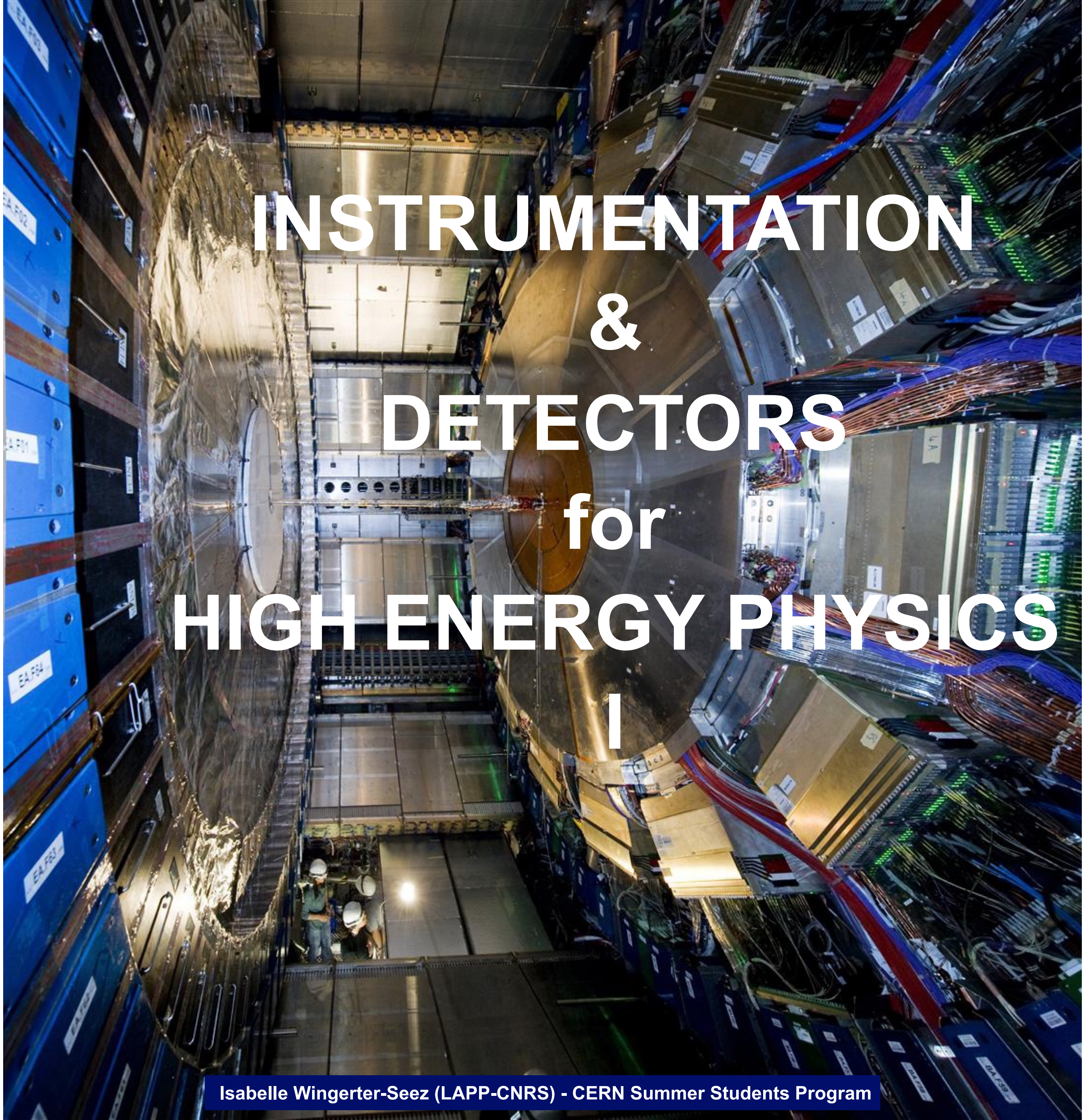


INSTRUMENTATION & DETECTORS for HIGH ENERGY PHYSICS I

Isabelle Wingerter-Seez (LAPP-CNRS) - CERN Summer Students Program

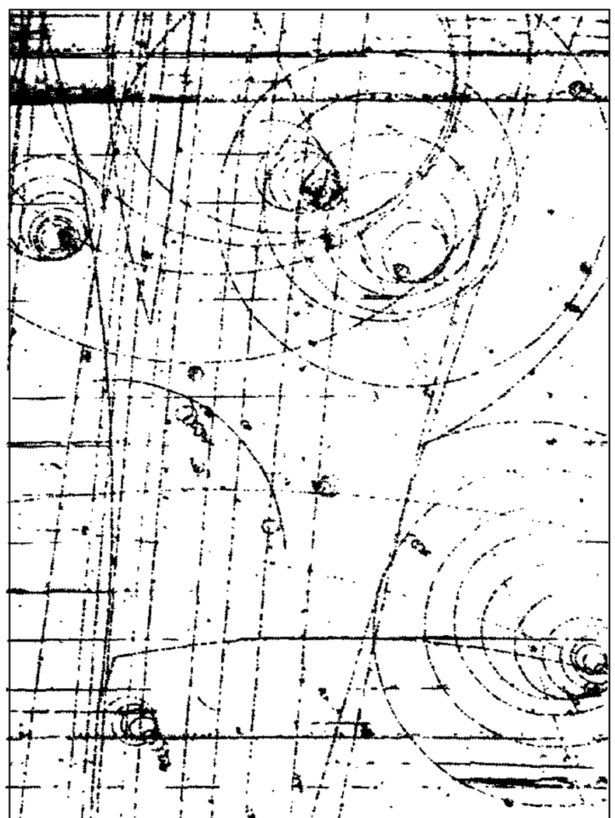
TODAY

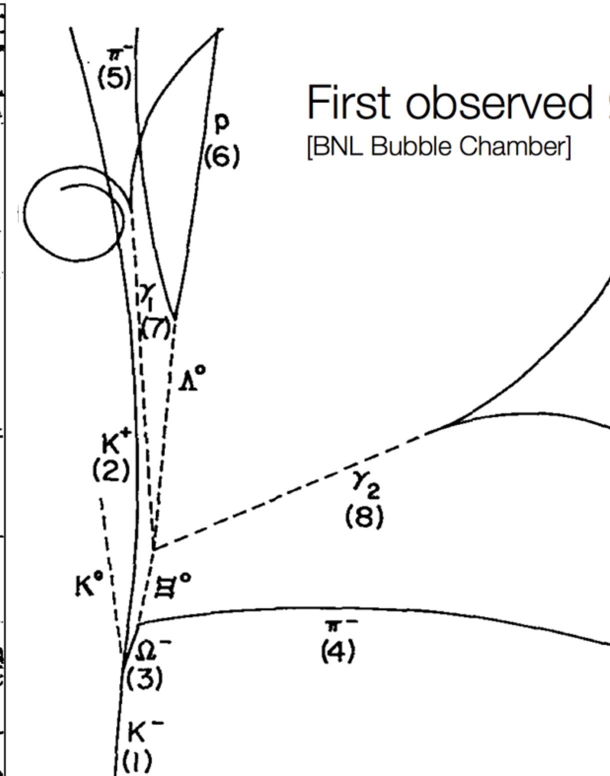
INTRODUCTION

WHAT IS A PARTICLE DETECTOR ?

An apparatus able to

- detect the passage of a particle
- and/or localise it
- and/or measure its momentum or energy
- and/or identify its nature
- and/or measure its time of arrival
- …..





First observed Ω^- event

[BNL Bubble Chamber]

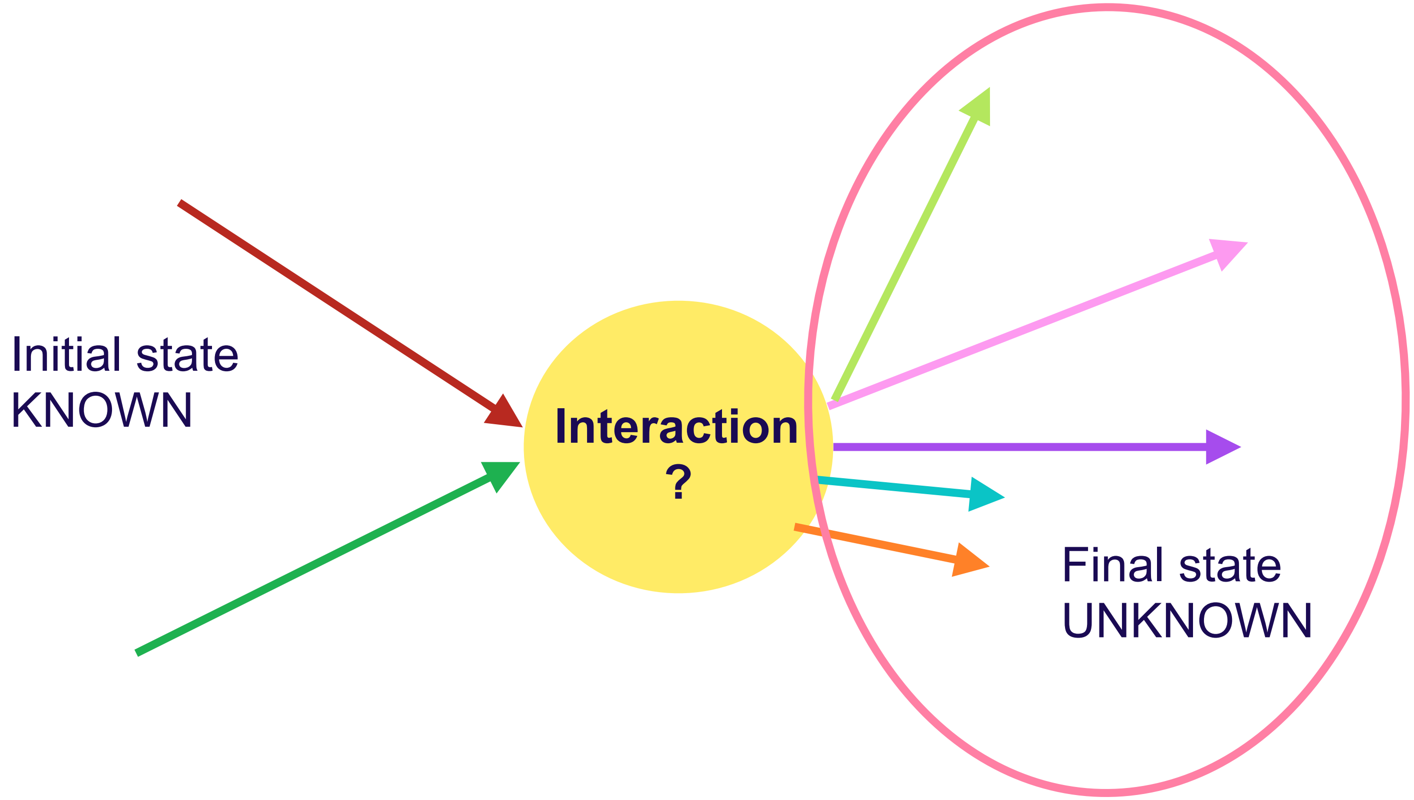
WHY DO WE NEED PARTICLE DETECTORS ?

An astronomer uses a telescope

A biologist uses a microscope

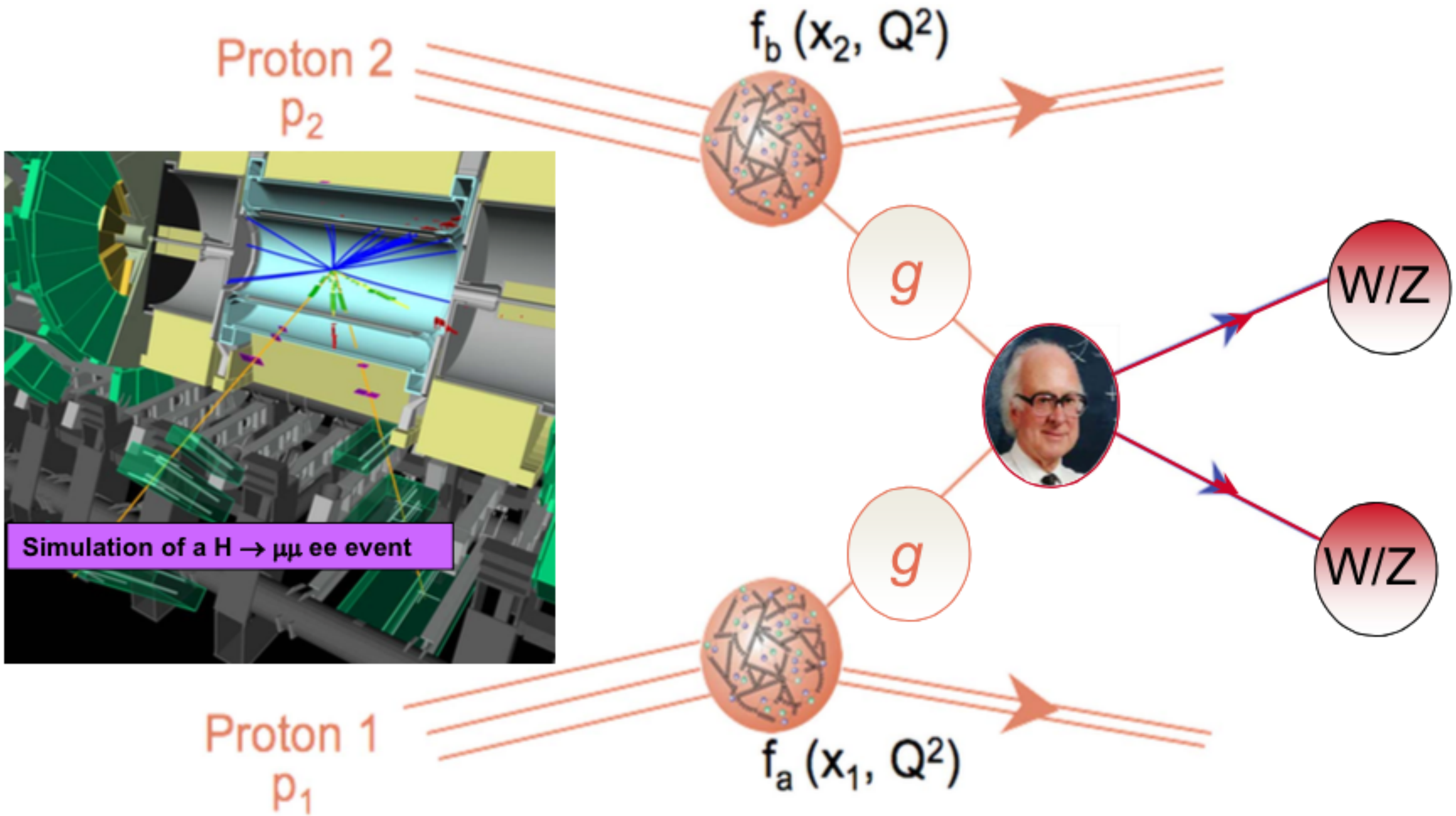
We (a lot of us at least) use a camera to take a snapshot of reality

Particle physicists invent, build and operate detectors to record the products of initial particles interactions:

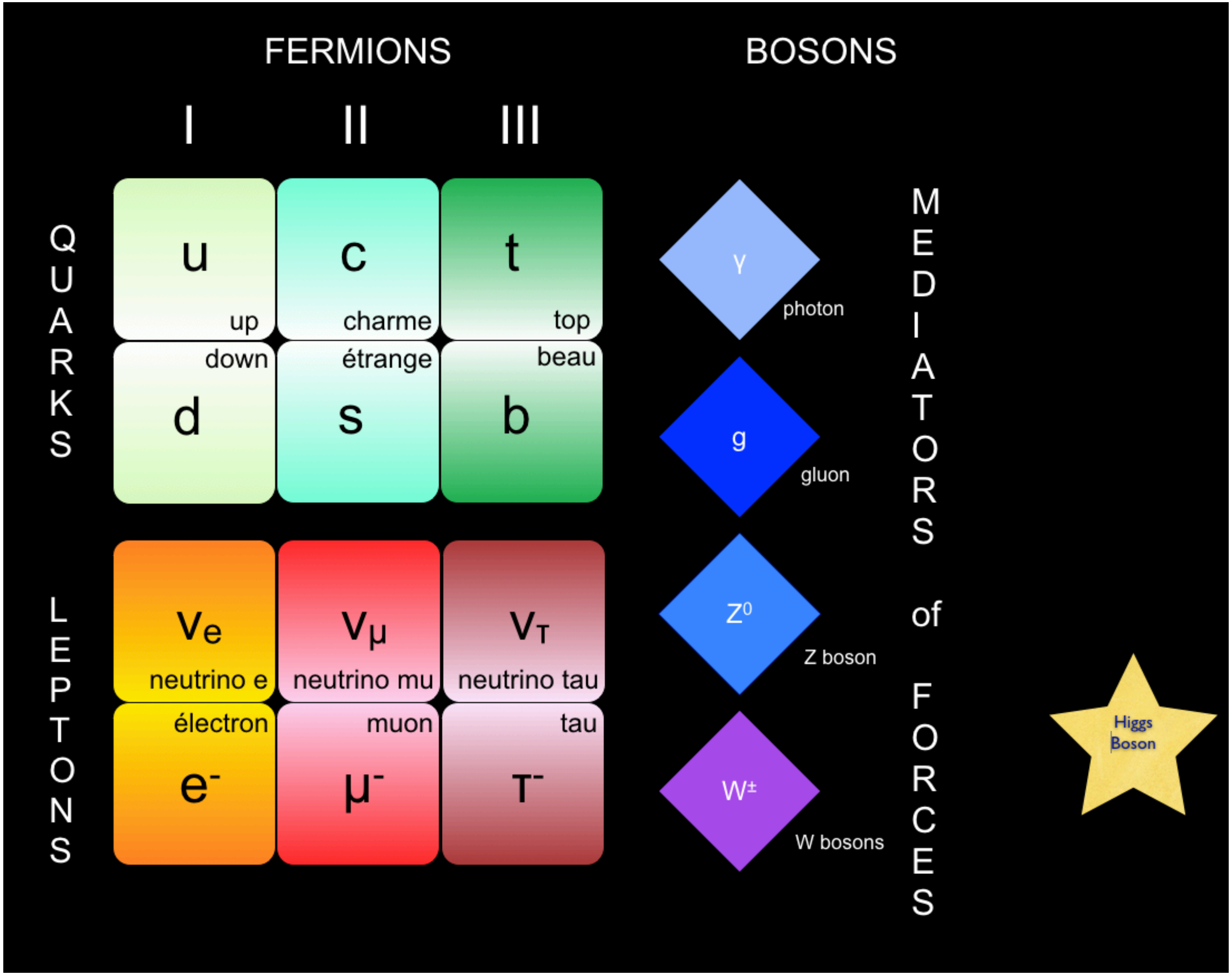


DETECTOR
to record the final state for physicists to interpret the nature of the interaction

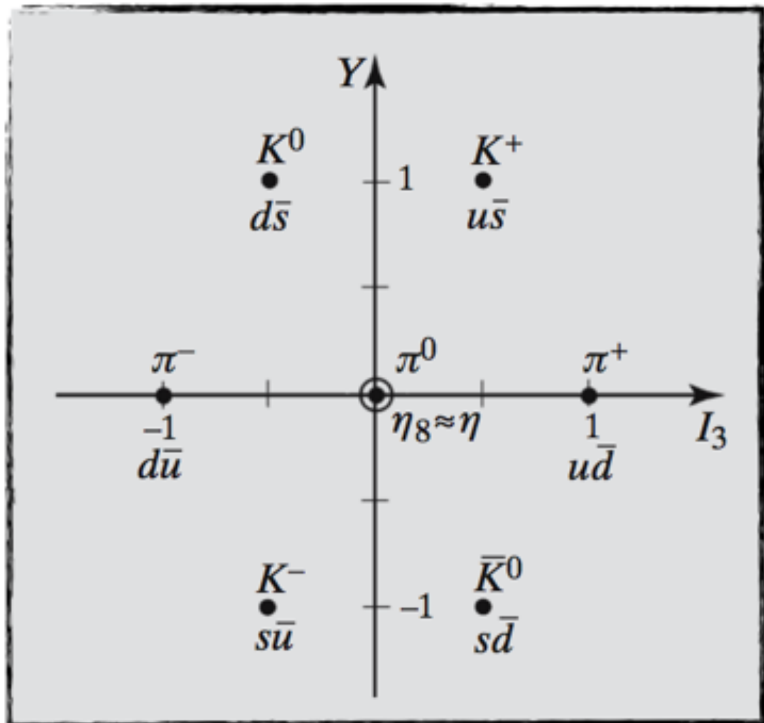
WHAT ARE WE LOOKING FOR ?



