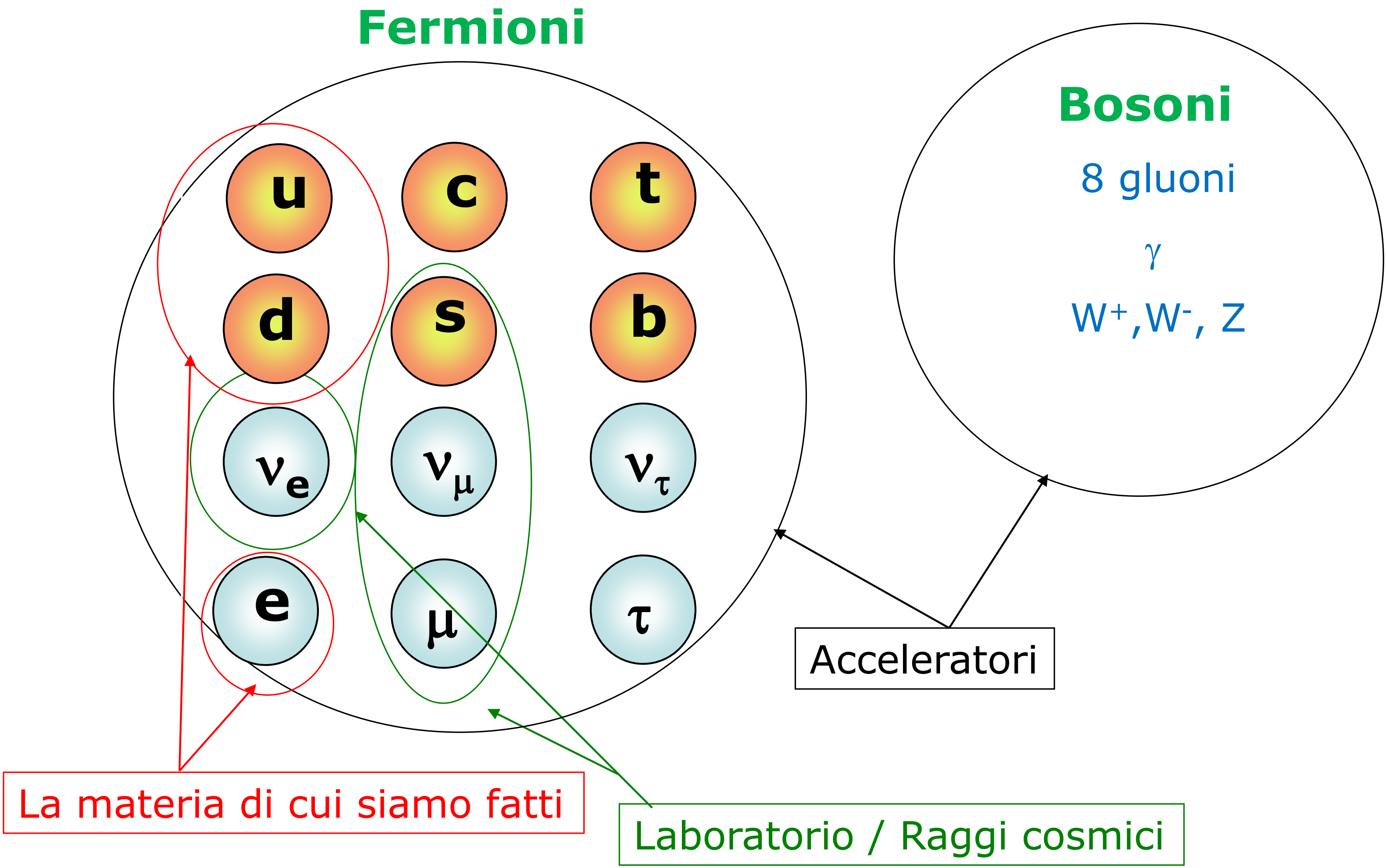
Il CERN e il
Large Hadron Collider

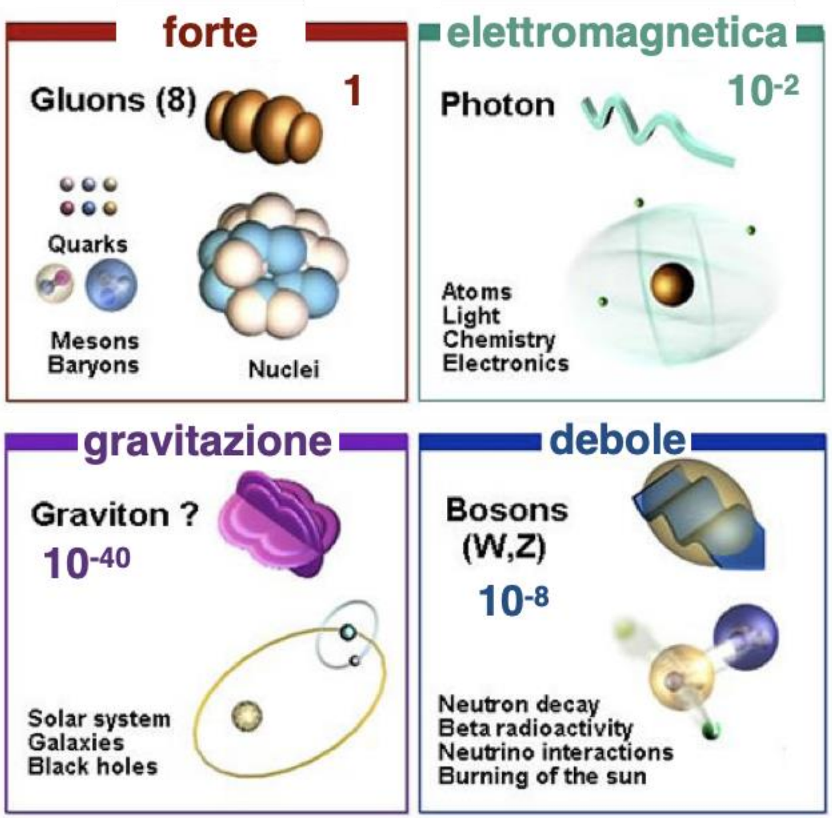
M. Paganoni

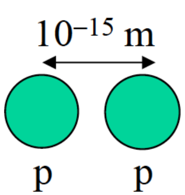
14/2/2023

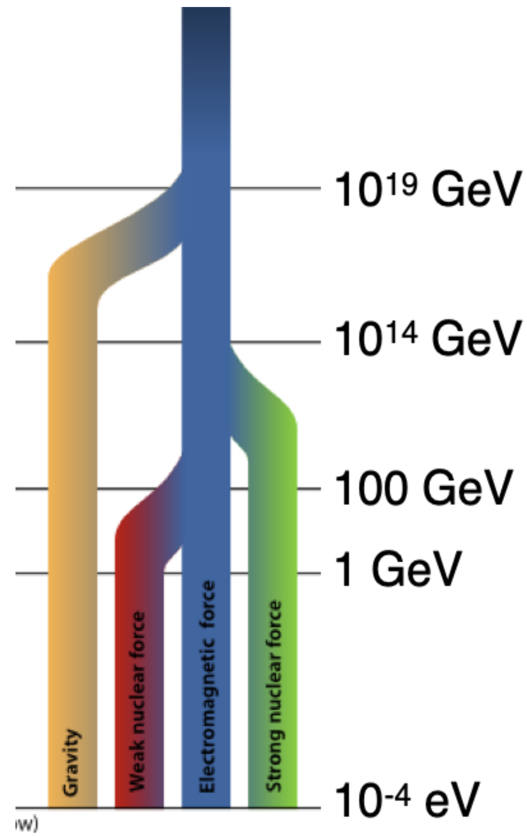
Le particelle elementari



Le interazioni Fondamentali



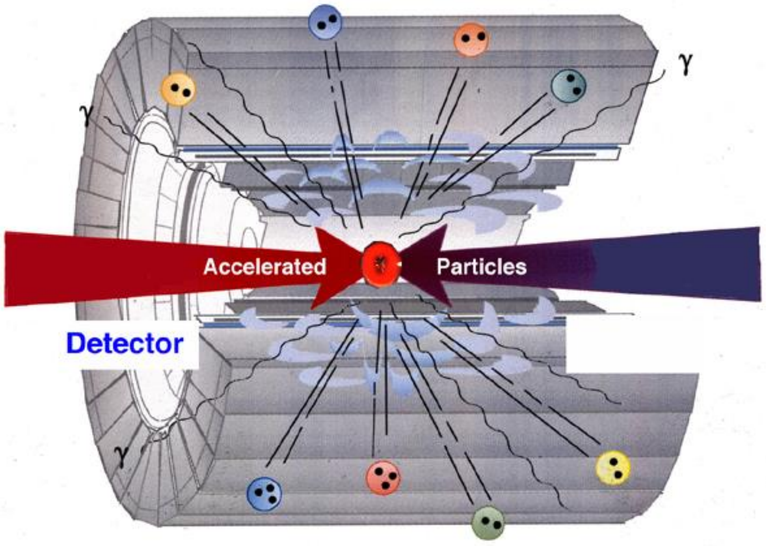




ToE

GUT

Rottura spontanea simmetria



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 barn = 10^{-24} 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:

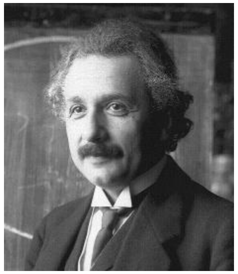
✓ sondare la materia su scale più piccole

$E = h\nu$, h = costante di Planck
1 TeV $\Rightarrow$ 0.001 fm

Louis
de Broglie

✓ creare nuove particelle a grande massa

$E = m c^2$



Albert
Einstein

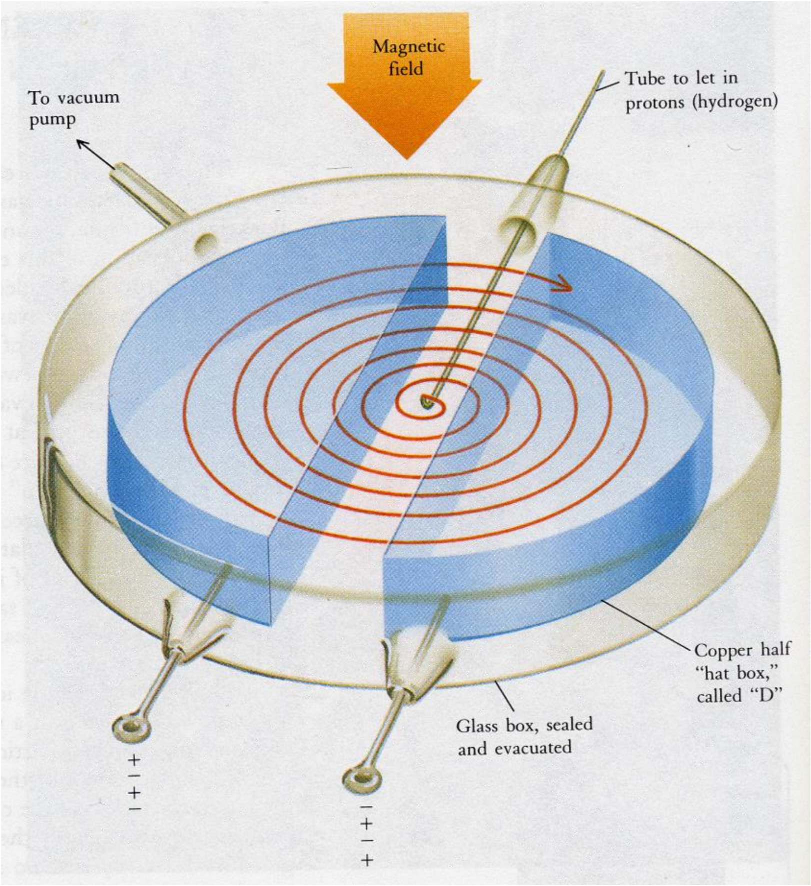
✓ studiare la dinamica dell' universo poco dopo il big bang

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

Ludwig
Boltzmann

I primi acceleratori

Ciclotrone



1930, E. Lawrence, protoni da 100 MeV

Cockroft Walton

CERN, protoni da 800 keV

Il sincrotrone

1959: Proton Synchrotron

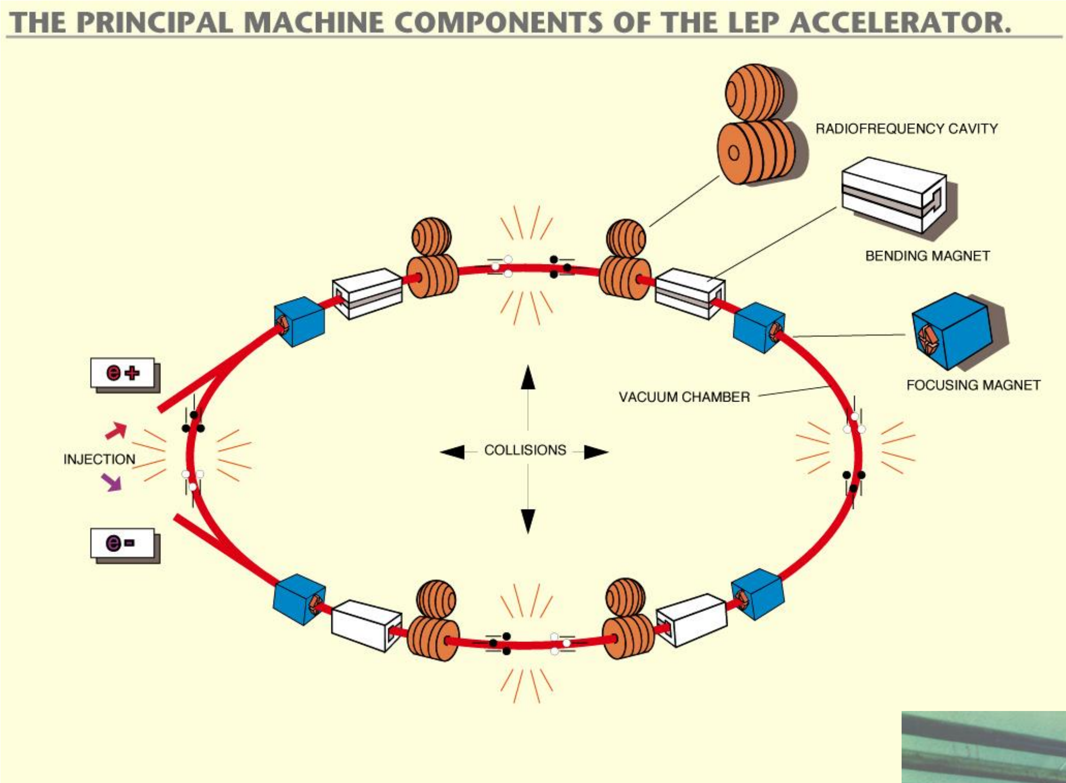
$2\pi R = 628$ m

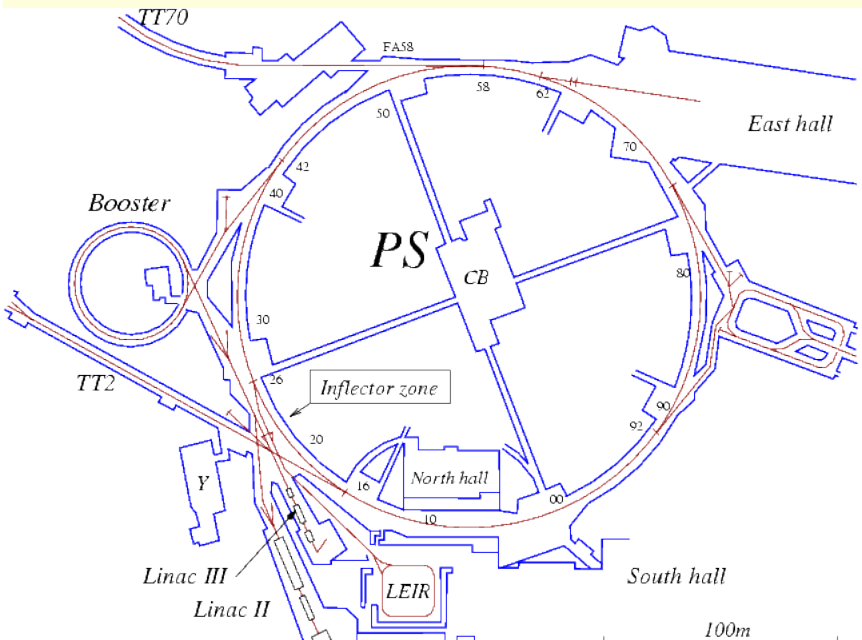
$E_{max}(p) = 28$ GeV

1975: Super Proton Synchrotron

$2\pi R = 7$ km

$E_{max}(p) = 450$ 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
- ✓ È il più grande laboratorio di Fisica Fondamentale al mondo
- ✓ 25 stati membri, 2300 staff, ~ 12000 utenti da 600 Istituzioni
- ✓ Budget ~ 1 G CHF / anno

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

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

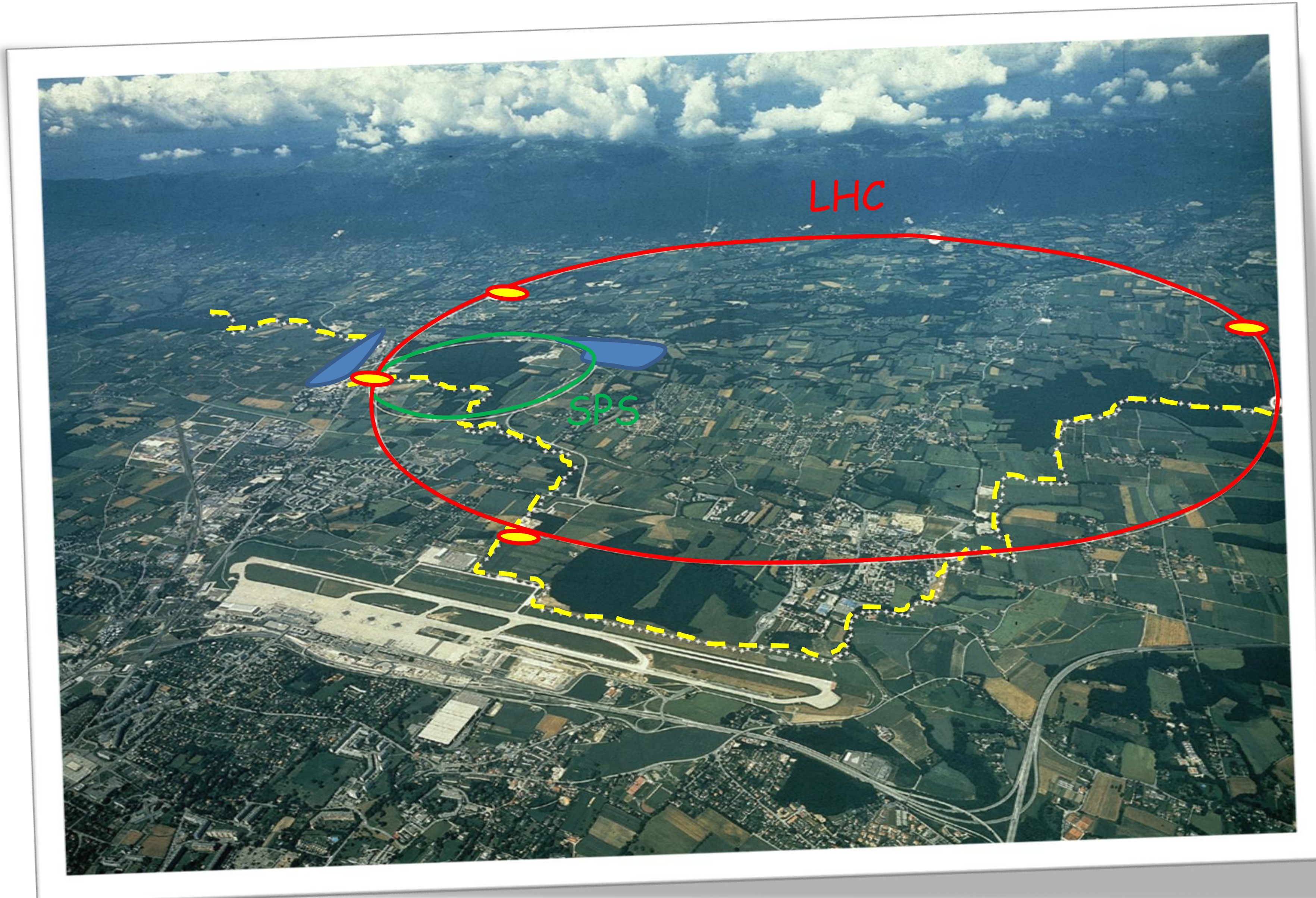
"Their goal…was not merely to construct a medium-sized accelerator, it was to awaken Europe and, through the construction of a giant accelerator, to make her understand the urgency and necessity of developing fundamental scientific research on a large scale as had happened in the US since the war".

The CERN Convention (1953)

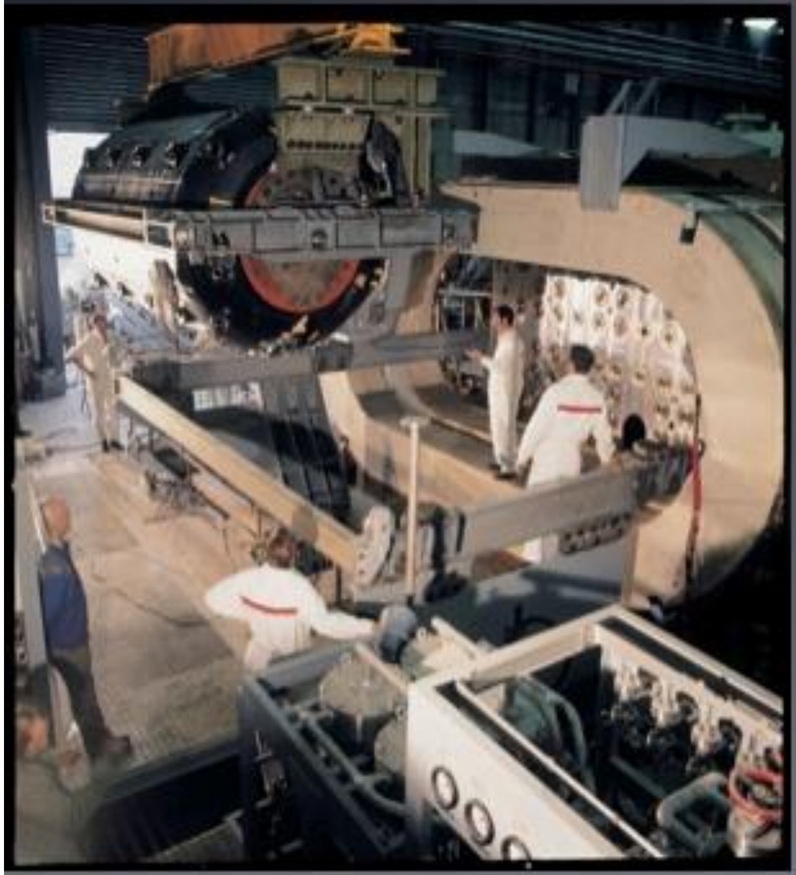
"The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available"

At CERN, our work helps to uncover what the universe is made of and how it works. We do this by providing a unique range of particle accelerator facilities to researchers, to advance the boundaries of human knowledge.

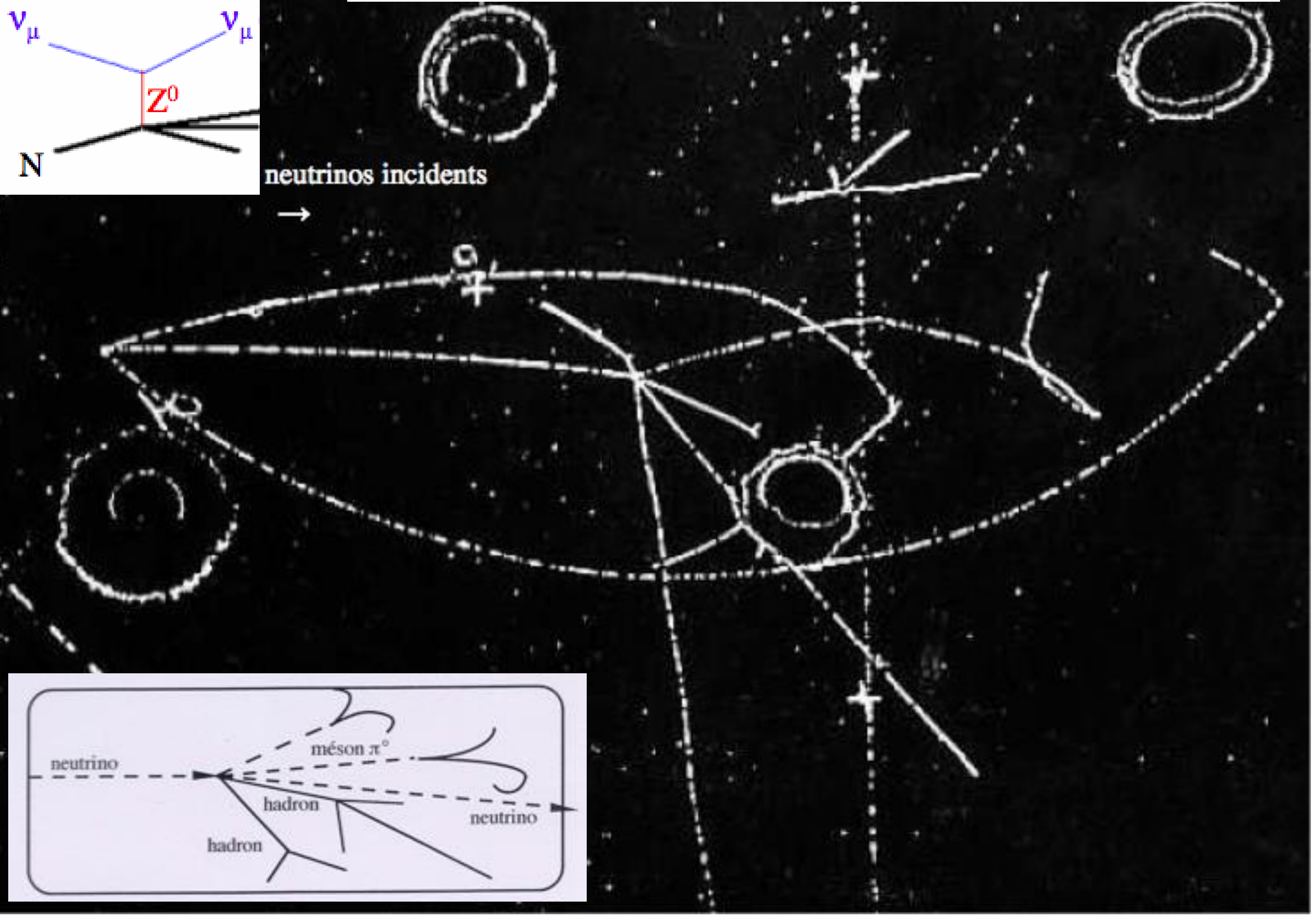
CERN site



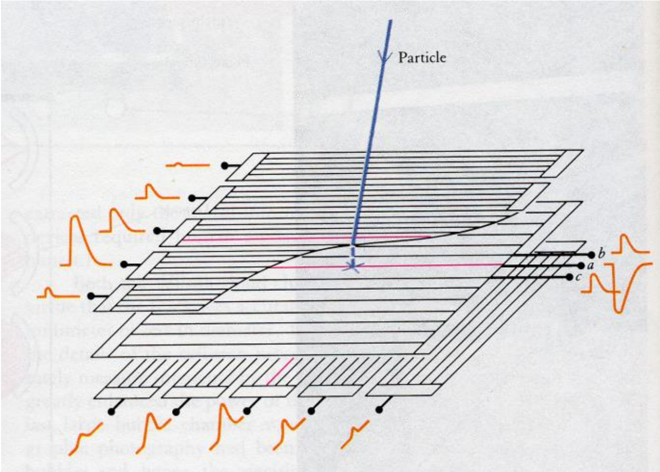
Installazione camera a bolle Gargamelle (1970)

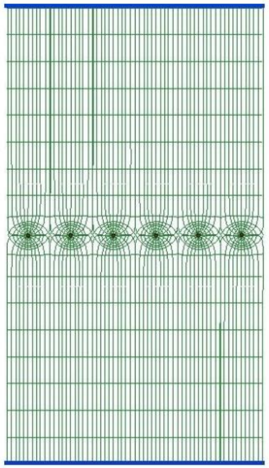


Evento di corrente debole neutra (1973)



