

Riconoscimento di eventi con bosoni W , Z e H a CMS

INTERNATIONAL MASTERCLASS IN PARTICLE PHYSICS

Linda Finco

13 marzo 2026

Bosoni carichi W

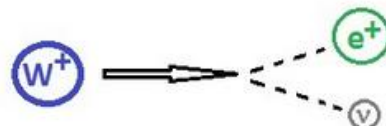
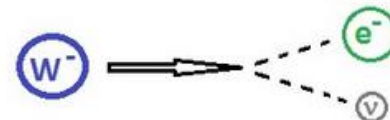
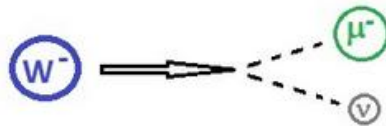
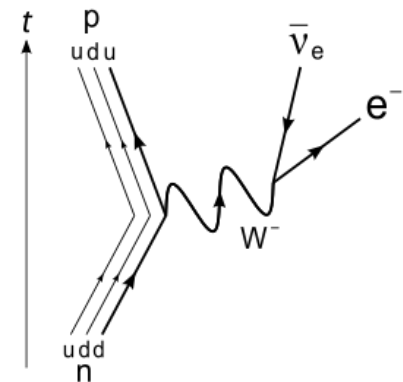
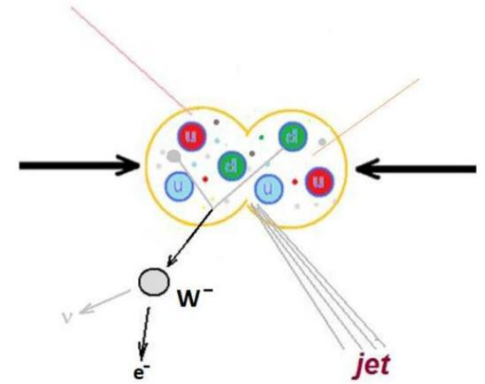
Mediatori dell'**interazione debole**, responsabile ad esempio del decadimento del neutrone, del carbonio-14, ecc...

L'interazione debole può cambiare sapore ai quark.

Esistono due tipi di bosoni W: W^+ e W^- (entrambi con carica = carica dell'elettrone)

Hanno vita molto breve e li riveliamo solo attraverso **i loro decadimenti**

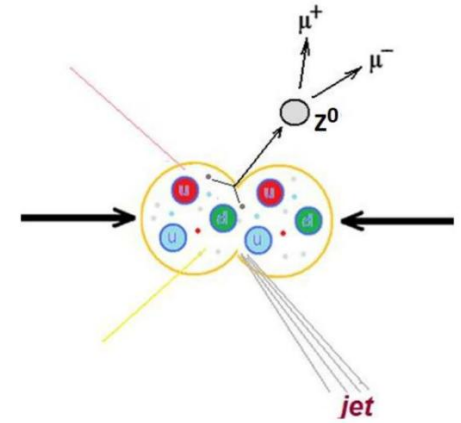
Possono decadere in vari modi, ci concentriamo su questi:



Bosoni neutri

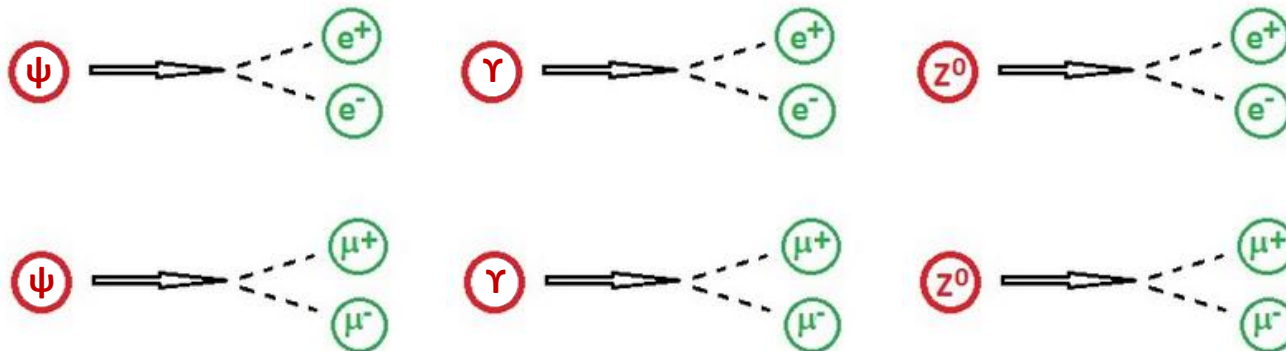
Ce ne sono di molti tipi, a seconda della massa:

- Intorno a **3 GeV**: stati legati di quark-antiquark di tipo c (ψ)
- Intorno a **10-12 GeV**: stati legati di quark-antiquark di tipo b (Υ)
- intorno a **90 GeV**: il **bosone Z**, l'altro mediatore dell'**interazione debole**, insieme ai bosoni W



Hanno vita molto breve e li riveliamo solo attraverso **i loro decadimenti**

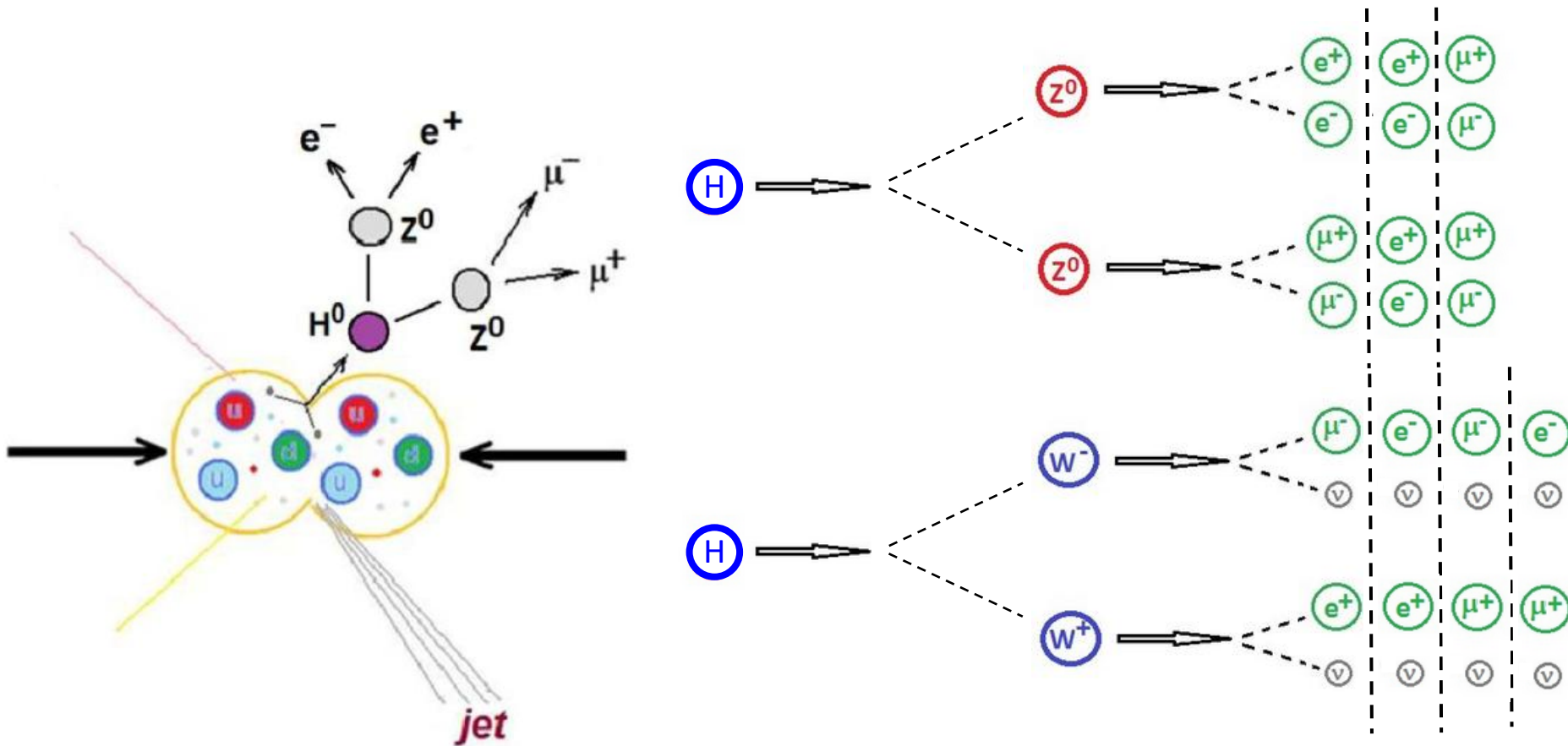
Possono decadere in vari modi, ci concentriamo su questi:



Il bosone di Higgs

Responsabile della **generazione delle masse** delle particelle fondamentali

Può essere individuato in vari modi, ma ci soffermeremo su:



Obiettivi

1. Misurare la massa del bosone Z e degli altri bosoni neutri
2. Misurare il numero di W^+ rispetto al numero di W^-
3. Misurare il numero di decadimenti in muone rispetto ai decadimenti in elettrone (sia per i W, che per i bosoni neutri)
4. Misurare il numero di W rispetto al numero di Z
5. “Scoprire” il bosone di Higgs cercando i (rarissimi) eventi del suo decadimento

Eseguiamo queste misure senza pregiudizi sul risultato: a esercizio concluso vedremo se il modello standard ne fornisce una interpretazione adeguata

Il rivelatore CMS

Magnete
superconduttore

Calorimetro
Elettromagnetico

Calorimetro
Adronico

Ferro del
magnete

Rivelatori
di muoni: "tappo"

