

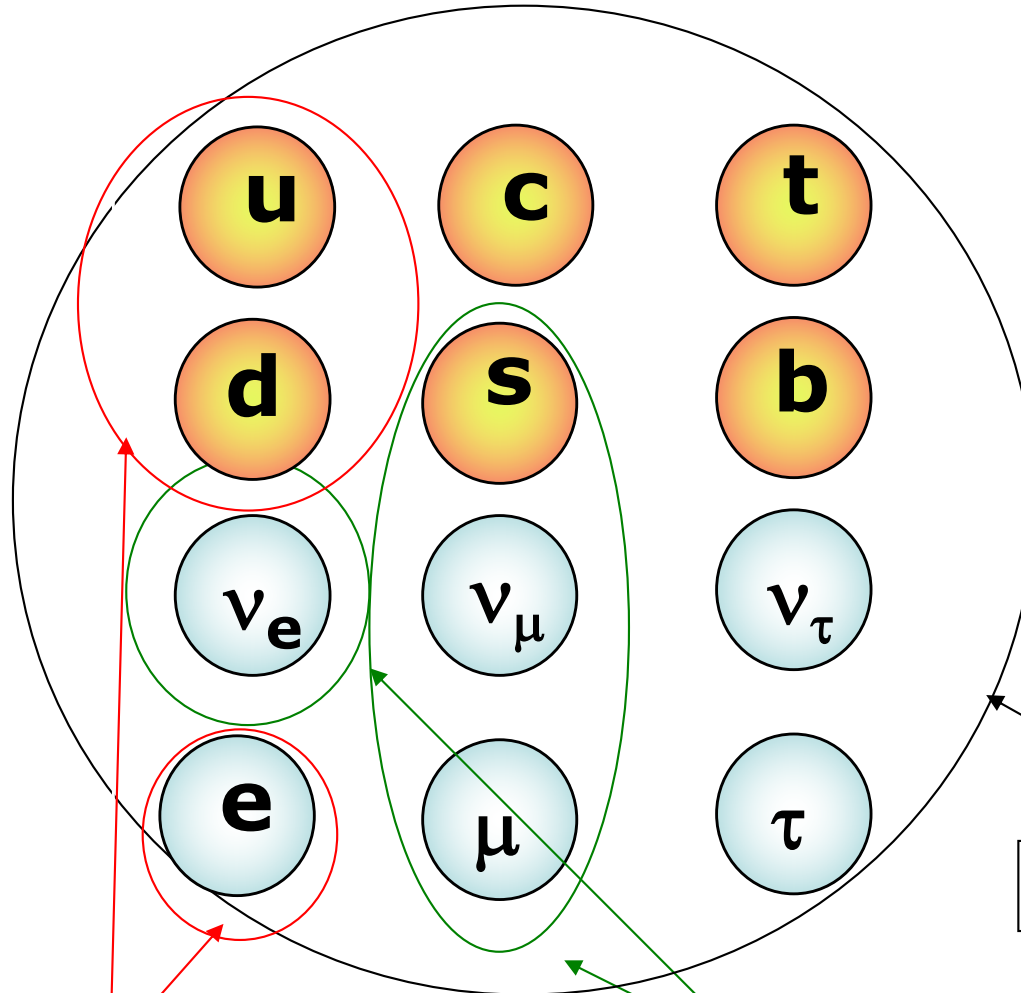
Il CERN e il Large Hadron Collider

M. Paganoni

11/5/2020

Le particelle elementari

Fermioni



Bosoni

8 gluoni

γ

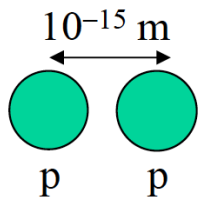
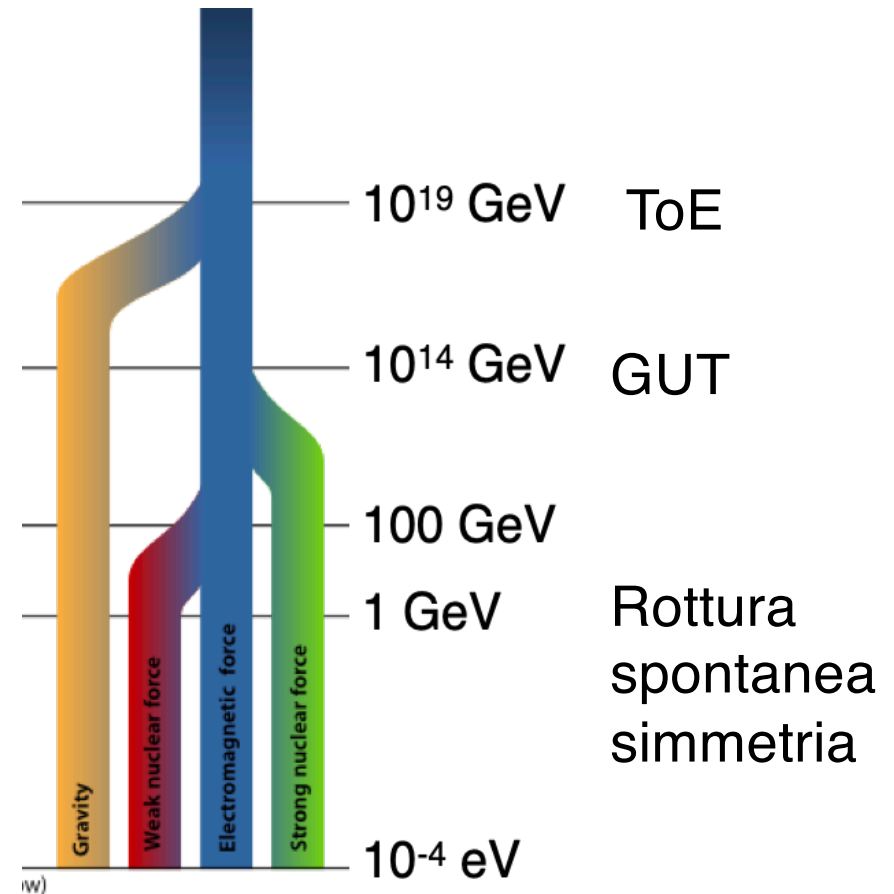
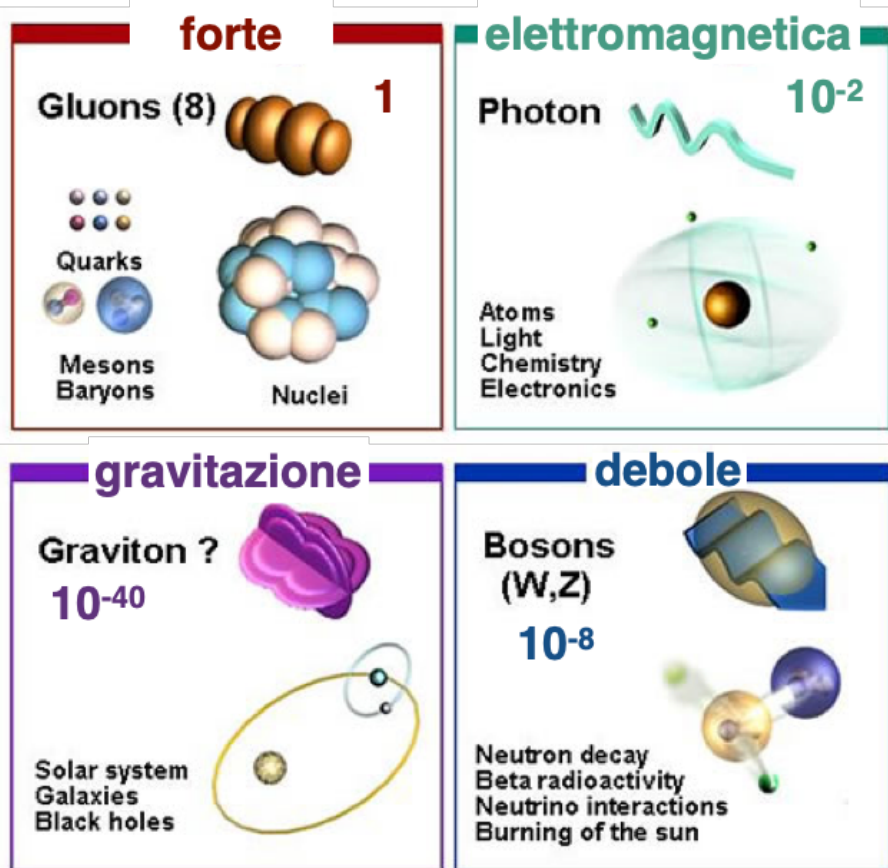
W^+, W^-, Z

Acceleratori

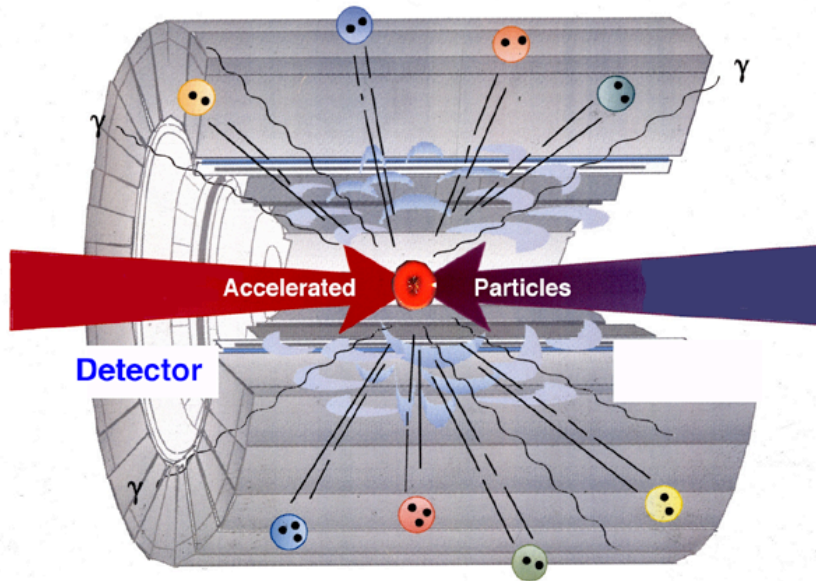
La materia di cui siamo fatti

Laboratorio / Raggi cosmici

Le interazioni Fondamentali



La fisica ai collisori



1) Concentrare energia sulle particelle nell' **Acceleratore**

2) Fare collidere le particelle

3) Identificare i prodotti dell' interazione nel **Rivelatore**

Studiando gli stati finali prodotti nelle collisioni capiamo quali sono i mattoni fondamentali della materia, a quali interazioni sono sensibili, come acquisiscono massa

$$N_X = \varepsilon \sigma_X \int \mathcal{L} dt$$

Confronto σ_X con σ_{SM} o previsioni teoriche di altri modelli

$$1 \text{ barn} = 10^{-24} \text{ cm}^2$$

$\sqrt{s} \sim E$ ai collisori, mentre $\sqrt{s} \sim \sqrt{E}$ su bersaglio fisso

Le alte energie delle particelle ci permettono di:

- ✓ sondare la materia su scale più piccole

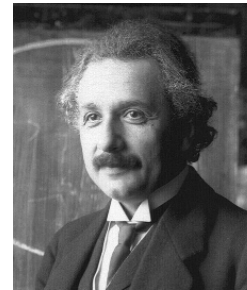
$$E = h \nu, \quad h = \text{costante di Planck}$$
$$1 \text{ TeV} \Rightarrow 0.001 \text{ fm}$$



Louis
de Broglie

- ✓ creare nuove particelle a grande massa

$$E = m c^2$$



Albert
Einstein

- ✓ studiare la dinamica dell' universo poco dopo il big bang

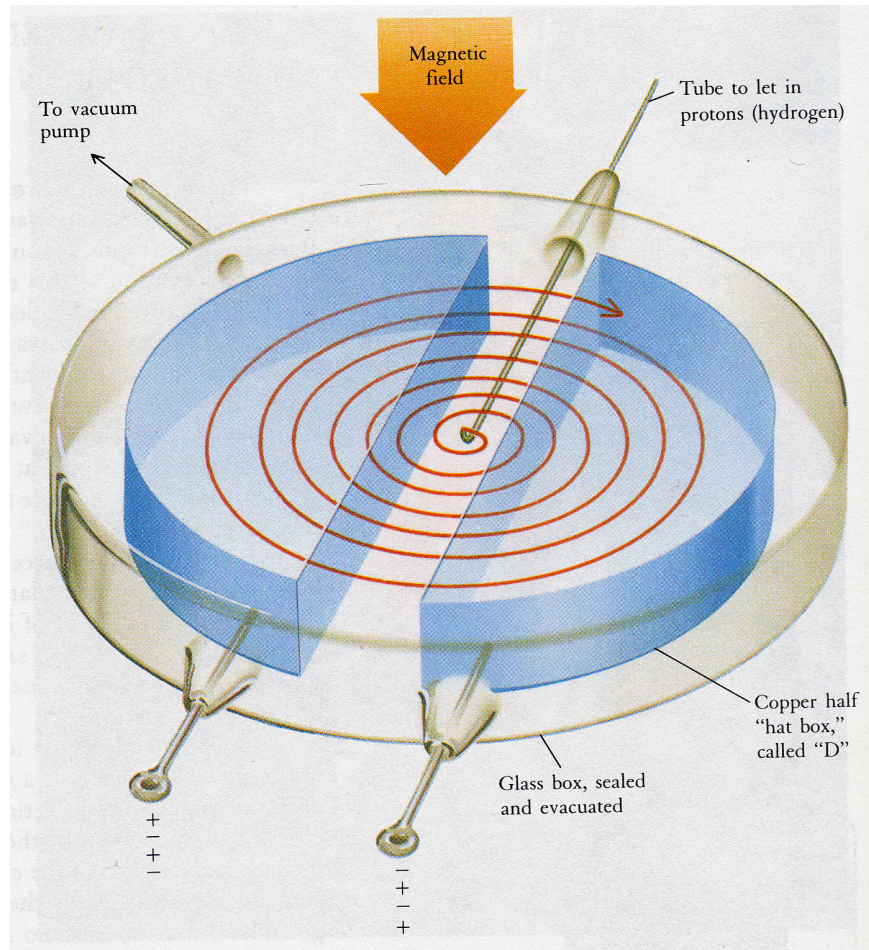
$$E = kT, \quad k = \text{costante di Boltzmann}$$
$$1 \text{ eV} \sim O(10^5) \text{ K} \quad 1 \text{ TeV} \sim O(10^{17}) \text{ K}$$



Ludwig
Boltzmann

I primi acceleratori

Ciclotrone



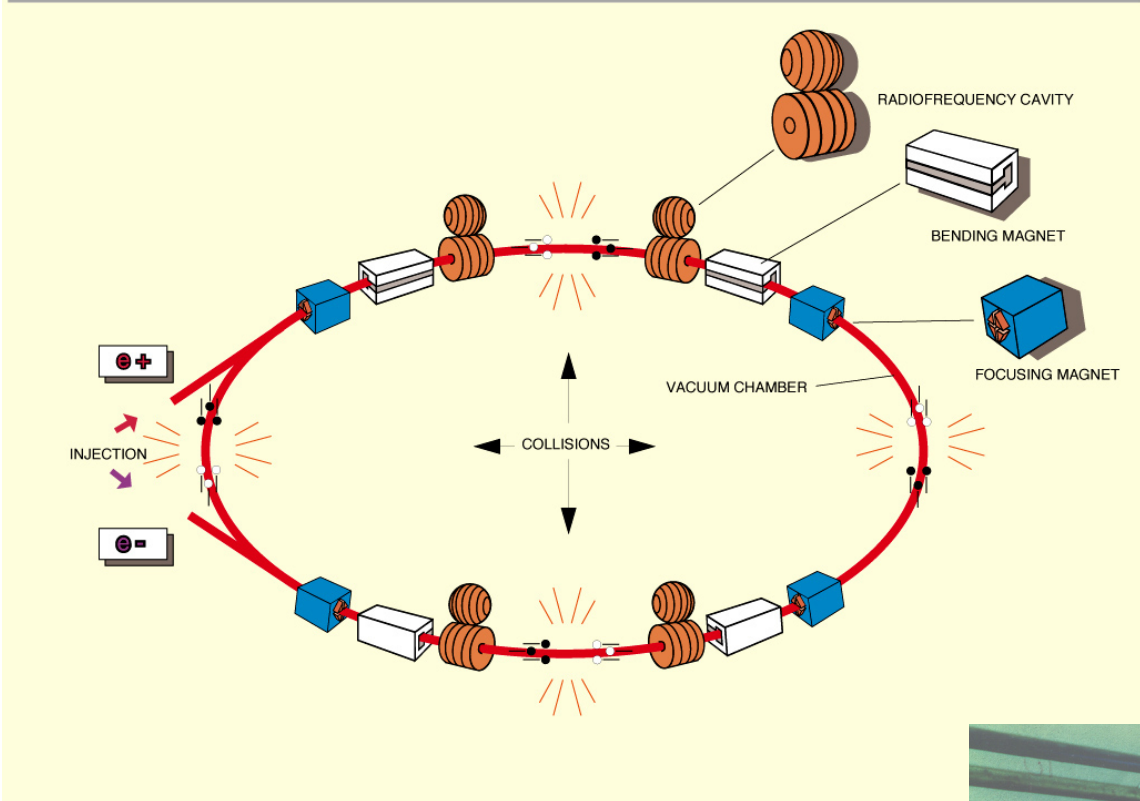
Cockroft Walton



1930, E. Lawrence, protoni da 100 MeV

CERN, protoni da 800 keV

THE PRINCIPAL MACHINE COMPONENTS OF THE LEP ACCELERATOR.



Il sincrotrone

1959: Proton Synchrotron

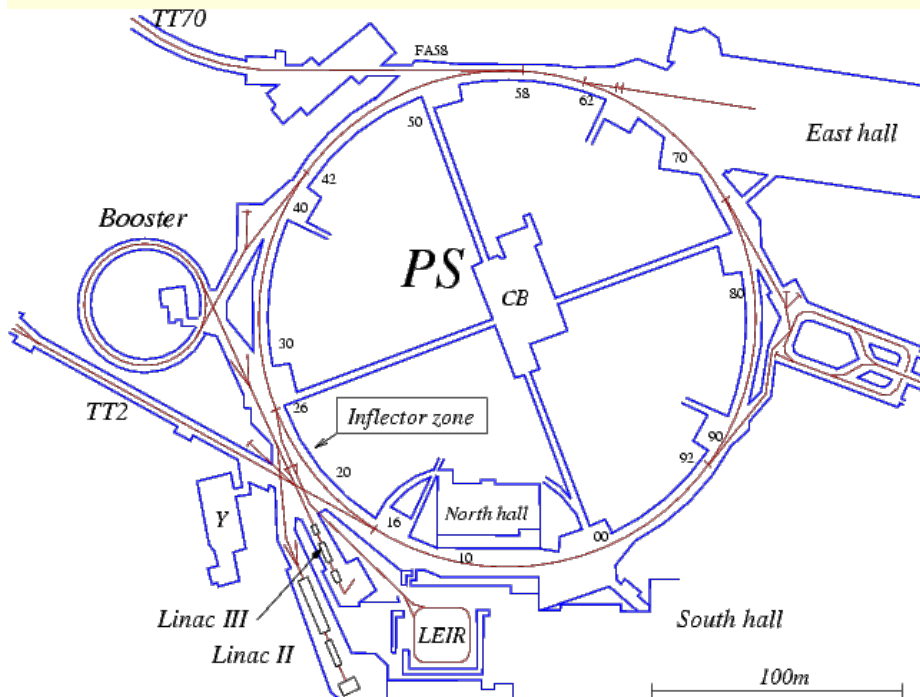
$$2\pi R = 628 \text{ m}$$

$$E_{\text{max}}(p) = 28 \text{ GeV}$$

1975: Super Proton Synchrotron

$$2\pi R = 7 \text{ km}$$

$$E_{\text{max}}(p) = 450 \text{ GeV}$$



CERN (Conseil Européen pour la Recherche Nucléaire)

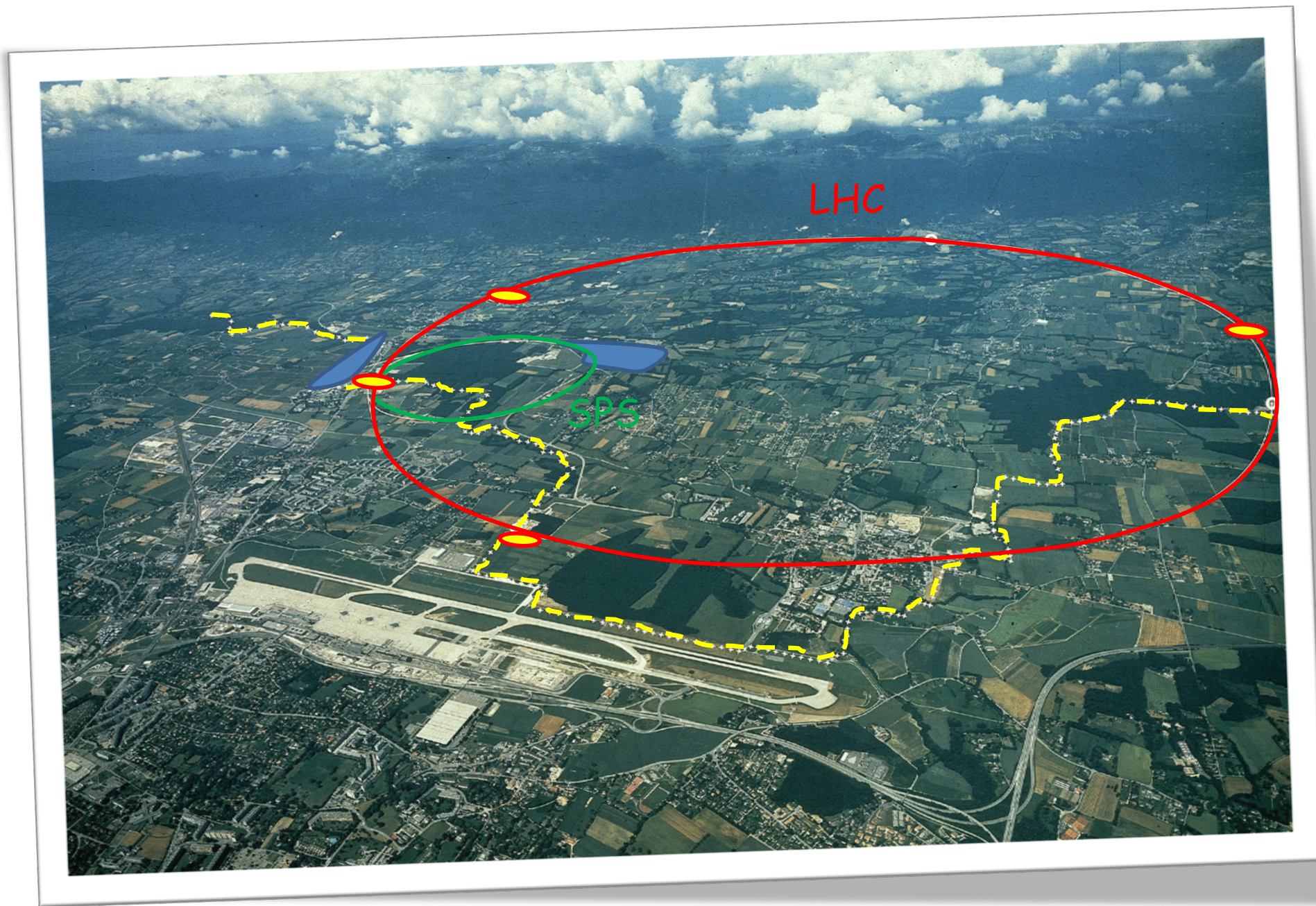
- ✓ Fondato nel 1954 da 12 Paesi tra cui l'Italia che, grazie all'Istituto Nazionale di Fisica Nucleare, ha un ruolo chiave
- ✓ Oggi CERN = European Laboratory for Particle Physics
- ✓ È il più grande laboratorio di Fisica Fondamentale al mondo



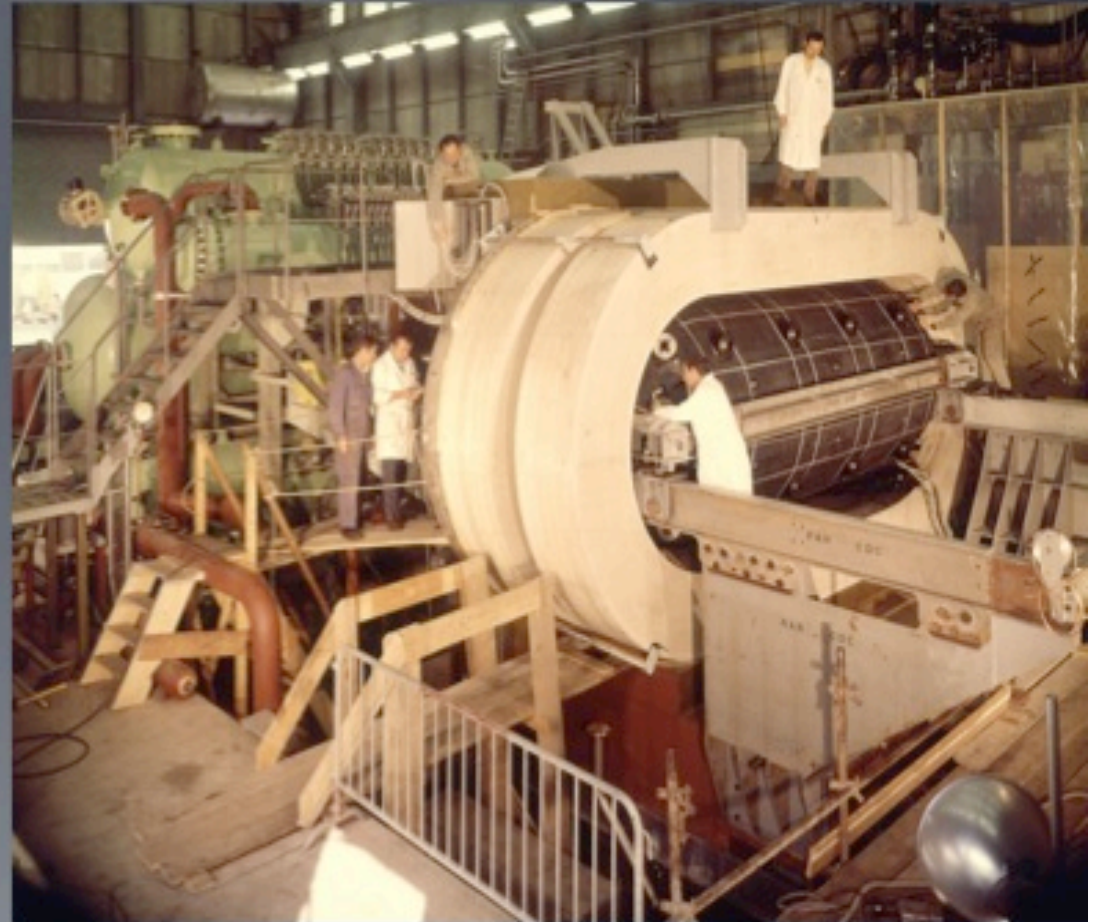
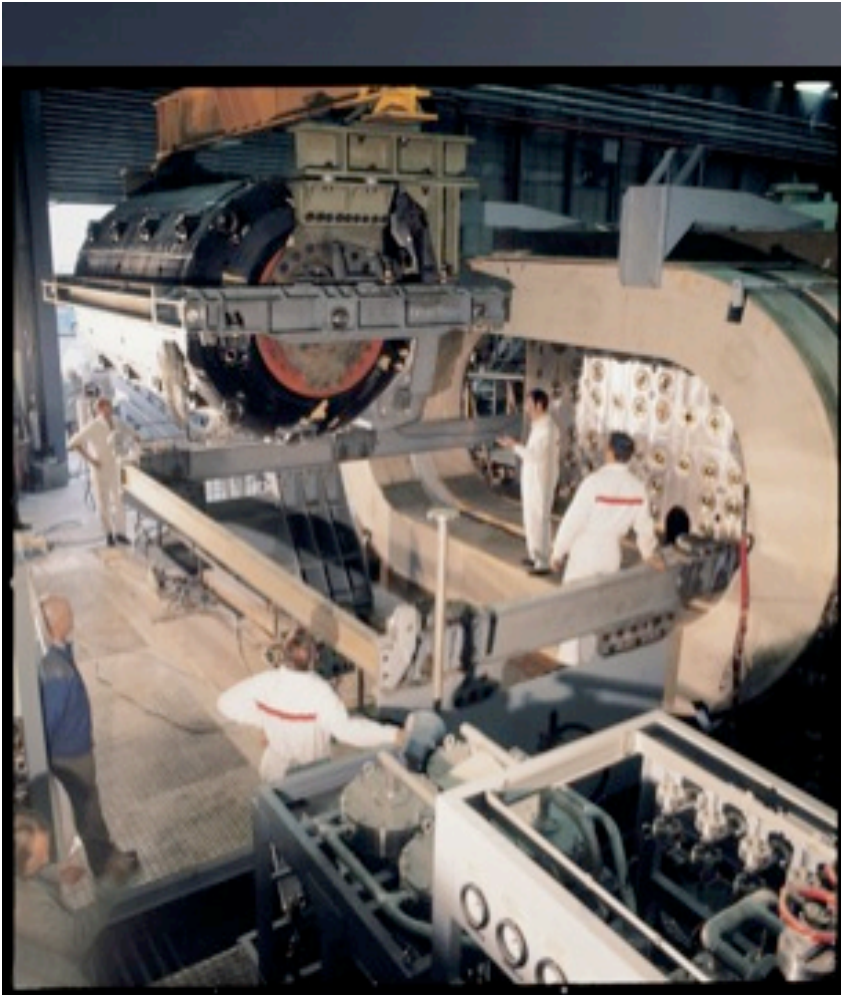
Premi Nobel: J. Steinberger, F. Bloch, S. Ting, G. Charpak, C. Rubbia, S. van der Meer



