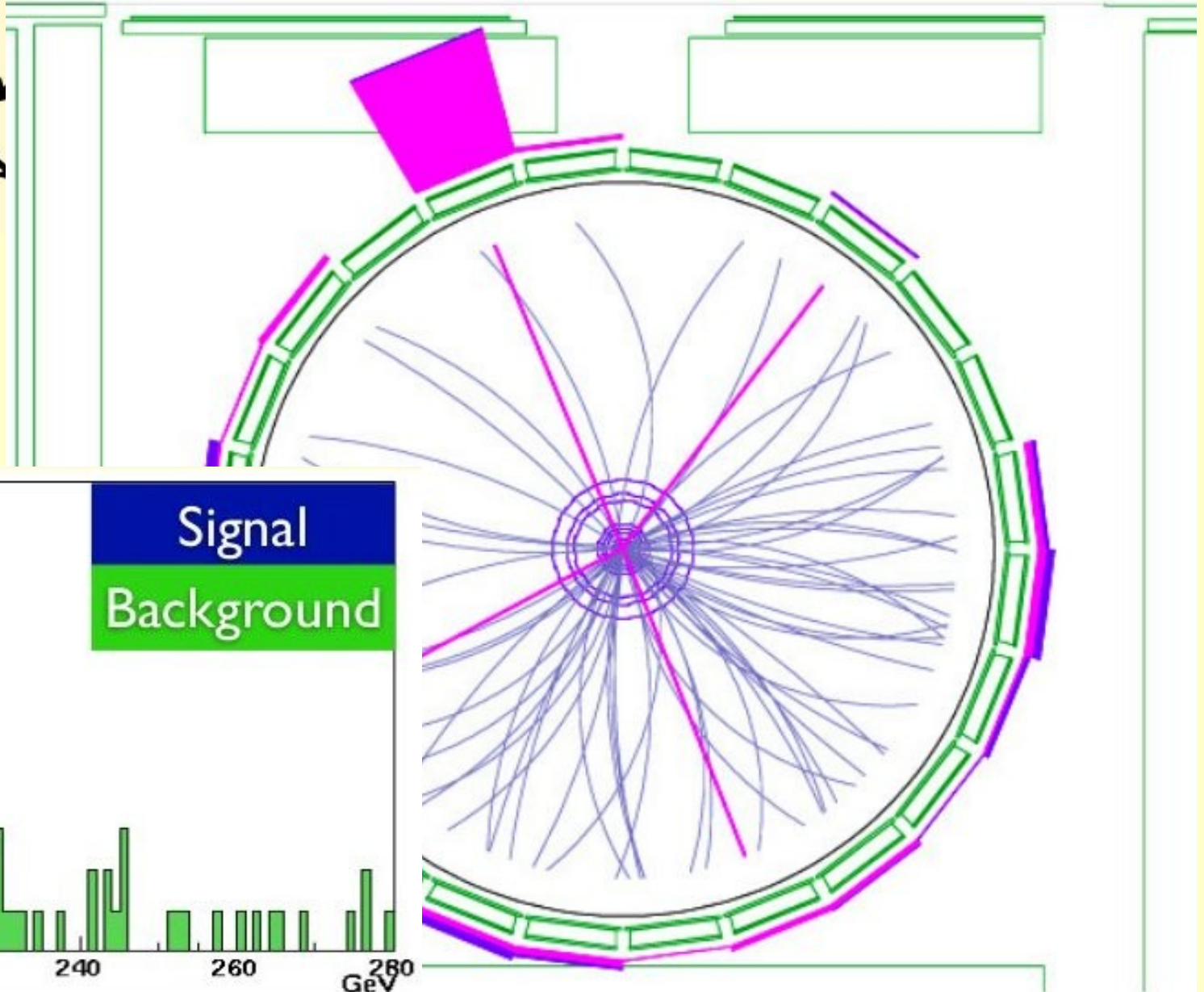
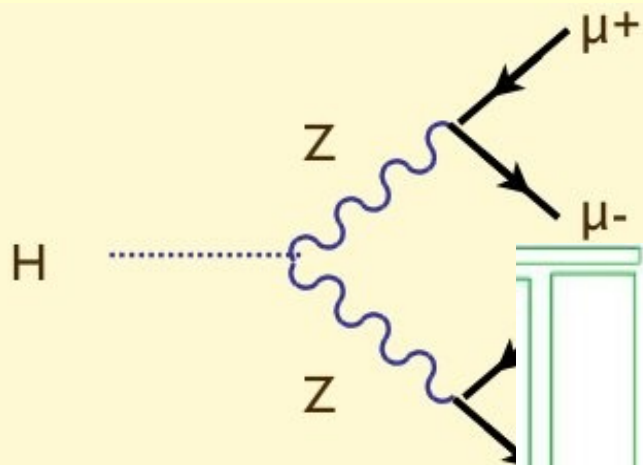