Tracciatore

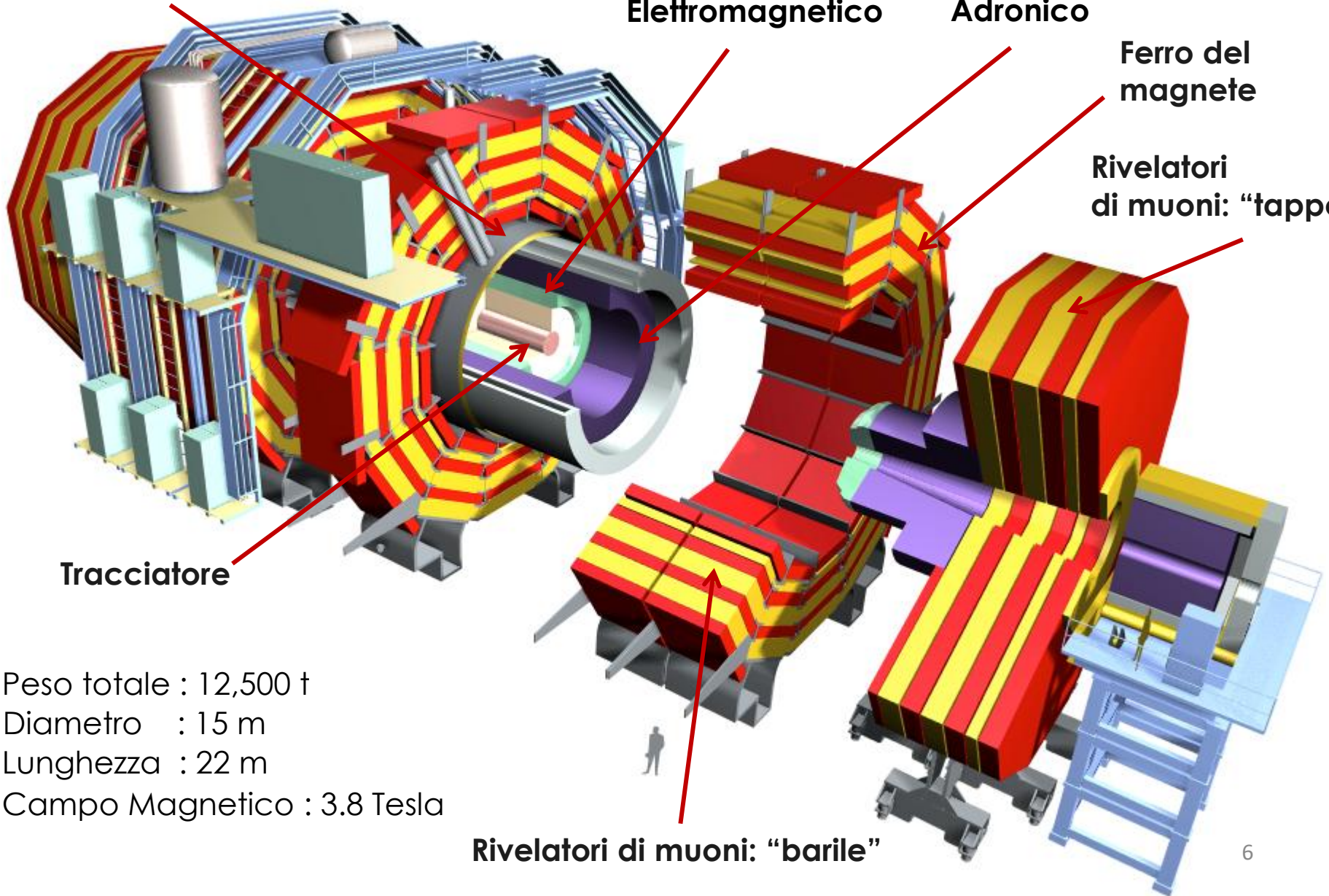
Peso totale : 12,500 t

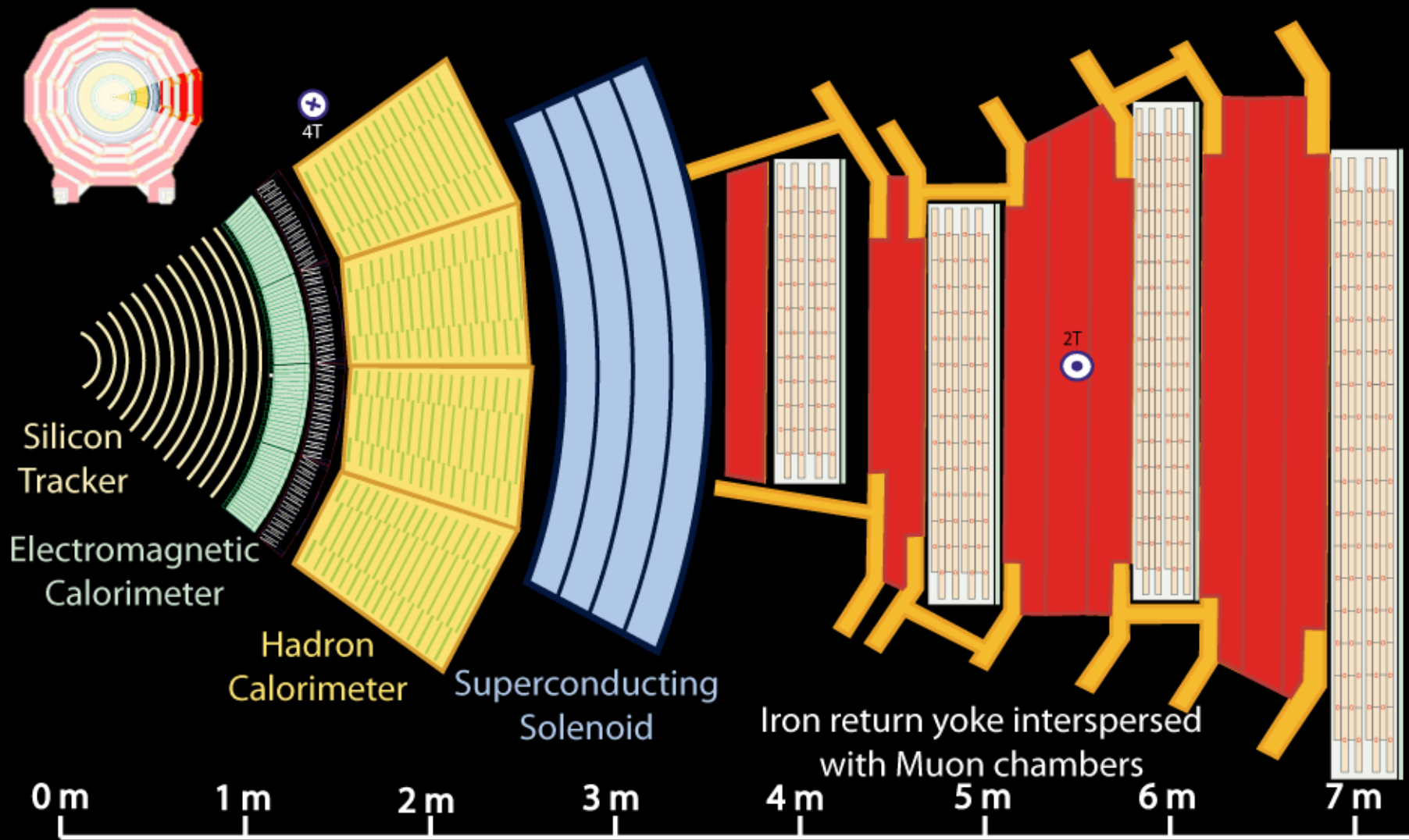
Diametro : 15 m

Lunghezza : 22 m

Campo Magnetico : 3.8 Tesla

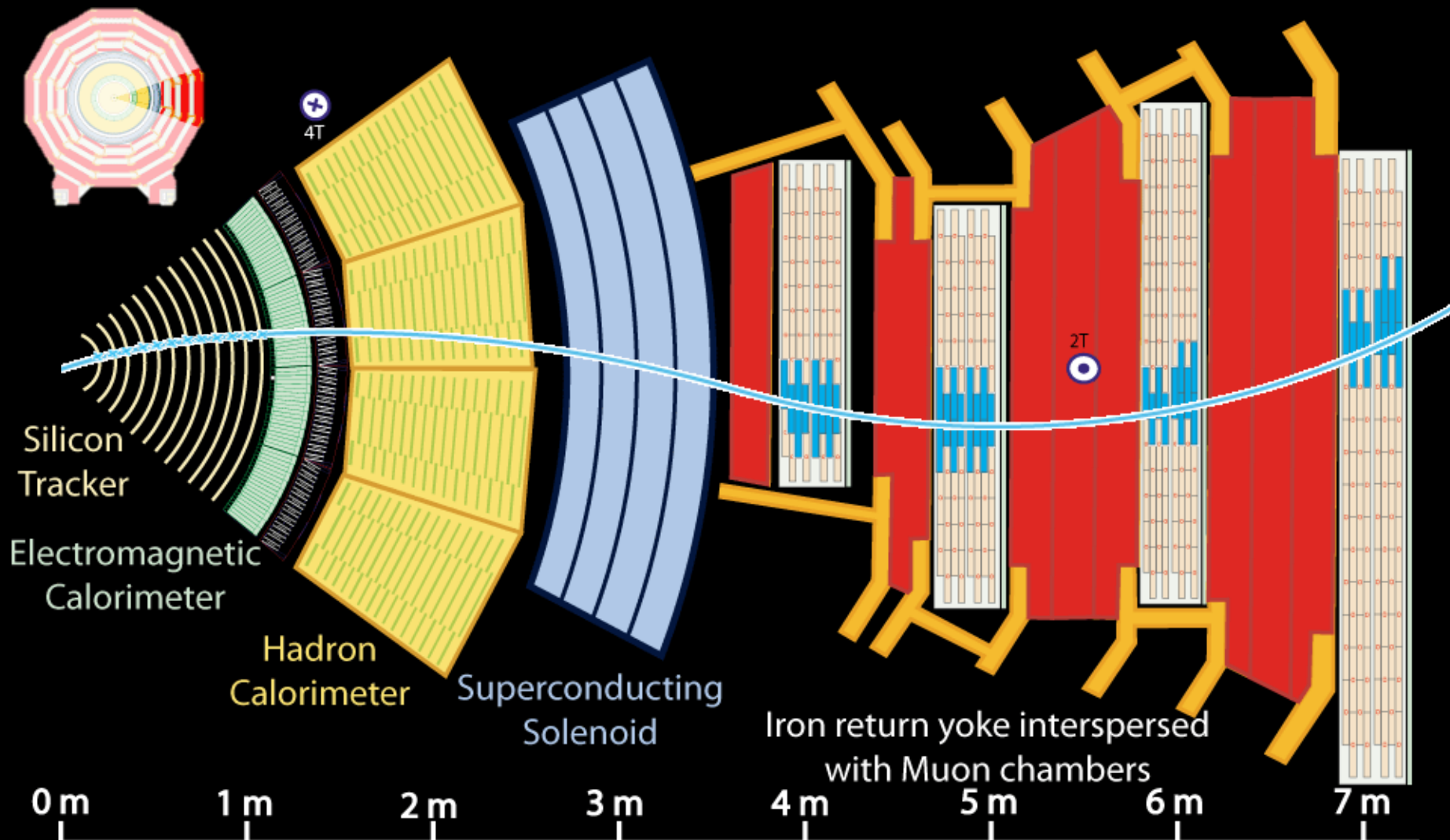
Rivelatori di muoni: "barile"



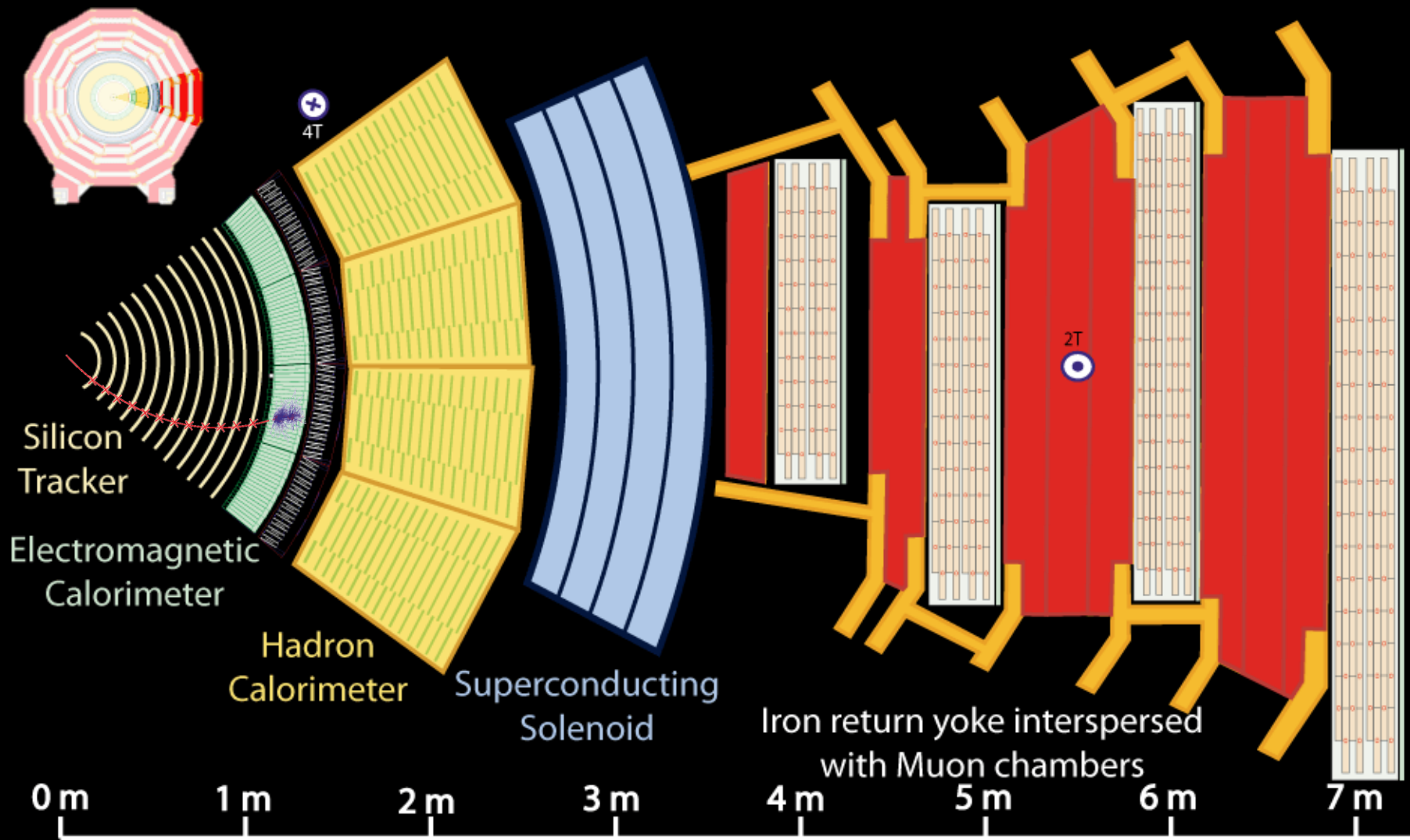


Key:

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

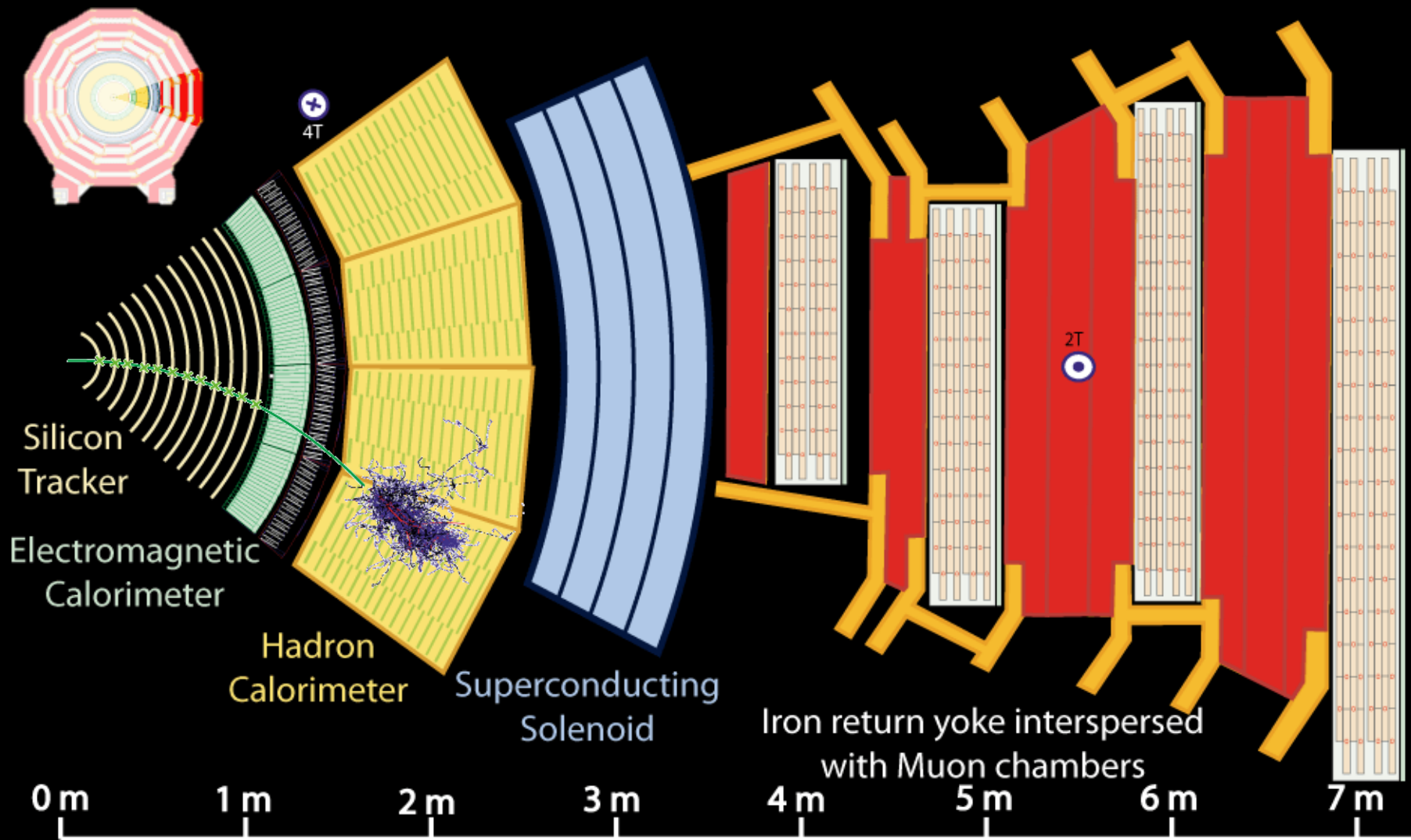


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- Muon
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Key:

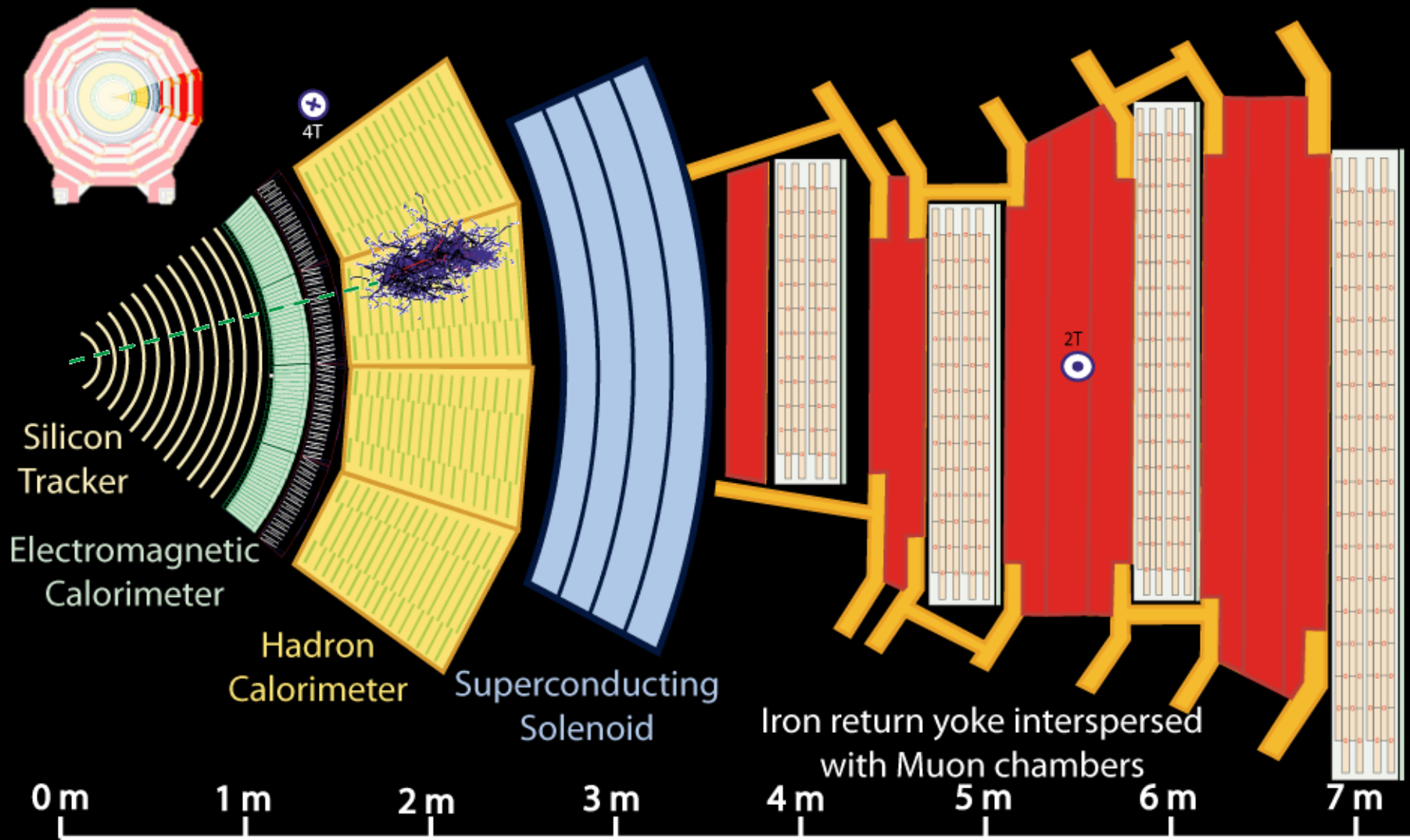
— Muon

— Electron

— Charged Hadron (e.g. Pion)

- - - Neutral Hadron (e.g. Neutron)

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Key:

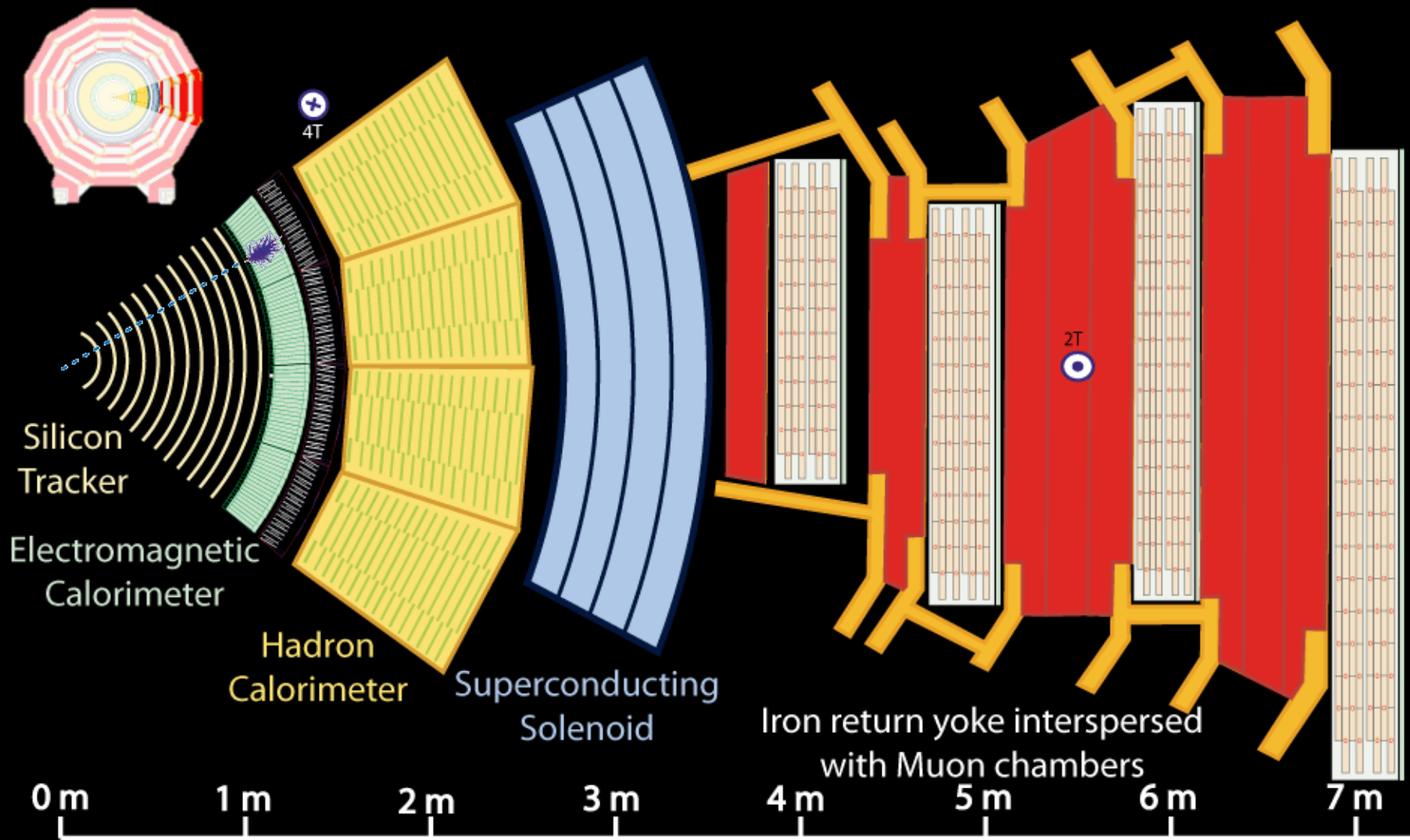
— Muon

— Electron

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Key:

— Muon

— Electron

— Charged Hadron (e.g. Pion)



- - - Neutral Hadron (e.g. Neutron)

- - - Photon

Riconoscere μ , e , ν

Le particelle cariche curvano nel campo magnetico secondo la forza di Lorentz  Dalla curvatura si risale all'energia (impulso).

CMS è costituito di vari strati di rivelatori, ciascuno in grado di rivelare certi tipi di particelle. Ogni rivelatore dà un'informazione "parziale" sulla particella che lo attraversa:

- il **tracciatore** rivela se la particella è carica, misura l'impulso, la carica e la direzione.
- Il **calorimetro elettromagnetico** (ECAL) misura l'energia dell'elettrone o fotone
 Tracciatore + ECAL = distinzione tra elettrone e fotone
- Il **calorimetro adronico** (HCAL) misura l'energia delle altre particelle (gli adroni)
 Tracciatore + HCAL = distinzione tra adrone neutro e carico
- Il **rivelatore a muoni** identifica le uniche particelle cariche che riescono ad attraversare i rivelatori precedenti, i muoni

I **neutrini** interagiscono troppo debolmente per essere rivelati, ma possiamo avere traccia della loro presenza attraverso **l'energia mancante** (*missing E_T* o **MET**): principio di conservazione dell'energia.