Multi Wire Proportional Chamber

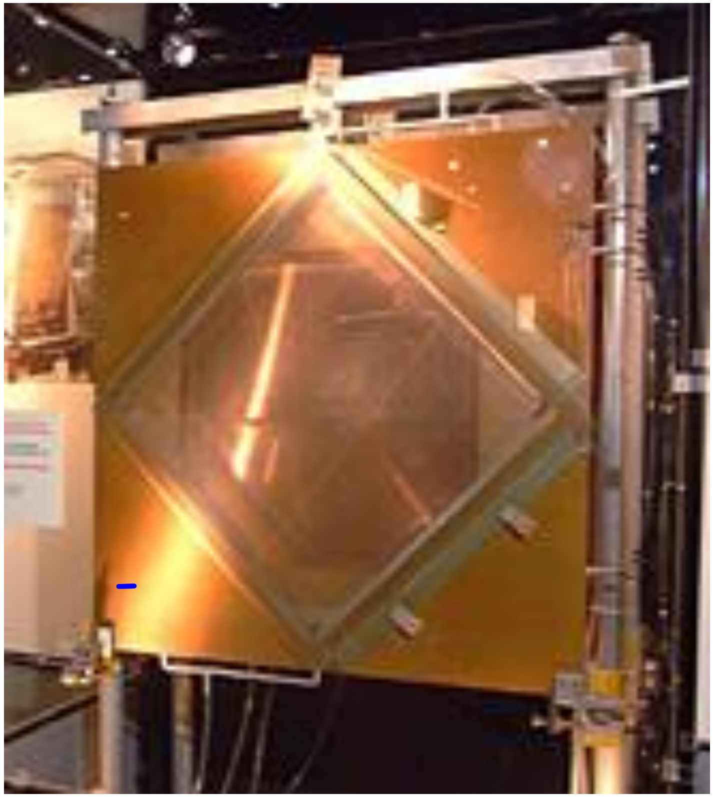




G.Charpak, 1967
(Premio Nobel nel 1992)

Primo rivelatore elettronico,
permette alte statistiche

d ~ 1 mm
R_{wire} ~ 20 μm



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

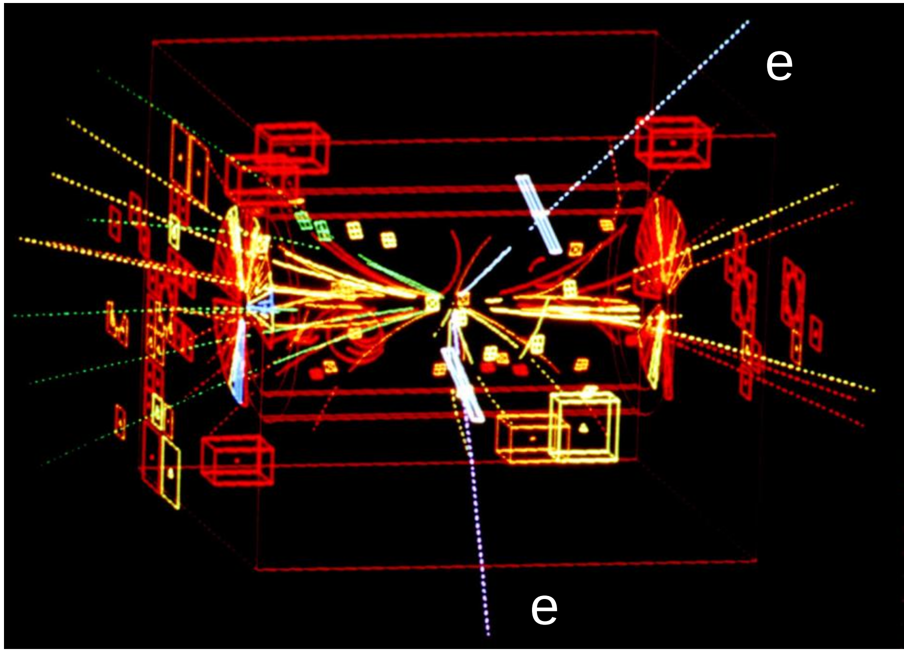
Amplficazione nel gas necessaria,
per un buon rapporto S/N

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

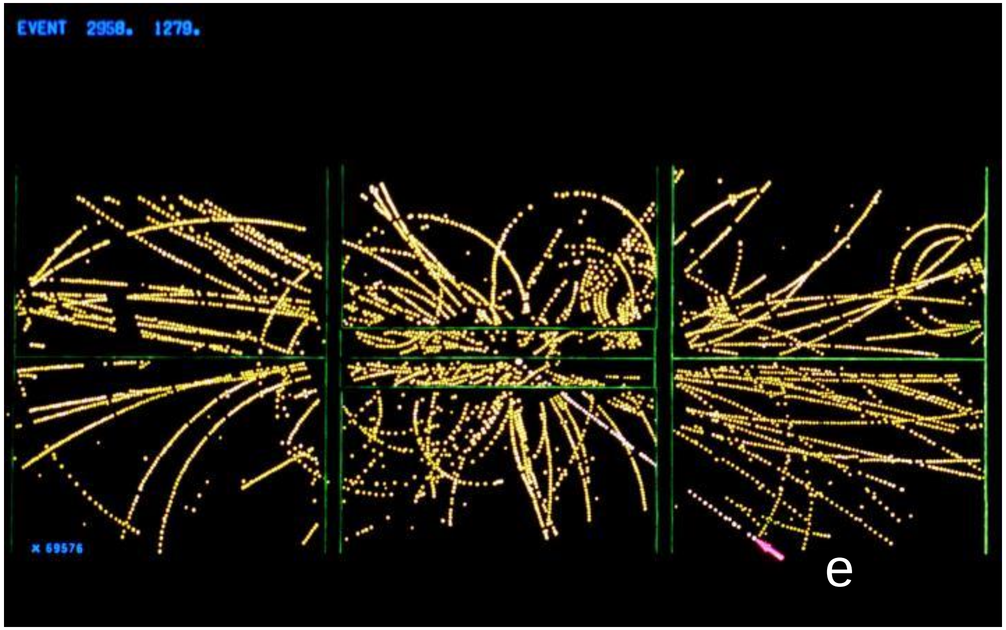
C.Rubbia e S. Van der Meer (Premio Nobel nel 1984) trasformano SPS in collisore $p\bar{p}$ con $\sqrt{s}$ ~ 540 GeV (630 GeV) e buona luminosità dei $\bar{p}$ grazie allo "stochastic cooling"

UA1 e UA2 prendono dati dal 1981 al 1990

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



$Z \rightarrow e^+e^-$



$W \rightarrow e\,\nu$

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 $\sqrt{s}$ ~ 91 GeV

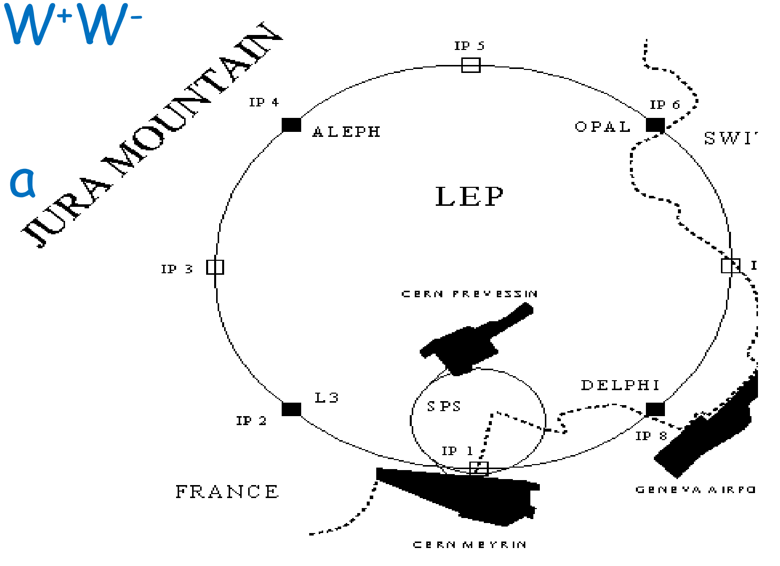
Ott.1989: viene misurata Numero famiglie neutrini = 3

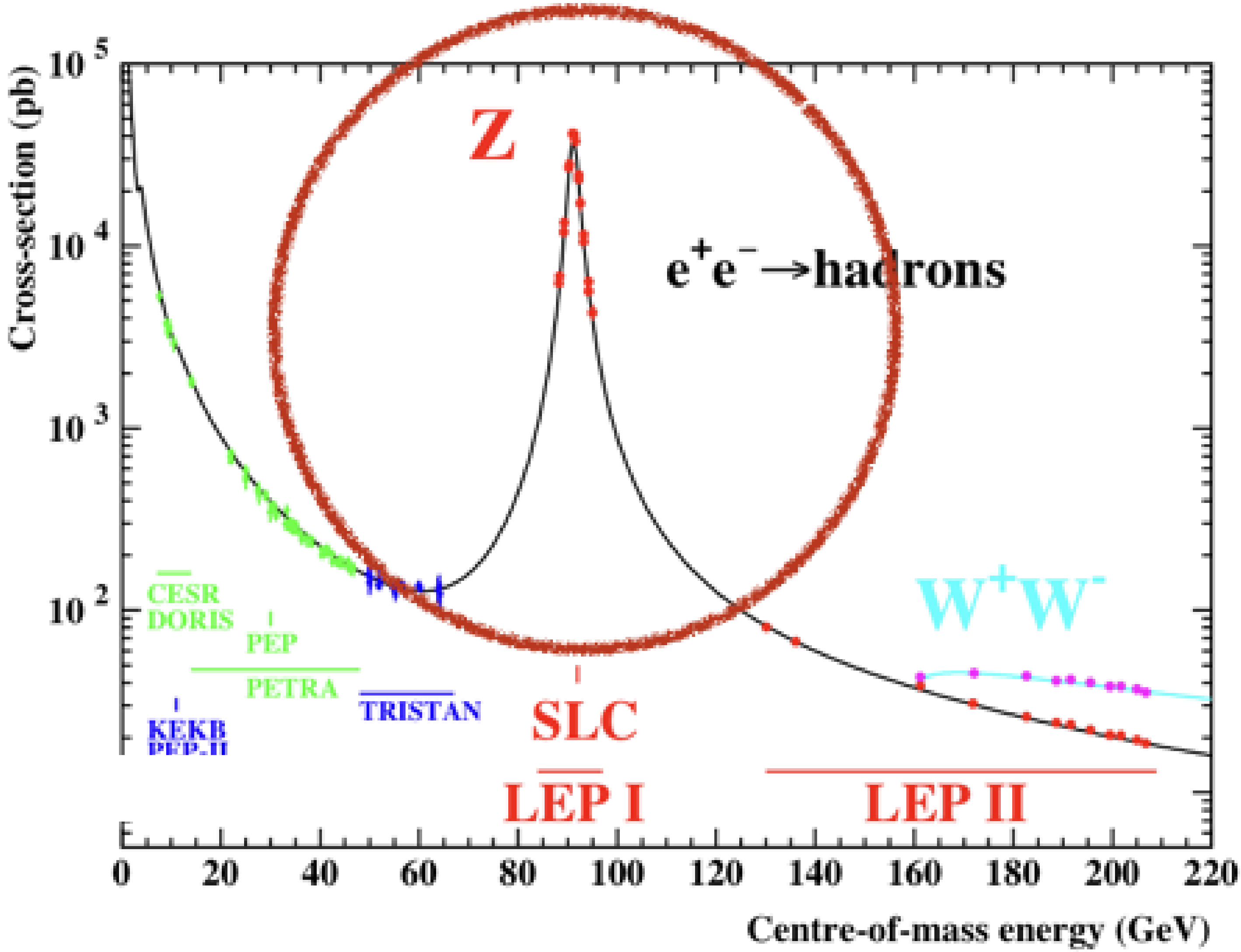
Vengono prodotte 17 milioni di Z

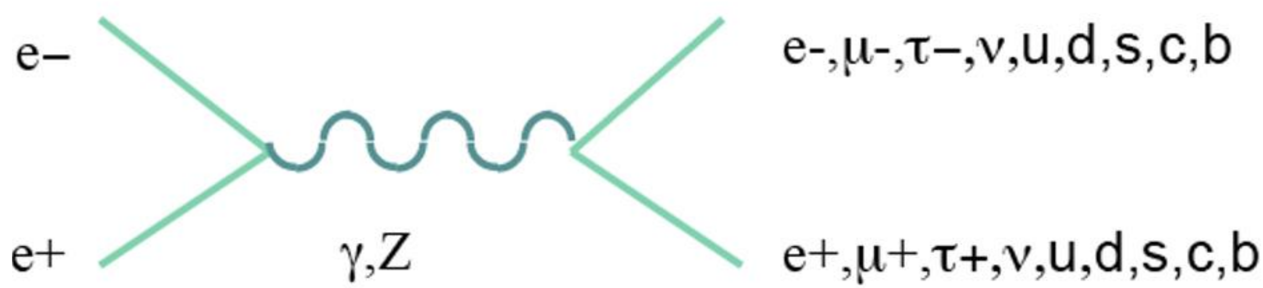
LEP-II (1995 - 2000)

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

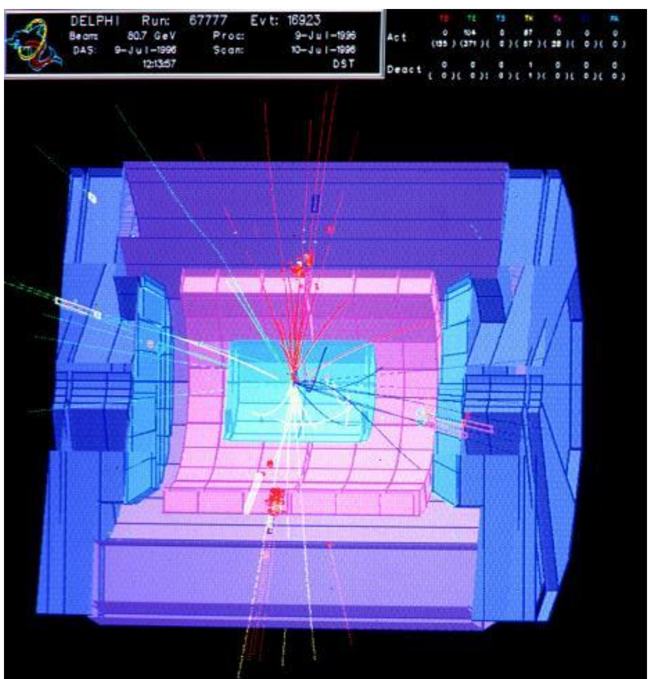
Possibilità di scoperta di Higgs SM fino a M_H ~ 110 GeV/c^2

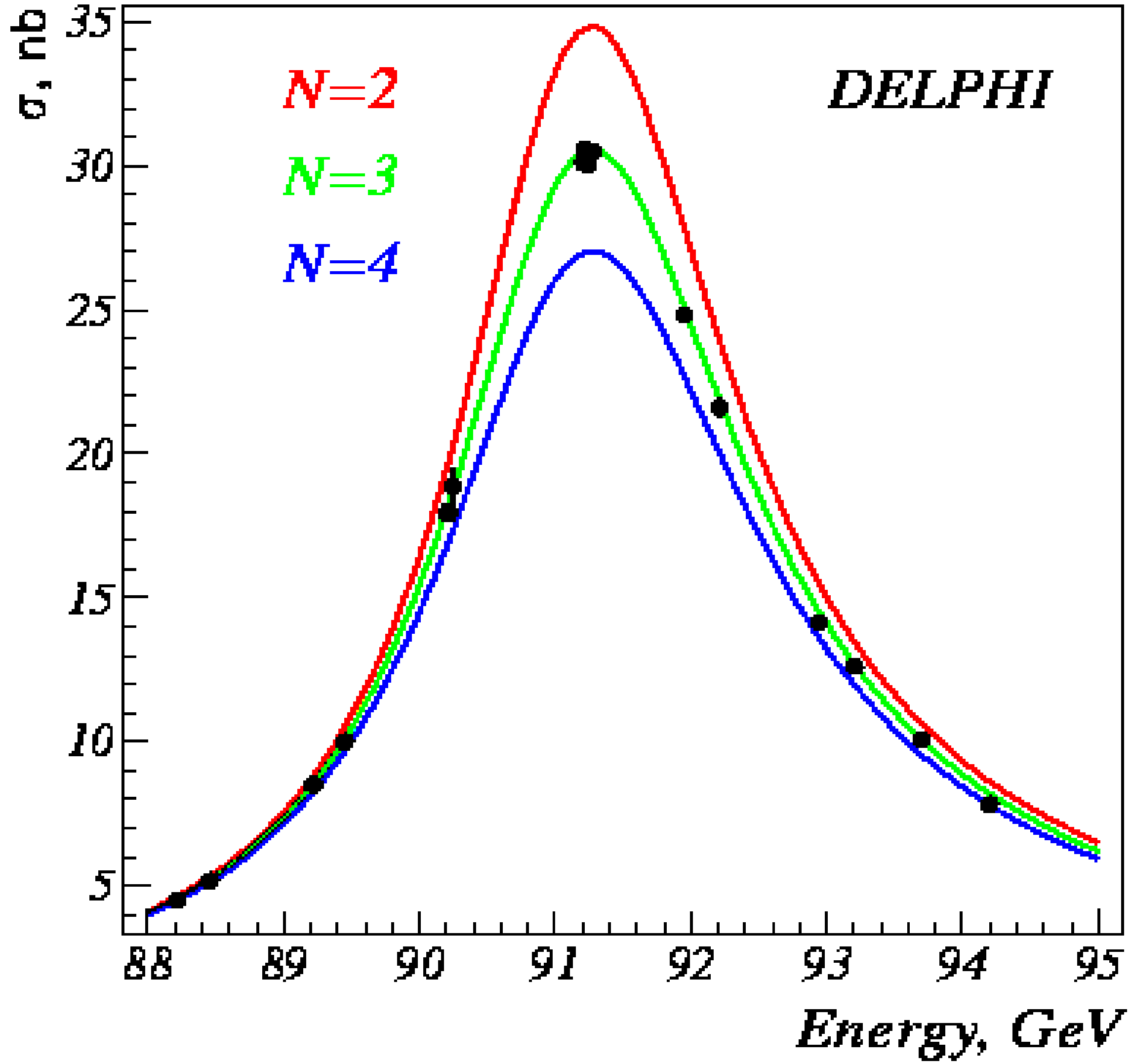



Cross-section (pb)
10^5
10^4
10^3
10^2
Z
e+e- → hadrons
W+W-
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
SLC
LEP I
LEP II
0 20 40 60 80 100 120 140 160 180 200 220
Centre-of-mass energy (GeV)


e−
e+
γ,Z
e-,μ-,τ−,ν,u,d,s,c,b
e+,μ+,τ+,ν,u,d,s,c,b

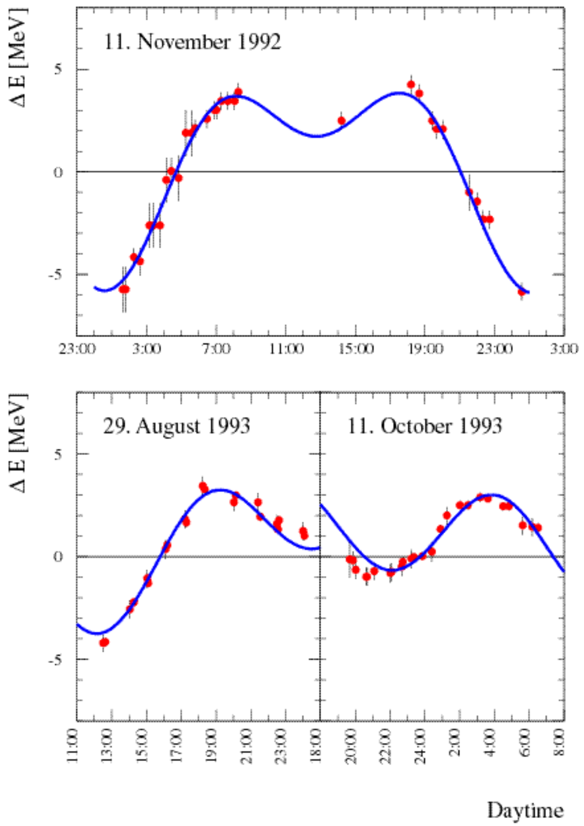
Misure di precisione del Modello Standard a LEP

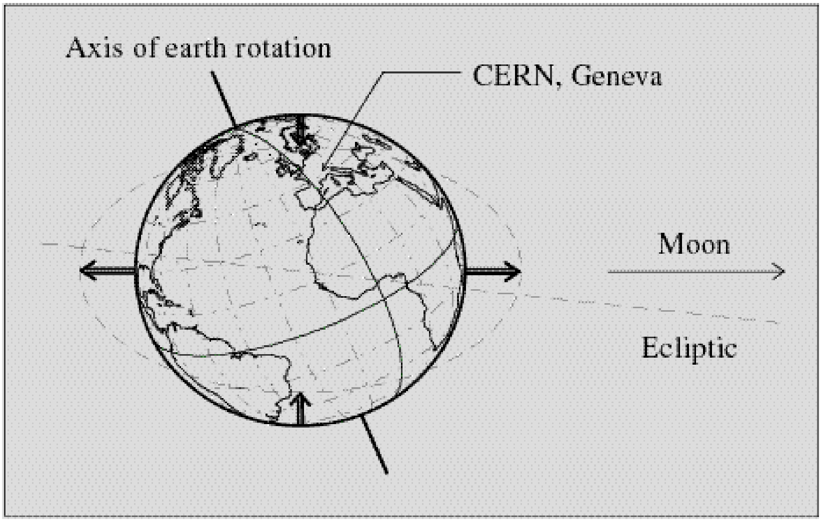




Misura energia del fascio a LEP

Precise determination of the LEP beam energy **(10^{-5} relative accuracy, ~ 1 MeV)**
Precise measurement of the Z mass and width





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

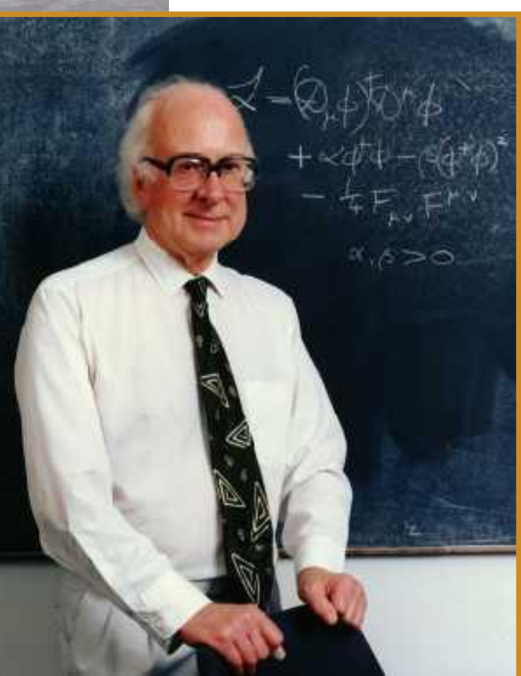
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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
athematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

S AND MASSLESS PARTICLES*

gen,‡ and T. W. B. Kibble
rial College, London, England
October 1964)

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

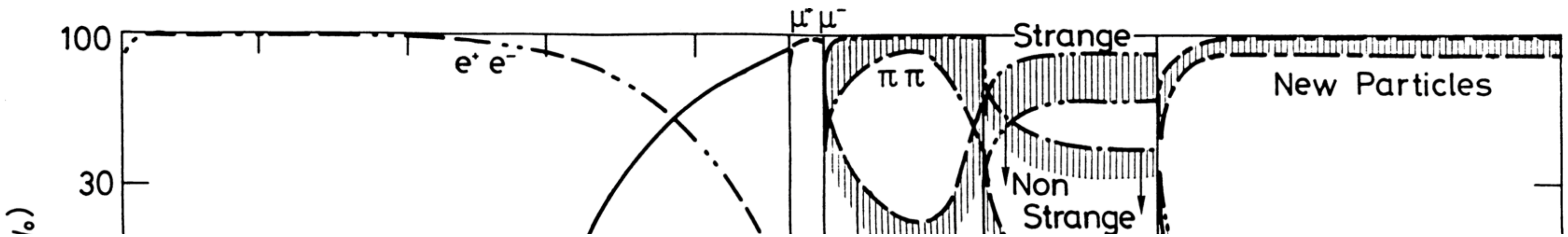
A. A. MIGDAL and A. M. POLYAKOV

Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966
J. Exptl. Theoret. Physics (U.S.S.R.) **51**, 135–146 (July, 1966)

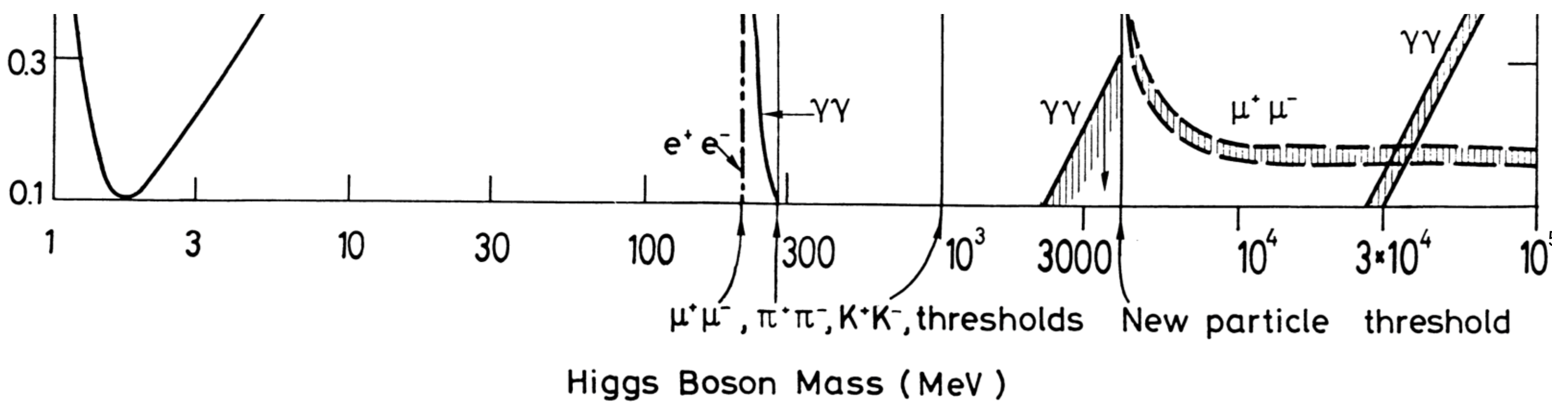
The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass

Higgs Boson Phenomenology – Summary in 1975

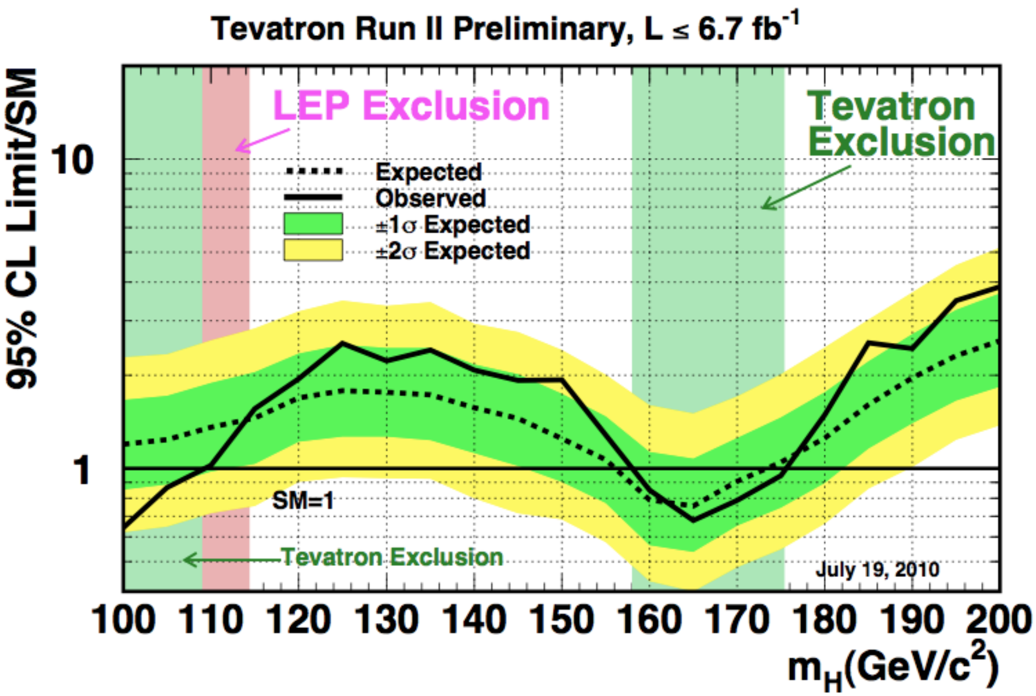
J. Ellis, M.K. Gaillard, D.V. Nanopoulos,

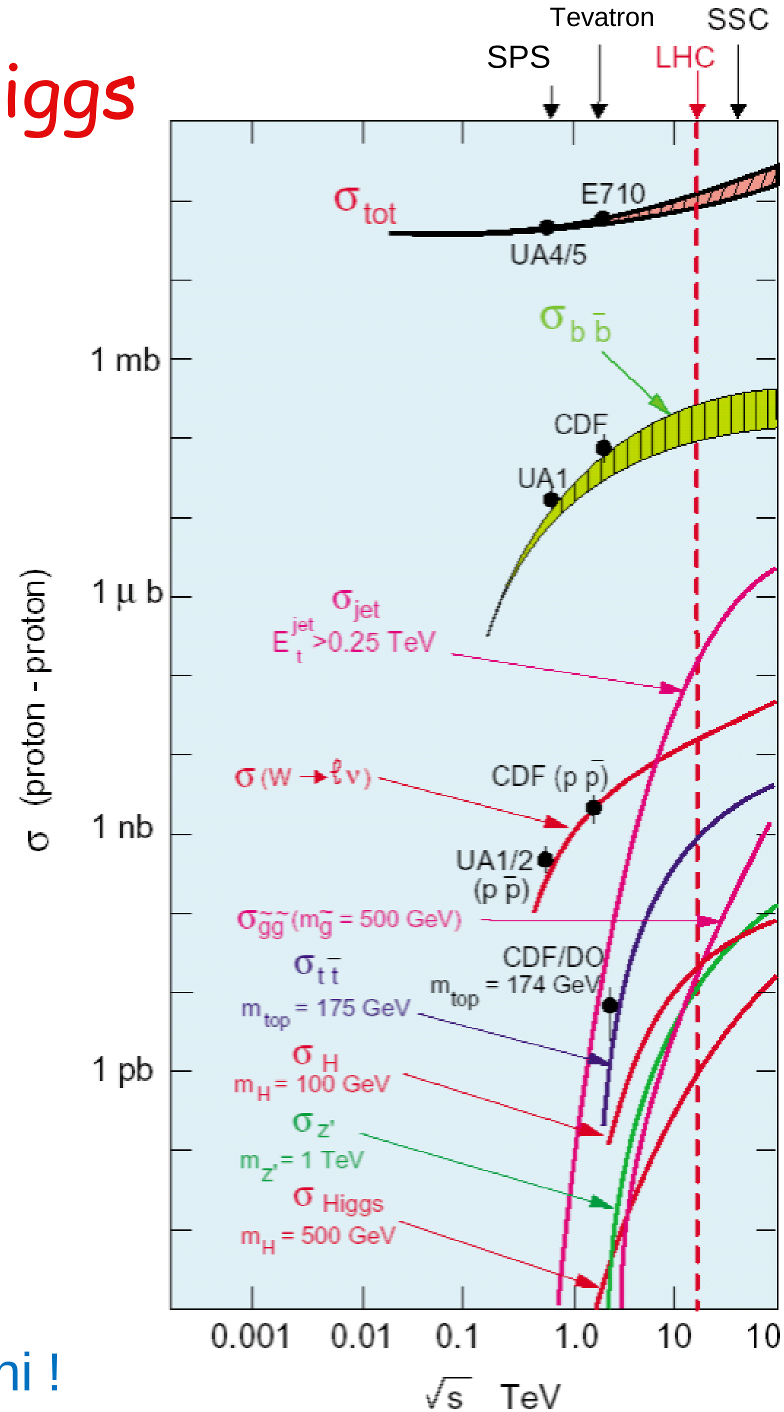


We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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.



