The Large Hadron Collider LHC

European Masterclasses 2007

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Large Hadron Collider

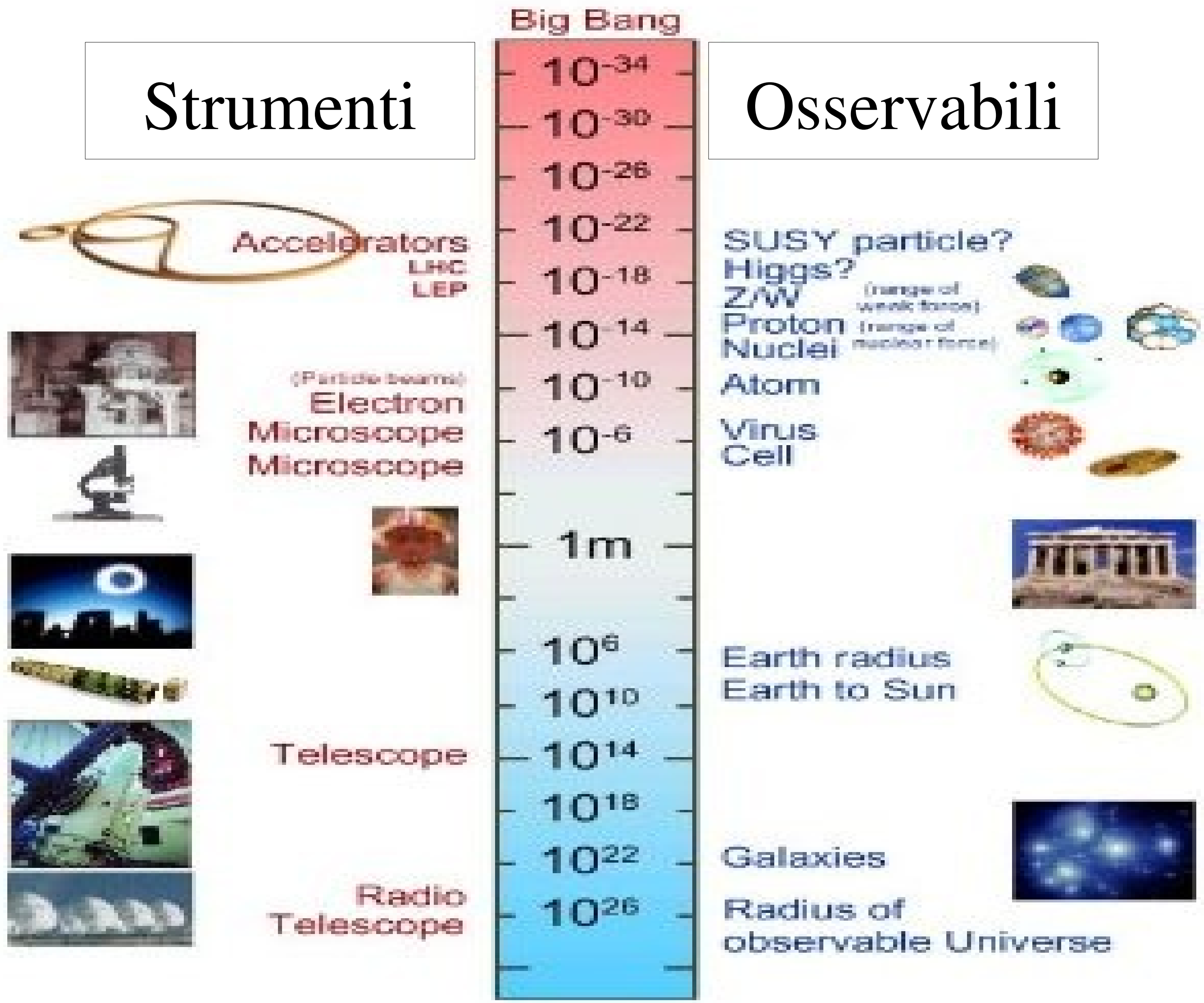
- Perche' lo facciamo
- Cos'e'
- Cosa guardiamo
- Cosa speriamo di vedere

Come sono fatte le cose?

- Bisogna guardare: con lo strumento giusto
- La lunghezza d'onda λ della sonda deve essere piu' piccola dell'oggetto da vedere

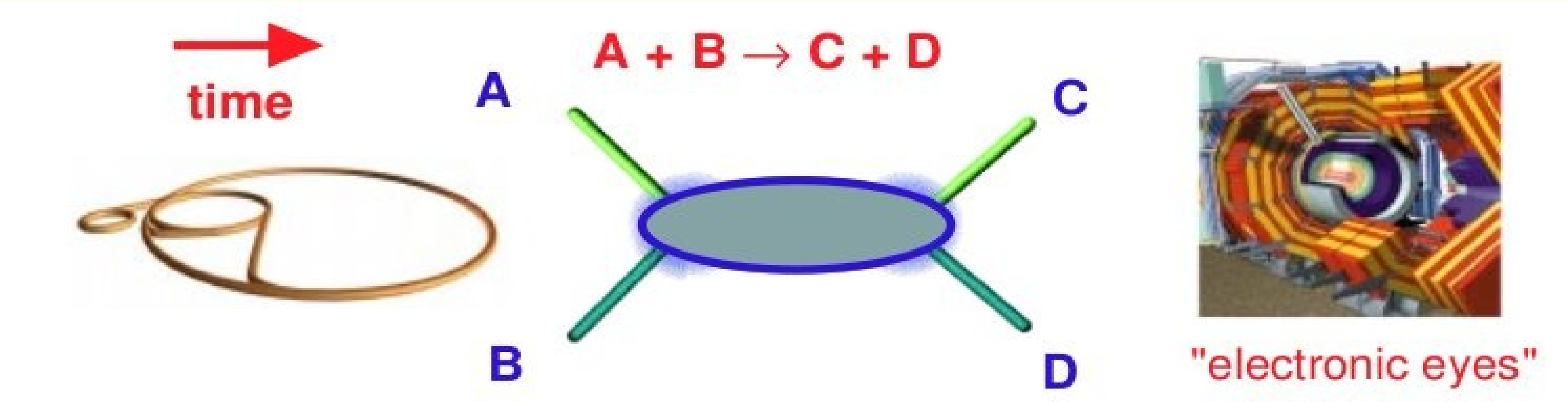
- $\lambda \propto 1/E$
  - Cellula ($d \sim 10\ \mu m = 10^{-5}$ m): luce visibile $E \sim eV$
  - Virus: ($d \sim 10$ nm$=10^{-8}$ m): microscopio elettronico $E \sim keV$
  - Protone: ($d \sim 1$ fm$=10^{-15}$ m): acceleratore di particelle $E \sim GeV$
  - Quark: ($d < 10^{-18}$ m): LHC $E \sim 10$ TeV $d \sim 0.0002$ fm

Strumenti e osservabili

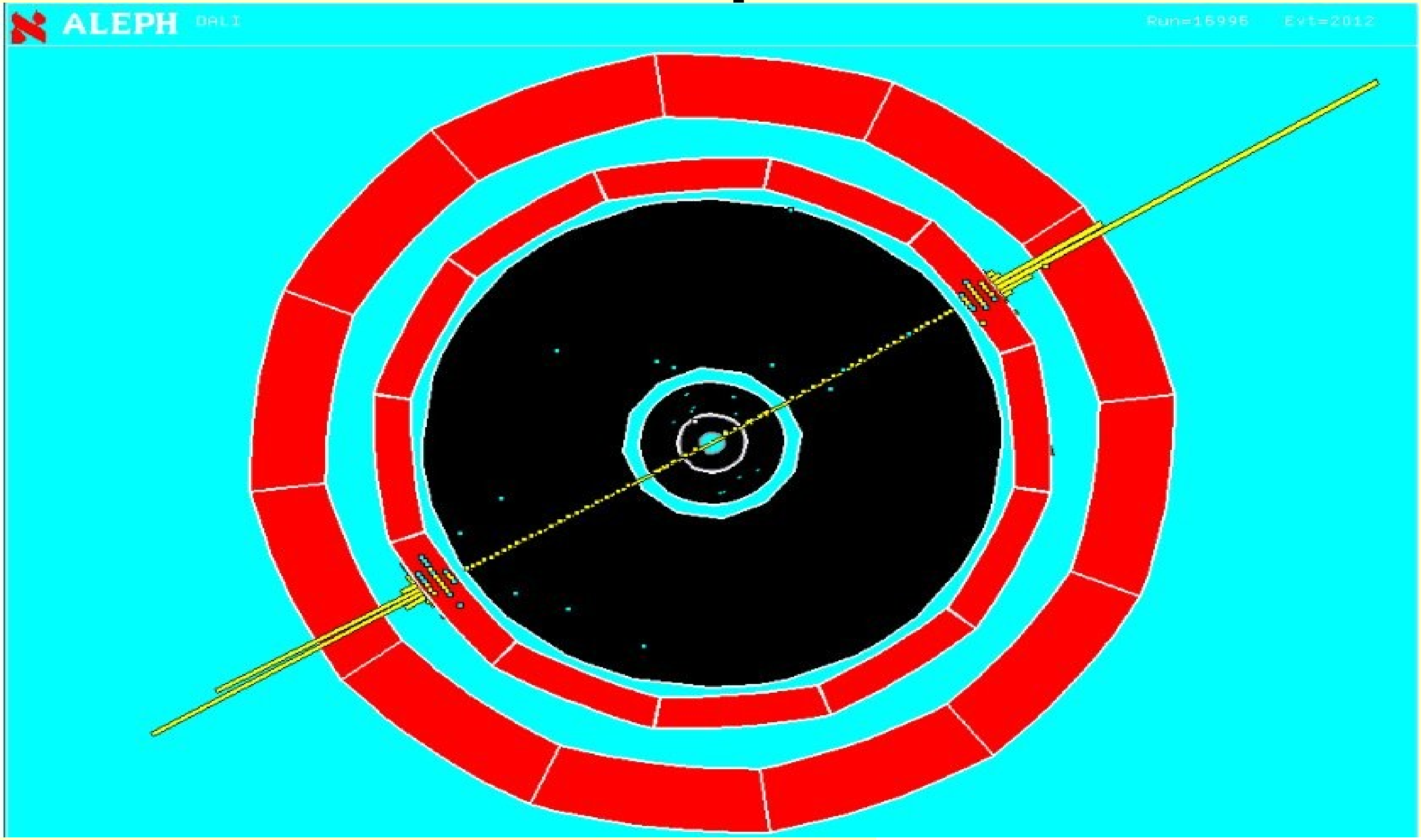


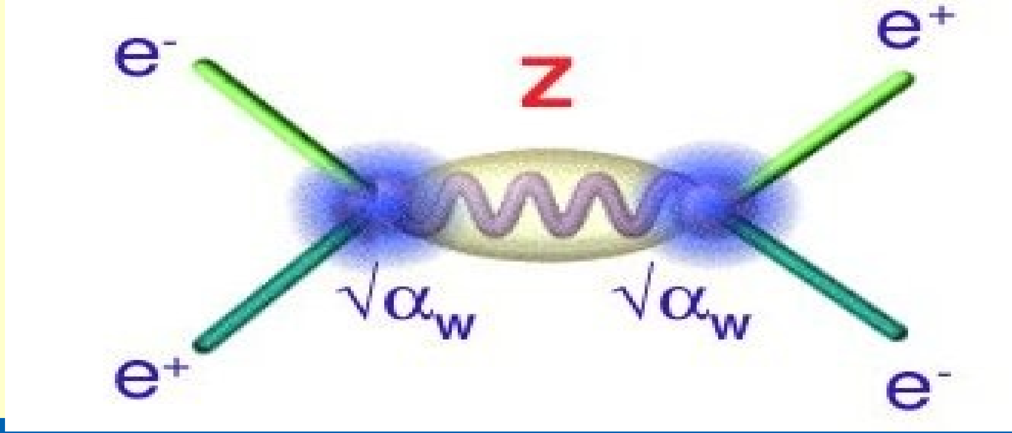
“Vedere” con gli acceleratori

- Non possiamo vedere davvero quello che succede a scale cosi' 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 e' successo nel “blob”

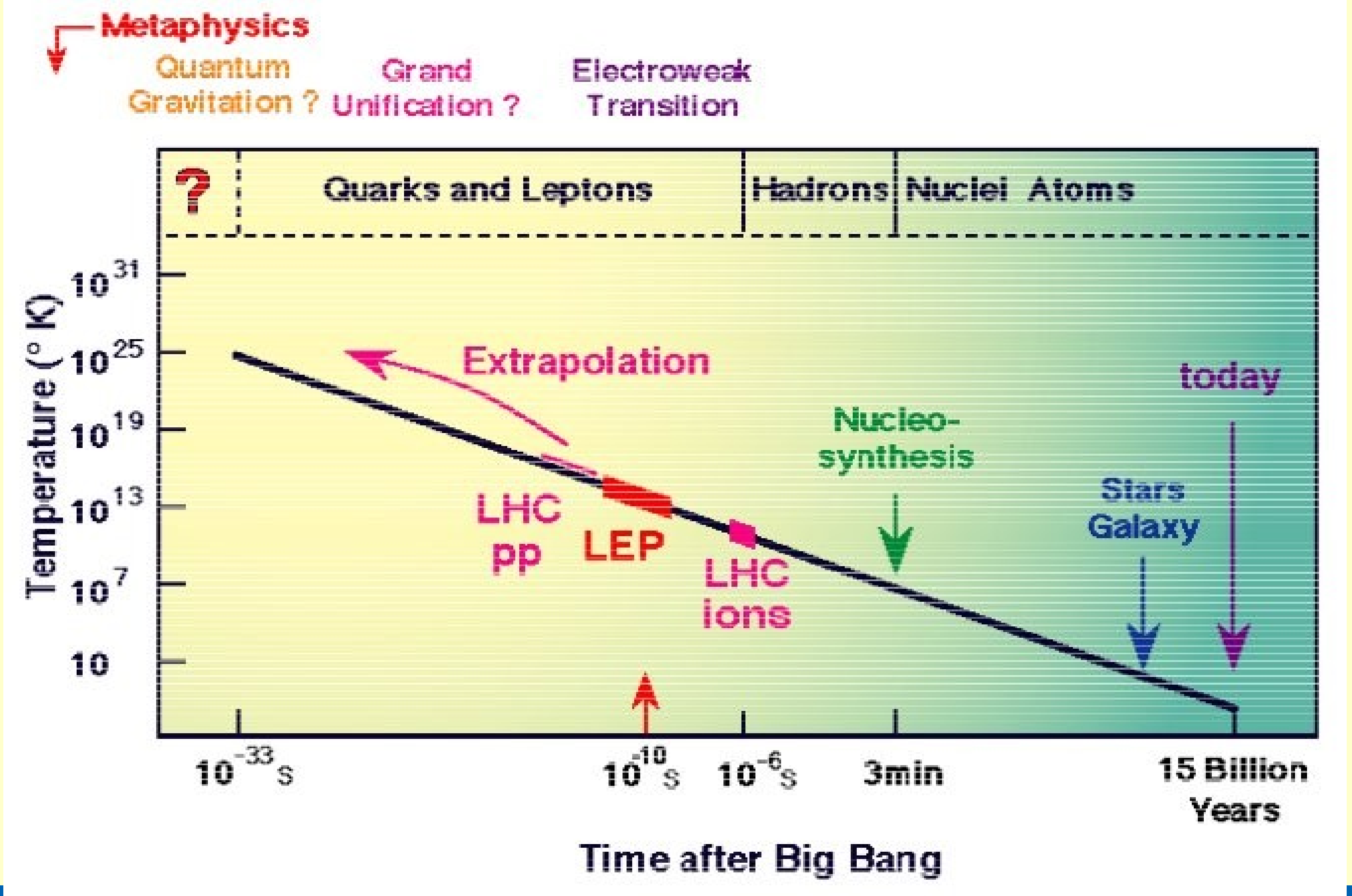


Esempio: Z a LEP

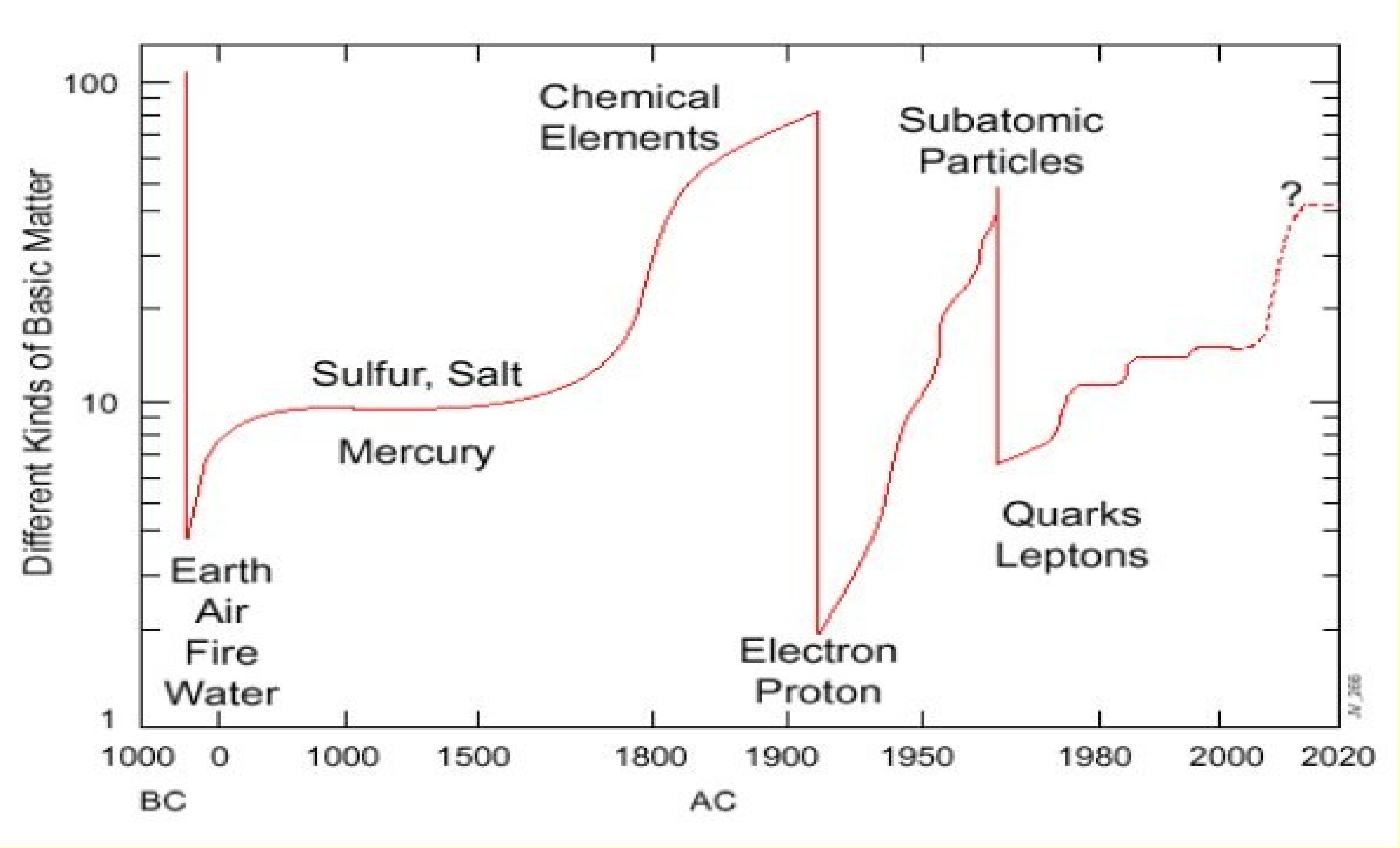




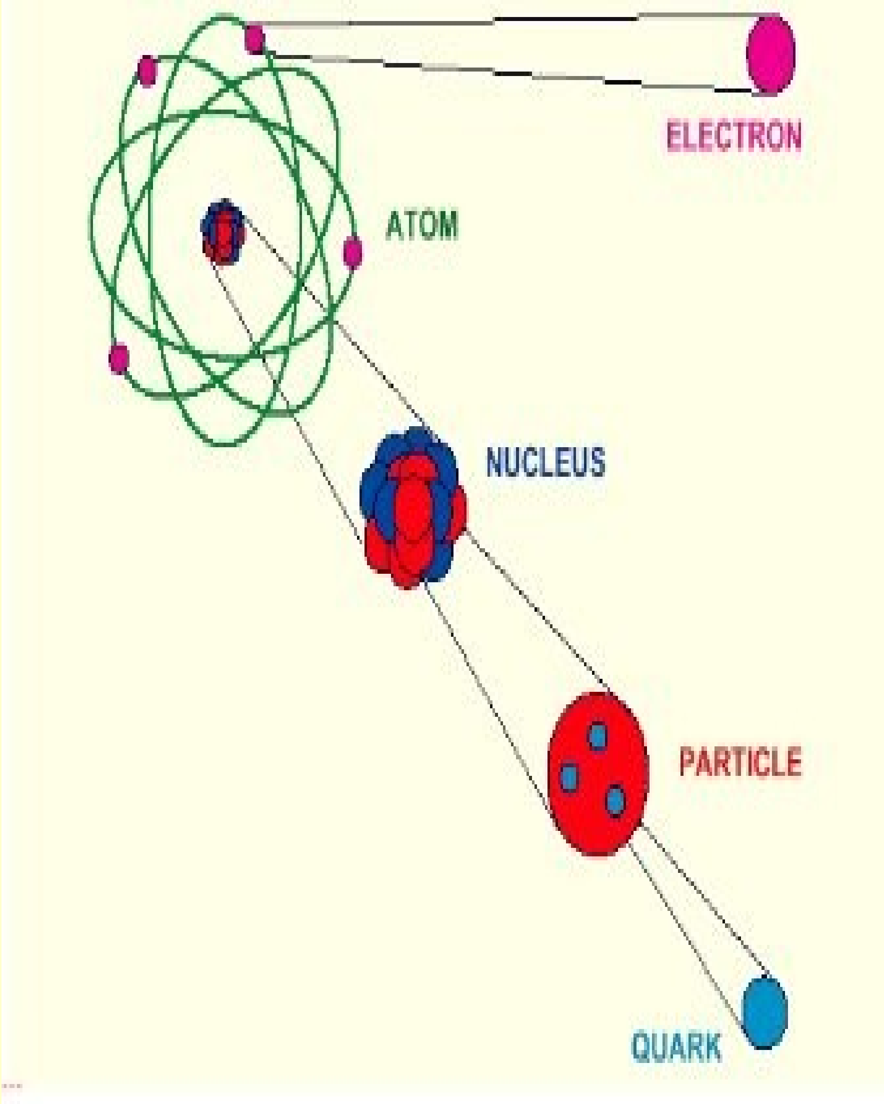
Energia e tempo



Quanti costituenti?