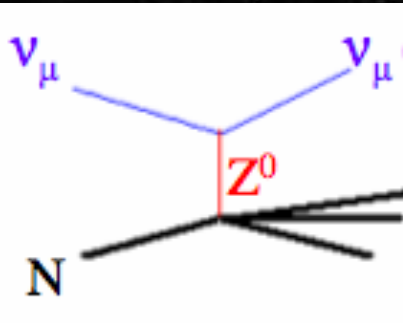
CERN site



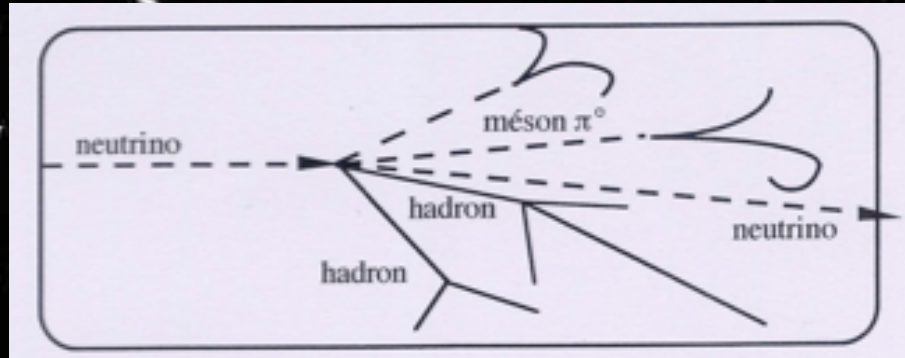
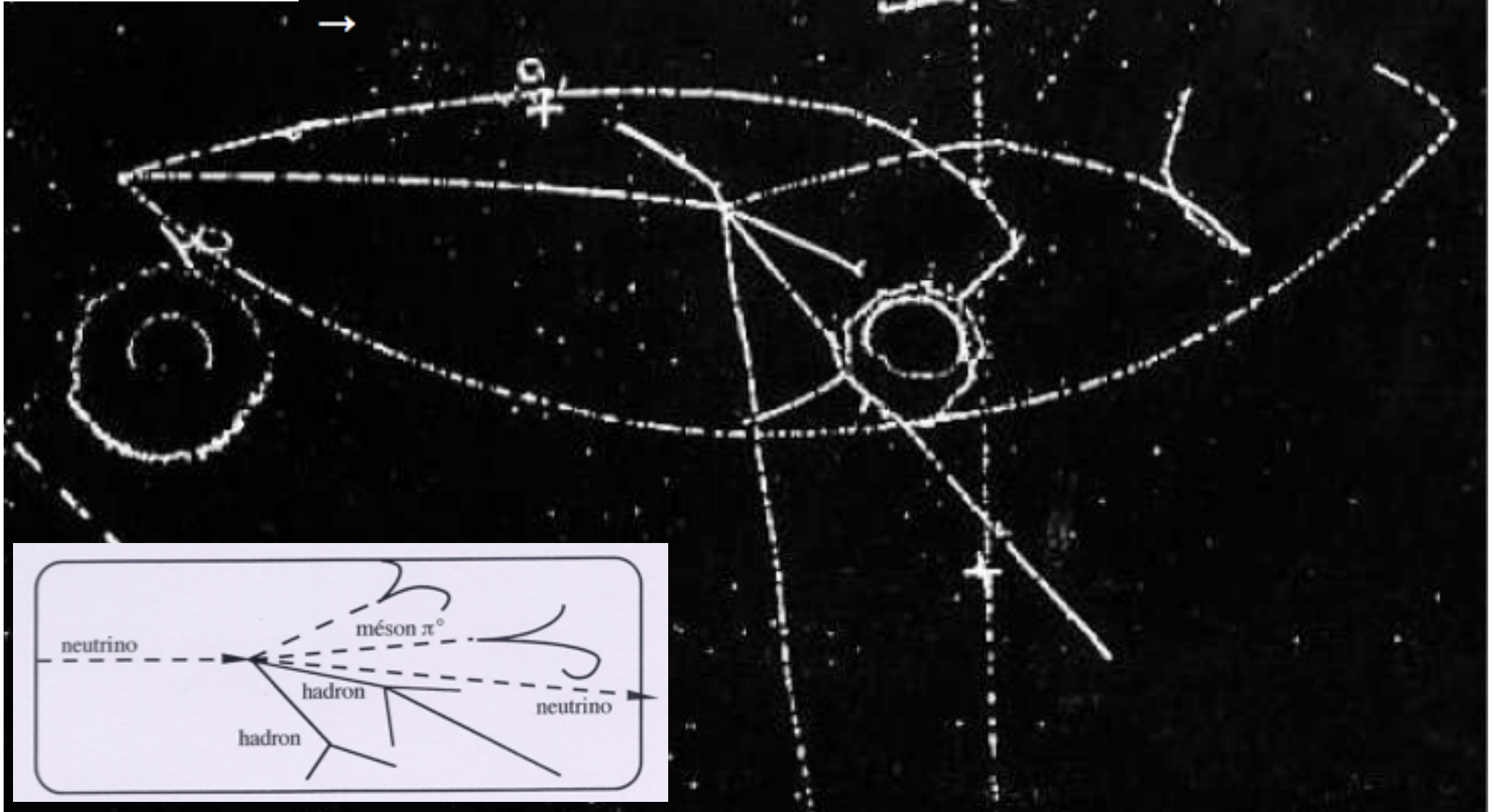
Installazione camera a bolle Gargamelle (1970)



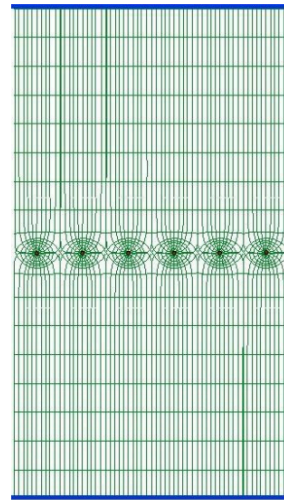
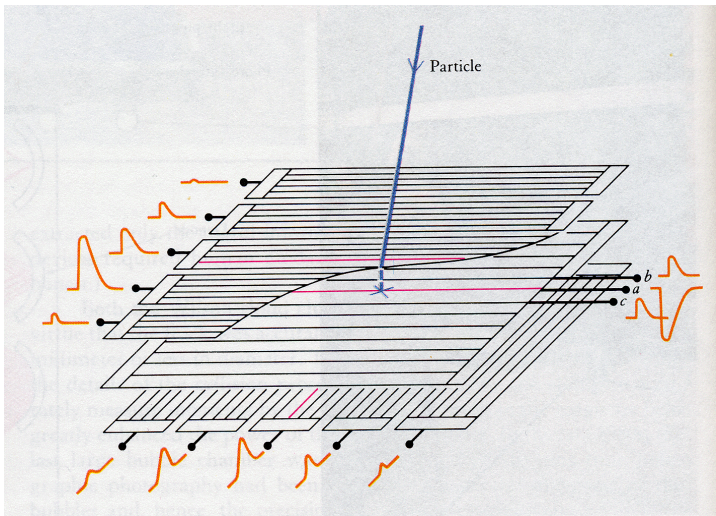
Evento di corrente debole neutra (1973)



neutrinos incident



Multi Wire Proportional Chamber



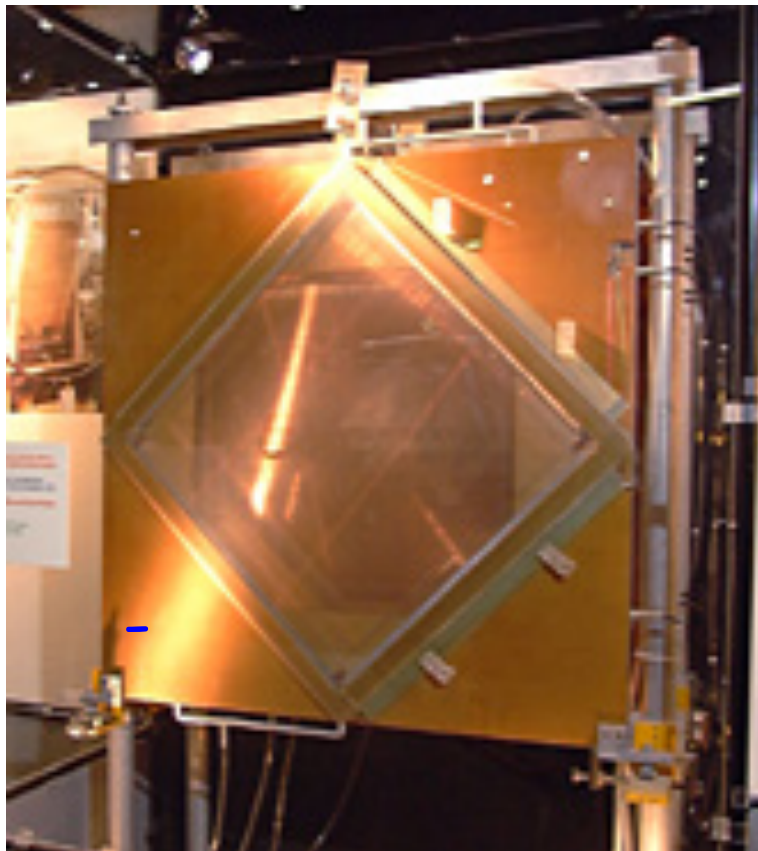
G.Charpak, 1967
(Premio Nobel nel 1992)

Primo rivelatore elettronico,
permette alte statistiche

$d \sim 1 \text{ mm}$
 $R_{\text{wire}} \sim 20 \text{ } \mu\text{m}$

$$\sigma \sim d / \sqrt{12} \sim 300 \text{ } \mu\text{m}$$

Amplificazione nel gas necessaria,
per un buon rapporto S/N



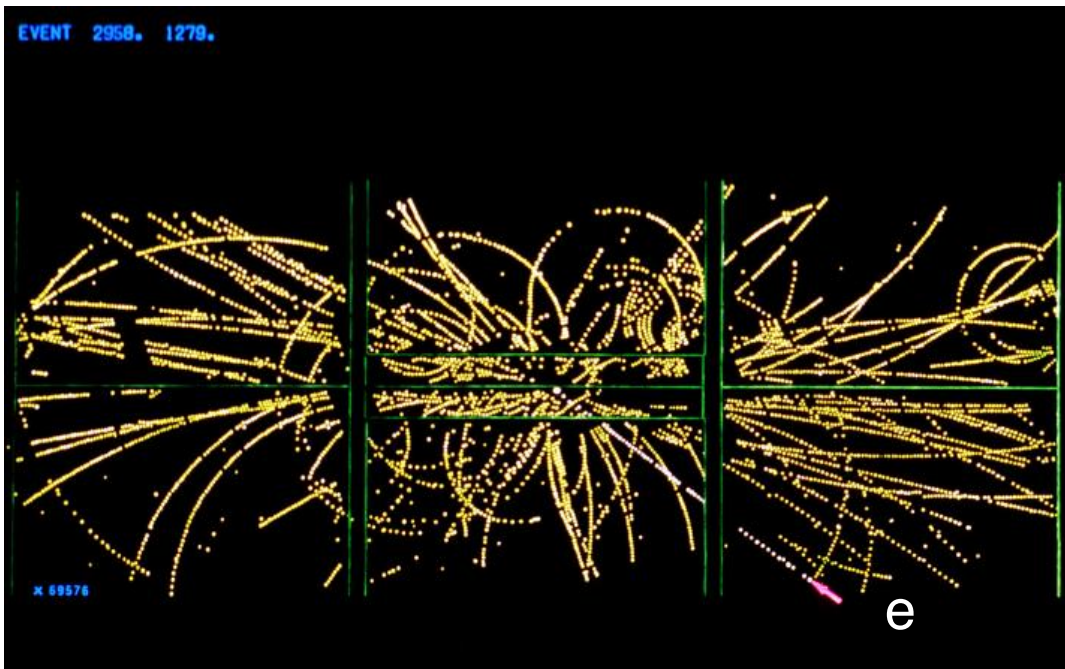
Scoperta W e Z (UA1 e UA2 a collider Sp \bar{p} S)

C.Rubbia e S. Van der Meer (Premio Nobel nel 1984)

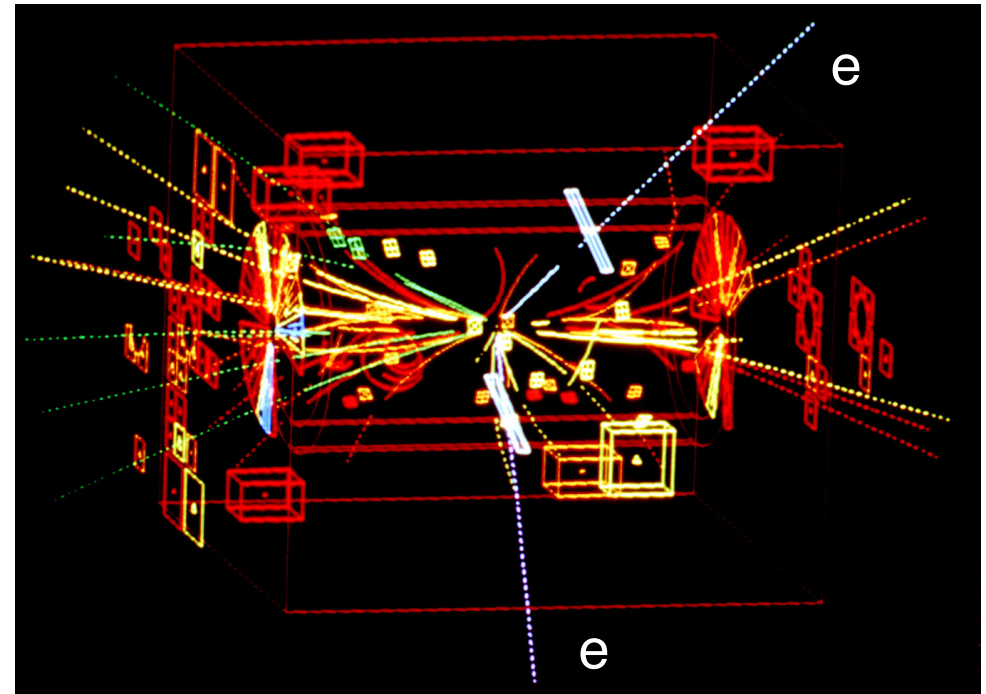
trasformano SPS in collisore $p\bar{p}$ con $\sqrt{s} \sim 540 \text{ GeV}$ (630 GeV)
e buona luminosità dei \bar{p} grazie allo "stochastic cooling"

UA1 e UA2 prendono dati dal 1981 al 1990

- Scoperta del W (1982)
- Scoperta della Z (1983)



$W \rightarrow e \nu$



$Z \rightarrow e^+e^-$

Large Electron Positron Collider (LEP)

Rivelatori ALEPH, DELPHI, L3 e OPAL al collisore e^+e^- di 27 km

LEP-I (1989 - 1995)

14/7/1989: i primi fasci circolano con $\sqrt{s} \sim 91 \text{ GeV}$

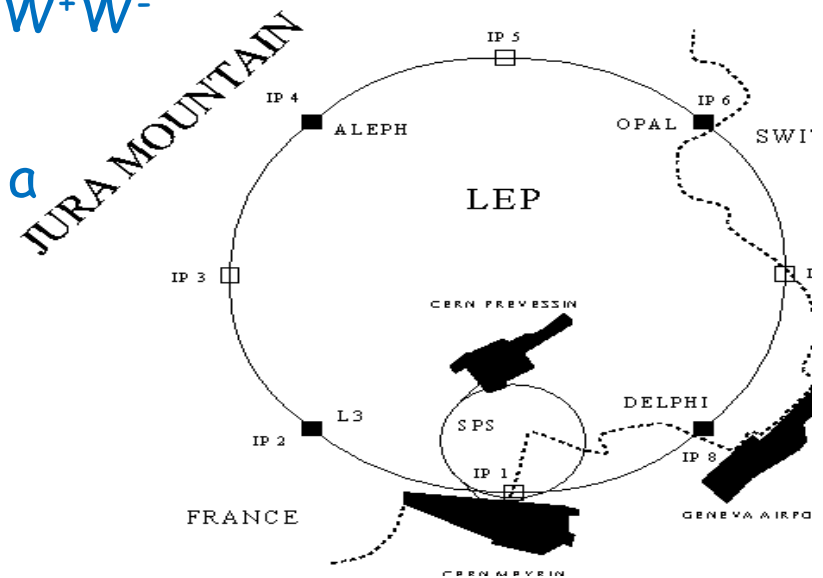
Ott.1989: viene misurata Numero famiglie neutrini = 3

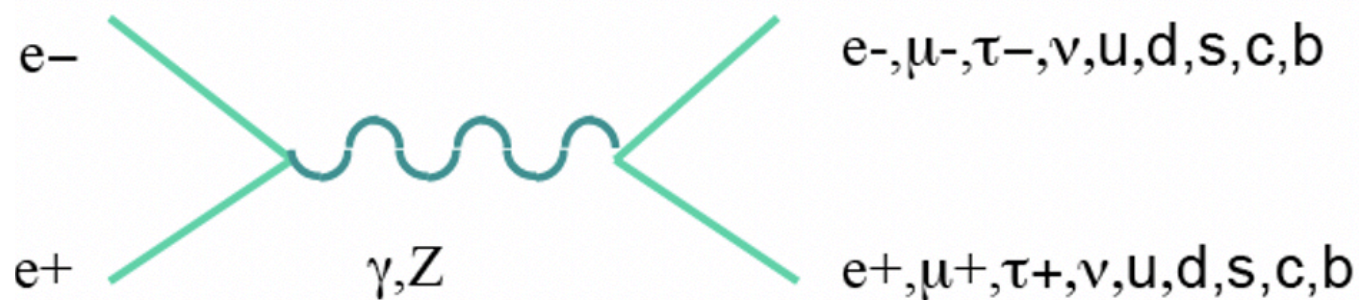
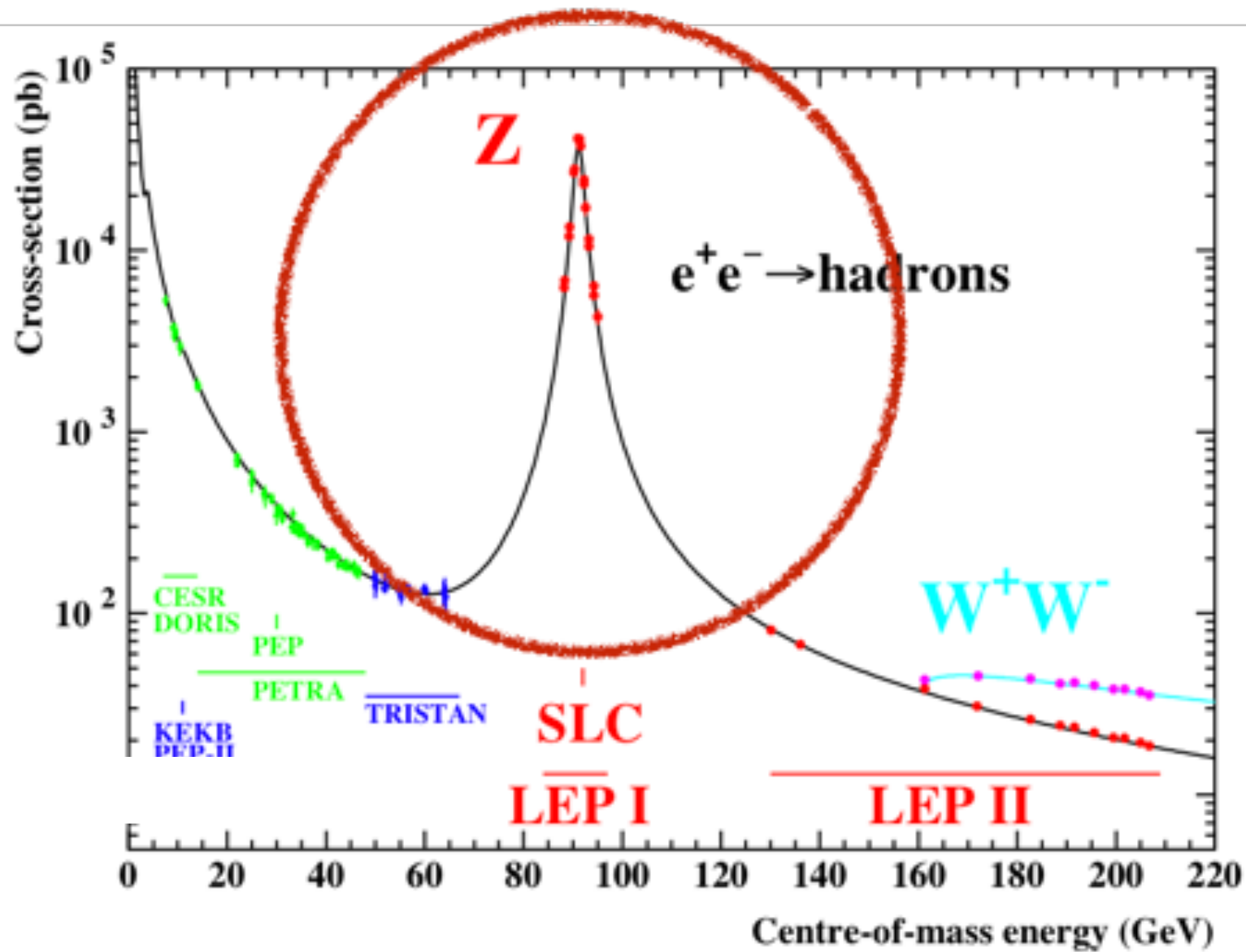
Vengono prodotte 17 milioni di Z

LEP-II (1995 - 2000)

Aggiungendo 288 cavità superconduttrici si raddoppia energia fino a $\sqrt{s} = 209 \text{ GeV}$ nel 2000, con produzione W^+W^-

Possibilità di scoperta di Higgs SM fino a $M_H \sim 110 \text{ GeV}/c^2$

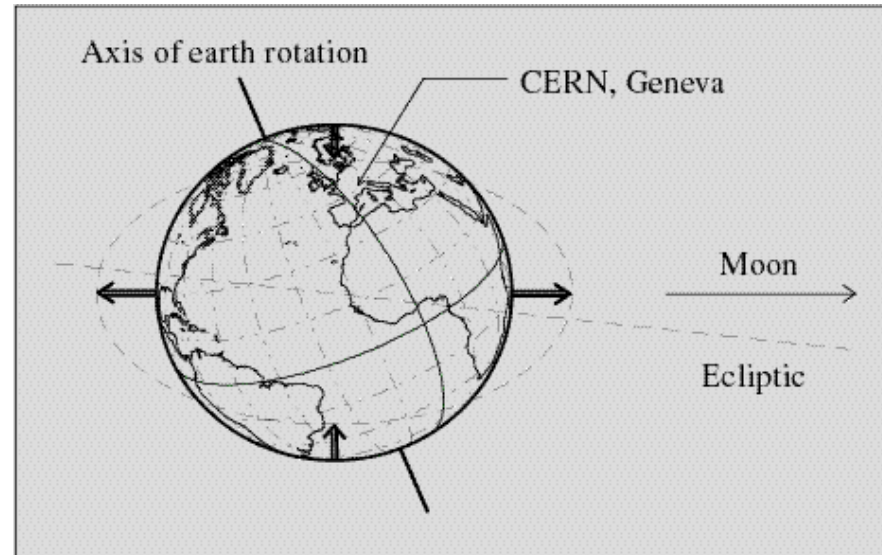
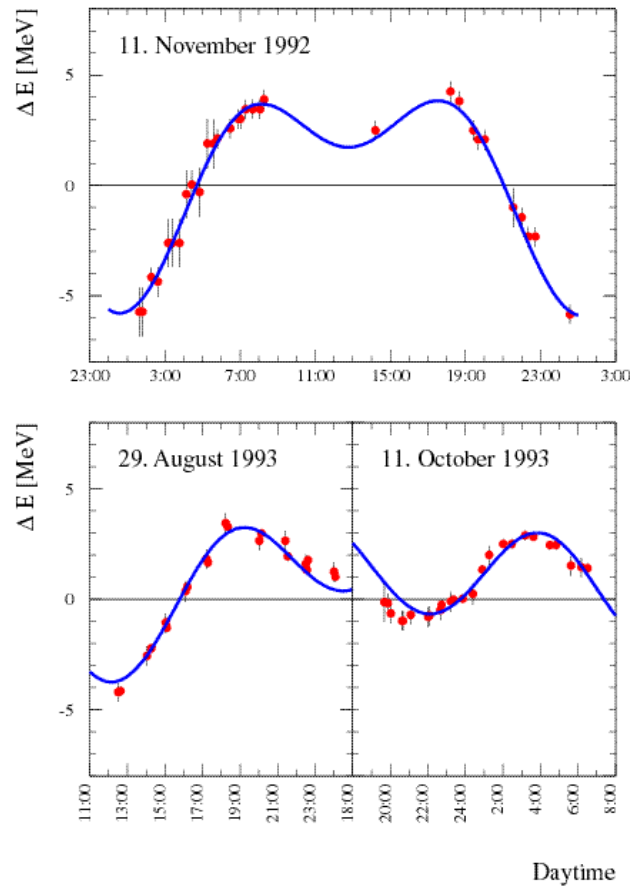




Misura energia del fascio a LEP

Precise determination of the LEP beam energy
Precise measurement of the Z mass and width

(10^{-5} relative accuracy, ~ 1 MeV)



Small changes of energy accurately measured
(energy change from 1mm circumference change)

Il modello standard non predice le masse delle particelle
Quale è l'origine della massa ?

Perché questo pattern di masse ?