Ricerca del bosone di Higgs





LEP direct exclusion: $m_H > 115$ GeV/c^2

LEP precision meas. $m_H < 200$ GeV/c^2

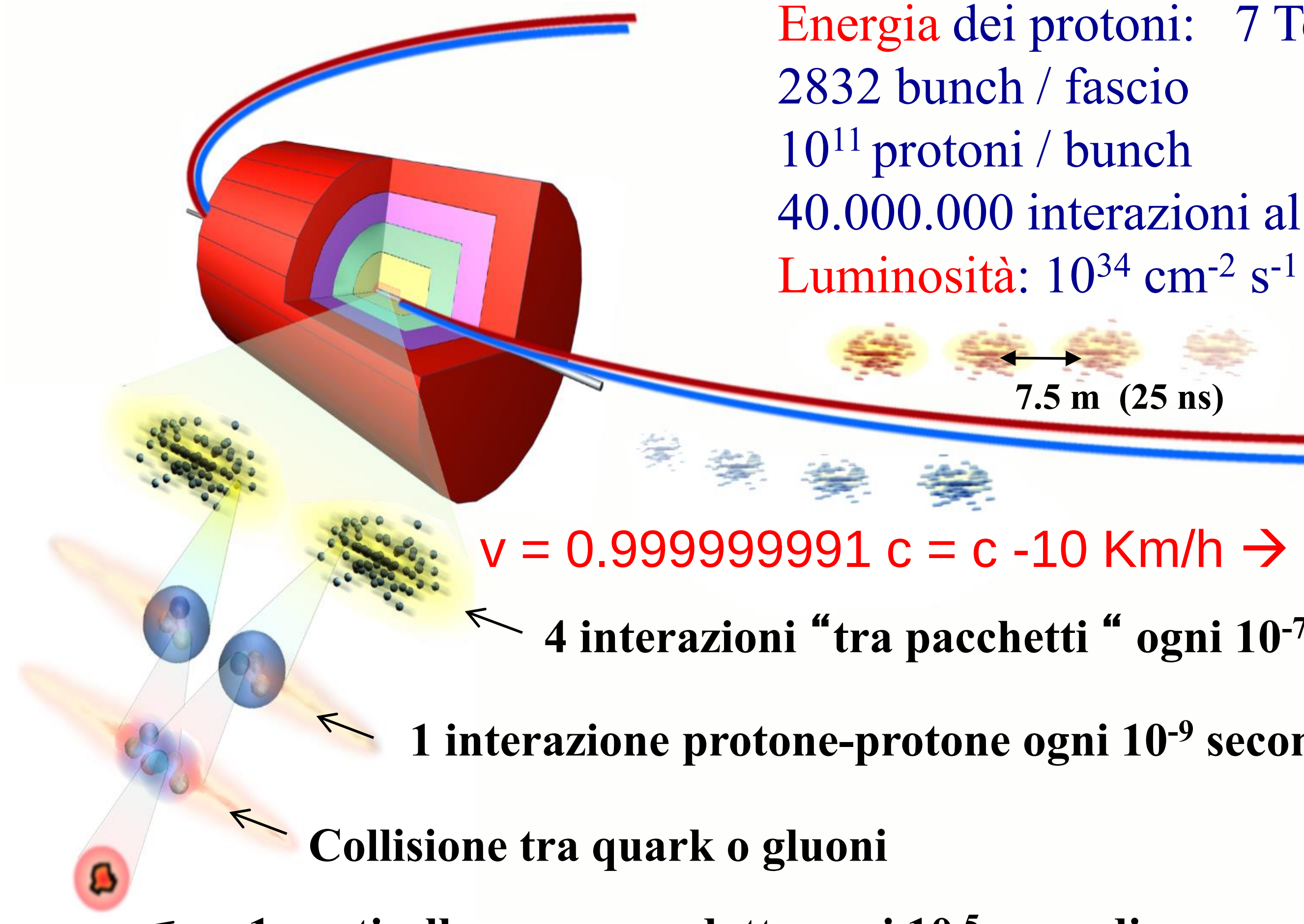
Fissata m_H nel Modello Standard si può calcolare sezione d'urto di produzione σ, branching ratio, …

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'Elio superfluido (1.9 K)

Energia dei protoni: 7 TeV
2832 bunch / fascio
10^{11} protoni / bunch
40.000.000 interazioni al secondo
Luminosità: 10^{34} cm^{-2} s^{-1}



$v = 0.999999991\ c = c - 10$ Km/h → 11000 giri/s

4 interazioni "tra pacchetti " ogni 10^{-7} secondi

1 interazione protone-protone ogni 10^{-9} secondi

Collisione tra quark o gluoni

1 particella nuova prodotta ogni 10^{-5} secondi

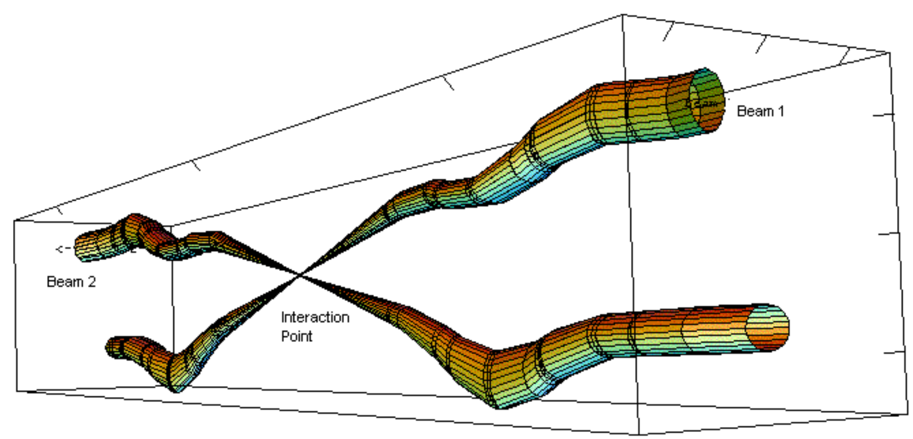
Large Hadron Collider /2

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

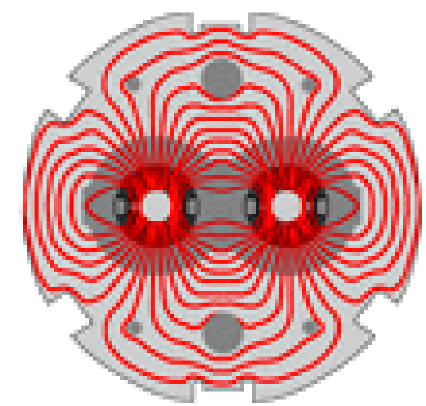
$E_{cinetica}$ di moto (1500 kg) con velocità 40 m/s ~ 1.3 x 10^5 J (1 bunch ad LHC)

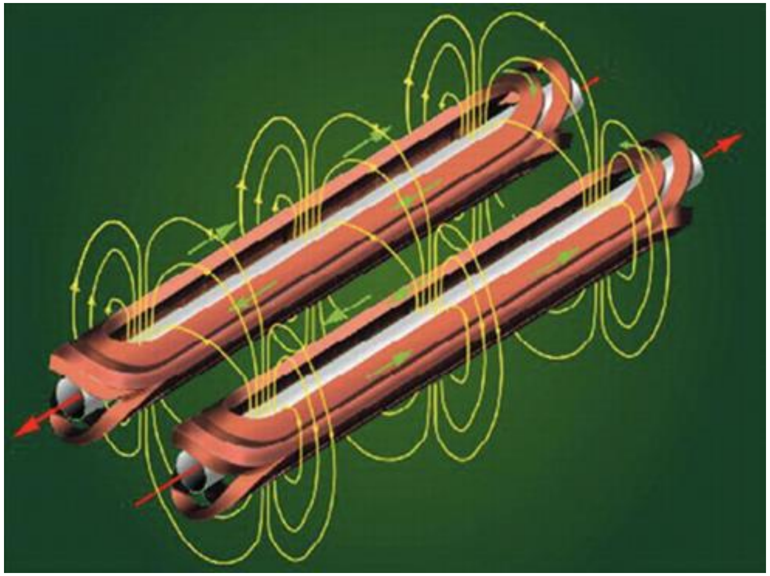
$E_{cinetica}$ di nave (20000 ton) con velocità 6 m/s ~ 360 MJ (1 fascio ad LHC)

Liquefa 500 kg di rame



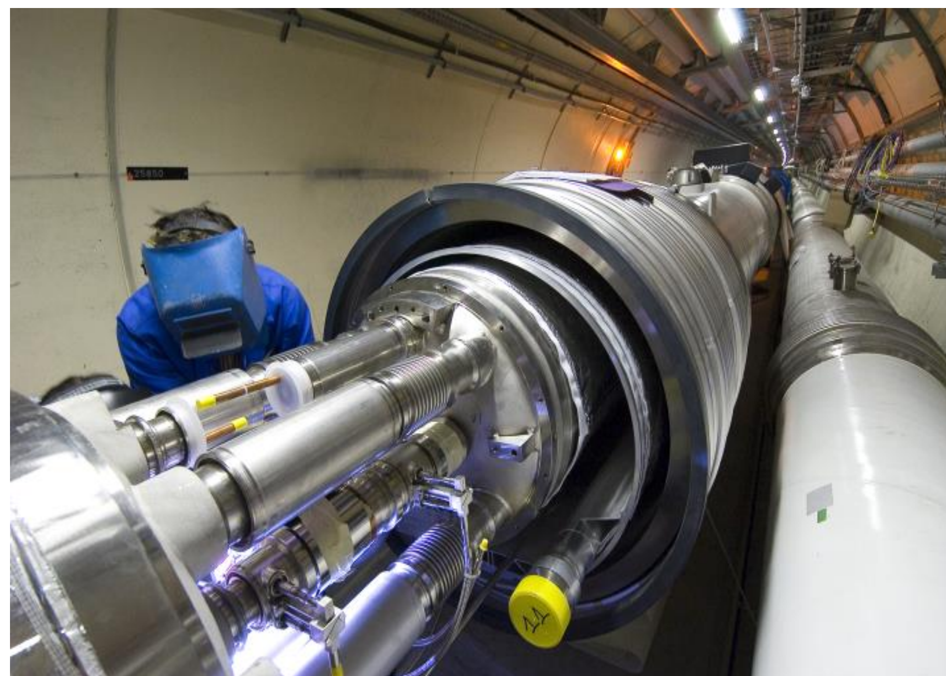
Relative beam sizes around IP1 (Atlas) in collision





Superconduttività permette di salire di un fattore 100 nella densità di corrente

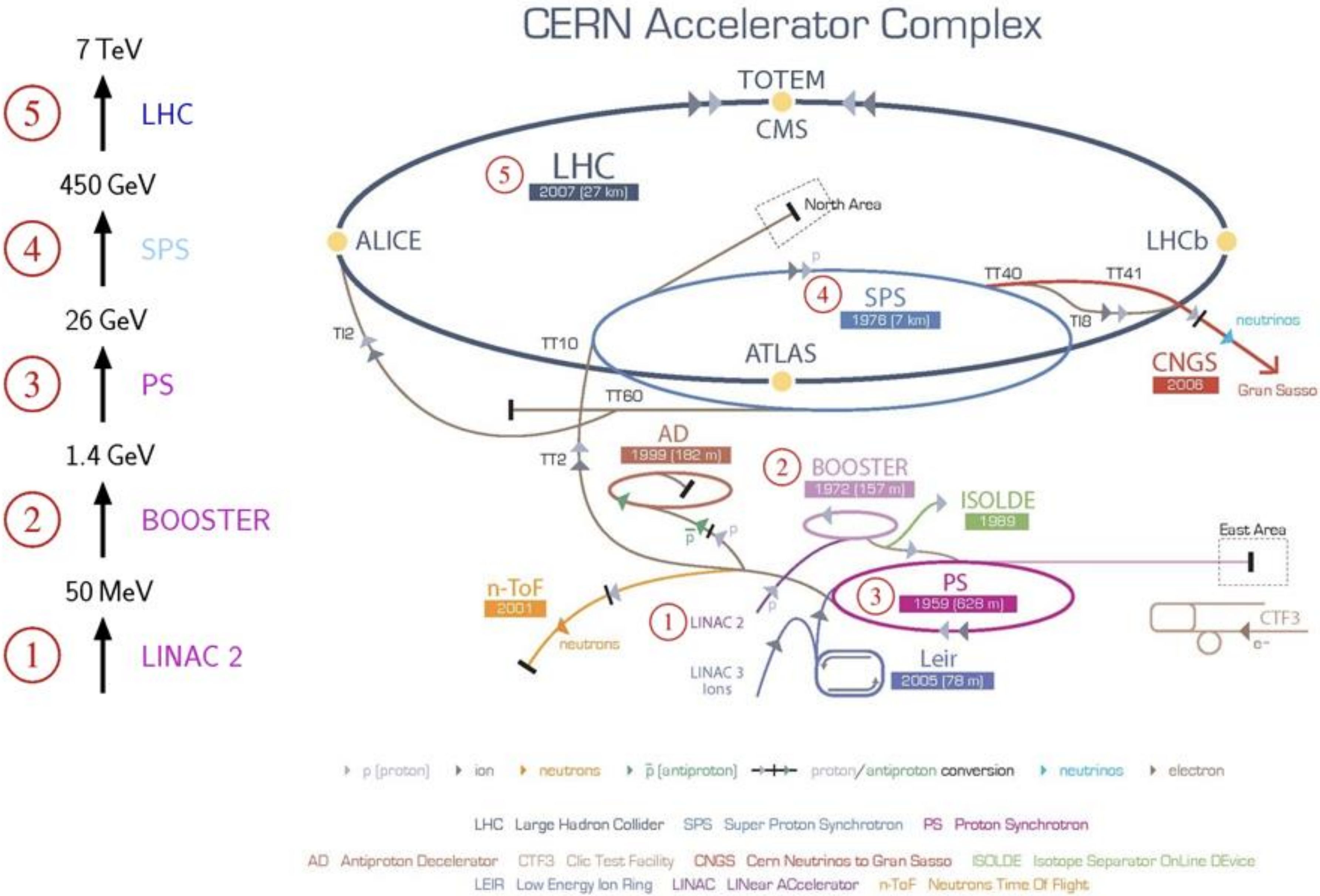
da 1-5 A/mm^2 a 100-500 A/mm^2



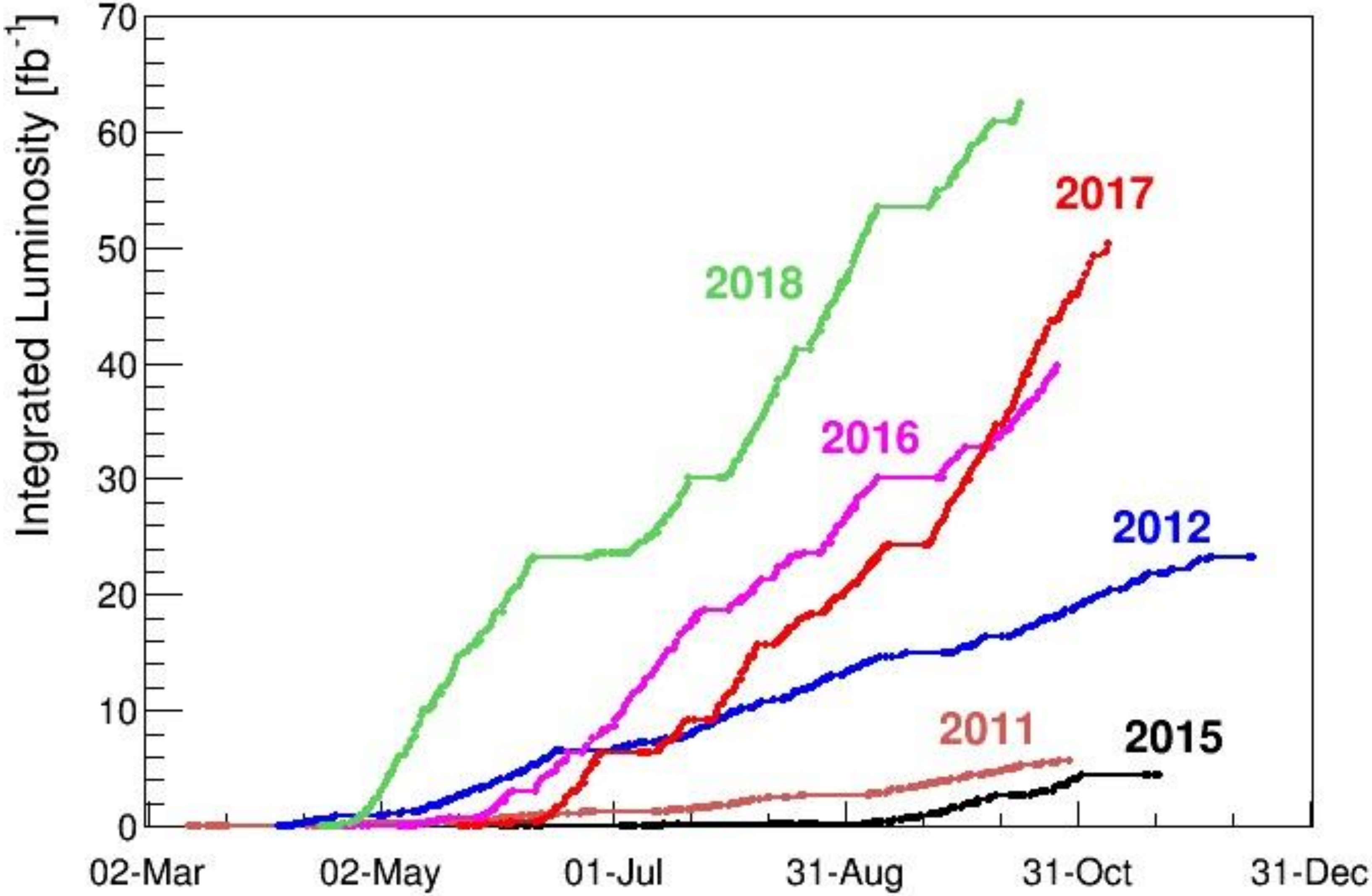
Filamento di Nb-Ti con spessore di 7 μm e lunghezza totale più di 6 volte dostanza Terra-Sole.

120 ton di He superfluido (1.9 K)

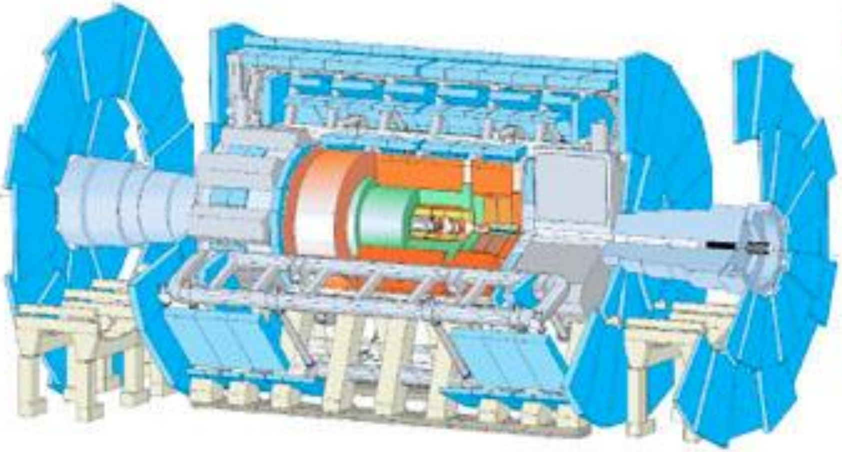
80 MW per LHC
30 MW per esperimenti


CERN Accelerator Complex
7 TeV
5 LHC
450 GeV
4 SPS
26 GeV
3 PS
1.4 GeV
2 BOOSTER
50 MeV
1 LINAC 2
TOTEM
CMS
5 LHC
2007 (27 km)
North Area
ALICE
LHCb
TT40
TT41
4 SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
2 BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
3 PS
1959 (628 m)
1 LINAC 2
CTF3
e–
neutrons
LINAC 3
Ions
Leir
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
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

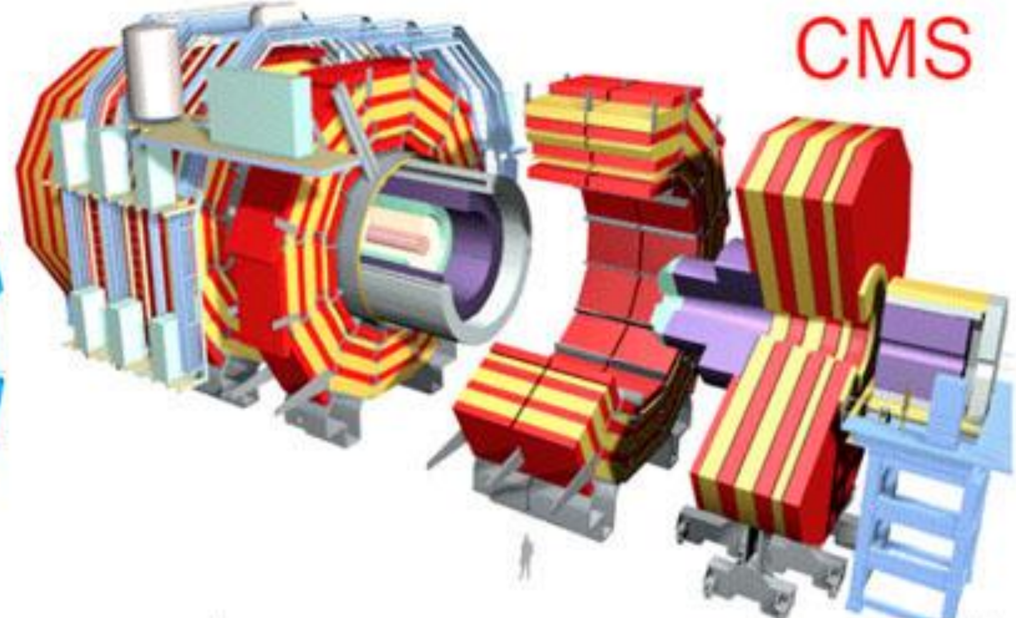
LHC: oltre ogni previsione

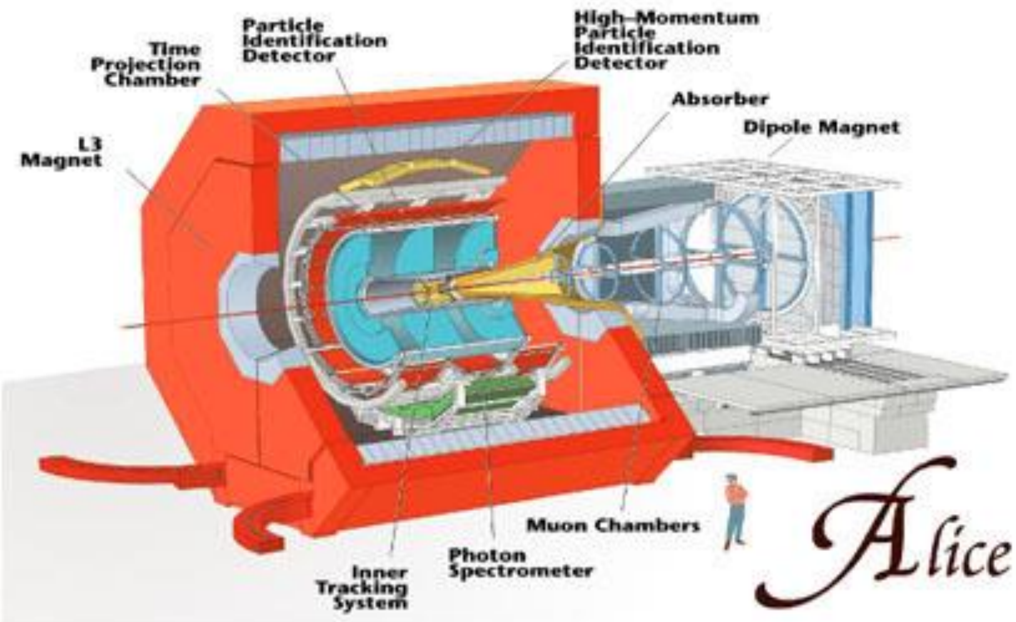


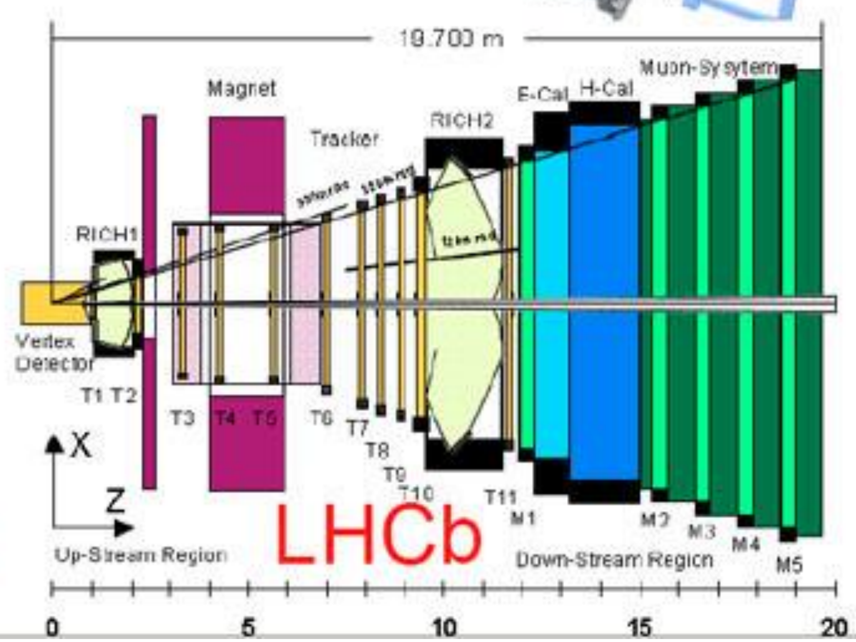
ATLAS



CMS







LHCb

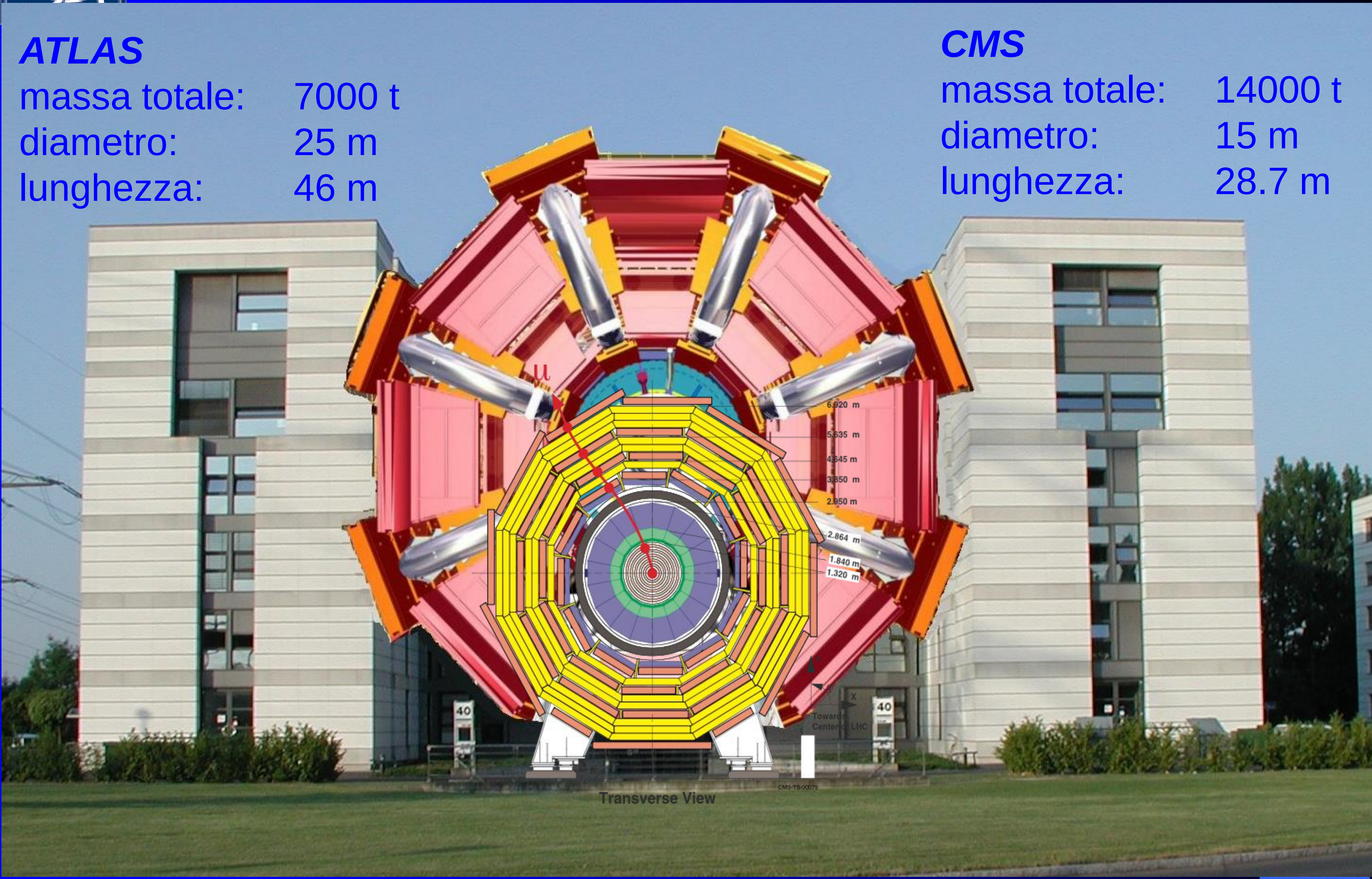
ATLAS and CMS size

ATLAS

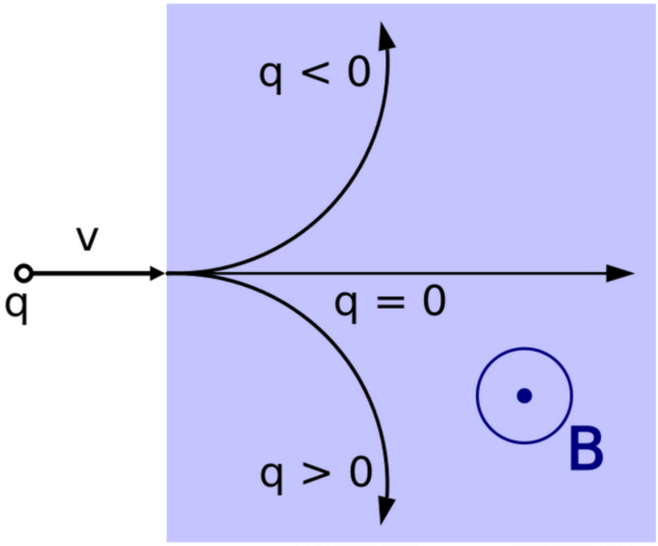
massa totale: 7000 t
diametro: 25 m
lunghezza: 46 m

