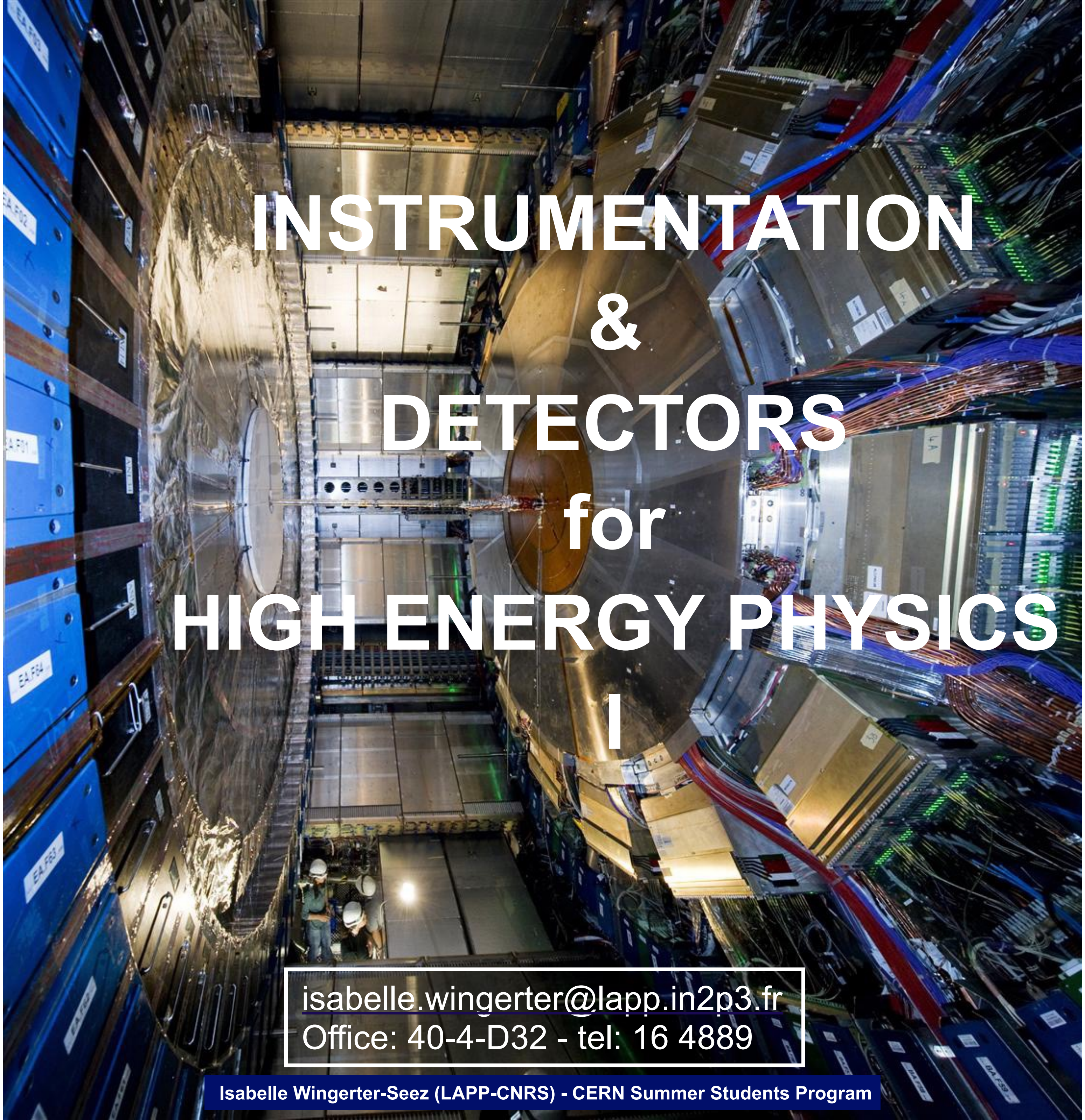

INSTRUMENTATION & DETECTORS for HIGH ENERGY PHYSICS I

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Tentative plan

I INTRODUCTION to HIGH ENERGY PARTICLE DETECTORS

II INTERACTIONS

III TRACKING

IV CALORIMETRY

V SOME EXAMPLES

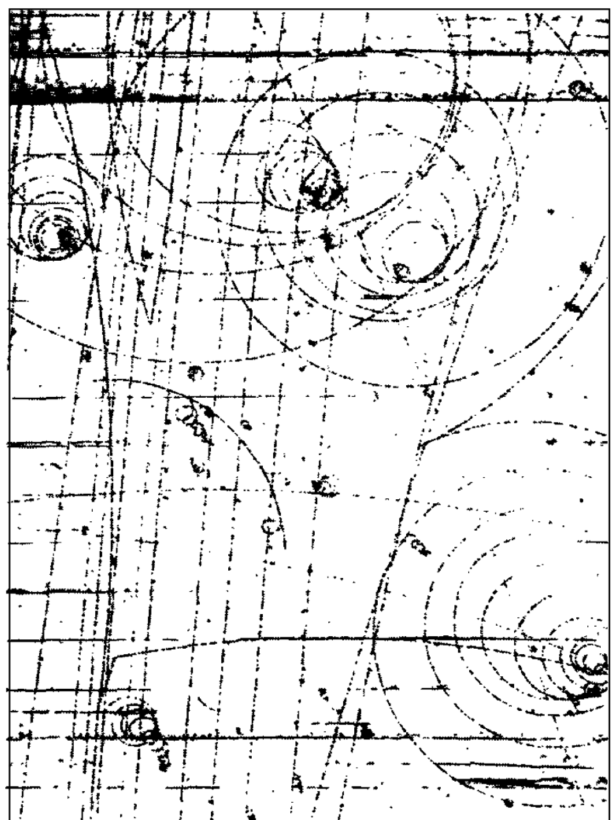
TODAY

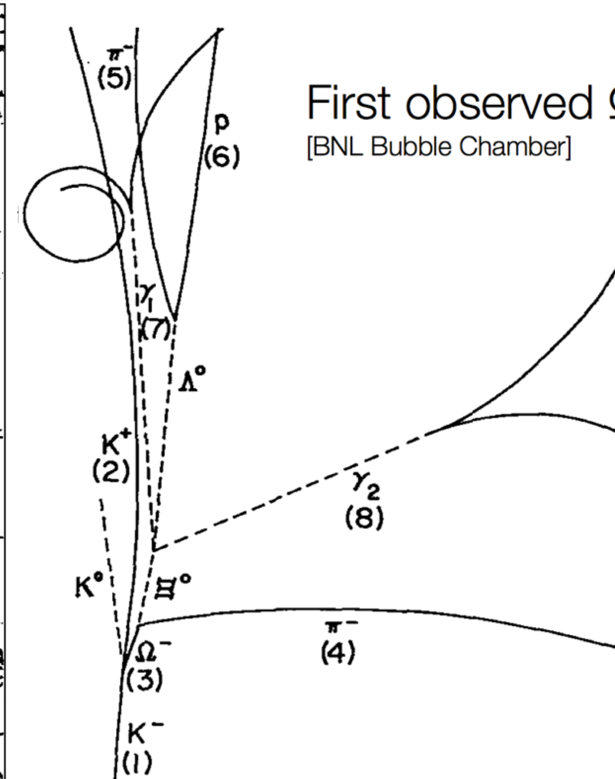
INTRODUCTION

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]

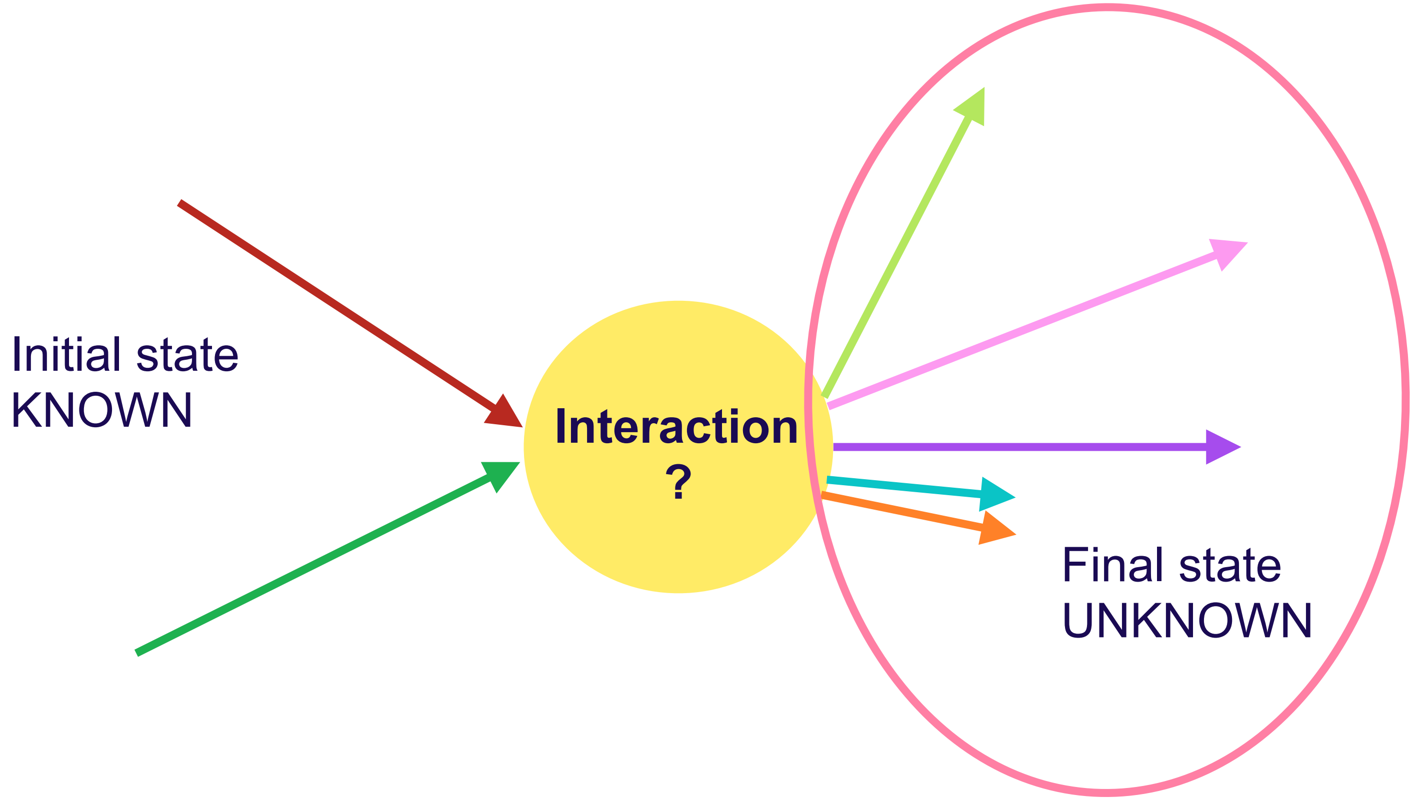
WHY DO WE NEED PARTICLE DETECTORS ?

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

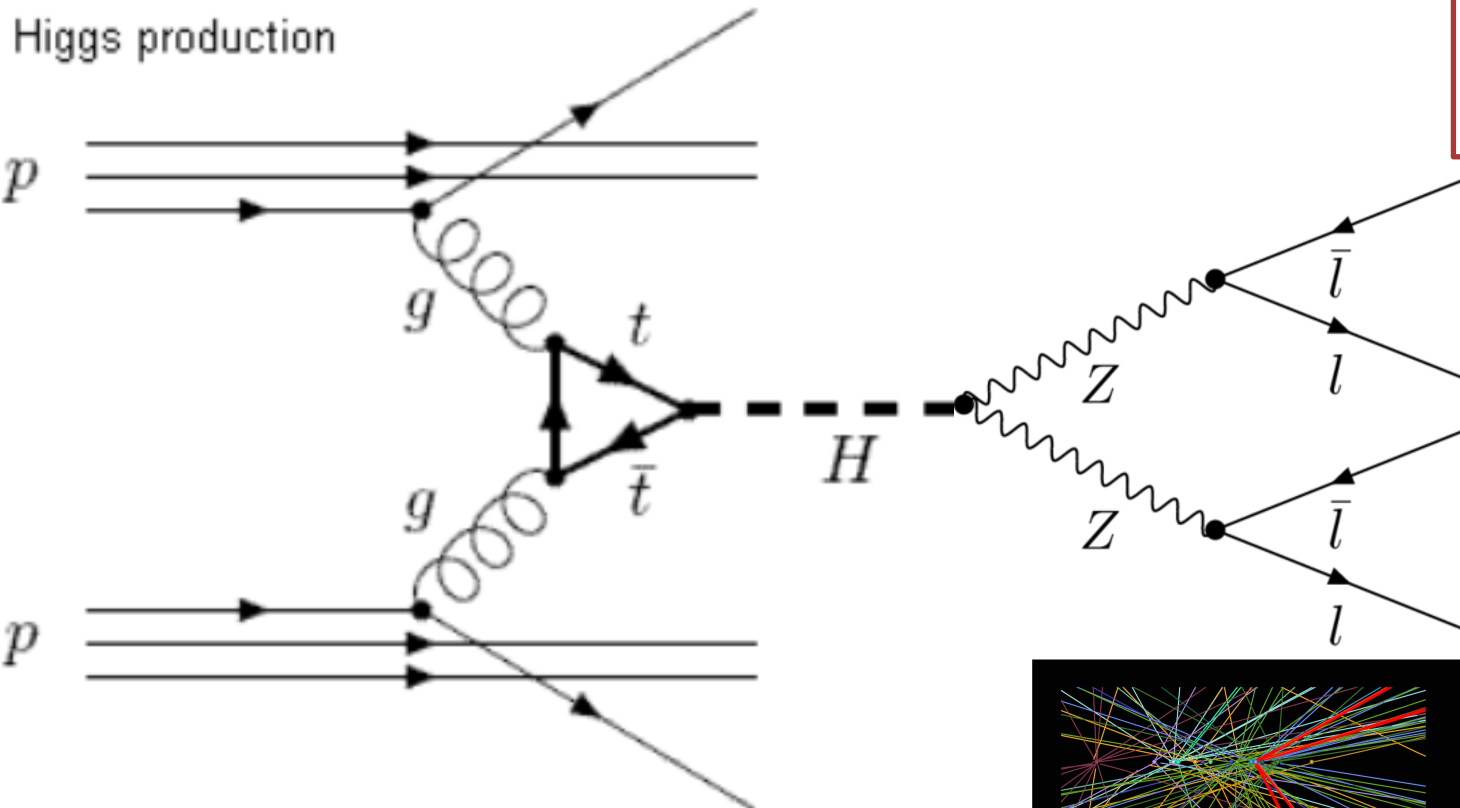
Particle physicists invent, build and operate detectors to record the products of initial particles interactions:

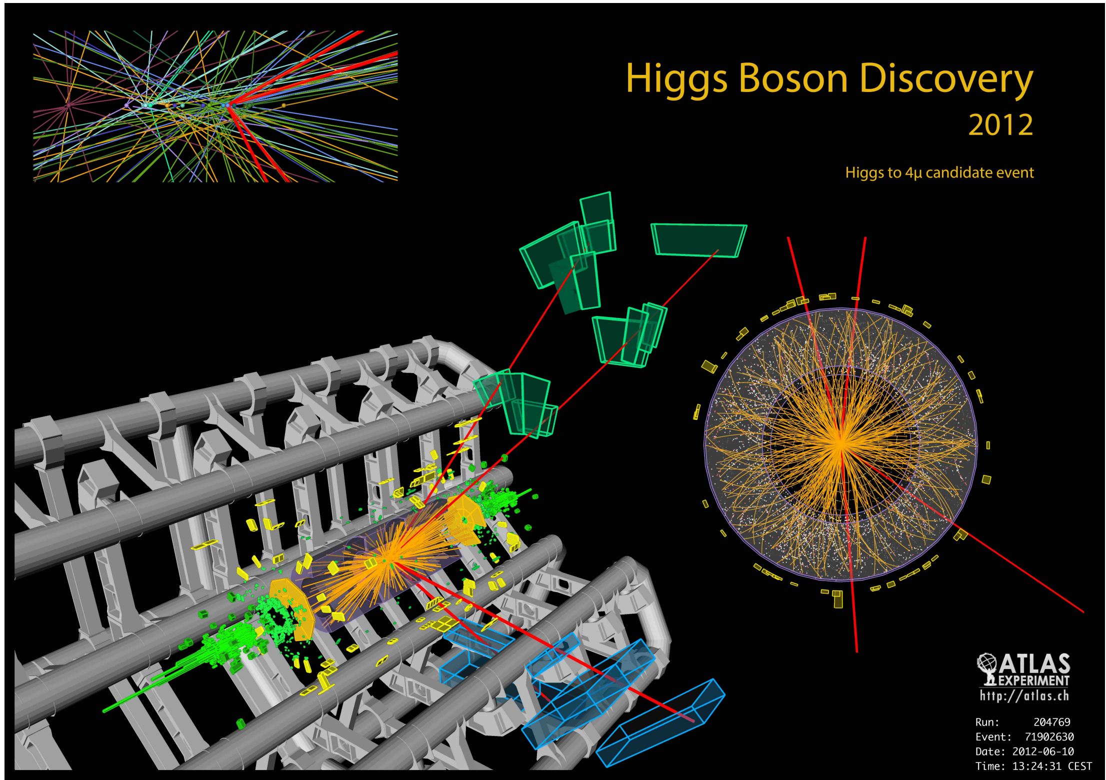


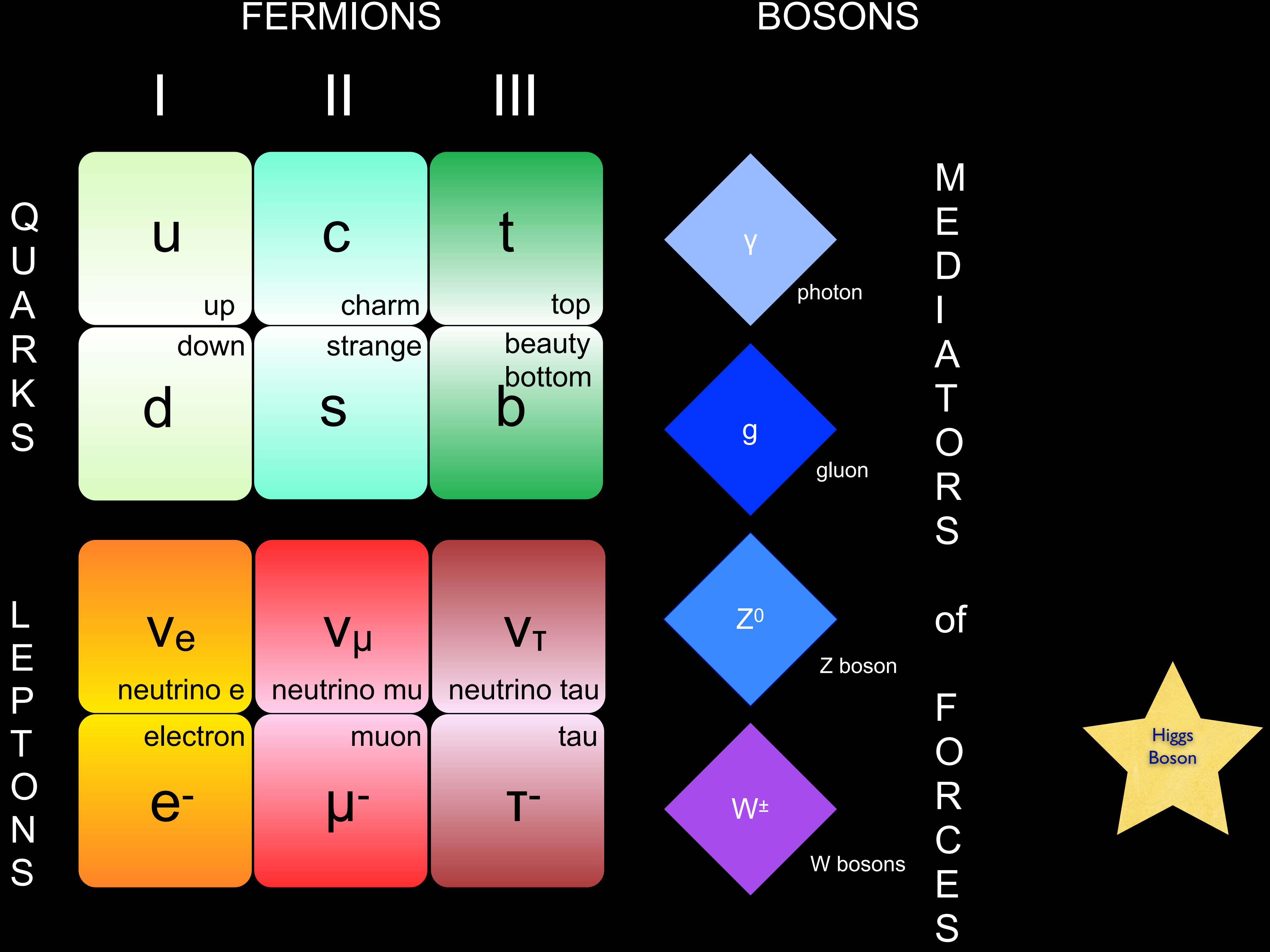
DETECTOR
to record the final state for physicists to interpret the nature of the interaction

WHAT ARE WE LOOKING FOR ?

