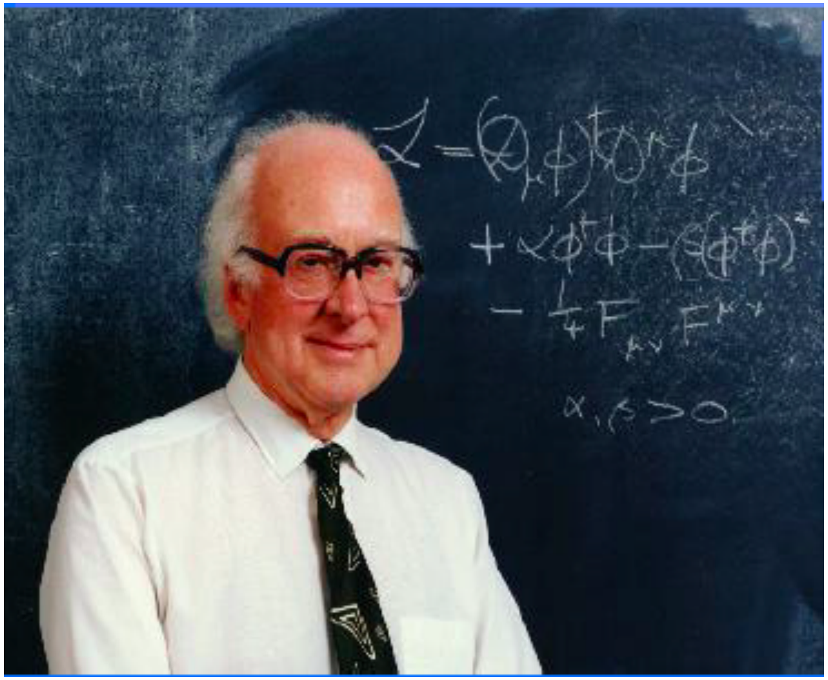
Capitolo 13
Il Bosone di Higgs
e la sua Scoperta a LHC
CON ATLAS E CMS

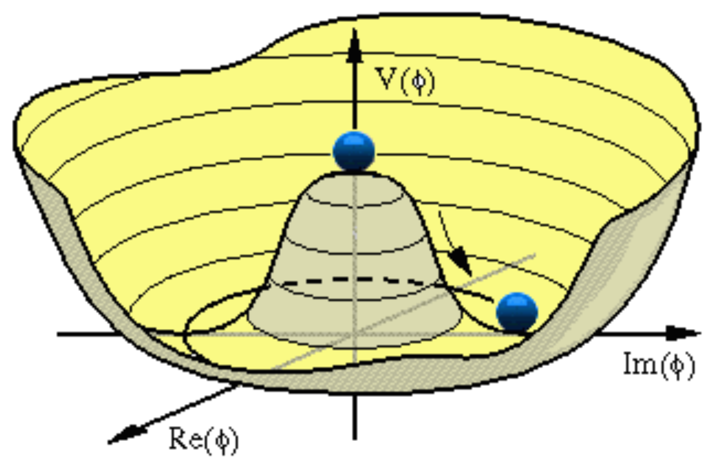
Carlo Dionisi,
AA 2012-2013, Corso FNSN II



Nel 1964 Prof. Peter Higgs propone l'esistenza di un campo scalare che rompe la simmetria elettrodebole

- in SM **electroweak symmetry broken via the Higgs** **mechanism**

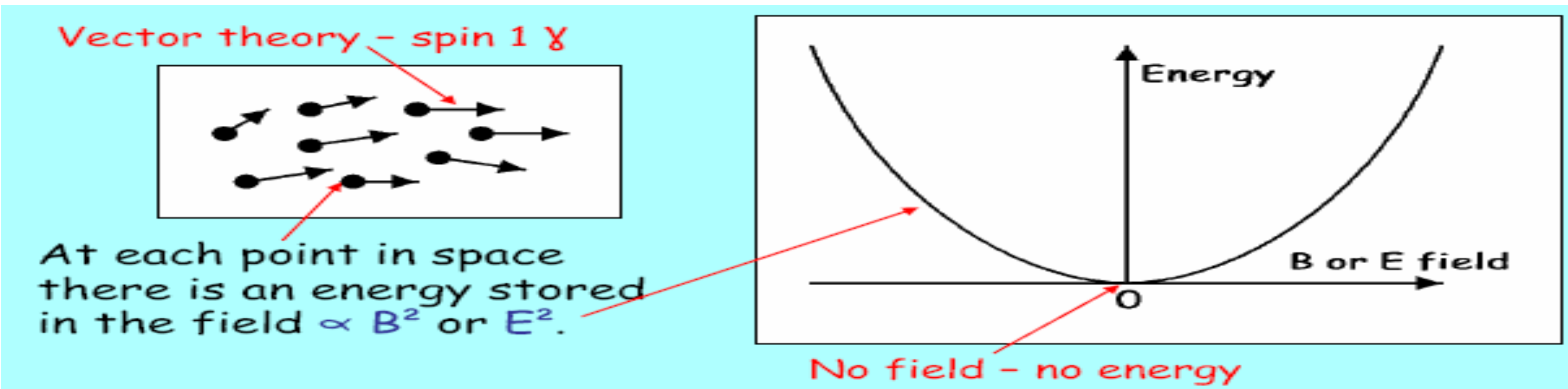
$$V(|\phi|) = \mu|\phi|^2 + \lambda|\phi|^4$$

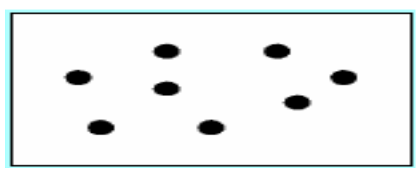


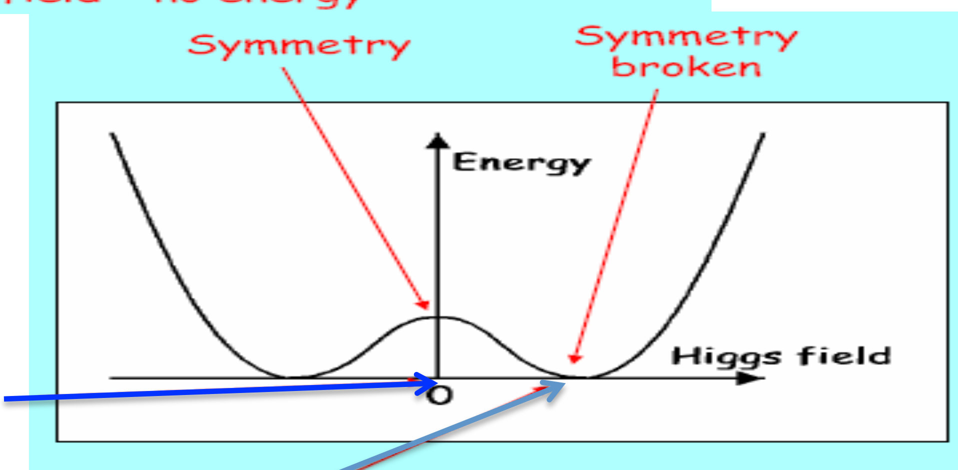
Il Campo di Higgs

Il campo di Higgs ha la peculiare proprieta' che lo stato in cui il valore del campo e' nullo NON e' quello di energia minima.

In elettromagnetismo ciascun punto dello spazio ha associati un valore e una direzione dei campi B e E.
Per il campo di Higgs non c'e' direzione: il campo e' scalare con spin nullo.
L'energia e' legata in modo diverso al valore del campo.







L'energia e' > 0 quando il campo e' = 0

Nel vuoto con energia uguale a zero, il campo di Higgs NON e' nullo: ➔ particella di Higgs.

SM Higgs couplings

$$m_H = \sqrt{\lambda/2}\; v$$

Higgs field vacuum expectation value ~246 GeV

Higgs mass: UNKNOWN

Higgs self-coupling: UNKNOWN
Bounds from Higgs potential stability and theory perturbativity

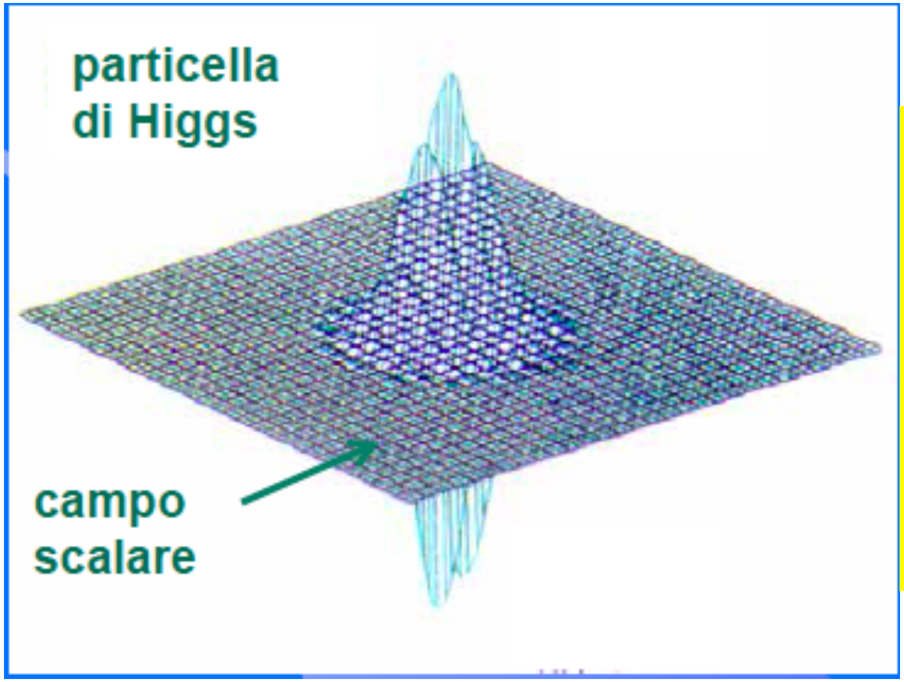
Couplings depend on the masses of the involved particles:

$$g_{Hf\bar{f}} = \frac{m_f}{v}, \quad g_{HVV} = \frac{2m_V^2}{v}, \quad g_{HHVV} = \frac{2m_V^2}{v^2}$$

$$g_{HHH} = \frac{3m_H^2}{v} \quad g_{HHHH} = \frac{3m_H^2}{v^2}$$

Relazione tra campo di Higgs, condensato di Higgs e Particella di Higgs

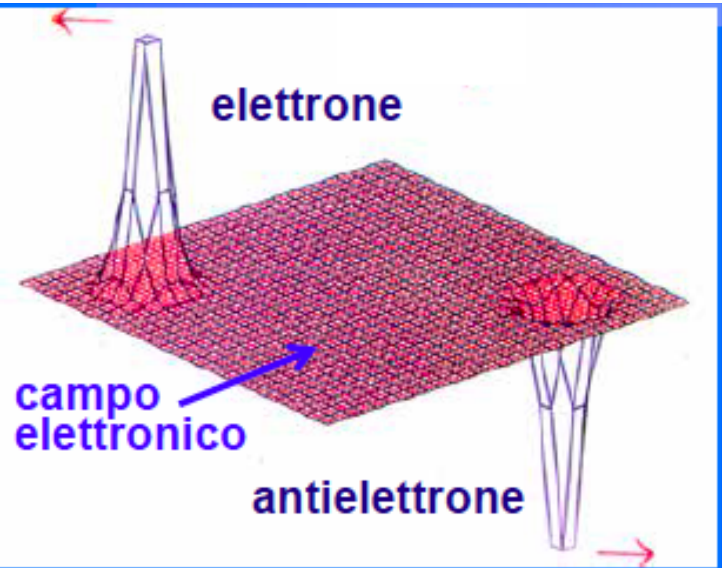
★ Se c'e' un campo che riempie lo spazio, ci devono essere le sue oscillazioni localizzate: la particella di Higgs

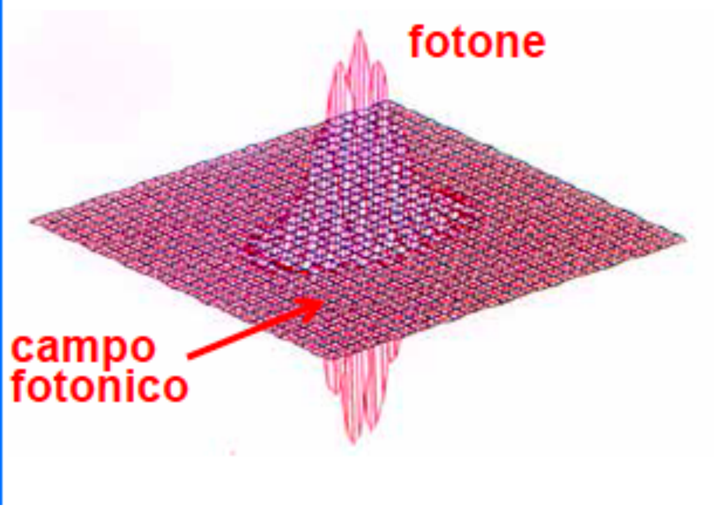


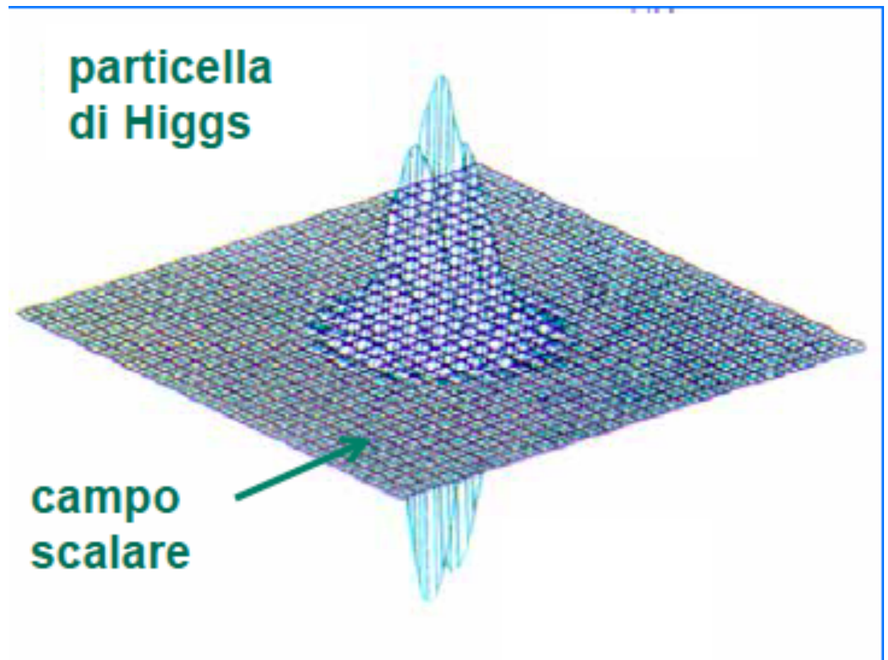
Il vuoto non e' il nulla ma un "*condensato*" di Higgs nel quale, dopo 10^{-12} s dal Bing Bang, alcune particelle si muovono a *"FATICA"*.