CMS

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



Misure di quantità di moto

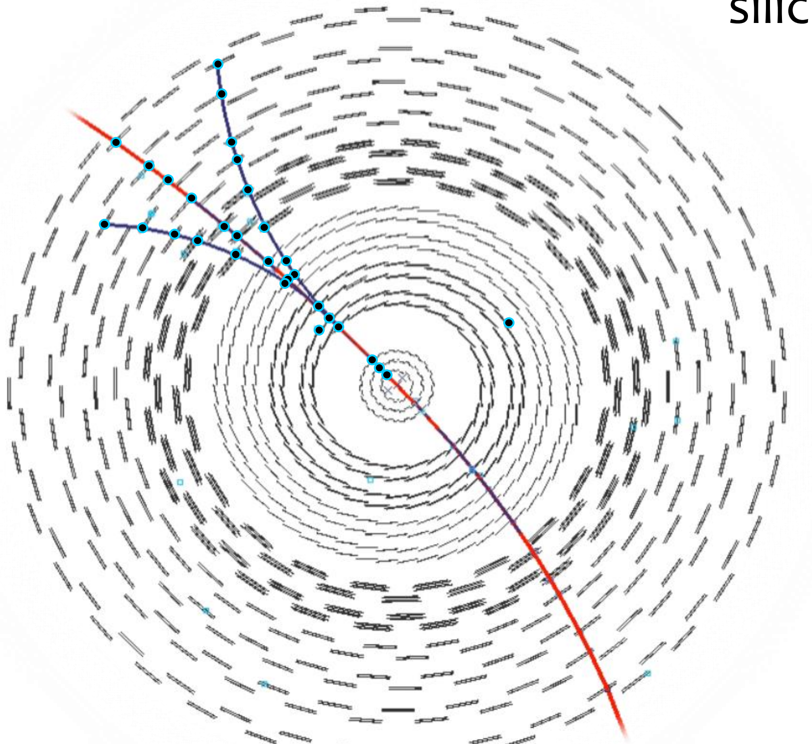


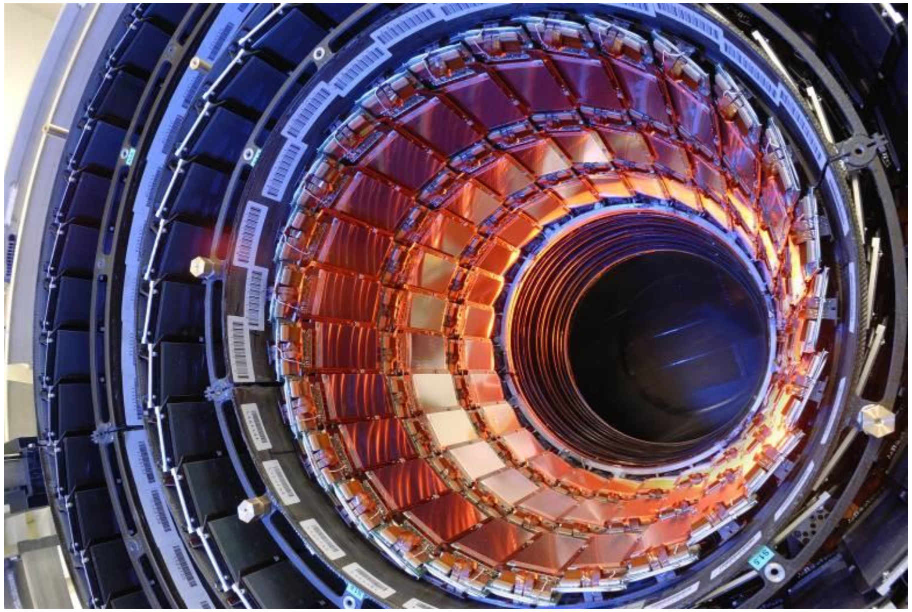
$$p\ (GeV/c) = 0.3\ B\ (T)\ R\ (m)$$

CMS Tracker

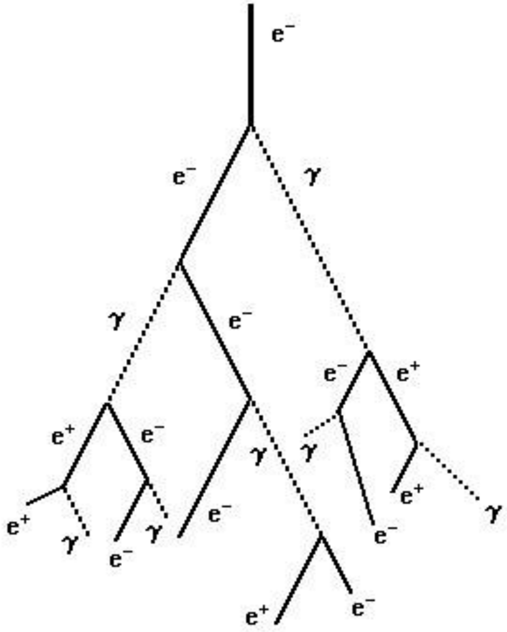
silicon strip: 200 m², 10M canali, σ = 80-180 μm

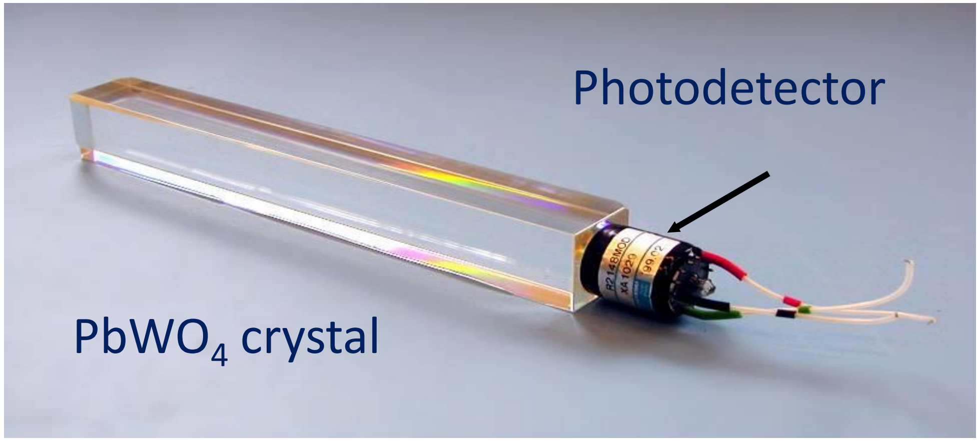
silicon pixel: 16m², 66M canali, σ = ~15 μm



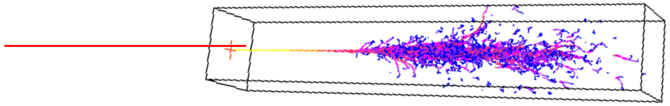


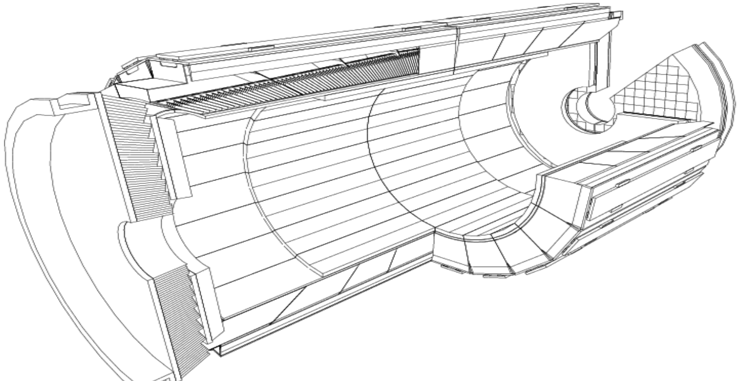
Misure di energia

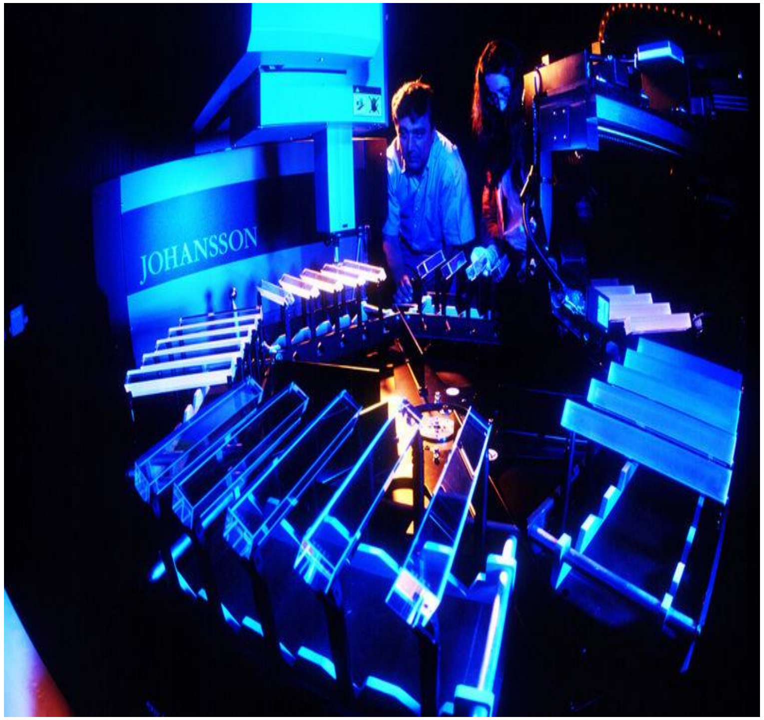


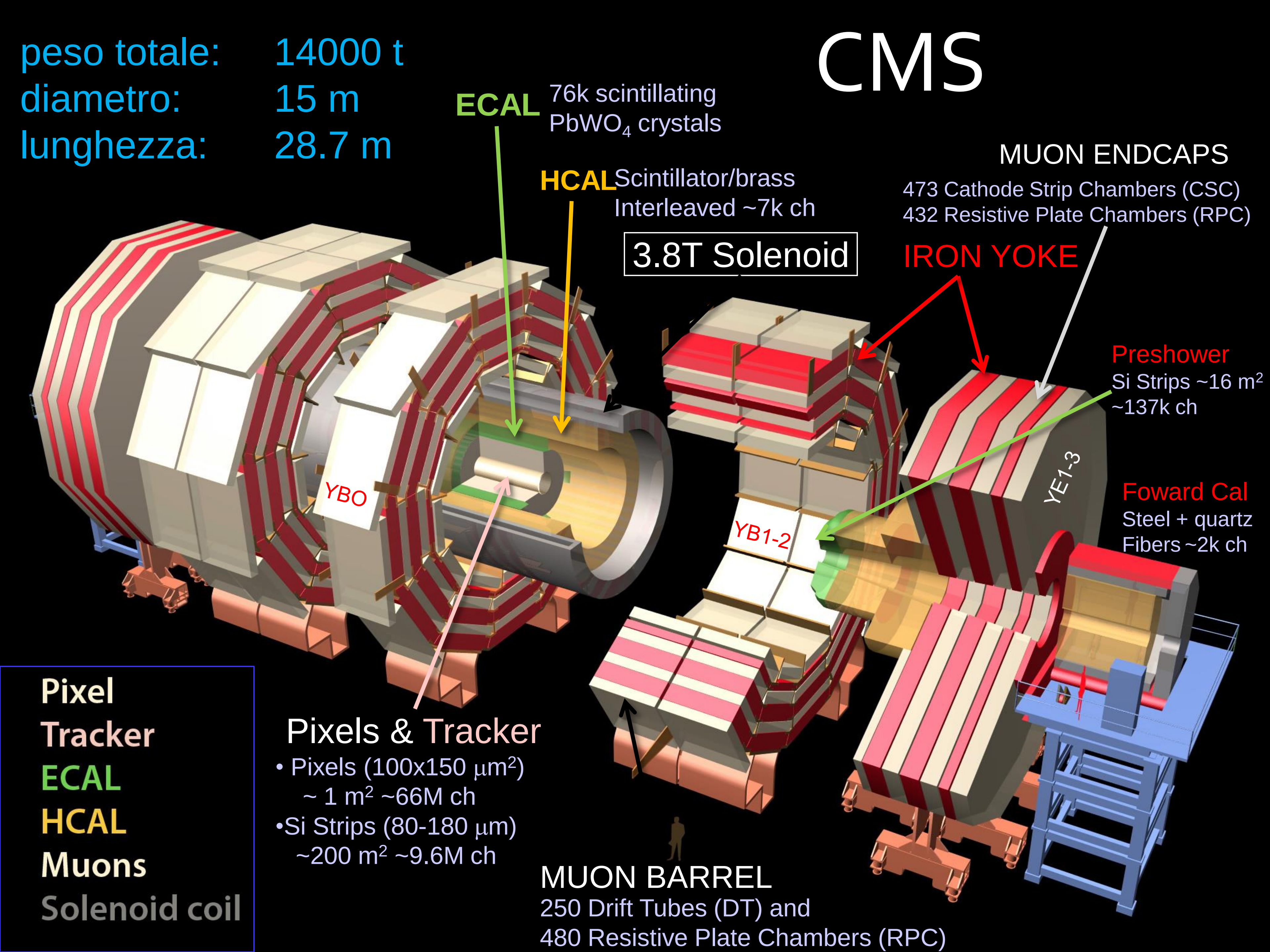


CMS e.m. calorimeter

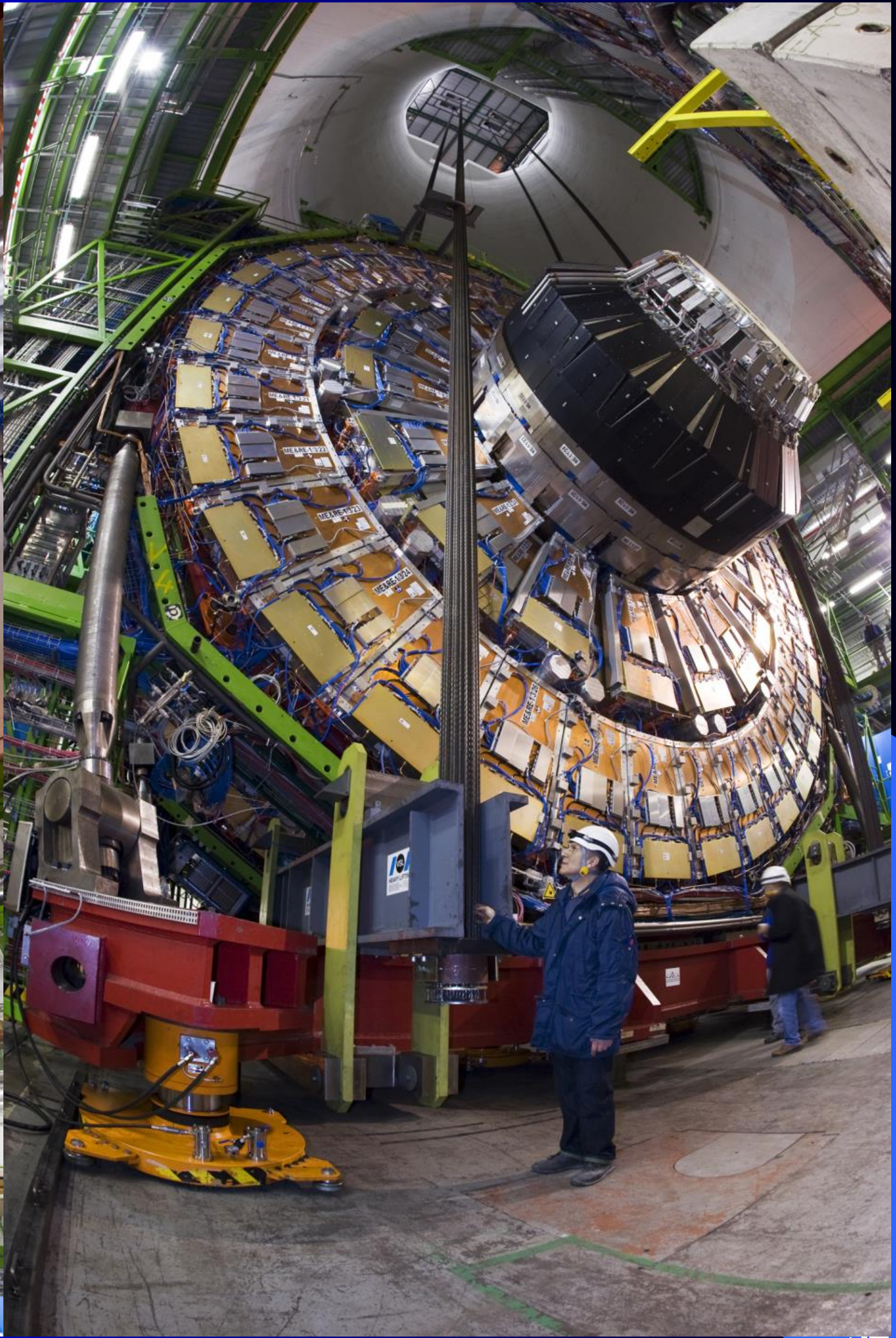


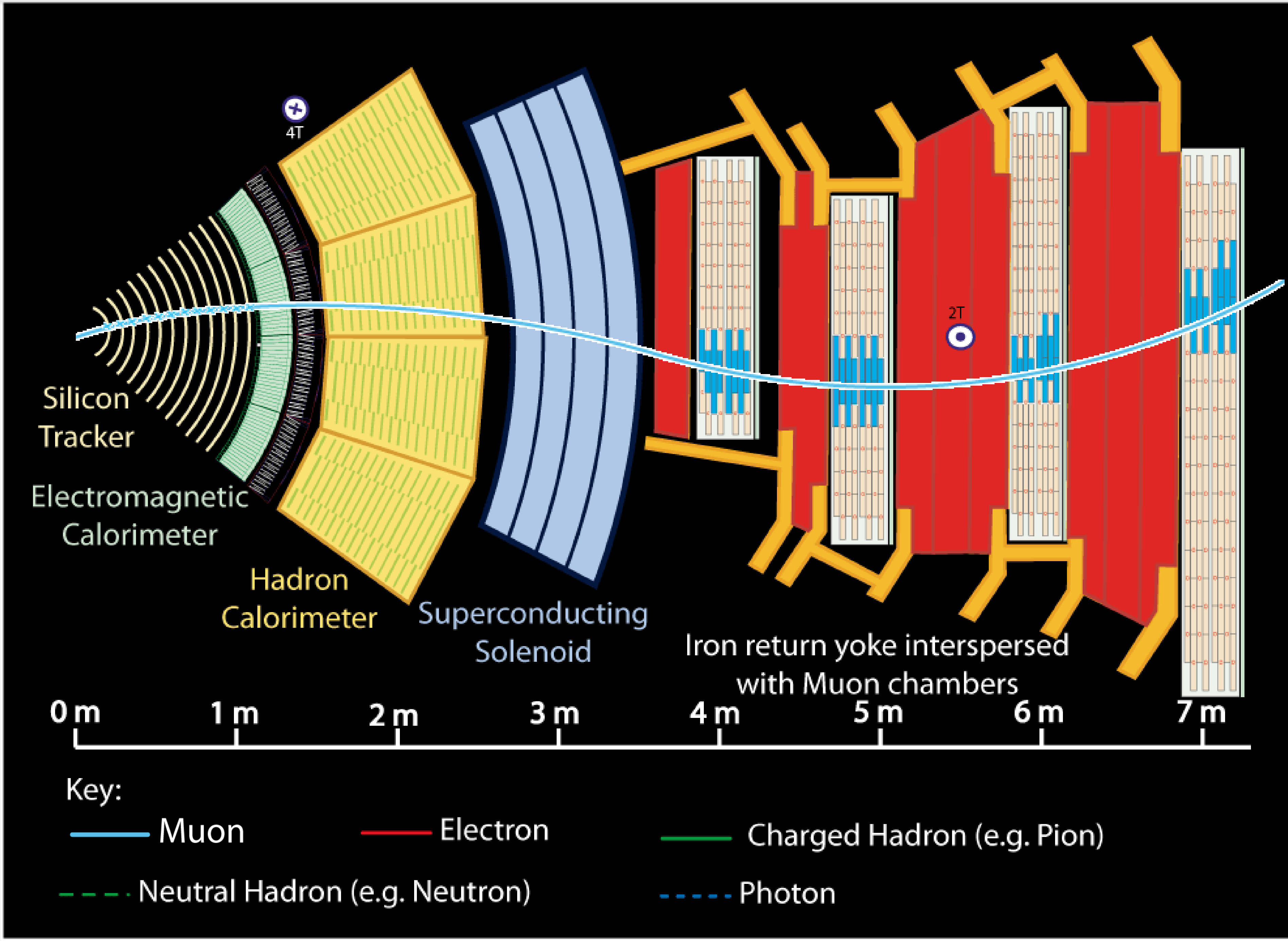


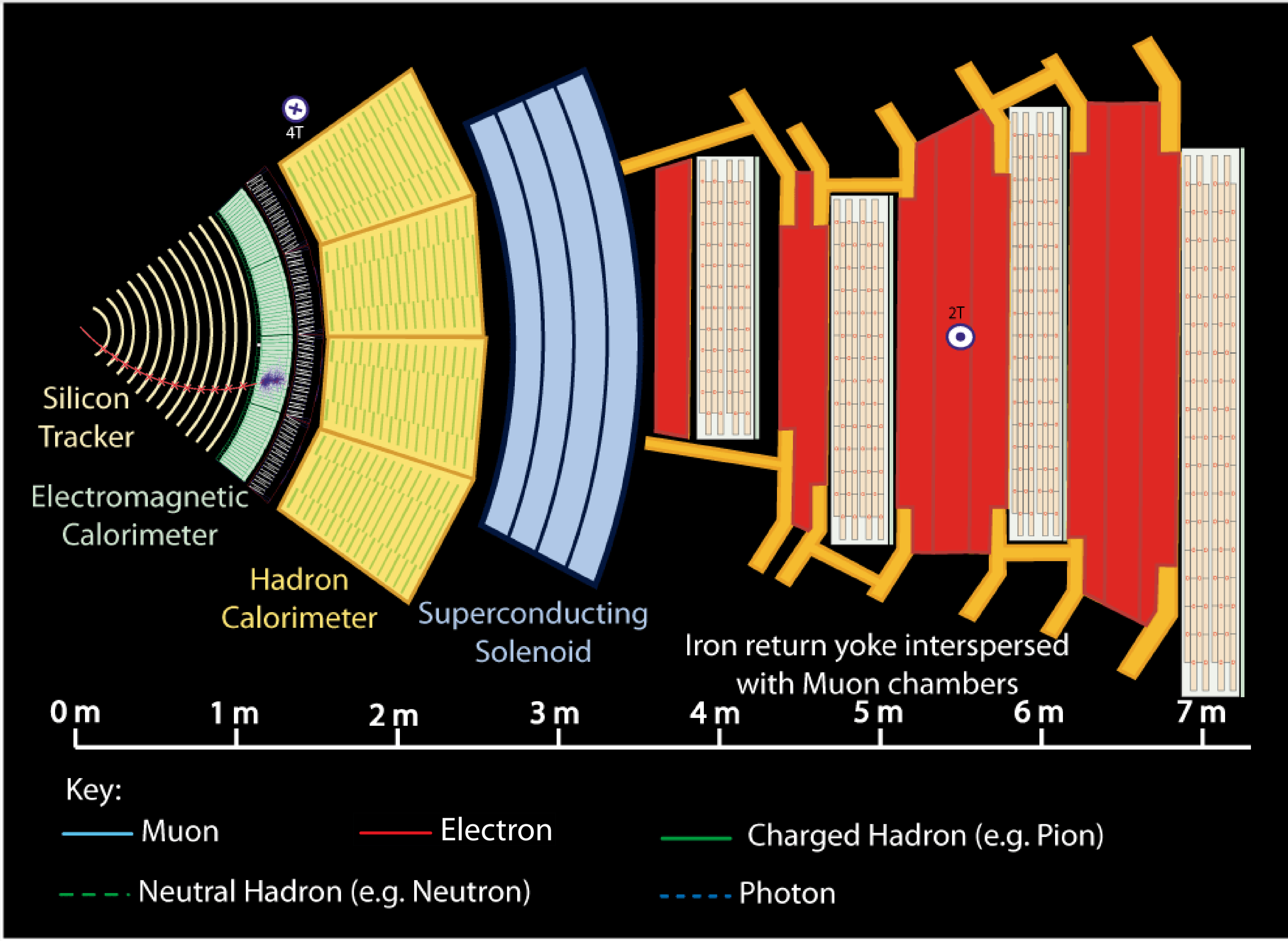




peso totale: 14000 t
diametro: 15 m
lunghezza: 28.7 m
CMS
ECAL
76k scintillating
PbWO4 crystals
HCAL
Scintillator/brass
Interleaved ~7k ch
3.8T Solenoid
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
IRON YOKE
Preshower
Si Strips ~16 m2
~137k ch
YE1-3
Foward Cal
Steel + quartz
Fibers ~2k ch
YBO
YB1-2
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
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)




4T
Silicon
Tracker
Electromagnetic
Calorimeter
Hadron
Calorimeter
Superconducting
Solenoid
2T
Iron return yoke interspersed
with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



