

La competizione per la scoperta dei bosoni W-Z e i risultati fallimentari sul quark Top nei primi anni '80

# Come cambia il modo di scoprire nuove particelle


- Fino agli anni '50 del secolo scorso si poteva ricostruire la massa di una nuova particella carica sia studiando la sua traccia in un campo magnetico che, in alternativa, studiando le particelle in cui decadeva
- A partire dagli anni '60 le nuove particelle sempre più spesso vivevano un tempo troppo breve per poterne osservare la traccia. Ci si doveva concentrare sullo studio delle tracce delle particelle figlie:
  - 1961 scoperta dei mesoni  $\rho^+$ ,  $\rho^-$ ,  $\rho^0$ , vita media  $4.4 \cdot 10^{-24}$  s
  - 1961 scoperta del mesone  $\omega^0$ , vita media  $7.6 \cdot 10^{-23}$  s
- In tempi così brevi era anche impossibile che le particelle arrivassero a fermarsi prima di decadere. Per questo motivo  $\rho$  e  $\omega^0$  furono le prime particelle per le quali si usò il metodo della **Massa Invariante**

**...Ma cosa è la massa invariante?**

**Occorre un minimo di Relatività Speciale  
per poterlo capire...**

# Molte differenze tra relatività galileiana e speciale

## Summary Table

Feature 	Galilean Relativity	Special Relativity
Distance ( $\mathbf{x}_2 - \mathbf{x}_1$ )	Invariant (Same for all)	Relative (Depends on velocity)
Time ( $\Delta t$ )	Absolute (Universal)	Relative (Time Dilation)
Transformations	Galilean ( $x' = x - vt$ )	Lorentz ( $x' = \gamma(x - vt)$ )
Speed of Light	Adds to velocity ( $c + v$ )	Constant ( $c$ )

# 4-vector notation

## Lorentz Transformations

$$\begin{pmatrix} t' \\ x' \\ y' \\ z' \end{pmatrix} = \begin{bmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} t \\ x \\ y \\ z \end{pmatrix}$$



$$\begin{aligned} \mathbf{x}' &= \Lambda \mathbf{x} \\ \text{or} \\ (\mathbf{x}')^\mu &= \sum_{\nu=0}^3 \Lambda_{\nu}^{\mu} \mathbf{x}^{\nu} \\ \text{or} \\ (\mathbf{x}')^\mu &= \Lambda_{\nu}^{\mu} \mathbf{x}^{\nu} \end{aligned}$$

4-vector: "An object that transforms like  $x^\mu$  between inertial frames"

E.g. **momentum** :  $\mathbf{p} \equiv (p^0, p^1, p^2, p^3) \equiv (E, p_x, p_y, p_z)$

Invariant: "quantities unchanged in all inertial frames"

E.g.:

4-vector scalar product:

$$\mathbf{a} \cdot \mathbf{b} \equiv a^0 b^0 - a^1 b^1 - a^2 b^2 - a^3 b^3 = a^0 b^0 - \vec{\mathbf{a}} \cdot \vec{\mathbf{b}}$$

4-vector length:


$$p^2 = p^0 p^0 - p^1 p^1 - p^2 p^2 - p^3 p^3 = E^2 - |\vec{\mathbf{p}}|^2 = m^2$$

# La massa invariante di un sistema di n particelle

La formula è derivata dalla norma del quadrimpulso totale del sistema: 

$$M_{inv} = \frac{1}{c^2} \sqrt{\left(\sum_{i=1}^n E_i\right)^2 - \left|\sum_{i=1}^n \vec{p}_i\right|^2 c^2}$$

Dove:

- $E_i$ : Energia totale della  $i$ -esima particella ( $E_i = \gamma_i m_i c^2 = \sqrt{p_i^2 c^2 + m_i^2 c^4}$ ) in Joule [J].
- $\vec{p}_i$ : Vettore quantità di moto della  $i$ -esima particella in [kg · m/s].
- $c$ : Velocità della luce nel vuoto ( $\approx 3 \times 10^8$  m/s).
- $M_{inv}$ : Massa invariante del sistema in Kilogrammi [kg]. 

### CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

SILICON TRACKERS  
Pixel (100x150  $\mu\text{m}$ )  $\sim 16\text{m}^2 \sim 66\text{M}$  channels  
Microstrips (80x180  $\mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

SUPERCONDUCTING SOLENOID  
Niobium-titanium coil carrying  $\sim 18,000\text{A}$

MUON CHAMBERS  
Barrel: 250 Drift Tube, 480 Res  
Endcaps: 468 Cathode Strip, 43

PRESHOWER  
Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

FORWARD CALORIMETER  
Steel + Quartz fibres  $\sim 2,000$  Channels

CRYSTAL  
ELECTROMAGNETIC  
CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillator  $\sim 7,000$  channels