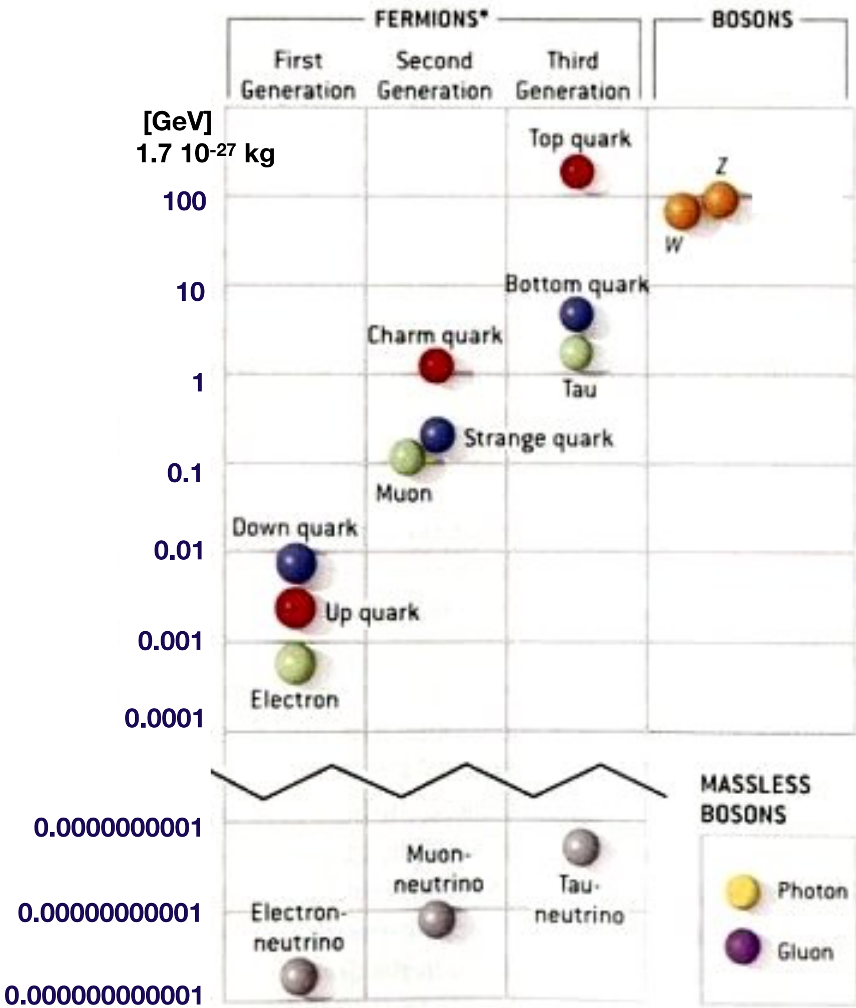
Production of a Higgs boson from
one proton-proton collision and its
decay to a pair of Z-bosons

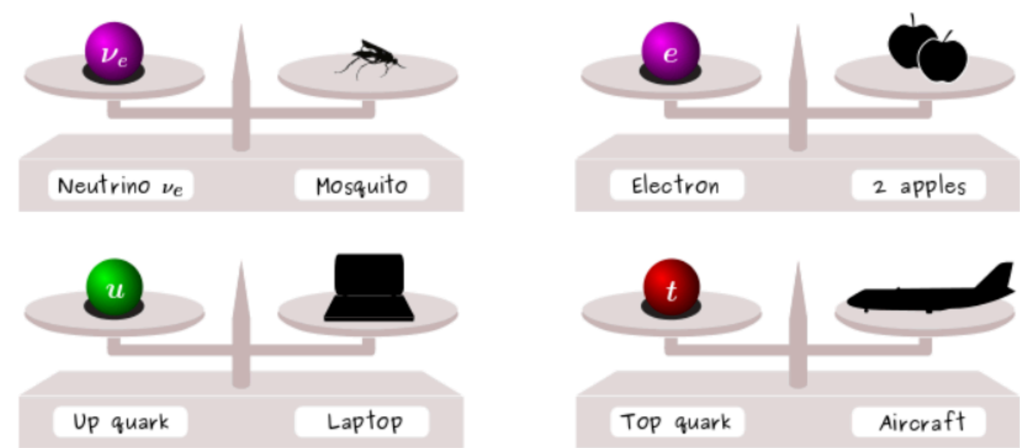





FERMIONS
BOSONS
I
II
III
QUARKS
u
up
c
charm
t
top
down
d
strange
s
beauty
bottom
b
LEPTONS
νe
neutrino e
νμ
neutrino mu
ντ
neutrino tau
electron
e-
muon
μ-
tau
τ-
γ
photon
g
gluon
Z0
Z boson
W±
W bosons
MEDIATORS of FORCES
Higgs Boson

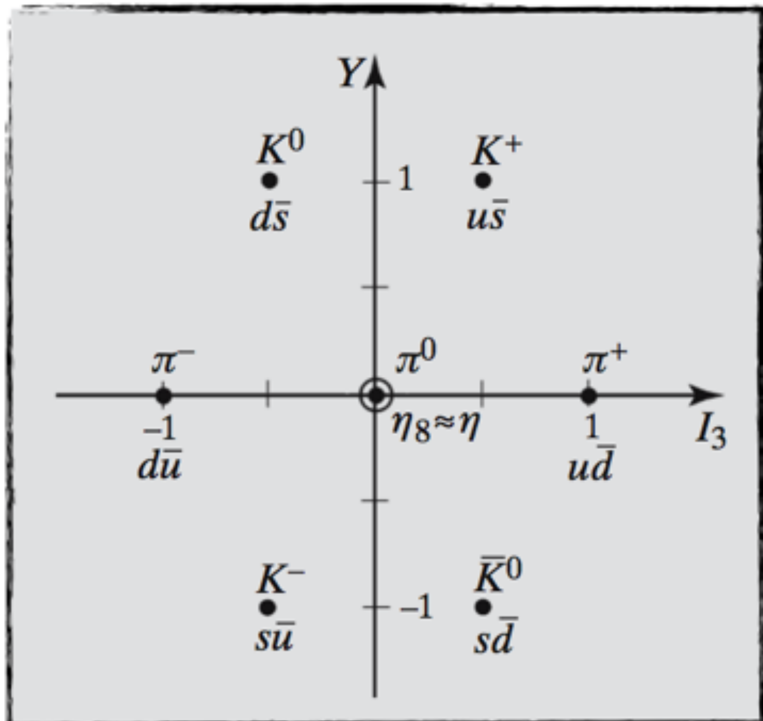
ELEMENTARY PARTICLES MASS



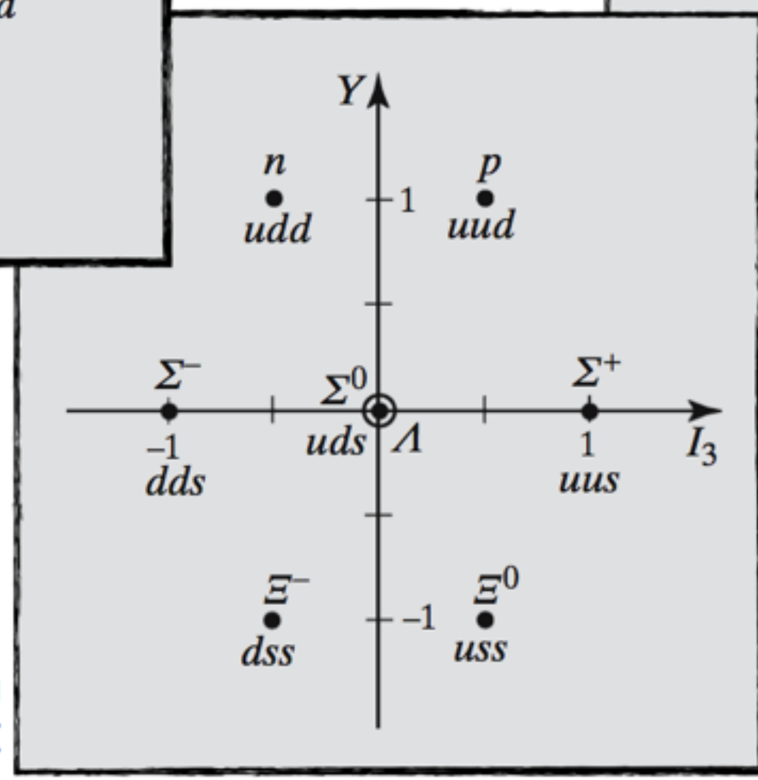


Mass of elementary particles in not predicted by the Standard Model of Particle Physics.

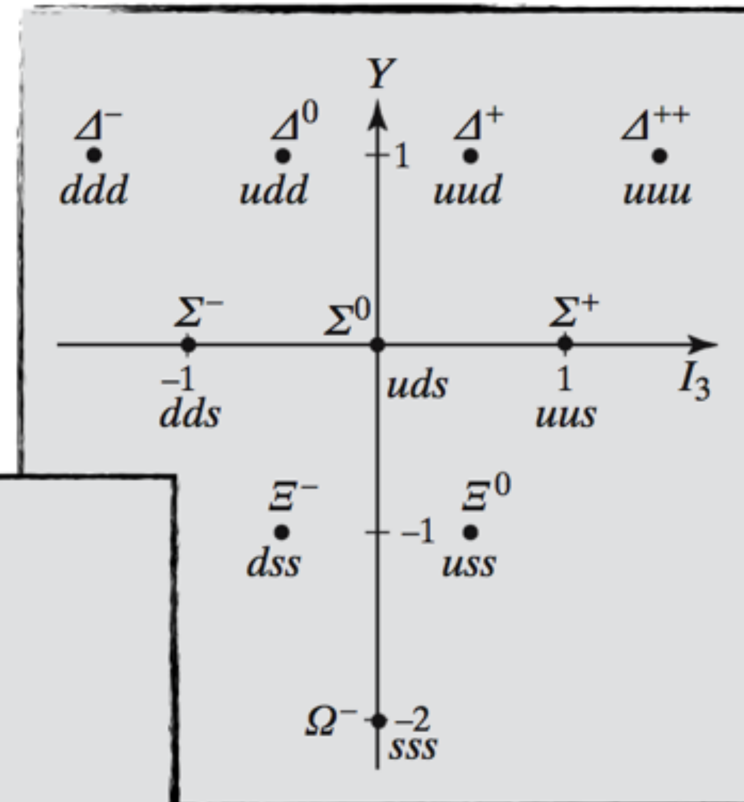
PARTICLES



Meson octet

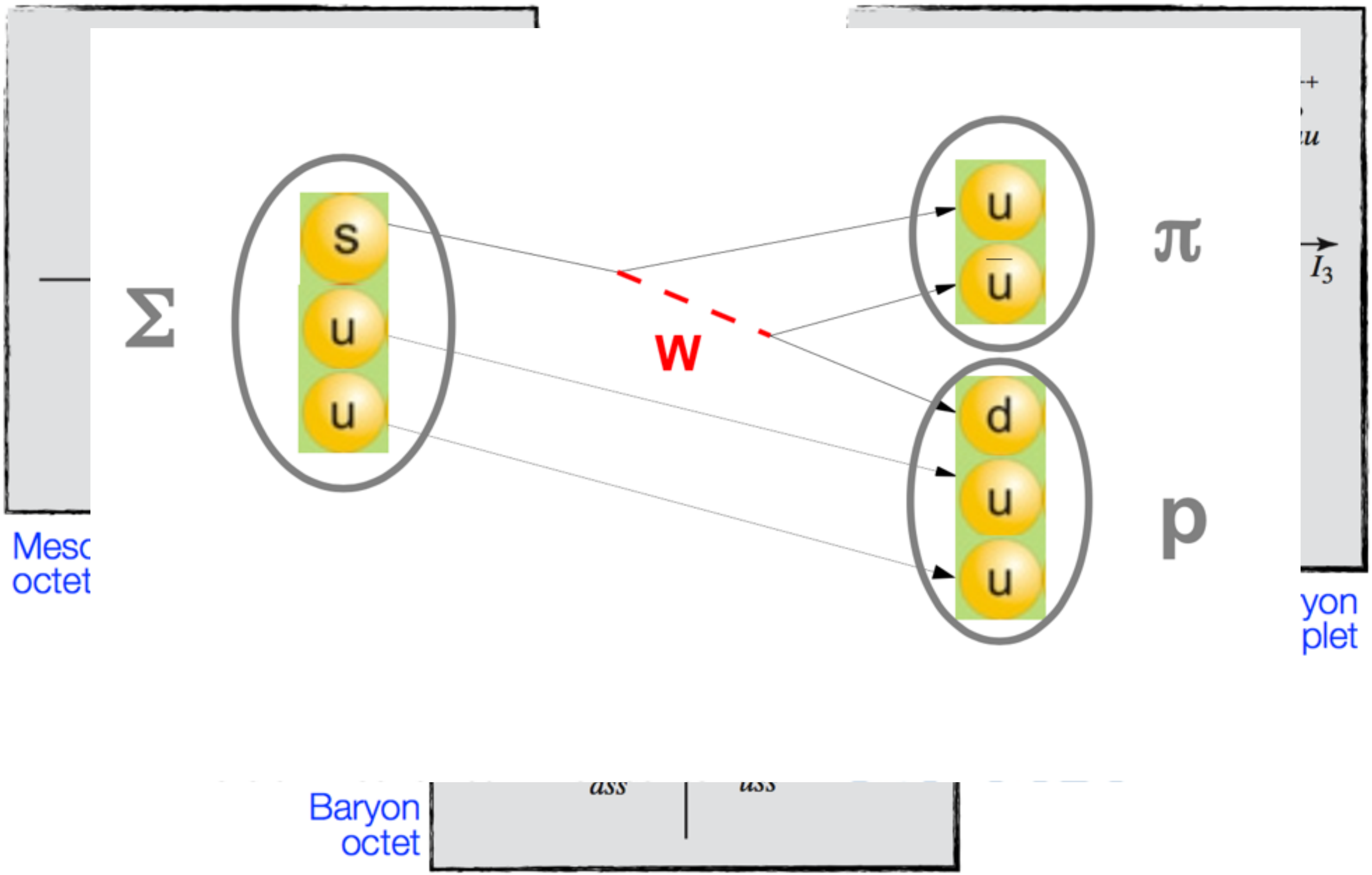


Baryon octet



Baryon decuplet

PARTICLES



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

$H, \gamma, W^{\pm}, Z^0, g, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \pi^{\pm}, \pi^0, \eta, f_0(600), \rho(770),$
$\omega(782), \eta'(958), f_0(980), a_0(980), \phi(1020), h_1(1170), b_1(1235),$
$a_1(1260), f_2(1270), f_1(1285), \eta(1295), \pi(1300), a_2(1320),$
$f_0(1370), f_1(1420), \omega(1420), \eta(1440), a_0(1450), \rho(1450),$
$f_0(1500), f_2'(1525), \omega(1650), \omega_3(1670), \pi_2(1670), \phi(1680),$
$\rho_3(1690), \rho(1700), f_0(1710), \pi(1800), \phi_3(1850), f_2(2010),$
$a_4(2040), f_4(2050), f_2(2300), f_2(2340), K^{\pm}, K^0, K^0_S, K^0_L, K^*(892),$
$K_1(1270), K_1(1400), K^*(1410), K_0^*(1430), K_2^*(1430), K^*(1680),$
$K_2(1770), K_3^*(1780), K_2(1820), K_4^*(2045), D^{\pm}, D^0, D^*(2007)^0,$
$D^*(2010)^{\pm}, D_1(2420)^0, D_2^*(2460)^0, D_2^*(2460)^{\pm}, D_s^{\pm}, D_s^{*\pm},$
$D_{s1}(2536)^{\pm}, D_{sJ}(2573)^{\pm}, B^{\pm}, B^0, B^*, B_s^0, B_c^{\pm}, \eta_c(1S), J/\psi(1S),$
$\chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160),$
$\psi(4415), \Upsilon(1S), \chi_{b0}(1P), \chi_{b1}(1P), \chi_{b2}(1P), \Upsilon(2S), \chi_{b0}(2P),$
$\chi_{b2}(2P), \Upsilon(3S), \Upsilon(4S), \Upsilon(10860), \Upsilon(11020), p, n, N(1440),$
$N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710),$
$N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600),$
$\Delta(1620), \Delta(1700), \Delta(1905), \Delta(1910), \Delta(1920), \Delta(1930), \Delta(1950),$
$\Delta(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690),$
$\Lambda(1800), \Lambda(1810), \Lambda(1820), \Lambda(1830), \Lambda(1890), \Lambda(2100),$
$\Lambda(2110), \Lambda(2350), \Sigma^+, \Sigma^0, \Sigma^-, \Sigma(1385), \Sigma(1660), \Sigma(1670),$
$\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^0, \Xi^-,$
$\Xi(1530), \Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030), \Omega^-, \Omega(2250)^-,$
$\Lambda_c^+, \Lambda_c^+, \Sigma_c(2455), \Sigma_c(2520), \Xi_c^+, \Xi_c^0, \Xi_c'^+, \Xi_c'^0, \Xi(2645)$
$\Xi_c(2780), \Xi_c(2815), \Omega_c^0, \Lambda_b^0, \Xi_b^0, \Xi_b^-, t\bar{t}$

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_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, $N(1440)$,
$N(1520)$, $N(1535)$, $N(1650)$, $N(1675)$, $N(1680)$, $N(1700)$, $N(1710)$,
$N(1720)$, $N(2190)$, $N(2220)$, $N(2250)$, $N(2600)$, $\Delta(1232)$, $\Delta(1600)$,
$\Delta(1620)$, $\Delta(1700)$, $\Delta(1905)$, $\Delta(1910)$, $\Delta(1920)$, $\Delta(1930)$, $\Delta(1950)$,
$\Delta(2420)$, 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, $\Xi_c'^+$, $\Xi_c'^0$, $\Xi(2645)$
$\Xi_c(2780)$, $\Xi_c(2815)$, 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

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

$\pi^\pm$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57061 \pm 0.00024$ MeV (S = 1.6)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^\pm \to \ell^\pm \nu\gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$	90%	70

Tables of decay modes for known particles (here for charged pion $\pi^\pm$)

PROPERTIES of PARTICULES

Ω BARYONS
$(S = -3,\ I = 0)$

$\Omega^- = sss$

Ω^- $\qquad I(J^P) = 0(\frac{3}{2}^+)$

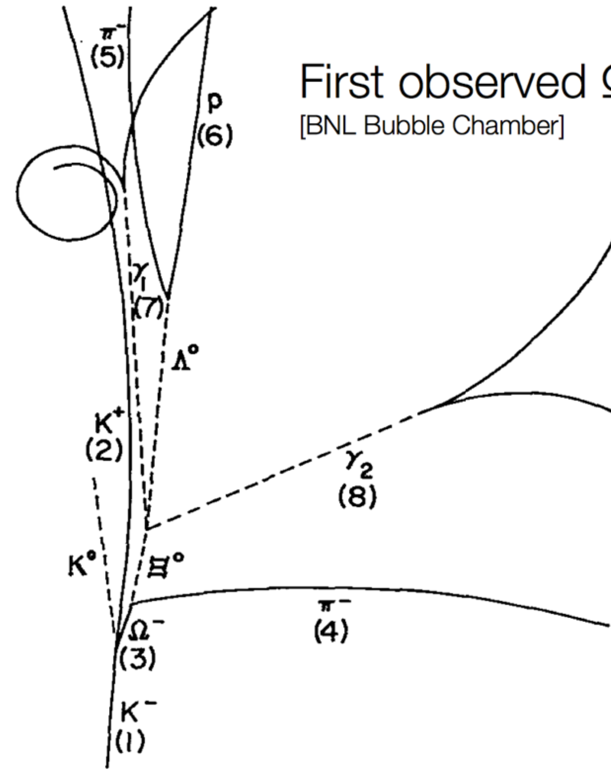
$J^P = \frac{3}{2}^+$ is the quark-model prediction; and $J = 3/2$ is fairly well established.

Mass $m = 1672.45 \pm 0.29$ MeV
$(m_{\Omega^-} - m_{\overline{\Omega}^+}) / m_{\Omega^-} = (-1 \pm 8) \times 10^{-5}$
Mean life $\tau = (0.821 \pm 0.011) \times 10^{-10}$ s
$c\tau = 2.461$ cm
$(\tau_{\Omega^-} - \tau_{\overline{\Omega}^+}) / \tau_{\Omega^-} = 0.00 \pm 0.05$
Magnetic moment $\mu = -2.02 \pm 0.05\ \mu_N$

Decay parameters

ΛK^- $\quad \alpha = 0.0180 \pm 0.0024$
$\Lambda K^-, \overline{\Lambda} K^+$ $\quad (\alpha + \overline{\alpha})/(\alpha - \overline{\alpha}) = -0.02 \pm 0.13$
$\Xi^0 \pi^-$ $\quad \alpha = 0.09 \pm 0.14$
$\Xi^- \pi^0$ $\quad \alpha = 0.05 \pm 0.21$

Ω^- DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
ΛK^-		(67.8 ± 0.7) %		211
$\Xi^0 \pi^-$		(23.6 ± 0.7) %		294
$\Xi^- \pi^0$		(8.6 ± 0.4) %		289
$\Xi^- \pi^+ \pi^-$		$(3.7^{+0.7}_{-0.6}) \times 10^{-4}$		189
$\Xi(1530)^0 \pi^-$		$< 7 \times 10^{-5}$	90%	17
$\Xi^0 e^- \overline{\nu}_e$		$(5.6 \pm 2.8) \times 10^{-3}$		319
$\Xi^- \gamma$		$< 4.6 \times 10^{-4}$	90%	314
$\Delta S = 2$ forbidden ($S2$) modes				
$\Lambda \pi^-$	$S2$	$< 2.9 \times 10^{-6}$	90%	449



First observed Ω^- event
[BNL Bubble Chamber]

Tables of decay modes for known particles (here for charged $\Omega^\pm$)

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	"Secondary Vertices"
$B^0(b\bar{d}, d\bar{b})$	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	

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 $\sim 1000\, m_e$
$p^{\pm}$ $m_p = 938.3$ MeV $\sim 2000\, m_e$

} EM, Strong

$\sim 3.5\, m_\pi$

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

HOW to MEASURE PARTICLE PROPERTIES

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 ...]

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

Relativistic kinematics:

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

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

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

Particle Identification via measurement of

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

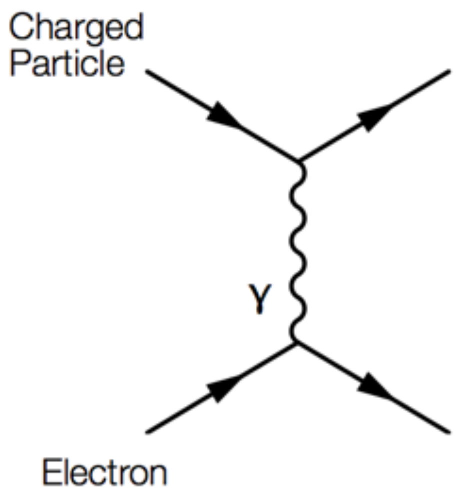
UNITS in HEP & International System

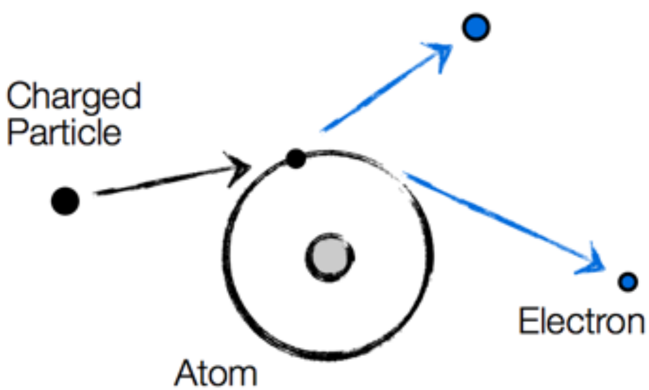
Quantity	HEP units	SI Units
length	1 fm	10^{-15} m
energy	1 GeV	$1.602 \cdot 10^{-10}$ J
mass	1 GeV/c^2	$1.78 \cdot 10^{-27}$ kg
$\hbar = h/2$	$6.588 \cdot 10^{-25}$ GeV s	$1.055 \cdot 10^{-34}$ Js
c	$2.988 \cdot 10^{23}$ fm/s	$2.988 \cdot 10^{8}$ m/s
$\hbar c$	0.1973 GeV fm	$3.162 \cdot 10^{-26}$ Jm