Ugo Amaldi
Sempre più veloci

Le Particelle sono la quantizzazione dei campi che riempiono lo spazio







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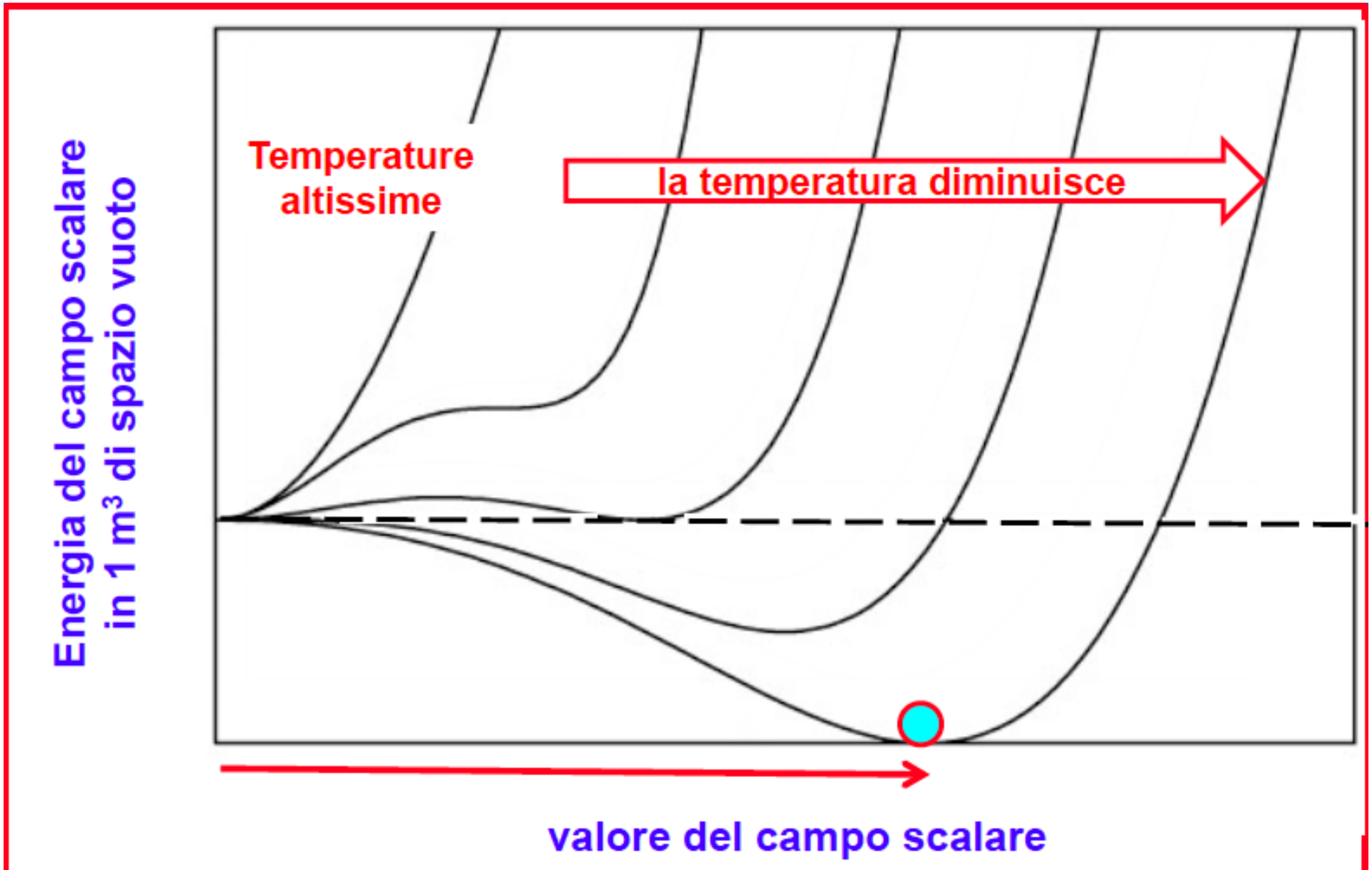
Come accadde la rottura di simmetria?



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Sempre più veloci

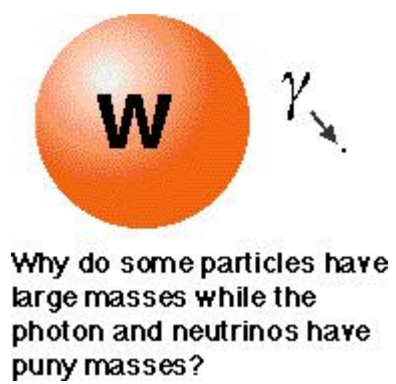
la particella di Higgs

♣ The Riddle of Mass

- Why do the fundamental particles have mass, and why are their masses different? It is remarkable that a concept as familiar as mass was not understood until the proposal of the Standard Model.
- Most of us are familiar with electric, magnetic, and gravitational fields. A person in Earth's gravitational field feels a force. Electromagnetic waves (such as radio waves) travel through space in the same way that ripples in a pond travel through water. If the pond was described in quantum language, the water surface that carries the waves would be called a "field".
- The Standard Model proposes that there is another field not yet observed, a field that is almost indistinguishable from empty space. We call this the Higgs field. We think that all of space is filled with this field, and that by interacting with this field, particles acquire their masses. Particles that interact strongly with the Higgs field are heavy, while those that interact weakly are light.
- The Higgs field has at least one new particle associated with it, the Higgs particle (or Higgs boson). The ATLAS detector at the LHC will be able to detect this particle if it exists. This would be one of the greatest scientific discoveries ever!.

la particella di Higgs

One of the main goals of the ATLAS and CMS program is to discover and study the Higgs particle. The Higgs particle is of critical importance in particle theories and is directly related to the concept of particle mass and therefore to all masses. What is the Higgs particle?



il meccanismo di Higgs

To understand the Higgs mechanism, imagine that a room full of physicists chattering quietly is like space filled with the Higgs field ...

... a well-known scientist walks in, creating a disturbance as he moves across the room and attracting a cluster of admirers with each step ...

... this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field...

il meccanismo di Higgs

... if a rumor crosses the room, ...

... it creates the same kind of clustering, but this time among the scientists themselves.

In this analogy, these clusters are the Higgs particles.

La migliore metafora

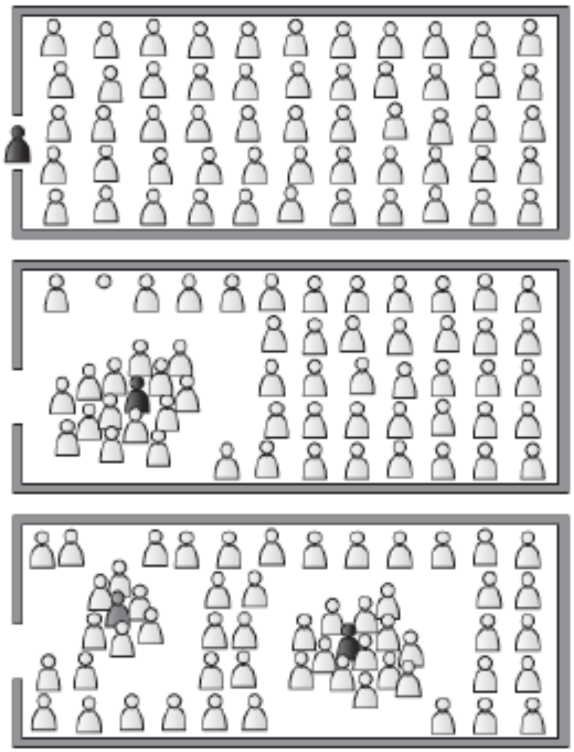


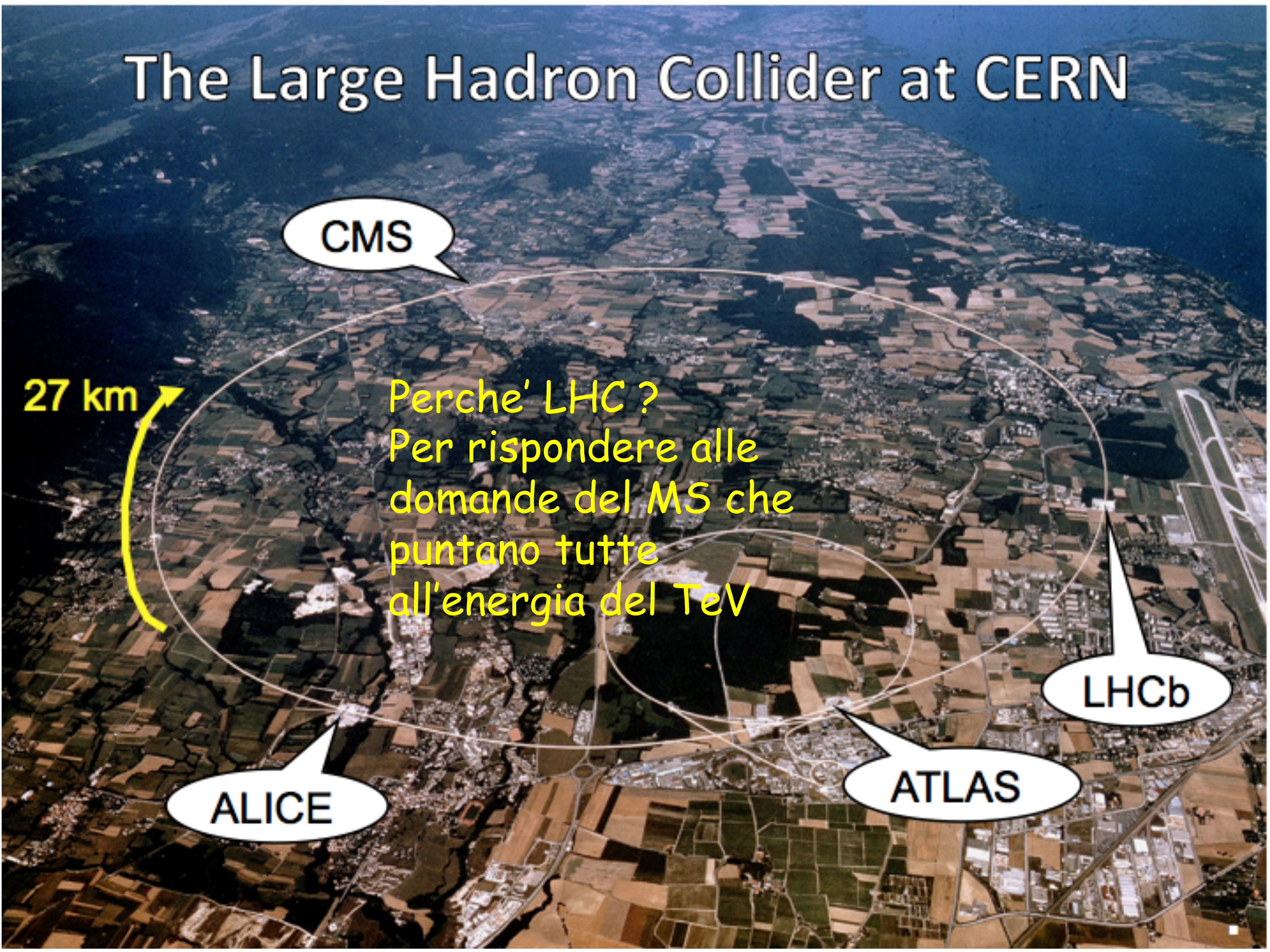
Figura 52. La metafora di Miller per il meccanismo di Higgs: all'arrivo del campione olimpico Usain Bolt, molti gli si accalcano intorno per chiedergli un autografo; così il movimento dell'atleta, «appesantito» dall'interazione con gli ammiratori, è rallentato. Se entra un atleta meno famoso, si forma un capannello più piccolo e la massa è minore.

DAVID MILLER, University College, Londra per il Ministro della Ricerca

"Si immagini un ricevimento di membri di partito che sono distribuiti uniformemente in una grande sala e che parlano ciascuno al proprio vicino. Allorché entra Mrs Thatcher, tutti coloro che le sono vicino sono fortemente attratti e fanno capannello. Quando lei si muove per attraversare la sala, attrae le persone a cui si avvicina, mentre quelle che rimangono indietro tornano a distribuirsi uniformemente. A causa del gruppo di persone che costantemente la circondano, la Signora Thatcher ha massa maggiore del solito, cioè quando si muove ha più difficoltà a fermarsi e, una volta ferma, ha più difficoltà a ripartire."