$M_{Higgs} = 125 \text{ GeV}$

Events/500 MeV for 100 fb⁻¹



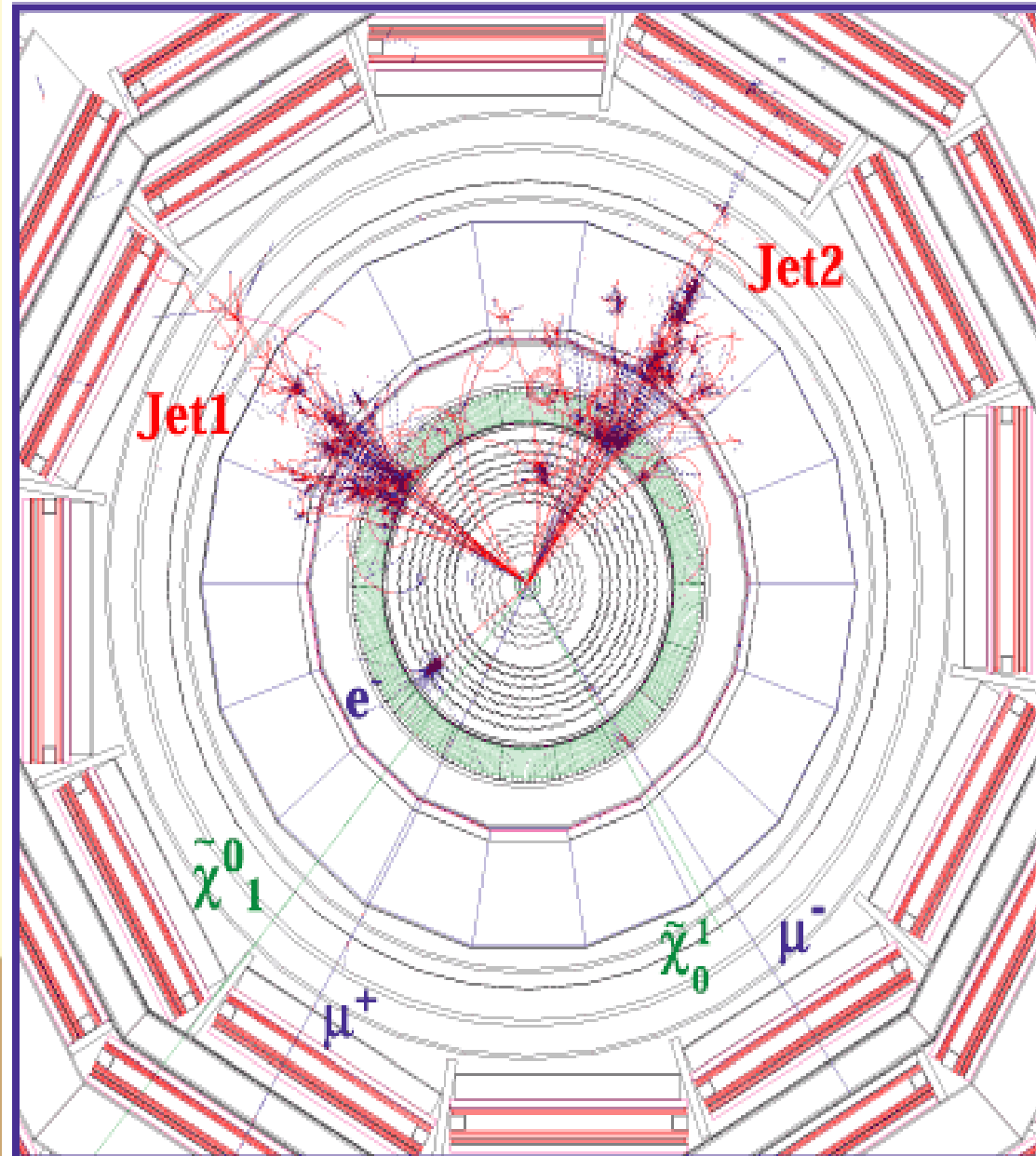