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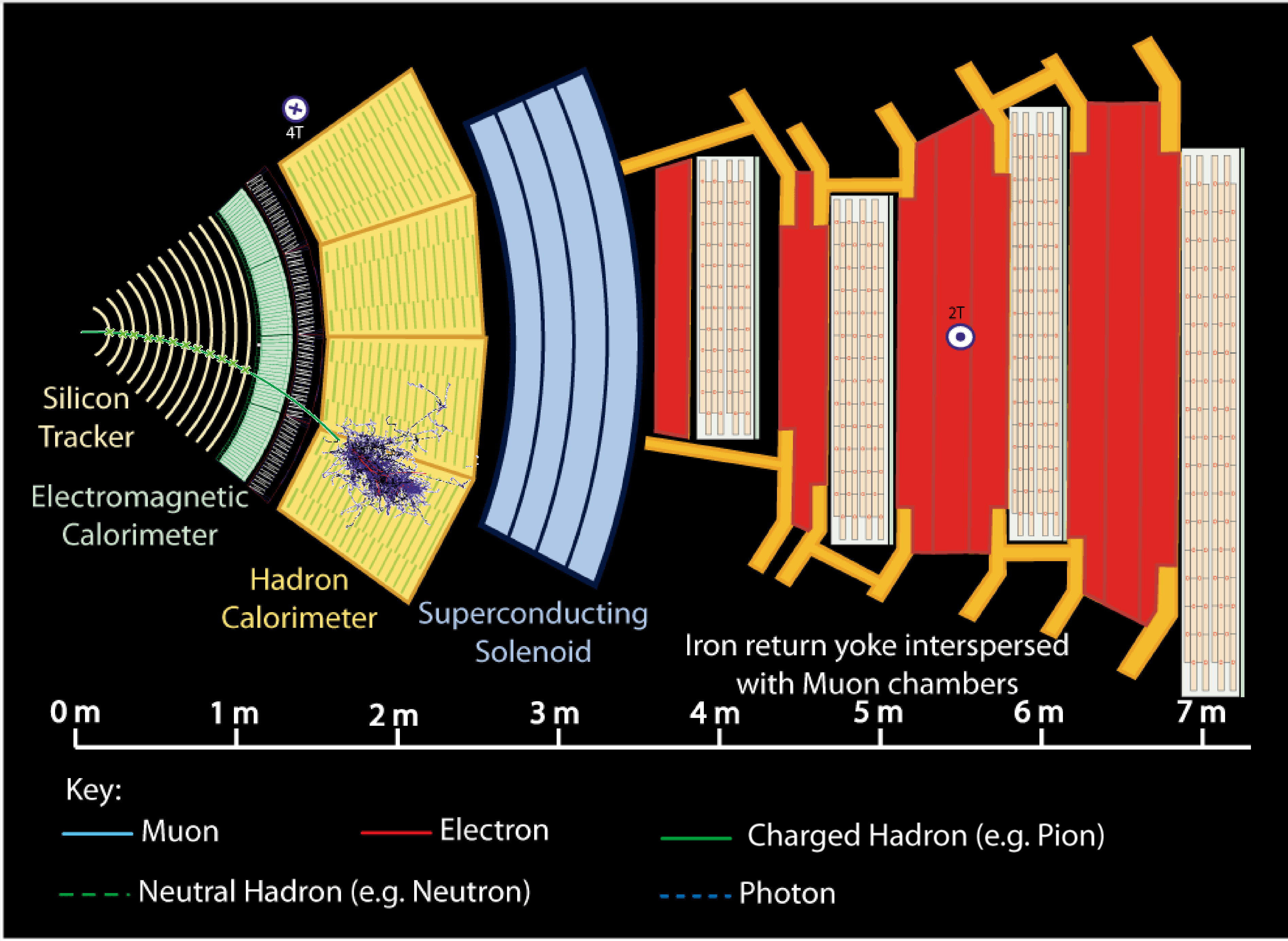
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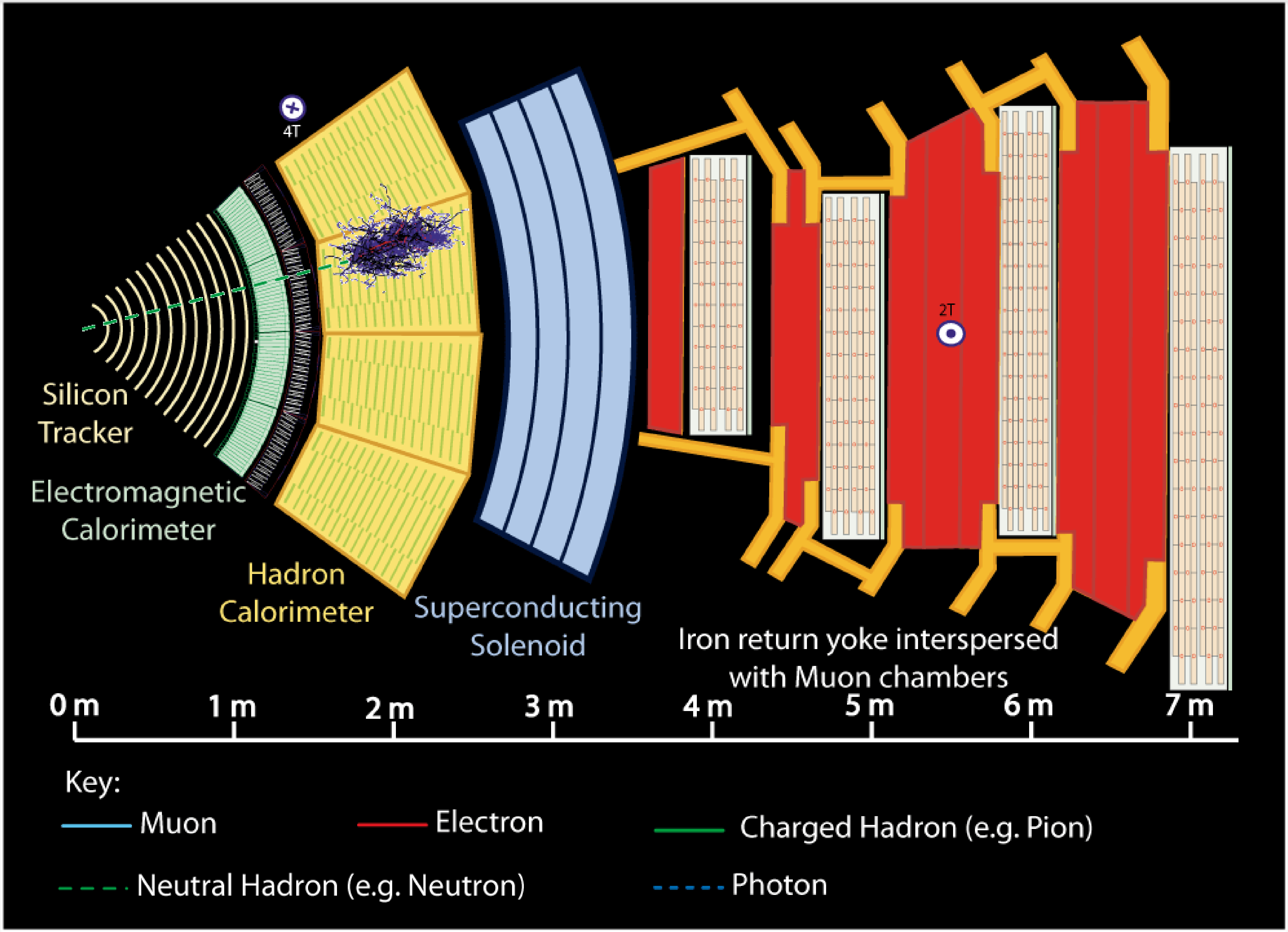

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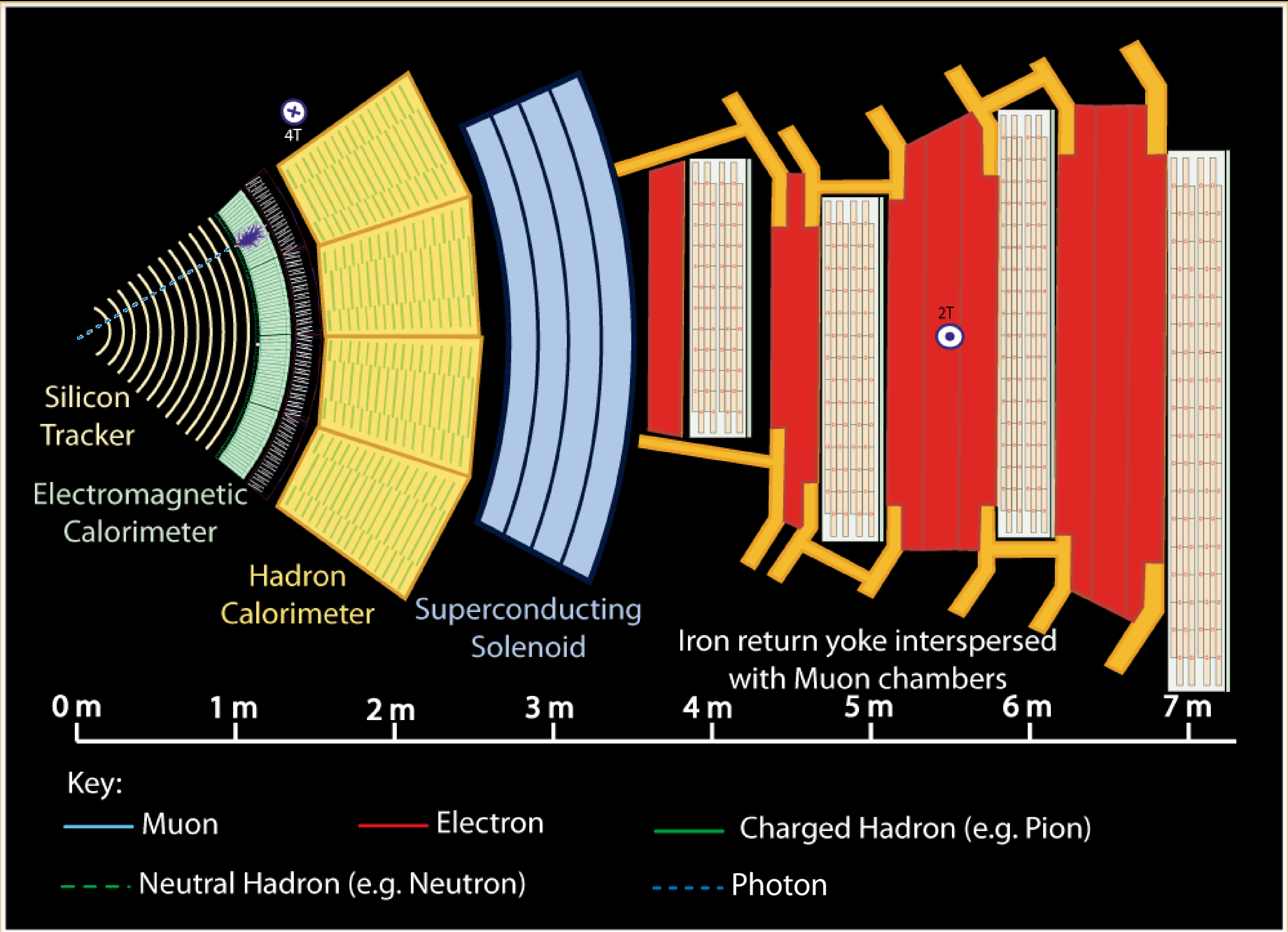
4T
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7 m
Key:
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Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

Trigger per esperimenti LHC

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

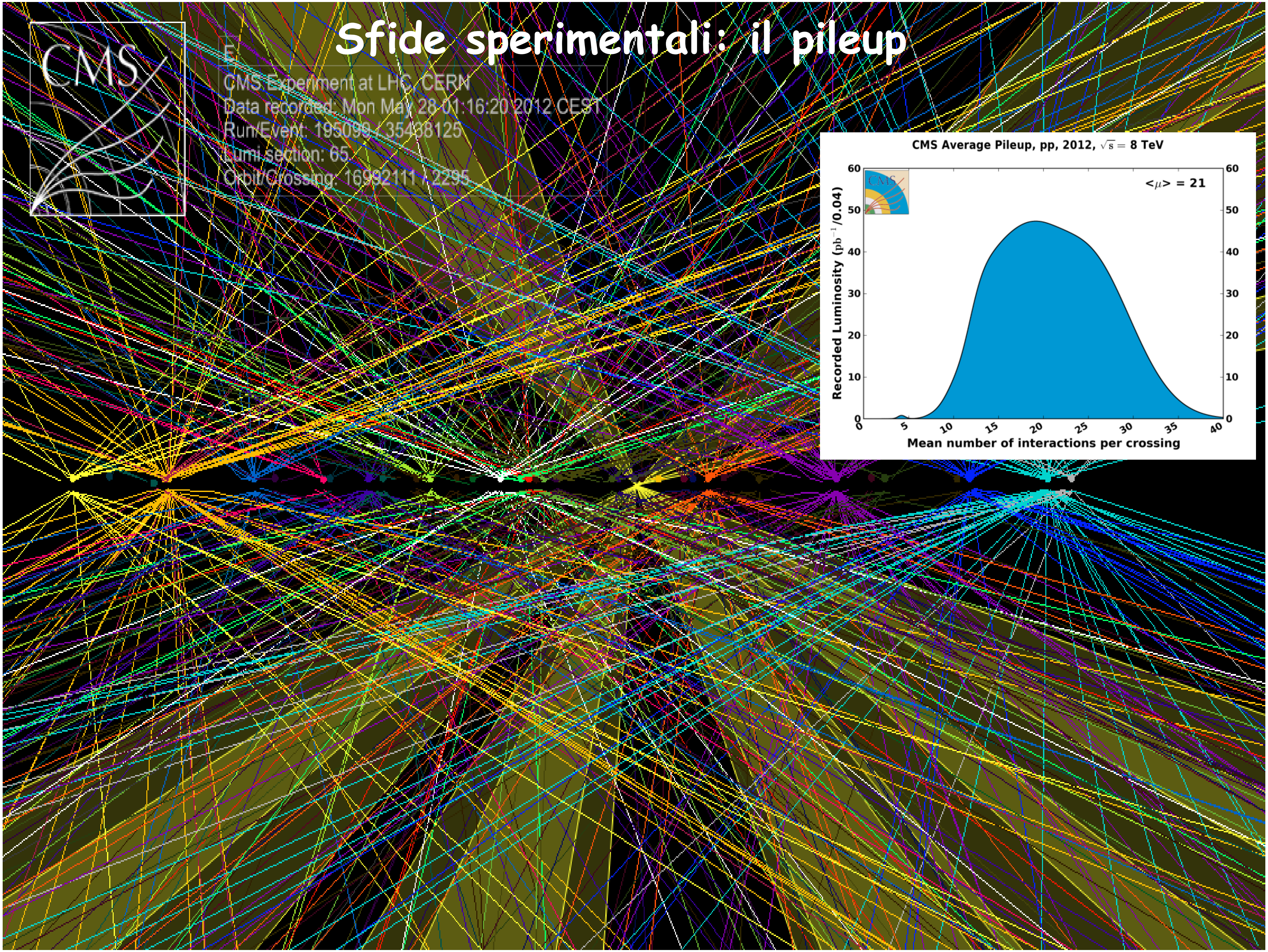
Eventi interessanti (alto q^2) hanno probabilità 10^5 - 10^6 volte più piccola di eventi di QCD soffice

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

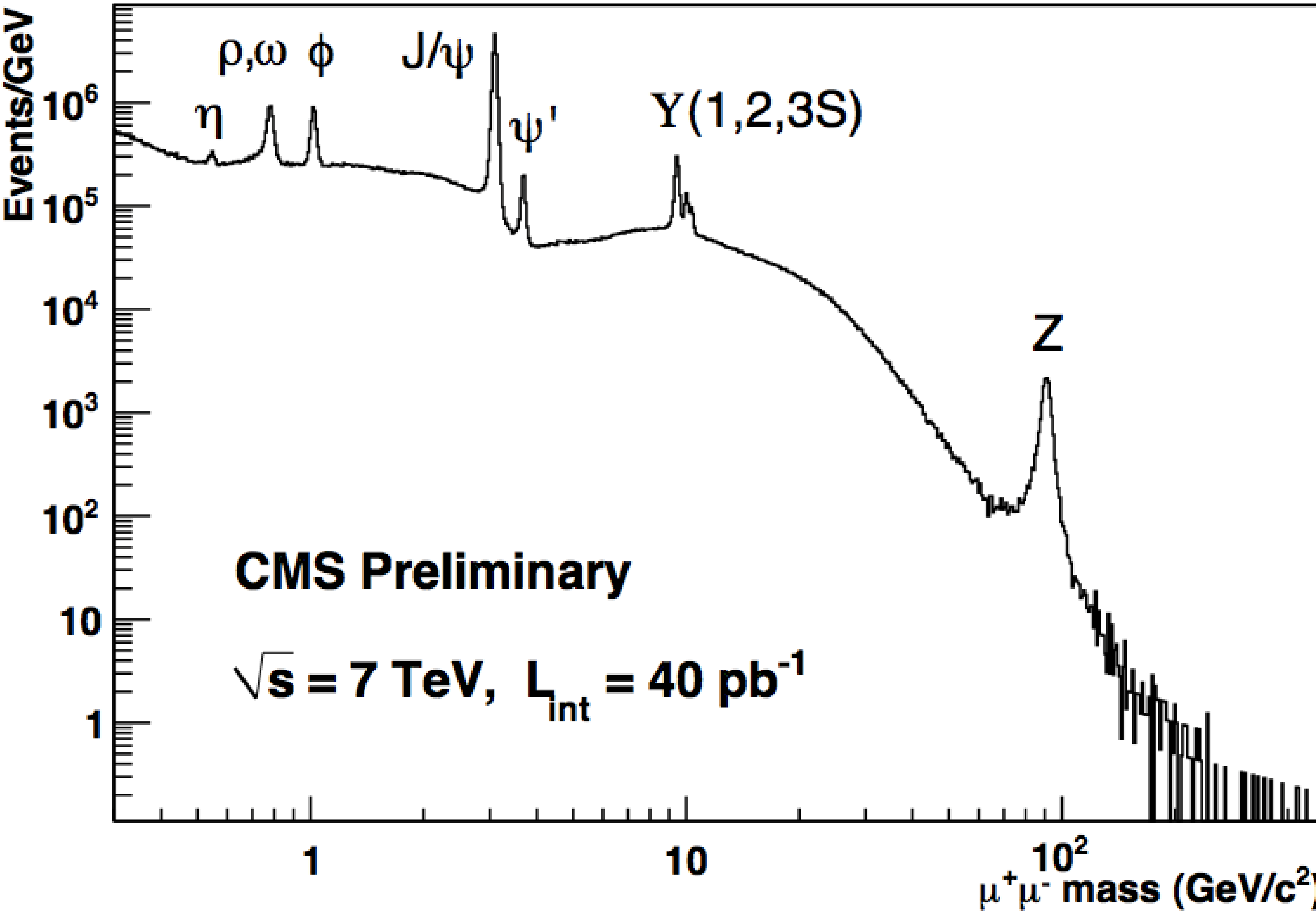
Il processo deve avvenire real time (entro 300 ms)

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

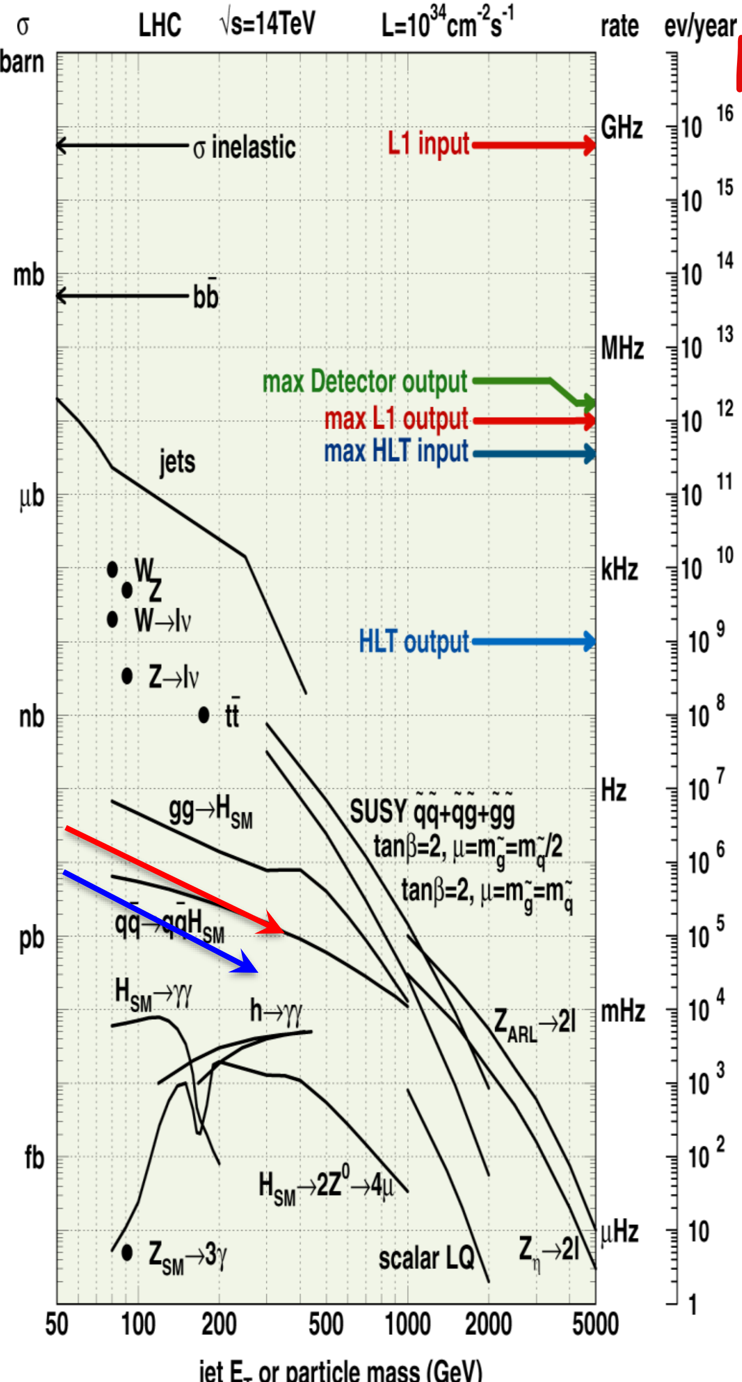
Sfide sperimentali: il pileup

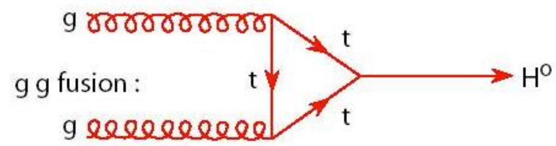


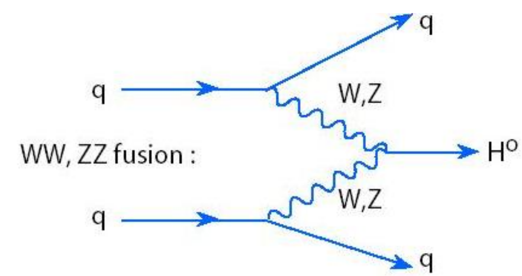
Riscoperta del Modello Standard nel 2010