Ugo Amaldi
Sempre più veloci

LHC
ATLAS e CMS


The Large Hadron Collider at CERN
CMS
27 km
Perche' LHC ?
Per rispondere alle
domande del MS che
puntano tutte
all'energia del TeV
LHCb
ATLAS
ALICE

LHC: Pronto per le Scoperte !

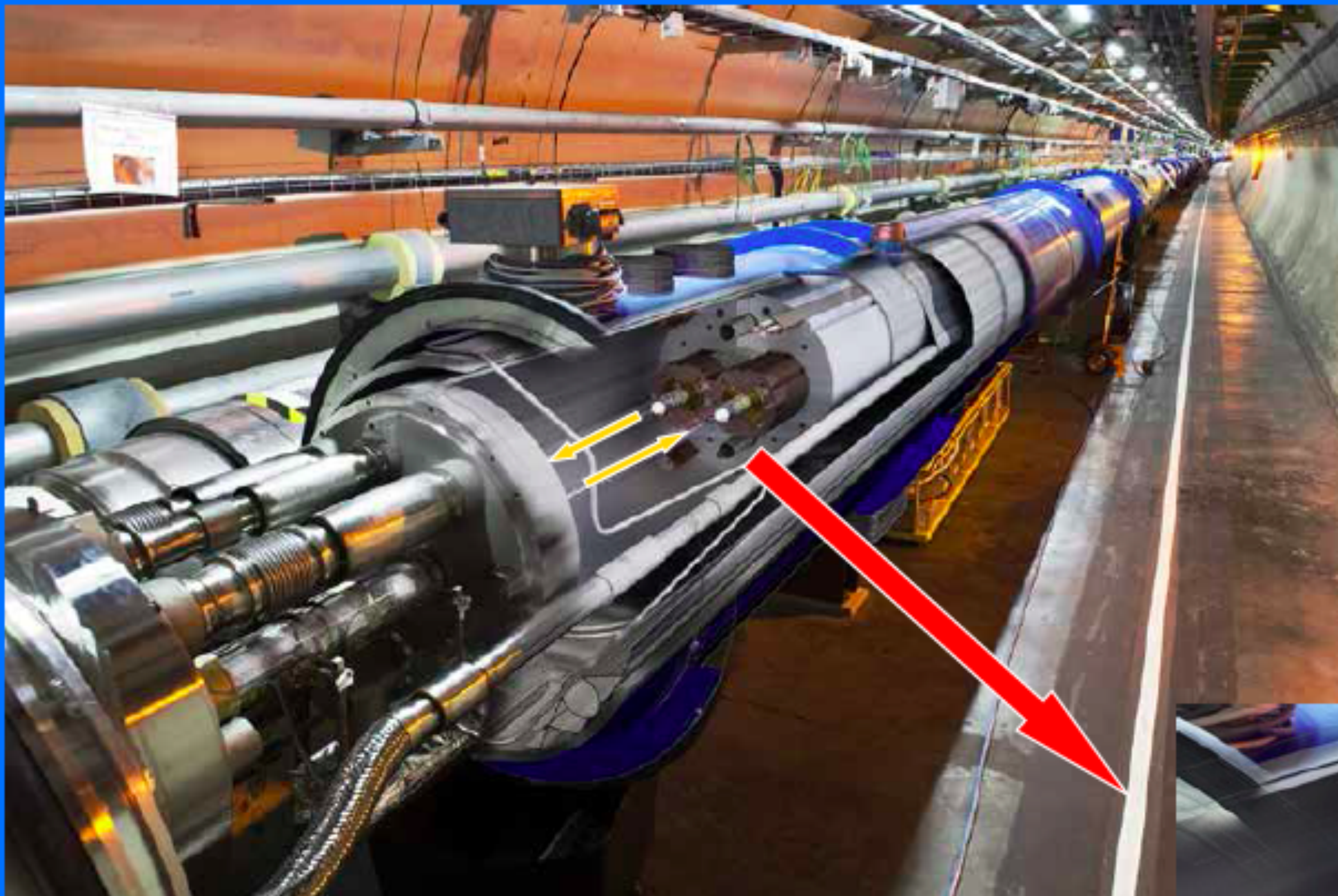
Sono necessarie 100 tonnellate di Helio liquido

E' il collisore di protoni che lavora alla piu' alta energia del mondo: 8 TeV.

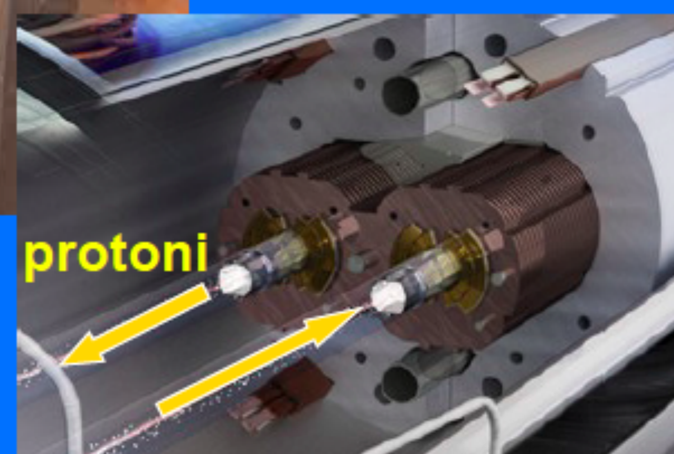
1 TeV = 10^{-7} Joule. E' una quantita' di energia enorme perche' concentrata in una sfera di raggio 15 micro-metri.

Da confrontare in una scala macroscopica con l'energia spesa da una zanzara che vola: 10^{-6} Joule

Per mantenere in orbita circolare i protoni con 1232 magneti super conduttori di 8 Tesla, ha realizzato l'impianto piu' freddo dell'Universo con una temperatura di 1.8° gradi sopra lo zero assoluto contro i 2,3° dell'Universo.



99.999 % velocità della luce (11 000 giri al secondo)

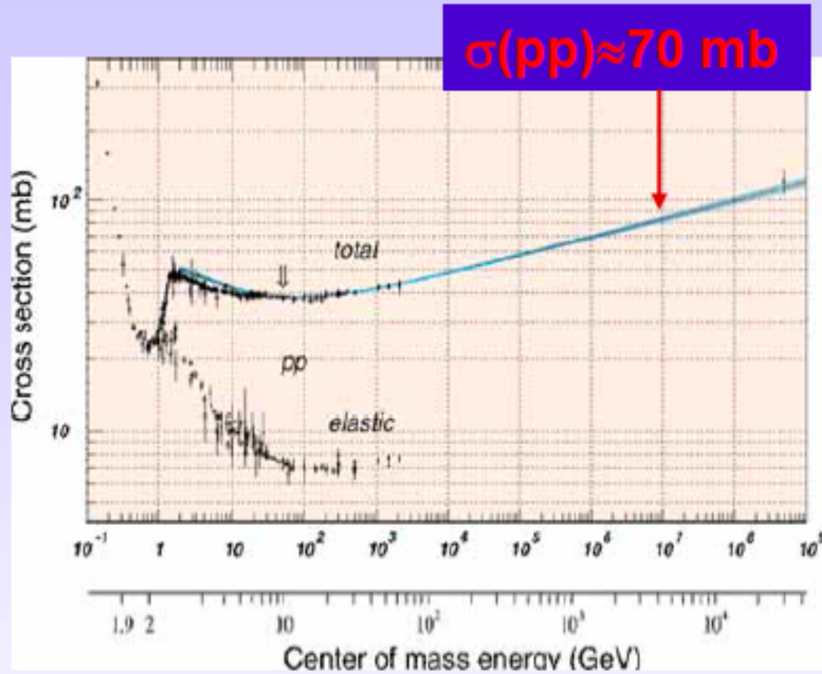


All' interno delle 'beam pipe': il posto più vuoto e freddo dell' universo

Sezione d'urto pp e min. bias

Challenge 1

- # di interazioni /bunch crossing:
  - Interazioni/s:
    - Lum = 10^{34} $cm^{-2}s^{-1}$=$10^{7}mb^{-1}$Hz
      σ(pp) = 70 mb
    - Rate di interazione, R = $7x10^{8}$ Hz
  - Eventi/bunch crossing:
      Δt = 25 ns = $2.5x10^{-8}$ s
    - Interazioni/crossing=17.5
  - Non tutti i bunches sono "pieni"
    - 2835 out of 3564 only
    - Interazioni/"active" crossing = 17.5 x 3564/2835 = 23



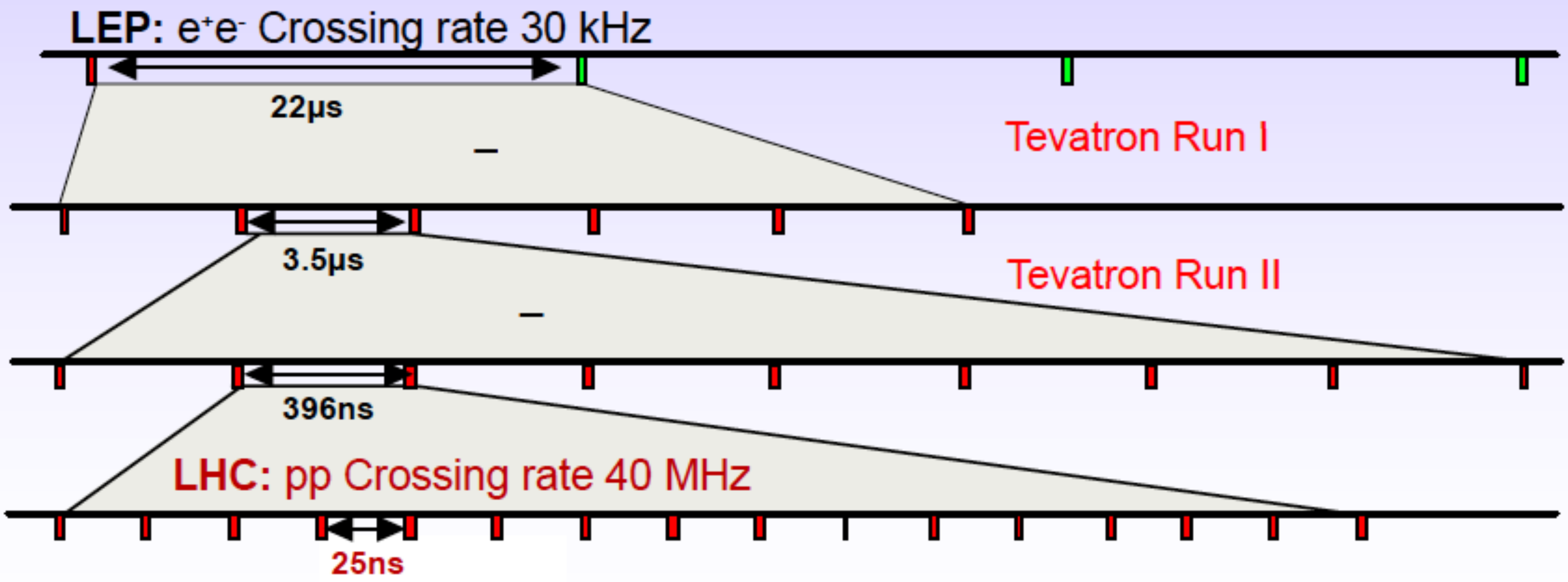
Un "buon" evento contiene un decadimento di scoperta + ≈ 25 extra (minimum bias)

- **Obiettivo limitare la quantita' di dati alla frazione interessante**

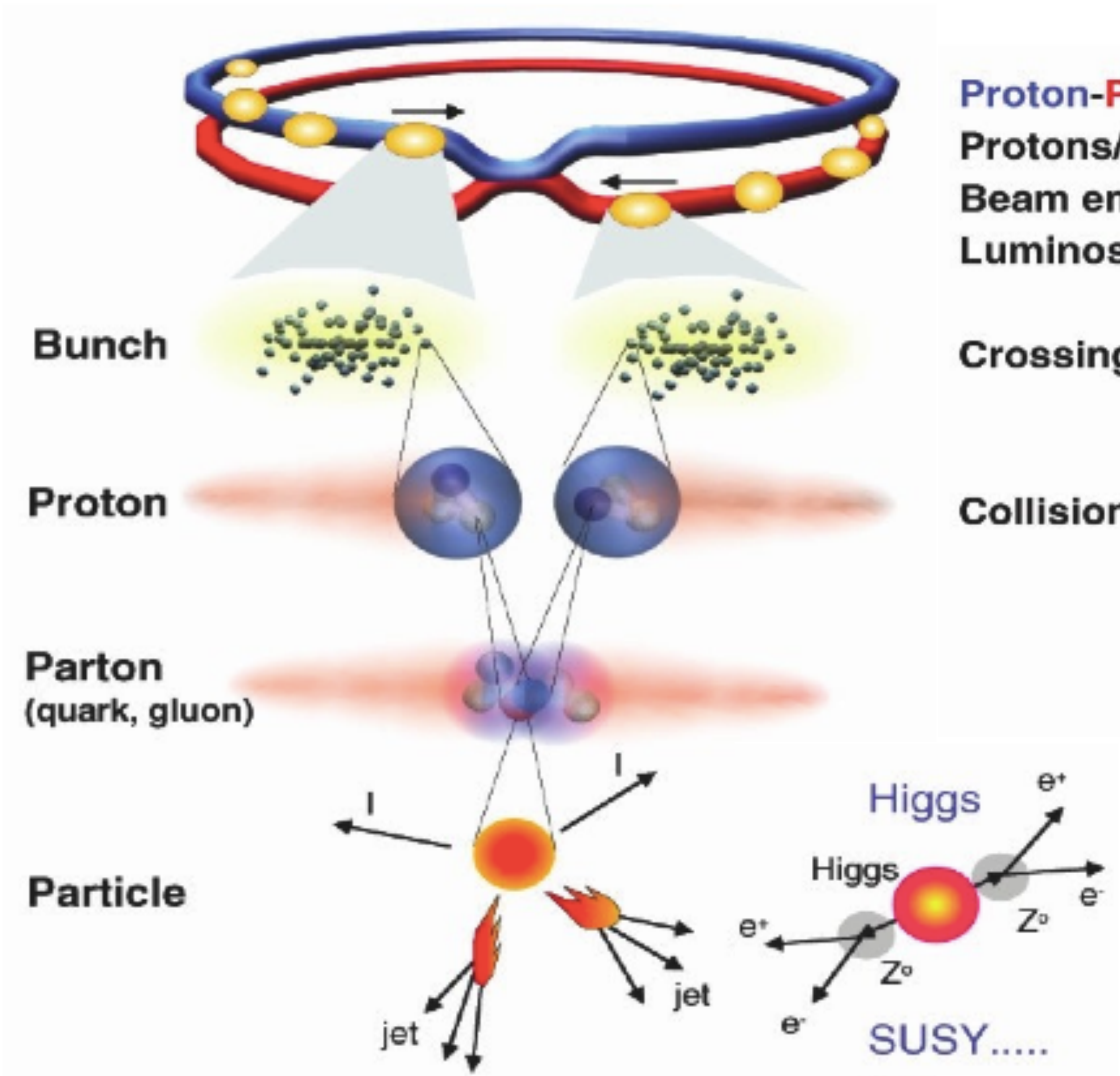
  event size: 1-2 Mbytes.