New readout for Muon system  
+ new stations  $1.6 < \eta < 2.4$

ECAL Barrel readout  
 $\rightarrow$  full granularity @ 40MHz

New detector  
MIP timing  
 $\sigma_t \sim 30\text{ps}$

New detector  
End-cap Calorimeter  
4D showers,  $\sigma_t \sim 20\text{ps}$

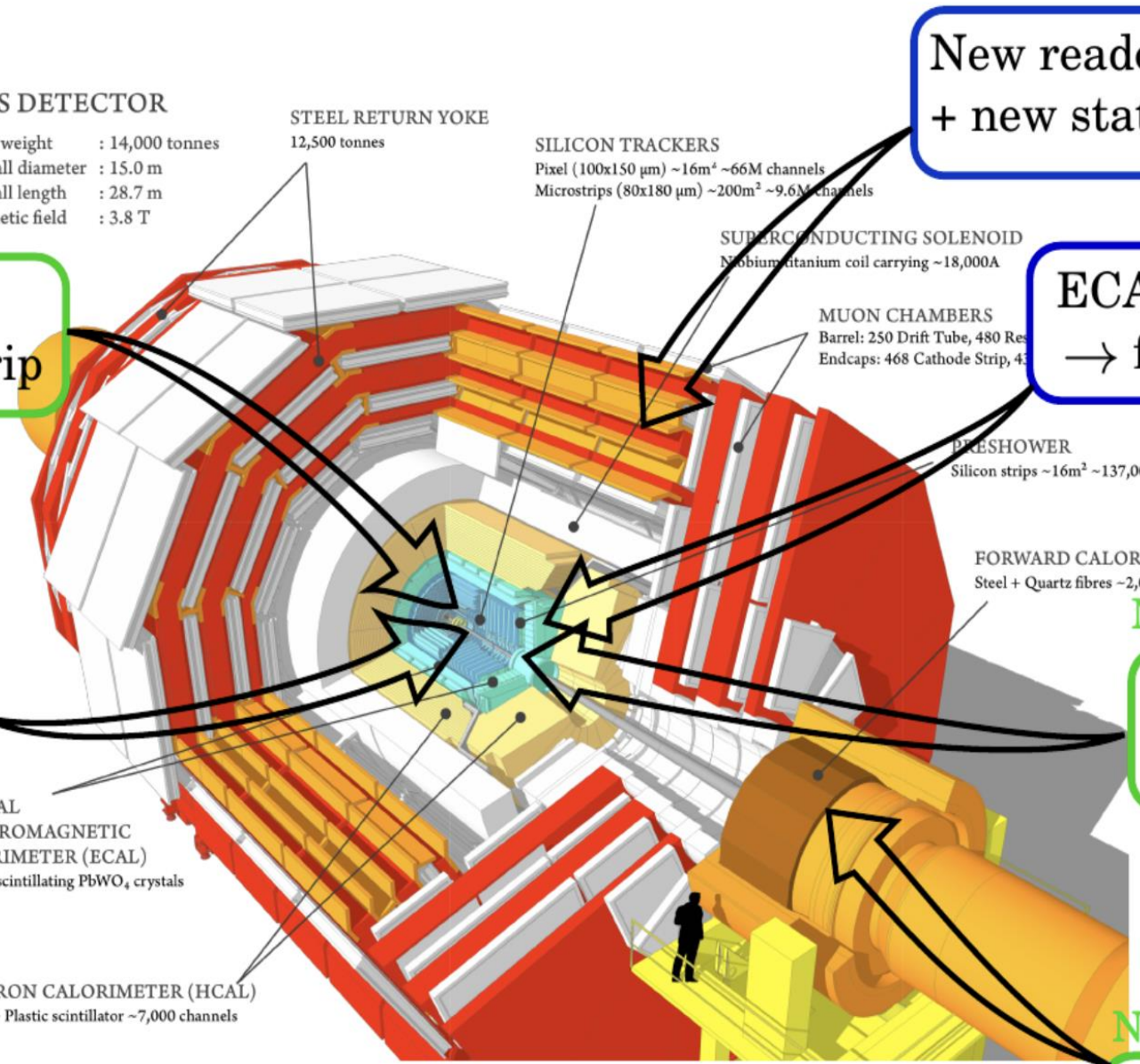
+ TDAQ modification to cope with modified detector  
and higher lumi (including tracking in hardware)