The Higgs Mechanism

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

PHYSICAL REVIEW LETTERS

19 OCTOBER 1964

SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES*

Englert,† and T. W. B. Kibble
Imperial College, London, England
October 1964)

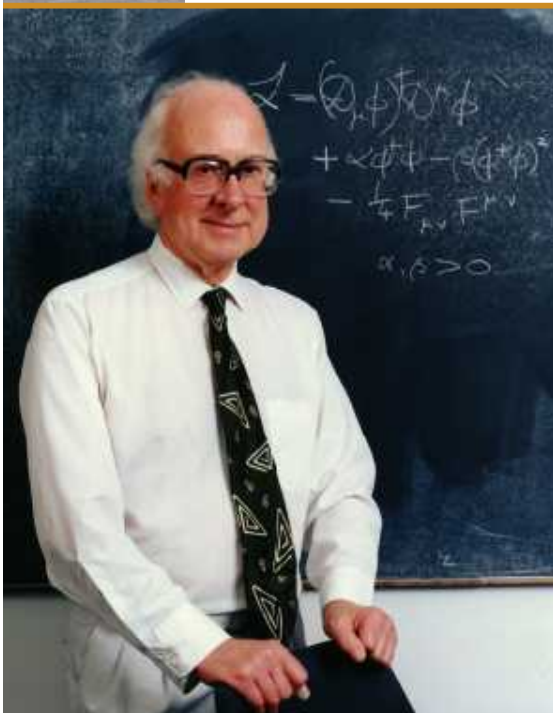
SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES

A. A. MIGDAL and A. M. POLYAKOV

Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966

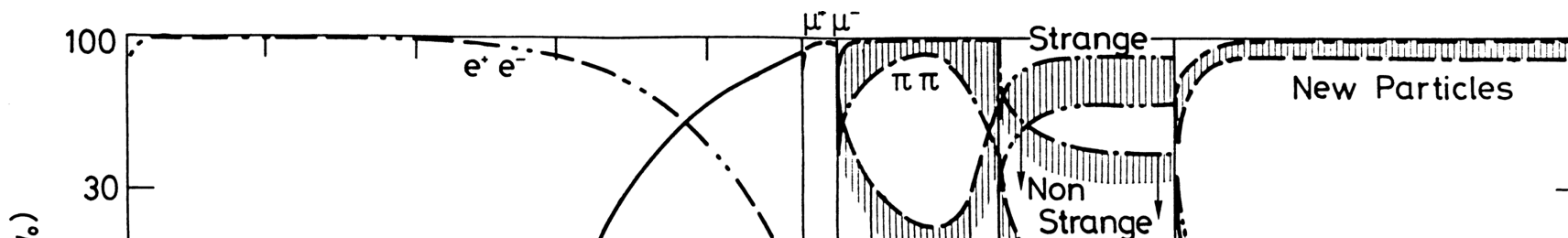
J. Exptl. Theoret. Physics (U.S.S.R.) 51, 135-146 (July, 1966)

The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass



Higgs Boson Phenomenology - Summary in 1975

J. Ellis, M.K. Gaillard, D.V. Nanopoulos,

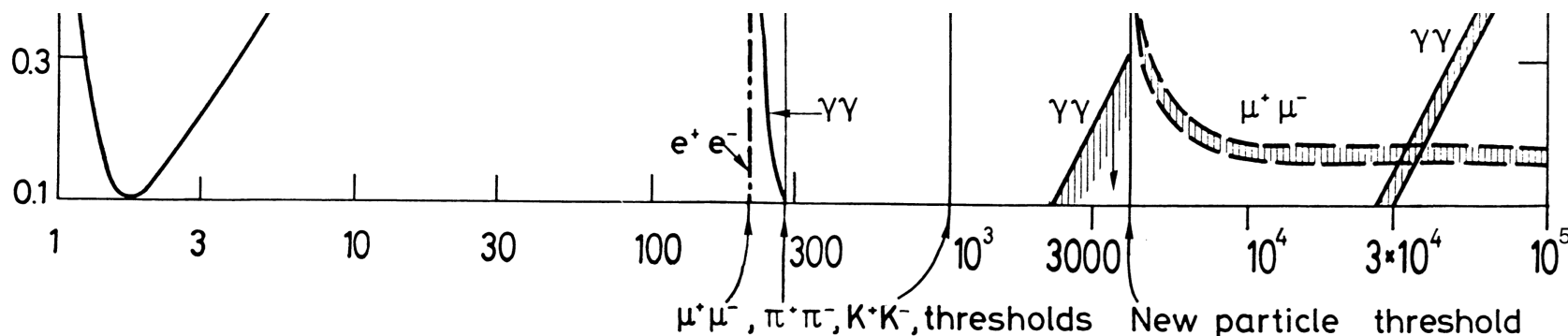


We should perhaps finish with an apology and a caution. We

apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm ^{3),4)} and for not being sure of

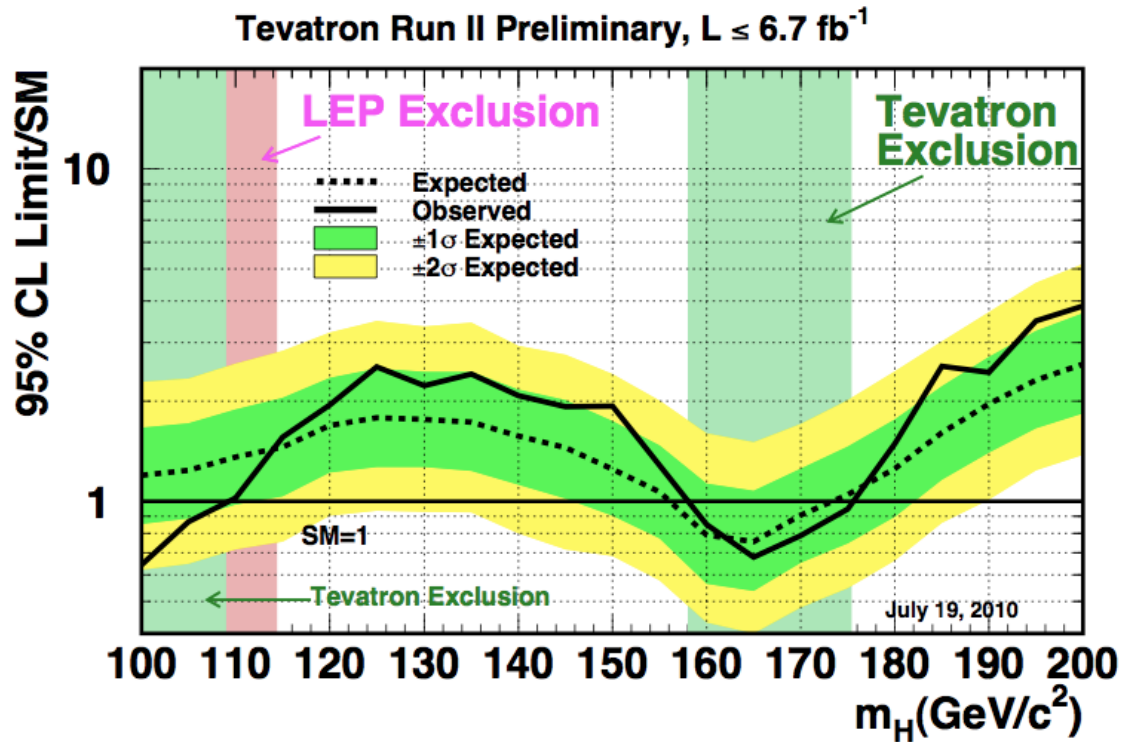
its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental

searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.



Higgs Boson Mass (MeV)

Ricerca del bosone di Higgs

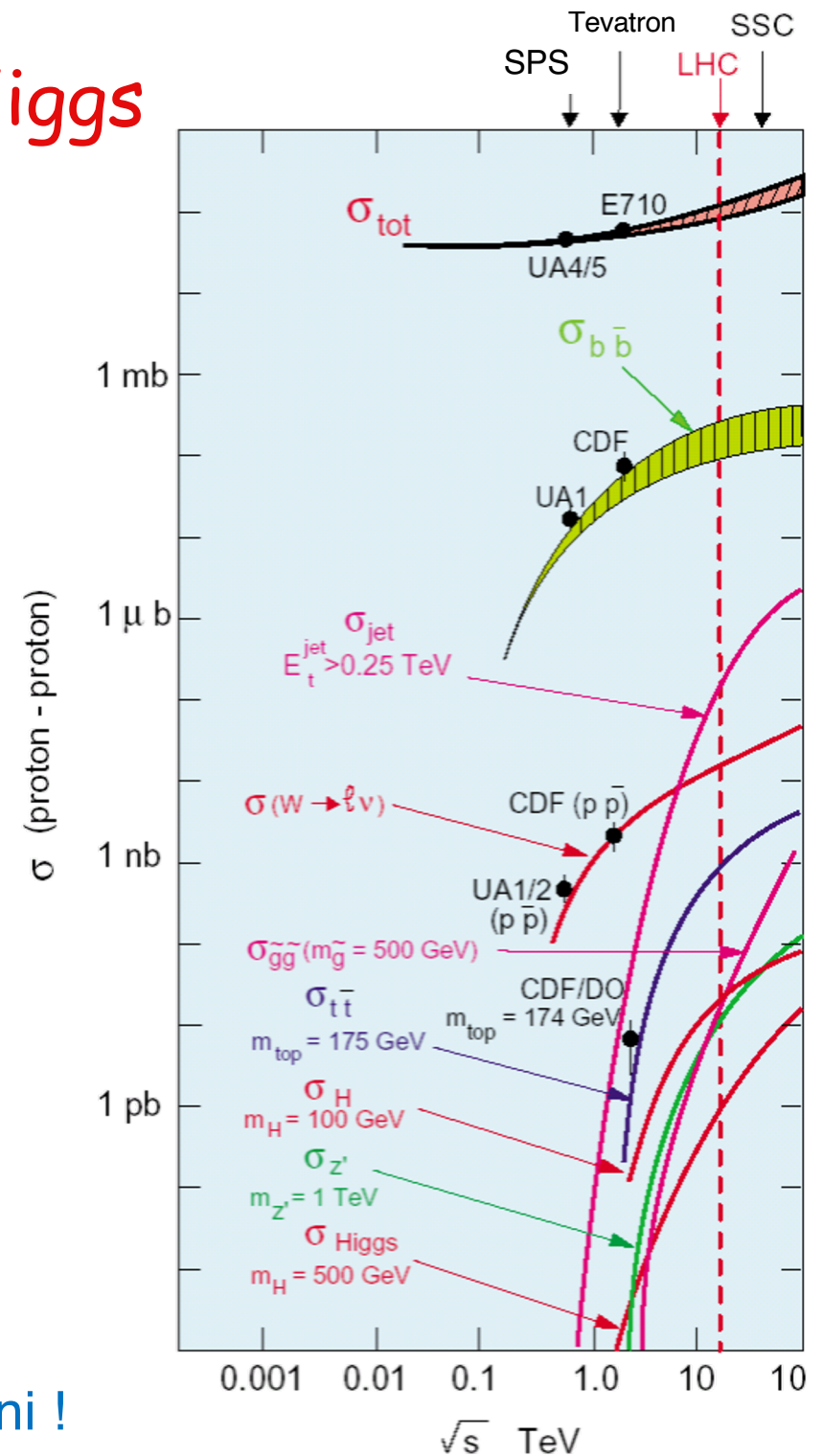


LEP direct exclusion: $m_H > 115 \text{ GeV}/c^2$

LEP precision meas. $m_H < 200 \text{ GeV}/c^2$

Fissata m_H nel Modello Standard si può calcolare sezione d'urto di produzione σ , branching ratio, ...

σ cresce molto rapidamente con E dei protoni !

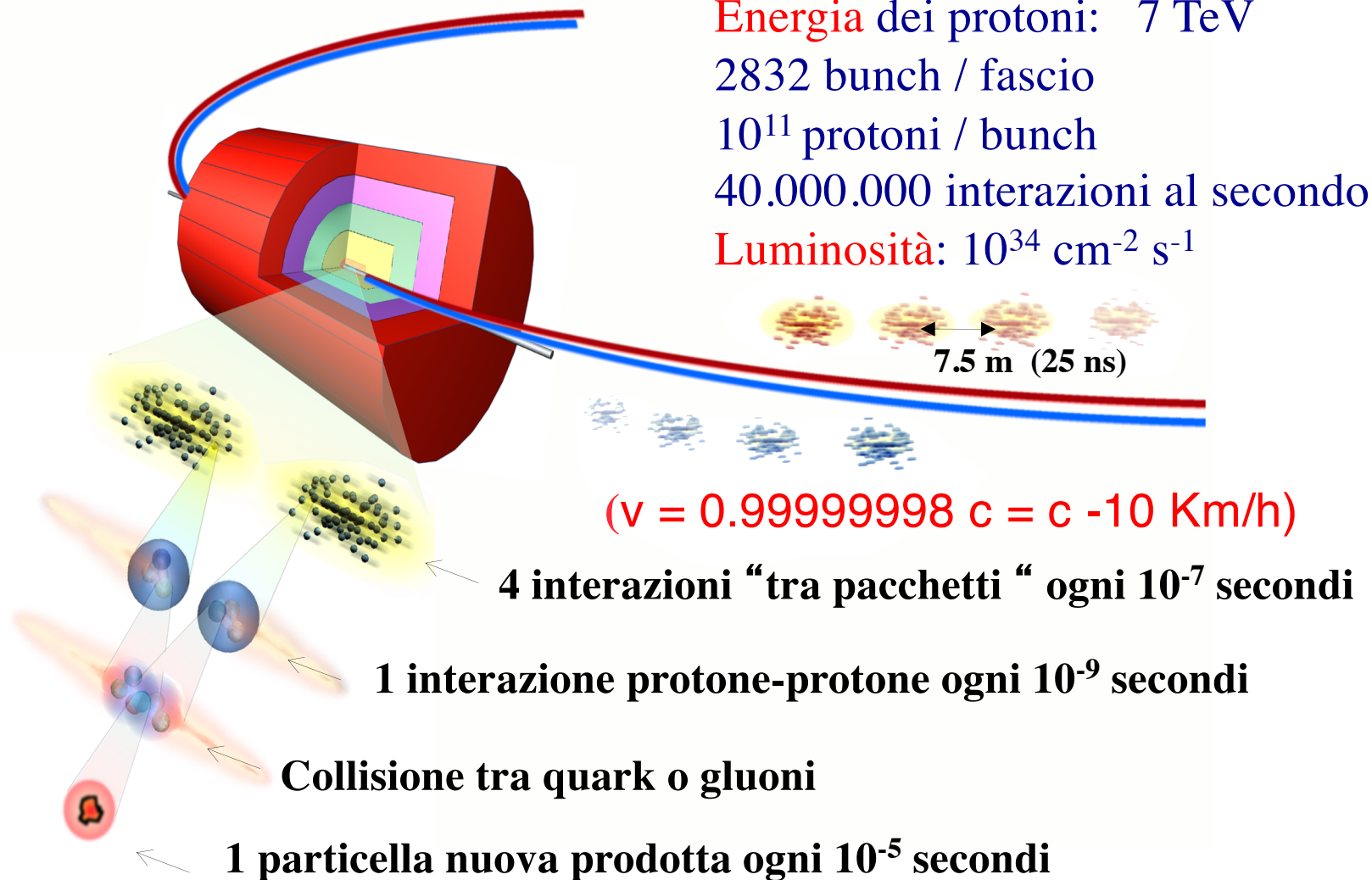


Large Hadron Collider

Approvato da ECFA nel 1984

Collisore protone protone nel tunnel di LEP ($2\pi R = 27$ km)

Elemento critico: 1232 **dipoli superconduttori** ($B = 8.3$ T) alla temperatura dell'Elío superfluido (1.9 K)

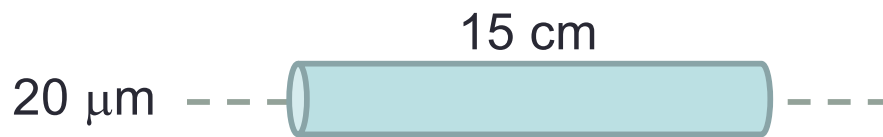


Large Hadron Collider /2

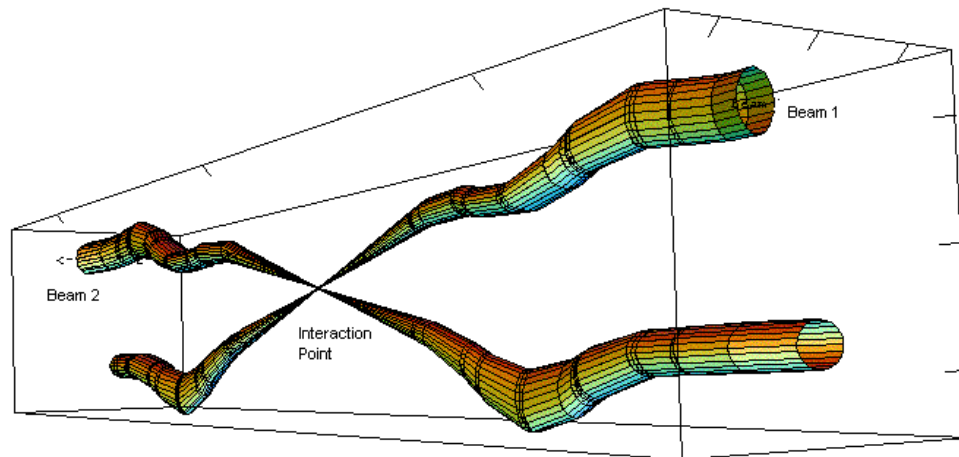
E_{cinetica} di moscerino (60 g) con velocità 20 cm/s \sim 7 TeV (1 protone ad LHC)

E_{cinetica} di moto (1500 kg) con velocità 40 m/s \sim 1.3×10^5 J (1 bunch ad LHC)

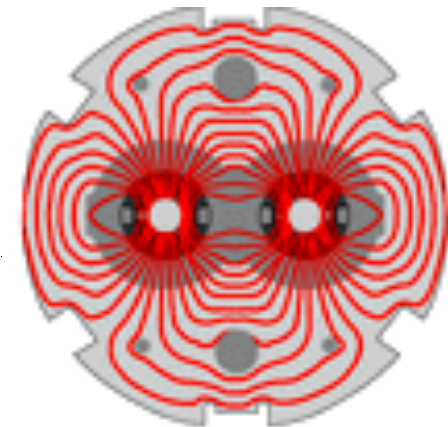
E_{cinetica} di moto (20000 ton) con velocità 6 m/s \sim **360 MJ** (1 fascio ad LHC)

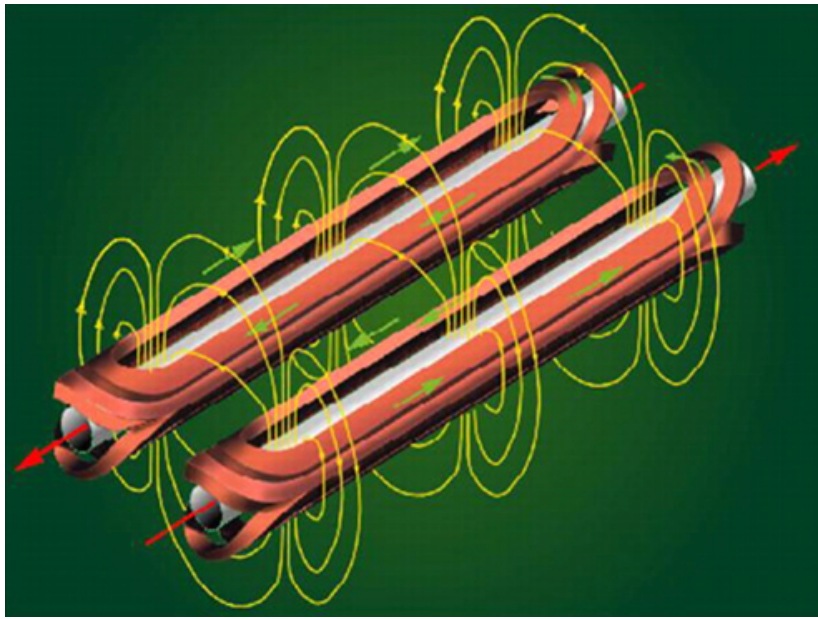


Liquefa 500 kg di rame



Relative beam sizes around IP1 (Atlas) in collision

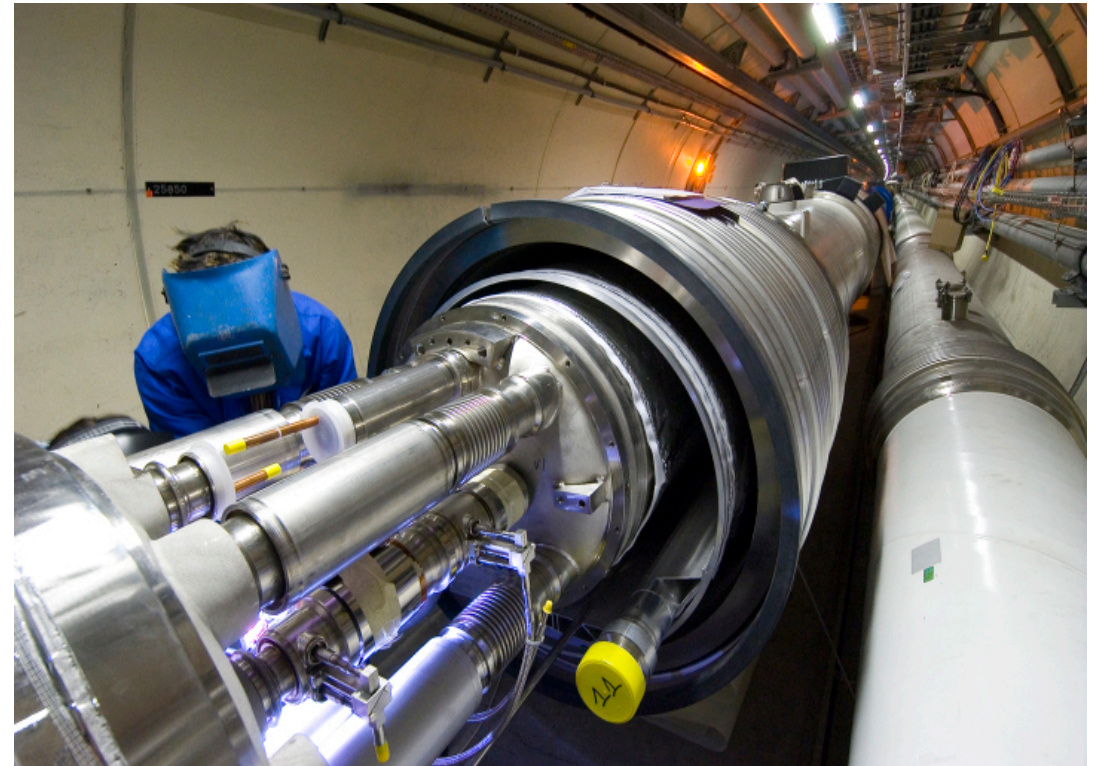




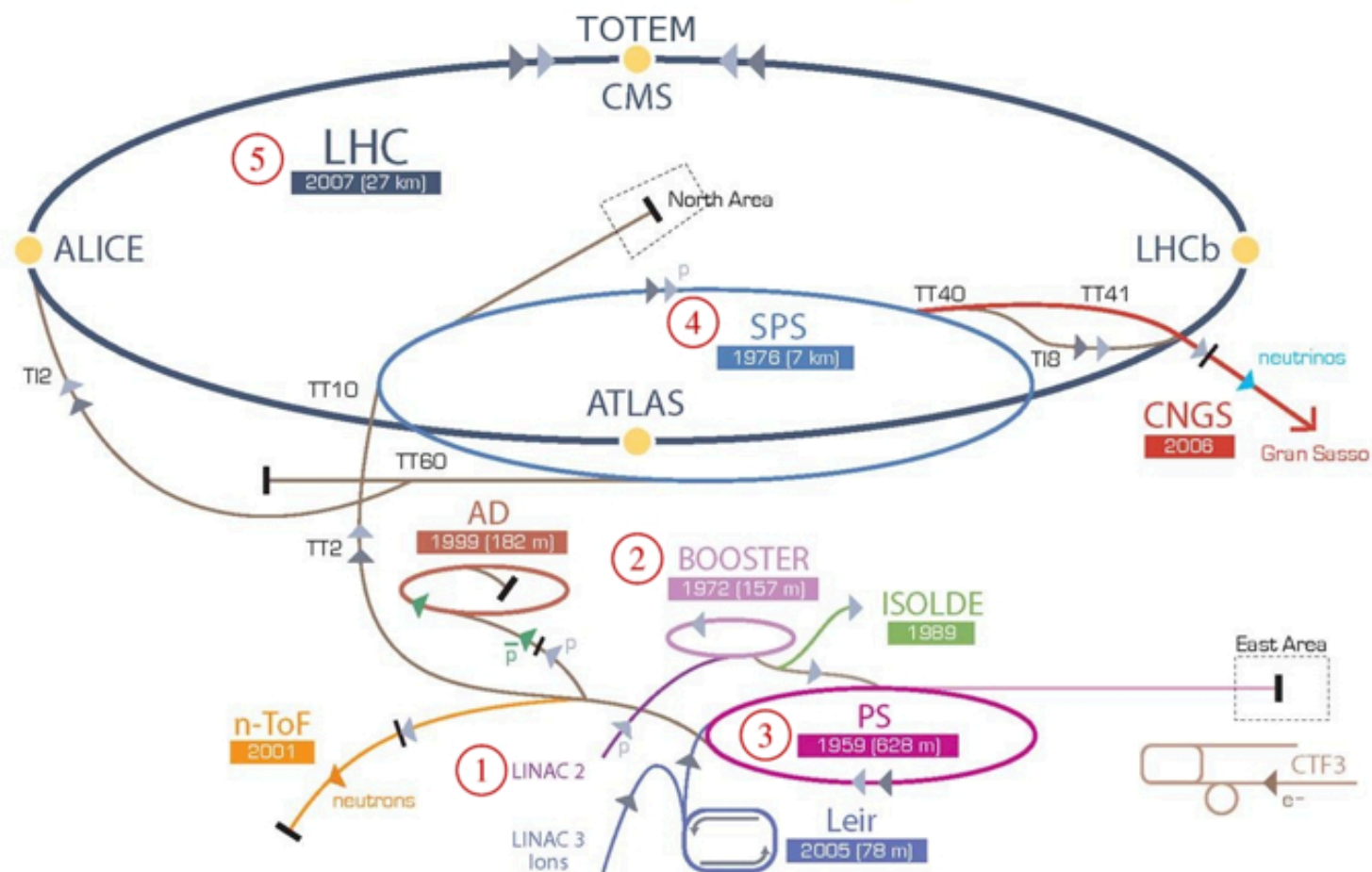
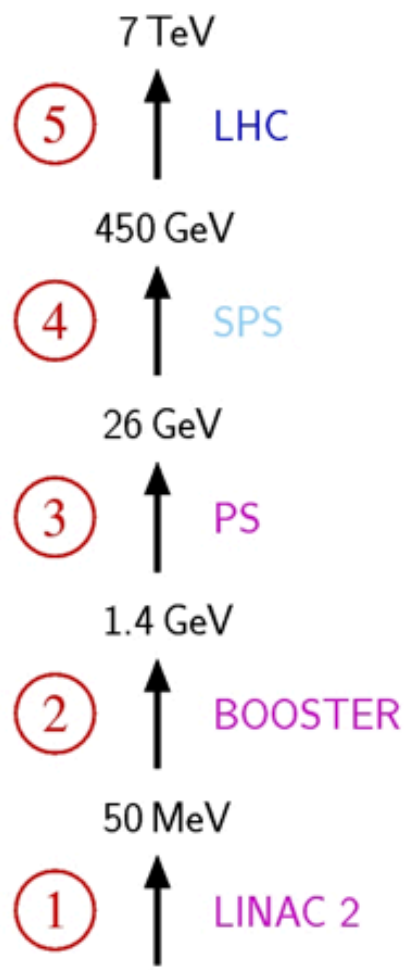
Superconduttività permette di salire di un fattore 100 nella densità di corrente, da $1-5 \text{ A/mm}^2$ a $100-500 \text{ A/mm}^2$, grazie al crollo della potenza dissipata