Beam crossings: LEP, Tevatron & LHC

- LHC ha ~3600 bunches
  - Stessa lunghezza di LEP (27 km)
  - Distanza fra bunches: 27km/3600=7.5m
  - Distanza tra bunches in tempo: 7.5m/c=25ns



Alcune caratteristiche di LHC



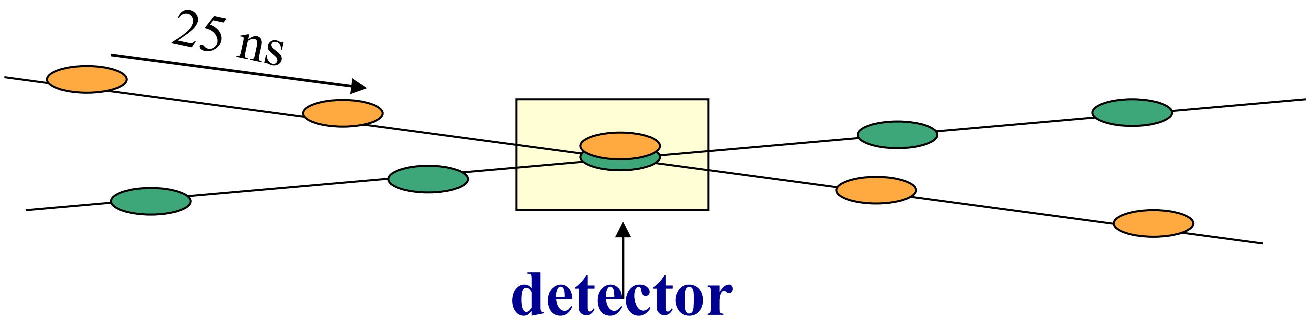
Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz — 20 MHz
Collisions ≈	10^7 - 10^9 Hz

25 nsec (design) between proton bunches

Multiple collisions per crossing

Problemi tipici di LHC

R = Ls = 10^9 interactions / second
Protons are grouped in bunches (of ≈ 10^{11} protons) colliding at interaction points every 25 ns



⇒ **At each interaction on average ≈25 minimum-bias events are produced. These overlap with interesting (high p_T) physics events, giving rise to so-called**

pile-up

~1000 charged particles produced over $|\eta| < 2.5$ at each crossing.
However $< p_T > \approx$ 500 MeV (particles from minimum-bias).
→ applying p_T cut allows extraction of interesting particles

Pile-up is one of the most serious experimental difficulty at LHC

Large impact on detector design:

- **LHC detectors must have fast response, otherwise integrate over many bunch crossings → too large pile-up**

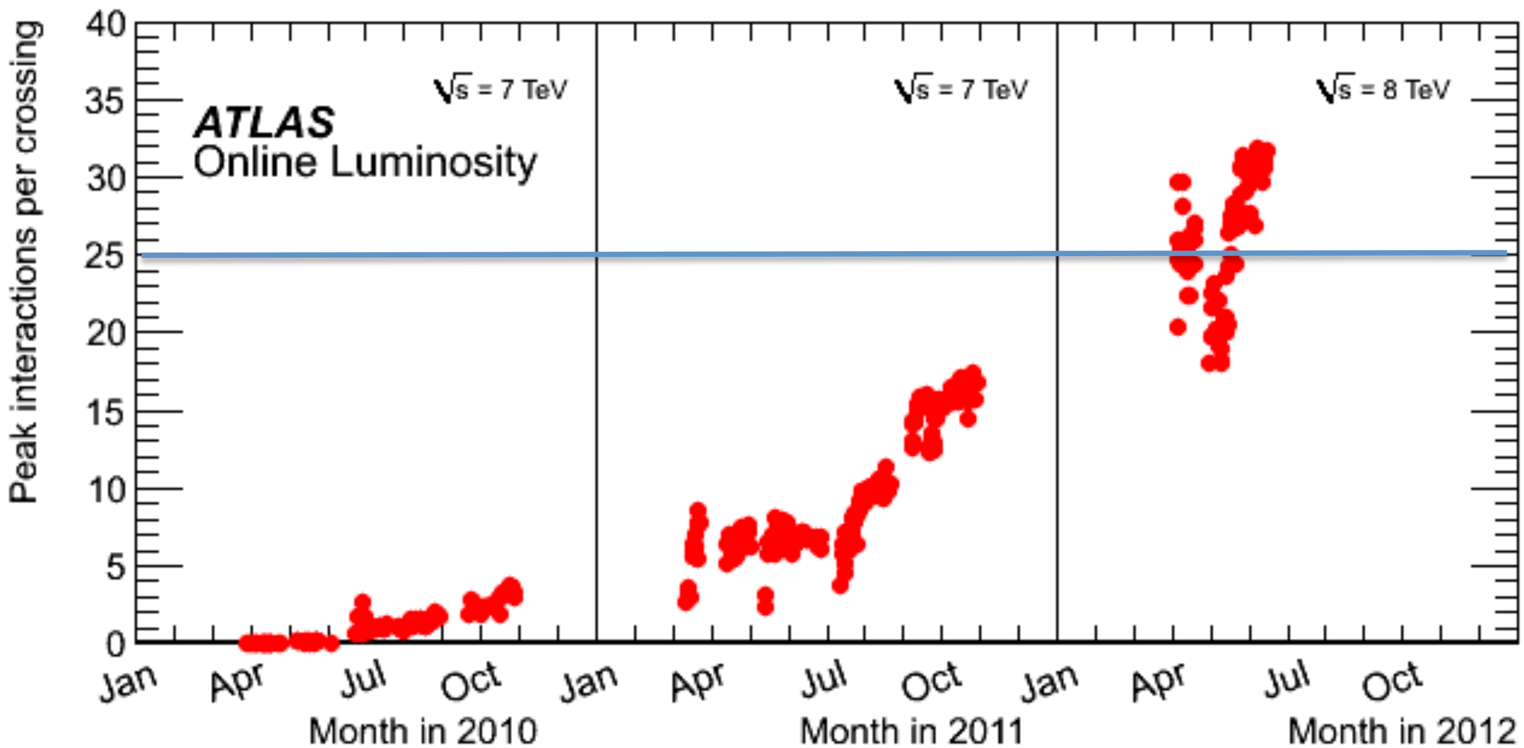
  Typical response time : 20-50 ns
  → integrate over 1-2 bunch crossings → pile-up of 25-50 minimum bias
  ⇒ very challenging readout electronics

- **LHC detectors must be highly granular to minimise probability that pile-up particles be in the same detector element as interesting object (e.g. γ from H → γγ decays)**
  → large number of electronic channels
  ⇒ high cost

- **LHC detectors must be radiation resistant: high flux of particles from pp collisions → high radiation environment**
  E.g. in forward calorimeters: up to 10^{17} n / cm^2 (up to 10^7 Gy) in 10 LHC Years

The BIG challenge in 2012: PILE-UP

25 is the design value
(expected to be reached at $L=10^{34}$! Already well passed !)



