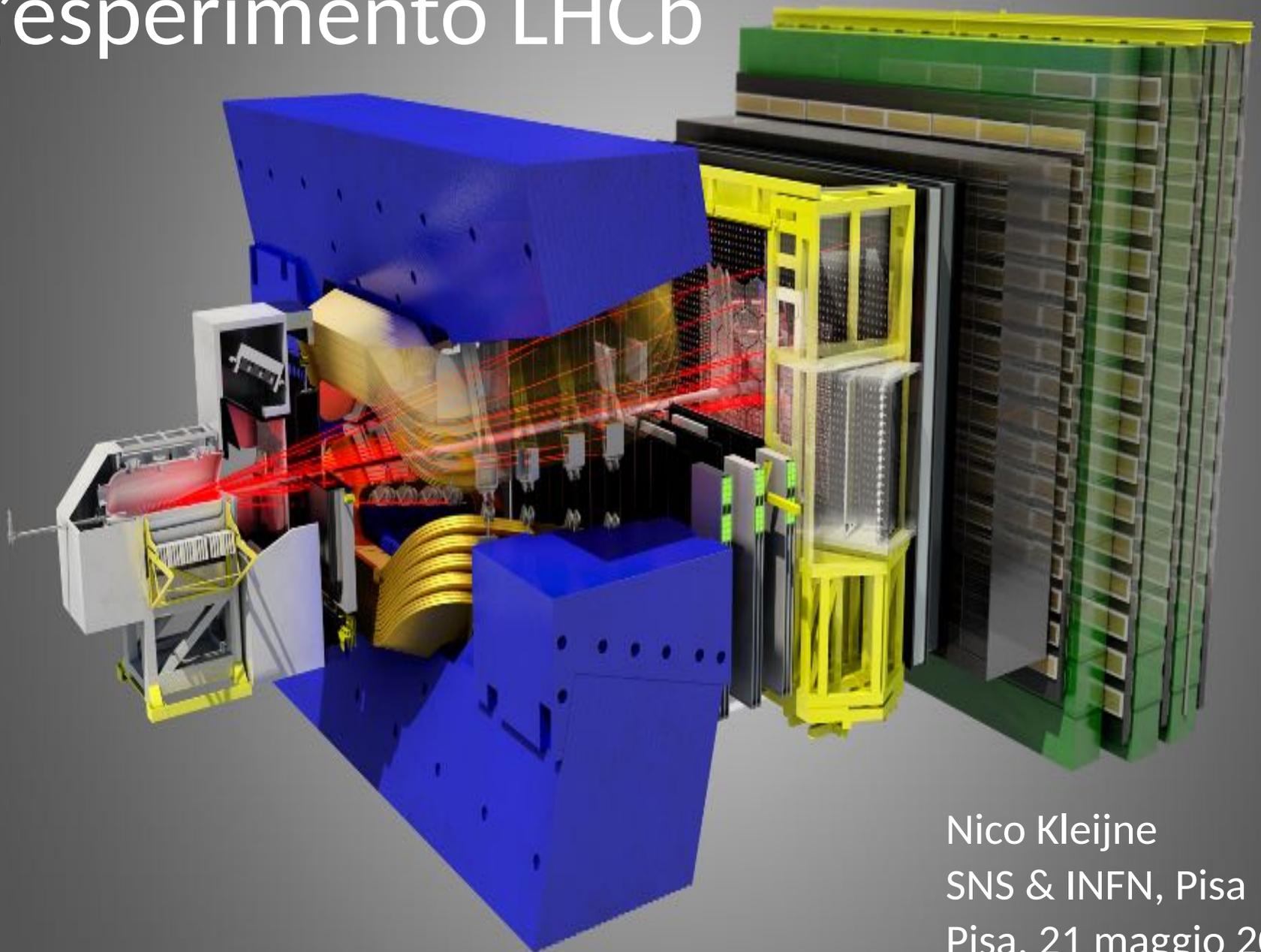


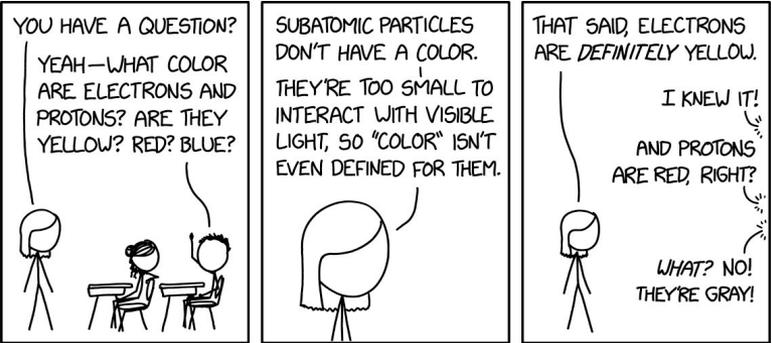
L'esperimento LHCb



Nico Kleijne
SNS & INFN, Pisa
Pisa, 21 maggio 2024

Fisica delle palline?

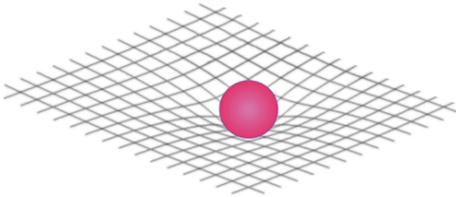
mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	0	0	± 1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS



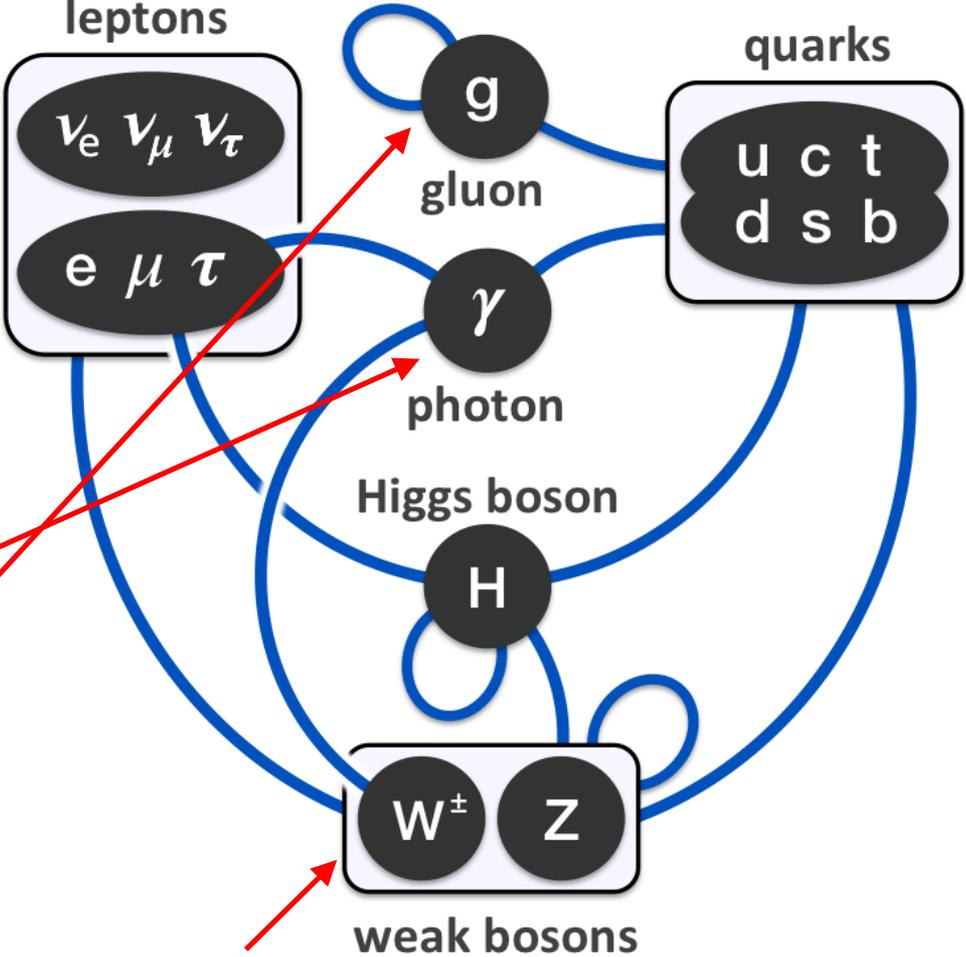
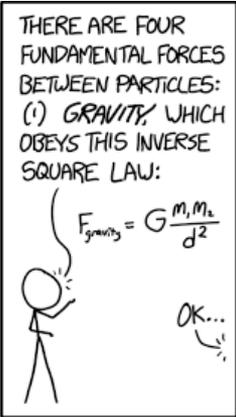
Lagrangiana del modello standard

$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\text{tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \\
 & +(\bar{\nu}_L, \bar{e}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.}) \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{\nu}_L, \bar{e}_L)\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] \\
 & -\frac{\sqrt{2}}{v} \left[(-\bar{e}_L, \bar{\nu}_L)\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} \right] \\
 & +(\bar{u}_L, \bar{d}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{u}_L, \bar{d}_L)\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] \\
 & -\frac{\sqrt{2}}{v} \left[(-\bar{d}_L, \bar{u}_L)\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix} \right] \\
 & +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.
 \end{aligned}$$

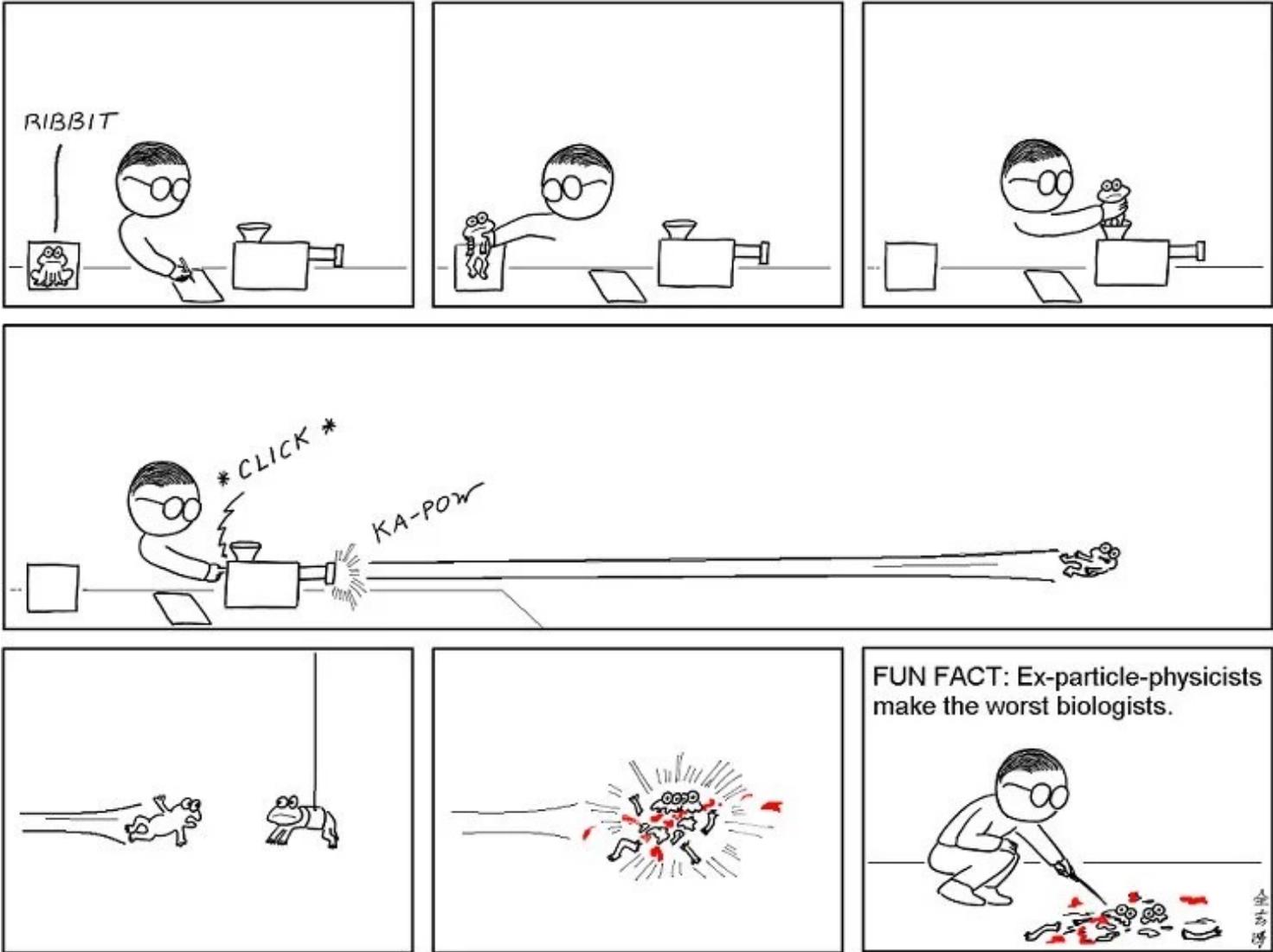
Forze fondamentali



$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

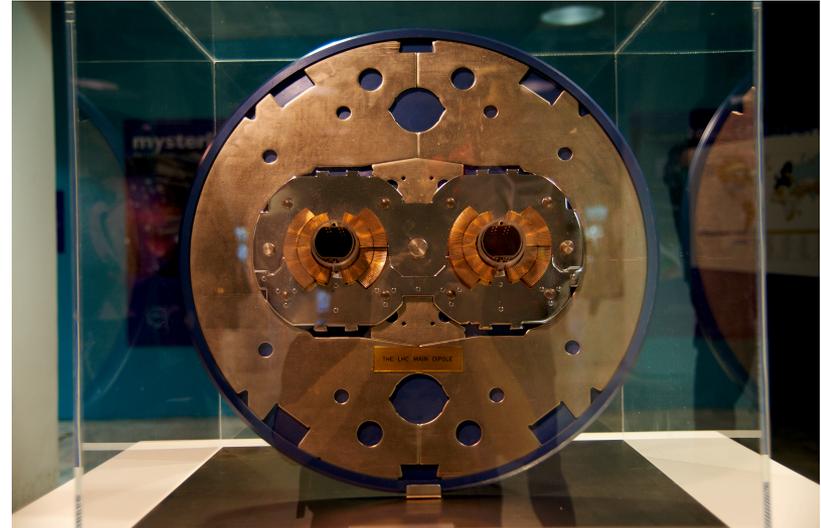


Perché le collisioni?