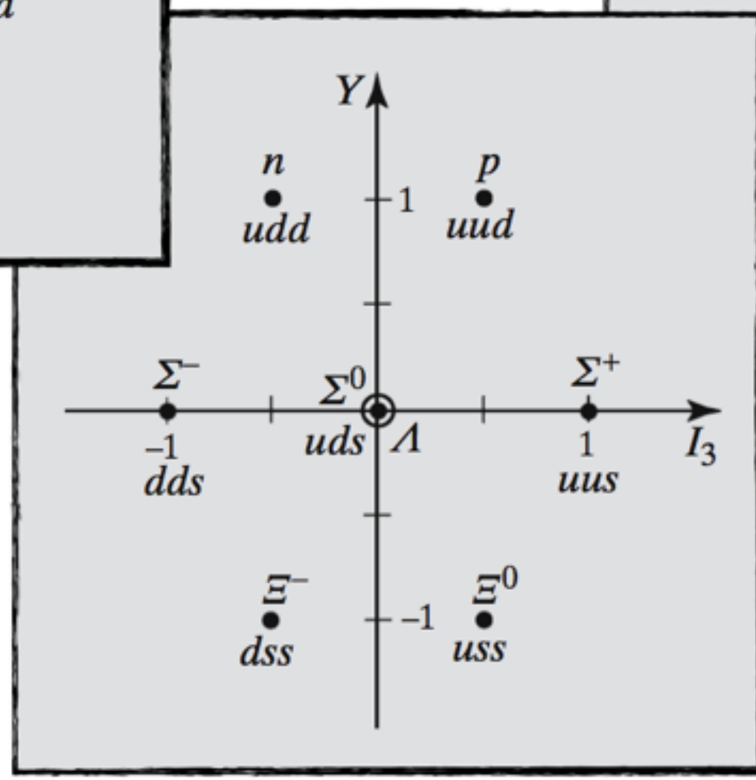
ELEMENTARY PARTICLES and FORCES



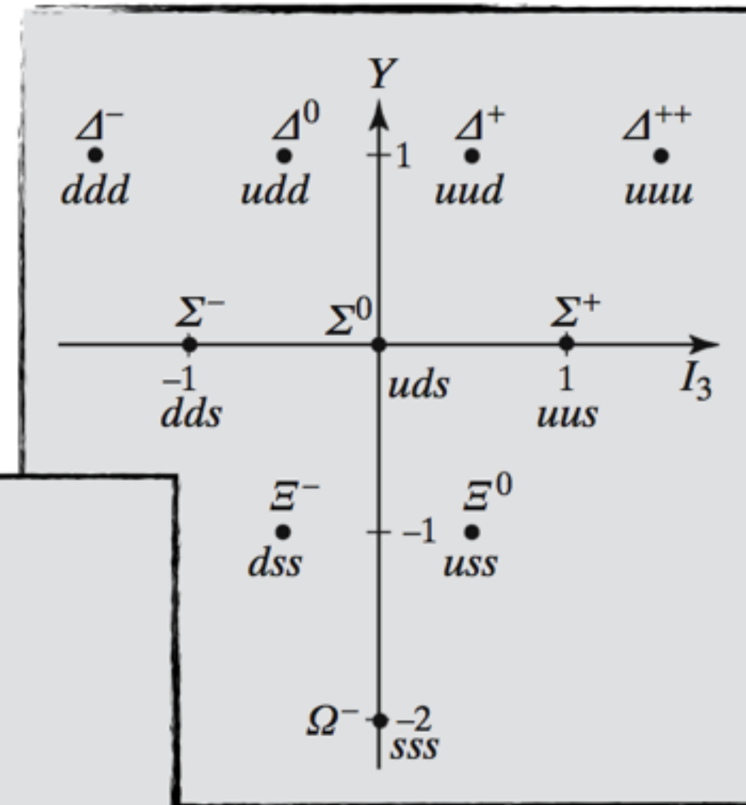
PARTICLES



Meson octet

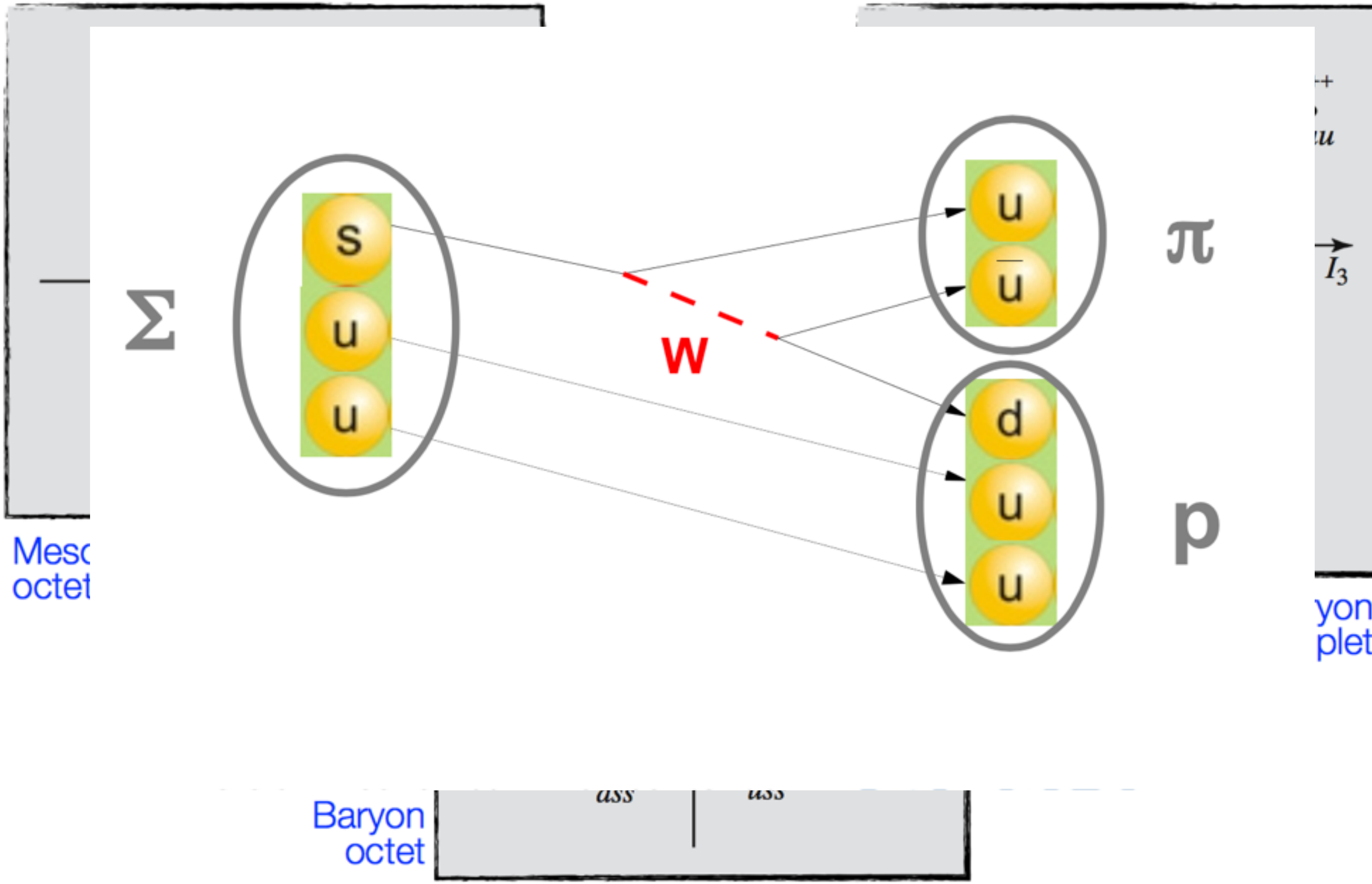


Baryon octet



Baryon decuplet

PARTICLES



http://pdg.lbl.gov ~ **180 Selected Particles**

$H, \gamma, W^{\pm}, Z^{0}, g, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \pi^{\pm}, \pi^{0}, \eta, f_0(600), \rho(770),$
$\omega(782), \eta'(958), f_0(980), a_0(980), \phi(1020), h_1(1170), b_1(1235),$
$a_1(1260), f_2(1270), f_1(1285), \eta(1295), \pi(1300), a_2(1320),$
$f_0(1370), f_1(1420), \omega(1420), \eta(1440), a_0(1450), \rho(1450),$
$f_0(1500), f_2'(1525), \omega(1650), \omega_3(1670), \pi_2(1670), \phi(1680),$
$\rho_3(1690), \rho(1700), f_0(1710), \pi(1800), \phi_3(1850), f_2(2010),$
$a_4(2040), f_4(2050), f_2(2300), f_2(2340), K^{\pm}, K^{0}, K^{0}_{S}, K^{0}_{L}, K^{*}(892),$
$K_1(1270), K_1(1400), K^{*}(1410), K_0^{*}(1430), K_2^{*}(1430), K^{*}(1680),$
$K_2(1770), K_3^{*}(1780), K_2(1820), K_4^{*}(2045), D^{\pm}, D^{0}, D^{*}(2007)^{0},$
$D^{*}(2010)^{\pm}, D_1(2420)^{0}, D_2^{*}(2460)^{0}, D_2^{*}(2460)^{\pm}, D_s^{\pm}, D_s^{*\pm},$
$D_{s1}(2536)^{\pm}, D_{sJ}(2573)^{\pm}, B^{\pm}, B^{0}, B^{*}, B_s^{0}, B_c^{\pm}, \eta_c(1S), J/\psi(1S),$
$\chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160),$
$\psi(4415), \Upsilon(1S), \chi_{b0}(1P), \chi_{b1}(1P), \chi_{b2}(1P), \Upsilon(2S), \chi_{b0}(2P),$
$\chi_{b2}(2P), \Upsilon(3S), \Upsilon(4S), \Upsilon(10860), \Upsilon(11020), p, n, N(1440),$
$N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710),$
$N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600),$
$\Delta(1620), \Delta(1700), \Delta(1905), \Delta(1910), \Delta(1920), \Delta(1930), \Delta(1950),$
$\Delta(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690),$
$\Lambda(1800), \Lambda(1810), \Lambda(1820), \Lambda(1830), \Lambda(1890), \Lambda(2100),$
$\Lambda(2110), \Lambda(2350), \Sigma^{+}, \Sigma^{0}, \Sigma^{-}, \Sigma(1385), \Sigma(1660), \Sigma(1670),$
$\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^{0}, \Xi^{-},$
$\Xi(1530), \Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030), \Omega^{-}, \Omega(2250)^{-},$
$\Lambda_c^{+}, \Lambda_c^{+}, \Sigma_c(2455), \Sigma_c(2520), \Xi_c^{+}, \Xi_c^{0}, \Xi_c'^{+}, \Xi_c'^{0}, \Xi(2645)$
$\Xi_c(2790), \Xi_c(2815), \Omega_c^{0}, \Lambda_b^{0}, \Xi_b^{0}, \Xi_b^{-}, t\bar{t}$

There are many more

+ the ones we have not yet observed

KNOWN PARTICLES

HOW CAN A PARTICLE DETECTOR

DISTINGUISH

THE PARTICLES WE KNOW

MEASURE PROPERTIES

of PHYSICS PROCESSES

IDENTIFY THE EXISTENCE
OF A NEW PARTICLE

?

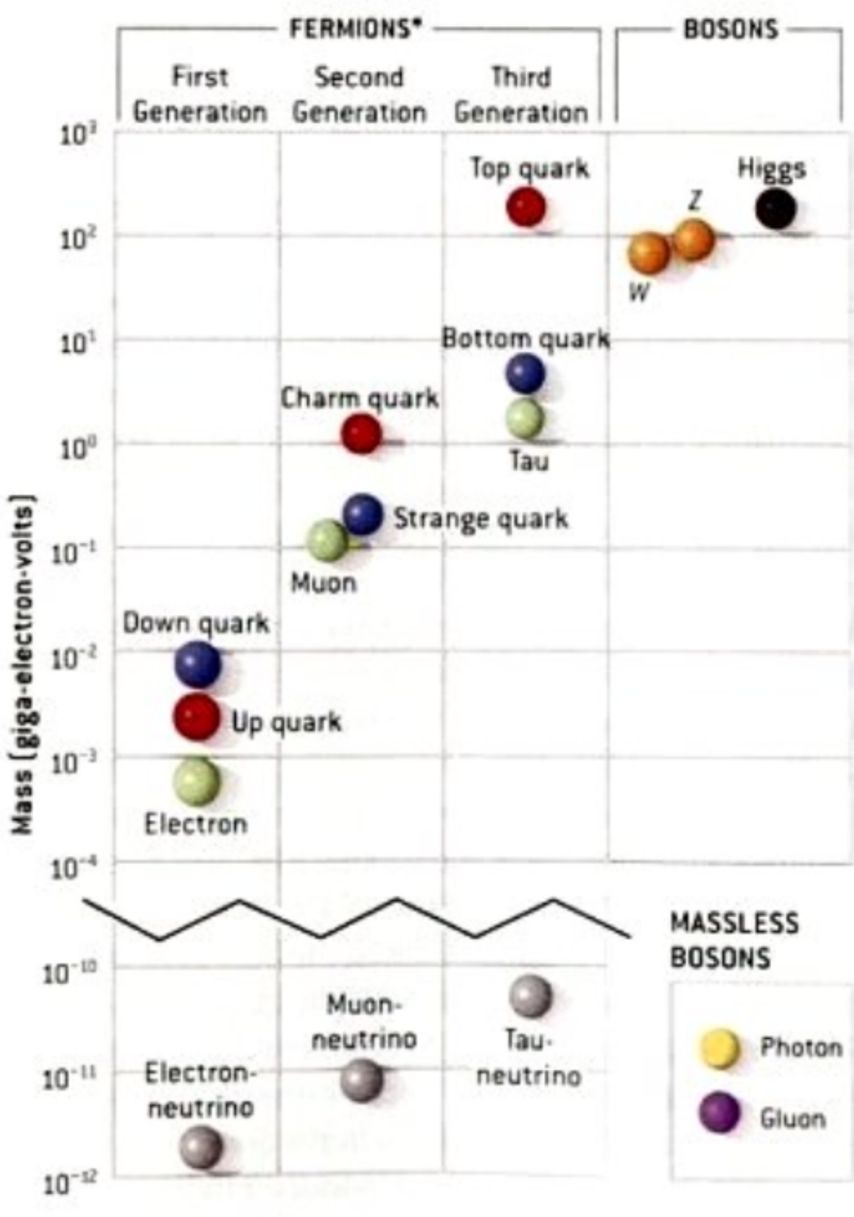
http://pdg.lbl.gov ~ 180 Selected Particles

H, γ, $W^{\pm}$, Z^0, g, e, μ, τ, ν_e, ν_μ, ν_τ, $\pi^{\pm}$, π^0, η, $f_0(600)$, $\rho(770)$,
$\omega(782)$, $\eta'(958)$, $f_0(980)$, $a_0(980)$, $\phi(1020)$, $h_1(1170)$, $b_1(1235)$,
$a_1(1260)$, $f_2(1270)$, $f_1(1285)$, $\eta(1295)$, $\pi(1300)$, $a_2(1320)$,
$f_0(1370)$, $f_1(1420)$, $\omega(1420)$, $\eta(1440)$, $a_0(1450)$, $\rho(1450)$,
$f_0(1500)$, $f_2'(1525)$, $\omega(1650)$, $\omega_3(1670)$, $\pi_2(1670)$, $\phi(1680)$,
$\rho_3(1690)$, $\rho(1700)$, $f_0(1710)$, $\pi(1800)$, $\phi_3(1850)$, $f_2(2010)$,
$a_4(2040)$, $f_4(2050)$, $f_2(2300)$, $f_2(2340)$, $K^{\pm}$, K^0, K^0_S, K^0_L, $K^*(892)$,
$K_1(1270)$, $K_1(1400)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$,
$K_2(1770)$, $K_3^*(1780)$, $K_2(1820)$, $K_4^*(2045)$, $D^{\pm}$, D^0, $D^*(2007)^0$,
$D^*(2010)^{\pm}$, $D_1(2420)^0$, $D_2^*(2460)^0$, $D_2^*(2460)^{\pm}$, $D_s^{\pm}$, $D_s^{*\pm}$,
$D_{s1}(2536)^{\pm}$, $D_{sJ}(2573)^{\pm}$, $B^{\pm}$, B^0, B^*, B^0_s, $B_c^{\pm}$, $\eta_c(1S)$, $J/\psi(1S)$,
$\chi_{c0}(1P)$, $\chi_{c1}(1P)$, $\chi_{c2}(1P)$, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$,
$\psi(4415)$, $\Upsilon(1S)$, $\chi_{b0}(1P)$, $\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\Upsilon(2S)$, $\chi_{b0}(2P)$,
$\chi_{b2}(2P)$, $\Upsilon(3S)$, $\Upsilon(4S)$, $\Upsilon(10860)$, $\Upsilon(11020)$, p, n, $N(1440)$,
$N(1520)$, $N(1535)$, $N(1650)$, $N(1675)$, $N(1680)$, $N(1700)$, $N(1710)$,
$N(1720)$, $N(2190)$, $N(2220)$, $N(2250)$, $N(2600)$, $\Delta(1232)$, $\Delta(1600)$,
$\Delta(1620)$, $\Delta(1700)$, $\Delta(1905)$, $\Delta(1910)$, $\Delta(1920)$, $\Delta(1930)$, $\Delta(1950)$,
$\Delta(2420)$, Λ, $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$,
$\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1820)$, $\Lambda(1830)$, $\Lambda(1890)$, $\Lambda(2100)$,
$\Lambda(2110)$, $\Lambda(2350)$, Σ^+, Σ^0, Σ^-, $\Sigma(1385)$, $\Sigma(1660)$, $\Sigma(1670)$,
$\Sigma(1750)$, $\Sigma(1775)$, $\Sigma(1915)$, $\Sigma(1940)$, $\Sigma(2030)$, $\Sigma(2250)$, Ξ^0, Ξ^-,
$\Xi(1530)$, $\Xi(1690)$, $\Xi(1820)$, $\Xi(1950)$, $\Xi(2030)$, Ω^-, $\Omega(2250)^-$,
Λ_c^+, Λ_c^+, $\Sigma_c(2455)$, $\Sigma_c(2520)$, Ξ_c^+, Ξ_c^0, $\Xi_c'^+$, $\Xi_c'^0$, $\Xi(2645)$
$\Xi_c(2790)$, $\Xi_c(2815)$, Ω_c^0, Λ_b^0, Ξ_b^0, Ξ_b^-, $t\bar{t}$

There are many more

\+ the ones we have not yet observed

ELEMENTARY PARTICLES MASS



Mass of elementary particles in not predicted by the Standard Model of Particle Physics.

PARTICLES MASSES

p	P_{11}	****
n	P_{11}	****
$N(1440)$	P_{11}	****
$N(1520)$	D_{13}	****
$N(1535)$	S_{11}	****
$N(1650)$	S_{11}	****
$N(1675)$	D_{15}	****
$N(1680)$	F_{15}	****
$N(1700)$	D_{13}	***
$N(1710)$	P_{11}	***
$N(1720)$	P_{13}	****
$N(1900)$	P_{13}	**
$N(1990)$	F_{17}	**
$N(2000)$	F_{15}	**
$N(2080)$	D_{13}	**
$N(2090)$	S_{11}	*
$N(2100)$	P_{11}	*
$N(2190)$	G_{17}	****
$N(2200)$	D_{15}	**
$N(2220)$	H_{19}	****
$N(2250)$	G_{19}	****
$N(2600)$	$I_{1,11}$	***
$N(2700)$	$K_{1,13}$	**

$\Delta(1232)$	P_{33}	****
$\Delta(1600)$	P_{33}	***
$\Delta(1620)$	S_{31}	****
$\Delta(1700)$	D_{33}	****
$\Delta(1750)$	P_{31}	*
$\Delta(1900)$	S_{31}	**
$\Delta(1905)$	F_{35}	****
$\Delta(1910)$	P_{31}	****
$\Delta(1920)$	P_{33}	***
$\Delta(1930)$	D_{35}	***
$\Delta(1940)$	D_{33}	*
$\Delta(1950)$	F_{37}	****
$\Delta(2000)$	F_{35}	**
$\Delta(2150)$	S_{31}	*
$\Delta(2200)$	G_{37}	*
$\Delta(2300)$	H_{39}	**
$\Delta(2350)$	D_{35}	*
$\Delta(2390)$	F_{37}	*
$\Delta(2400)$	G_{39}	**
$\Delta(2420)$	$H_{3,11}$	****
$\Delta(2750)$	$I_{3,13}$	**
$\Delta(2950)$	$K_{3,15}$	**
Λ	P_{01}	****
$\Lambda(1405)$	S_{01}	****
$\Lambda(1520)$	D_{03}	****
$\Lambda(1600)$	P_{01}	***
$\Lambda(1670)$	S_{01}	****
$\Lambda(1690)$	D_{03}	****
$\Lambda(1800)$	S_{01}	***
$\Lambda(1810)$	P_{01}	***
$\Lambda(1820)$	F_{05}	****
$\Lambda(1830)$	D_{05}	****
$\Lambda(1890)$	P_{03}	****
$\Lambda(2000)$		*
$\Lambda(2020)$	F_{07}	*
$\Lambda(2100)$	G_{07}	****
$\Lambda(2110)$	F_{05}	***
$\Lambda(2325)$	D_{03}	*
$\Lambda(2350)$	H_{09}	***
$\Lambda(2585)$		**

Σ^+	P_{11}	****
Σ^0	P_{11}	****
Σ^-	P_{11}	****
$\Sigma(1385)$	P_{13}	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	D_{13}	*
$\Sigma(1620)$	S_{11}	**
$\Sigma(1660)$	P_{11}	***
$\Sigma(1670)$	D_{13}	****
$\Sigma(1690)$		**
$\Sigma(1750)$	S_{11}	***
$\Sigma(1770)$	P_{11}	*
$\Sigma(1775)$	D_{15}	****
$\Sigma(1840)$	P_{13}	*
$\Sigma(1880)$	P_{11}	**
$\Sigma(1915)$	F_{15}	****
$\Sigma(1940)$	D_{13}	***
$\Sigma(2000)$	S_{11}	*
$\Sigma(2030)$	F_{17}	****
$\Sigma(2070)$	F_{15}	*
$\Sigma(2080)$	P_{13}	**
$\Sigma(2100)$	G_{17}	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	P_{11}	****
Ξ^-	P_{11}	****
$\Xi(1530)$	P_{13}	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	D_{13}	***
$\Xi(1950)$		***
$\Xi(2030)$		***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-		****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Λ_c^+	****
$\Lambda_c(2595)^+$	***
$\Lambda_c(2625)^+$	***
$\Lambda_c(2765)^+$	*
$\Lambda_c(2880)^+$	***
$\Lambda_c(2940)^+$	***
$\Sigma_c(2455)$	****
$\Sigma_c(2520)$	***
$\Sigma_c(2800)$	***
Ξ_c^+	***
Ξ_c^0	***
$\Xi_c'^+$	***
$\Xi_c'^0$	***
$\Xi_c(2645)$	***
$\Xi_c(2790)$	***
$\Xi_c(2815)$	***
$\Xi_c(2930)$	*
$\Xi_c(2980)$	***
$\Xi_c(3055)$	**
$\Xi_c(3080)$	***
$\Xi_c(3123)$	*
Ω_c^0	***
$\Omega_c(2770)^0$	***
Ξ_{cc}^+	*
Λ_b^0	***
Σ_b	***
Σ_b^*	***
Ξ_b^0, Ξ_b^-	***
Ω_b^-	***

Tables of masses for known particles
(here baryons - 3 quarks)

PROPERTIES of PARTICULES

τ^- **DECAY MODES**		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Modes with one charged particle				
particle$^-$ ≥ 0 neutrals $\geq 0K^0\nu_\tau$ ("1-prong")		(85.35 ± 0.07) %	S=1.3	–
particle$^-$ ≥ 0 neutrals $\geq 0K_L^0\nu_\tau$		(84.71 ± 0.08) %	S=1.3	–
$\mu^-\overline{\nu}_\mu\nu_\tau$	[g]	(17.41 ± 0.04) %	S=1.1	885
$\mu^-\overline{\nu}_\mu\nu_\tau\gamma$	[e]	$(3.6 \pm 0.4) \times 10^{-3}$		885
$e^-\overline{\nu}_e\nu_\tau$	[g]	(17.83 ± 0.04) %		888
$e^-\overline{\nu}_e\nu_\tau\gamma$	[e]	(1.75 ± 0.18) %		888
$h^- \geq 0K_L^0\ \nu_\tau$		(12.06 ± 0.06) %	S=1.2	883
$h^-\nu_\tau$		(11.53 ± 0.06) %	S=1.2	883
$\pi^-\nu_\tau$	[g]	(10.83 ± 0.06) %	S=1.2	883
$K^-\nu_\tau$	[g]	$(7.00 \pm 0.10) \times 10^{-3}$	S=1.1	820
$h^- \geq 1$ neutralsν_τ		(37.10 ± 0.10) %	S=1.2	–
$h^- \geq 1\pi^0\nu_\tau(\text{ex.}K^0)$		(36.58 ± 0.10) %	S=1.2	–
$h^-\pi^0\nu_\tau$		(25.95 ± 0.09) %	S=1.1	878
$\pi^-\pi^0\nu_\tau$	[g]	(25.52 ± 0.09) %	S=1.1	878
$\pi^-\pi^0$ non-$\rho(770)\nu_\tau$		$(3.0 \pm 3.2) \times 10^{-3}$		878
$K^-\pi^0\nu_\tau$	[g]	$(4.29 \pm 0.15) \times 10^{-3}$		814

Tables of decay modes for known particles
(here for lepton τ)

LIMITED SIZE DETECTOR

Among these 180 listed particles,

27 have a long enough lifetime

such that, for GeV energies, they travel more than one micrometer

Among these 27,

14 have c.τ <0.5 mm and leave a very short track in the detector

All Particles with $c\tau > 1\mu m$ @ GeV level — 19

Particle	Mass (MeV)	Lifetime τ (s)	$c\tau$
γ	0	∞	∞
$\pi^\pm (u\bar{d}, d\bar{u})$	140	$2.6 \cdot 10^{-8}$	7.8 m
$K^\pm (u\bar{s}, \bar{u}s)$	494	$1.2 \cdot 10^{-8}$	3.7 m
$K^0 (d\bar{s}, \bar{d}s)$	497	$5.1 \cdot 10^{-8}$ $8.9 \cdot 10^{-11}$	15.5 m 2.7 cm
$D^\pm (c\bar{d}, \bar{c}d)$	1869	$1.0 \cdot 10^{-12}$	315 μm
$D^0 (c\bar{u}, u\bar{c})$	1864	$4.1 \cdot 10^{-13}$	123 μm
$D_s^\pm (c\bar{s}, \bar{c}s)$	1969	$4.9 \cdot 10^{-13}$	147 μm
$B^\pm (u\bar{b}, \bar{b}u)$	5279	$1.7 \cdot 10^{-12}$	502 μm
$B^0 (b\bar{d}, d\bar{b})$	5279	$1.5 \cdot 10^{-12}$	462 μm
$B_s^0 (s\bar{b}, \bar{s}b)$	5370	$1.5 \cdot 10^{-12}$	438 μm
$B_c^\pm (c\bar{b}, \bar{c}b)$	~6400	$\sim 5 \cdot 10^{-13}$	150 μm
$p (uud)$	938.3	$> 10^{33}$ y	∞
$n (udd)$	939.6	885.7 s	$2.655 \cdot 10^{8}$ km
$\Lambda^0 (uds)$	1115.7	$2.6 \cdot 10^{-10}$	7.89 cm
$\Sigma^+ (uus)$	1189.4	$8.0 \cdot 10^{-11}$	2.404 cm
$\Sigma^- (dds)$	1197.4	$1.5 \cdot 10^{-10}$	4.434 cm
$\Xi^0 (uss)$	1315	$2.9 \cdot 10^{-10}$	8.71 cm
$\Xi^- (dss)$	1321	$1.6 \cdot 10^{-10}$	4.91 cm
$\Omega^- (sss)$	1672	$8.2 \cdot 10^{-11}$	2.461 cm
$\Lambda_c^+ (udc)$	2285	$\sim 2 \cdot 10^{-13}$	60 μm
$\Xi_c^+ (usc)$	2466	$4.4 \cdot 10^{-13}$	132 μm
$\Xi_c^0 (dcs)$	2472	$\sim 1 \cdot 10^{-13}$	29 μm
$\Omega_c^0 (ssc)$	2698	$6.0 \cdot 10^{-14}$	19 μm
$\Lambda_b (udb)$	5620	$1.2 \cdot 10^{-12}$	368 μm

"Secondary Vertices" ($D^\pm$ through $B_c^\pm$)

THE 13 PARTICLES A DETECTOR MUST BE ABLE TO MEASURE AND IDENTIFY

$e^{\pm}$ $m_e = 0.511$ MeV

$\mu^{\pm}$ $m_\mu = 105.7$ MeV $\sim 200\, m_e$

γ $m_\gamma = 0$, $Q = 0$

} EM

$\pi^{\pm}$ $m_\pi = 139.6$ MeV $\sim 270\, m_e$

$K^{\pm}$ $m_K = 493.7$ MeV $\sim 1000\, m_e$ $\sim 3.5\, m_\pi$

$p^{\pm}$ $m_p = 938.3$ MeV $\sim 2000\, m_e$

} EM, Strong

K^0 $m_{K^0} = 497.7$ MeV $Q = 0$

n $m_n = 939.6$ MeV $Q = 0$

} Strong

The Difference in

Mass, Charge, Interaction

is the key to the Identification

W. Riegler/CERN

UNITS in HEP & International System

Quantity	HEP units	SI Units
length	1 fm	10^{-15} m
energy	1 GeV	$1.602 \cdot 10^{-10}$ J
mass	1 GeV/c^2	$1.78 \cdot 10^{-27}$ kg
$\hbar = h/2$	$6.588 \cdot 10^{-25}$ GeV s	$1.055 \cdot 10^{-34}$ Js
c	$2.988 \cdot 10^{23}$ fm/s	$2.988 \cdot 10^{8}$ m/s
$\hbar c$	0.1973 GeV fm	$3.162 \cdot 10^{-26}$ Jm

Natural units ($\hbar = c = 1$)	
mass	1 GeV
length	1 $\text{GeV}^{-1} = 0.1973$ fm
time	1 $\text{GeV}^{-1} = 6.59 \cdot 10^{-25}$ s

HOW to MEASURE PARTICLE PROPERTIES

$eV = 1.6 \cdot 10^{-19}$ J
$c = 299\,792\,458$ m/s
$e = 1.602176487(40) \cdot 10^{-19}$ C

Particles are characterized by

Mass	[Unit: eV/c^2 or eV]
Momentum	[Unit: eV/c or eV]
Energy	[Unit: eV]
Charge	[Unit: e]

[+ Spin, Lifetime ...]