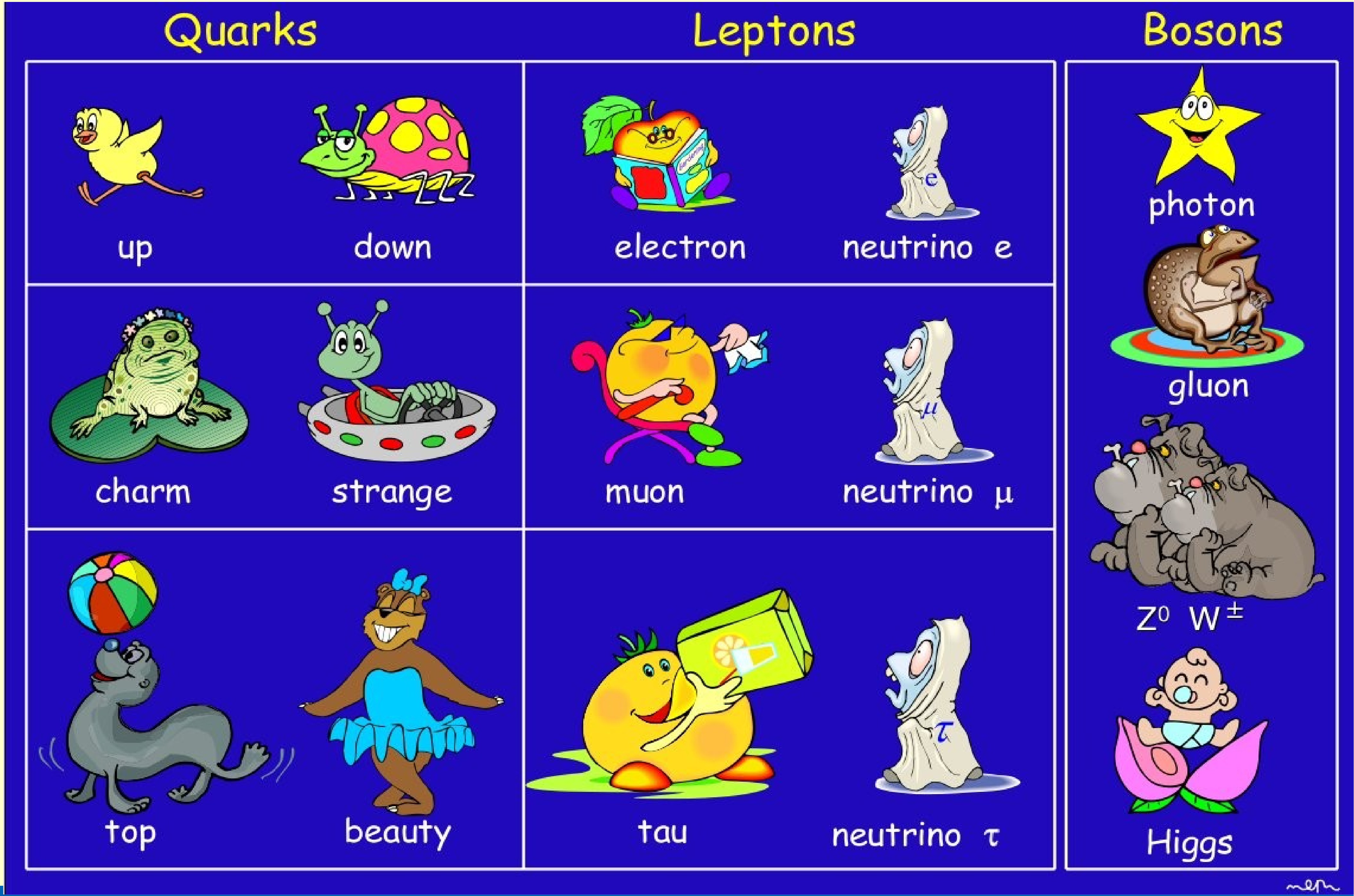


Modello attuale

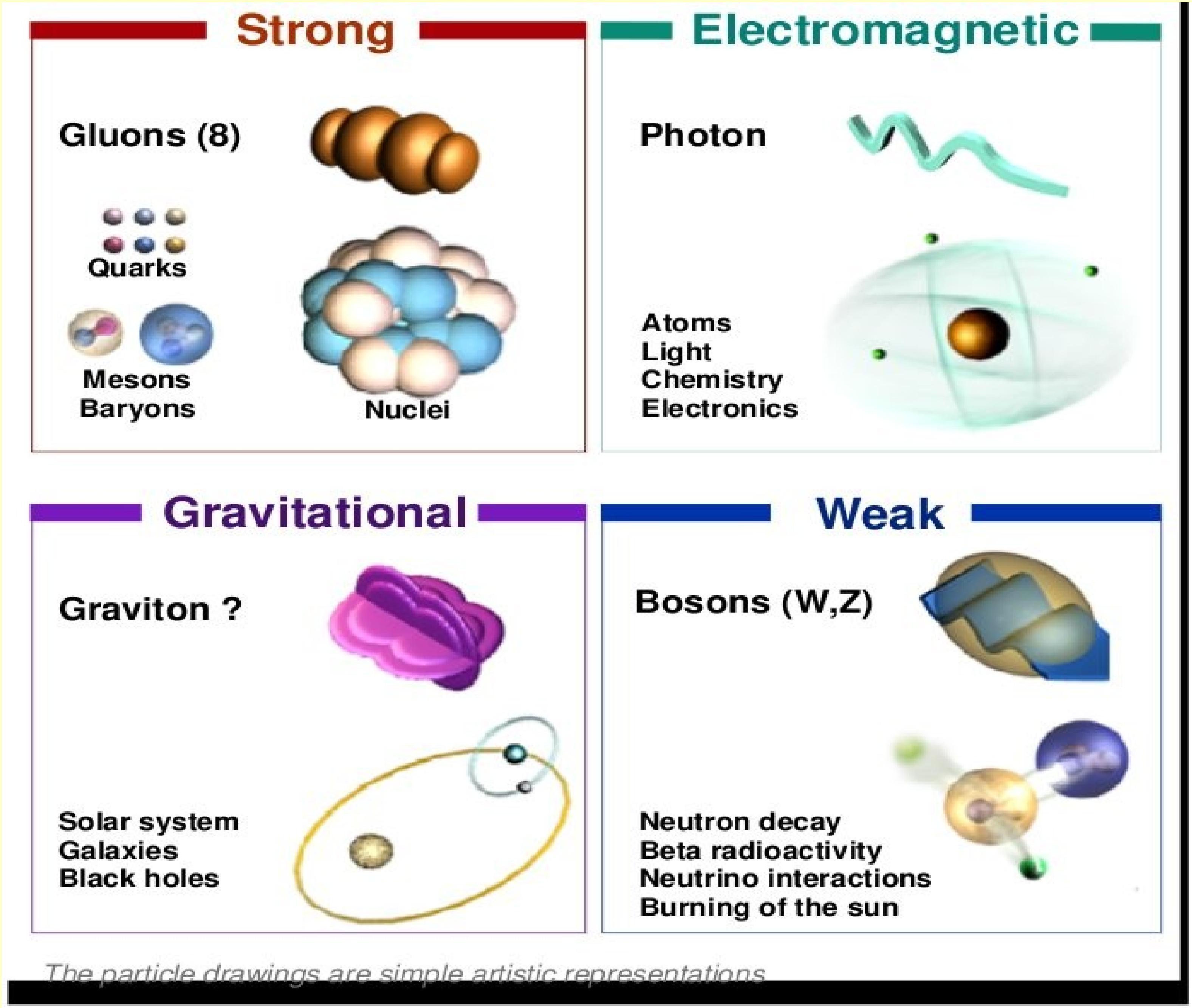


- Atomo: nucleo + elettrone
- Nucleo: protoni + neutroni (nucleoni)
- Nucleoni: quark
- Quark: ???

Particelle

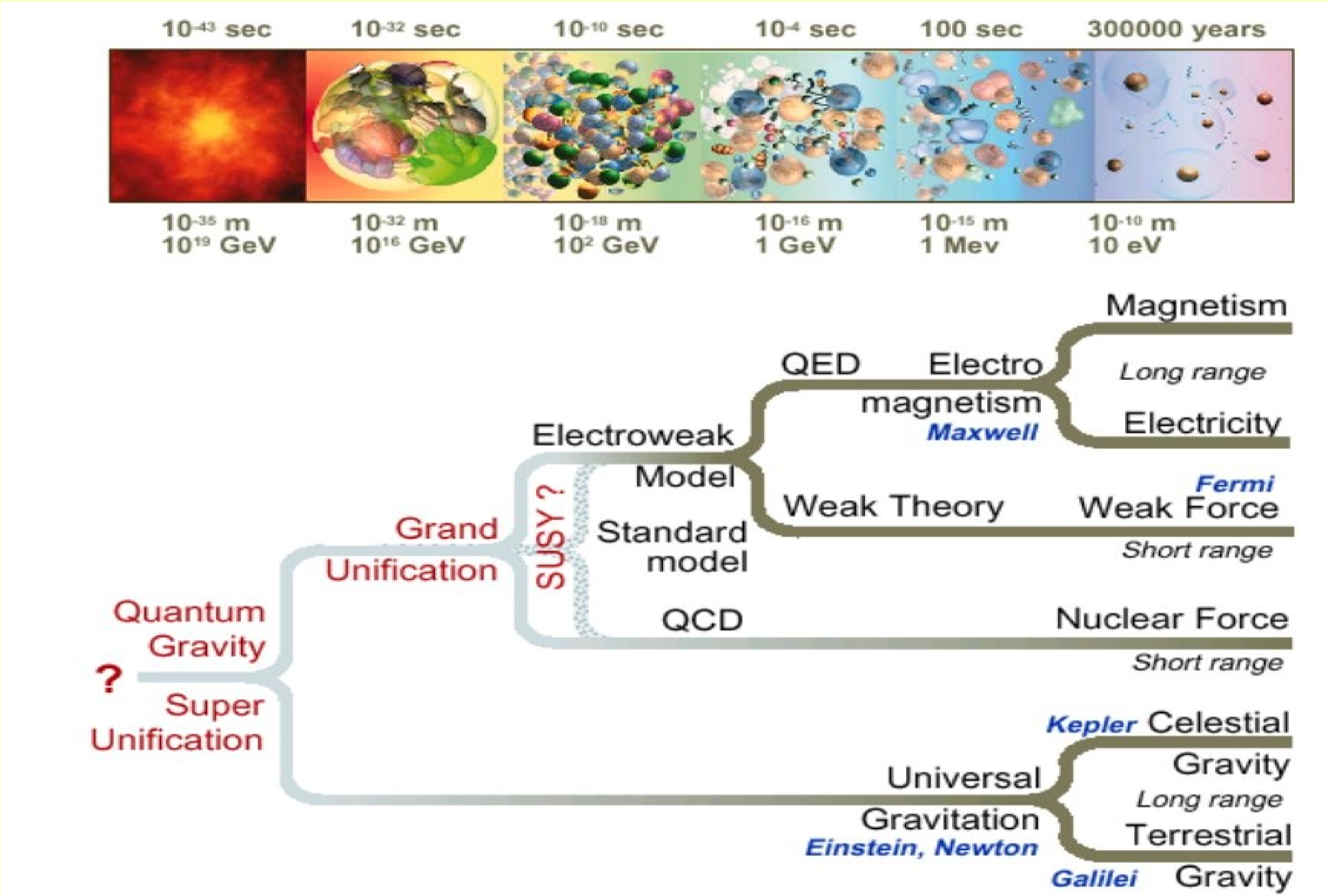

Quarks
Leptons
Bosons
up
down
electron
neutrino e
photon
charm
strange
muon
neutrino μ
gluon
top
beauty
tau
neutrino τ
Z0 W±
Higgs

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

$$\mathcal{L}_{SM} =$$

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu$$

$$-\partial_\nu W^+_\mu\partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^-$$

$$-M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h\left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h$$

$$-igc_w\left[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)\right]$$

$$-igs_w\left[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)\right]$$

$$-\frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2\left(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu\right) + g^2 s_w^2\left(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu\right)$$

$$+g^2 s_w c_w\left[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu\right] - g\alpha\left[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right]$$

$$-\frac{1}{8}g^2\alpha_h\left[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H$$

$$-\frac{1}{2}ig\left[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right] + \frac{1}{2}g\left[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right]$$

$$+\frac{1}{2}g\frac{1}{c_w}Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^-$$

$$-\phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu\left[H^2+(\phi^0)^2+2\phi^+\phi^-\right] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2$$

$$+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+)$$

$$+\frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda$$

$$-\bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu\left[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right]$$

$$+\frac{ig}{4c_w}Z^0_\mu\left[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2-1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)\right]$$

$$+\frac{ig}{2\sqrt{2}}W^+_\mu\left[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right] + \frac{ig}{2\sqrt{2}}W^-_\mu\left[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right]$$

$$+\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}\left[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)\right] - \frac{g}{2}\frac{m_e^\lambda}{M}\left[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)\right]$$

$$+\frac{ig}{2M\sqrt{2}}\phi^+\left[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right] + \frac{ig}{2M\sqrt{2}}\phi^-\left[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right]$$

$$-\frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^-$$

$$+\bar{X}^0\left(\partial^2 - \frac{M^2}{c_w^2}\right)X^0 + \bar{Y}\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+)$$

$$+igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H$$

$$+\frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-]$$

$$+\frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

M. Veltman “Diagrammatica”

Ma allora...

- Abbiamo le particelle, abbiamo le forze, abbiamo l'equazione: sappiamo gia' tutto!
- Molte caratteristiche sono apparentemente arbitrarie:
  - Perche' 3 famiglie di particelle (e non 4 o 5 o 87?)
- 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'.

Questioni aperte

- Le particelle elementari (quark, elettroni) potrebbero avere una struttura
- Ci sono davvero solo 3 famiglie di quark e leptoni?
- Quale e' l'origine delle masse delle particelle
  - Perche' sono cosi' diverse?
- Ci sono altre particelle che non abbiamo ancora visto?
  - Materia oscura?
  - SUSY: Supersimmetria?
  - 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

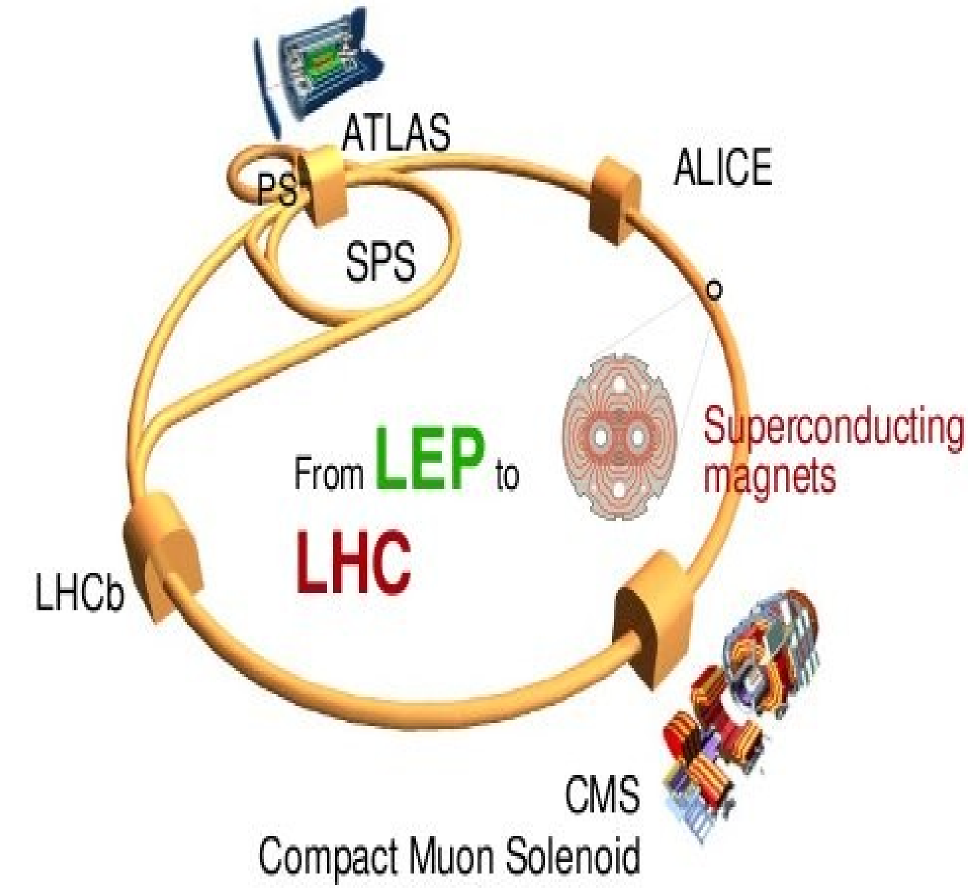
CMS ATLAS ALICE LHCb

CERN

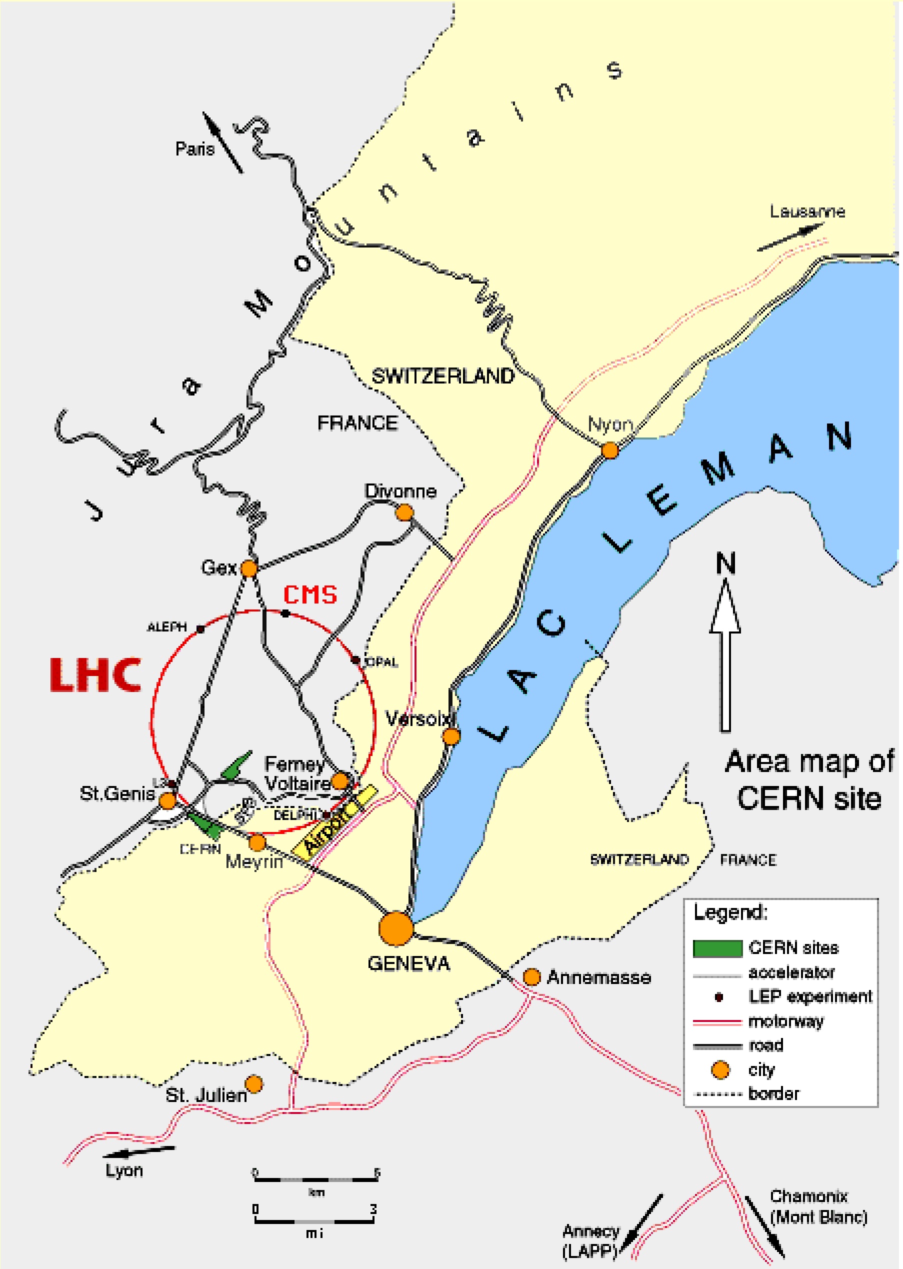
- Centro Europeo per la Ricerca Nucleare
- Organizzazione internazionale fondata nel 1954 (Italia e' un membro fondatore)
- Vicino a Ginevra (Svizzera) sul confine con la Francia
- 19 stati membri (+ osservatori)
- Dedicato a ricerca di base su elementi costitutivi della materia e le loro interazioni fondamentali
- www.cern.ch (WWW inventato al CERN!)