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

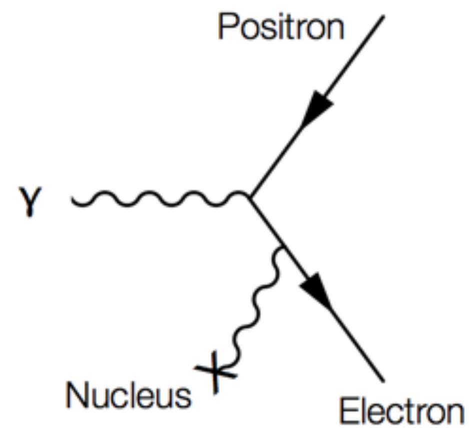
EXAMPLES of INTERACTIONS

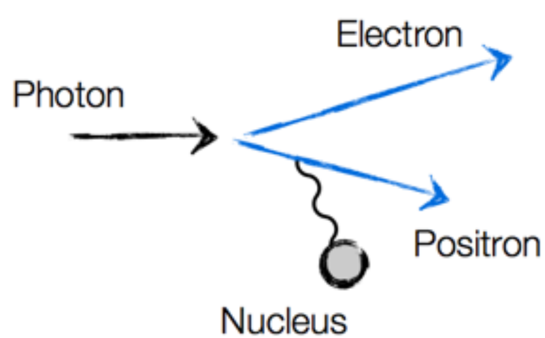
Ionisation



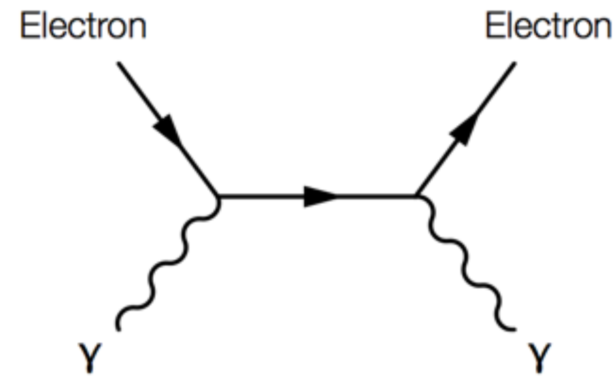


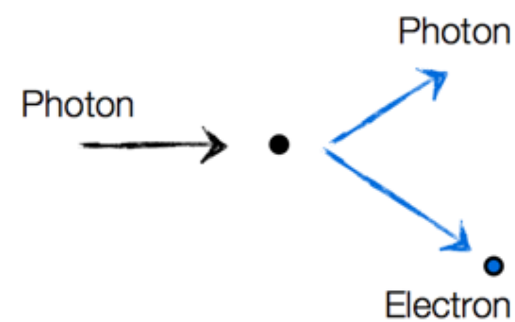
Production de paires e^+e^-



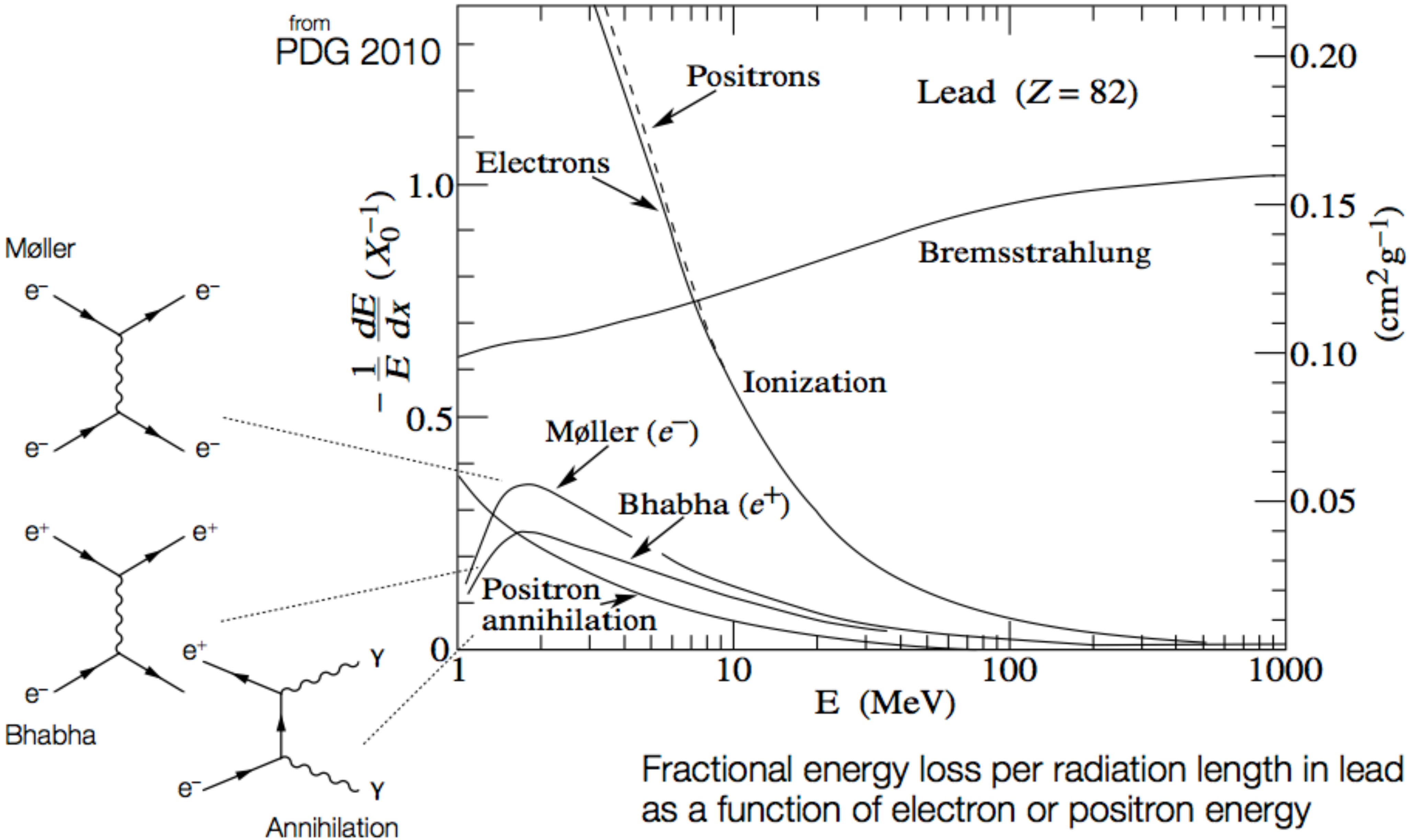


Diffusion Compton



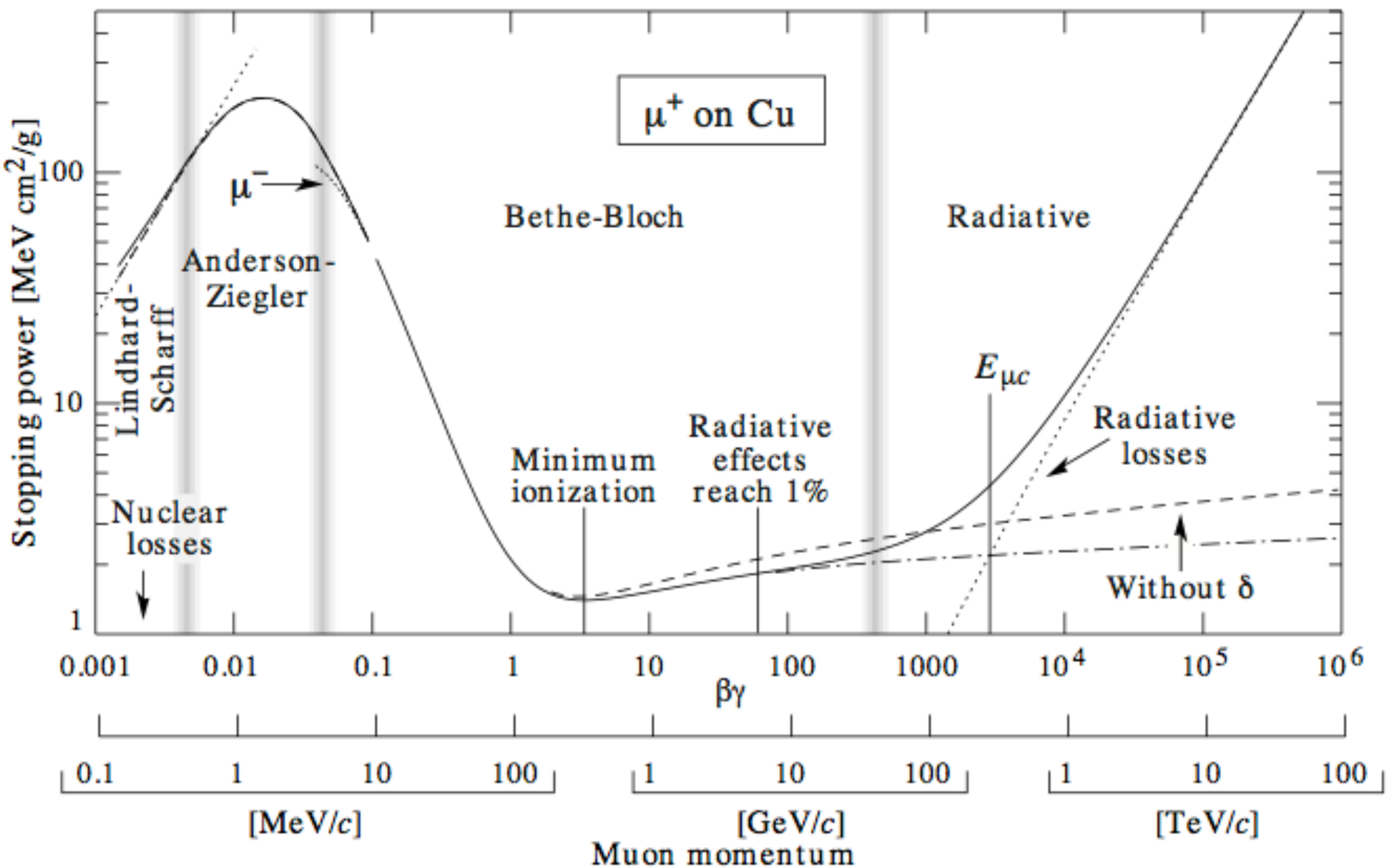


TOTAL ENERGY LOSS by ELECTRONS



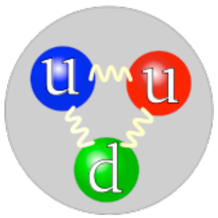
Fractional energy loss per radiation length in lead as a function of electron or positron energy

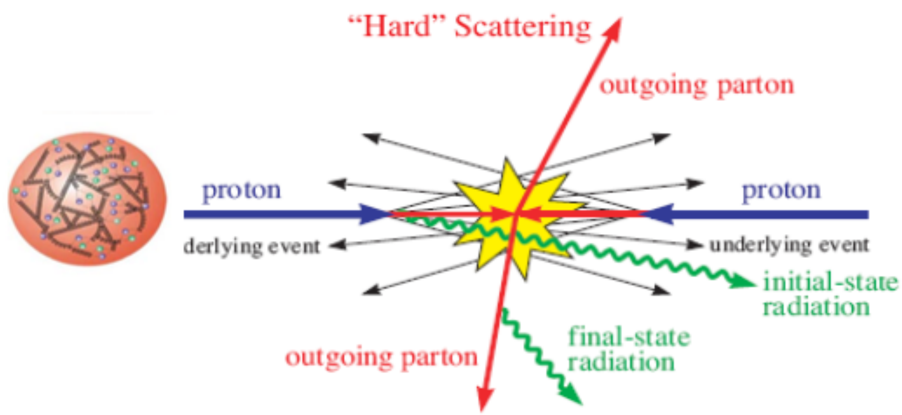
μ^+ in COPPER



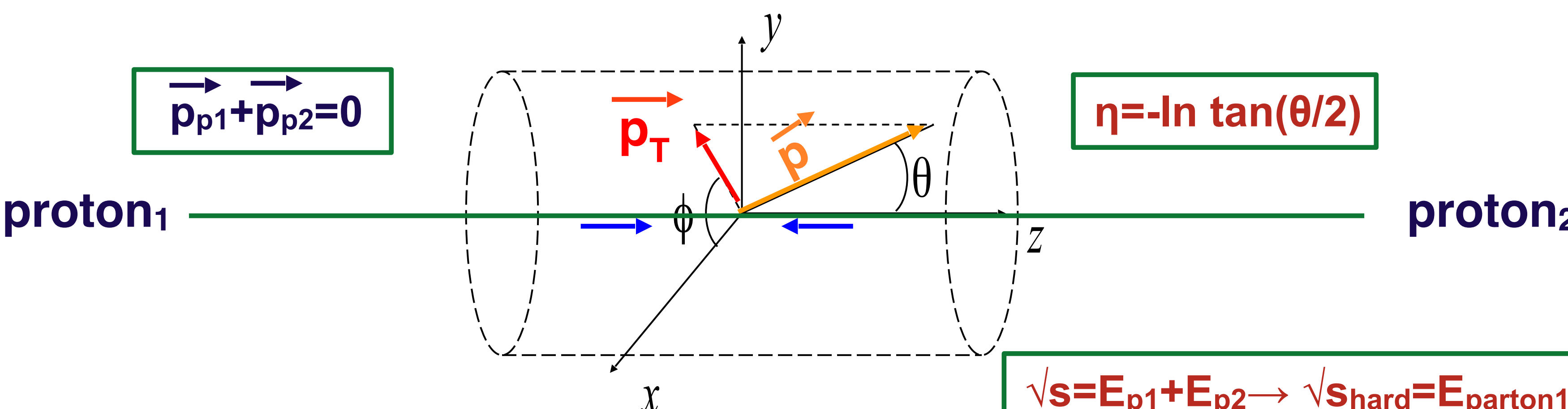
μ+ on Cu
Stopping power [MeV cm2/g]
Lindhard-Scharff
Anderson-Ziegler
μ−
Bethe-Bloch
Radiative
Nuclear losses
Minimum ionization
Radiative effects reach 1%
Eμc
Radiative losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