Particle Identification via measurement of

e.g. $(E, \vec{p}, Q)$ or $(\vec{p}, \beta, Q)$
$(\vec{p}, m, Q)$ ...

Relativistic kinematics:

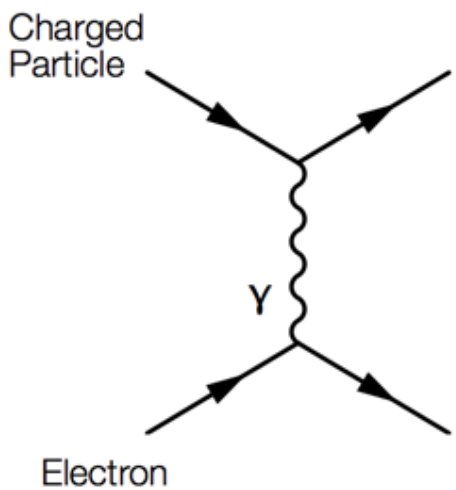
$$E^2 = \vec{p}\,^2 c^2 + m^2 c^4$$

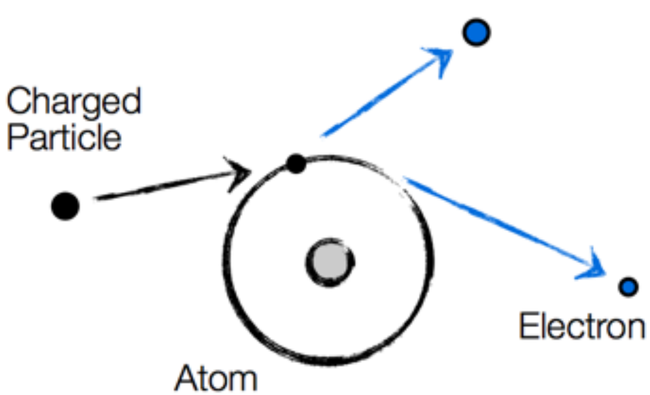
$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$E = m\gamma c^2 = mc^2 + E_{\text{kin}} \qquad \vec{p} = m\gamma\vec{\beta}c \qquad \vec{\beta} = \frac{\vec{p}c}{E}$$

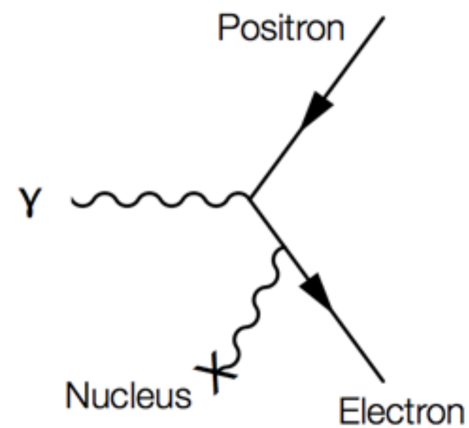
EXAMPLES of INTERACTIONS

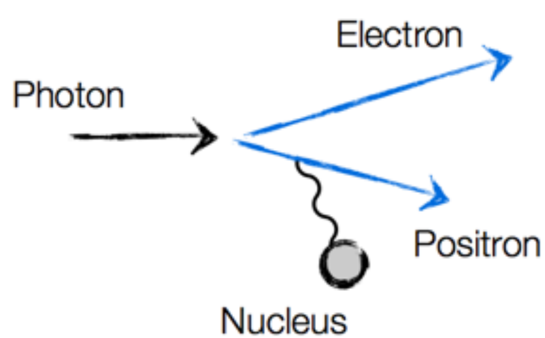
Ionisation



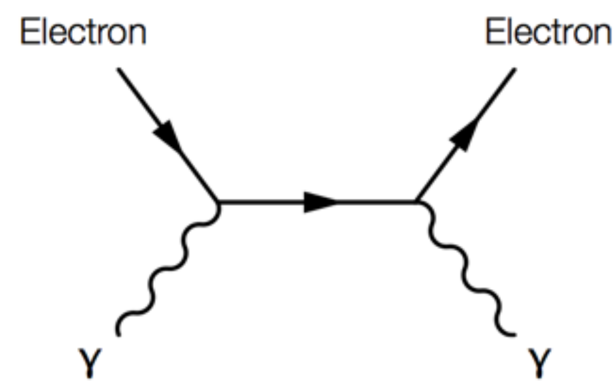


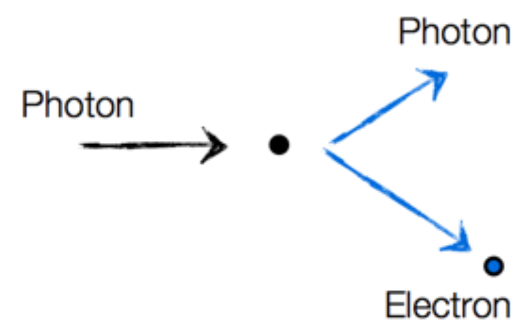
Production de paires e^+e^-





Diffusion Compton

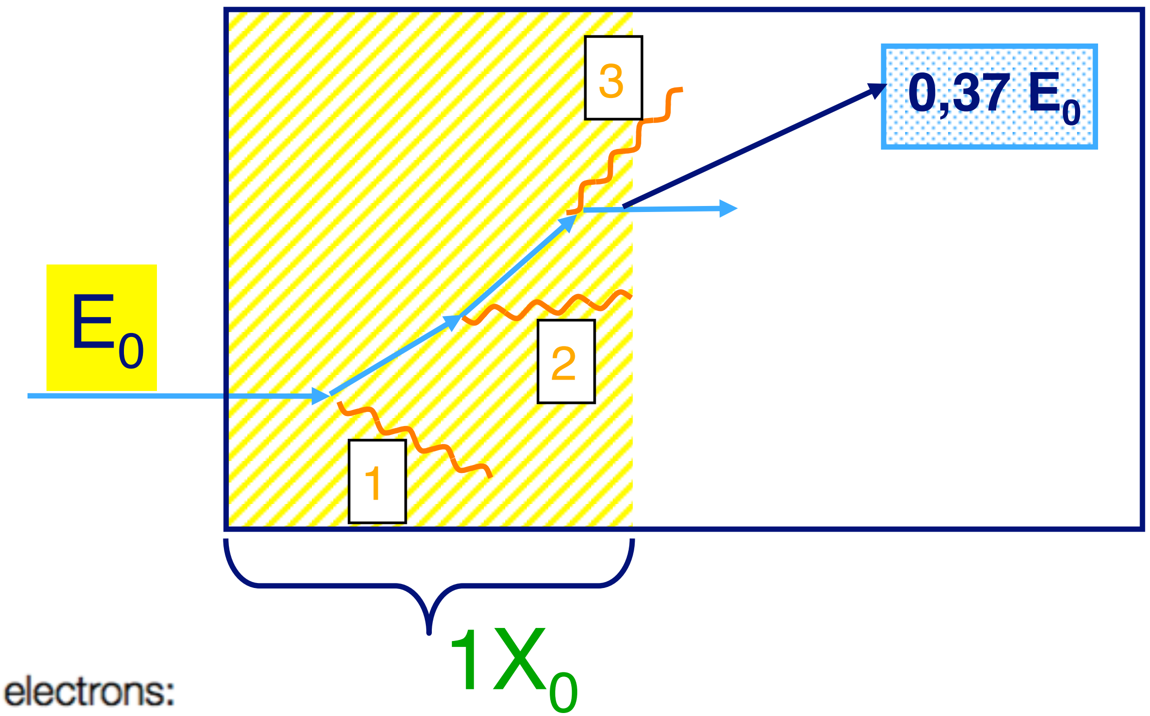




RADIATION LENGTH

The radiation length is a "universal" distance, very useful to describe electromagnetic showers (electrons & photons)

X_0 is the distance after which the incident electron has radiated (1-1/e) 63% of its incident energy, via Bremsstrahlung.



Consider electrons:

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \ln \frac{183}{Z^{\frac{1}{3}}}$$

$$\frac{dE}{dx} = \frac{E}{X_0} \quad \text{with} \quad X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{\frac{1}{3}}}}$$

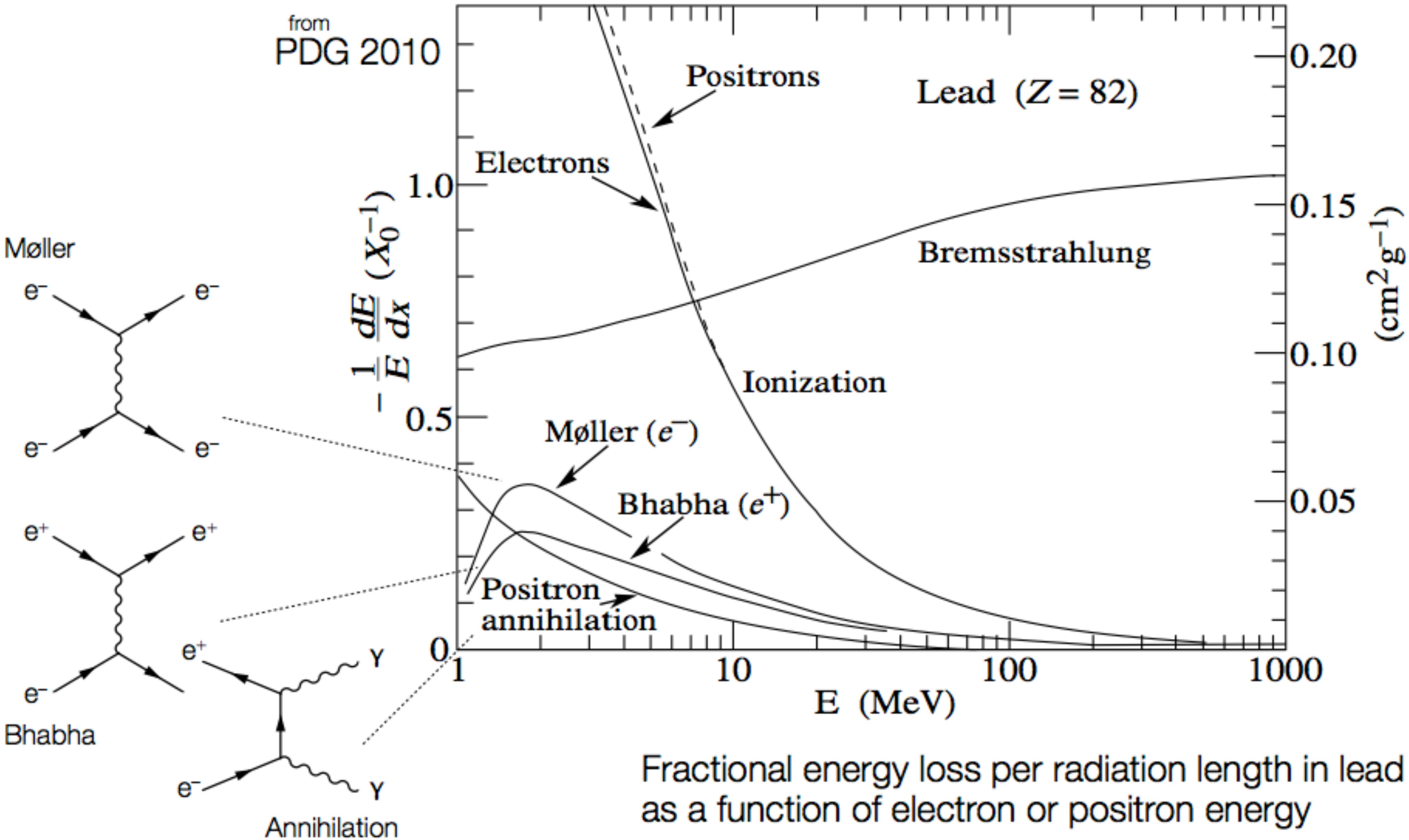
[Radiation length in g/cm²]

$$\Rightarrow E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has lost all but $(1/e)^{th}$ of its energy

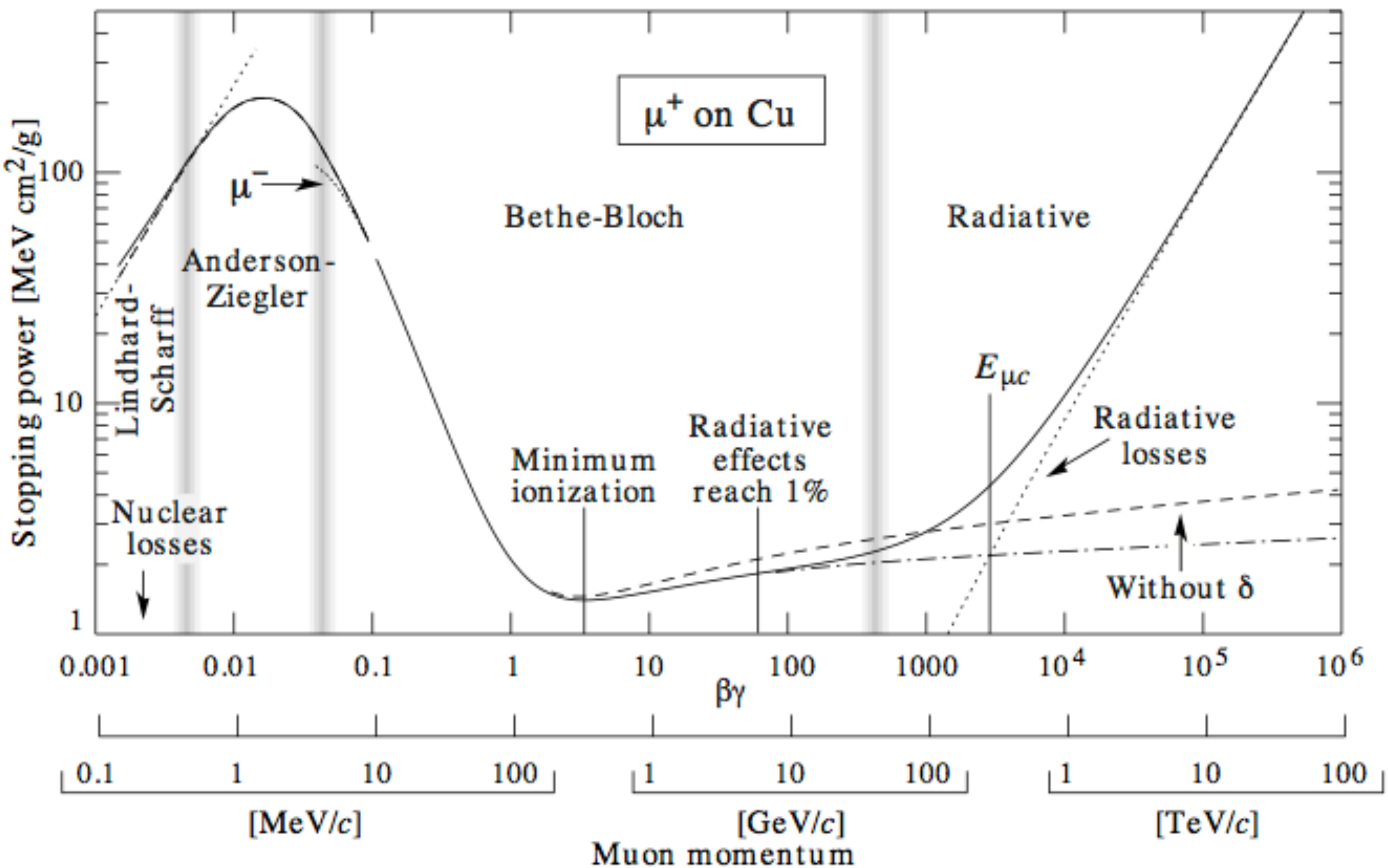
[i.e. 63%]

TOTAL ENERGY LOSS by ELECTRONS



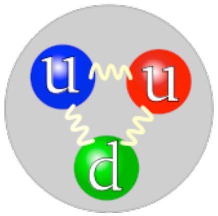
Fractional energy loss per radiation length in lead as a function of electron or positron energy

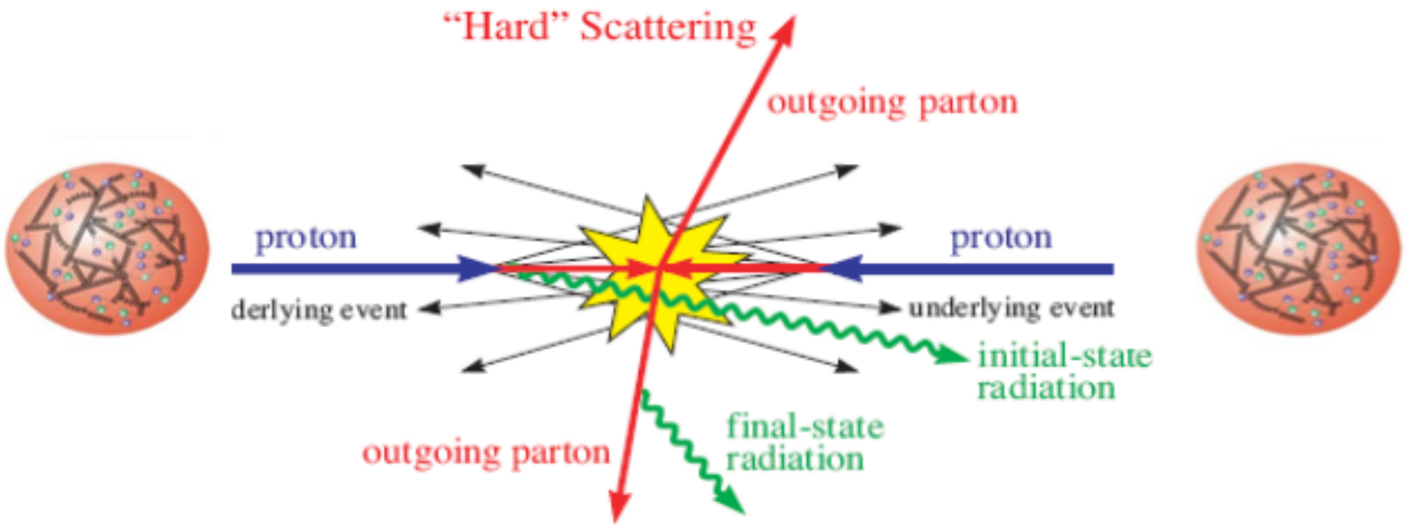
μ^+ in COPPER



μ+ on Cu
Stopping power [MeV cm2/g]
100
10
1
μ−
Bethe-Bloch
Radiative
Anderson-
Ziegler
Lindhard-
Scharff
Eμc
Radiative
losses
Minimum
ionization
Radiative
effects
reach 1%
Nuclear
losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

