



Rivelatori e Apparati

Lezione 1 – Introduzione corso

“Rivelatori a Semiconduttore e Apparati per la Fisica Nucleare e Subnucleare”

- Insegnamento *a scelta*
- 1° anno Magistrale (aperto anche agli studenti del 2° anno M.)
- 5h a settimana per un totale di 52h
 - Probabile pausa intorno all’ultima settimana di Novembre
 - Completamento del Corso previsto entro Natale
- Lezioni frontali + dimostrazioni di laboratorio & discussione articoli
- Esame orale su contenuti insegnamento e applicazioni
 - Data da concordare individualmente
- Materiale aggiunto su moodle durante il corso

- Orario: Lun 14-16, Gio 11-13, Gio 16-17*

- *Contattatemi qui:* giacomo.contin@units.it – stanza 122

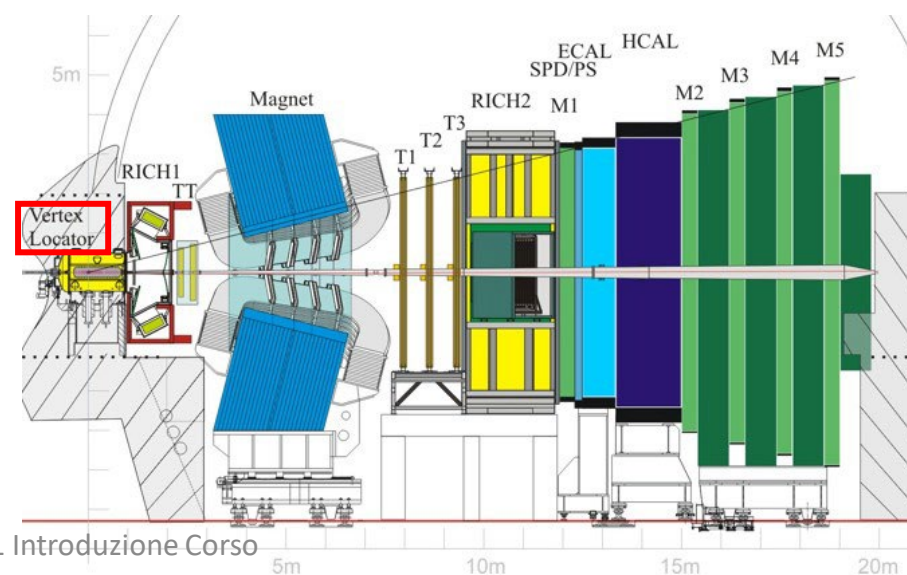
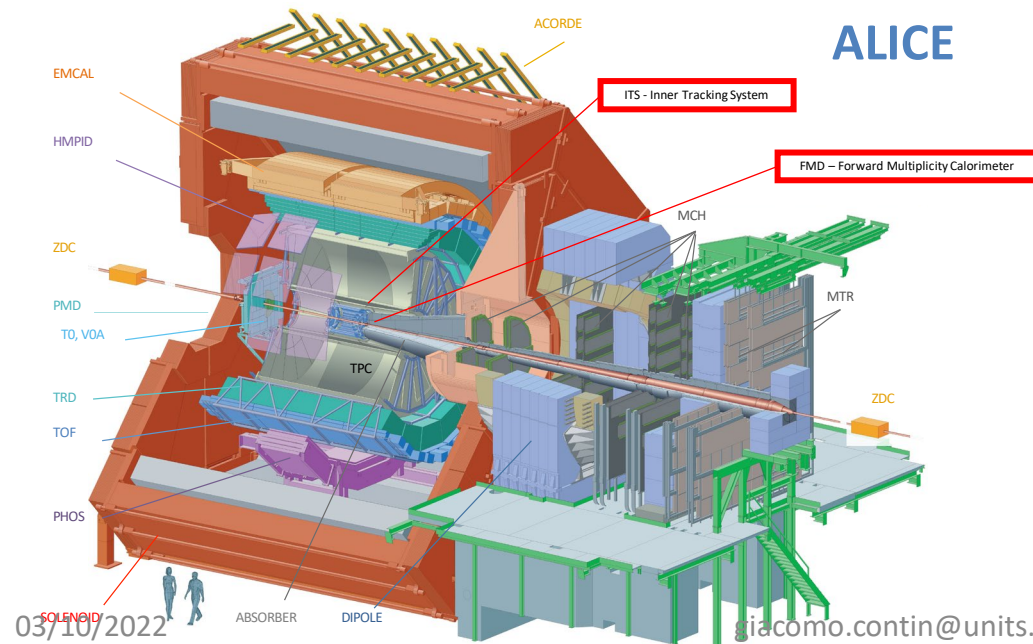
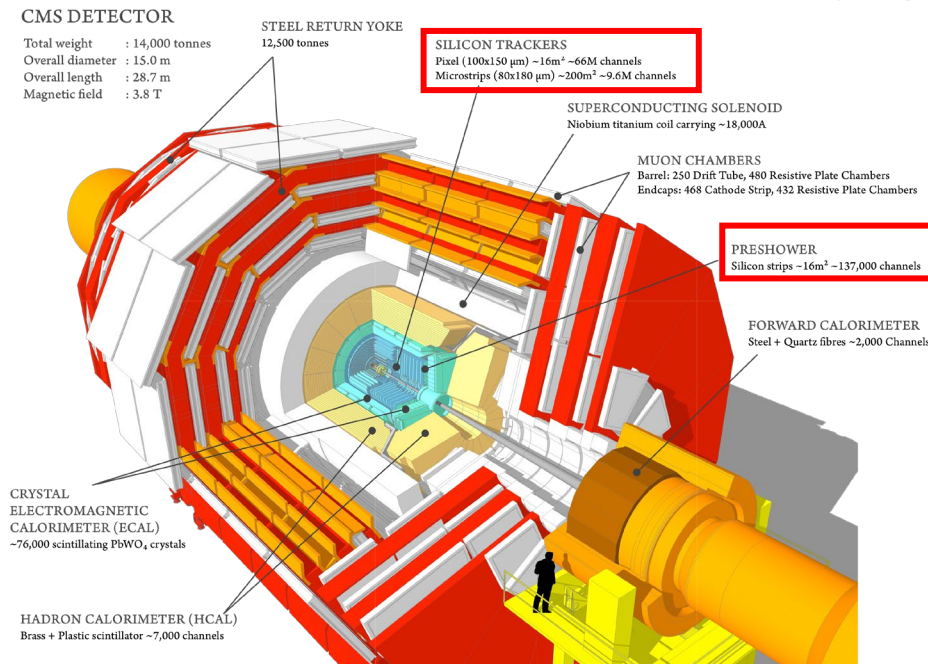
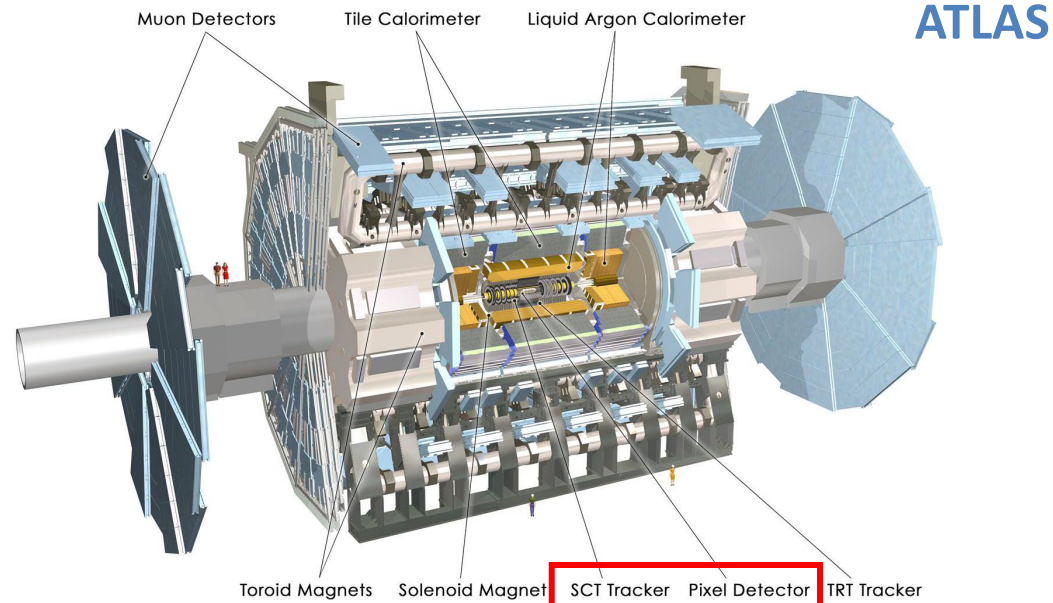
Programma del corso (in sintesi)

