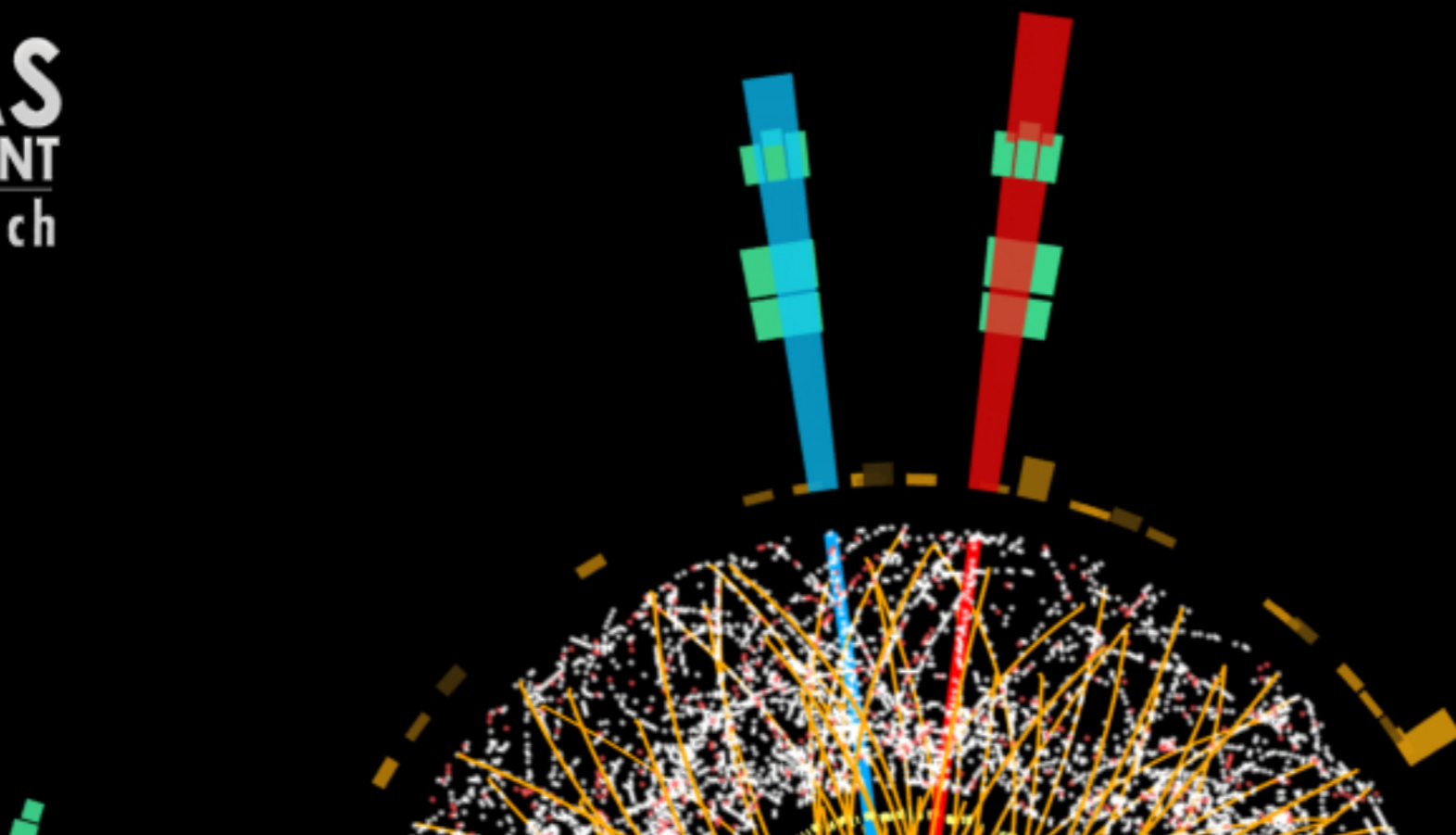


Introduzione al mondo delle particelle elementari e degli strumenti utilizzati per studiarle: l'acceleratore LHC e l'esperimento ATLAS

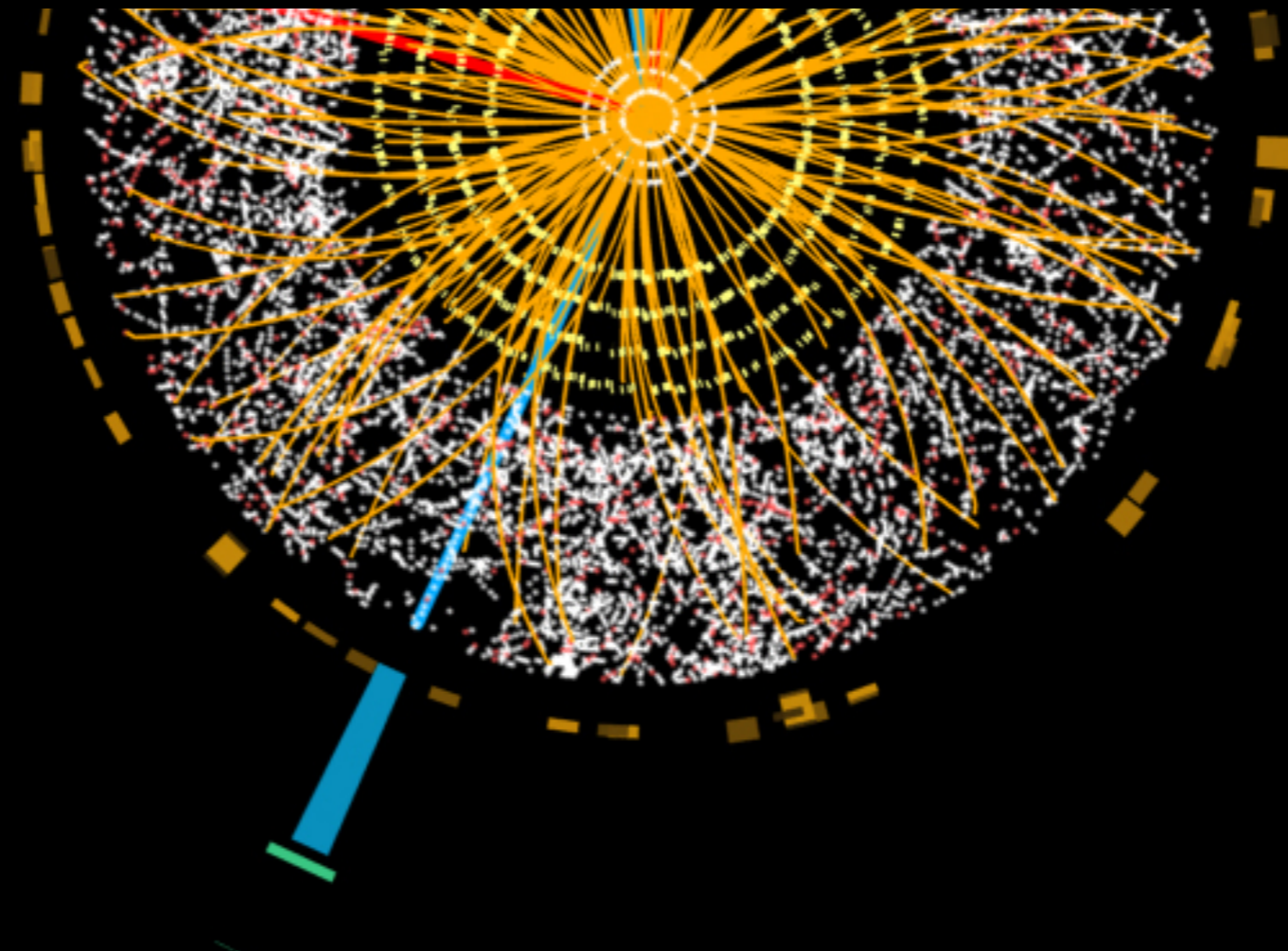


Paolo Francavilla
INFN Sezione di Pisa
Pisa, 19/2/2018

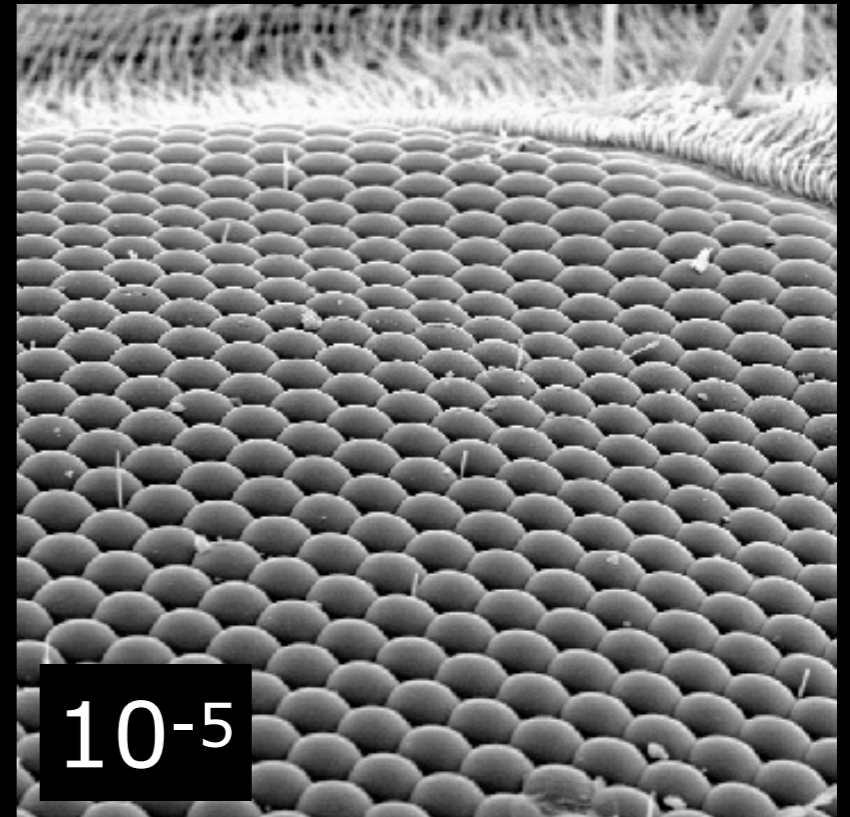
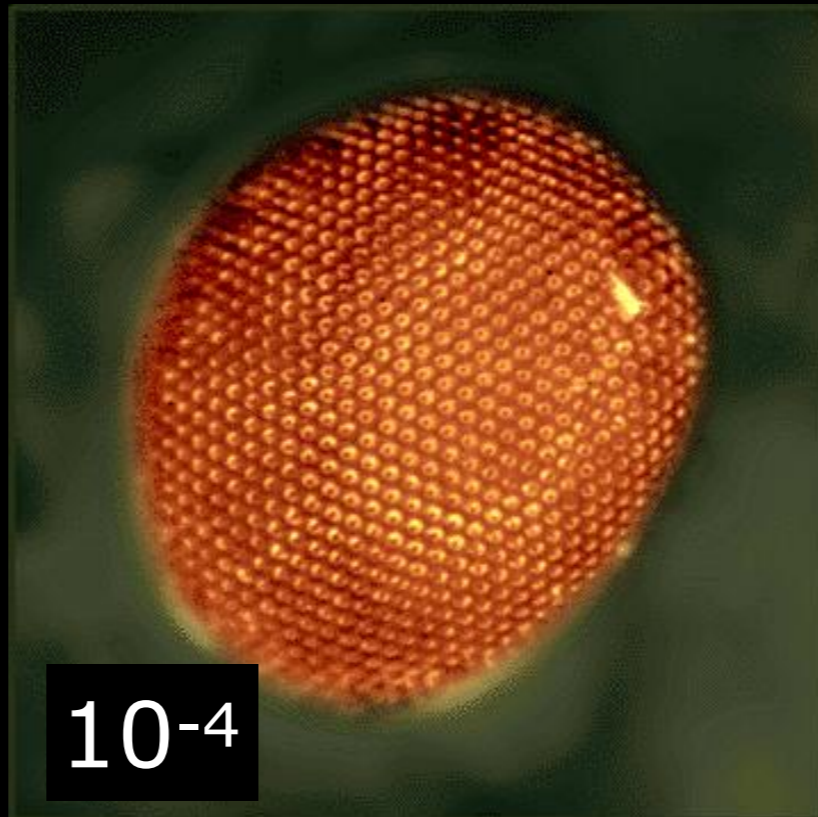
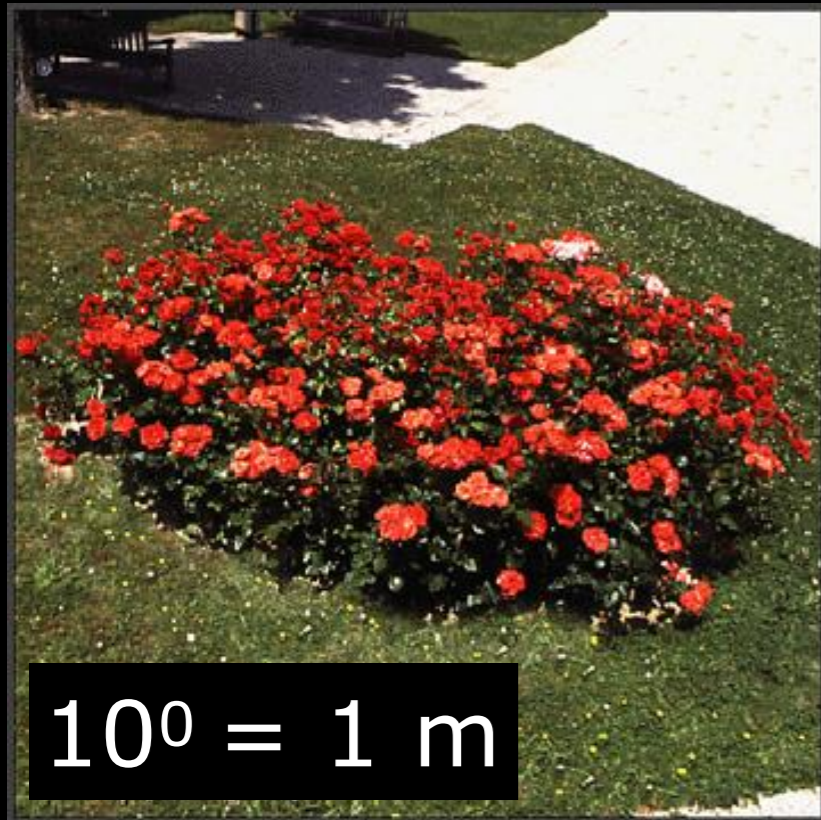




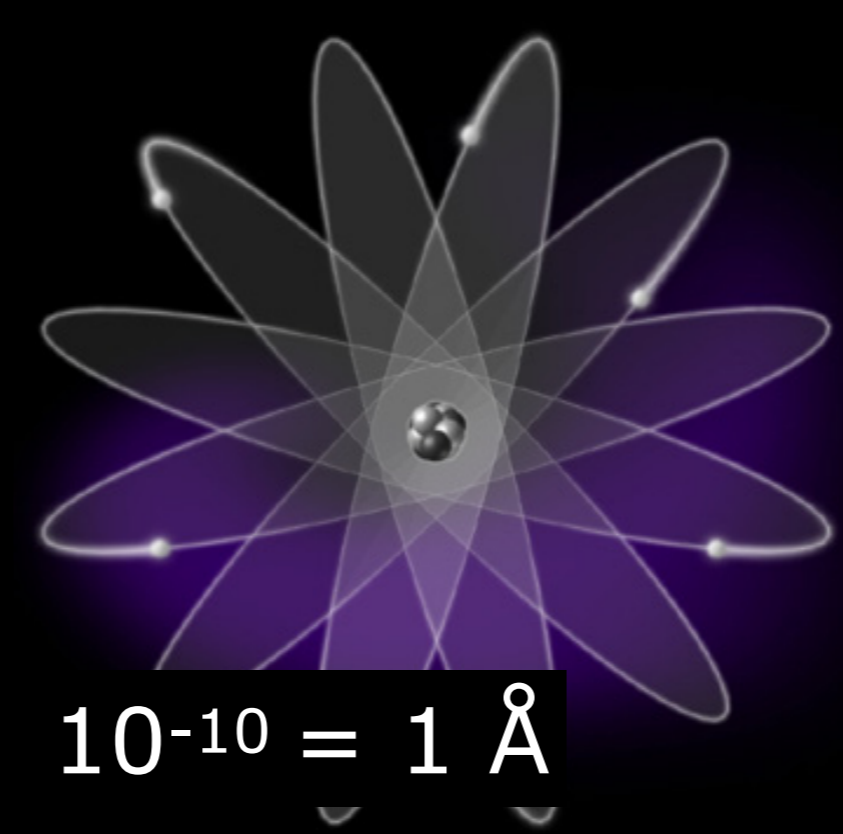
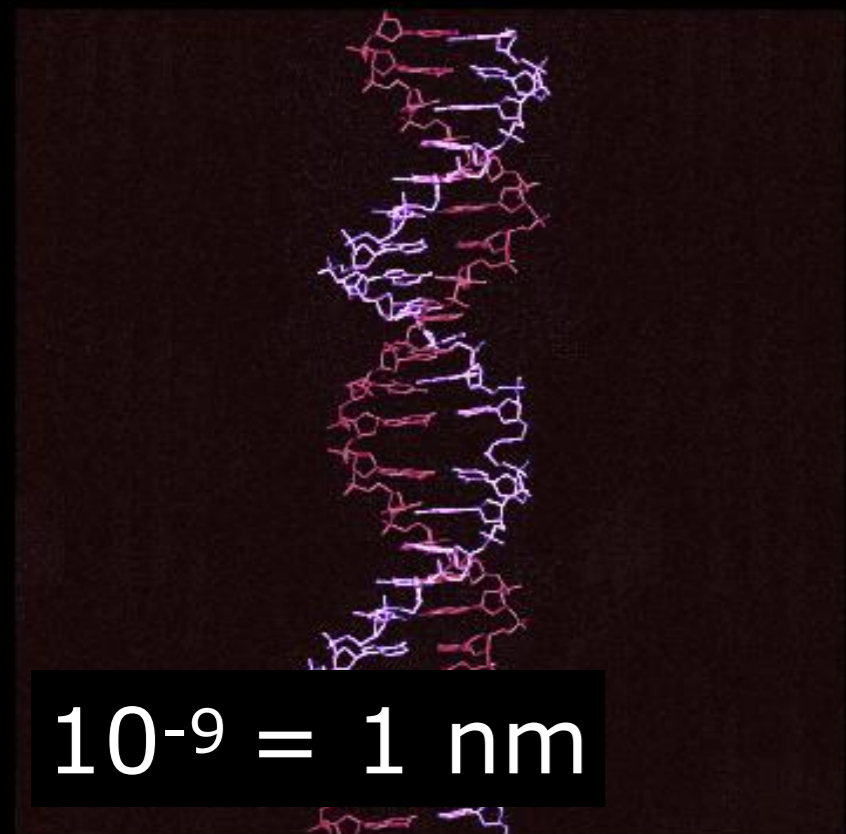
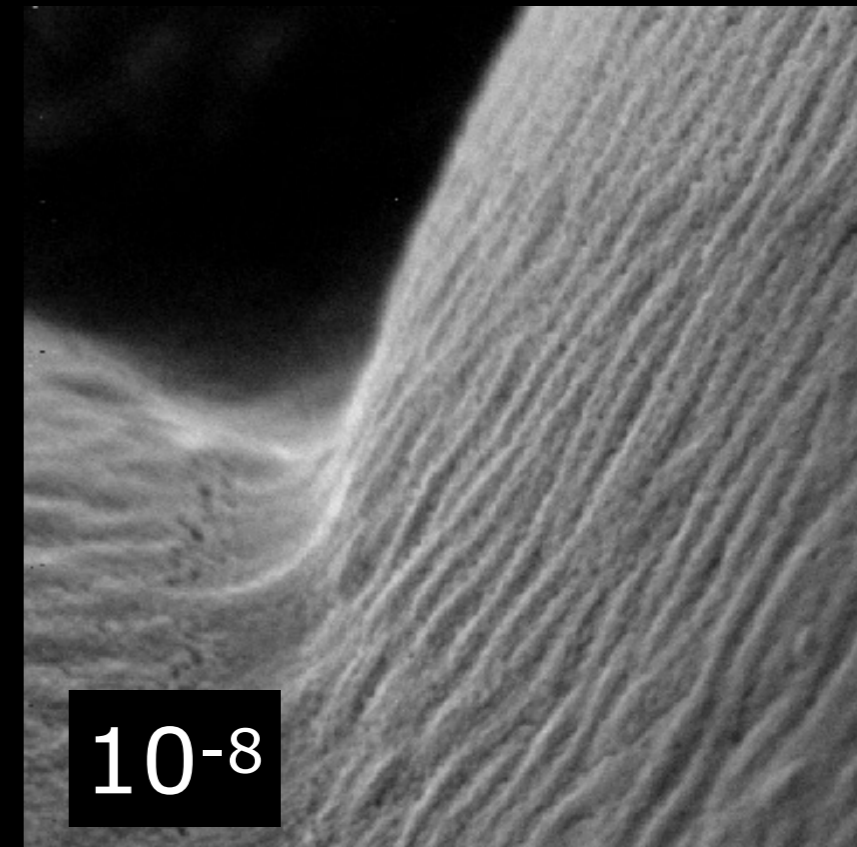
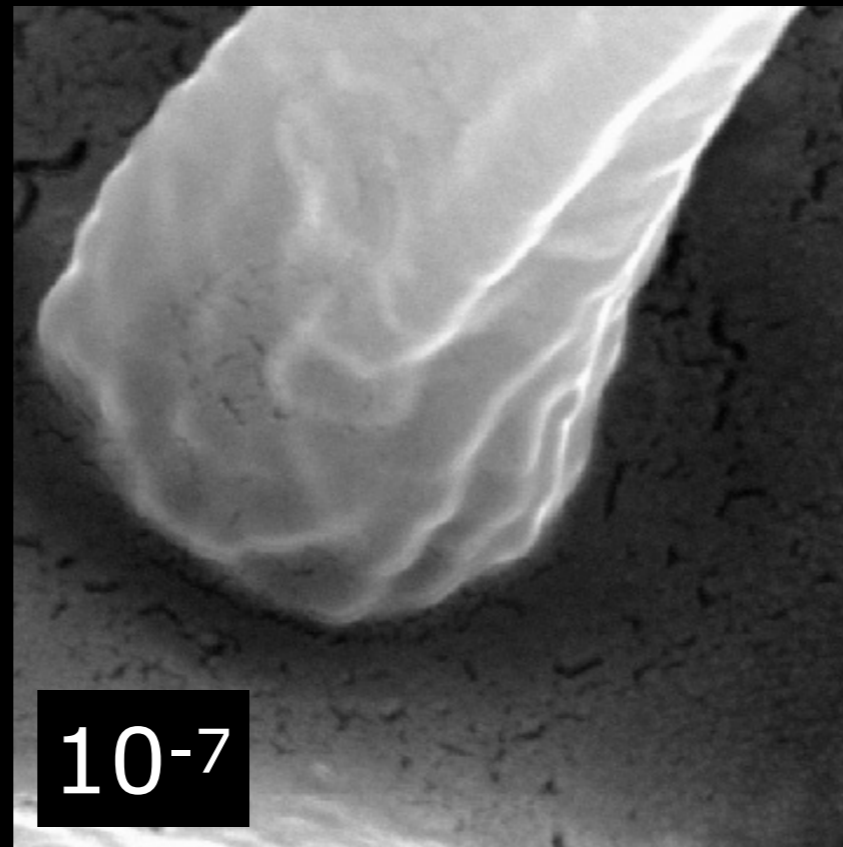
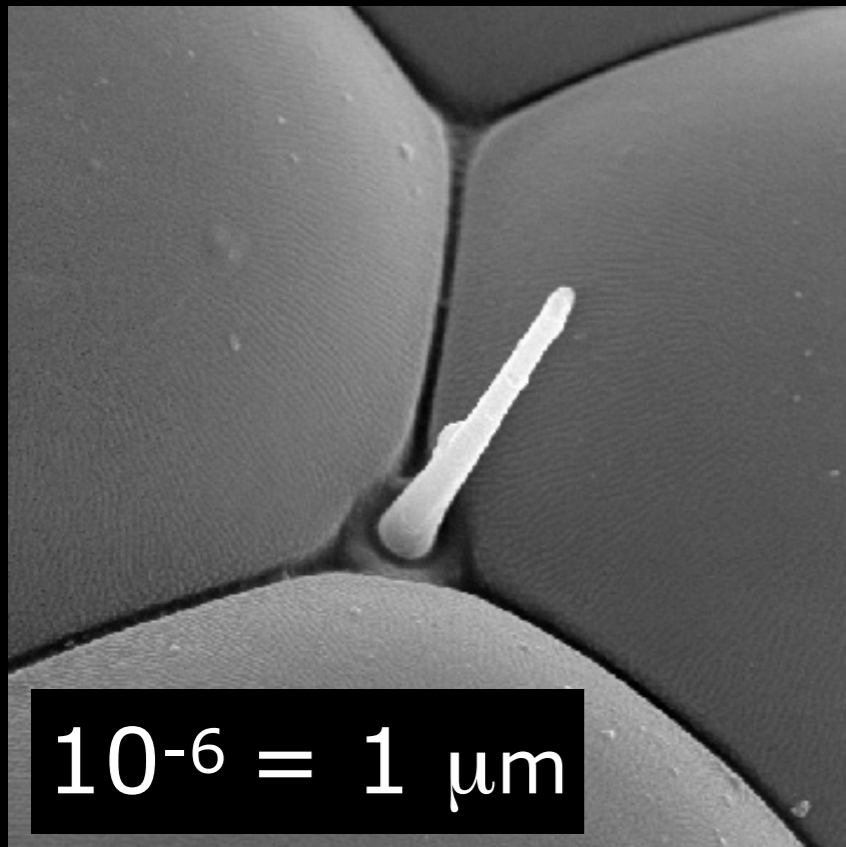
Materia



Verso l'infinitamente piccolo...



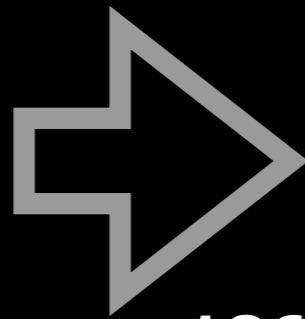
Verso l'infinitamente piccolo...



L'atomo non é poi così indivisibile....



~400 AC: Democrito
Ipotesi che la materia
sia fatta da costituenti
indivisibili
**Nascita dell'idea di
atomo**



1869: Mendeleev
Tavola periodica degli
elementi

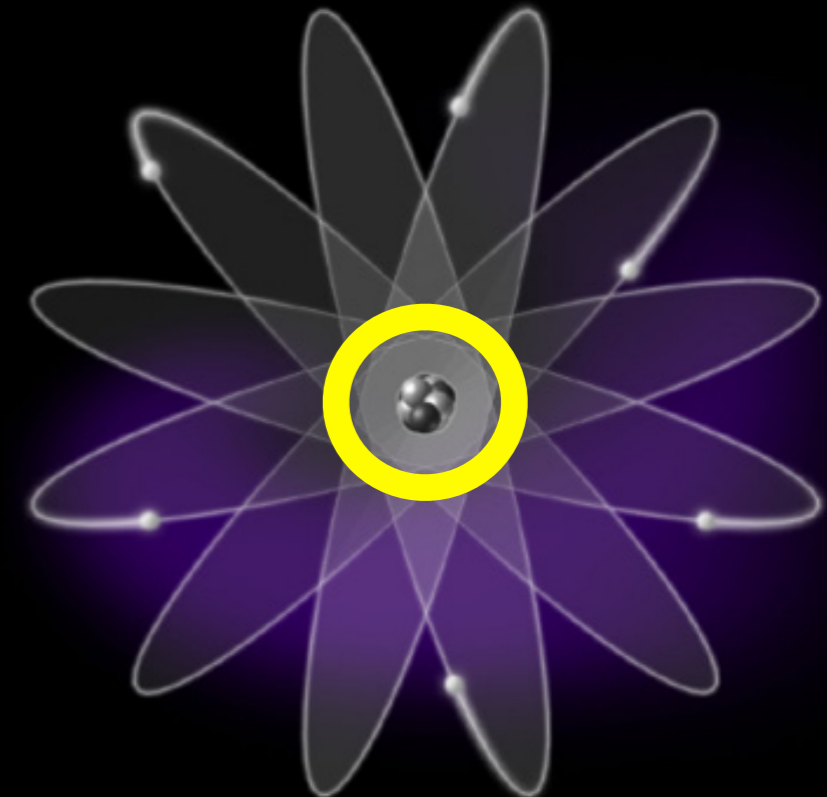
Periodic Table of the Elements																	
IA											0						
1 H											2 He						
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar										
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106	107	108	109	110	111	112						

Naming conventions of new elements

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



1911: Rutherford
Scoperta del nucleo

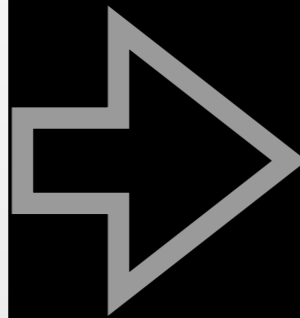


e il nucleo? (in meno di 100 anni)

nucleo

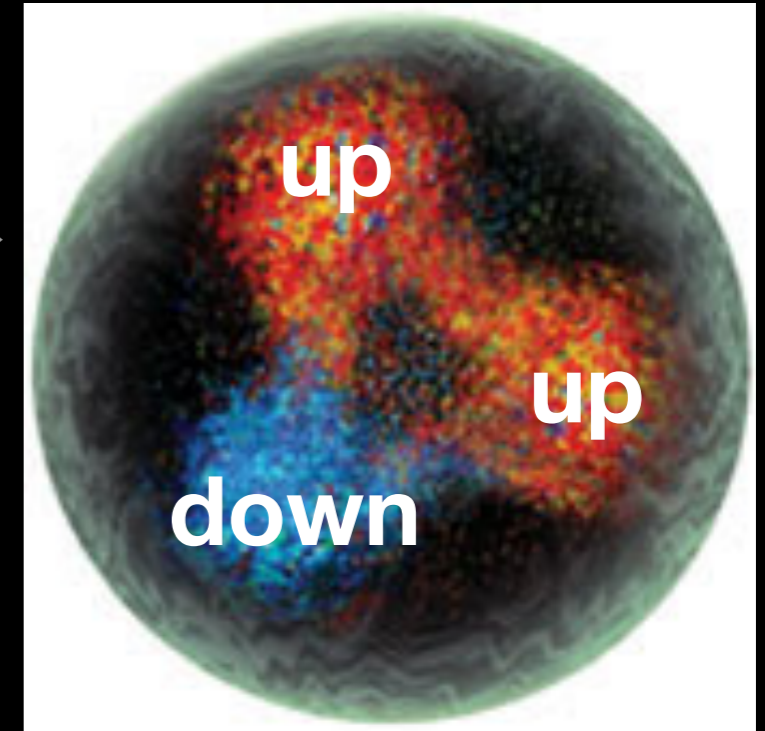
nucleoni

quarks



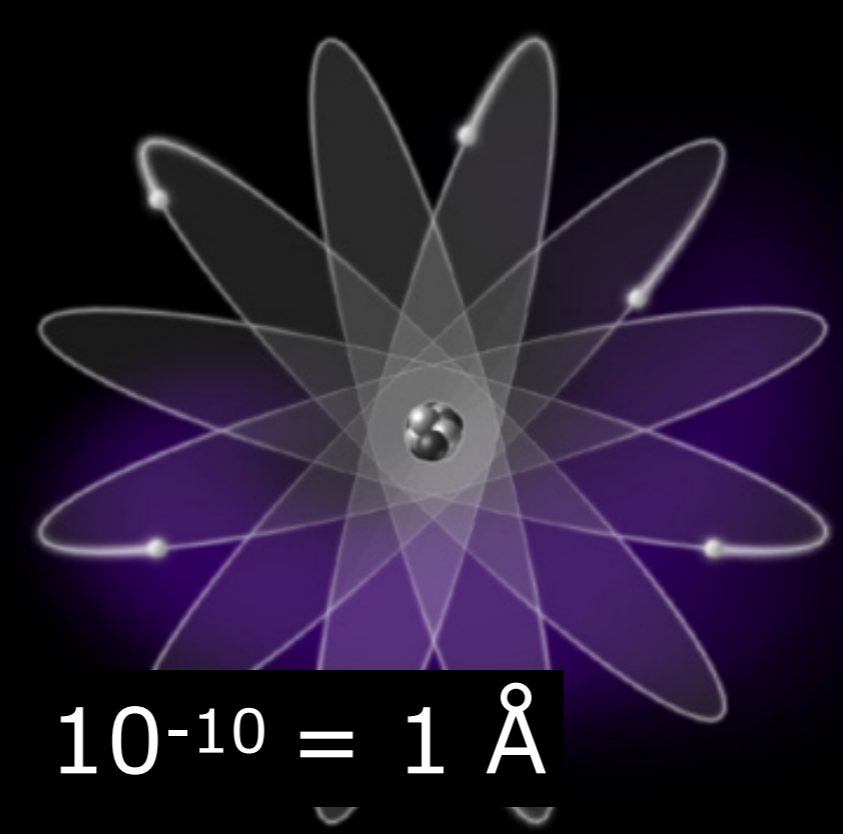
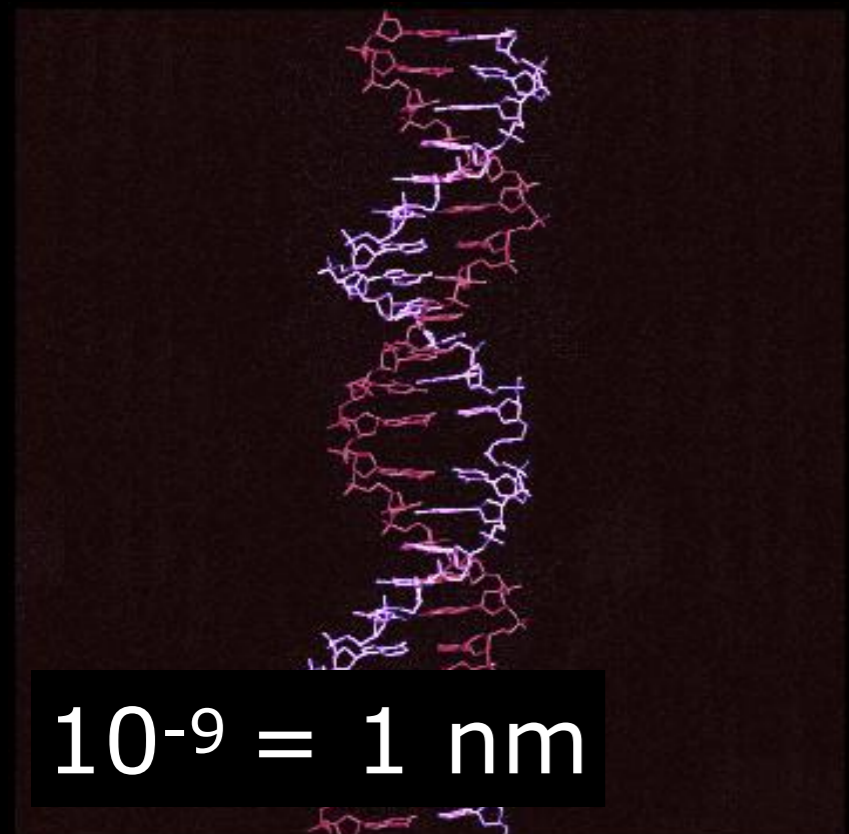
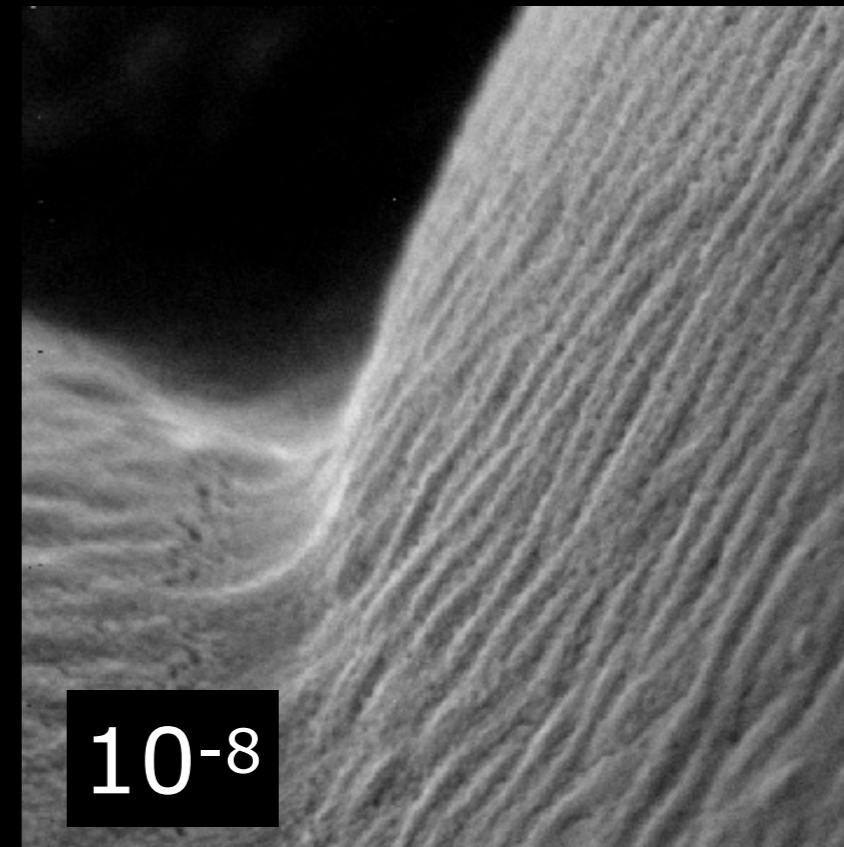
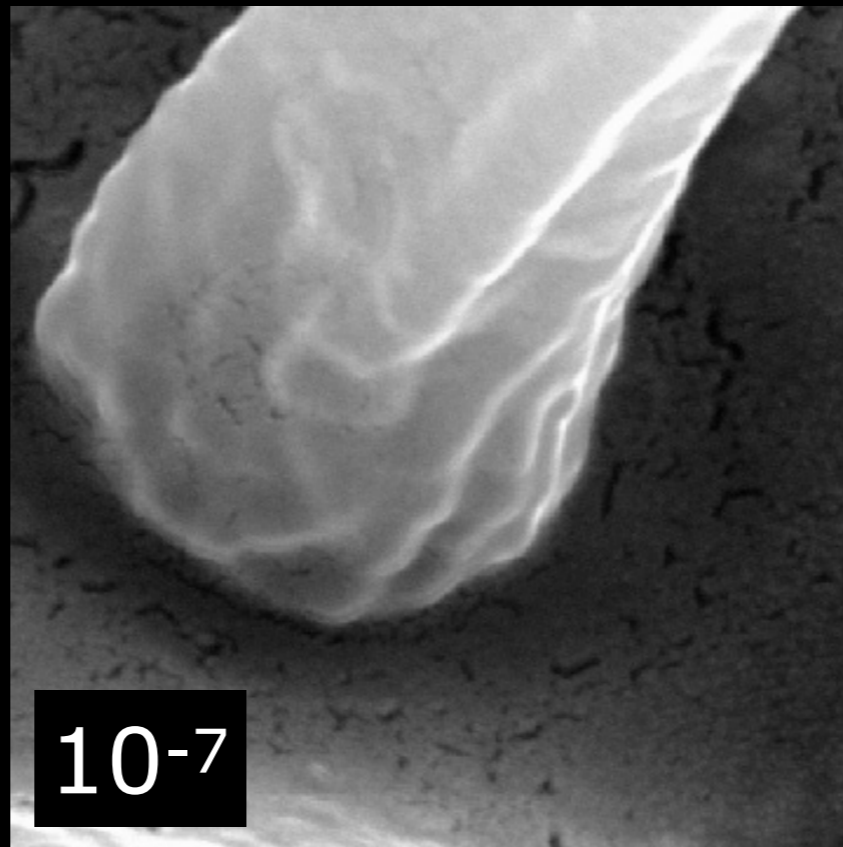
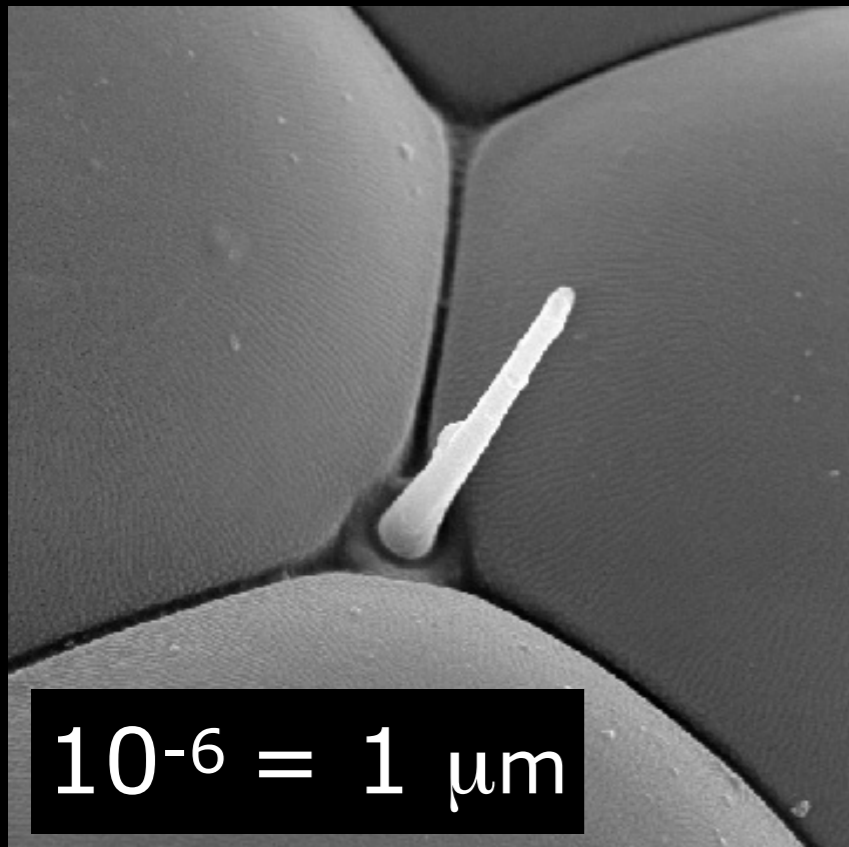
Protone