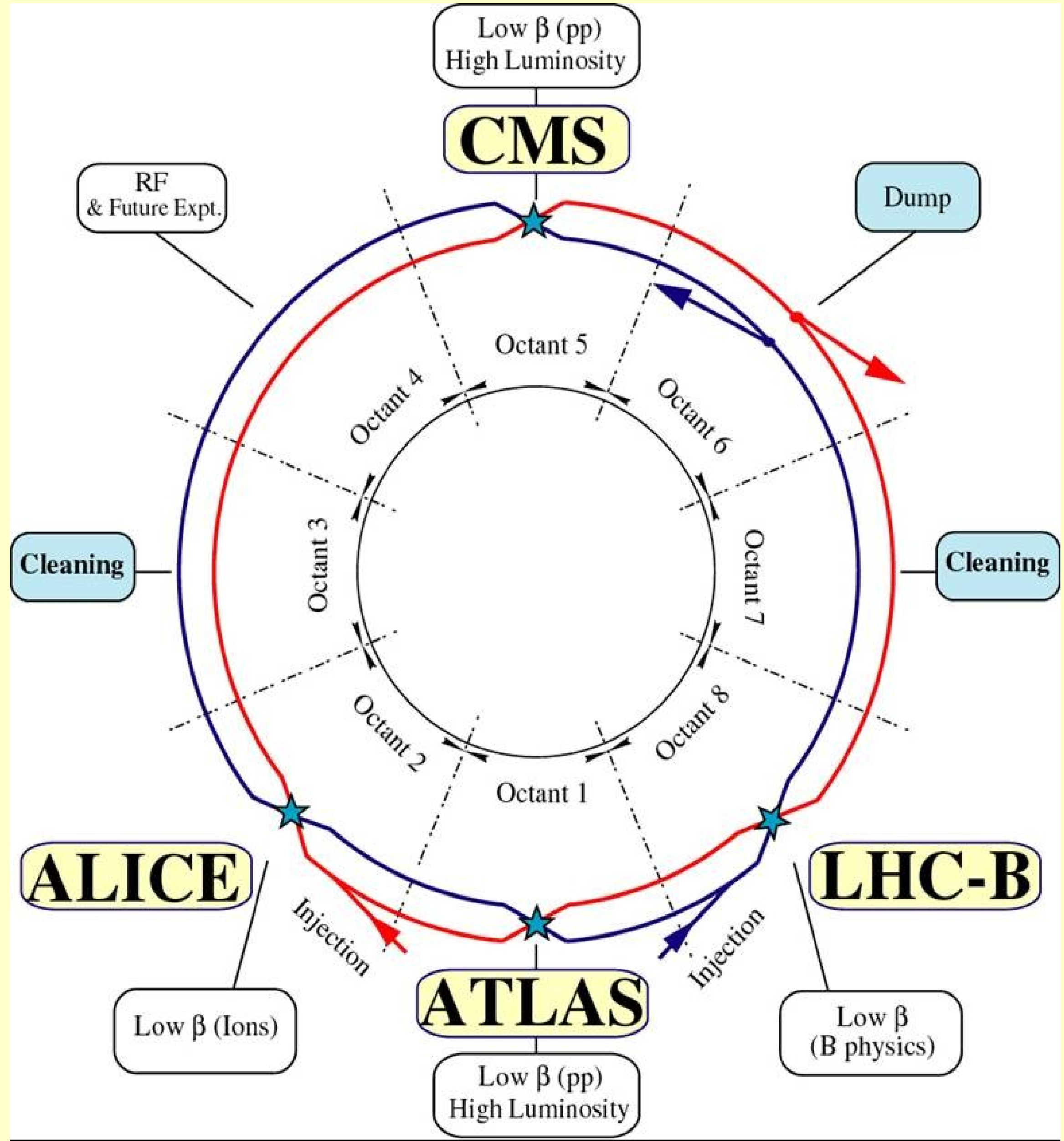
Acceleratore

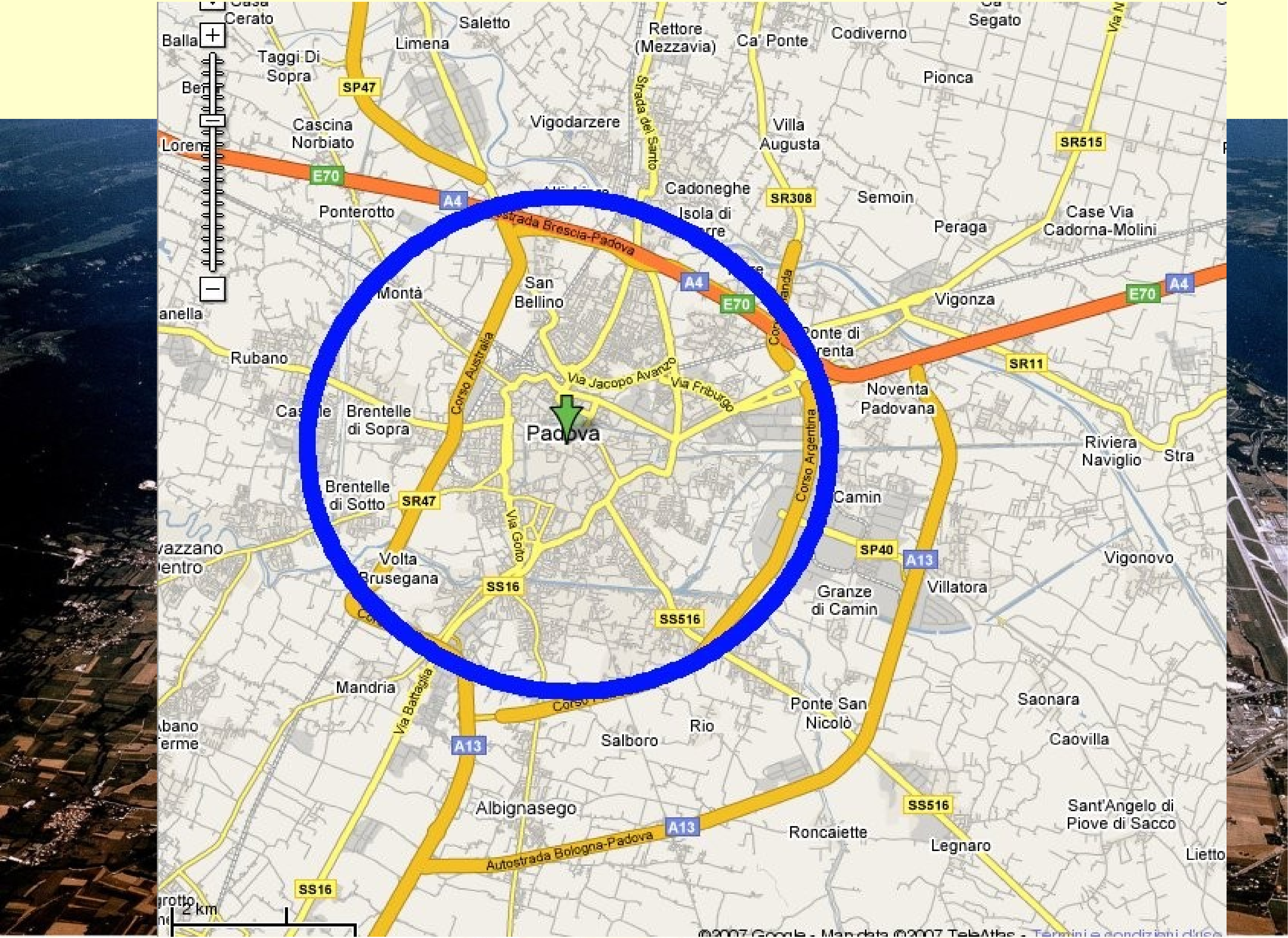
- Energia piu' grande possibile
  - Limite: dimensione tunnel campo magnetico dipoli
- Luminosita' piu' alta possibile



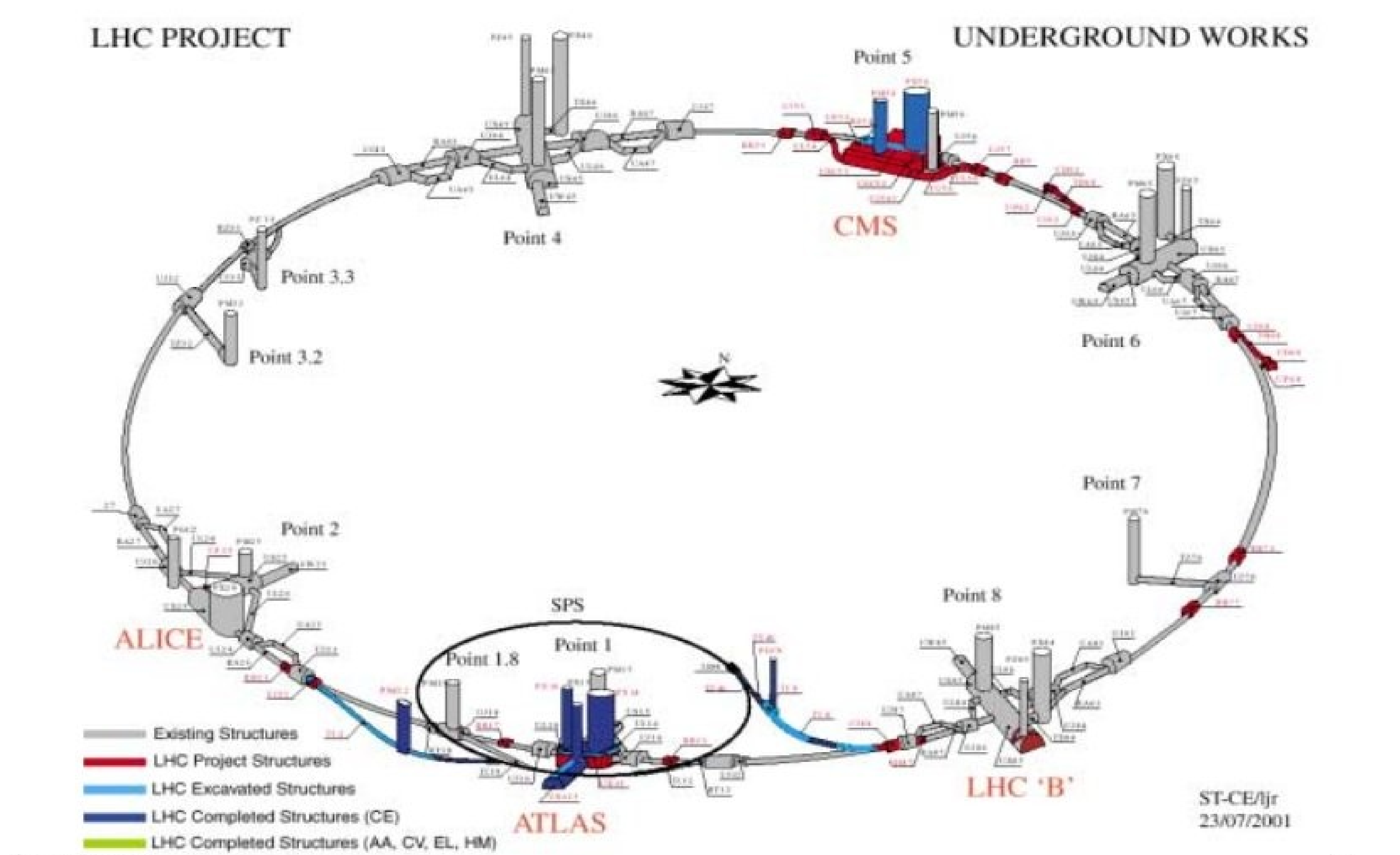
	Beams	Energy GeV	Luminosity
LEP	e+ e-	200	$10^{32}\ cm^{-2}s^{-1}$
LHC	p p	14000	10^{34}
	Pb Pb	1,312,000	10^{27}


Paris
Jura Mountains
Lausanne
SWITZERLAND
FRANCE
Nyon
Divonne
Gex
CMS
ALEPH
LHC
OPAL
Versoix
LAC LEMAN
N
Area map of CERN site
Ferney Voltaire
St.Genis
DELPHI
CERN
Meyrin
Airport
SWITZERLAND
FRANCE
GENEVA
Annemasse
Legend:
CERN sites
accelerator
LEP experiment
motorway
road
city
border
St. Julien
Lyon
km
mi
Annecy (LAPP)
Chamonix (Mont Blanc)


Low β (pp) High Luminosity
CMS
RF & Future Expt.
Dump
Octant 5
Octant 4
Octant 6
Cleaning
Octant 3
Octant 7
Cleaning
Octant 2
Octant 8
Octant 1
ALICE
Injection
Injection
LHC-B
Low β (Ions)
ATLAS
Low β (B physics)
Low β (pp) High Luminosity

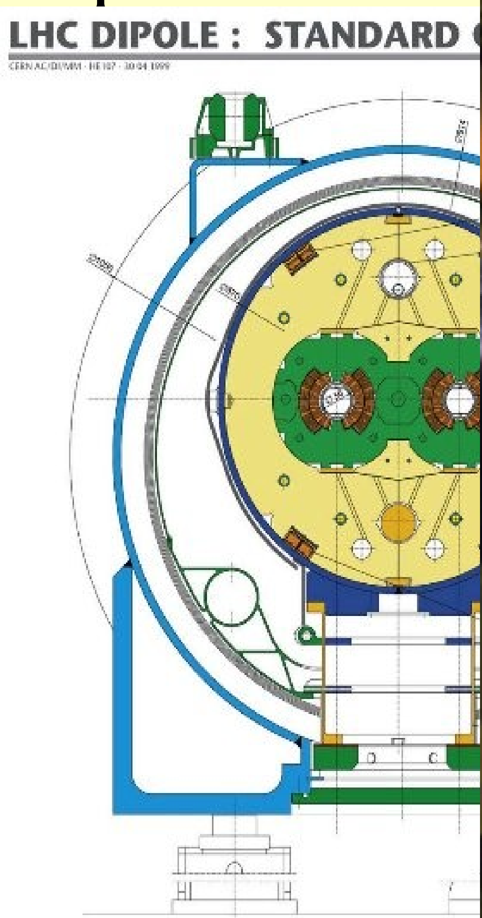

Cerato
Balla
Saletto
Limena
Taggi Di Sopra
SP47
Rettore (Mezzavia)
Ca' Ponte
Codiverno
Segato
Pionca
Cascina Norbiato
Vigodarzere
Strada del Santo
Villa Augusta
SR515
Lorena
E70
A4
Cadoneghe
SR308
Semoin
Ponterotto
Peraga
Case Via Cadorna-Molini
Autostrada Brescia-Padova
San Bellino
Montà
Vigonza
Rubano
Via Jacopo Avanzo
Via Friburgo
SR11
Noventa Padovana
Brentelle di Sopra
Padova
Corso Australia
Corso Argentina
Riviera Naviglio
Stra
Brentelle di Sotto
SR47
Camin
Via Goito
SP40
A13
Vigonovo
Volta Brusegana
SS16
Villatora
Granze di Camin
SS516
Mandria
Via Battaglia
Ponte San Nicolò
Saonara
Rio
Salboro
Caovilla
Albignasego
SS516
Sant'Angelo di Piove di Sacco
Roncaiette
Legnaro
Autostrada Bologna-Padova
Lietto
2 km
©2007 Google - Map data ©2007 TeleAtlas -