120 ton di He liquido

80 MW per LHC
30 MW per esperimenti



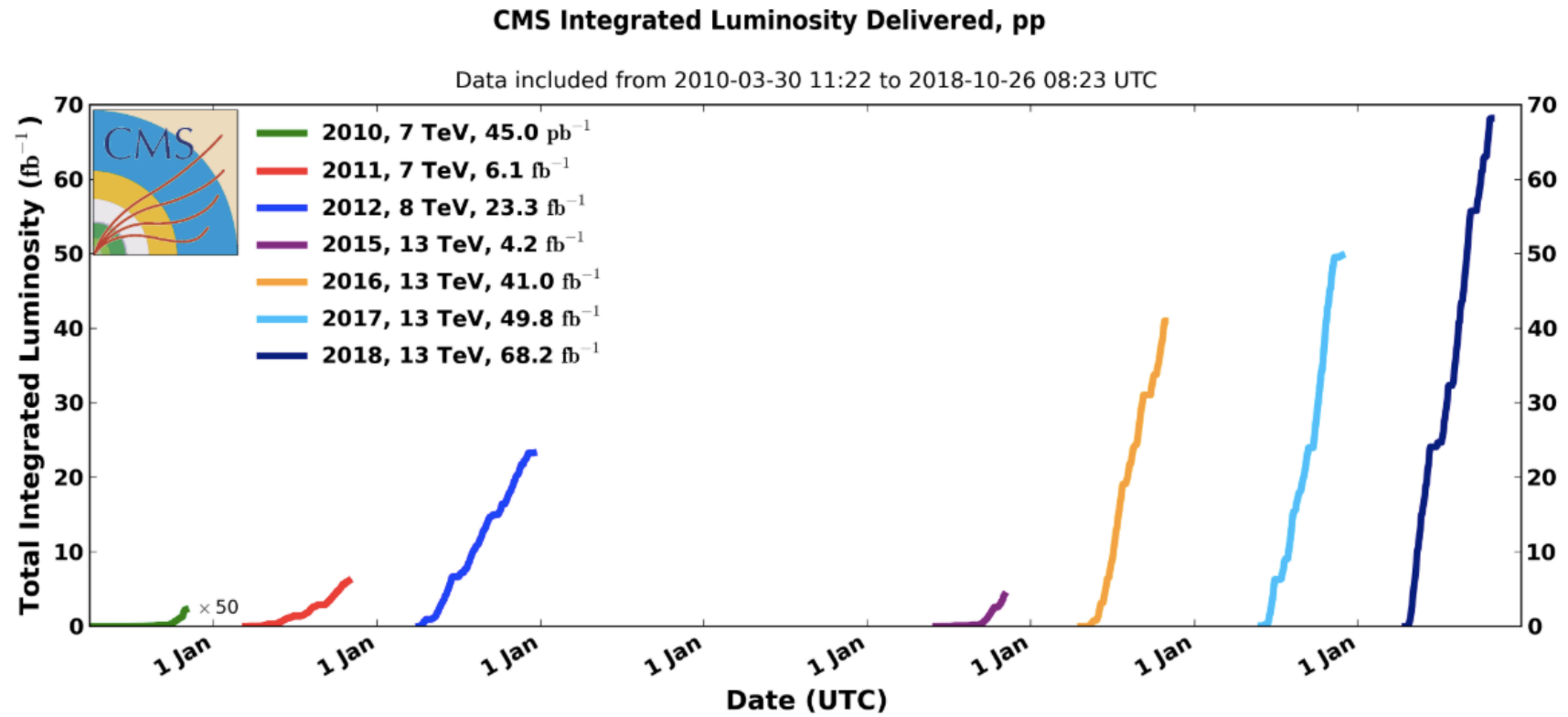
CERN Accelerator Complex



▶ p [proton] ▶ ion ▶ neutrons ▶ \bar{p} [antiproton] \leftrightarrow proton/antiproton conversion ▶ neutrinos ▶ electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
 AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
 LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

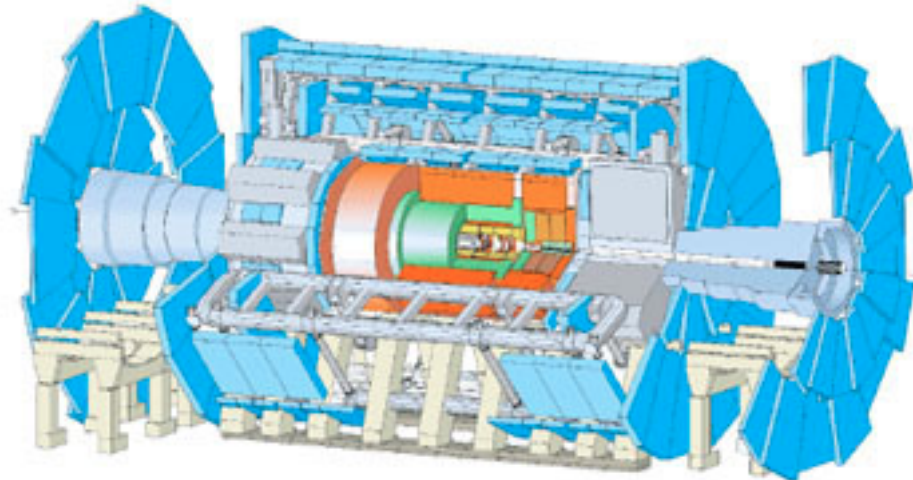
LHC: oltre ogni previsione



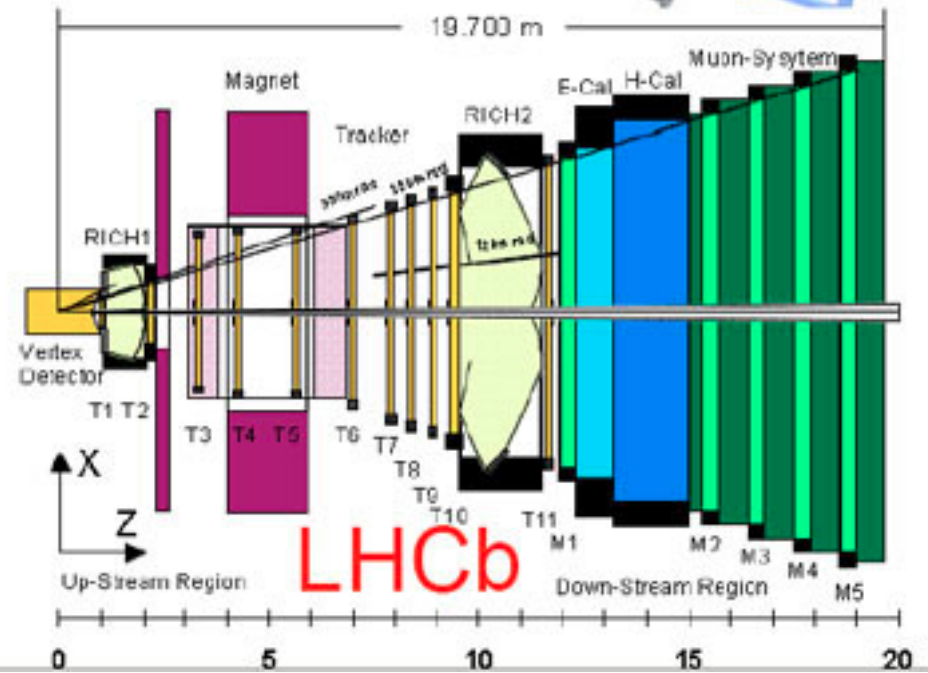
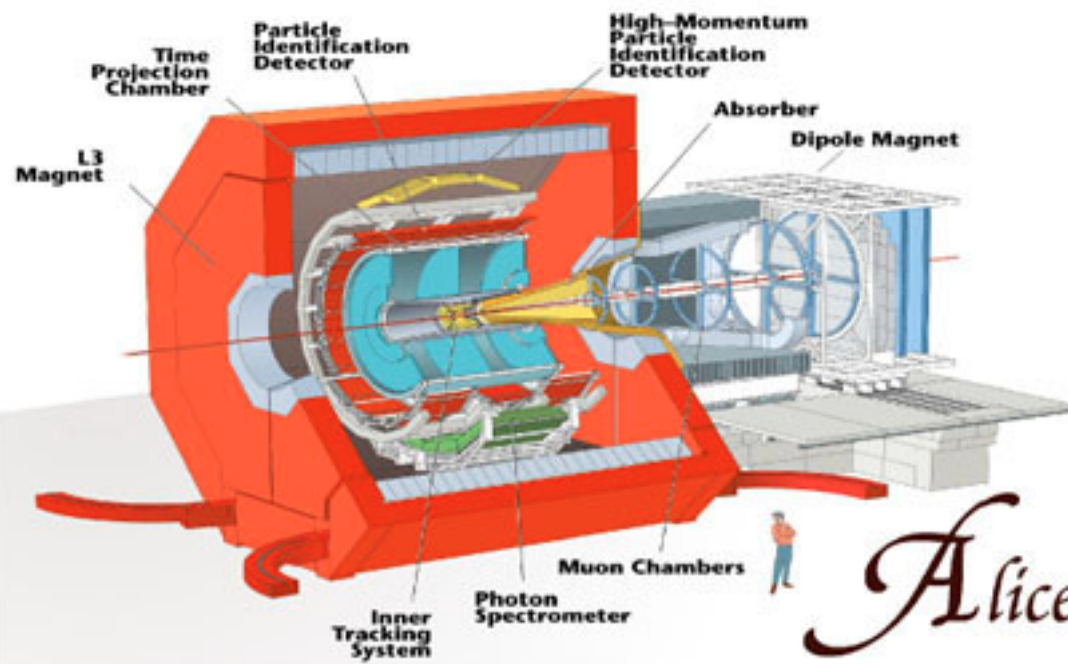
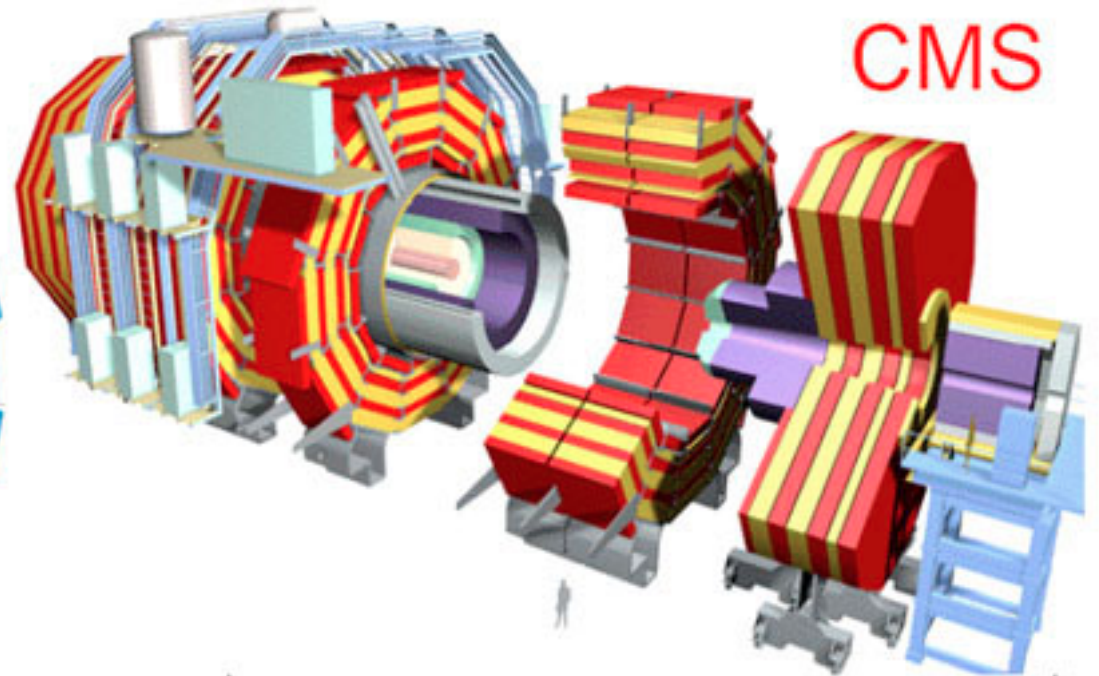
Run-I (2010 – 2012)

Run-II (2015 – 2018)

ATLAS



CMS





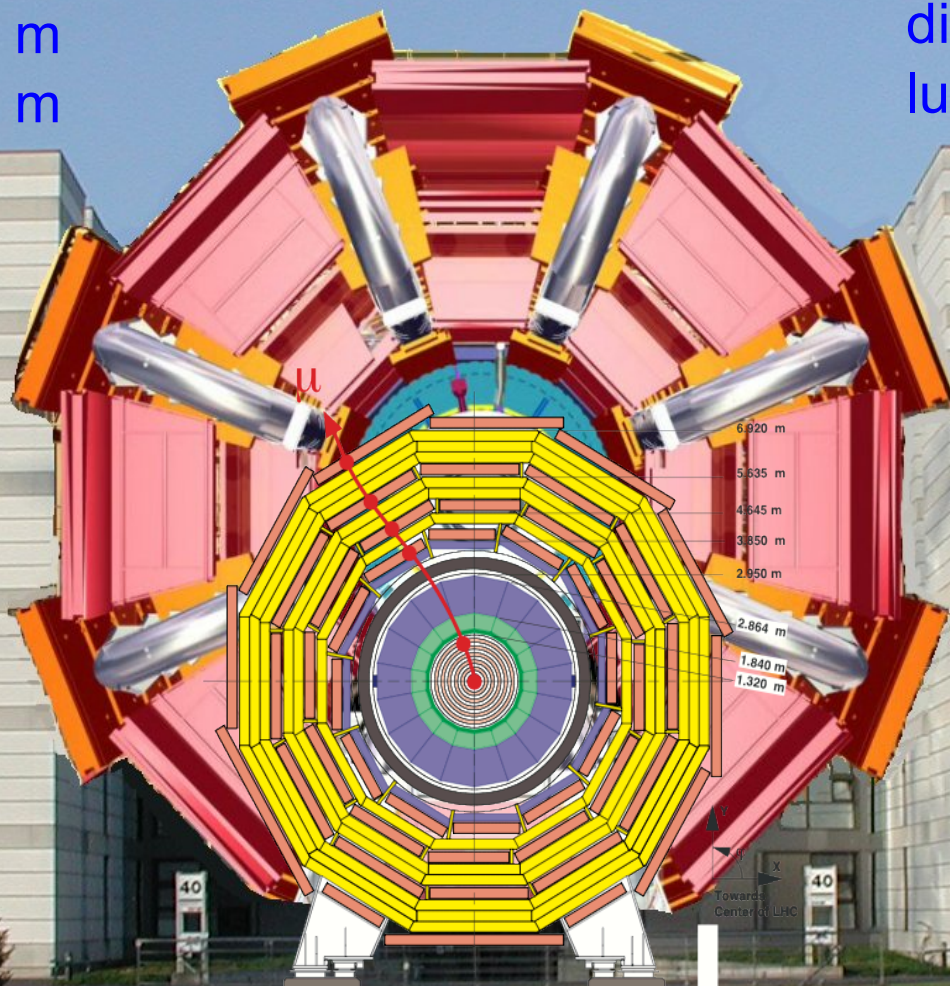
ATLAS and CMS size

ATLAS

massa totale: 7000 t
diametro: 25 m
lunghezza: 46 m

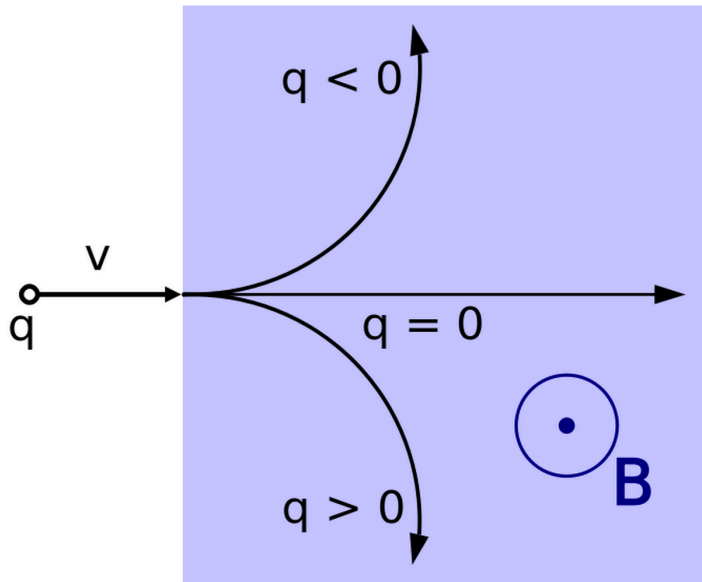
CMS

massa totale: 14000 t
diametro: 15 m
lunghezza: 28.7 m



Transverse View

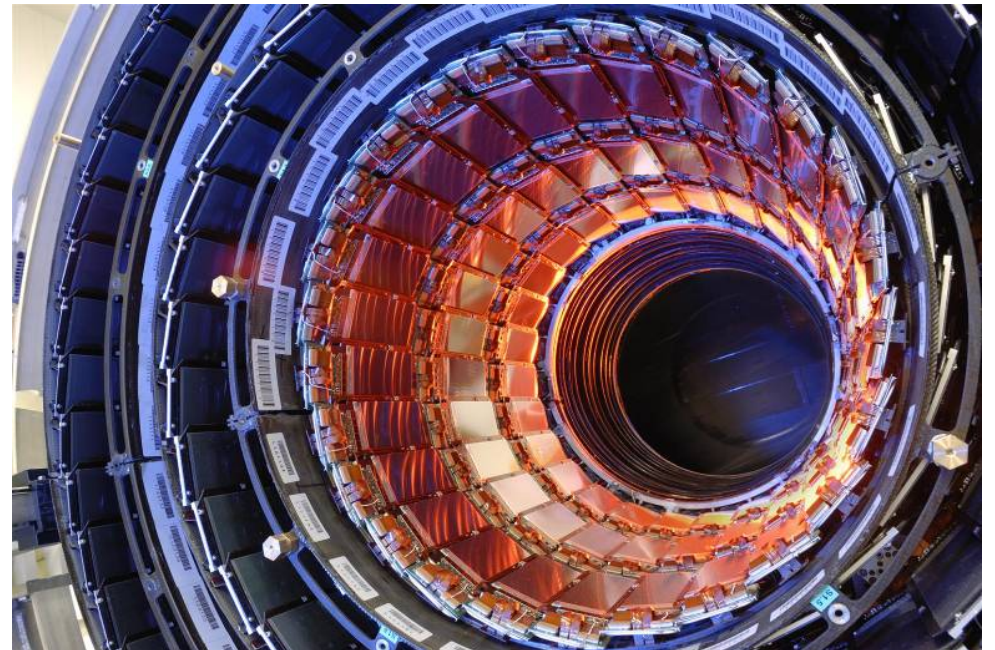
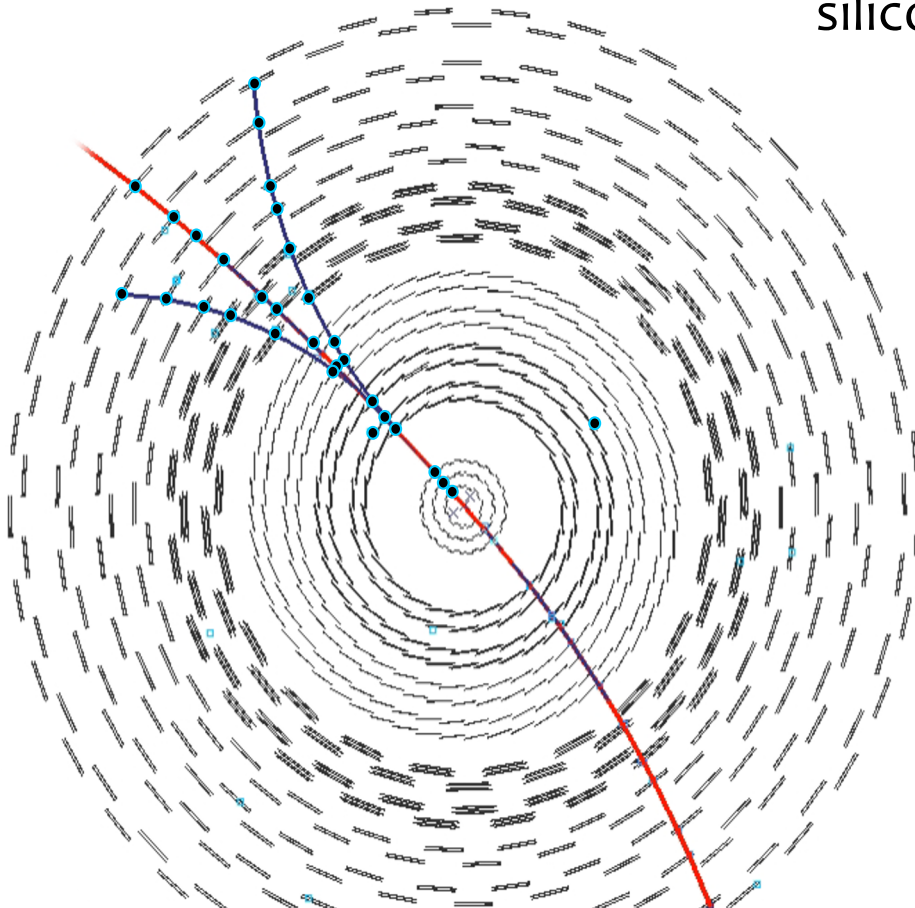
Misure di quantità di moto



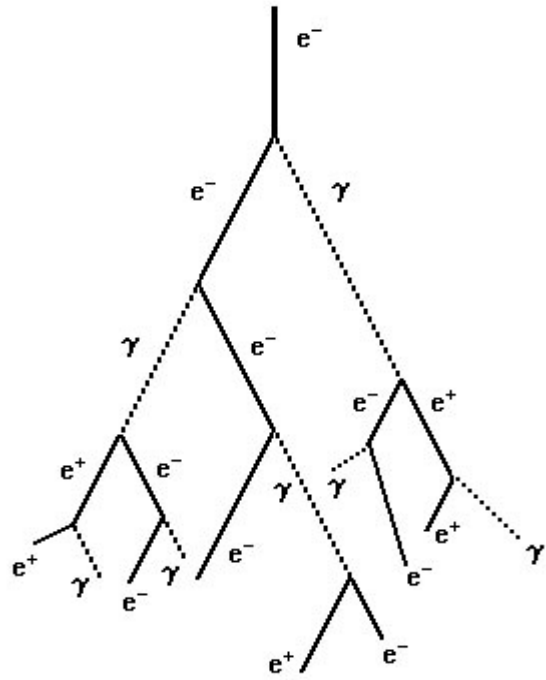
$$p \text{ (GeV/c)} = 0.3 B \text{ (T)} R \text{ (m)}$$

CMS Tracker

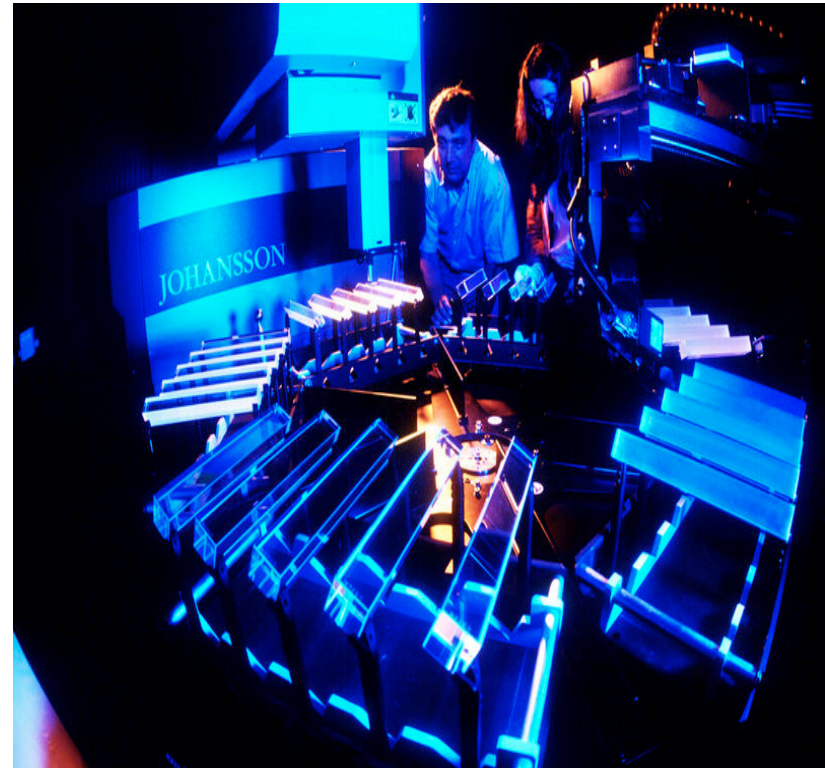
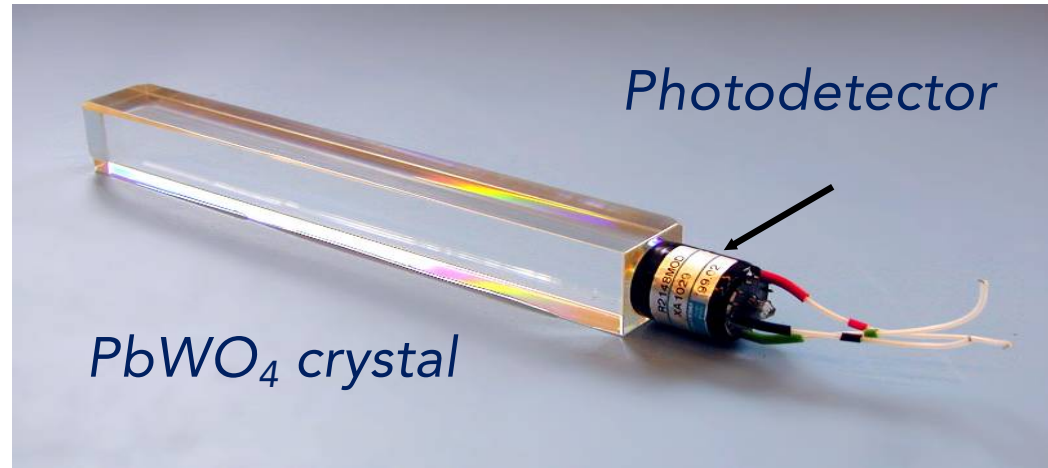
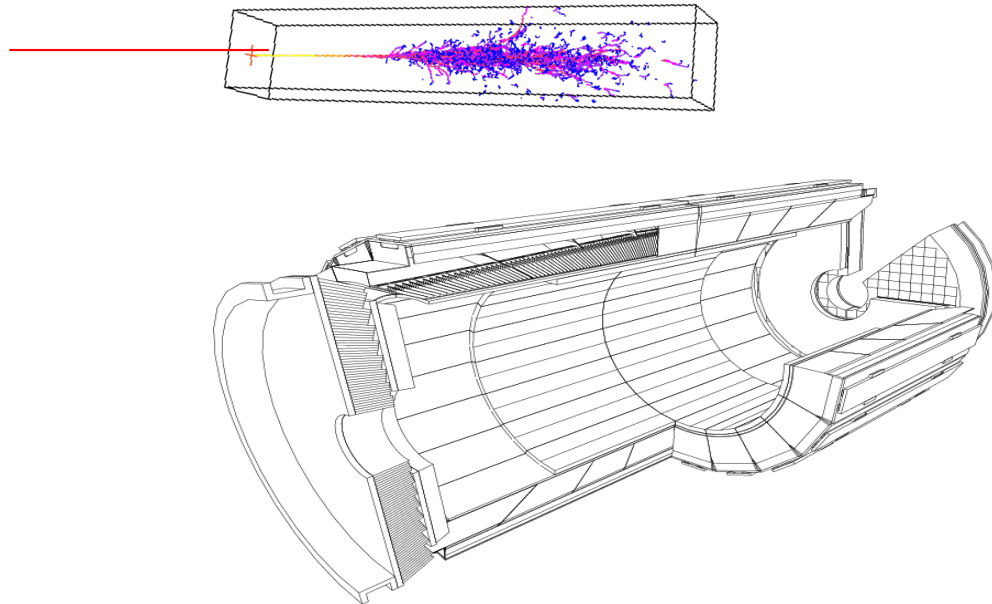
silicon strip: 200 m², 10M canali, $\sigma = 80\text{-}180 \mu\text{m}$
silicon pixel: 16m², 66M canali, $\sigma = \sim 15 \mu\text{m}$