Neutrone

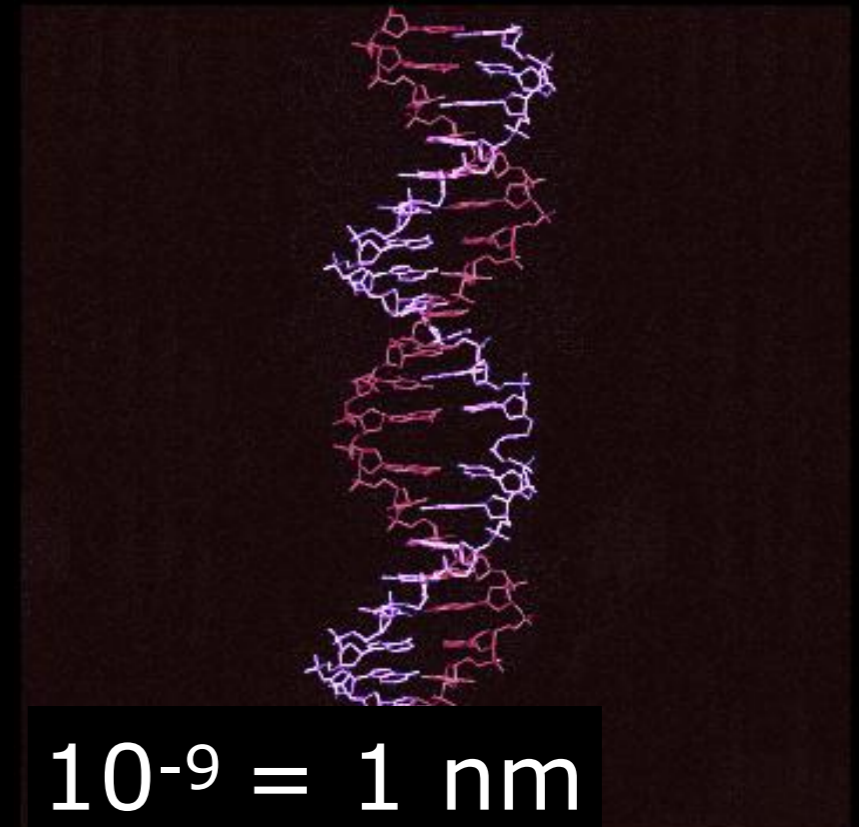
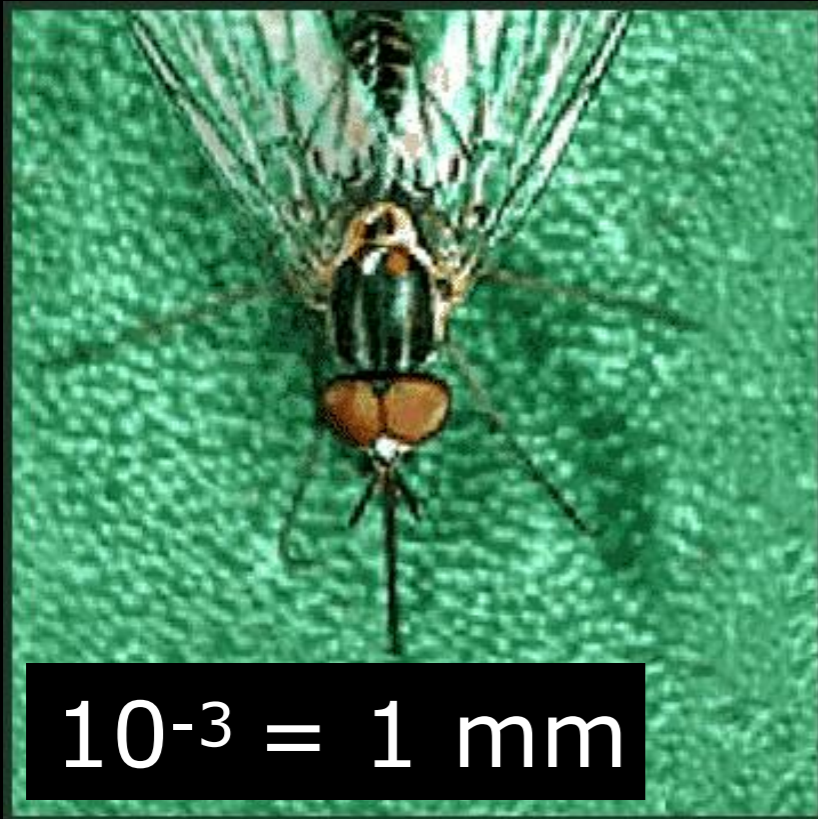


Protone

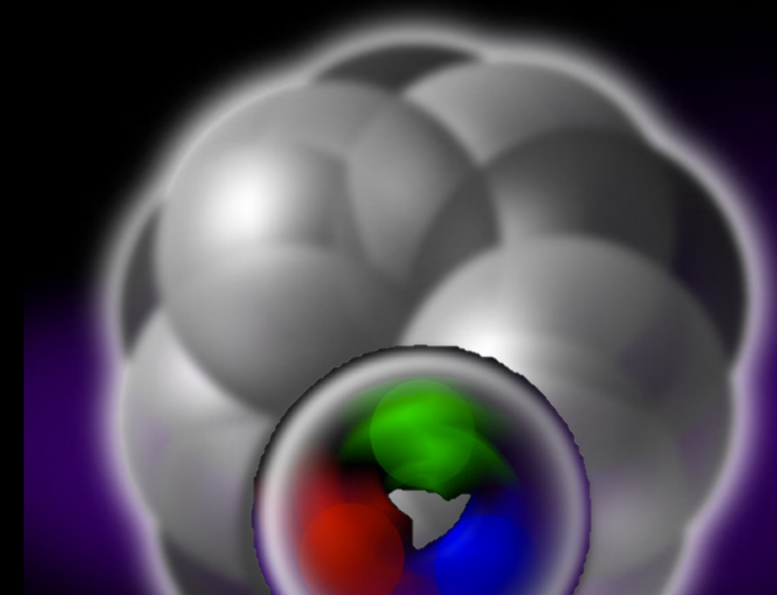
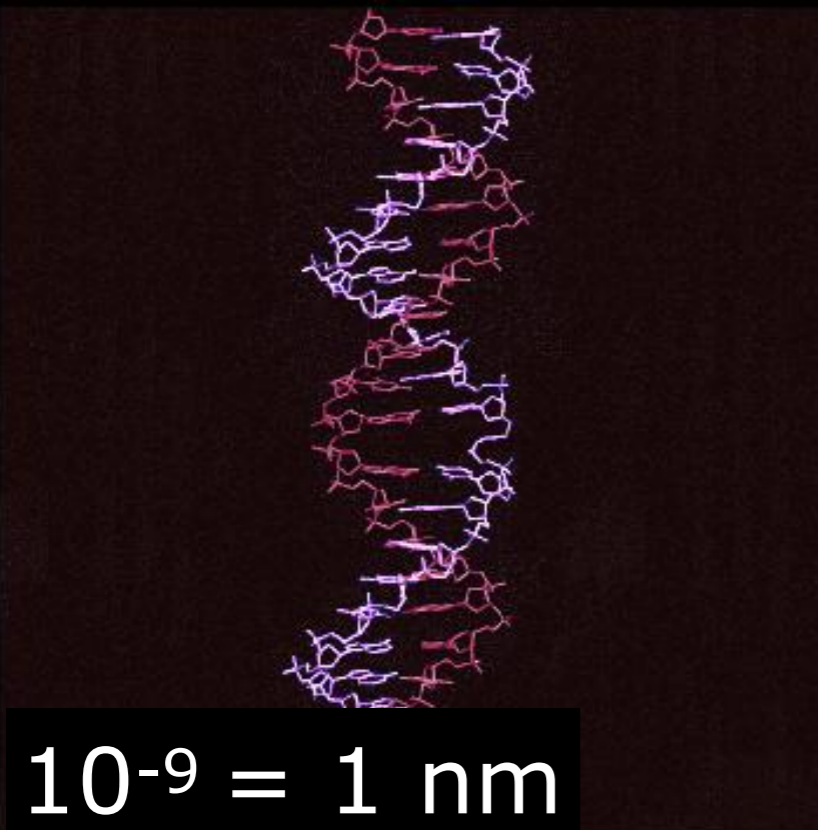
Verso l'infinitamente piccolo...



Zoom: x 1.000.000

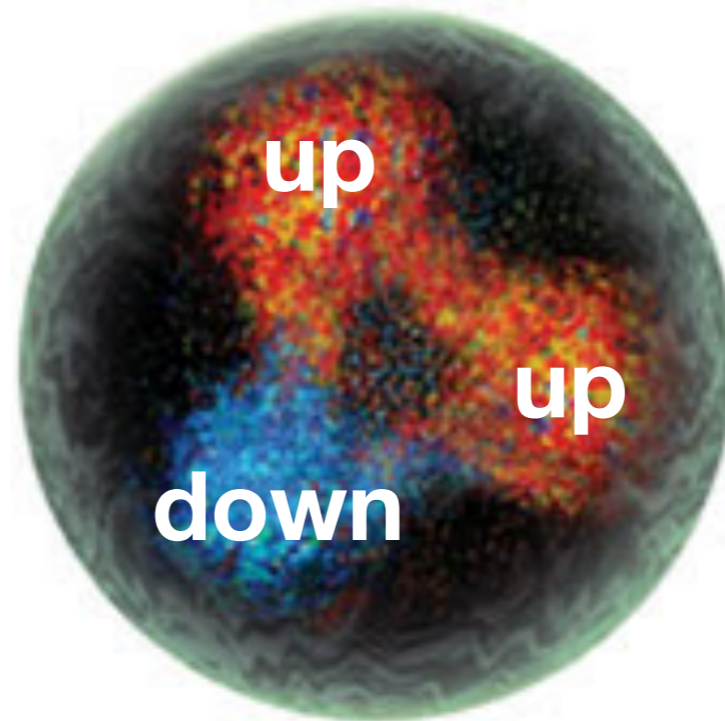
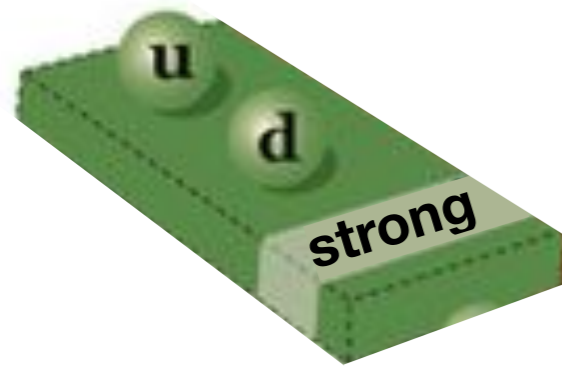


=



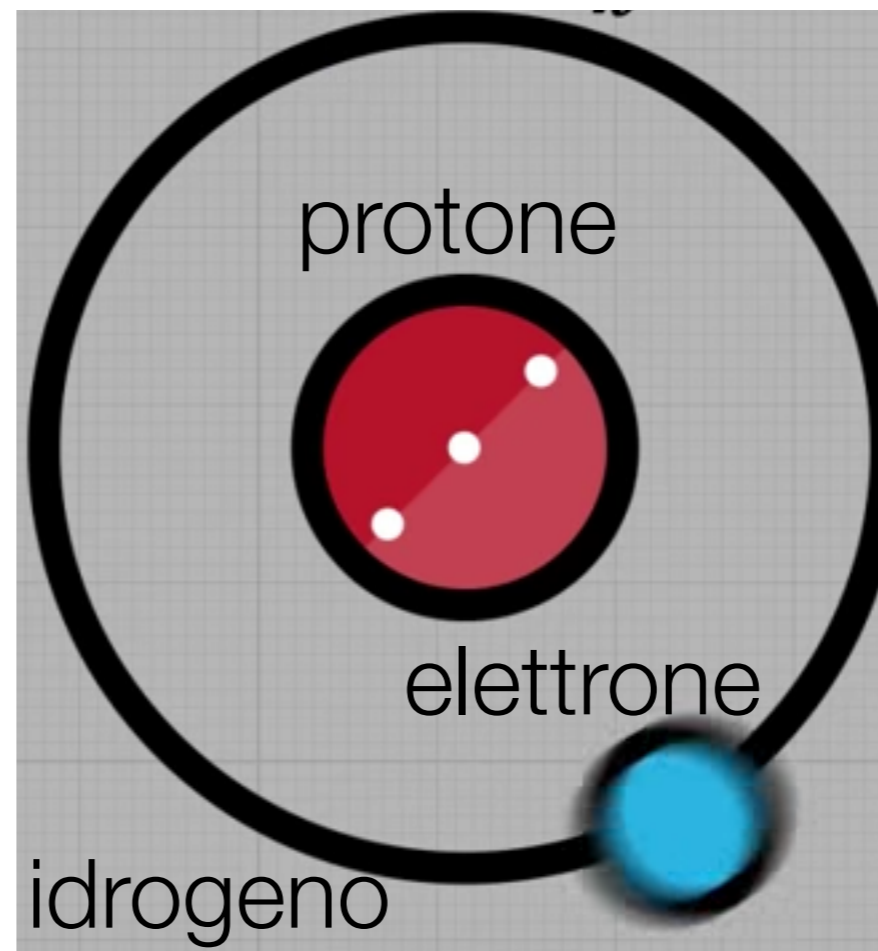
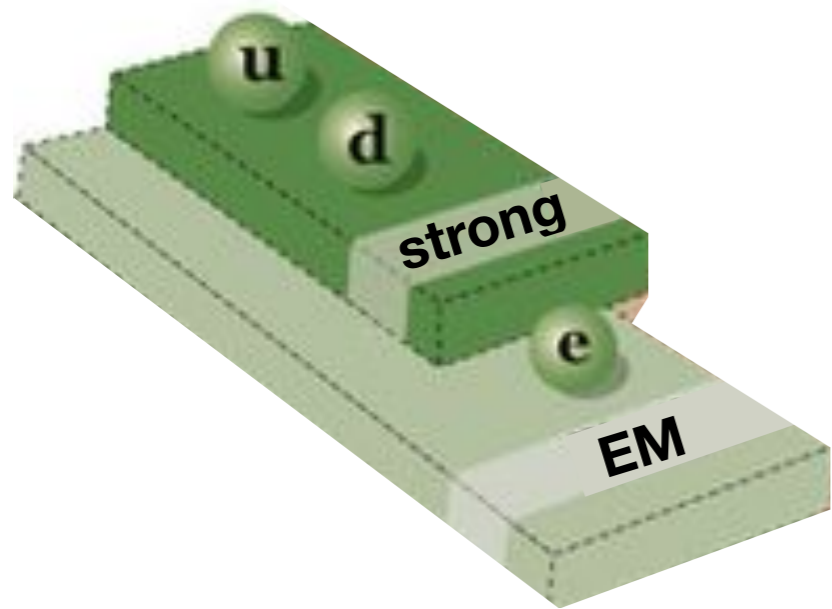
La particelle elementari e le loro interazioni

2 up + 1 down + forza forte (**strong**)
= protone



La particelle elementari e le loro interazioni

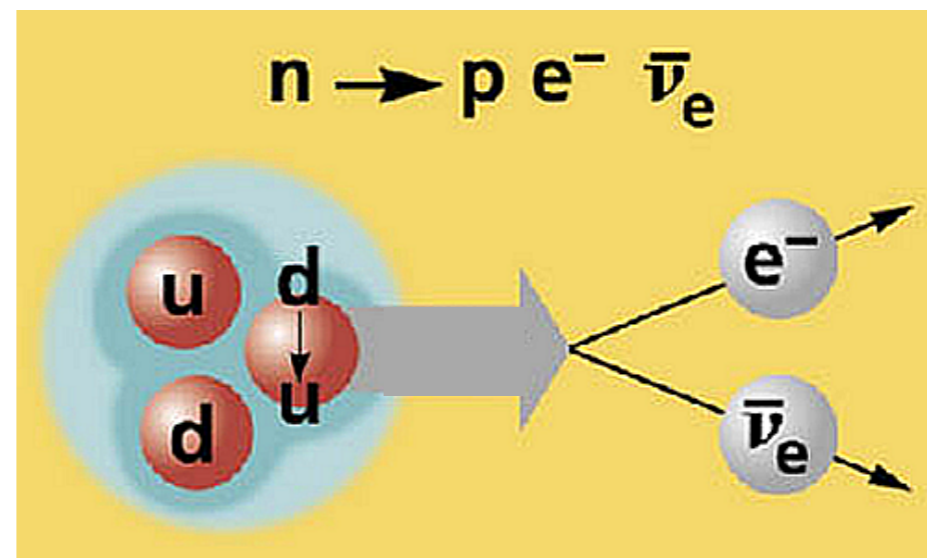
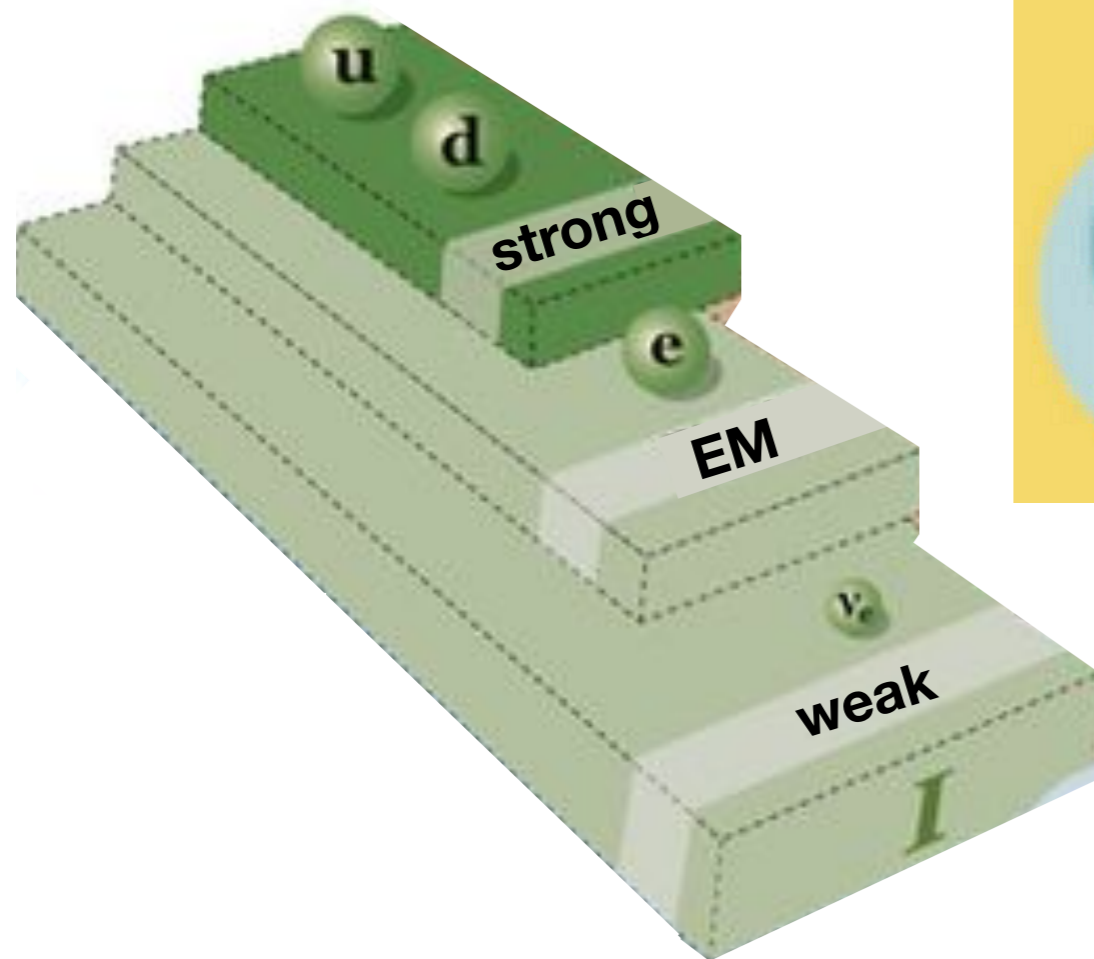
1 protone + 1 elettrone + forza **ElettroMagnetica**
= 1 atomo di idrogeno



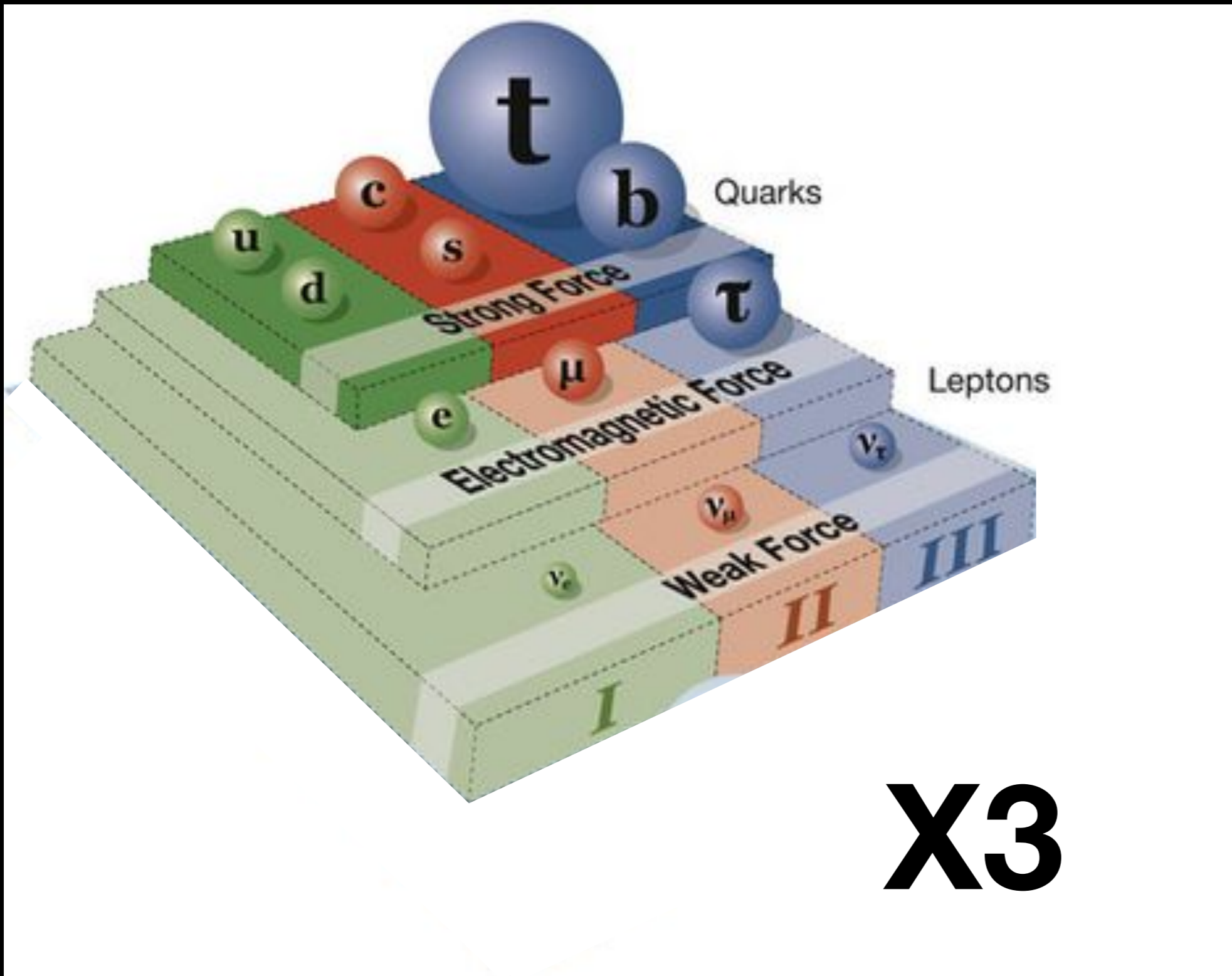
La particelle elementari e le loro interazioni

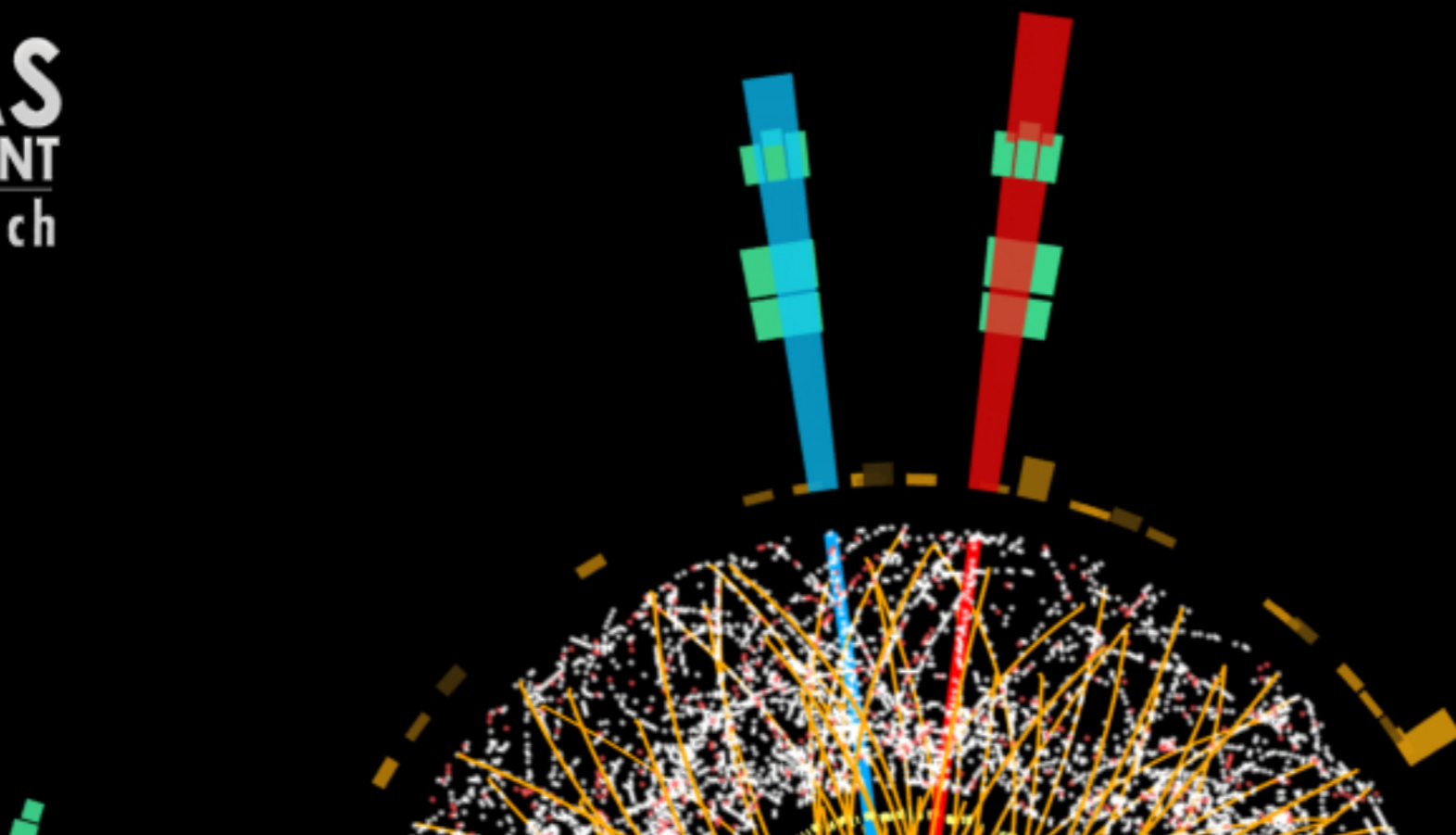
ma i neutroni hanno una vita media di 15 minuti...