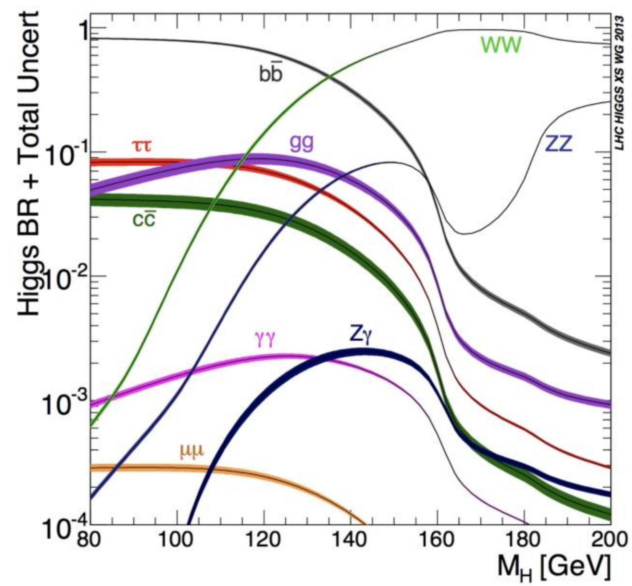


Produzione bosone di Higgs a LHC



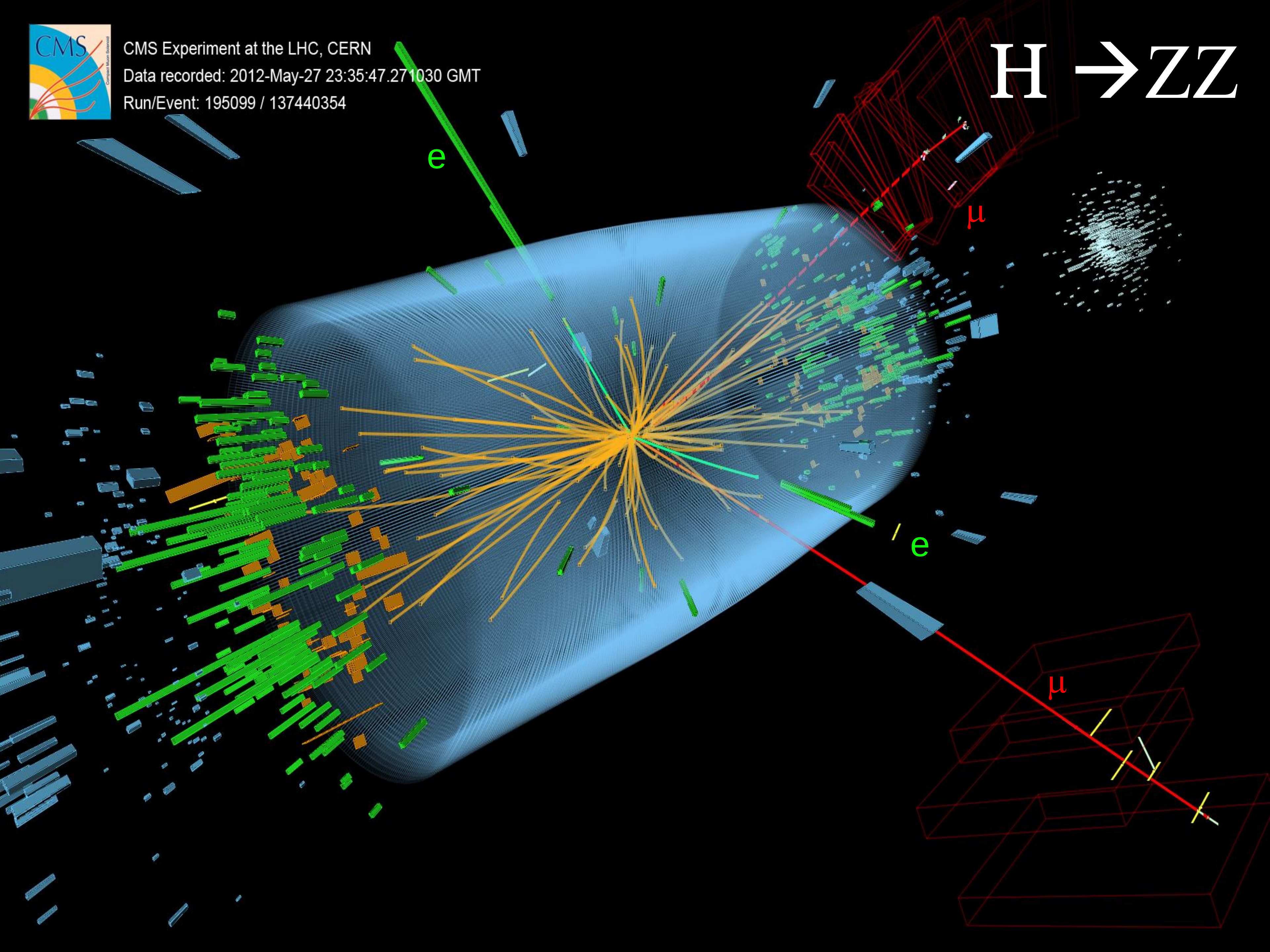


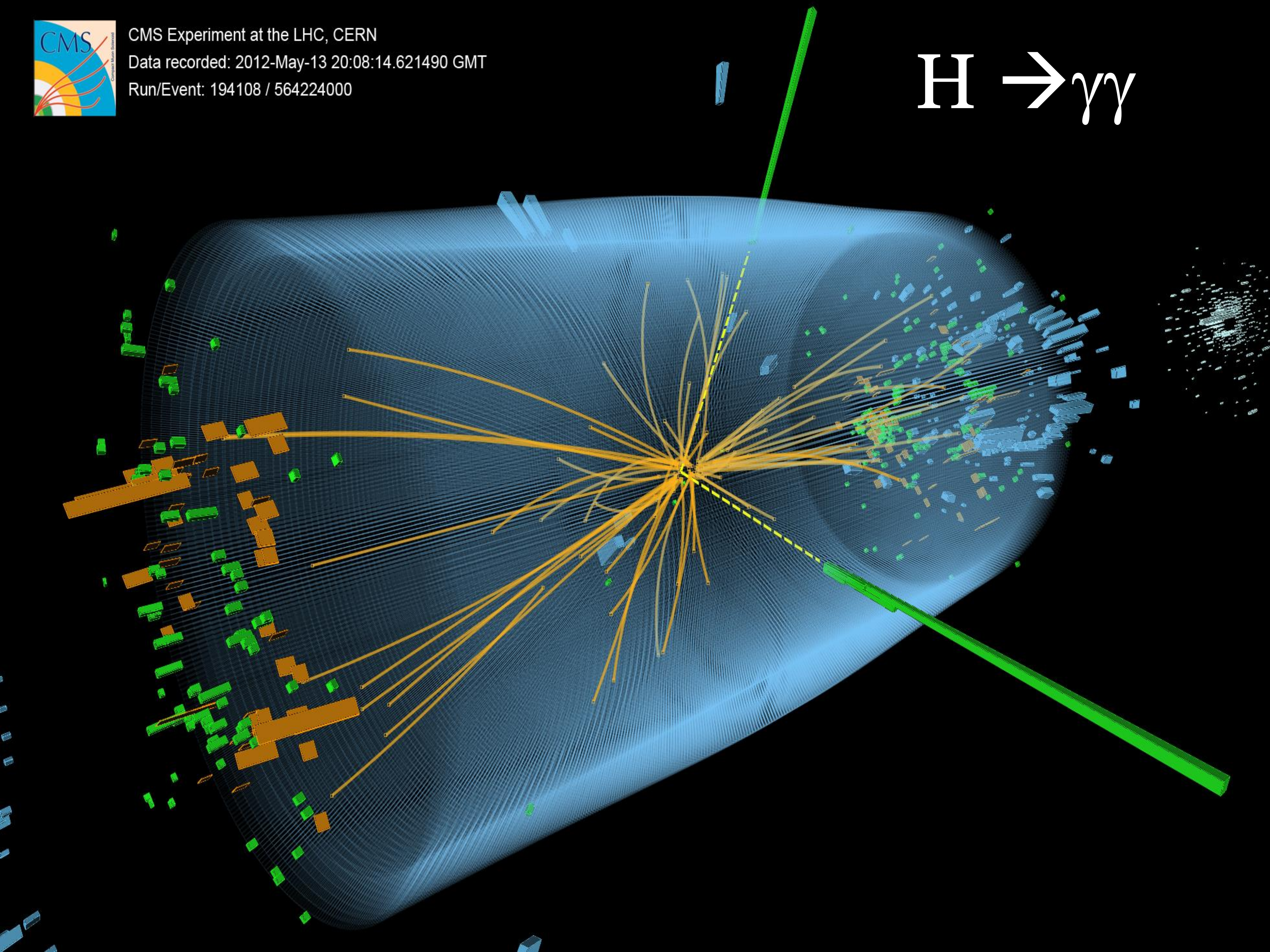




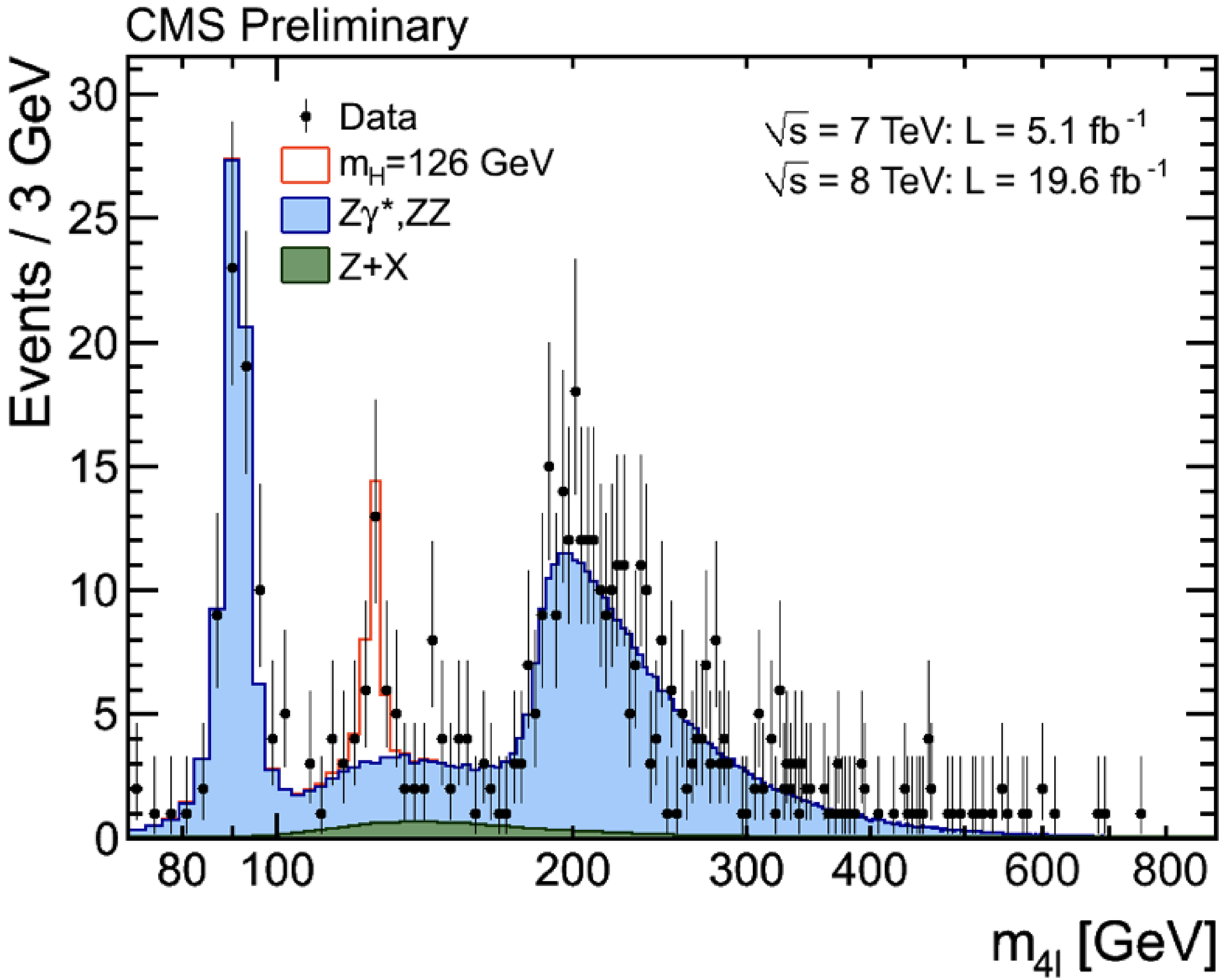
H->γγ ~ 40/settimana (ricostruiti ~16)

H->ZZ-> 4leptoni ~ 8/mese (ricostruiti ~3)

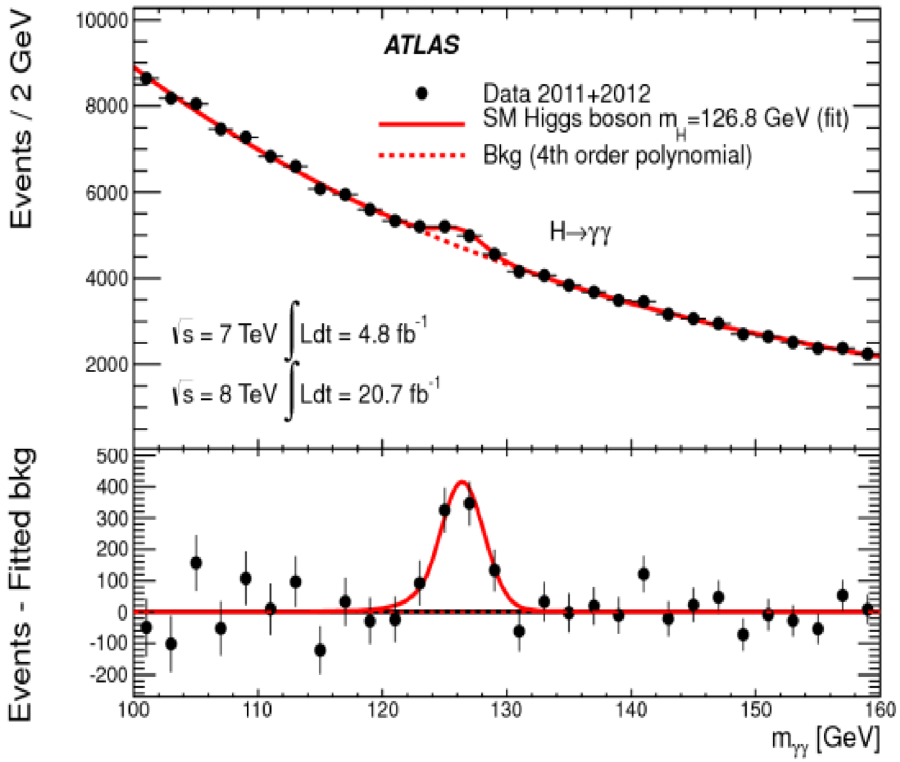

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354
H →ZZ
e
e
μ
μ


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ

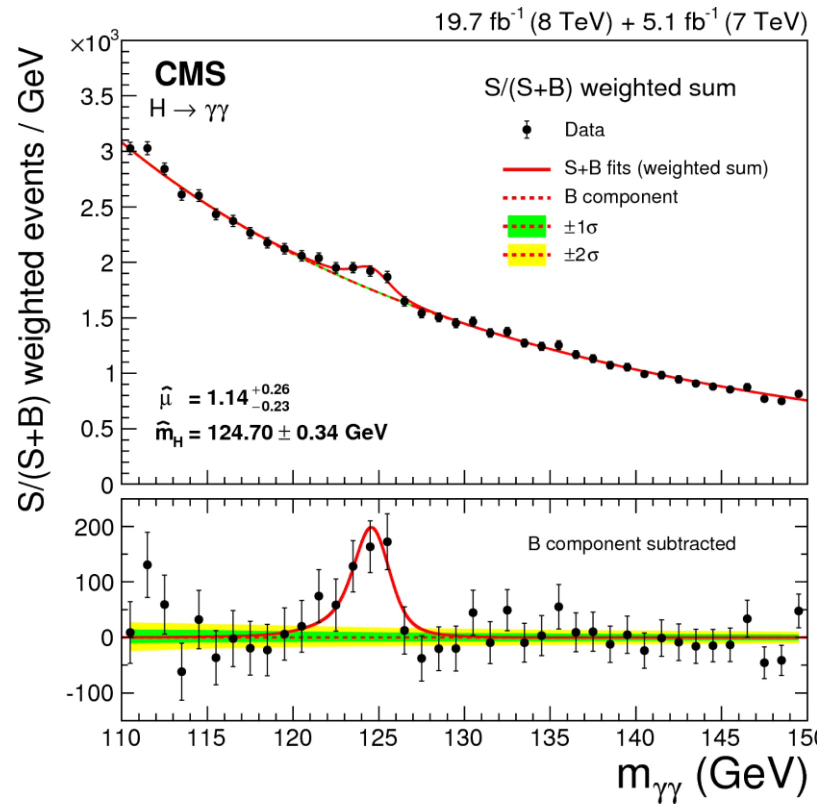
H→eeee H→ eeμμ H→ μμμμ



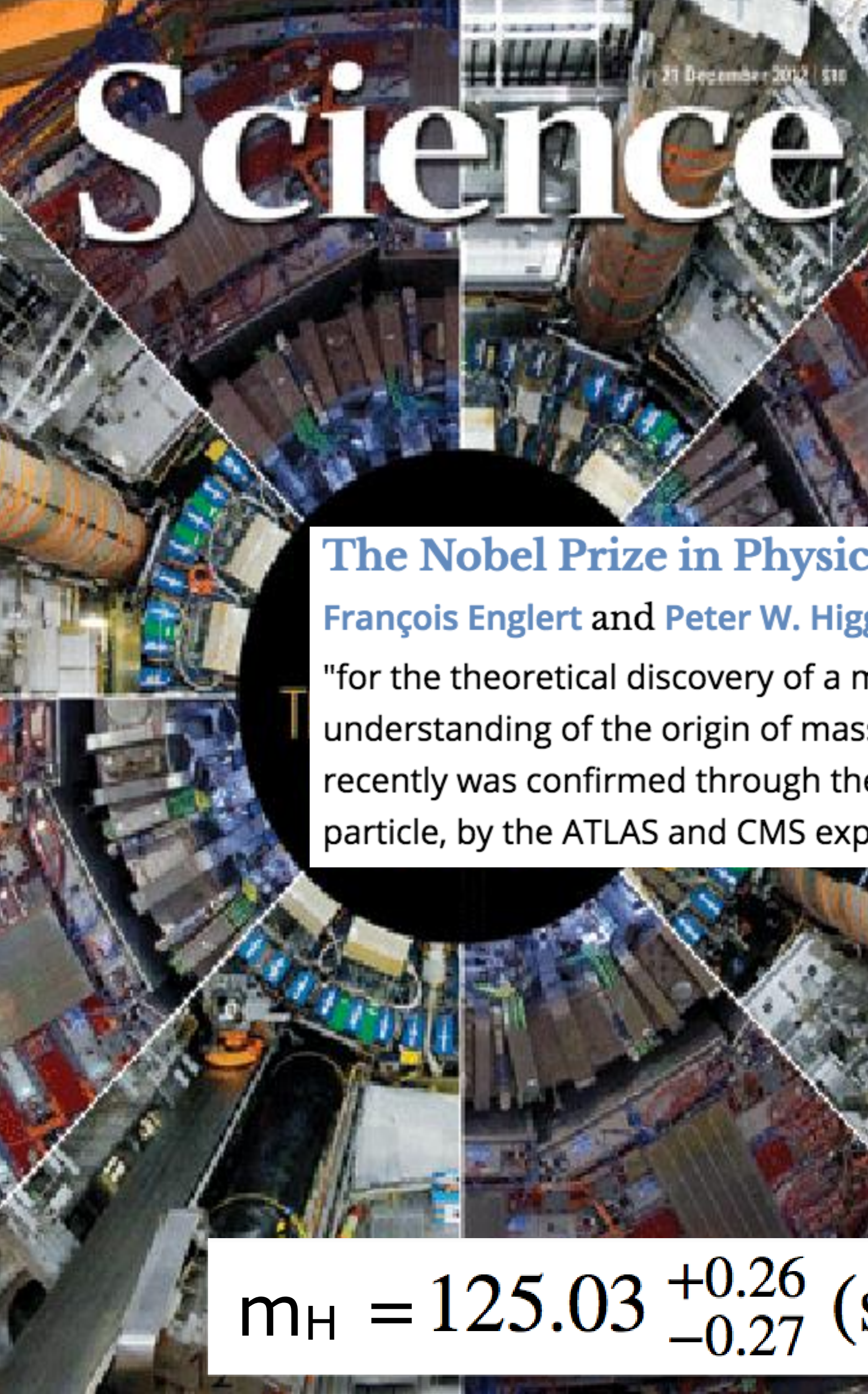
H→ γγ

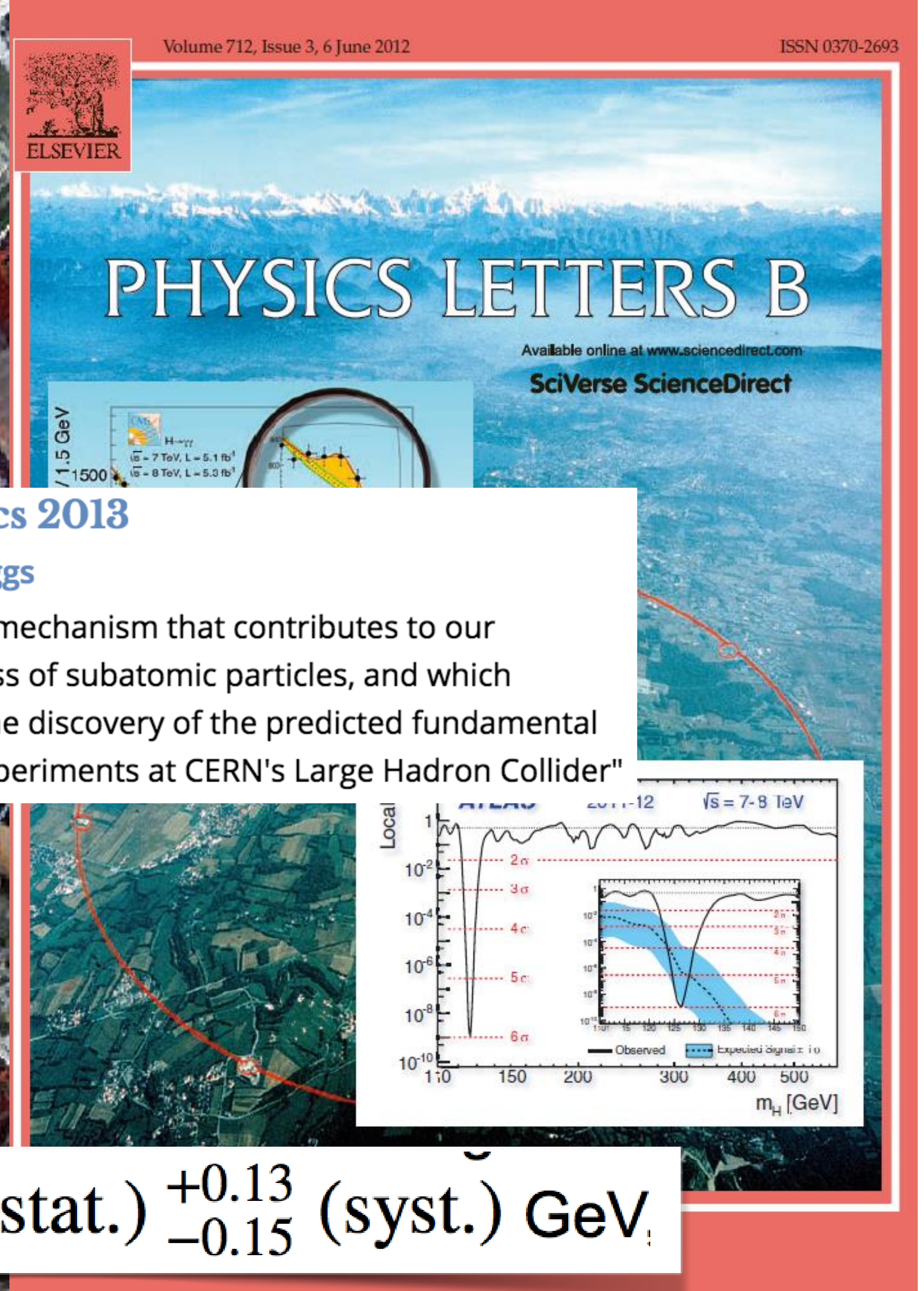


ATLAS
Data 2011+2012
SM Higgs boson m_H=126.8 GeV (fit)
Bkg (4th order polynomial)
H→γγ
√s = 7 TeV ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
Events / 2 GeV
Events - Fitted bkg
m_γγ [GeV]



19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
CMS
H → γγ
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
μ̂ = 1.14 +0.26 −0.23
m̂_H = 124.70 ± 0.34 GeV
B component subtracted
S/(S+B) weighted events / GeV
m_γγ (GeV)





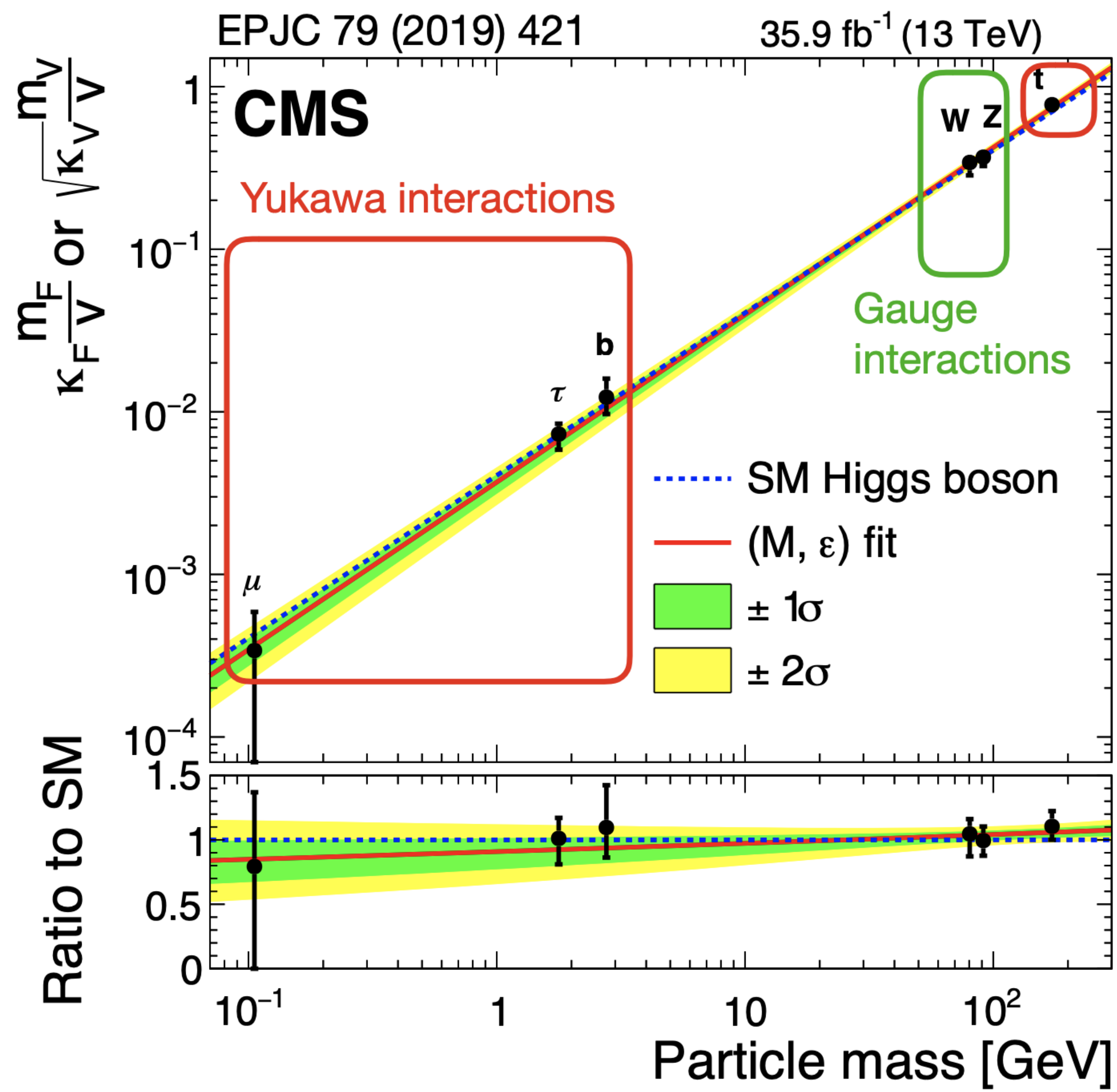
The Nobel Prize in Physics 2013

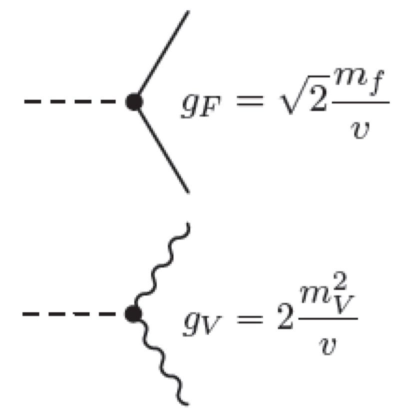
François Englert and Peter W. Higgs

"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"

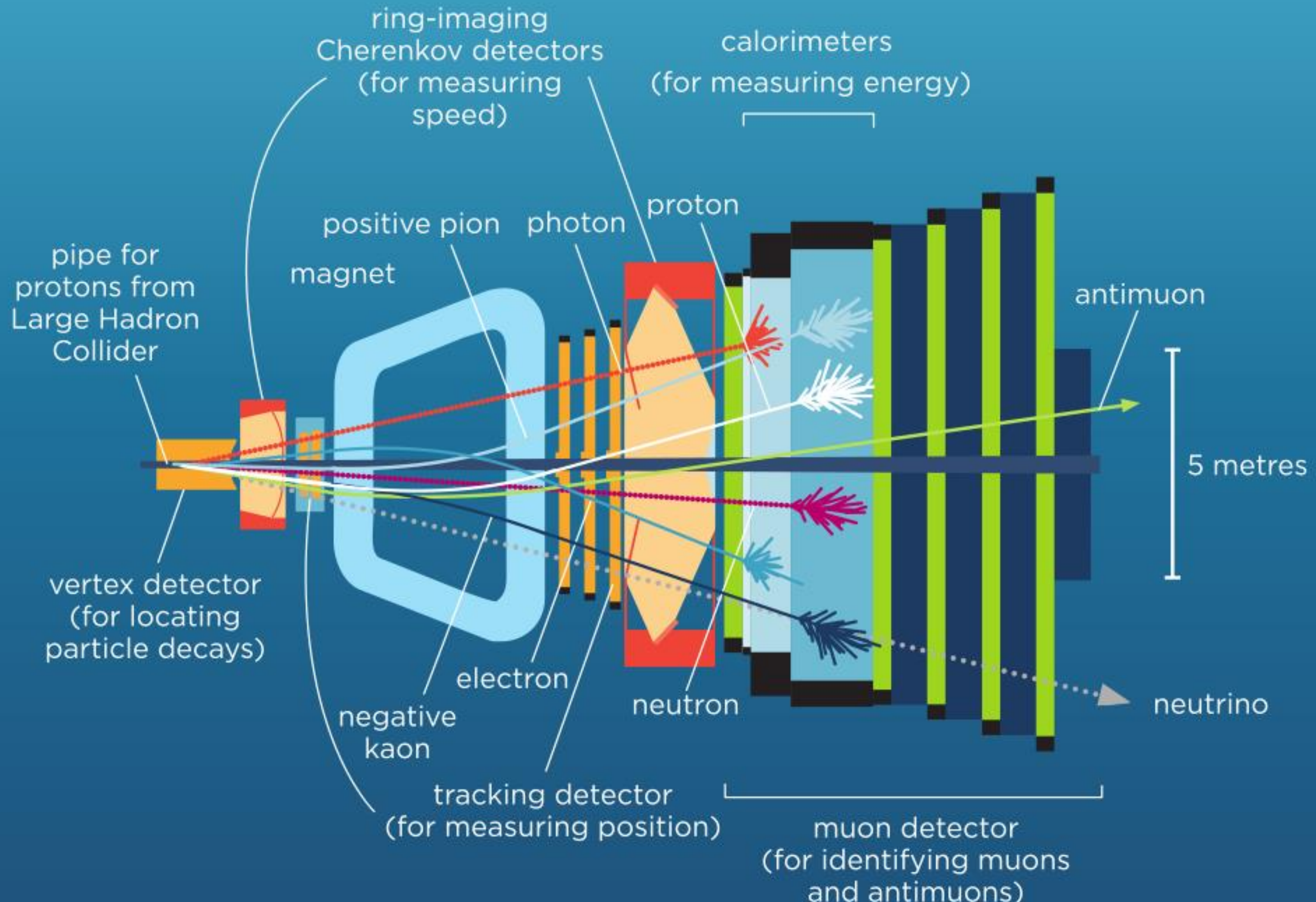
$$m_H = 125.03 \, ^{+0.26}_{-0.27} \, (\text{stat.}) \, ^{+0.13}_{-0.15} \, (\text{syst.}) \ \text{GeV}$$