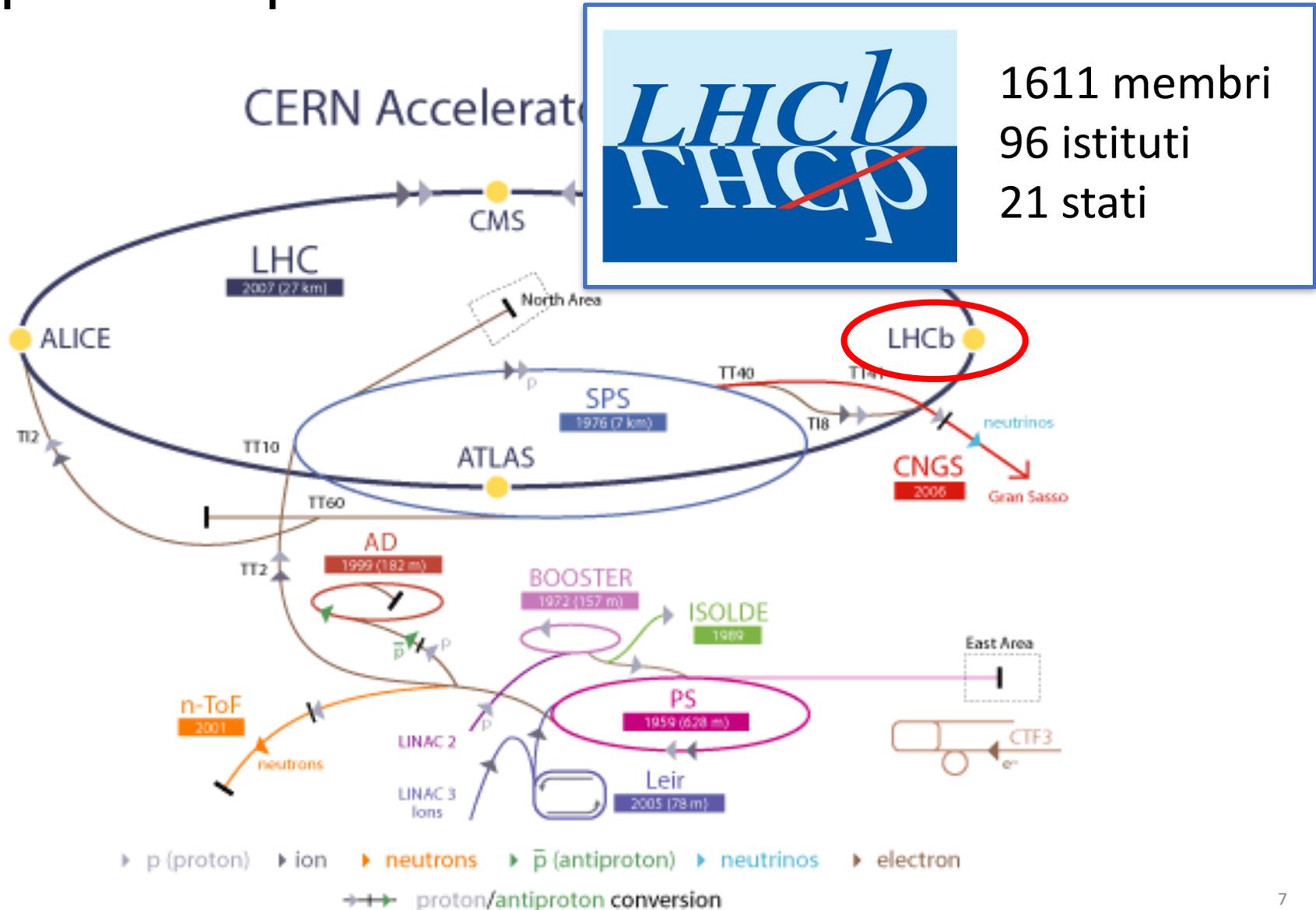


LHC (Large Hadron Collider)

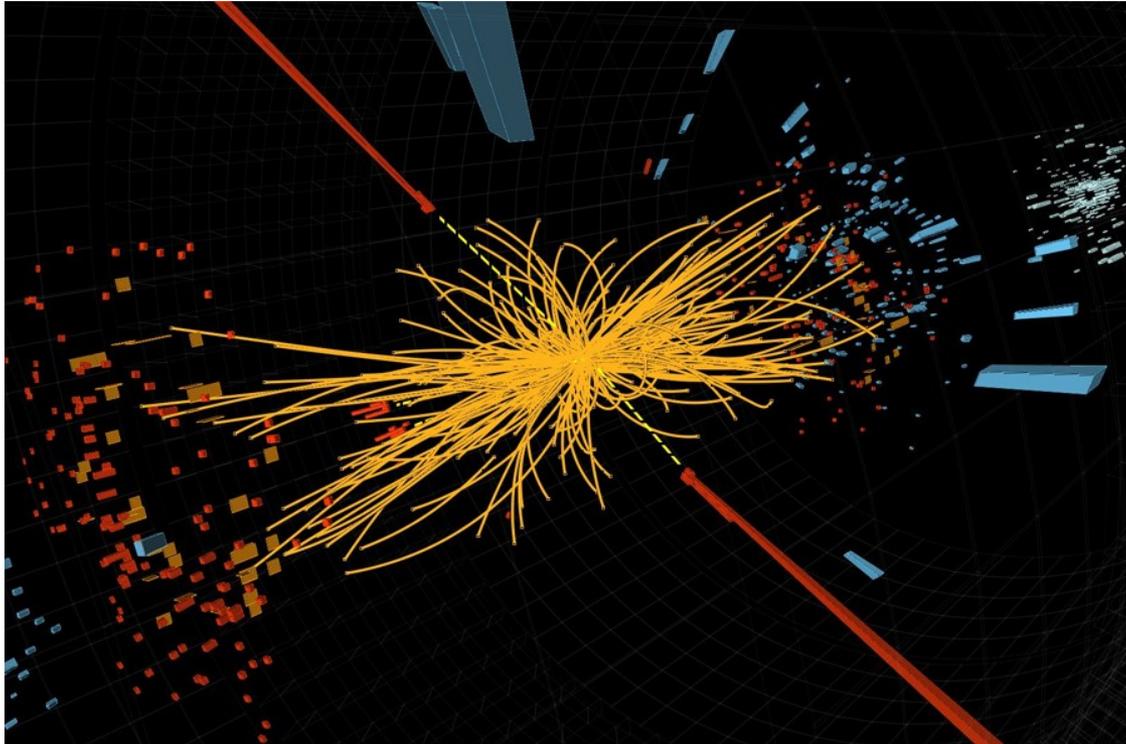
- 27 km di circonferenza, a una profondità di 50 ÷ 175 m
- protoni accelerati a 7 TeV ($\beta\gamma \approx 7000$)
- 1232 magneti dipolari superconduttori (15 m, 1.9 K, 8.3 T)
- 392 quadrupoli (5 ÷ 7 m)
- pacchetti di $1.5 \cdot 10^{11}$ protoni
- Collisioni a 40 MHz
- vuoto ultra-spinto (10^{-13} atm)
- 6 miliardi di € per la costruzione (bolletta elettrica: 30 milioni di € all'anno)



I quattro esperimenti

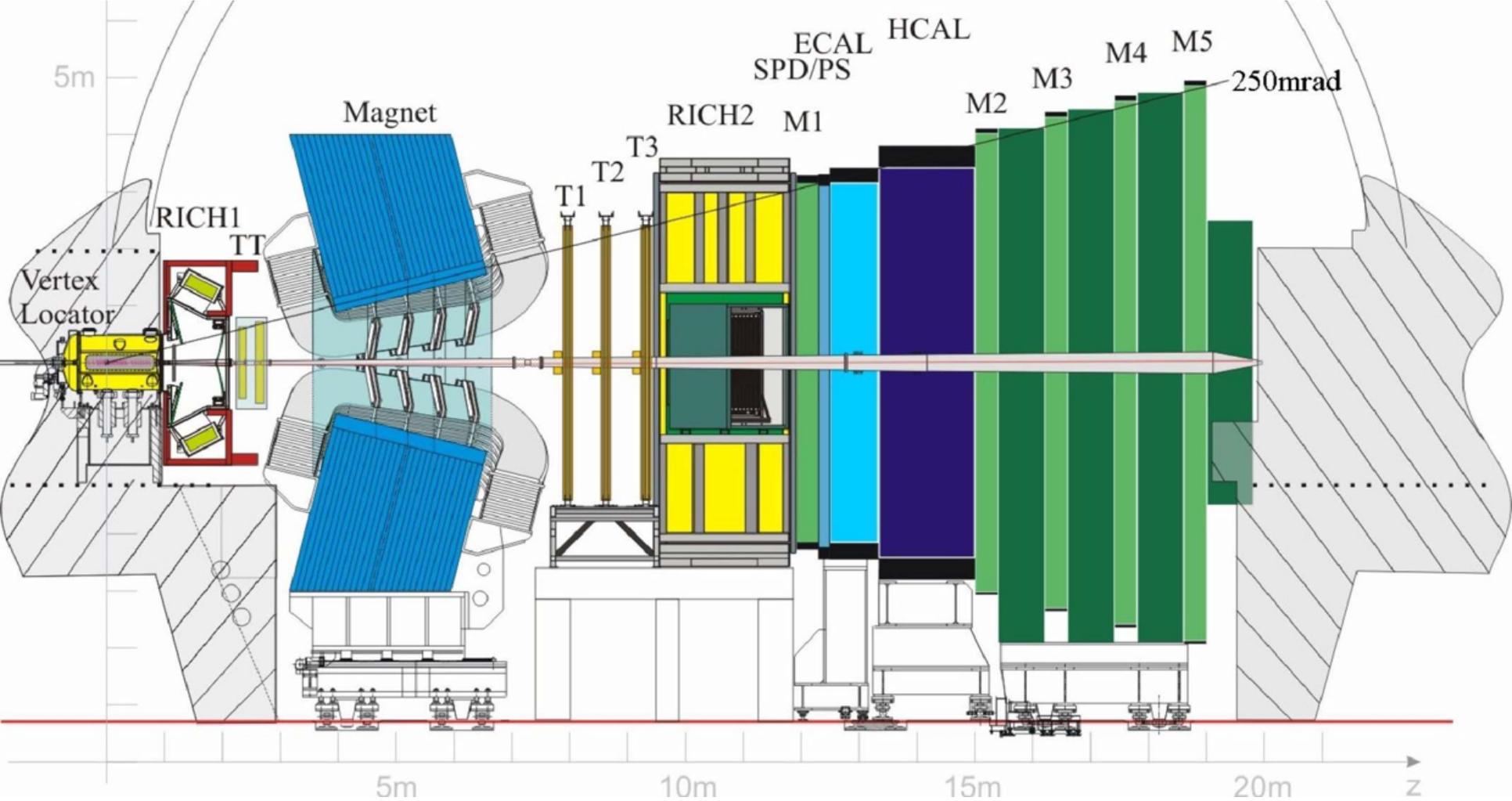


Come misurare le particelle?



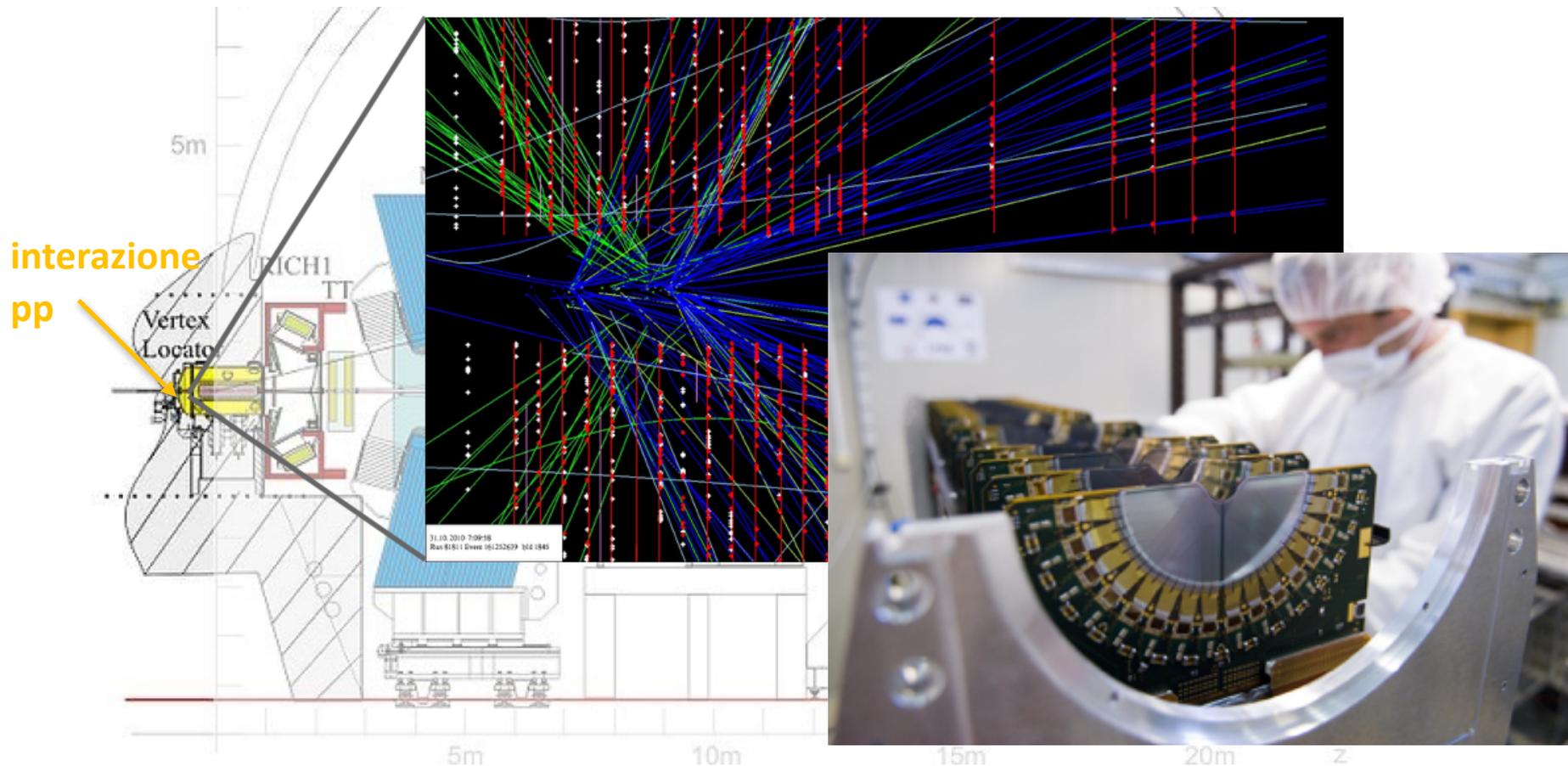
particelle stabili/a vita media lunga: possiamo misurare le loro proprietà «direttamente»
particelle instabili: misuriamo i prodotti di decadimento per inferire le loro proprietà