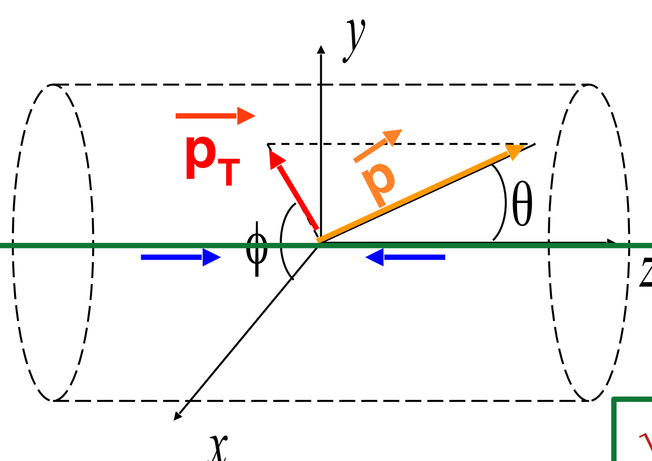
PROTON-PROTON INTERACTIONS





$\vec{p}_{p1}+\vec{p}_{p2}=0$

proton$_1$



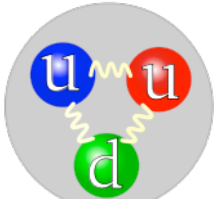
proton$_2$

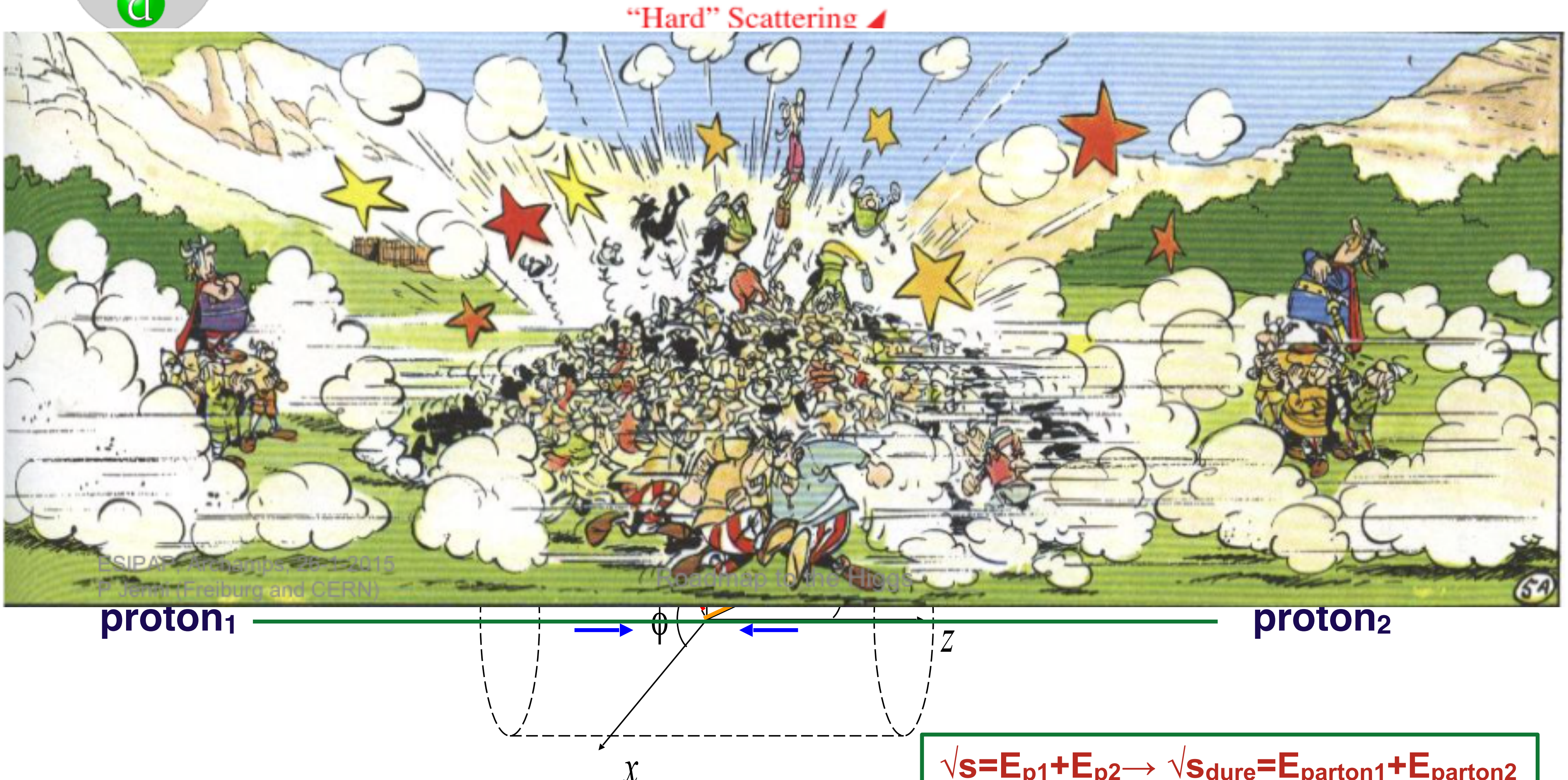
$\eta=-\ln\tan(\theta/2)$

$\sqrt{s}=E_{p1}+E_{p2} \rightarrow \sqrt{s_{dure}}=E_{parton1}+E_{parton2}$

$M_{12}=\sqrt{[2E_1.E_2(1-\cos\alpha_{12})]}$

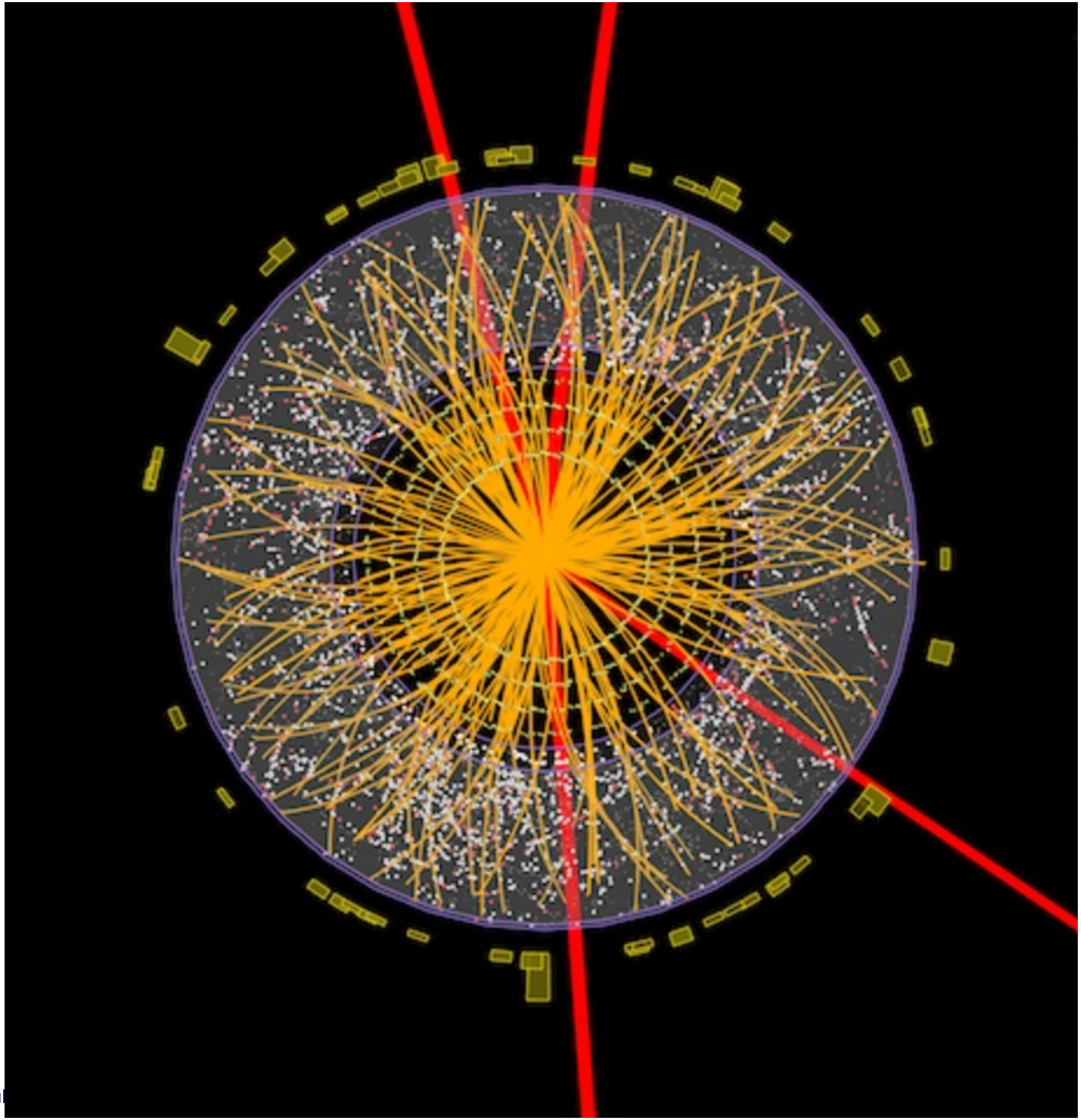
PROTON-PROTON INTERACTIONS



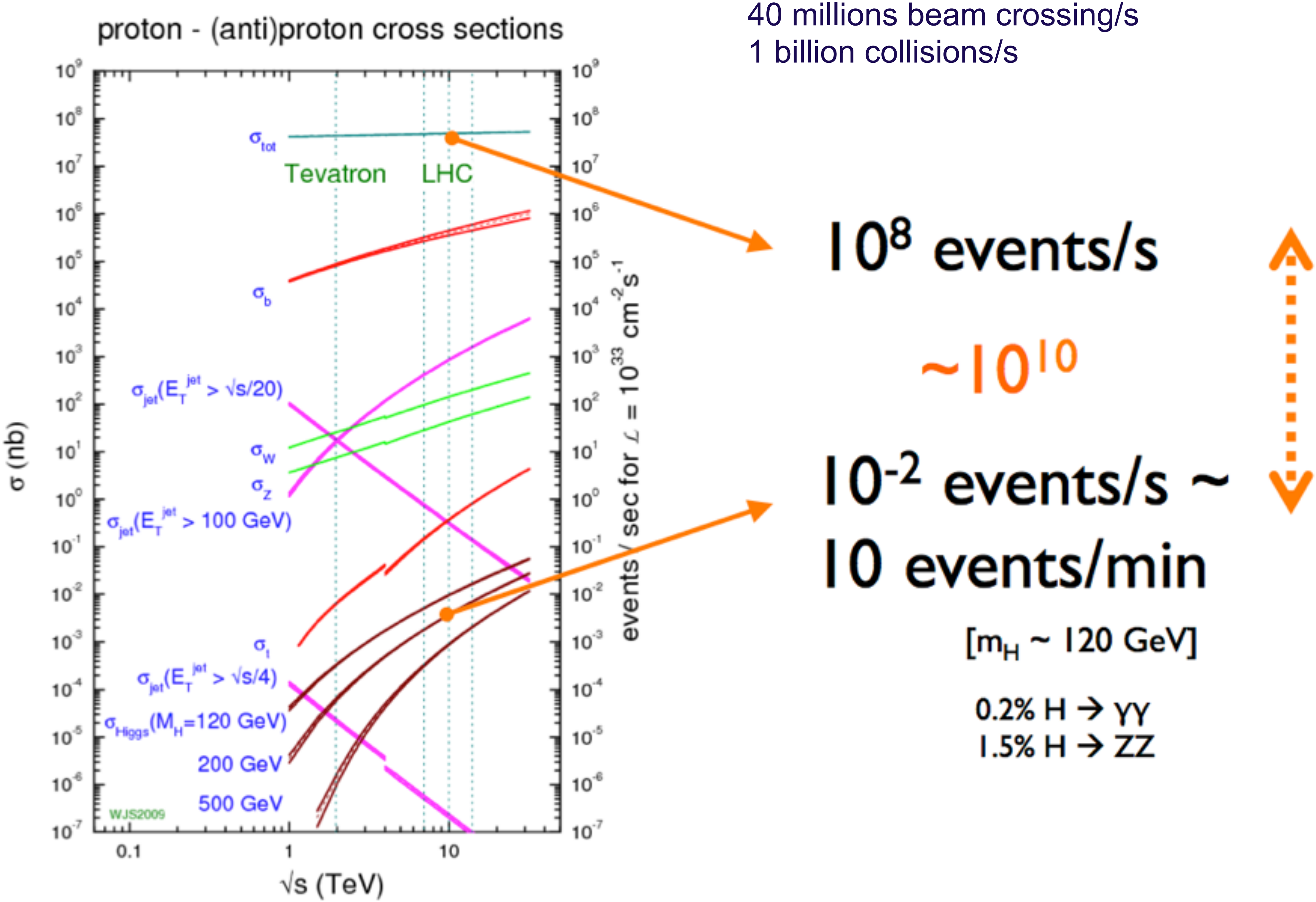


$\sqrt{s}=E_{p1}+E_{p2} \rightarrow \sqrt{s_{dure}}=E_{parton1}+E_{parton2}$

$M_{12}=\sqrt{[2E_1.E_2(1-\cos\alpha_{12})]}$



DETECTOR at LHC - Challenge

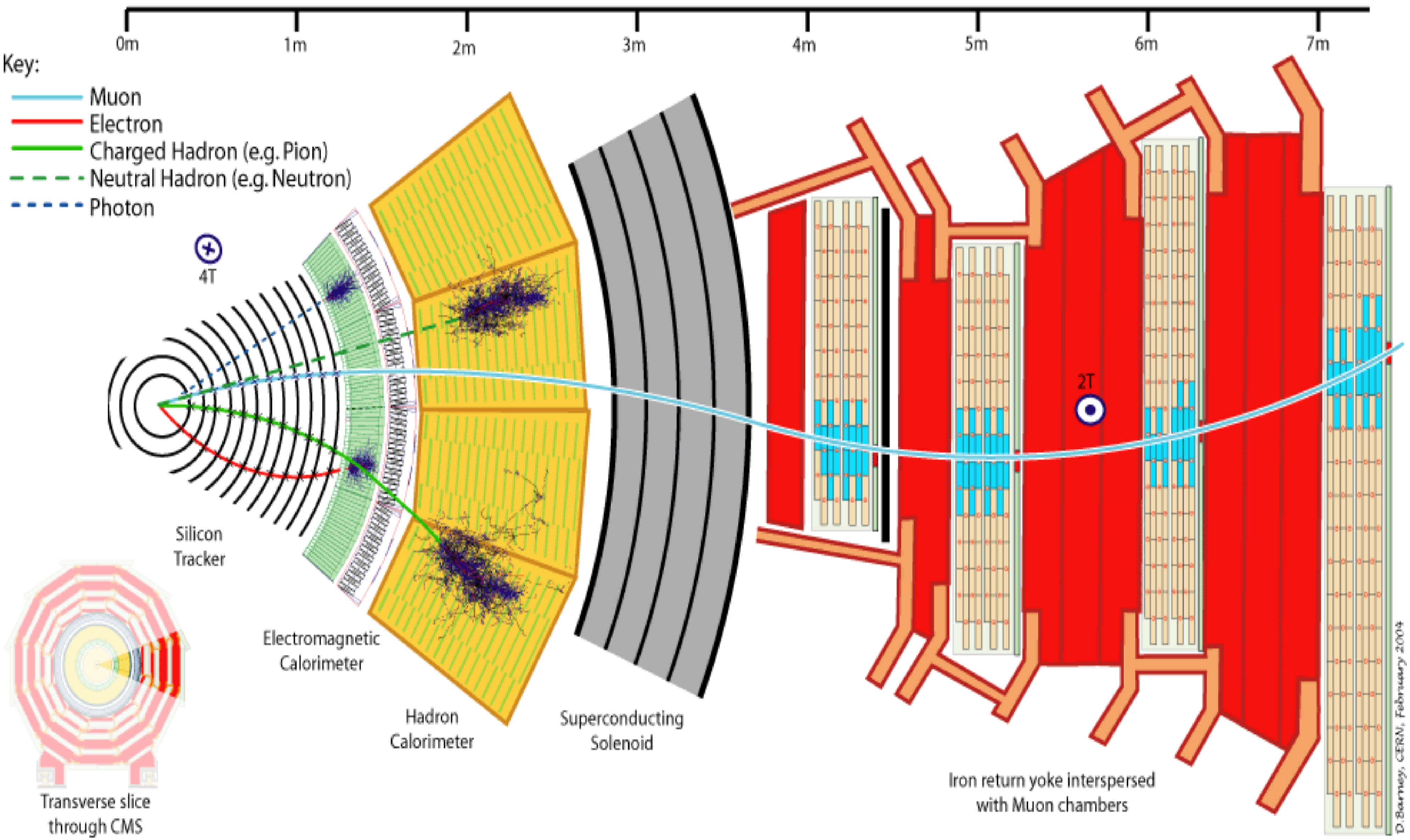


40 millions beam crossing/s
1 billion collisions/s

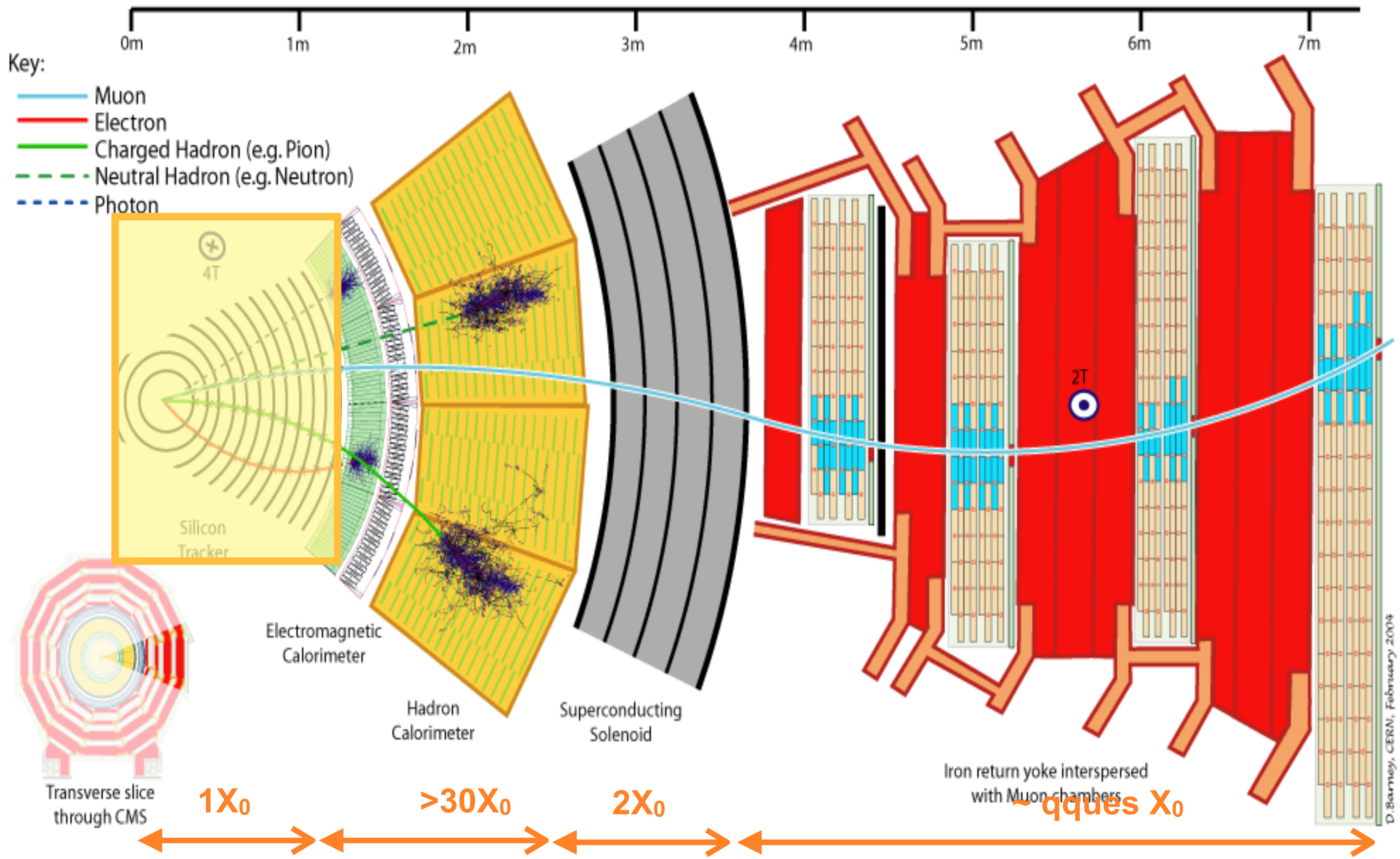
[m_H ~ 120 GeV]

0.2% H → γγ
1.5% H → ZZ

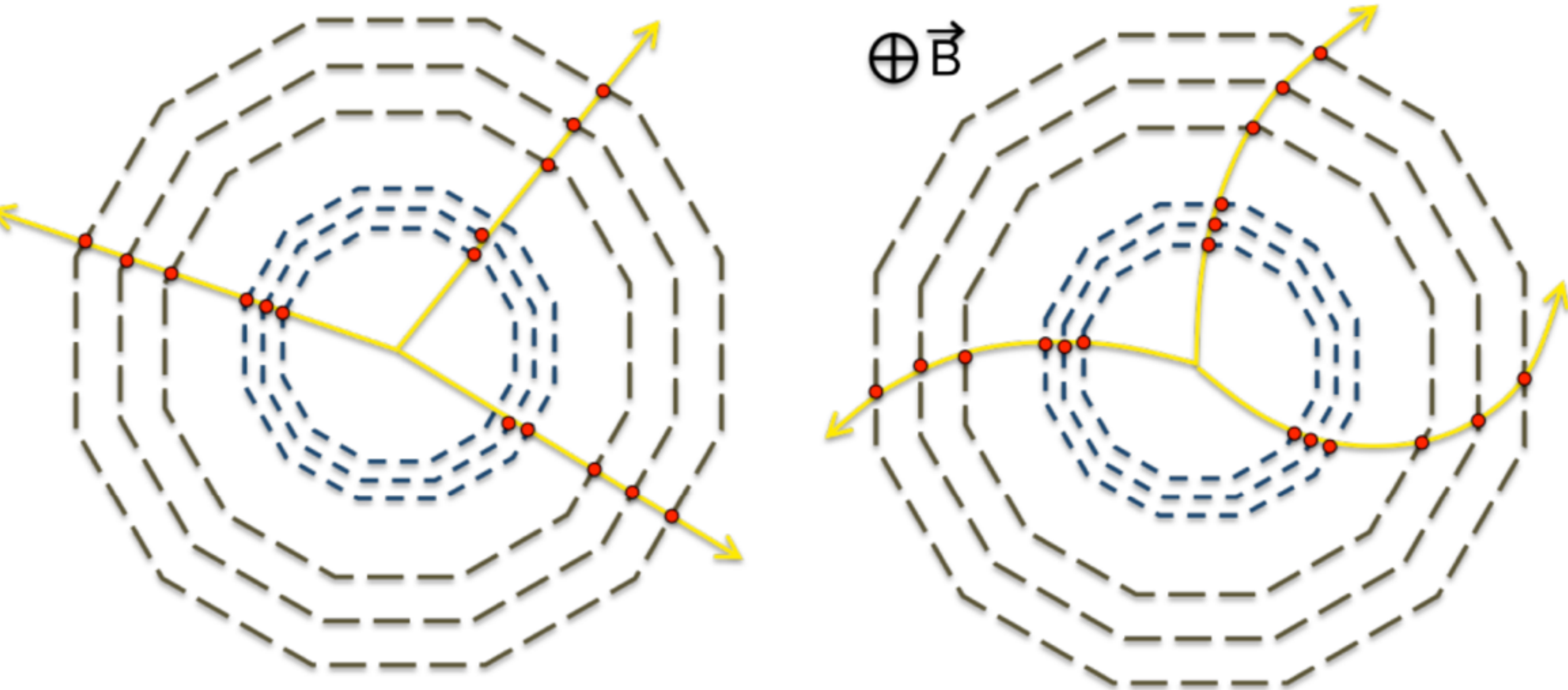
DETECTOR: PRINCIPLE



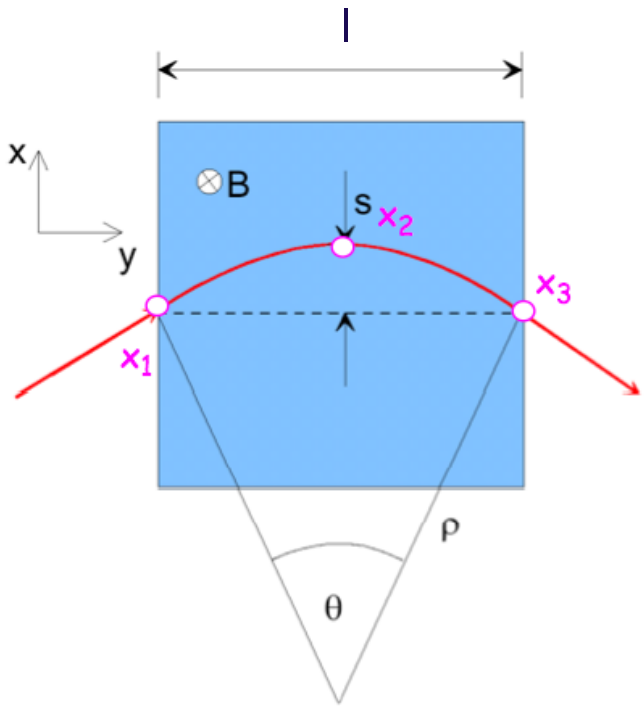
DETECTORS: TRACKING



MAGNETIC ANALYSIS



MAGNETIC ANALYSIS



s = sagitta

l = chord

ρ = radius

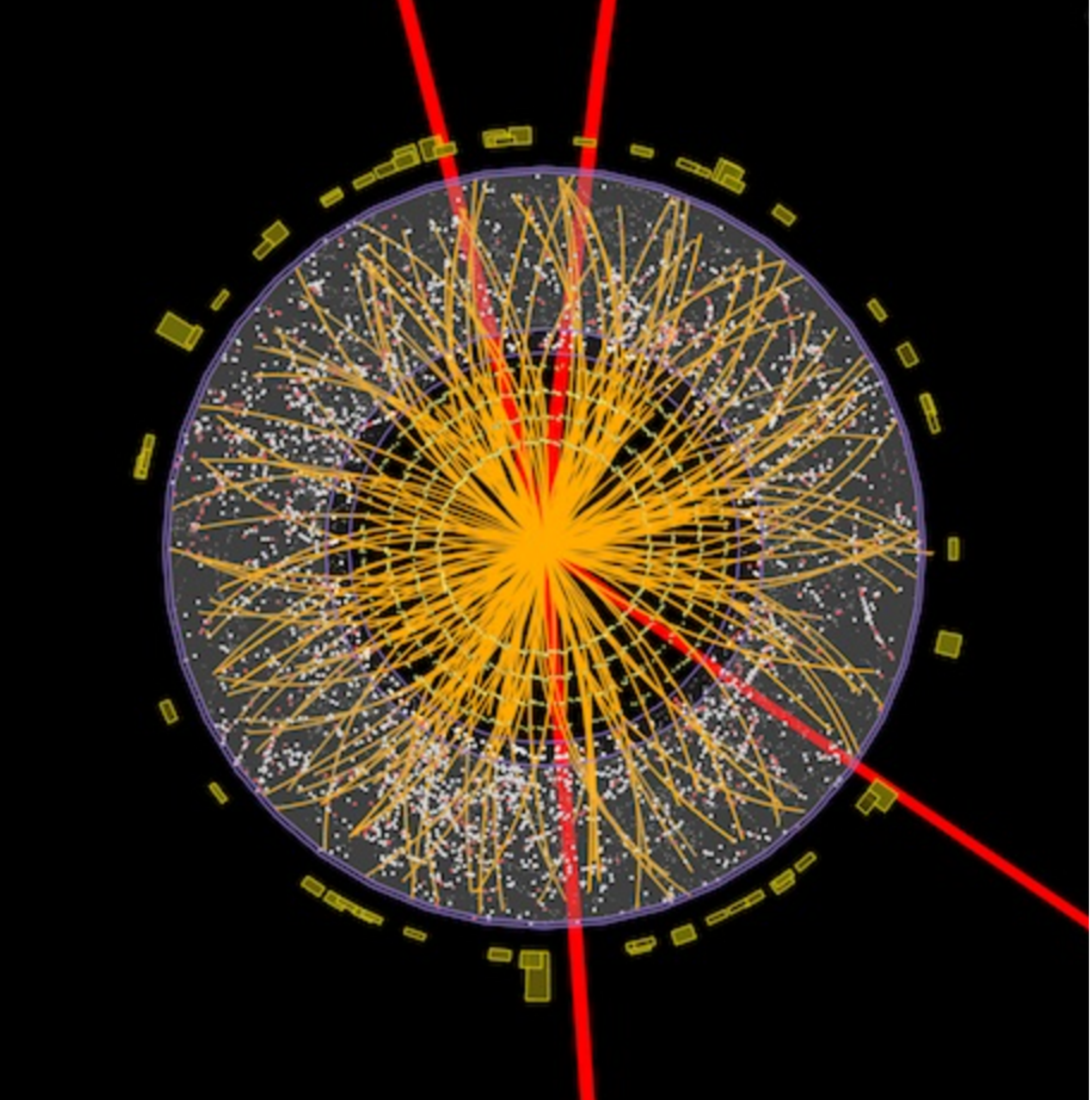
$$\rho \simeq \frac{l^2}{8s} \qquad p = 0.3\frac{Bl^2}{8s} \qquad \left|\frac{\delta p}{p}\right| = \left|\frac{\delta s}{s}\right|$$

Charged particle of momentum p in a magnetic field B

$$\frac{d\vec{p}}{dt} = q\vec{\beta} \times \vec{B}$$

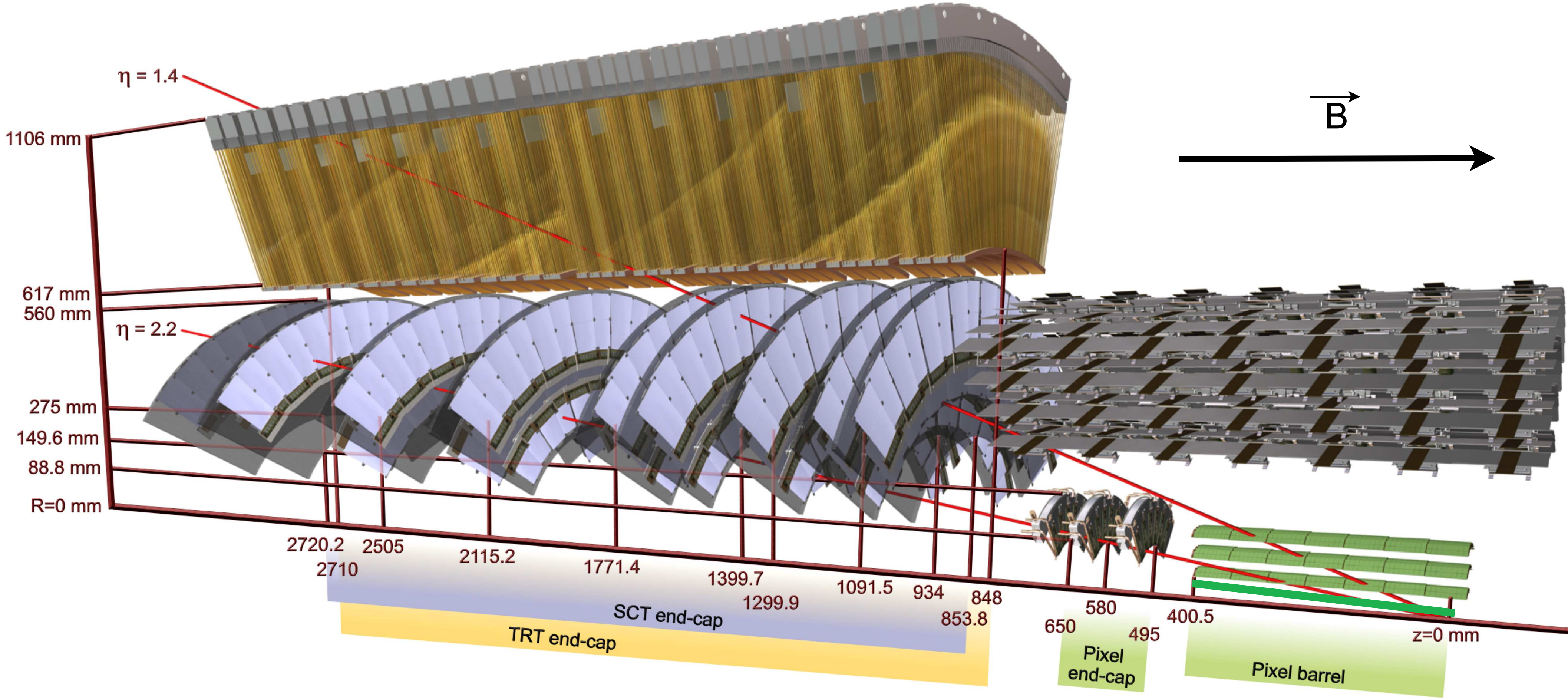
If the field is constant and we neglect the presence of matter, the momentum is constant with time, the trajectory is helical.

$$p[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$$



What can you say about this event ?