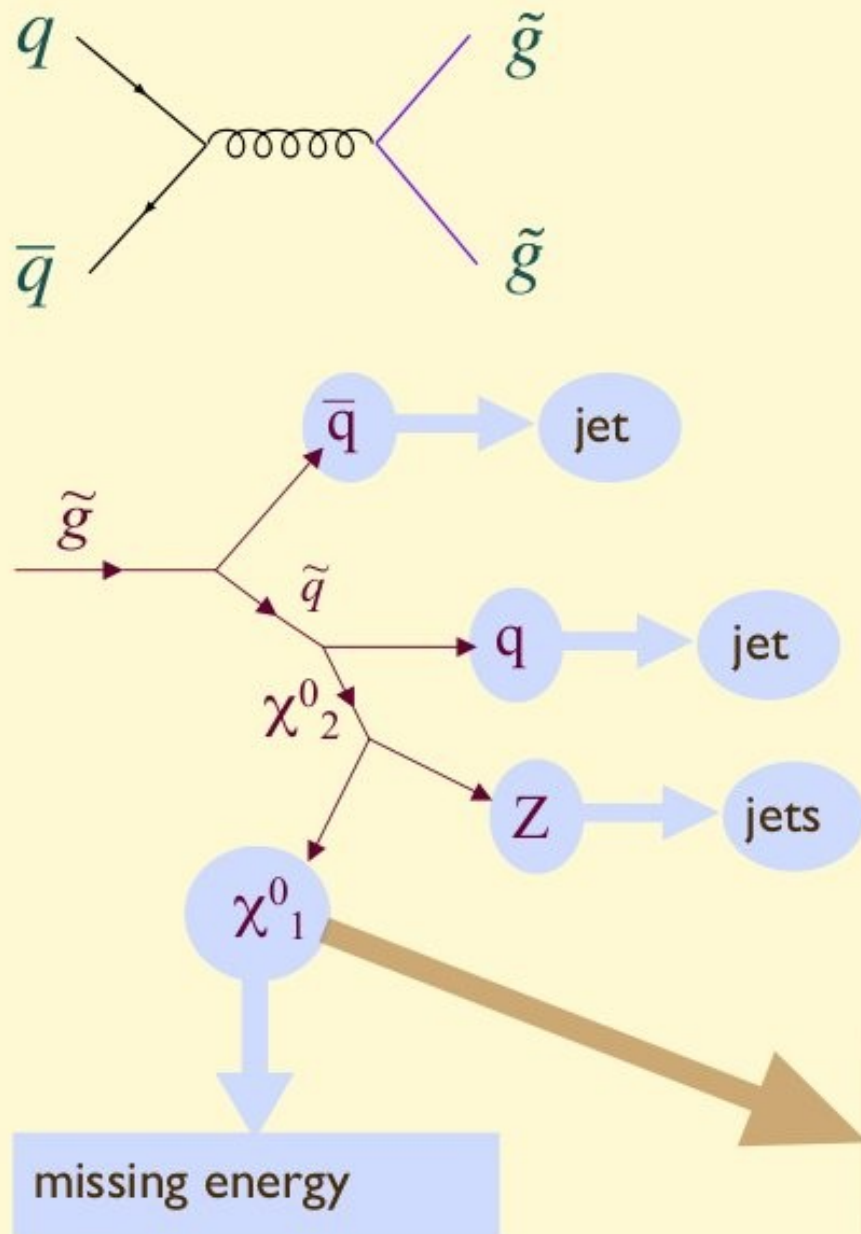
$$H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$$