LHCb

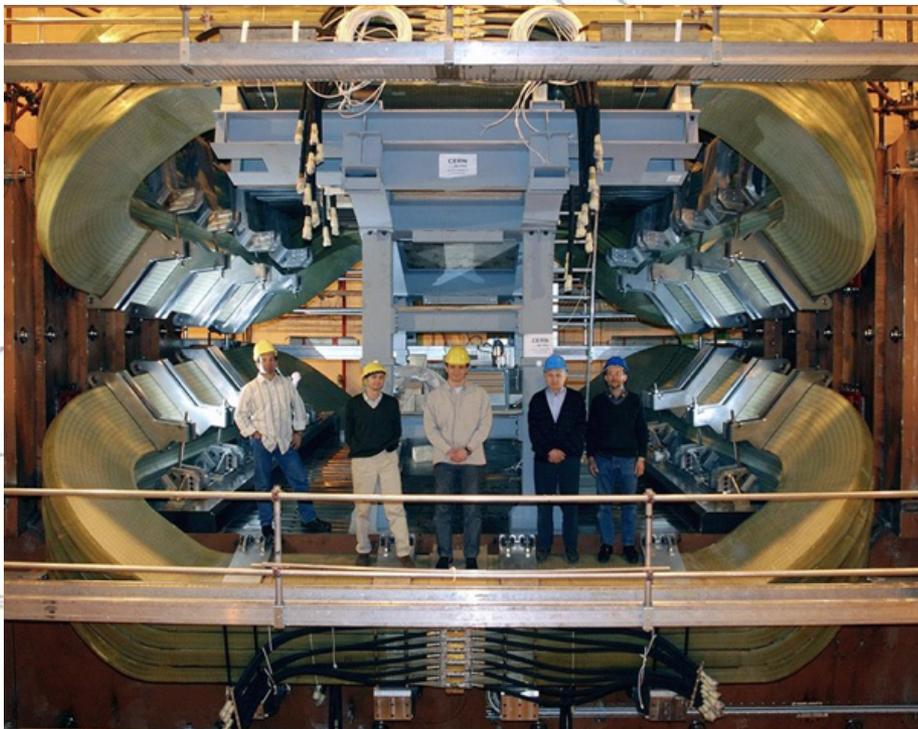
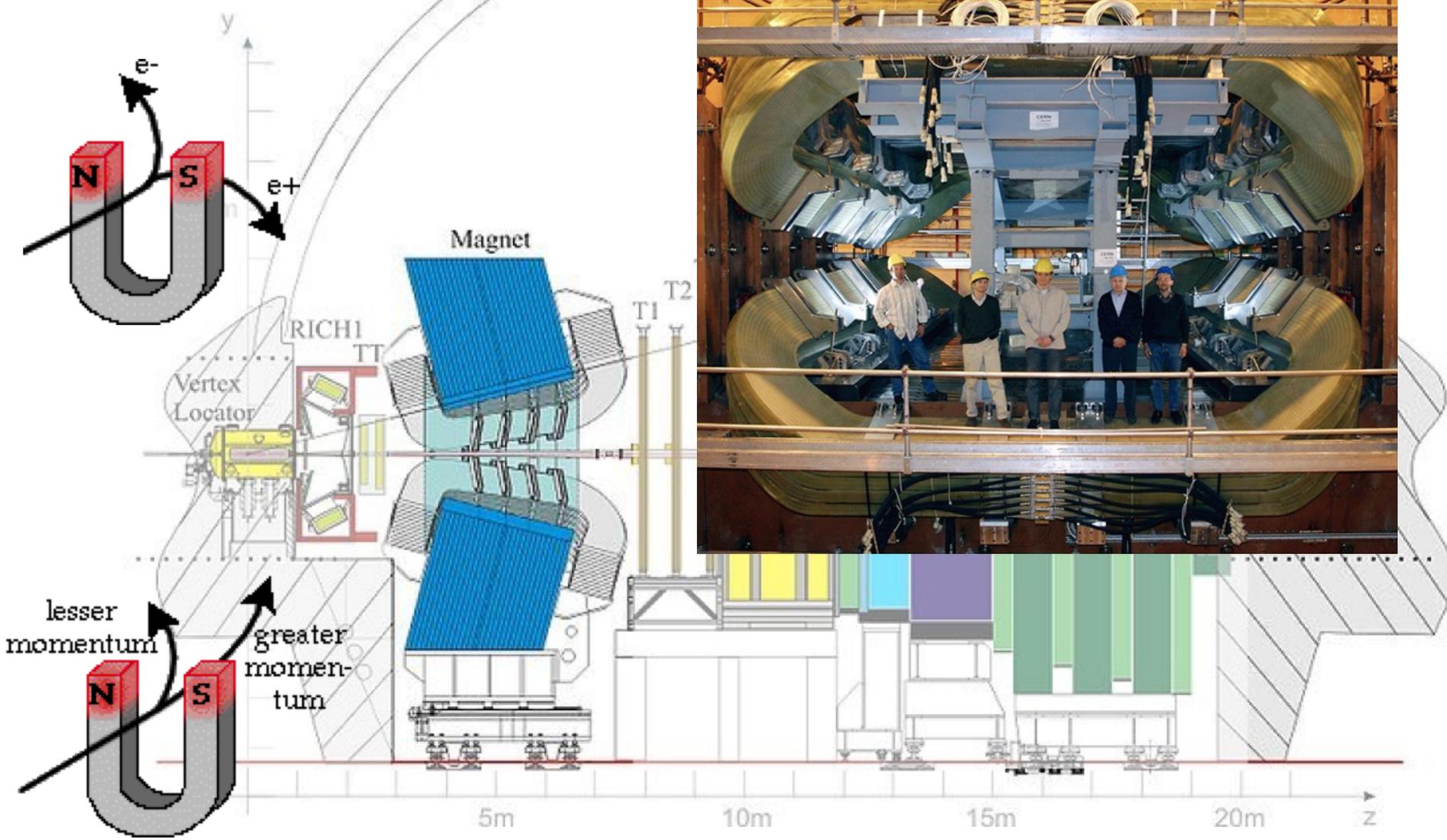


Particelle cariche

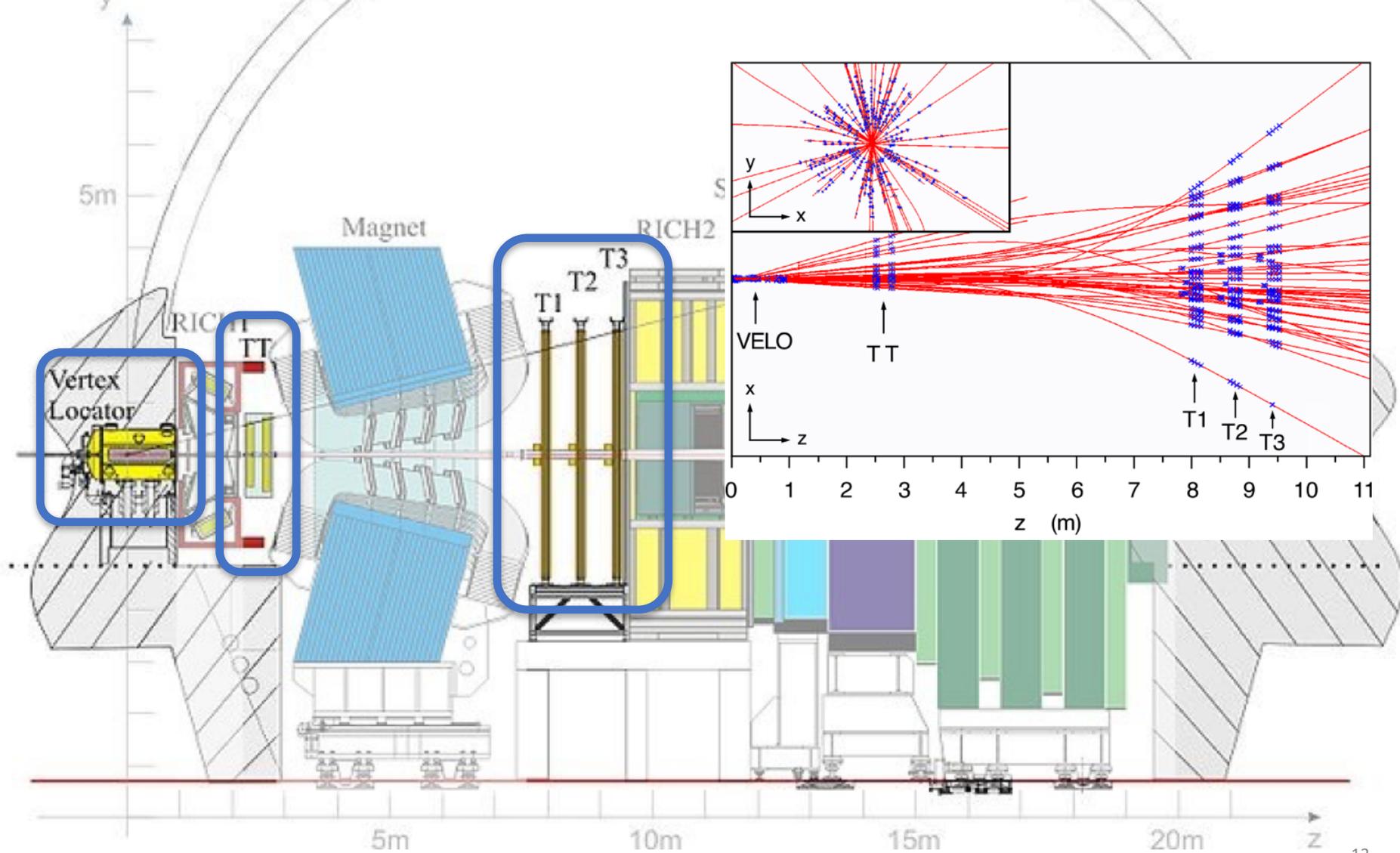
- Rilasciano dell'energia (ionizzazione, luce ecc.) quando passano attraverso la materia -> «tracce»
- rivelatori (sottili!) di silicio per alta risoluzione - *pixel* o *strip*
- gas altrove (raccolgo la carica di ionizzazione con un catodo e un anodo)



Magnete



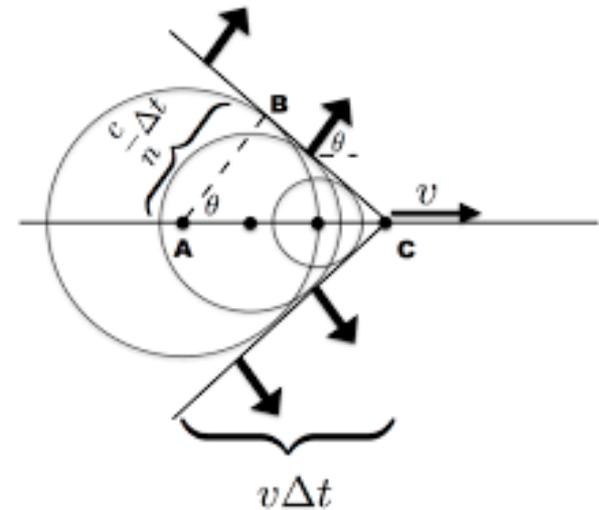
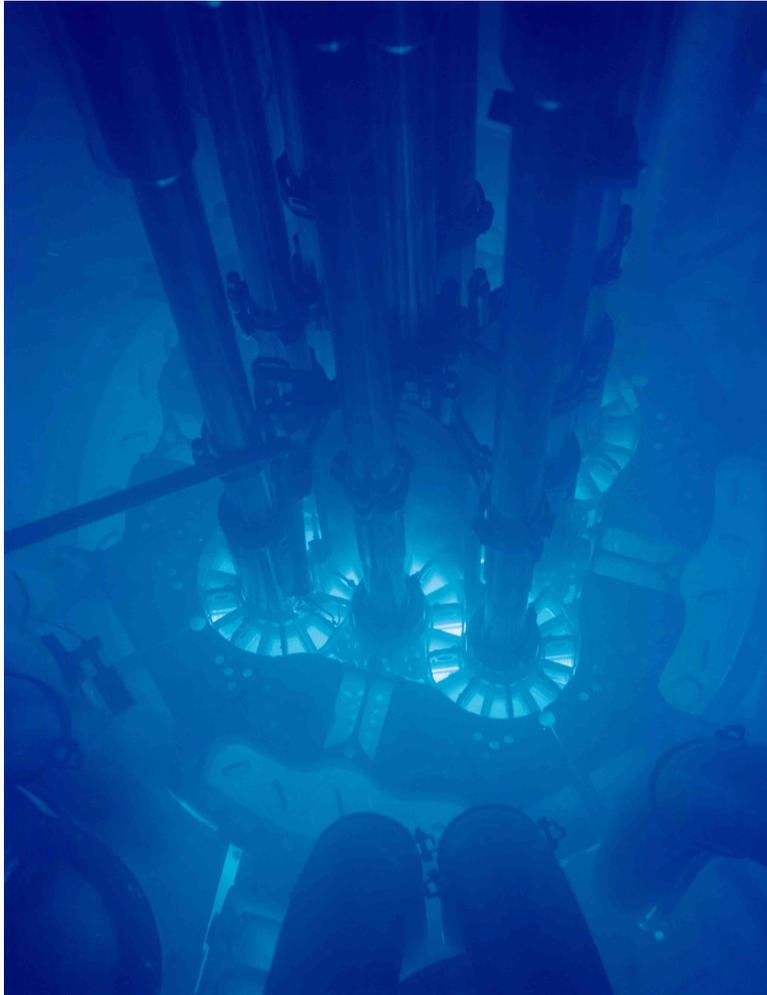
Traiettoria delle particelle cariche



E le altre proprietà?