- Perdita di energia e Scattering Coulombiano
- Semiconduttori intrinseci e drogati
- Giunzione pn inversamente polarizzata
- Raccolta della carica
- Corrente di perdita o leakage
- Il rumore nei rivelatori a semiconduttore
- Preamplificatori e formatori del segnale
- Contatto Schottky e struttura MOS
- Transistor Bipolari e Unipolari
- Rivelatori ad accoppiamento di carica
- Rivelatori a microstrisce di silicio
- Rivelatori a deriva di silicio
- Pixel Ibridi e Monolitici
- Rivelatori di silicio per misure di tempo
- Semiconduttori nei calorimetri
- Fabbricazione sensori
- Danni da radiazione
- Apparati di rivelazione e sistemi di servizio

Testi consigliati corso Rivelatori e Apparati

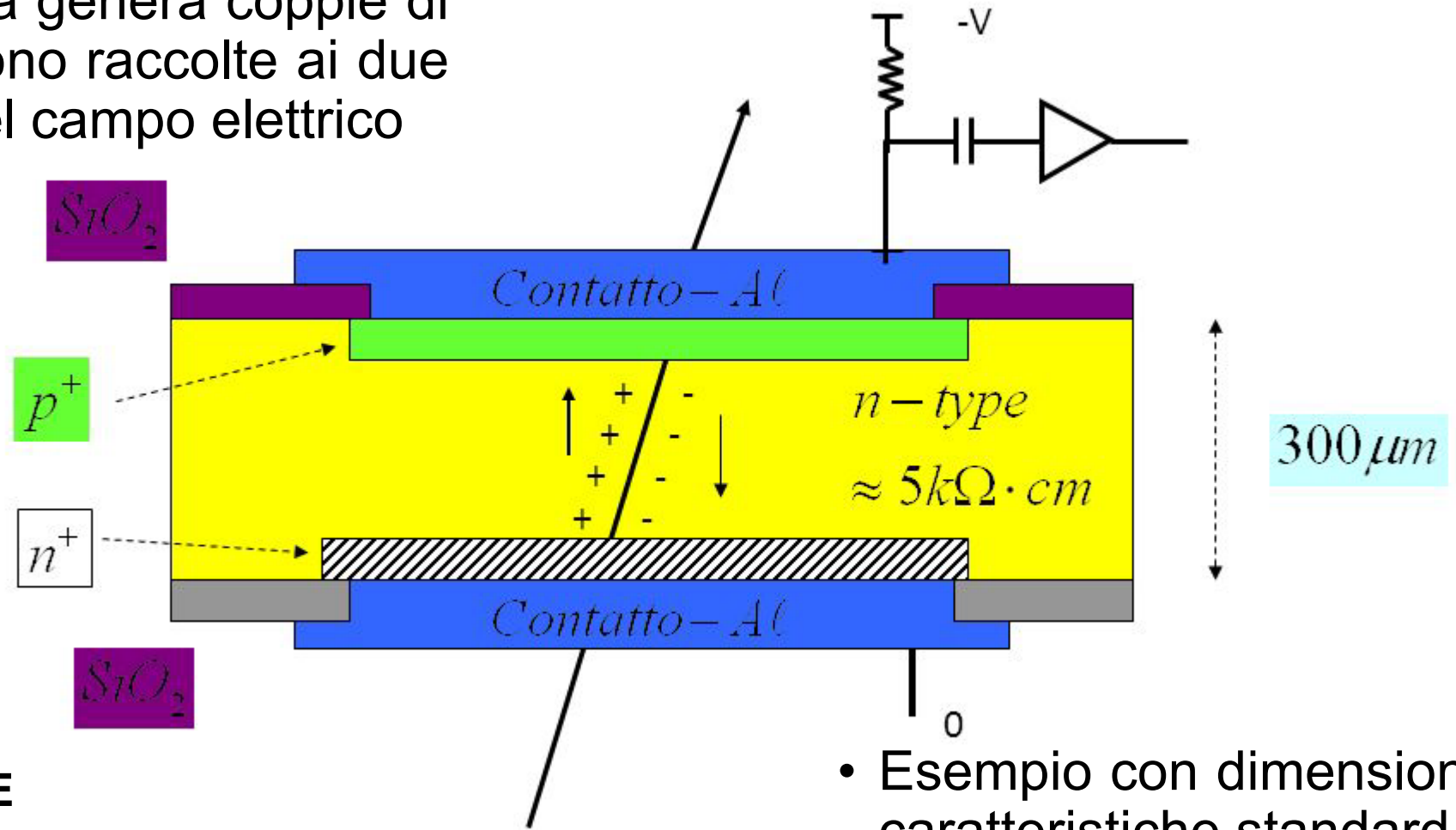
- H. Spieler, “Semiconductor Detector Systems”
- L. Rossi, P. Fischer, T. Rohe, N. Wermes, "Pixel Detectors. From Fundamentals to Applications”
- W.R.Leo, “Techniques for nuclear and particle physics experiments”
- C. Leroy, P.-G. Rancoita, “Principles of Radiation Interaction in Matter and Detection”
- G. Lutz, “Semiconductor Radiation Detectors”
- C. Grupen, B. Shwartz, “Particle detectors”