Misure di energia

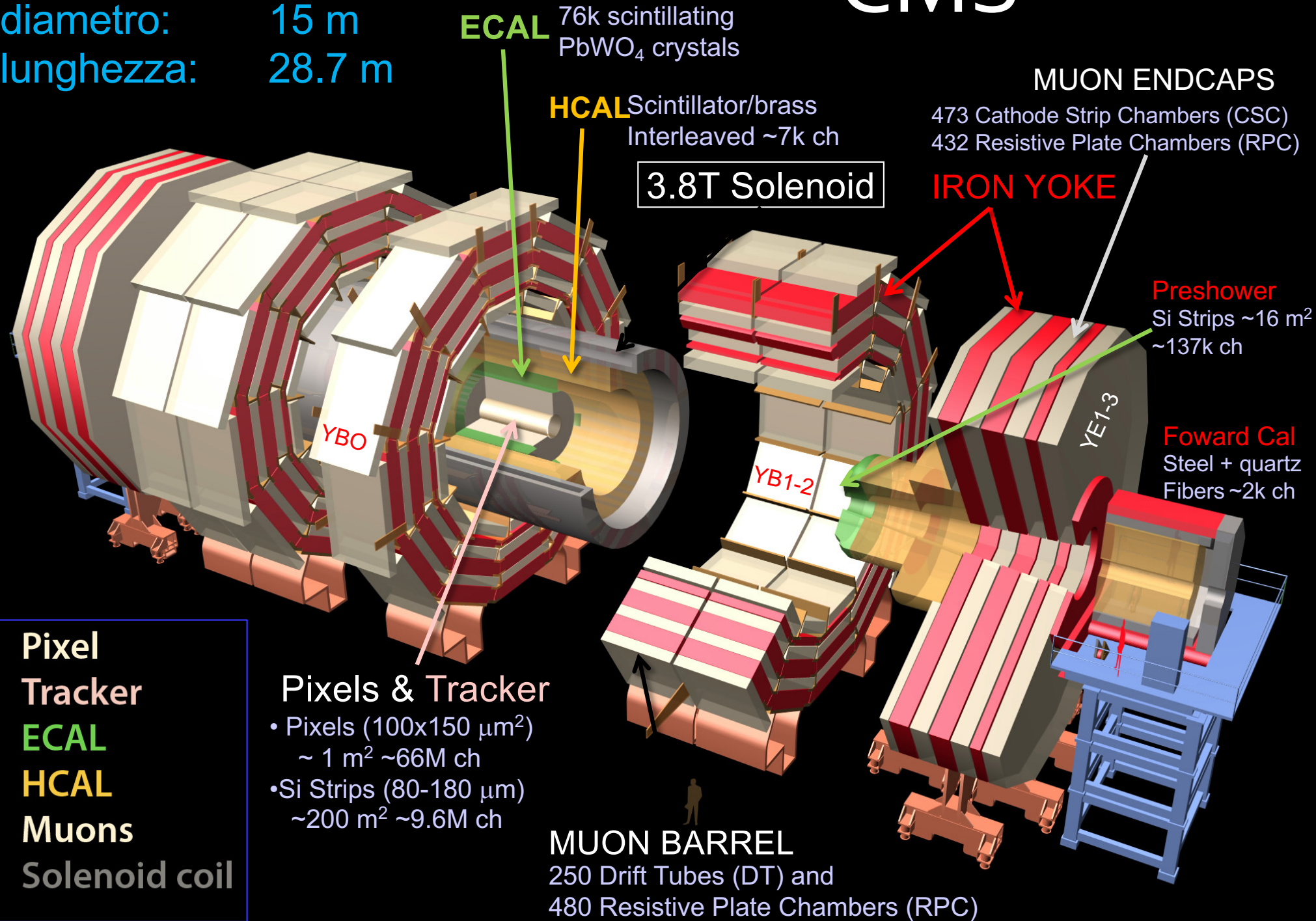


CMS e.m. calorimeter



peso totale: 14000 t
diametro: 15 m
lunghezza: 28.7 m

CMS



3.8T Solenoid

MUON ENDCAPS

473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

IRON YOKE

Preshower
Si Strips ~16 m²
~137k ch

Foward Cal
Steel + quartz
Fibers ~2k ch

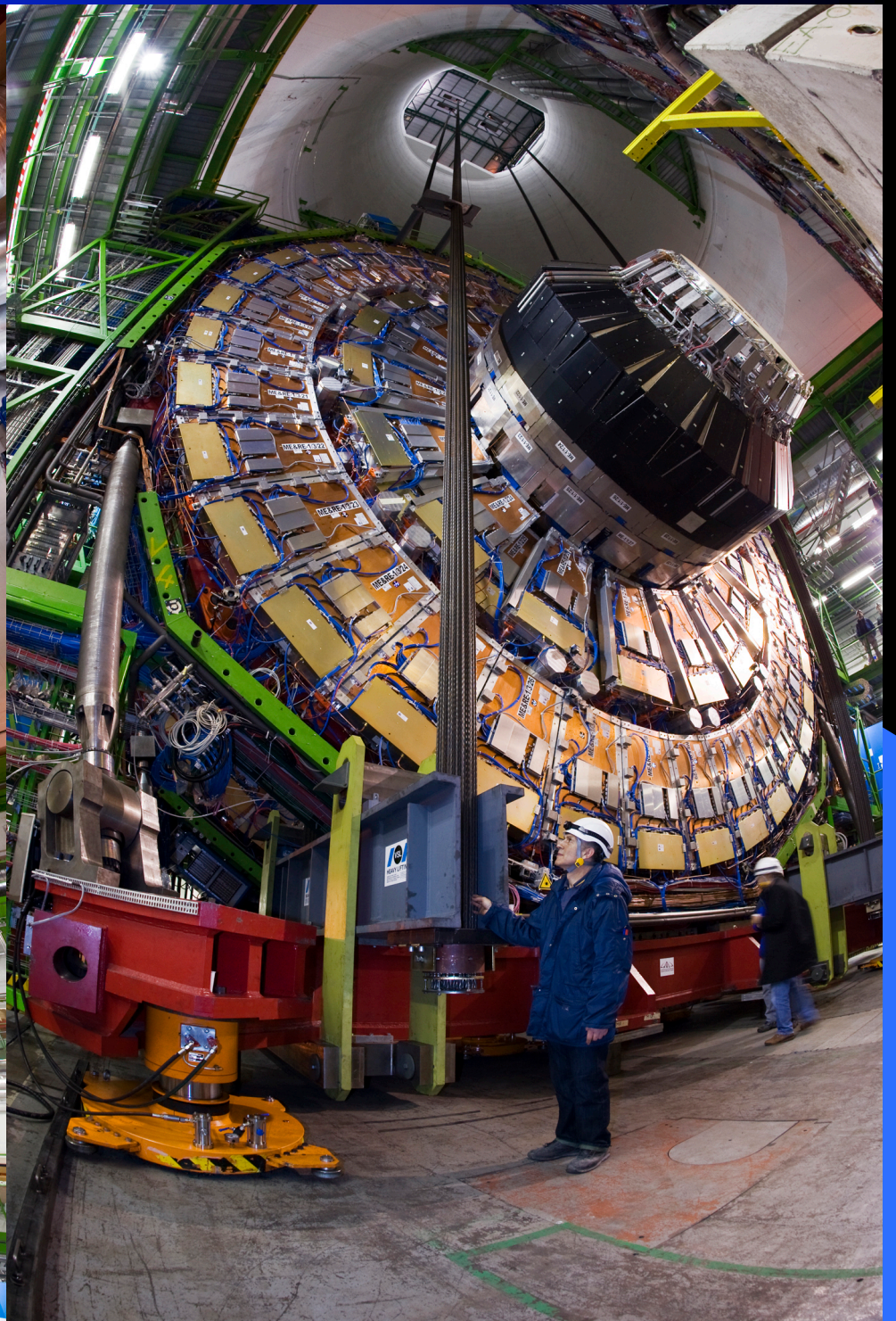
Pixels & Tracker

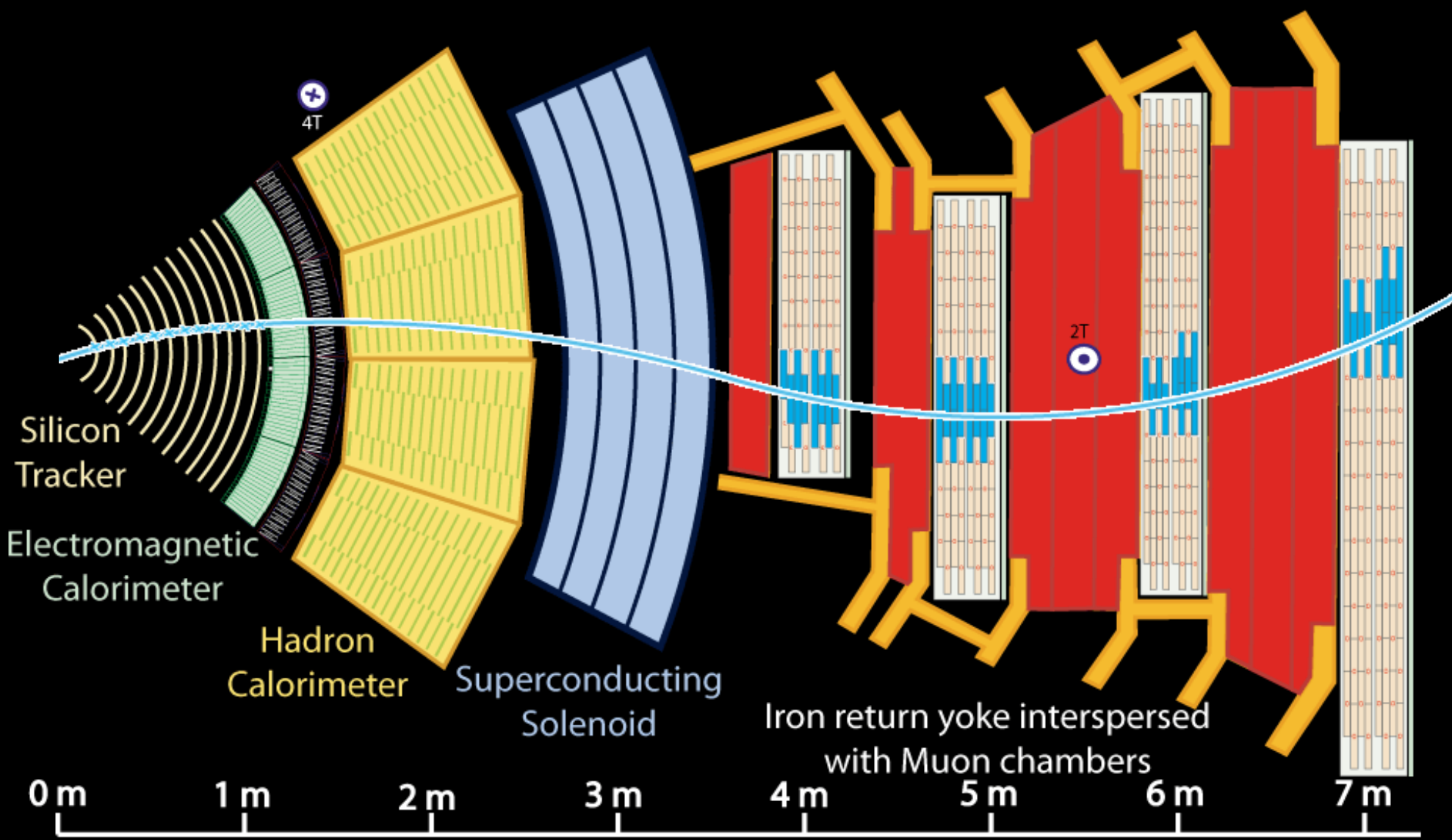
- Pixels (100x150 μm²)
~ 1 m² ~66M ch
- Si Strips (80-180 μm)
~200 m² ~9.6M ch

MUON BARREL

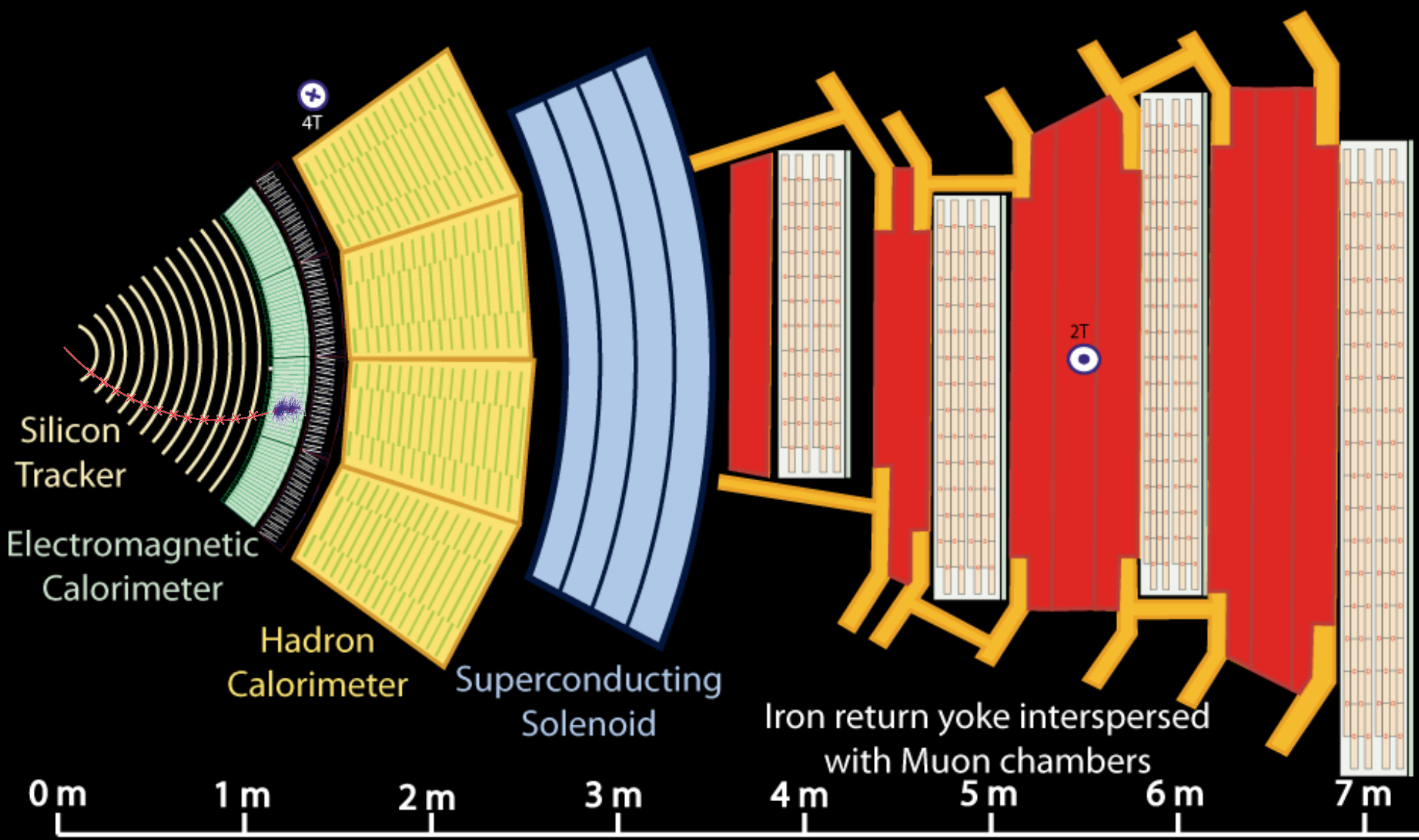
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

- Pixel
- Tracker
- ECAL
- HCAL
- Muons
- Solenoid coil

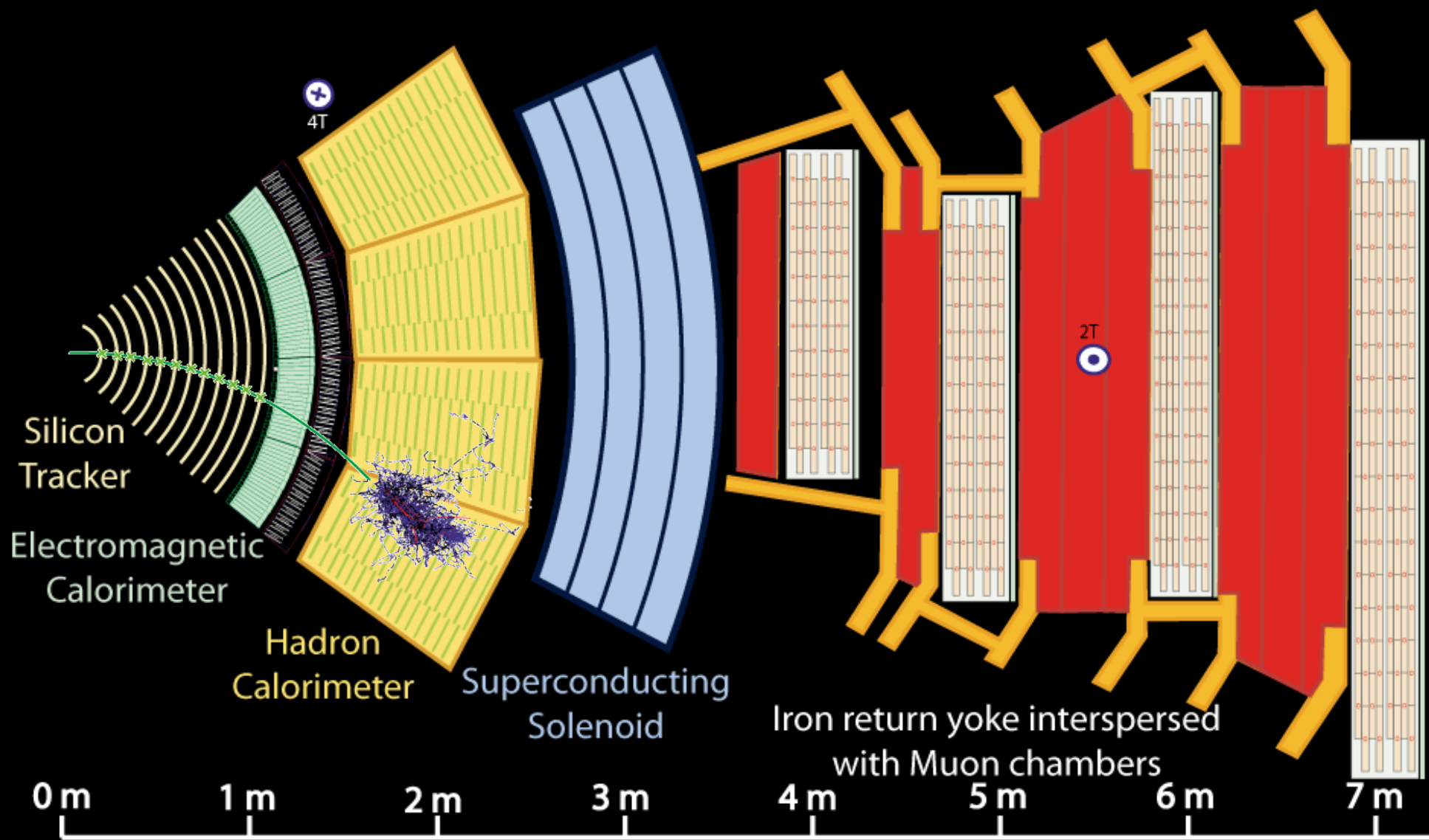




- Key:
- Muon
 - Electron
 - Charged Hadron (e.g. Pion)
 - - - Neutral Hadron (e.g. Neutron)
 - - - Photon

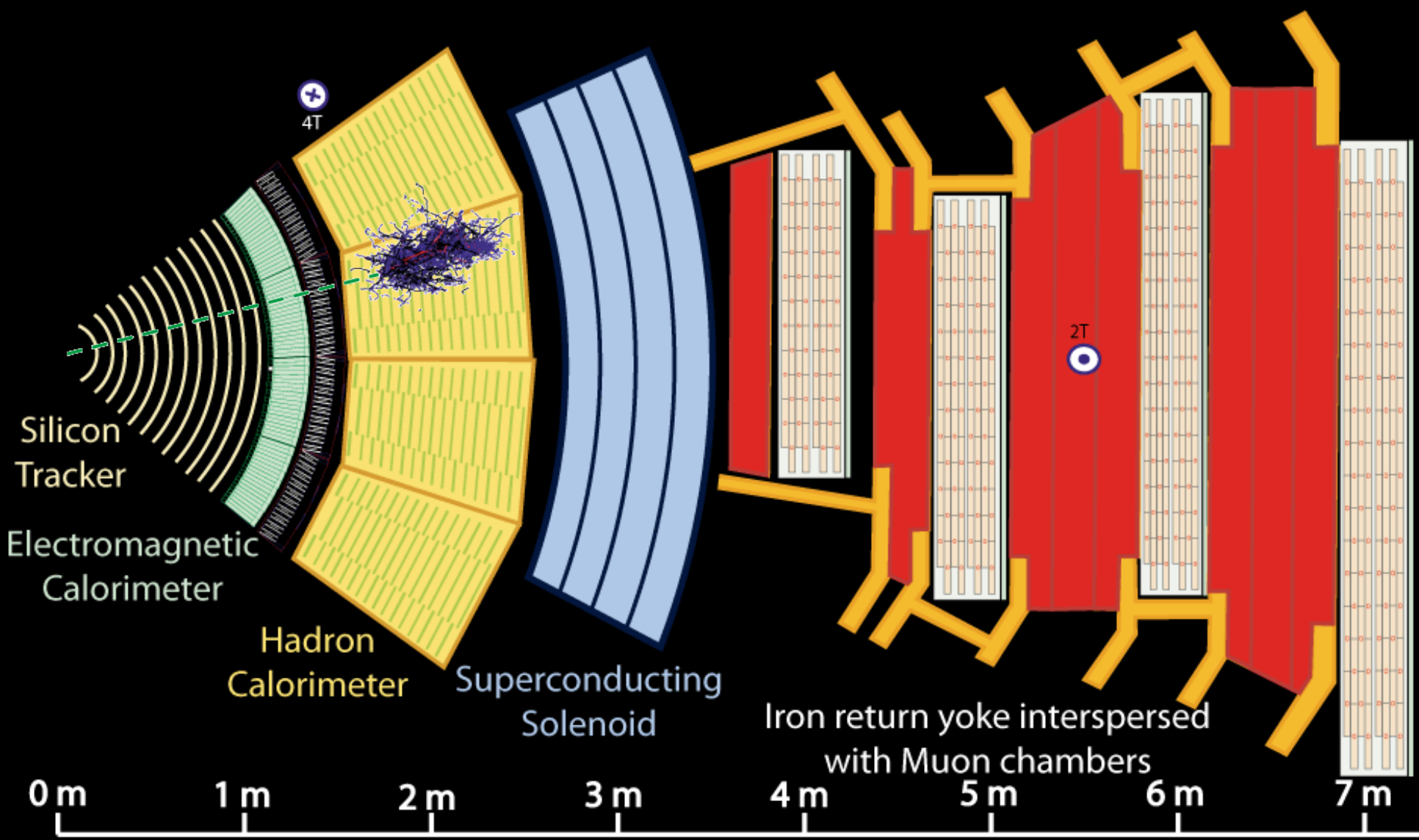


- Key:
- Muon
 - Electron
 - Charged Hadron (e.g. Pion)
 - - - Neutral Hadron (e.g. Neutron)
 - - - Photon

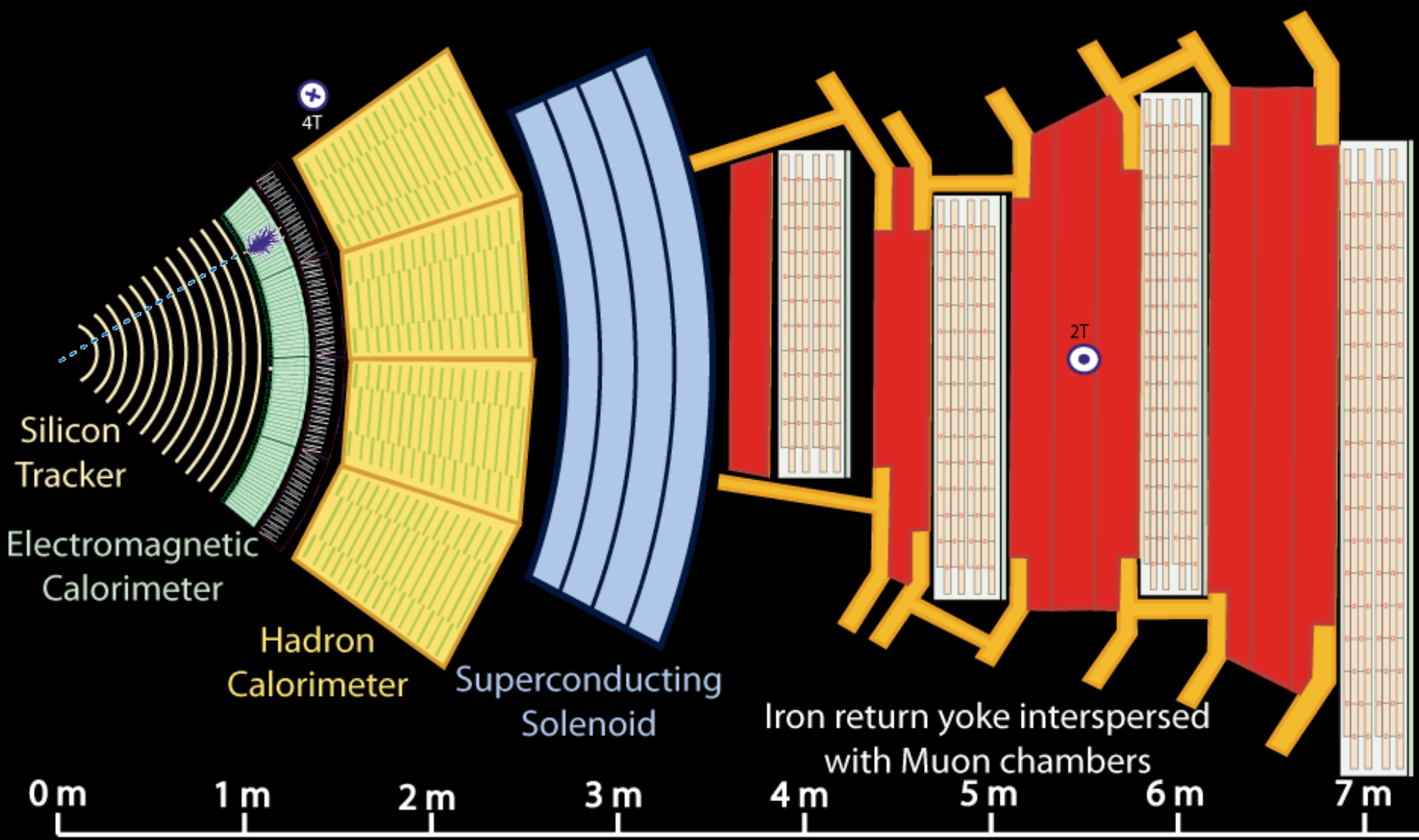


Key:

- Muon
- Electron
- Charged Hadron (e.g. Pion)
- - - Neutral Hadron (e.g. Neutron)
- - - Photon



- Key:
- Muon
 - Electron
 - Charged Hadron (e.g. Pion)
 - - - Neutral Hadron (e.g. Neutron)
 - - - Photon



- Key:
- Muon
 - Electron
 - Charged Hadron (e.g. Pion)
 - - - Neutral Hadron (e.g. Neutron)
 - - - Photon

Trigger per esperimenti LHC

40×10^6 collisioni/s * 10^8 canali di acquisizione * 1 Byte =
4 PB/s di output (impossibile da gestire !)