PROTON-PROTON INTERACTIONS





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

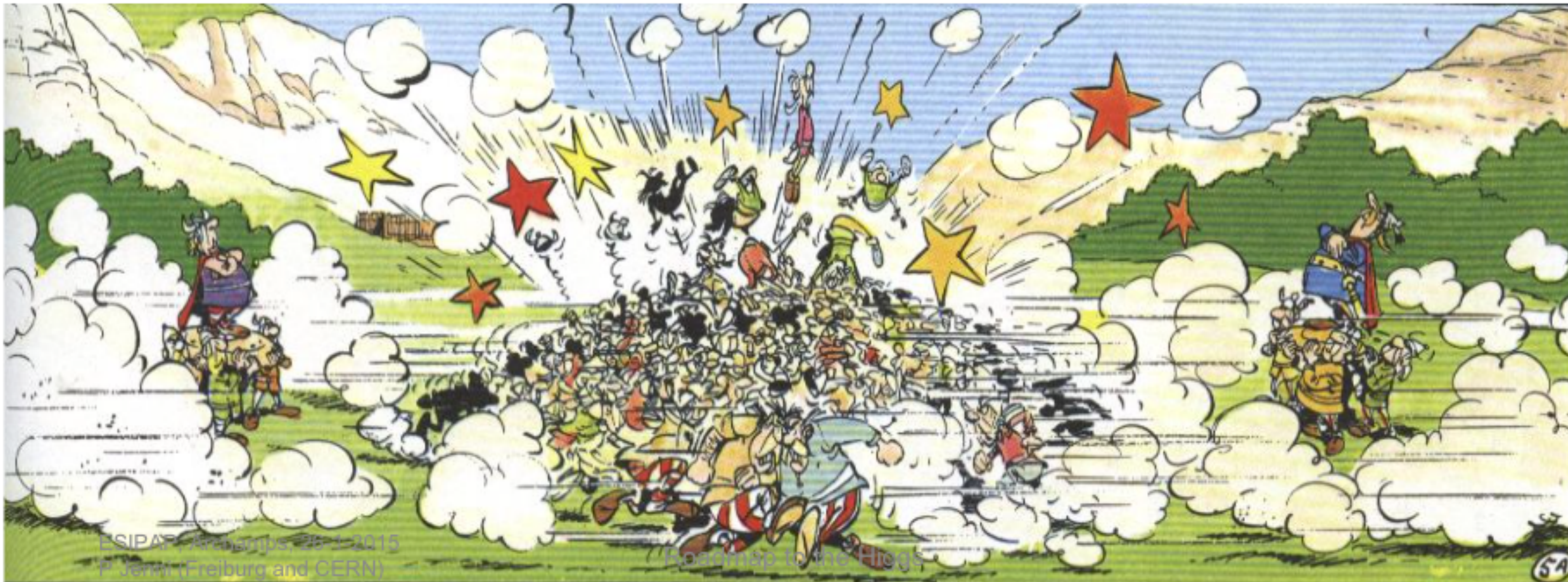


$\eta=-\ln\tan(\theta/2)$

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

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

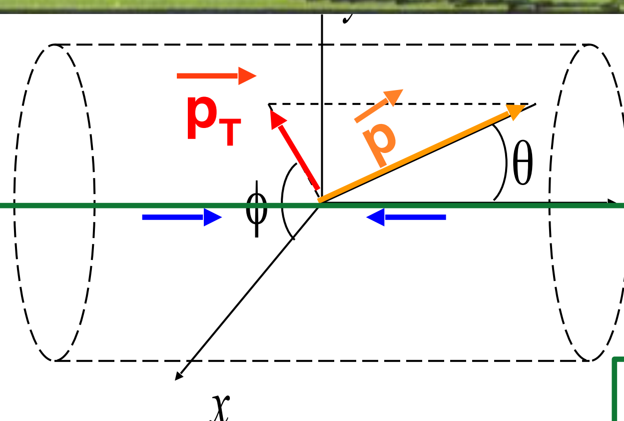
PROTON-PROTON INTERACTIONS



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

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

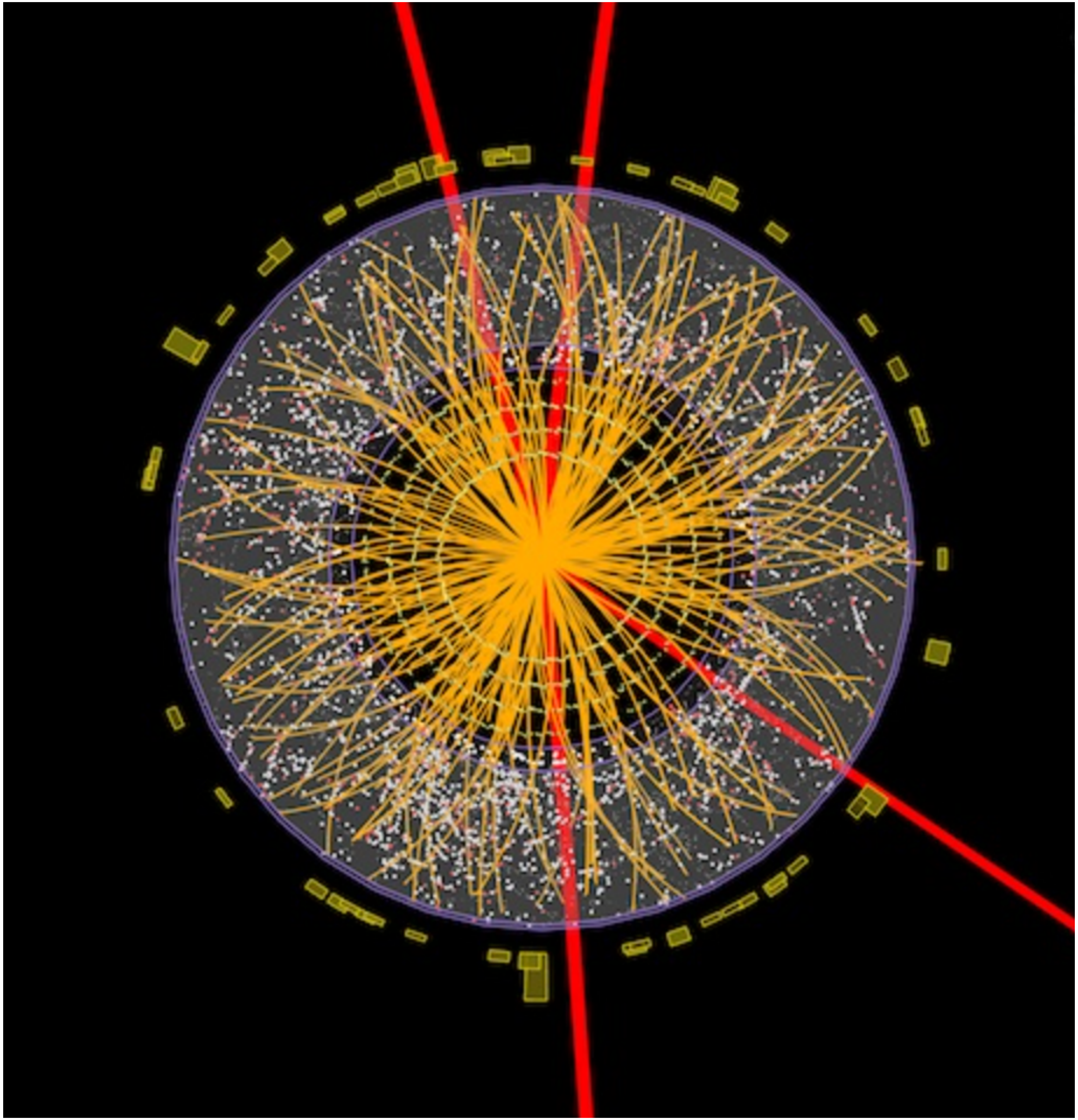
proton$_1$



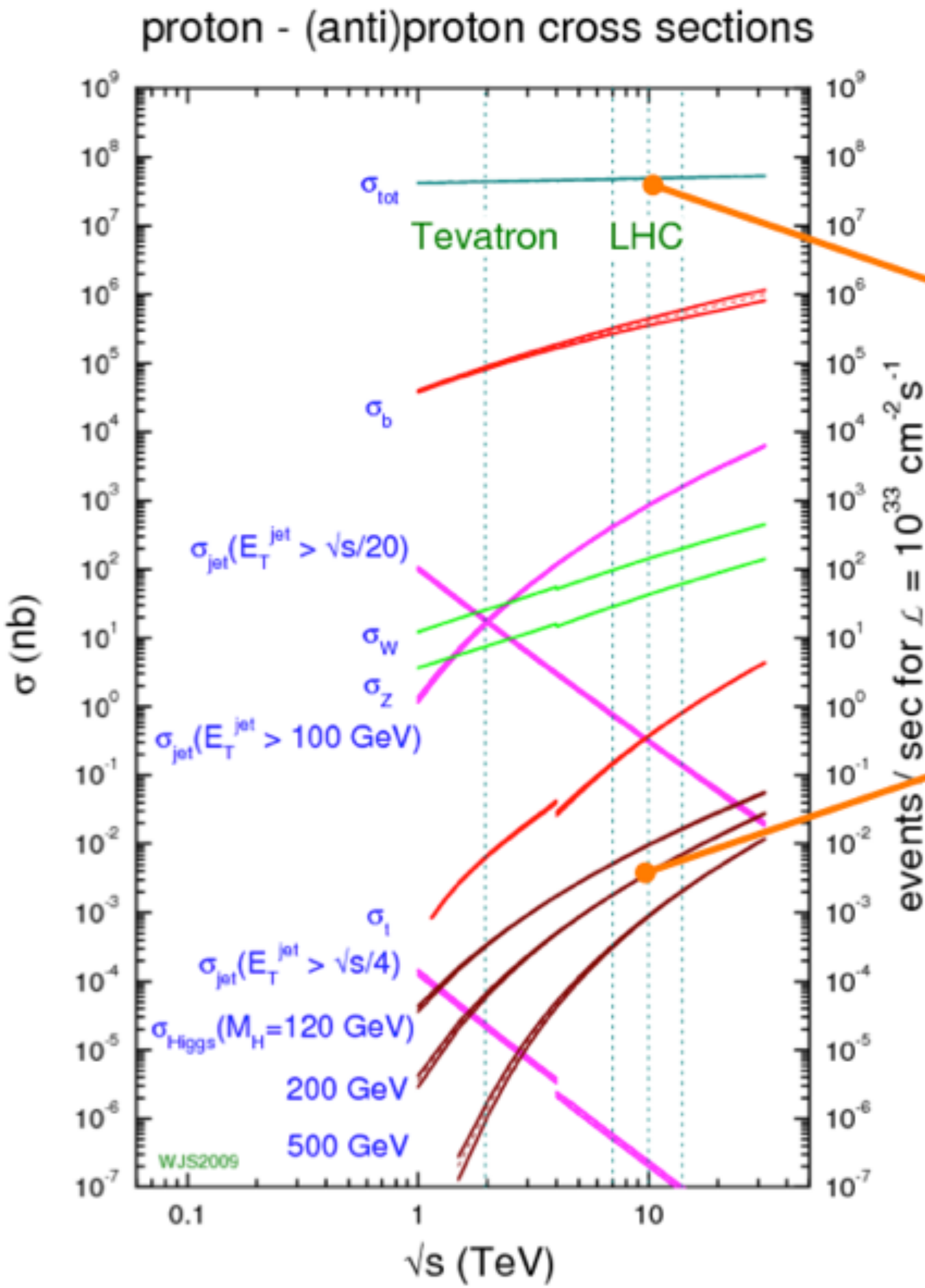
proton$_2$

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

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



DETECTOR at LHC - Challenge



40 millions beam crossing/s
1 billion collisions/s

10^8 events/s

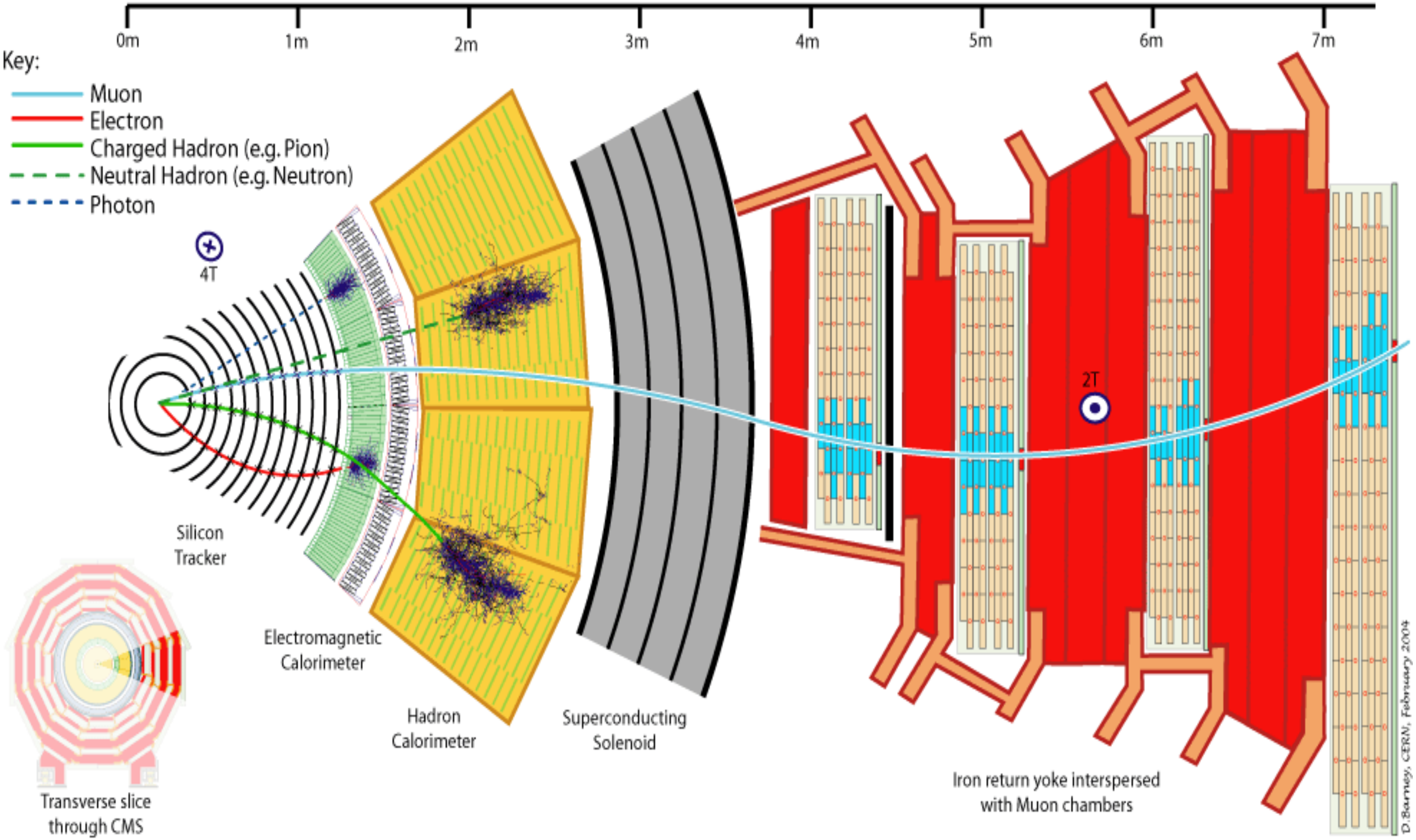
$\sim 10^{10}$

10^{-2} events/s ~
10 events/min

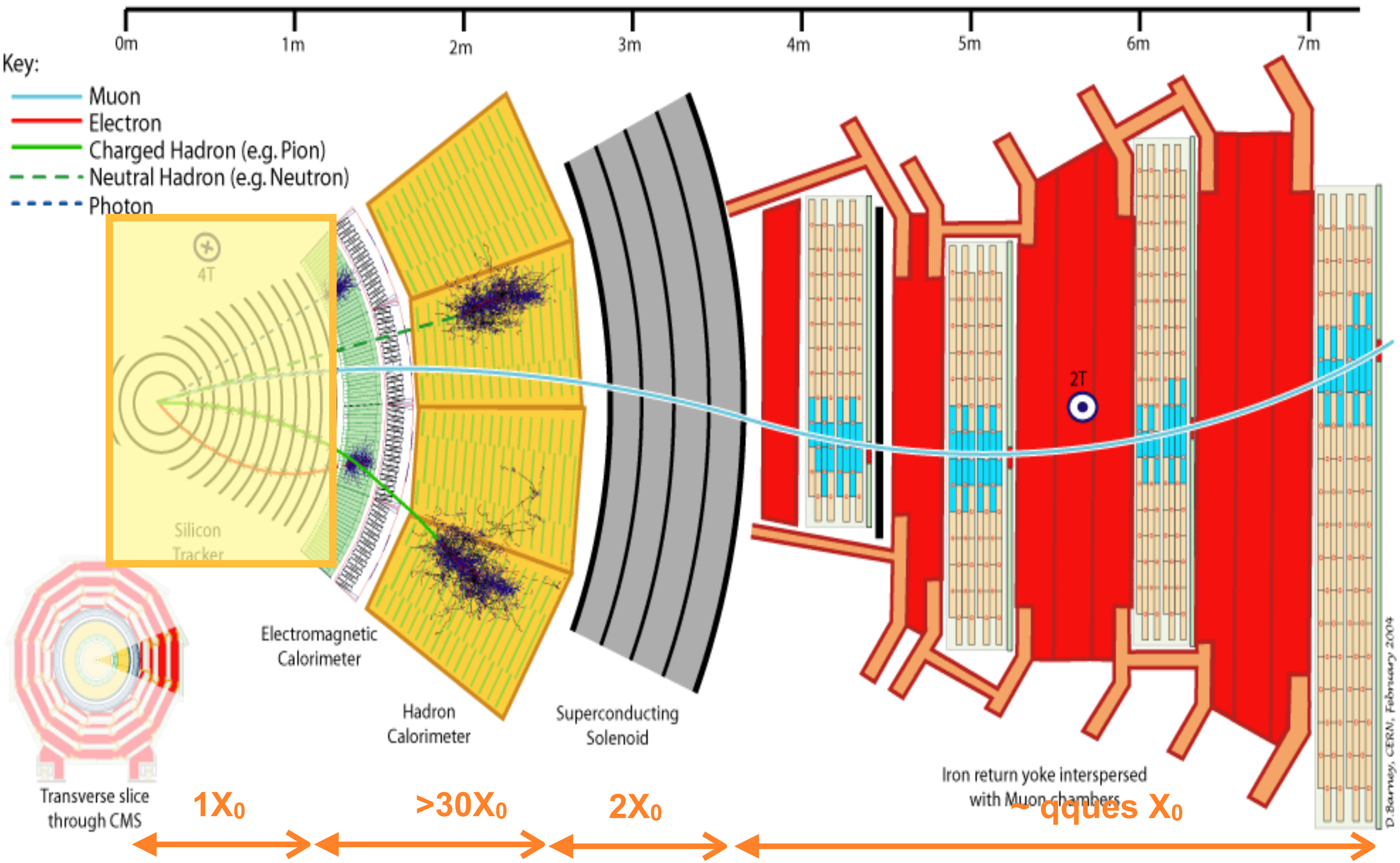
[m_H ~ 120 GeV]

0.2% H → γγ
1.5% H → ZZ

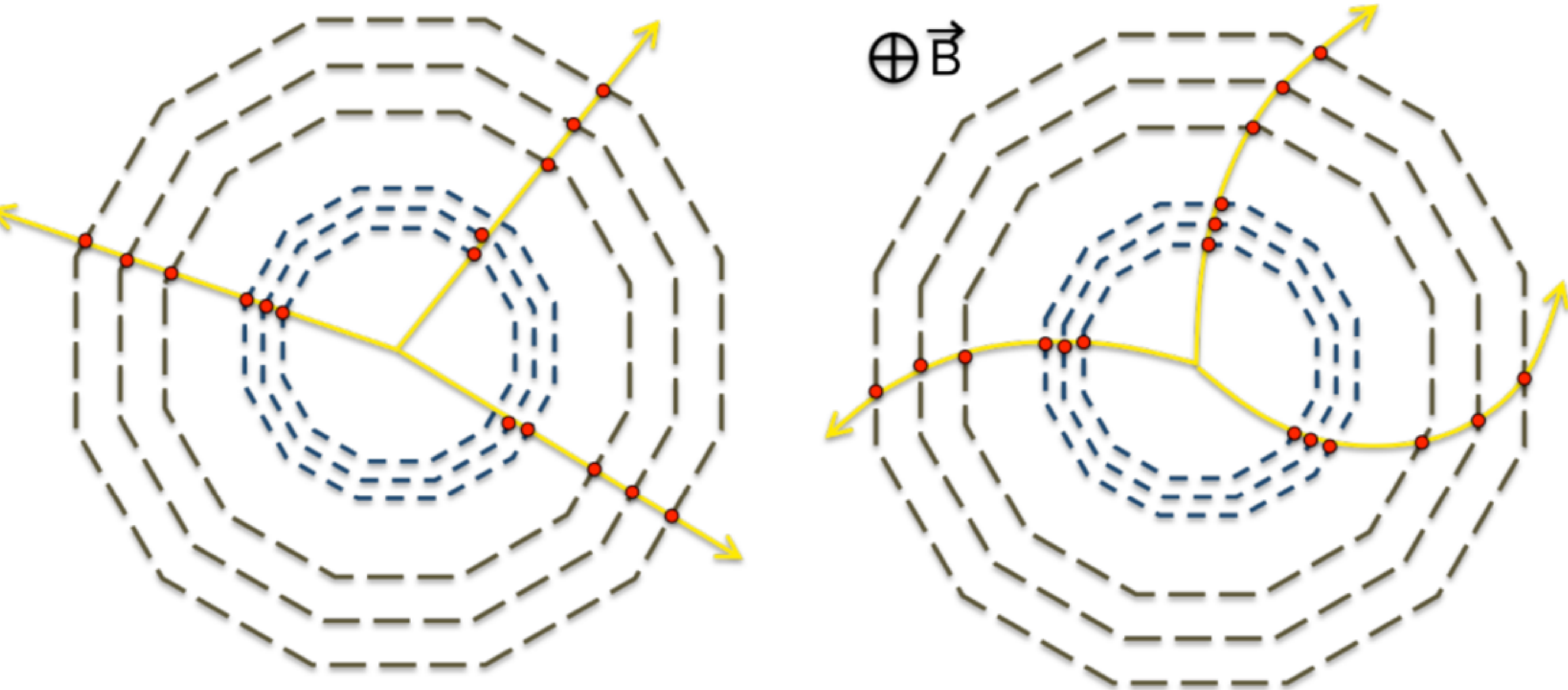
DETECTOR: PRINCIPLE



DETECTORS: TRACKING - CHARGED PARTICLES



MAGNETIC ANALYSIS



Charged particles are deflected in a magnetic field

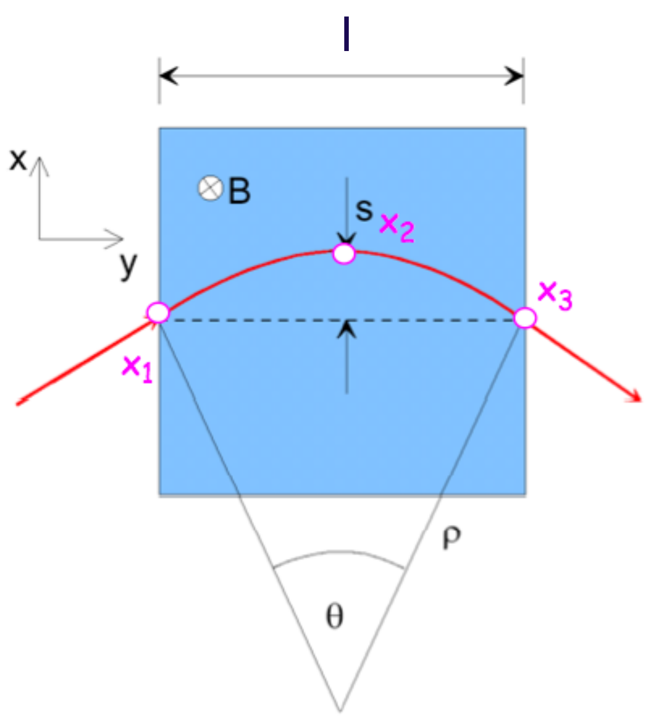
MAGNETIC ANALYSIS

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.

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

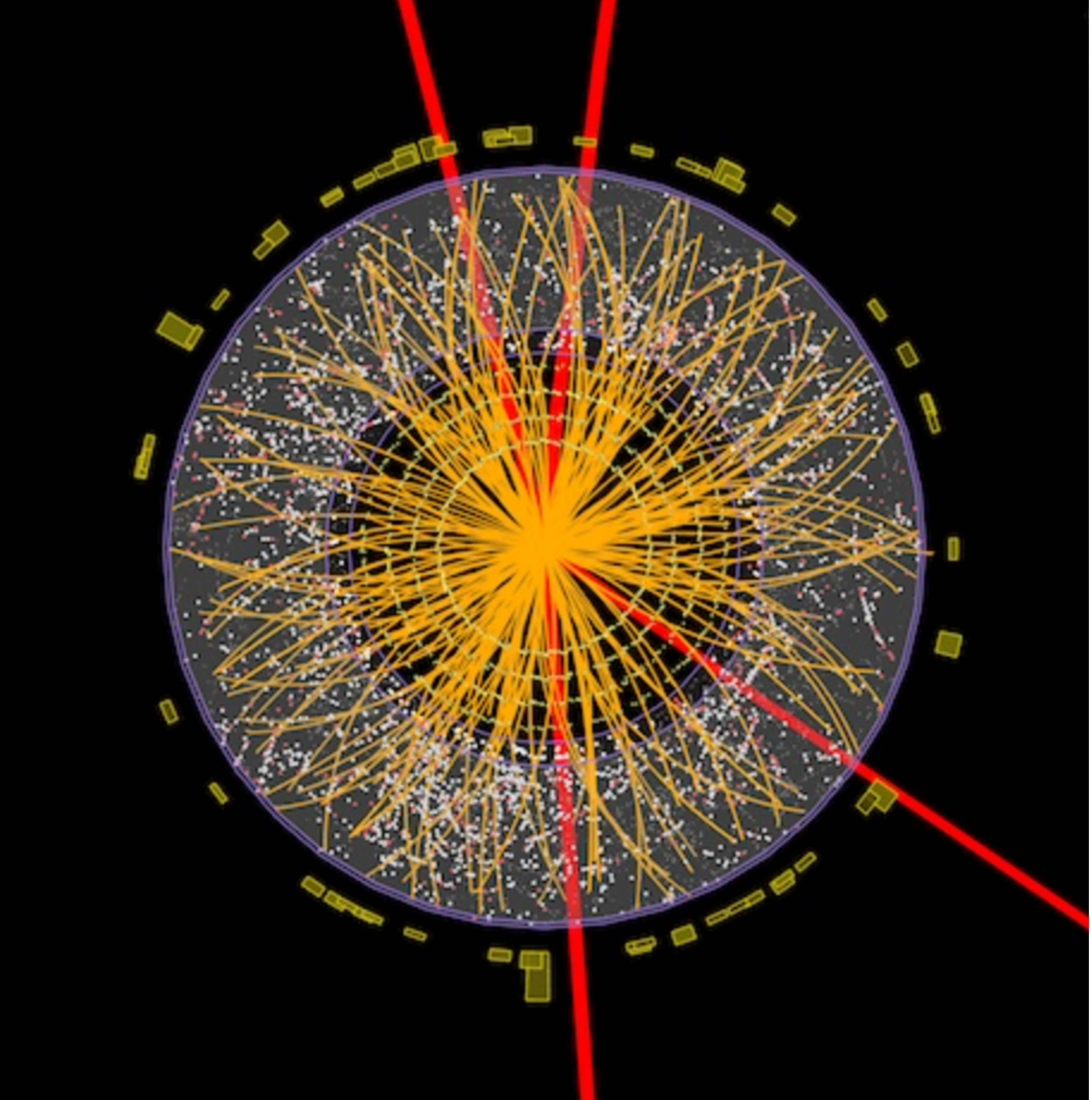


s = sagitta

l = chord

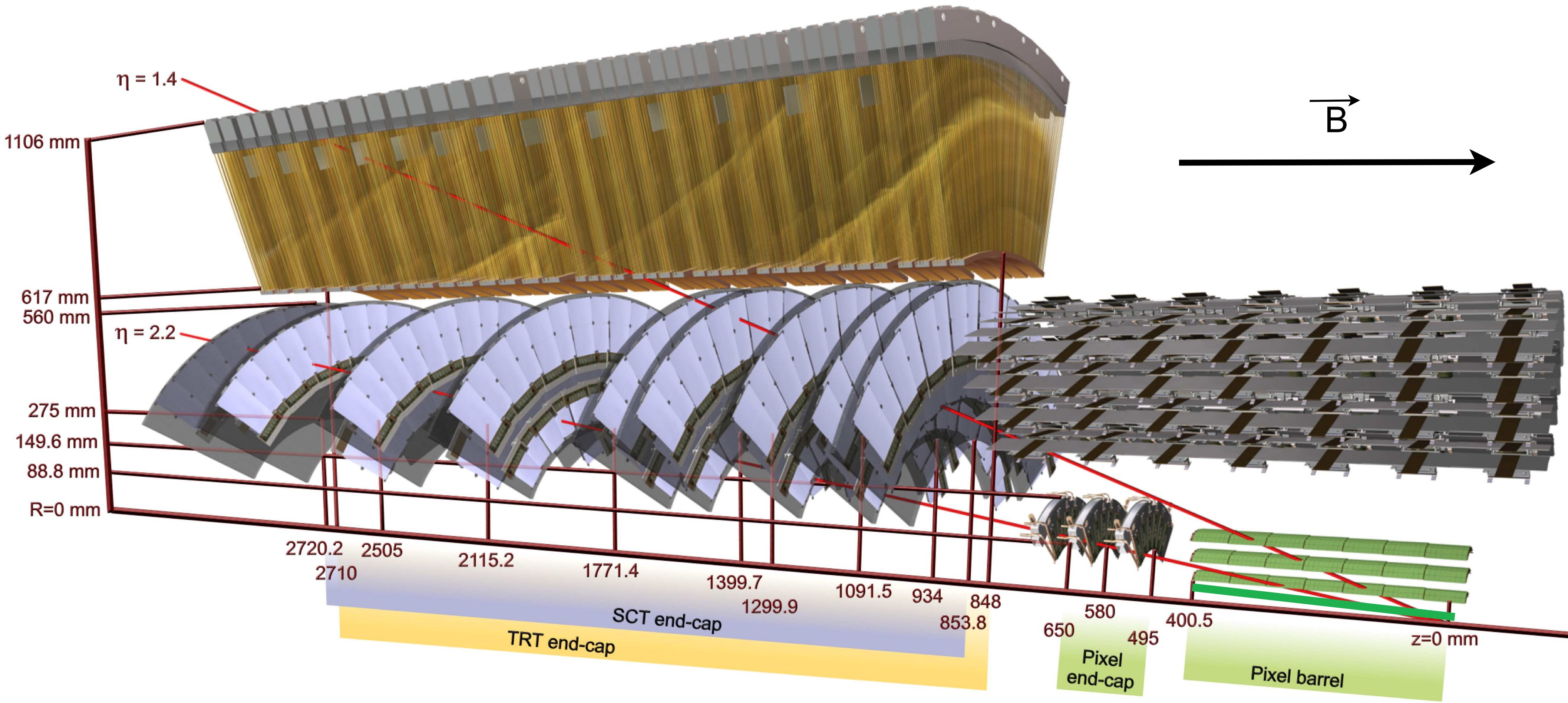
ρ = radius

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



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 $\Longrightarrow$ σ_{pos} = 23 µm

8 points per trace

Pixels detector 1.7 m² - 80 M channels

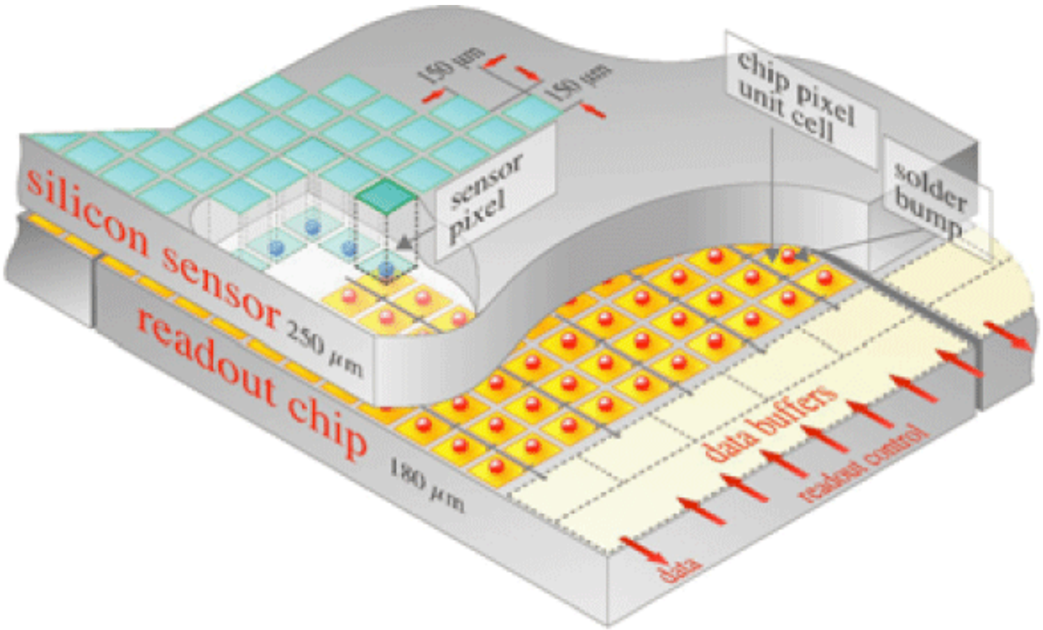
1744 pixel modules with 46080 pixels/mod.