I rivelatori degli esperimenti di LHC – Ruolo dei rivelatori al silicio è fondamentale



Per cosa li usiamo: rivelare il passaggio

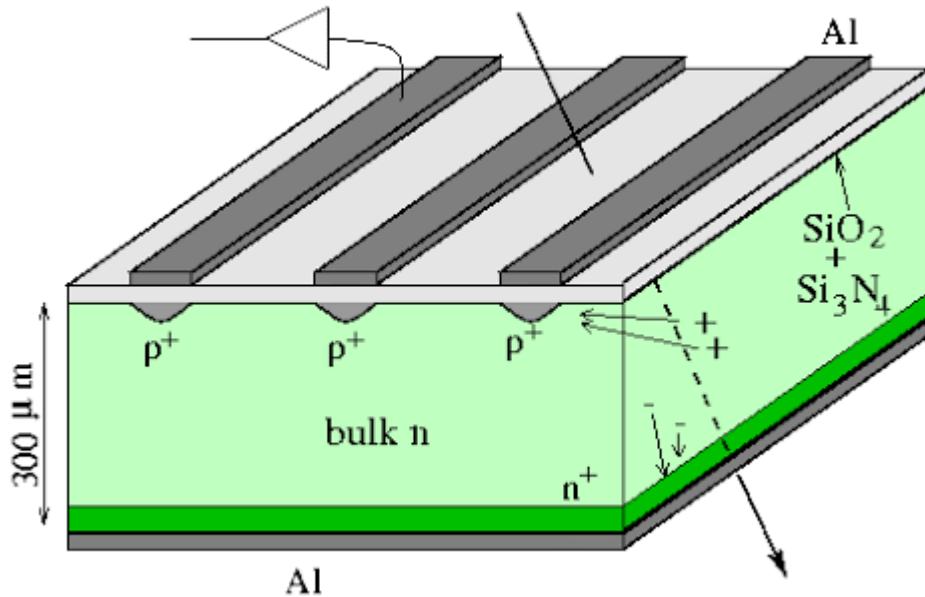
- La particella carica genera coppie di cariche che vengono raccolte ai due capi per **deriva** nel campo elettrico



GIUNZIONE SEMPLICE

- Esempio con dimensioni e caratteristiche standard

Per cosa li usiamo: misurare la posizione (1D)

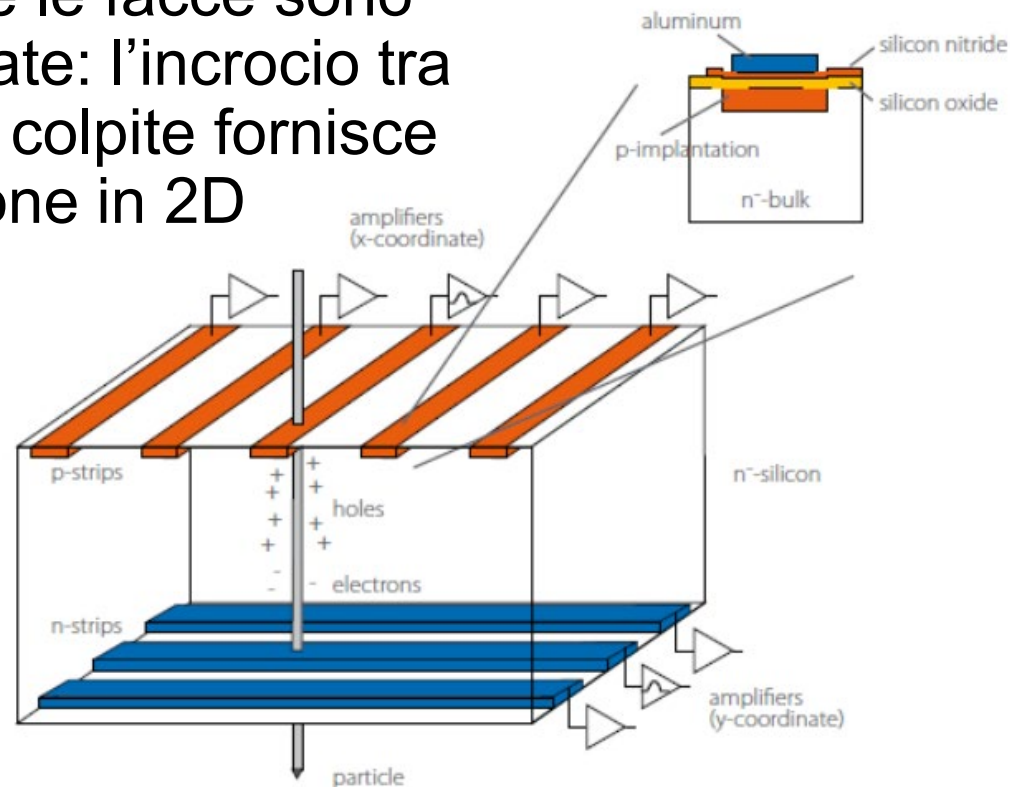


- La superficie del sensore e' segmentata in strisce parallele lungo una direzione: la posizione dei contatti che raccolgono e trasmettono le cariche corrisponde alla coordinata della particella
- La risoluzione spaziale e' data dal passo tra strisce, e puo' essere migliorata misurando l'ampiezza dei segnali