⇒ neutrini e forza debole (**weak**)

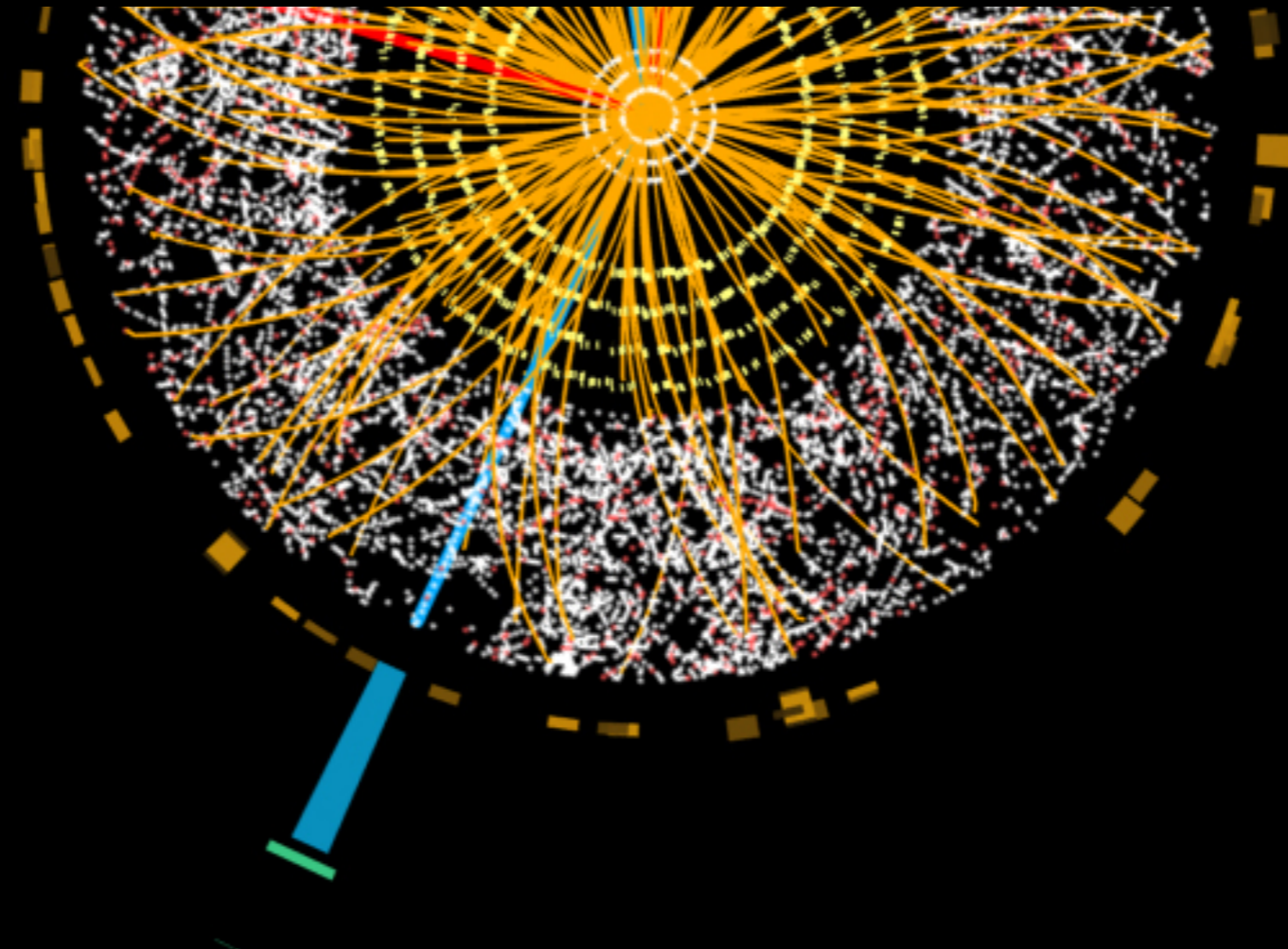


La particelle elementari e le loro interazioni





Interazioni



Interazioni



Forza di Gravità

Interazioni



Forza elettrica



Forza di Gravità



Interazioni



Forza elettrica

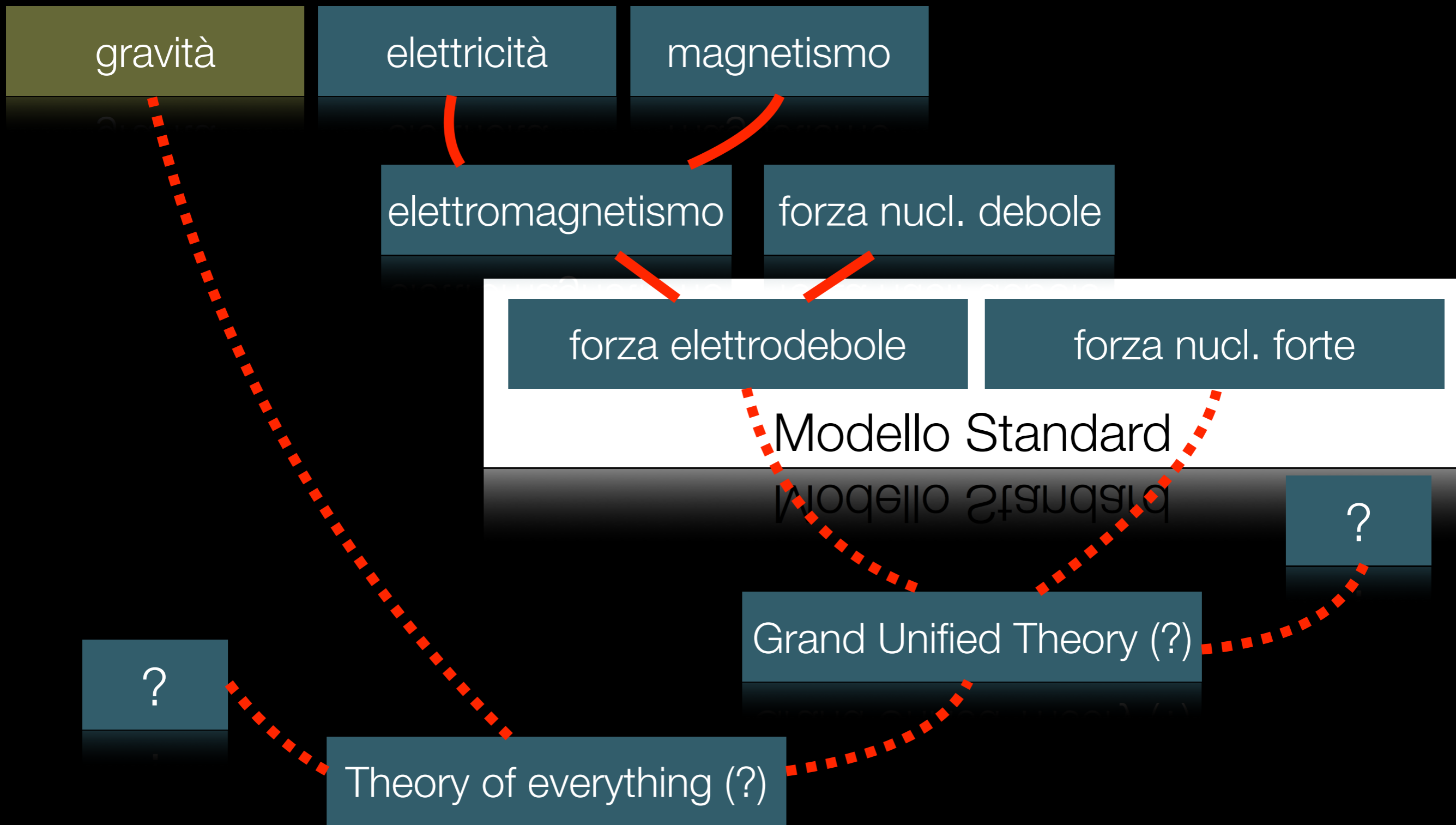


Forza magnetica

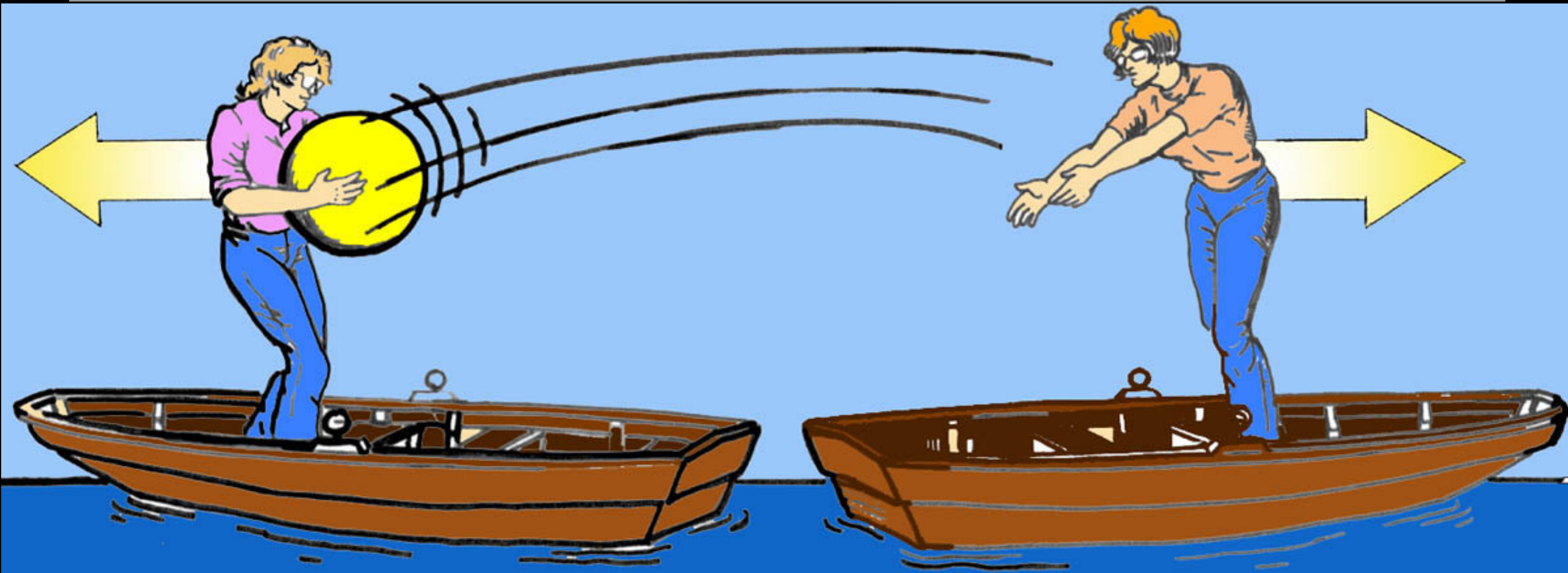


Forza di Gravità

Le interazioni



Interazioni



Tutte le interazioni della natura possono essere descritte come scambio di particelle che trasmettono la forza

La particelle elementari e le loro interazioni

	$2.4 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$1.27 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$171.2 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 γ photon	$? \text{ GeV}/c^2$ 0 0 H Higgs boson
Quarks	$4.8 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$104 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$4.2 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon	
	$<2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$<0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$<15.5 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	$91.2 \text{ GeV}/c^2$ 0 1 Z^0 Z boson	
	$0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$105.7 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$1.777 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau	$80.4 \text{ GeV}/c^2$ ± 1 1 W^\pm W boson	Gauge boson

Interazioni fondamentali

- Elettromagnetica
- Nucleare forte
- Nucleare debole

$$\begin{aligned}
& -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
& \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
& \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \right. \\
& \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
& W_\nu^- \partial_\nu W_\mu^+)] - igs_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
& W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
& \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\
& g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
& \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
& gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
& W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
& \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
& igs_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2s_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
& igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
& \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
& g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + \\
& m_d^\lambda) d_j^\lambda + igs_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \\
& \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + \\
& (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \\
& \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \\
& \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H(\bar{e}^\lambda e^\lambda) + \\
& i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \\
& \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \\
& \frac{g}{2} \frac{m_e^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_e^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_e^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_e^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \\
& \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + \\
& igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + \\
& igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + \\
& igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \\
& \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \\
& \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igM s_w [\bar{X}^0 X^- \phi^+ - \\
& \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}$$

Il modello standard

- E questa é l'equazione che descrive come queste particelle interagiscono. (non é elfico....)
- Dove sta la bellezza???
- e la semplicità?

Il modello standard

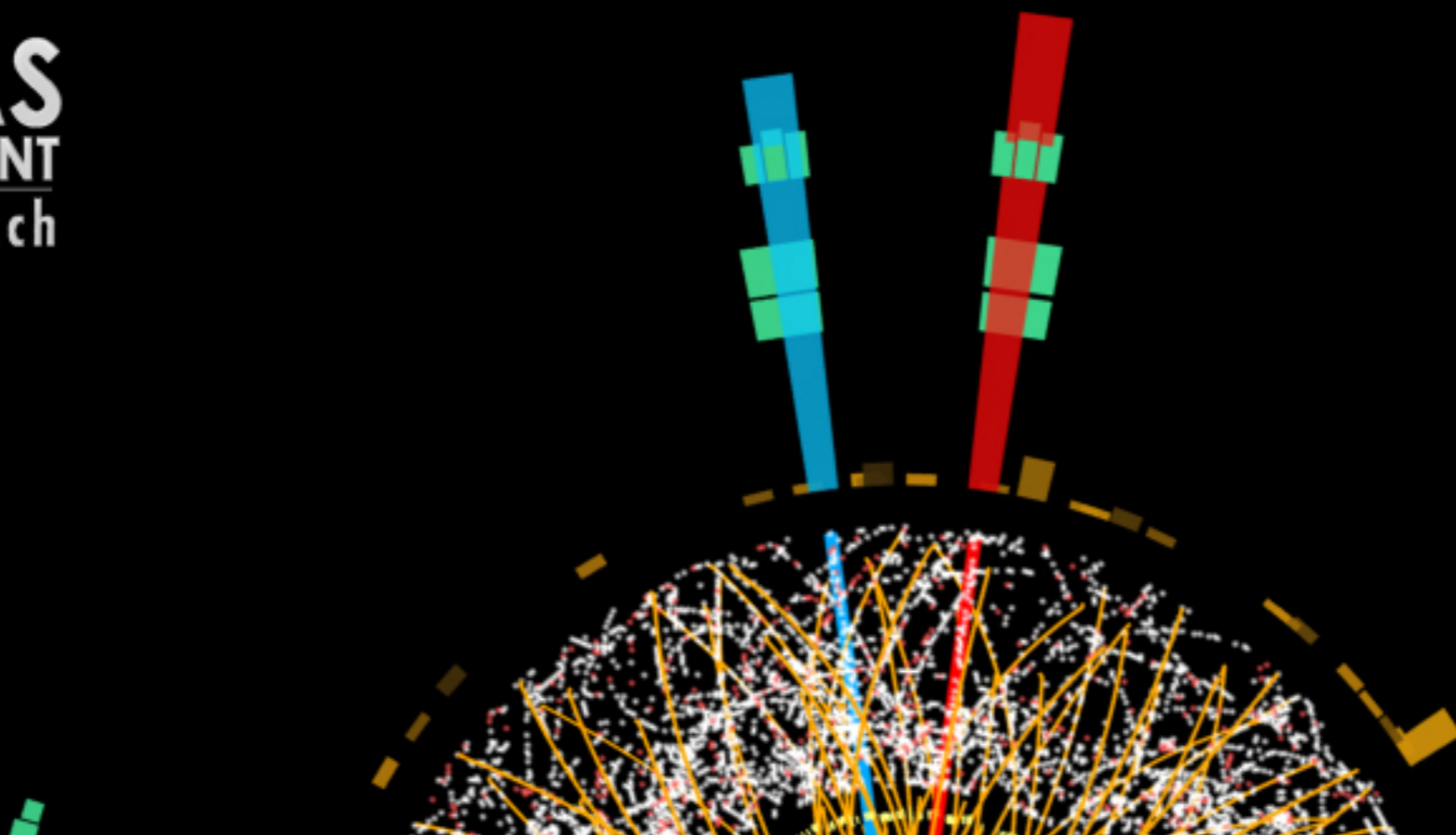
$$\begin{aligned} & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\ & \frac{1}{2}i g_s^2 (\bar{q}_i^\mu \gamma^\mu q_j^\nu) g_\mu^a + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\ & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\ & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \right. \\ & \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\mu^- - \\ & W_\mu^- \partial_\nu W_\mu^+)] - igs_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\ & W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\ & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\ & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - 2A_\nu Z_\mu^0 W_\mu^+ W_\nu^-] - g_c [H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \\ & \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + \\ & g M W_\mu^+ W_\mu^- H - \\ & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0) \\ & \phi^+ \partial_\mu H] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 \\ & igs_w M A_\mu (W_\mu^+ \phi^- - \\ & igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \\ & \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + \\ & W_\mu^- \phi^+ - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} \\ & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu \\ & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \\ & m_d^\lambda) d_j^\lambda + igs_w A_\mu [- \\ & \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu \\ & (d_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \\ & \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} \\ & \frac{ig}{2\sqrt{2}} \frac{m_c^\lambda}{M} [-\phi^+ (\bar{D}^\lambda (1 \\ & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)) + \frac{ig}{2\sqrt{2}} \\ & \gamma^5) d_j^\lambda] + \frac{ig}{2M\sqrt{2}} \phi^- \\ & \frac{g m_s^\lambda}{2M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g m_t^\lambda}{2M} \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \\ & igs_w W_\mu^+ (\partial_\mu \bar{X}^0 X \\ & igs_w W_\mu^- (\partial_\mu \bar{X}^- X \\ & igs_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ \\ & \frac{1}{2}g M [\bar{X}^+ X^+ H + \\ & \bar{X}^- X^0 \phi^-] + \frac{1}{2}ig \\ & \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0] \end{aligned}$$



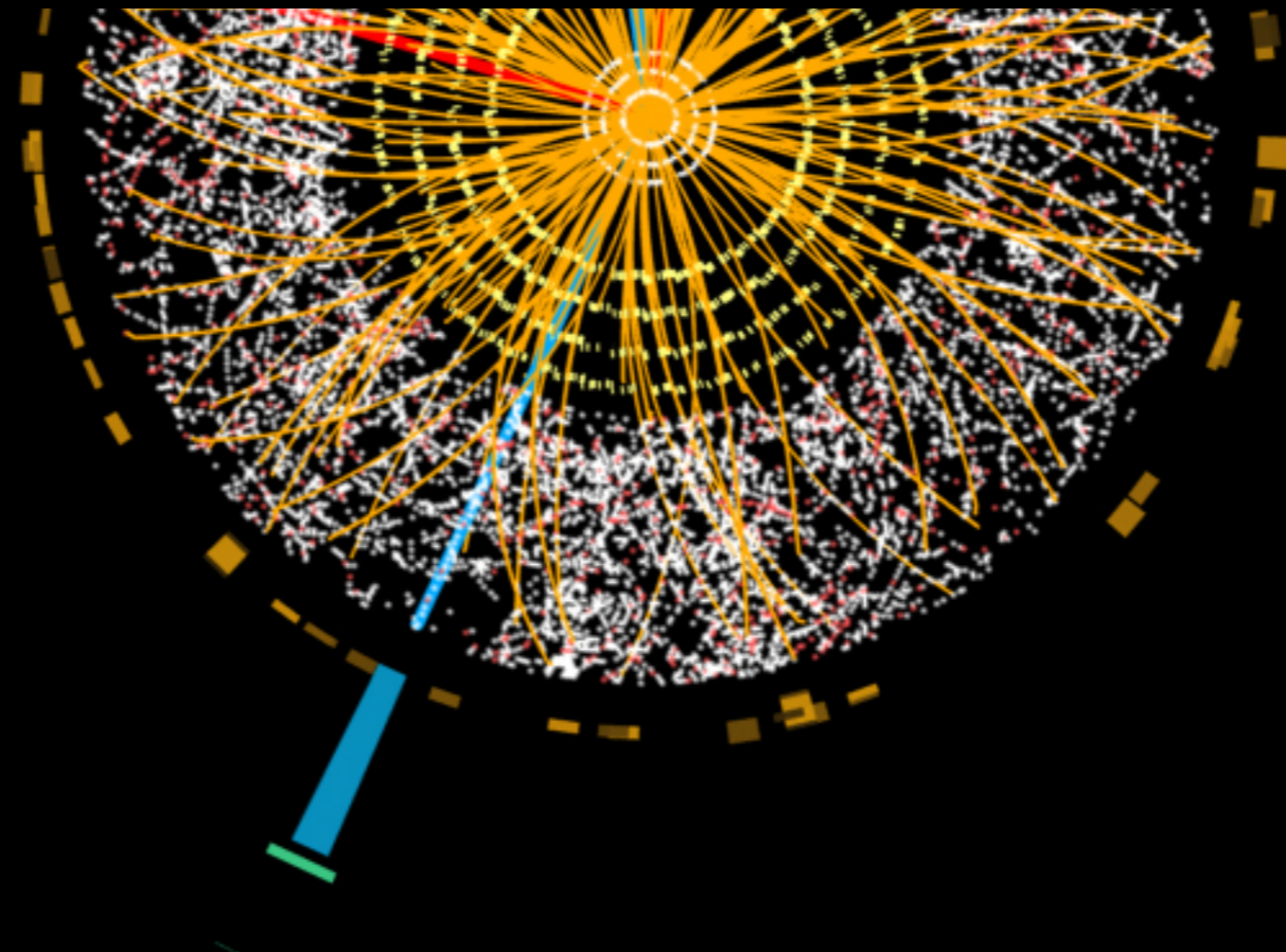
La versione "compressa"

one

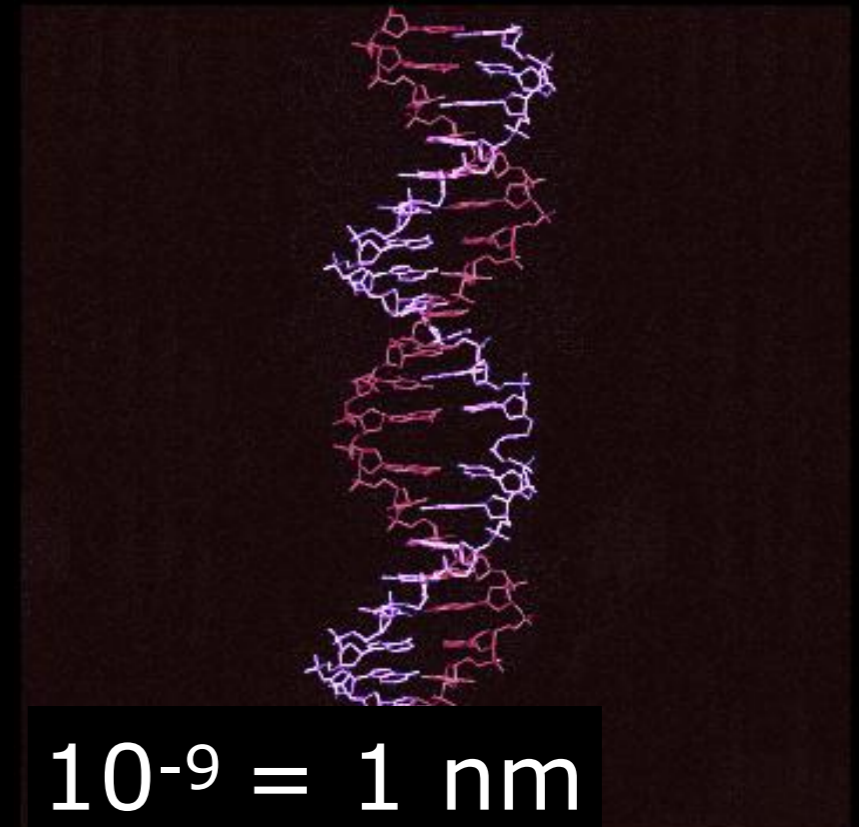
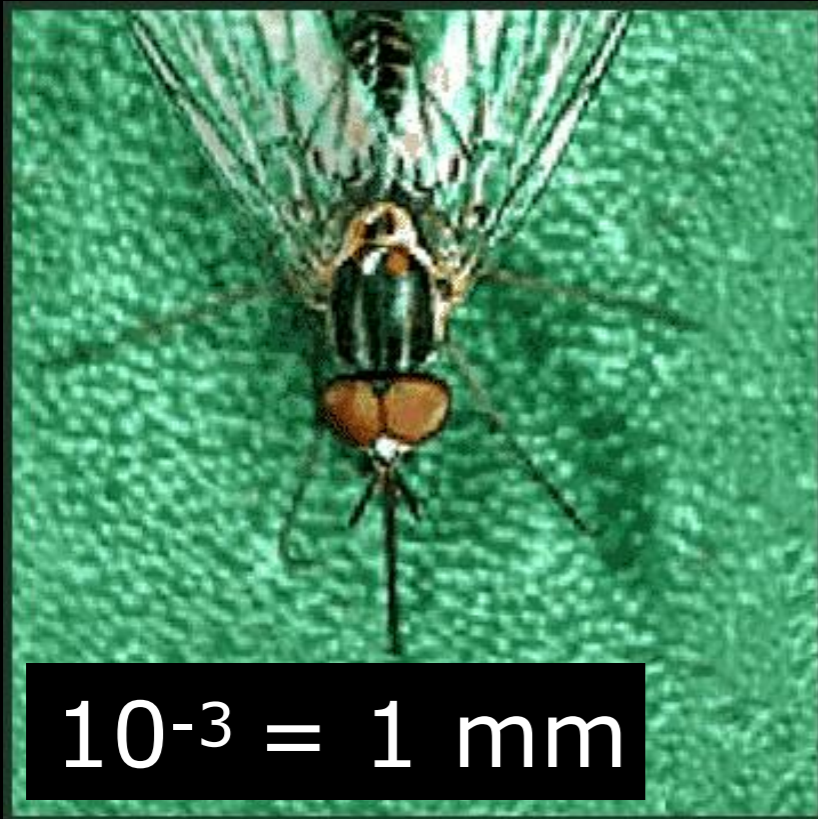
???



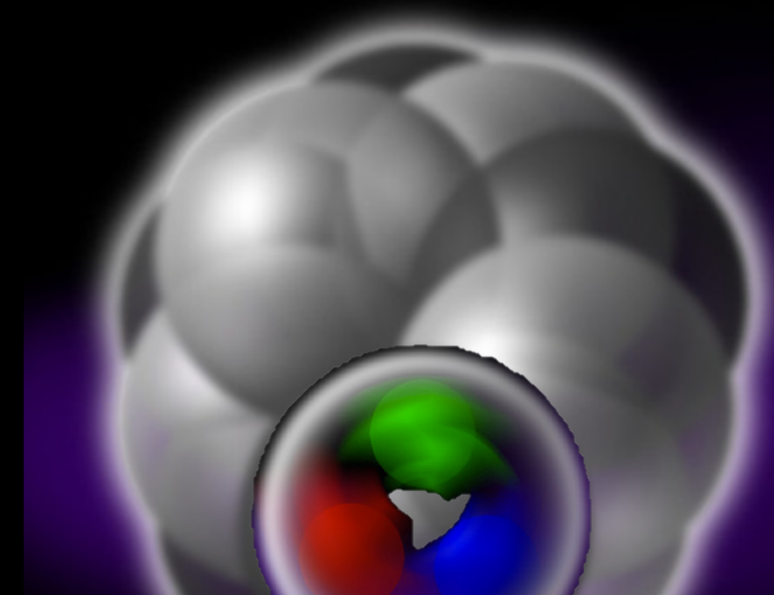
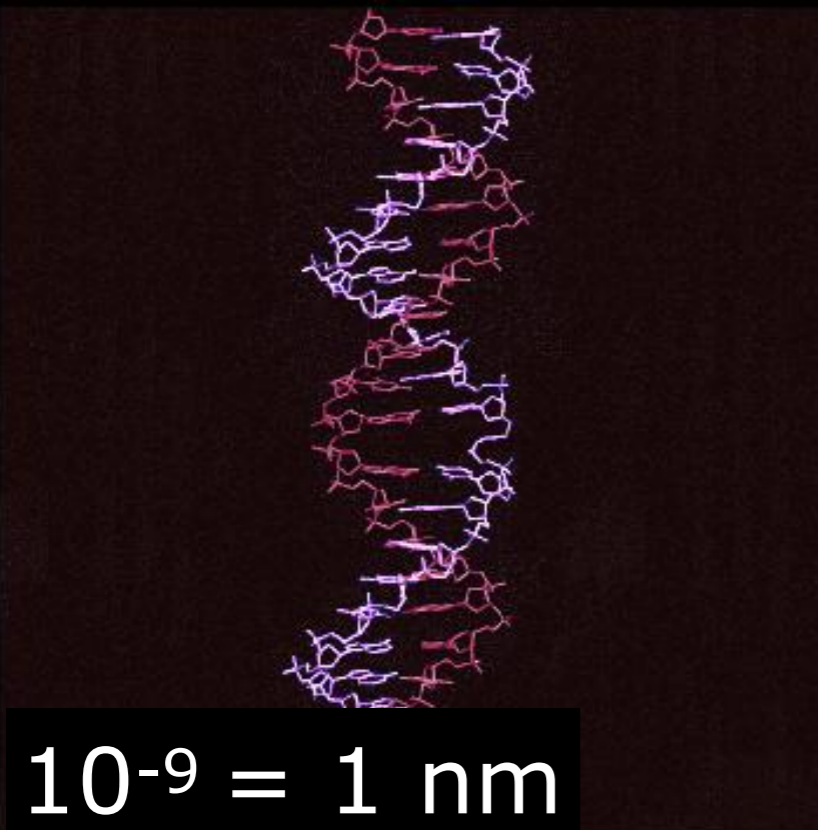
Strumenti e collaborazioni



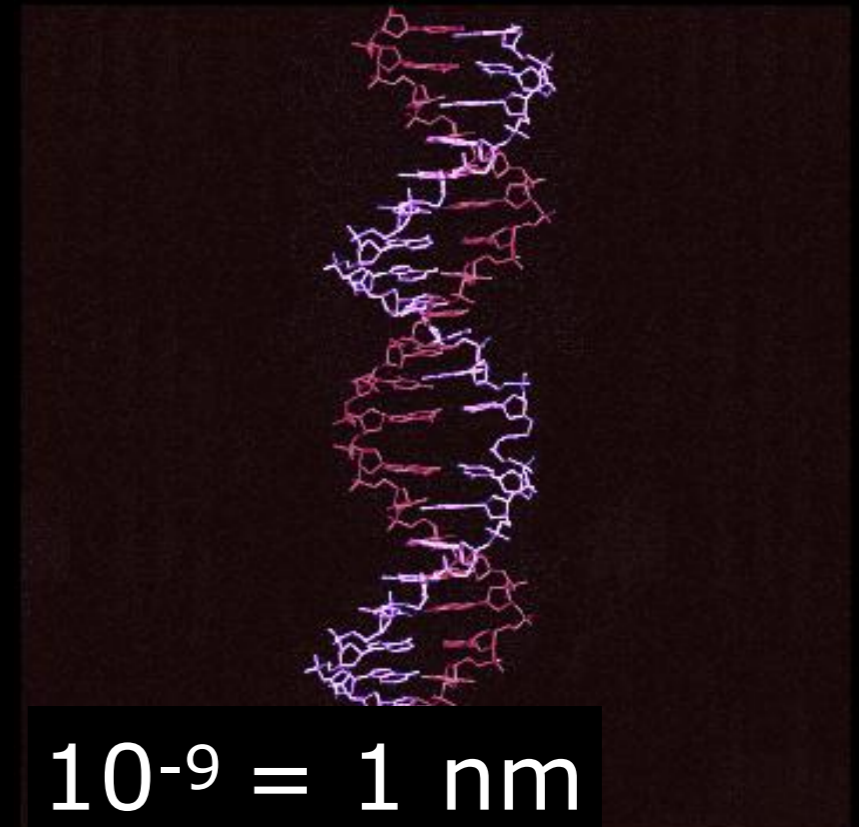
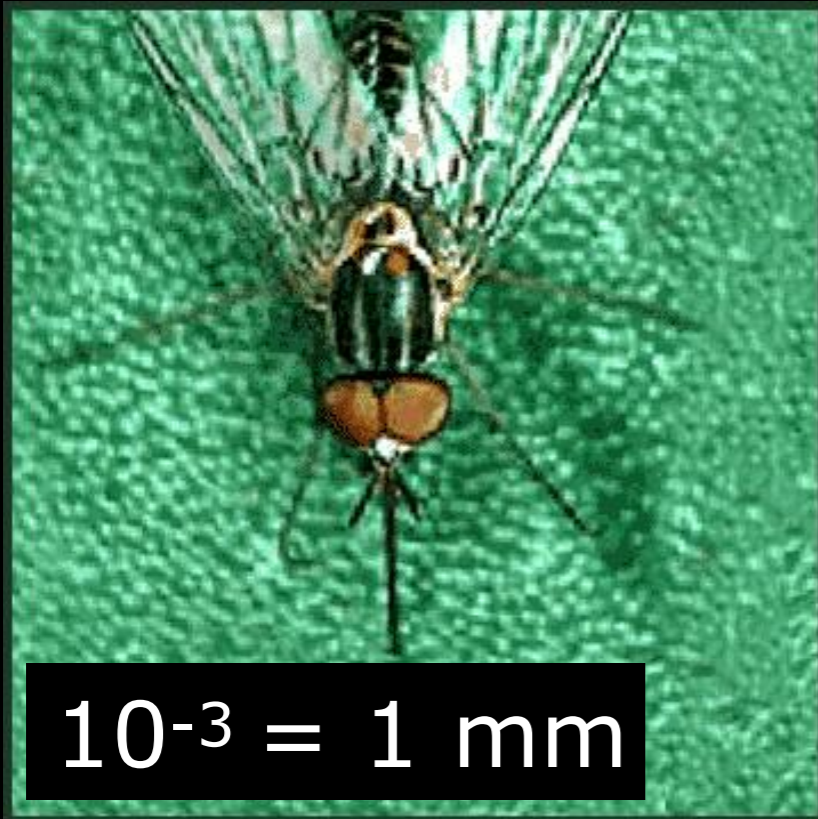
Zoom: x 1.000.000



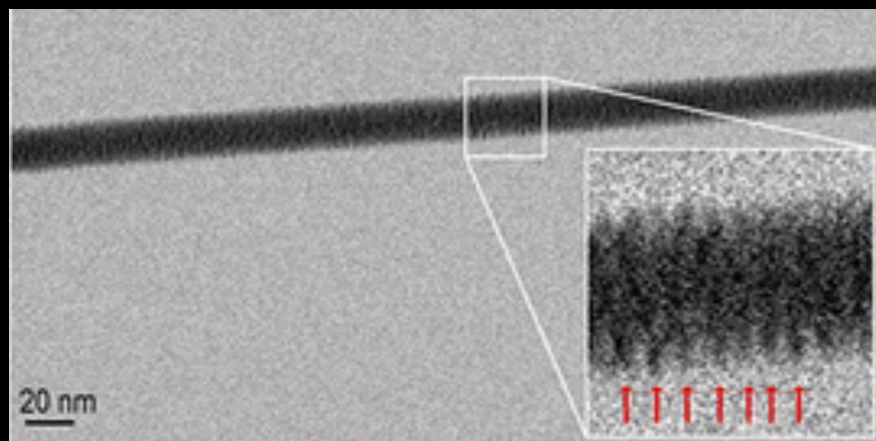
=



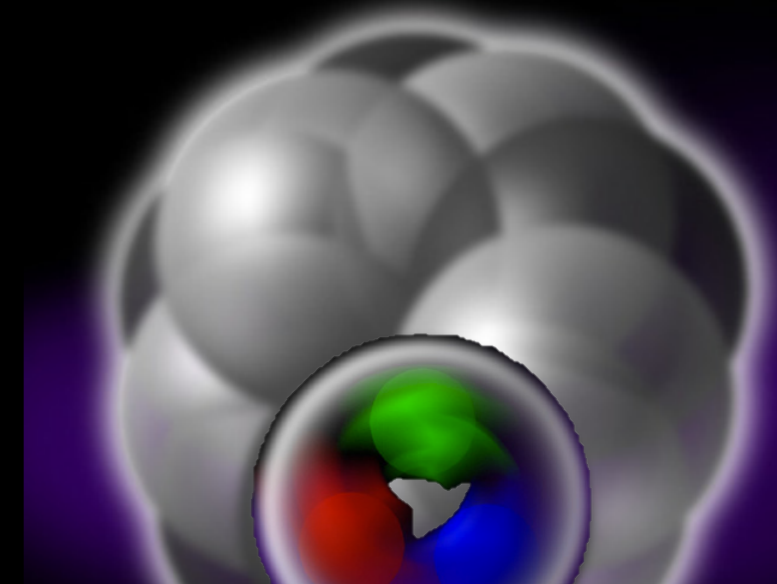
Zoom: x 1.000.000



DNA visto
da microscopio elettronico
<http://pubs.acs.org/doi/abs/10.1021/nl3039162>

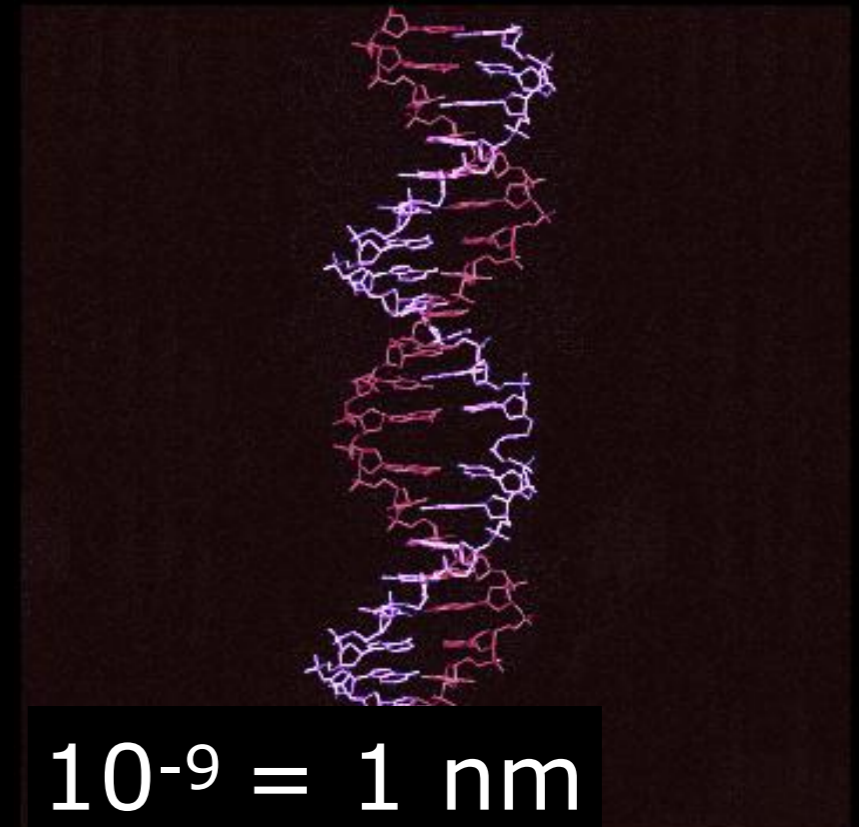
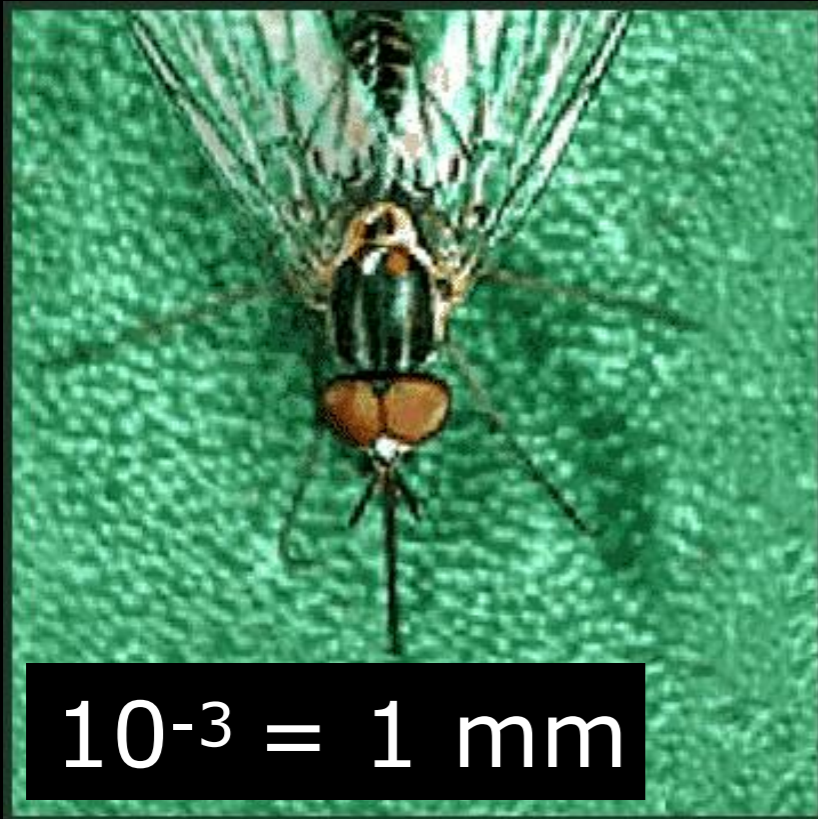