ATLAS TRACKING SYSTEM



Detector SCT 60 m² - 6 M channels

Barrel 4 cylindres at R=300, 373, 447 & 520 mm

Forward 9 disks on each side

~4000 modules

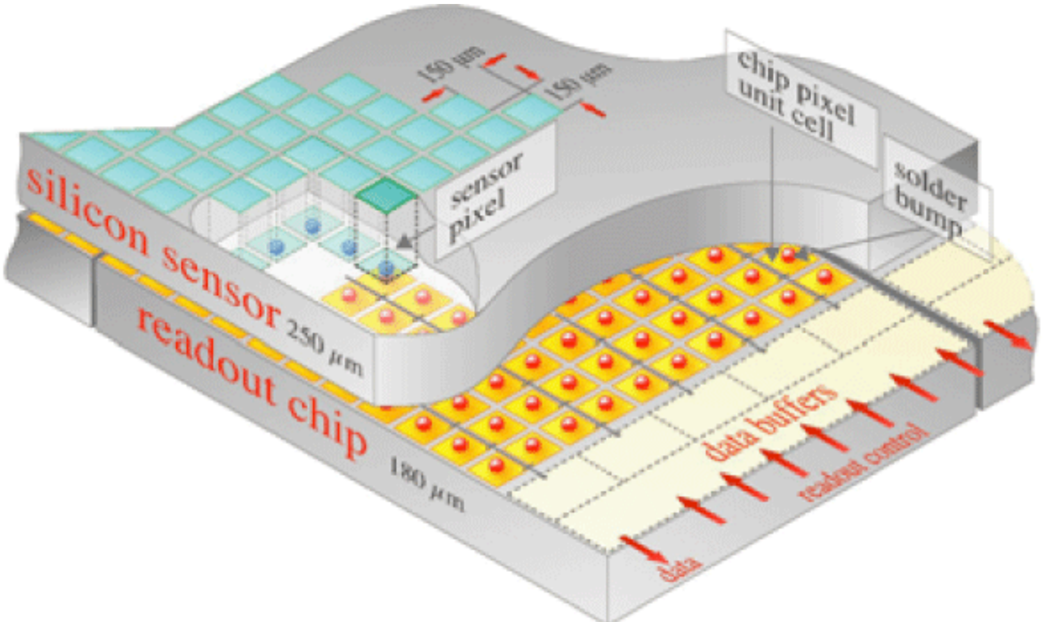
Cell width 80 μm $\Longrightarrow \sigma_{pos} = 23$ μm

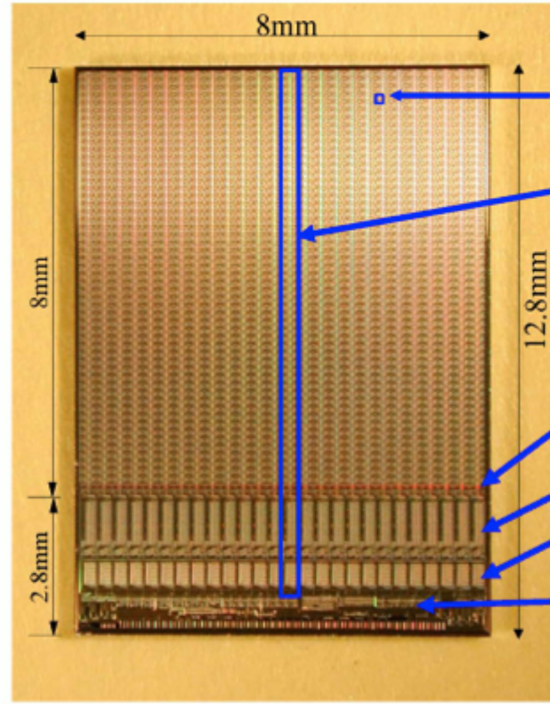
8 points per trace

Pixels detector 1.7 m² - 80 M de canaux

1744 pixel modules avec 46080 pixels/mod.
Each cell : 50x400 μm² $\Longrightarrow \sigma_{pos}$=14/115 μm
Barrel R= 33.6, 50.5, 88.5 & 122.5 mm
Forward R coverage 9-15 cm

TRACKING DETECTOR: CMS pixel module

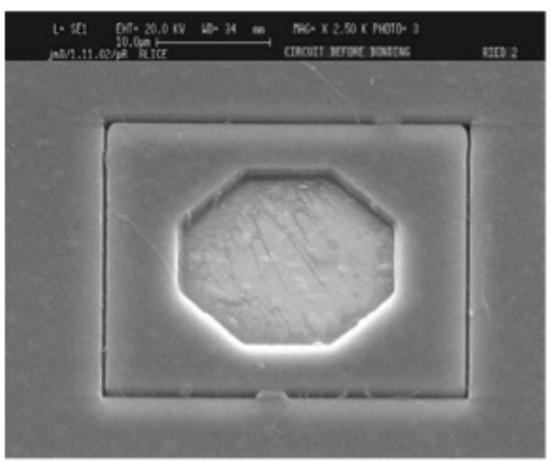


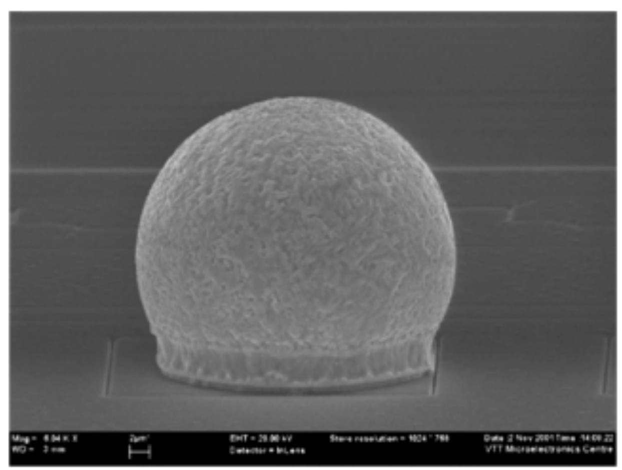


PSI43

- 150 μm x 150 μm pixel
- 52x53 pixels in 26 double columns 345 k transistors
- Periphery: 78 k transistors
- Pixel−column interface
- Data buffers (4x24 capacitors)
- Timestamp buffers (8x8 bits)
- I2C, DACs, regulators, counters, readout, wirebonds 6 k transistors

10 μm



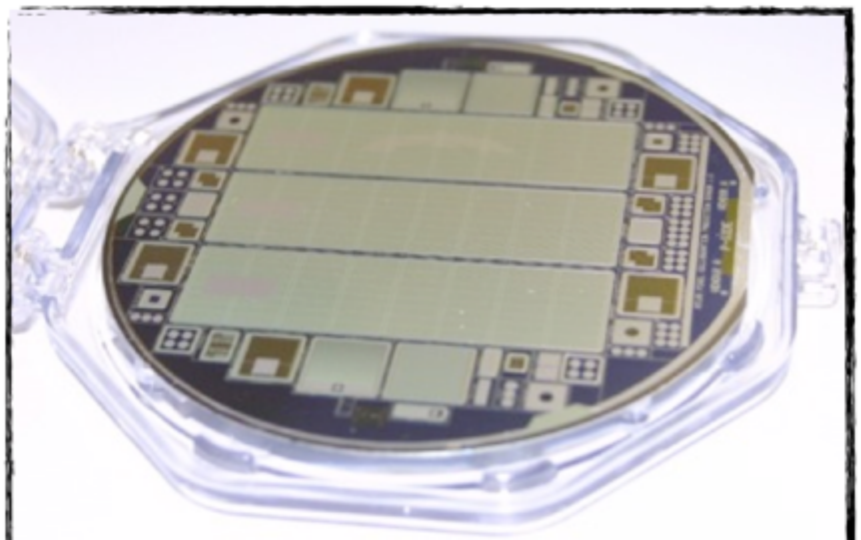


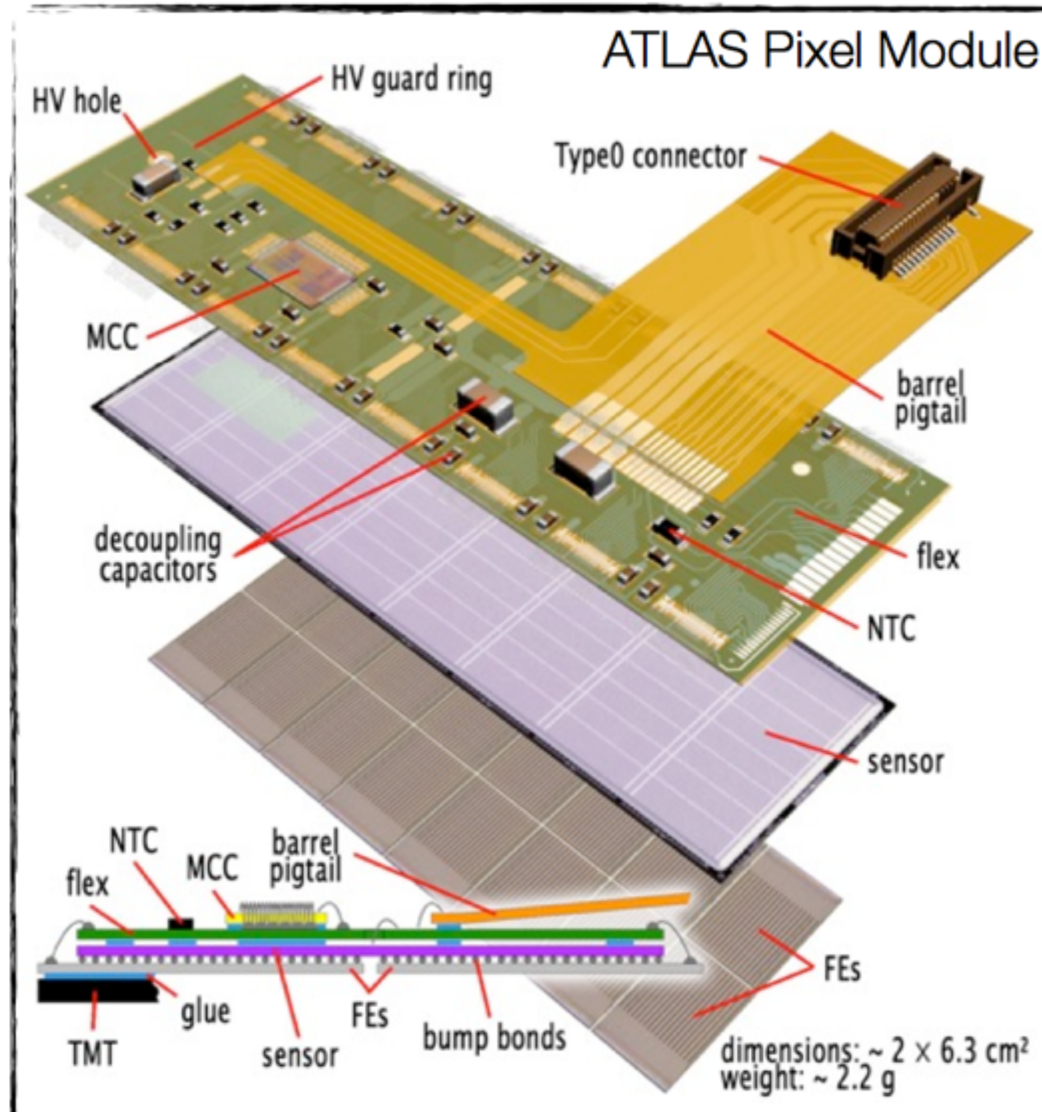
TRACKING DETECTOR: ATLAS pixel module

ATLAS
Pixel Detector

[Details]

Pixel Sensor



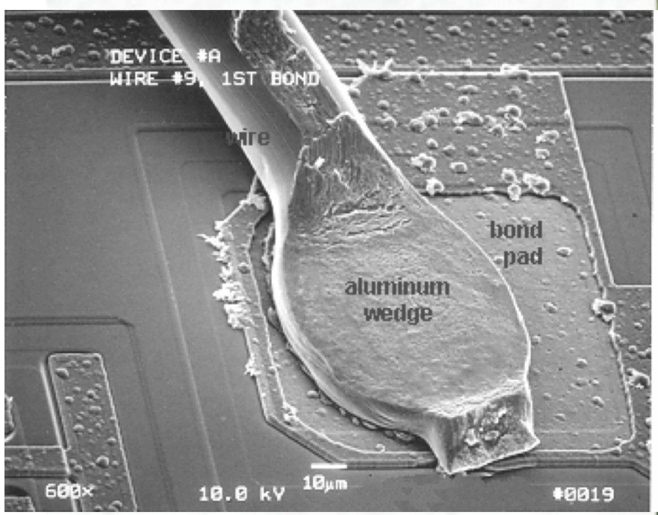


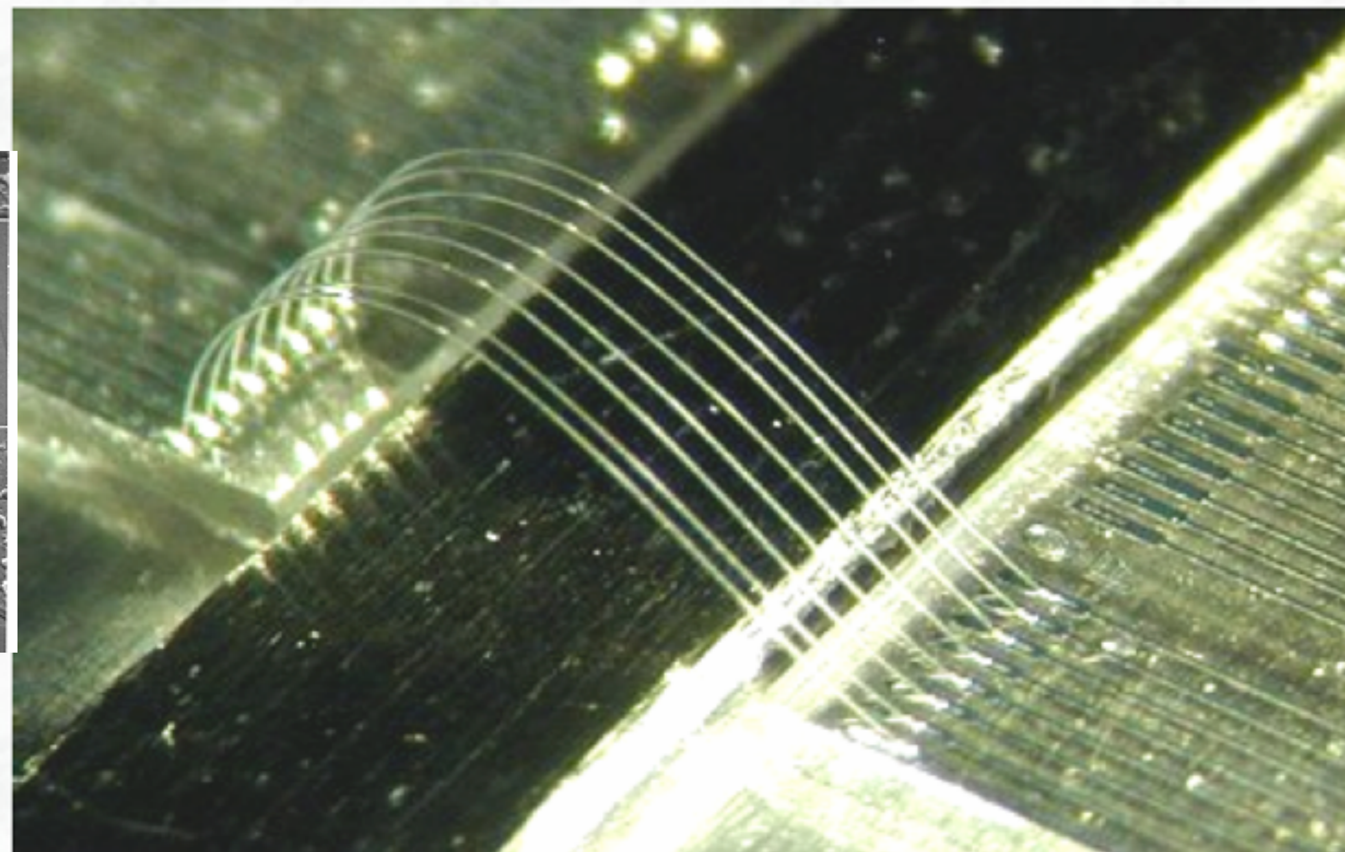
CONNECTION SENSOR-ELECTRONICS

Connection between the silicium sensor and the reluctancies chip readout

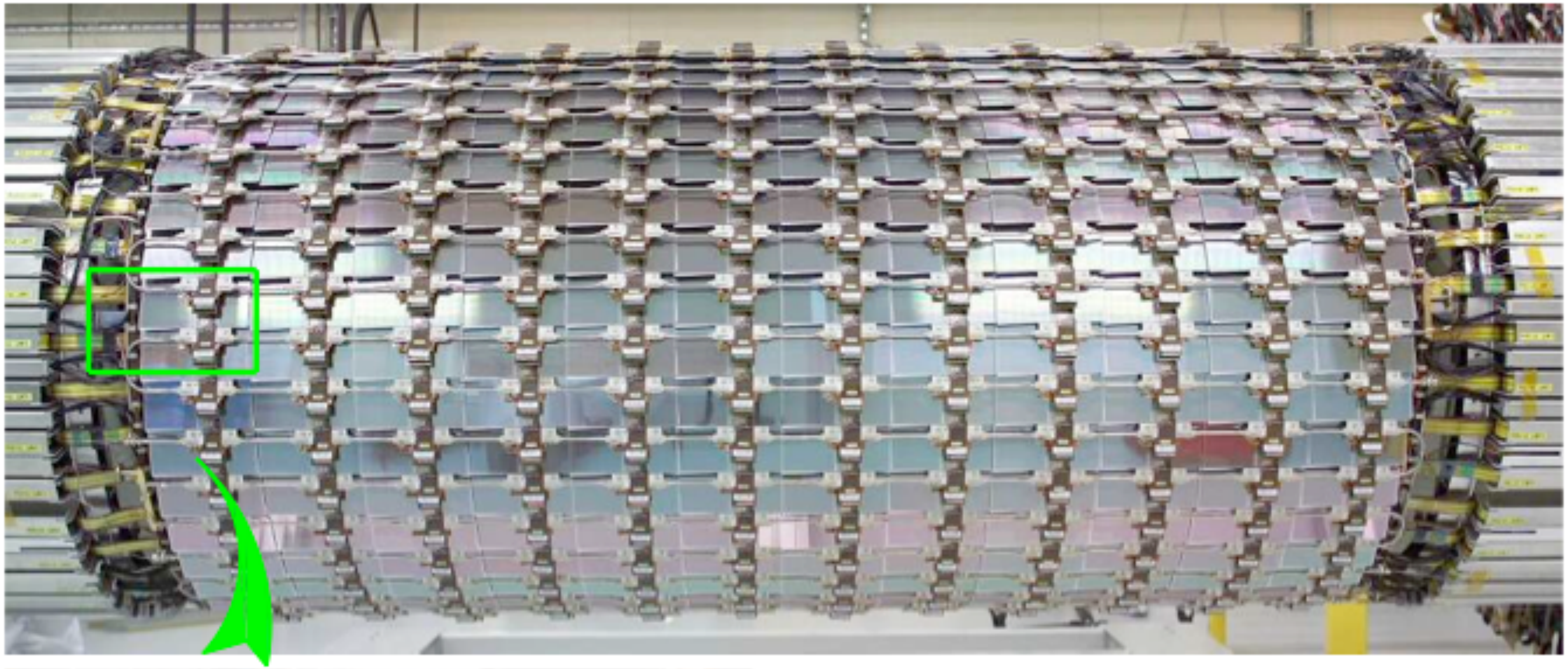
Very high density ~15 wires/mm

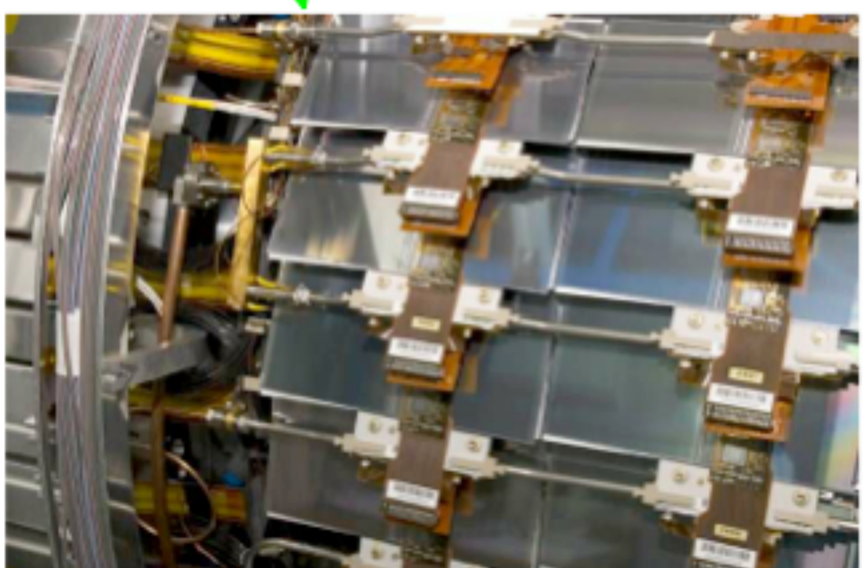
Connection via ultrasounds of wires of thickness ~20µm