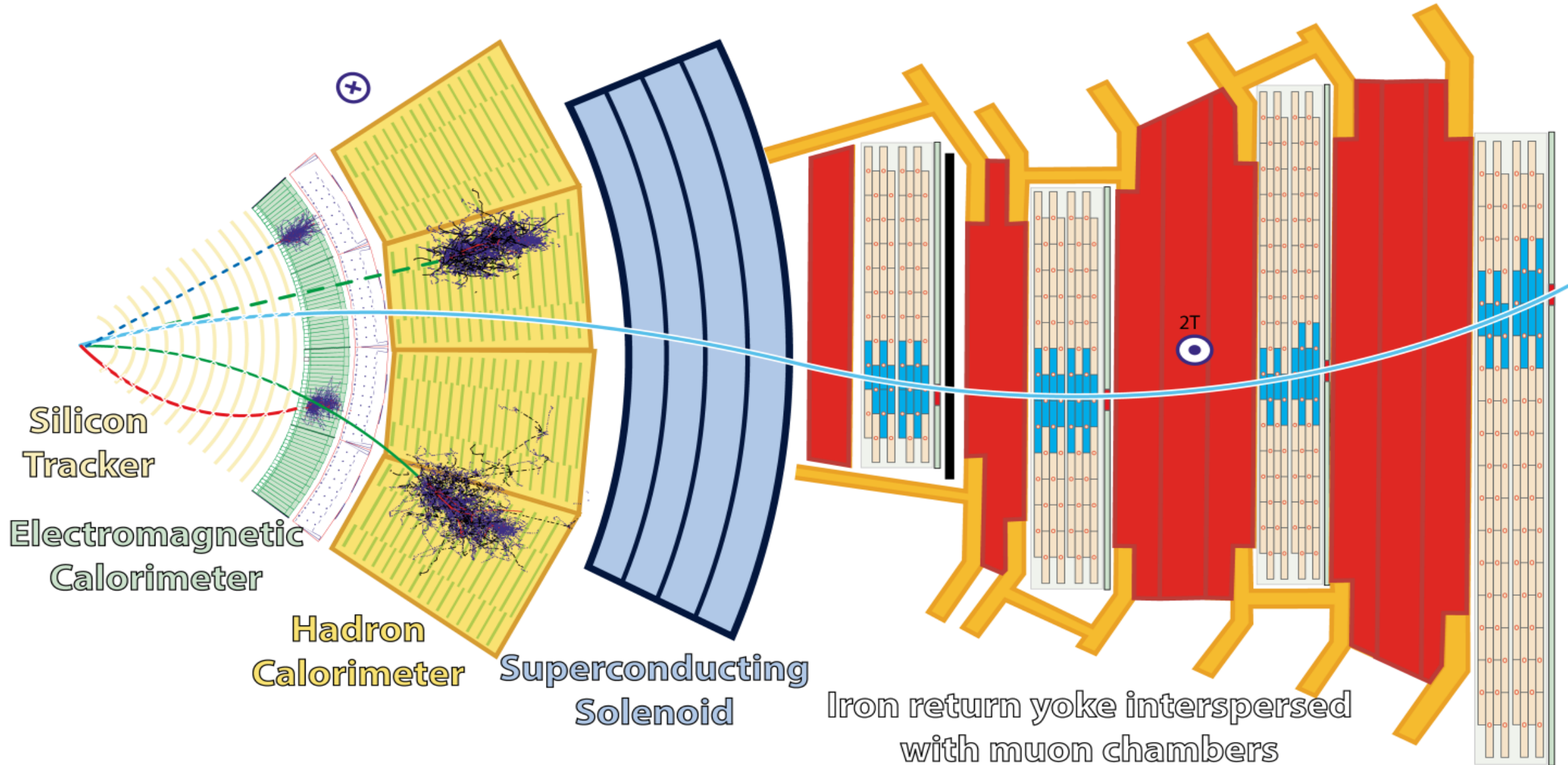
New detector

Outer tracker  
Si macro-pixel + strip

New detector

Inner tracker  
Si Pixel





— Muon

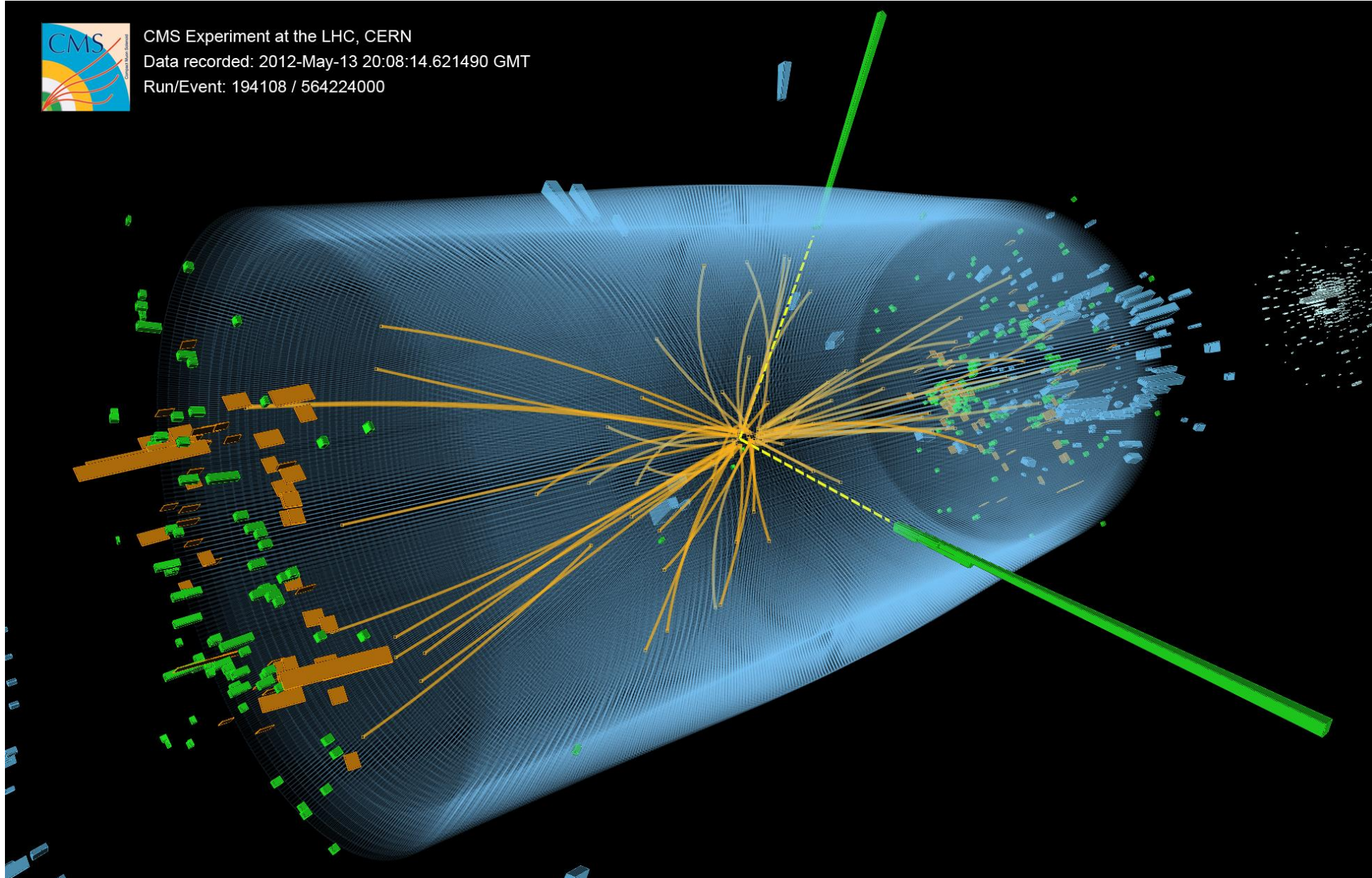
— Electron

— Charged hadron (e.g. pion)

- - - Neutral hadron (e.g. neutron)

- - - Photon

# Decadimento in $2 \gamma$ di un bosone di Higgs



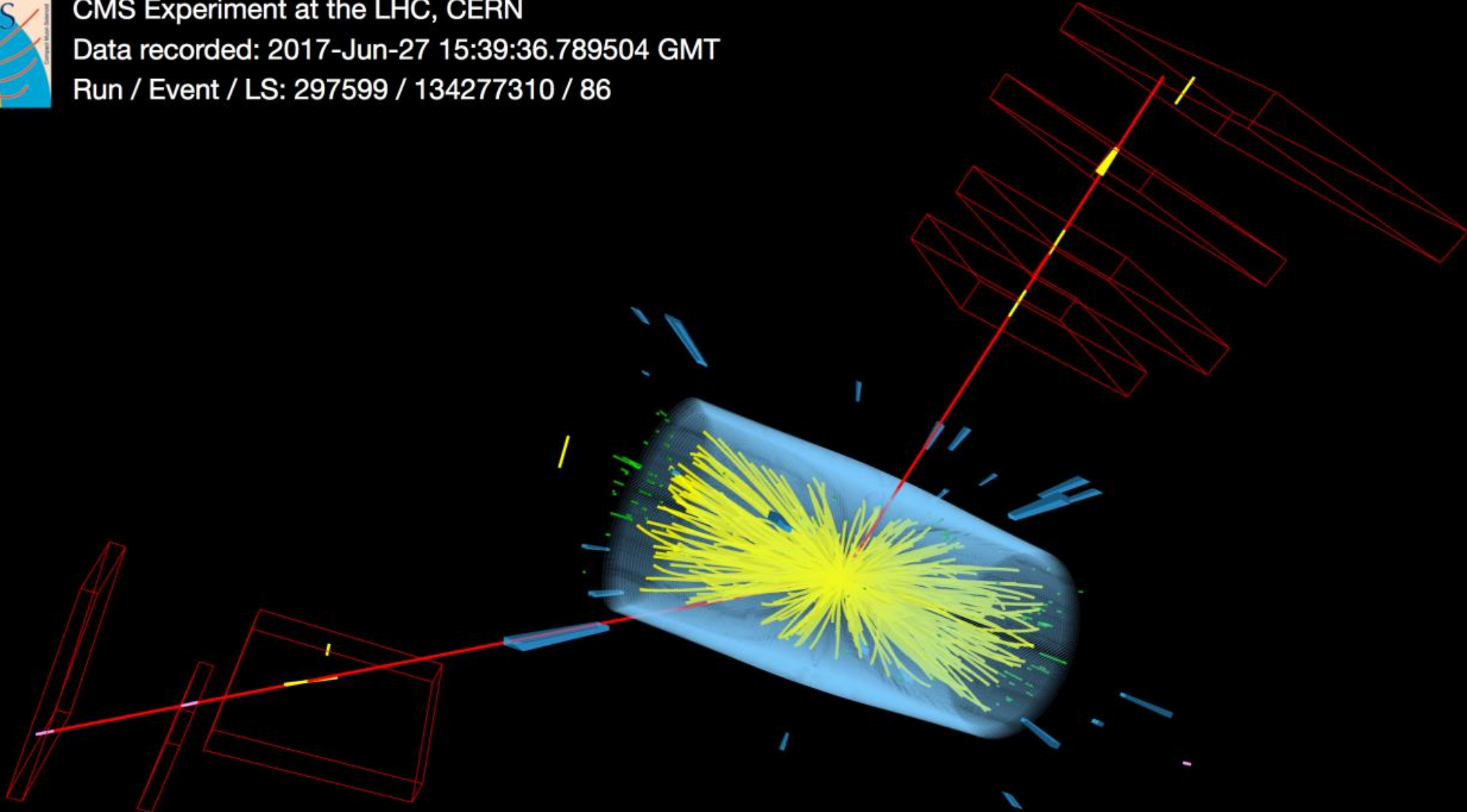
# Decadimento in 2 muoni di una particella neutra