Eventi interessanti (alto q^2) hanno probabilità $10^5 - 10^6$
volte più piccola di eventi di QCD soffice

Trigger reduce rate di acquisizione da 40 MHz a 300 Hz
selezionando gli eventi ad alto q^2 con buona efficienza

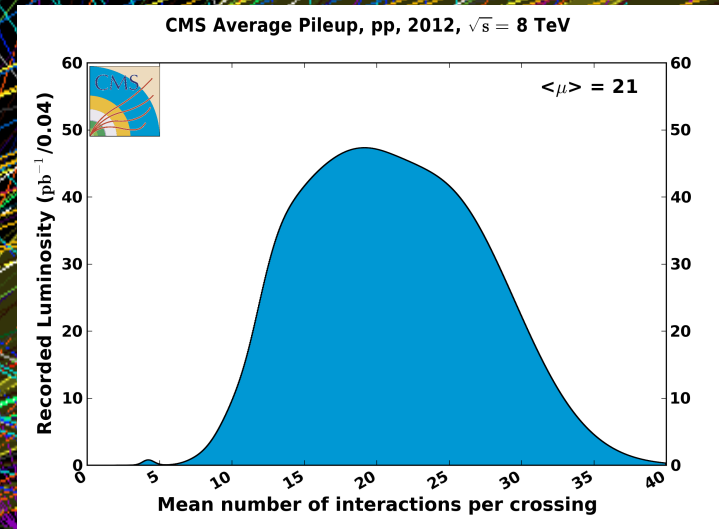
Il processo deve avvenire **real time** (entro 300 ms)

Con "zero suppression" dimensioni di 1 evento ~ 1 MB

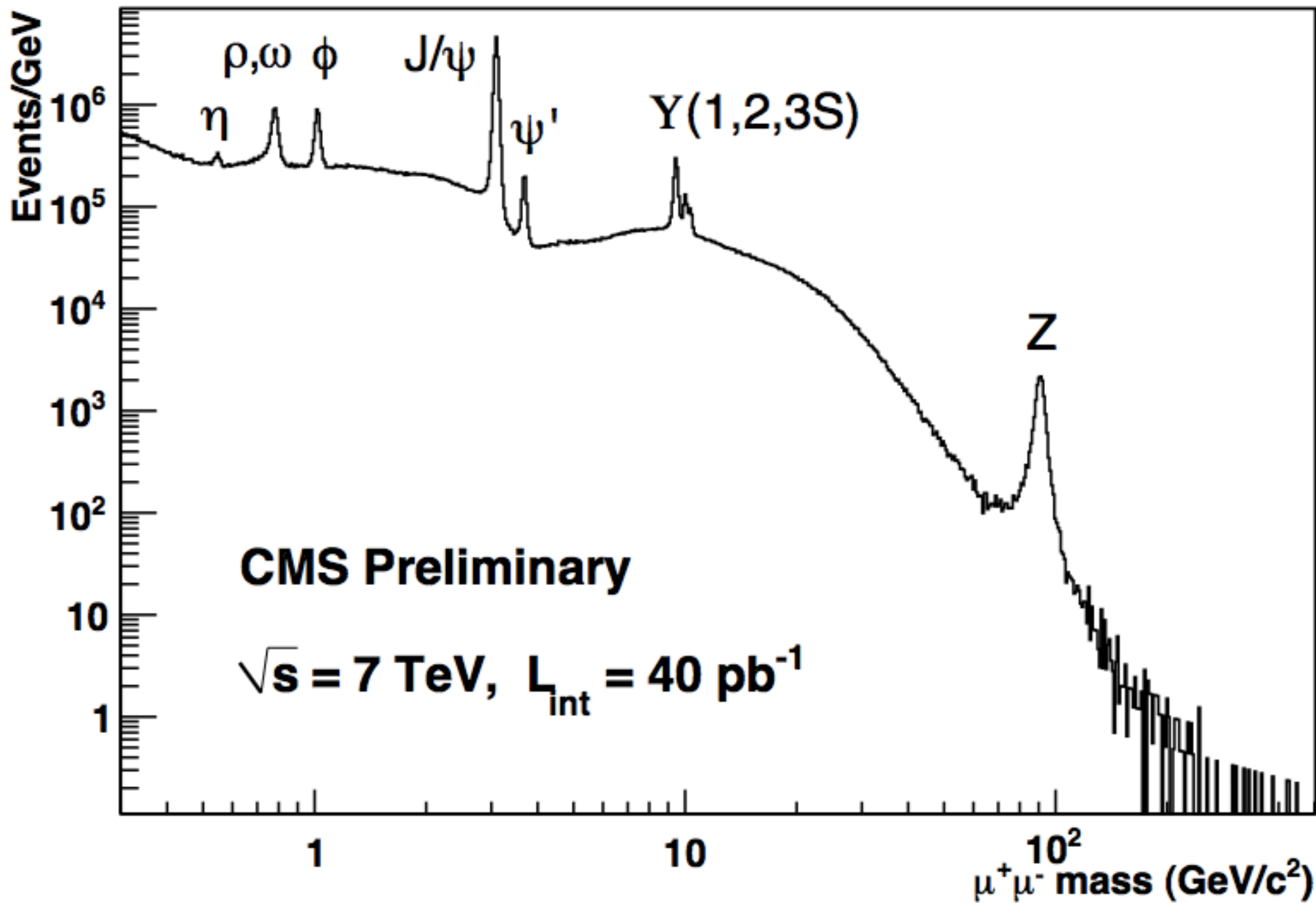


Sfide sperimentali: il pileup

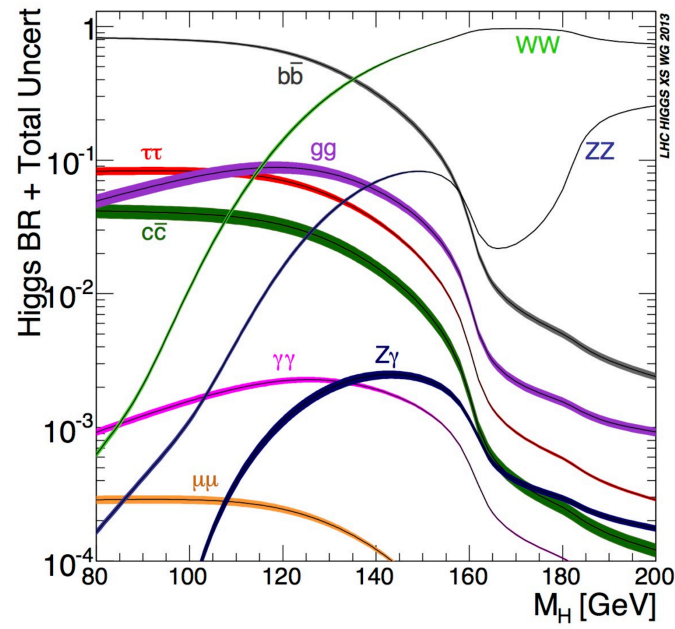
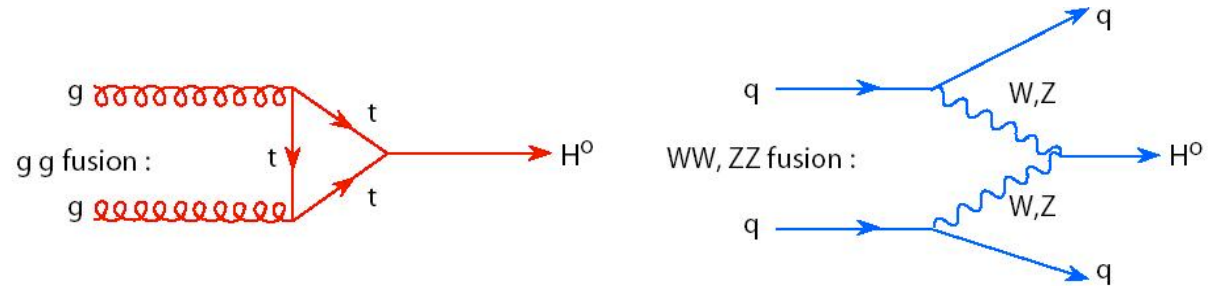
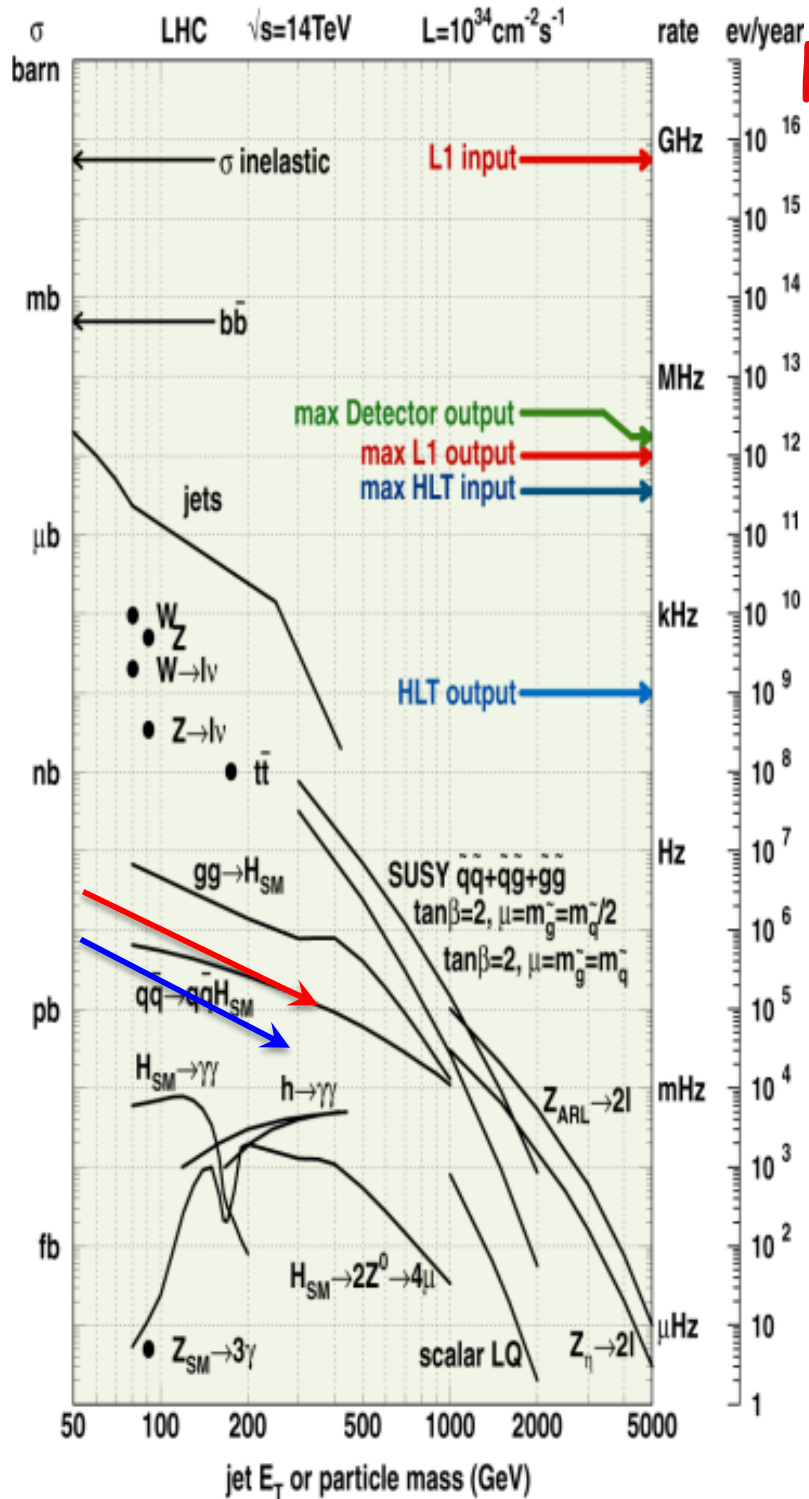
E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CERN
Run/Event: 195098 / 35438125
Lumi section: 65
Orbit Crossing: 16992111 / 2295



Riscoperta del Modello Standard nel 2010



Produzione bosone di Higgs a LHC



$H \rightarrow \gamma\gamma \sim 40/\text{settimana}$ (ricostruiti ~ 16)

$H \rightarrow ZZ \rightarrow 4\text{leptoni} \sim 8/\text{mese}$ (ricostruiti ~ 3)

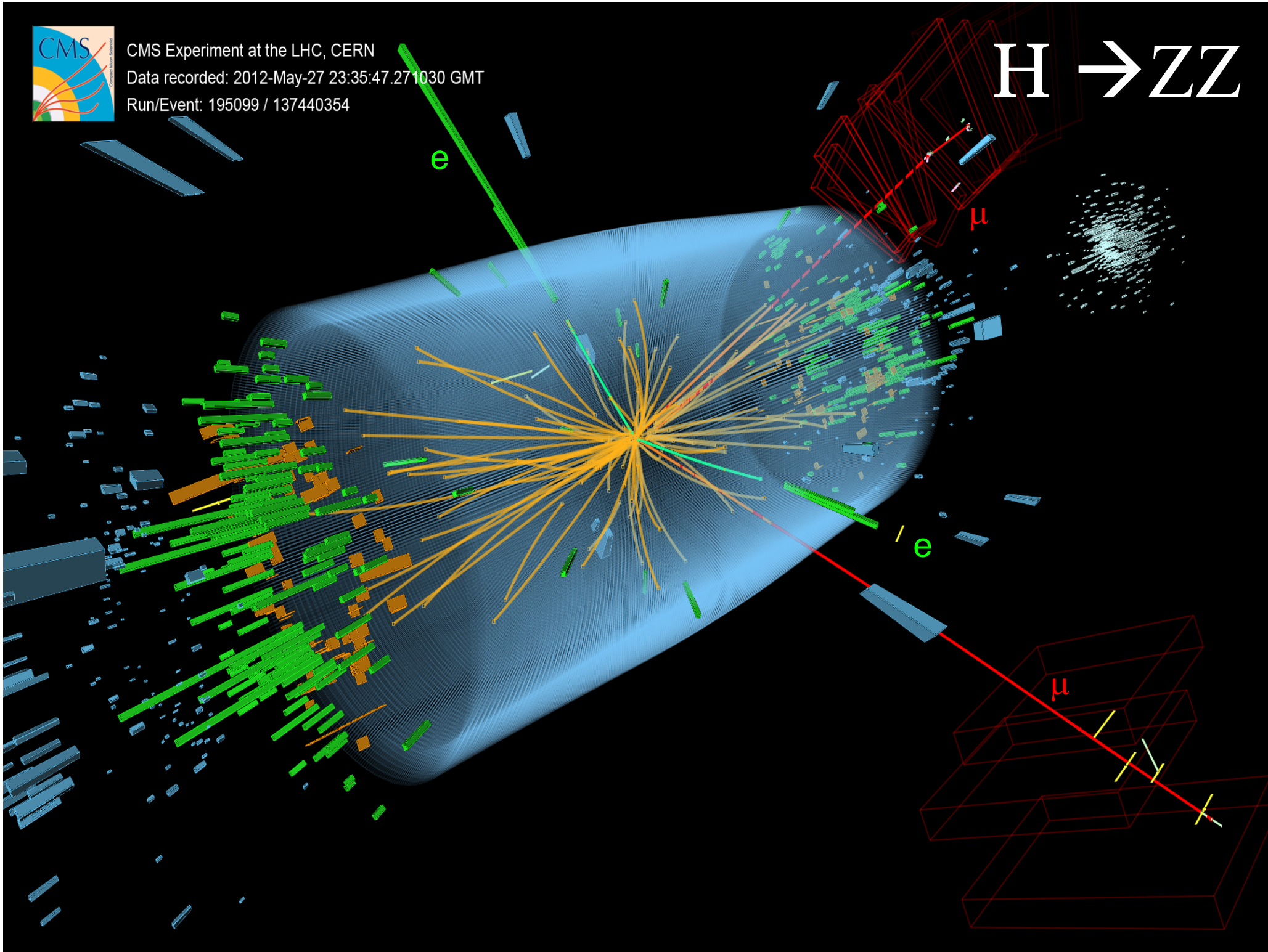


CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354

$H \rightarrow ZZ$



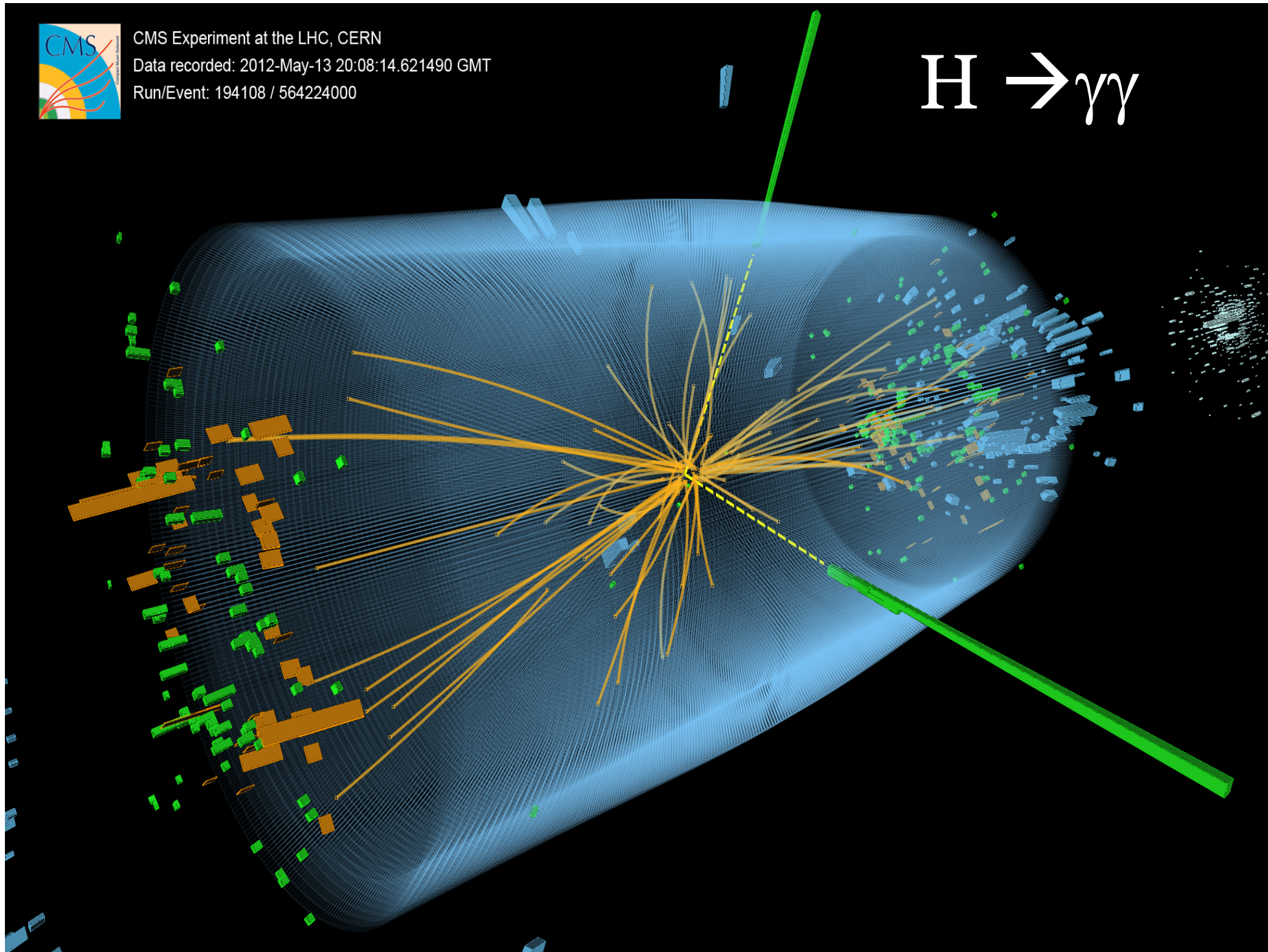


CMS Experiment at the LHC, CERN

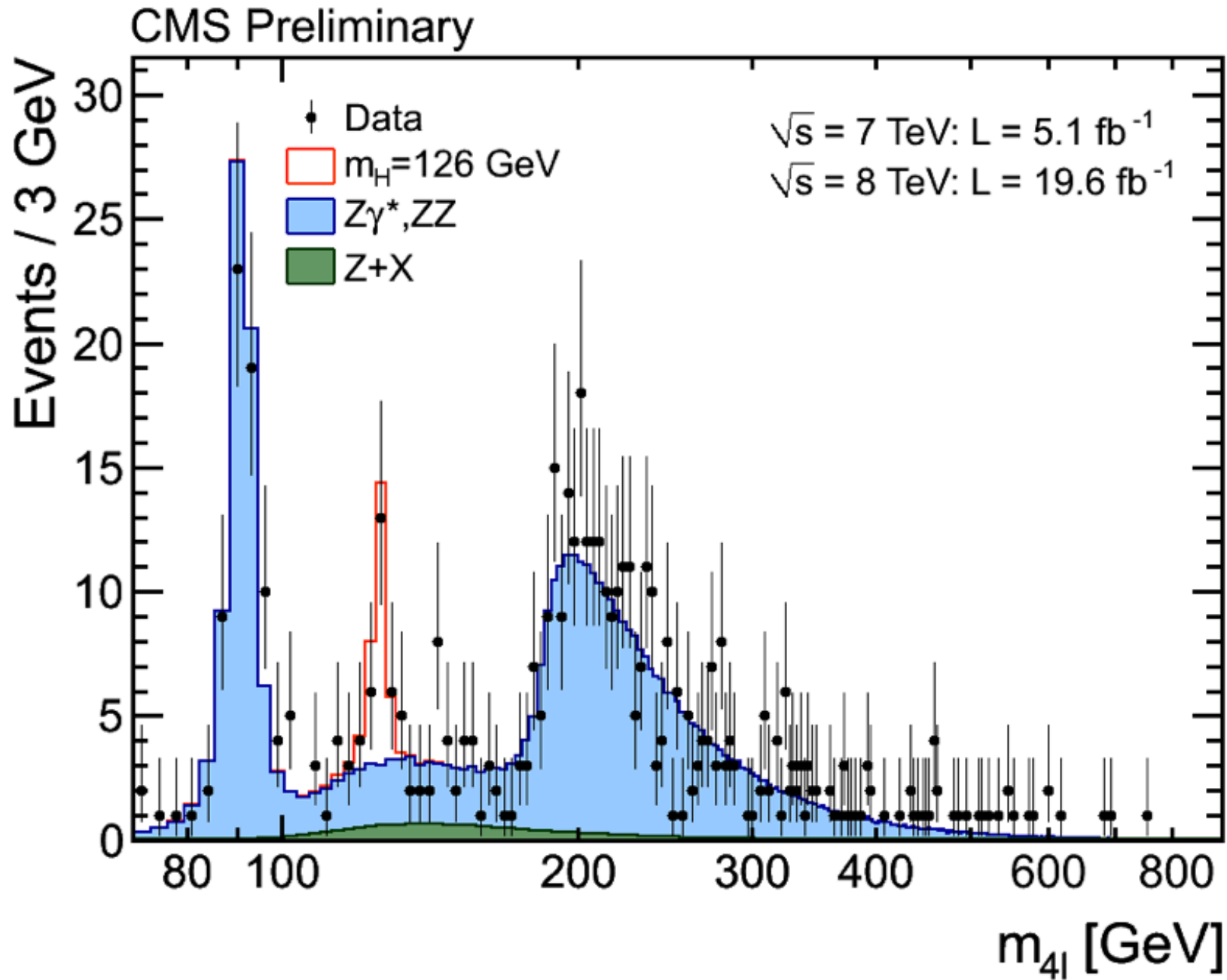
Data recorded: 2012-May-13 20:08:14.621490 GMT

Run/Event: 194108 / 564224000

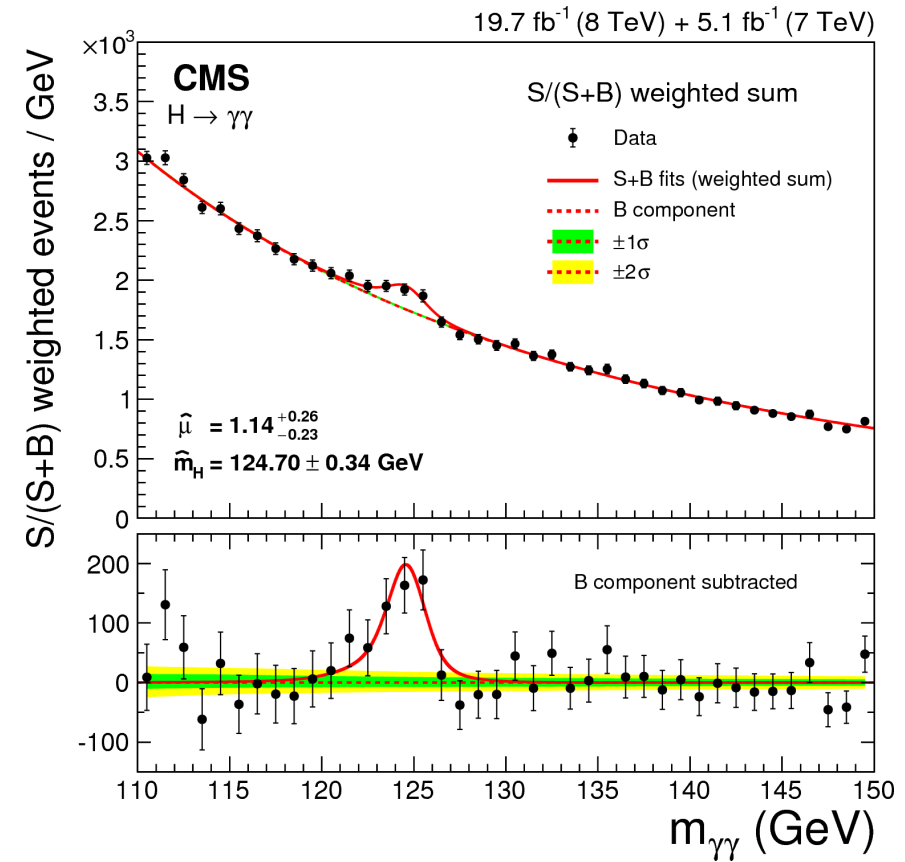
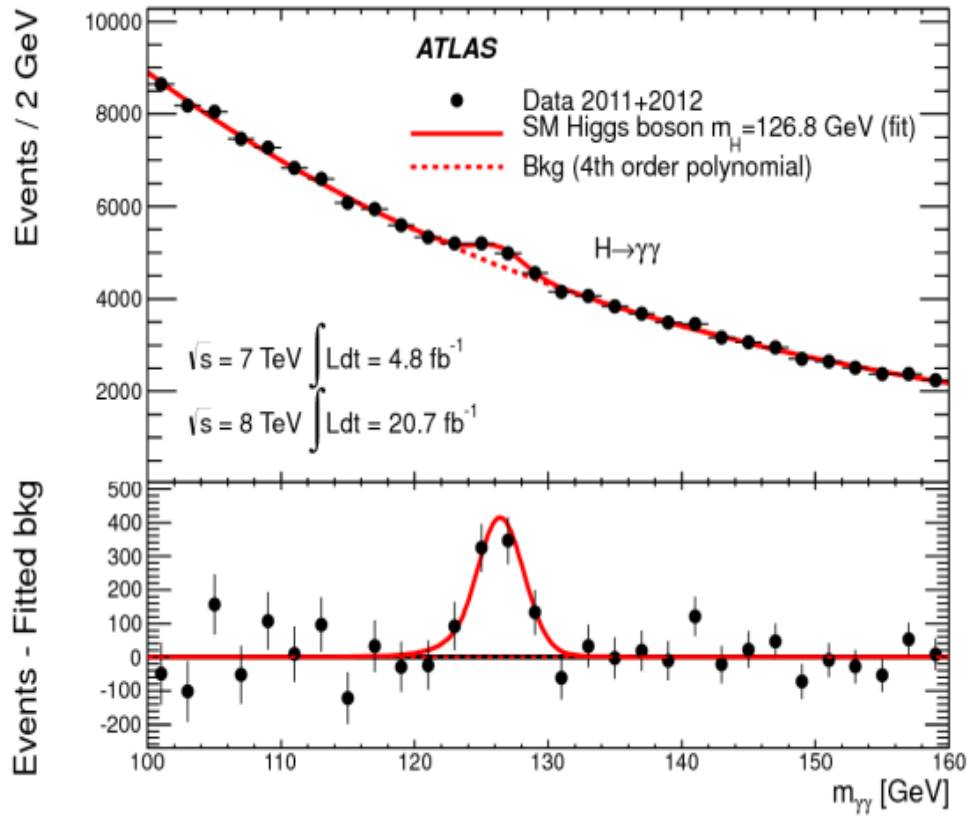
$H \rightarrow \gamma\gamma$