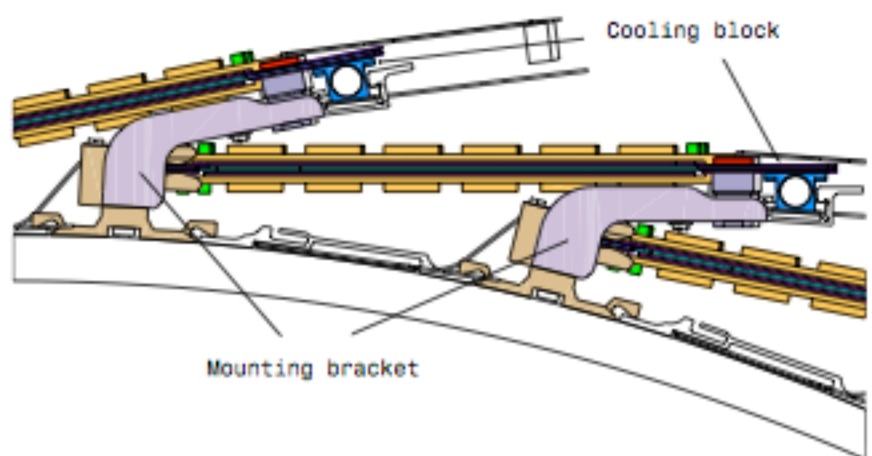


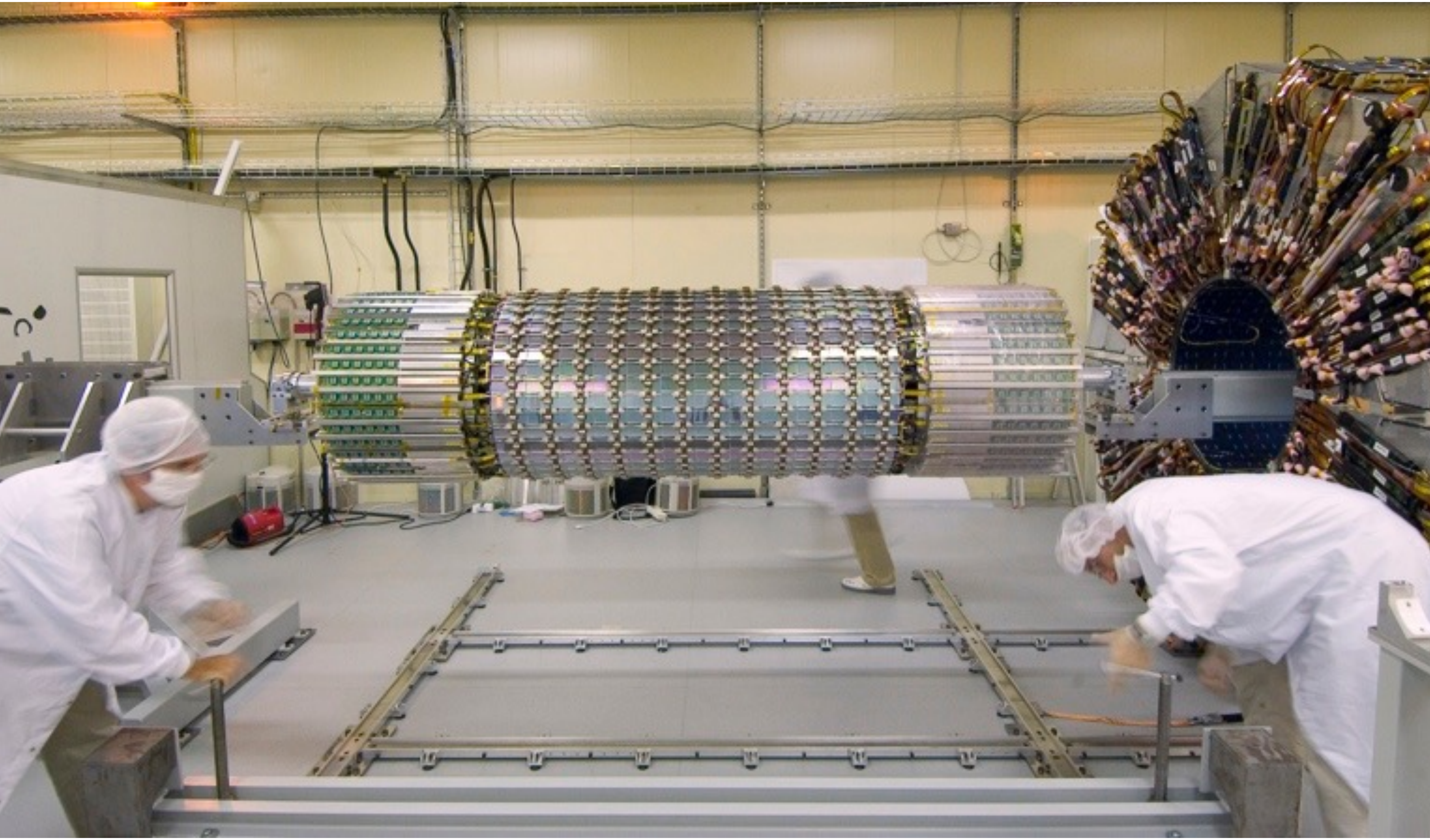


TRACKING DETECTOR: new PIXEL layer installed in 2014 at R=3.3 cm





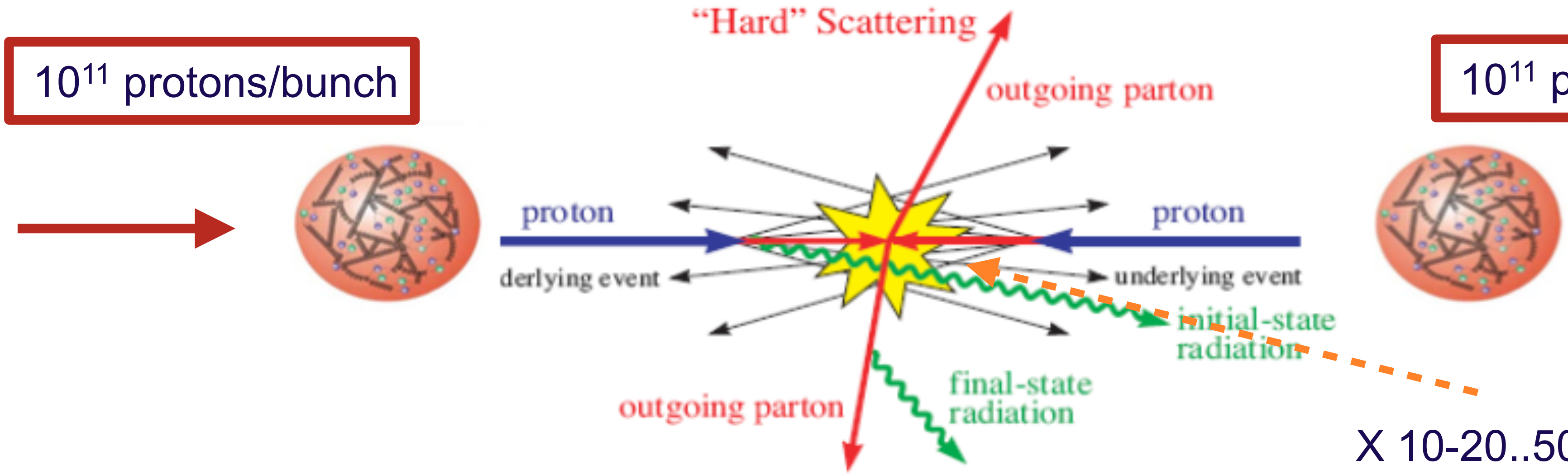

Cooling block
Mounting bracket



PILE-UP of COLLISIONS

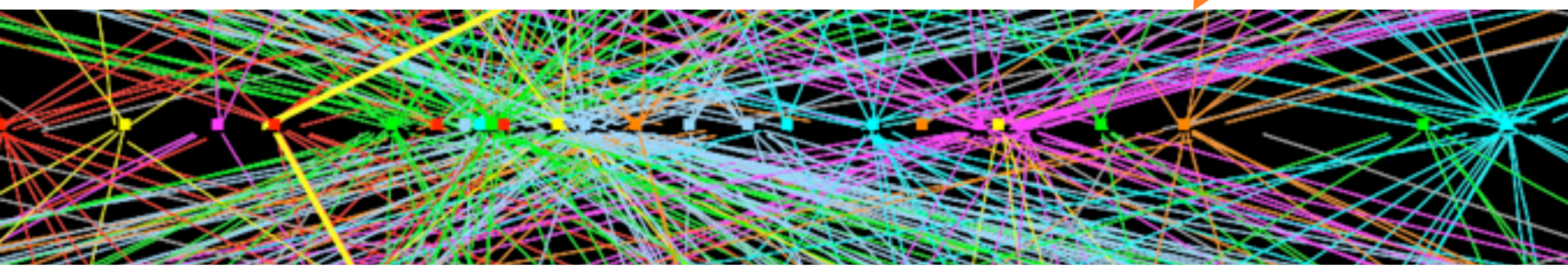
10^{11} protons/bunch

10^{11} protons/bunch



X 10-20..50

Multi-collisions per beam crossing



Ability to separate individual collisions - 40 MHz

TRACKING DETECTOR

Measure charged particles momentum

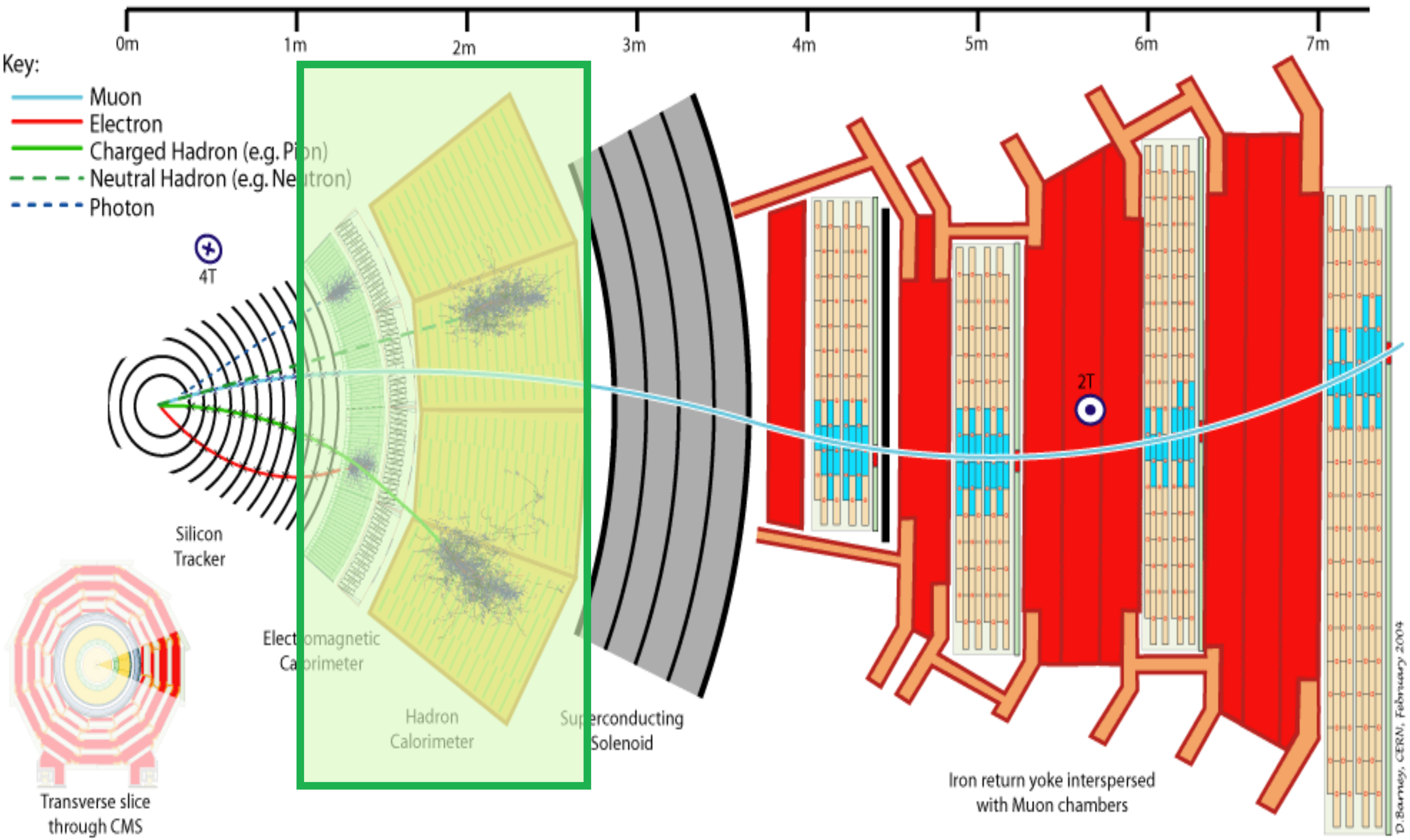
Uniform magnetic field

High position resolution ⟶ high momentum resolution

Close to the beams

- **⟶ high particle density**
- **⟶ small cell size**

DETECTOR: CALORIMETERS



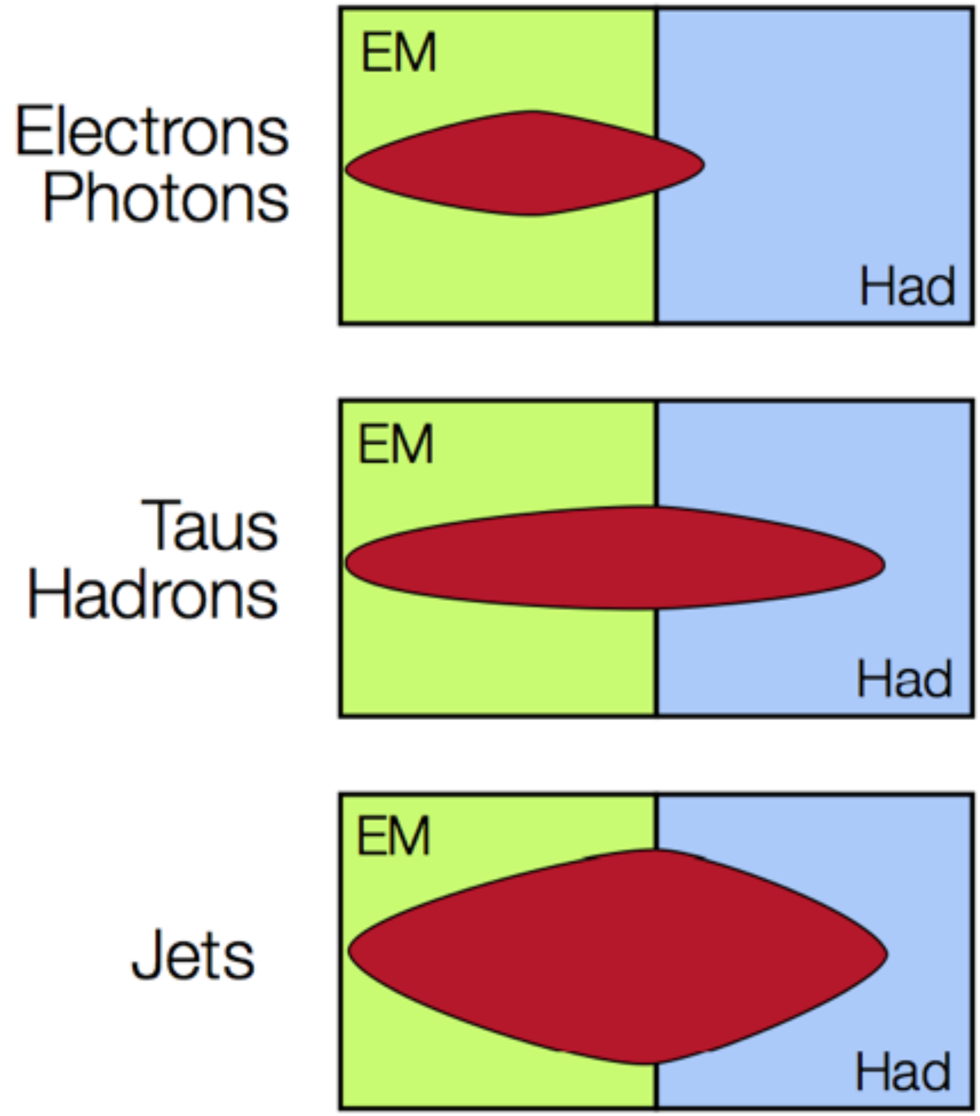
INTERACTIONS vs INCOMING PARTICLES

CALORIMETERS ARE DESTRUCTIVE

PARTICLES DO NOT COME OUT of THE CALORIMETER

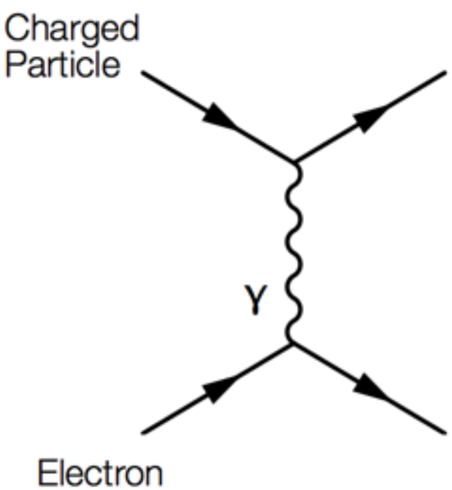
ELECTRONS, PHOTONS, HADRONS ARE ABSORBED by the CALORIMETERS

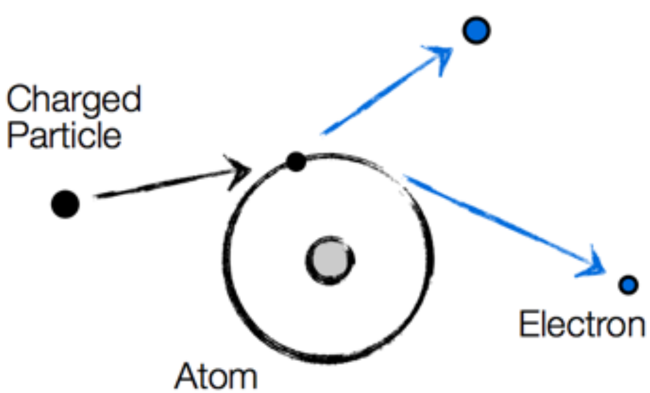
ONLY MUONS and NEUTRINOS ESCAPE



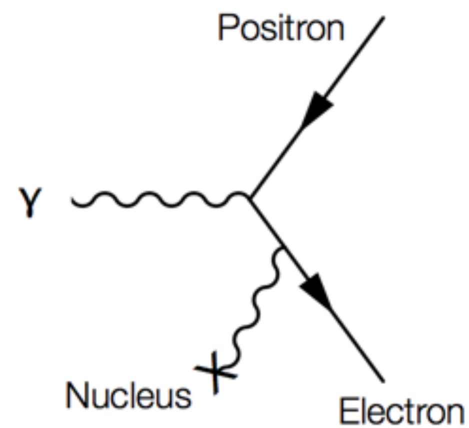
EXAMPLES of INTERACTIONS

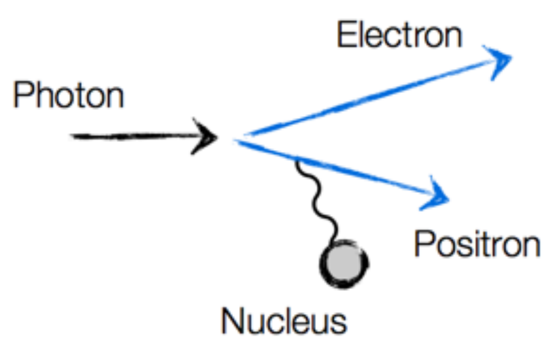
Ionisation



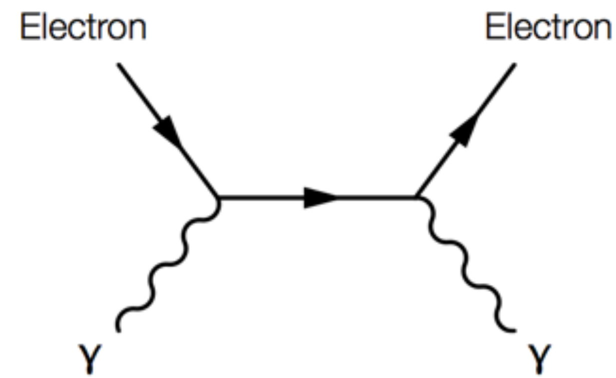


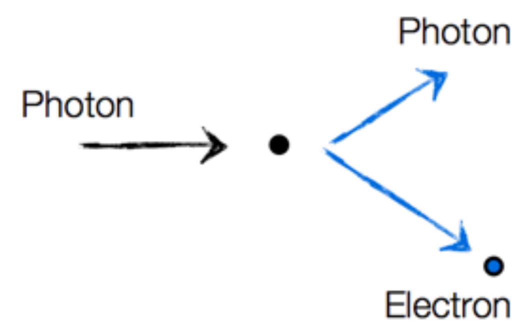
Production de paires e^+e^-



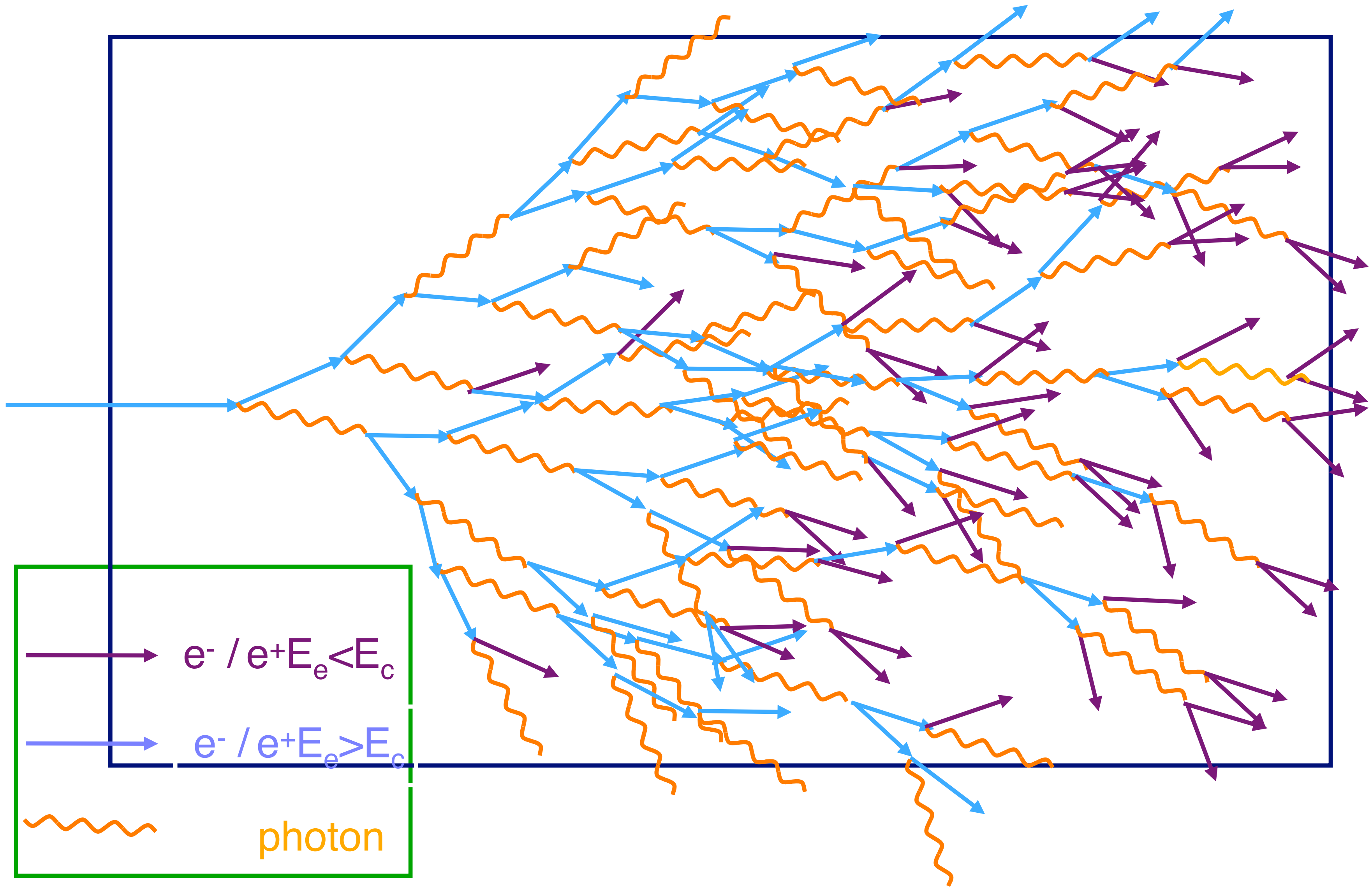


Diffusion Compton





ELECTROMAGNETIC SHOWER

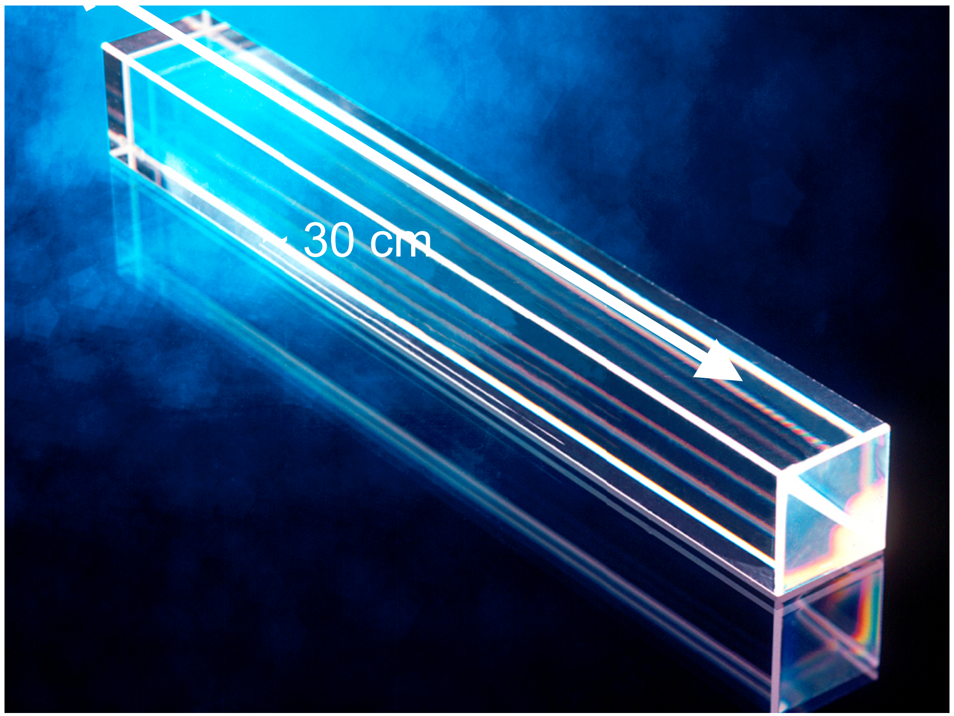


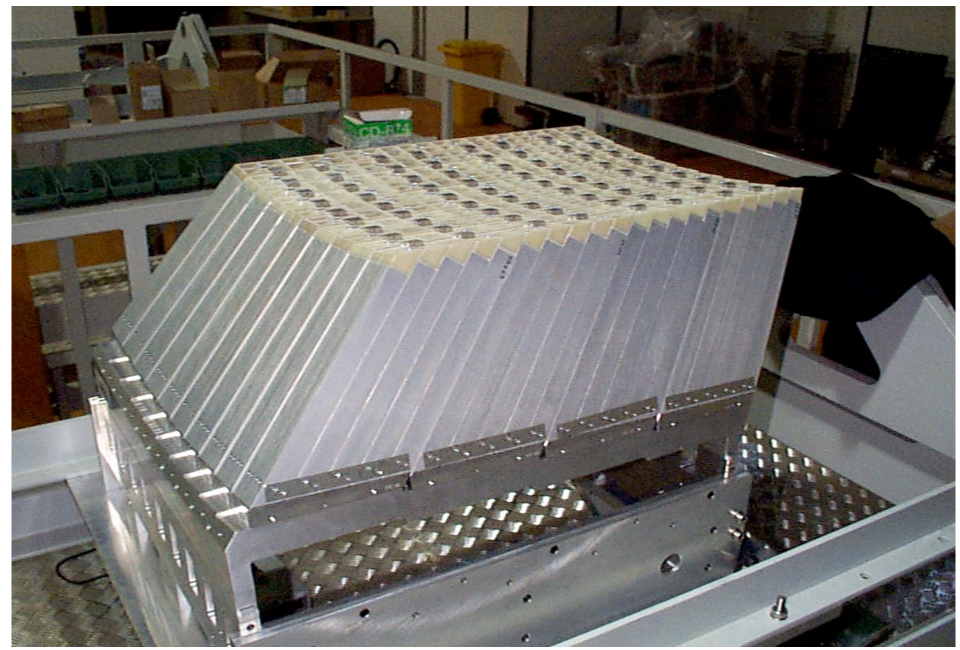
The CAVERN has a FINITE SIZE

CALORIMETERS measure PARTICLE ENERGY

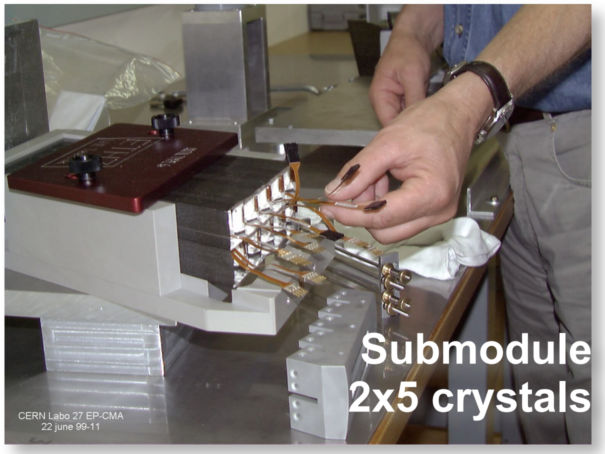
75k channels

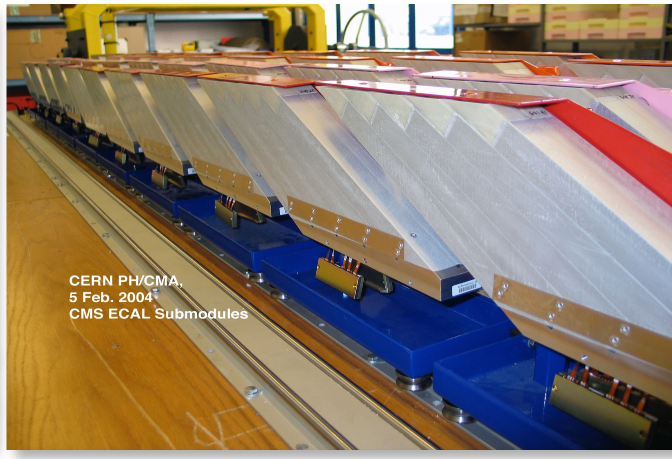
$\Delta E/E \sim 3\text{-}5\%/\sqrt{E} \oplus 150\ \mathrm{MeV}/E \oplus 0.5\%$