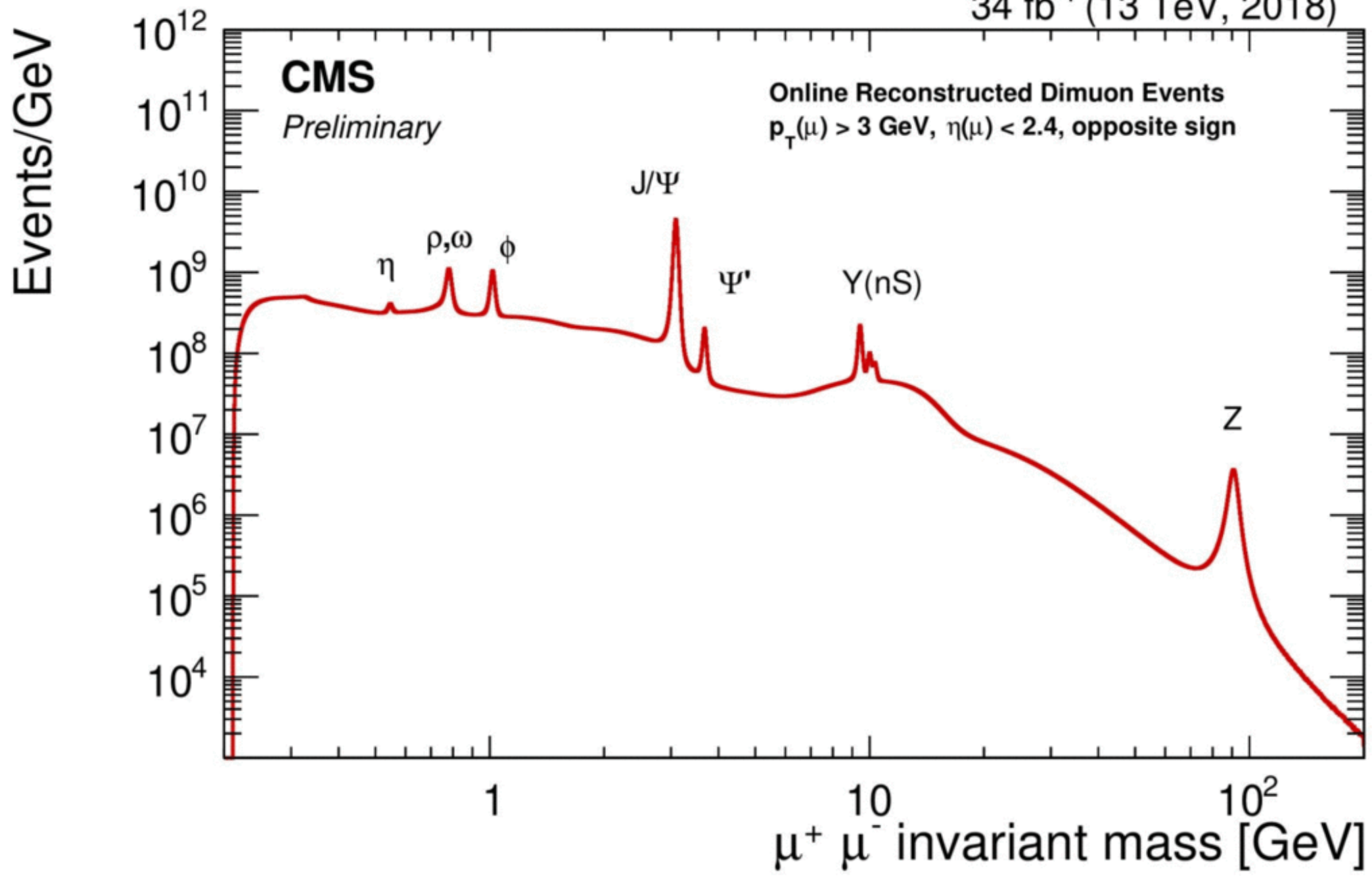
CMS Experiment at the LHC, CERN

Data recorded: 2017-Jun-27 15:39:36.789504 GMT

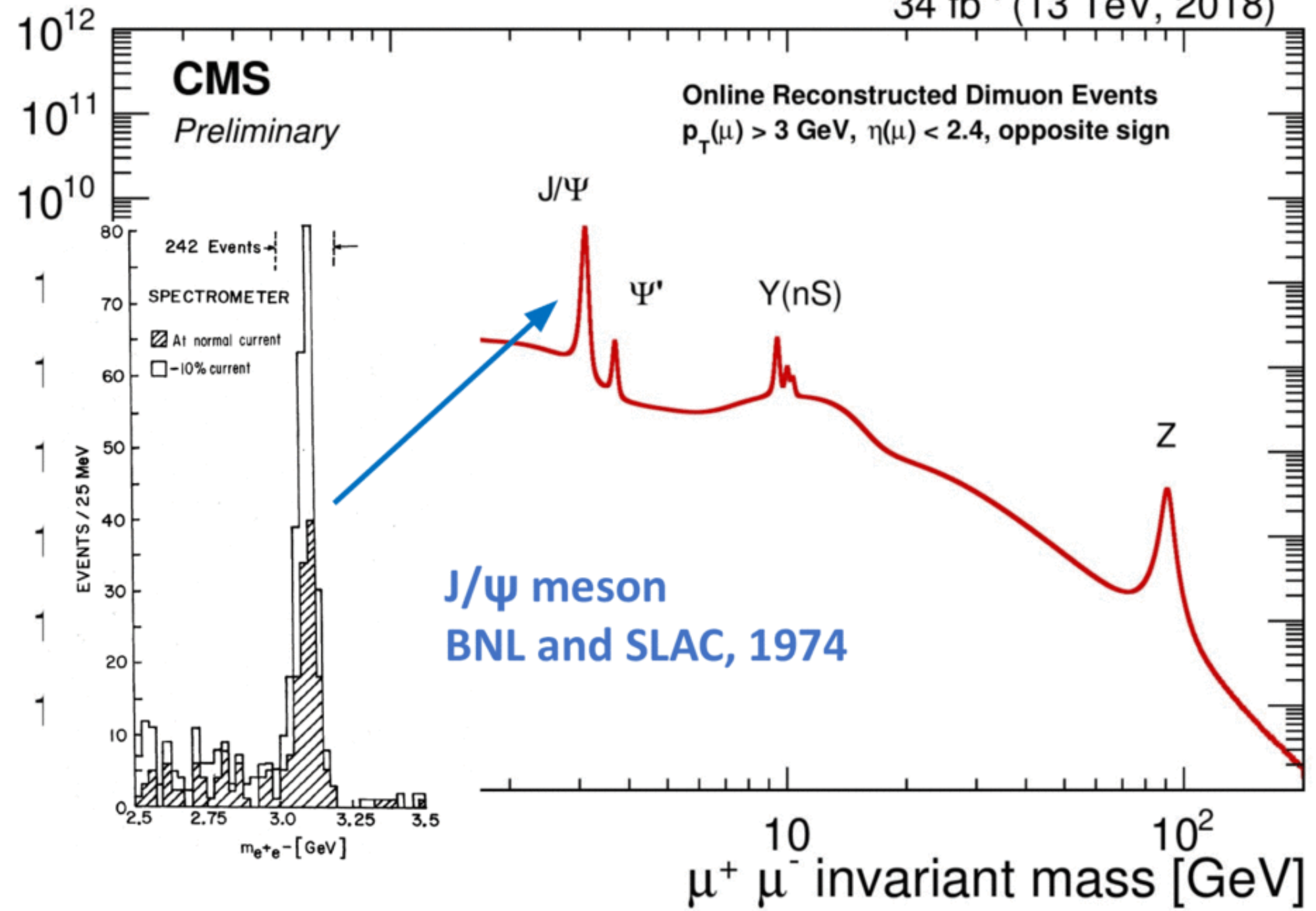