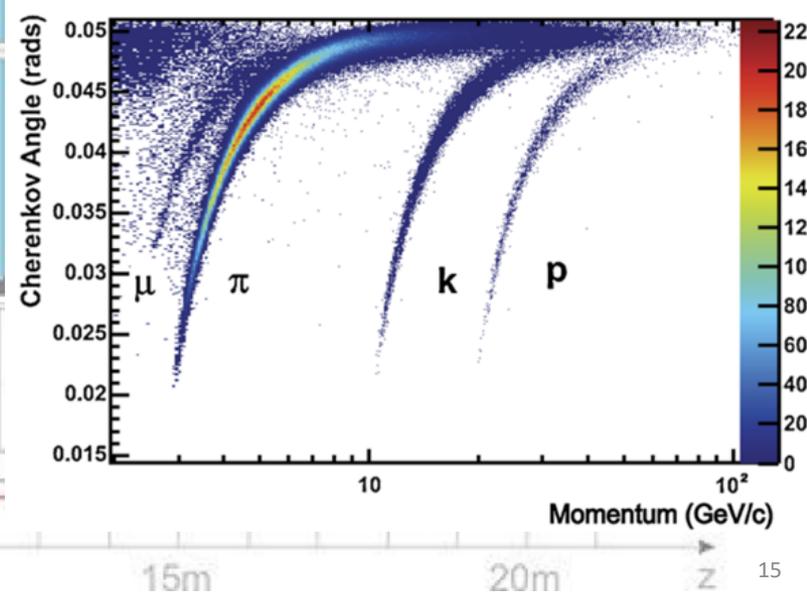
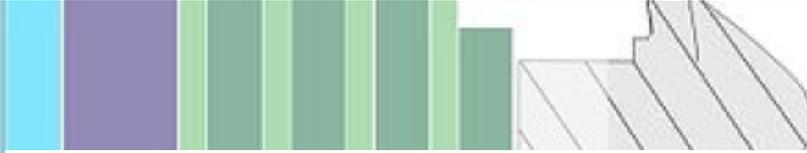
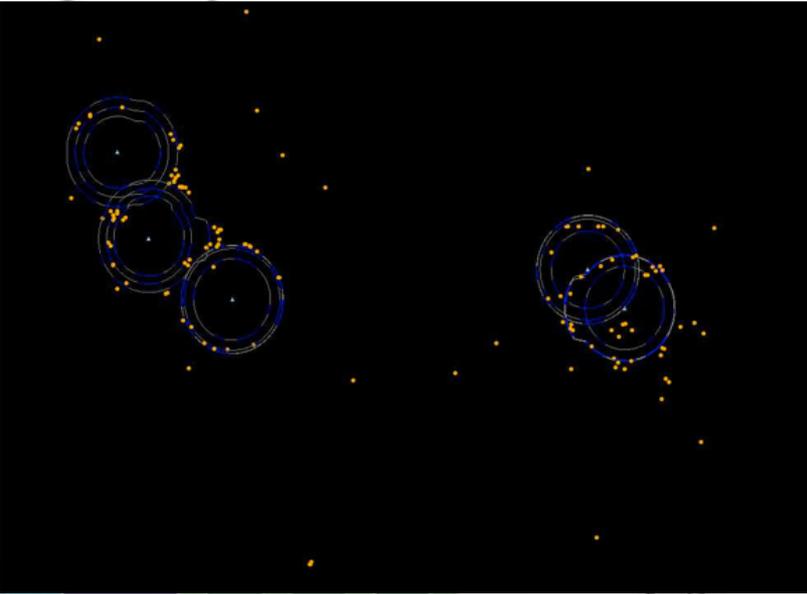
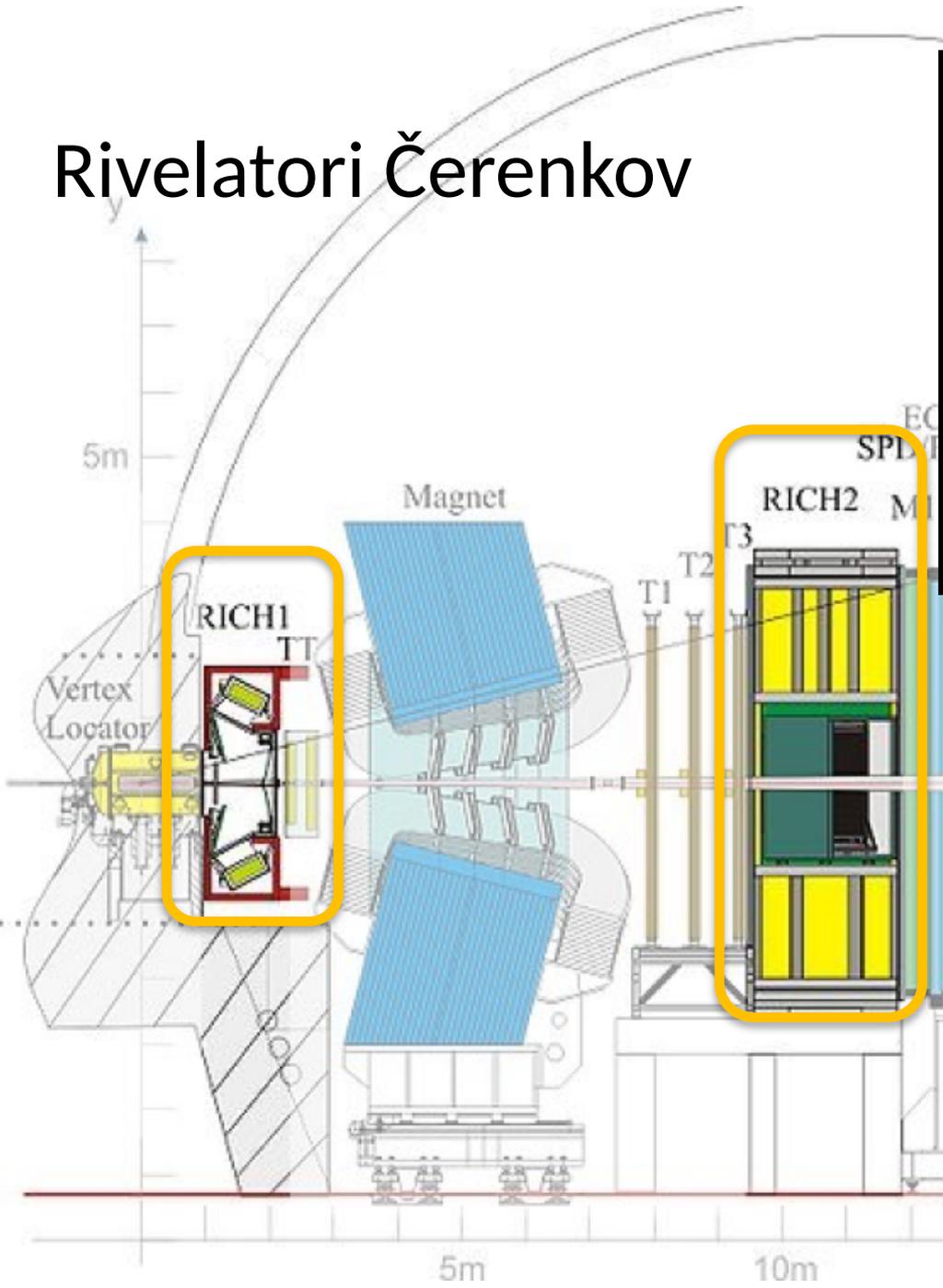
Rivelatori Čerenkov



Se $v > \frac{c}{n} \rightarrow$ emissione di luce
Čerenkov con angolo di emissione

$$\theta = \cos^{-1} \frac{1}{\beta n}$$

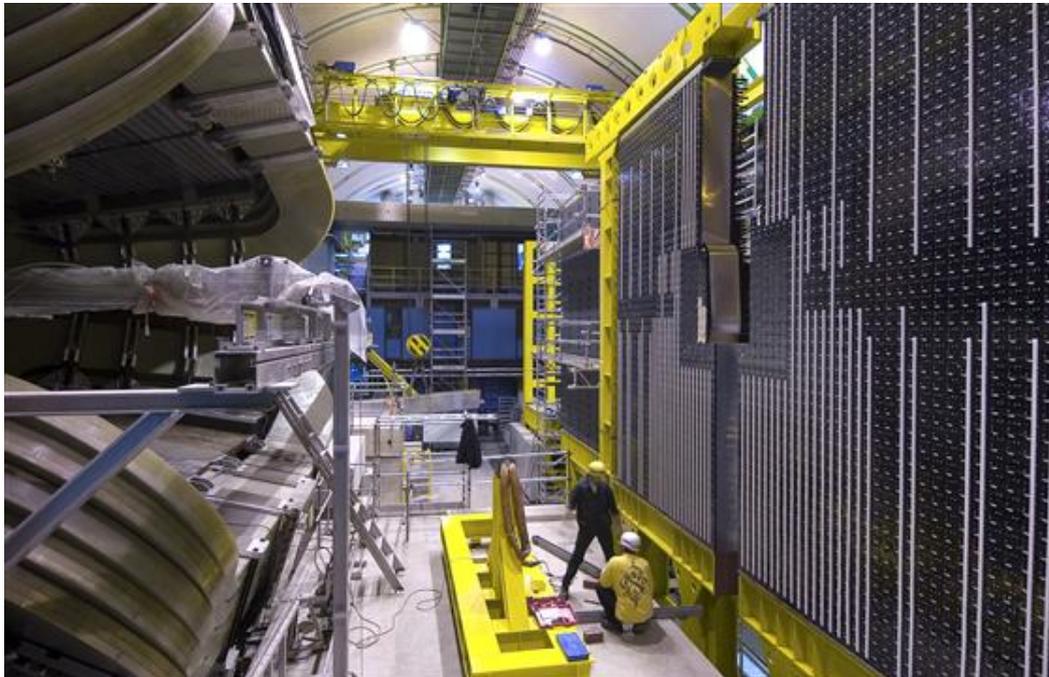
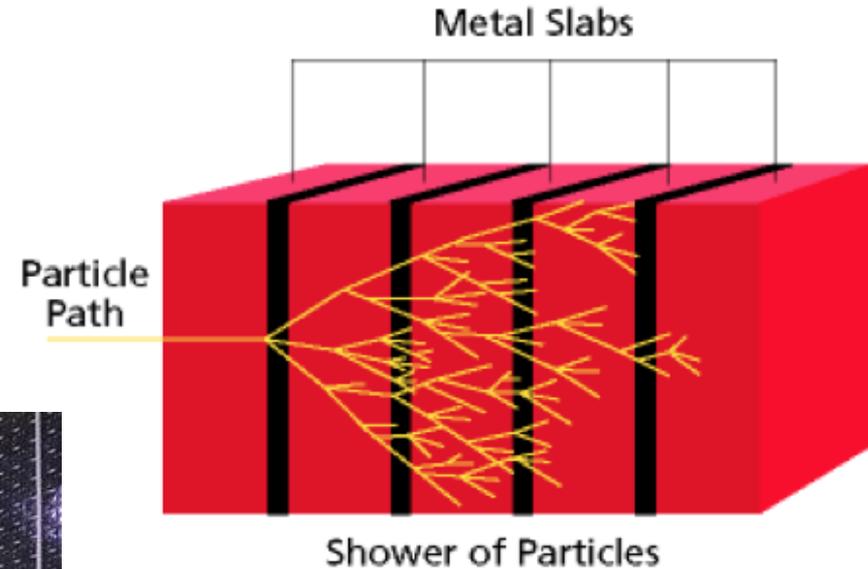
Rivelatori Čerenkov



Calorimetri (= misurare l'energia)

Passaggio attraverso la materia

-> parte dell'energia in nuove particelle



Interazione elettromagnetica ($\approx Z^2$)

e^- , γ

e^- hanno massa molto più piccola delle altre particelle

-> interagiscono con e^- degli atomi

Interazione forte ($\approx A$)