MICROSTRISCE MONOFACCIA

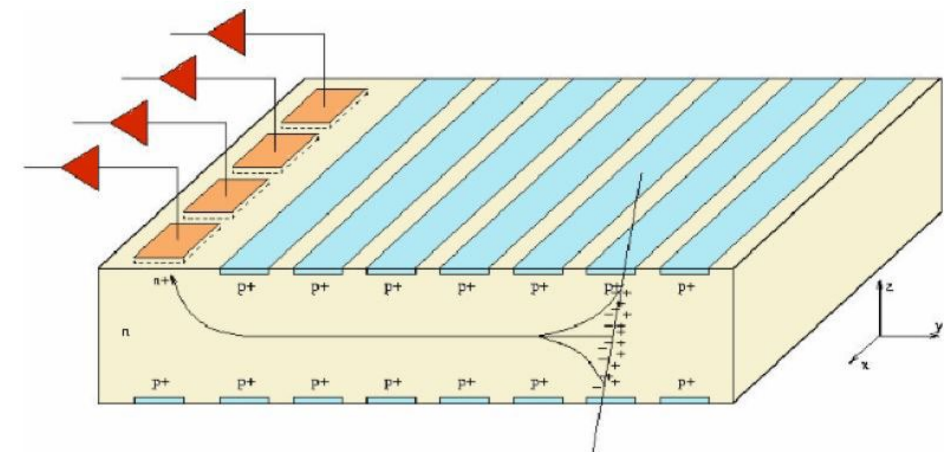
Per cosa li usiamo: misurare la posizione (2D)

- Entrambe le facce sono segmentate: l'incrocio tra le strisce colpite fornisce la posizione in 2D



MICROSTRISCE A DOPPIA FACCIA

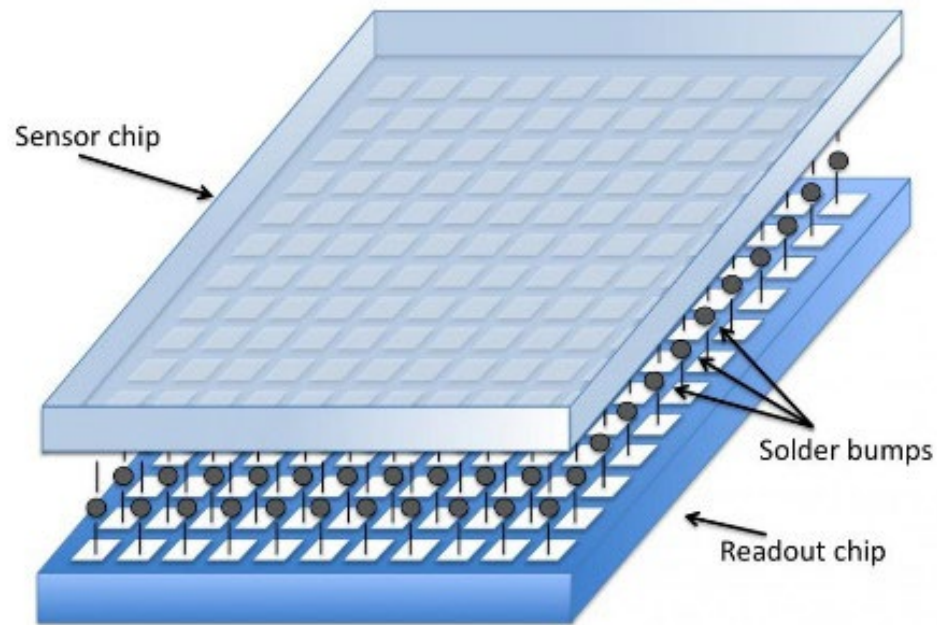
- La seconda coordinata può essere ricavata dal tempo di deriva delle cariche fino al secondo elettrodo



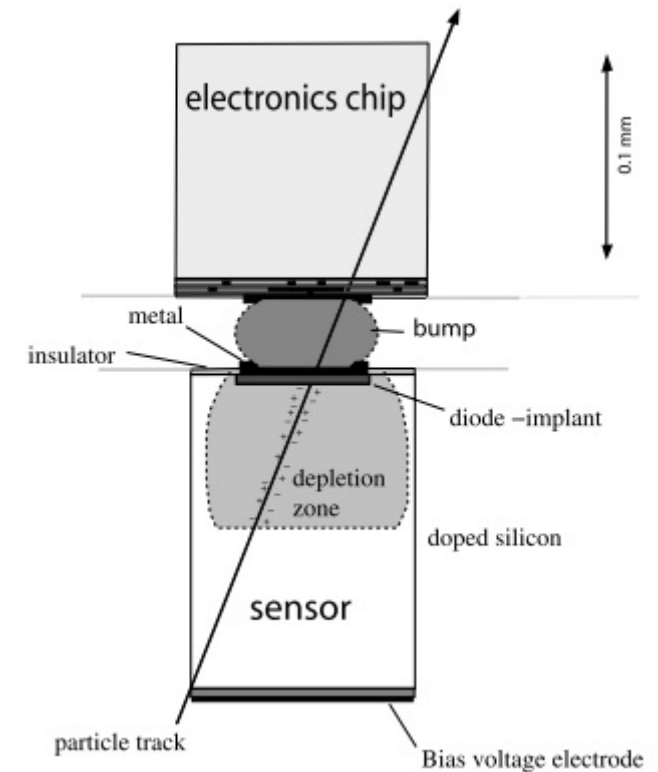
CAMERA A DERIVA DI SILICIO

Per cosa li usiamo: misurare la posizione (2D)