Run / Event / LS: 297599 / 134277310 / 86



34 fb<sup>-1</sup> (13 TeV, 2018)



Events/GeV

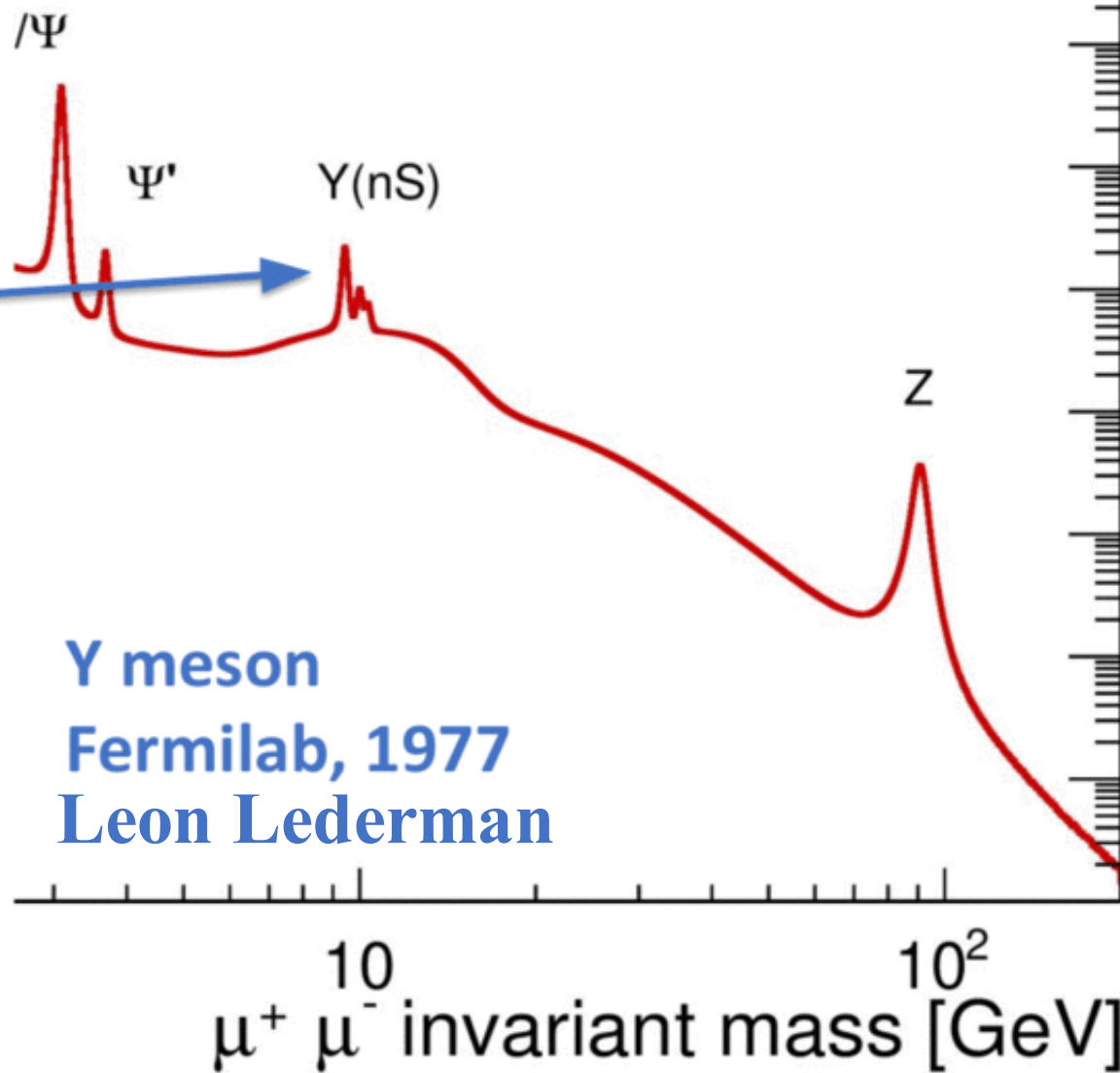
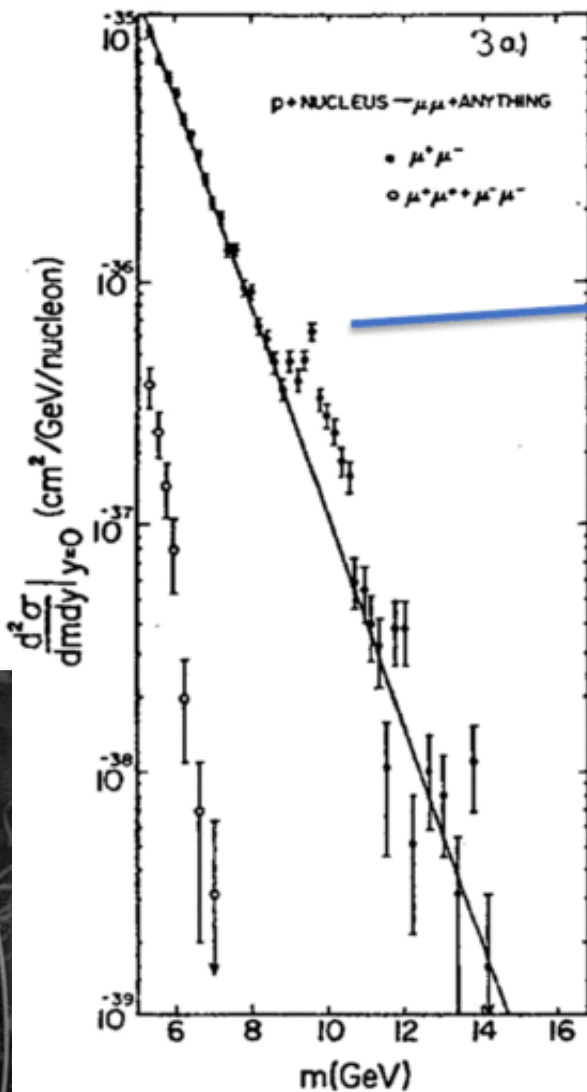