Eventi candidati W, Z e H

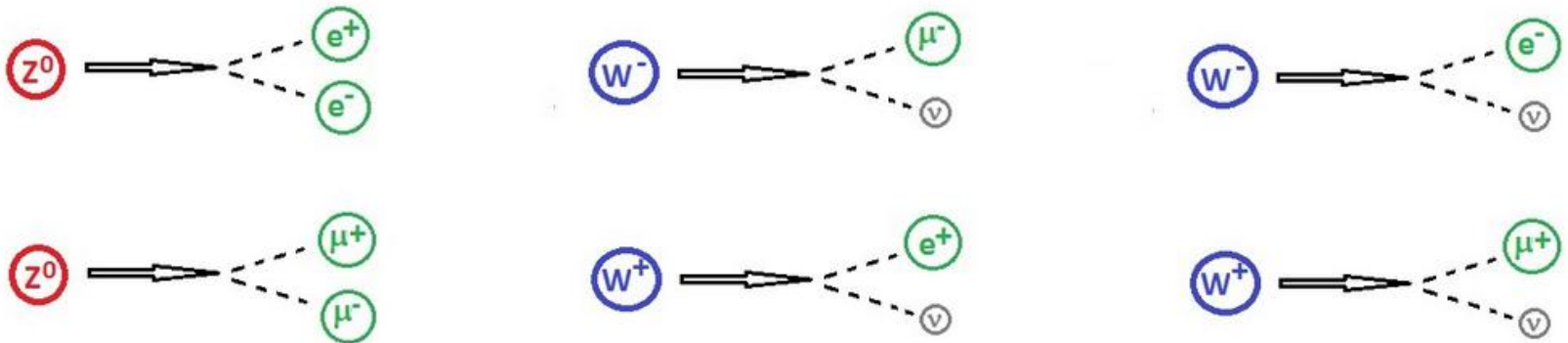
In eventi con **W** troveremo un leptone (e oppure μ) di alta energia e energia mancante (MET)

In eventi con bosoni **Z** o altri **bosoni neutri** troveremo due leptoni (e oppure μ) di alta energia

Eventi candidati **H** hanno due Z o due W (con carica opposta)

I μ sono caratterizzati da una traccia nel tracciatore e segnale nelle DT o CSC (strati più esterni del rivelatore)

Gli e sono caratterizzati da una traccia nel tracciatore e segnale in ECAL



Riconoscere la carica

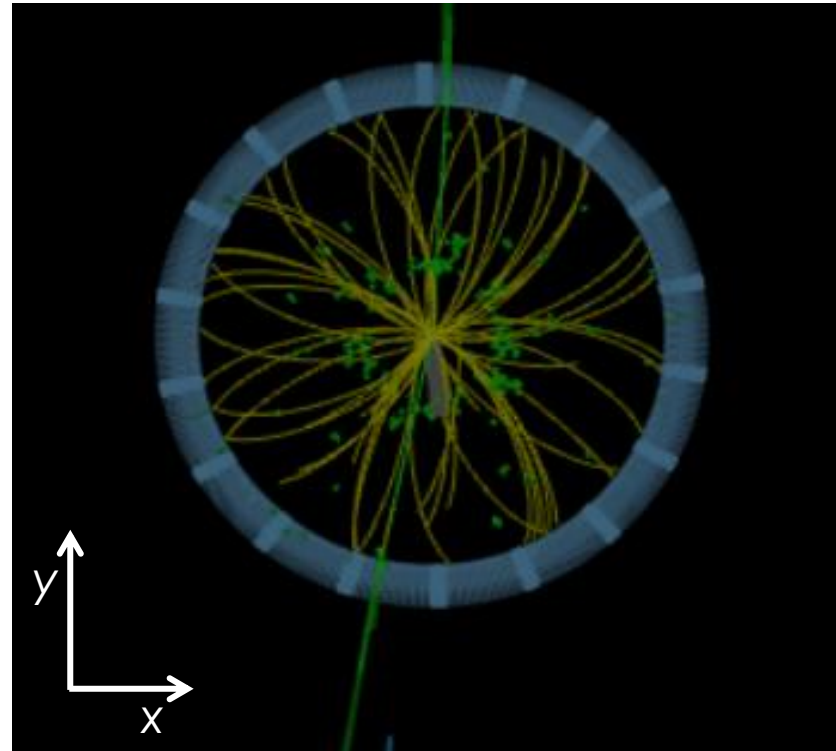
Il campo magnetico di CMS è parallelo all'asse **z** dentro al solenoide, antiparallelo fuori.

Quindi le particelle curvano prima in una direzione e poi nell'altra sotto l'azione della **forza di Lorentz**

$$\vec{F} = q \vec{v} \times \vec{B}$$

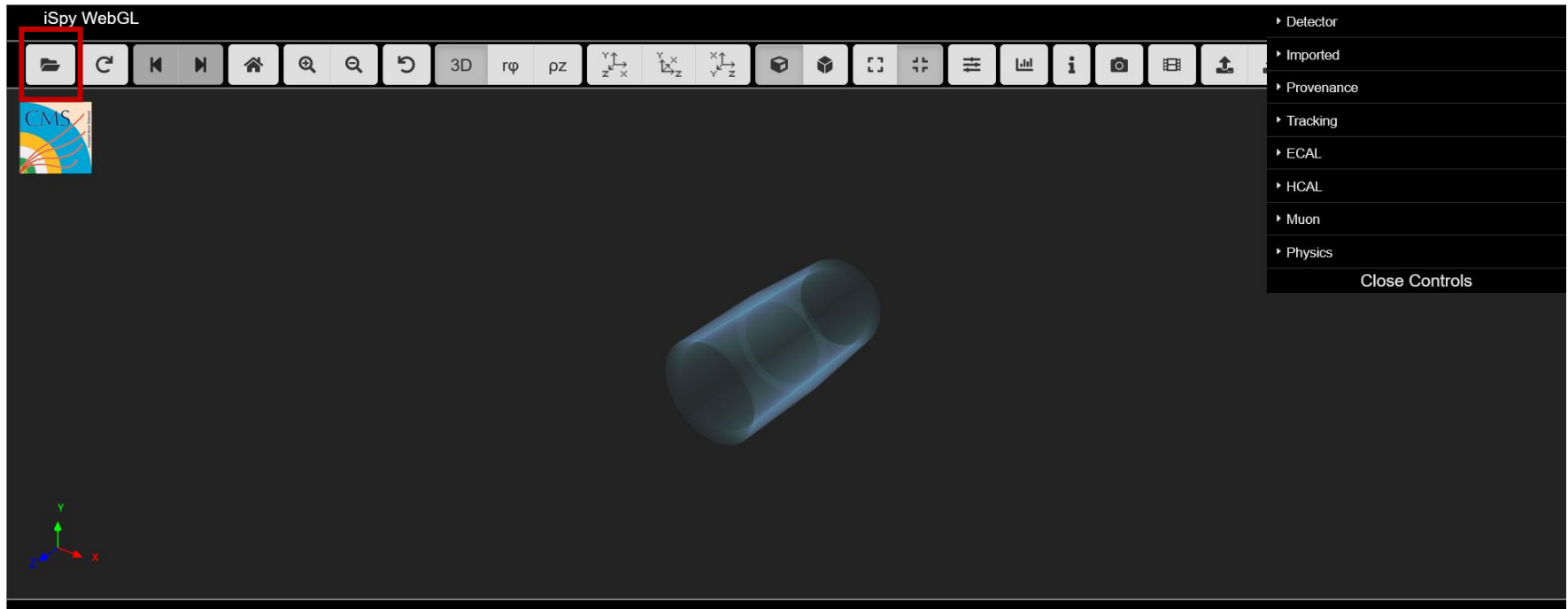
La curvatura avviene **solo nel piano xy**

Particelle positive (negative) curvano dentro al solenoide in senso orario (antiorario) nel piano xy (quando B, e quindi l'asse z, sono uscenti nello schermo).

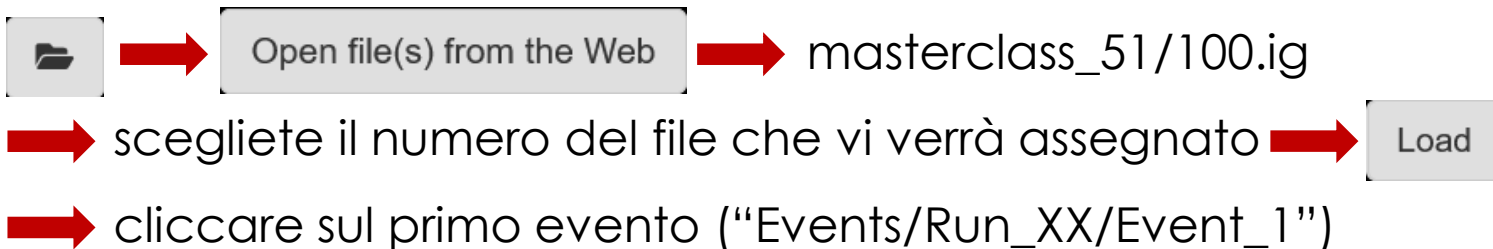


Event Display

Con l'aiuto dell'*Event Display* esaminiamo i nostri eventi (iSpy)



Per aprire il file su iSpy:

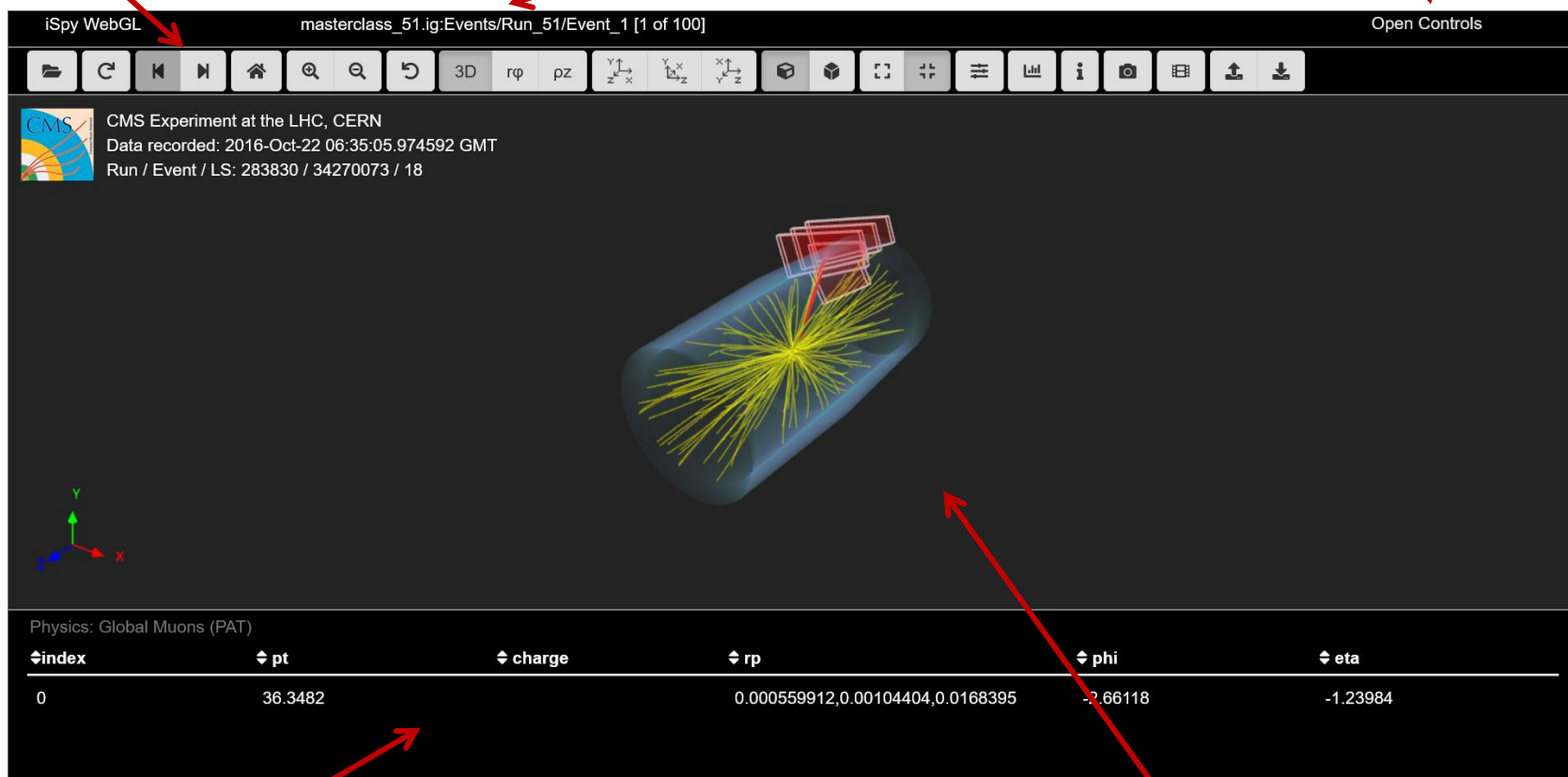


Event Display

Per spostarsi tra gli eventi

Numero dell'evento

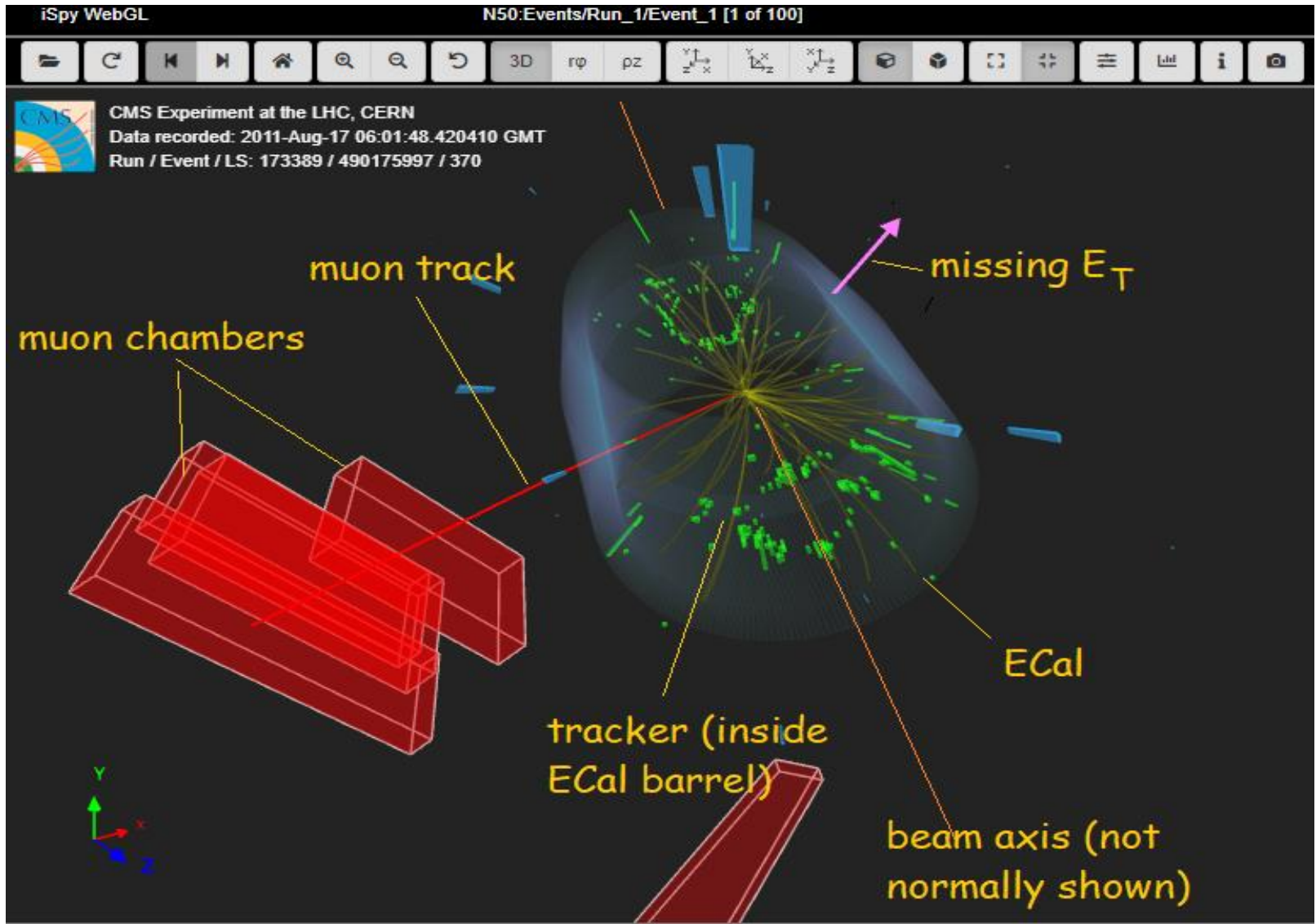
Menu di visualizzazione



Informazioni sulla particella selezionata

Finestra interattiva (si può ruotare, zoomare, ecc...)

Event Display



Event Display

iSpy WebGL N50:Events/Run_1/Event_1 [1 of 100]

CMS Experiment at the LHC, CERN
Data recorded: 2011-Aug-17 06:01:48.420410 GMT
Run / Event / LS: 173389 / 490175997 / 370

muon track

muon chambers

missing E_T

tracker (inside ECal barrel)

beam axis (not normally shown)

Physics

Missing Et (PAT)

number 1

key PATMETs_V1

show

opacity 1

color #ff7ff7

Logbook analisi

Salvate i vostri risultati sul logbook  Foglio Google (lo stesso per tutti!)

- Scorrete il foglio Google verso il basso fino a quando non trovate il vostro numero di dataset (colonna **A**)
- Il numero di ciascun evento si trova nella colonna **B** (da 1 a 100)

A **B**

Dataset	Event	Final State							Primary State				Mass [GeV]	
		e-v	μ -v	e-e	μ - μ	4e	4 μ	2 e 2 μ	W+	W-	NP (Z,H)	?		
1	1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	
	2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	3	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	4	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	5	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	6	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	7	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	8	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	9	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	
	10	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	11	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	12	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	13	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	14	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	88.99
	15	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	9.81

Logbook analisi

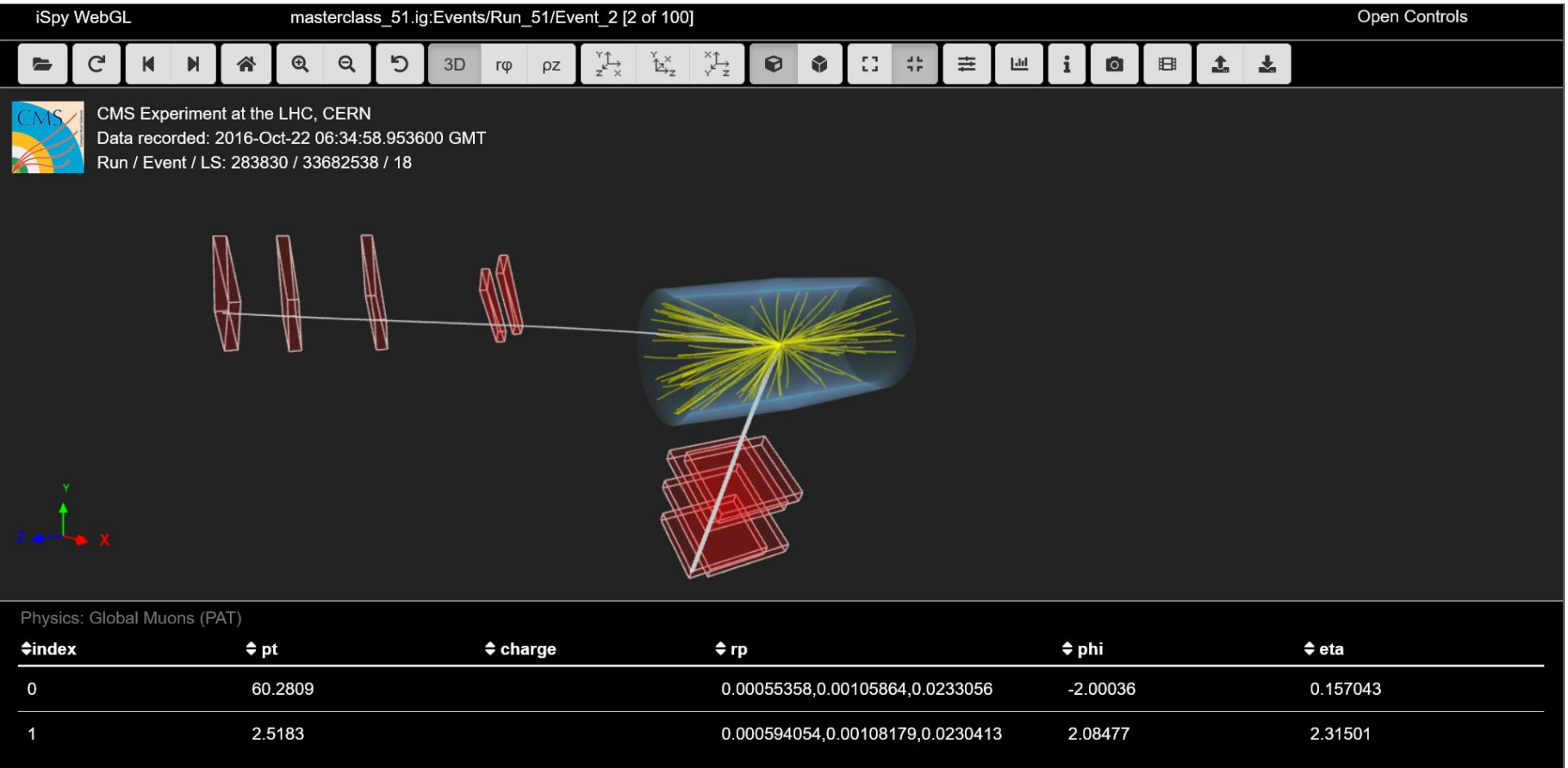
- I risultati di ciascun evento sono da inserire dalla colonna C a N
- Attenzione:
 - Stato finale C o D \rightarrow Stato primario J o K
 - Stato finale da E a I \rightarrow Stato primario L, da completare in N
 - Non sai la risposta? \rightarrow M (raro)

		C	D	E	F	G	H	I	J	K	L	M	N
Dataset	Event	Final State							Primary State				Mass [GeV]
		e-v	μ -v	e-e	μ - μ	4e	4 μ	2 e 2 μ	W+	W-	NP (Z,H)	?	
1	1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	
	2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	3	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	4	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	5	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	6	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	7	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	8	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	9	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	
	10	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	11	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	12	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	
	13	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
	14	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	88.99
	15	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	9.81

Calcolare la massa invariante

Selezionare le tracce col mouse → diventano grigie → premere “m”

iSpy WebGL masterclass_51.ig:Events/Run_51/Event_2 [2 of 100] Open Controls



CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-22 06:34:58.953600 GMT
Run / Event / LS: 283830 / 33682538 / 18

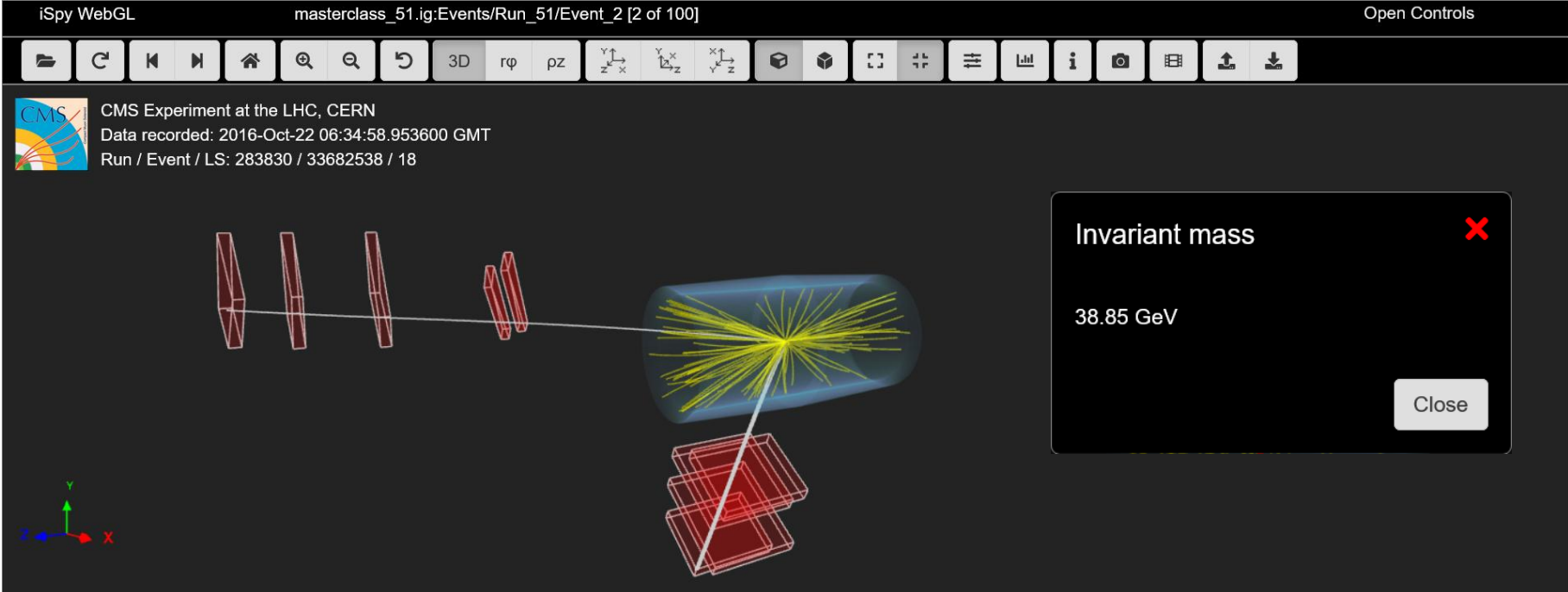
Physics: Global Muons (PAT)

↕ index	↕ pt	↕ charge	↕ rp	↕ phi	↕ eta
0	60.2809		0.00055358,0.00105864,0.0233056	-2.00036	0.157043
1	2.5183		0.000594054,0.00108179,0.0230413	2.08477	2.31501