$10^{-9} = 1 \text{ nm}$



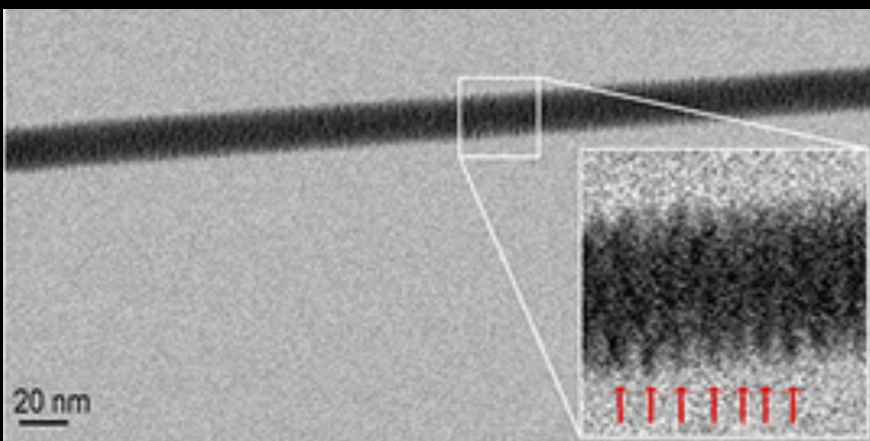
$10^{-15} = 1 \text{ Fermi}$

Zoom: x 1.000.000



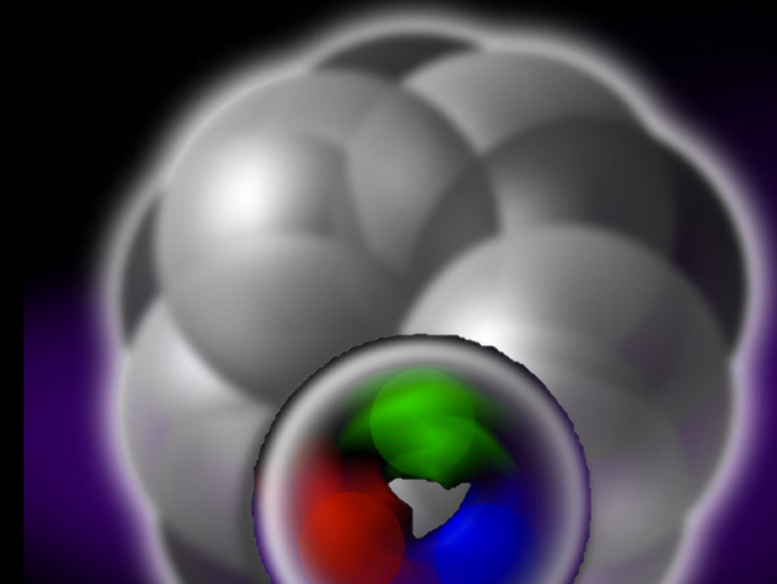
=

DNA visto
da microscopio elettronico
<http://pubs.acs.org/doi/abs/10.1021/nl3039162>

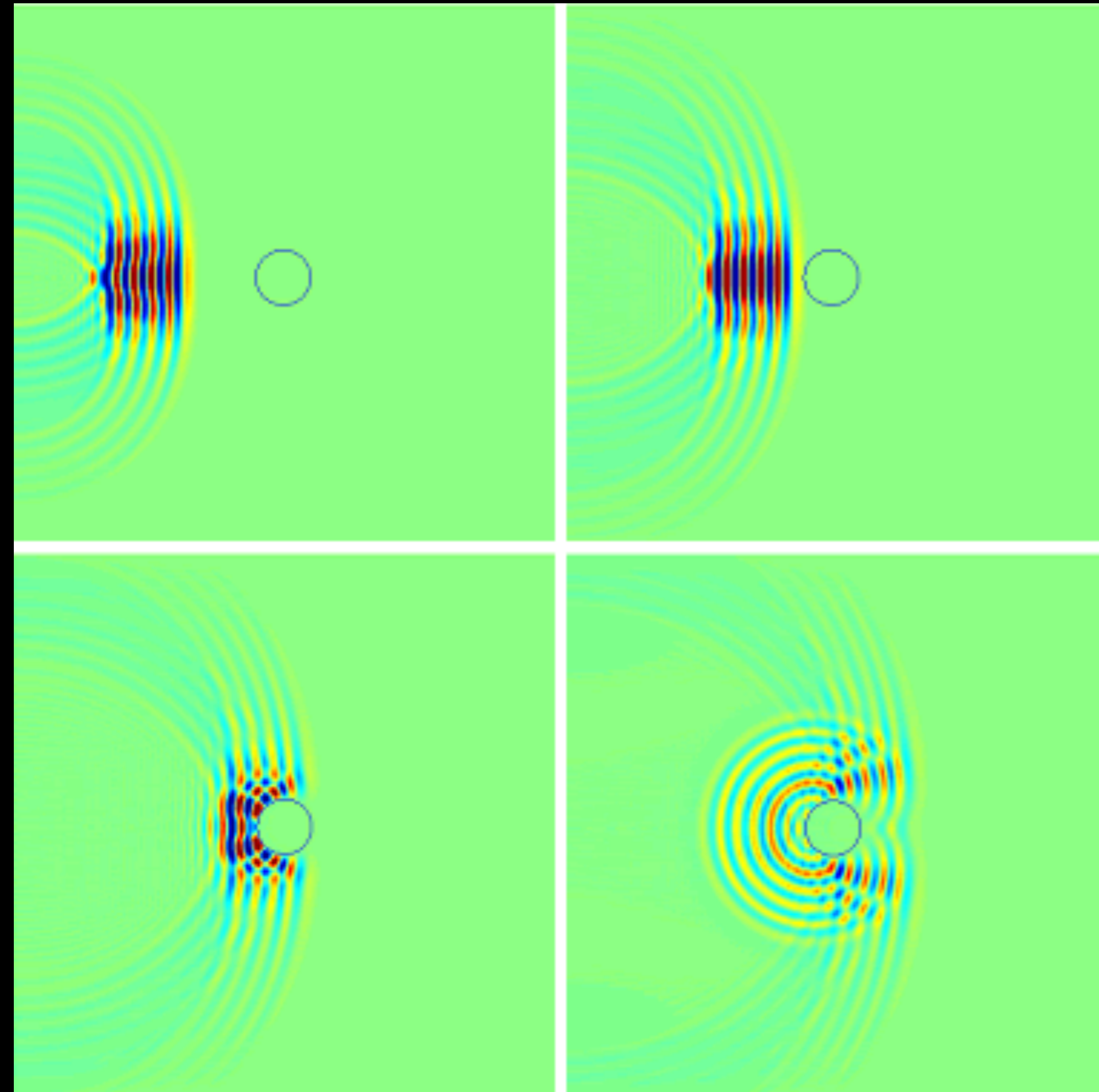


$10^{-9} = 1 \text{ nm}$

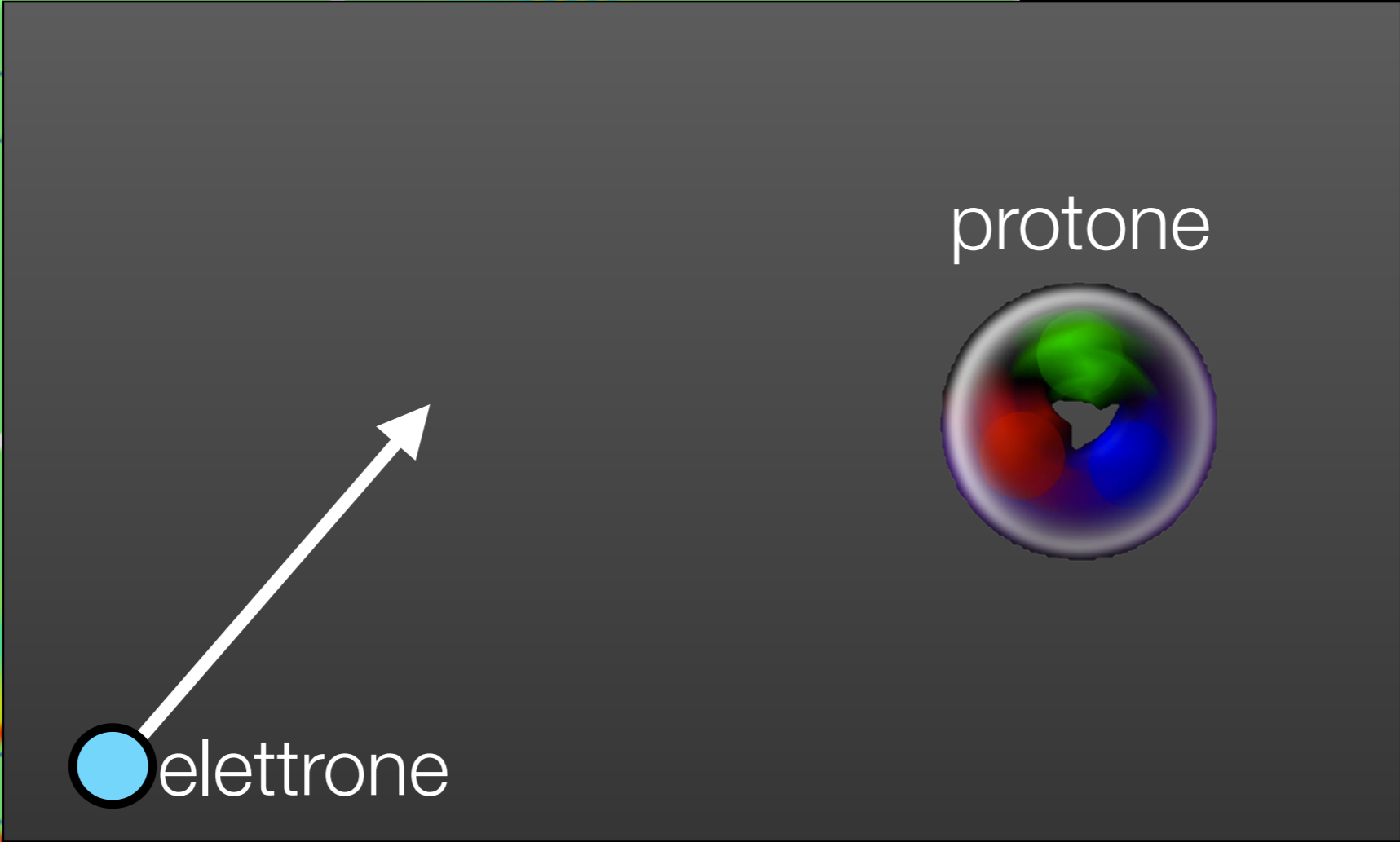
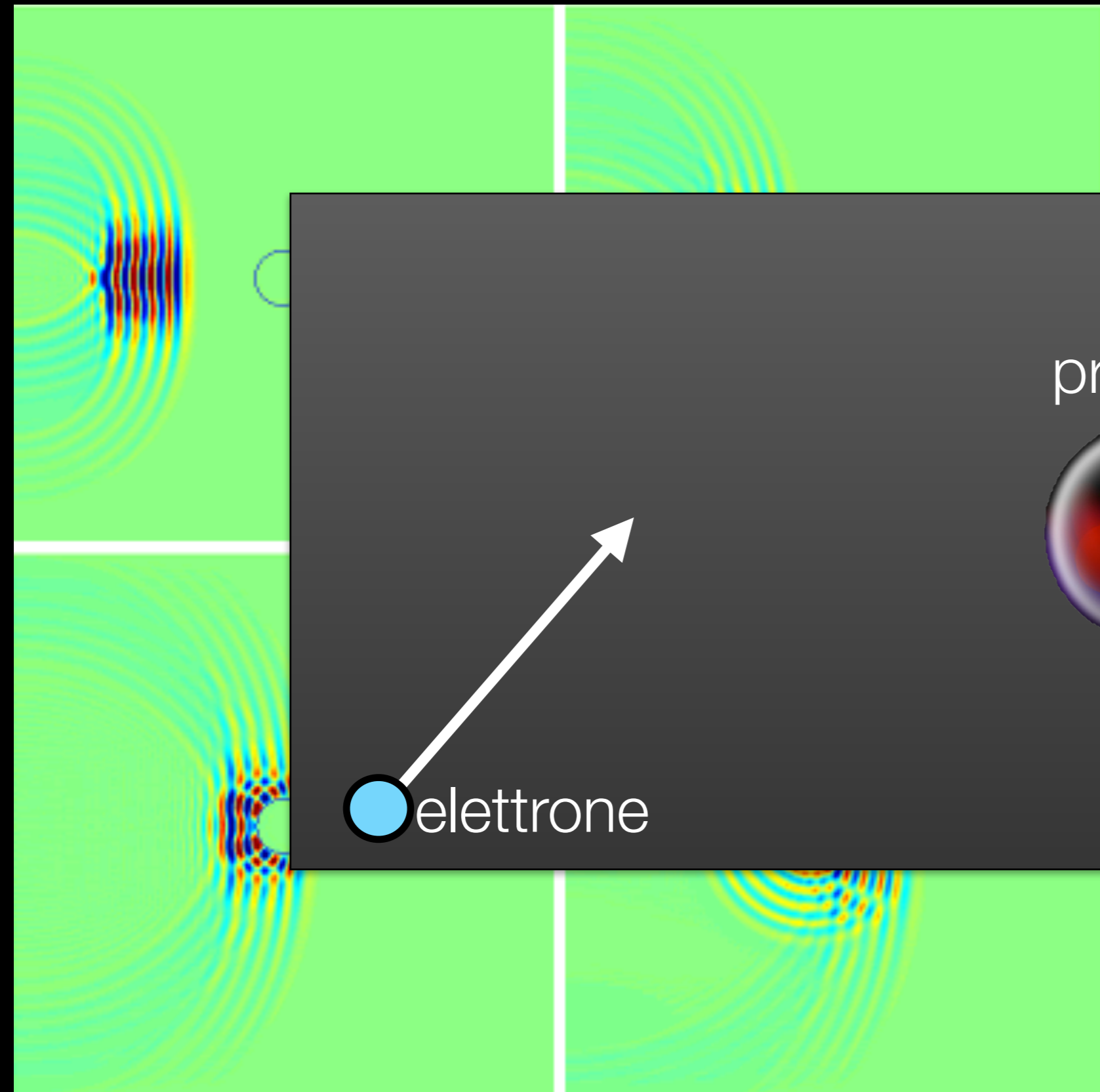
?

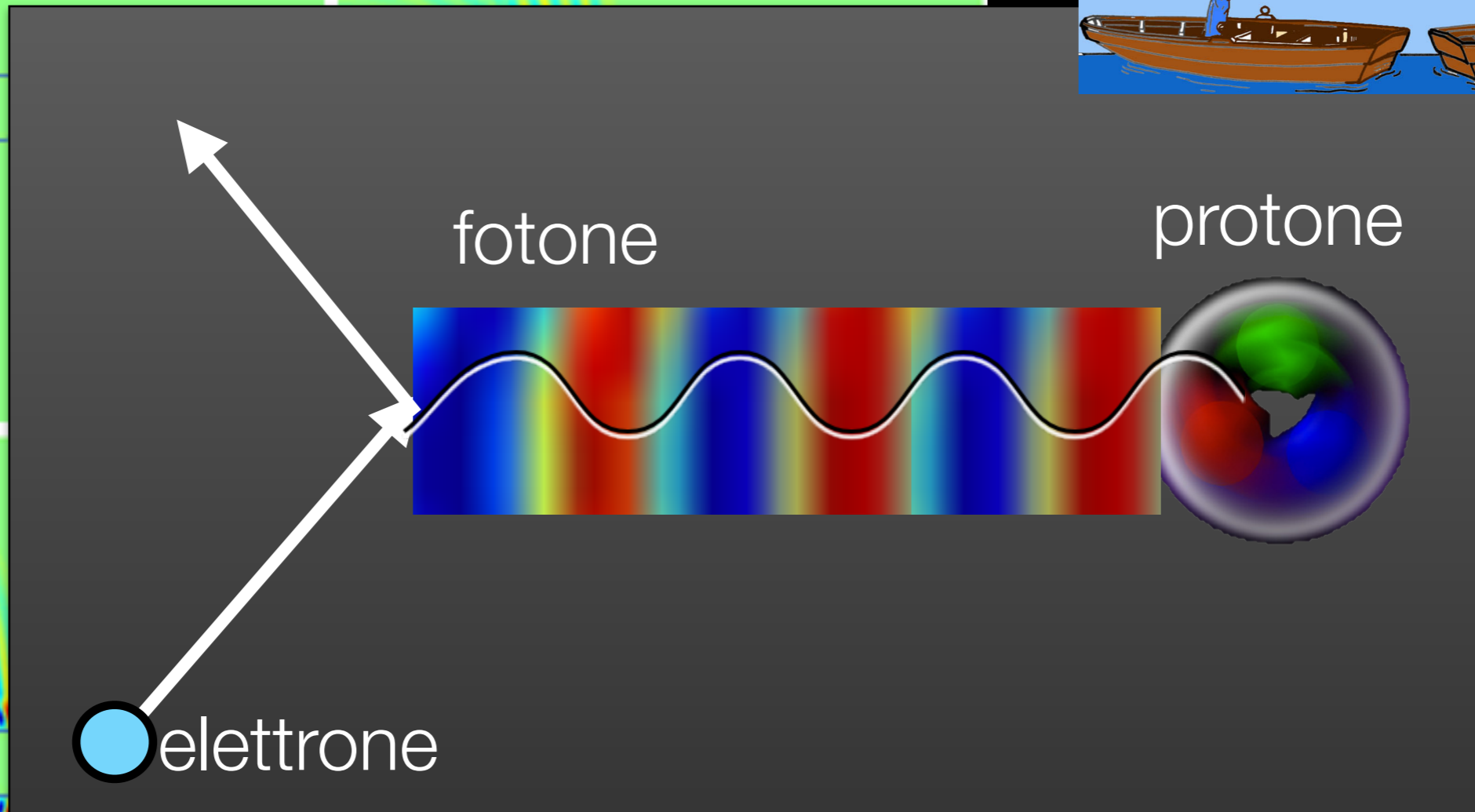
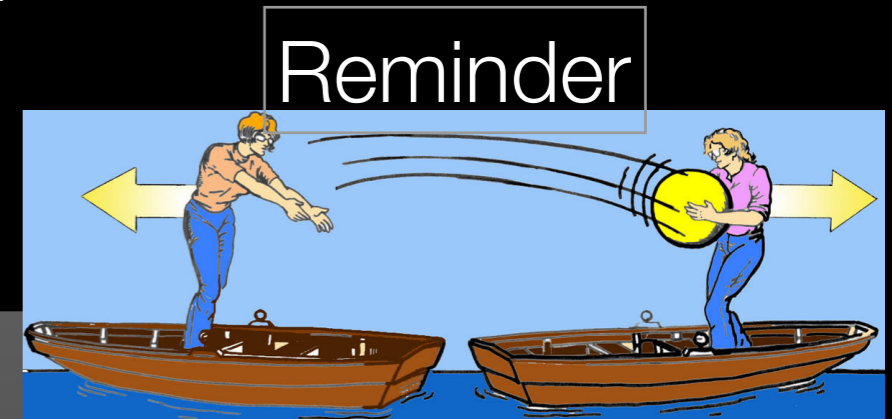


<https://it.mathworks.com/matlabcentral/fileexchange/12097-soundsim-2-5d-acoustic-wave-and-sphere-scattering-simulator?requestedDomain=www.mathworks.com>

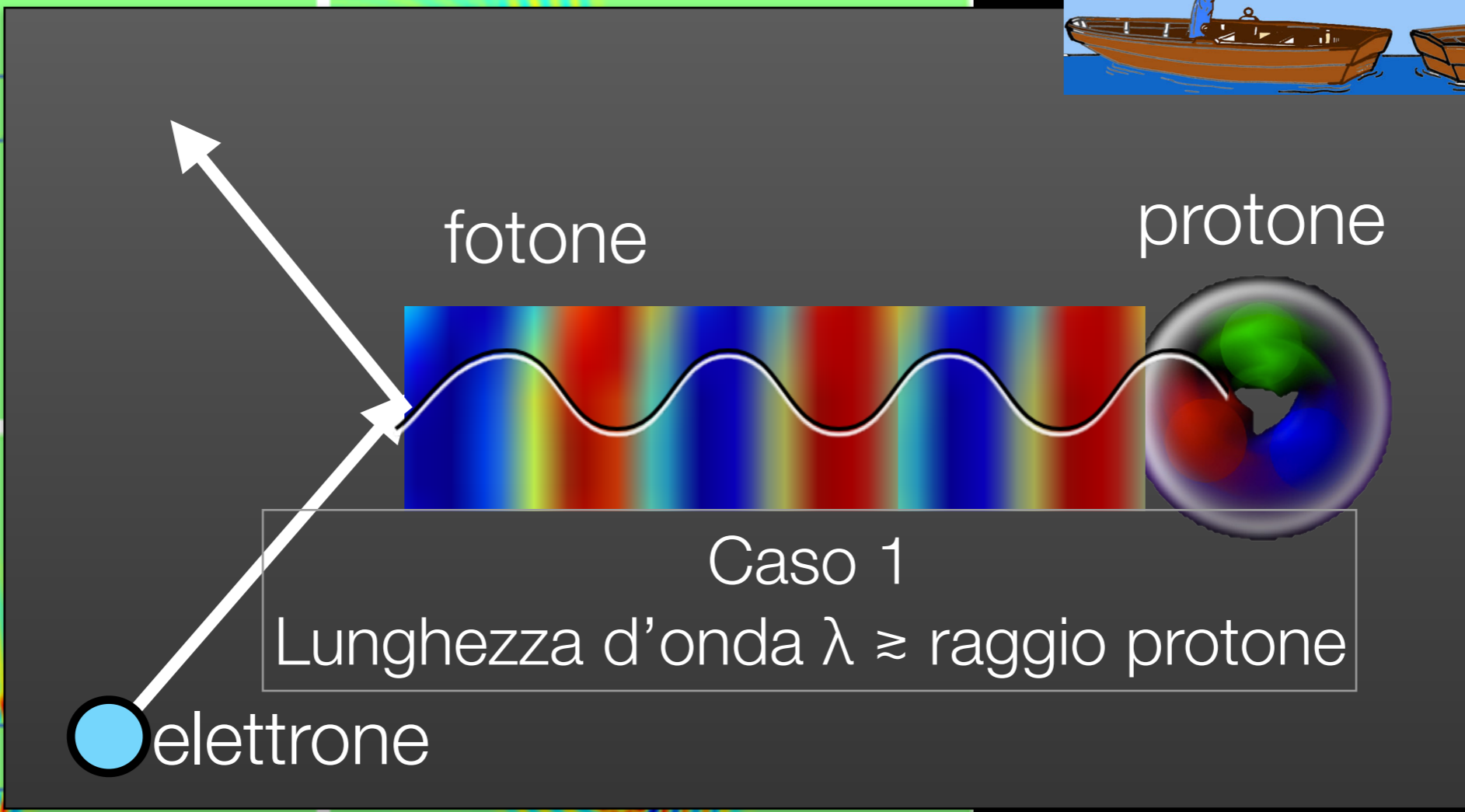
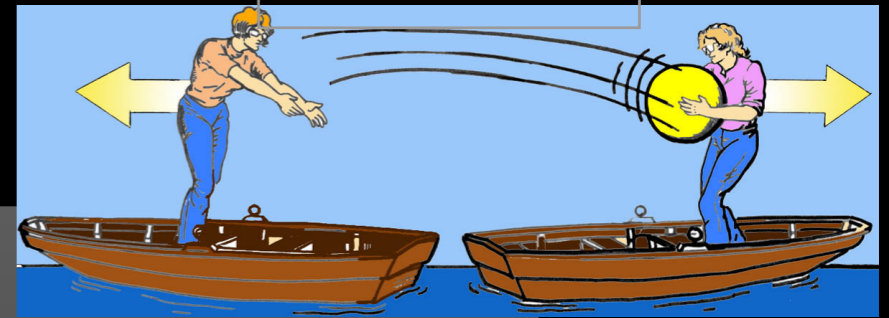


<https://it.mathworks.com/matlabcentral/fileexchange/12097-soundsim-2-5d-acoustic-wave-and-sphere-scattering-simulator?requestedDomain=www.mathworks.com>





Reminder



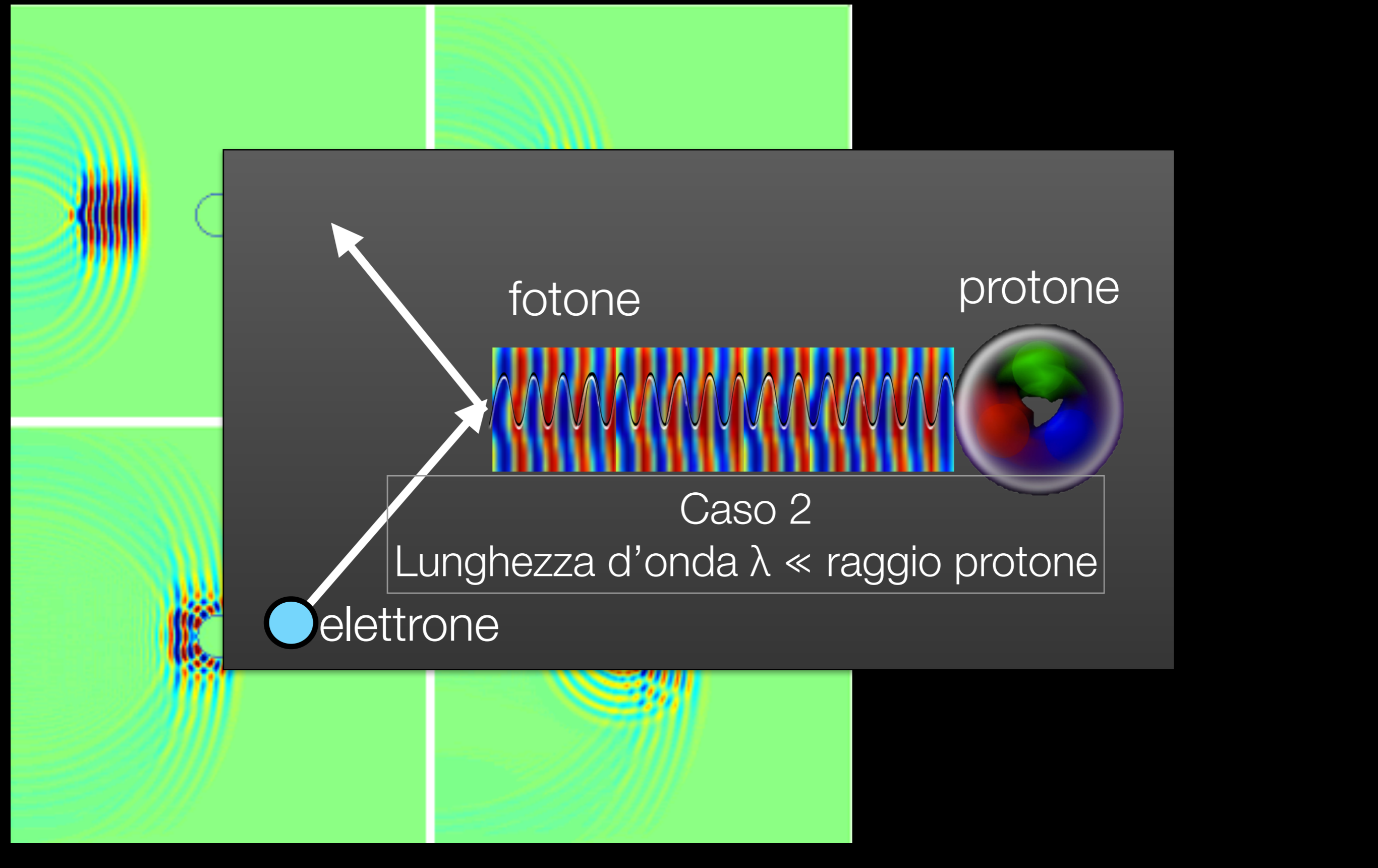
fotone

protone

Caso 1

Lunghezza d'onda $\lambda \approx$ raggio protone

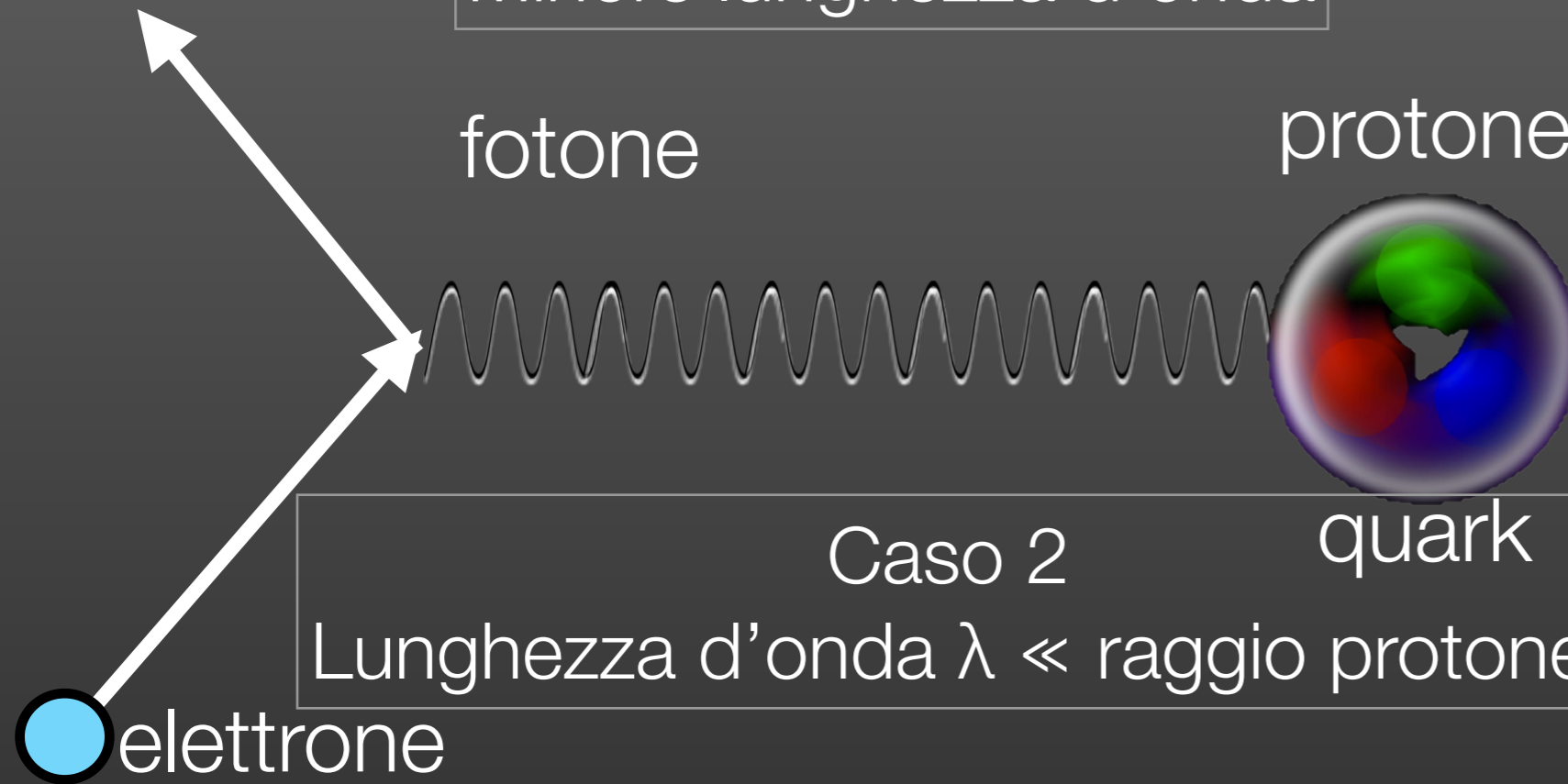
elettrone



Maggiore lunghezza d'onda



Minore lunghezza d'onda



$$\lambda \propto 1/E$$

piccole λ
=
grandi E

**Raggio protone:
1 fm (=10⁻¹⁵ m)**

**Per risolvere
i quarks:
 $\lambda \ll 1$ fm**

\Rightarrow

E \gg 0.2 GeV

**GeV: 10⁹ eV
1.6 x 10⁻¹⁰ J**

THE THING IS, WE HAVE THIS COLLIDER...

... the quantum magic



THE MAGIC OF A COLLIDER IS THAT YOU CAN MAKE KINDS OF MATTER THAT YOU DON'T HAVE AROUND.

YOU TAKE TWO KINDS OF PARTICLES AND ANNIHILATE THEM...



IT'S A KIND OF QUANTUM MAGIC WHERE IT SORT OF DISAPPEARS INTO PURE ENERGY...*

WHAT COMES OUT DOESN'T HAVE TO BE A RE-ARRANGEMENT OF WHAT WENT IN.

YOU CAN MAKE ANY SORT OF PARTICLE FOR WHICH YOU HAVE ENOUGH ENERGY.

* a force-carrying boson

IT'S LIKE HAVING A MENU...
what can i get in the 500 GeV range?



YOU CAN MAKE ANYTHING THAT COSTS THAT MUCH ENERGY OR LESS.

THAT'S WHY YOU WANT TO HAVE AS MUCH ENERGY AS POSSIBLE.

EVERY TIME YOU CRANK UP THE ENERGY, YOU COULD BE EXPLORING A WHOLE NEW REGIME.

JORGE CHAM © 2012

$$\lambda \propto 1/E$$

piccole λ
=
grandi E

**Raggio protone:
1 fm (=10⁻¹⁵ m)**

**Per risolvere
i quarks:**

$$\lambda \ll 1 \text{ fm}$$

⇒

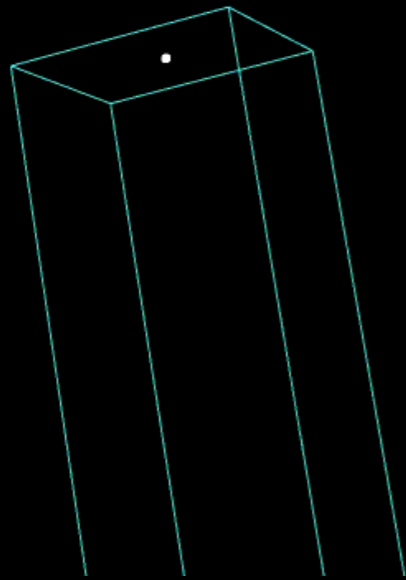
$$E \gg 0.2 \text{ GeV}$$

$$\text{GeV: } 10^9 \text{ eV}$$

$$1.6 \times 10^{-10} \text{ J}$$

Alte energie: Come?