The BIG challenge in 2012: PILE-UP

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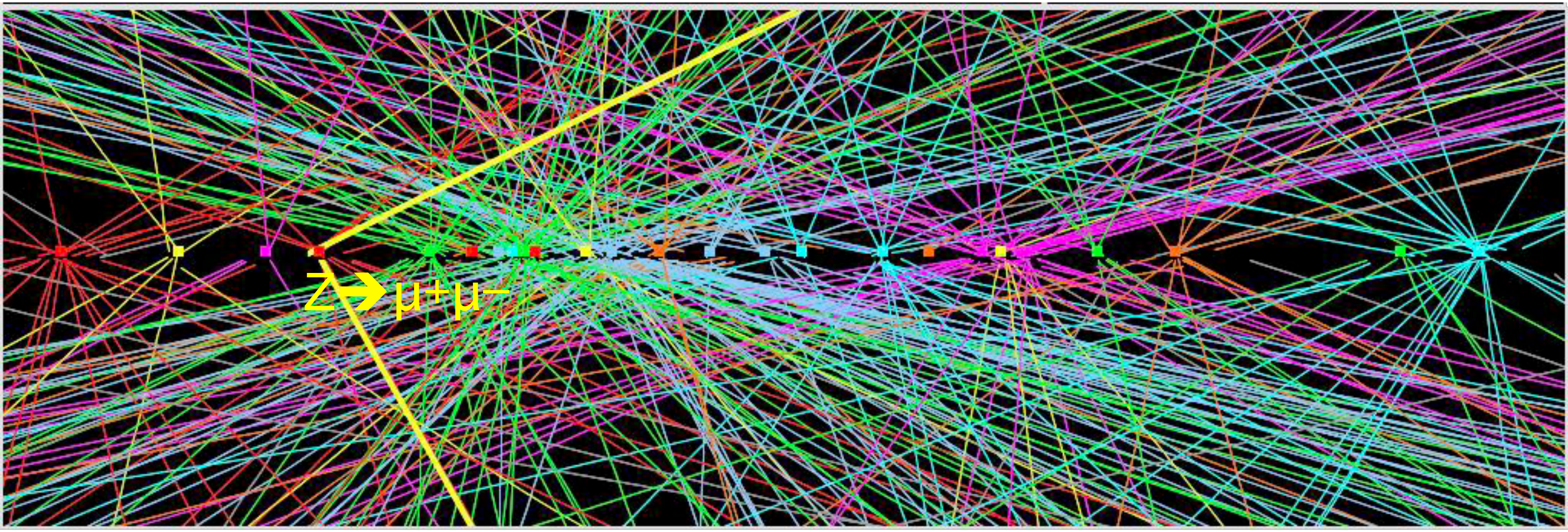
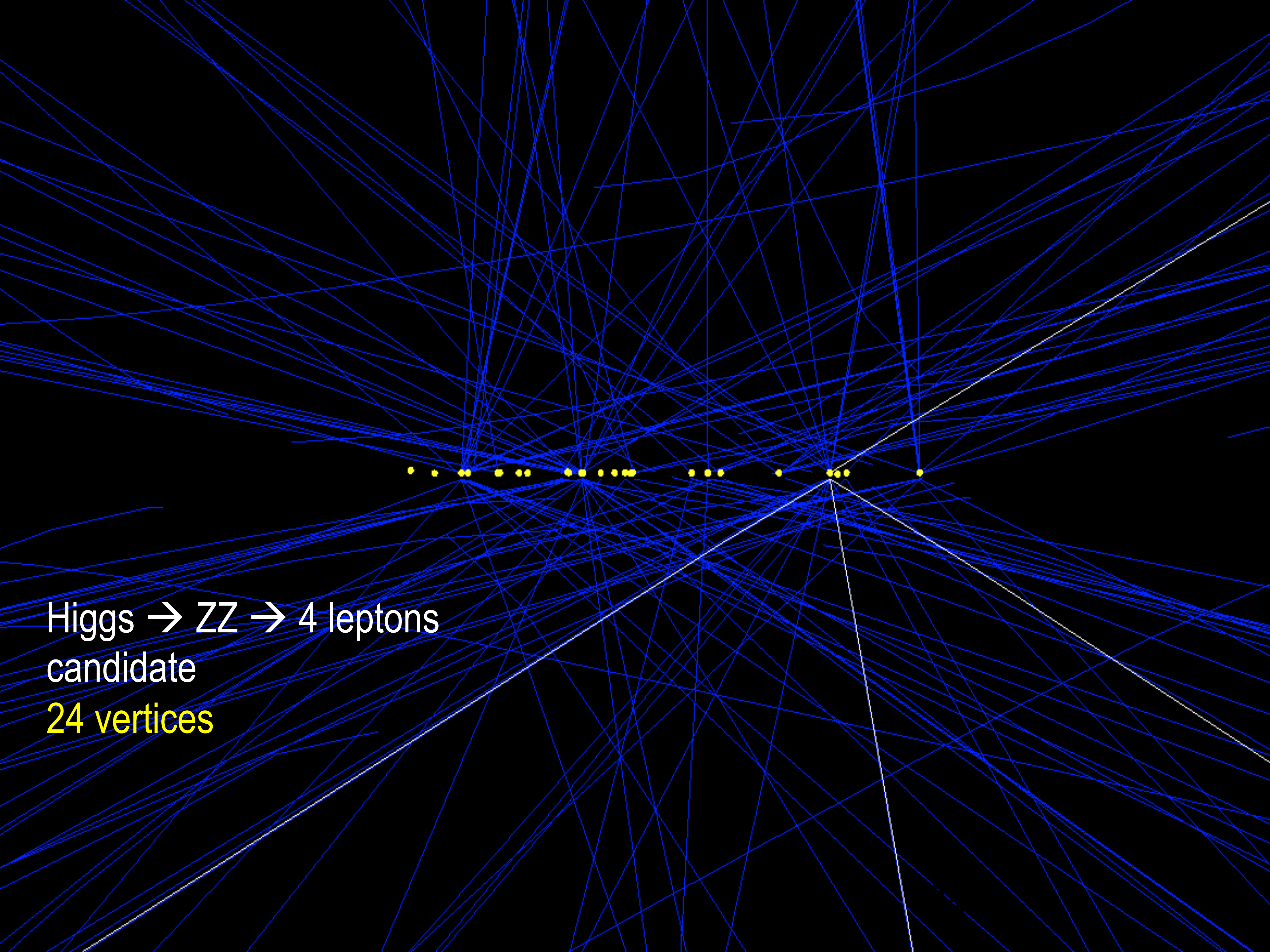
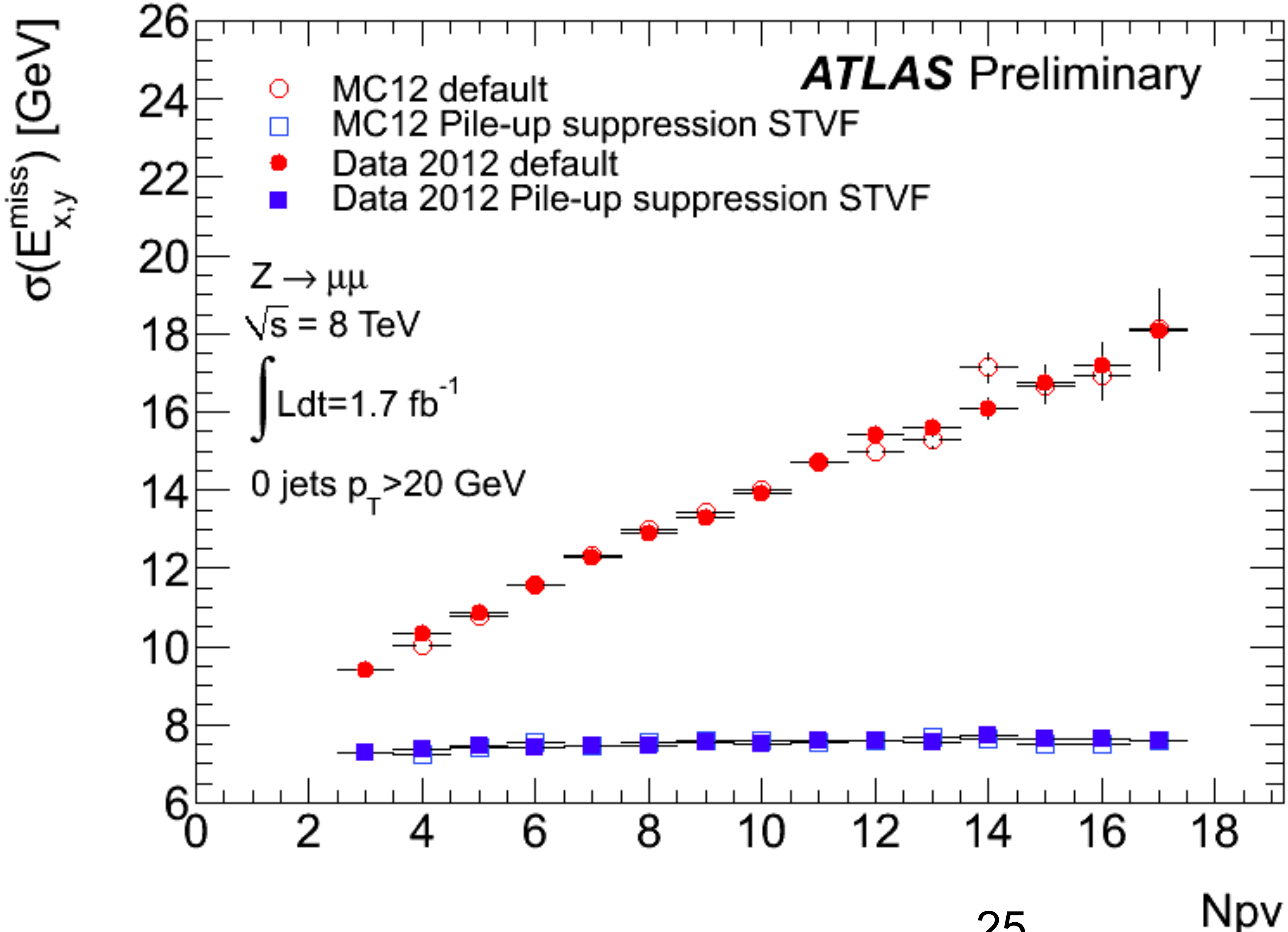


Z → $\mu^+\mu^-$ event from 2012 data
with 25 reconstructed vertices

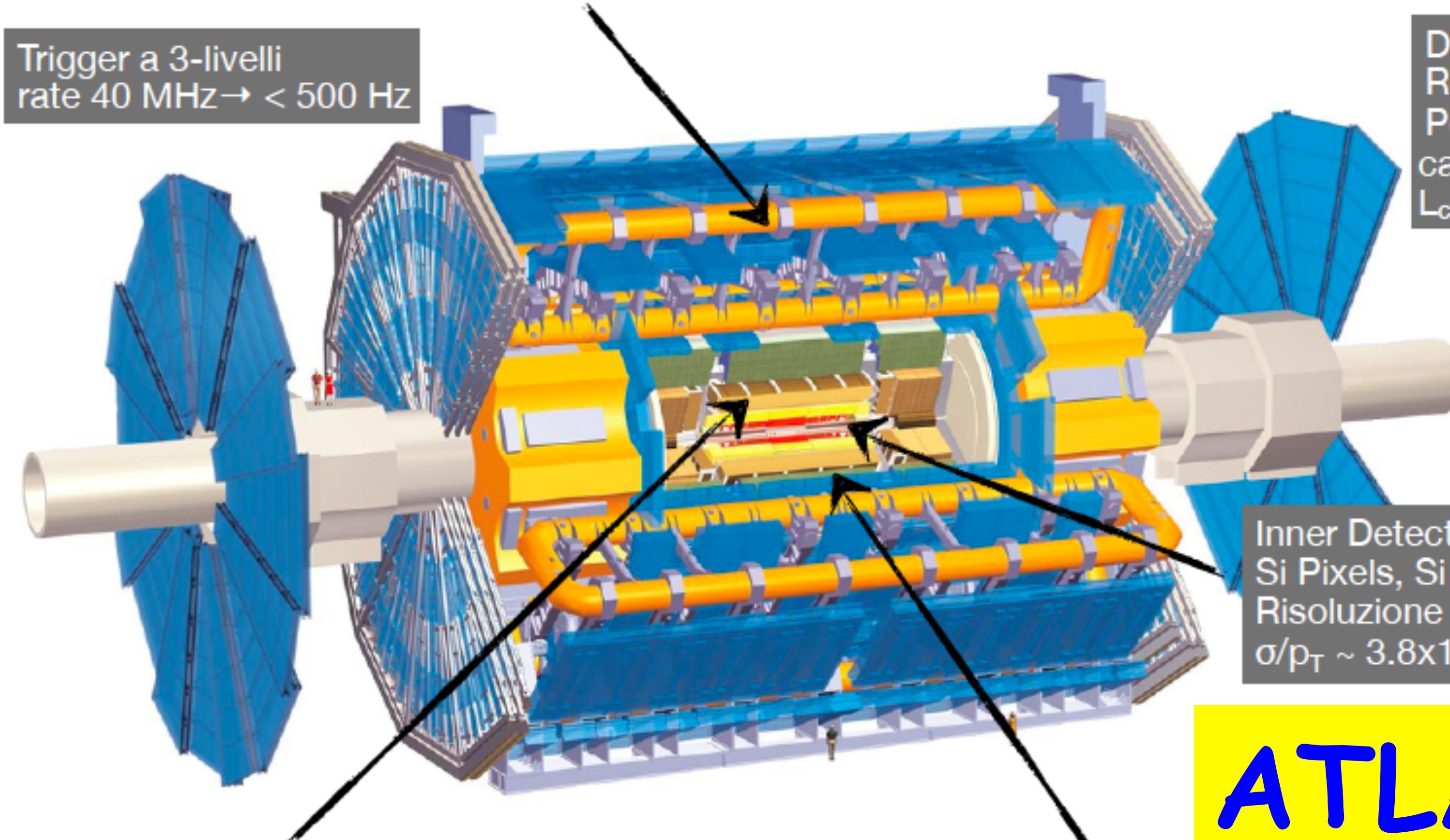

Higgs → ZZ → 4 leptons
candidate
24 vertices


ATLAS Preliminary
MC12 default
MC12 Pile-up suppression STVF
Data 2012 default
Data 2012 Pile-up suppression STVF
Z → μμ
√s = 8 TeV
∫Ldt=1.7 fb⁻¹
0 jets p_T>20 GeV
σ(E_{x,y}^{miss}) [GeV]
Npv

Spettrometro per muoni ($|\eta|<2.7$) : air-core toroids + gas-based muon chambers
Trigger muonico standalone e misura di impulso con risoluzione < 10% fino a $E_\mu \sim 1$ TeV

Trigger a 3-livelli
rate 40 MHz→ < 500 Hz

Dim. : LxR ~46x12 m^2
R : ~ 12 m
Peso : ~ 7000 tonn.
canali elettronica: ~10^8
L_{cavi} ~3000 km



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, TRT (straws)
Risoluzione in impulso:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

ATLAS

Calorimetro EM: Pb-LAr geometria a fisarmonica
e/γ trigger, ID
Risoluzione in energia: $\sigma/E \sim 10\%/\sqrt{E}$

Calorimetro Adronico ($|\eta|<5$): segmentato, ermetico
Fe/scintill. (central), Cu-LAr (fwd)
Trigger, ricostruzione Jets, missing E_T
Risoluzione in energia: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

- rivelatore general purpose
- design ottimizzato per le dure condizioni imposte da LHC

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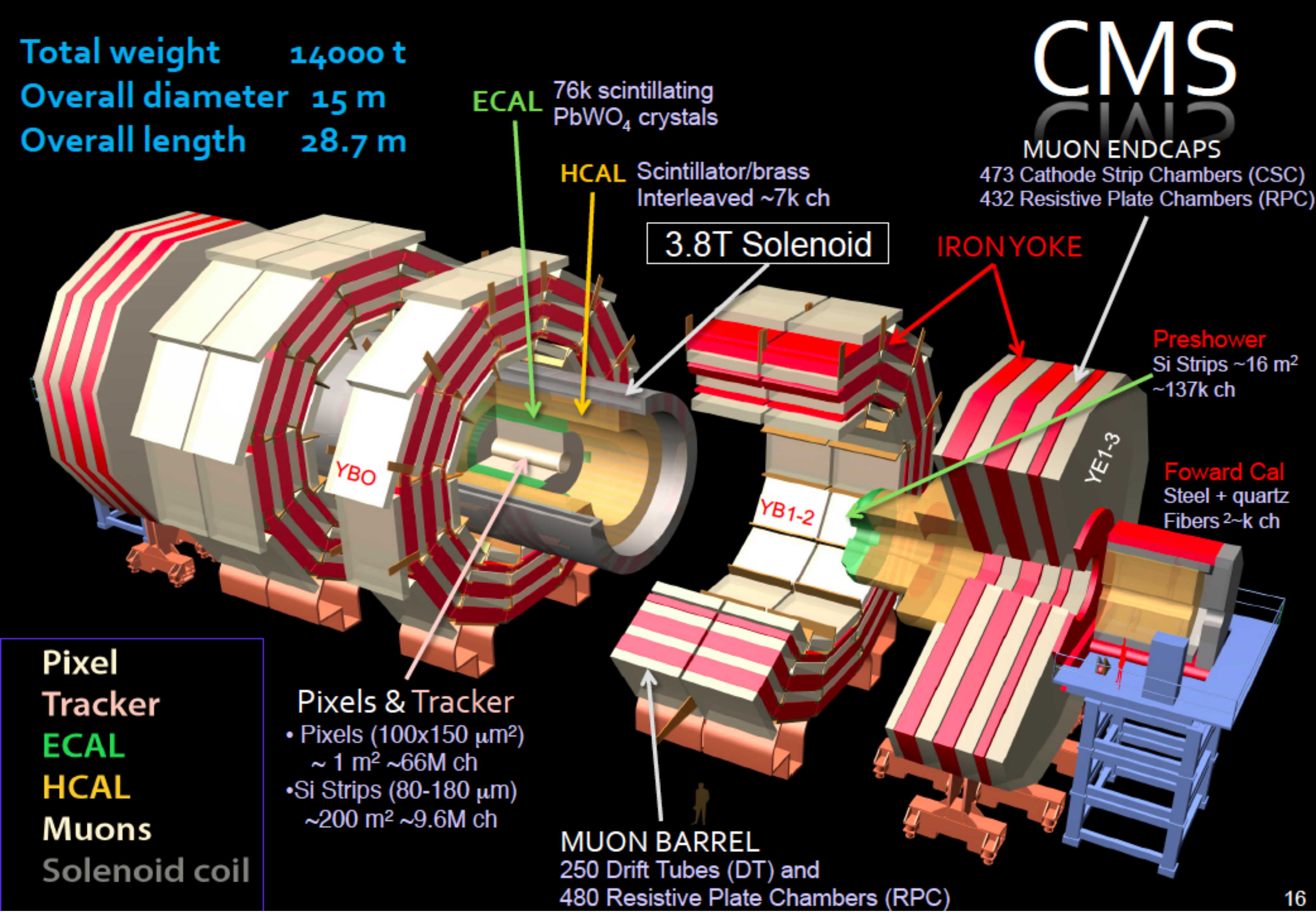