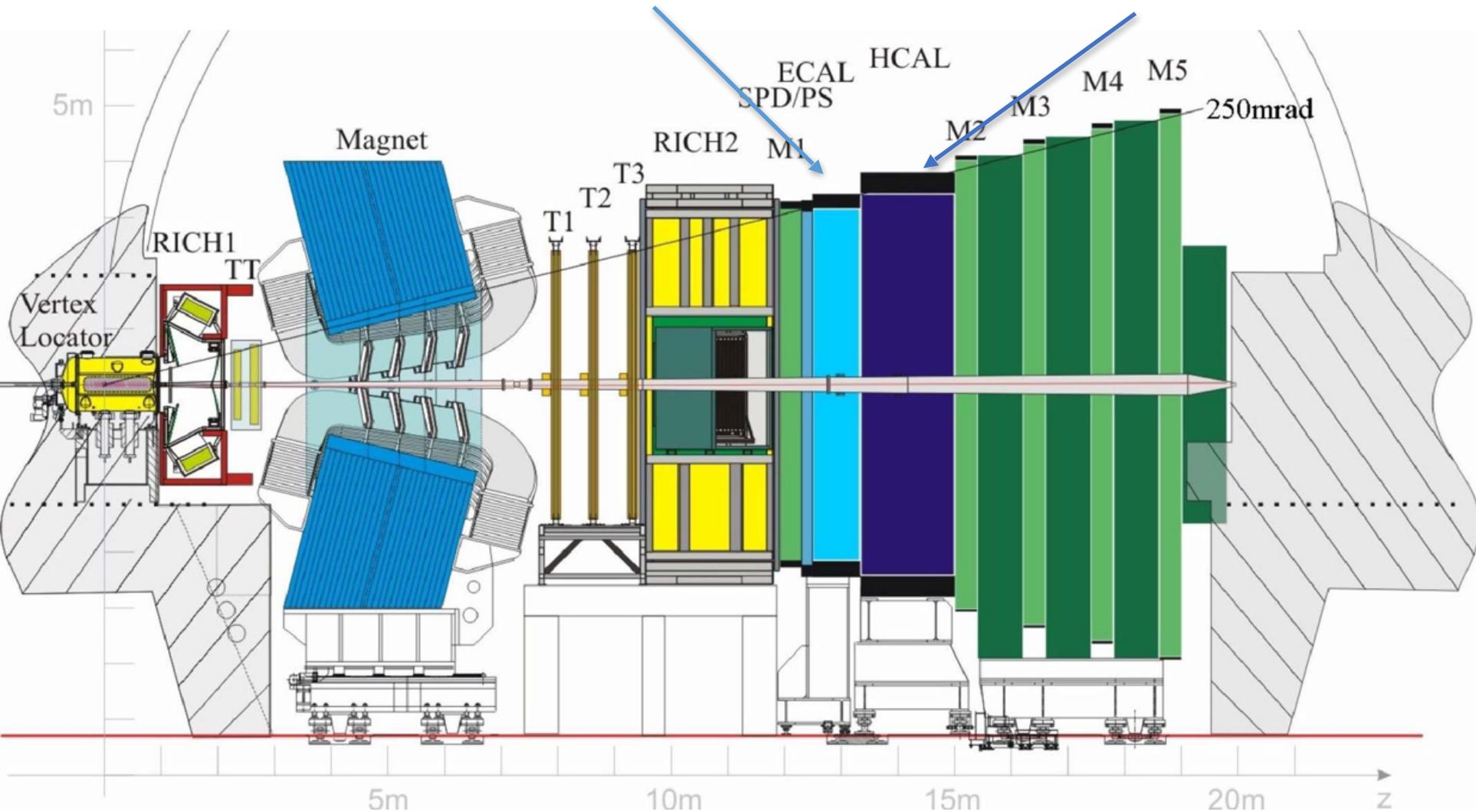
adroni = particelle formate da quark (2->mesoni; 3->barioni)

anche i neutroni!

Calorimetri

calorimetro elettromagnetico (Pb, alto Z)

calorimetro adronico (Fe)

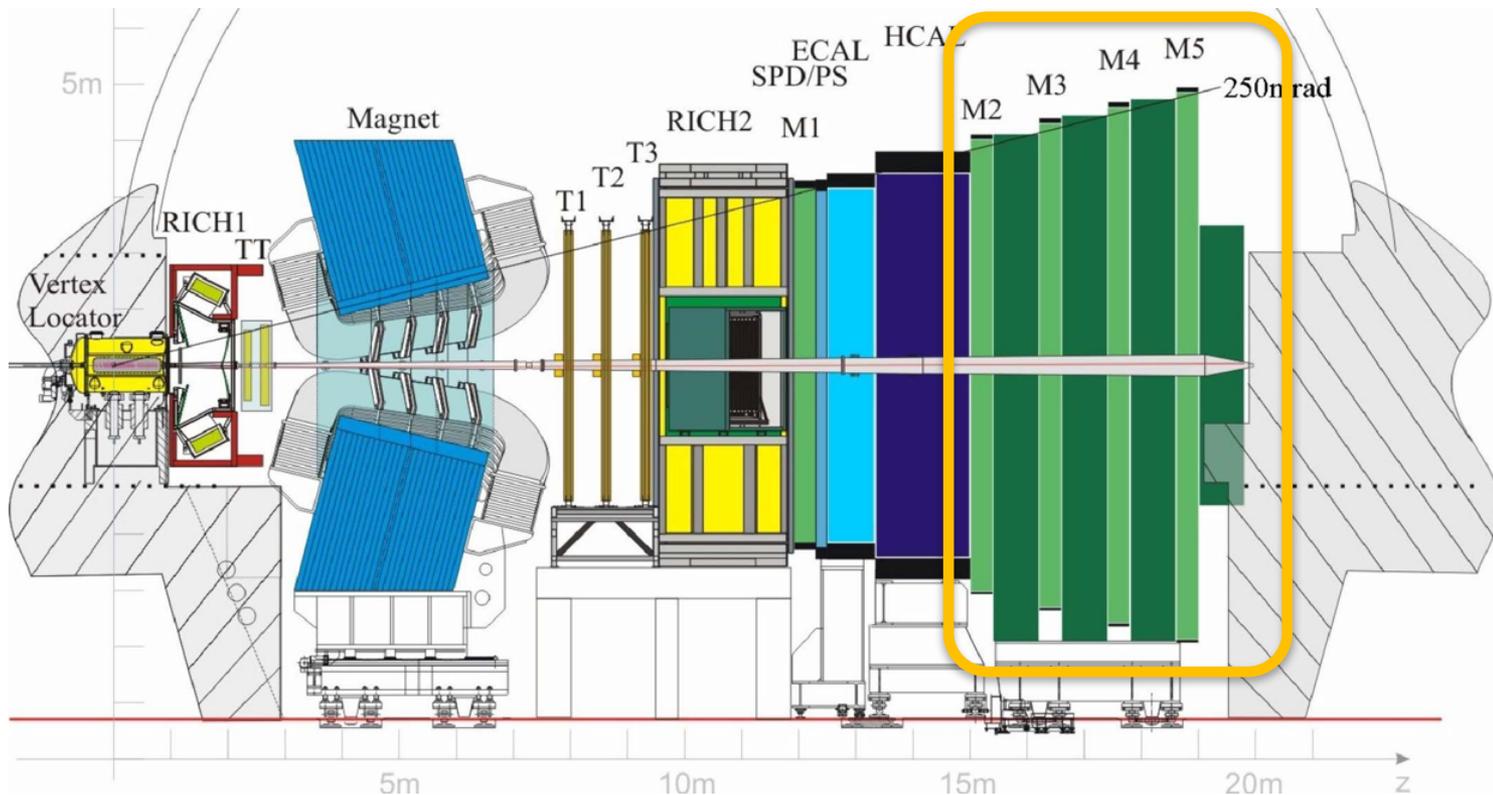


Muoni

«Cugini pesanti degli elettroni», la massa è 200 volte più grande:

- non perdono quasi energia per interazione elettromagnetica
- non interagiscono fortemente
- non li ferma nessuno...

strato spesso di ferro
(ferma tutte le altre particelle,
i sopravvissuti sono μ)



Ricapitoliamo...

Menu:

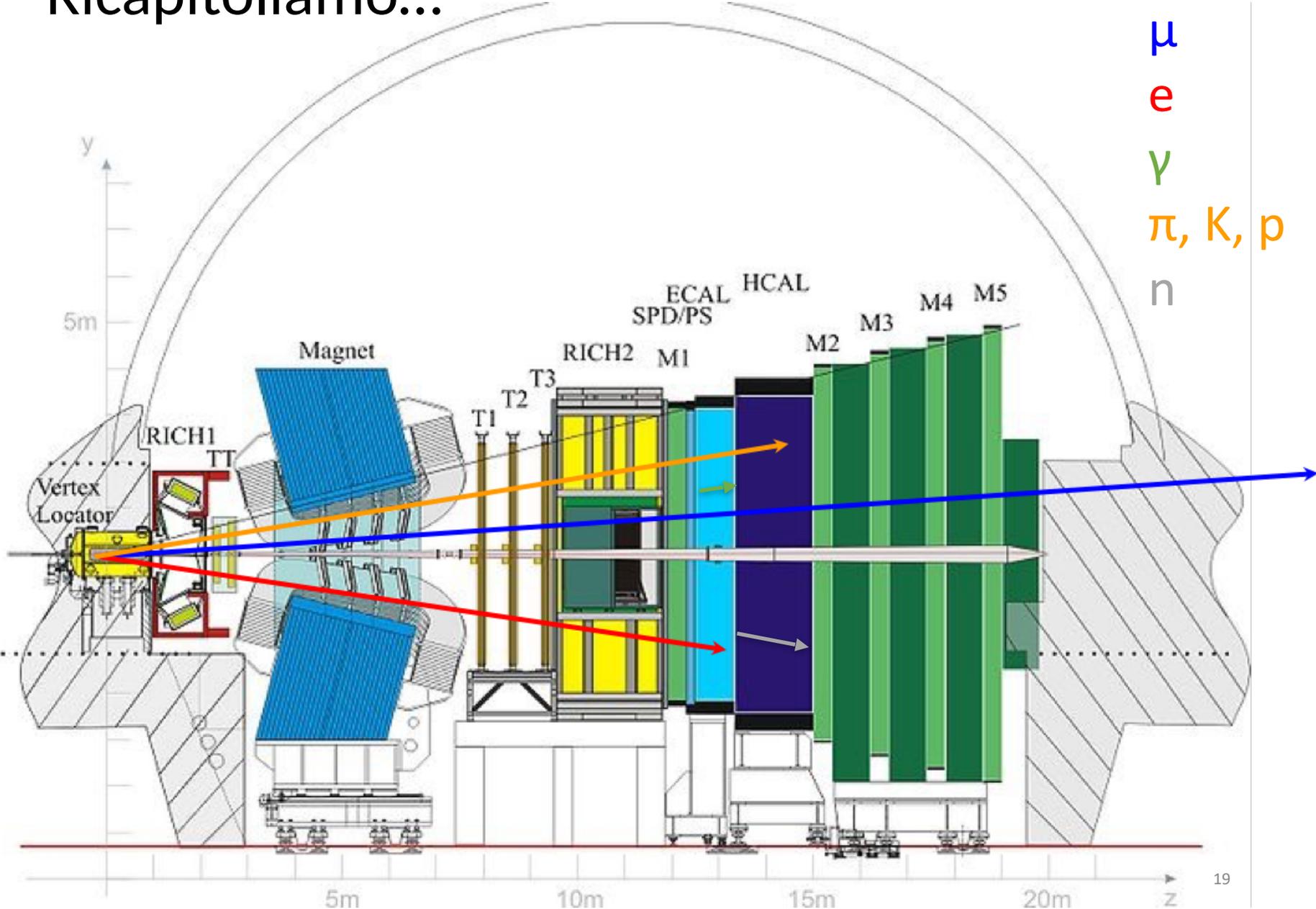
μ

e

γ

π, K, ρ

n



Problema...

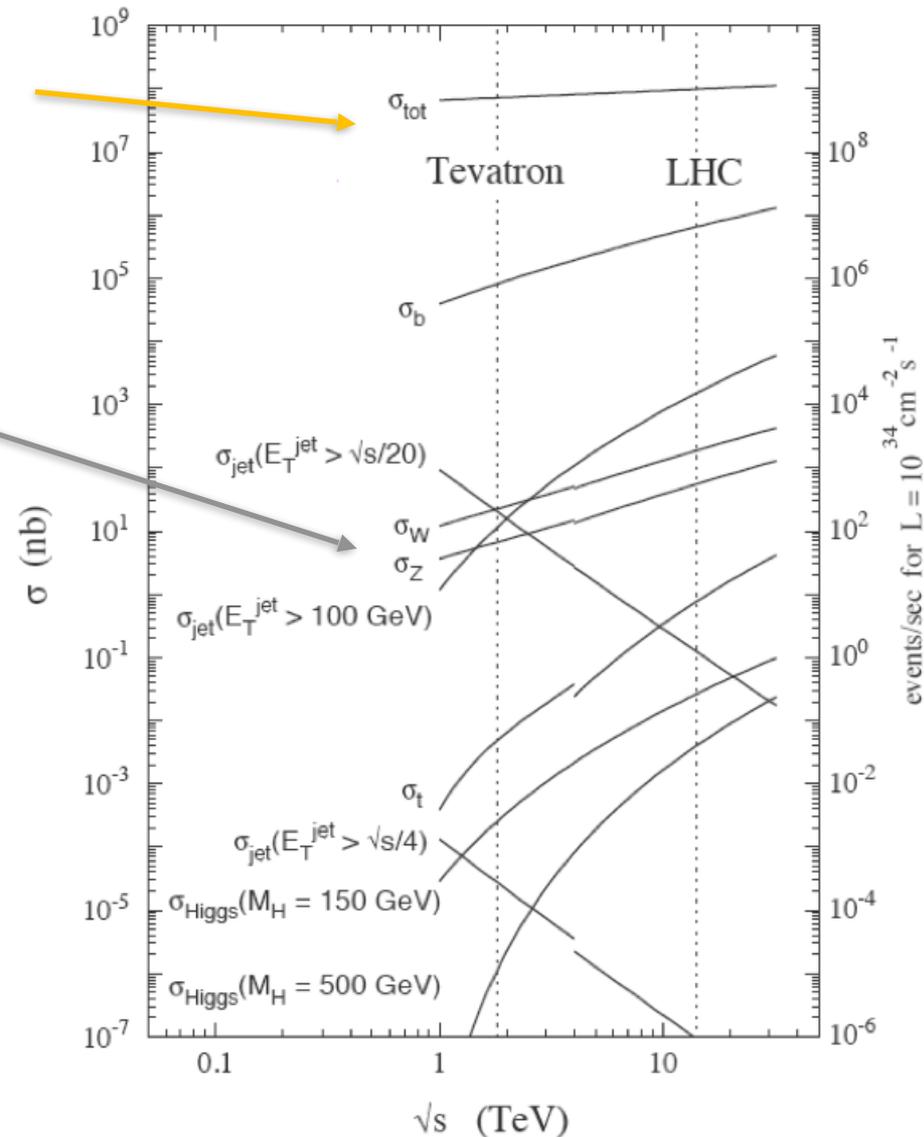
- Vorremmo salvare tutte le informazioni che arrivano dal nostro rivelatore (≈ 100 kB / collisione)
- 30 MHz di collisioni
- $100 \text{ kB} \times 30 \text{ MHz} = 3 \text{ TB/s}$

Soluzione... il *trigger*

Non tutte le collisioni prodotte a LHC sono interessanti.