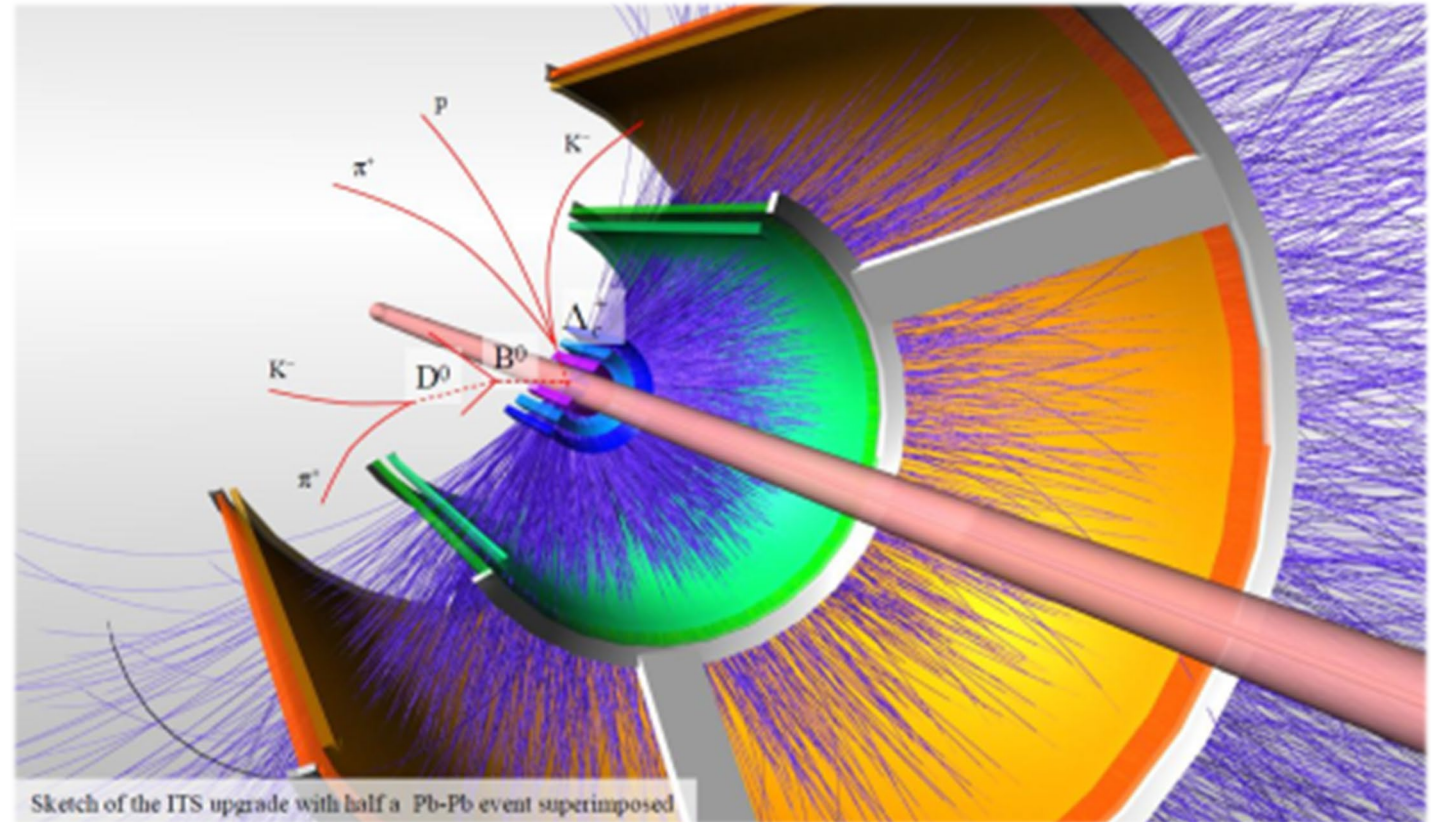
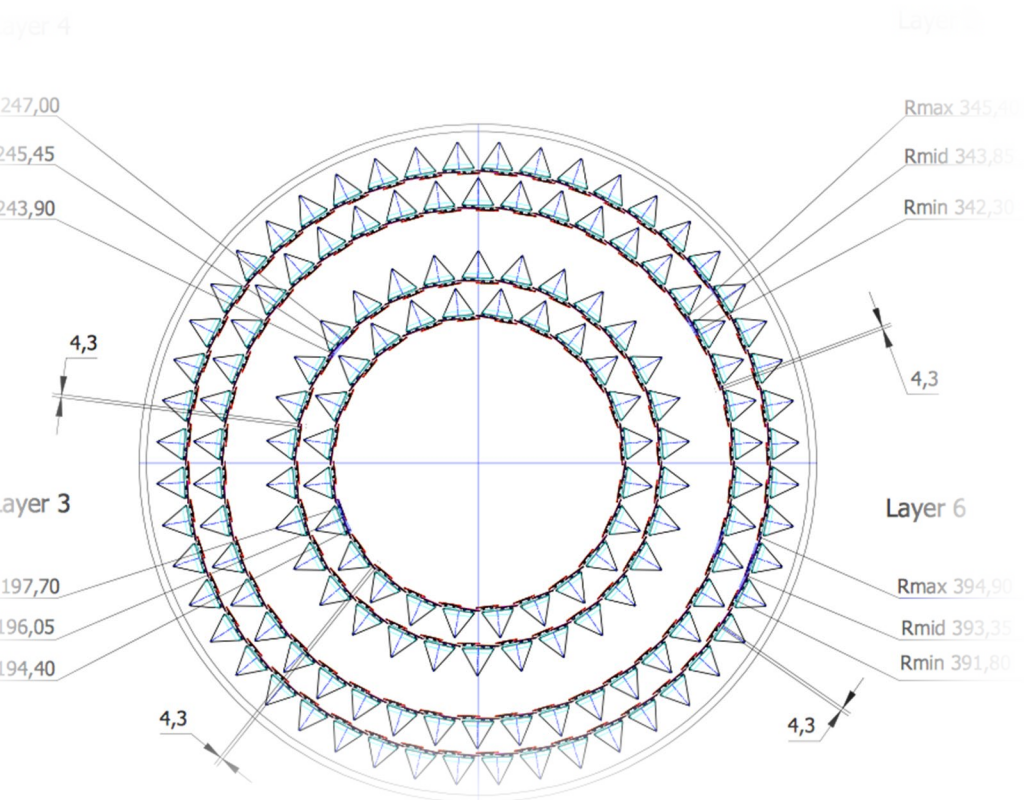
- Posso segmentare la superficie del sensore nelle due direzioni formando una matrice di pixel
- L'elettronica deve essere connessa direttamente sopra ogni pixel: serve un secondo chip, accoppiato