34 fb<sup>-1</sup> (13 TeV, 2018)

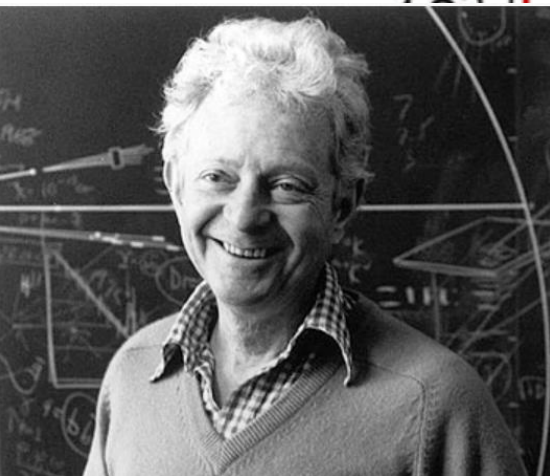
Events/GeV

**CMS**  
Preliminary

Online Reconstructed Dimuon Events  
 $p_T(\mu) > 3 \text{ GeV}$ ,  $\eta(\mu) < 2.4$ , opposite sign



Y meson  
Fermilab, 1977  
Leon Lederman

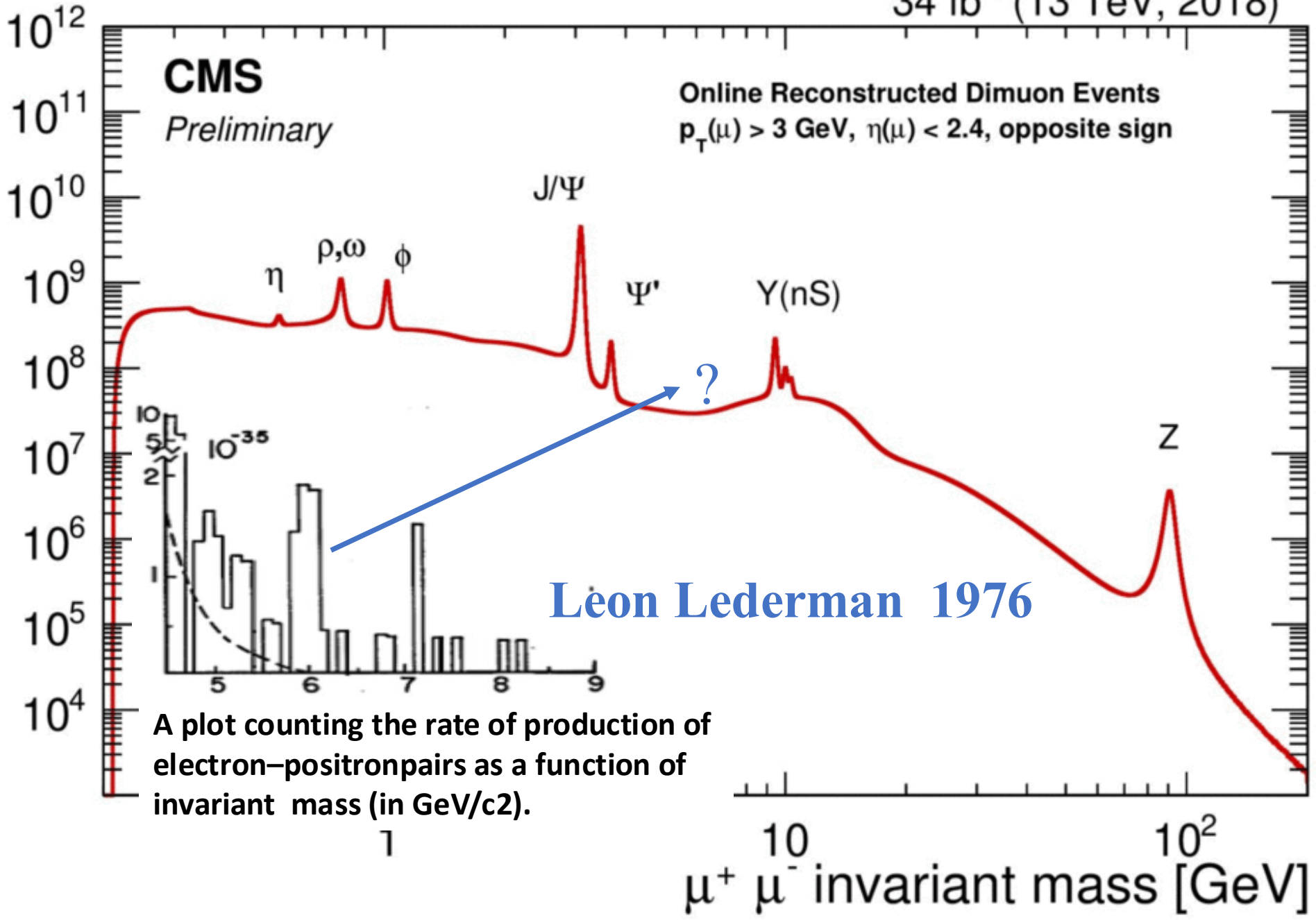


34 fb<sup>-1</sup> (13 TeV, 2018)