Misure di precisione sul bosone di Higgs



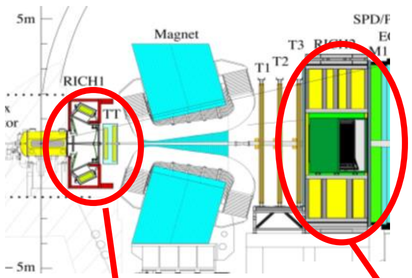


Il rivelatore LHCb



http://antimatter-matters.org/

Il rivelatore RICH di LHCb

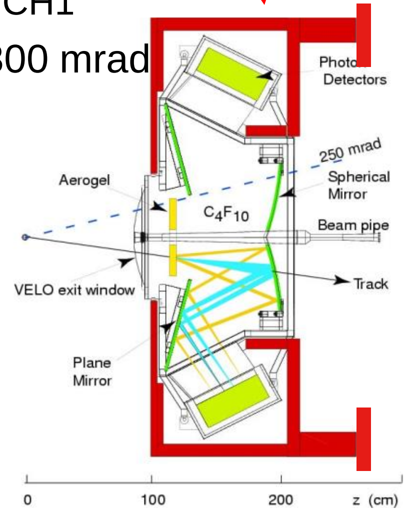


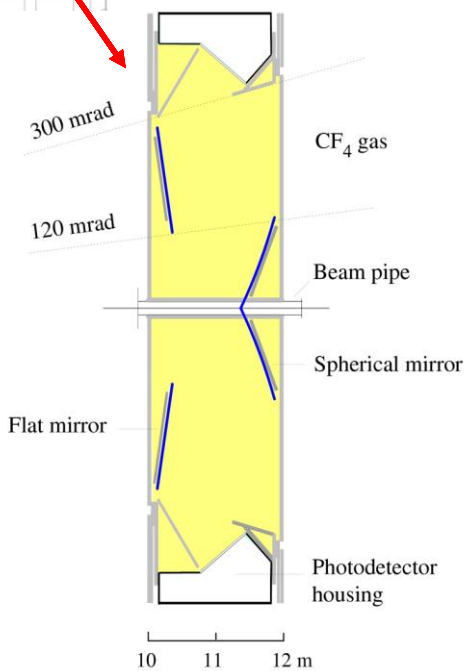
RICH2

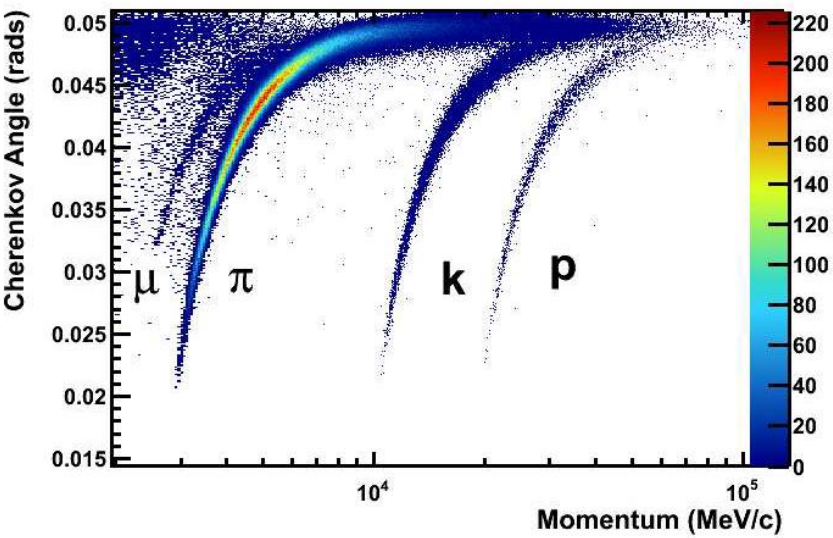
15-120 mrad

RICH1

25-300 mrad





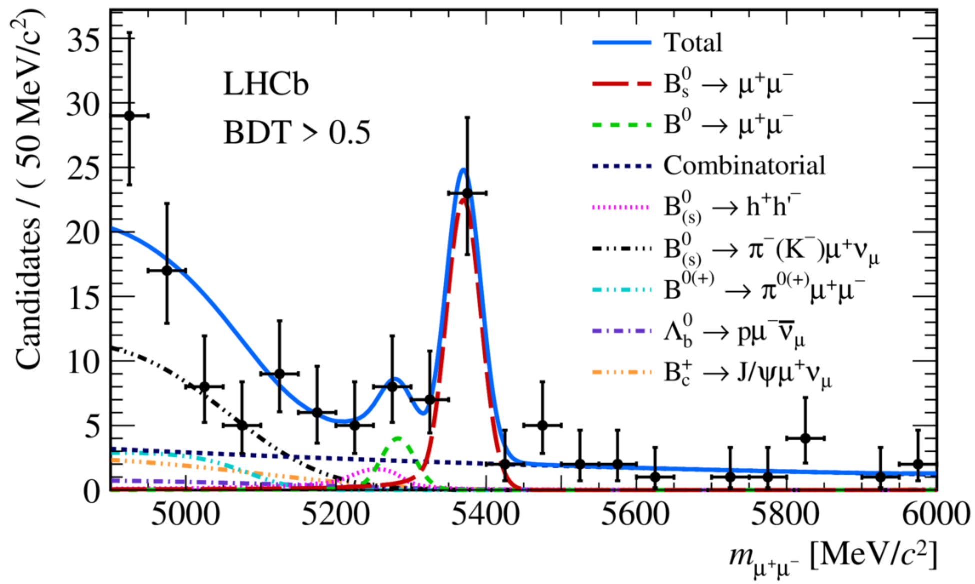


Ricerca di Fisica oltre il Modello Standard a LHCb

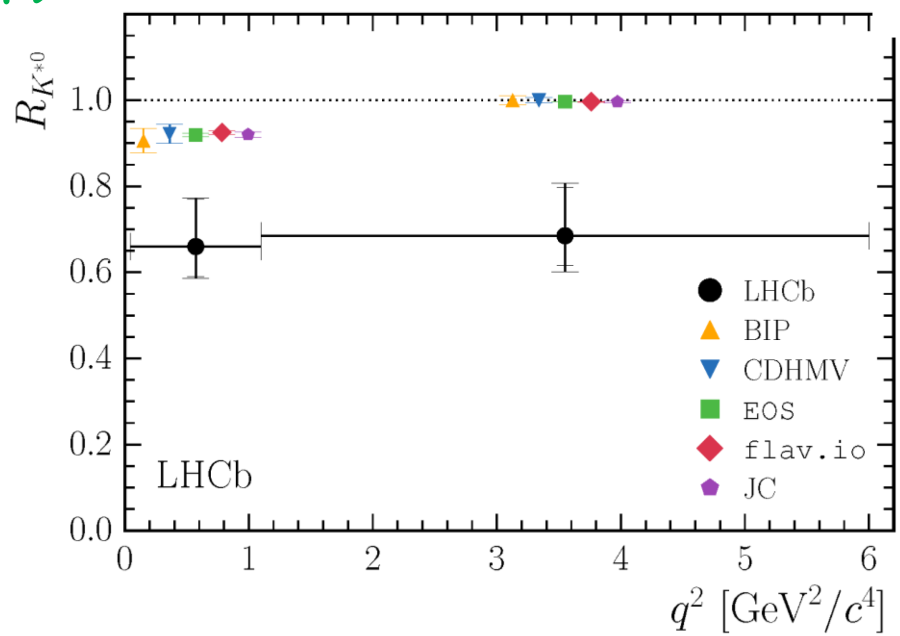
Decadimenti rari: $B_{(s)} \rightarrow \mu^+\mu^-$

scoperta a 7.8 σ

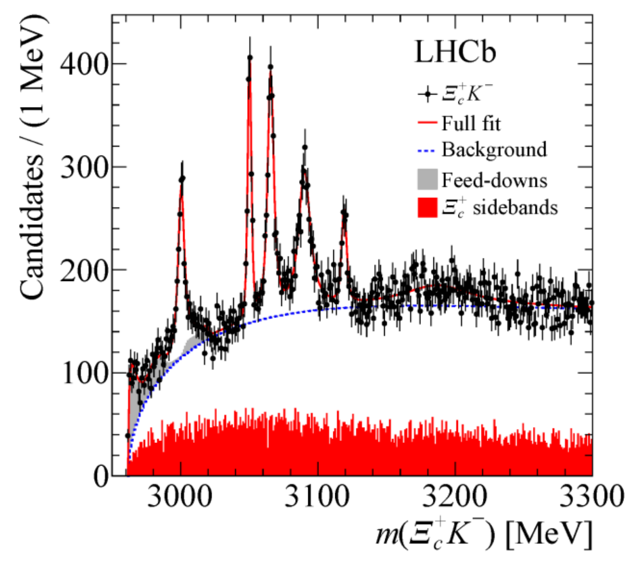
$BR(B^0_s \rightarrow \mu+\mu-) = (3.0 \pm 0.6 \pm 0.3) \times 10^{-9}$



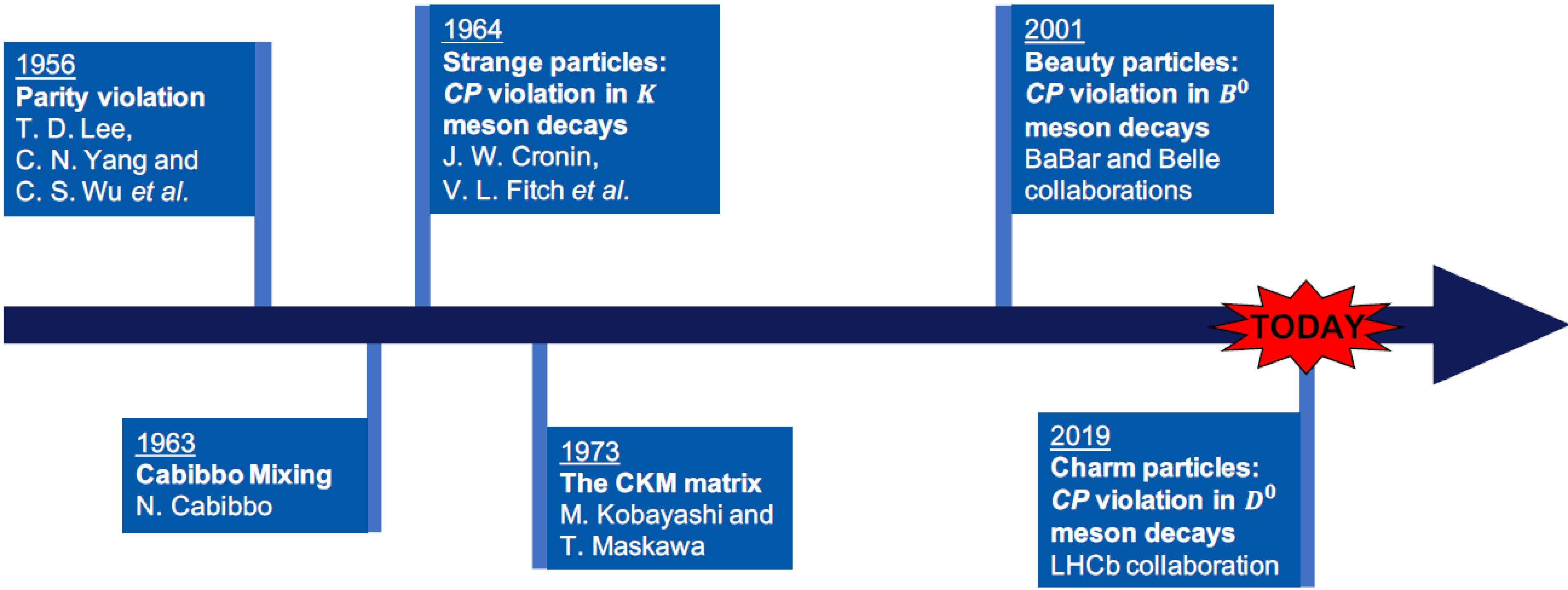
Test universalità leptonica (e, μ)



Spettroscopia Ω_c^0



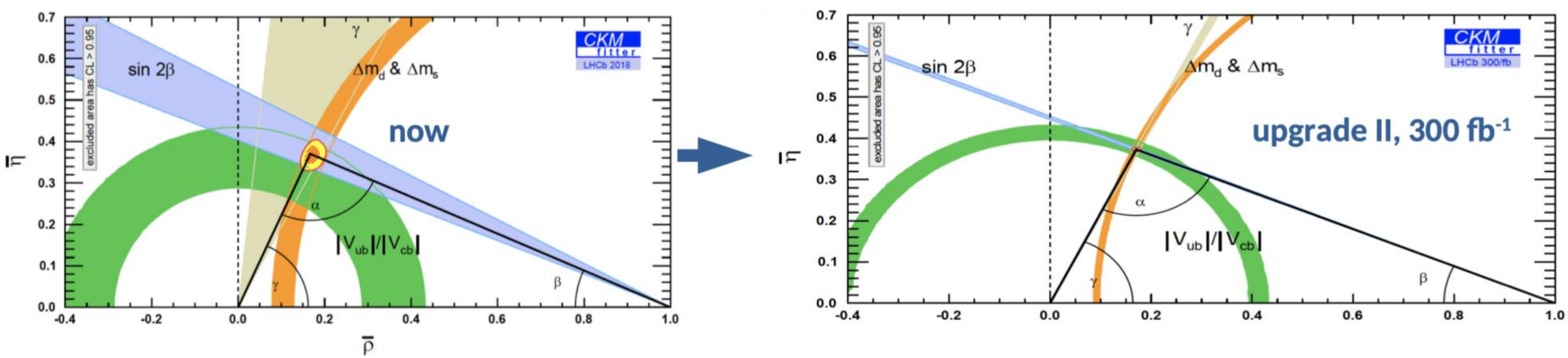
Violazione di CP nel settore dei quark



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:

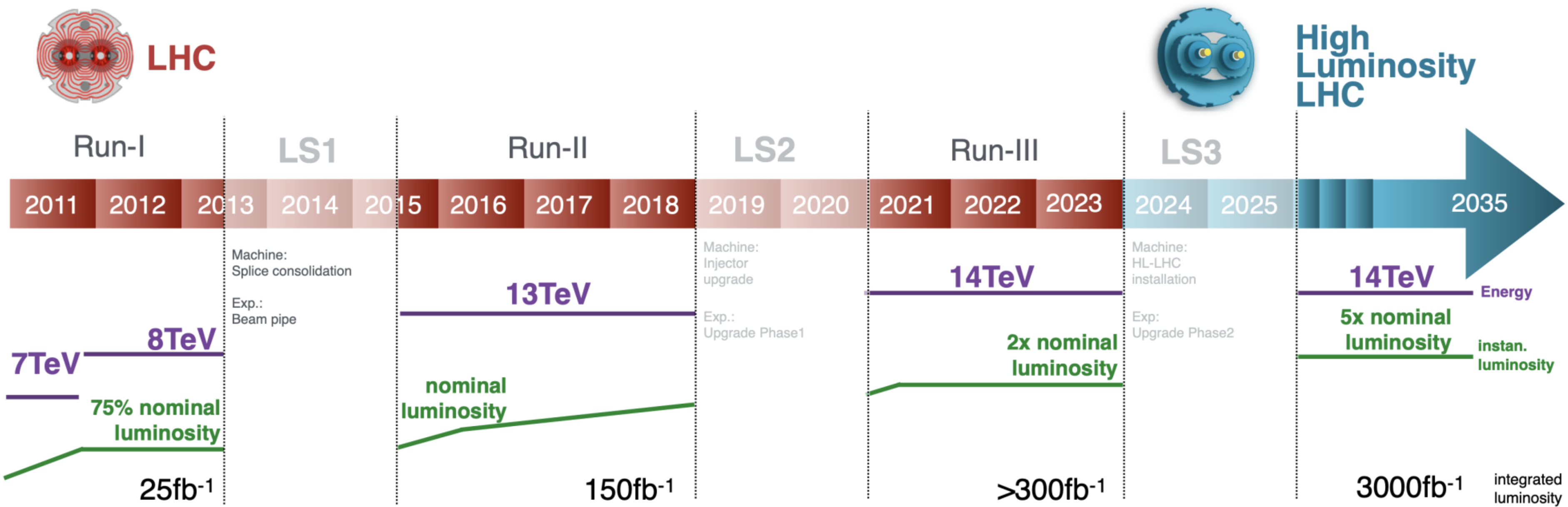


LHCb ha la prima evidenza della violazione di CP nel charm, misurando le diverse probabilità di decadimento di $\overline{D}^0$ e D^0 in $\pi^+\pi^-$ e K^+K^-: $\Delta A_{CP} = (-0.154 \pm 0.029)\%$

Il futuro di LHC

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

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



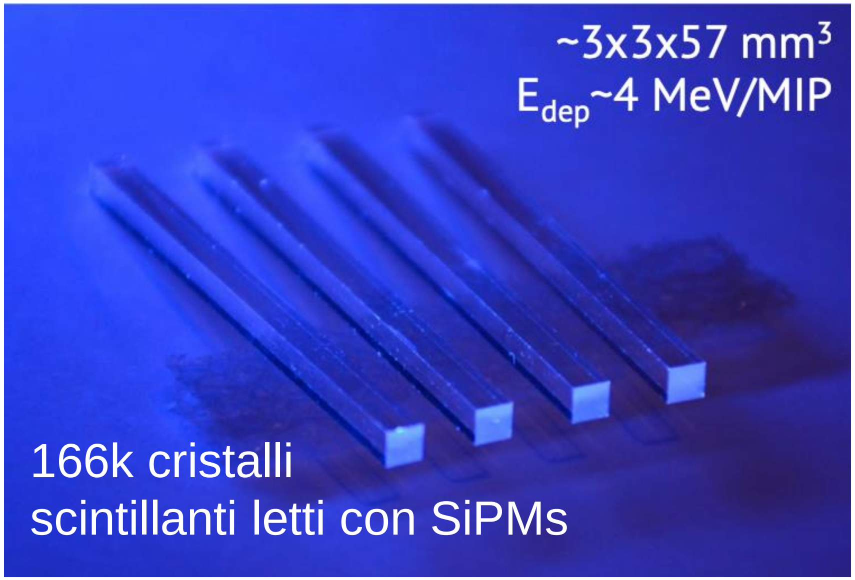
L'obiettivo di HL-LHC è una luminosità integrata 20 volte superiore rispetto ad oggi. Pileup fino a 200 eventi per beam crossing (oggi fino a 50)

Upgrade di CMS

MIP Timing Detector

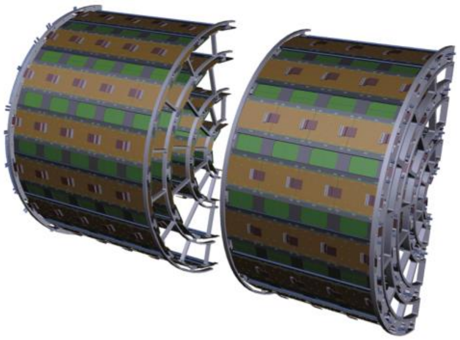
30-50 ps time tagging of individual tracks to |η|<3

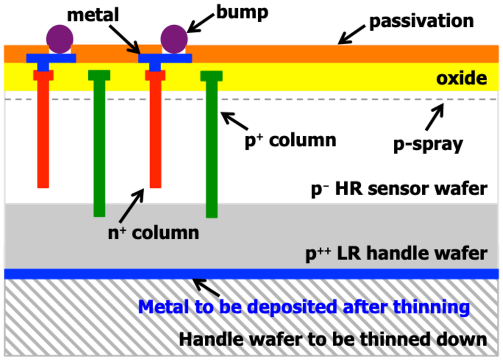
<u>Barrel</u>: LYSO Crystals + SiPM readout (40 m^2)
<u>Endcaps</u>: low gain avalanche silicon detectors (14 m^2)



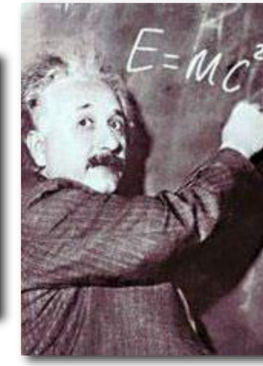
Pixel Detector

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



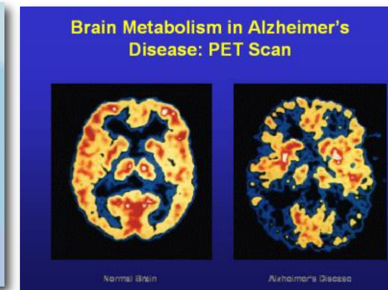


The Mission of CERN



- Push back the frontiers of knowledge

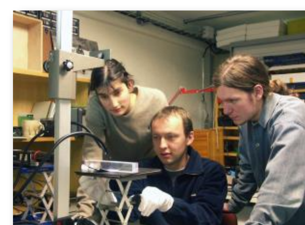
  E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe's existence?



- Develop new technologies for accelerators and detectors

  Information technology - the Web and the GRID

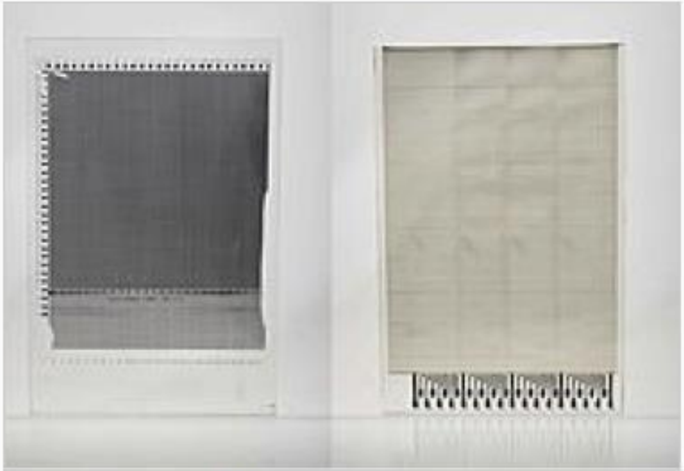
  Medicine - diagnosis and therapy



- Train scientists and engineers of tomorrow

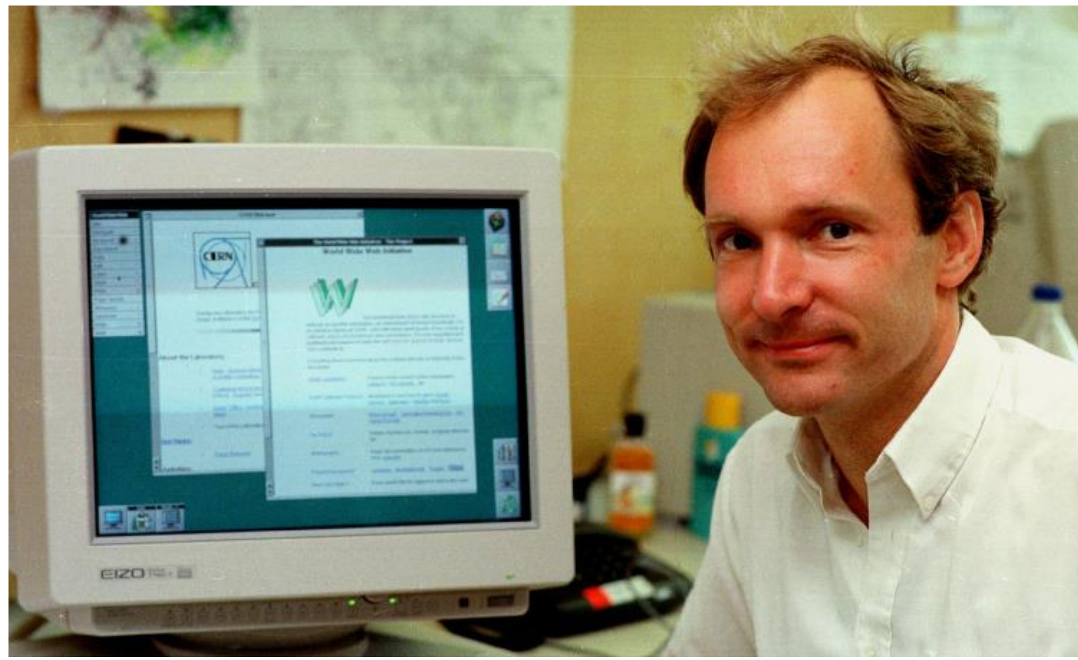
- Unite people from different countries and cultures

Born at CERN



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.

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

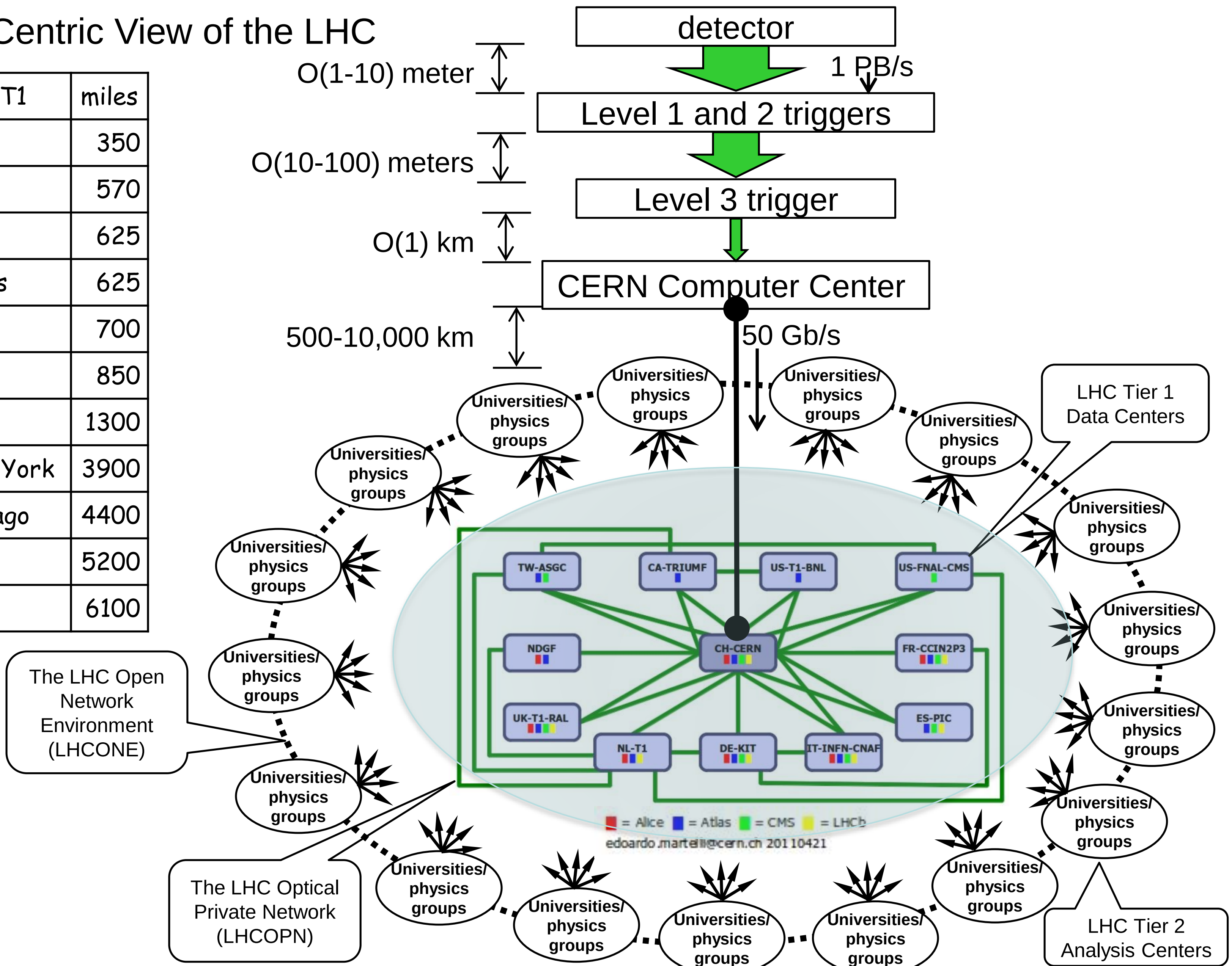


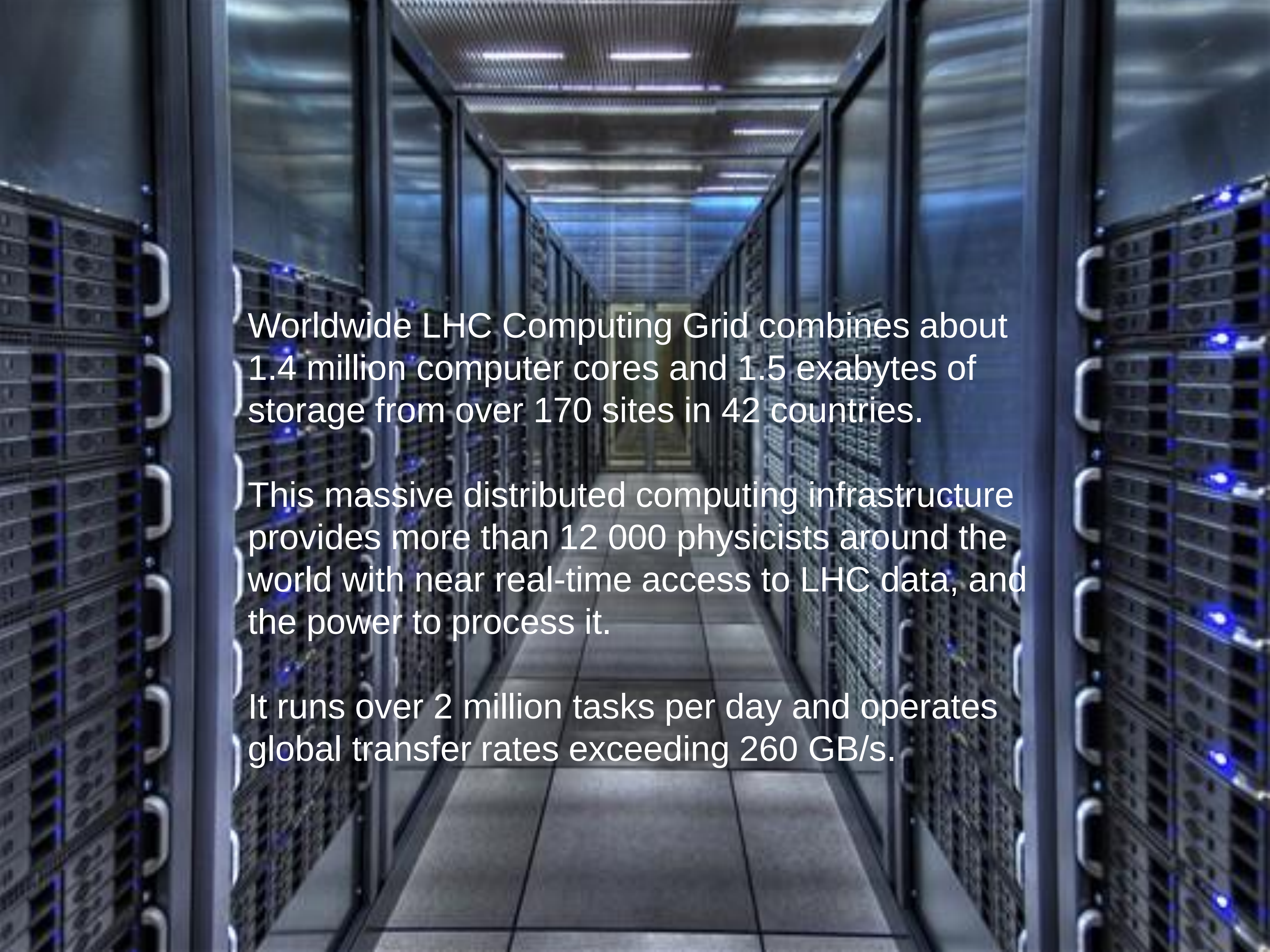
Nel 1993 il CERN rinuncia a qualunque diritto, distribuendo il codice sorgente

Distributed Computing: the Grid

A Network Centric View of the LHC

CERN → T1	miles
France	350
Italy	570
UK	625
Netherlands	625
Germany	700
Spain	850
Nordic	1300
USA - New York	3900
USA - Chicago	4400
Canada - BC	5200
Taiwan	6100



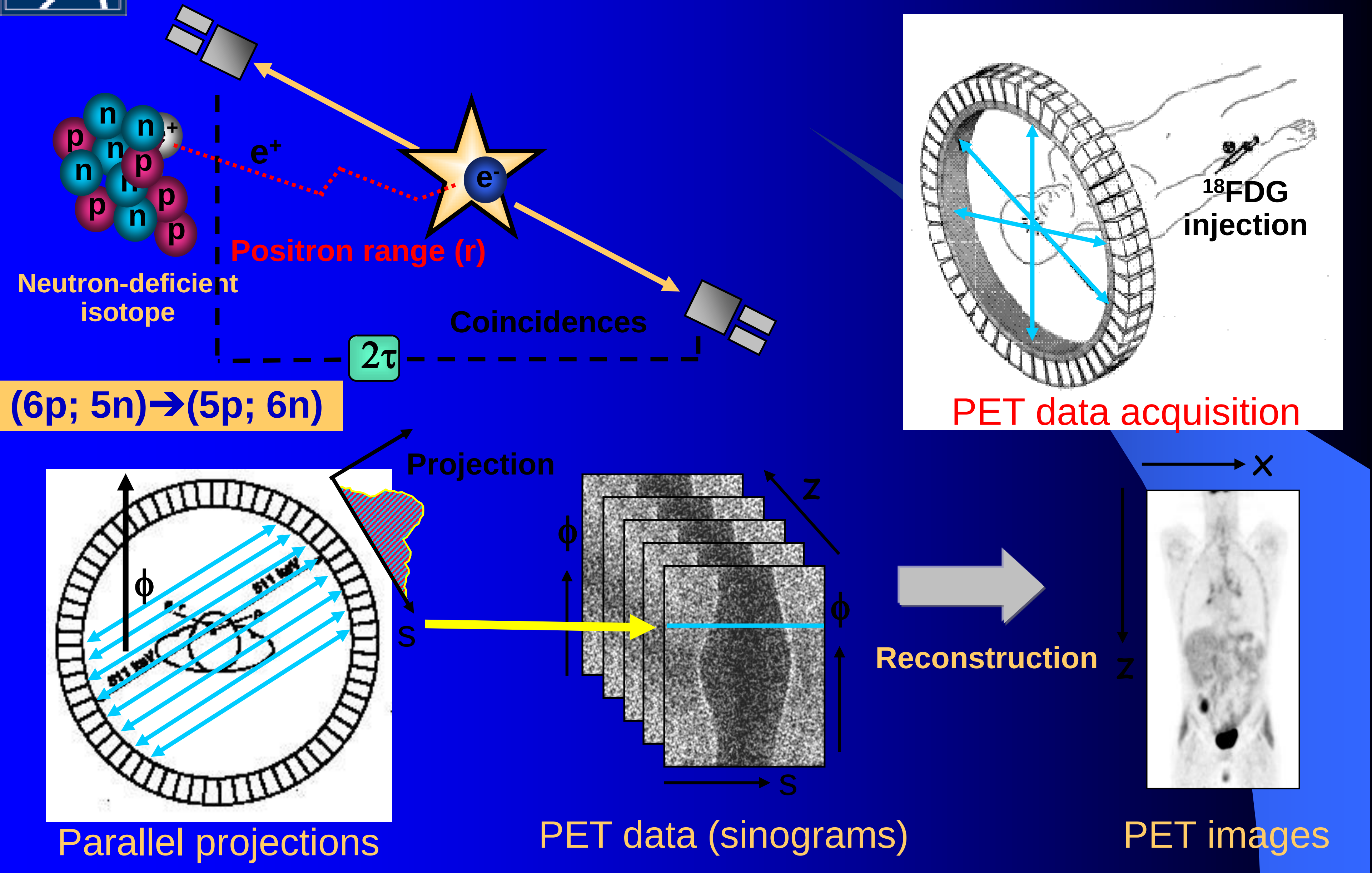


Worldwide LHC Computing Grid combines about 1.4 million computer cores and 1.5 exabytes of storage from over 170 sites in 42 countries.