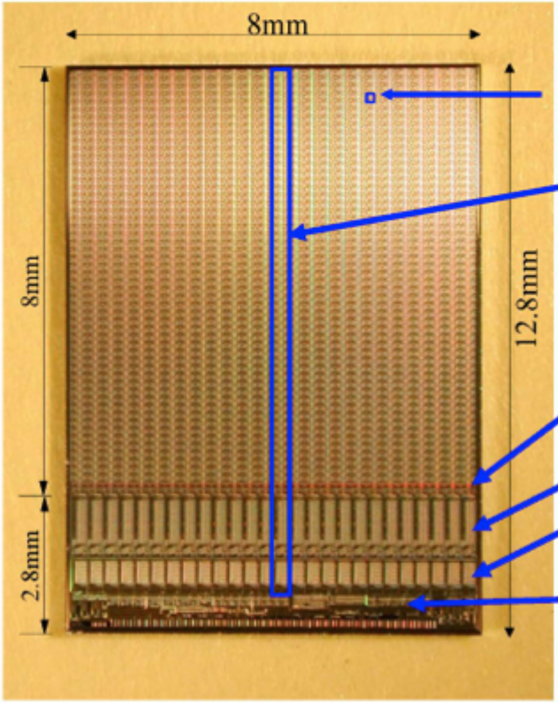
Each cell : 50x400 µm² $\Longrightarrow$ σ_{pos}=14/115 µm

Barrel R= 33.6, 50.5, 88.5 & 122.5 mm

Forward R coverage 9-15 cm

TRACKING DETECTOR: CMS pixel module



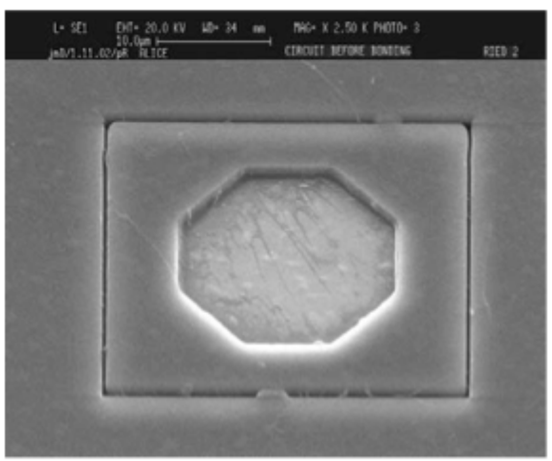


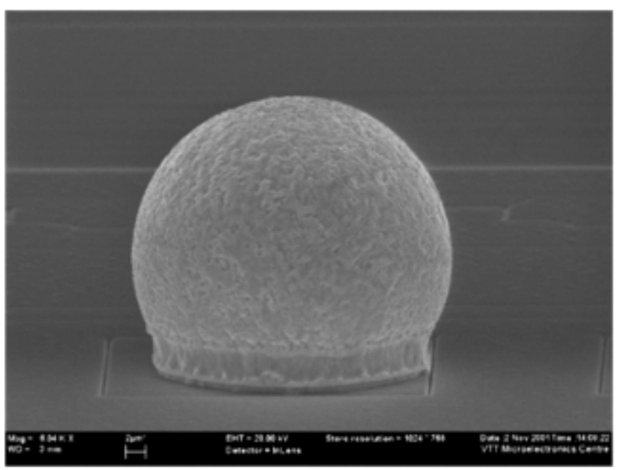
PSI43

- 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



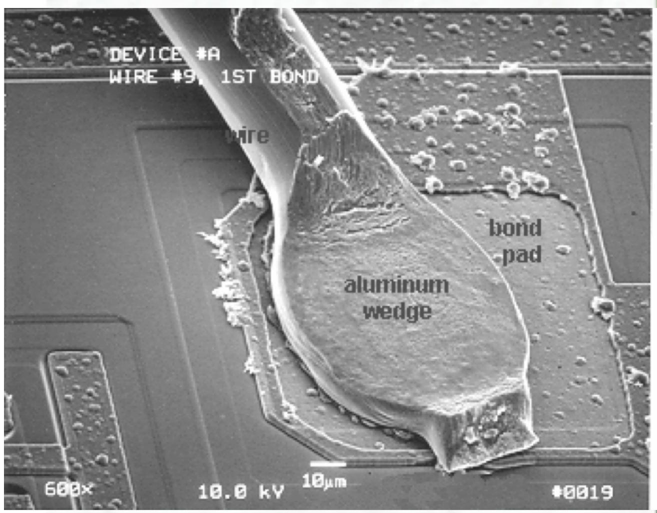


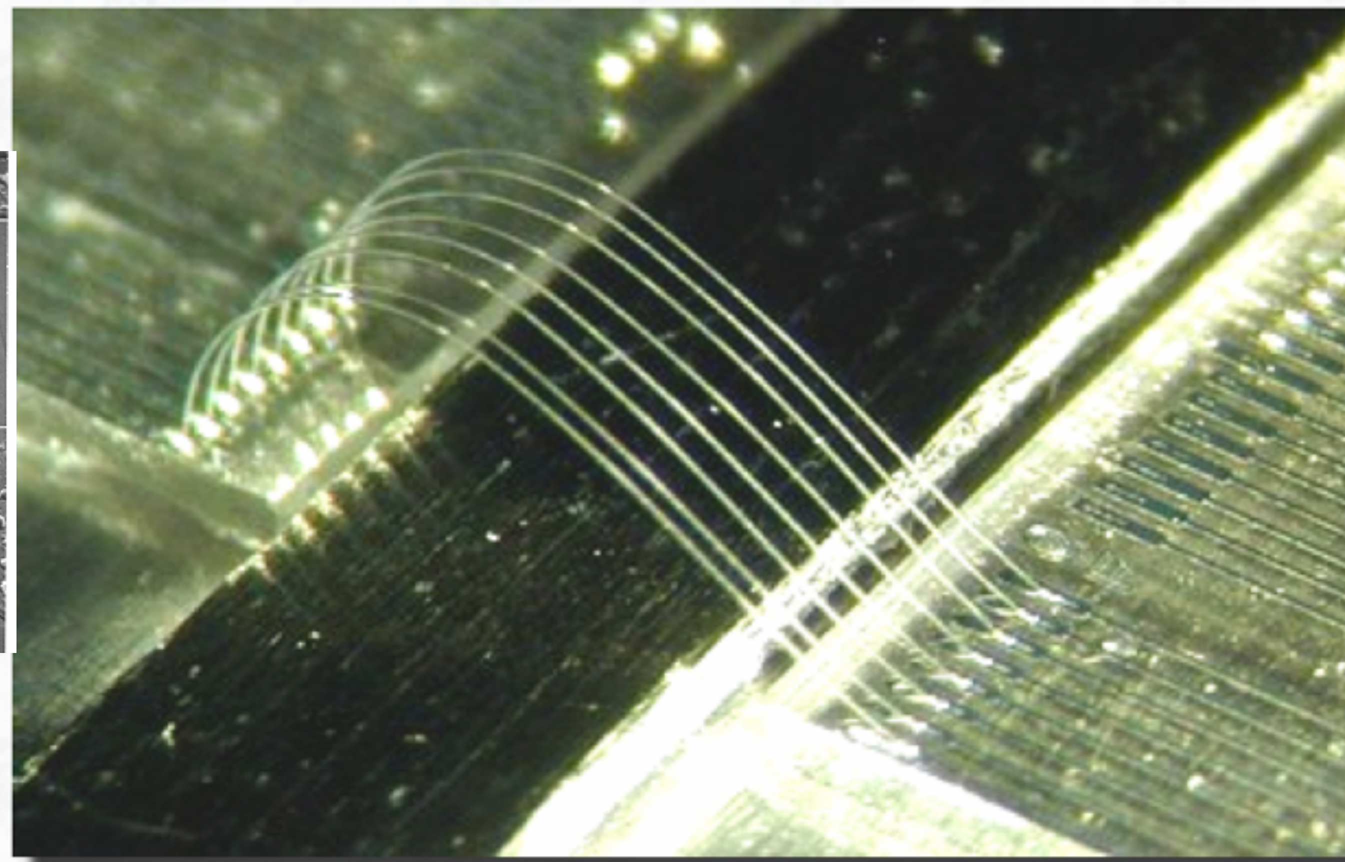
CONNECTION SENSOR-ELECTRONICS

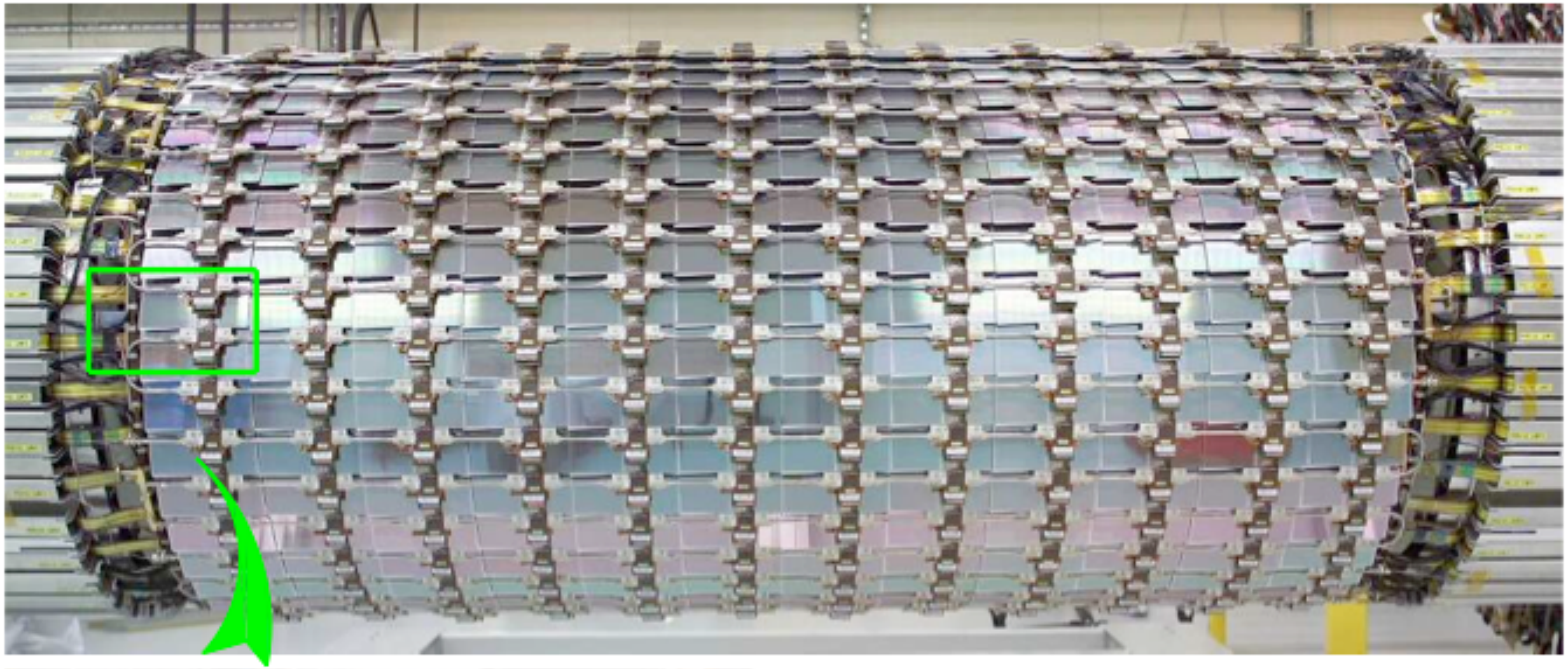
Connection between the silicium sensor and the chip readout

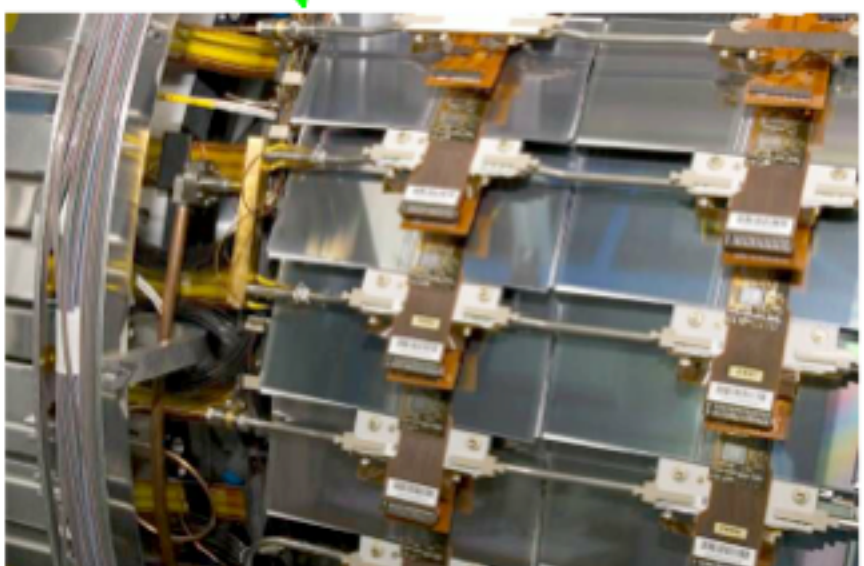
Very high density ~15 wires/mm

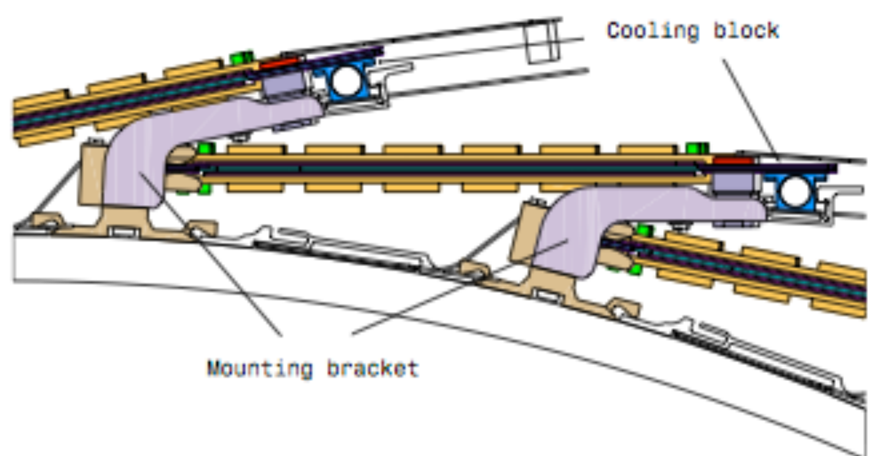
Connection via ultrasounds of wires of thickness ~20μm

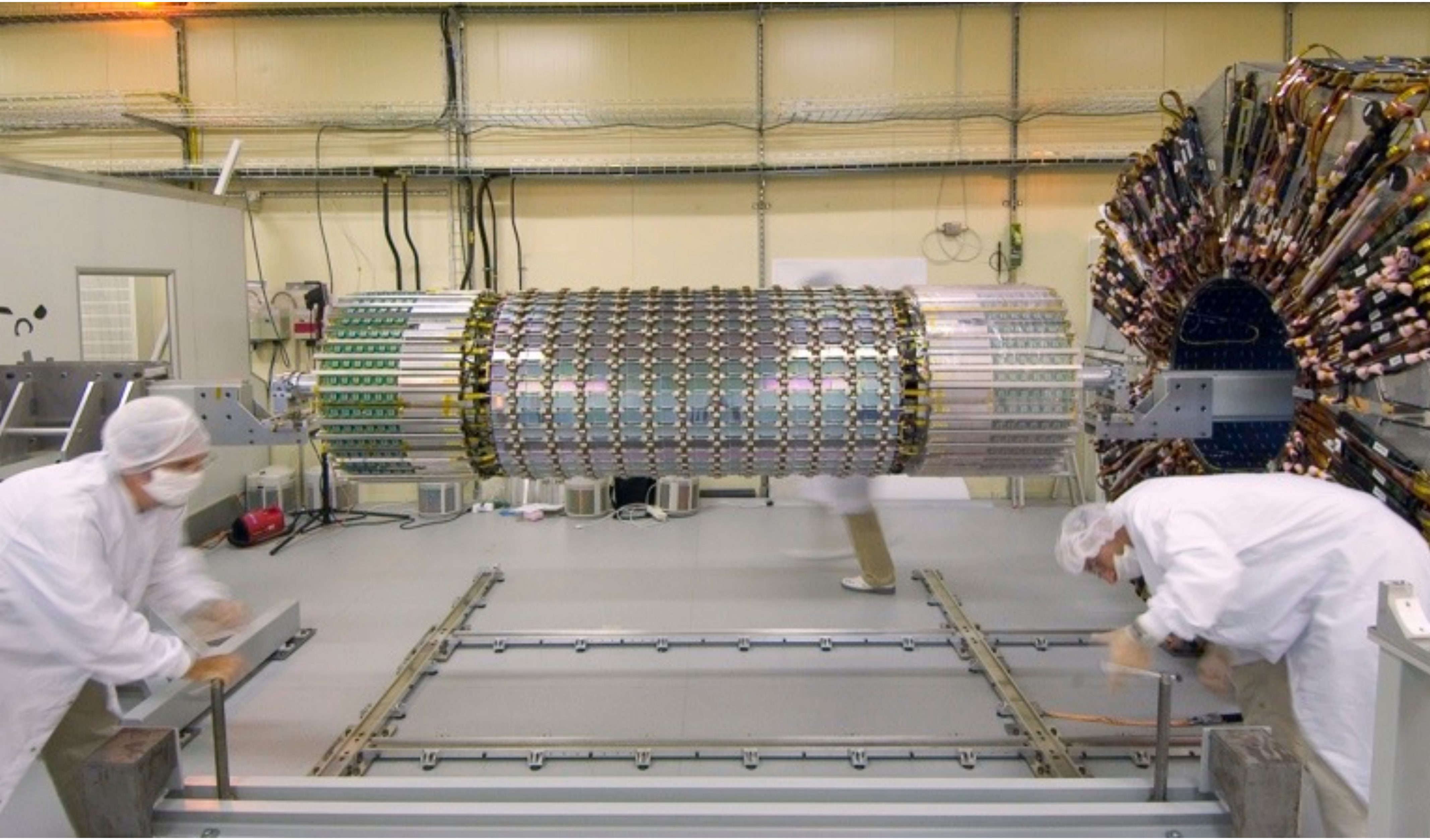








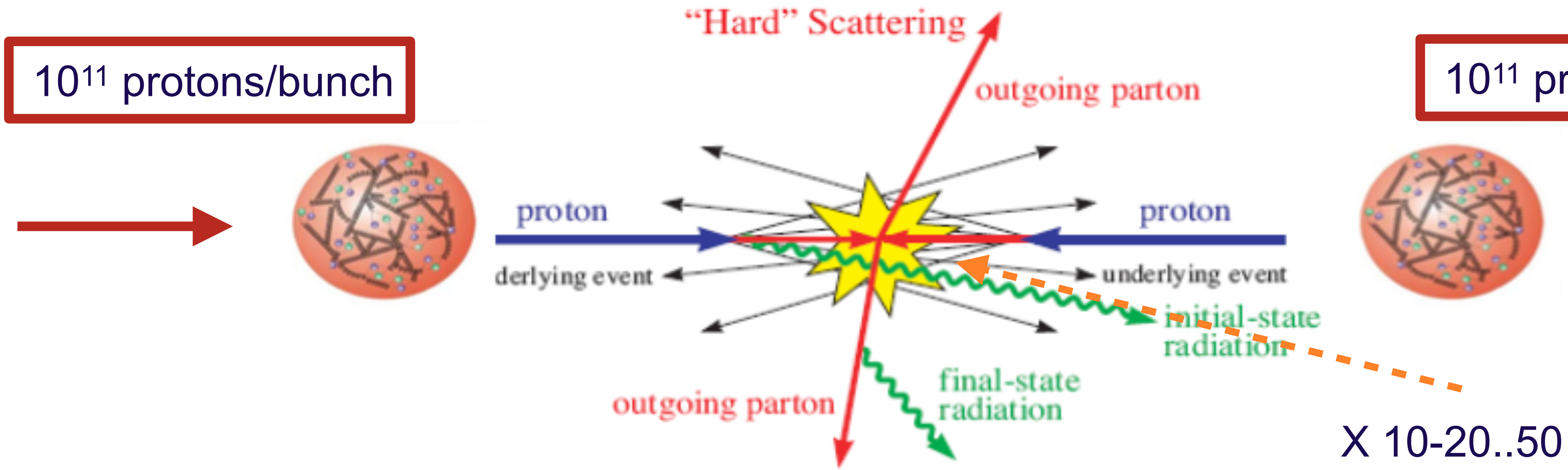

Cooling block
Mounting bracket



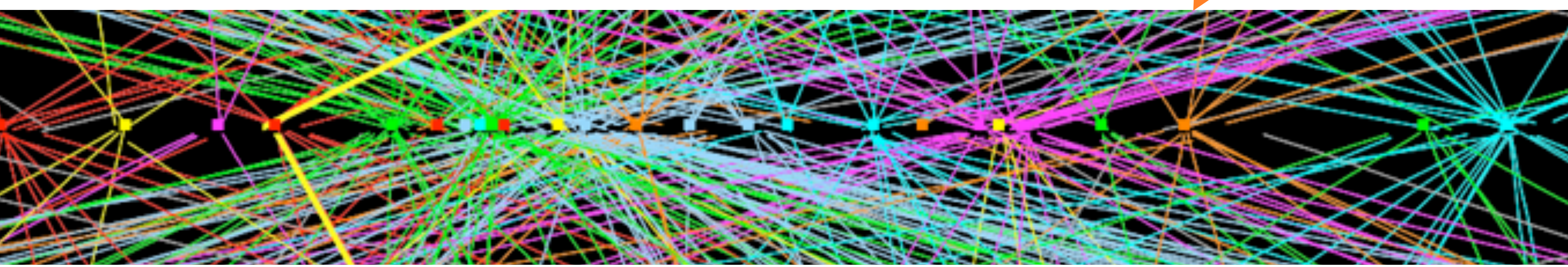
PILE-UP of COLLISIONS

10^{11} protons/bunch

10^{11} protons/bunch



Multi-collisions per beam crossing



Ability to separate individual collisions - 40 MHz

TRACKING DETECTOR

Measure charged particles momentum

Uniform magnetic field

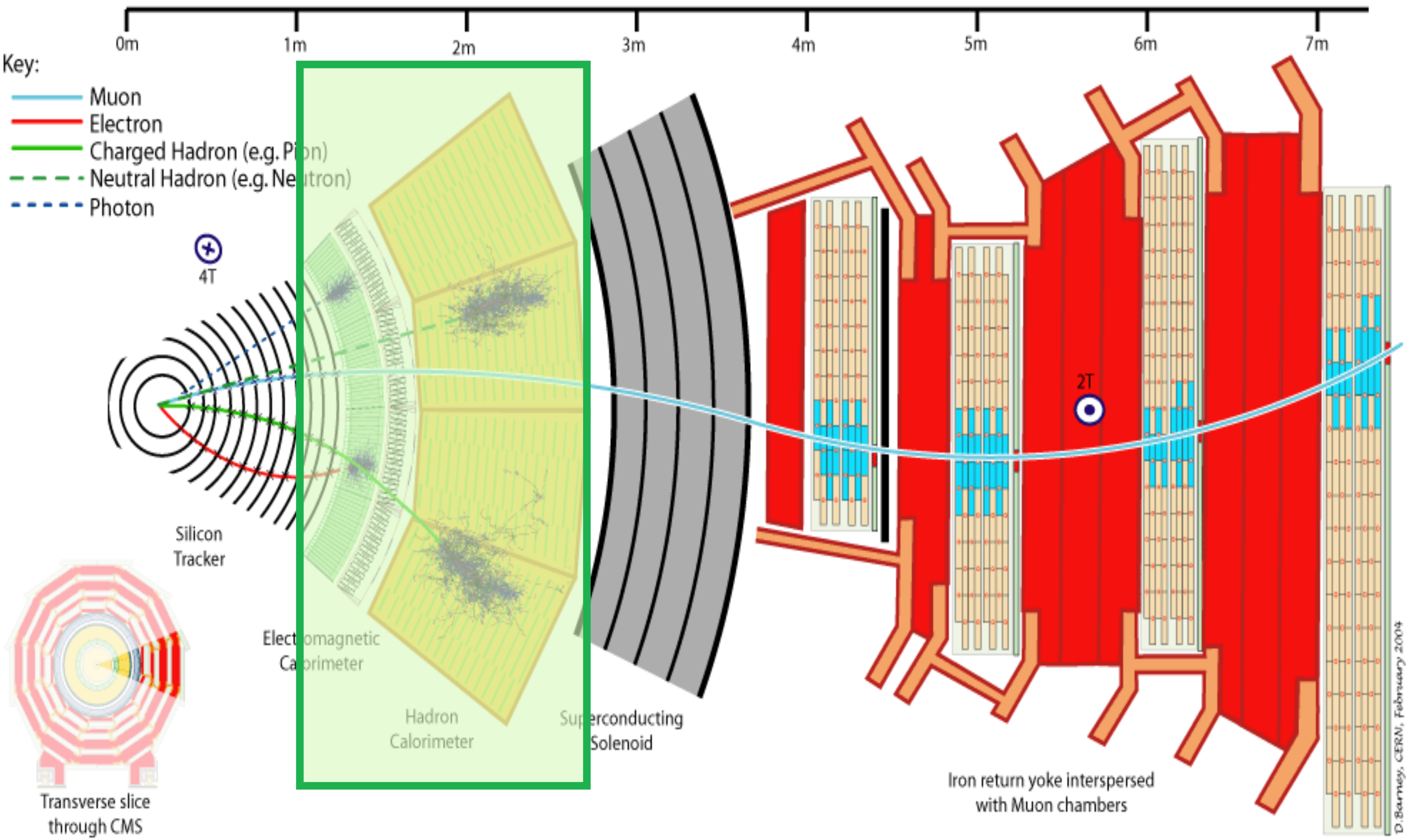
High position resolution $\longrightarrow$ high momentum resolution