CMS
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
ECAL 76k scintillating $PbWO_4$ crystals
HCAL Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m^2
~137k ch
Foward Cal
Steel + quartz
Fibers 2~k ch
YE1-3
YB1-2
YBO
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)
16

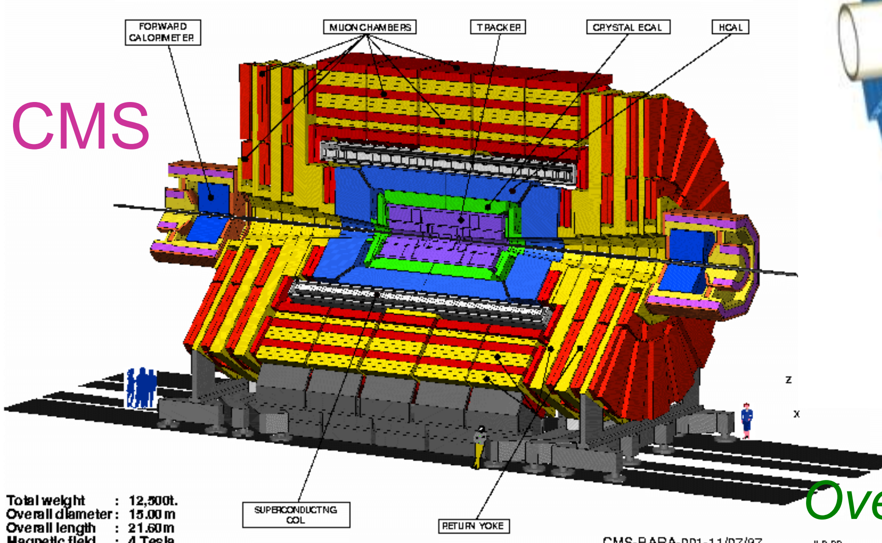
Quanto sono " HUGE " ATLAS e CMS ?

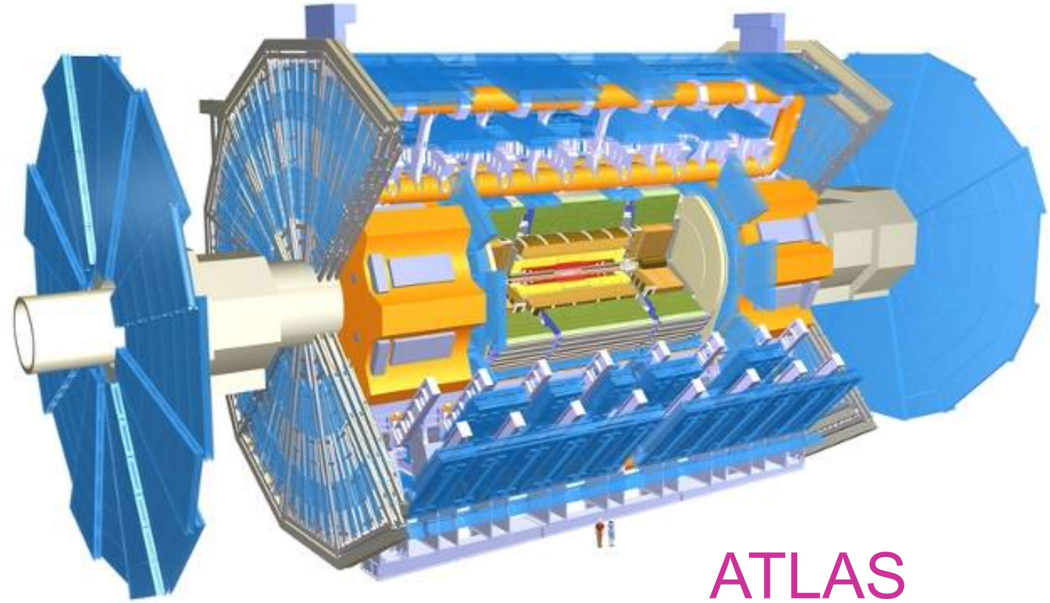
Dimensioni dei Rivelatori

- Volume: 20 000 m^3 per ATLAS
- Peso : 12 500 tons for CMS
- Da 66 fino a 80 million pixel readout channels vicino al vertice
- Superfice di 200 m^2 di Silicio attivo per il tracker di CMS
- 175 000 readout channels nel calorimetro elettromagnetico ad Argon liquido di ATLAS
- 1 million channels e 10 000 m^2di superfice delle camere a muoni
- Very selective trigger/DAQ system
- Large-scale offline software and worldwide computing (GRID)

How huge are ATLAS and CMS?

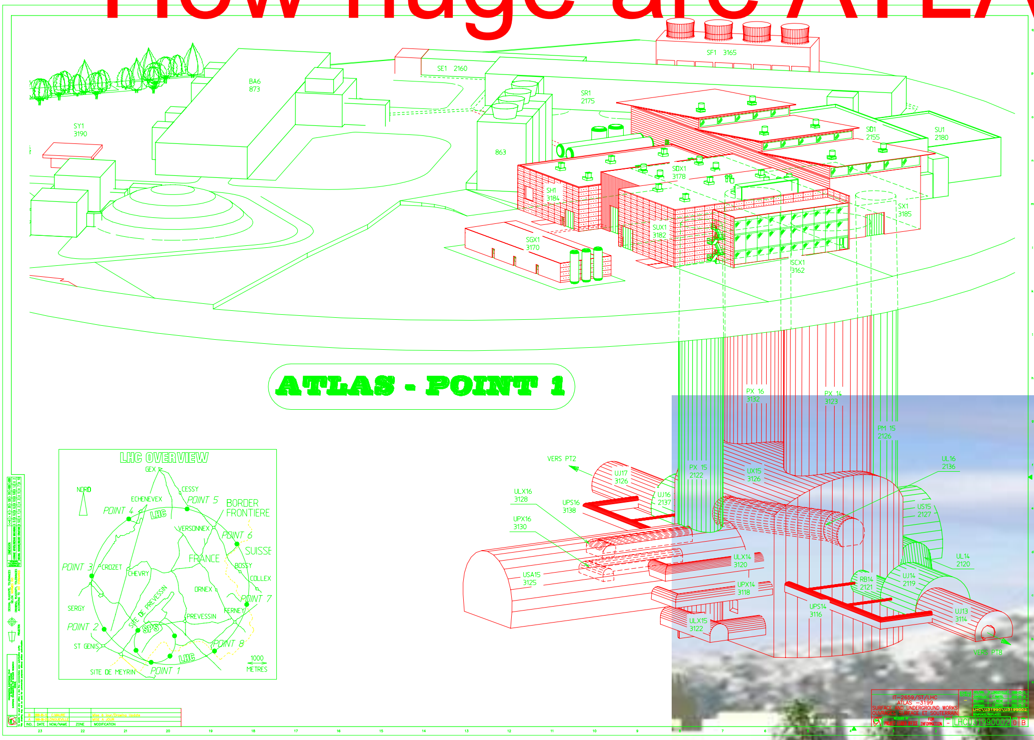
ATLAS superimposed to the 5 floors of building 40



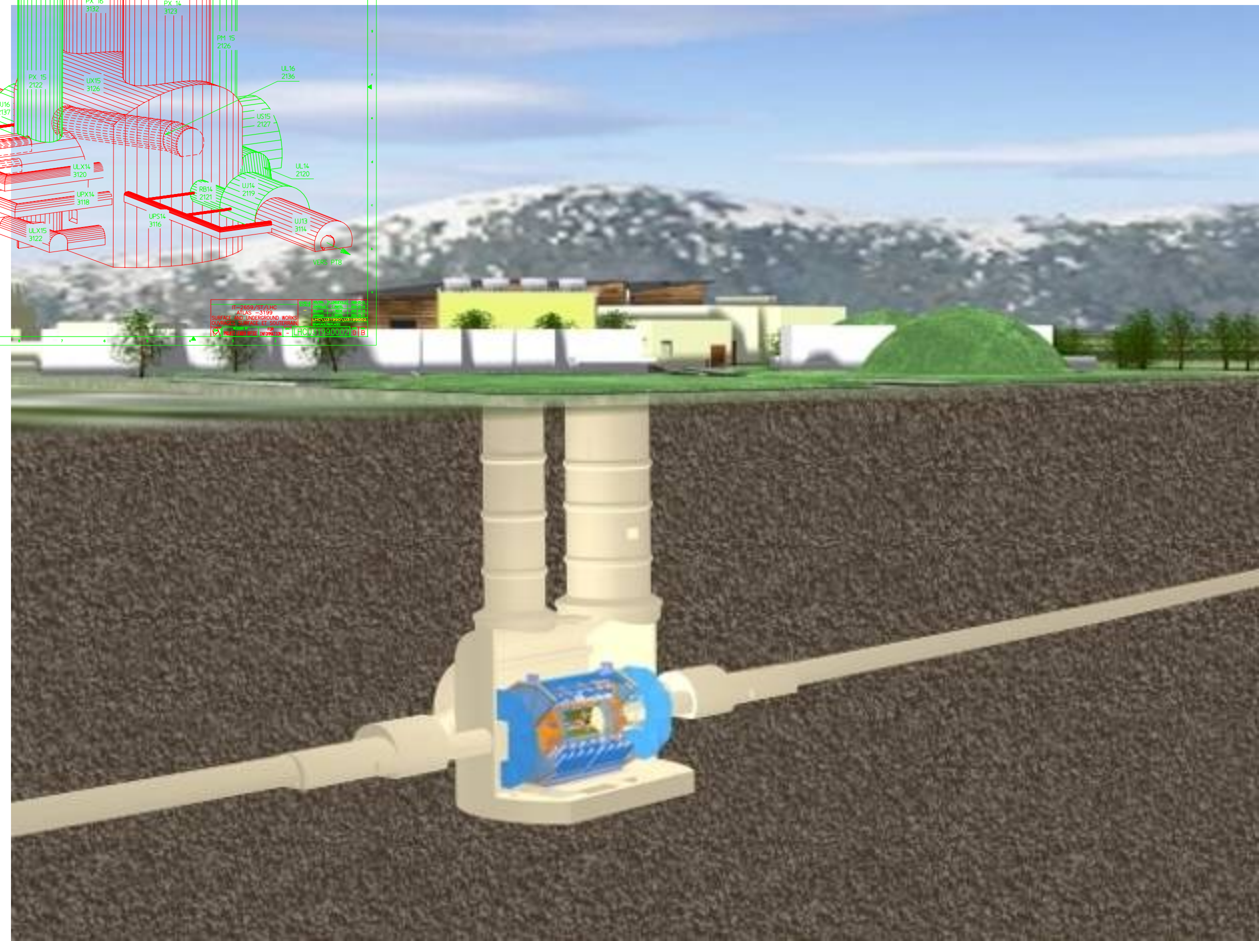


	ATLAS	*CMS*
Overall weight (tons)	*7000*	*12500*
Diameter	*22 m*	*15 m*
Length	*46 m*	*22 m*
Solenoid field	*2 T*	*4 T*

How huge are ATLAS and CMS?



The Underground Cavern at Pit-1 for the ATLAS Detector



Length = 55 m
Width = 32 m
Height = 35 m

How huge are ATLAS and CMS?

An Aerial View of Point-1

(Across the street from the CERN main entrance)

Generic features required of ATLAS and CMS

Detectors must survive for 10 years or so of operation

Radiation damage to materials and electronics components

Problem pervades whole experimental area (neutrons): NEW!

Detectors must provide precise timing and be as fast as feasible

25 ns is the time interval to consider: NEW!

Detectors must have excellent spatial granularity

Need to minimise pile-up effects: NEW!

Detectors must identify extremely rare events, mostly in real time

Lepton identification above huge QCD backgrounds (e.g. e/jet ratio at the LHC is ~ 10^{-5}, i.e. ~ 100 worse than at Tevatron)

Signal X-sections as low as 10^{-14} of total X-section: NEW!

Online rejection to be achieved is ~ 10^7: NEW!