Events/GeV

**CMS**  
*Preliminary*

Online Reconstructed Dimuon Events  
 $p_T(\mu) > 3 \text{ GeV}$ ,  $\eta(\mu) < 2.4$ , opposite sign



**Leon Lederman 1976**

A plot counting the rate of production of electron-positron pairs as a function of invariant mass (in GeV/c<sup>2</sup>).

# Oops-Leon

---

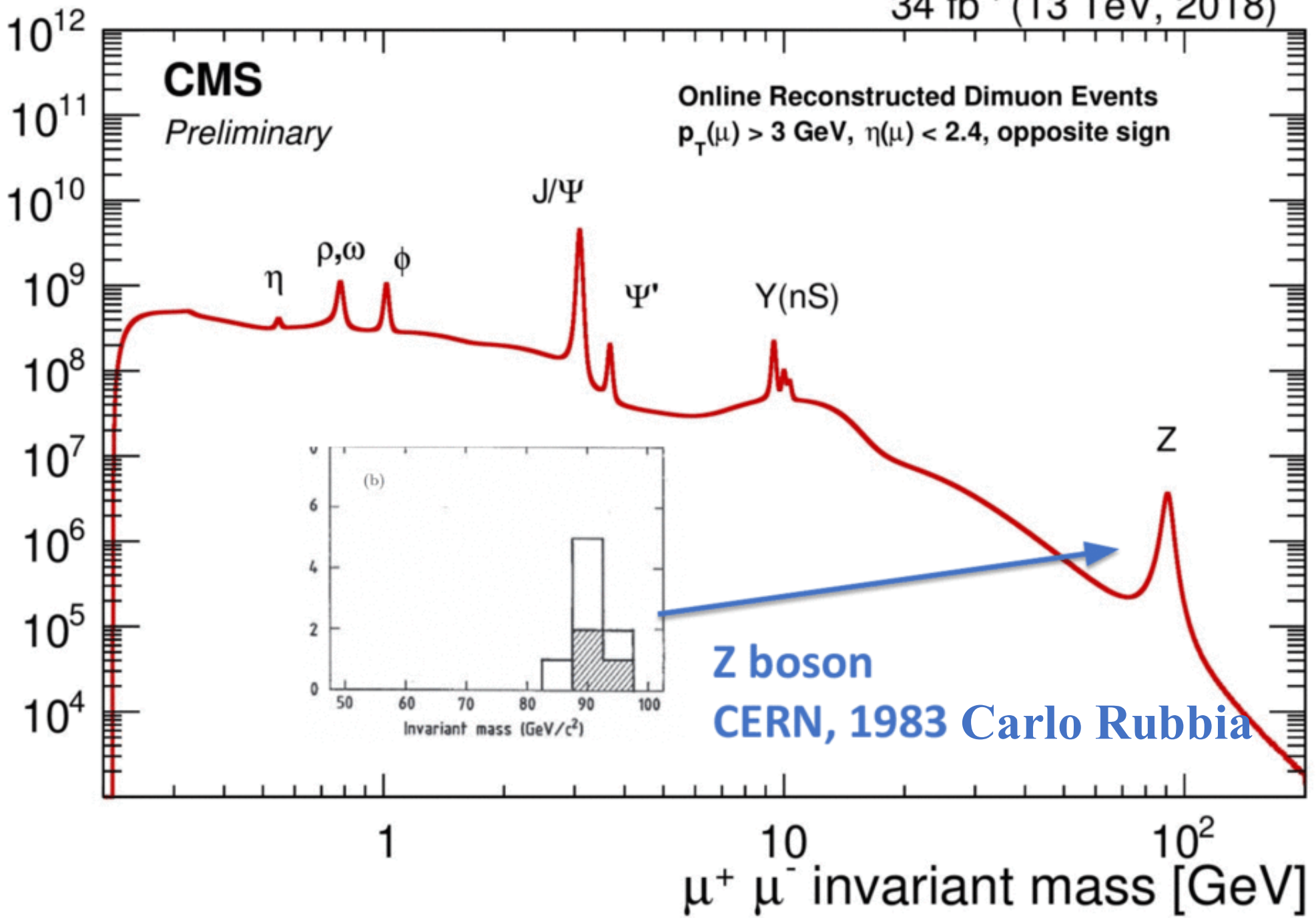
**Oops-Leon** is the name given by particle physicists to what was thought to be a new subatomic particle "discovered" at Fermilab in 1976. The E288 experiment team, a group of physicists led by Leon Lederman who worked on the E288 particle detector, announced that a particle with a mass of about  $6.0 \text{ GeV}/c^2$ , which decayed into an electron and a positron, was being produced by the Fermilab particle accelerator.<sup>[1]</sup> The particle's initial name was the Greek letter Upsilon ( $\Upsilon$ ). After taking further data, the group discovered that this particle did not exist, and the "discovery" was named "Oops-Leon" as a pun on the original name and the first name of the E288 collaboration leader.<sup>[2]</sup>

34 fb<sup>-1</sup> (13 TeV, 2018)

Events/GeV

**CMS**  
*Preliminary*

Online Reconstructed Dimuon Events  
 $p_T(\mu) > 3 \text{ GeV}$ ,  $\eta(\mu) < 2.4$ , opposite sign



# La scoperta dei bosoni W



- UA1 e UA2 avevano raggiunto risultati analoghi, ma UA2 aveva chiesto qualche settimana per verificare la correttezza delle proprie analisi, mentre UA1 era già perfettamente convinto della correttezza dei propri risultati.

**Figure 3.** The press conference in CERN's main auditorium at which the discovery of the W was announced on 25 January 1983. Seated, left to right: Carlo Rubbia, Simon van der Meer, Herwig Schopper, Erwin Gabathuler, and Pierre Darriulat. (Photo: Courtesy CERN.)