Che altro? SuperSimmetria

- Nuova teoria che sistema alcuni dei problema del modello standard
- Prezzo da pagare: per ogni particella che conosciamo, esiste un partner supersimmetrico
 - Elettrone -> selettrone
 - Quark -> squark
 - Fotone -> fotino ...
- Abbiamo i nomi, ma non le abbiamo mai viste!
- Potremmo essere in grado di vederle a LHC
- La sparticella piu' leggera e' stabile e interagisce poco
- Candidato Materia Oscura

Esempio di Susy

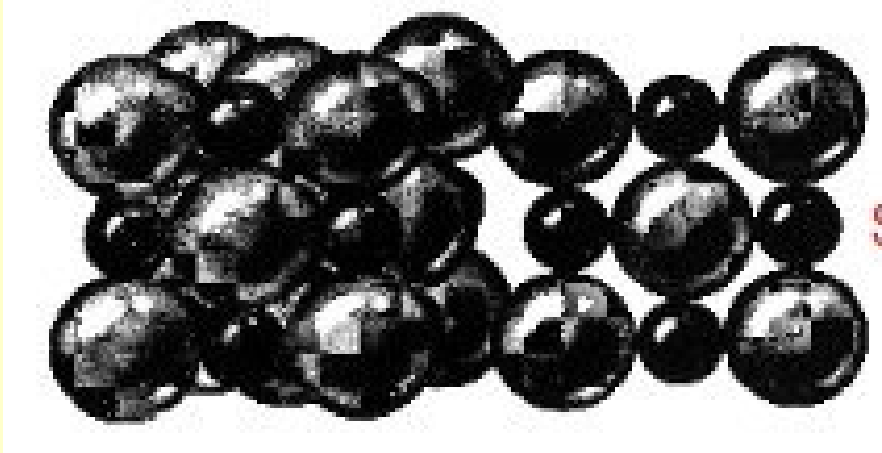


- Guardando dentro il piu' grande microscopio del mondo
- Potremmo vedere l'universo!

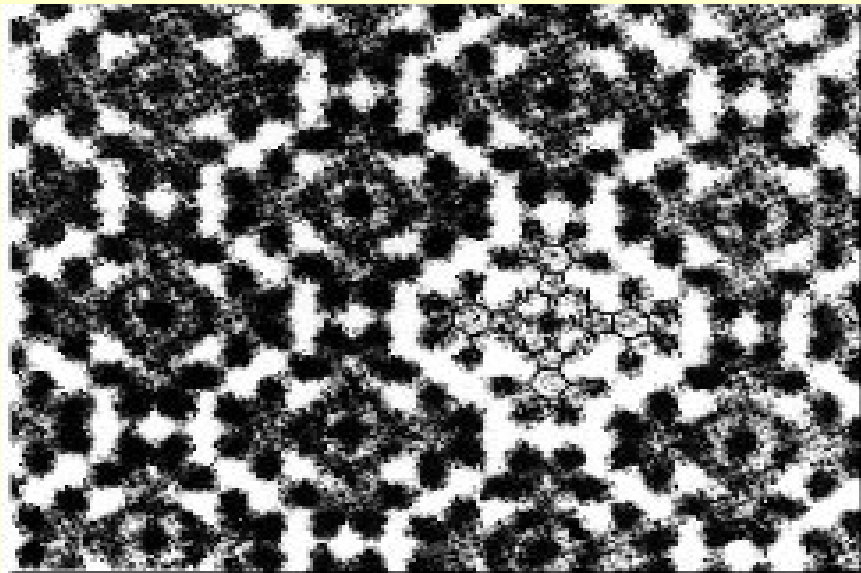


Backup

Vedere...



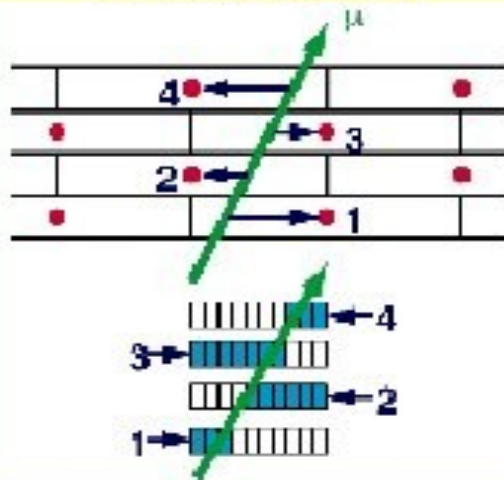
- Sale da cucina NaCl
- Modello teorico
- E' giusto?



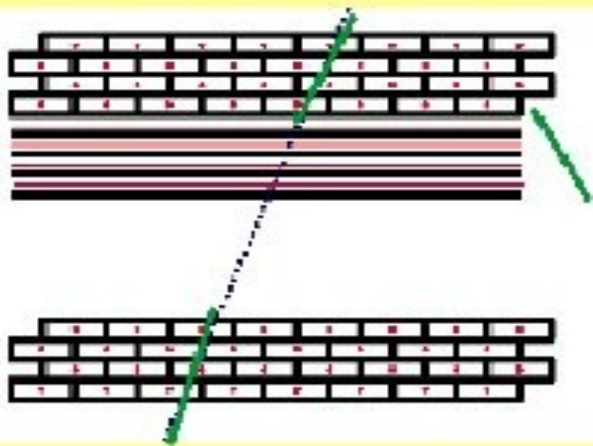
- Riesco a “vederlo”
- Con microscopio elettronico
- Modello e' giusto!