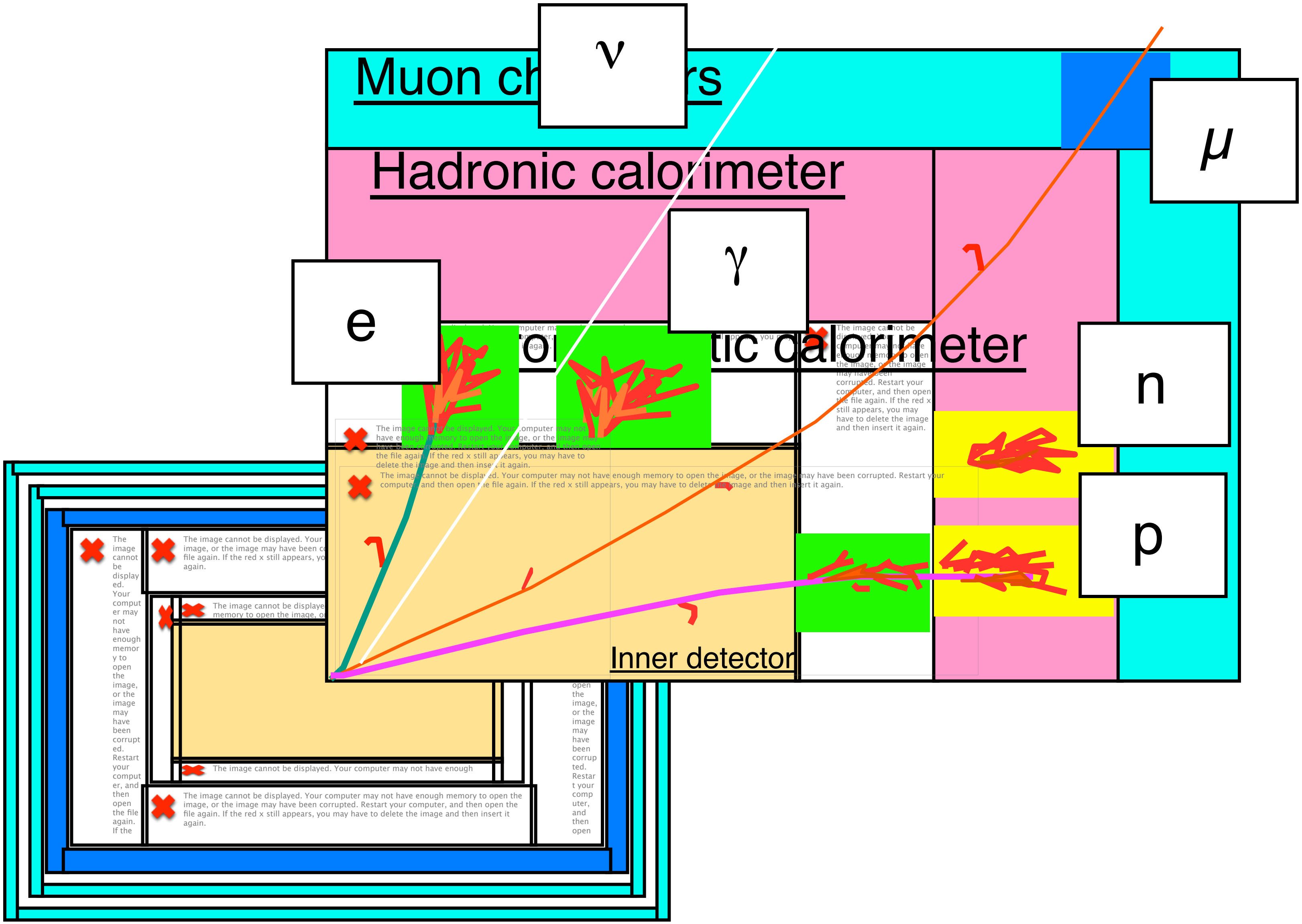
Store huge data volumes to disk/tape (~ 10^9 events of 1 Mbyte size per year: NEW!

Generic features required of ATLAS and CMS

Detectors must measure and identify according to certain specs

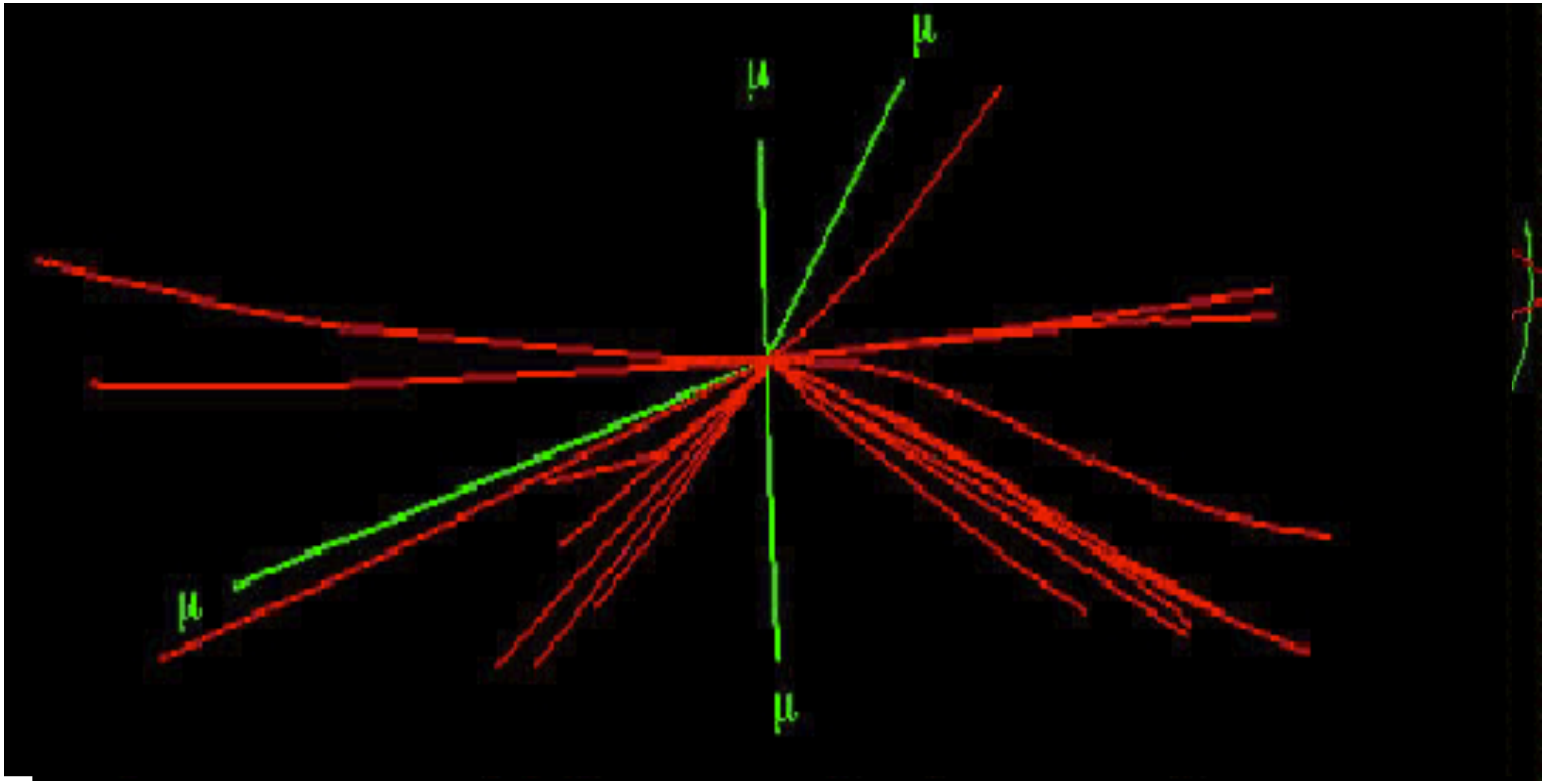
- Tracking and vertexing: ttH with $H \to bb$
- Electromagnetic calorimetry: $H \to \gamma\gamma$ and $H \to ZZ \to eeee$
- Muon spectrometer: $H \to ZZ \to \mu\mu\mu\mu$
- Missing transverse energy: supersymmetry

Higgs at the LHC: the challenge



Higgs at the LHC: the challenge

How to extract this… … from this …



Higgs ⟶ 4μ +30 min. bias events

Without knowing really where to look for!

Higgs at the LHC: the challenge

Small x-sections

need highest luminosity

⇒ $L = 10^{34-35}\ cm^{-2}s^{-1}$

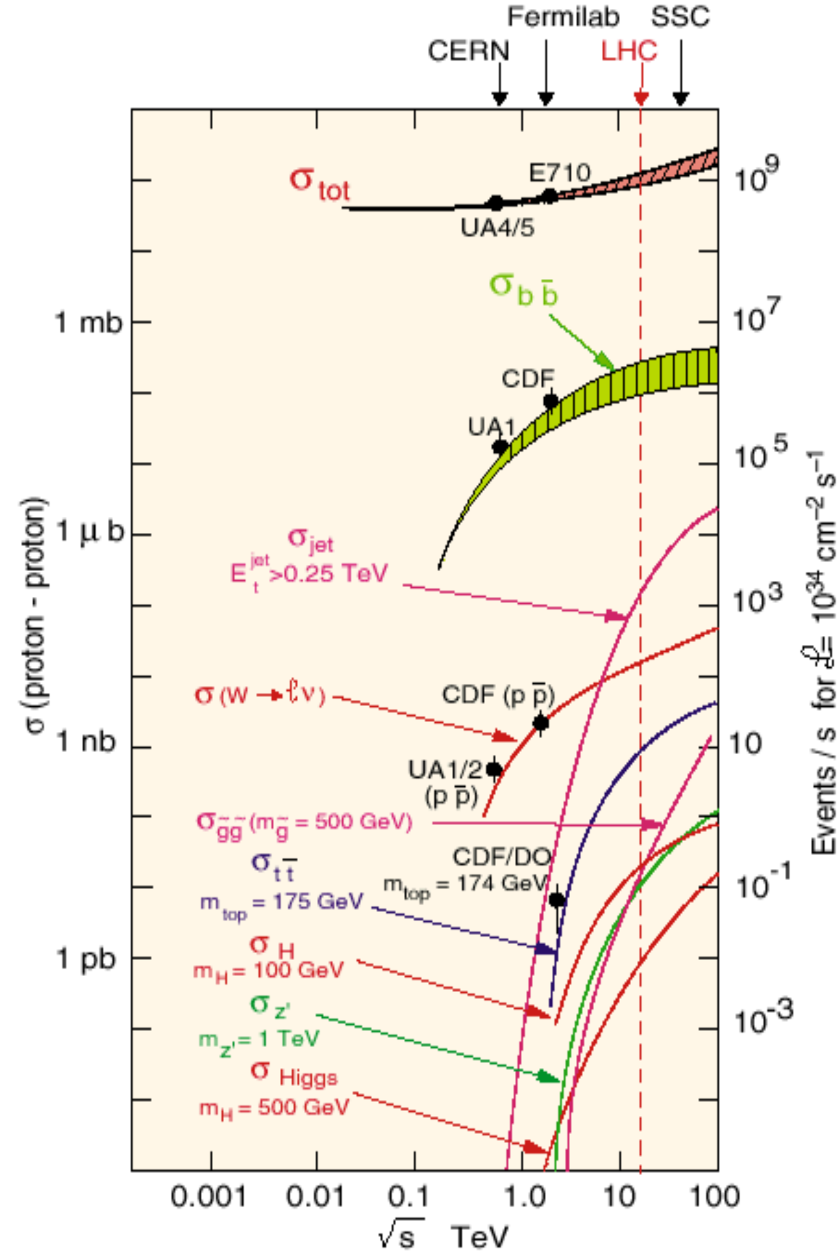
Orders of magnitude of event rates for various physics channels:

- Inelastic : 10^{10} Hz
- W -> lν : 10^{3} Hz
- tt production : 10^{2} Hz
- Higgs (m=100 GeV) : 1 Hz
- Higgs (m=600 GeV) : 10^{-1} Hz

(and include branching ratios: ~ 10^{-2})

Selection power for Higgs discovery ≈ 10^{14-15}

i.e. 100 000 times better than achieved at Tevatron so far for high-p_T leptons!



La Scoperta dell'Higgs a LHC

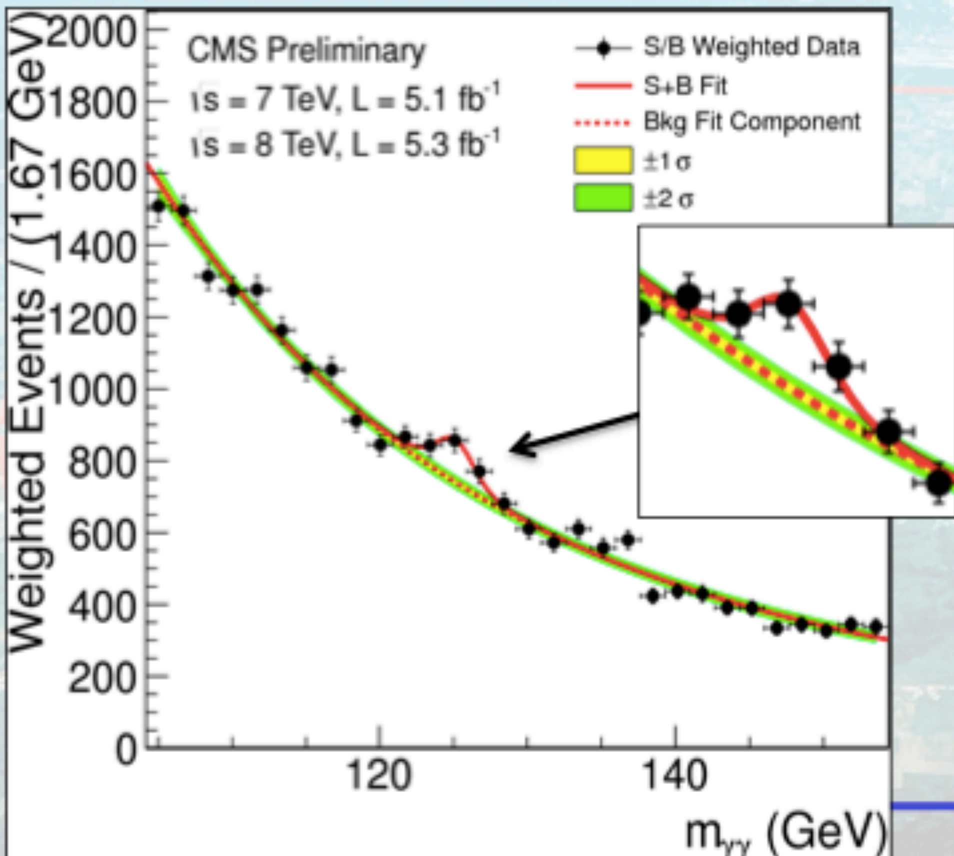
July 4, 2012

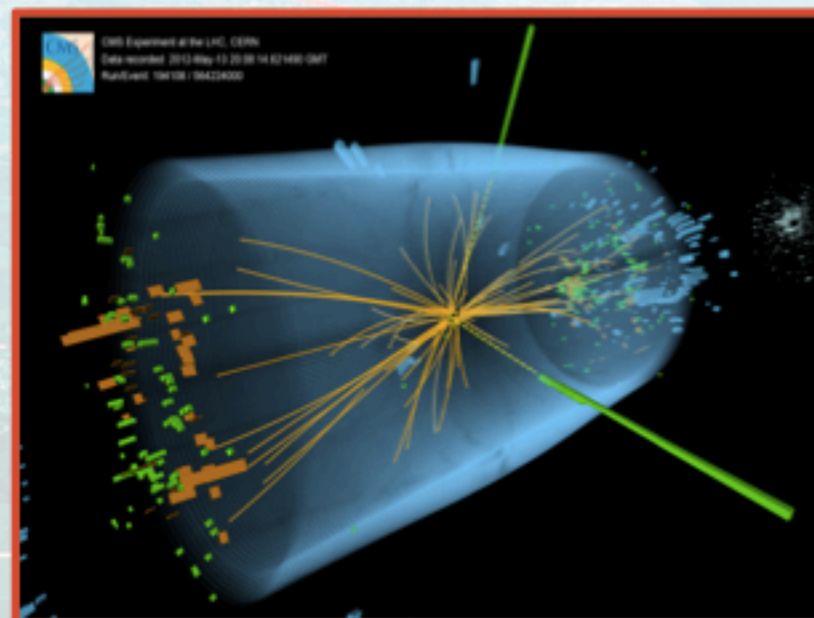
Si e' tenuto un seminario congiunto al CERN e alla Conferenza Internazionale sulla Fisica delle Alte Energie a Melbourne, Australia