$H \rightarrow eeee$ $H \rightarrow ee\mu\mu$ $H \rightarrow \mu\mu\mu\mu$



H → $\gamma\gamma$



Science

21 December 2012 | \$10



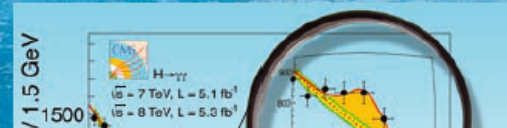
Volume 712, Issue 3, 6 June 2012

ISSN 0370-2693

PHYSICS LETTERS B

Available online at www.sciencedirect.com

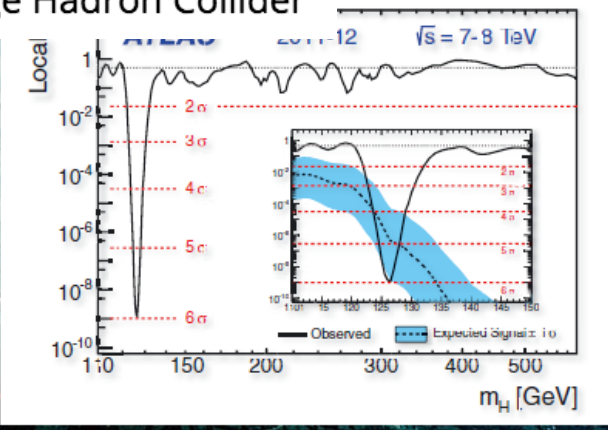
SciVerse ScienceDirect



The Nobel Prize in Physics 2013

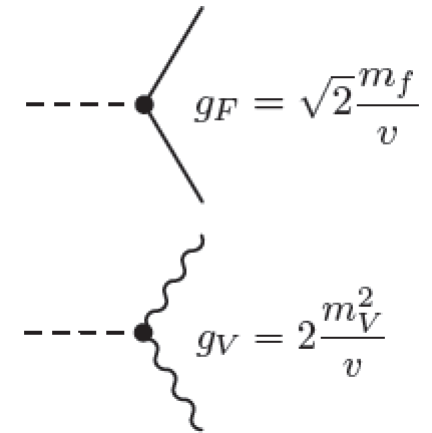
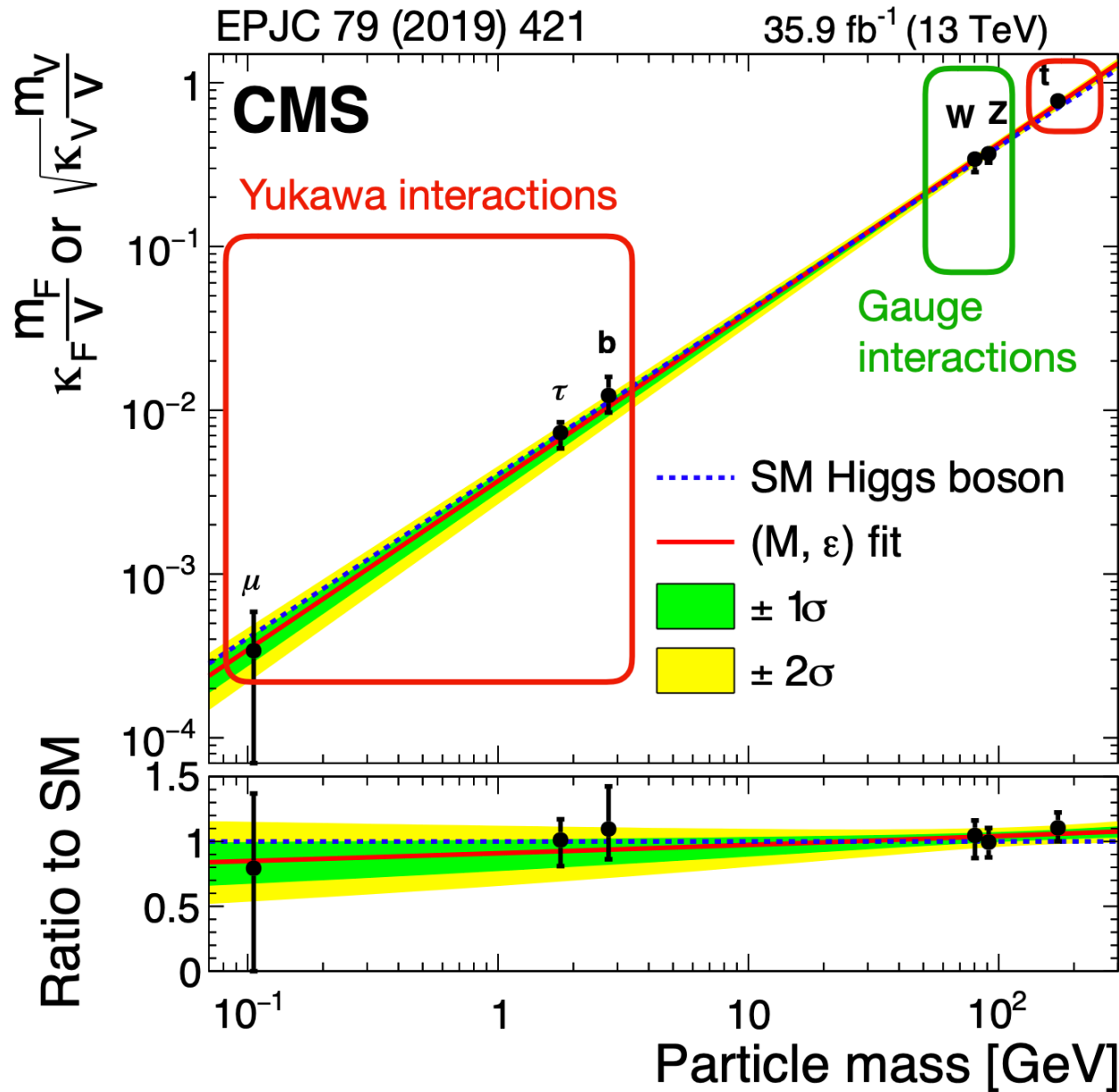
François Englert and Peter W. Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

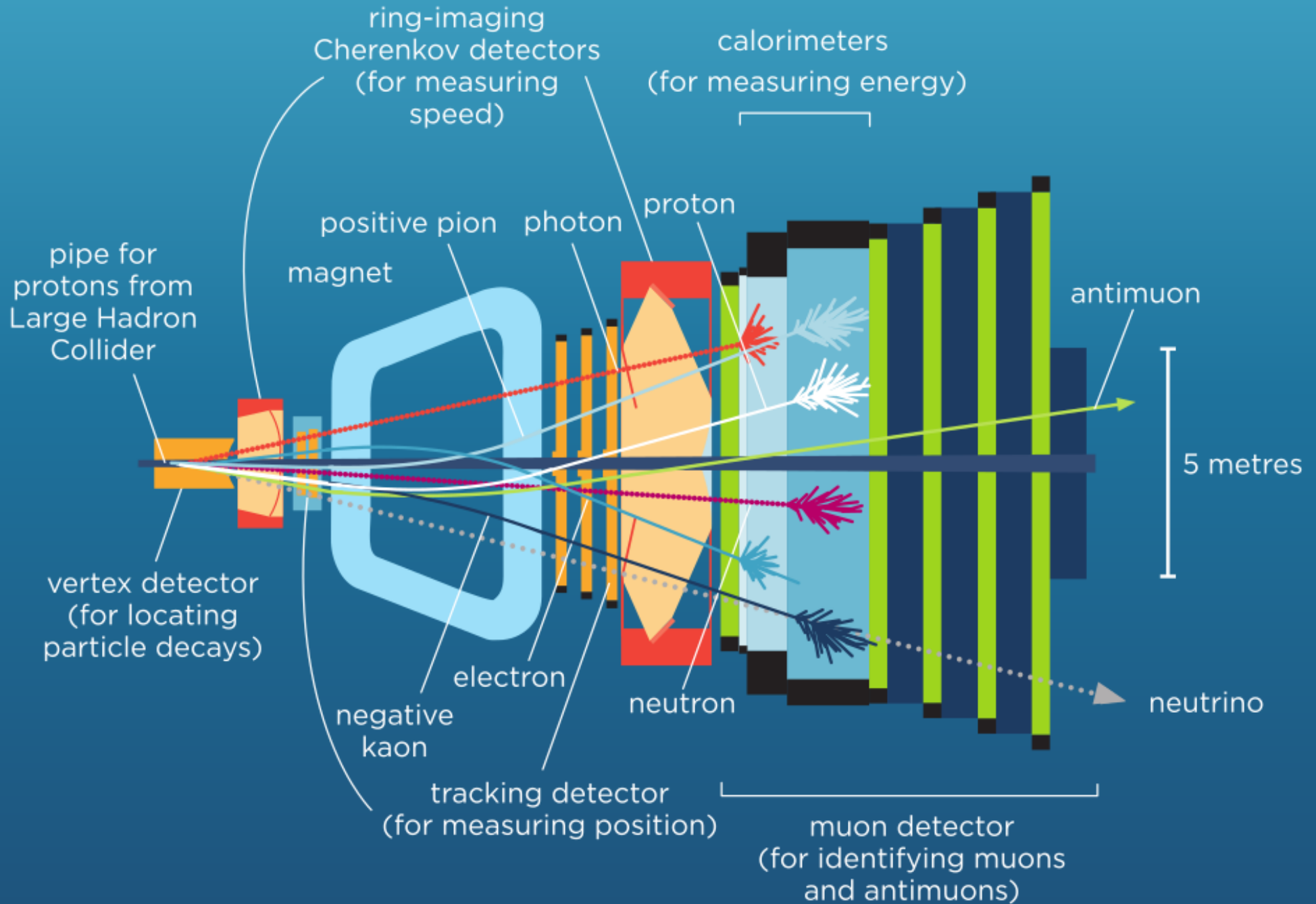


$$m_H = 125.03^{+0.26}_{-0.27} \text{ (stat.) } ^{+0.13}_{-0.15} \text{ (syst.) GeV}$$

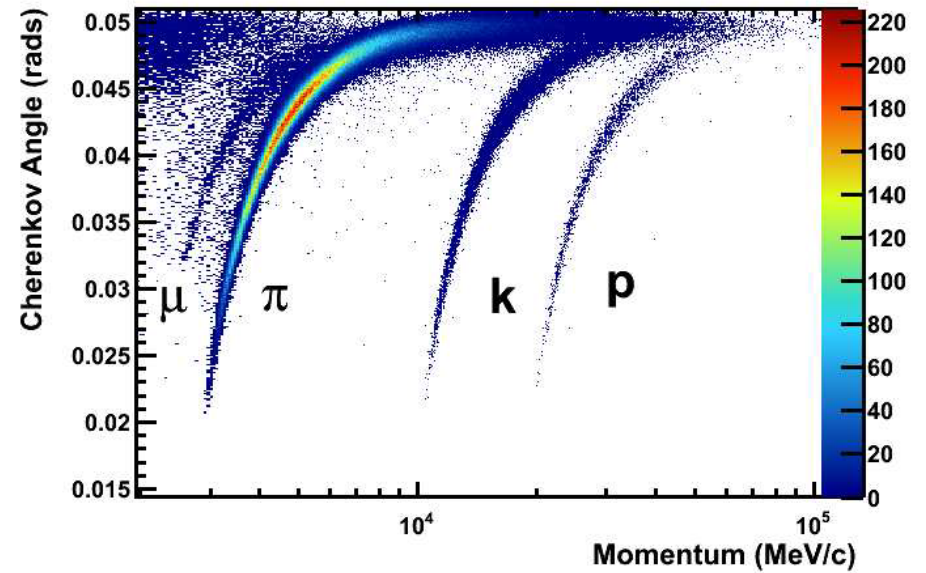
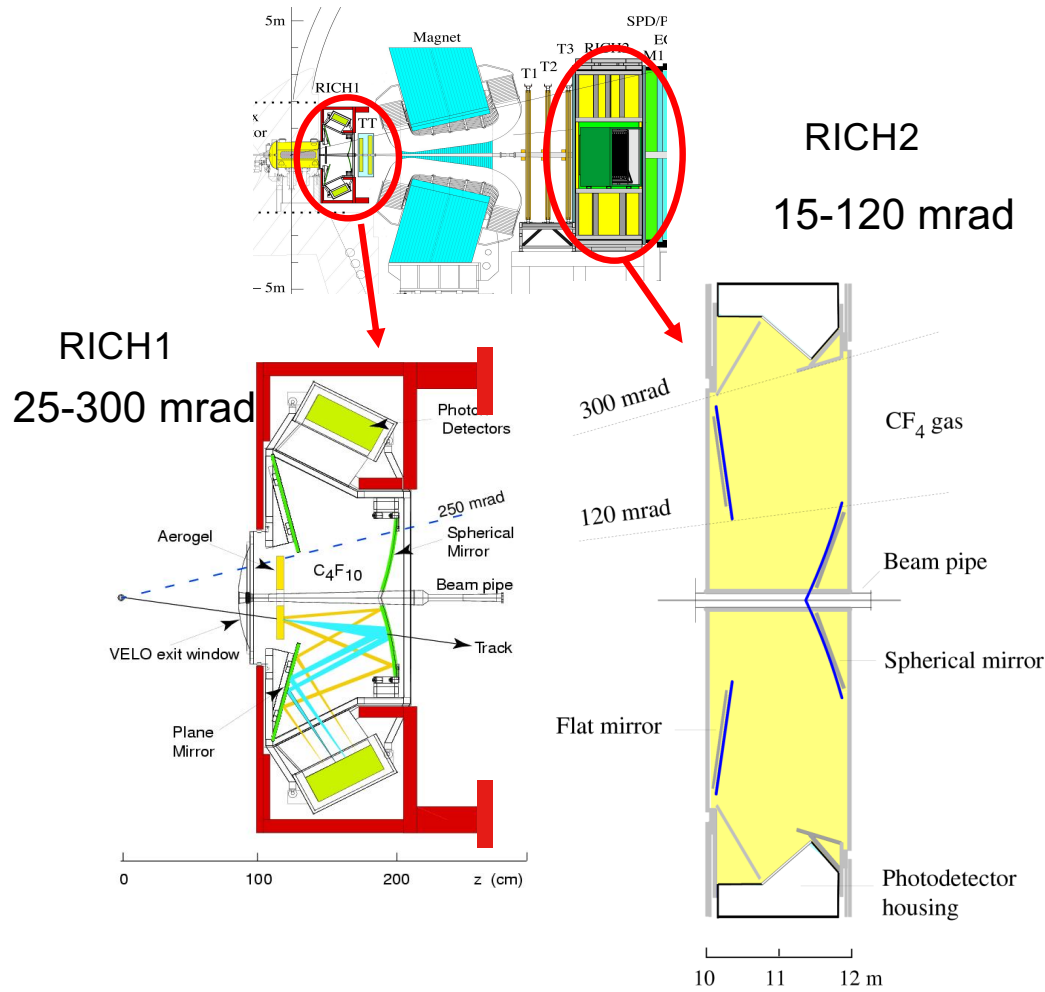
Misure di precisione sul bosone di Higgs



Il rivelatore LHCb



Il rivelatore RICH di LHCb



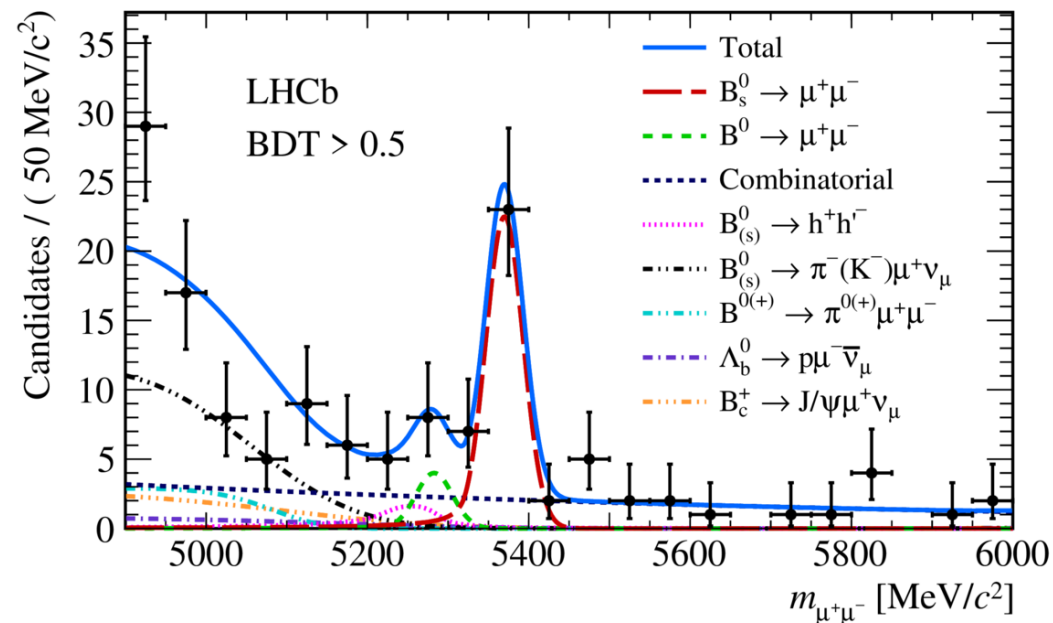
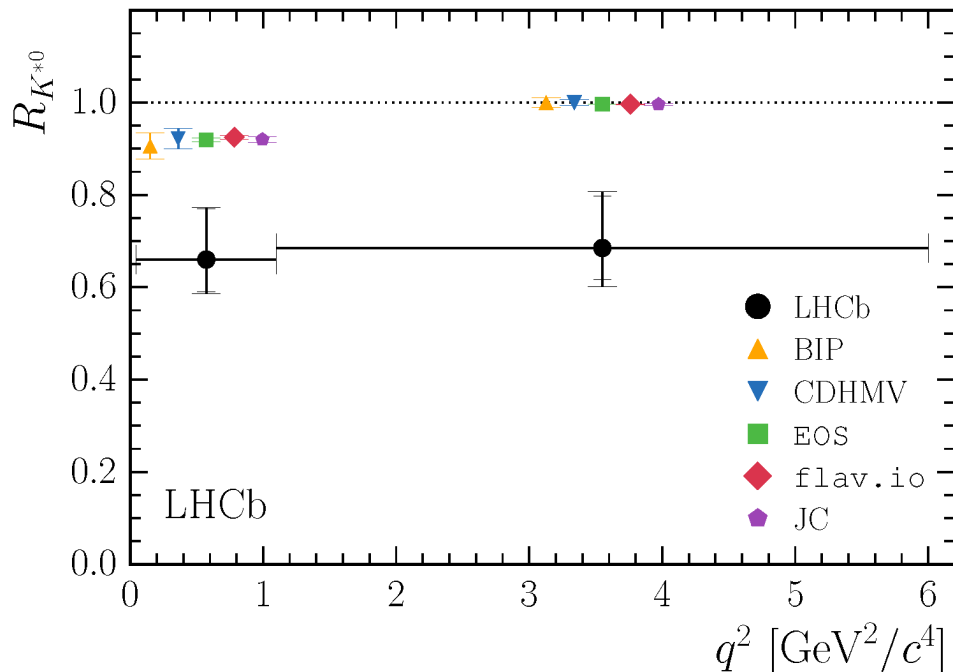
Ricerca di Fisica oltre il Modello Standard a LHCb

Decadimenti rari: $B_{(s)} \rightarrow \mu^+\mu^-$

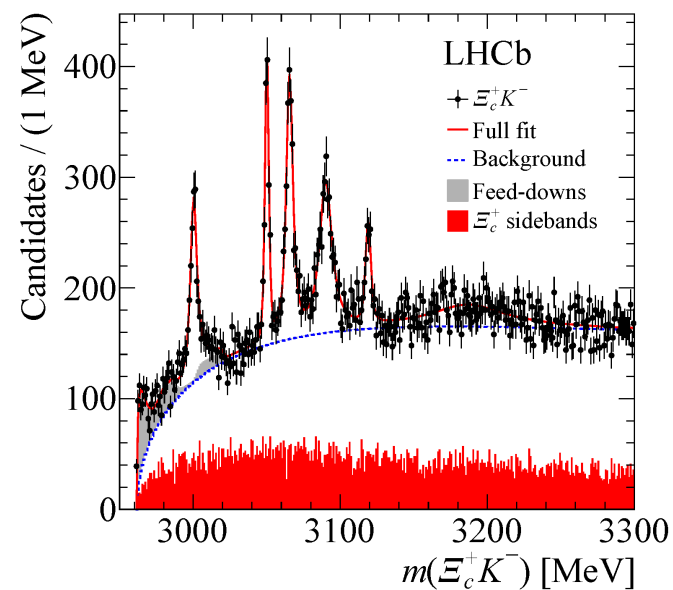
scoperta a 7.8σ

$$BR(B^0_s \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6 \pm 0.3) \times 10^{-9}$$

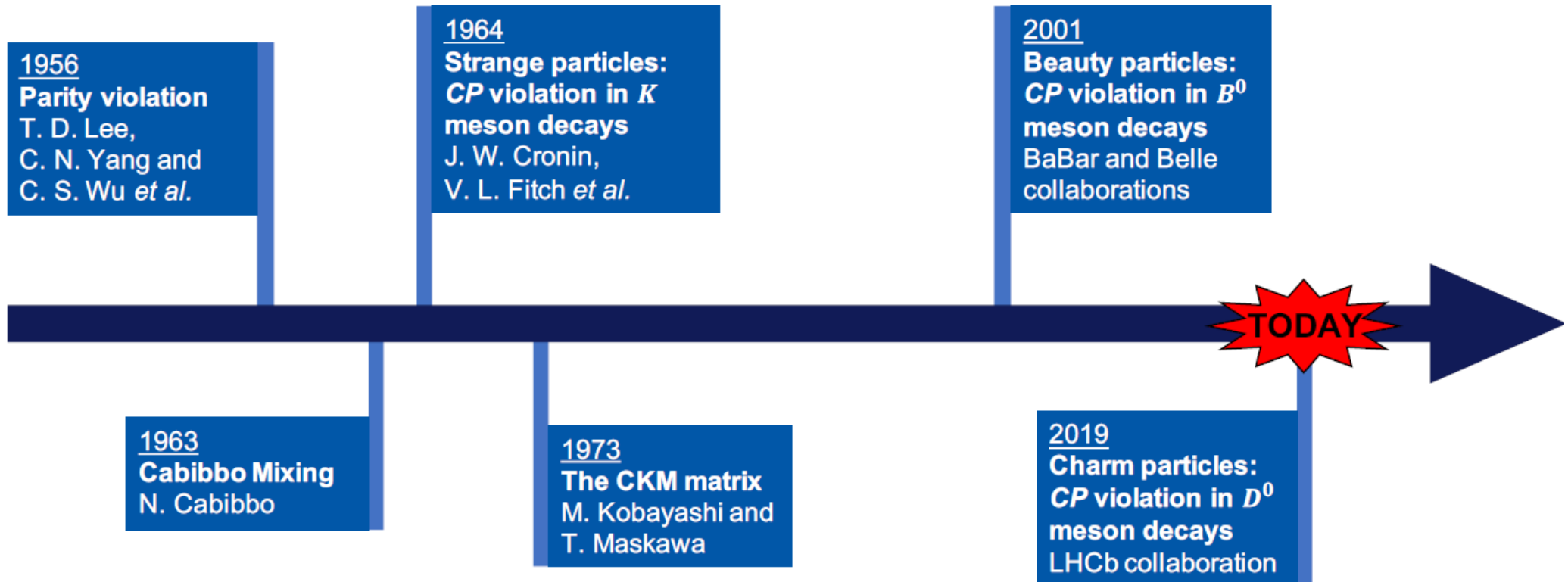
Test universalità leptonica (e, μ)



Spettroscopia Ω_c^0



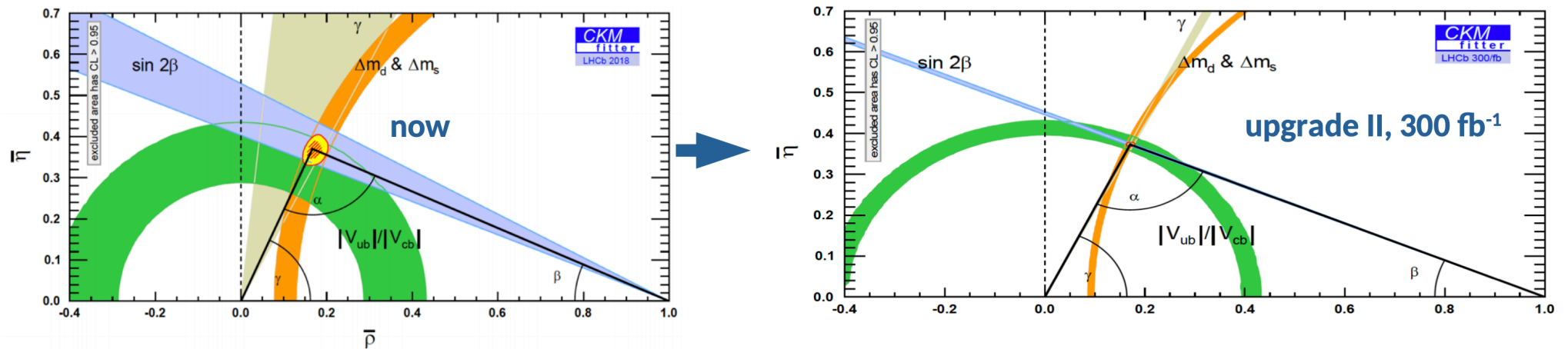
Violazione di CP nel settore dei quark



Matrice CKM e violazione di CP nel settore dei quark

LHCb ha migliorato la precisione con cui è misurato l'angolo γ del triangolo di unitarietà da 25° a 5°

Il miglioramento previsto nel futuro:

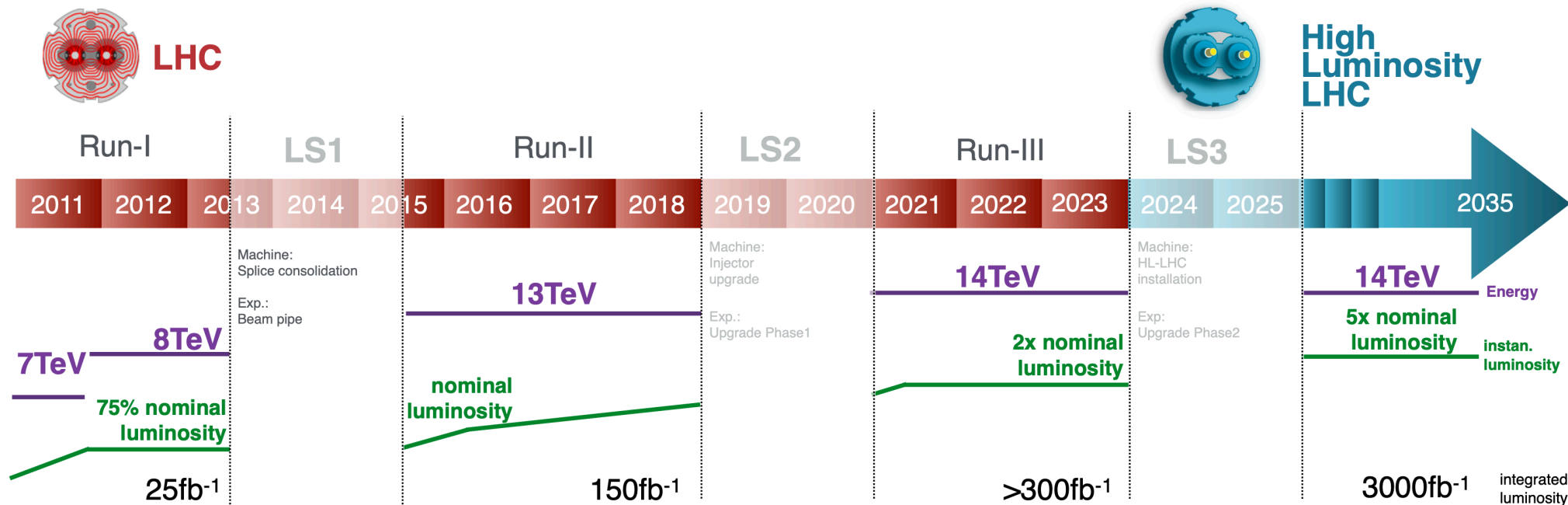


LHCb ha la prima evidenza della violazione di CP nel charm, misurando le diverse probabilità di decadimento di \bar{D}^0 e D^0 in $\pi^+\pi^-$ e K^+K^- : $\Delta A_{CP} = (-0.154 \pm 0.029)\%$

Il futuro di LHC

LHC progettato per $\sqrt{s} = 14 \text{ TeV}$ e $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Nel Run-II ha raggiunto un picco di luminosità pari al doppio della nominale a $\sqrt{s} = 13 \text{ TeV}$



L'obiettivo di HL-LHC è una luminosità integrata 20 volte superiore rispetto ad oggi. Pileup fino a 200 eventi per beam crossing (oggi fino a 50)