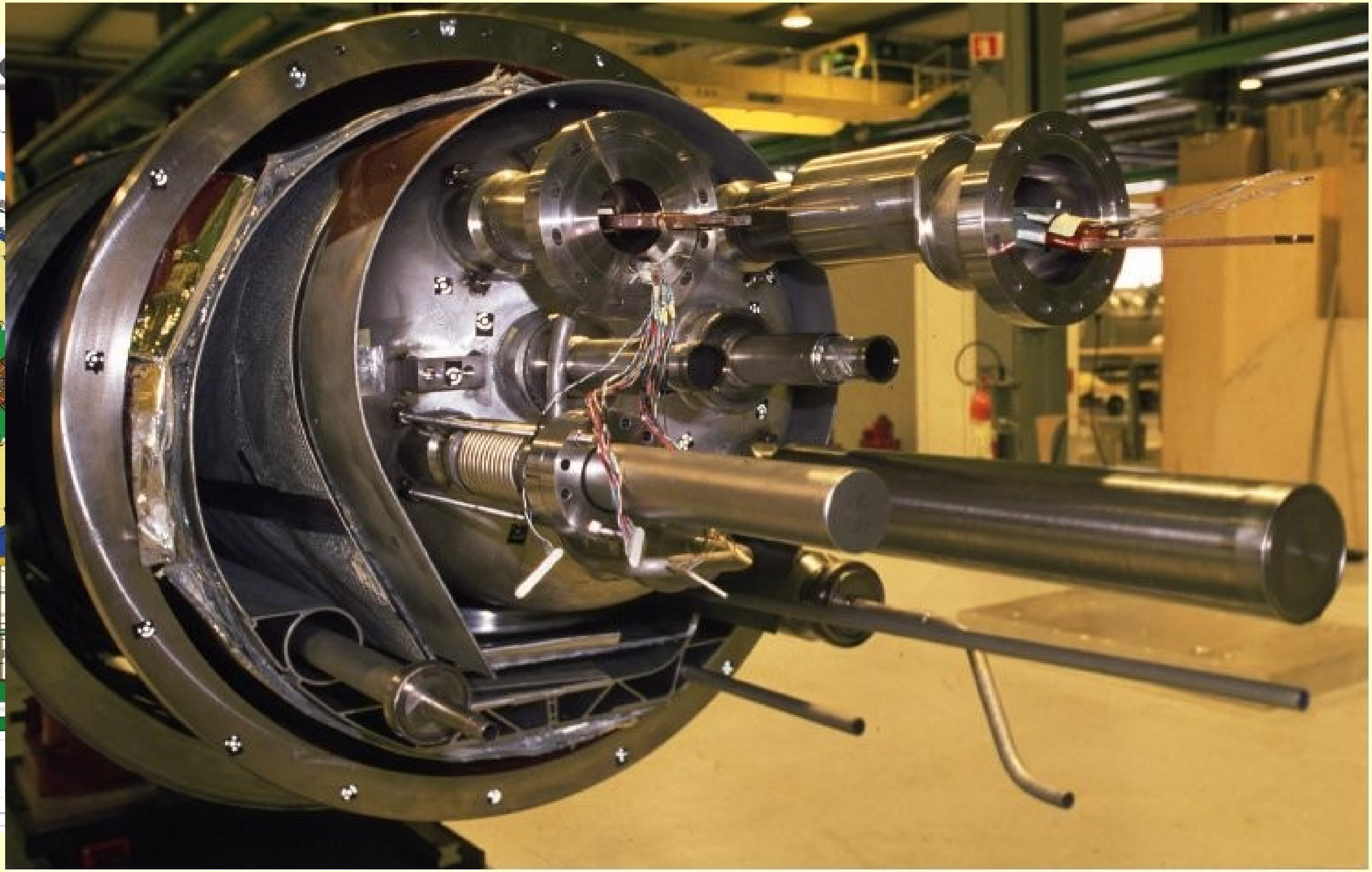
Il tunnel sottoterraneo



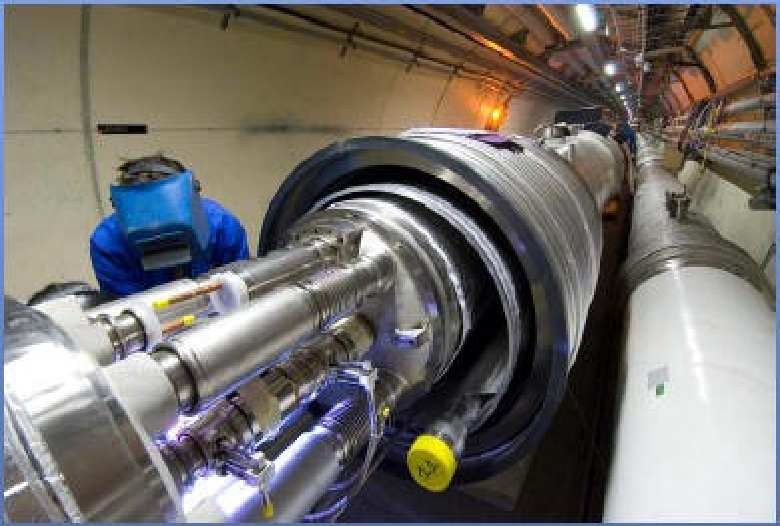
Magneti @ LHC

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

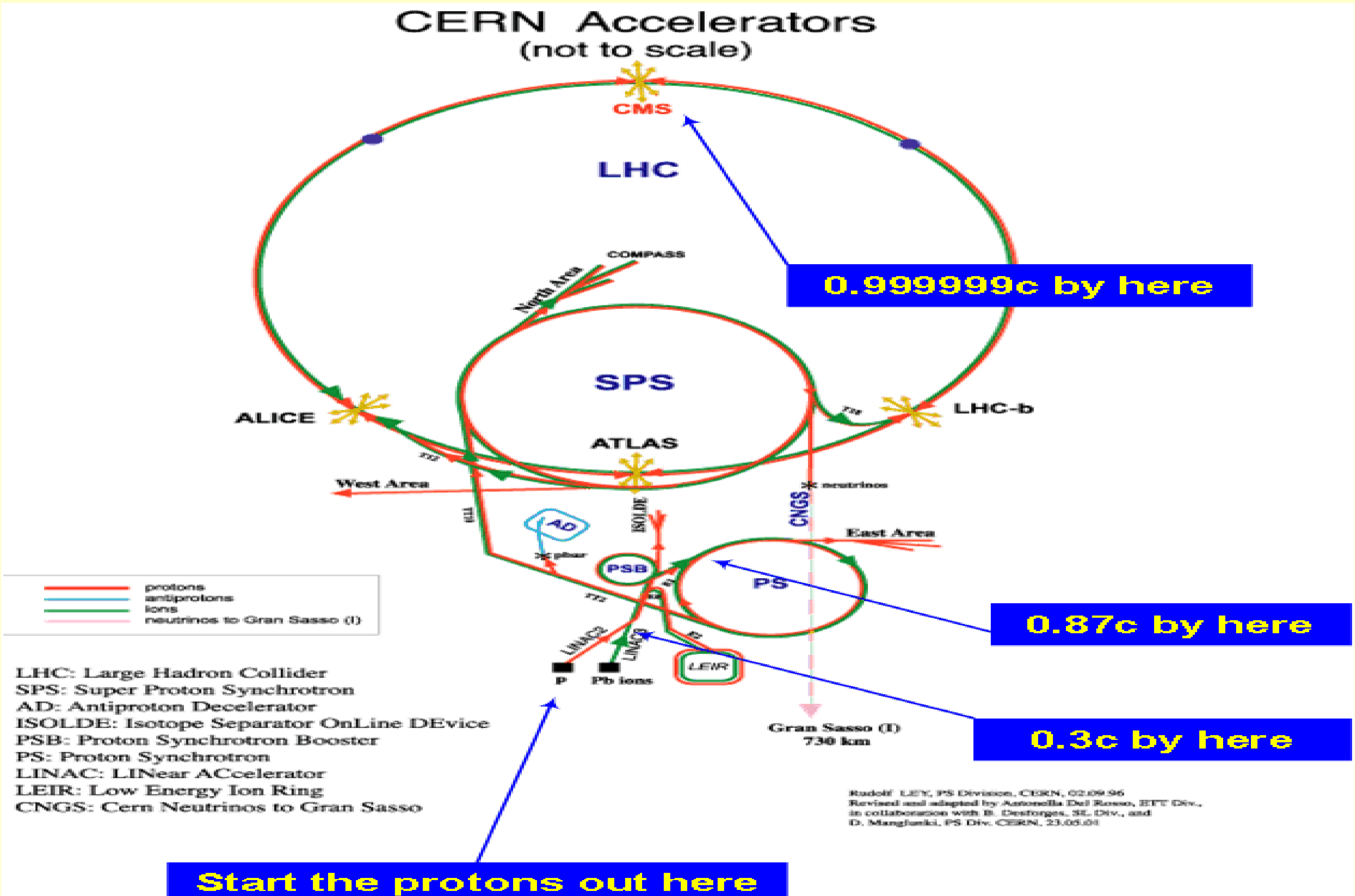




Underground



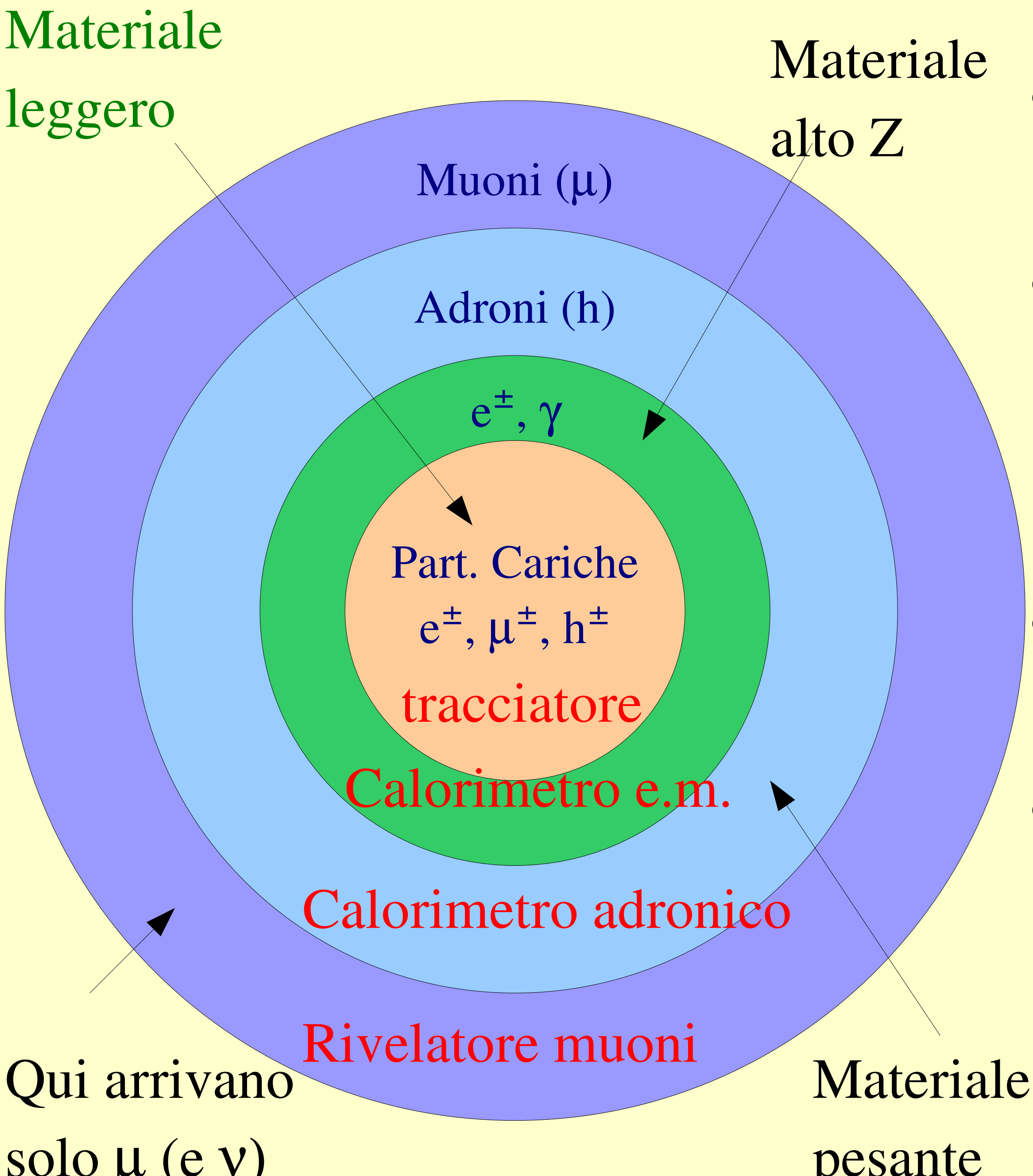
Catena di accelerazione



Cosa vediamo?

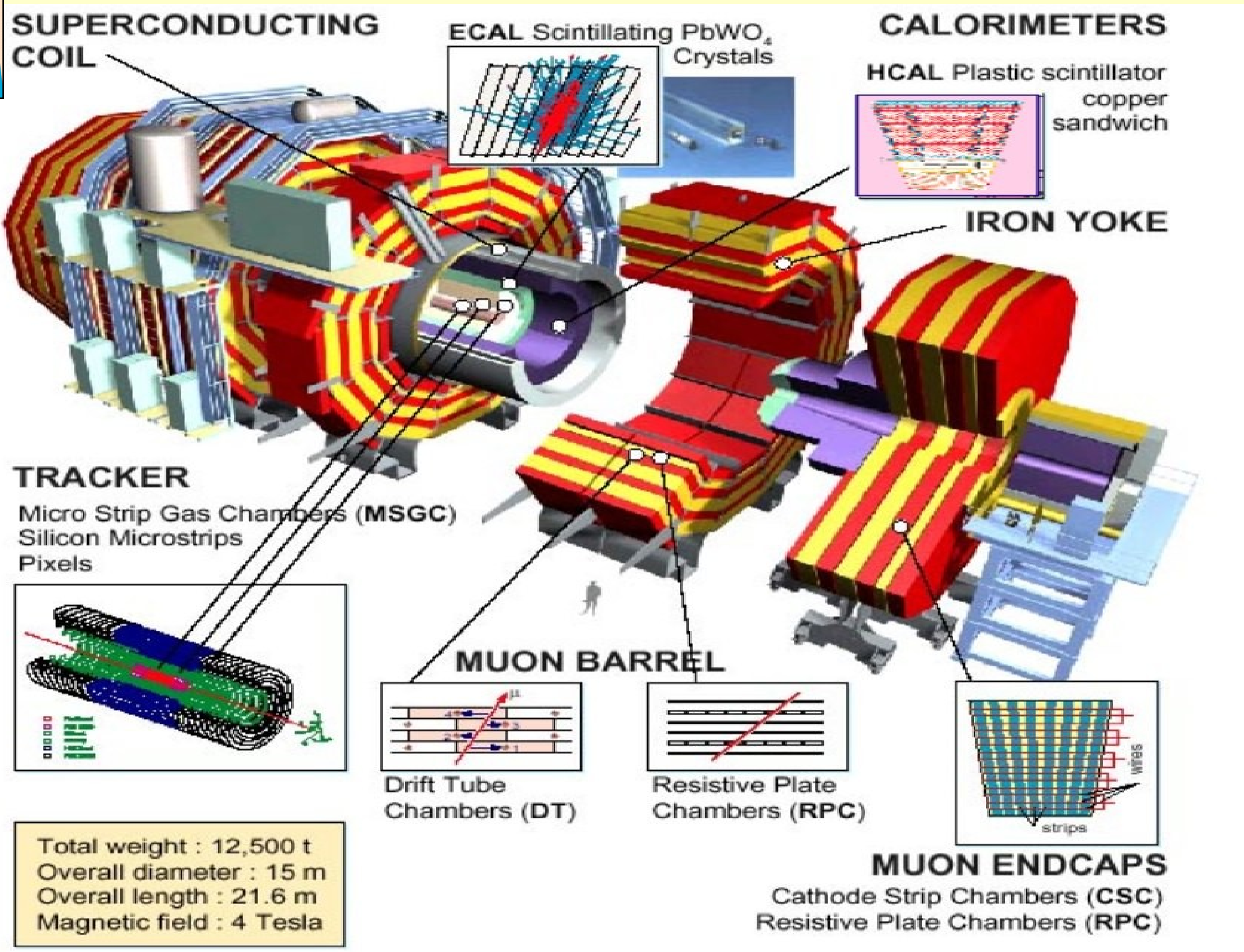
- I prodotti della collisione primaria
- Particelle stabili (o comunque con vita abbastanza lunga)
  - Elettroni e Muoni
  - Fotoni
  - Jets (quark) (particelle cariche e neutre)
  - Energia mancante (neutrini)
- Di tutte vogliamo ricostruire direzione e energia (momento) oltre ad identificarle