Protone, 1000 GeV



LHC
CERN
Svizzera

Pierre Auger Observatory
Argentina



3000 km²

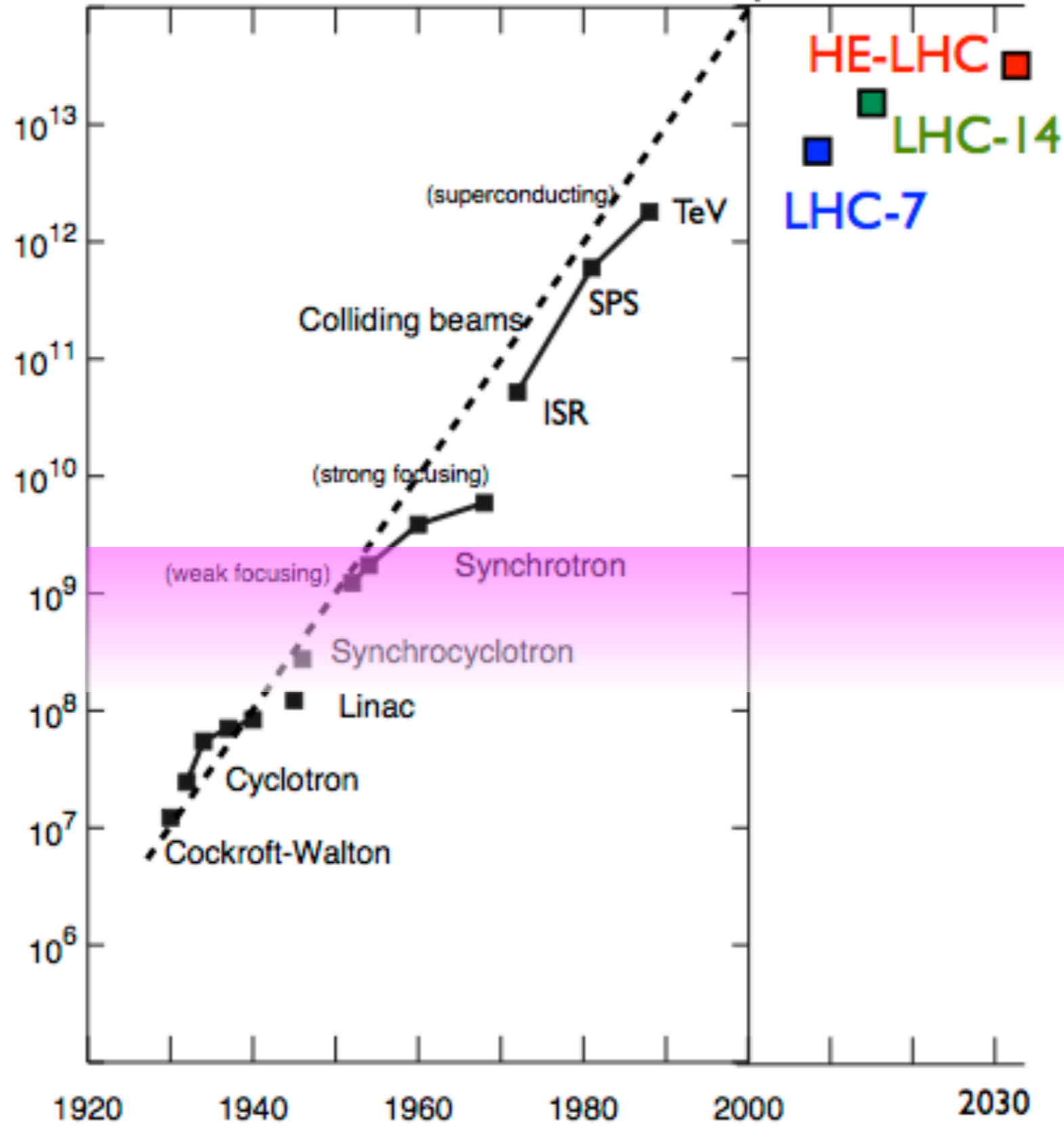
Raggi cosmici,
altissime energie, ma rari



Acceleratori
Energie limitate, ma alte intensità

La corsa agli acceleratori

energia (eV)



risolviamo la
struttura del
protone



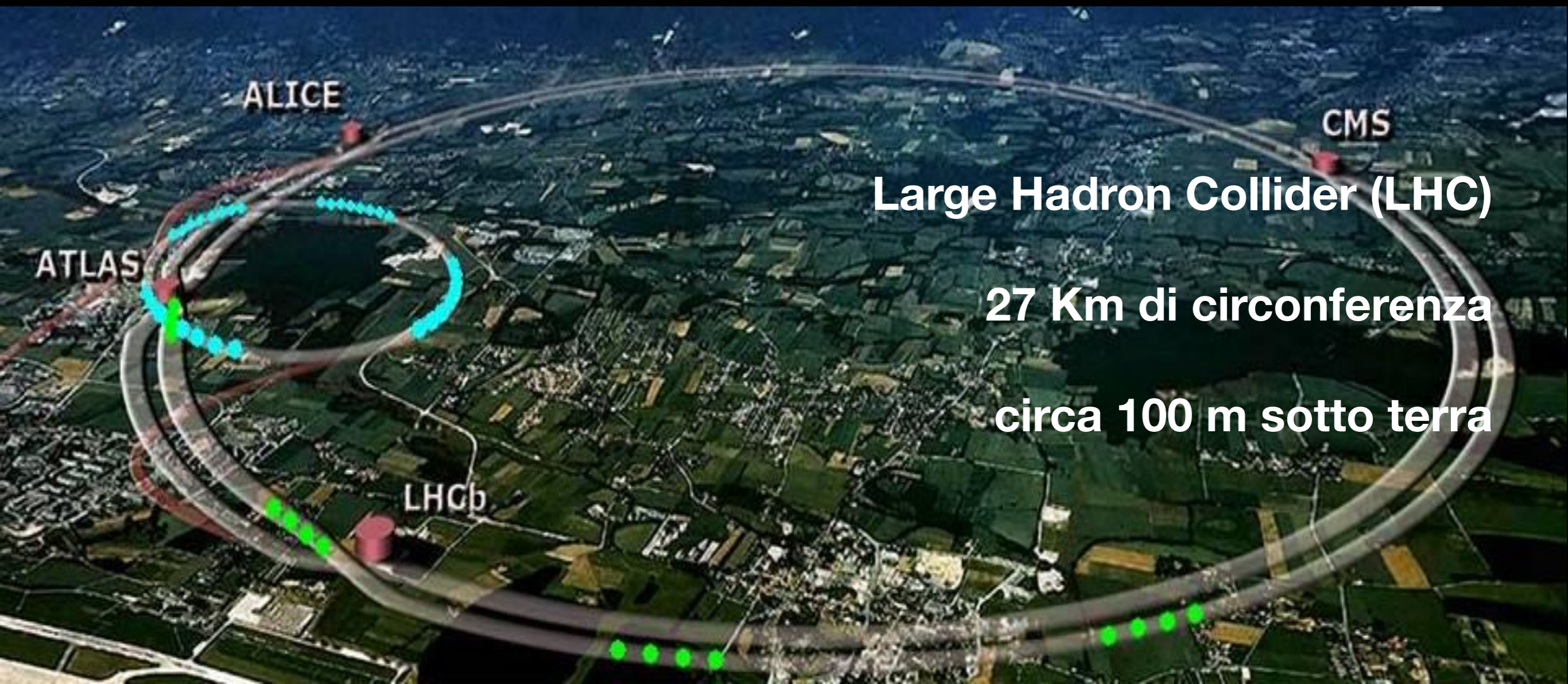
C'è chi ne costruisce uno a casa

Certamente, un gioco da ragazzi se sei un genio, miliardario, playboy, filantropo.

Ma torniamo ai fatti...

A differenza di Toni Stark, nessuno di noi ha un acceleratore di alta energia a casa.

MA, in questo caso, le dimensioni contano!!!



Large Hadron Collider (LHC)

27 Km di circonferenza

circa 100 m sotto terra

Large Hadron Collider

Le particelle viaggiano ad una velocità molto vicina a quella della luce (99.99999998%).

Far curvare le particelle a queste energie richiede una grande forza.

Magneti

superconduttori

8.3 T

2000 volte campo
magnetico terrestre

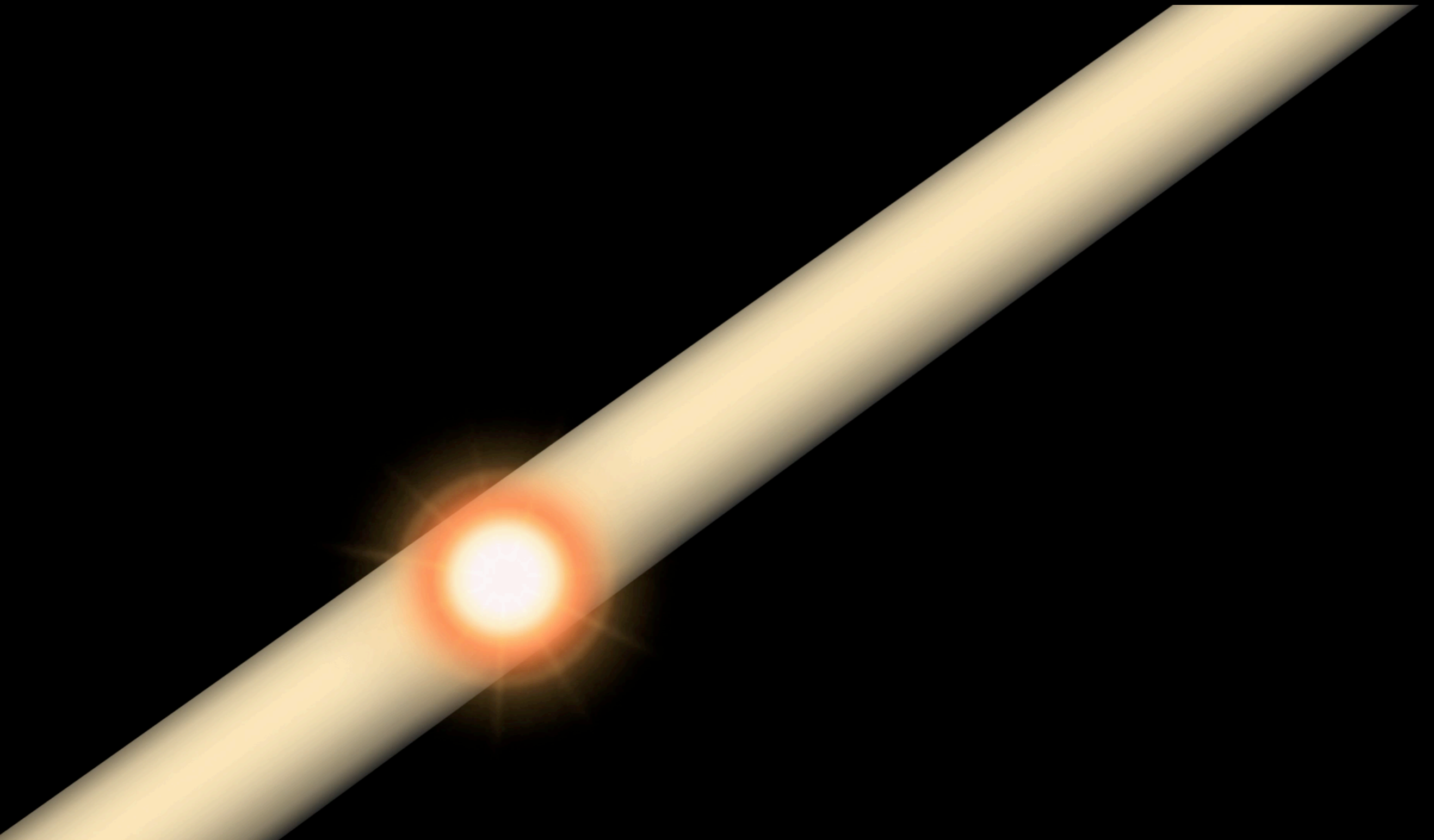
Temperatura

di 1.9K, circa un
grado in meno dello
spazio intergalattico

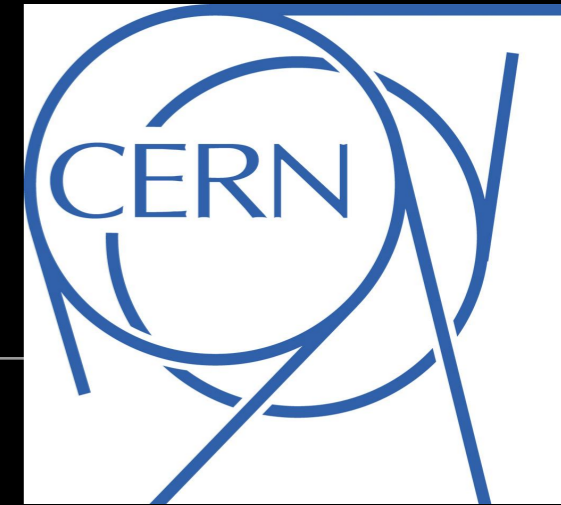


sicuri che curva?

Large Hadron Collider



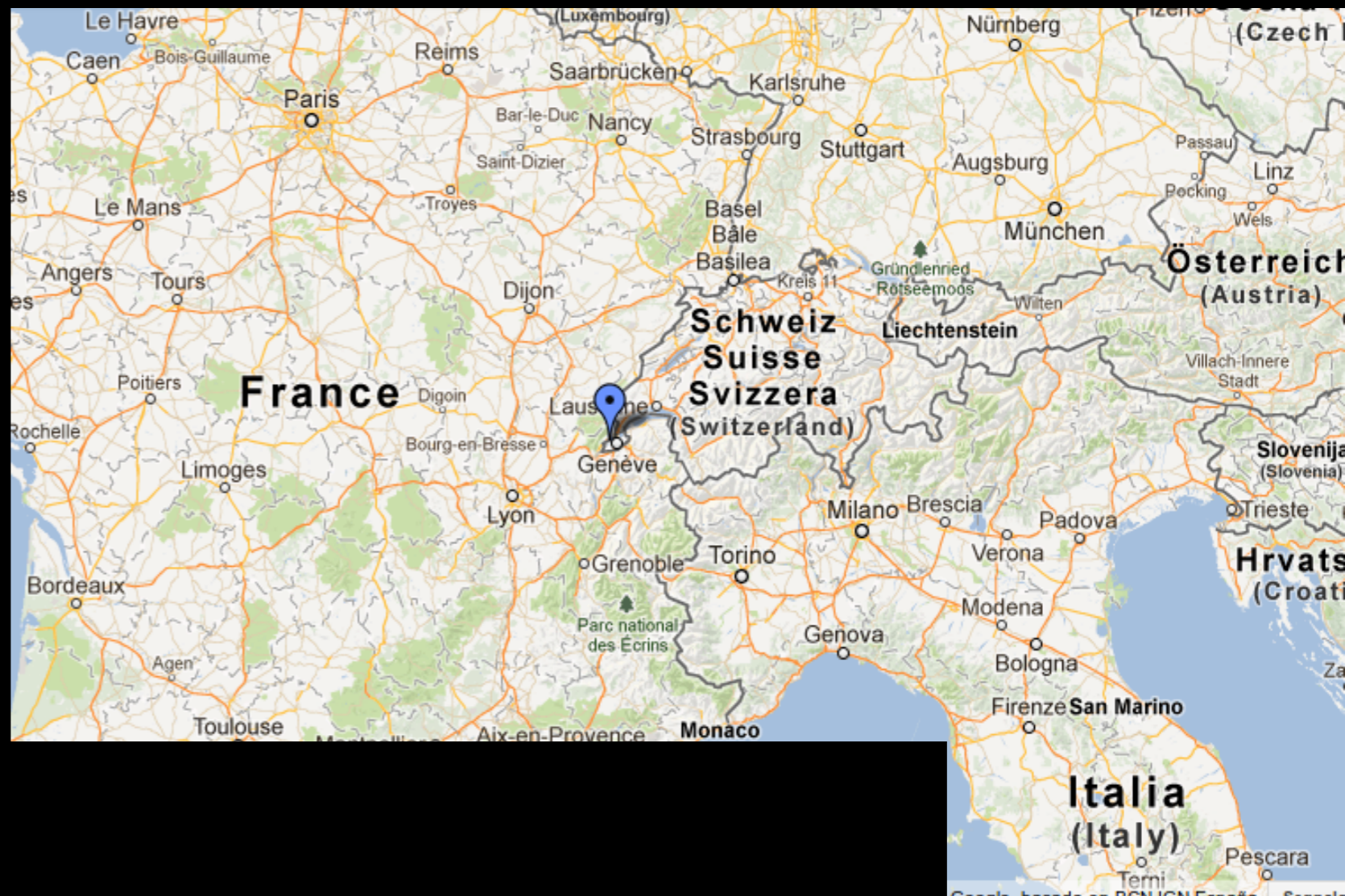
Dove? il CERN !



Il Large Hadron Collider e' il fiore all'occhiello del CERN:
Consiglio Europeo per la Ricerca Nucleare.

Nato negli anni '50,
come centro europeo,
libero e votato alla
collaborazione internazionale.

Tra Svizzera e Francia



Studi di fisica delle **interazioni fondamentali, fisica nucleare,**
fisica medica, fisica degli acceleratori,...

Nella realtà non siamo proprio come Tony Stark



Anche se ogni tanto qualcuno



Ma non siamo neanche così:

Anche se ogni tanto qualcuno...



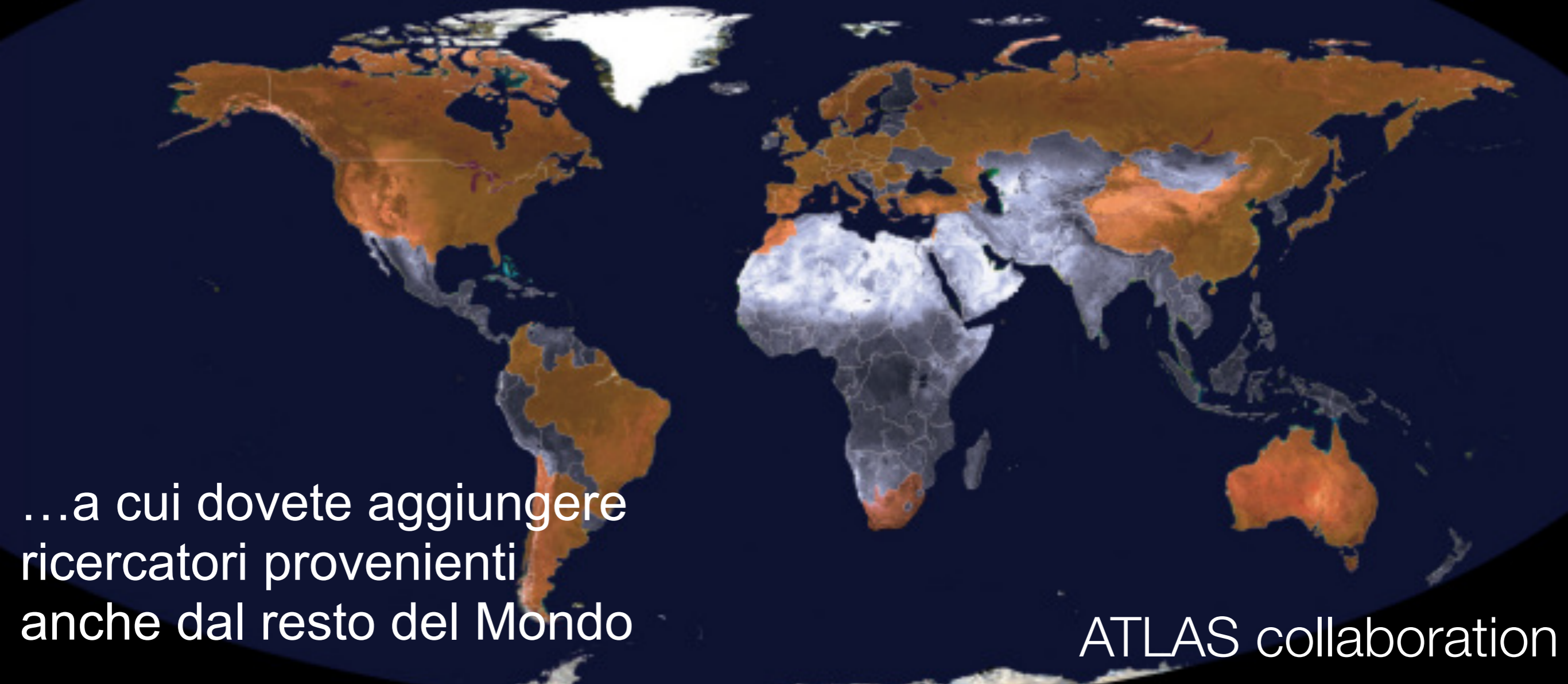
La pulisci tu la lavagna, vero?



Ufficio del gruppo ATLAS di Pisa 2011

Ma c'è tanta
ricchezza in più

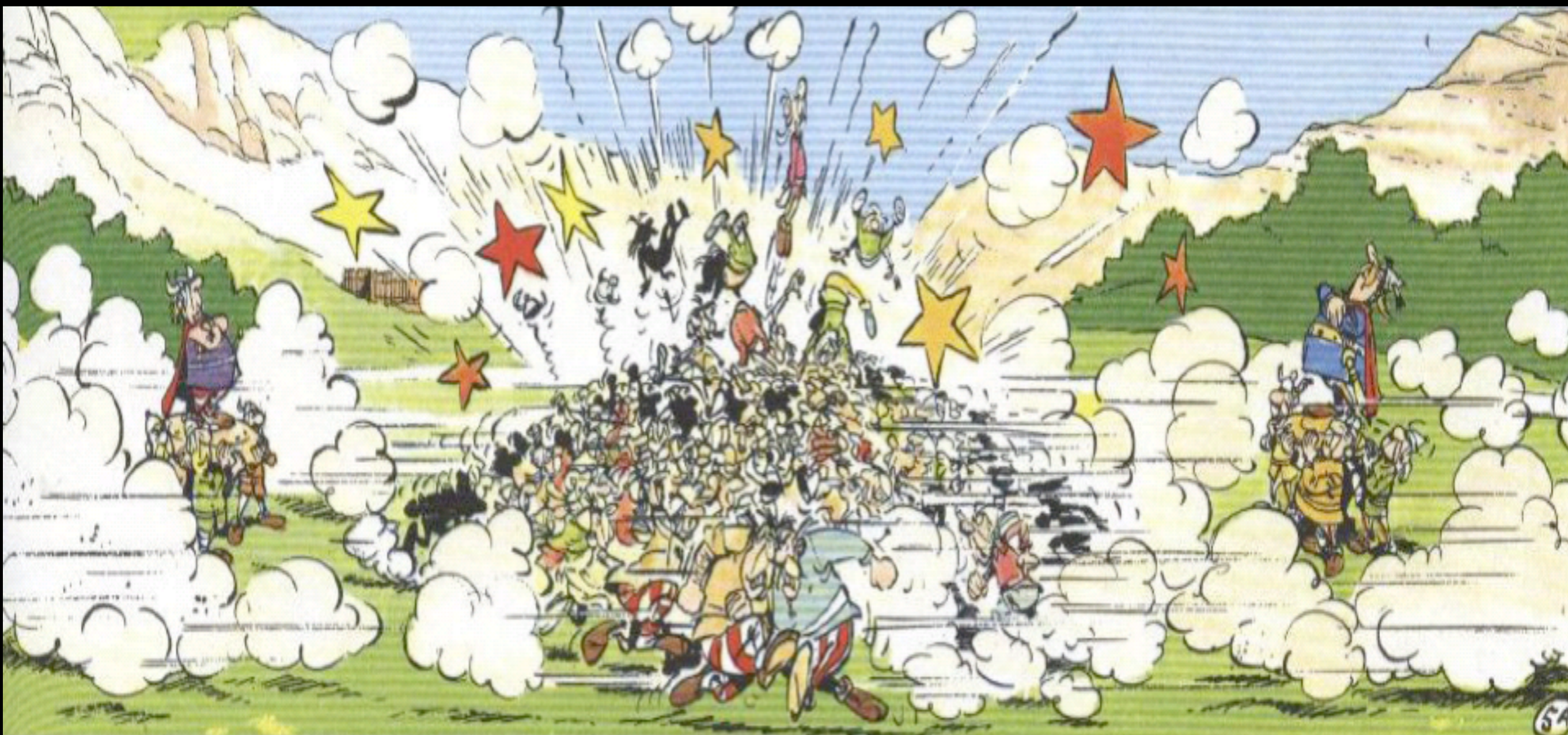
Collaborazioni
internazionali, in alcuni
casi con più di 4000
persone



...a cui dovete aggiungere
ricercatori provenienti
anche dal resto del Mondo

ATLAS collaboration

Torniamo alle nostre collisioni!!!



Question time:

È più probabile

un urto tra due protoni
accelerati in LHC,

o fare 6 al superenalotto?



Question time:

Probabilità di urto tra due protoni accelerati in LHC:

circa 1 su 10 miliardi.

Probabilità di vincere il superenalotto:

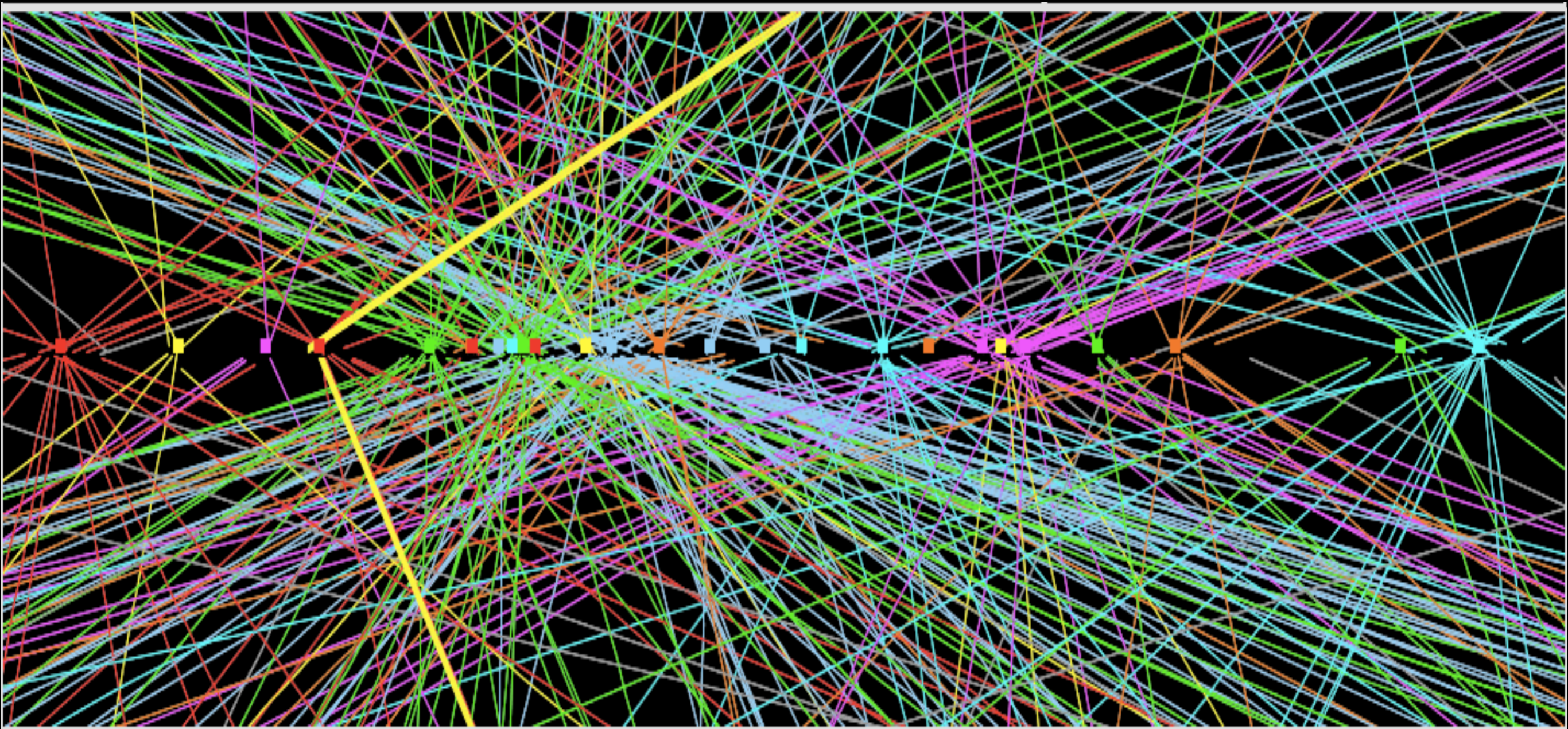
circa 1 su 600 milioni. Molto più probabile.

Ma LHC fa molte più "estrazioni":

I fasci sono divisi in circa 3000 pacchetti, ogni pacchetto ha 100 miliardi di particelle:

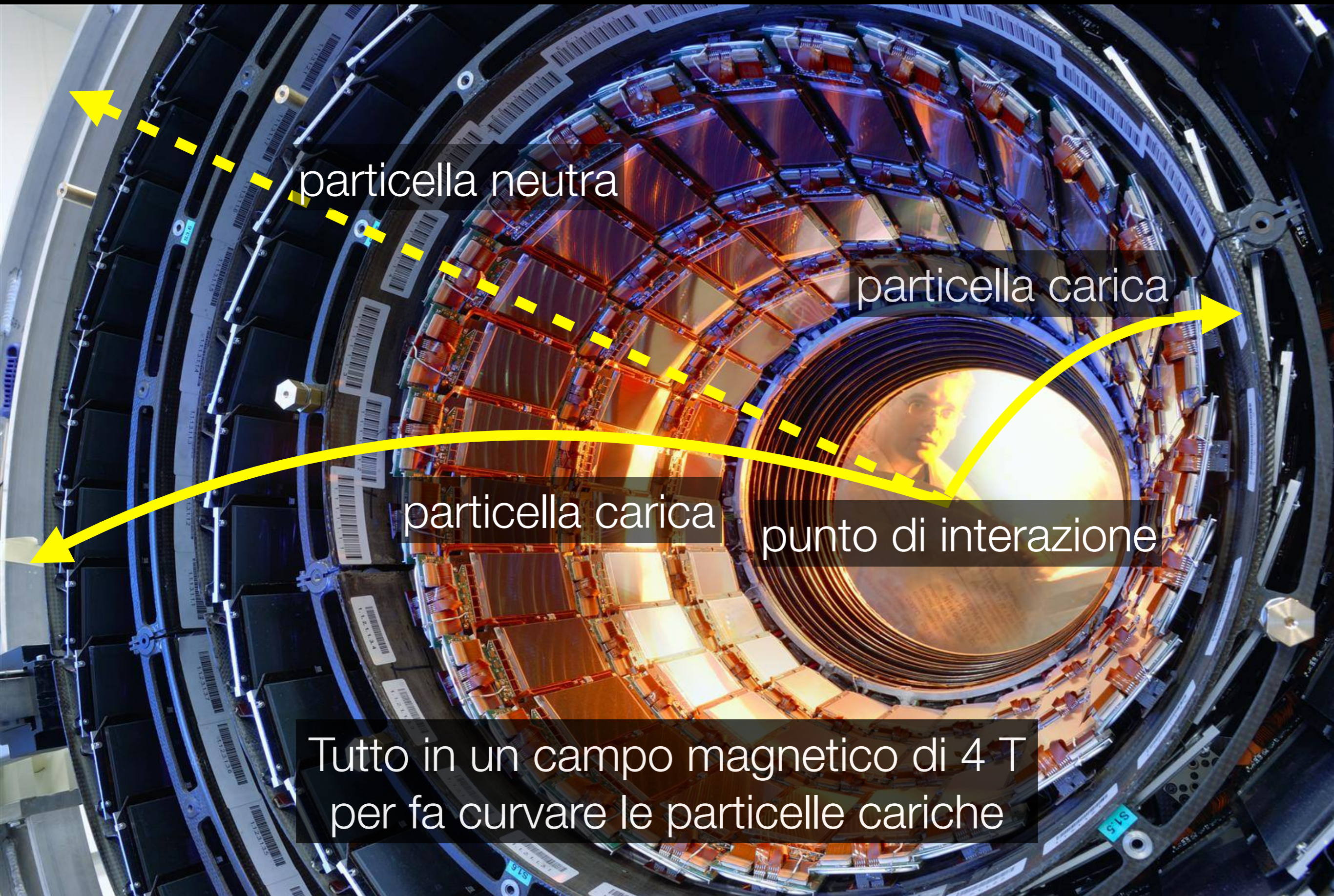
Mezzo miliardo di collisioni al secondo.

Nella Realtà...