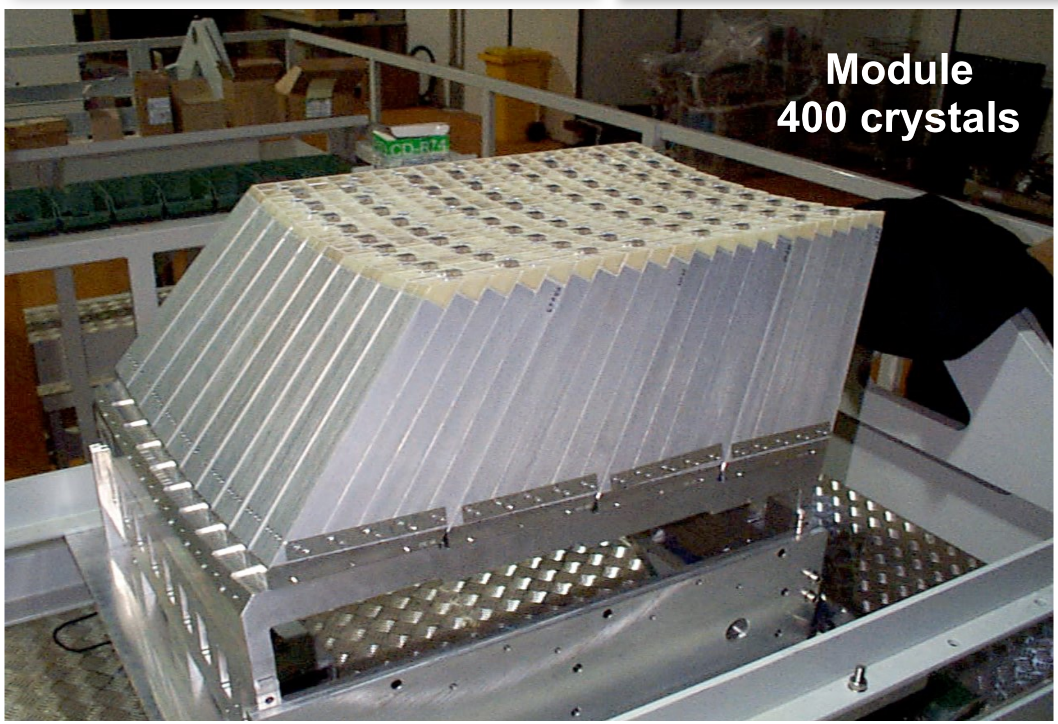


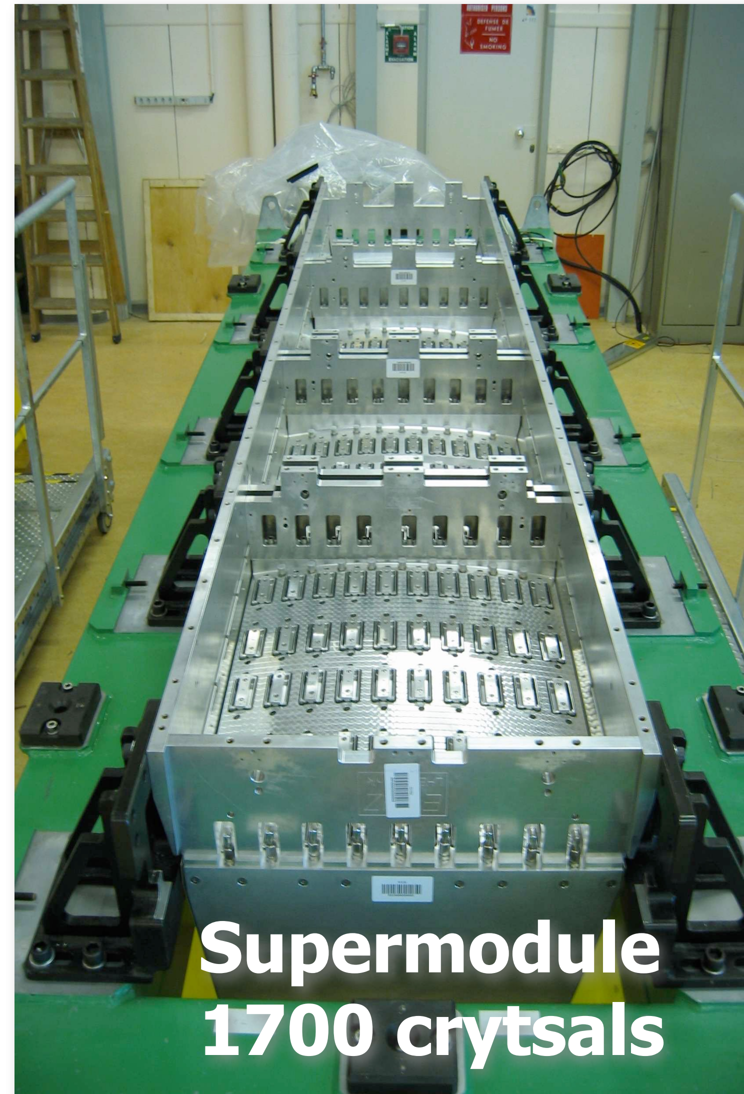


CONSTRUCTION of the CMS CALORIMETER



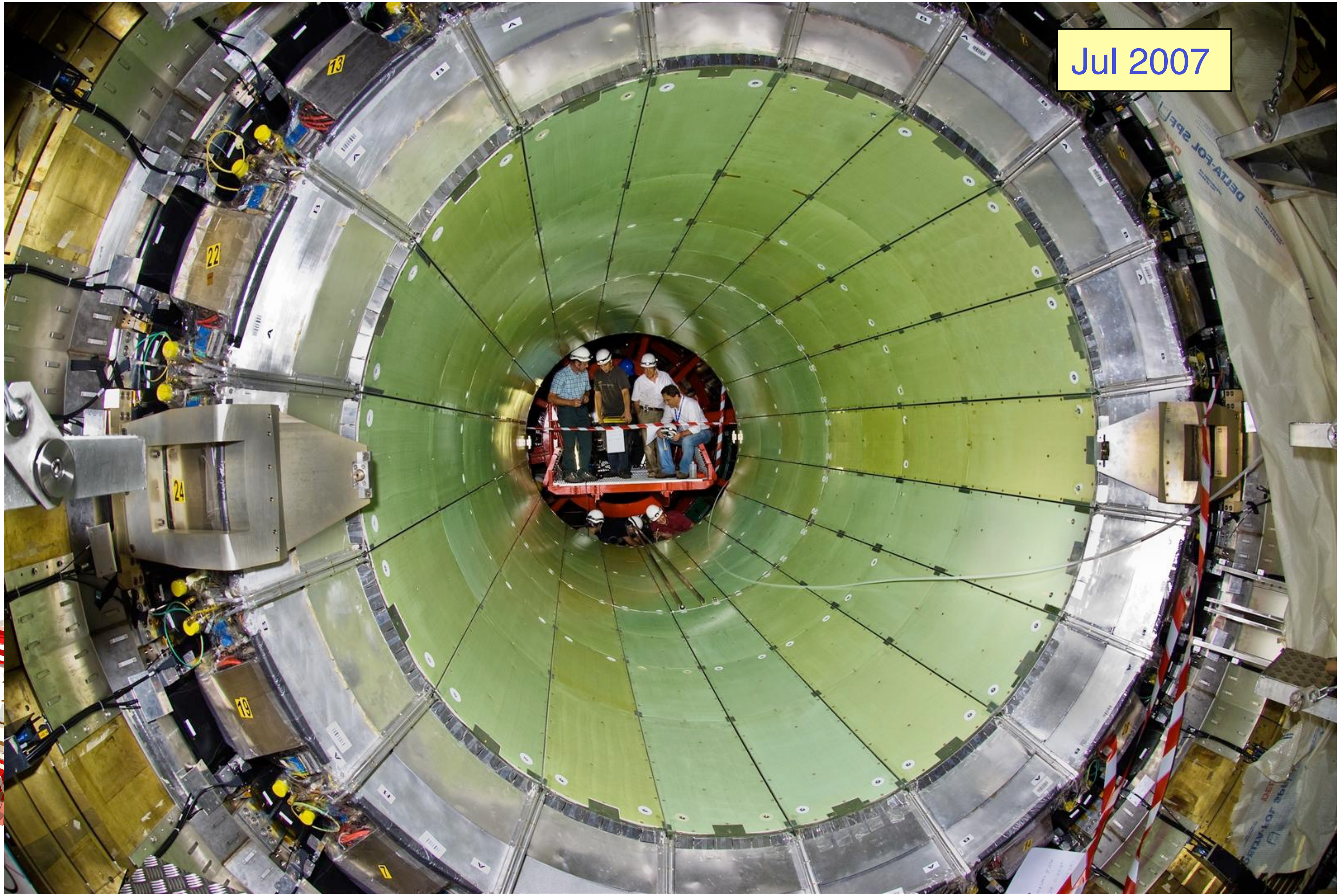




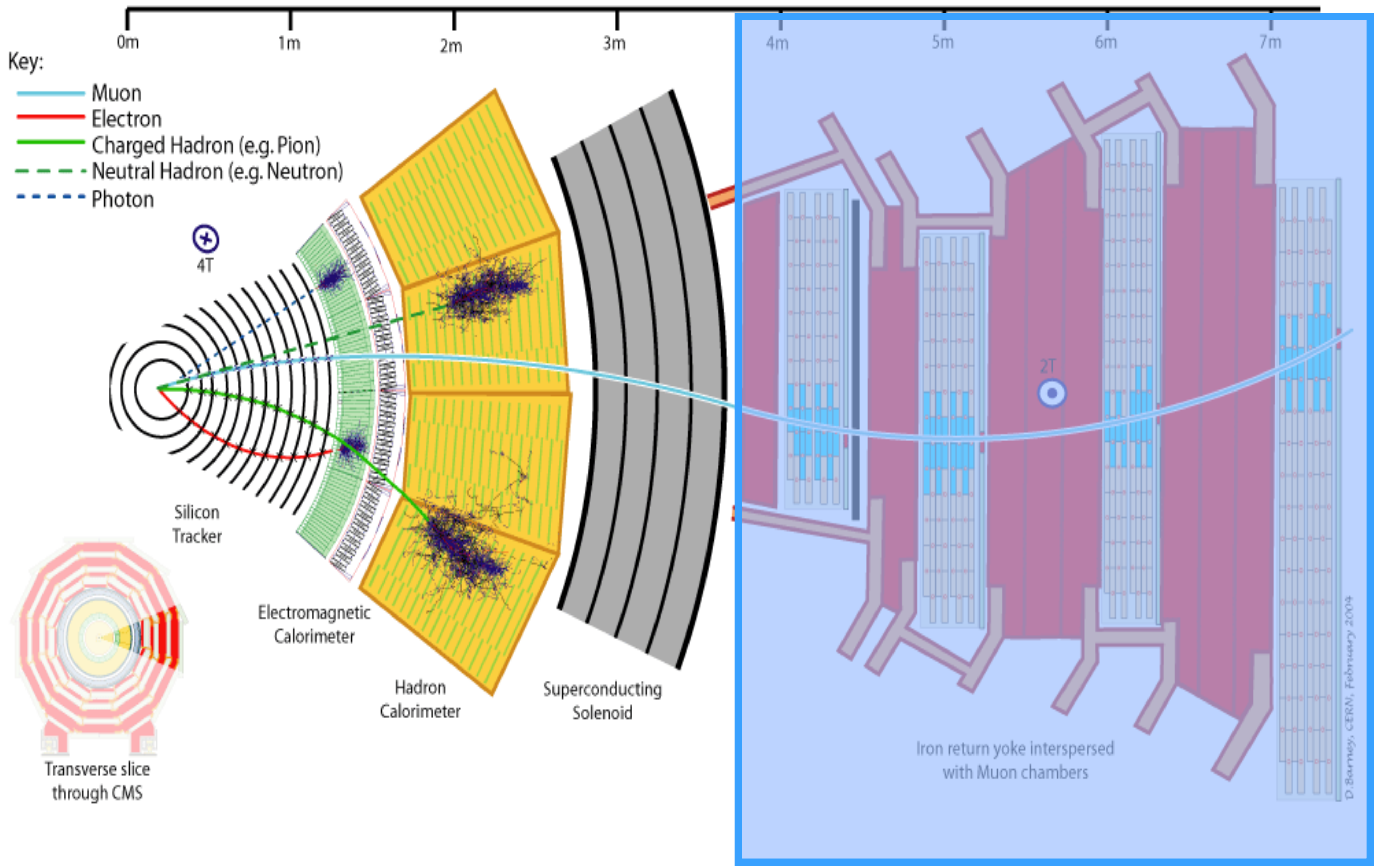


Total 36 Supermodules

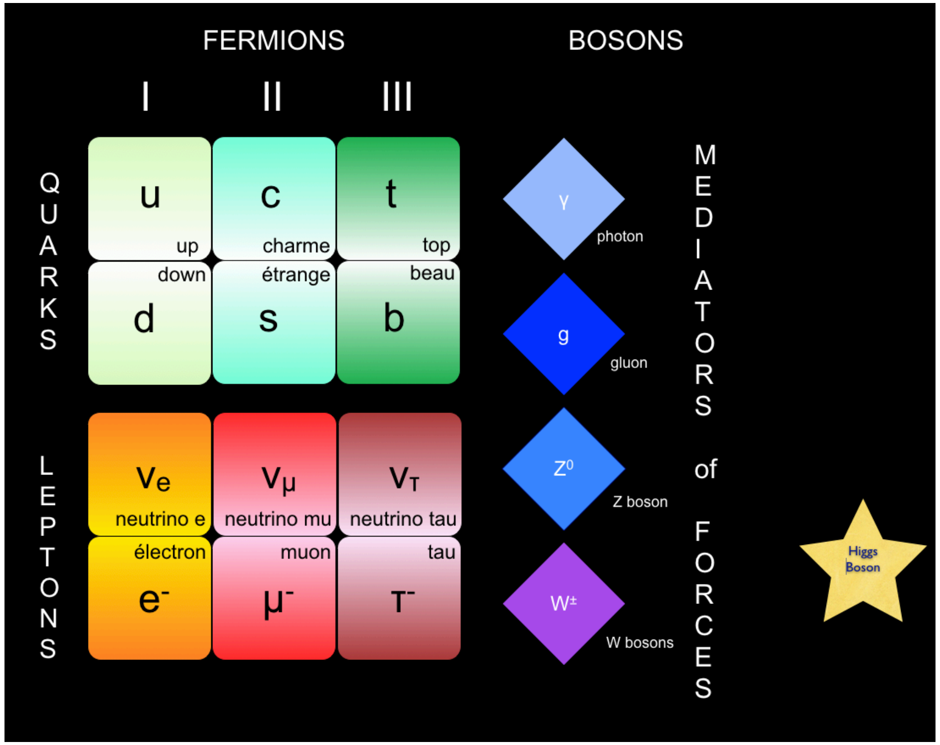
CONSTRUCTION du CALORIMETRE de CMS



DETECTEURS: SPECTROMETRE à MUONS



MUONS



μ is the brother **of the electron with m_μ=200 x me**

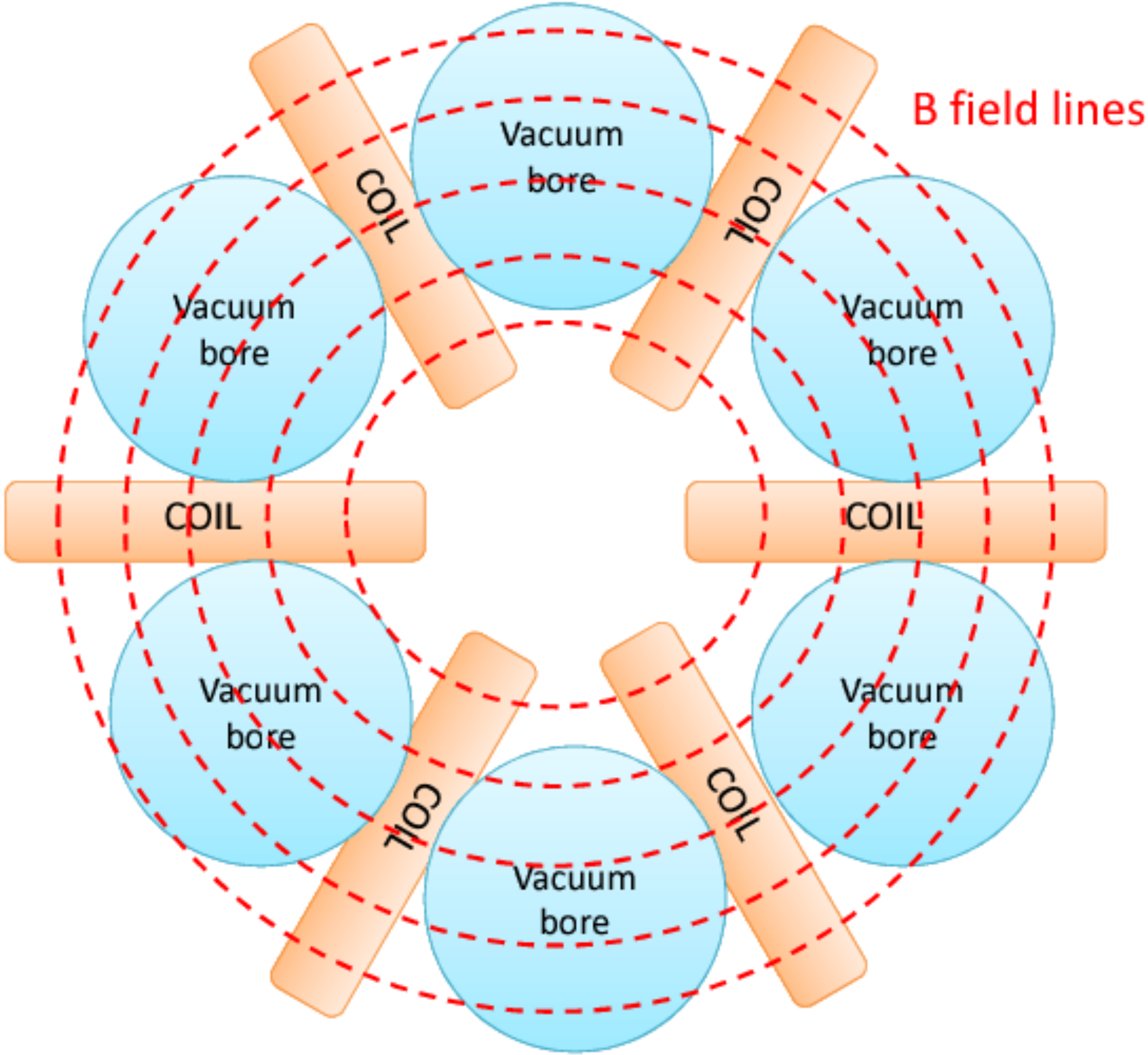
Electromagnetic interaction: $1/m^2$

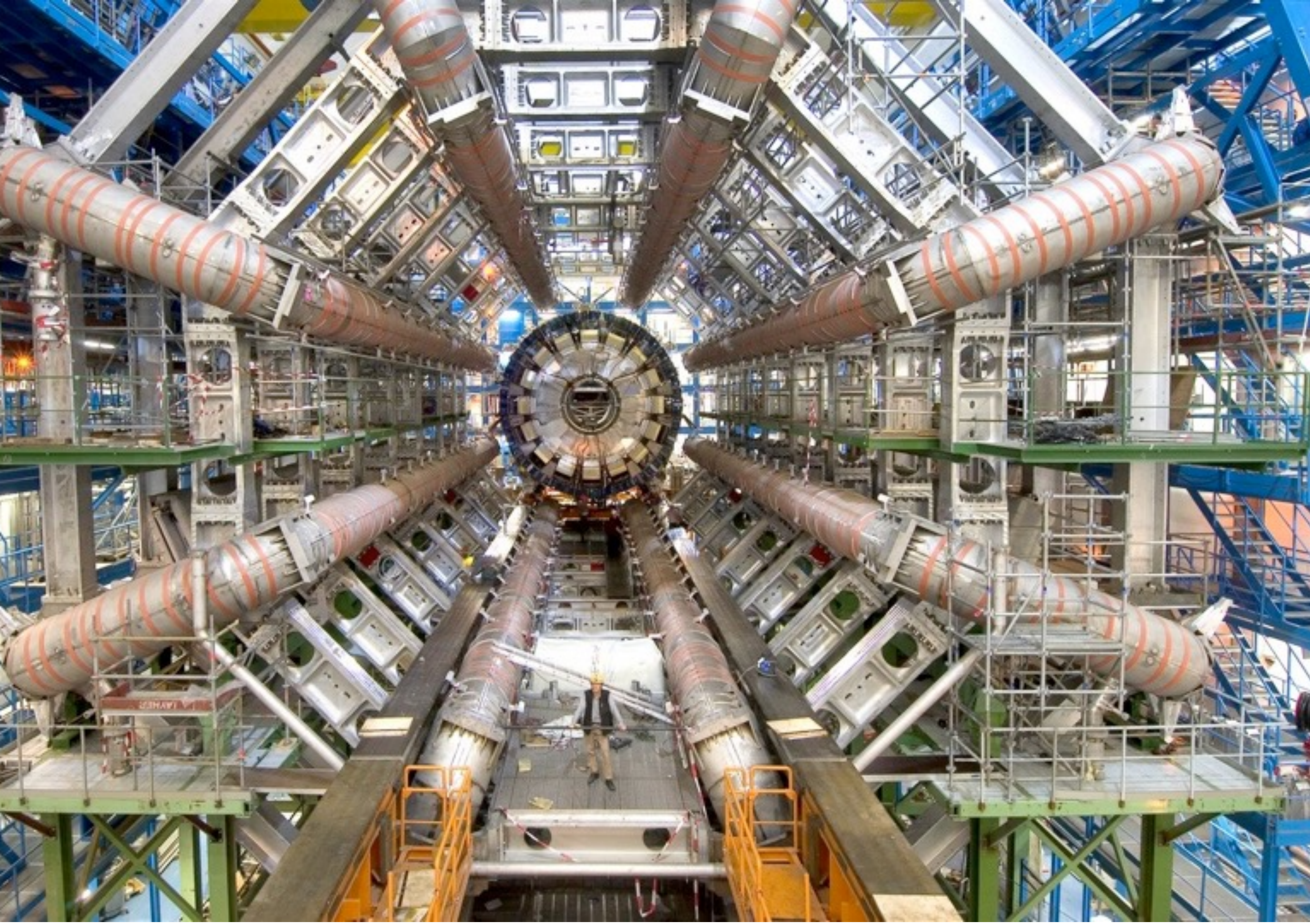
μ interact with matter 40000 times less than electrons