Close to the beams

$\longrightarrow$ **high particle density**

$\longrightarrow$ **small cell size**

DETECTOR: CALORIMETERS



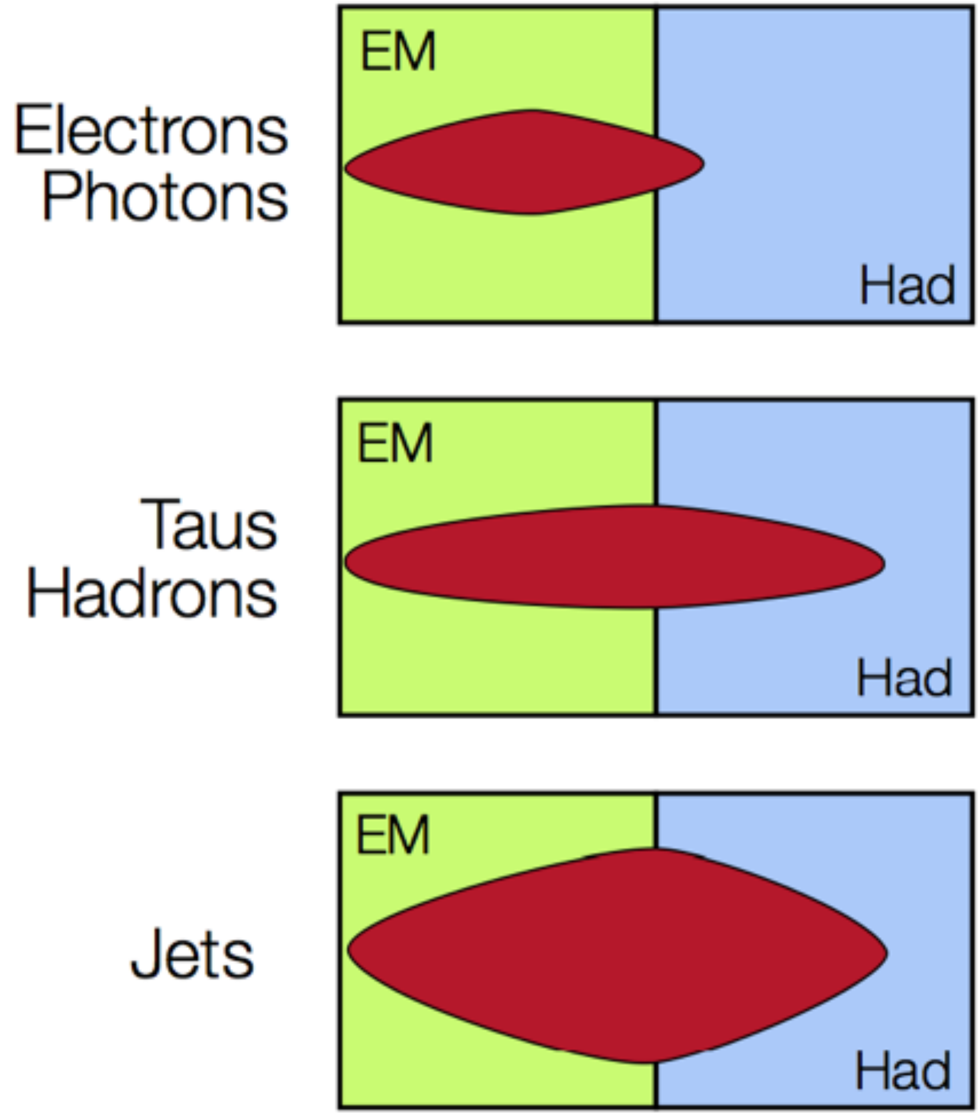
INTERACTIONS vs INCOMING PARTICLES

CALORIMETERS ARE DESTRUCTIVE

PARTICLES DO NOT COME OUT of THE CALORIMETER

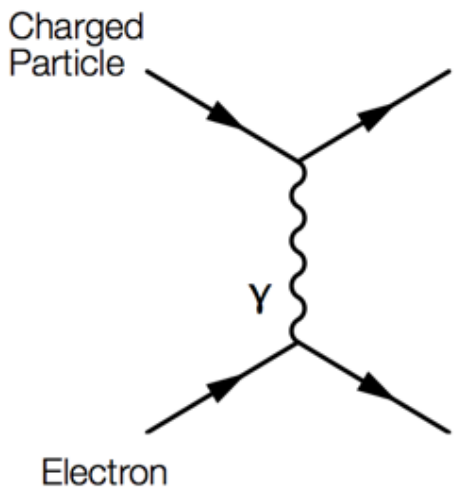
ELECTRONS, PHOTONS, HADRONS
ARE ABSORBED by the CALORIMETERS

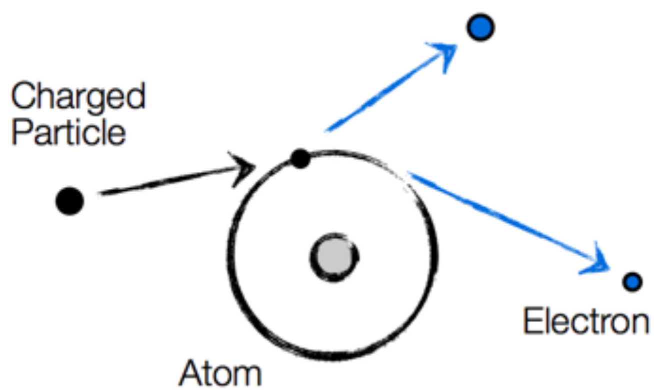
ONLY MUONS and NEUTRINOS ESCAPE



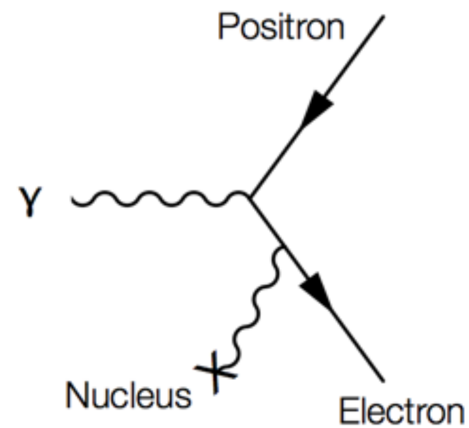
EXAMPLES of INTERACTIONS

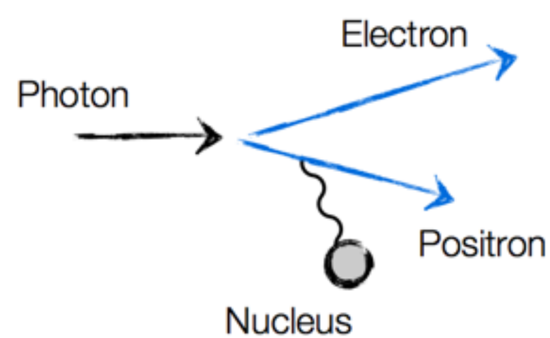
Ionisation



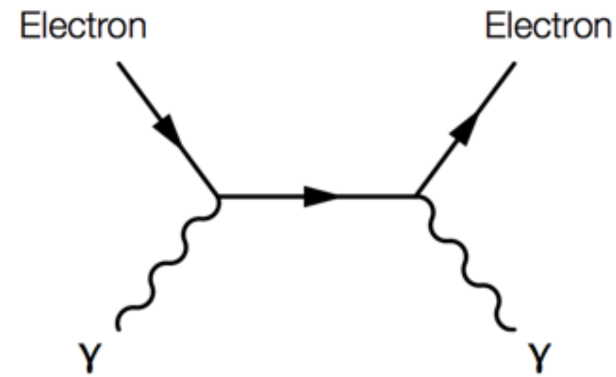


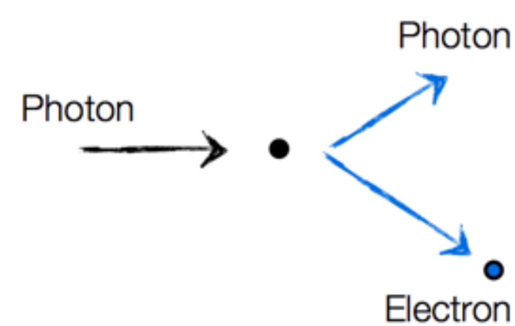
Production de paires e^+e^-



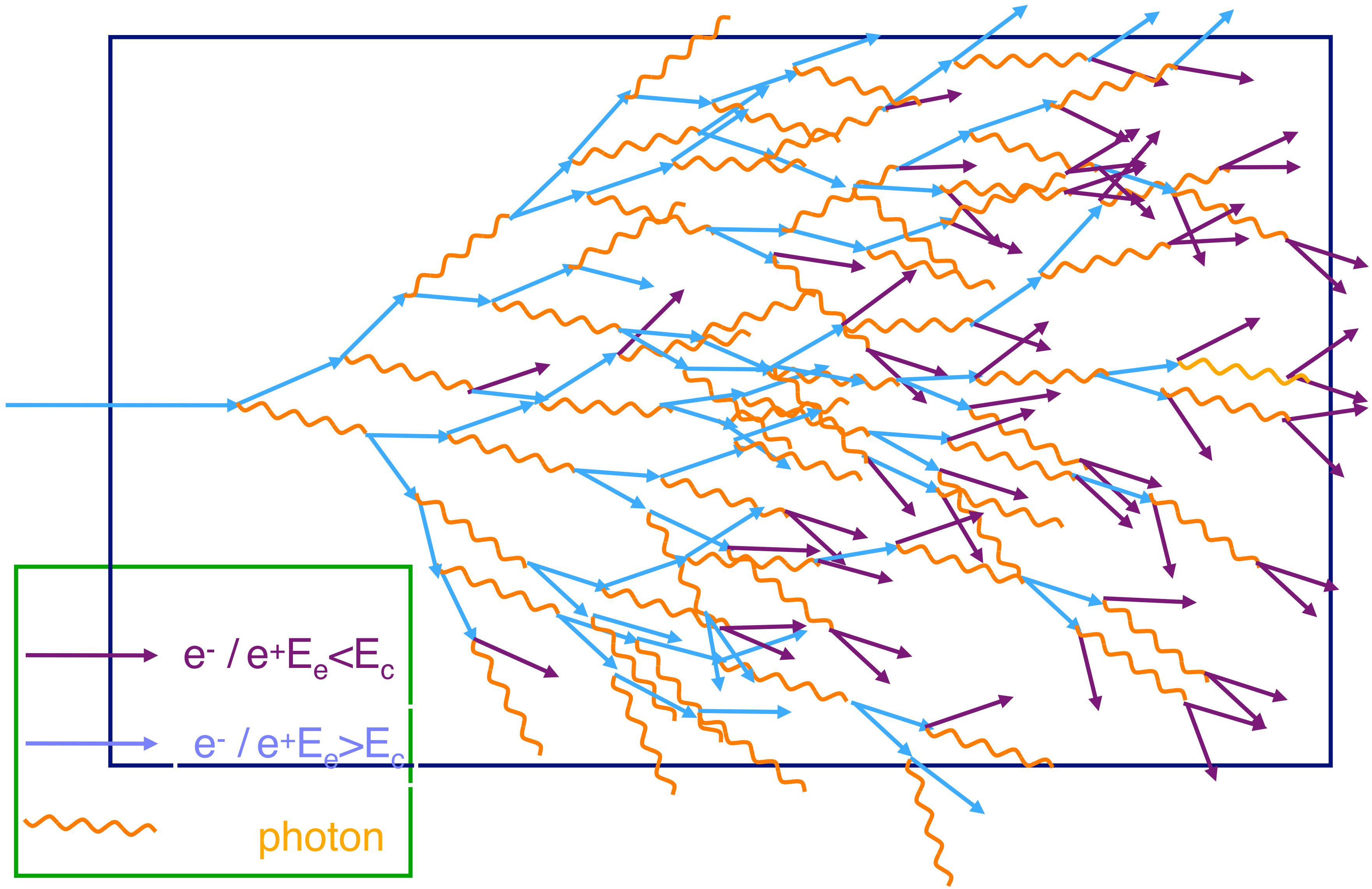


Diffusion Compton





ELECTROMAGNETIC SHOWER

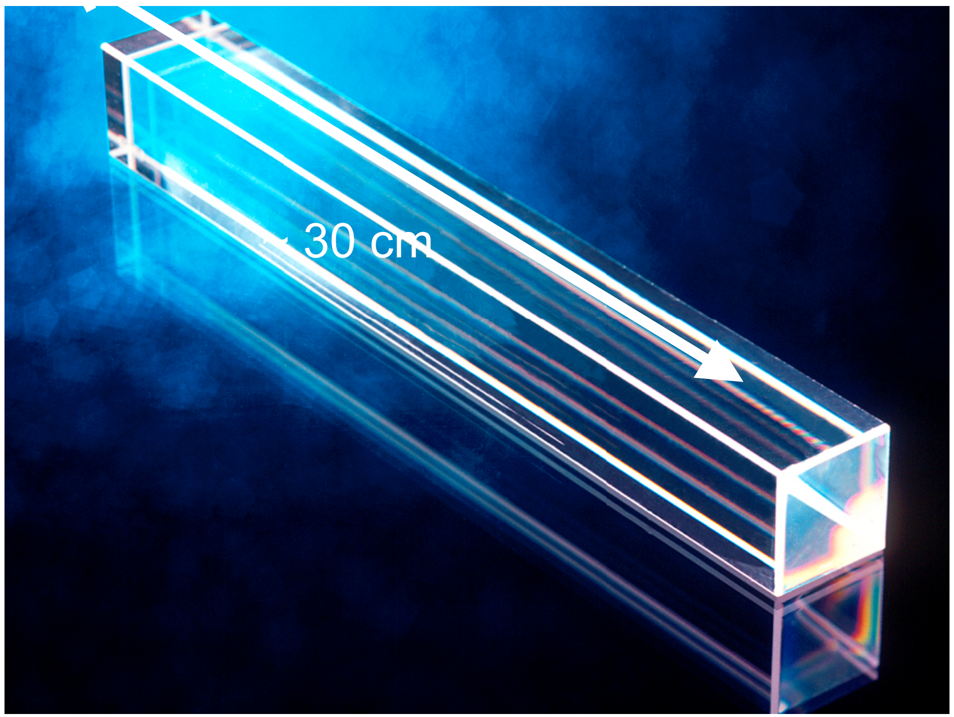


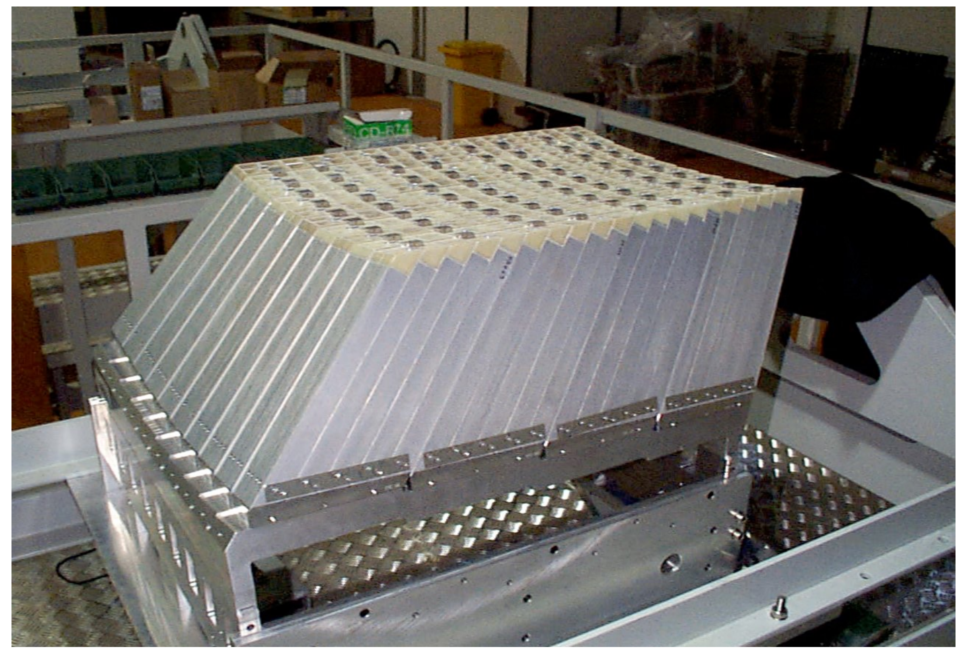
The CAVERN has a FINITE SIZE

CALORIMETERS measure PARTICLE ENERGY

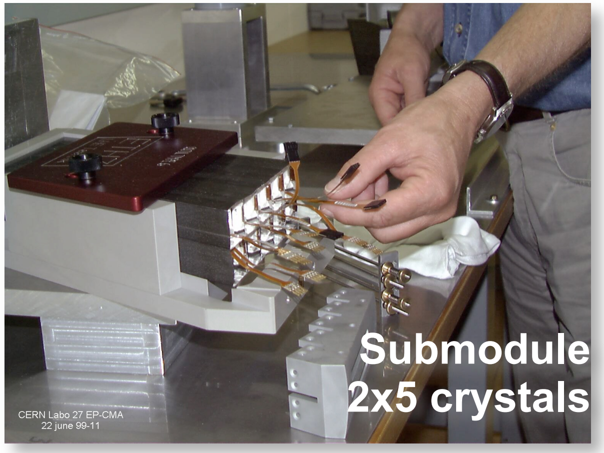
75k channels

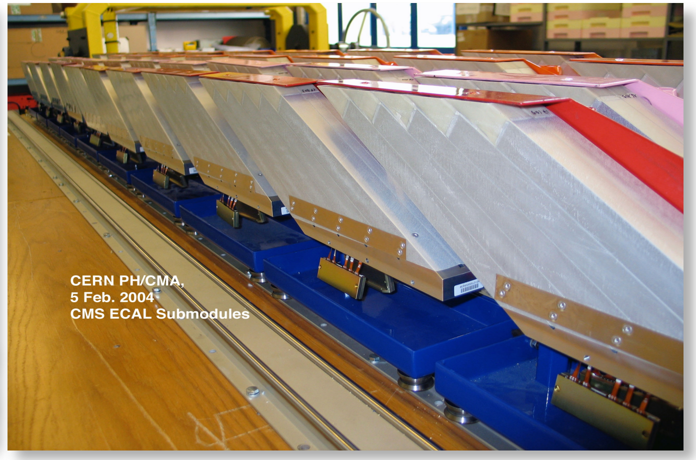
$\Delta E/E \sim 3\text{-}5\%/\sqrt{E} \oplus 150\ \mathrm{MeV}/E \oplus 0.5\%$