This massive distributed computing infrastructure provides more than 12 000 physicists around the world with near real-time access to LHC data, and the power to process it.

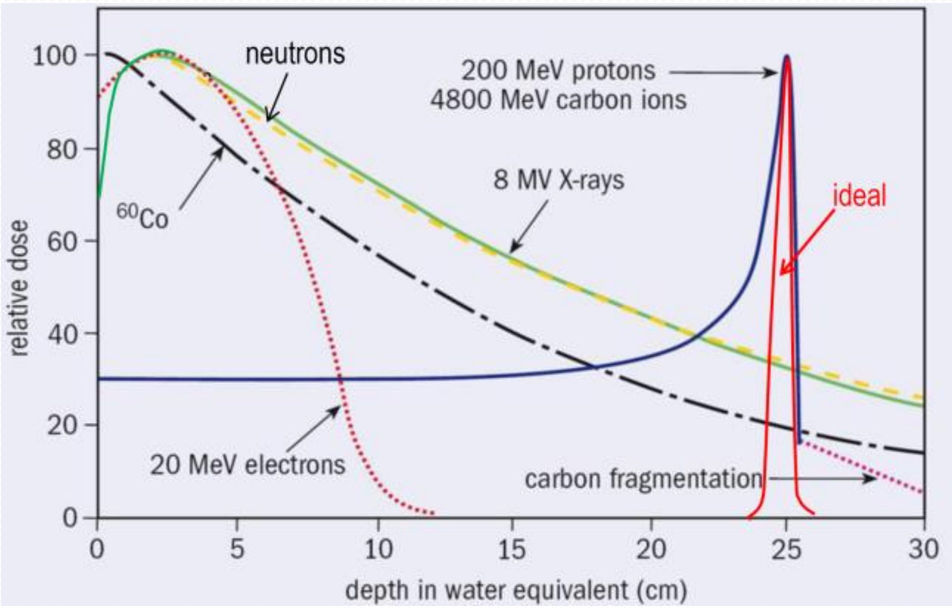
It runs over 2 million tasks per day and operates global transfer rates exceeding 260 GB/s.

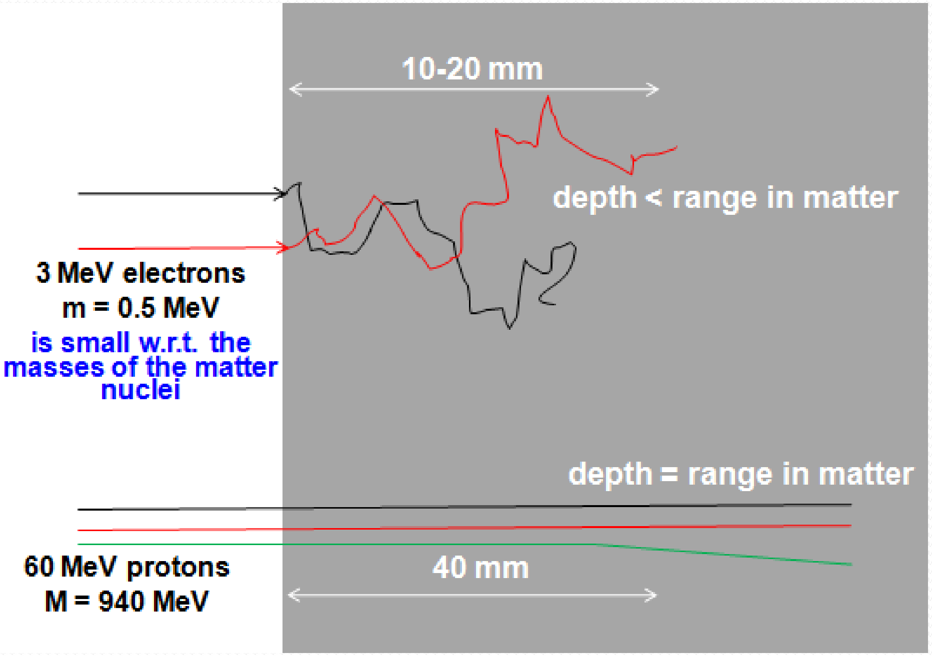
PET Principle



Adroterapia oncologica

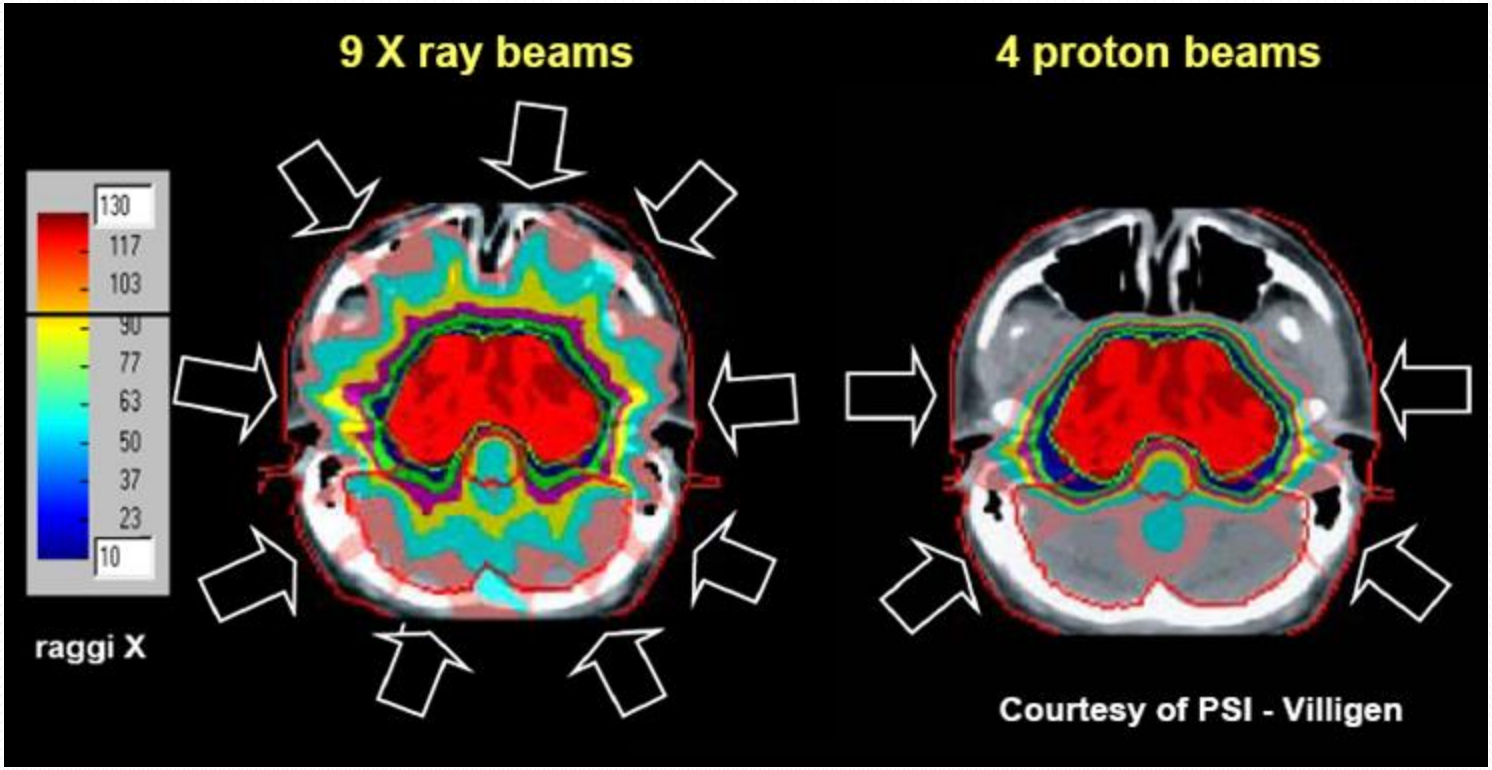
1. Energia massima nel picco di Bragg → riduzione della dose nei tessuti attraversati, quasi nessuna dose nei tessuti più in profondità del picco
2. Diffusione laterale molto piccola





Adroterapia oncologica

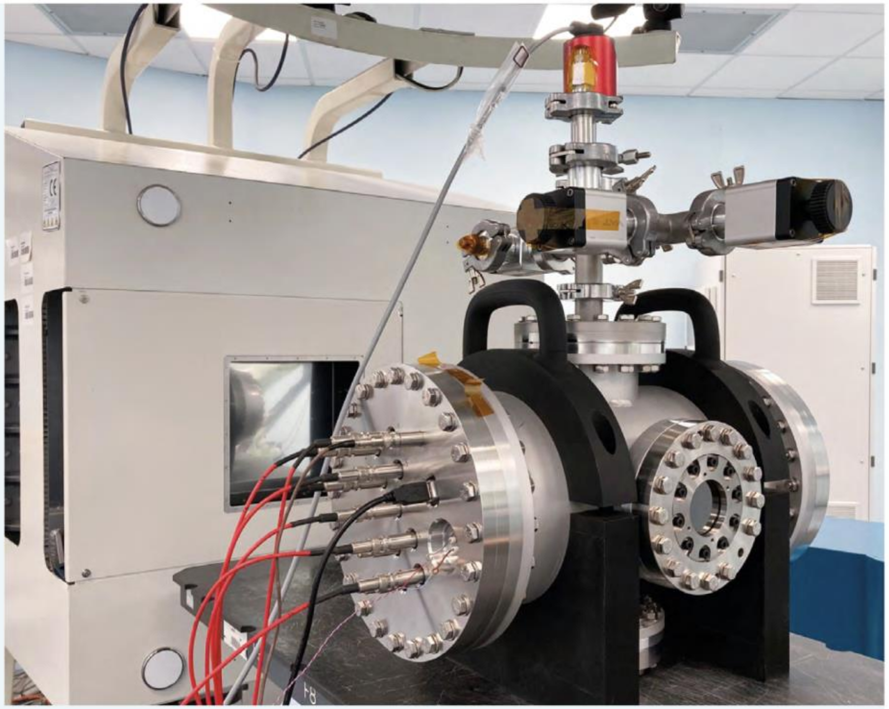
Possibilità di fare trattamenti altamente conformi per tumori profondi con precisione ~mm e dando una dose minima ai tessuti circostanti




fondazioneCNAO
National Center of Oncological Hadrontherapy for the treatment of tumours
OMIS

PORTABLE DETECTORS FOR MICRODOSIMETRY AND ION THERAPY

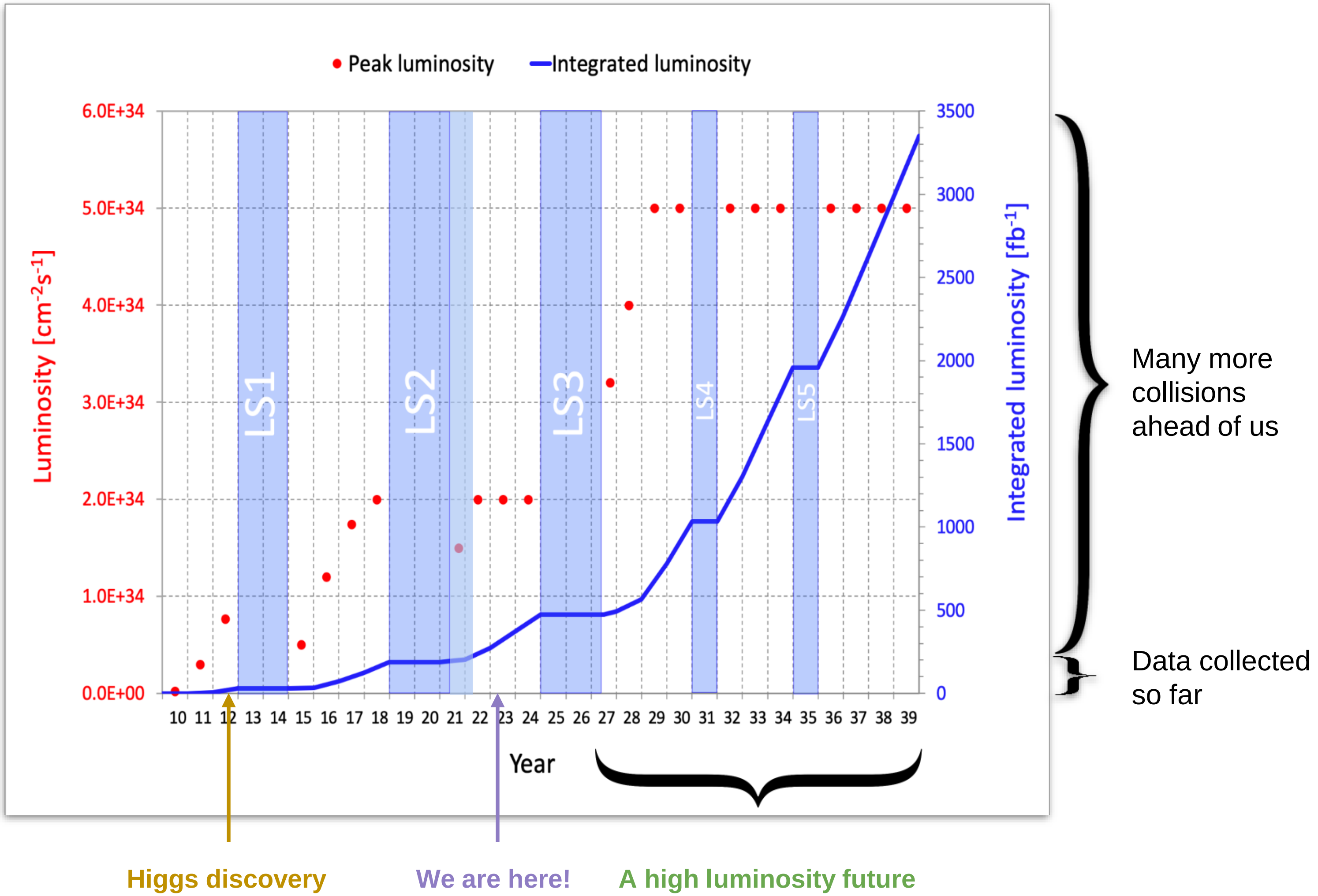
The new GEMTEQ detector developed at CERN could be used to improve the effectiveness of cancer treatments. The detector is based on GEMPix, which combines two CERN technologies, Gas Electron Multipliers and Timepix, both used for detection of ionising radiation. It will be used in microdosimetry, which studies the absorbed dose in biological matter at cell level, for a better understanding of radiation effects in human tissue. To further increase portability, a sealed and low-pressure version of the GEMTEQ was designed, assembled and made fully operational at CERN. It was then successfully used for measurements with protons and carbon ions at CNAO (The National Center for Oncological Hadrontherapy) in Italy, one of the few centres in Europe treating cancer patients with carbon ions.

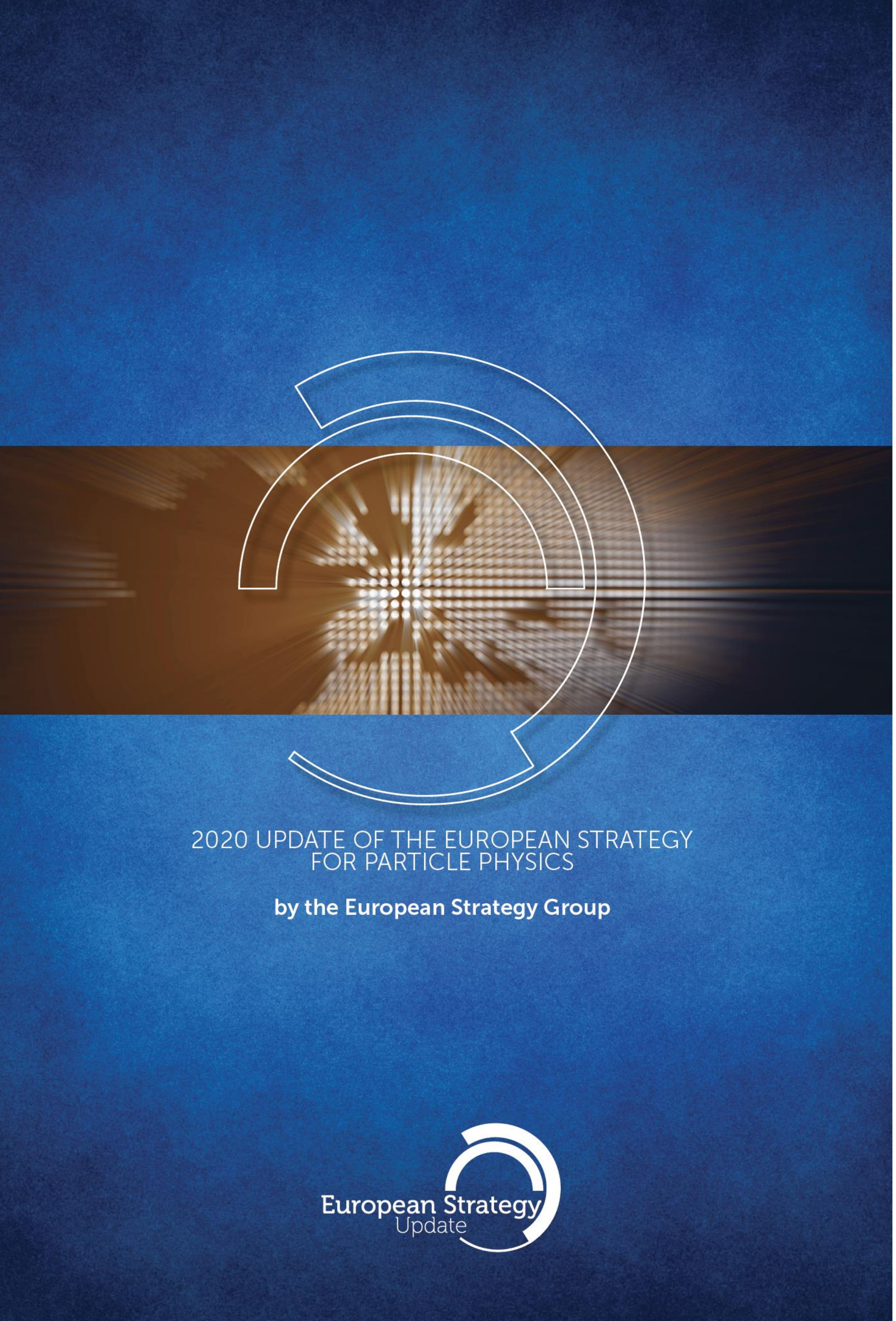


GEMPix at CNAO for the latest measurements in October and December 2021

High Luminosity LHC

The best opportunity and highest priority for the next decade:
increase the luminosity up to 5x in order to collect 10x more data





General considerations for the 2020 update

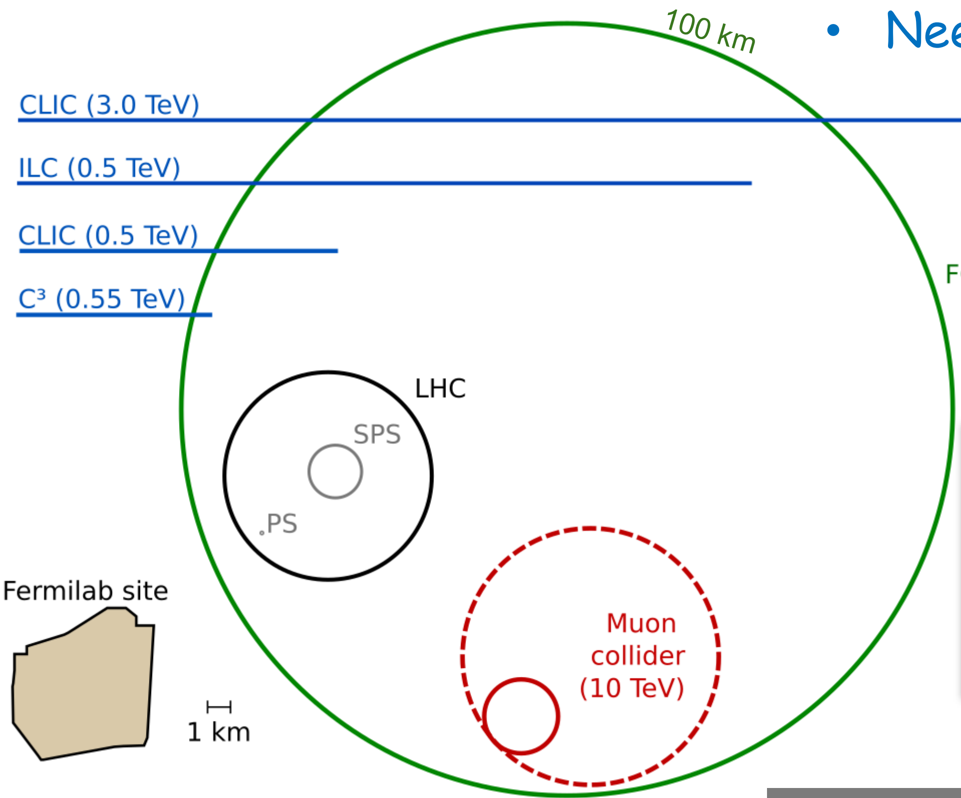
A. Europe, through CERN, has world leadership in accelerator-based particle physics and related technologies. The future of the field in Europe and beyond depends on the continuing ability of CERN and its community to realise compelling scientific projects. ***This Strategy update should be implemented to ensure Europe's continued scientific and technological leadership.***

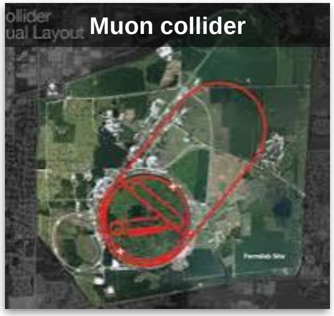
B. The European organisational model centred on close collaboration between CERN and the national institutes, laboratories and universities in its Member and Associate Member States is essential to the enduring success of the field. This has proven highly effective in harnessing the collective resources and expertise of the particle, astroparticle and nuclear physics communities, and of many interdisciplinary research fields. Another manifestation of the success of this model is the collaboration with non-Member States and their substantial contribution. ***The particle physics community must further strengthen the unique ecosystem of research centres in Europe. In particular, cooperative programmes between CERN and these research centres should be expanded and sustained with adequate resources in order to address the objectives set out in the Strategy update.***

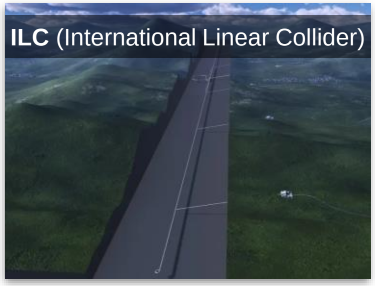
C. The broad range of fundamental questions in particle physics and the complexity of the diverse facilities required to address them, together with the need for an efficient use of resources, have resulted in the establishment of a global particle physics community with common interests and goals. This Strategy takes into account the rich and complementary physics programmes being undertaken by Europe's partners across the globe and of scientific and technological developments in neighbouring fields. ***The implementation of the Strategy should proceed in strong collaboration with global partners and neighbouring fields.***

Future collider options (for 21st century)

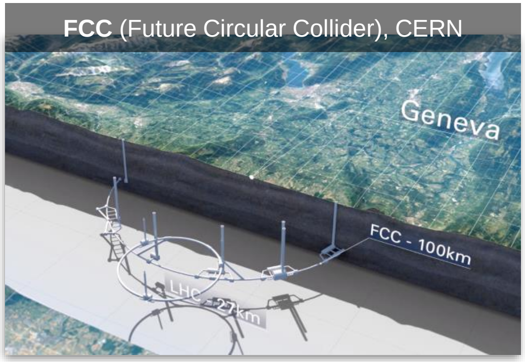
- A major **civil engineering** challenge!
- It has to be sustainable.
- Needs substantial R&D



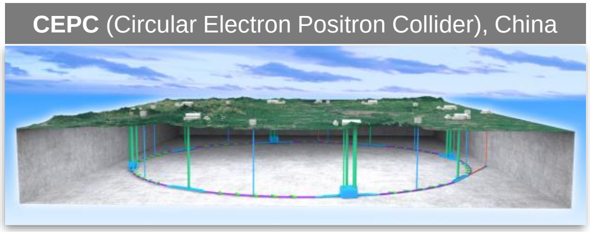

Muon collider


ILC (International Linear Collider)


CLIC (Compact Linear Collider)



FCC (Future Circular Collider), CERN


CEPC (Circular Electron Positron Collider), China

Istituto Nazionale di Fisica Nucleare

- Italy is a CERN founding member CERN with a strong tradition in particle physics
- Edoardo Amaldi: one of the founding fathers of CERN

- Three Directors General from Italy:

  Carlo Rubbia, Luciano Maiani, Fabiola Gianotti
- INFN brings together ~ 5000 researchers
- ~ 600 Italian physicists have collaborated to the realisation of the LHC
- Italian industries have constructed extremely important high-tech components for the LHC (Ansaldo is one of the three contractors for LHC magnets and a key contractor for CMS coil (the world's largest superconducting coil)
- Italian Nobel Prizes related to advance of Particle Physics:

  1938: E. Fermi

  1984: C. Rubbia

  2022: G. Parisi