I processi più studiati sono molto rari
-> salvo solo quelli

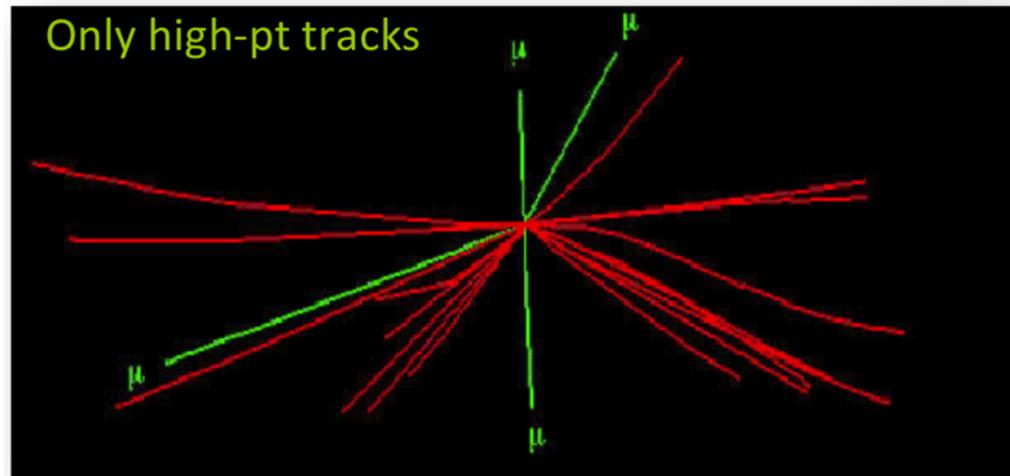
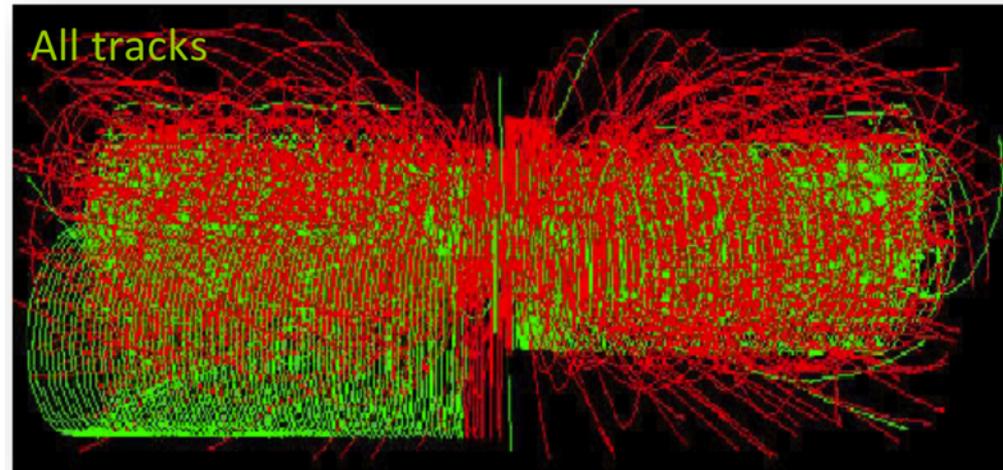
È una grande sfida:
devo capire come sono fatti gli eventi interessanti prima che l'esperimento inizi la presa dati,
se sbaglio non posso tornare indietro per correggermi!



Trigger

Algoritmo che decide, in breve tempo e usando una piccola parte delle informazioni disponibili, se un evento è interessante o no

- eventi con alto impulso
- eventi con muoni
- ecc.



Trigger

Prima fase: hardware-implemented
- selezione rozza (calorimetri, muoni, ...)



Seconda fase: super-computer
- ricostruisco (quasi) tutta la collisione



Un esempio

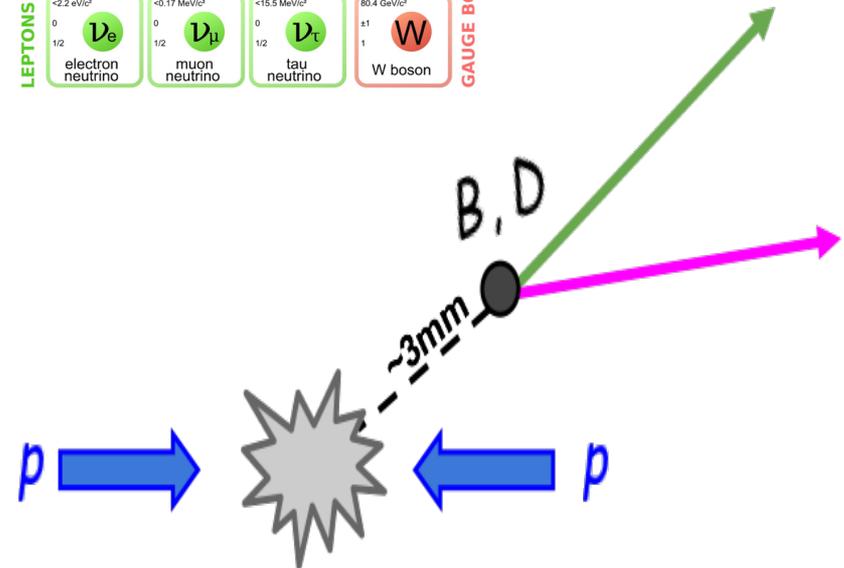
mass →	~2.3 MeV/c ²	~1.275 GeV/c ²	~173.07 GeV/c ²	0	~126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS					
	~4.8 MeV/c ²	~95 MeV/c ²	~4.18 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	91.2 GeV/c ²	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS					
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	80.4 GeV/c ²	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	GAUGE BOSONS

Le particelle contenenti i quark b e c hanno "lunghe" vite medie ~ps (10⁻¹² s)



Prima di decadere percorrono distanze dell'ordine del mm

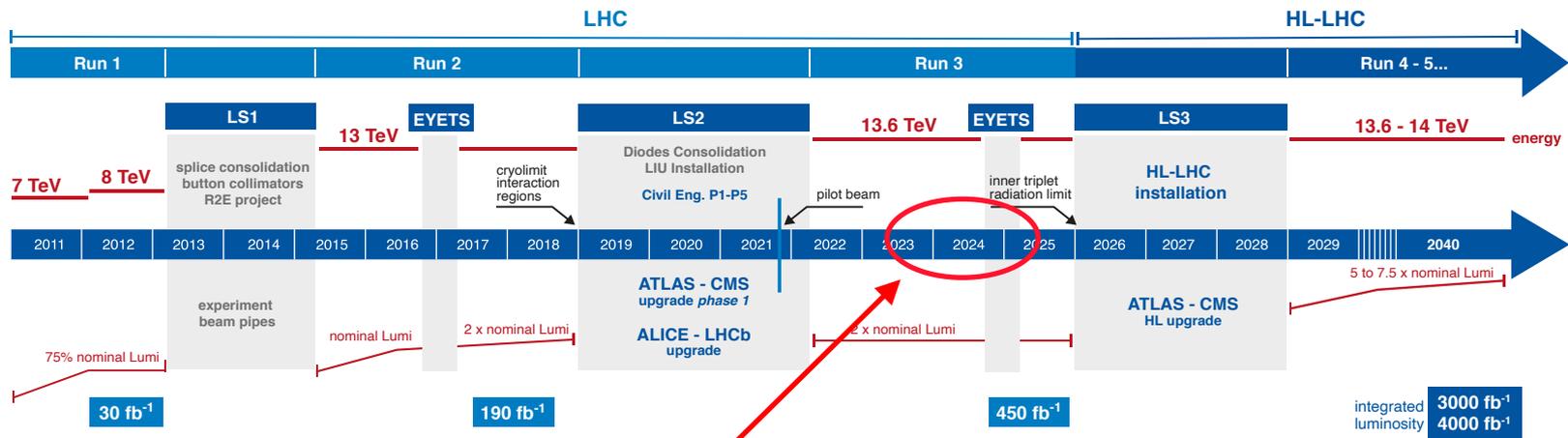
$$c\tau = 3 \cdot 10^{10} \frac{\text{cm}}{\text{s}} \cdot 10^{-12} \text{s} = 0.3 \text{mm}$$



Ci stiamo dimenticando della dilatazione dei tempi della relatività:

$$c\tau\gamma\beta \simeq 3 \div 5 \text{mm}$$

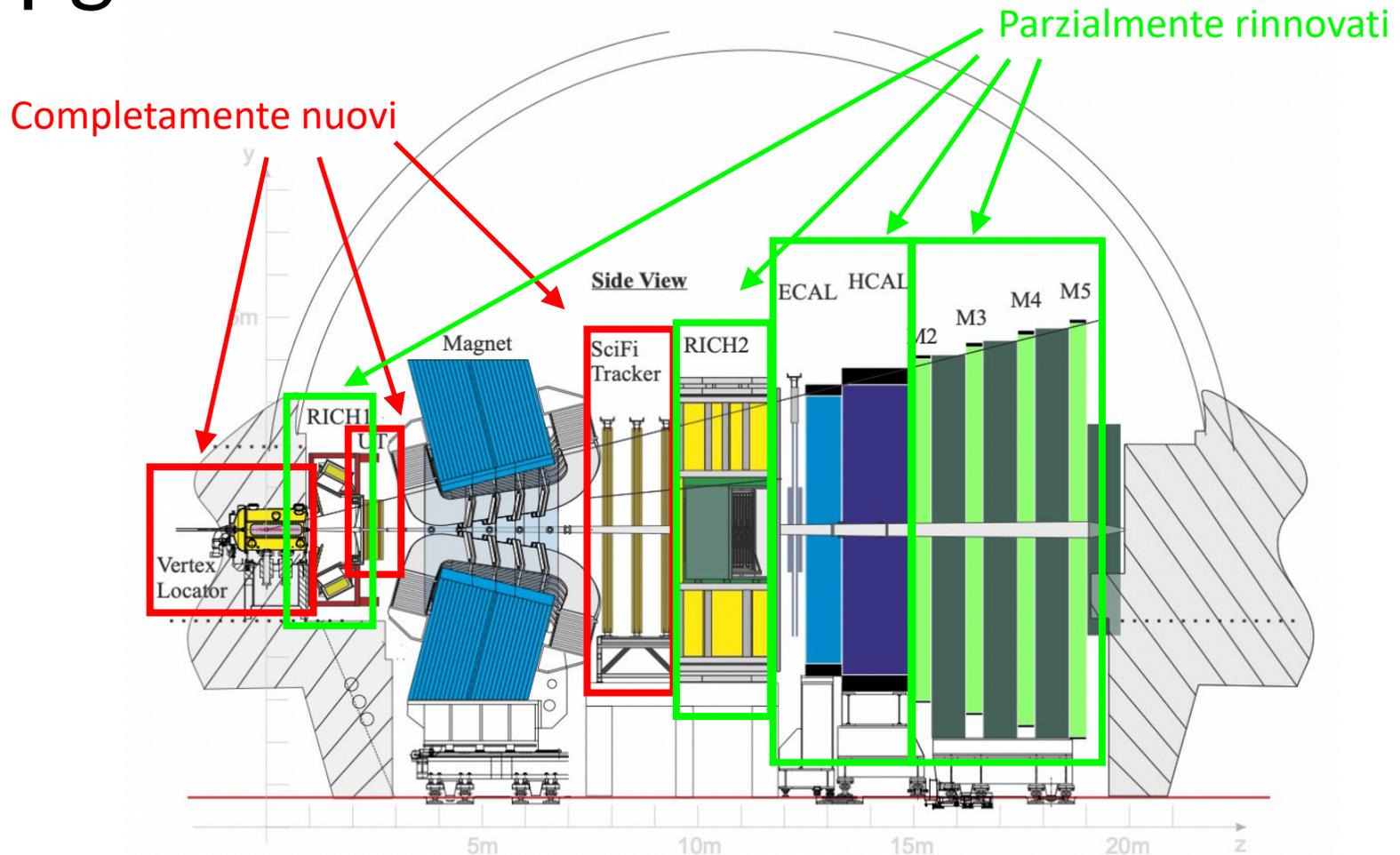
Upgrade di LHCb



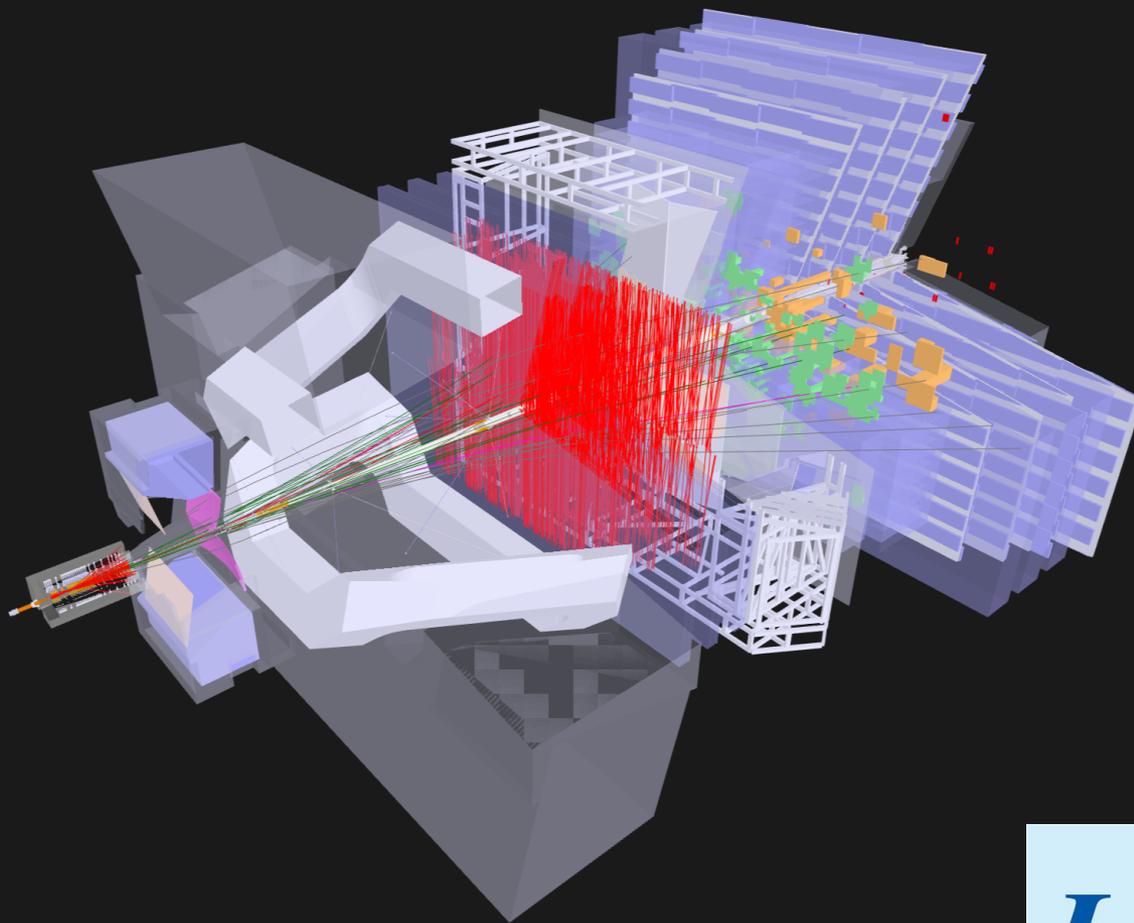
Ora siamo qua: a LHCb il numero di collisioni protone-protone in a ogni incrocio di pacchetti ora è circa 5 anziché 1.

Serve un nuovo detector

Upgrade di LHCb



In più c'è un nuovo sistema di trigger che al primo livello ricostruisce le tracce in tutti gli eventi a 30 MHz usando delle GPU.



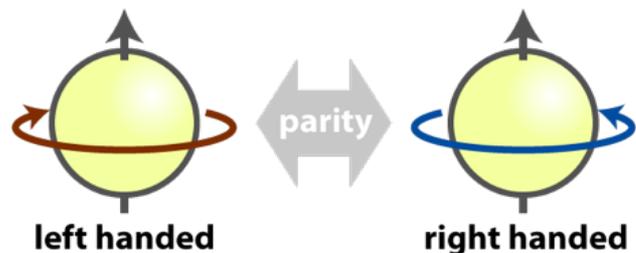
Alla fine dei giochi...

Che cosa misuriamo?

Trasformazioni di C e di P

Parità

(= inverte il verso degli assi)

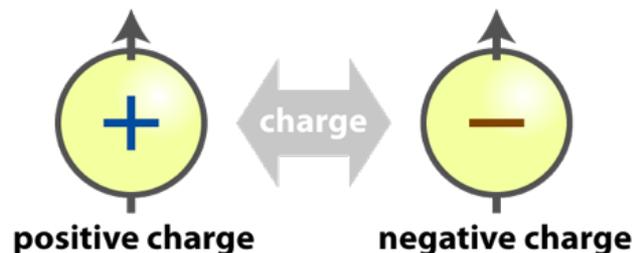


$$\begin{aligned}\rho(\mathbf{x},t) &\rightarrow \rho(-\mathbf{x},t) \\ \mathbf{j}(\mathbf{x},t) &\rightarrow -\mathbf{j}(-\mathbf{x},t) \\ \mathbf{E}(\mathbf{x},t) &\rightarrow -\mathbf{E}(-\mathbf{x},t) \\ \mathbf{B}(\mathbf{x},t) &\rightarrow \mathbf{B}(-\mathbf{x},t)\end{aligned}$$

In E.M.

Coniugazione di carica

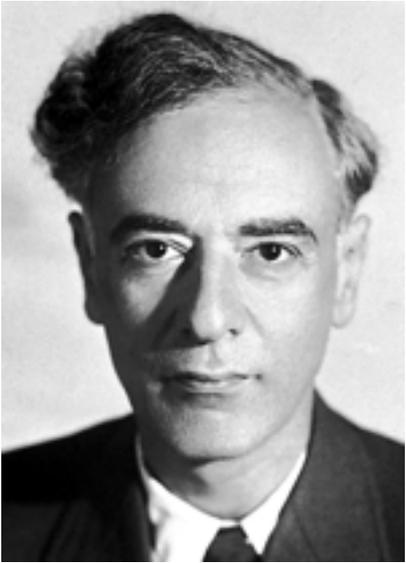
(= inverte il segno delle cariche)



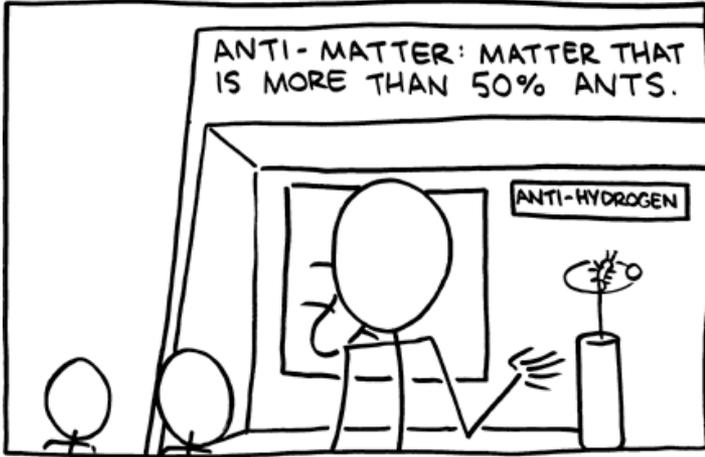
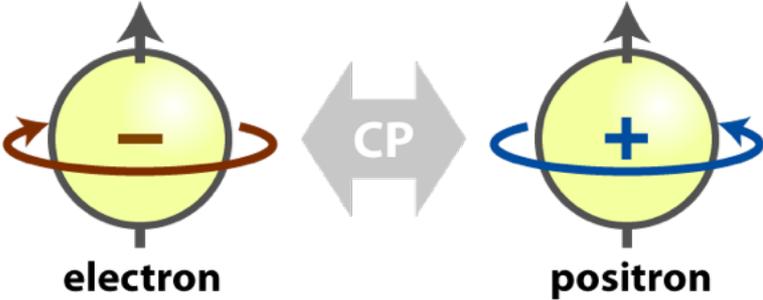
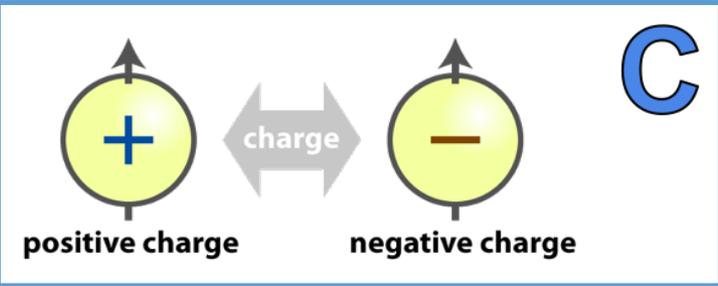
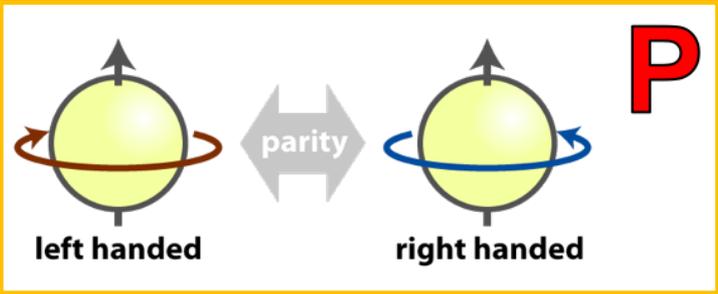
$$\begin{aligned}\rho(\mathbf{x},t) &\rightarrow -\rho(\mathbf{x},t) \\ \mathbf{j}(\mathbf{x},t) &\rightarrow -\mathbf{j}(\mathbf{x},t) \\ \mathbf{E}(\mathbf{x},t) &\rightarrow -\mathbf{E}(\mathbf{x},t) \\ \mathbf{B}(\mathbf{x},t) &\rightarrow -\mathbf{B}(\mathbf{x},t)\end{aligned}$$

Simmetrie dell'interazione e.m., ma non di quella debole!

Trasformazione di CP: una simmetria della natura?



Lev Landau



Ma...

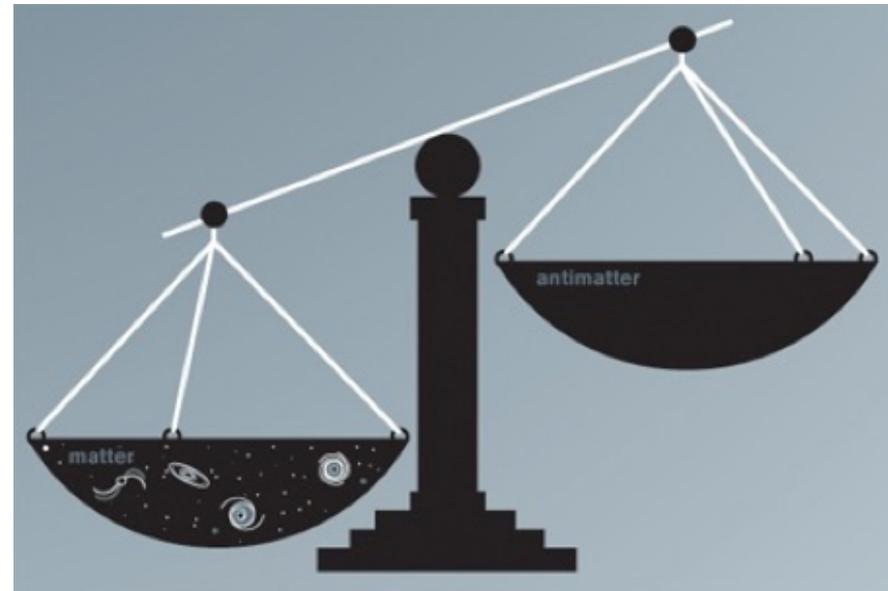
Anche la simmetria di CP è violata dalla natura.

-> posso distinguere fra materia e antimateria.

È importante?

L'universo è fatto quasi esclusivamente di materia. Ma all'inizio del Big Bang non c'è motivo per cui dovremmo supporre che ci fosse più materia che antimateria.

Ci dev'essere qualche interazione che distingue tra le due...

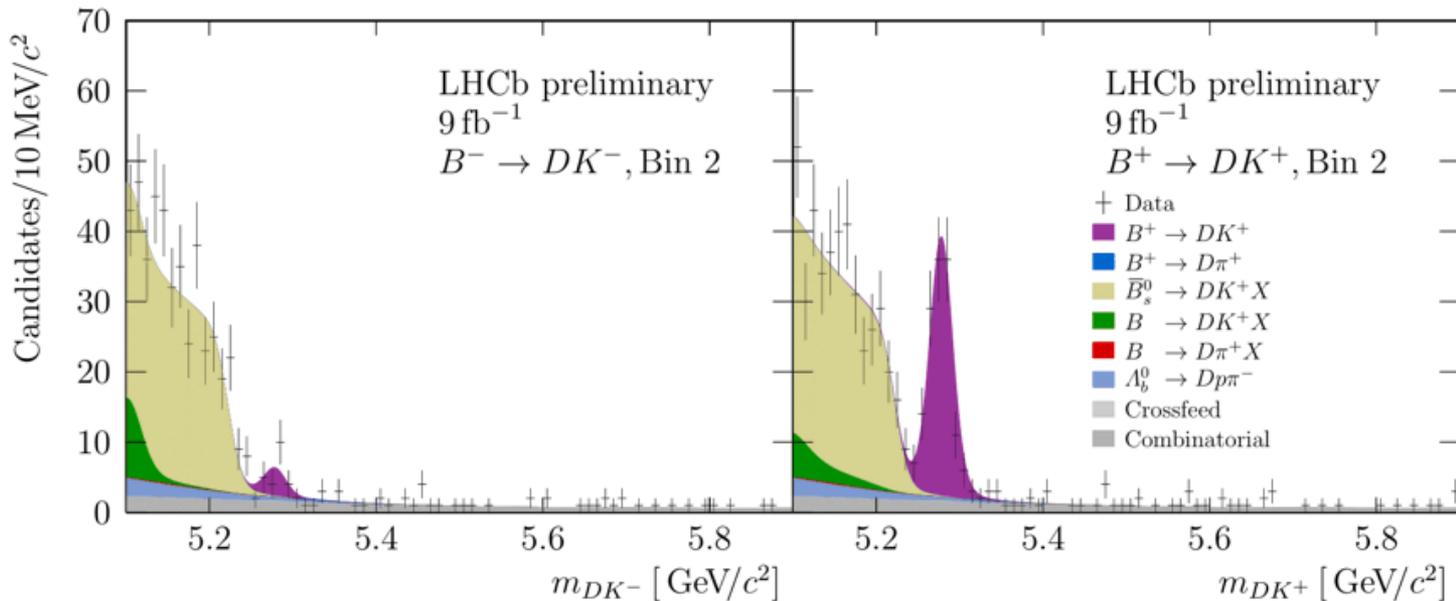


A LHCb...