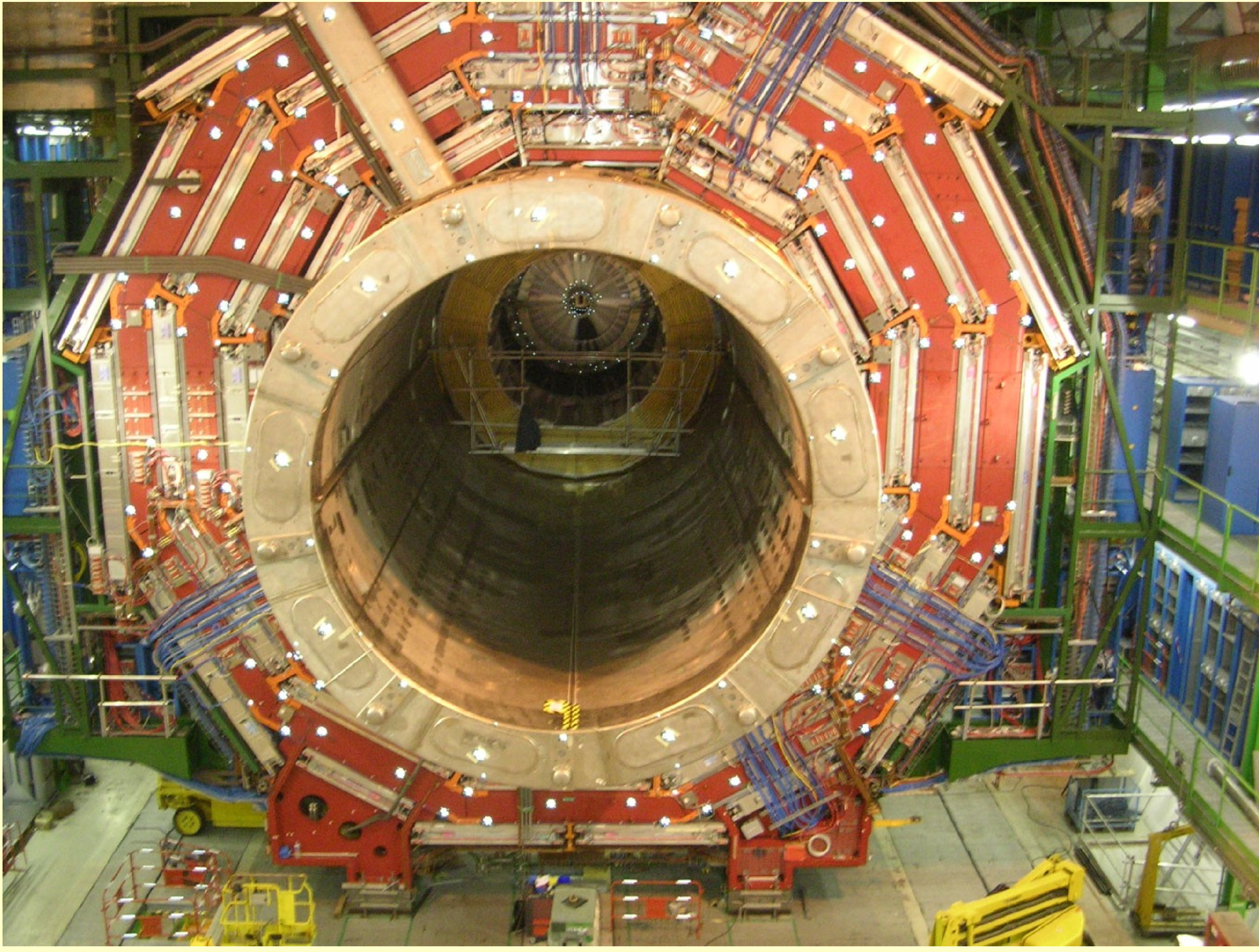
Rivelatore a cipolla



- 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

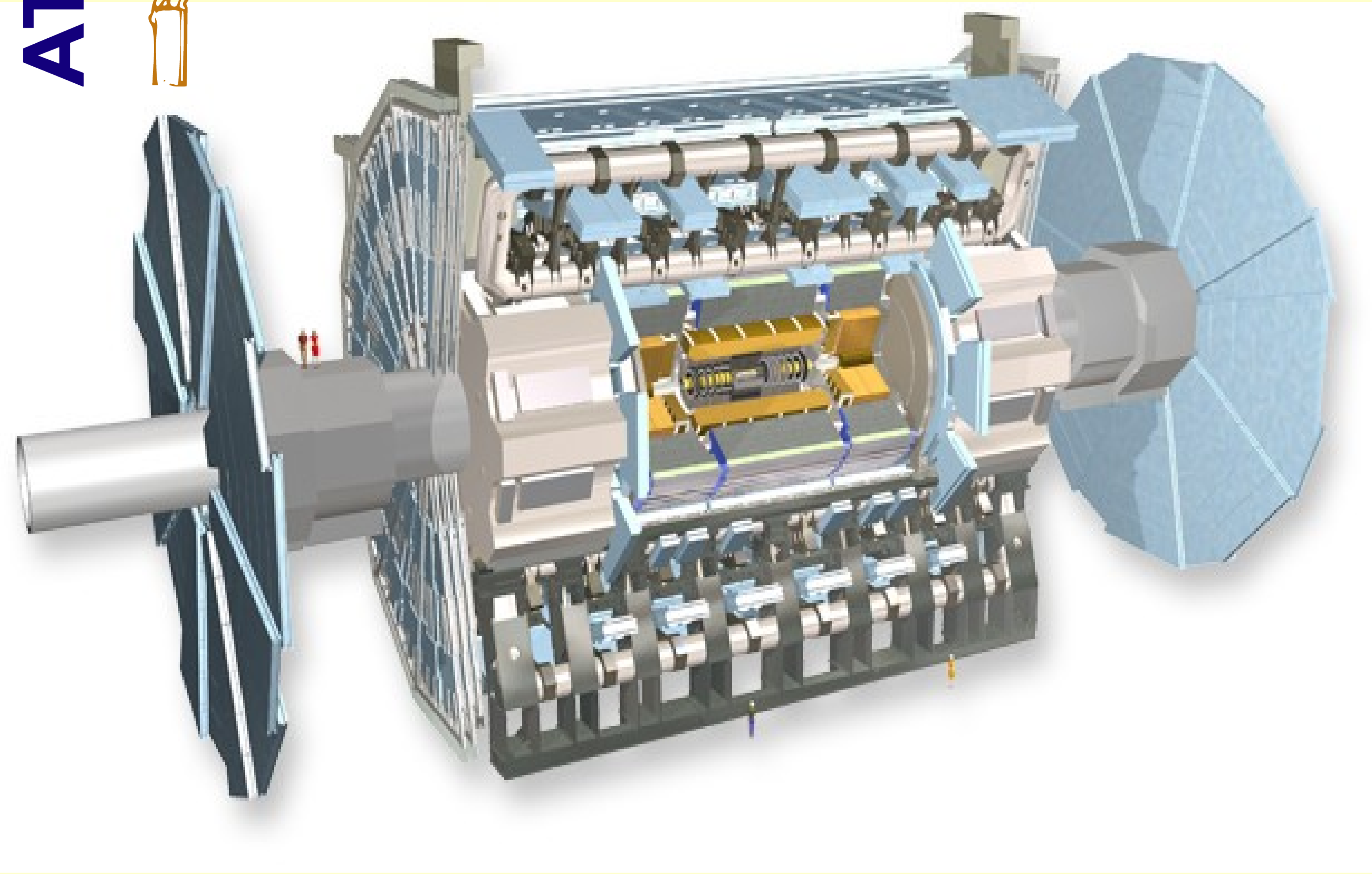
CMS: Compact Muon Solenoid

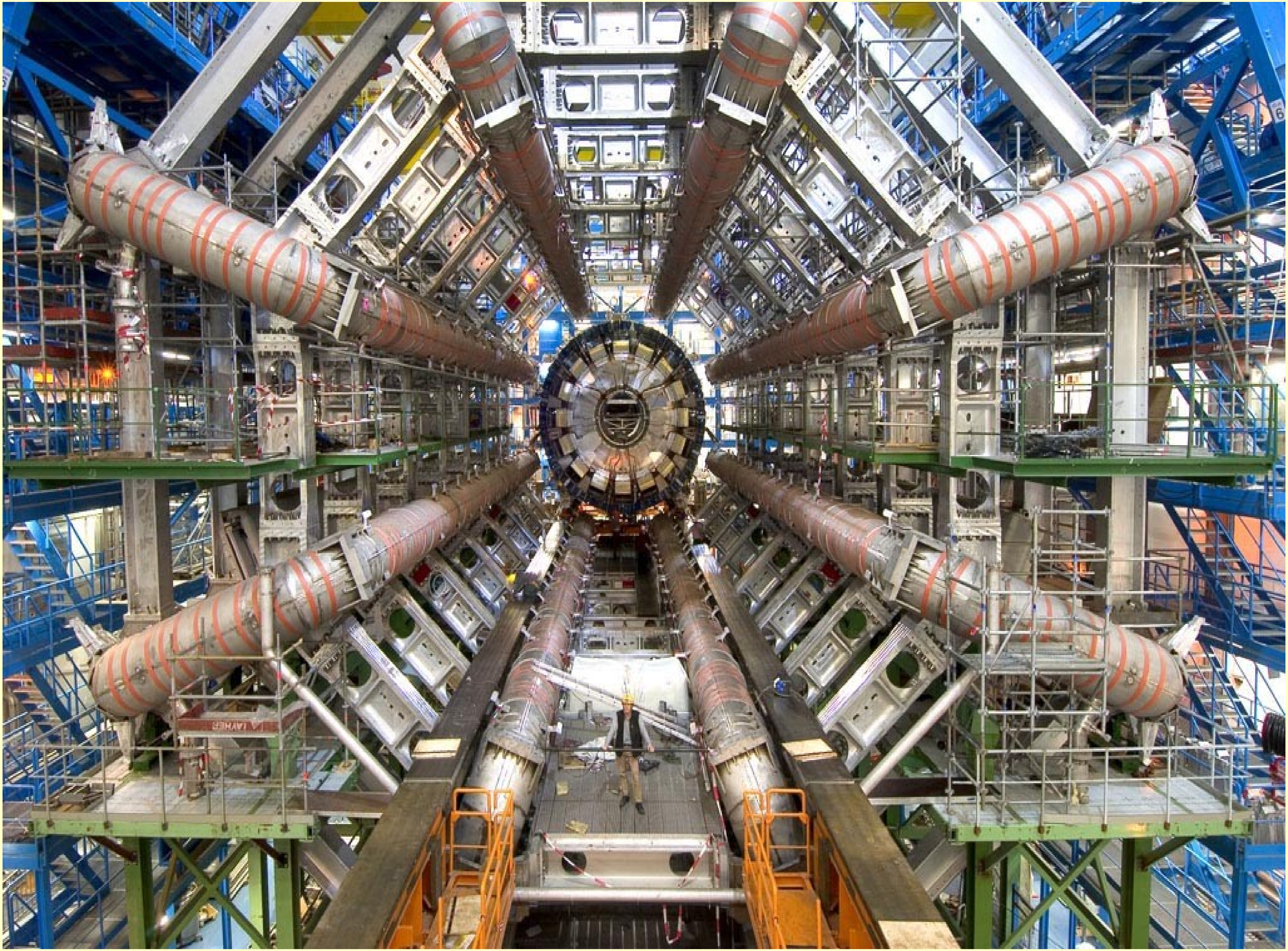




ATLAS

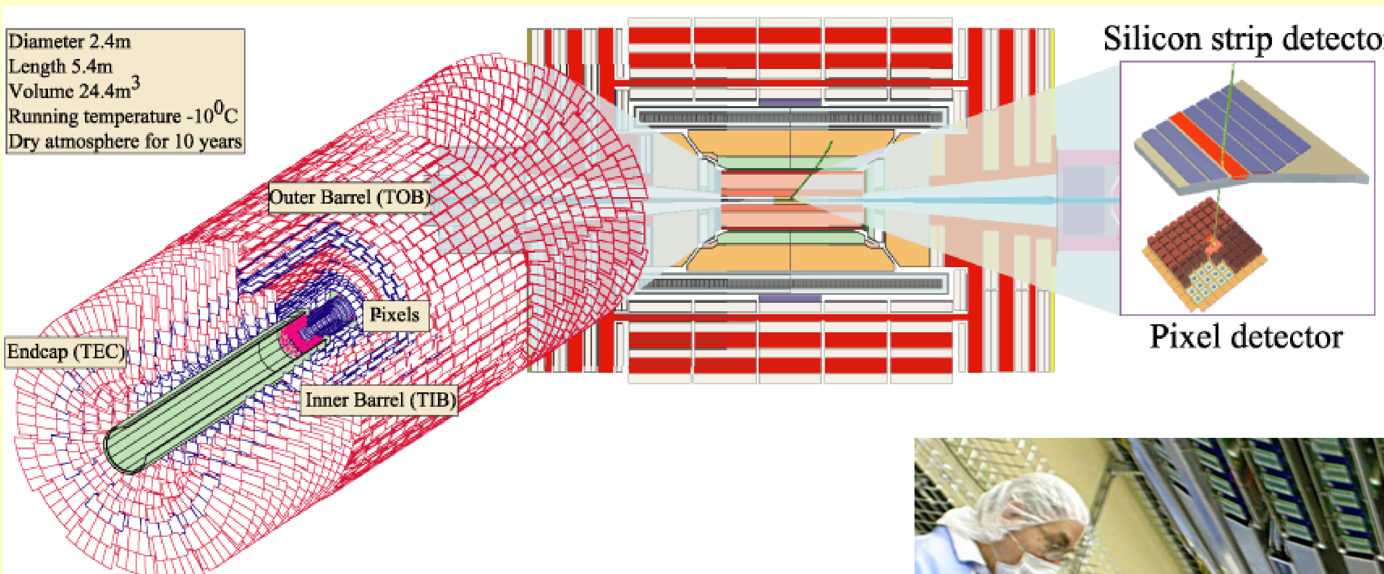
A ToroidalL ApparatuS

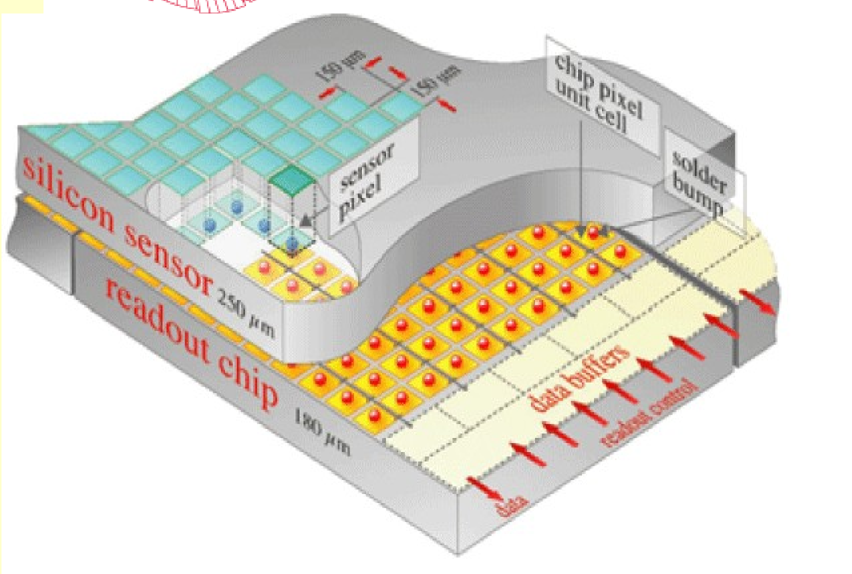


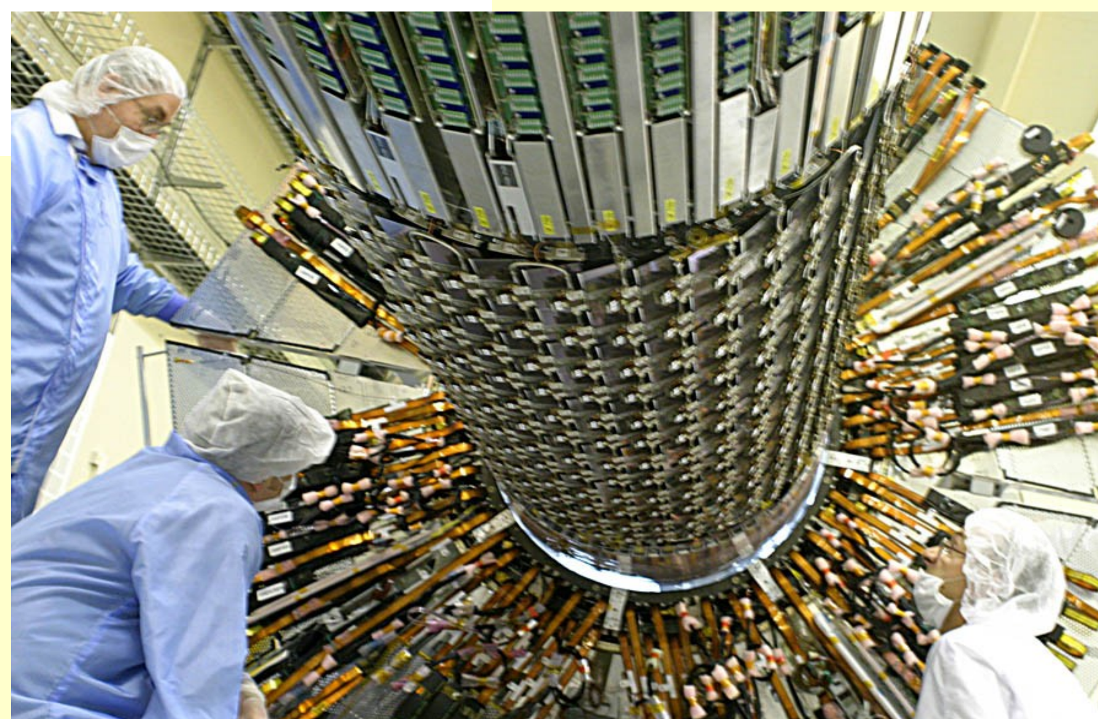


Tracciatore

- Elementi sensibili a passaggio particelle cariche (silici)
- In campo magnetico: misuro traiettoria => curvatura => momento

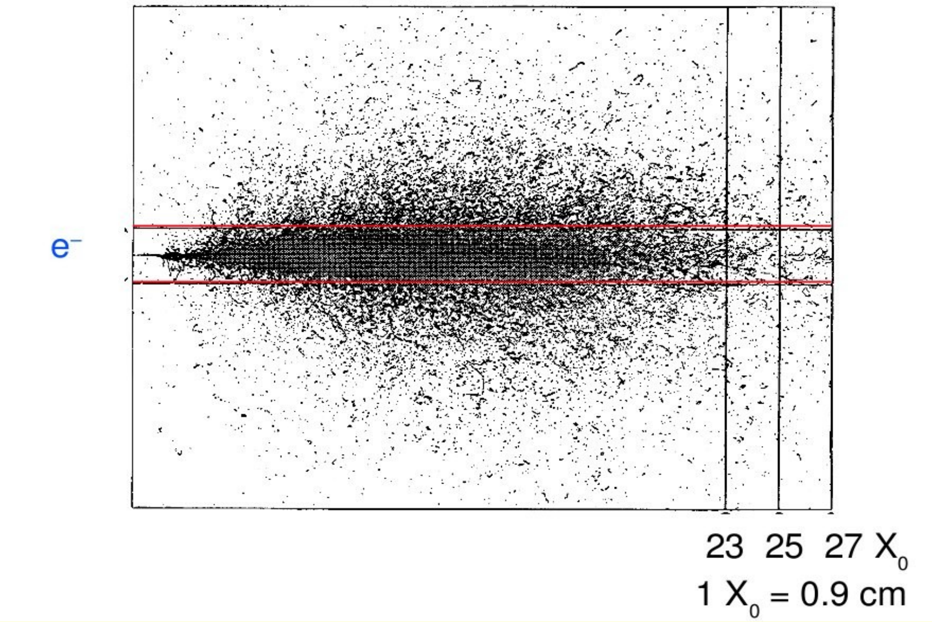


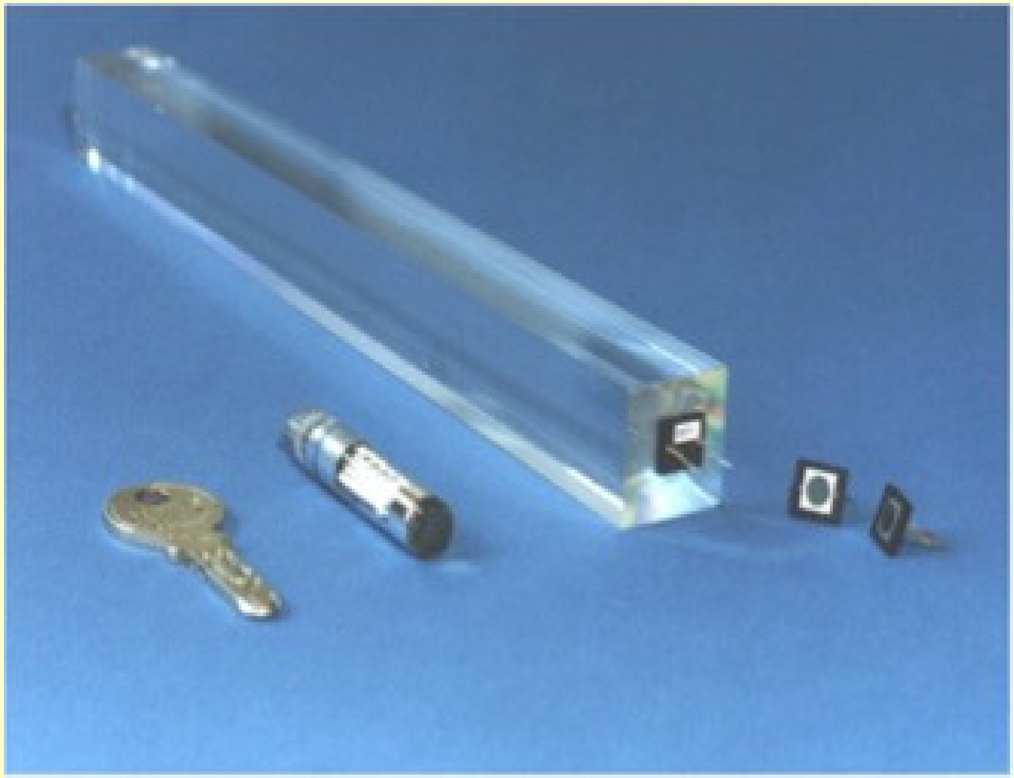


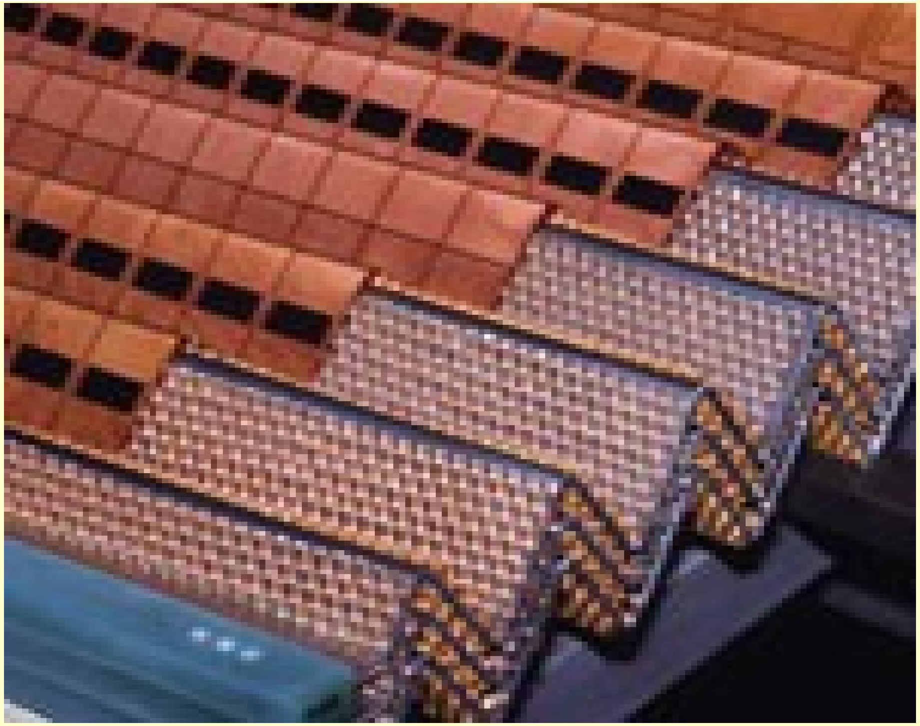


Calorimetro e.m. (e, γ)

- Elettroni e fotoni sono assorbiti dal calorimetro elettromagnetico
- Producono luce che viene raccolta e misurata
- La quantita' di luce e' proporzionale all'energia della particella

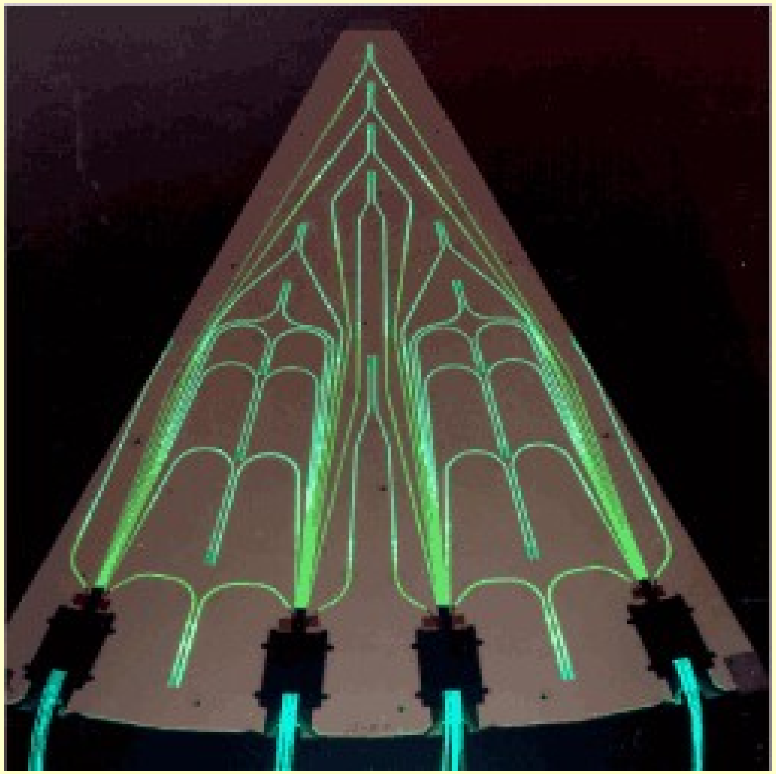






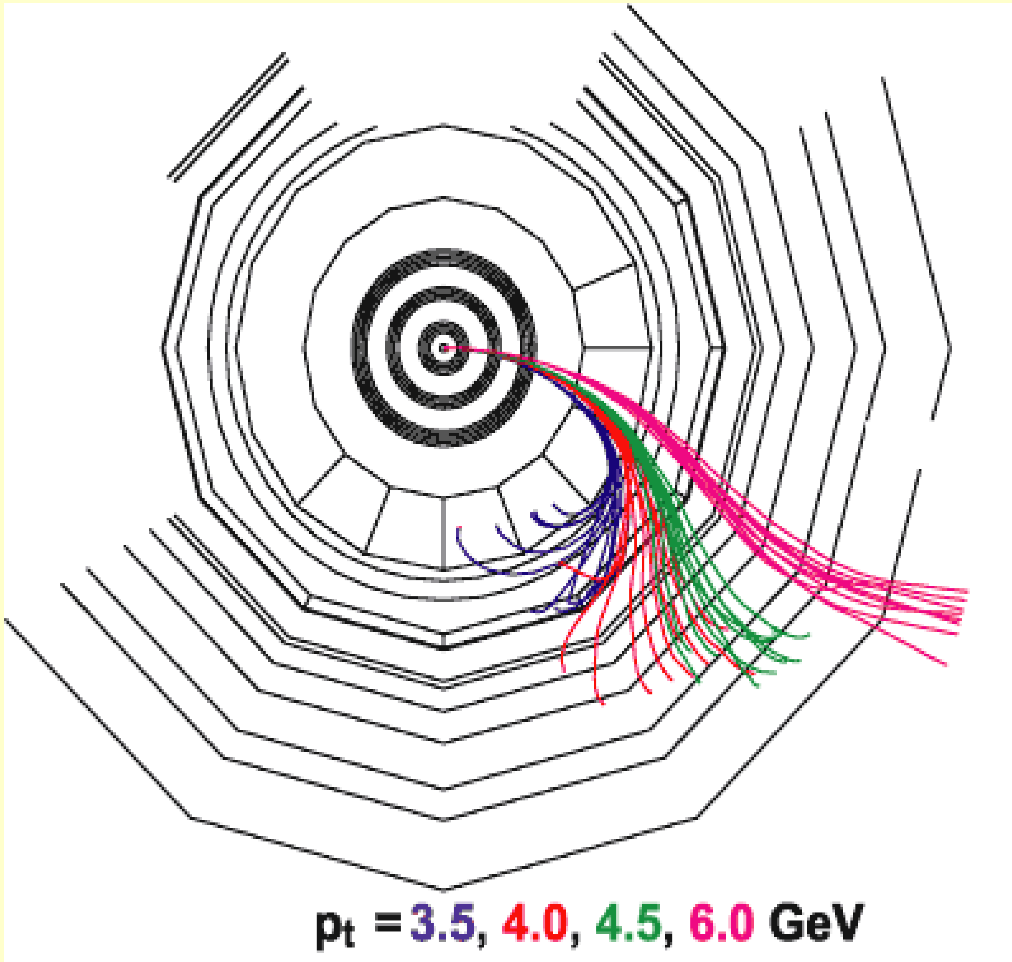
Calorimetro adronico

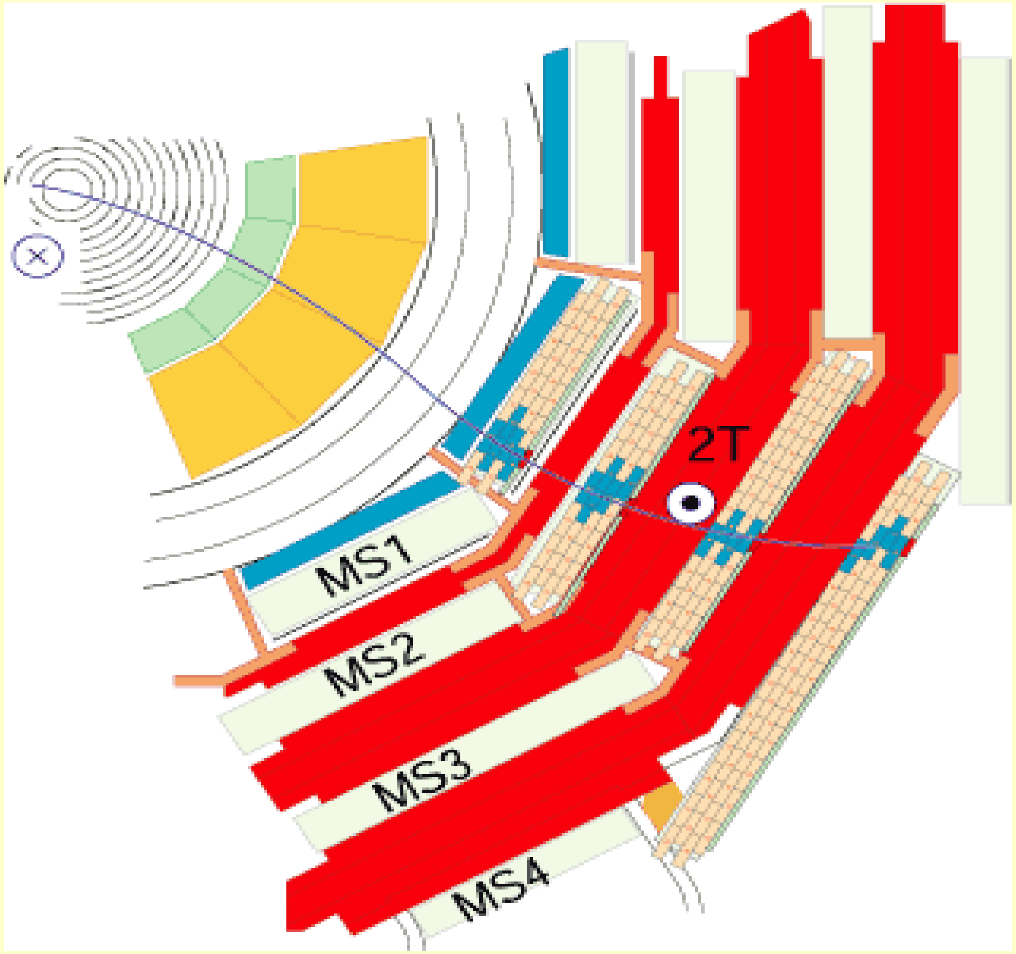
- Concettualmente simile a quello e.m.
- Serve piu' pesante e profondo (sciami adronici sono piu' profondi)
- Materiale assorbitore (Fe Cu) + materiale attivo (produce luce poi raccolta)