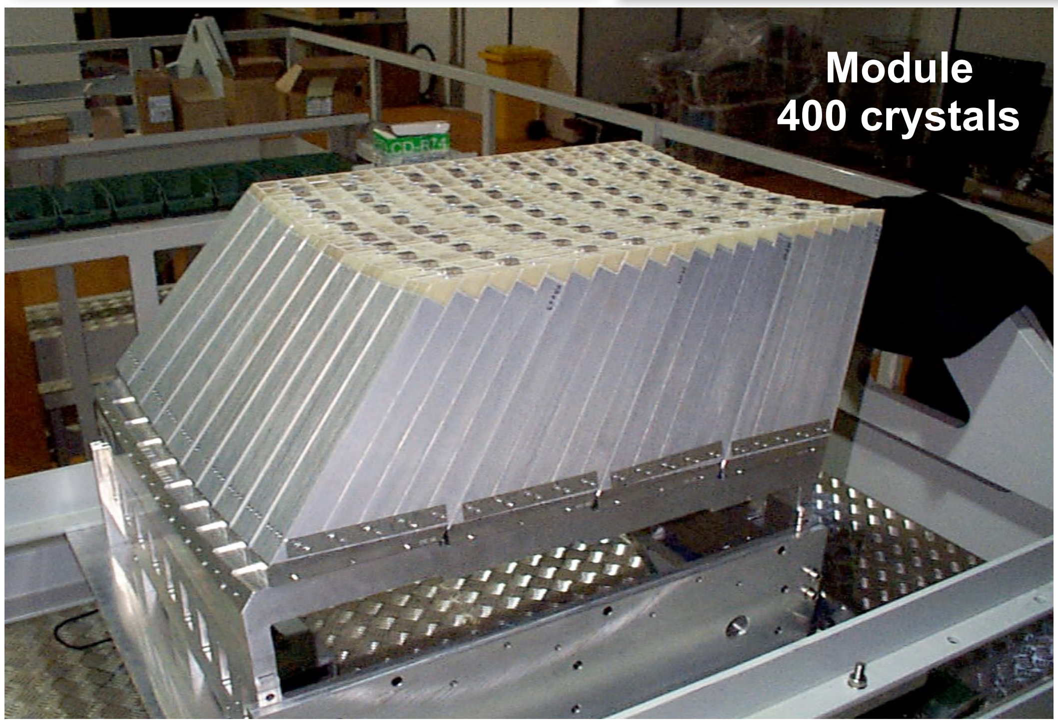


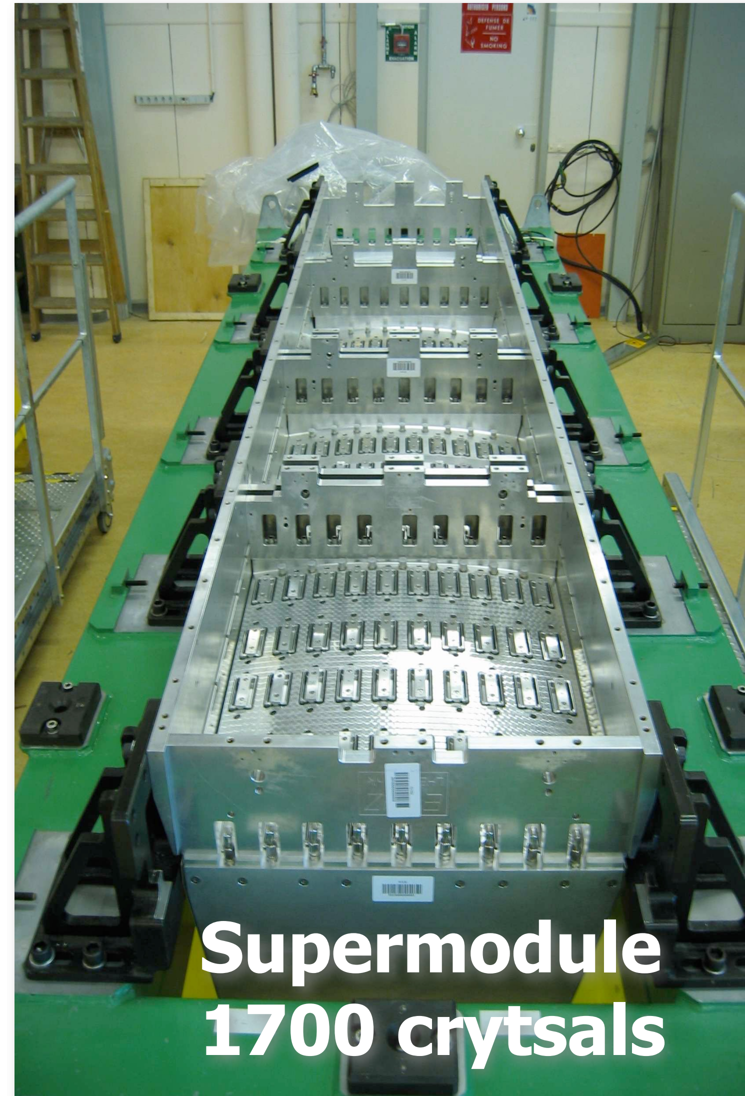


CONSTRUCTION of the CMS CALORIMETER



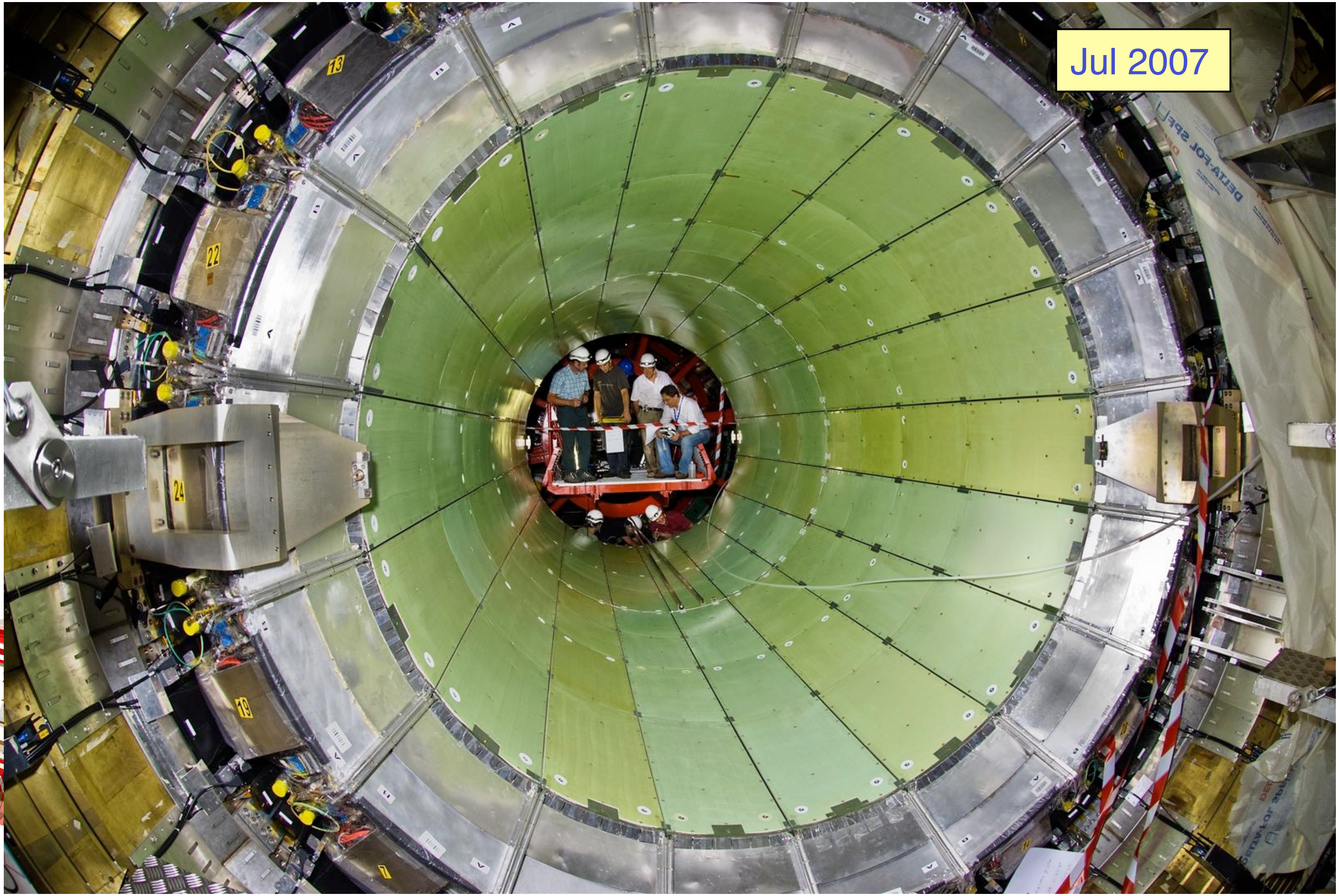




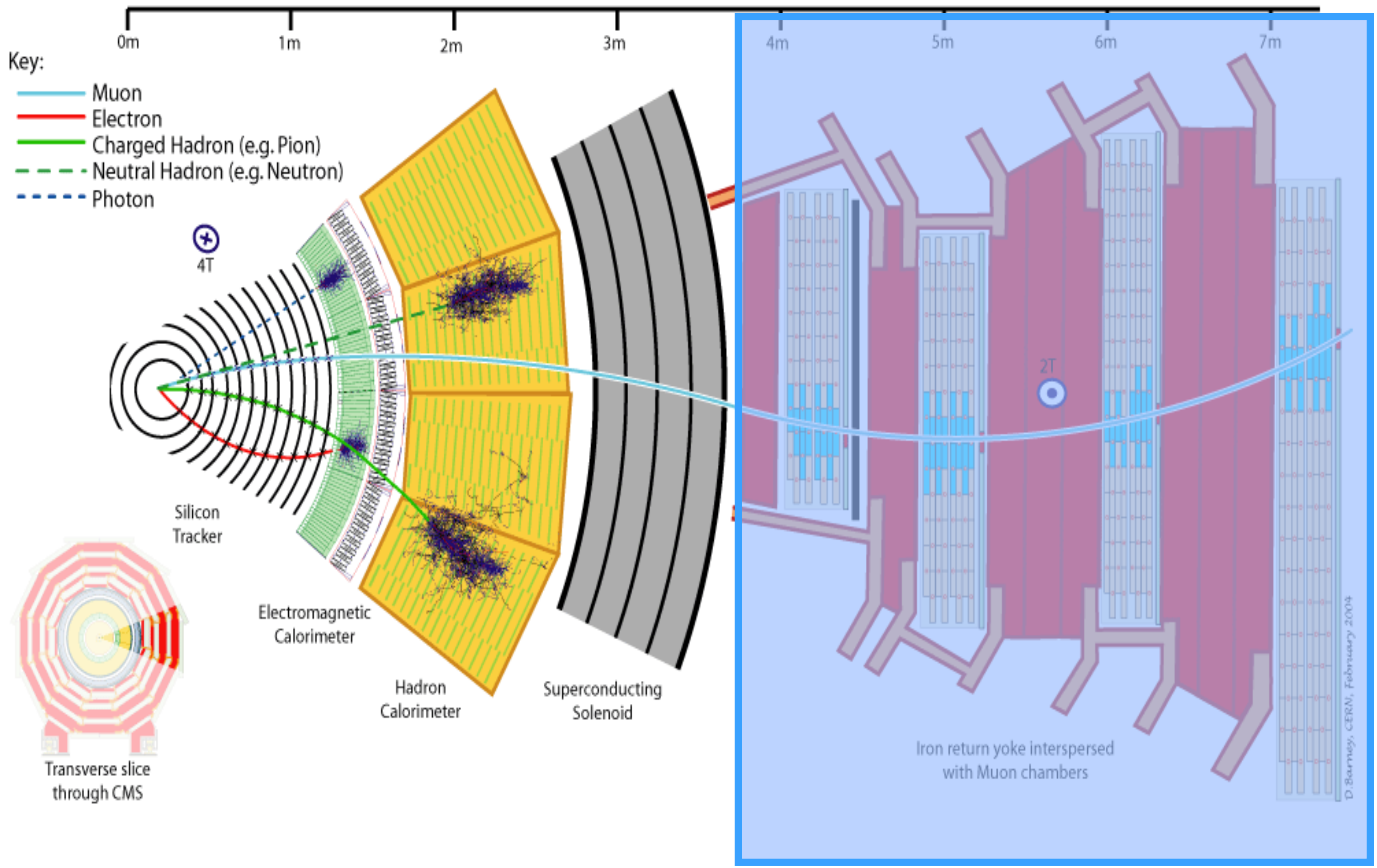


Total 36 Supermodules

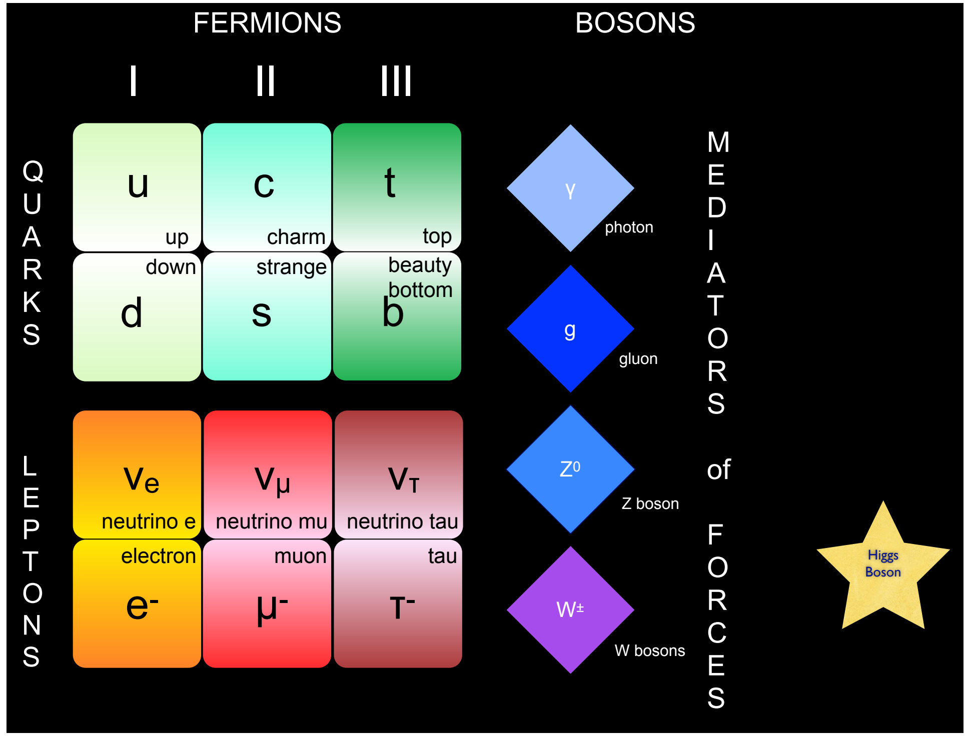
CONSTRUCTION of the CMS CALORIMETER



DETECTORS: MUON SPECTROMETER



MUONS



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

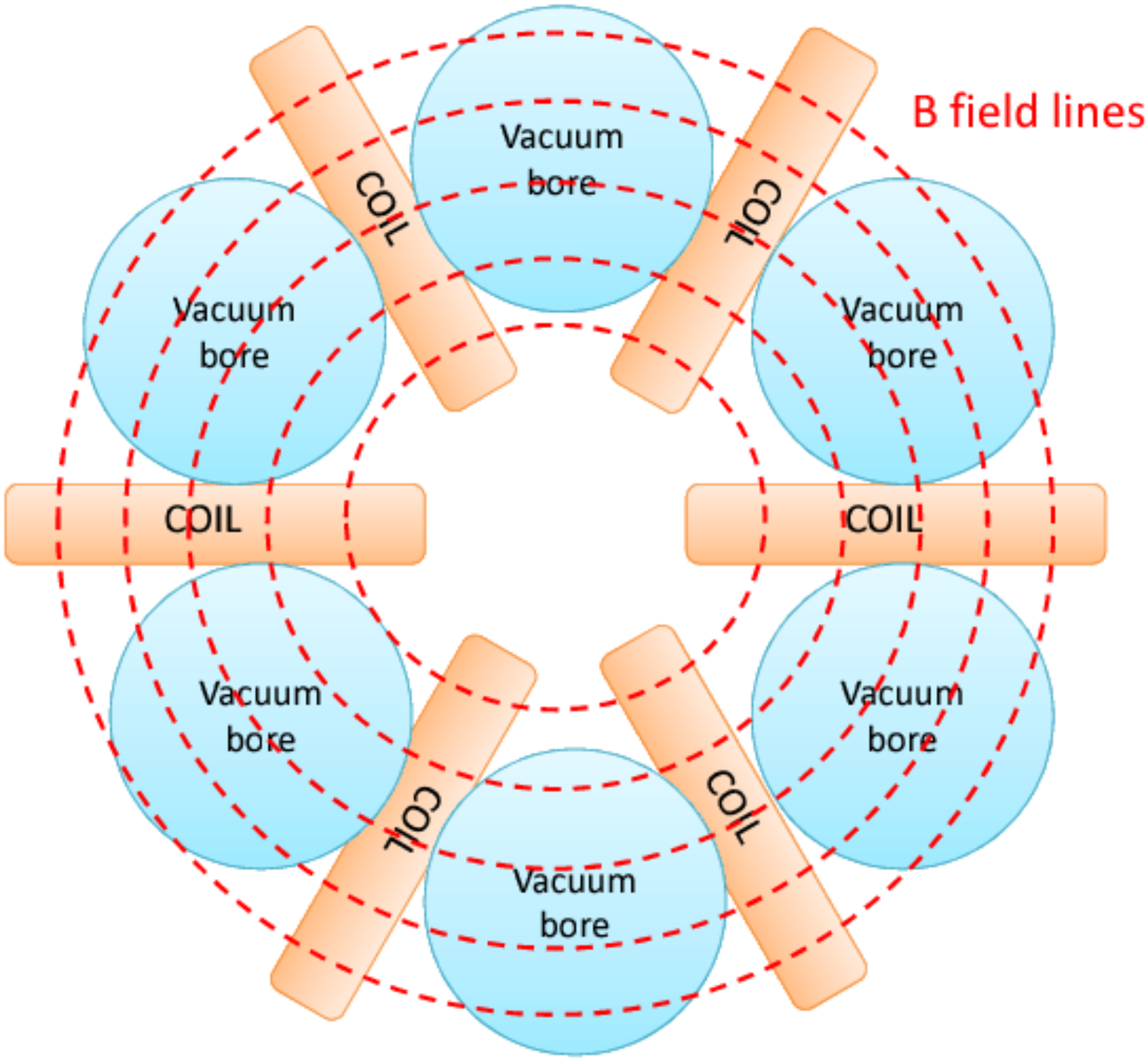
Electromagnetic interaction: $1/m^2$

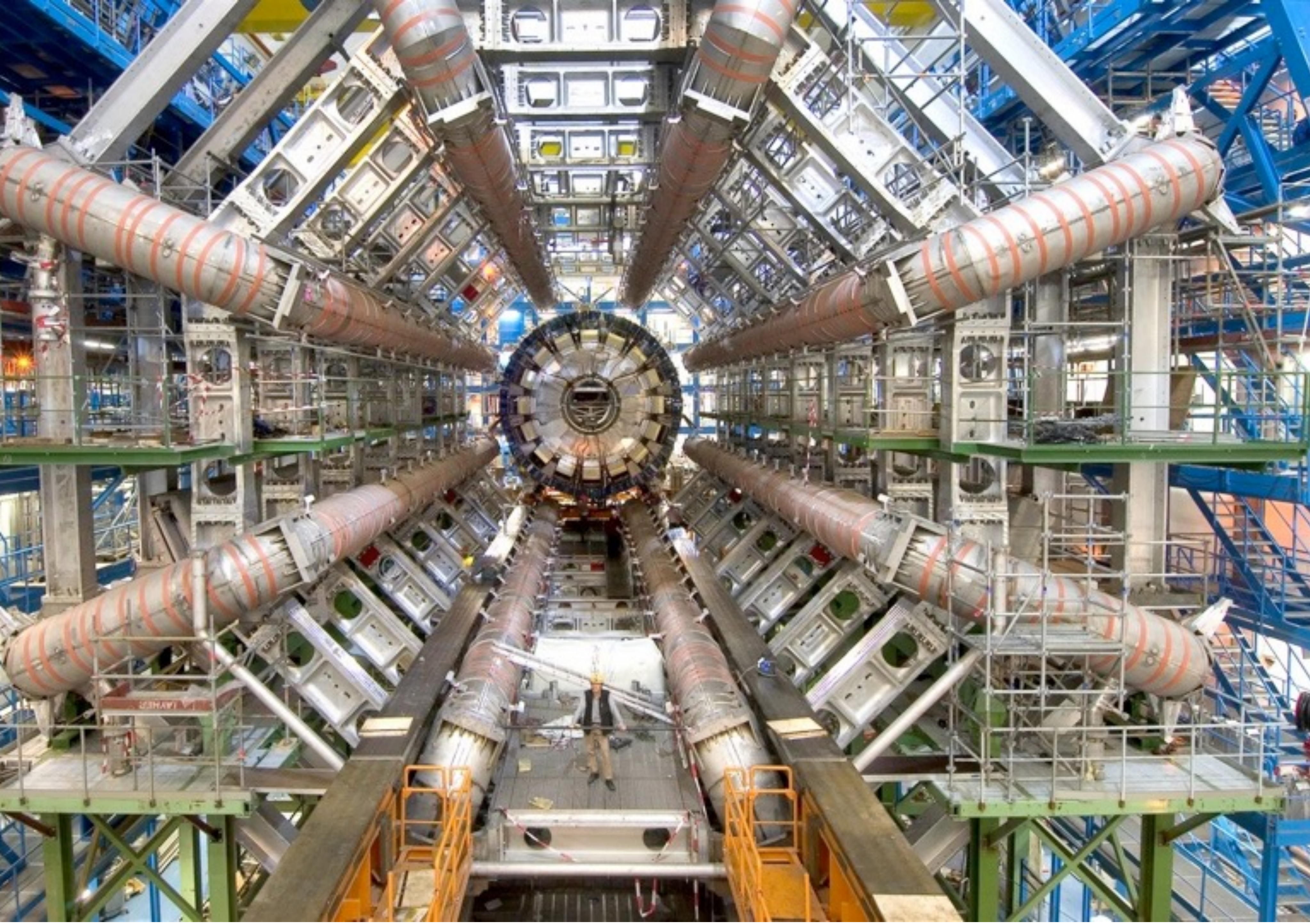
μ interact with matter 40000 times less than electrons