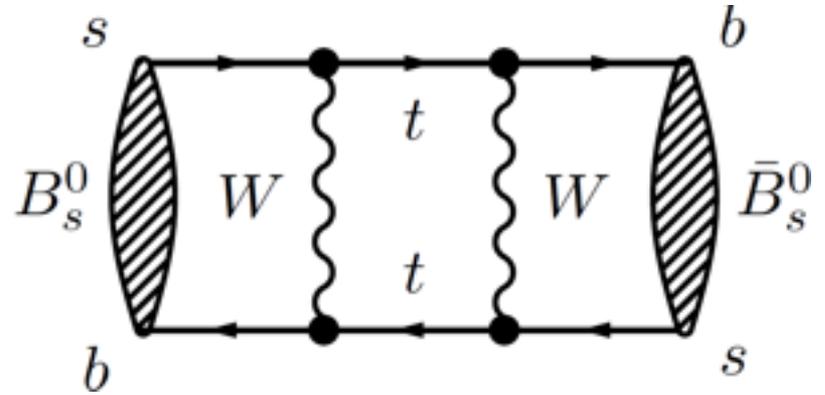
- Fino a vent'anni anni fa si misuravano asimmetrie di CP dell'ordine di 10^{-3}

mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS					
	≈4.8 MeV/c ²	≈95 MeV/c ²	≈4.18 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	91.2 GeV/c ²	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS					
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	80.4 GeV/c ²	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS

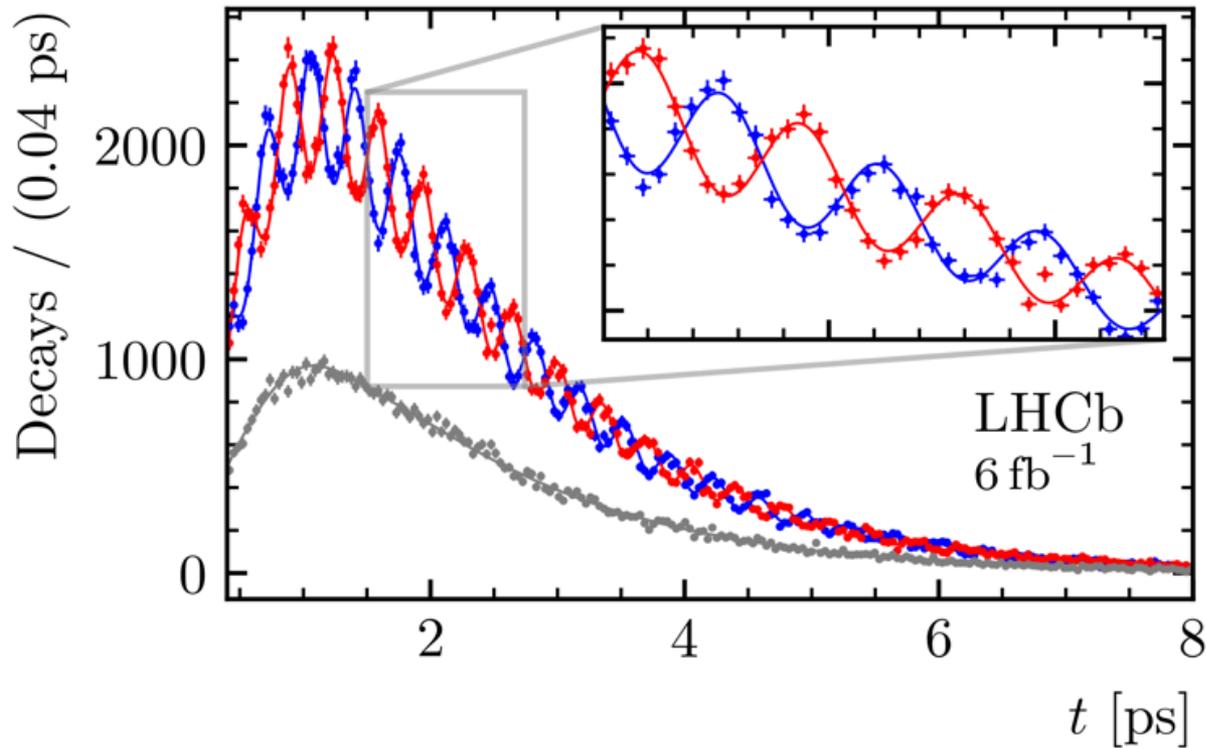
- Oggi a LHCb violazione di CP 85%:



Oscillazioni



— $B_s^0 \rightarrow D_s^- \pi^+$ — $\bar{B}_s^0 \rightarrow D_s^- \pi^+$ — Untagged



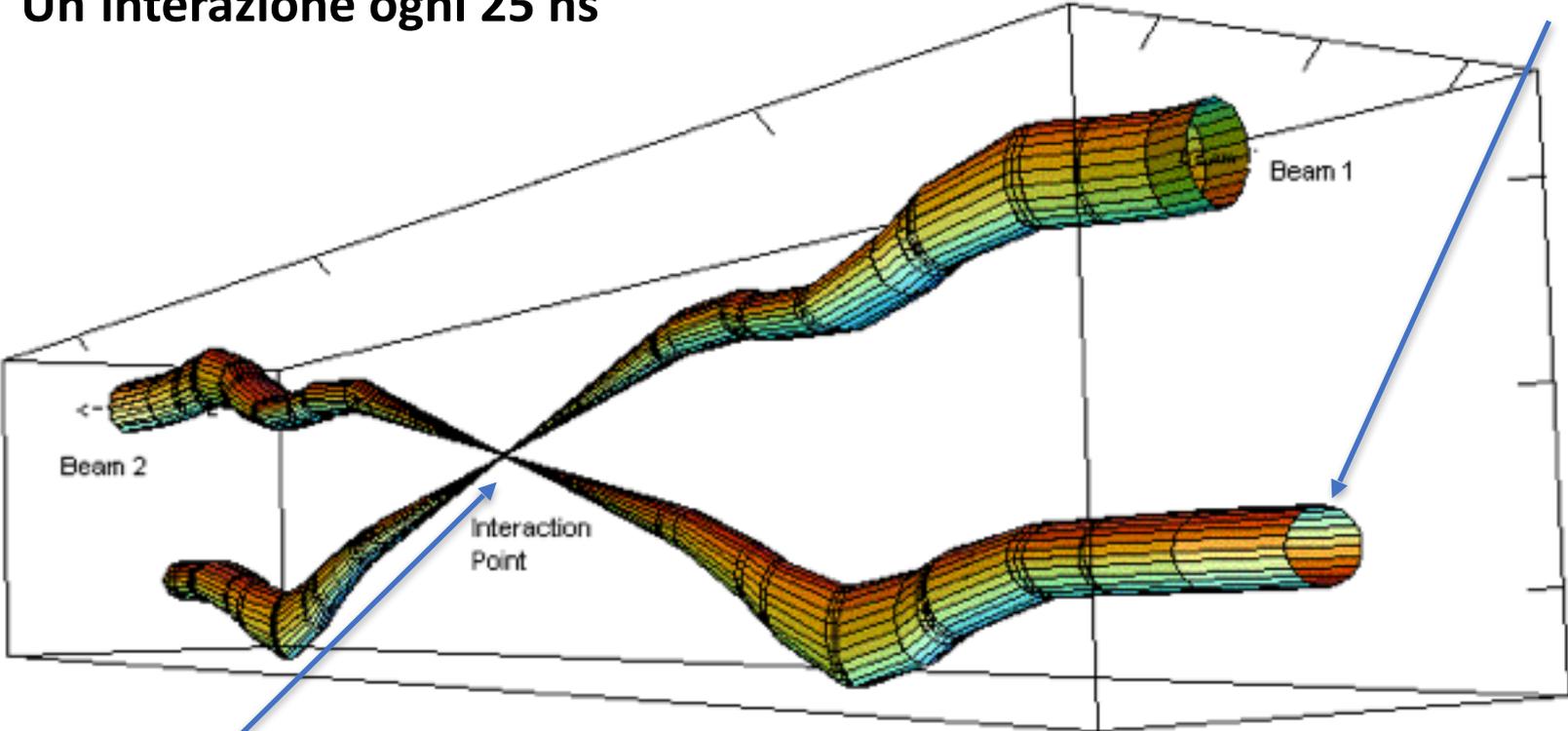


BACKUP

Punto di interazione

Un'interazione ogni 25 ns

1 mm

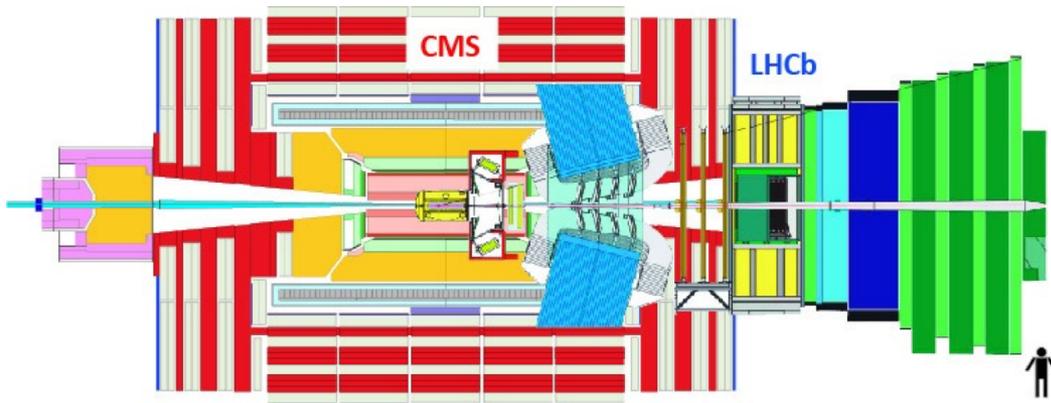


Relative beam sizes around IP1 (Atlas) in collision

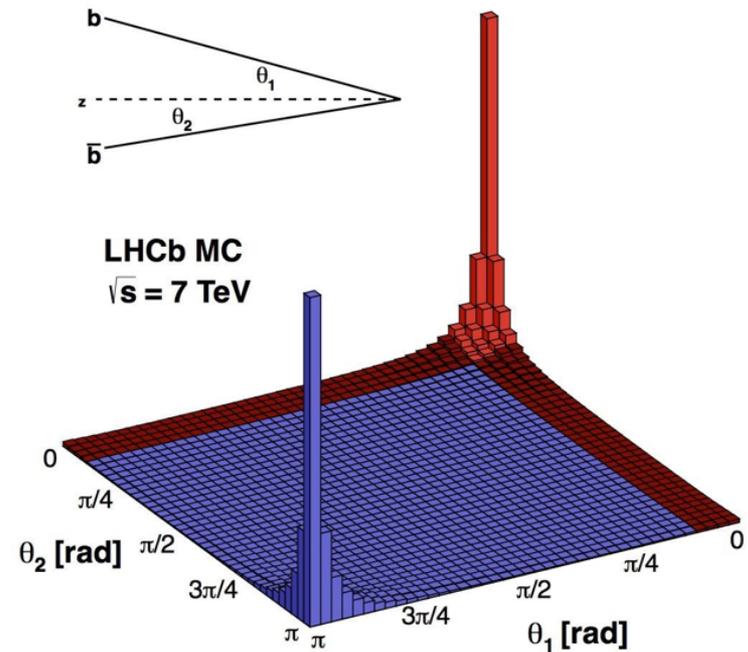
16 μm

Perché è necessario strizzare i fasci?

Breve appendice - 1: perché LHCb copre un piccolo angolo solido?



Sezione d'urto (“probabilità”)
di produrre dei quark b



Breve appendice - 2: cosa contiene la lagrangiana dello SM?

Standard Model Lagrangian (including neutrino mass terms)

From *An Introduction to the Standard Model of Particle Physics, 2nd Edition*,

W.N. Cottingham and D. A. Greenwood, Cambridge University Press, Cambridge, 2007,

Extracted by J.A. Shiflett, updated from Particle Data Group tables at pdg.lbl.gov, 2 Feb 2015.

$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\text{tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
 & +(\bar{\nu}_L, \bar{e}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.}) && \text{(lepton dynamical term)} \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{\nu}_L, \bar{e}_L)\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] && \text{(electron, muon, tauon mass term)} \\
 & -\frac{\sqrt{2}}{v} \left[(-\bar{e}_L, \bar{\nu}_L)\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} \right] && \text{(neutrino mass term)} \\
 & +(\bar{u}_L, \bar{d}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) && \text{(quark dynamical term)} \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{u}_L, \bar{d}_L)\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] && \text{(down, strange, bottom mass term)} \\
 & -\frac{\sqrt{2}}{v} \left[(-\bar{d}_L, \bar{u}_L)\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix} \right] && \text{(up, charmed, top mass term)} \\
 & +(\overline{D_\mu\phi})D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
 \end{aligned}$$