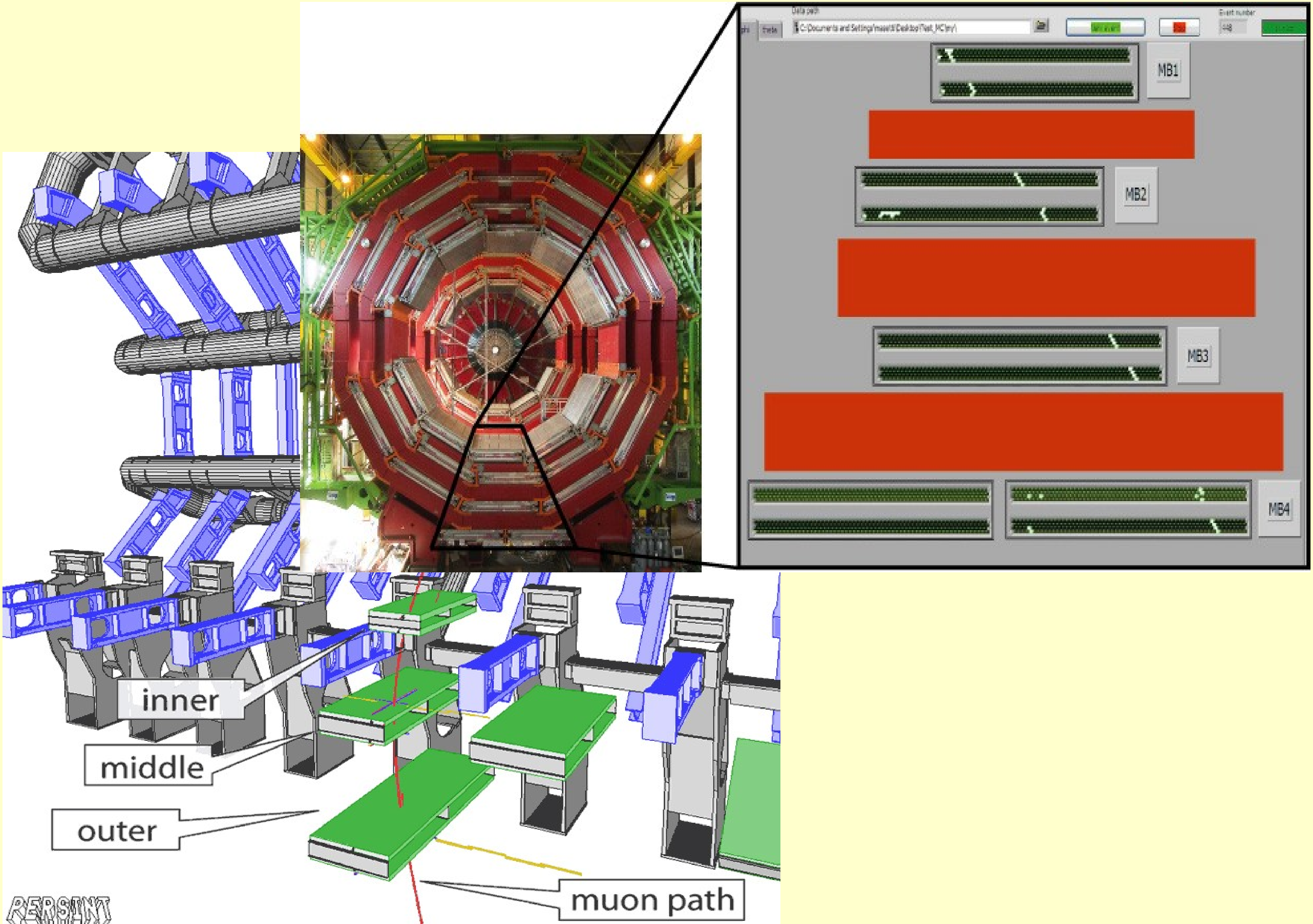


Rivelatore di Muoni

- 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

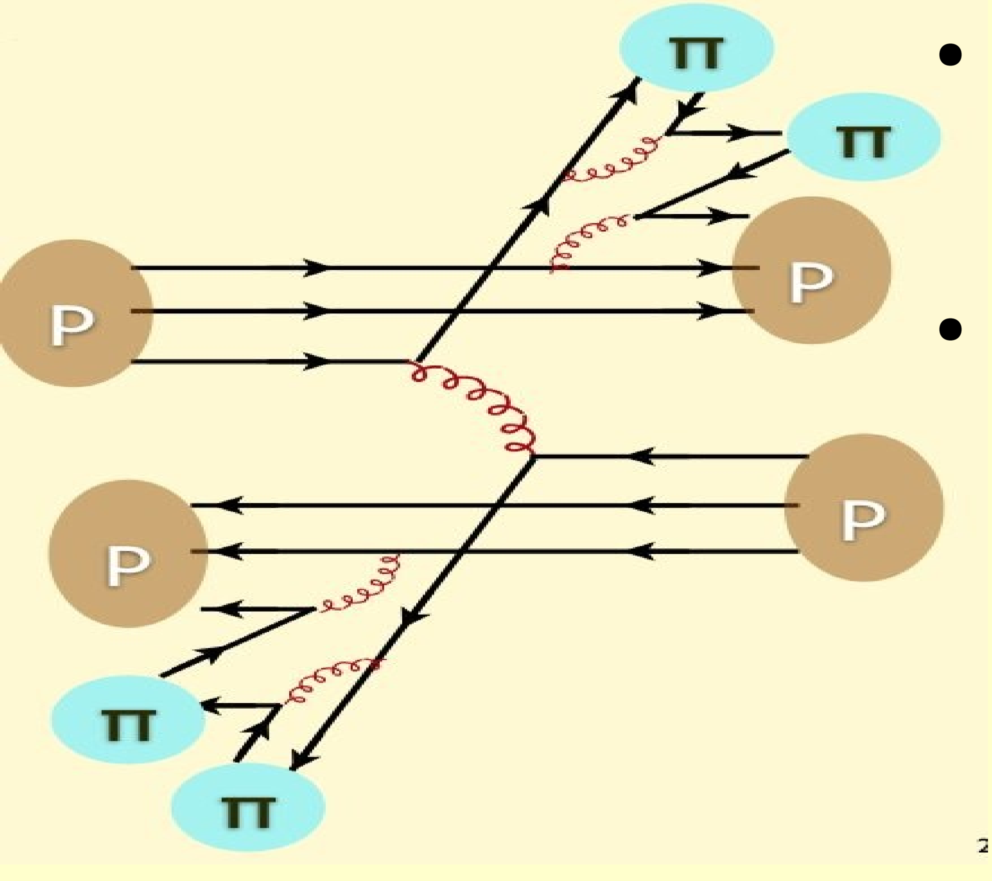





MB1
MB2
MB3
MB4
inner
middle
outer
muon path
PERSINT

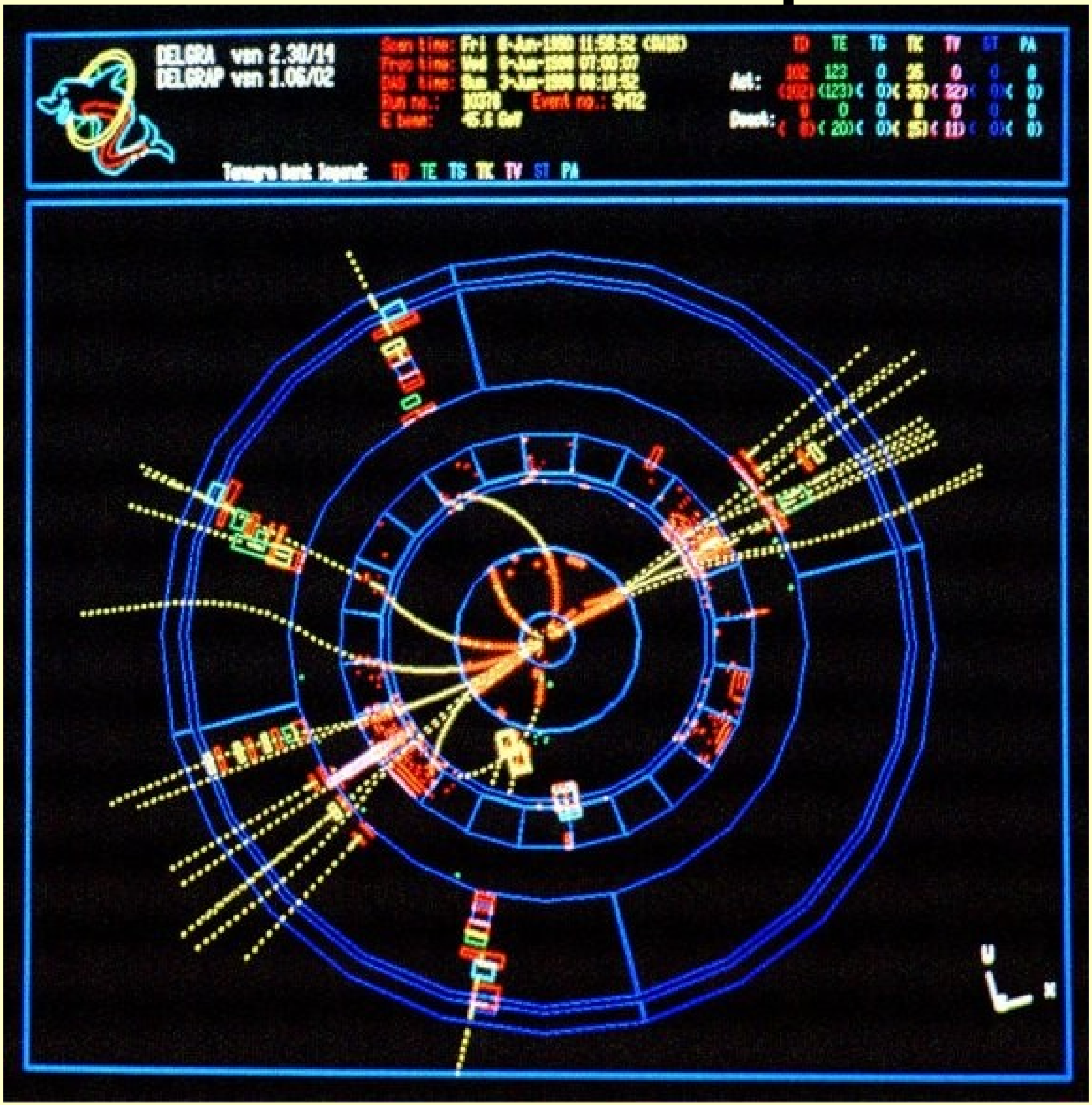
Jet (Getti)

- Le interazioni primatie 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



2

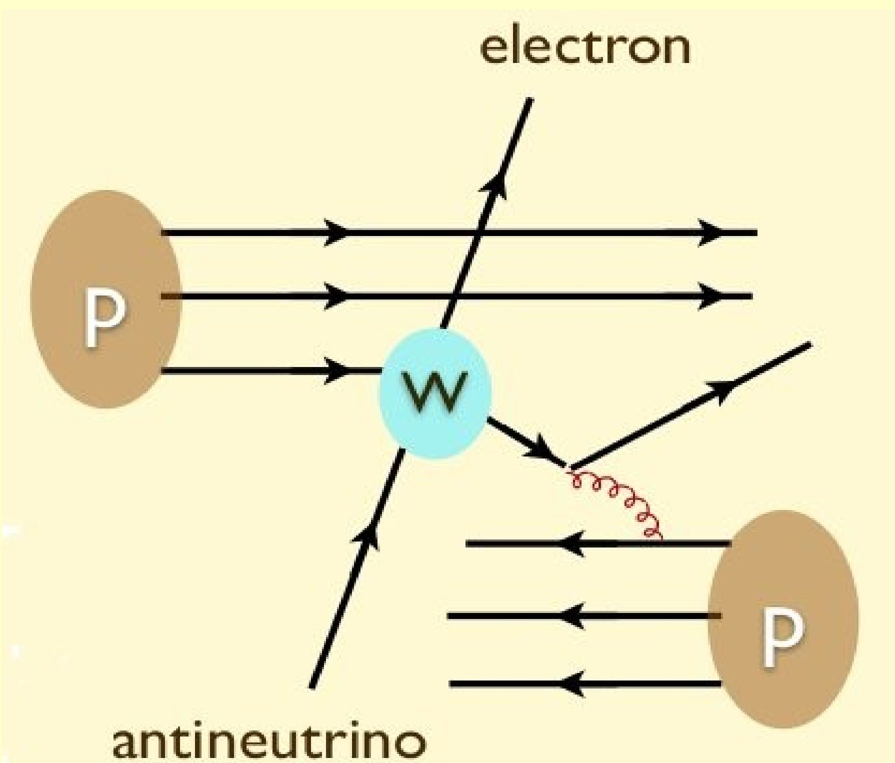
Jet in pratica

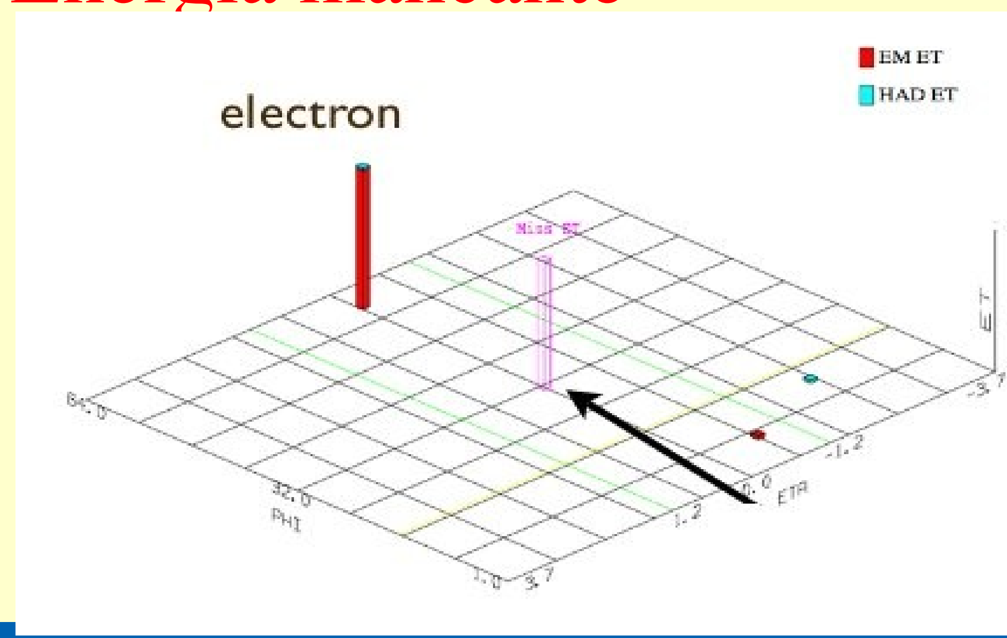


$e^+e^- \to Z \to q\,\bar{q}$ (bar)

Energia mancante

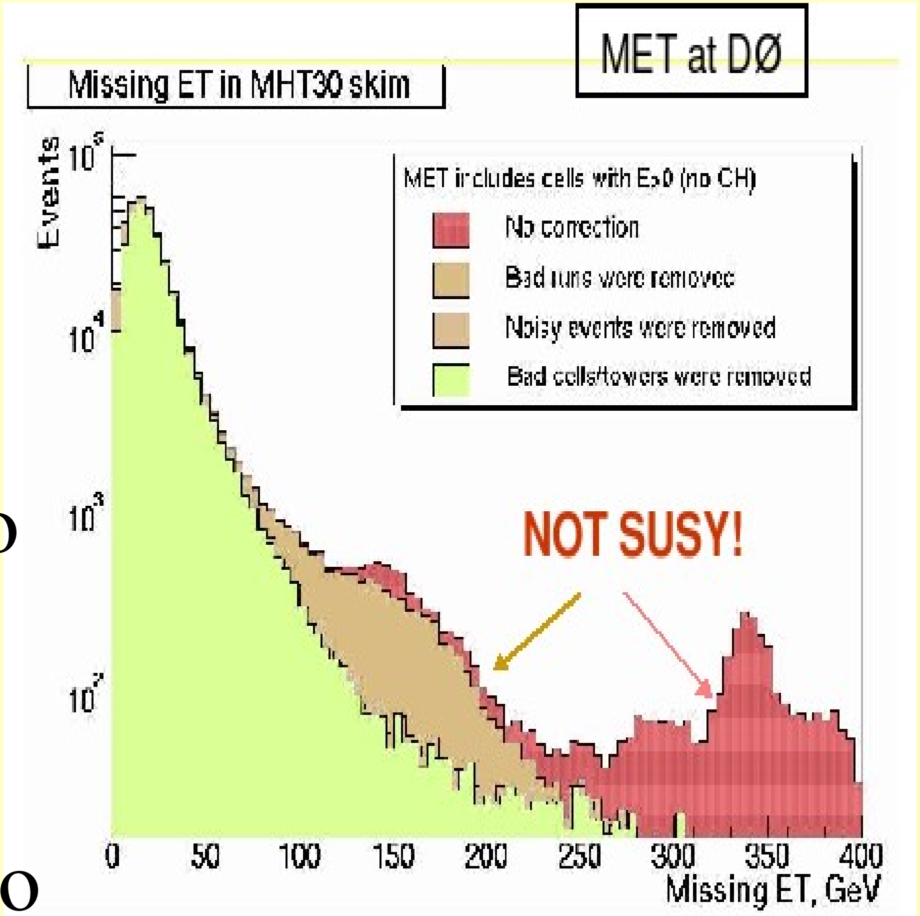
- Vedere l'invisibile!
- Con i nostri rivelatori vediamo tutto tranne i neutrini
- E altre particelle che non interagiscono (vedi dopo)
- Energia mancante





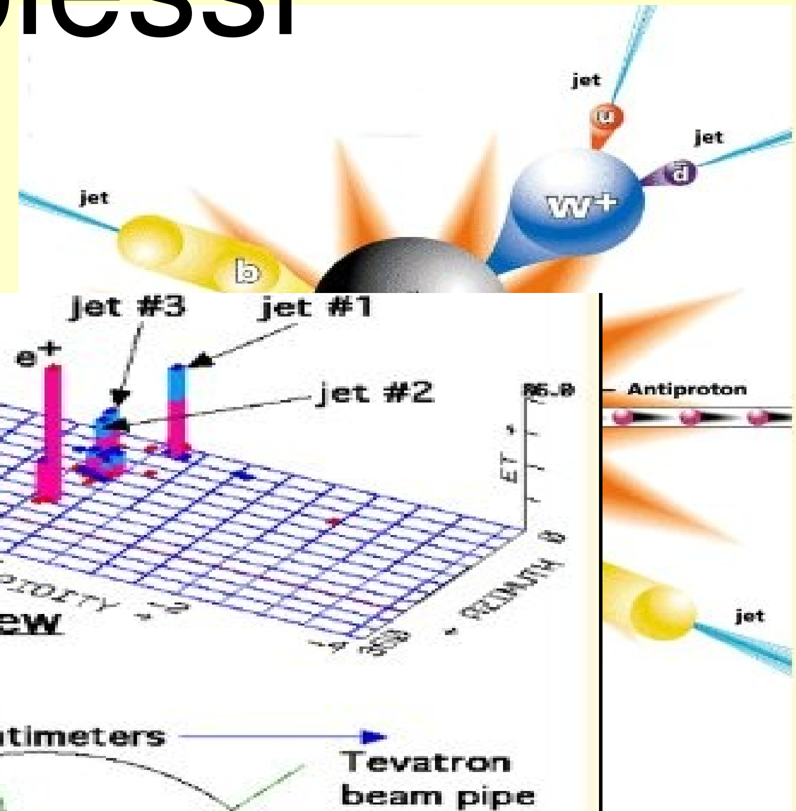
Come si fa?

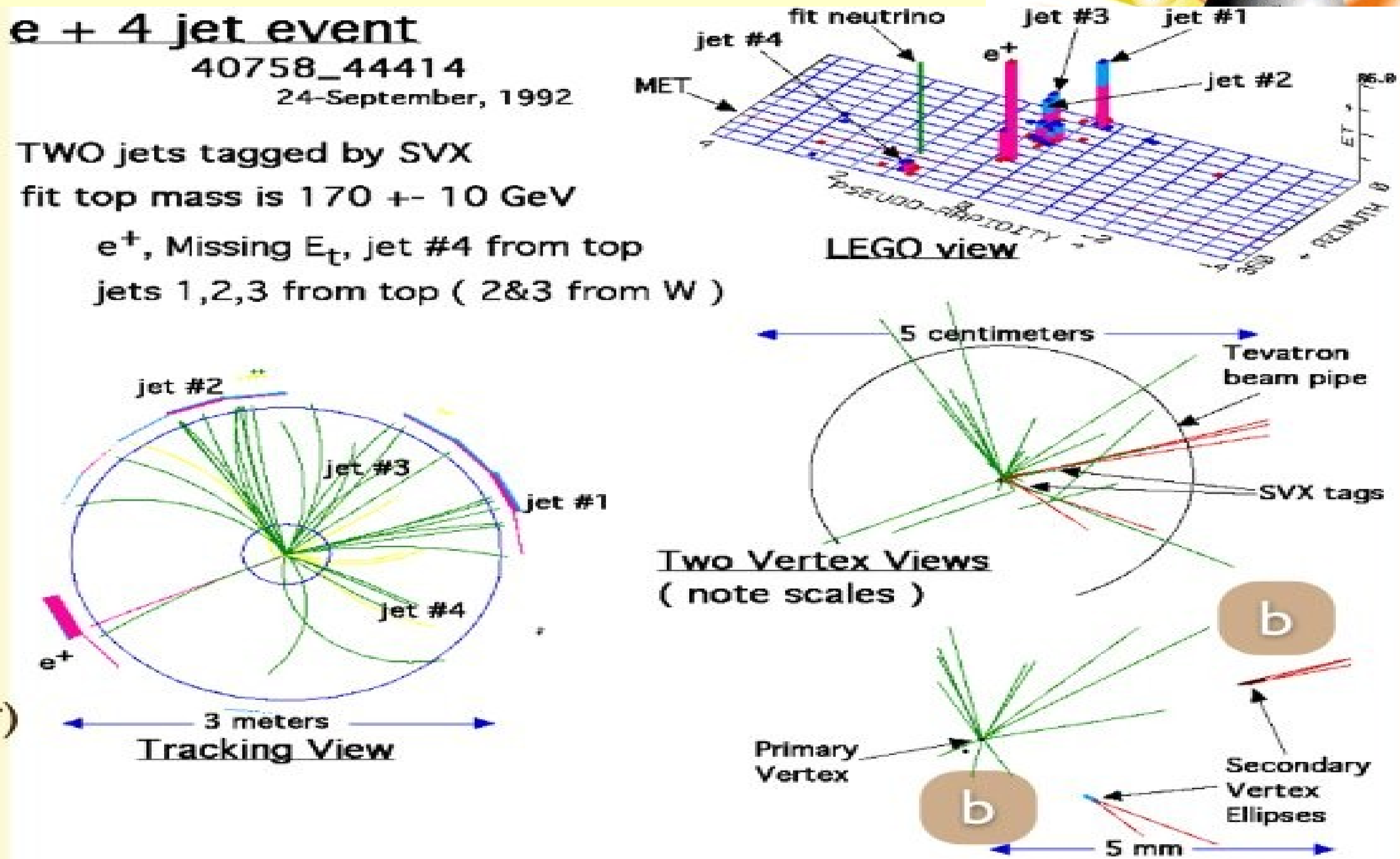
- Sommo tutto quello che vedo (e, γ, h, μ, ...)
- Nel piano trasverso ai fasci l'energia si deve bilanciare
- Se manca, allora mi sono perso qualcosa in quella direzione (neutrino o altro)
- Rivelatore deve essere ermetico
- E' difficile da fare (cavi, tubi, servizi...): bisogna stare attenti!