Trigger Muoni

Drift Tubes

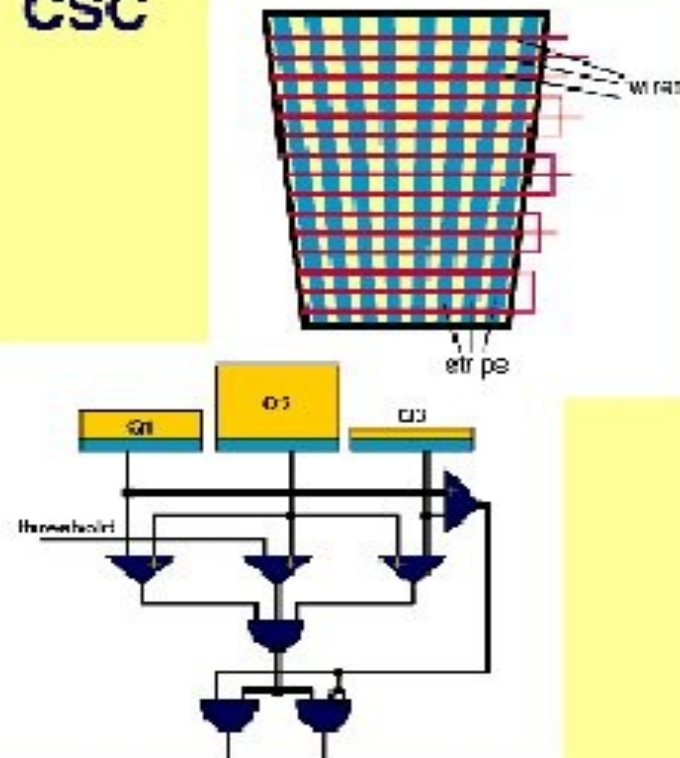


Meantimers recognize tracks and form vector / quartet.

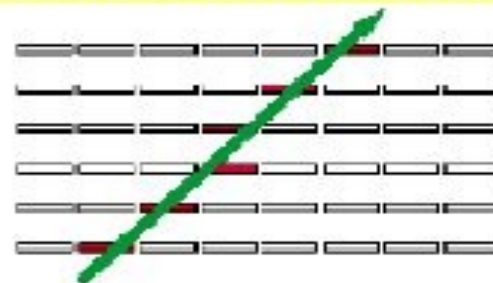


Correlator combines them into one vector / station.

CSC

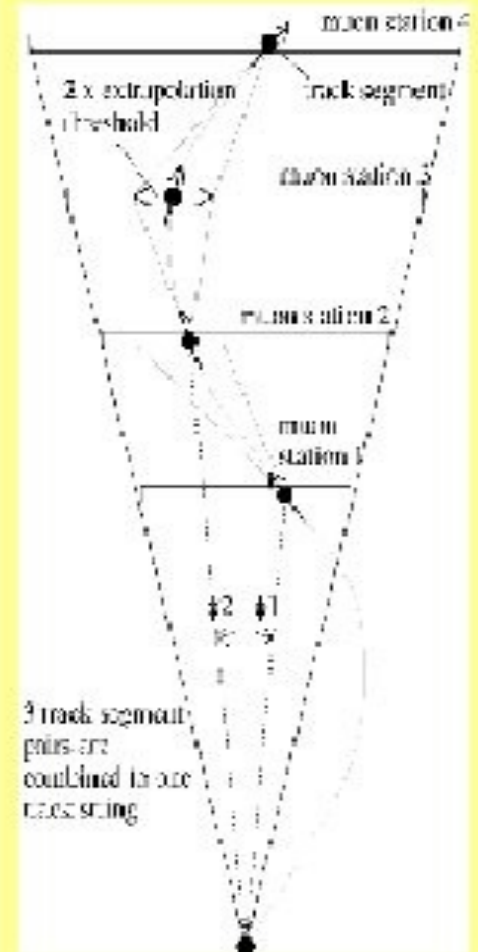


Comparators give 1/2 strip resol.



Hit strips of 6 layers form a vector.

Track Finder



3 track segment priors are combined to one track string

combines vectors, forms a track, assigns p_t value.

Strumenti e osservabili