They essentially do not notice the presence of the calorimeter

Detection with the muon spectrometer

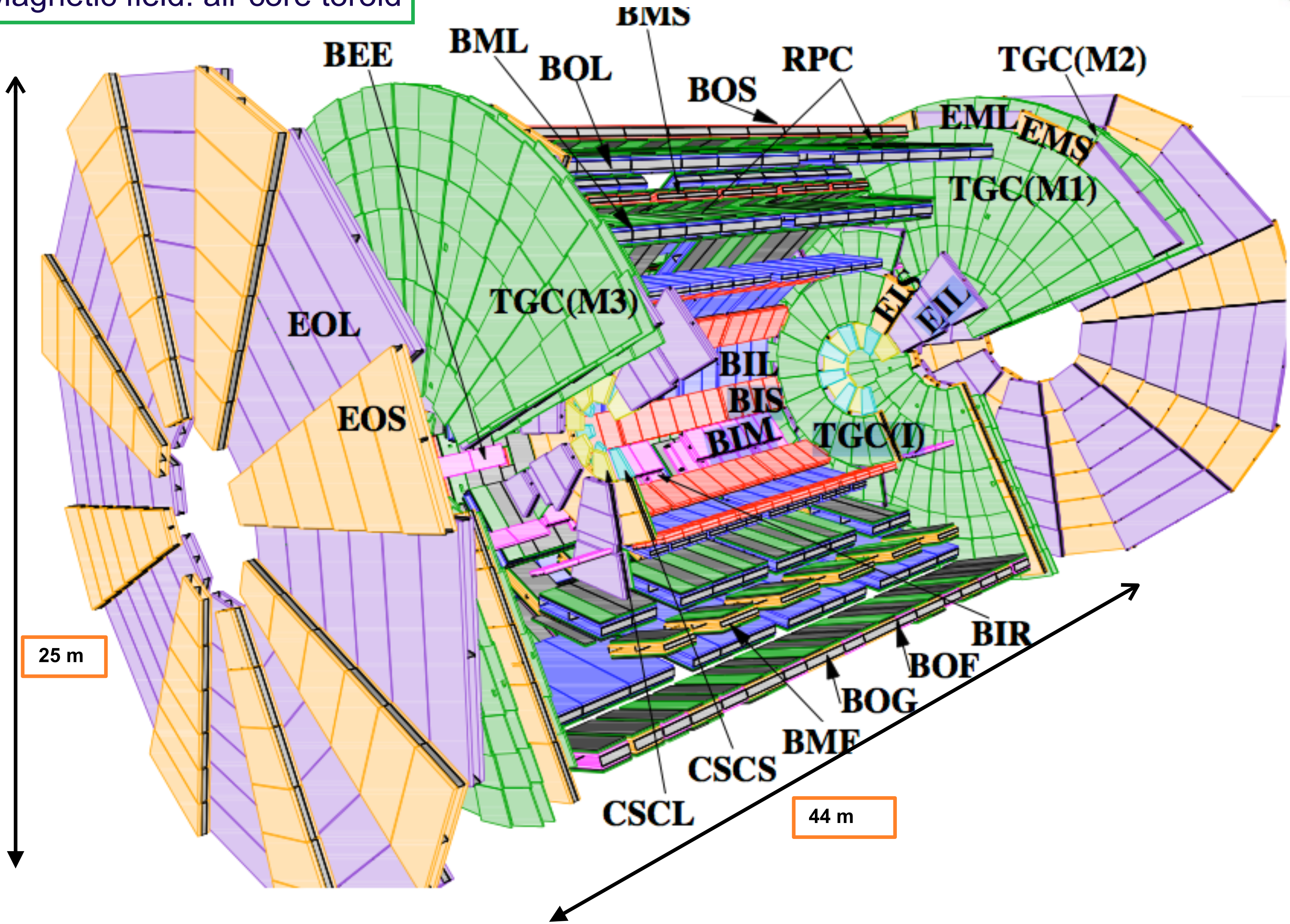
AIR CORE TOROID



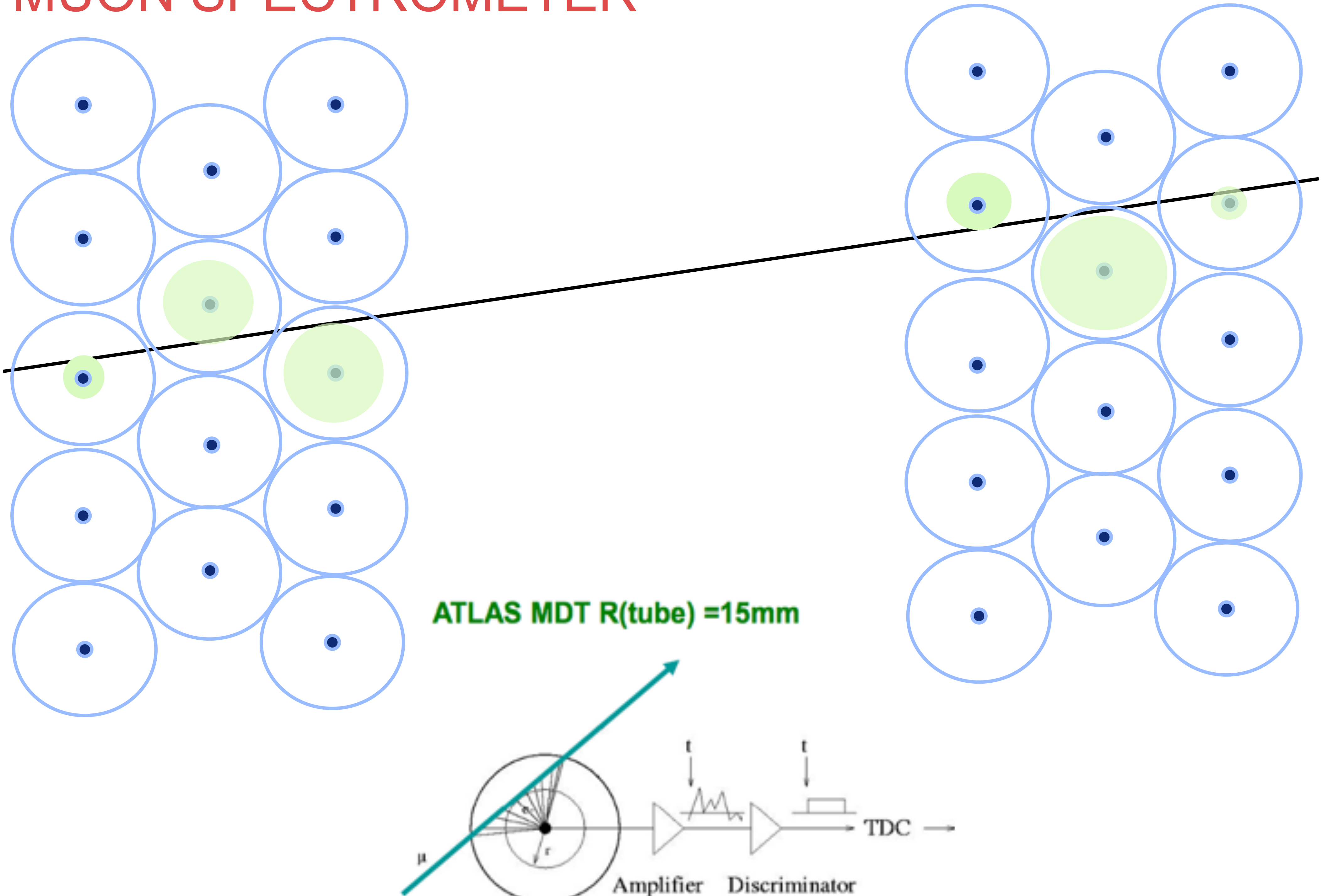


MUON SPECTROMETER

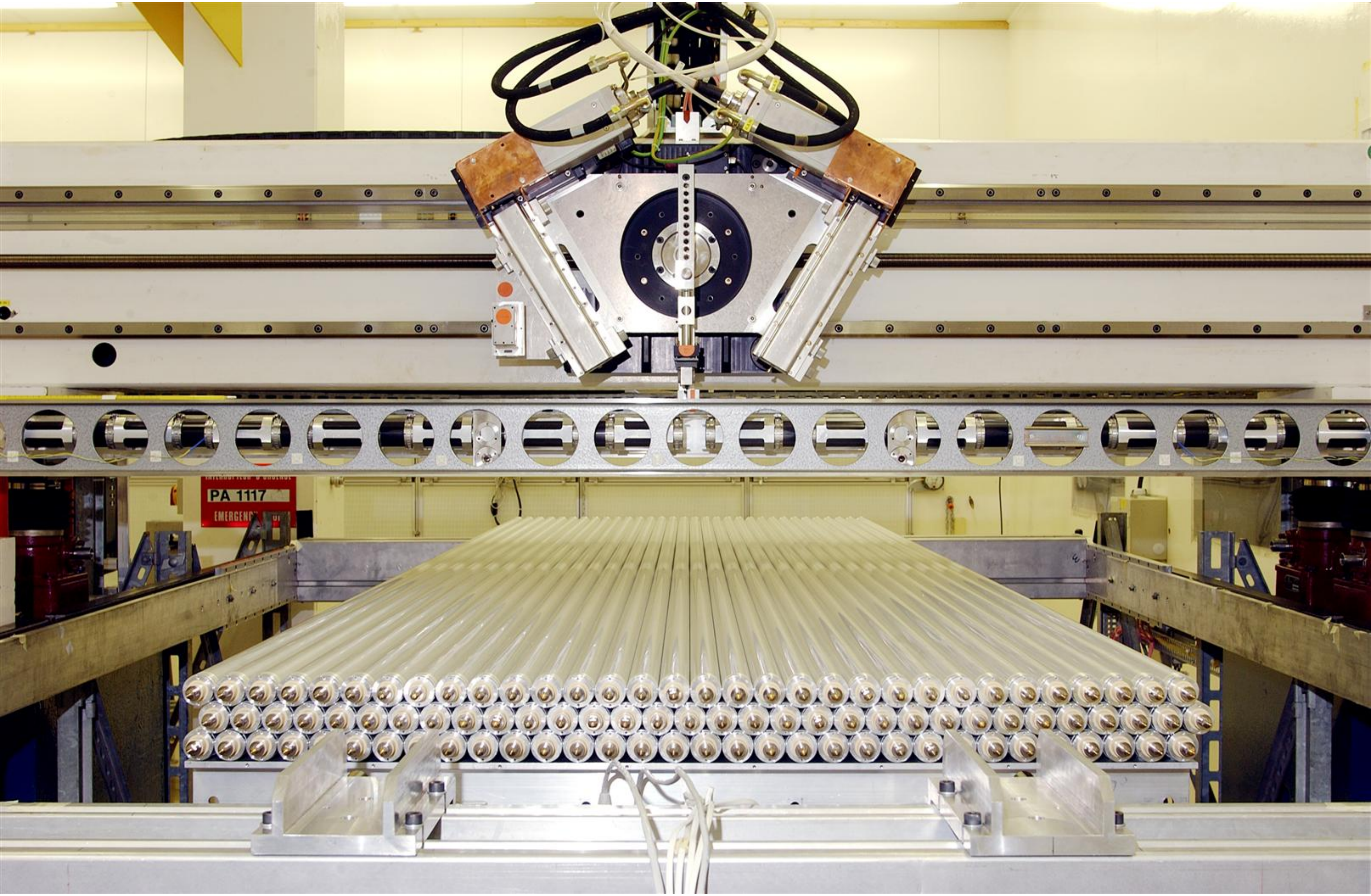
Magnetic field: air core toroid



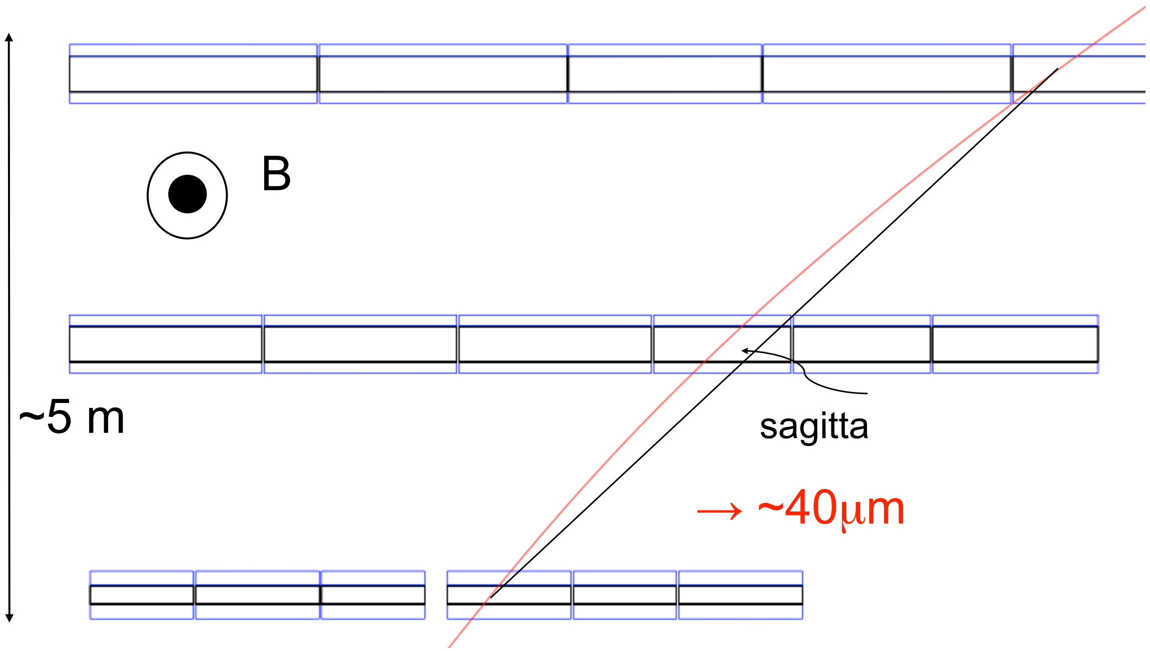
MUON SPECTROMETER

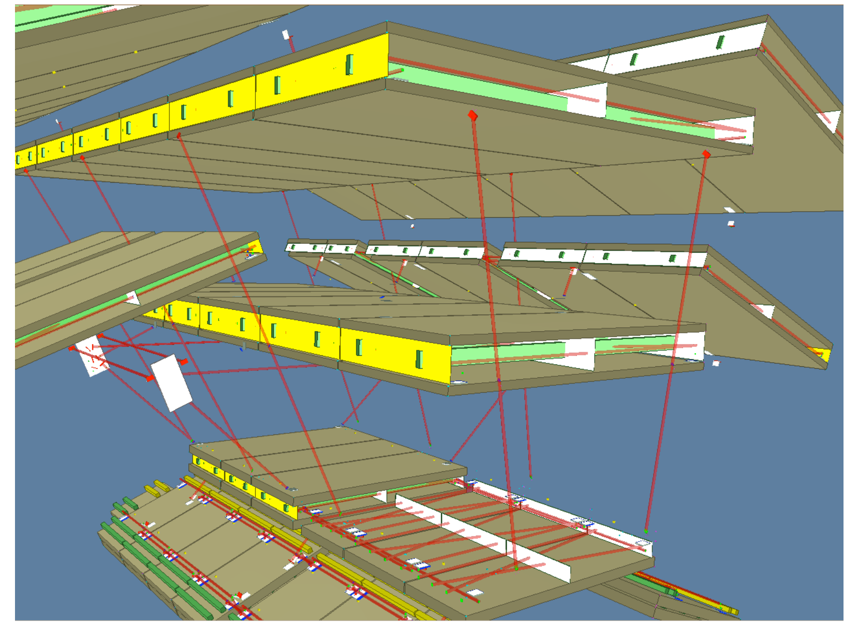


Drift tubes for μ detection - ATLAS muon spectrometer



MUON SPECTROMETER





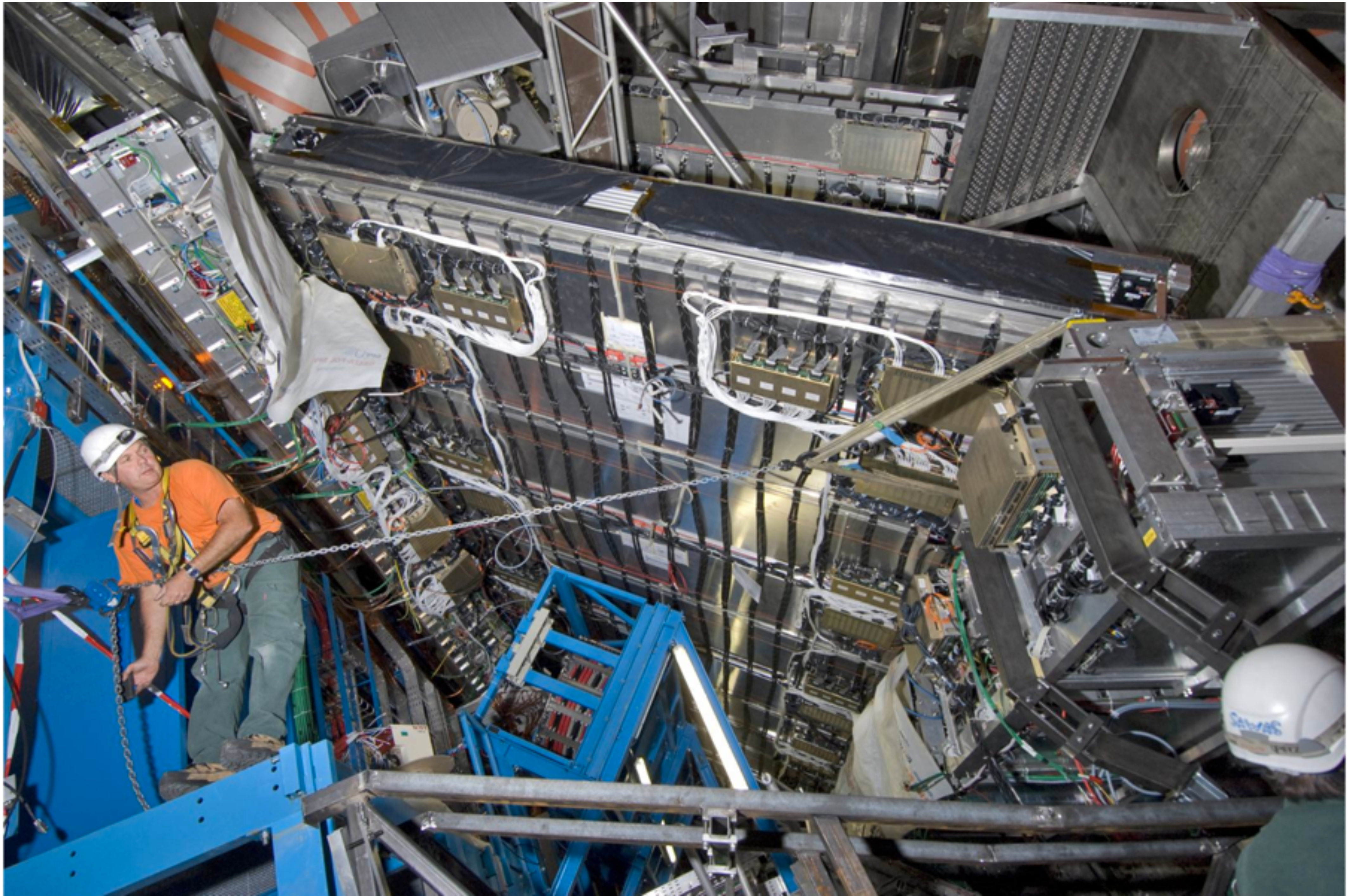
Specific to ATLAS : Air core Toroïd
Minimise matter encountered by muons

WHY ???

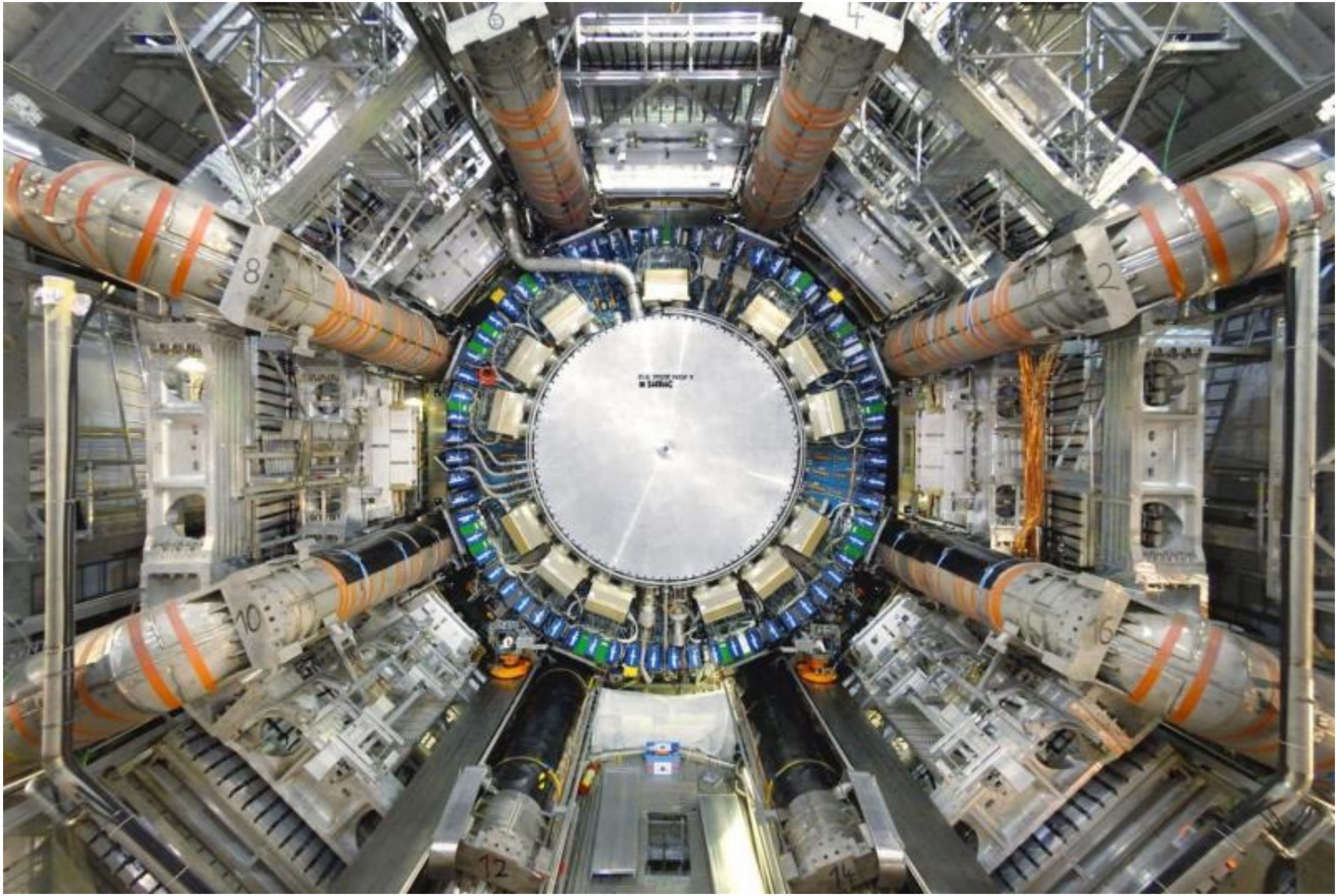
p_T<100 GeV	$\delta p_T/p_T$ ~2%
p_T~1 TeV	$\delta p_T/p^T$ ~10%


Friderici
special s.a.

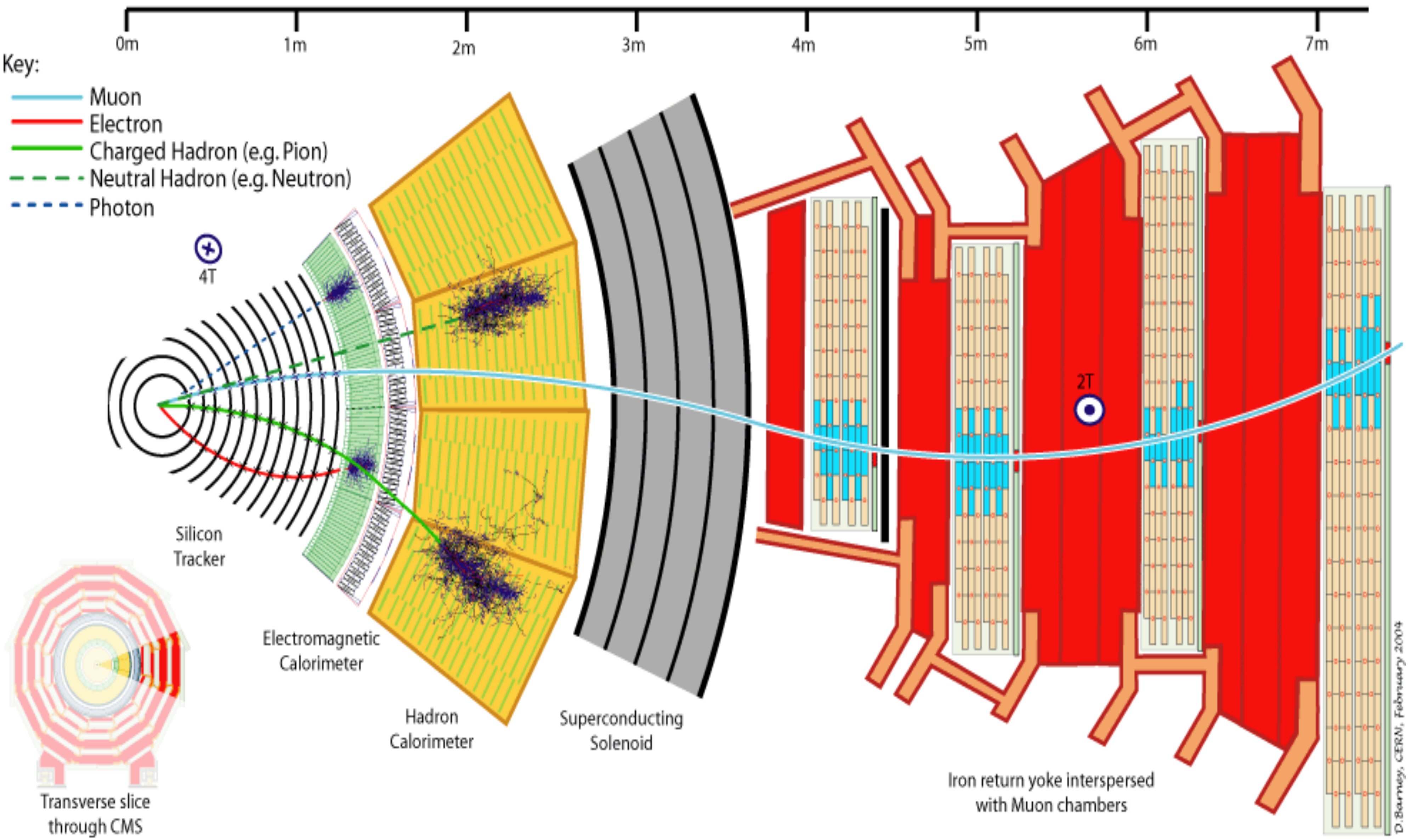
MUON CHAMBERS in ATLAS



TOROID + MUON CHAMBERS

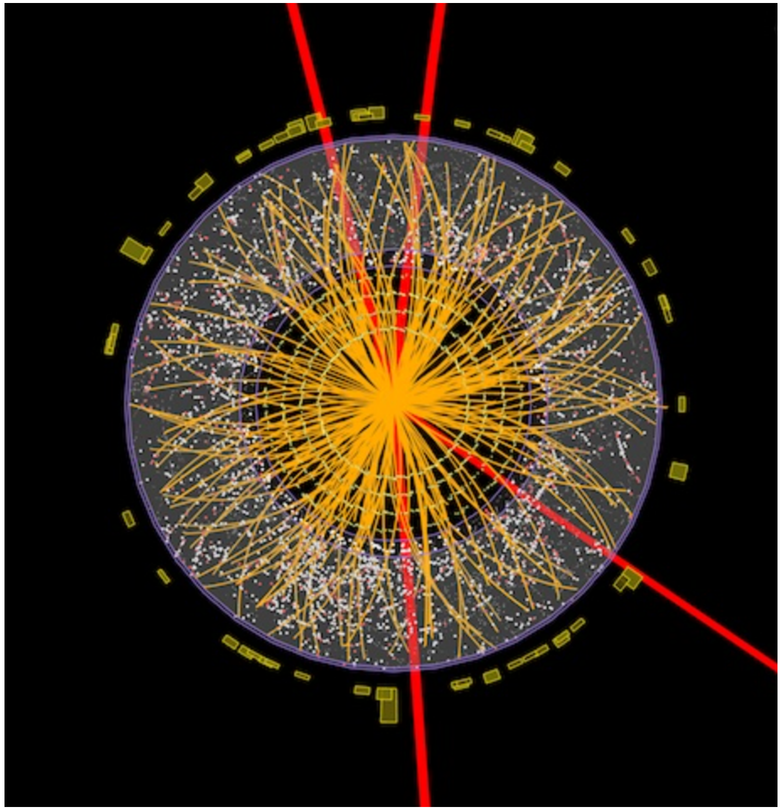


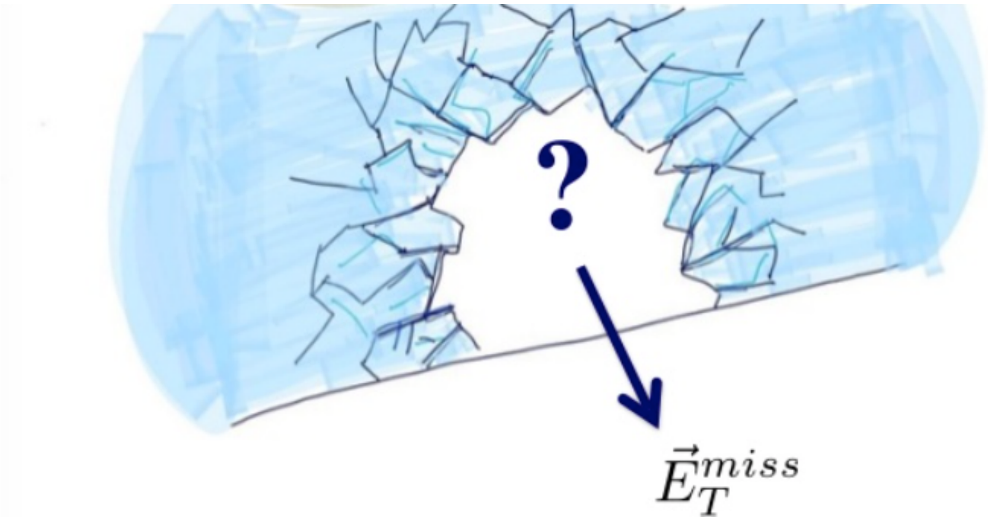
DETECTOR MISSING TRANSVERSE ENERGY

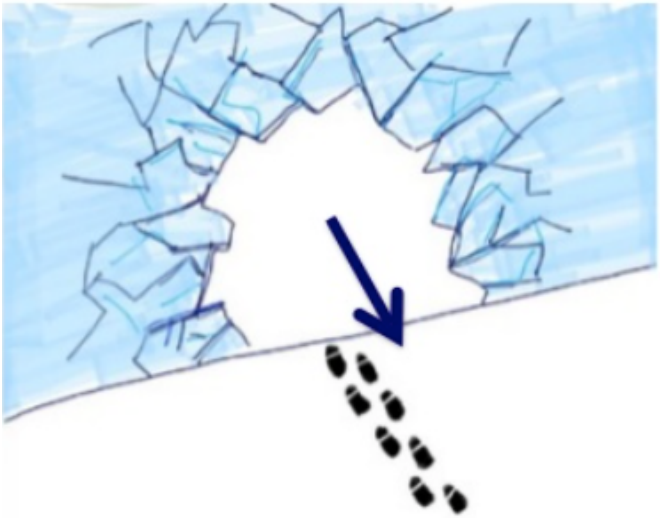


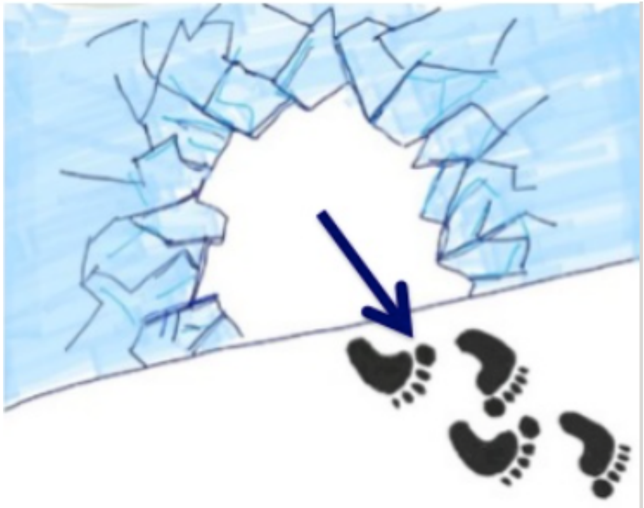
ENERGY BALANCE

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









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