PIXEL IBRIDI

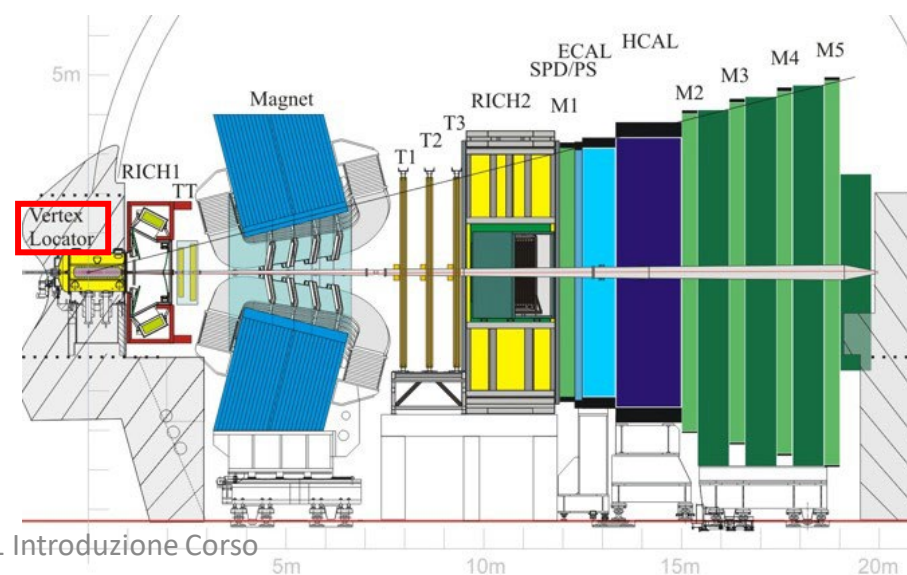
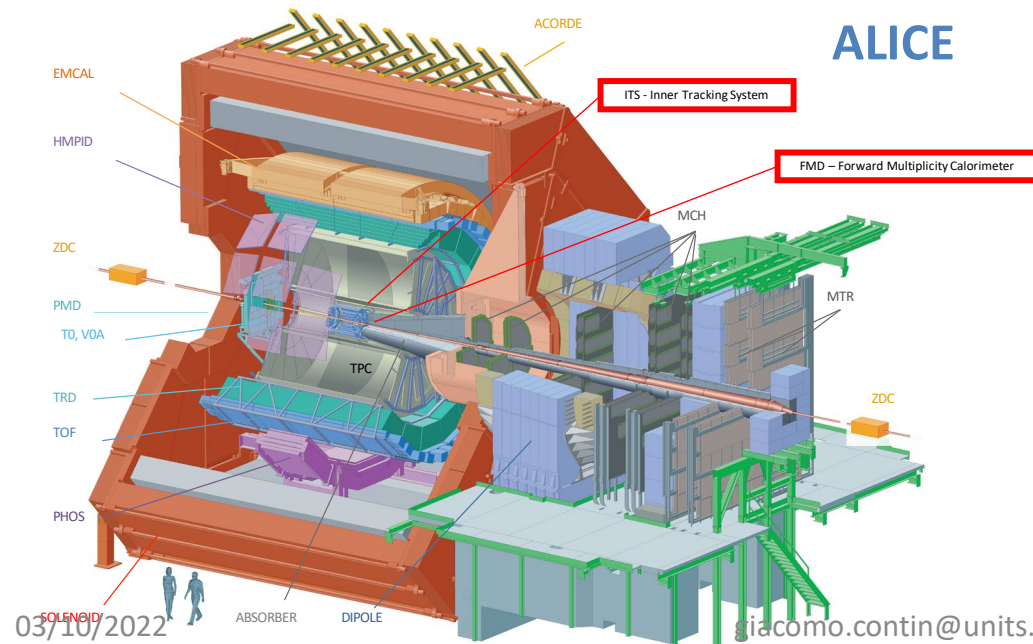
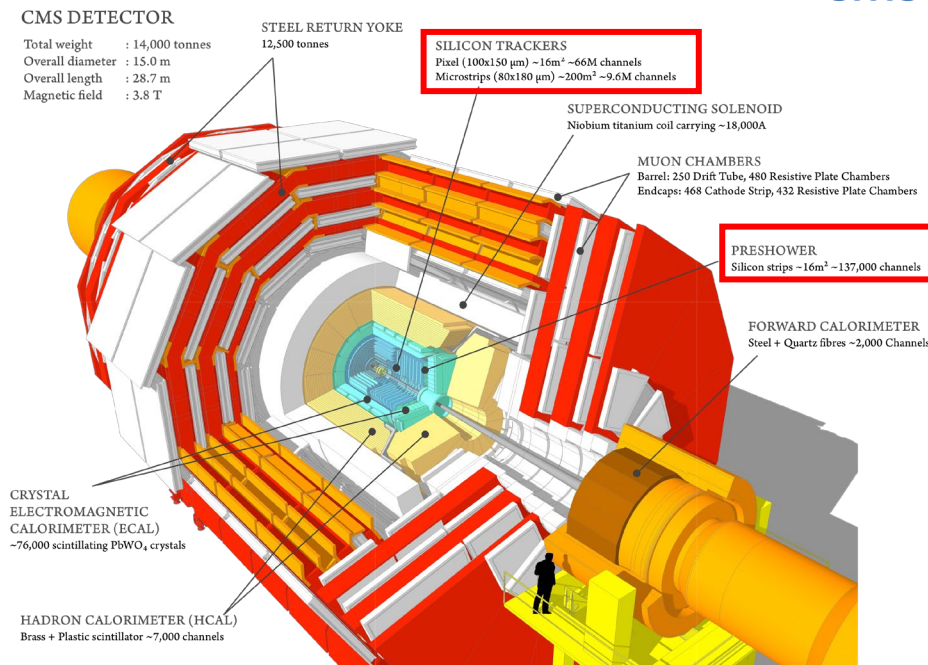
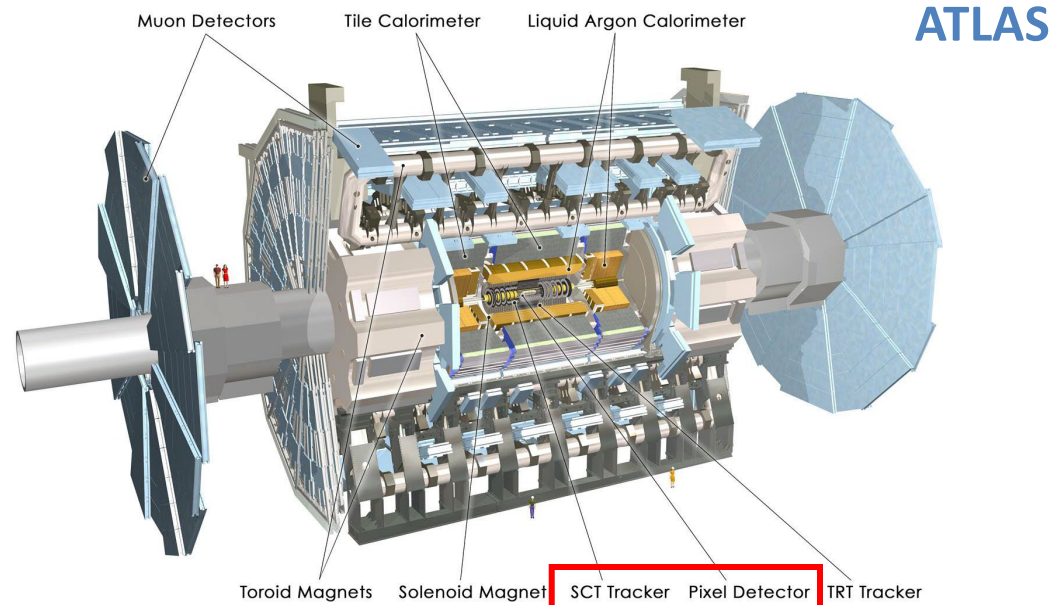


Per cosa li usiamo: seguire la traiettoria...