Evento registrato in ATLAS con 25 interazioni protone protone sovrapposti

Tracciatore interno di CMS



particella neutra

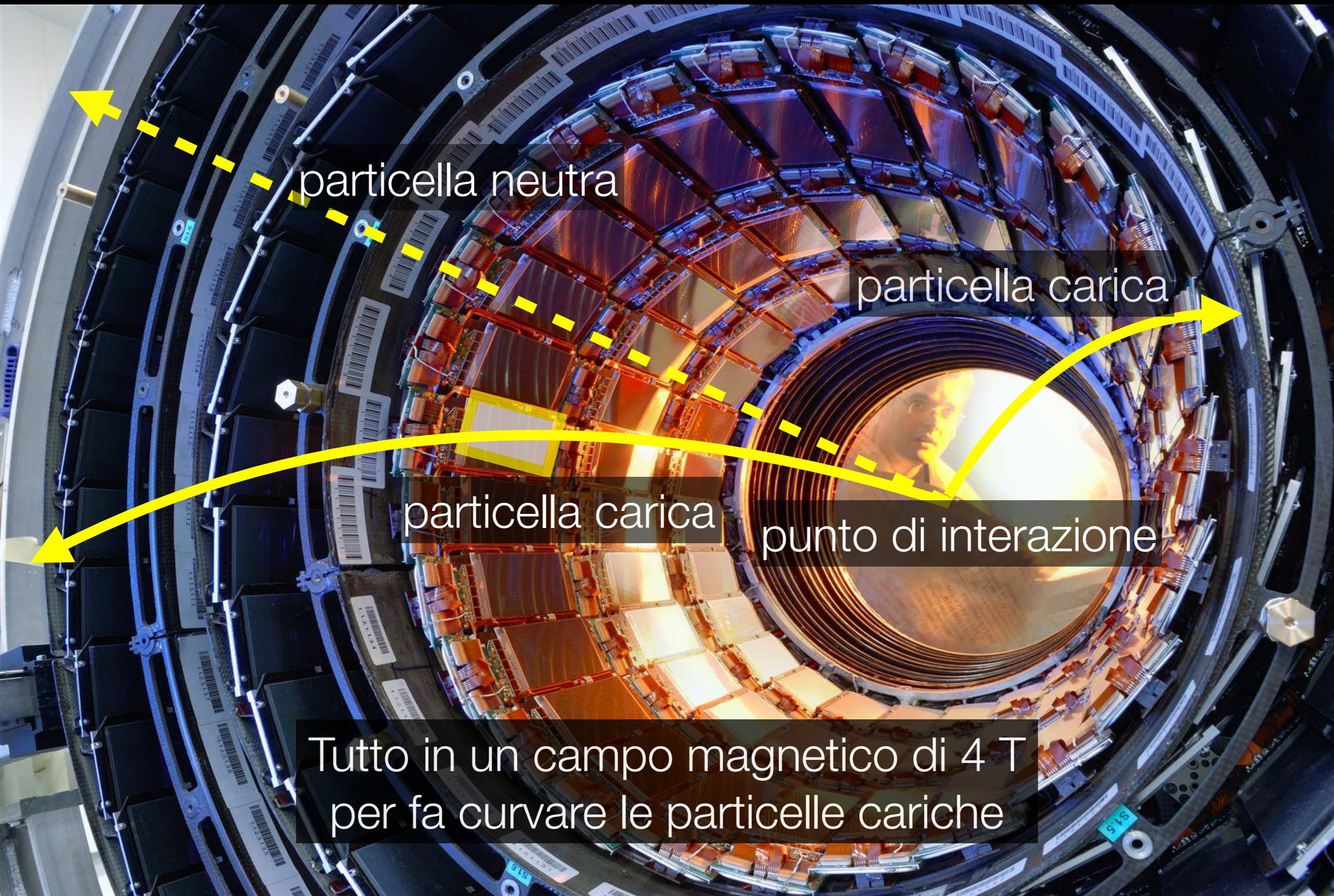
particella carica

particella carica

punto di interazione

Tutto in un campo magnetico di 4 T
per fa curvare le particelle cariche

Tracciatore interno di CMS



particella neutra

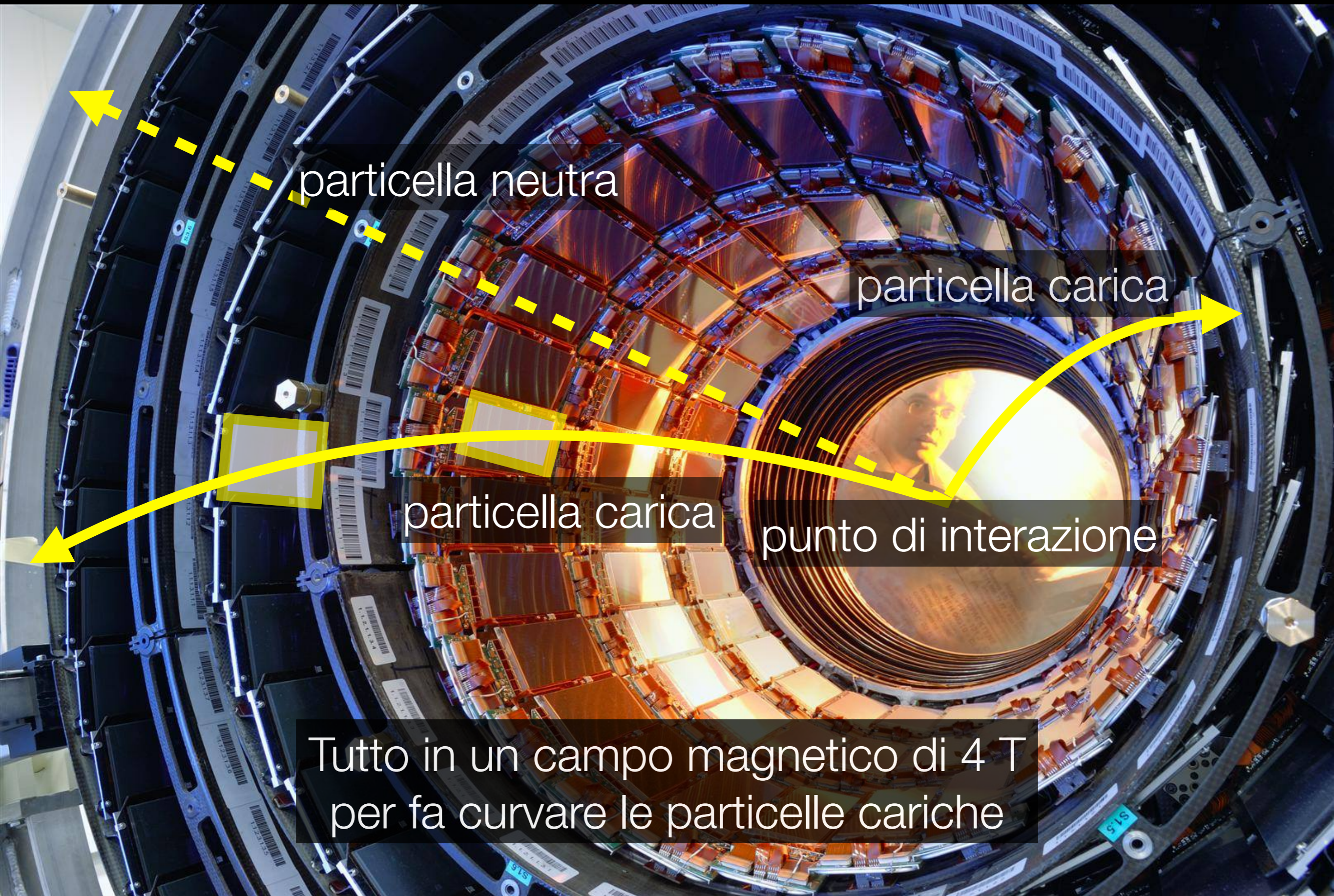
particella carica

particella carica

punto di interazione

Tutto in un campo magnetico di 4 T
per fa curvare le particelle cariche

Tracciatore interno di CMS



particella neutra

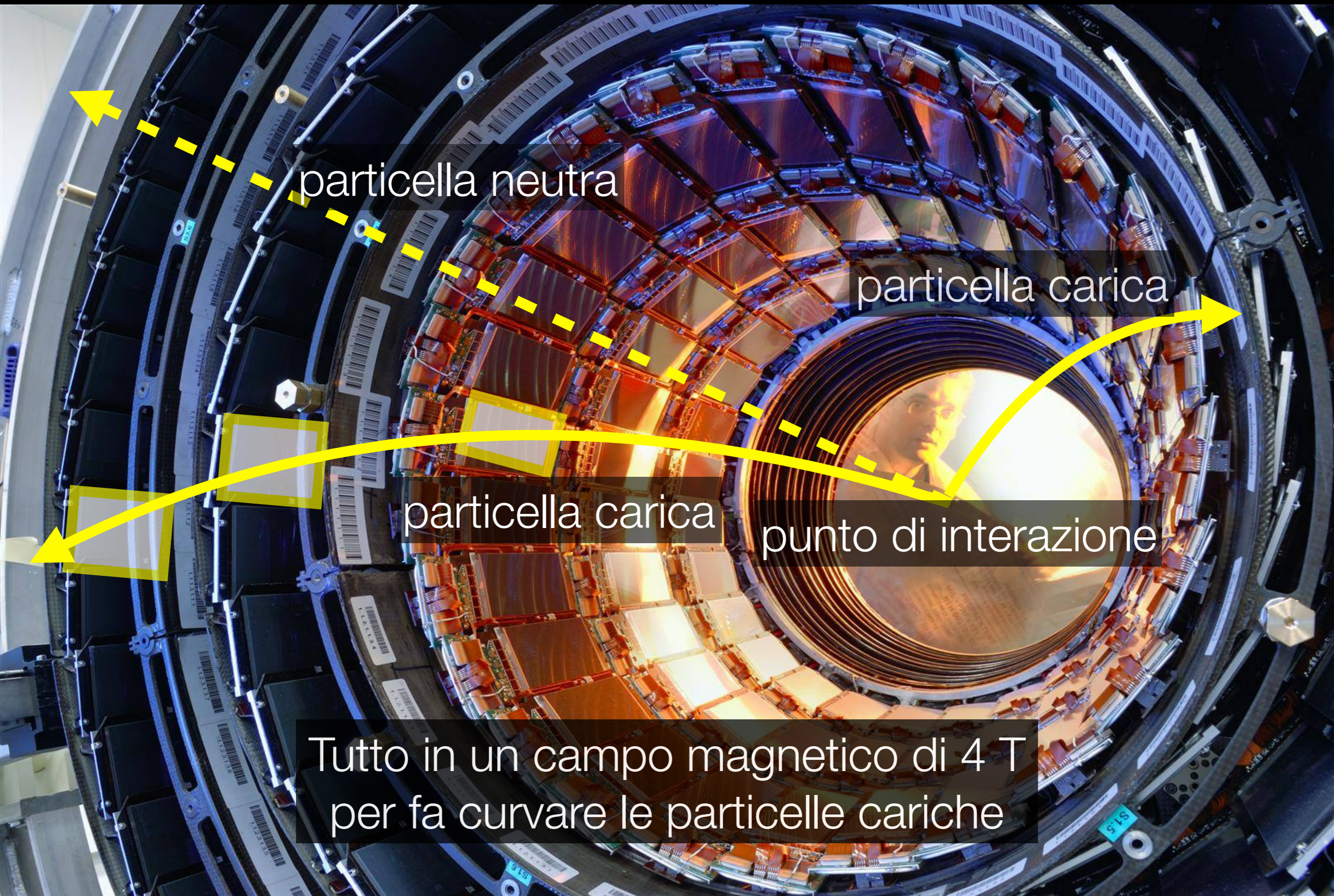
particella carica

particella carica

punto di interazione

Tutto in un campo magnetico di 4 T
per fa curvare le particelle cariche

Tracciatore interno di CMS



particella neutra

particella carica

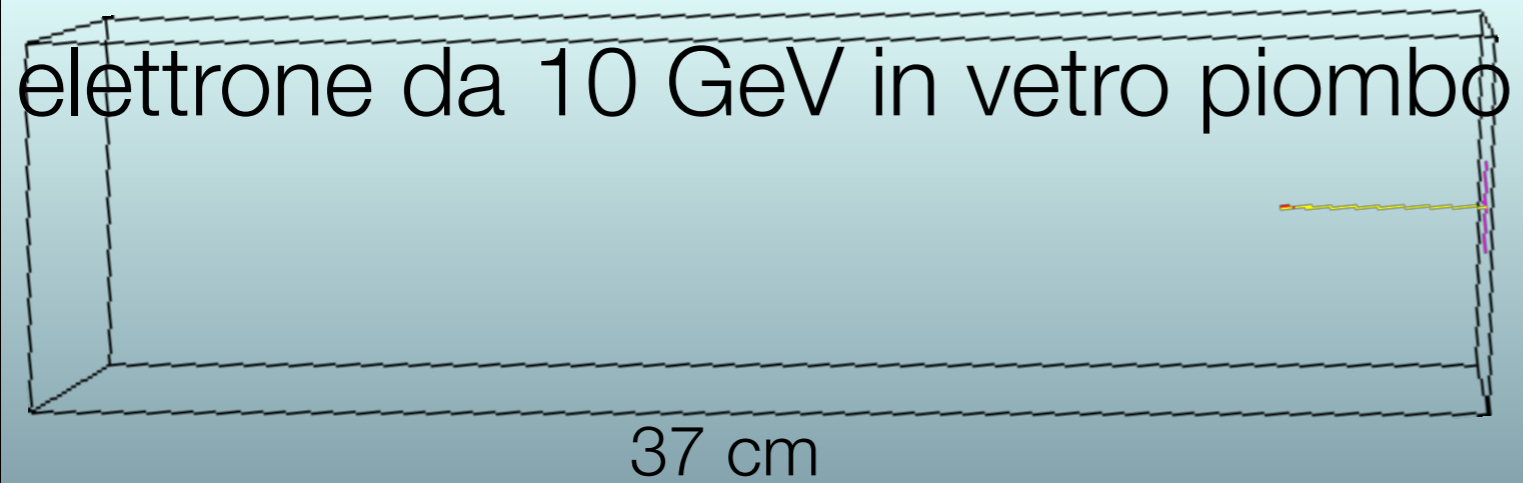
particella carica

punto di interazione

Tutto in un campo magnetico di 4 T
per fa curvare le particelle cariche

Quali segnali ci lasciano le particelle?

https://www.mpp.mpg.de/~menke/elss/anim_OPAL_EB_80GeV.shtml



Una particella di alta energia penetra nel materiale prima di interagire,

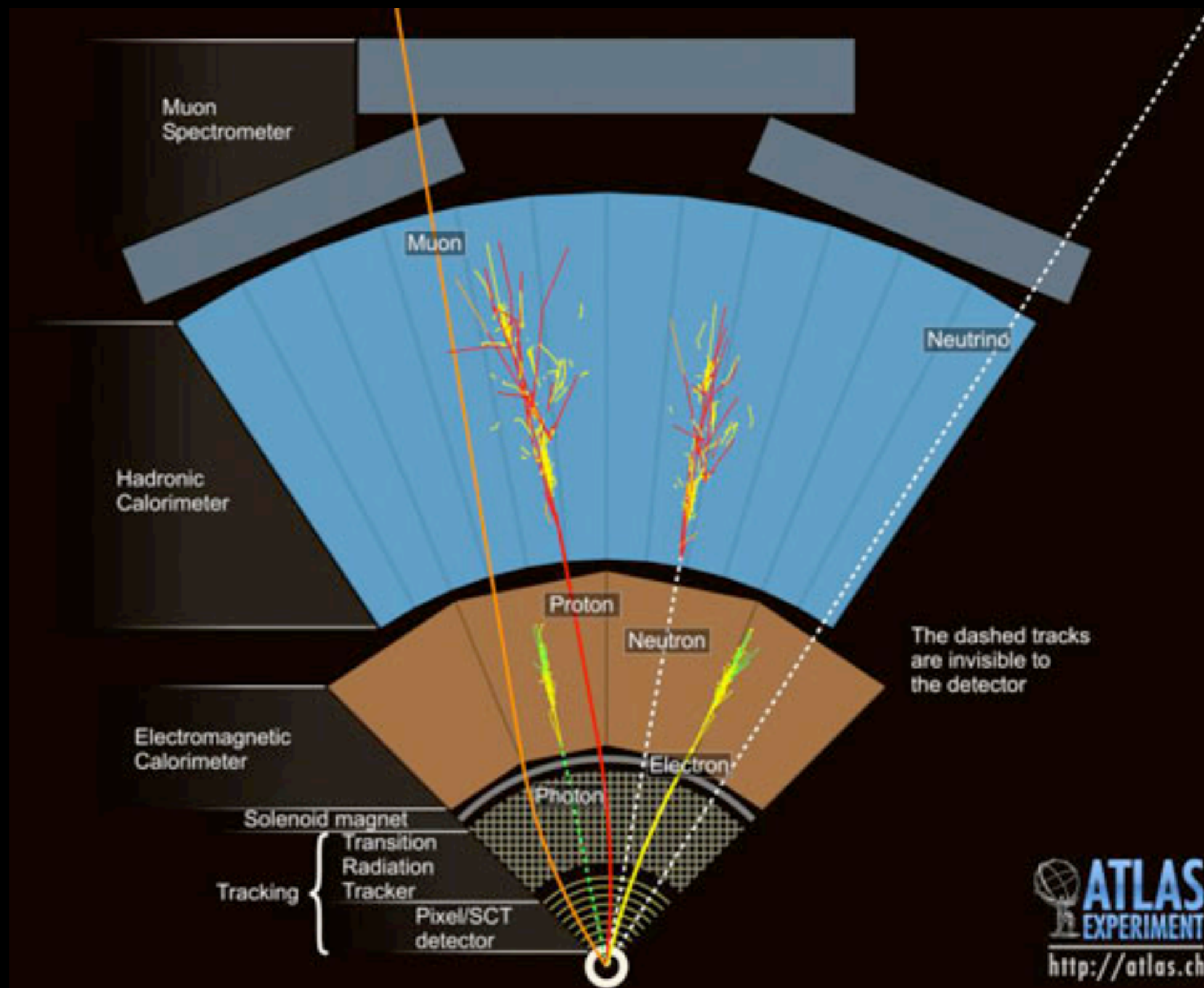
Cristalli di tungstato di piombo
CMS



per poi creare uno sciame di particelle secondarie

(eccezioni: μ ed ν)

Un rivelatore di particelle: Concept



Un rivelatore di particelle: Concept

Elettrone

Una traccia nel tracciatore

+

Uno sciame nel calorimetro elettromagnetico



Un rivelatore di particelle: Concept



Un rivelatore di particelle: Concept



Un rivelatore di particelle: Concept

Neutrino

Nessun segnale

I neutrini praticamente NON interagiscono con il rivelatore.

Capiamo che ci sono solo perché il principio di conservazione dell'energia ci dice che tra le particelle di un evento "manca qualcuno"



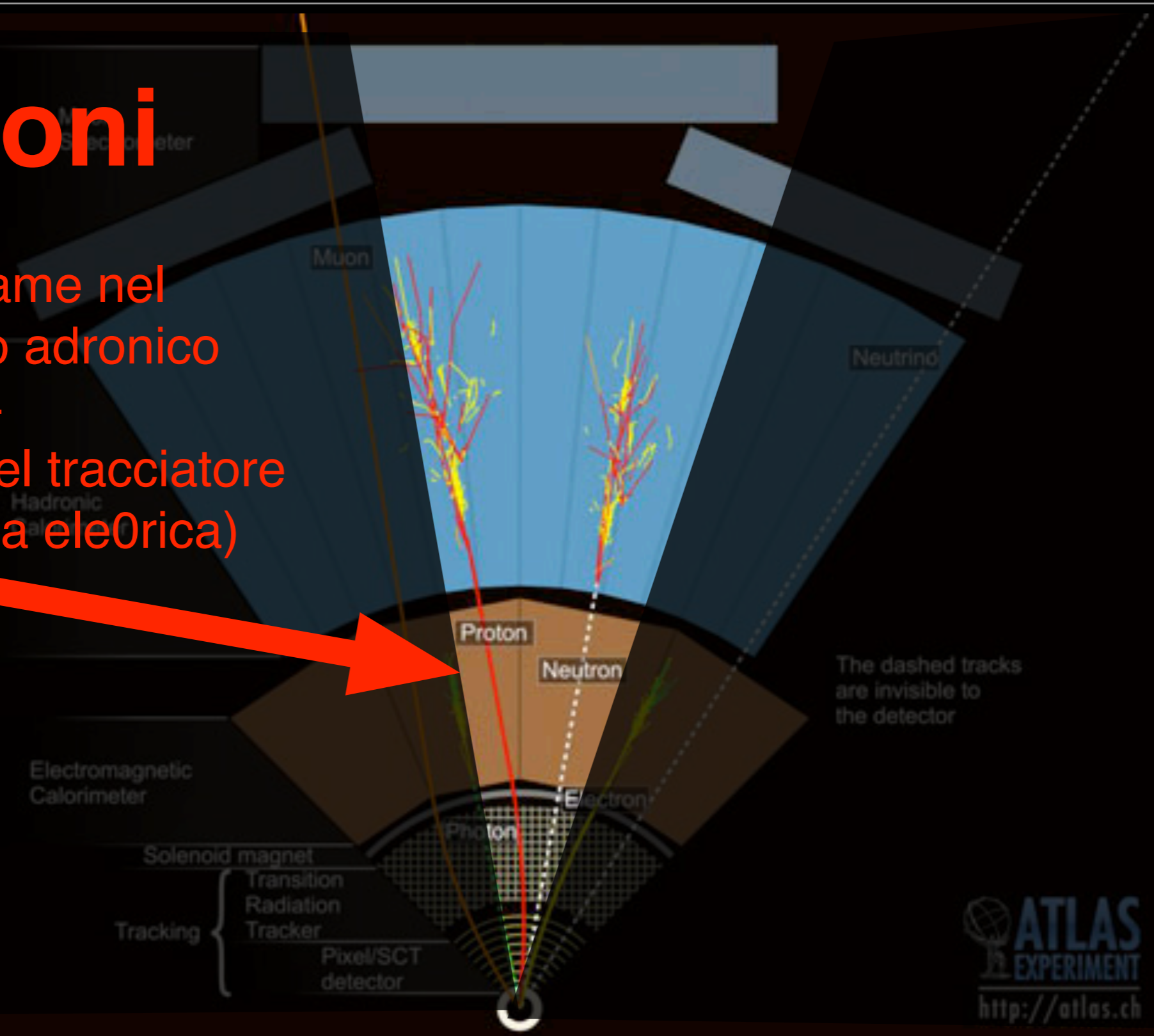
Un rivelatore di particelle: Concept

Adroni

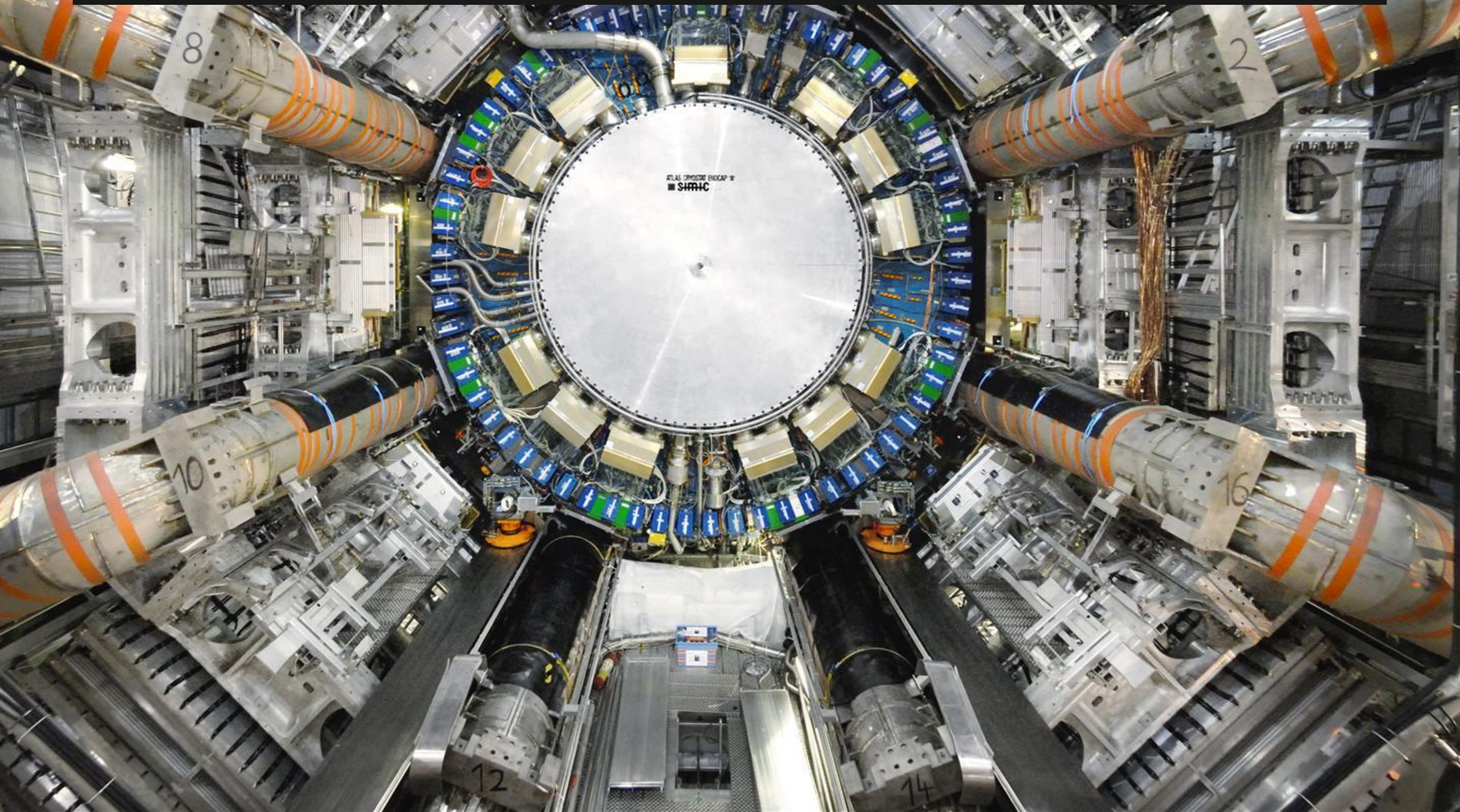
Uno sciame nel calorimetro adronico

+

Una traccia nel tracciatore
(se ha carica elettrica)



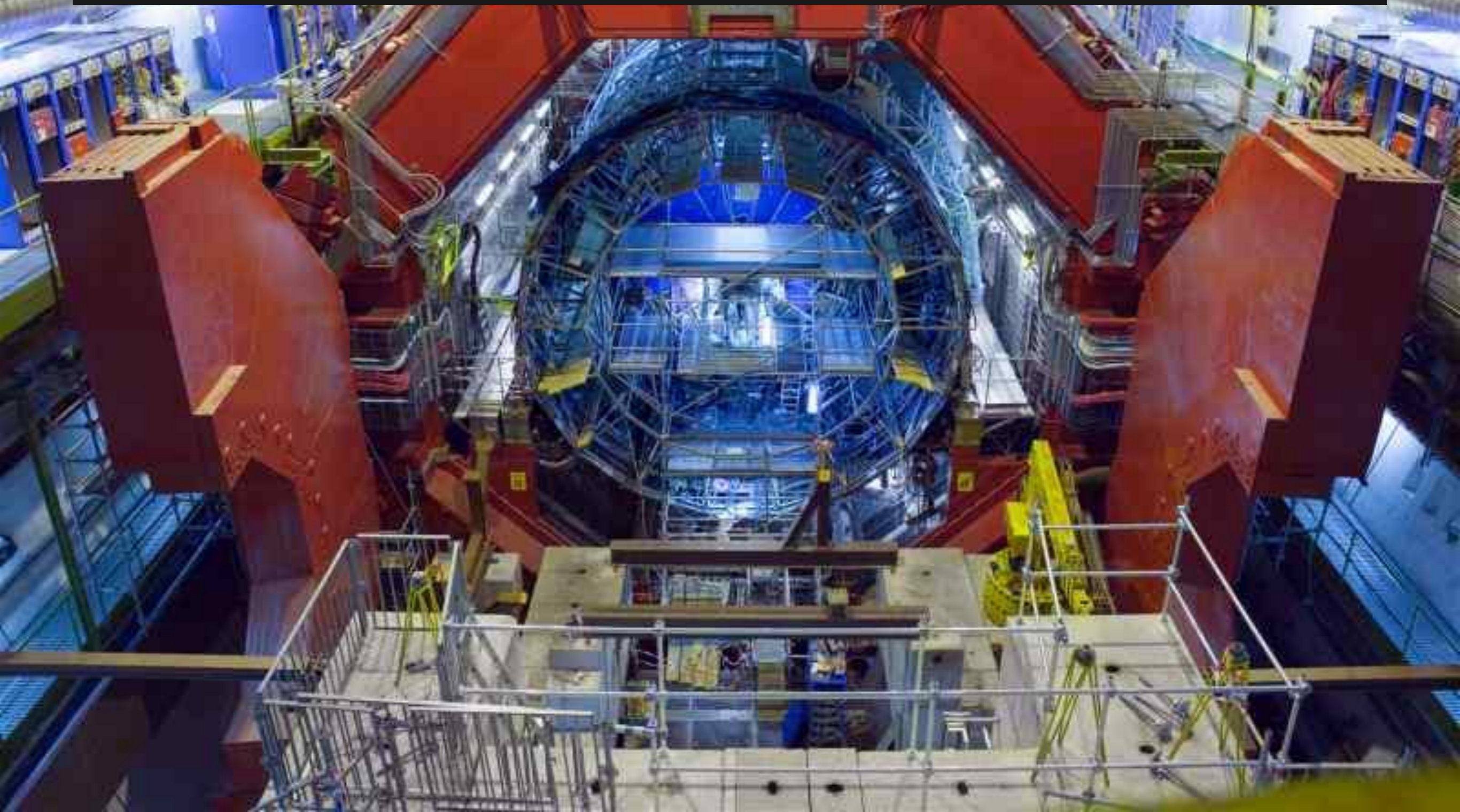
ATLAS



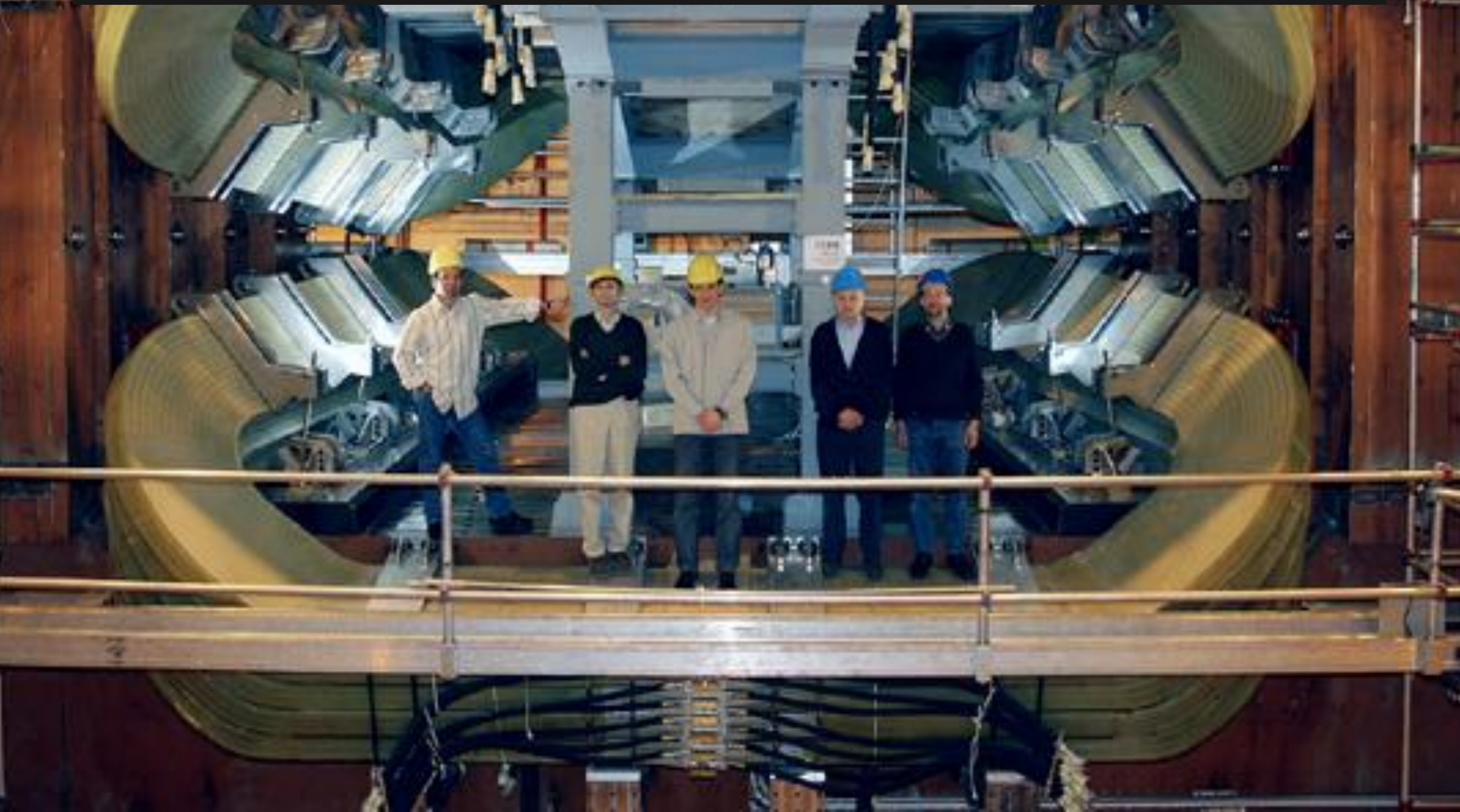
CMS



ALICE



LHCB



Qualche notizia tecnica...

Riguardanti ATLAS, ma gli altri rivelatori hanno numeri altrettanto incredibili:

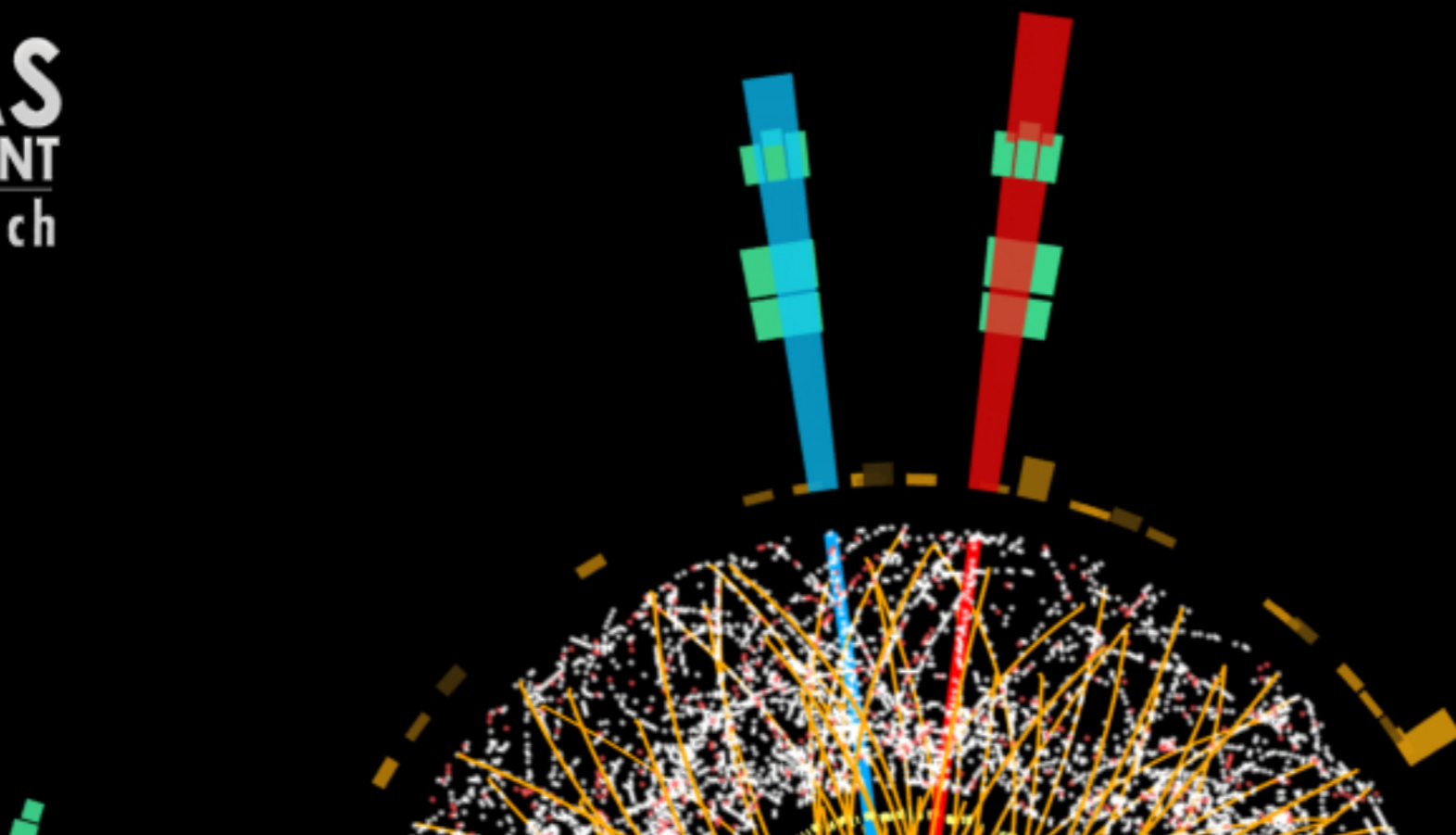
Altezza: ~ 25 metri (quasi un palazzo di 9-10 piani)

Peso: 7000 tonnellate (quasi come la torre Eiffel)

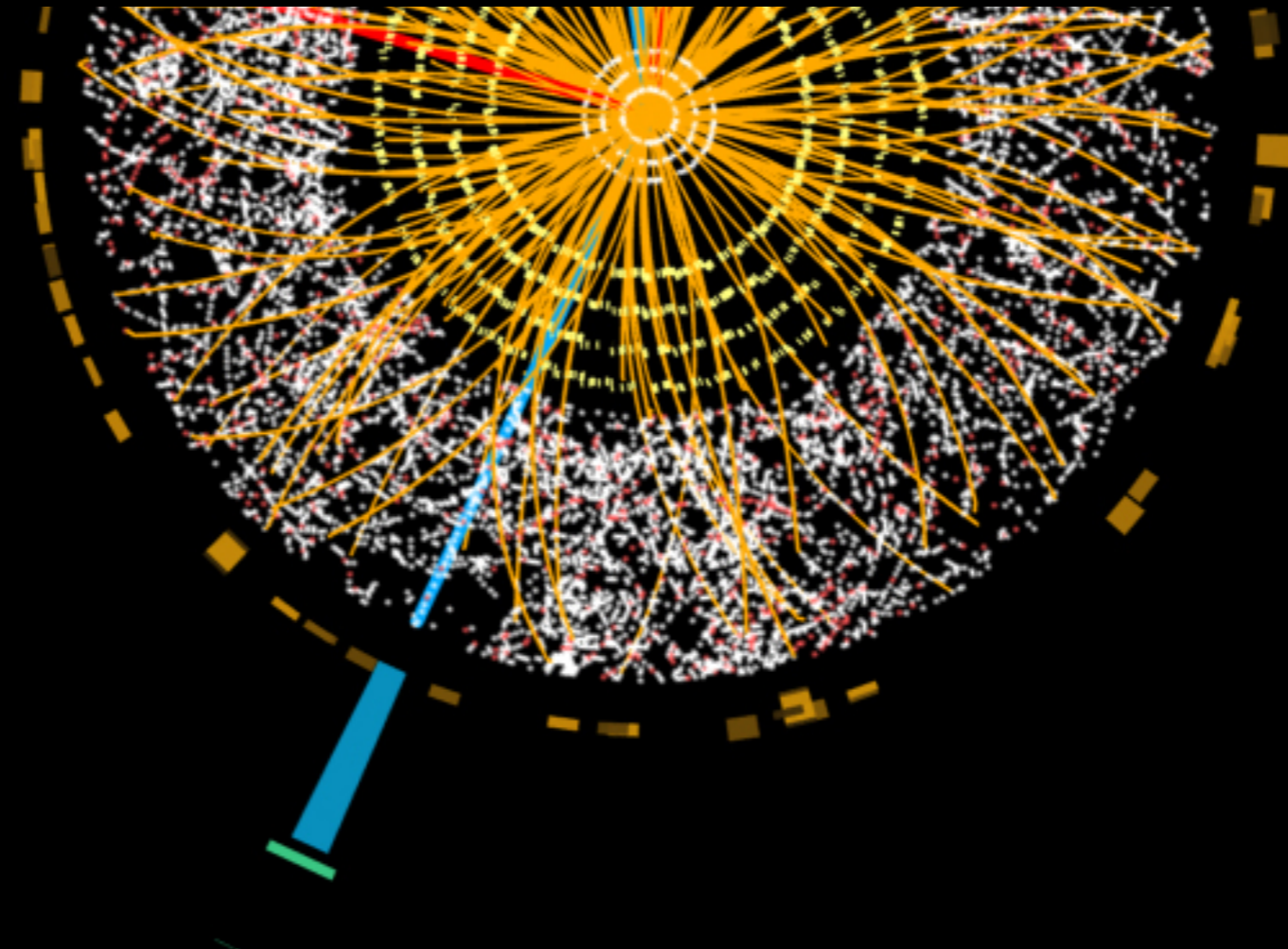
Risultato della progettazione di laboratori da tutto il Mondo.

e anche assemblarlo è stata una sfida....

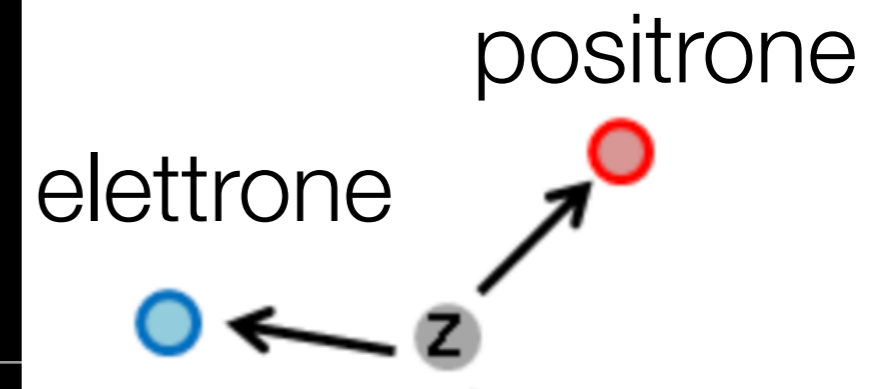
Assemblare ATLAS in 1 minuto



Dati e scoperte



Decadimento



Molte delle particelle subatomiche che studiamo sono instabili

Decadono spontaneamente in altre particelle (a loro volta instabili o stabili) dette prodotti del decadimento

È un evento probabilistico che avviene dopo un certo tempo.
Il valor medio di questo tempo si chiama vita media della particella.