# La scoperta dei bosoni W e Z



**Carlo Rubbia e  
Simon van der Meer  
Vincitori del premio  
Nobel 1984**

**Figure 1.** Carlo Rubbia and Simon van der Meer celebrate the announcement that they had won the 1984 Nobel Prize for physics. (Photo: Courtesy CERN.)

# La scoperta del quark top

- June-July 1984 Rubbia discovers Top!
  - Articles (*Nature*, *NY Times*) and press release
  - Mass peak between 30-50 GeV

Carlo Rubbia nel 1984  
 Pubblica la scoperta del  
 Quark top, ma questa  
 Volta l'articolo viene  
 Ritirato dopo poche  
 Settimane, a causa di un  
 Errore nella selezione dei  
 Dati. Il quark Top verrà  
 scoperto solo 10 dopo a  
 Fermilab, a un valore di  
 Massa di 172 GeV.



Nature, July 1984

NEWS AND VIEWS

## CERN comes out again on top

With the discovery of the electroweak bosons ( $W^+$  and  $Z^0$ ) in the bag, CERN now announces the discovery of the quark called top. What will come next?

The Matthew principle — "to him that hath shall be given" — is working in favour of CERN, the European high-energy physics laboratory at Geneva, and of the UA1 collaboration which, at the end of last year, announced the discovery of the  $W^+$  and  $Z^0$  particles which mediate the electroweak interaction. Last week, the same 10 strong collaborations, under the leadership of Carlo Rubbia, announced the discovery of the missing sixth quark, called top, long-predicted but hitherto elusive. By doing so, they have put yet another cap on the electroweak theory while restoring a seemingly symmetry to the cooking pot of quarks in the elementary constituents of the material Universe.

The new development at CERN follows almost exactly along the lines expected and described, for example, by Dr F. Close in his column on the electroweak bosons, see *Nature* 303, 536 (1983). The source of the sixth quark is a charged boson,  $W^+$  or  $W^0$ , first recognized at CERN by their decay into an electron (with electric charge of the same sign), with excess momentum carried away by a neutrino. Events of this kind accumulated at CERN in the past two years have amply confirmed that the mass of the  $W^+$  particles is that predicted by the electroweak theory, the equivalent of  $82 \pm 2$  GeV. The actual number of events is very small, in fact, it was frequently produced (by a factor of about 10) in the proton-antiproton collisions at CERN, has a greater mass (to the tune of an extra 12 GeV) and is chiefly recognizable by its decay into a pair of electrons, positive and negative.

Although the chief decay path for the  $W^+$  boson is that by which its existence was first recognized, it has from the outset been accepted that decay schemes leading to the production of quarks should be respectable alternatives. Briefly, a  $W^+$  particle should be capable of yielding a top quark and the anti-matter version of a bottom quark, ( $W^+$  would then yield anti-top and anti-bottom.) For the past two years, there has been general agreement on the way in which these particles could be recognized. The bottom quark (or anti-quark) would itself decay into a narrow jet of nuclear matter — pi-mesons for example. And the top quark, with a greater mass, would first decay into bottom and then yield another jet of particles, this time less easily collimated. Since the first evidence for  $W^+$  particles began to appear at CERN, people have been wondering whether some of the events recorded by UA1 were signs of decay of this kind. Six events have now been unambiguously identified as the decay of  $W^+$  into top and bottom; the mass of top, estimated at 40 GeV, remains substantially uncertain.

For the time being, however, the proof that top exists is enough to be going on with. In the simplest terms, the asymmetry that has now been removed is that between the set of known electron-like particles and the set of quarks. For reasons which are frankly not understood, the natural world contains not just one material lepton, the electron (and its anti-particle, the positron), but also others, the muon and the tauon (each with its oppositely charged anti-particle). With each of these three leptons is associated a distinctive neutrino, recognizably different in the mechanisms by which they interact with matter but, on present form, not otherwise distinguishable — they have no electrical charge and no mass. But neutrinos are, like electrons, true leptons — they are involved symmetrically with the other particles in the working of the weak nuclear interaction (as in beta decay).

The idea that quarks should also come in pairs, and that these should be as many pairs of quarks as there are pairs of leptons, is more an act of faith than a consequence of theoretical expectation. To be sure, if the world is symmetrical in this way, it is possible to build rather theories, more symmetrical than would otherwise be the case. But that is merely a sign that, in its foundations, theoretical physics remains Pythagorean.

Phenomenologically, the need for symmetry has nevertheless been urgent since the late 1960s. The recognition of the difference between the pion-meson and the muon (a pair raised the puzzle of the apparently superfluous lepton. The discovery (as cosmic rays) at the same time of a new kind of hadronic (nuclear) matter, called strange because that is what it was, let the scene for Gellman's radical proposal that mesons such as the pion-meson, but also the strange particles themselves, are pairs of quarks — the pi-meson is a pair called up and down for example. But nucleons, such as protons and neutrons, and other baryons, are combinations of three quarks — the proton, for example, is two up quarks and one down. The partner of strange, discovered only in 1975, is charmed, evidence for bottom, also known as beauty, was found in 1977 in the proton-proton collisions arranged at Fermilab, where a meson whose mass exceeds the equivalent of 9.4 GeV was surmised to be a bound state of bottom and anti-bottom.

The quark called top (and also, seemingly, truth) has the missing number of the series. Its appearance has been expected for some time, but is no less welcome to the closet-Pythagoreans on that account. What will, in the short term, matter more is that the steady refinement of the mass now on the cards should make possible a degree of certainty about the nature of some still eluded hadronic particles and resonances. While the electroweak theory itself has been further confirmed, CERN and its UA1 collaboration have provided a more stringent test both of theories of quantum chromodynamics (theories of the strong nuclear interaction) and of Grand Unified Theories (which would roll that together with the electroweak theory but not yet — see gravitation). Only time will tell whether the outcome is any confirmation of some version or another hypothesis — yet another pair of leptons or quarks, for example.

Obviously, the question still arises in Britain: whether the discovery of the top quark at the collaborative high-energy physics laboratory will bear on the decision, now delegated to a committee under Sir John Kendrew, or whether Britain should continue to collaborate. The arguments run both ways. The discovery of top means that CERN's list of unattained achievements has been reduced by one, but at the same time the laboratory's reputation for success has been enhanced. It is, however, unlikely that the committee's recommendations will be determined by soap-counting of this kind, while high-energy physicists will properly draw attention to the need, now, for the careful understanding of the relationships between the six quarks that will come only from more careful measurements of the decay schemes now recognized, and of the alternatives still to be found.

John Madsen