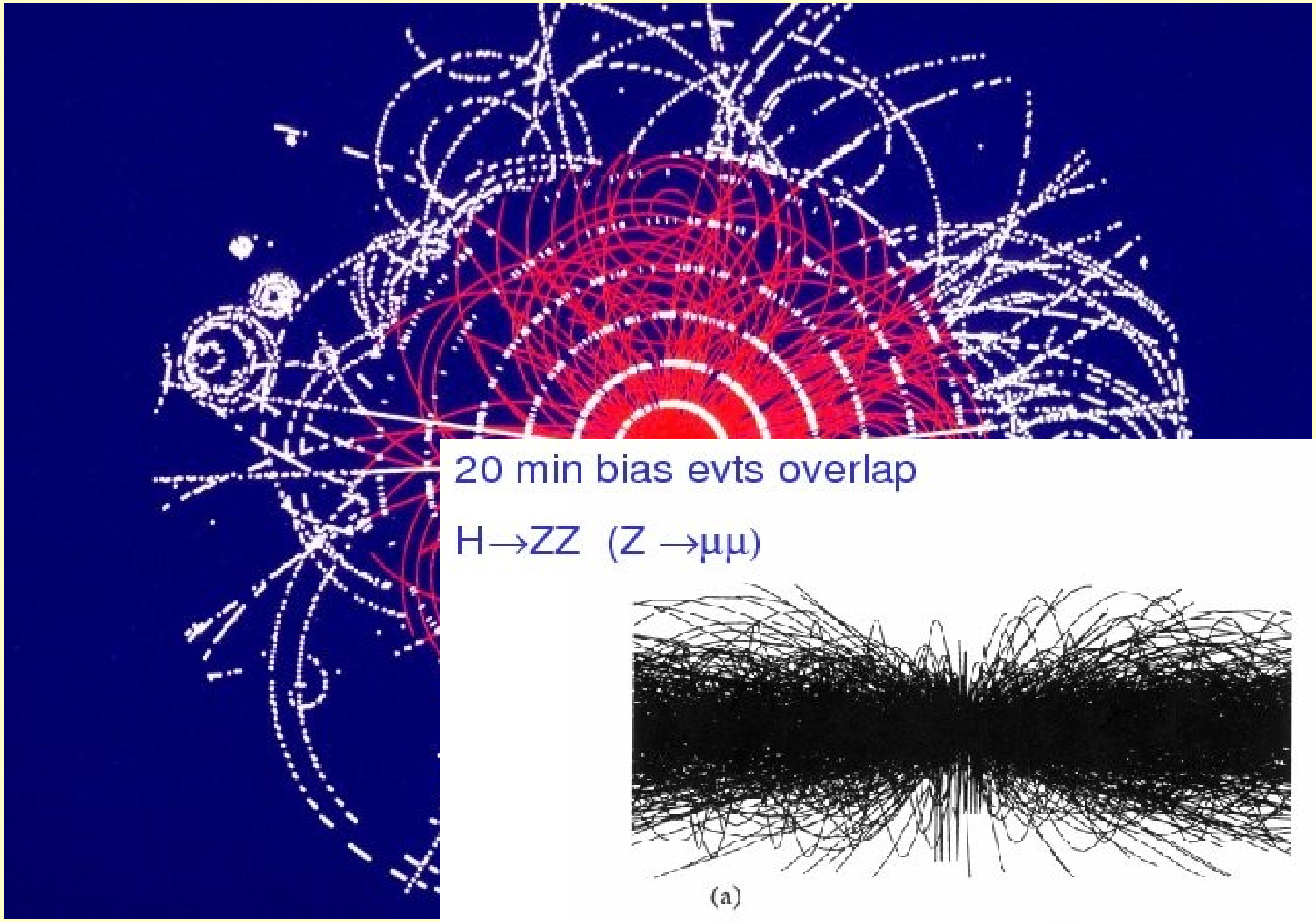
Oggetti complessi

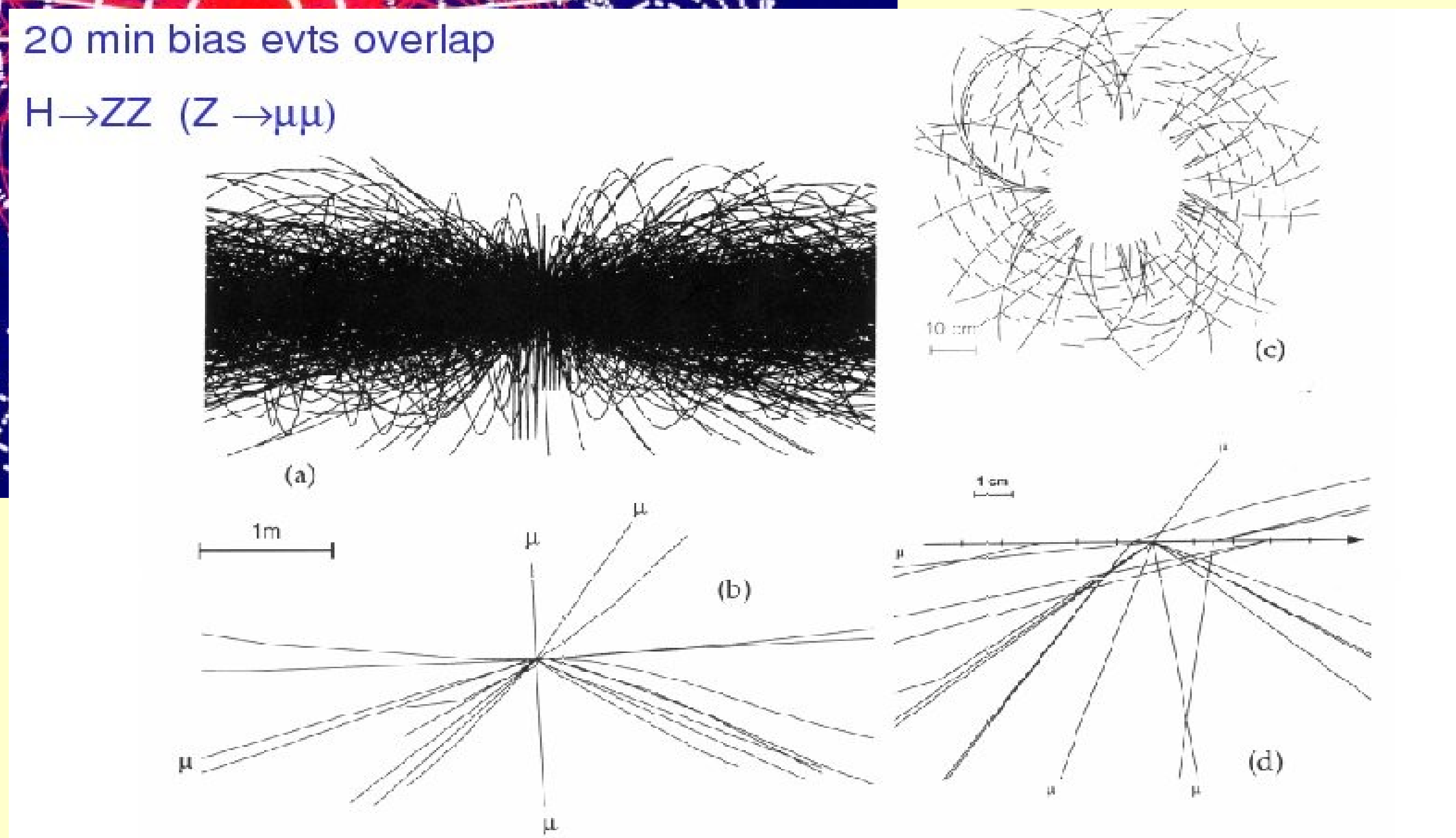
Si combinano i vari pezzi
misurati dai vari rivelatori



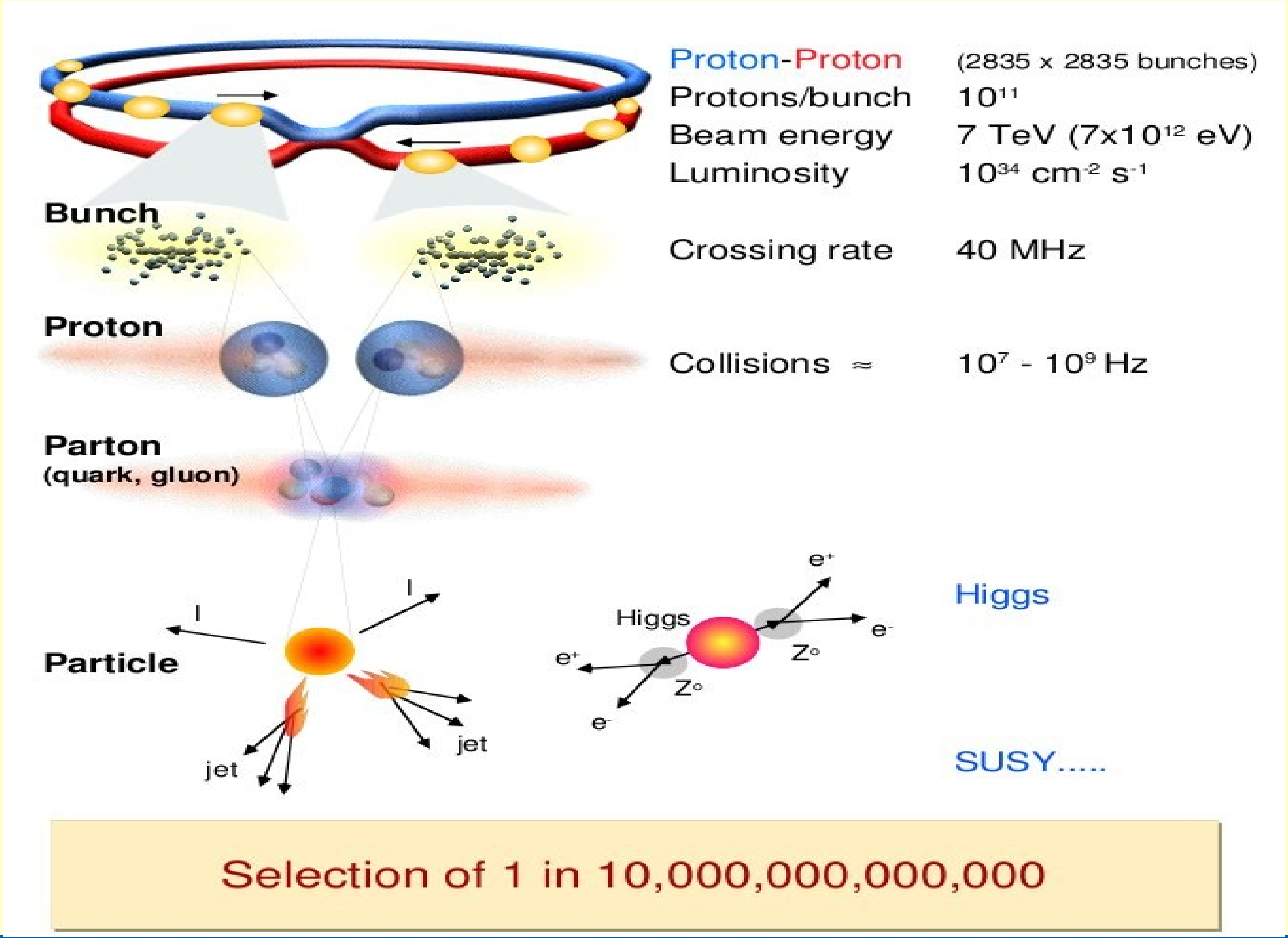


Evento @ LHC





Selezione (Trigger)

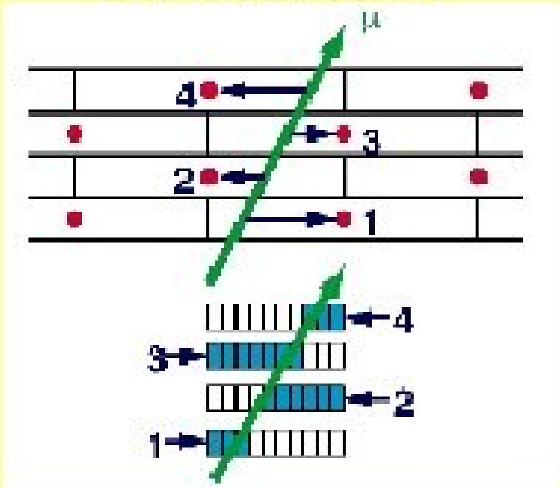


Trigger

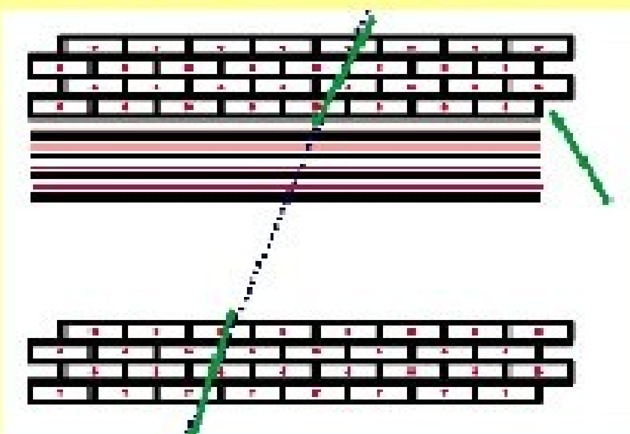
- Ogni 25 ns arriva una nuova interazione 40'000'000 al secondo
- Io ne posso salvare solo 100/200
- Devo selezionare 100 eventi su 40M
- Devo capire (velocemente) se un evento e' interessante e vale la pena salvarlo oppure no
- Cerco e, μ, j, MET, ... (o combinazioni) con alta energia
- Se li vedo,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

Trigger Muoni

Drift Tubes

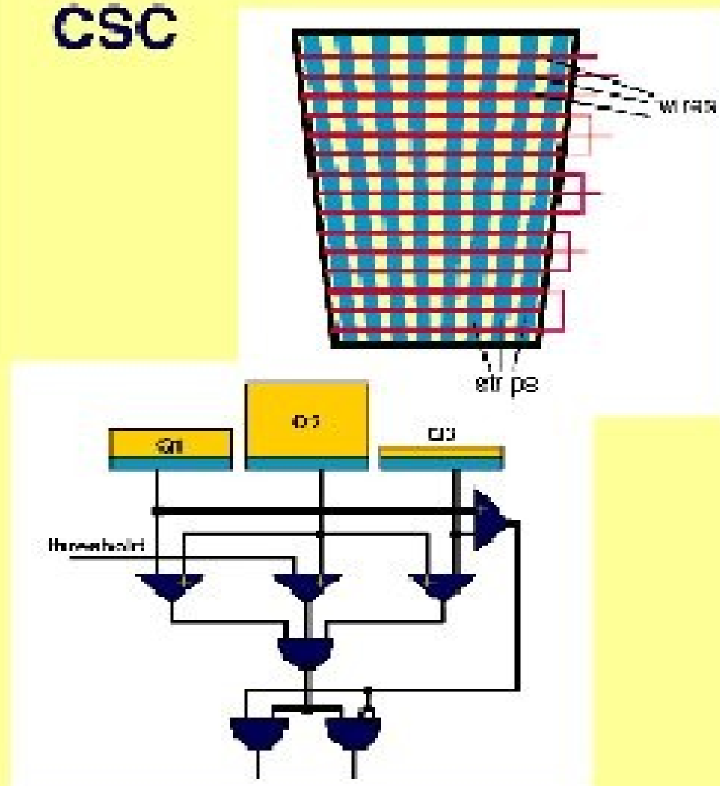


Meantimers recognize tracks and form vector / quartet.

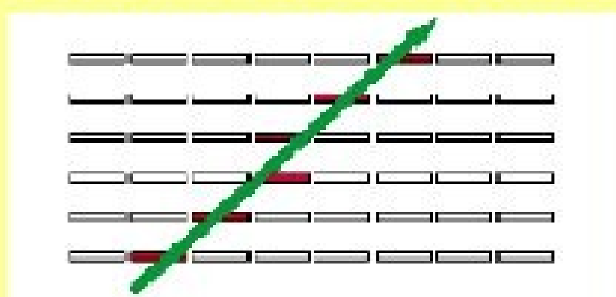


Correlator combines them into one vector / station.

CSC

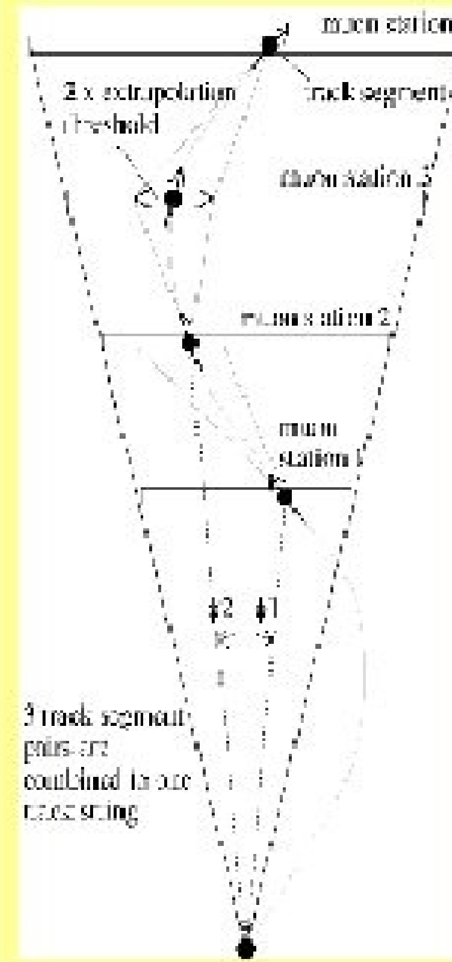


Comparators give 1/2strip resol.

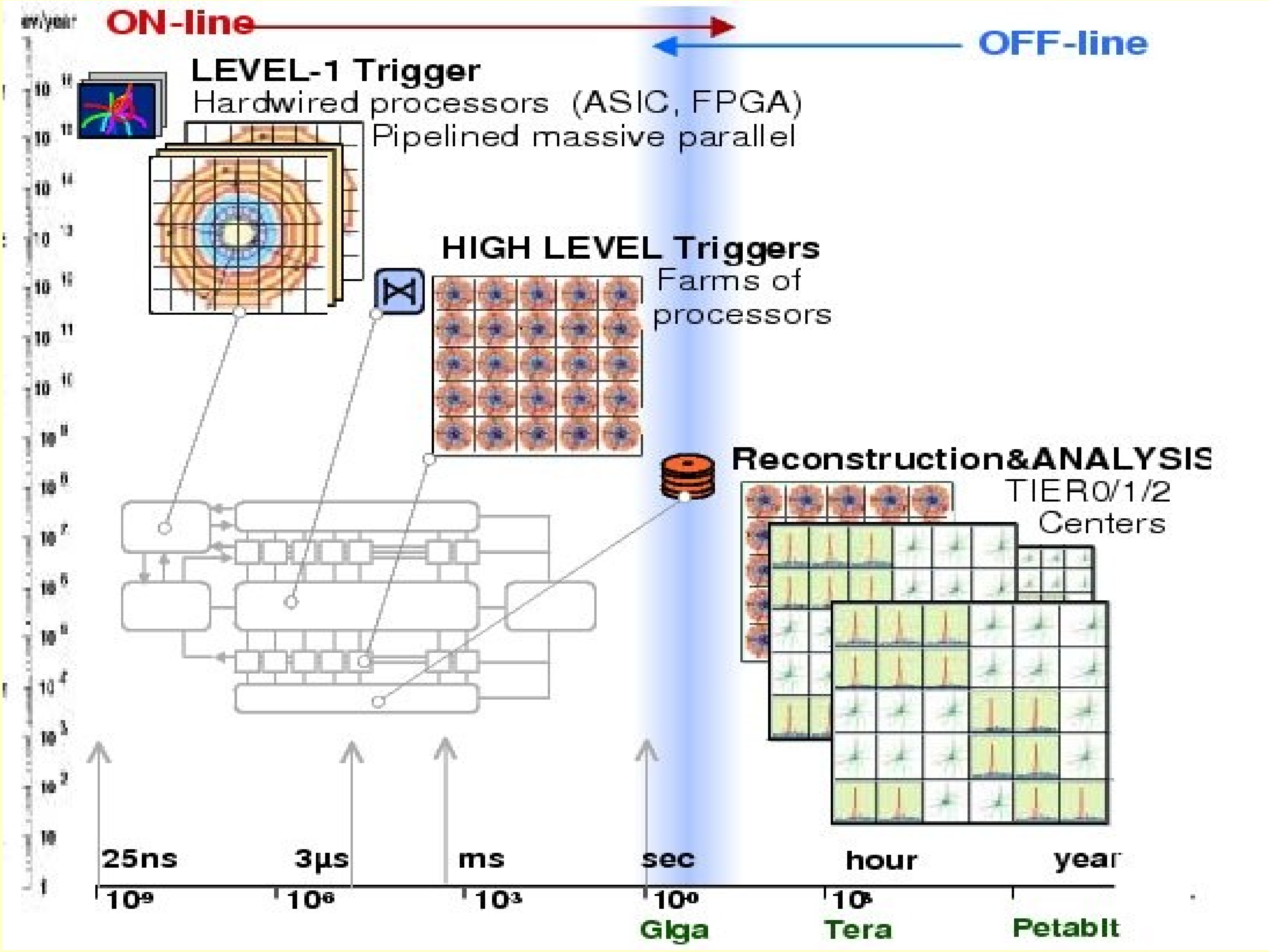


Hit strips of 6 layers form a vector.

Track Finder

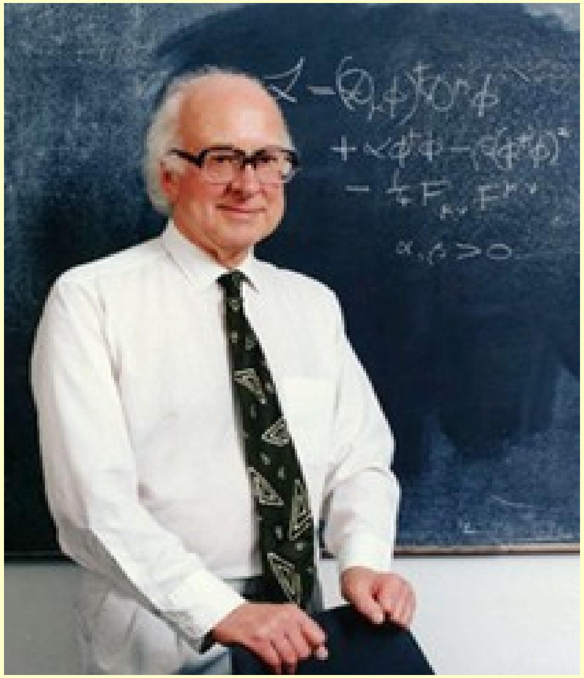


combines vectors, forms a track, assigns p_t value.