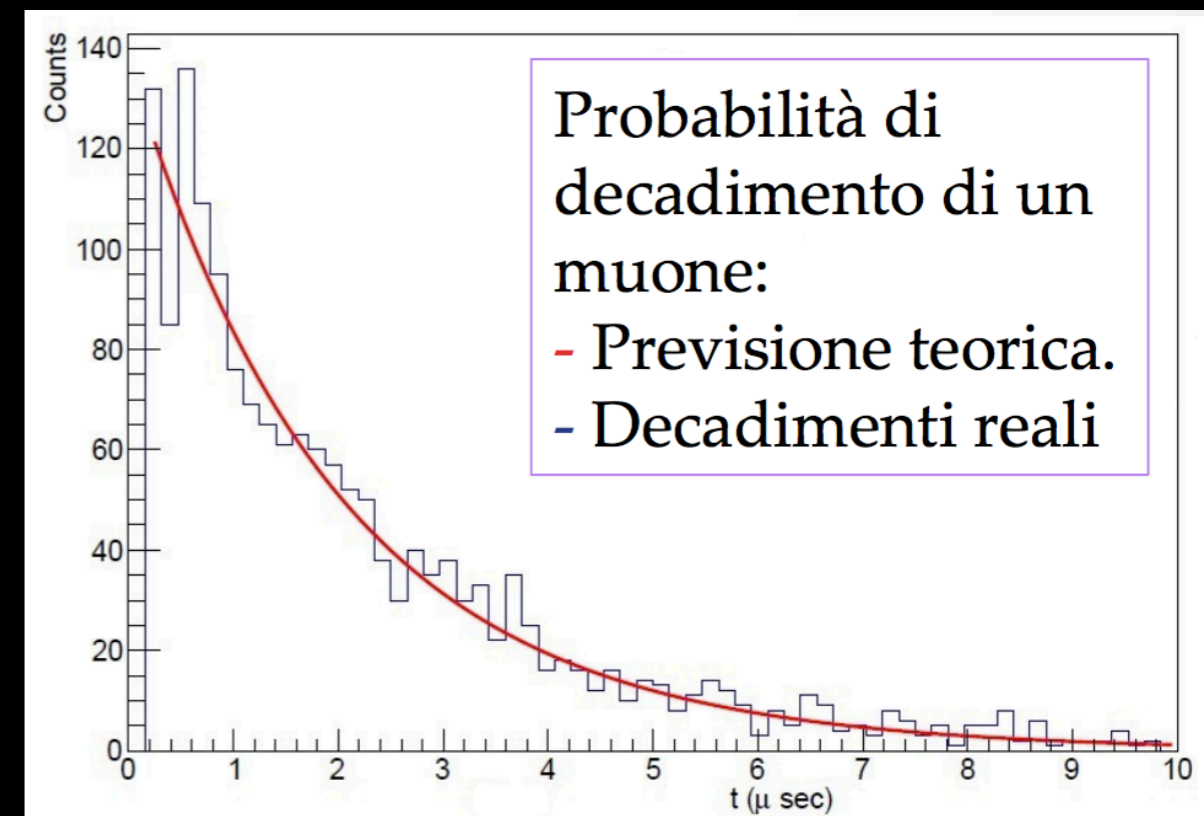
Vita media del bosone Z:

0.2 ys (0.2×10^{-24} s)

Vita media del muone μ :

2.2 μ s (2.2×10^{-6} s)

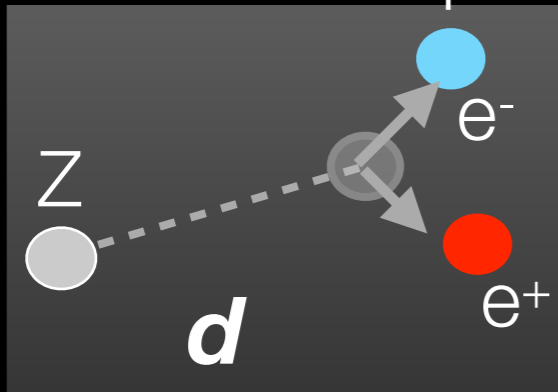
L'andamento temporale è rappresentato da una curva che chiamiamo esponenziale



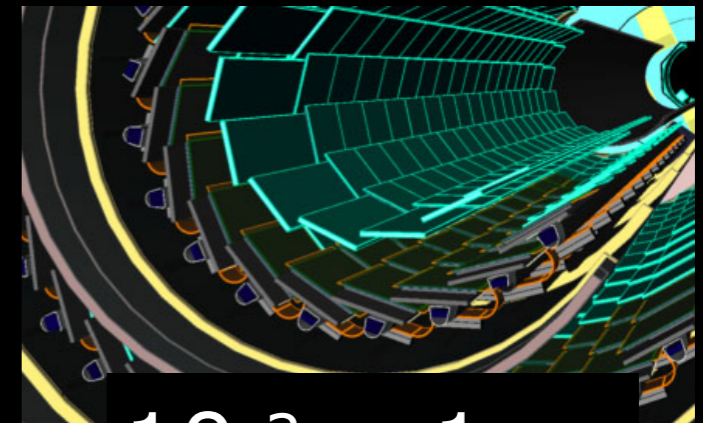
Vita media della Z: é tanto o poco?

Per una Z con impulso di 1000 GeV la distanza media percorsa prima di decadere ($d = v \times t$) é circa **$d \sim 1 \text{ fm}$ (10^{-15} m)**

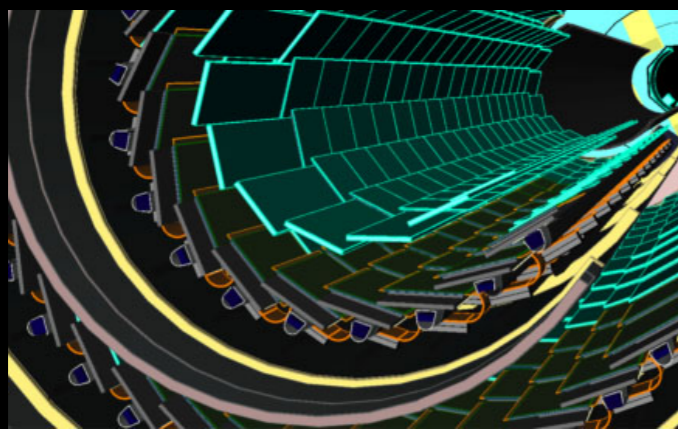
I sensori di ATLAS piú vicini al punto di produzione della Z sono a circa **3.3 cm**



$$10^{-15} = 1 \text{ fm}$$



$$10^{-2} = 1 \text{ cm}$$



$$10^{-2} = 1 \text{ cm}$$



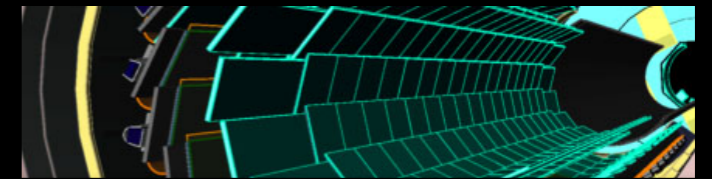
$$10^{11} = 100 \text{ M km}$$

Per un muone da 1000 GeV, $d \sim 6500 \text{ km}$ - é praticam. stabile per ATLAS

Vita media della Z: é tanto o poco?

Per una Z con impulso di 1000 GeV la distanza media percorsa prima di decadere ($d = v \times t$) é circa **$d \sim 1 \text{ fm}$ (10^{-15} m)**

I sensori di ATLAS piú vicini al punto di produzione della Z sono a circa **3.3 cm**



La probabilità che un bosone Z arrivi ad interagire con il rivelatore é praticamente nulla.

Se vogliamo scoprire e studiare il bosone Z, dobbiamo puntare sui suoi prodotti di decadimento.

I prodotti del decadimento, se sono particelle stabili, possono essere misurati e ci raccontano qualcosa delle particelle madri

$$10^{-2} = 1 \text{ cm}$$

$$10^{11} = 100 \text{ M km}$$

Per un muone da 1000 GeV, $d \sim 6500 \text{ km}$ - é praticam. stabile per ATLAS

Massa invariante

Ingredienti:

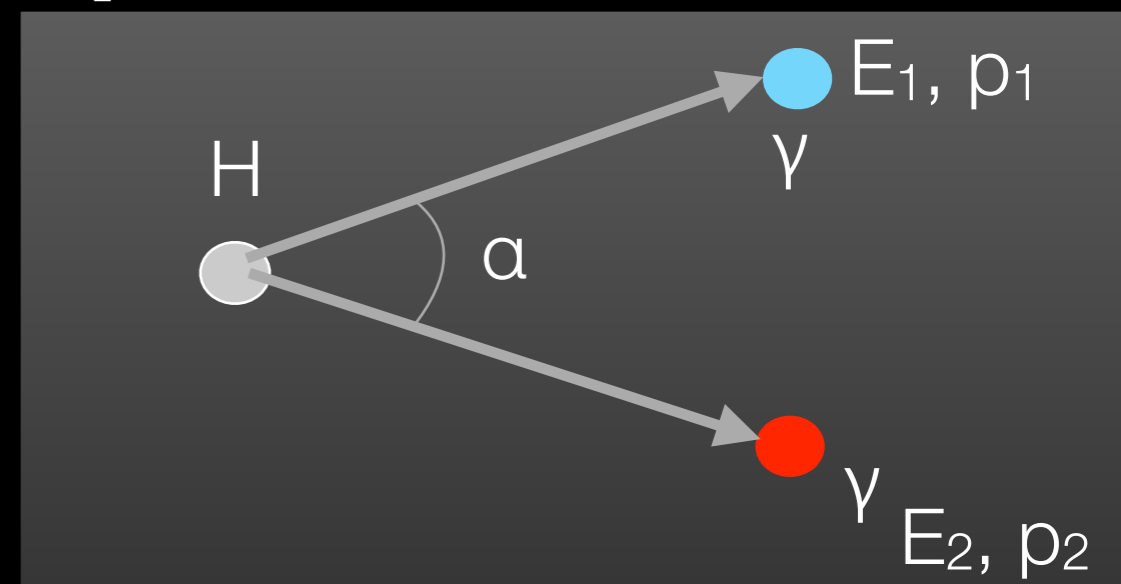
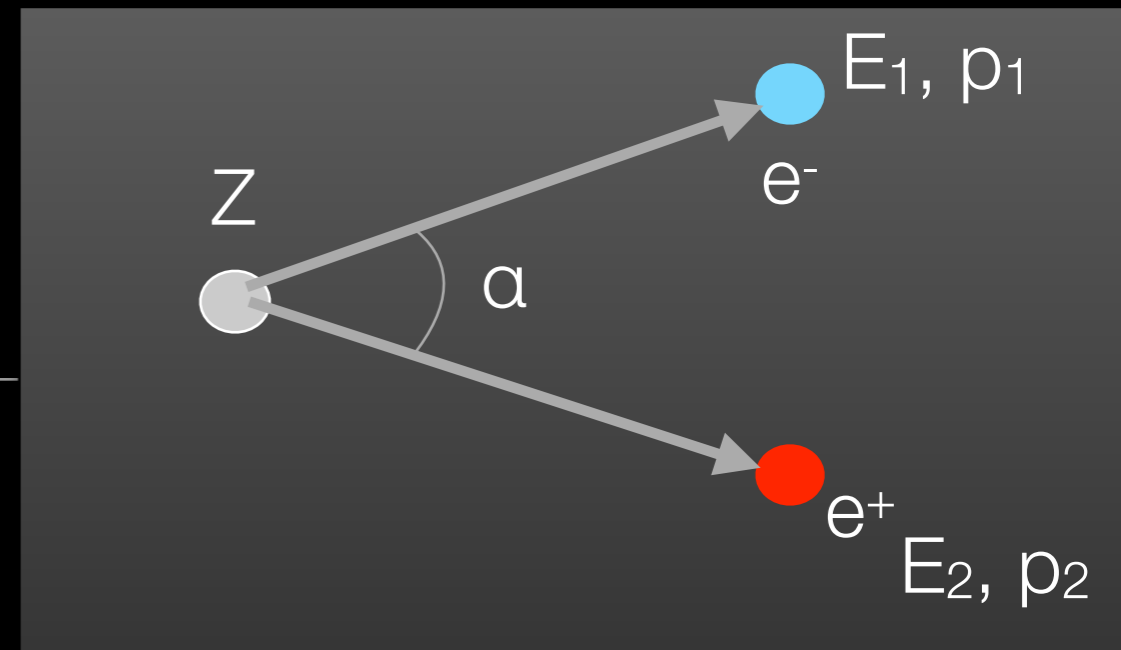
- l'energia E si conserva
- il momento p si conserva
- $E=mc^2$
- un po' di relatività ristretta

Se misuriamo l'energia e l'impulso dei prodotti di decadimento, possiamo calcolare il valore della massa della particella madre nel sistema di riferimento a riposo
Questa si chiama massa invariante

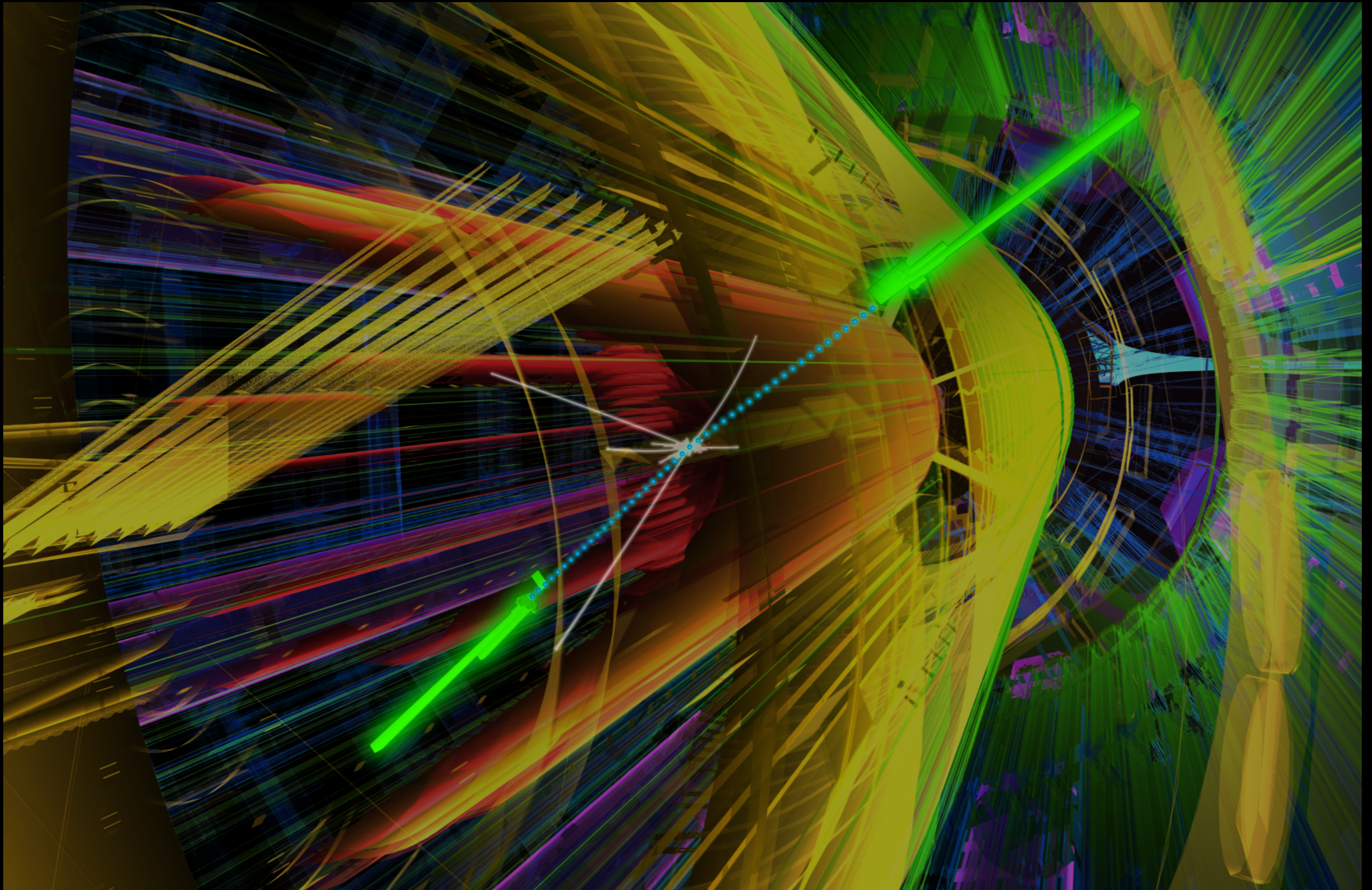
$$M^2_Z = 2 E_1 E_2 - 2 p_1 p_2 \cos \alpha$$

per Z $M_Z \sim 90$ GeV

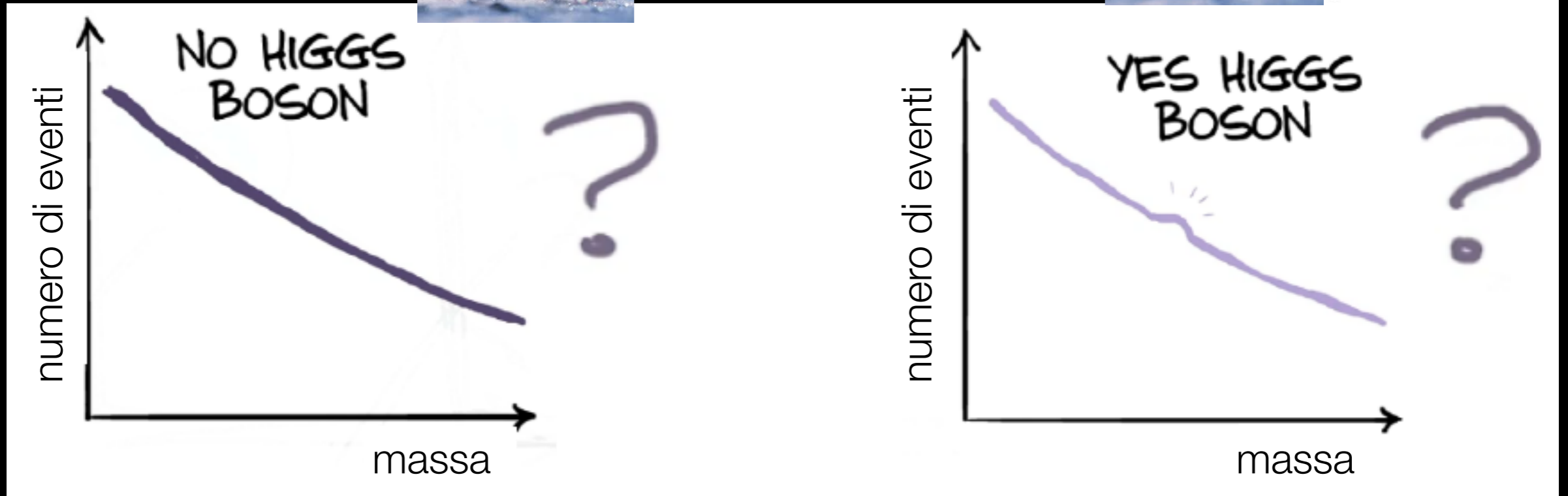
per Higgs boson: $M_H \sim 125$ GeV



Higgs in 2 fotoni



Come stabilire una scoperta

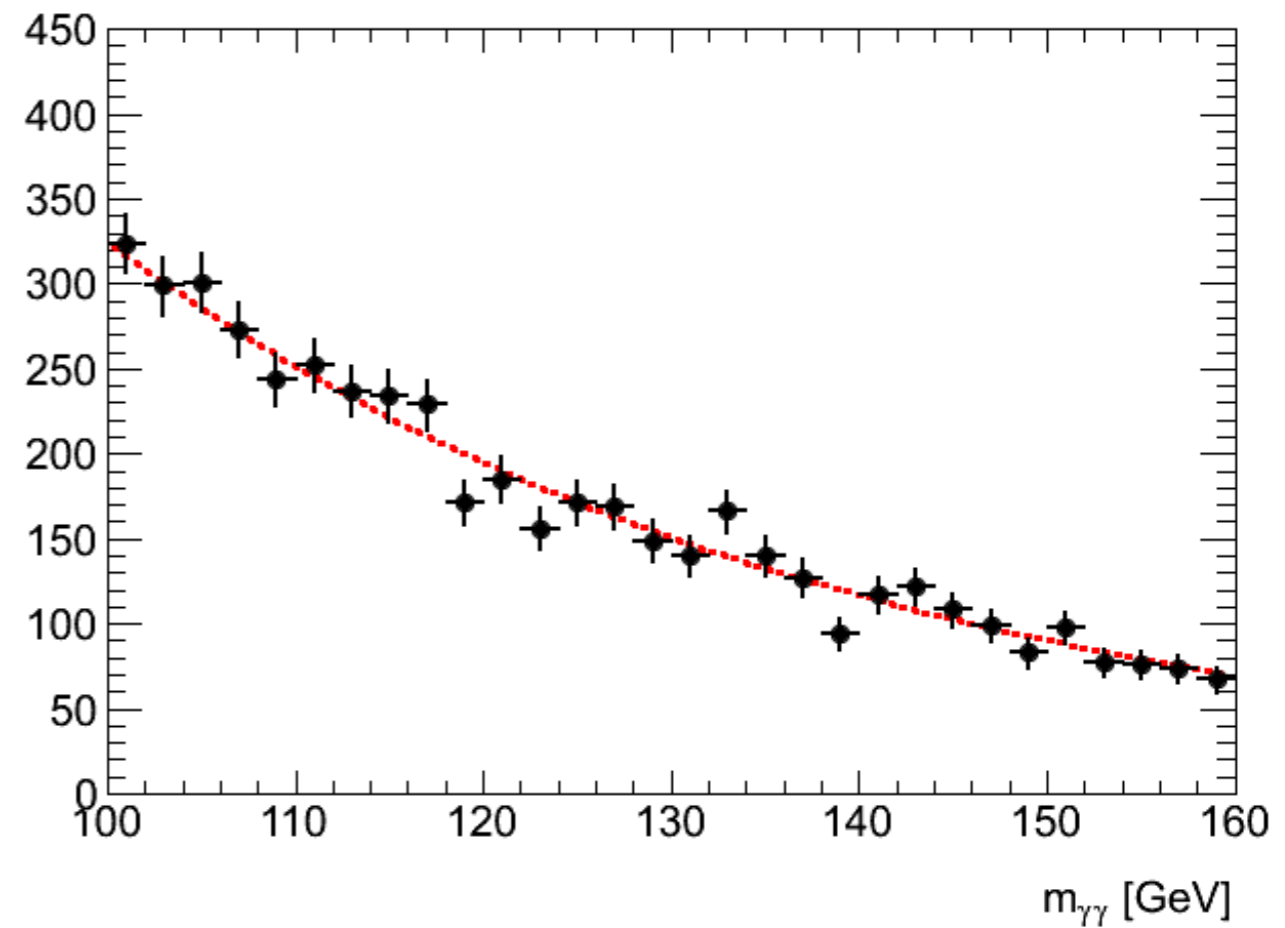
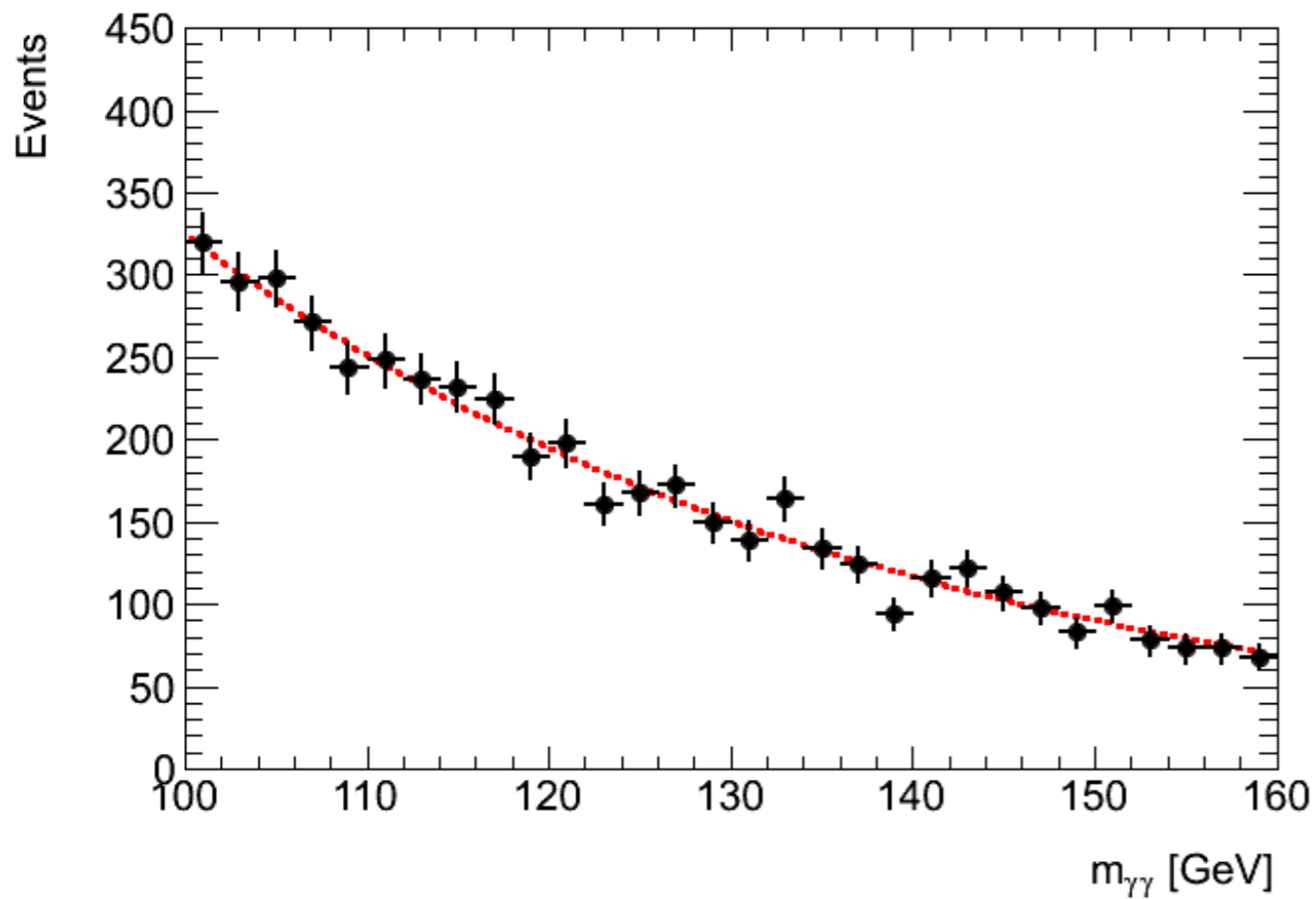


Valutare la probabilità che il fondo possa formare un falso segnale dovuto a fluttuazioni statistiche.

Come dipende questo con il numero di eventi?

Facciamo l'analisi insieme

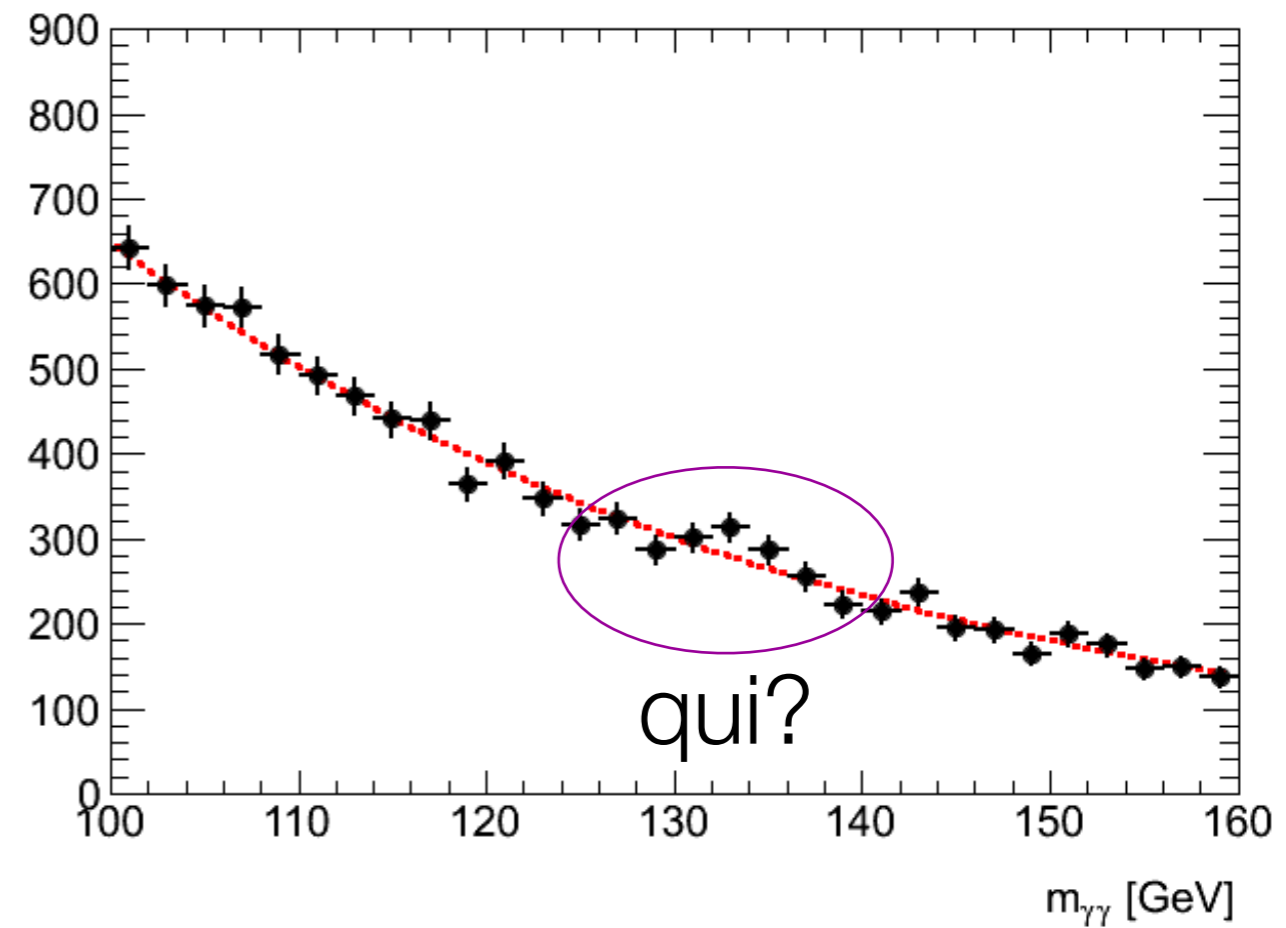
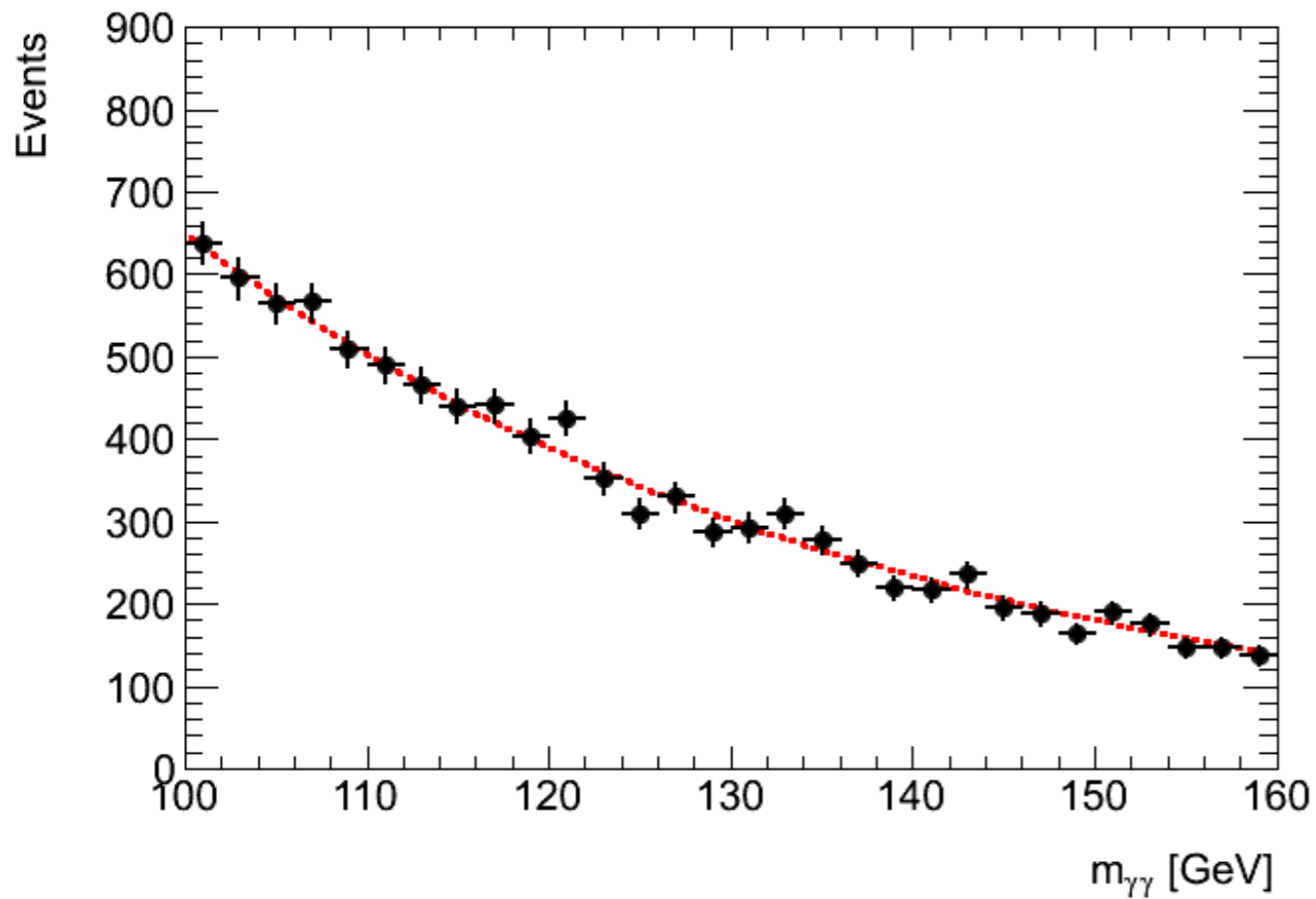
~100 miliardi di collisioni



dove si trova l'Higgs?

Facciamo l'analisi insieme

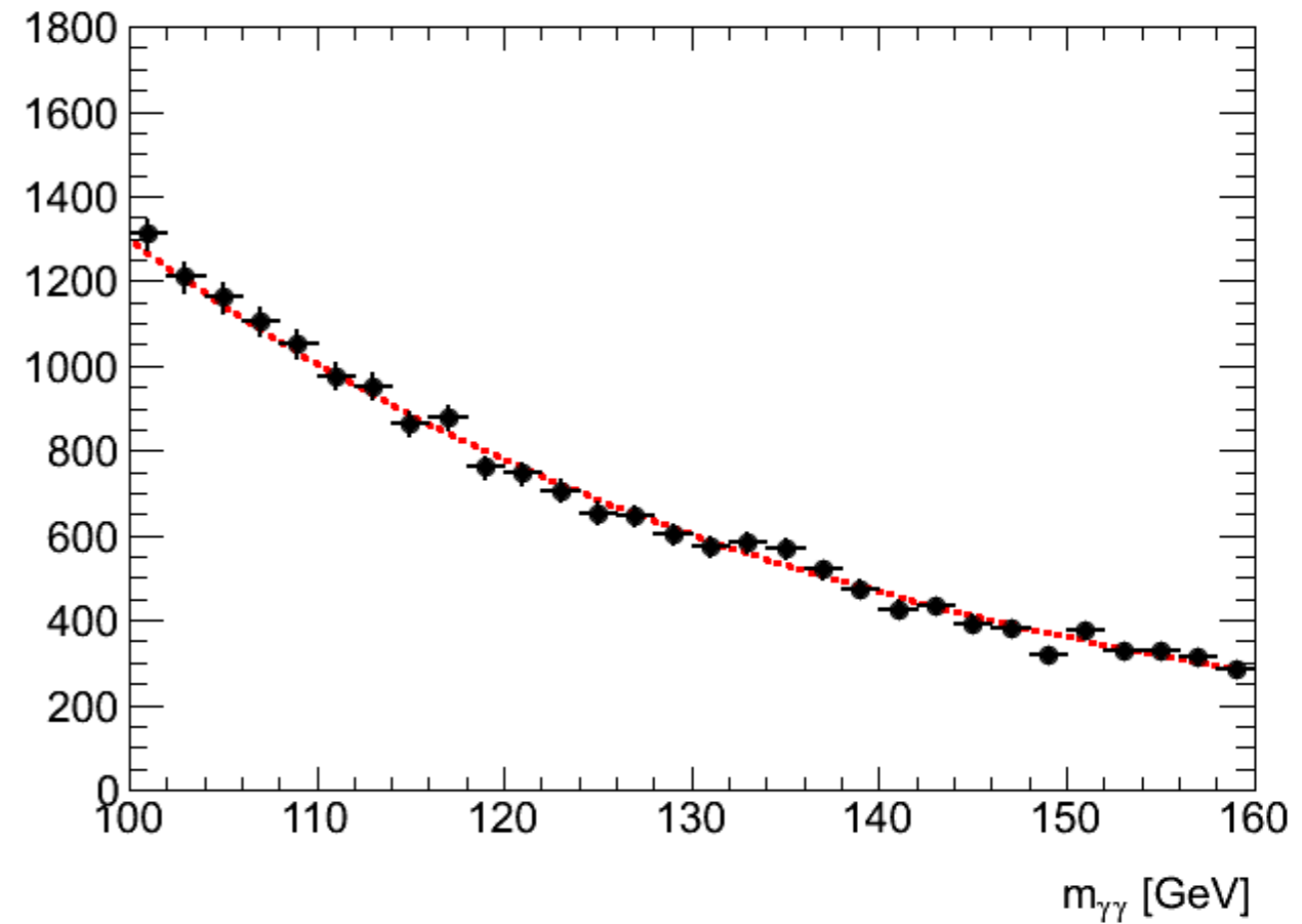
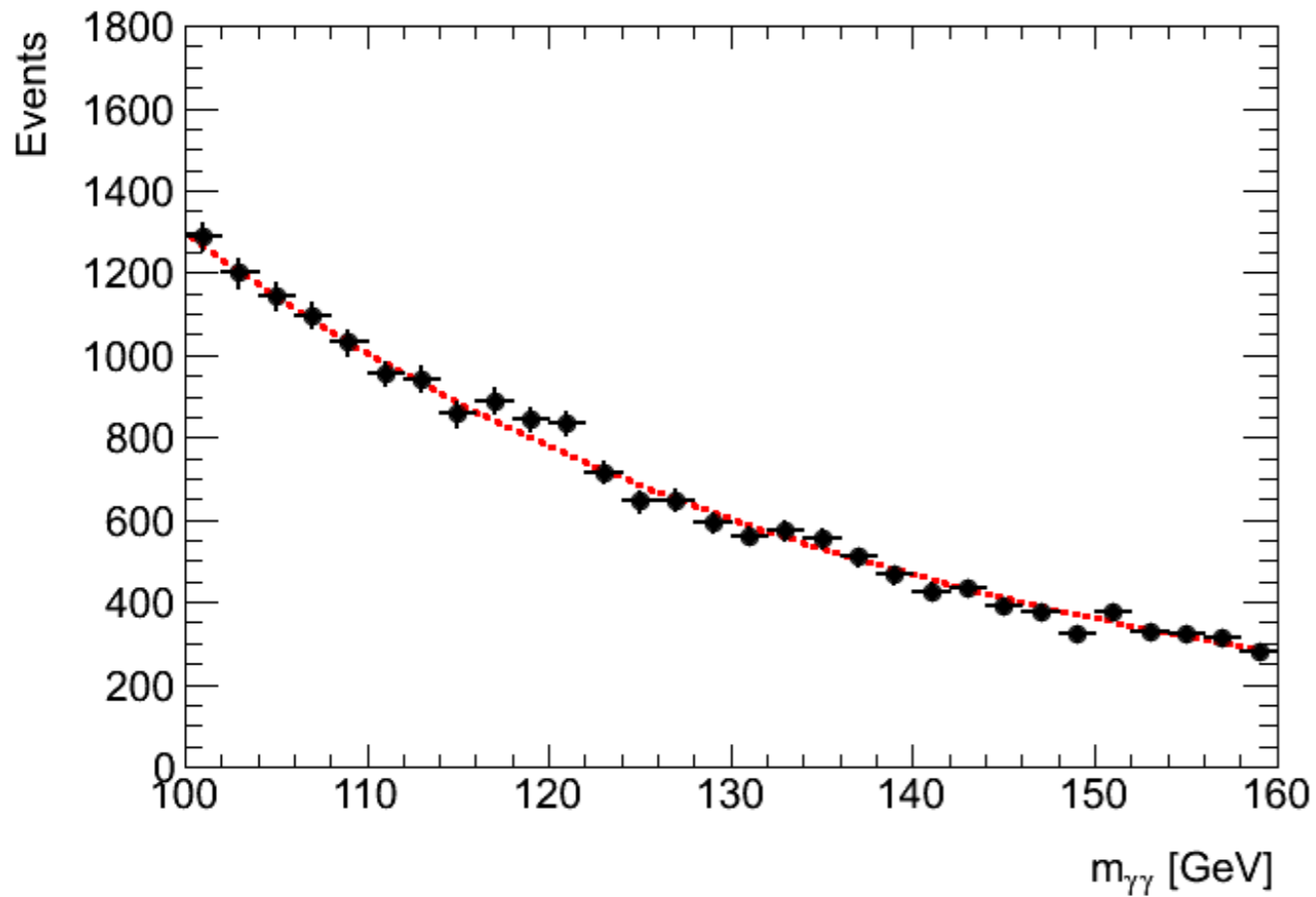
~200 miliardi di collisioni



dove si trova l'Higgs?