Calcolare la massa invariante

Selezionare le tracce col mouse → diventano grigie → premere “m”

iSpy WebGL masterclass_51.ig:Events/Run_51/Event_2 [2 of 100] Open Controls



CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-22 06:34:58.953600 GMT
Run / Event / LS: 283830 / 33682538 / 18

Invariant mass ✖
38.85 GeV
Close

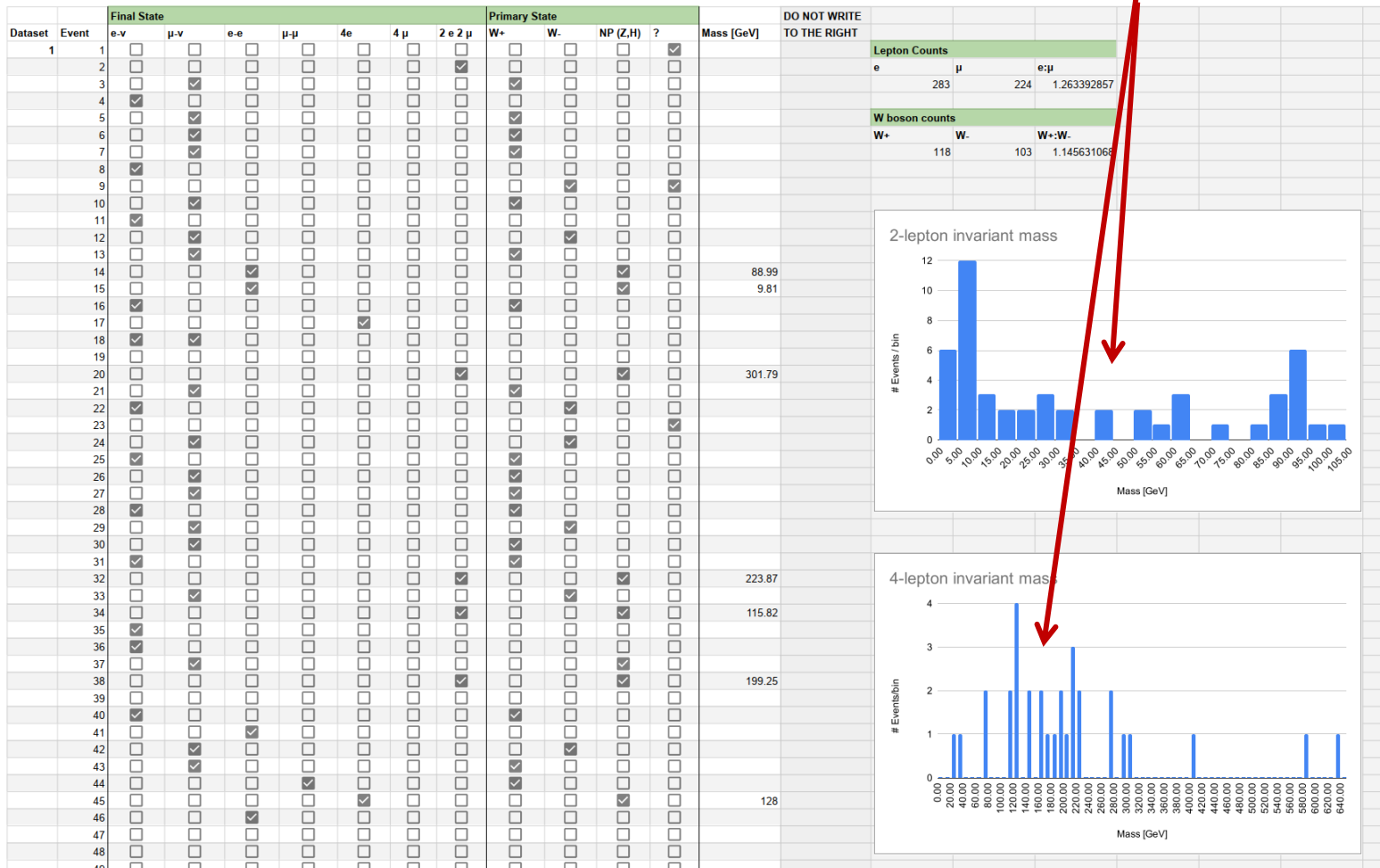
Physics: Global Muons (PAT)

↕ index	↕ pt	↕ charge	↕ rp	↕ phi	↕ eta
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1	2.5183		0.000594054,0.00108179,0.0230413	2.08477	2.31501

Logbook analisi

Salvate i vostri risultati sul logbook ➔ Foglio Google

Automaticamente verranno creati i plot di **massa invariante**



Logbook analisi

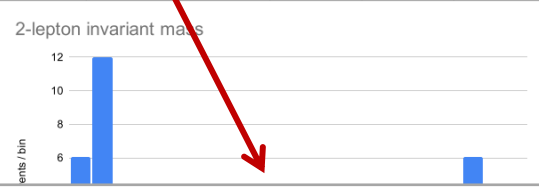
Salvate i vostri risultati sul logbook  Foglio Google

Automaticamente verranno calcolati i **rapporti tra particelle**

Dataset	Event	Final State								Primary State				Mass [GeV]	DO NOT WRITE TO THE RIGHT
		e-v	μ -v	e-e	μ - μ	4e	4 μ	2 e 2 μ	W+	W-	NP (Z,H)	?			
1	1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		
	2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		
	3	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		
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Lepton Counts		
e	μ	e: μ
283	224	1.263392857

W boson counts		
W+	W-	W+:W-
118	103	1.145631068

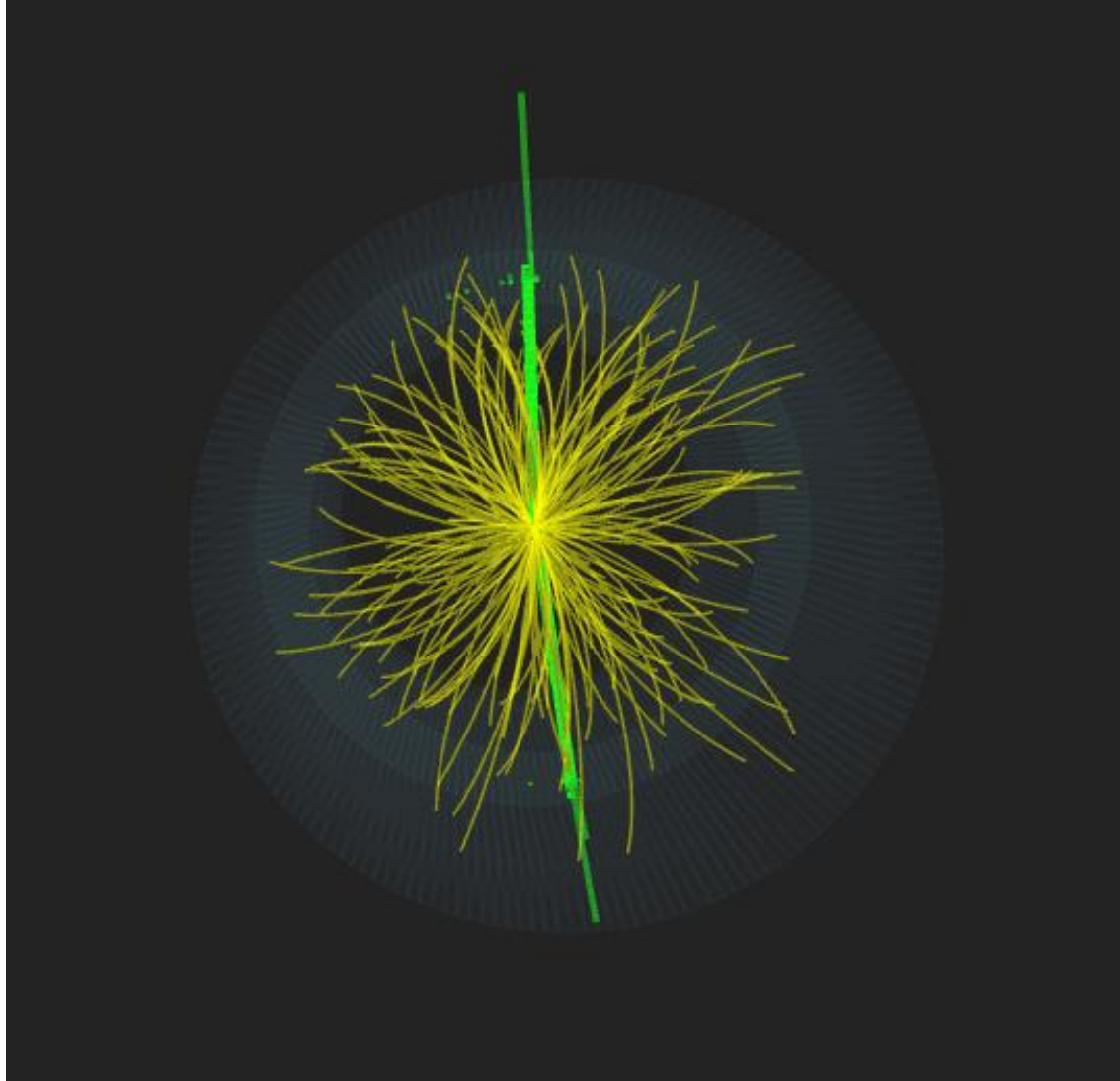


2-lepton invariant mass

leptons / bin

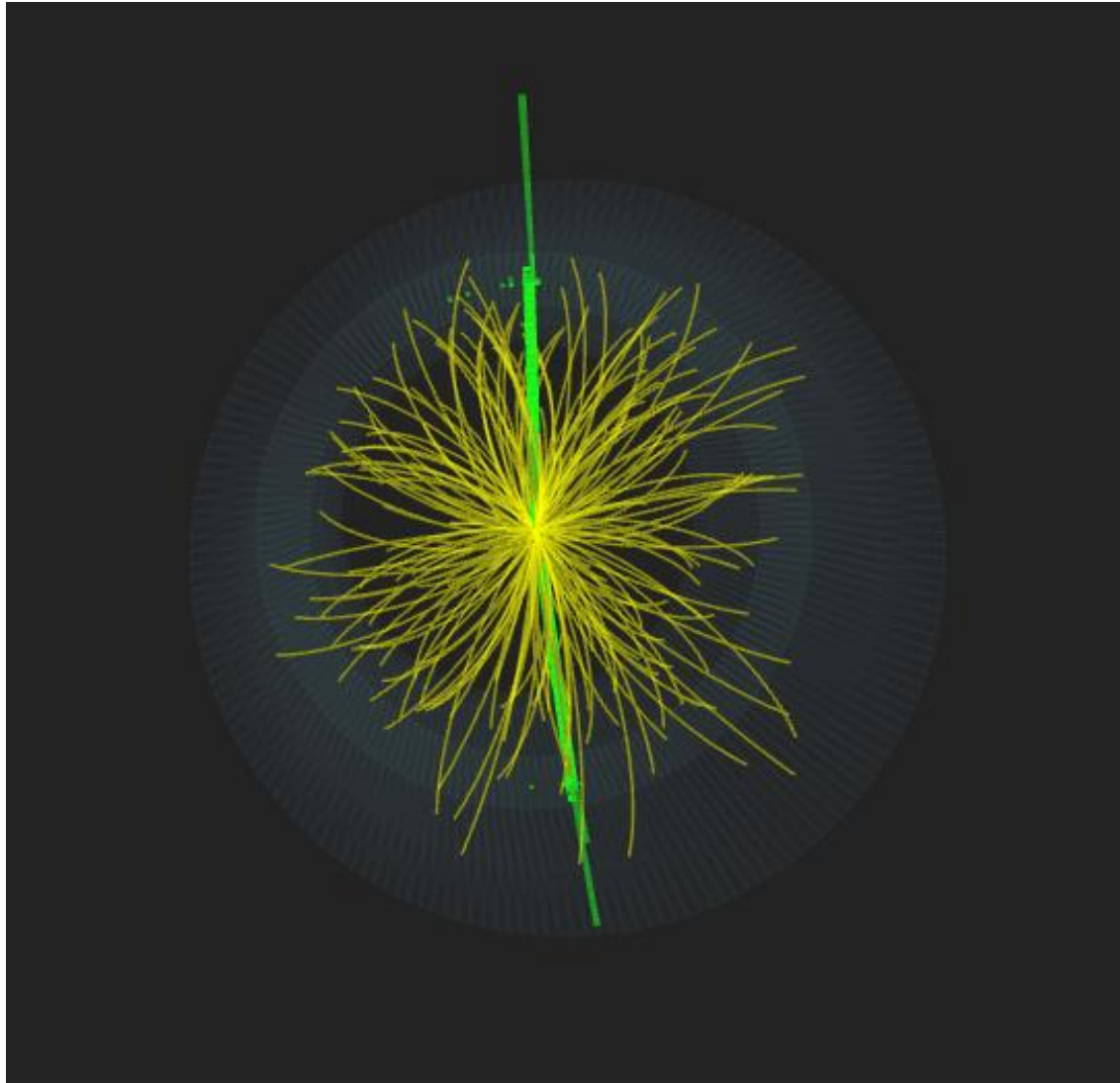
Mass [GeV]