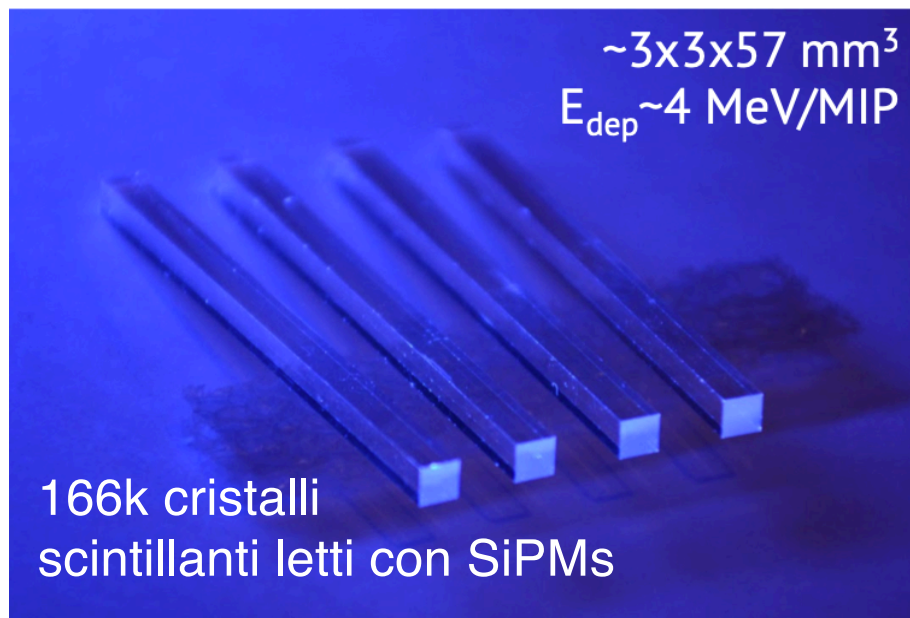
Upgrade di CMS

MIP Timing Detector

30-50 ps time tagging of individual tracks to $|\eta| < 3$

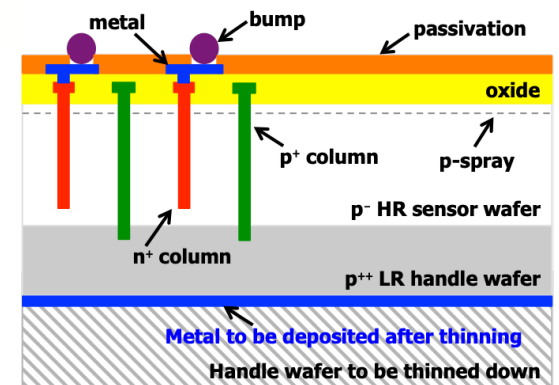
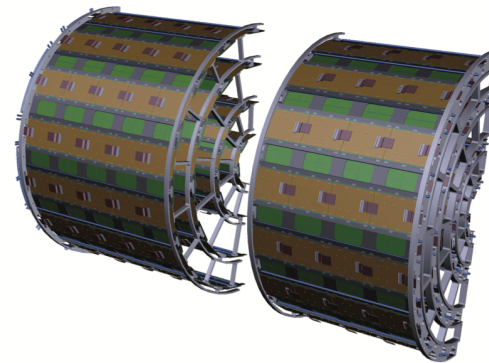
Barrel: LYSO Crystals + SiPM readout (40 m²)

Endcaps: low gain avalanche silicon detectors (14 m²)



Pixel Detector

Sensori 3D al silicio per rivelatore a pixel con migliore granularità e resistenza alle radiazioni



CERN: founded in 1954 by 12 European States

23 Member States

2500 staff

1800 other paid personnel

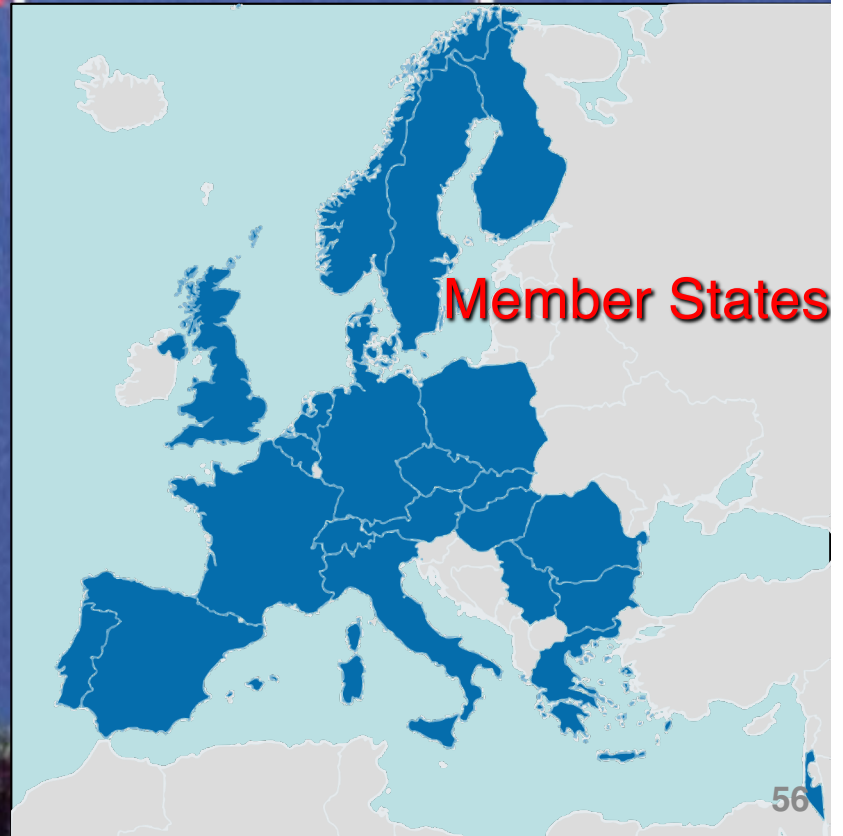
13000 scientific users from 600
scientific institutions

Budget ~ 1.2 Billion CHF /year

Pre-Stage to Membership: Cyprus, Serbia, Slovenia

Associate Member States: Croatia, India, Lithuania,
Pakistan, Turkey, Ukraine

Observers to Council: Japan, Russia, United States
of America, European Union, JINR and UNESCO



The History of CERN(Vol.1, p.130), a proposito di di Auger, Amaldi e Kowarski:

"Their goal... was not merely to construct a medium-sized accelerator, it was to awaken Europe and, through the construction of a giant accelerator, to make her understand the urgency and necessity of developing fundamental scientific research on a large scale as had happened in the US since the war".

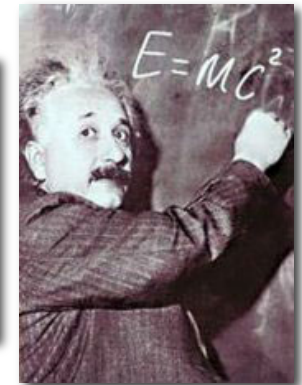
The CERN Convention (signed in 1953)

"The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available"

The Mission of CERN

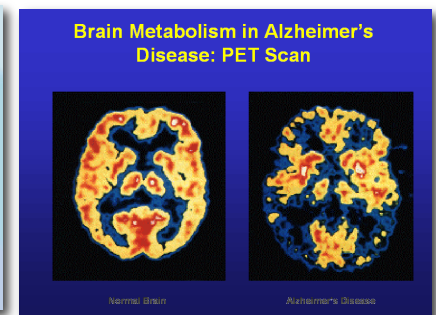
□ Push back the frontiers of knowledge

E.g. the secrets of the Big Bang ...what was the matter like within the first moments of the Universe's existence?

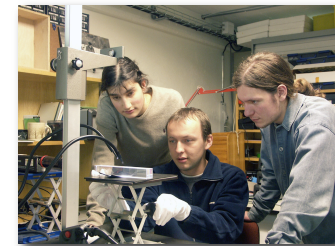


□ Develop new technologies for accelerators and detectors

Information technology - the Web and the GRID
Medicine - diagnosis and therapy



□ Train scientists and engineers of tomorrow



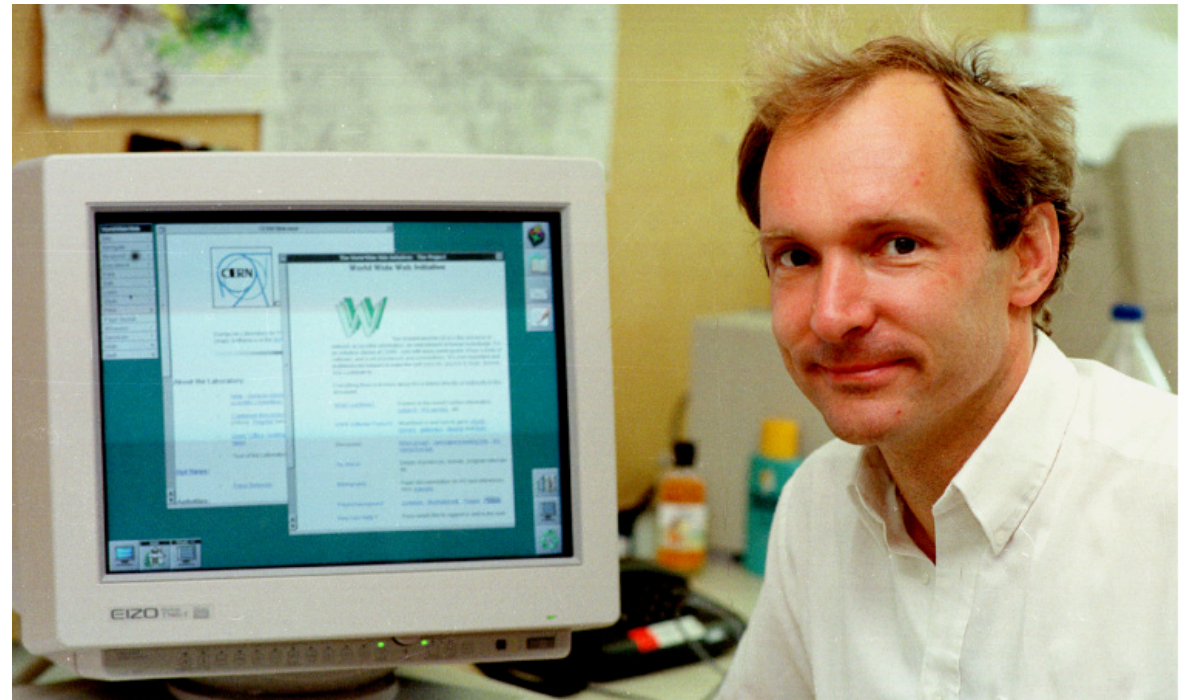
□ Unite people from different countries and cultures



Born at CERN

Tim Berners Lee di fronte ad uno schermo con un immagine del primo browser WWW (1991) per condividere documenti

The prototype^[1] x-y mutual capacitance touchscreen (left) developed at CERN^{[2][3]} in 1977 by Bent Stumpe, a Danish electronics engineer, for the control room of CERN's accelerator SPS (Super Proton Synchrotron). This was a further development of the self-capacitance screen (right), also developed by Stumpe at CERN^[4] in 1972.

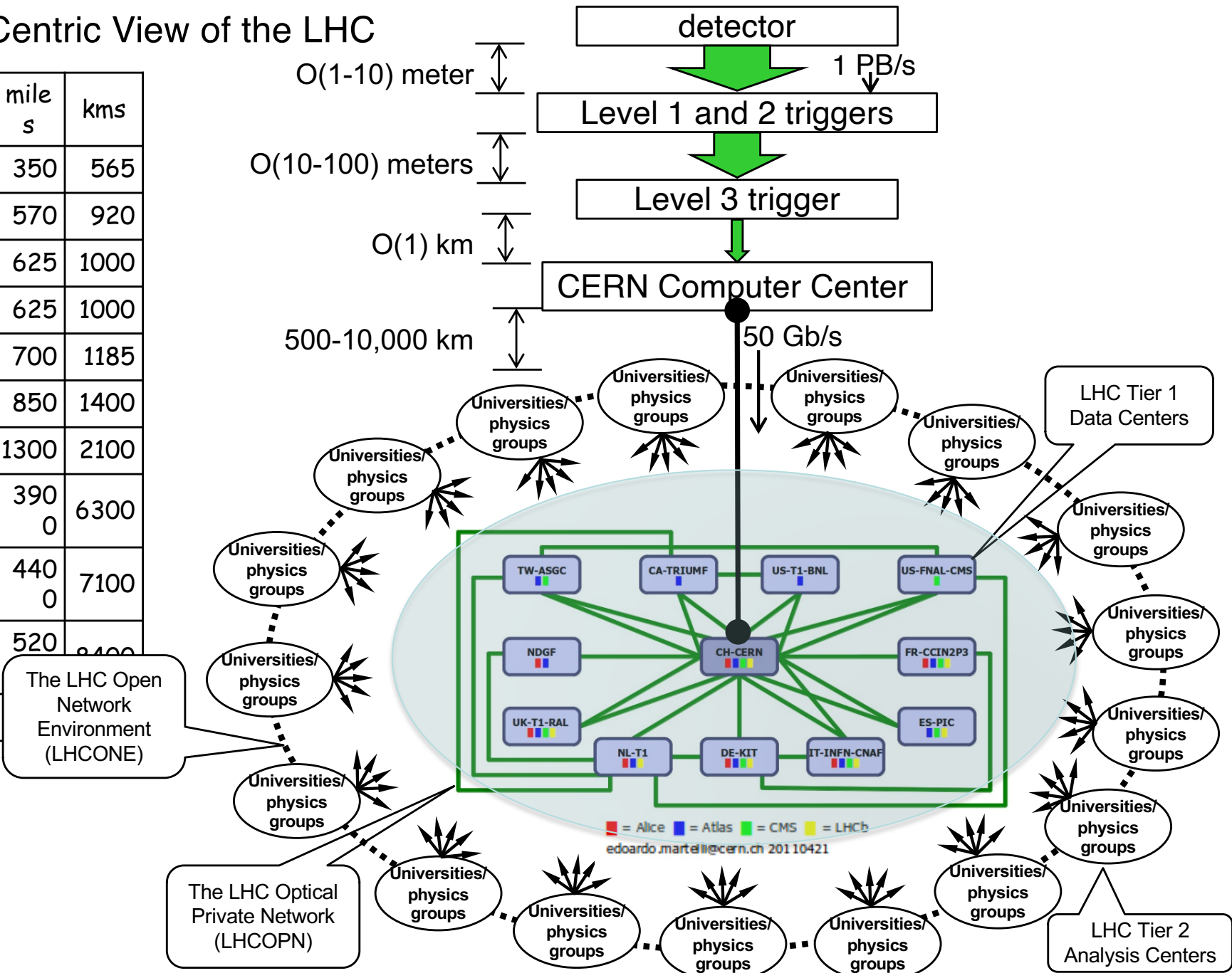


Nel 1993 il CERN rinuncia a qualunque diritto, distribuendo il codice sorgente

Distributed Computing: the Grid

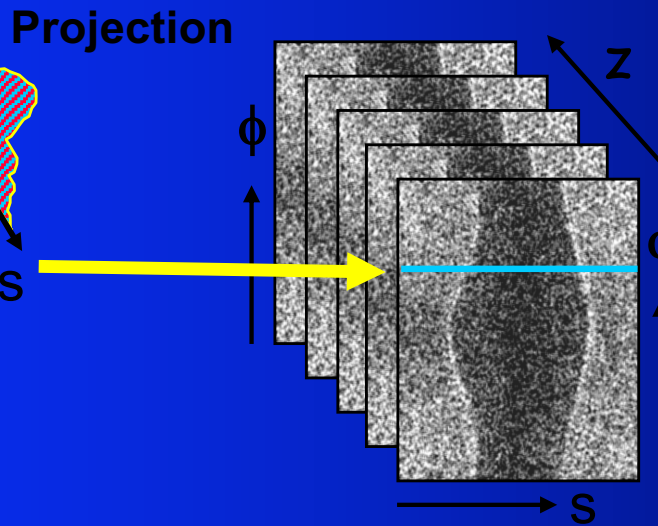
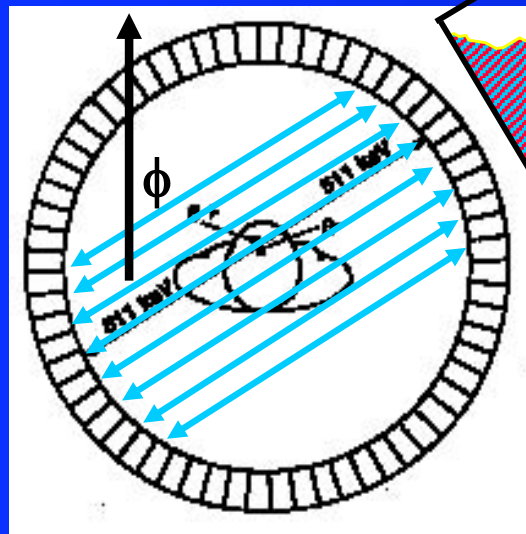
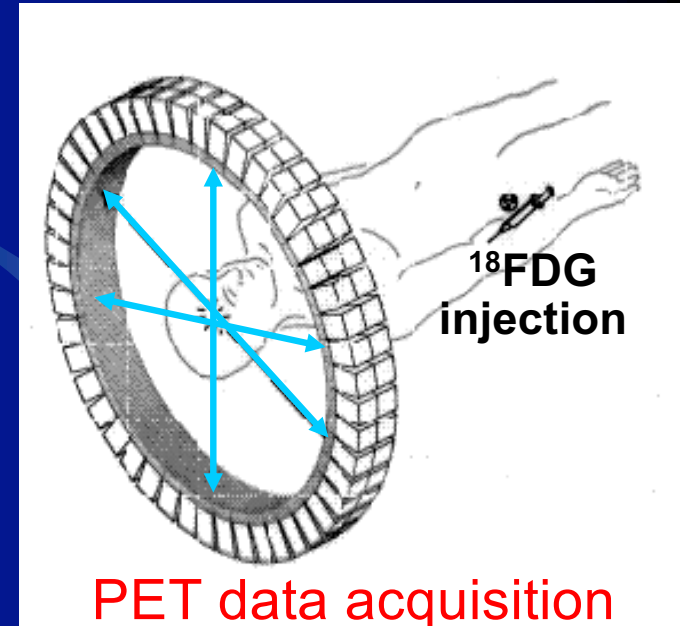
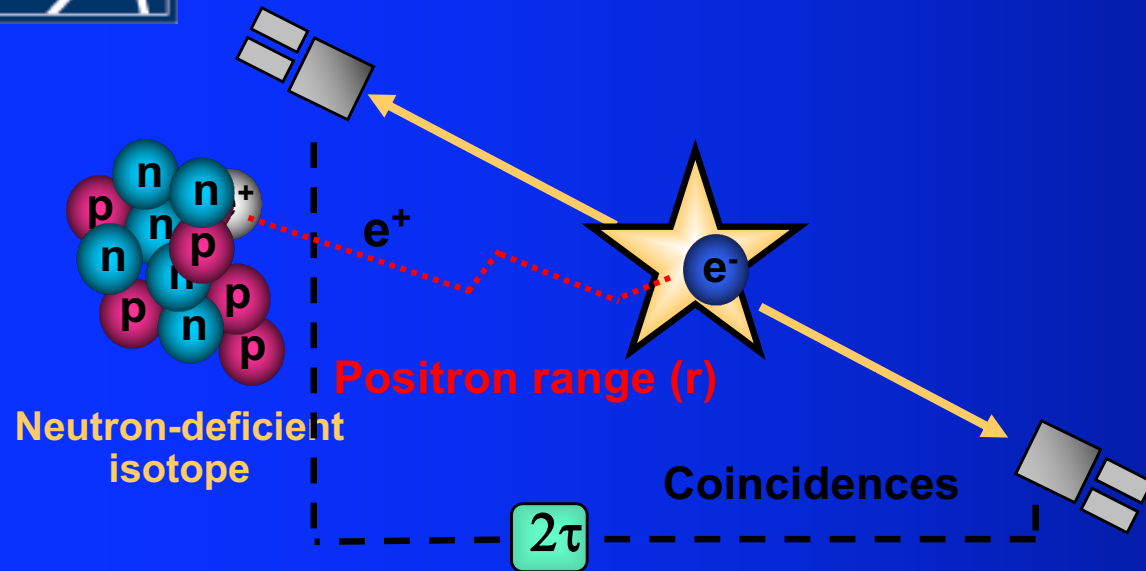
A Network Centric View of the LHC

CERN → T1	miles	kms
France	350	565
Italy	570	920
UK	625	1000
Netherlands	625	1000
Germany	700	1185
Spain	850	1400
Nordic	1300	2100
USA - New York	3900	6300
USA - Chicago	4400	7100
Canada - BC	5200	8400
Taiwan		

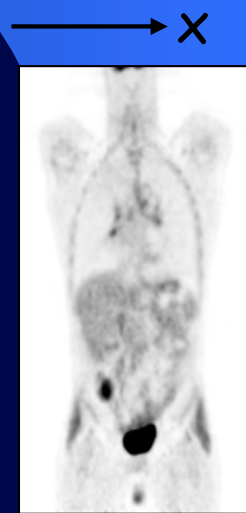




PET Principle

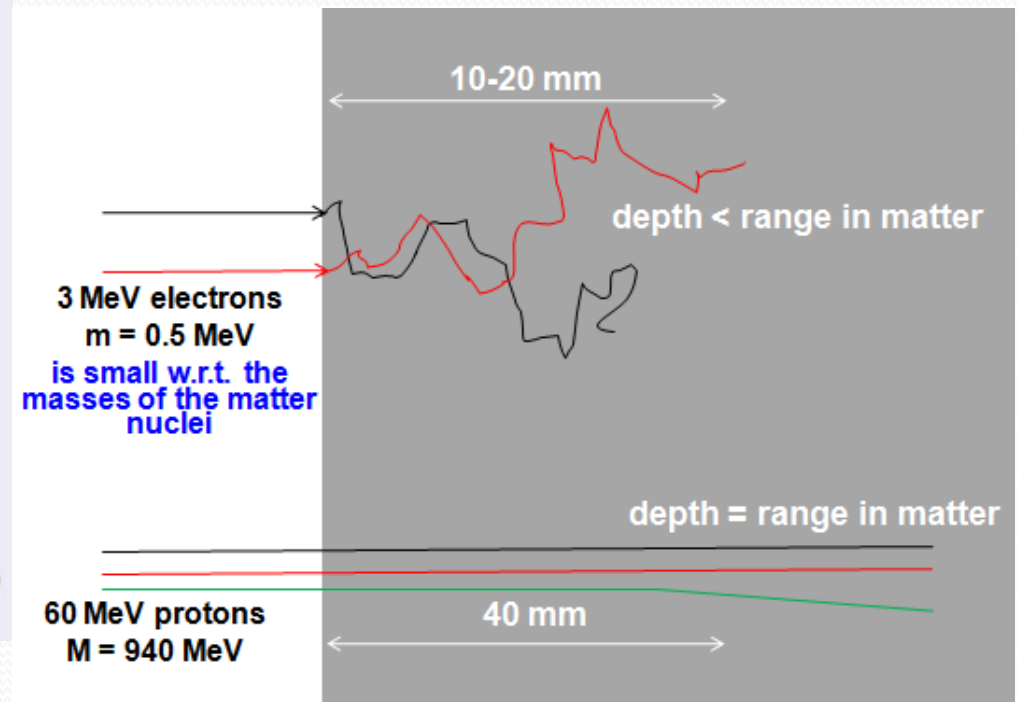
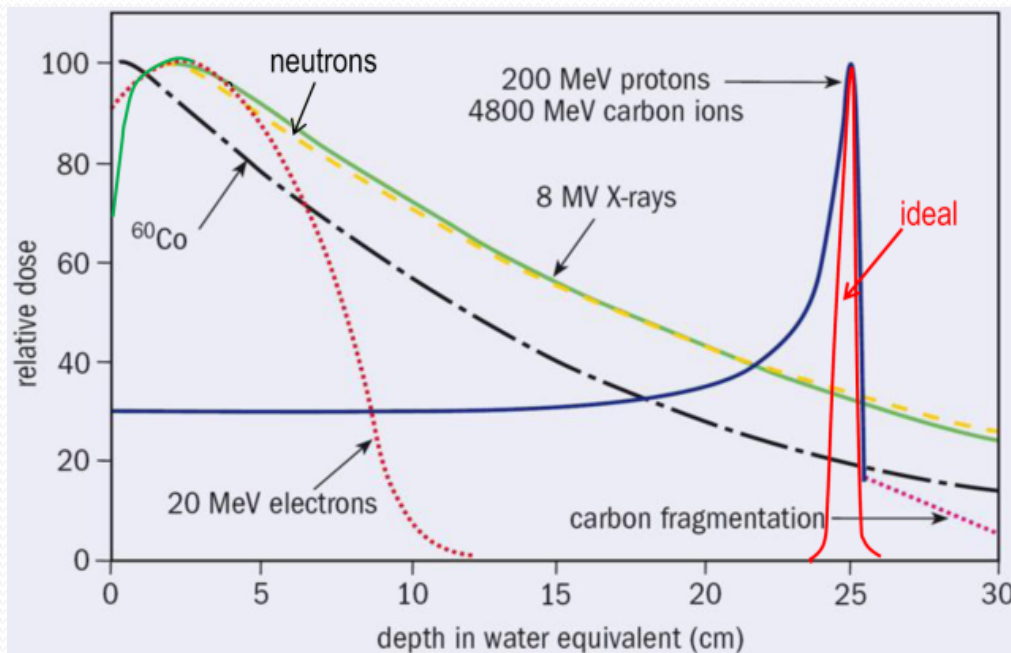


Reconstruction



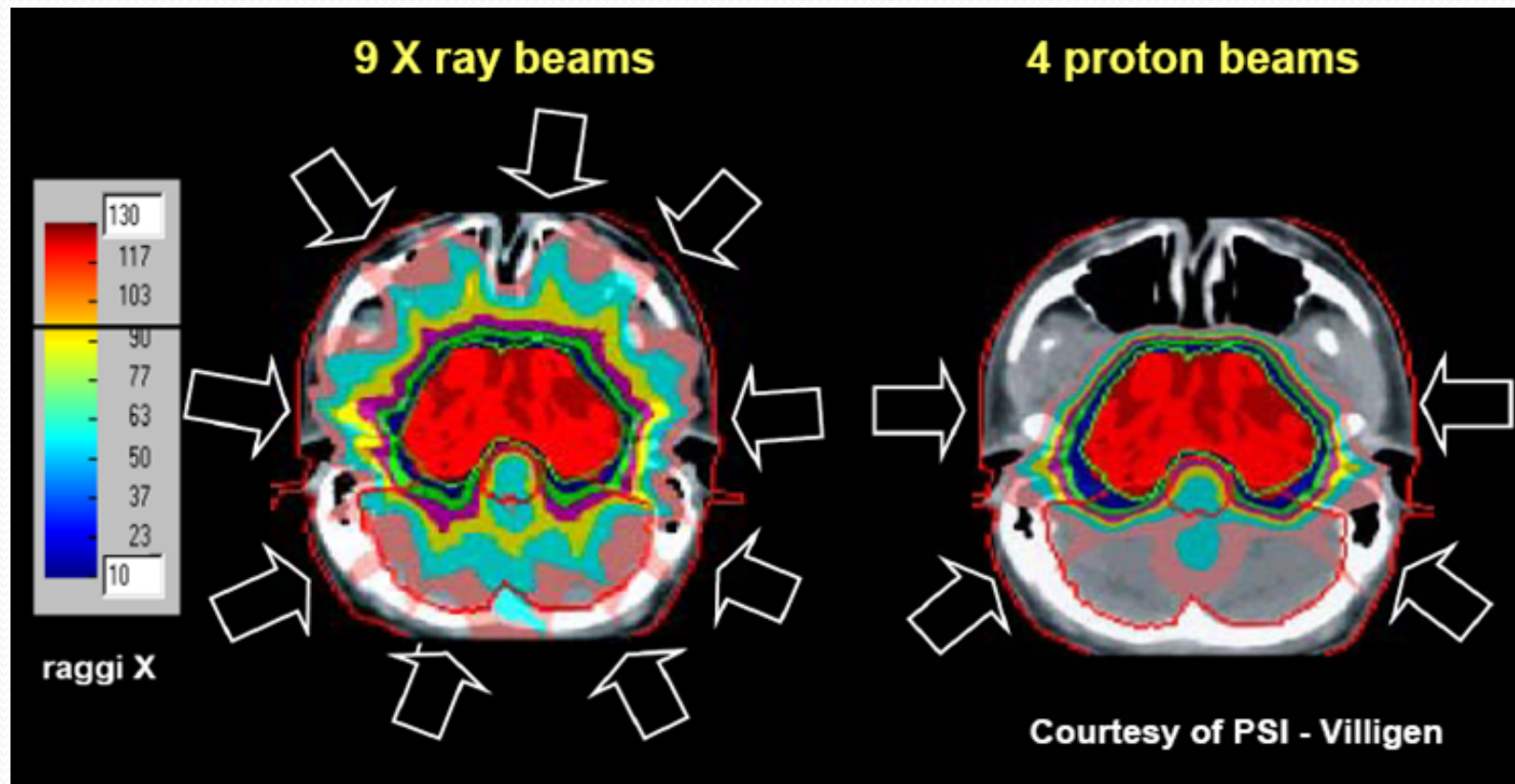
Adroterapia oncologica

1. Energia massima nel picco di Bragg → riduzione della dose nei tessuti attraversati, quasi nessuna dose nei tessuti più in profondità del picco
2. Diffusione laterale molto piccola



Adroterapia oncologica

Possibilità di fare trattamenti altamente conformi per tumori profondi con precisione ~mm e dando una dose minima ai tessuti circostanti



Il futuro del CERN ?

European Particle Physics Strategy deve essere definita a breve

Future Circular Collider è una possibile opzione