They essentially do not notice the presence of the calorimeter

Detection with the muon spectrometer

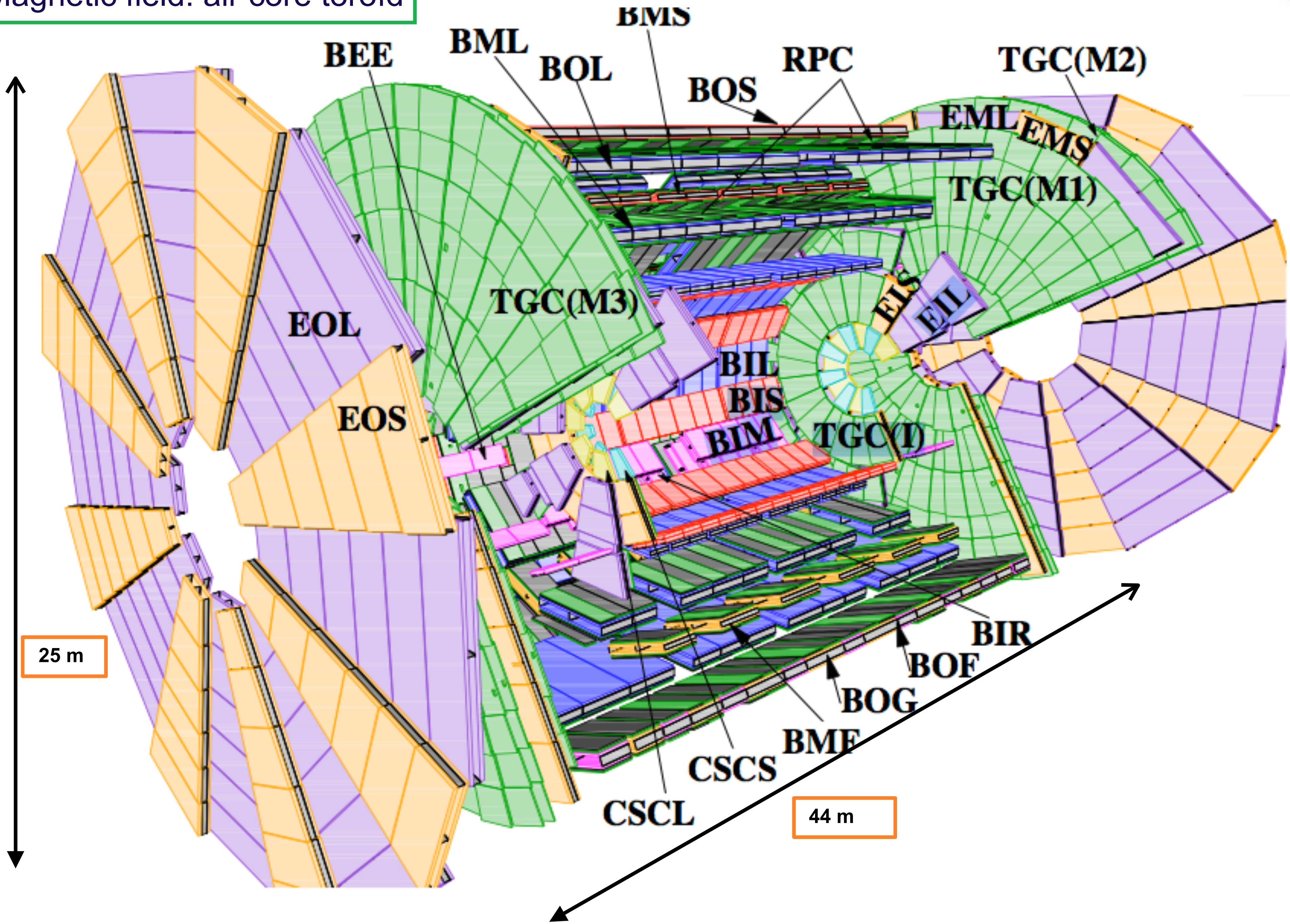
AIR CORE TOROID





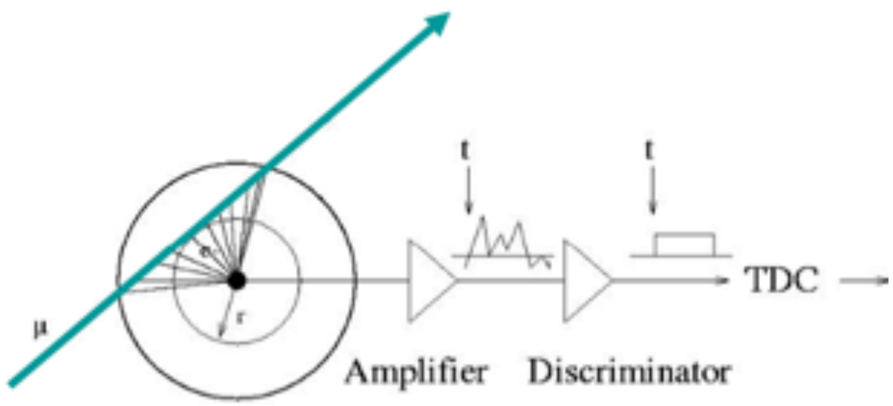
MUON SPECTROMETER

Magnetic field: air core toroïd

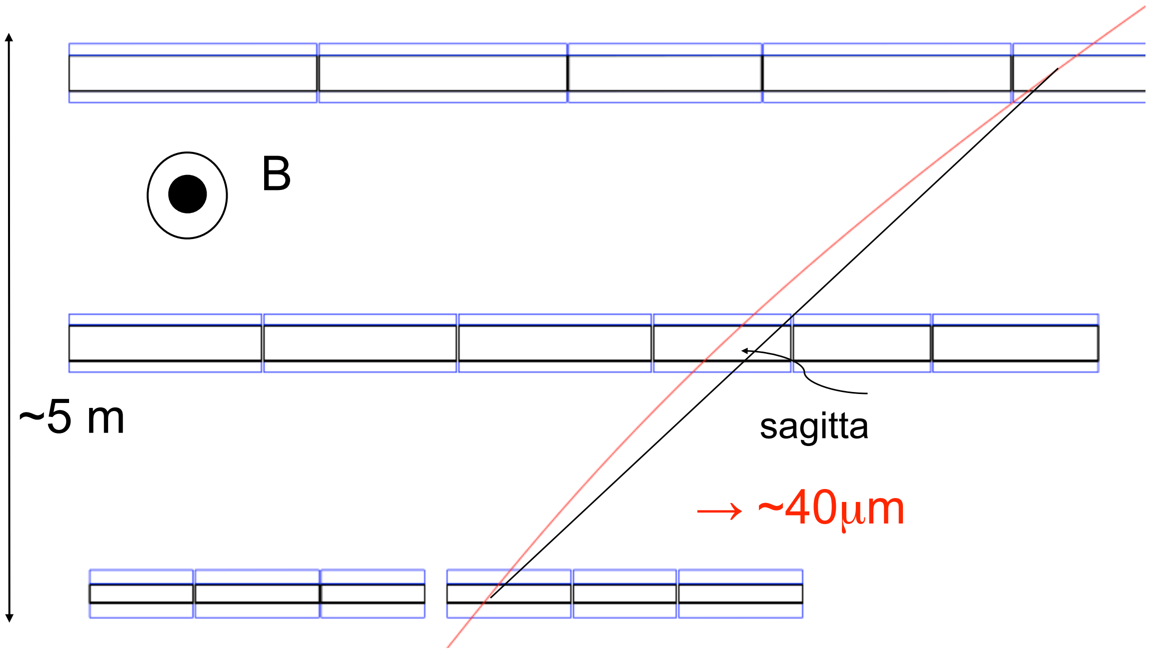


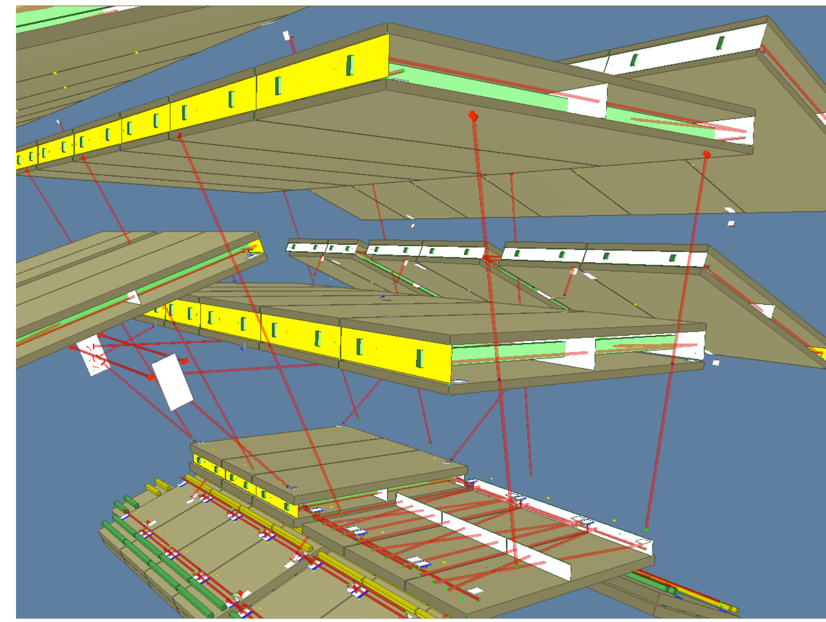
MUON SPECTROMETER

ATLAS MDT R(tube) =15mm



MUON SPECTROMETER





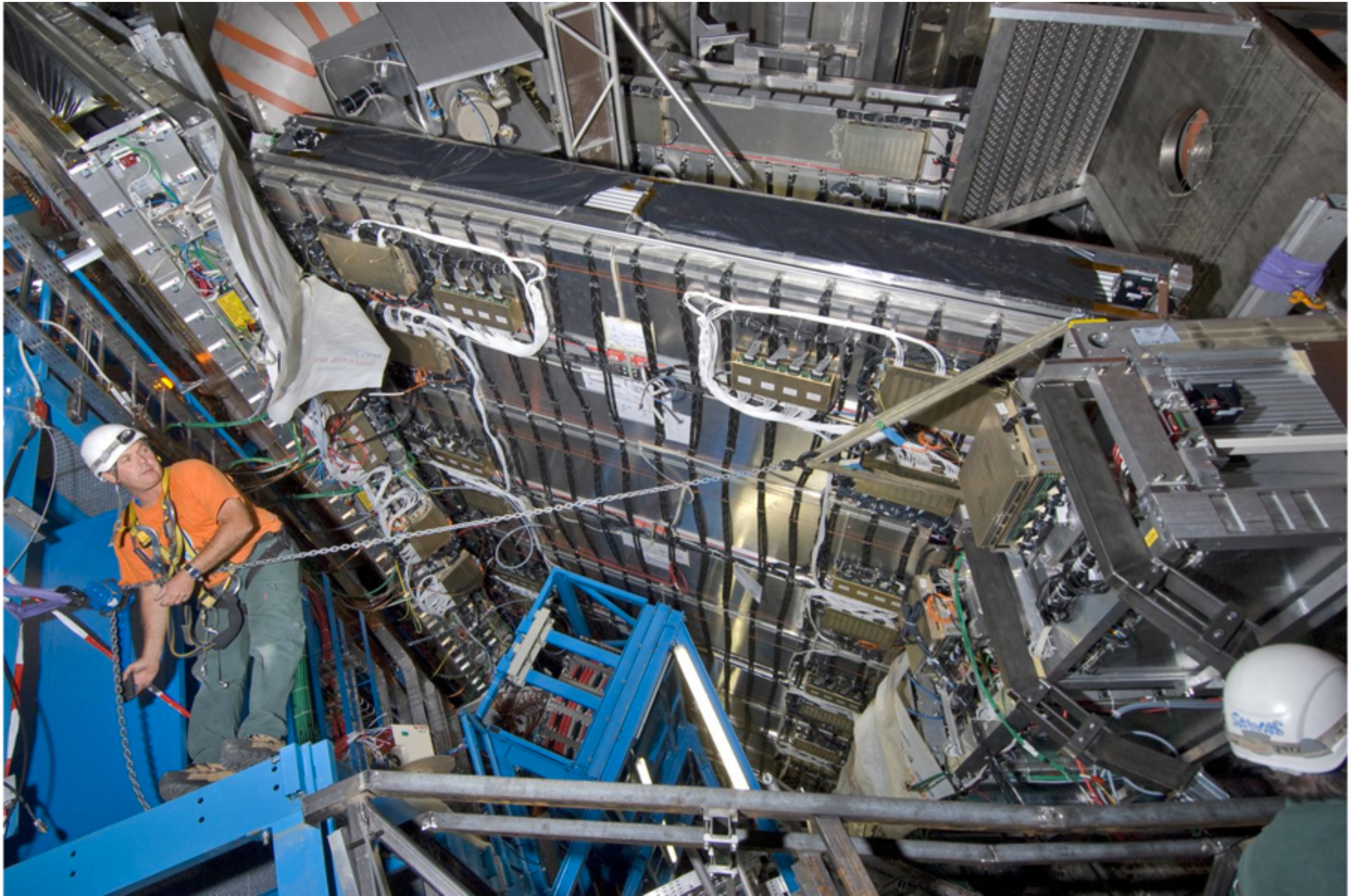
Specific to ATLAS : Air core Toroïd
Minimise matter encounter by muons

WHY ???

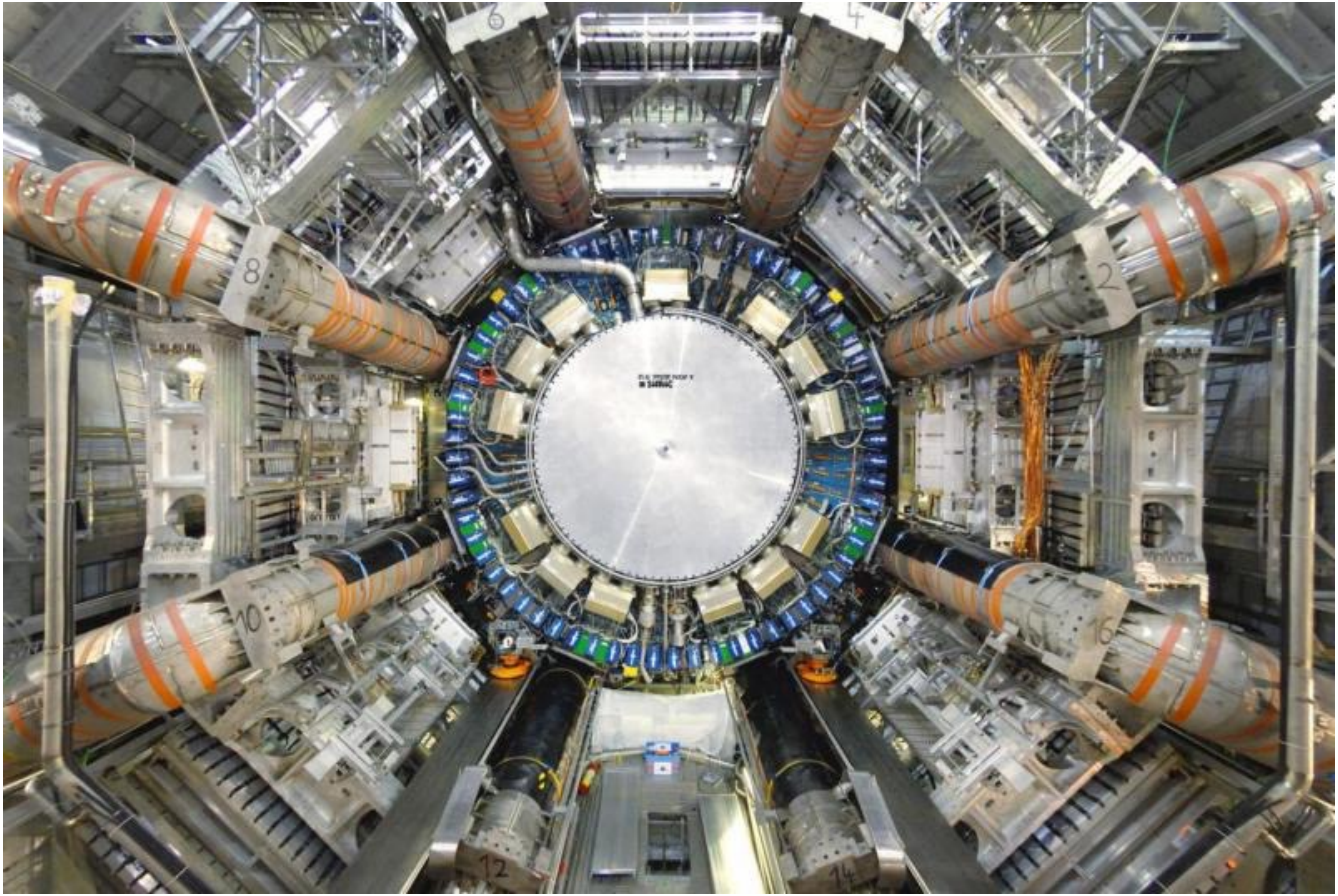
p_T<100 GeV $\delta p_T/p_T$ ~2%
p_T~1 TeV $\delta p_T/p^T$ ~10%


SCHELDE
Friderici
special s.a.

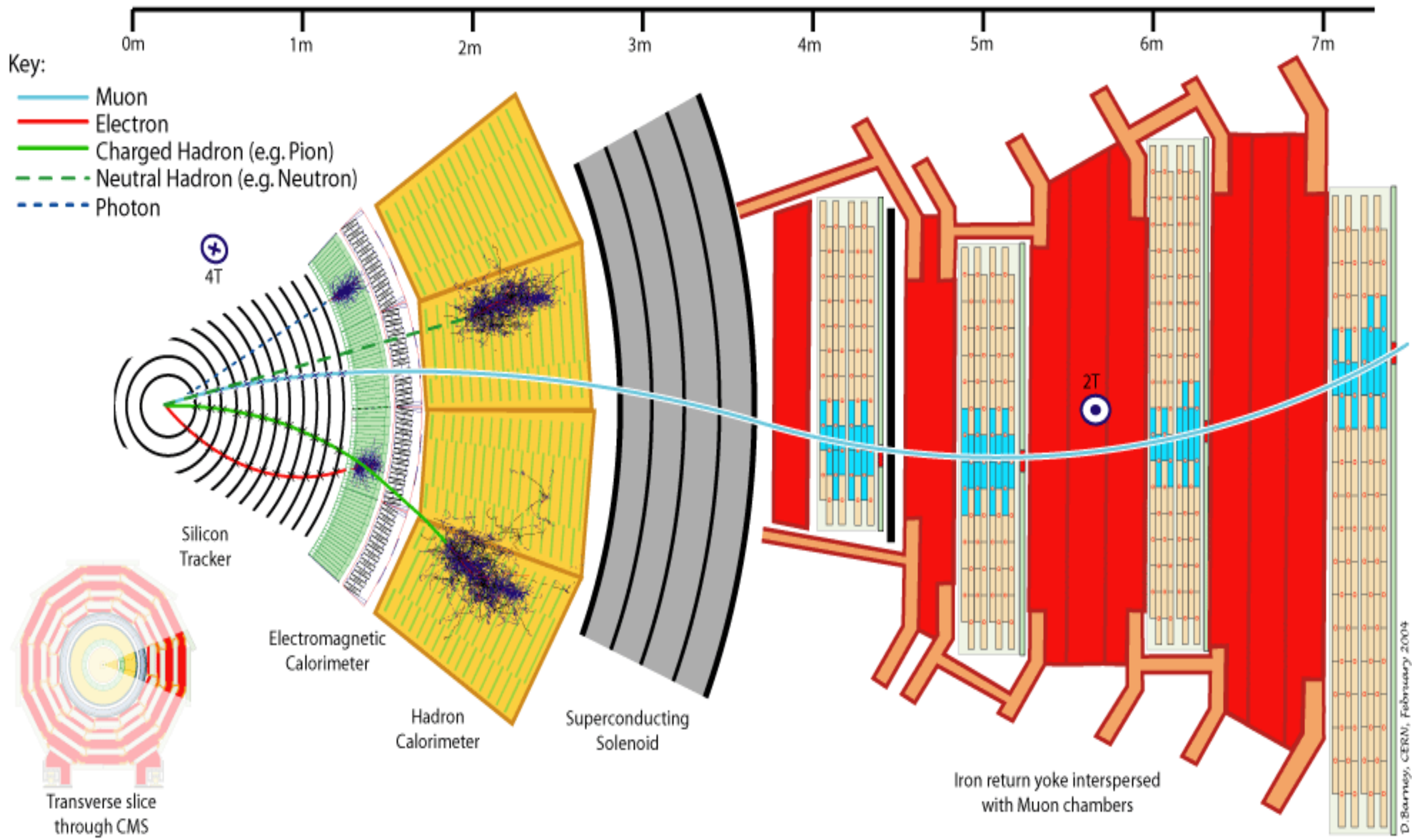
MUON CHAMBERS in ATLAS



TOROID + MUON CHAMBERS

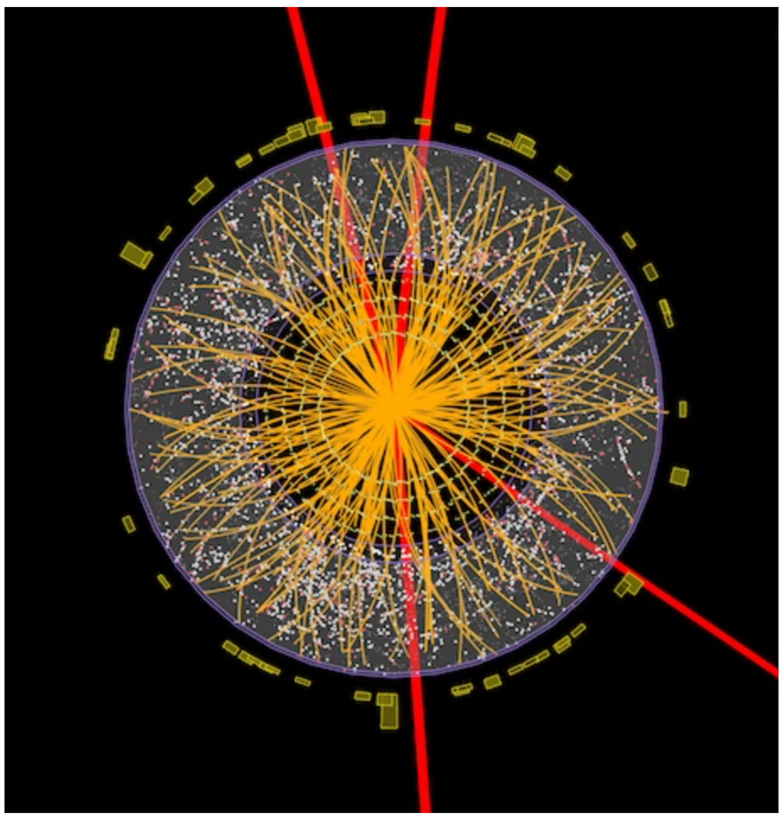


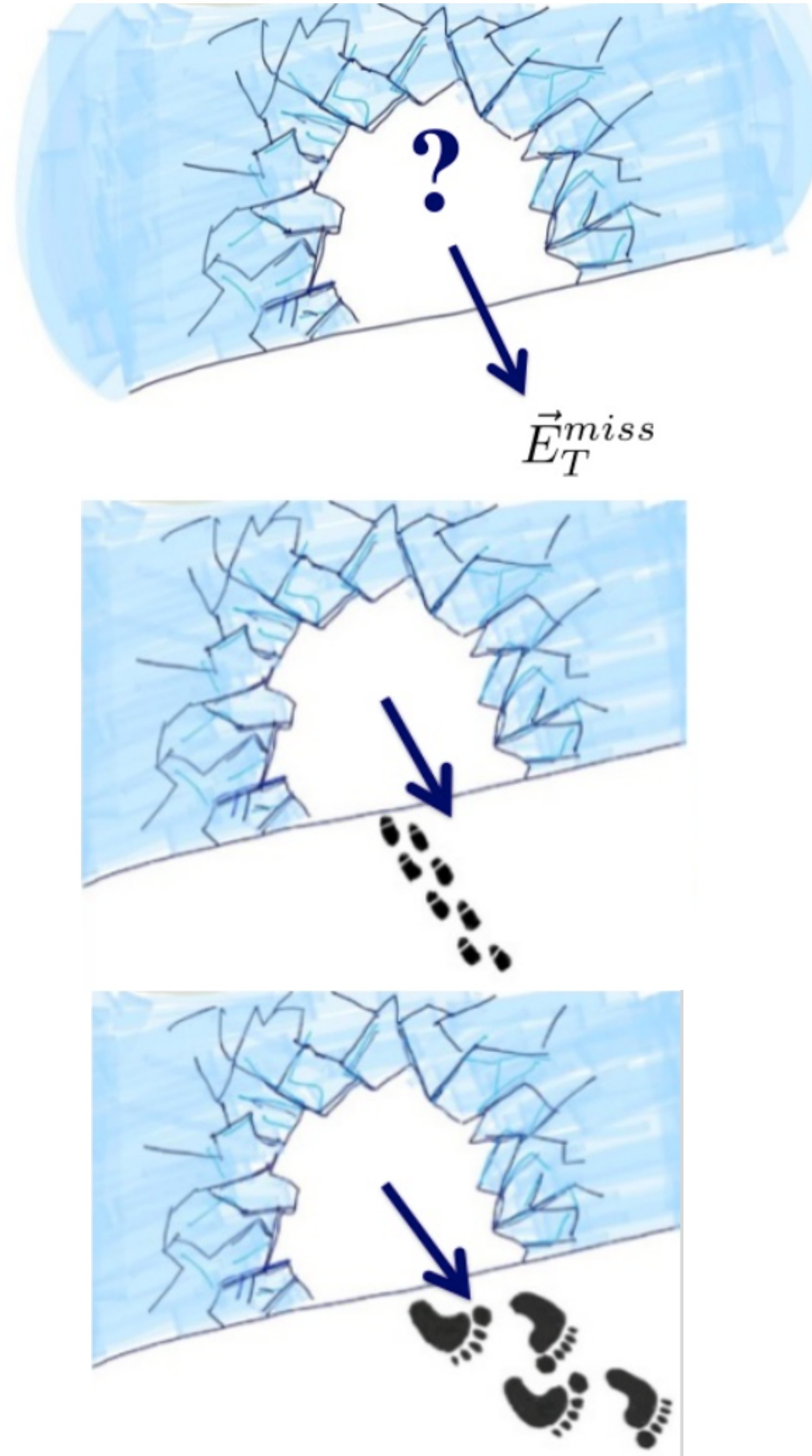
DETECTOR MISSING TRANSVERSE ENERGY



ENERGY BALANCE

$$\vec{E}_T^{miss} = -\sum_{i}^{cells} \vec{E}_T$$





DETECTOR: INTRODUCTION QUIZZ

What is a detector ?

What does a detector measure ?

How is a detector designed ?

Compare a digital camera with the ATLAS detector

Would you join an experiment where the calorimeter is in front of the tracking system ?

CREDIT and BIBLIOGRAPHY

A lot of material in these lectures are from:

- Daniel Fournier @ EDIT2011
- Marco Delmastro @ ESIPAP 2014
- Weiner Raigler @ AEPSHEP2013
  - Hans Christian Schultz-Coulon's lectures
- Carsten Niebuhr's lectures [1][2][3]
- Georg Streinbrueck's lecture
- Pippa Wells @ EDIT2011
- Jérôme Baudot @ ESIPAP2014