Facciamo l'analisi insieme

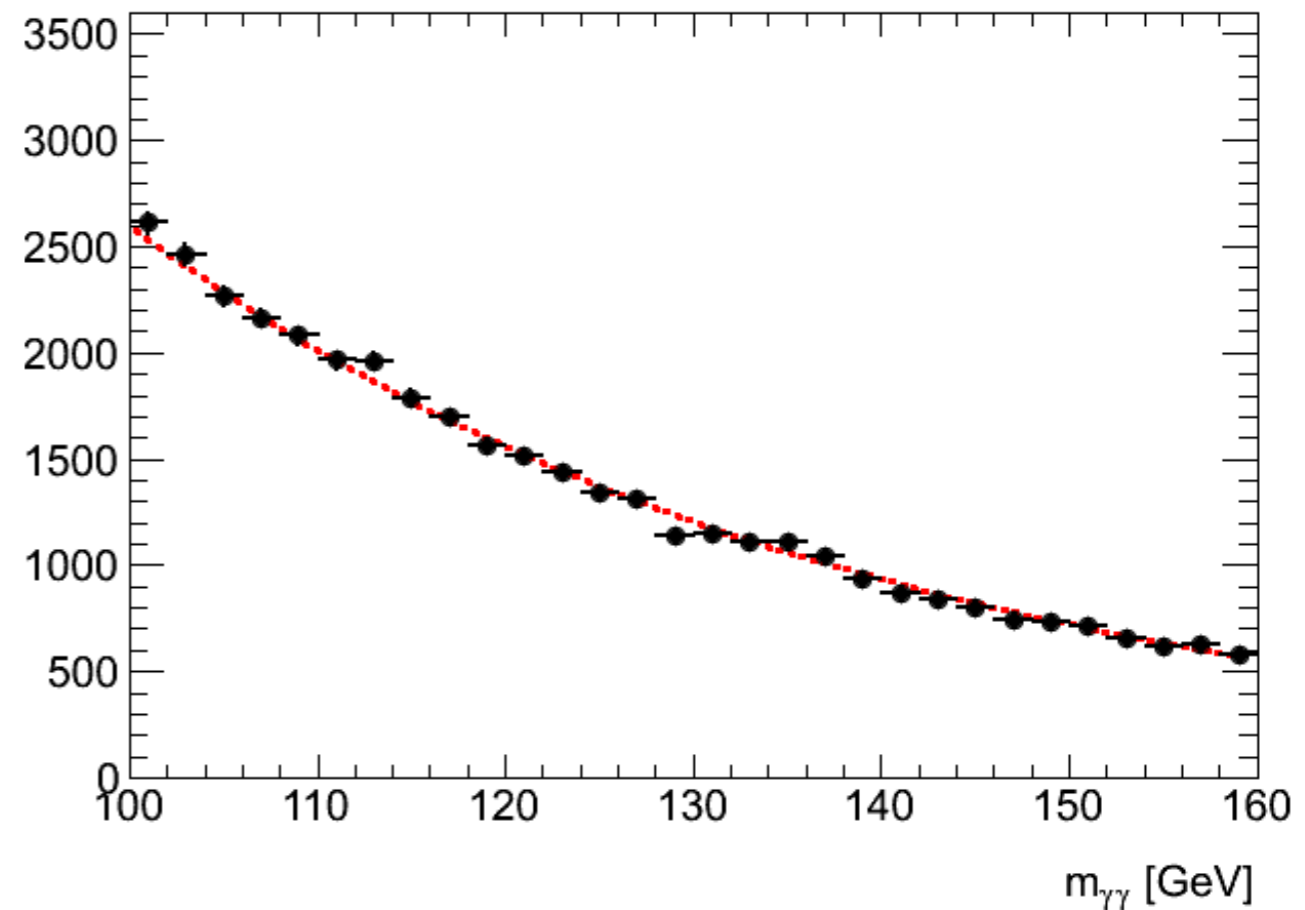
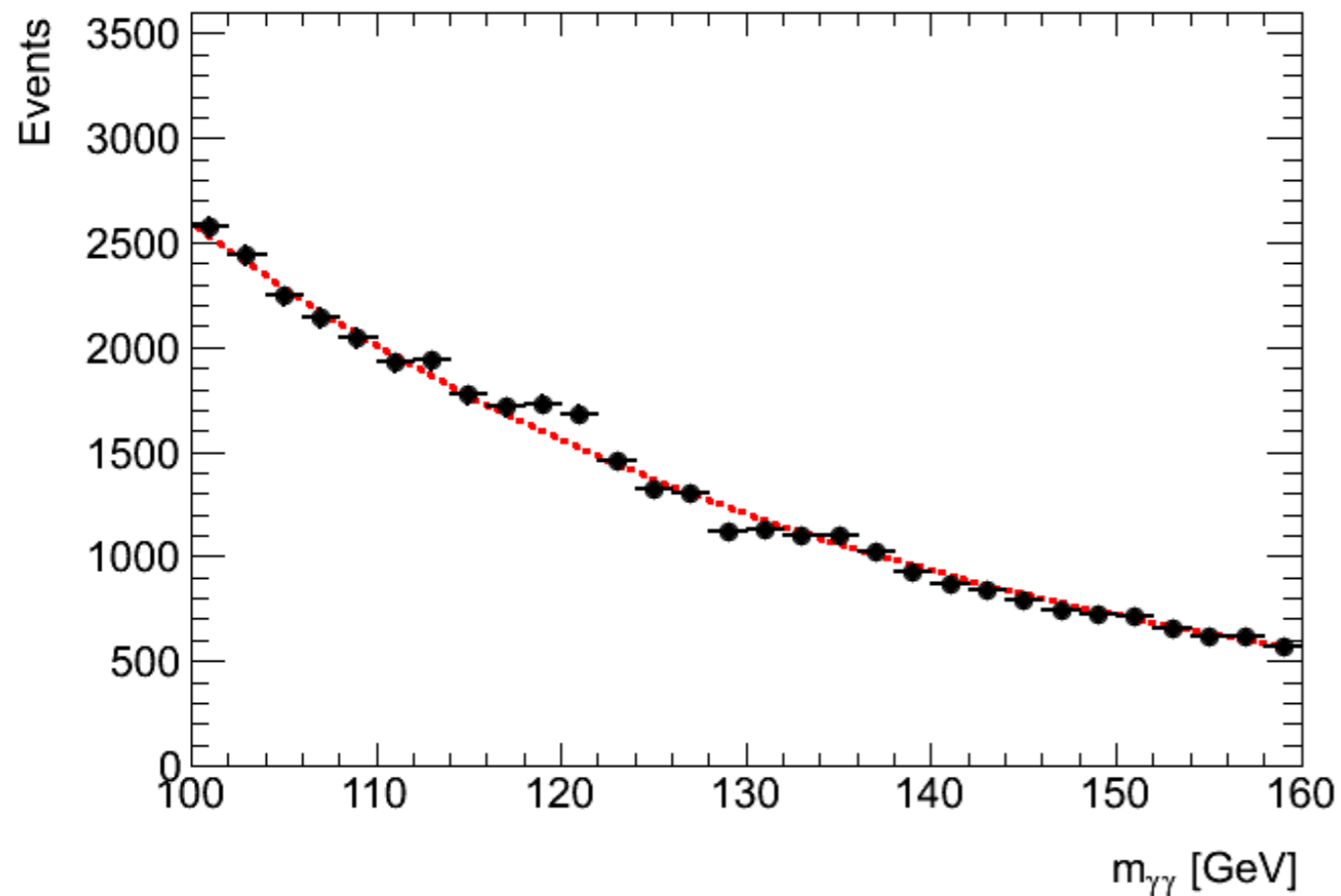
~400 miliardi di collisioni



dove si trova l'Higgs?

Facciamo l'analisi insieme

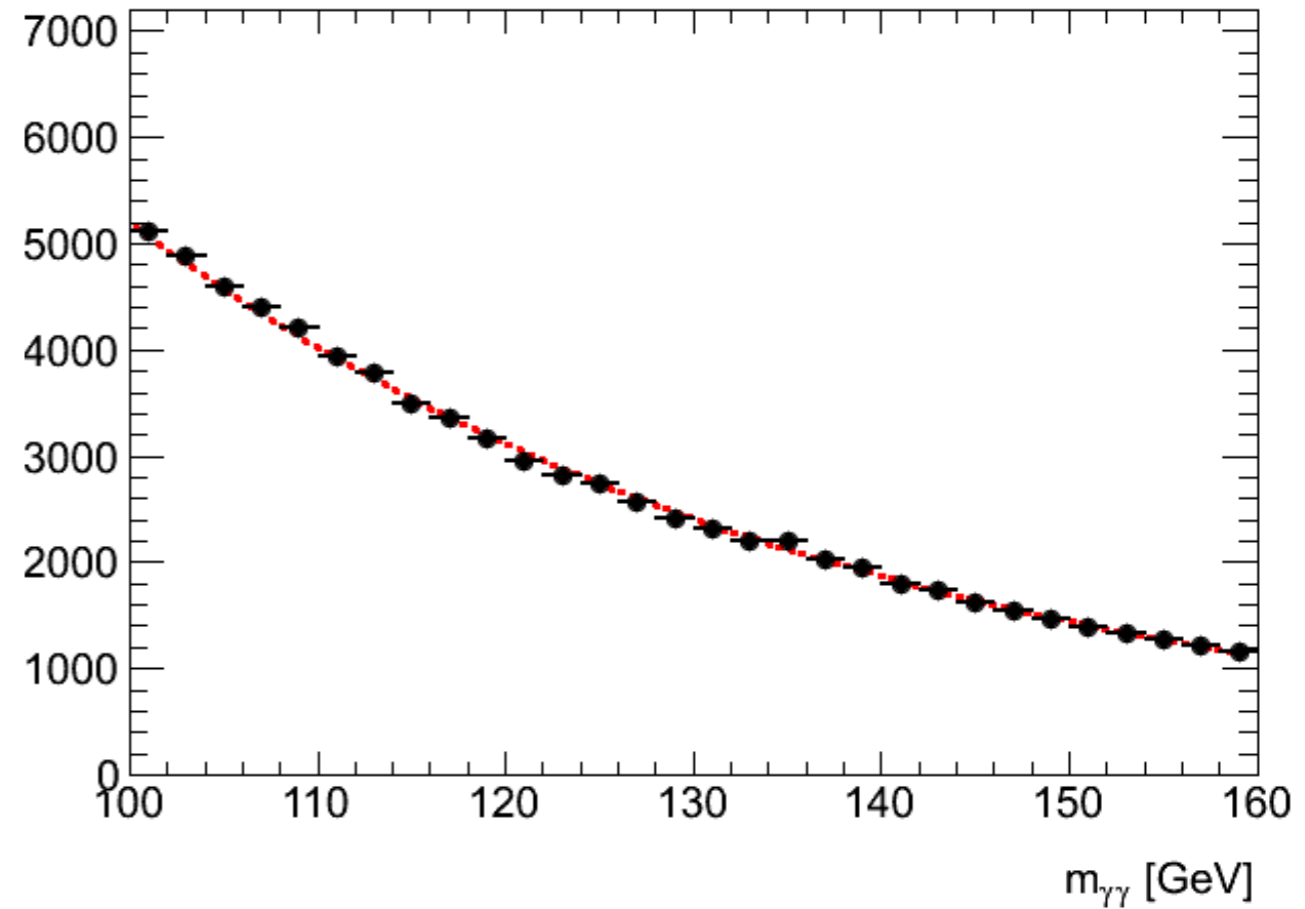
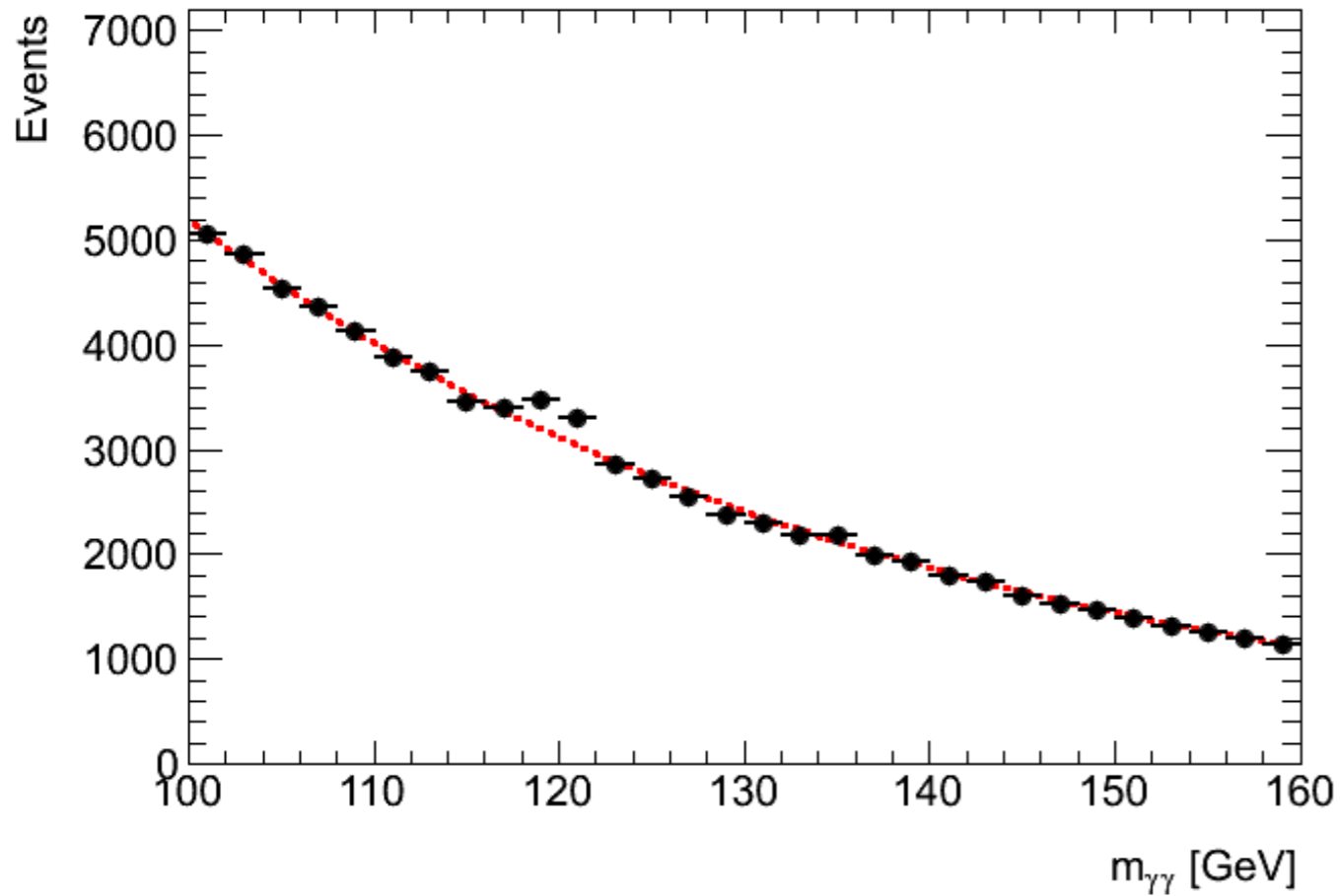
~800 miliardi di collisioni



dove si trova l'Higgs?

Facciamo l'analisi insieme

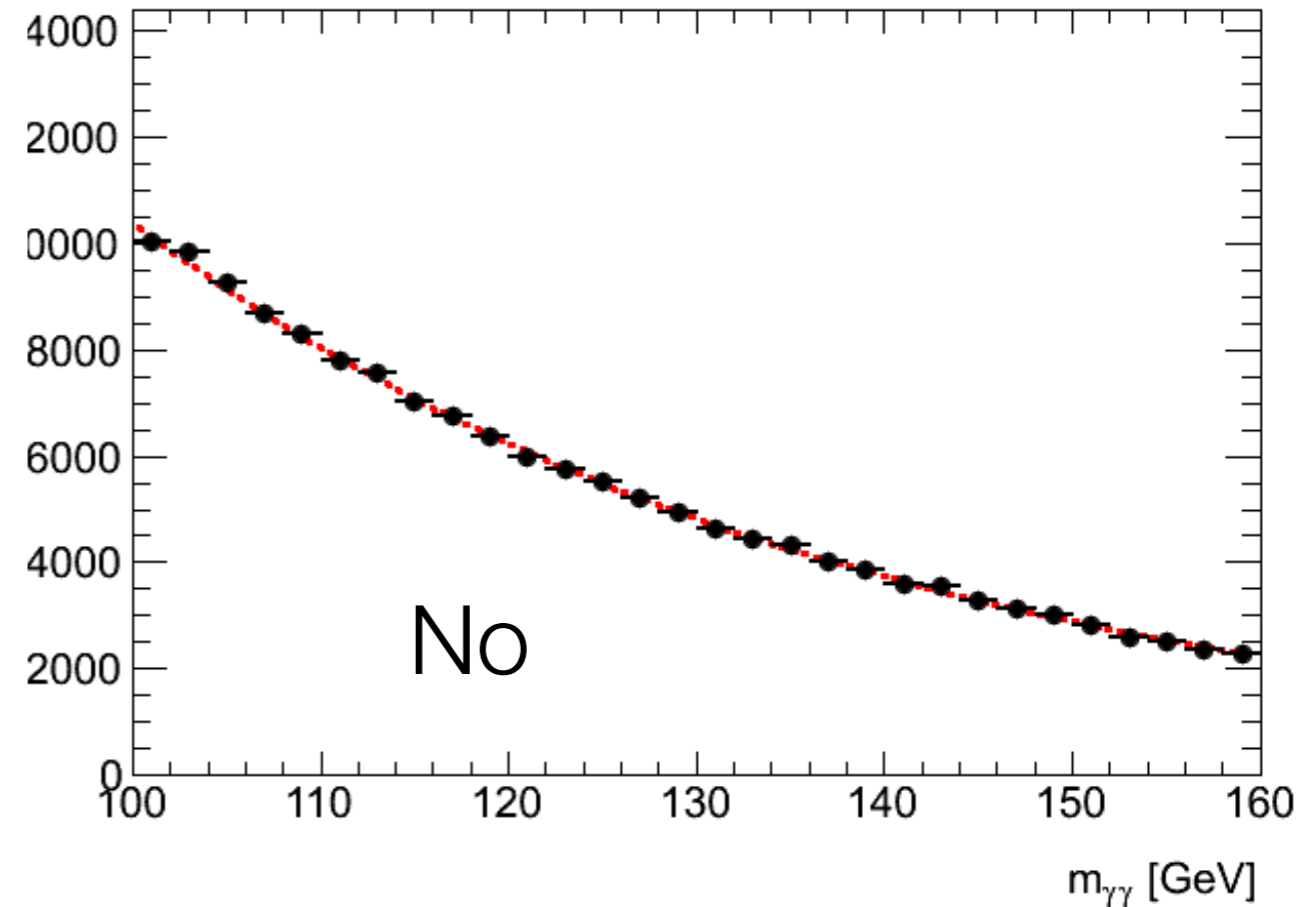
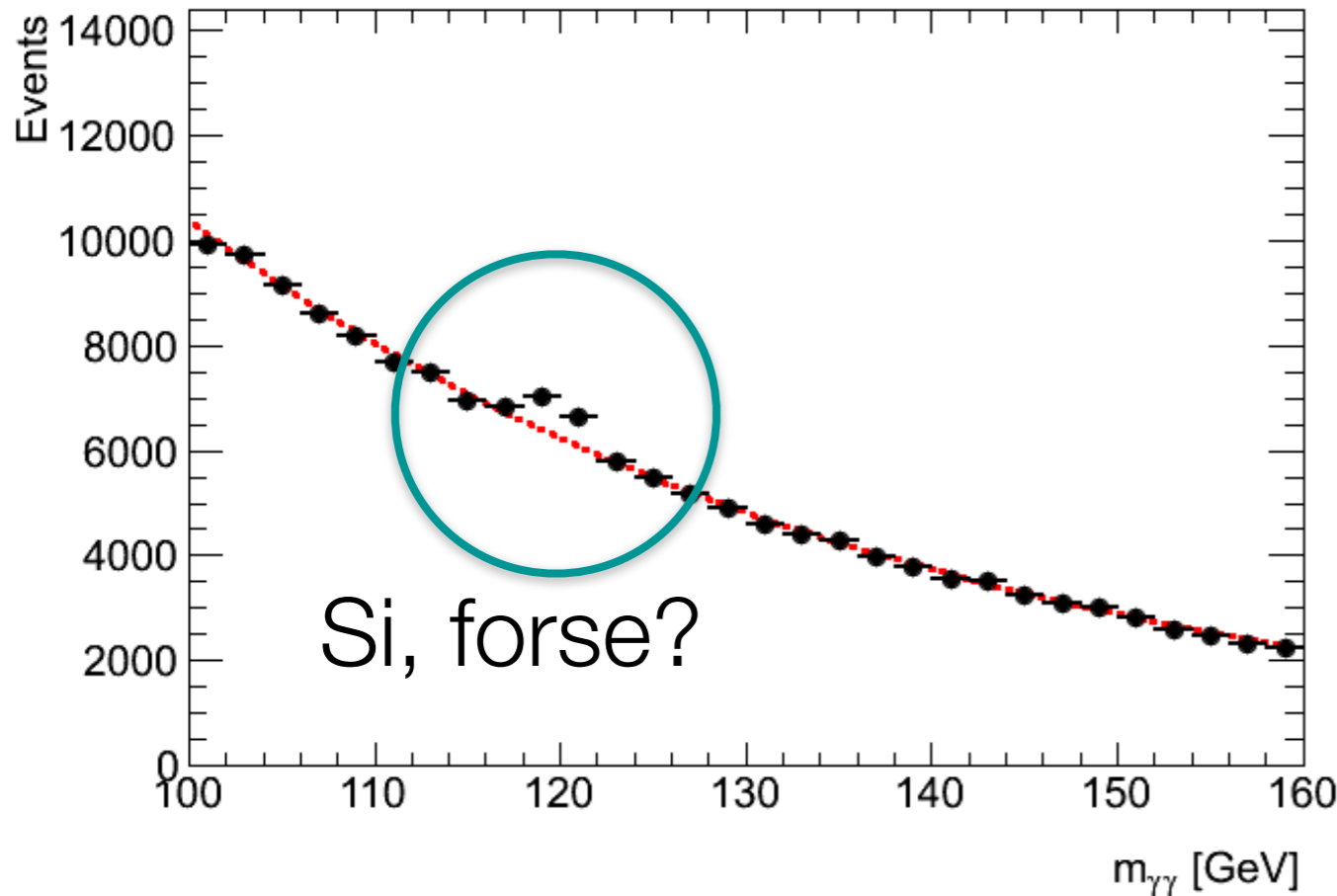
~1600 miliardi di collisioni



dove si trova l'Higgs?

Facciamo l'analisi insieme

~3200 miliardi di collisioni

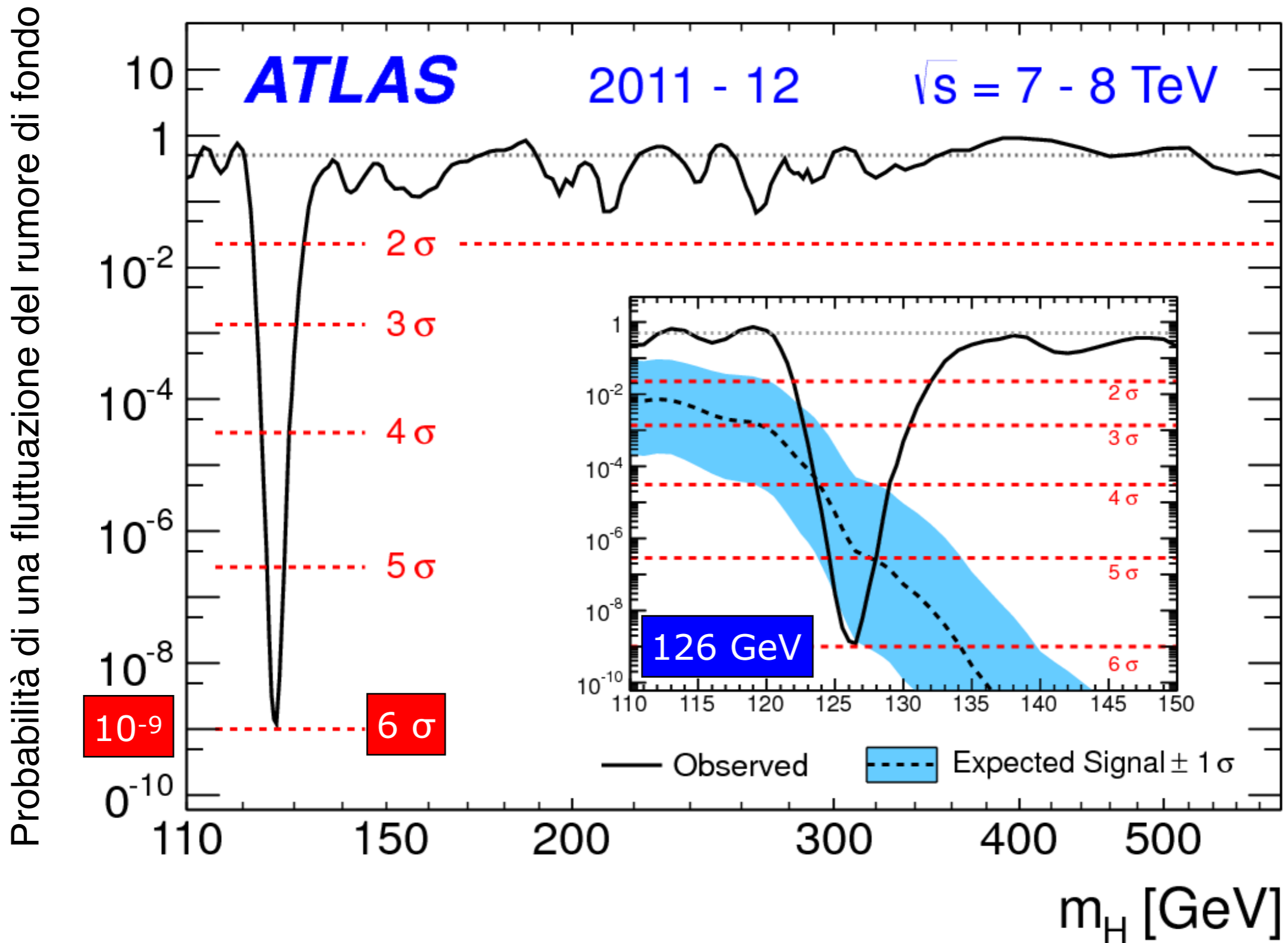


Quanto é "significativo" l'eccesso?

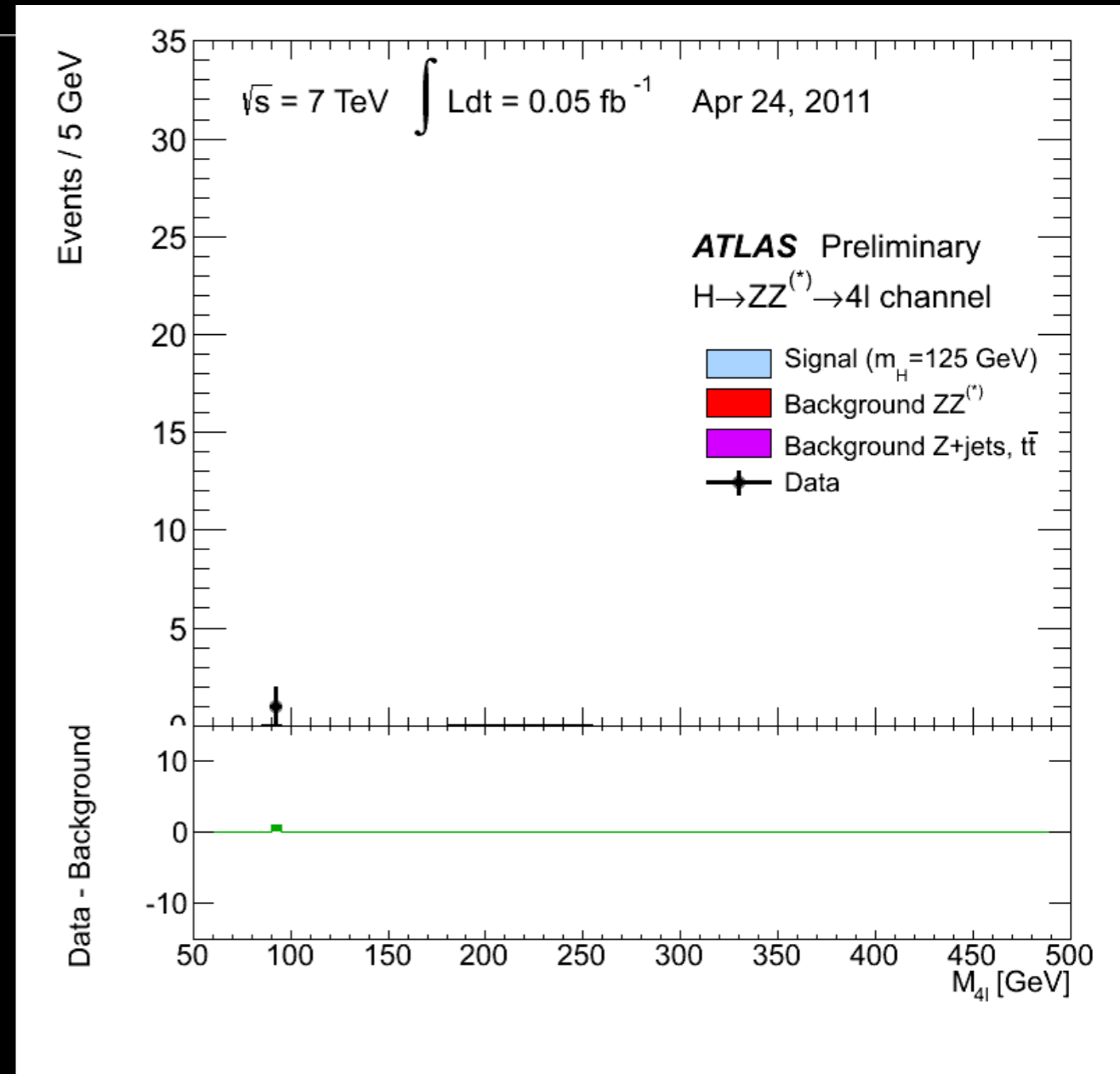
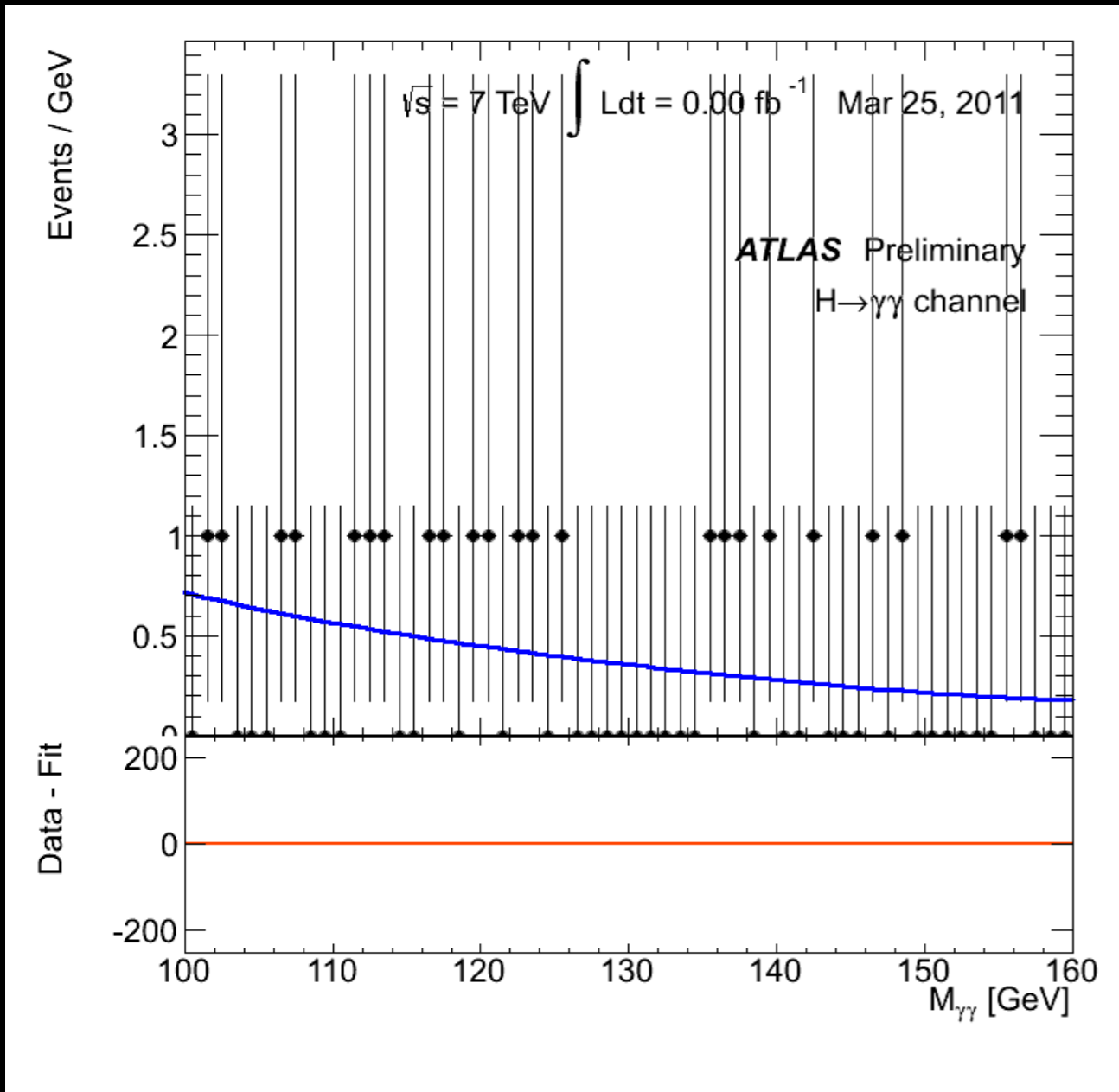
più la probabilità di fluttuazione é piccola, più un eccesso diventa significativo.

Come definiamo una scoperta?

Abbiamo una scoperta?



La nascita di una scoperta



Buona Scoperta!