- 500,000 spettatori hanno guardato l'evento in webcast
- Piu' di un miliardo nei canali TV
- Alcuni perfino dall' antartide

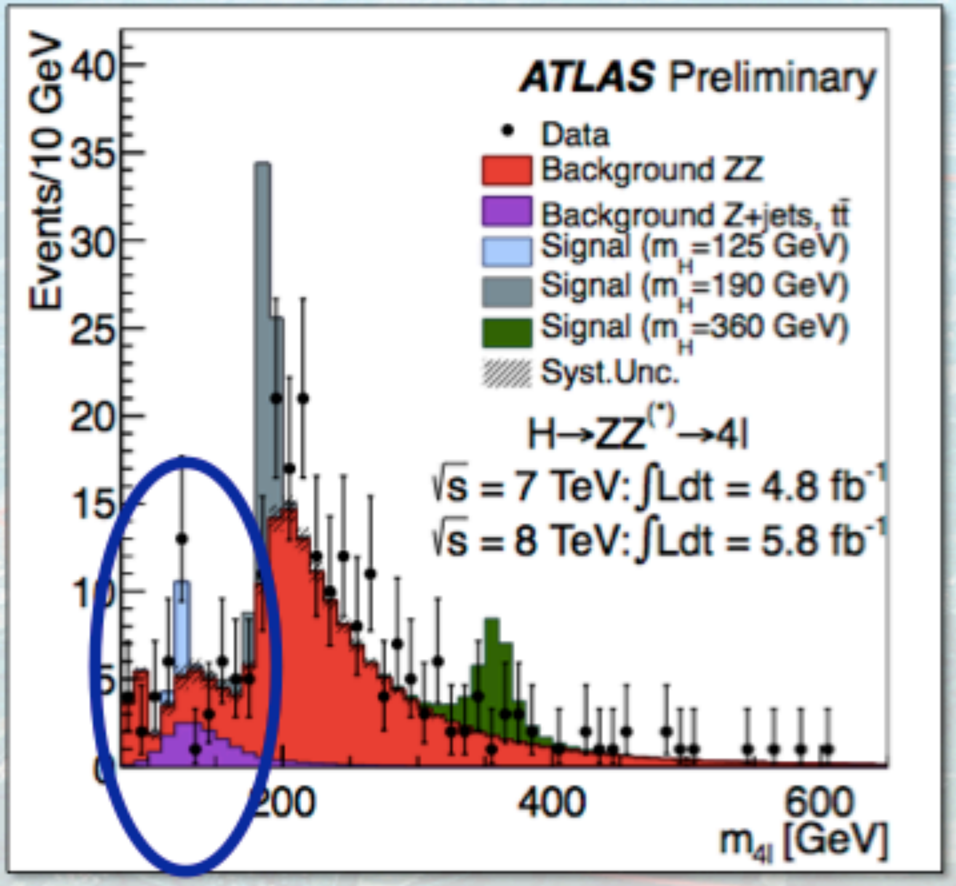
July 4, 2012

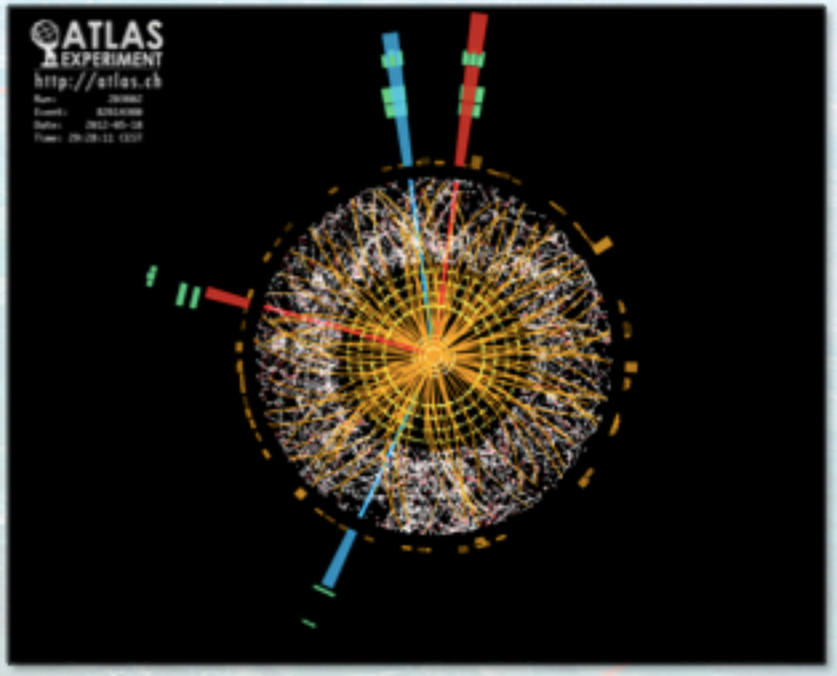
I due esperimenti ATLAS e CMS hanno presentato risultati preliminari sulla ricerca del Bosone di Higgs dai dati accumulati nel 2911 e nel 2012



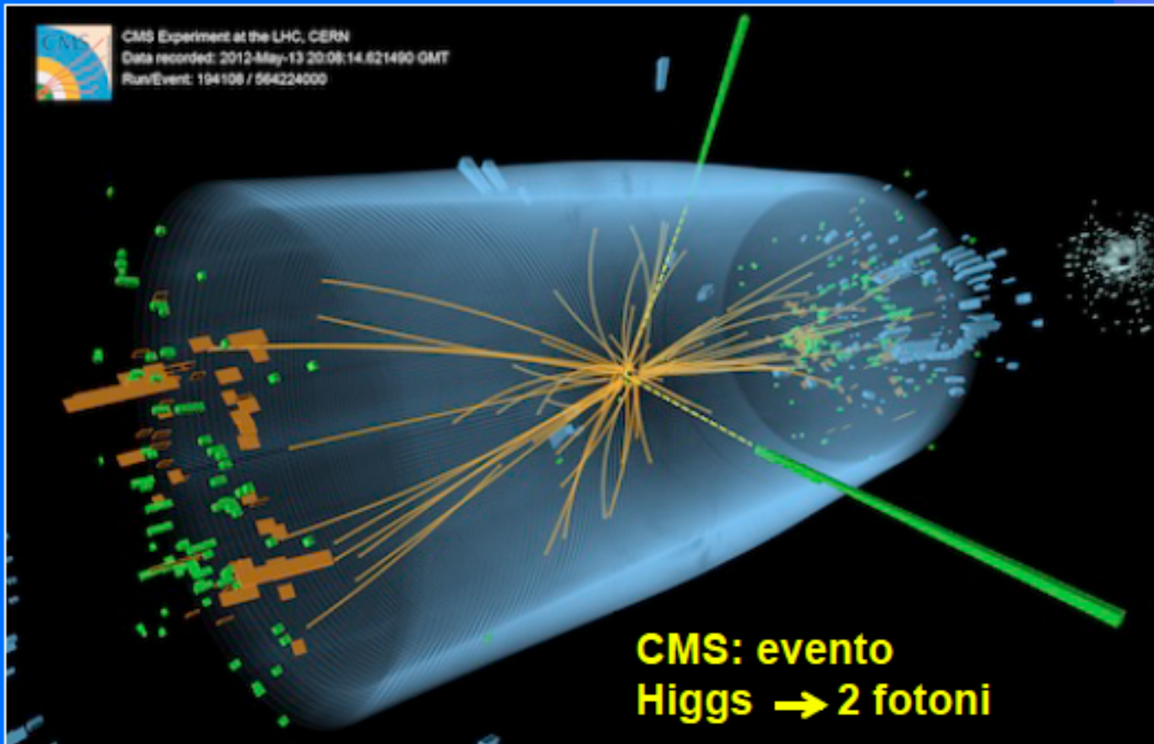


CERN 4 luglio 2012:
Entrambi gli esperimenti presentano un significativo eccesso di eventi a circa 125 GeV nel plot di massa in diversi canali di decadimento



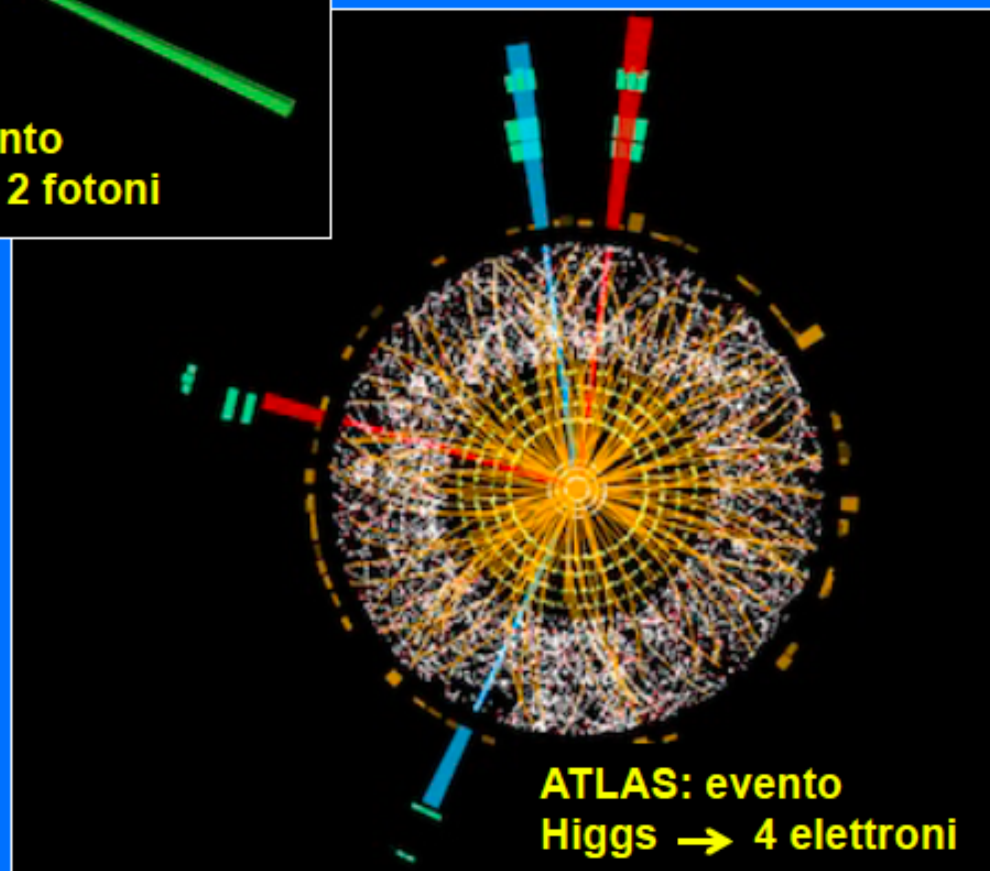


2 eventi che hanno fatto il giro del mondo



Massa di H = 125 GeV

200-300 eventi osservati su un milione di miliardi di collisione protone-protone



July 4, 2012

Questa notizia ha reso felice tutto il mondo !

ATLAS EXPERIMENT

La scoperta annunciata,

Perche' ?

Perche' abbiamo cercato il bosone di Higgs senza successo dal 1989, prima a LEP e poi, al Tevatron di Chicago.

Perche' ci sono voluti piu' di 20 anni per realizzare la costruzione di LHC e degli esperimenti ATLAS e CMS

Perche' la scoperta del 4 luglio apre un nuovo mondo alla fisica delle Particelle:

" Negli anni che verranno vedremo una chiara discontinuita' nella fisica delle particelle: PRIMA e DOPO la presentazione del 4 luglio 2012 ! "

The god(damn) particle

Bibliografia

- A. Bettini: Introduction to Elementary particle physics cap 9 pag 304 - 313
- Burcham and Jobes: Nuclear and Particle Physics cap 13 pag 507 – 524
- Ugo Amaldi: Sempre piu' veloci
- Luciano Maiani: A caccia del Bosone di Higgs
- Phys. Lett. B 716 (2012) 1-29