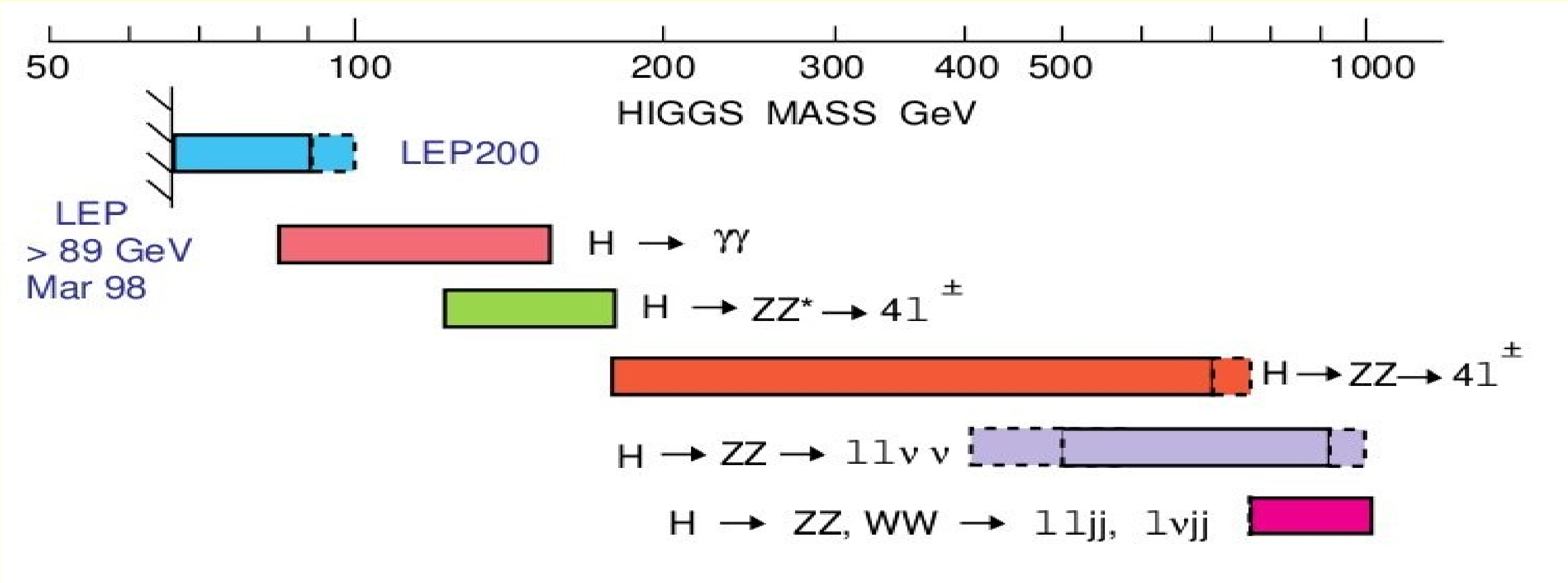


ON-line
OFF-line
LEVEL-1 Trigger
Hardwired processors (ASIC, FPGA)
Pipelined massive parallel
HIGH LEVEL Triggers
Farms of
processors
Reconstruction&ANALYSIS
TIER0/1/2
Centers
25ns
3µs
ms
sec
hour
year
10^9
10^6
10^3
10^0
10^{-3}
Giga
Tera
Petabit

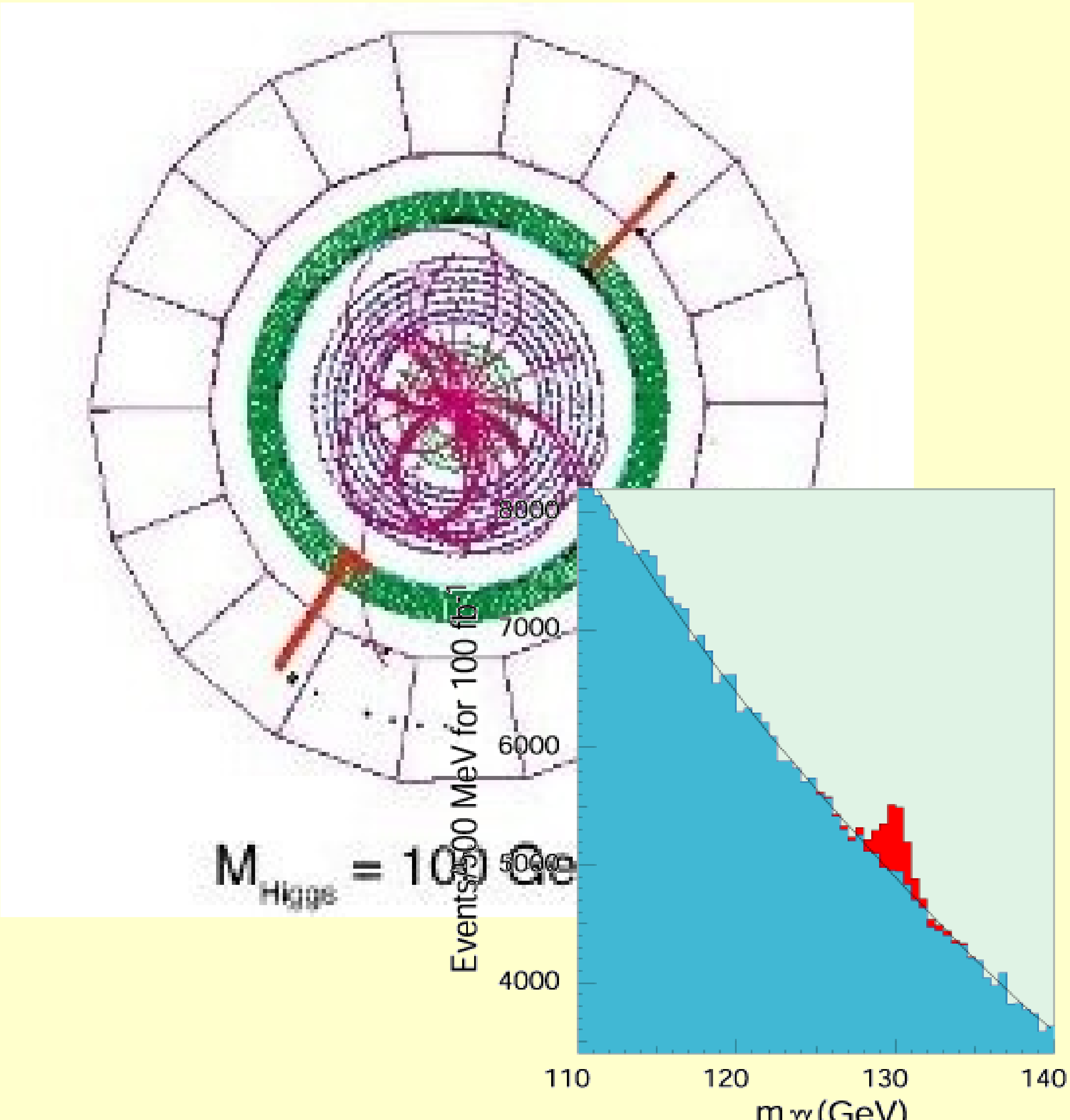
Cosa spero di vedere?



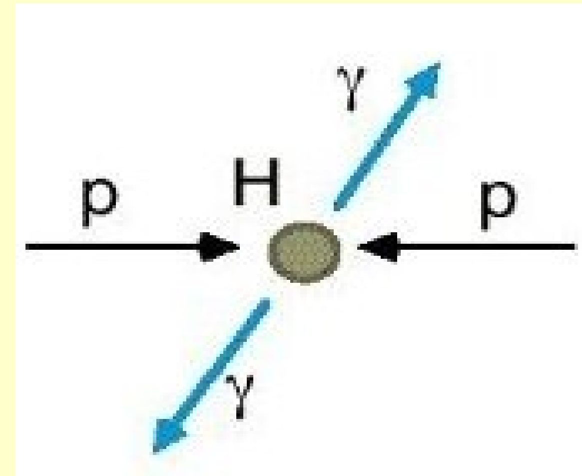
- In primis: l'Higgs!
- Come lo vedo?
- Prodotto da interazione p-p
- Osservo i prodotti del decadimento
- Diversi canali possibili



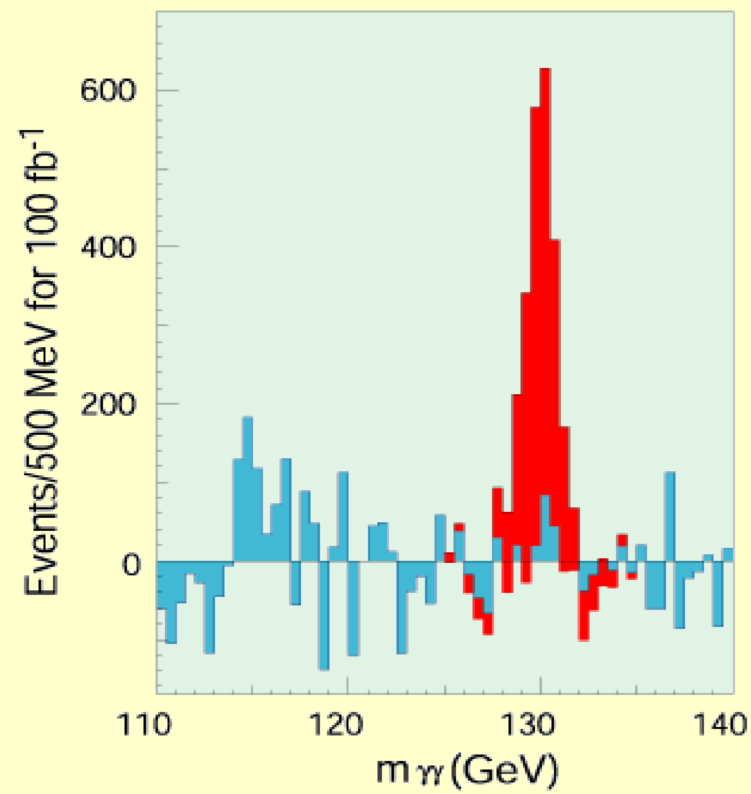
Esempio: H->γγ



8000
7000
6000
5000
4000
Events/500 MeV for 100 fb-1
110
120
130
140
m γγ (GeV)

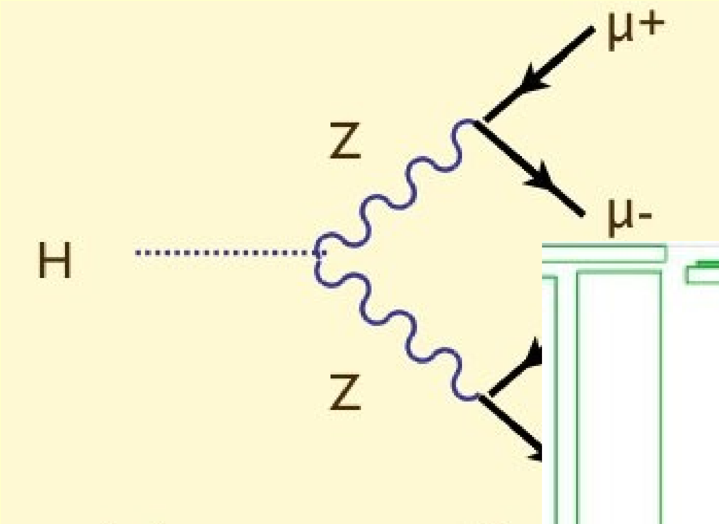


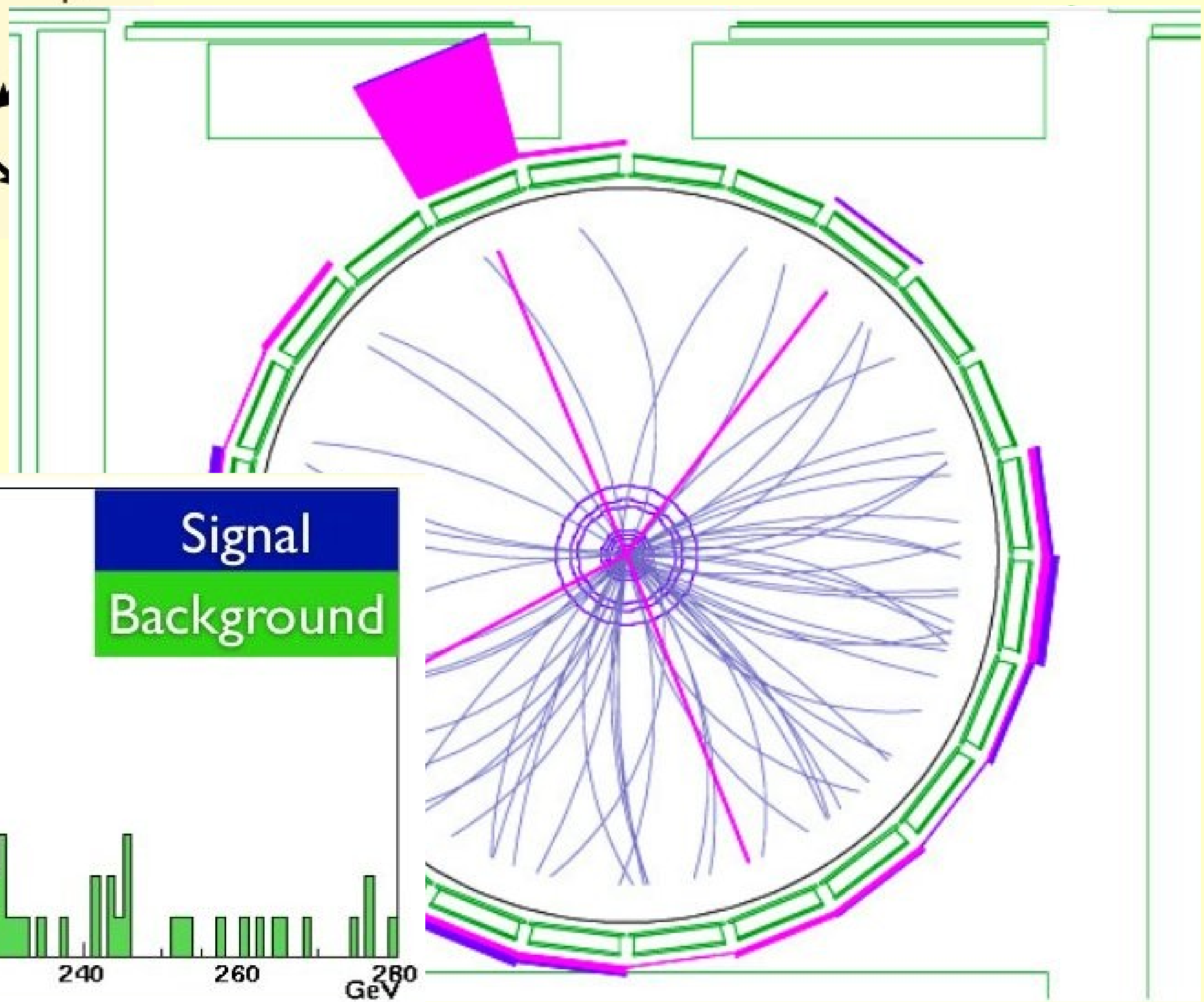
p
H
p
γ
γ

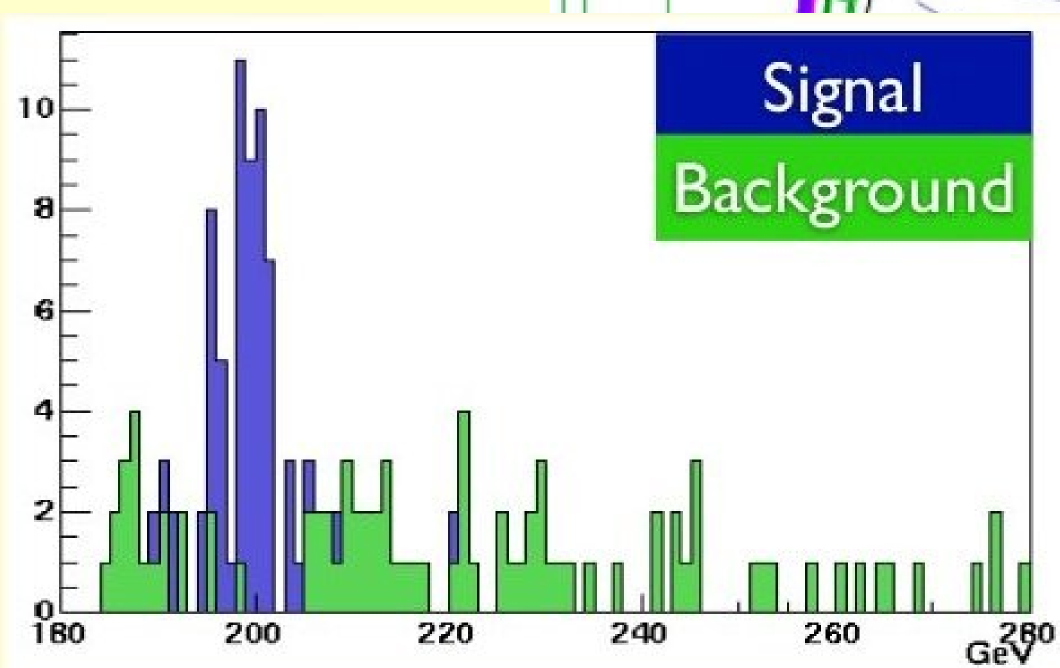


600
400
200
0
Events/500 MeV for 100 fb-1
110
120
130
140
m γγ (GeV)

H->ZZ->μμμμ



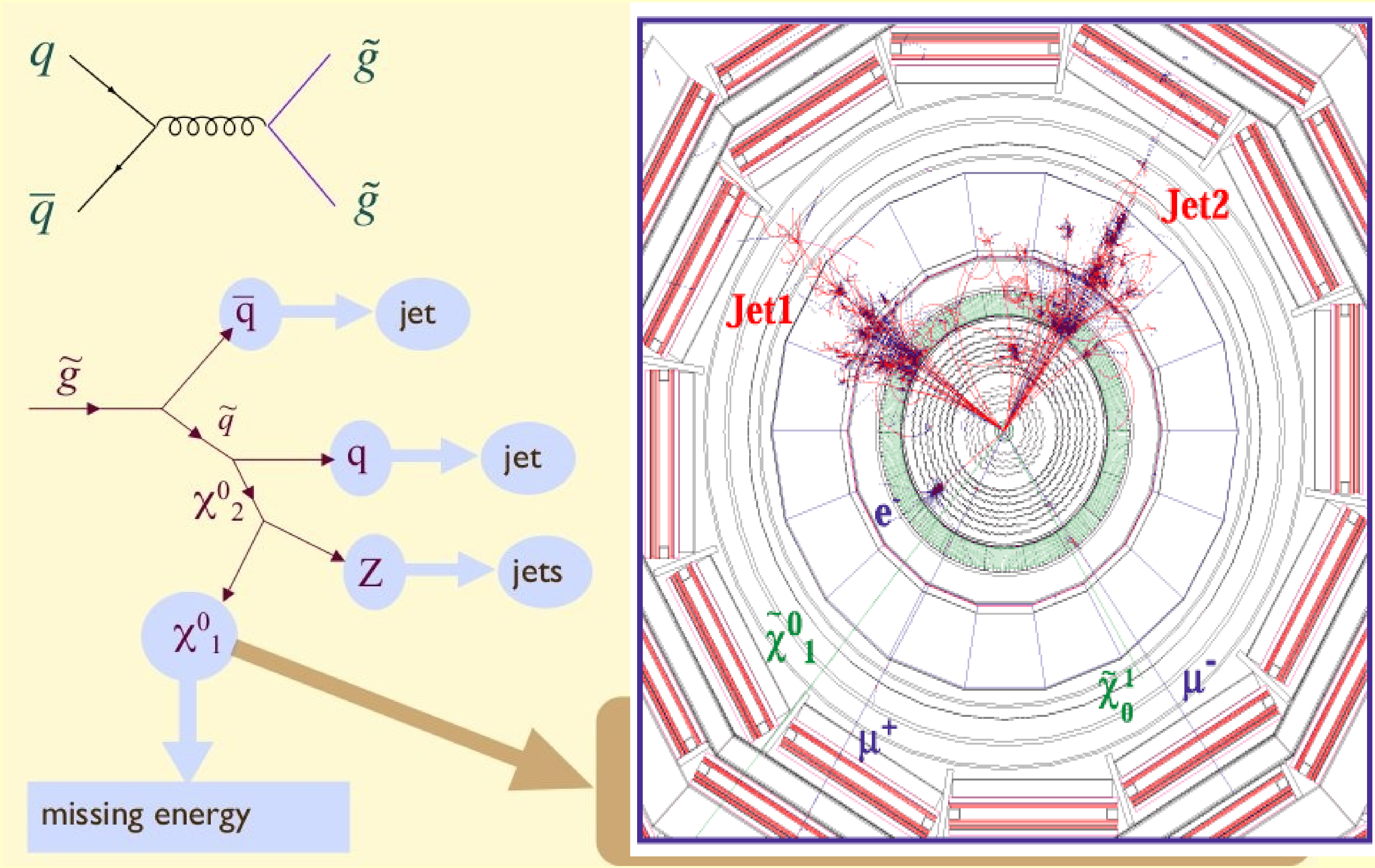




Che altro? SuperSimmetria

- 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

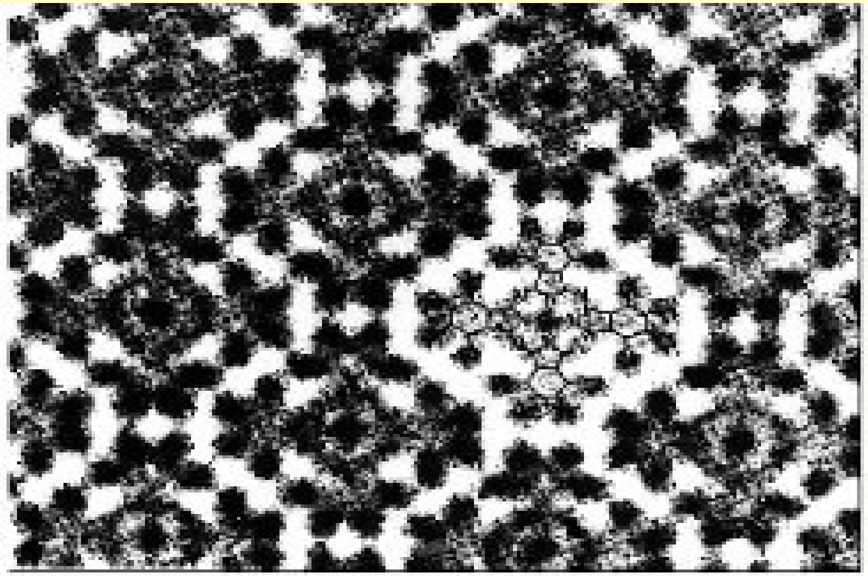


- Guardando dentro il piu' grande microscopio del mondo
- Potremmo vedere l'universo!

Backup

Vedere...

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



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