- Disponendo i rivelatori in modo da formare cilindri concentrici attorno alla linea del fascio possiamo “seguire” la traccia mentre si allontana

I rivelatori degli esperimenti di LHC – Ruolo dei rivelatori al silicio e' fondamentale



Esempi di rivelatori al silicio: canali e superficie

Esperimento	Tecnologia usata	Canali [M]	Superficie [m ²]	m ² /Mch
ATLAS	Pixel ibridi	80	1.7	0.021
	+ Pixel ibridi (Insertable B-Layer)	12	2	0.170
	Micro-strip	6	60	10.000
CMS	Pixel ibridi	66	1	0.015
	Micro-strip	10	200	20.000
ALICE	Pixel ibridi	10	0.3	0.030
	Silicon Drift	0.1	1.3	13.000
	Micro-strip	2.6	5.2	2.000
	→ Rimpiazzati da Pixel Monolitici (ITS)	1260	10	0.008
LHCb	Micro-strip	0.2	0.22	1.100
	→ Rimpiazzate da Pixel Ibridi (VELO Upgr.)	41	0.12	0.003

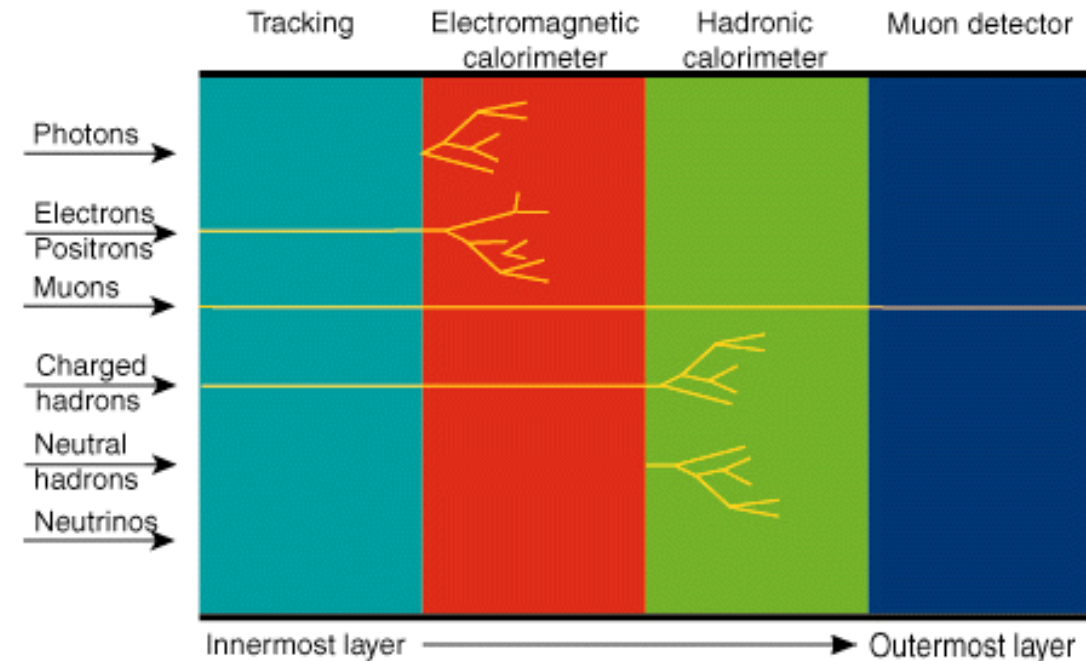
Rivelatori di tracciamento al silicio a LHC per Run1, Run2, Run3

Notare il rapporto canali/superficie per le diverse tecnologie usate

Tutti i pixel elencati sono ibridi, eccetto per il caso dell'ALICE ITS Upgrade (monolitici)