Event Display

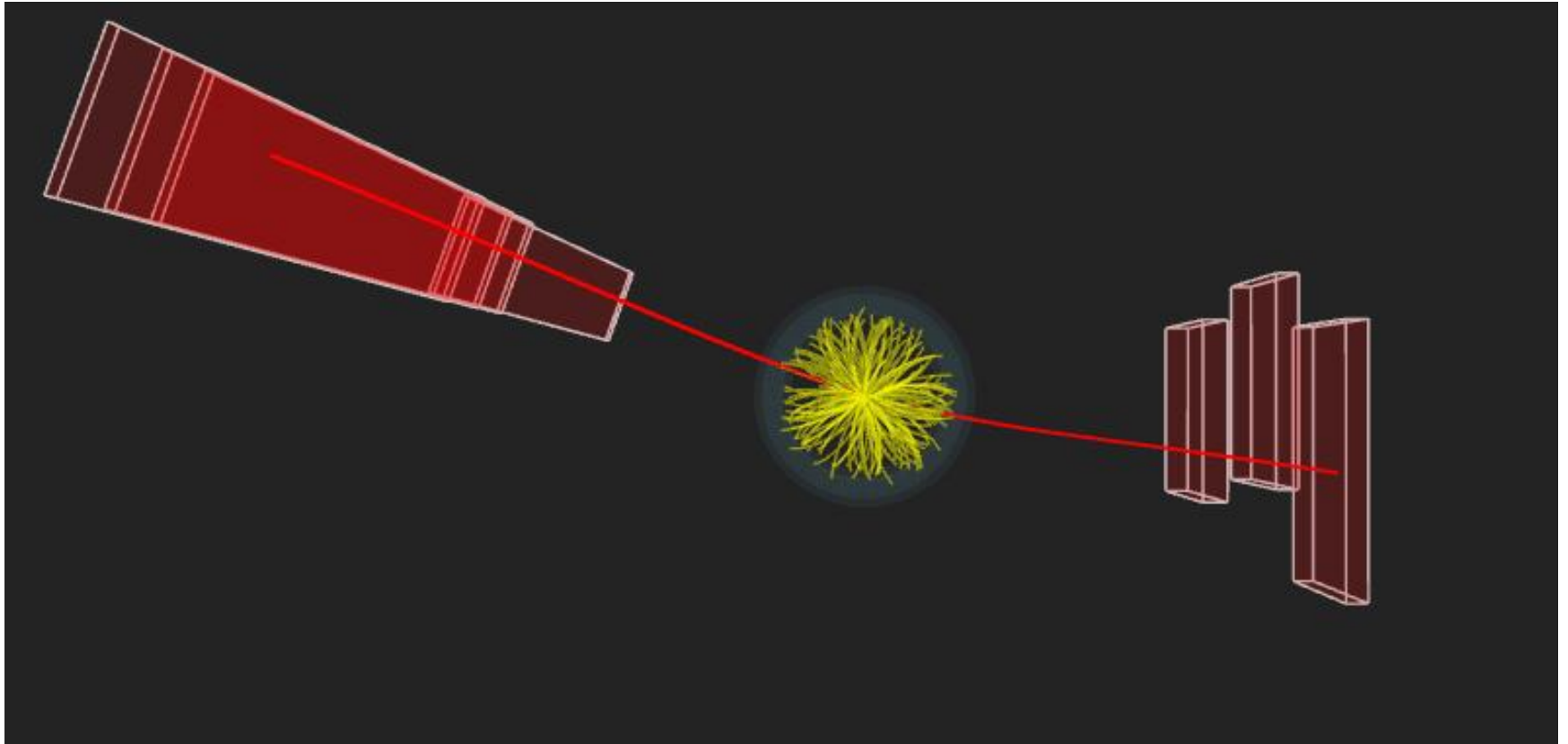


Event Display

Evento con due elettroni: possibile candidato Z?

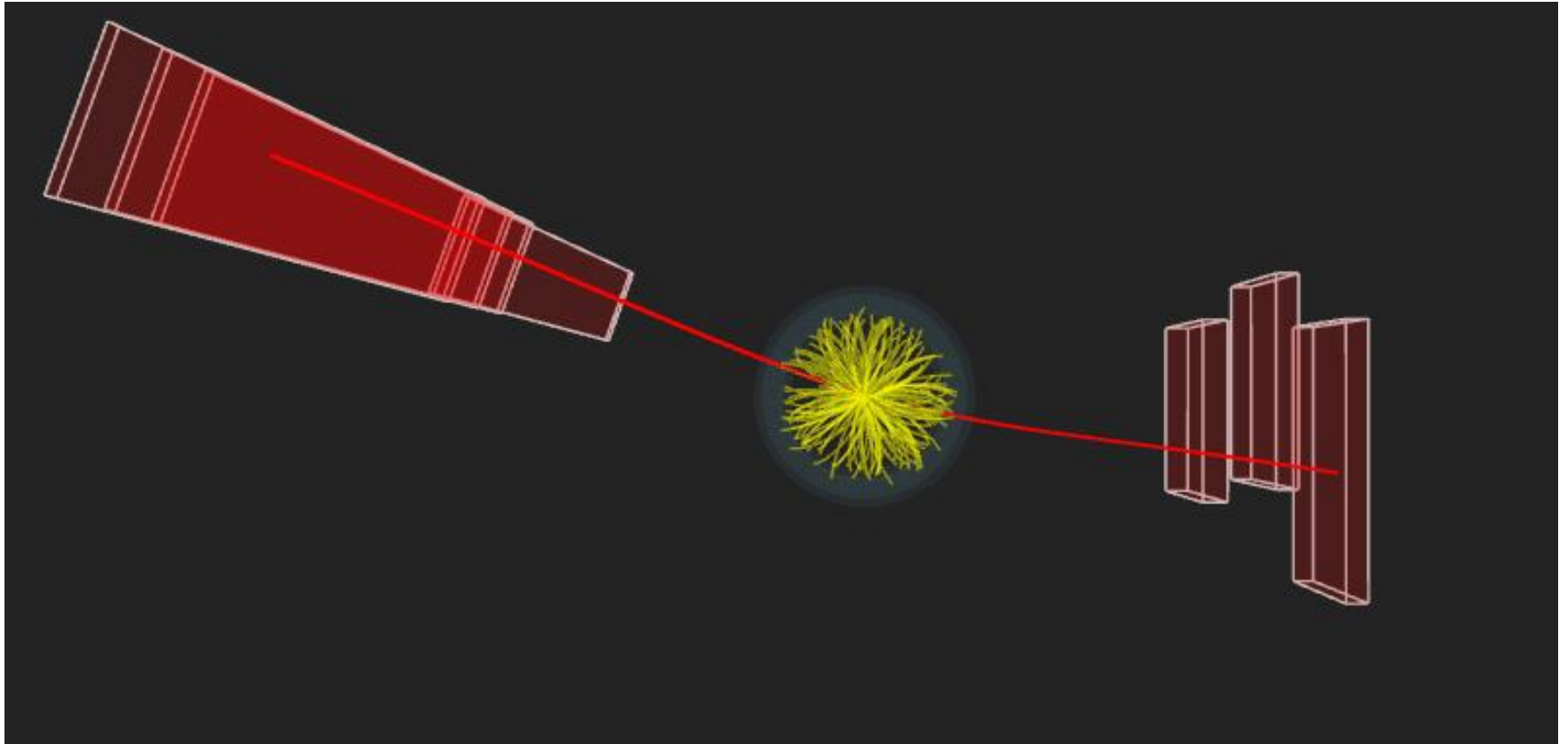


Event Display

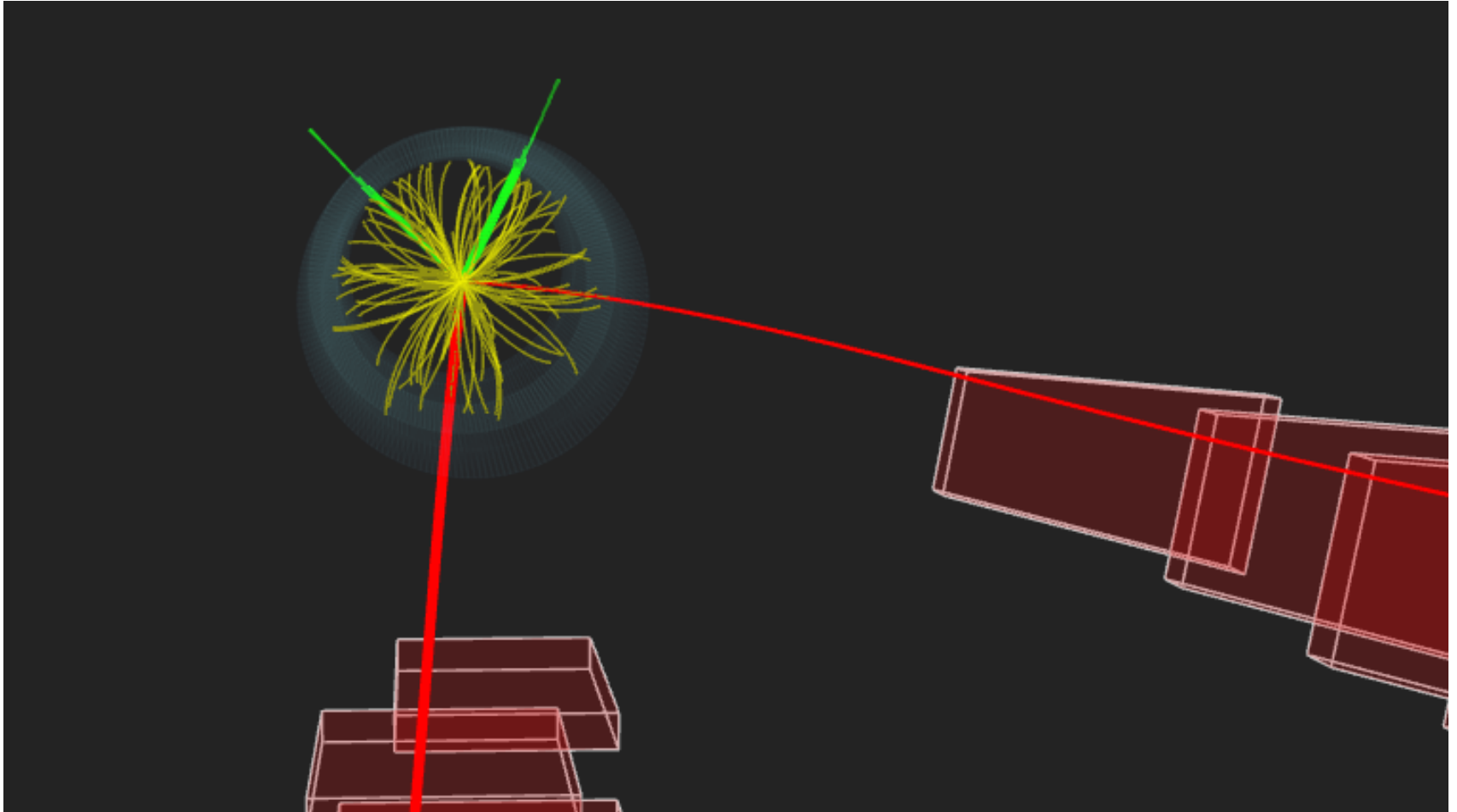


Event Display

Evento con due muoni: possibile candidato Z?

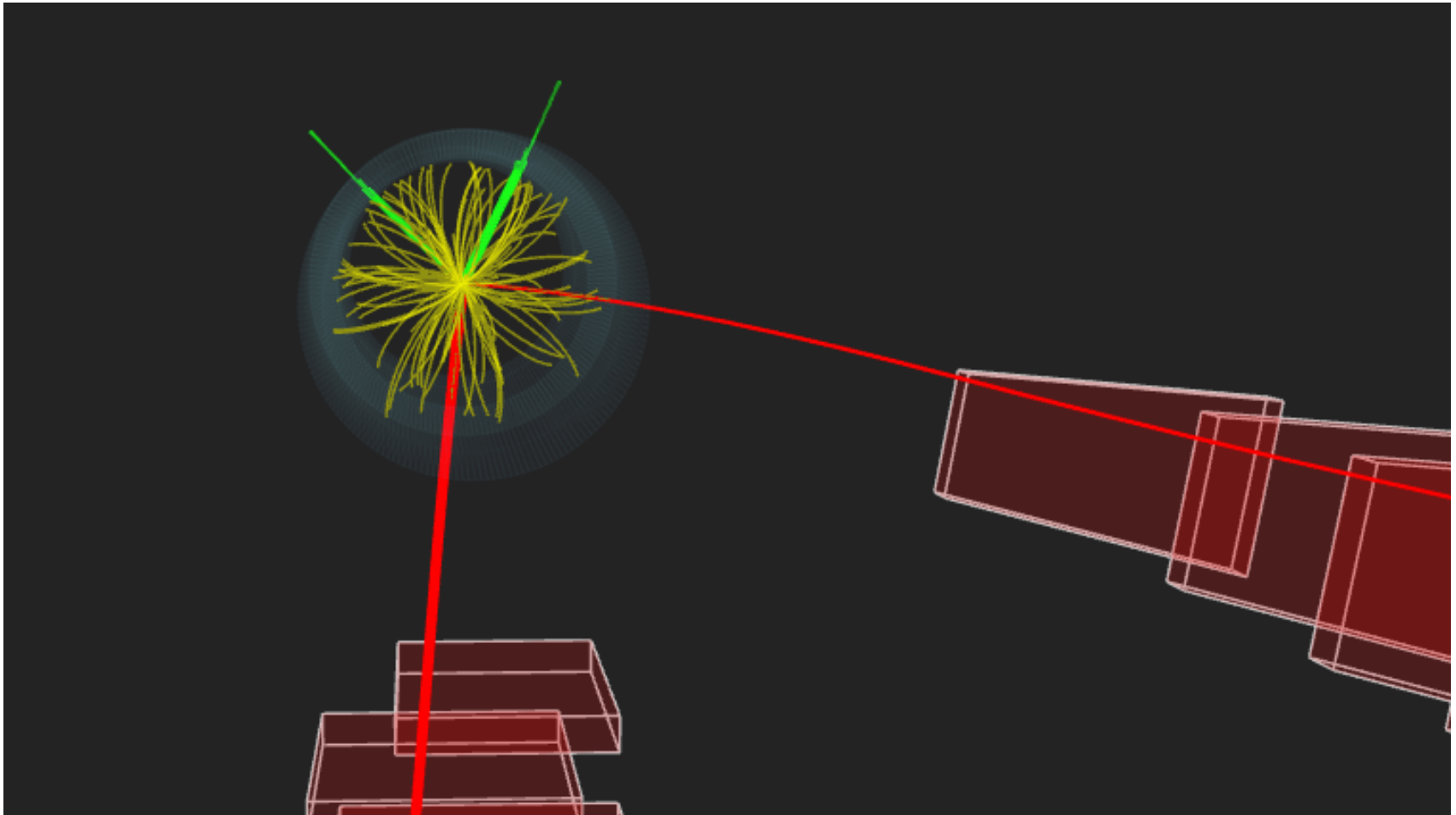


Event Display



Event Display

Evento con quattro leptoni: possibile candidato H?



Link utili

Pagina della masterclass

→ **Presentazione attività**

Registro analisi eventi

→ **Foglio Google**

Software visualizzazione eventi

→ **iSpy**



Social Media



<https://www.facebook.com/IstitutoFisicaNucleare>

<https://www.facebook.com/asimmetrieInfn>

<https://www.facebook.com/InternationalParticlePhysicsMasterclasses/>



INFN @INFN_

International Masterclass @physicsIMC



infn_insights

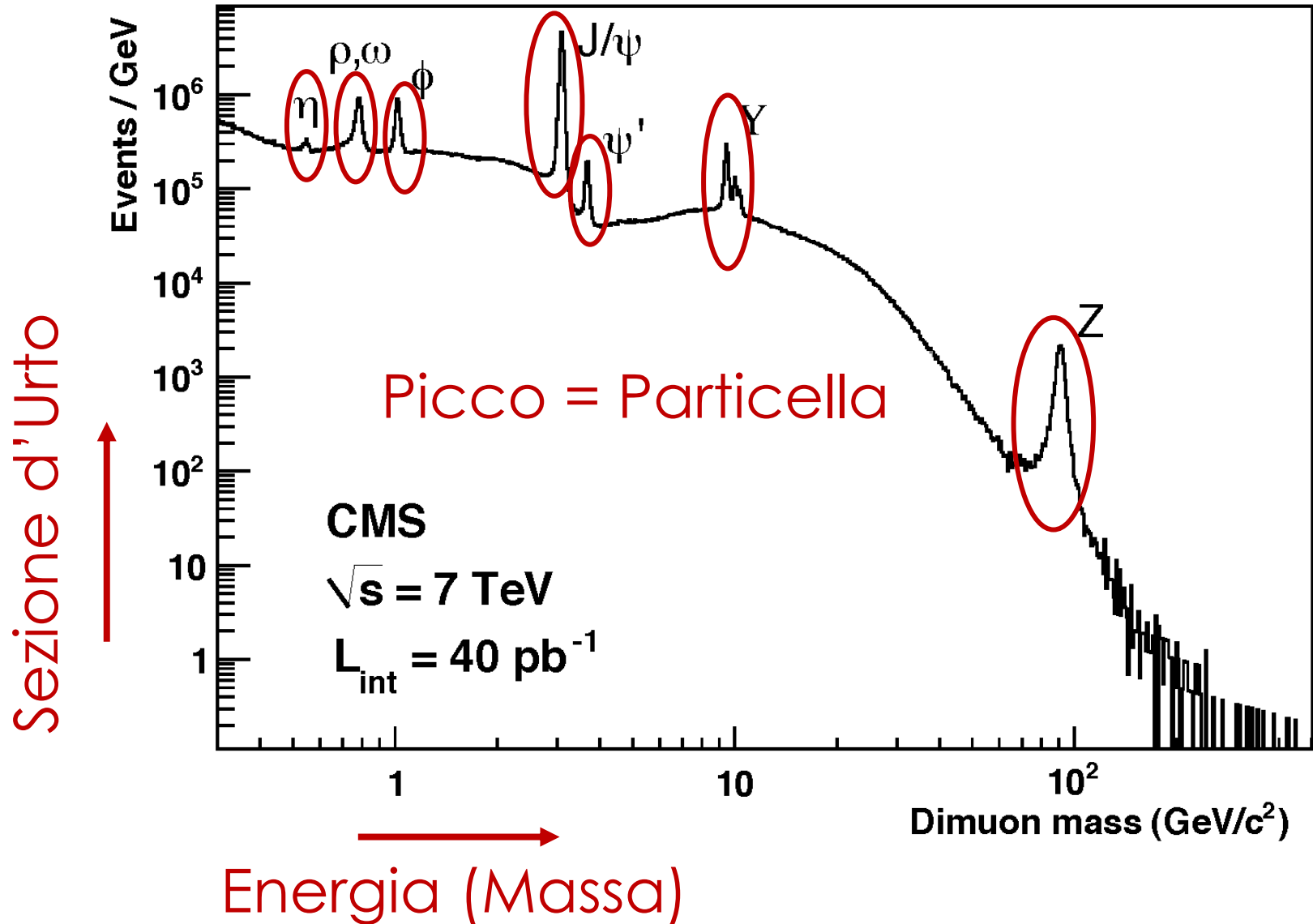


<https://www.youtube.com/@INFN>



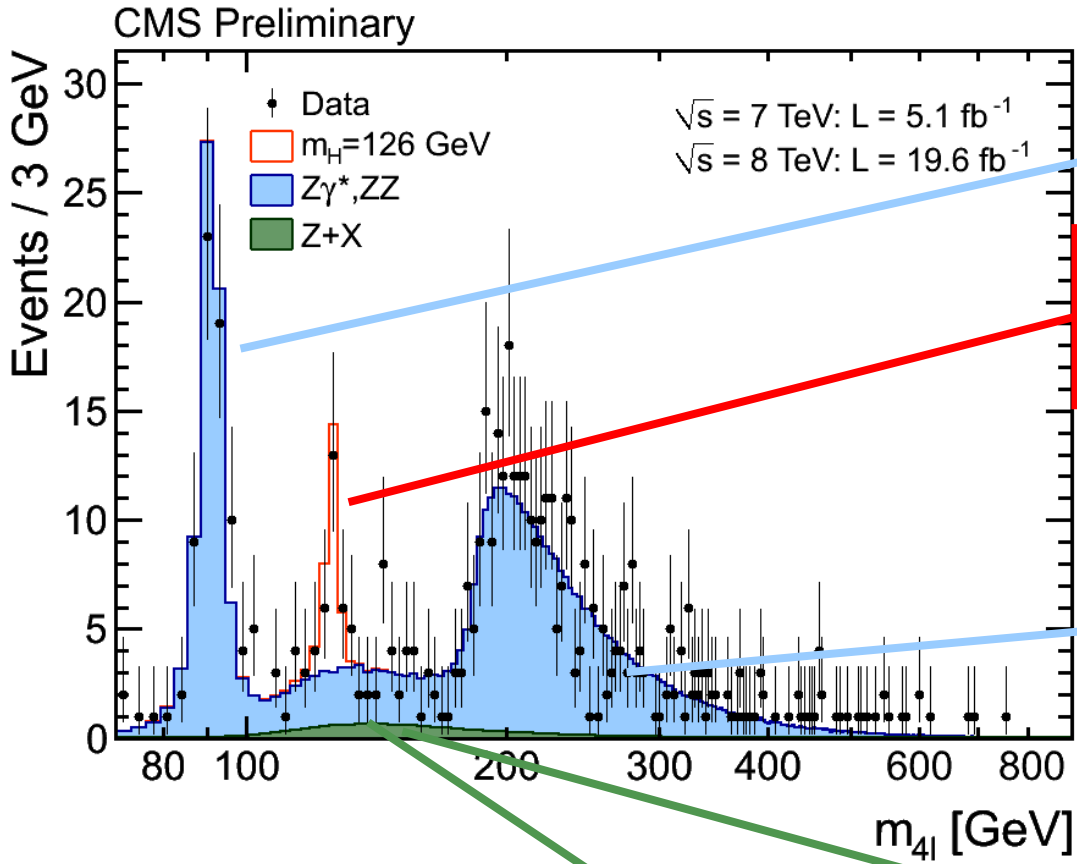
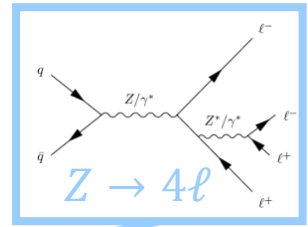
Backup

La sezione d'urto

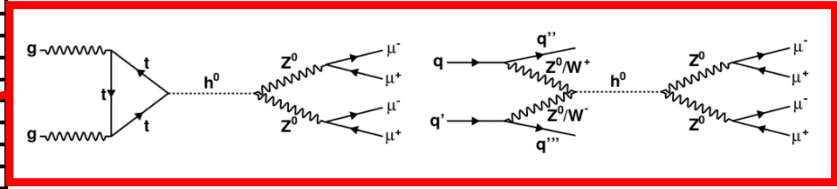


Domanda

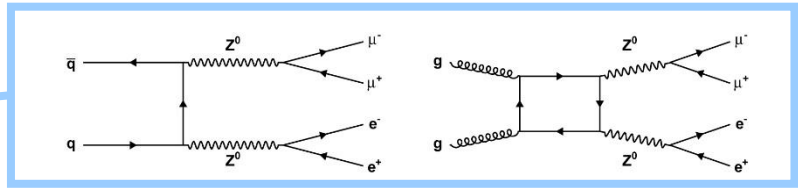
Spettro di massa invariante



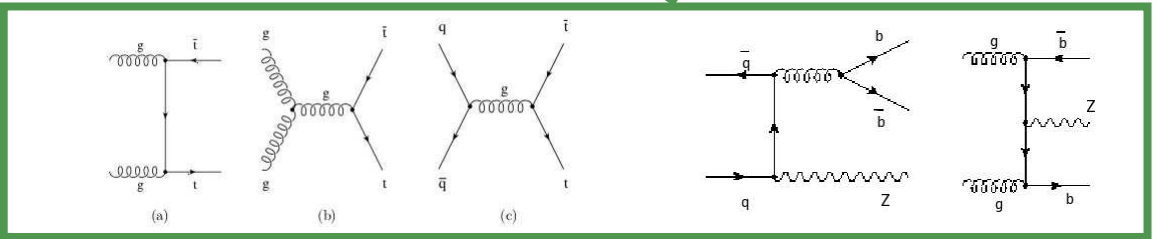
SIGNAL: $H \rightarrow 4\ell$



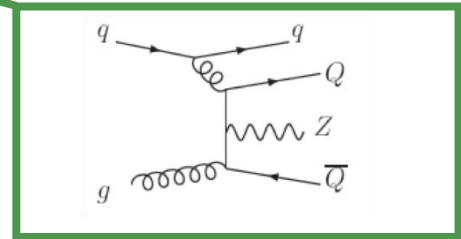
IRR.BKG: $qq/gg \rightarrow ZZ$



RED. BKG: $qq(gg) \rightarrow t\bar{t}, Zb\bar{b}$



INSTR. BKG: $Z + \text{light jets}$



Sezioni d'urto