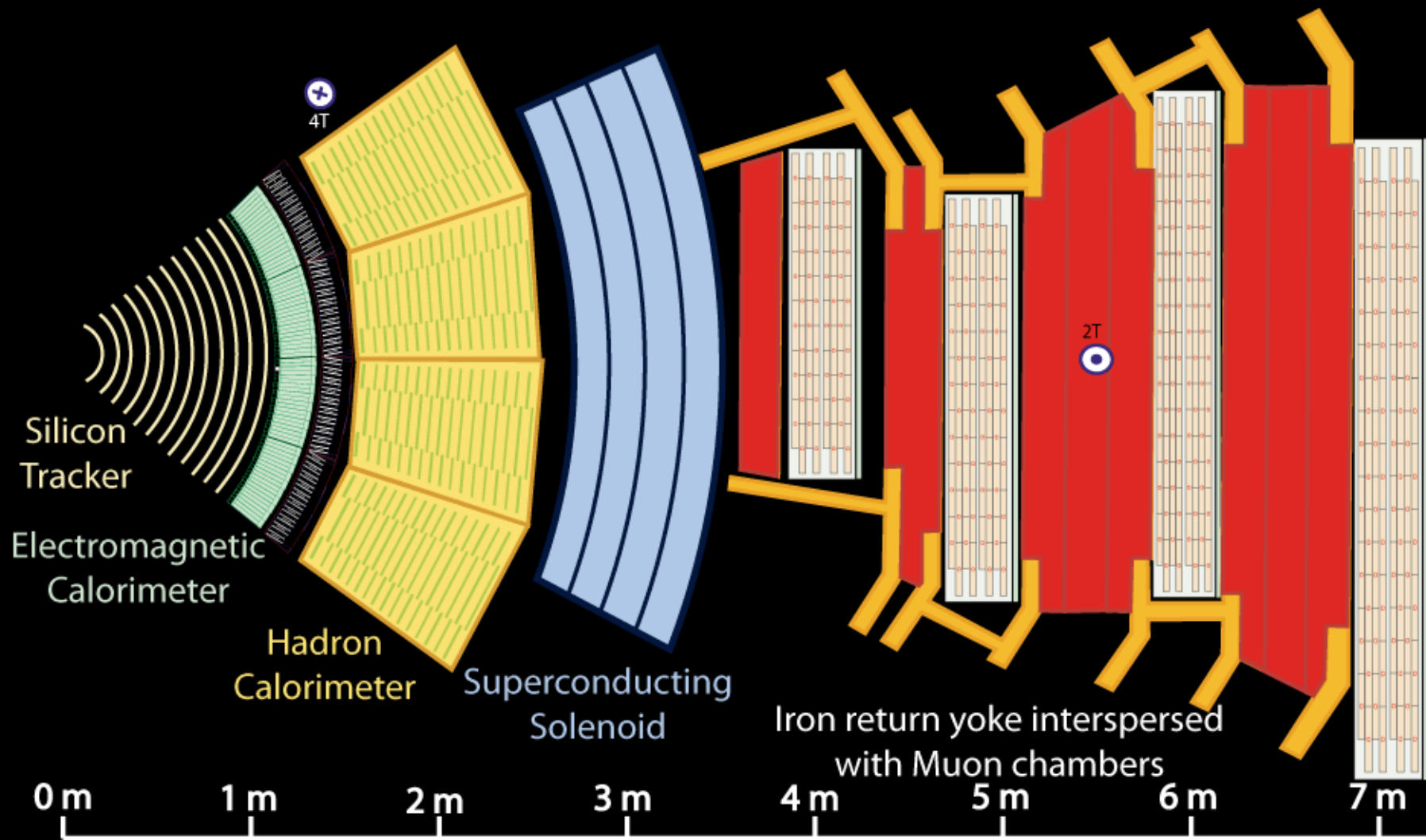
Interazione di particelle diverse con rivelatori diversi

- Particelle cariche sono visibili nei tracciatori
- Fotoni, elettroni, positroni vengono fermati nel calorimetro elettromagnetico, permettendone la misura di energia
- Gli adroni carichi vengono solo visti dal calorimetro elettromagnetico
- Gli adroni (carichi e neutri) vengono fermati nel calorimetro adronico, permettendone la misura di energia
- Solo i muoni sono visibili in tutti i 4 tipi di rivelatori



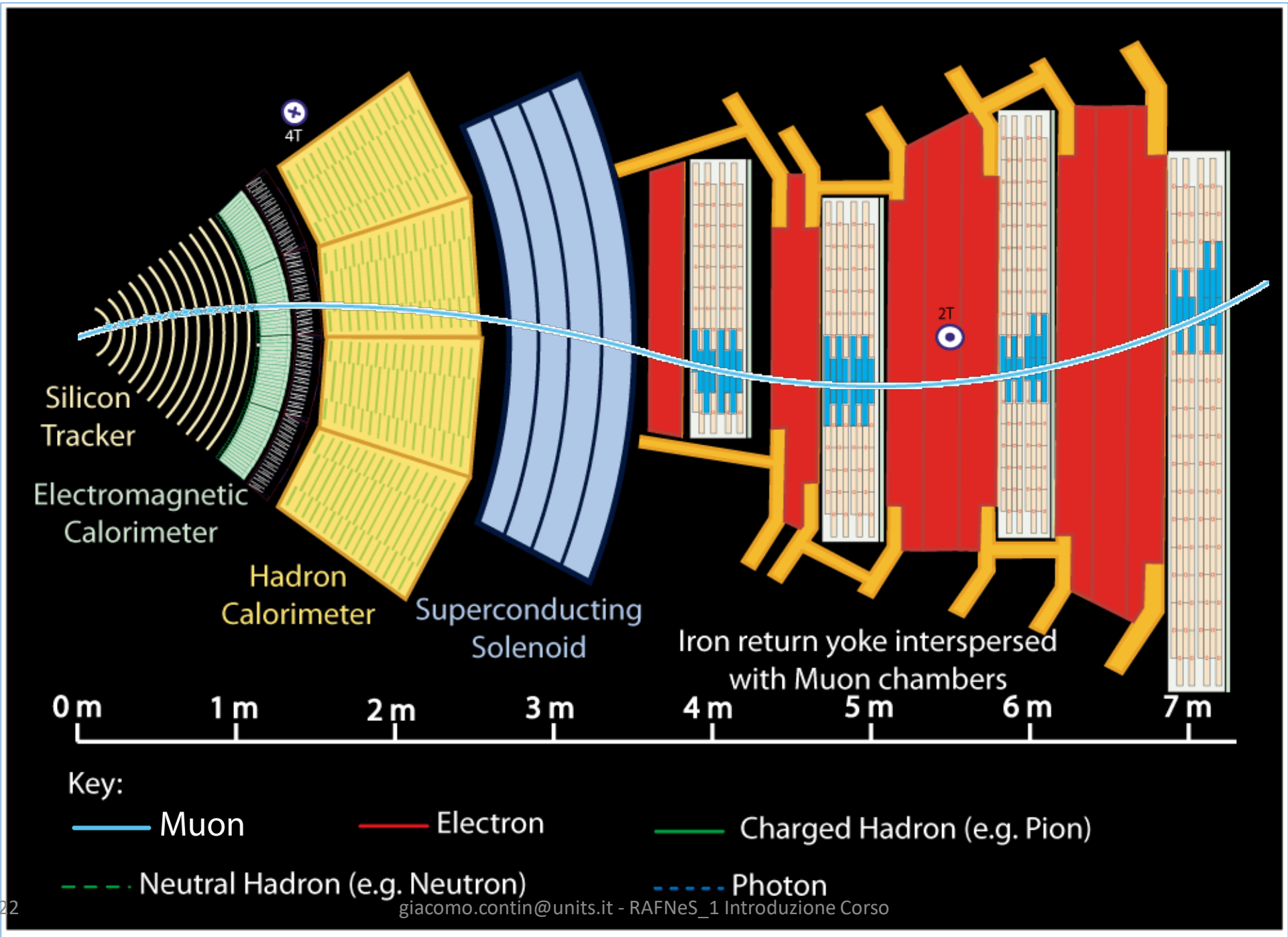
Per queste ragioni viene rispettato questo ordine nella sequenza dei diversi sistemi di rivelazione

CMS slice

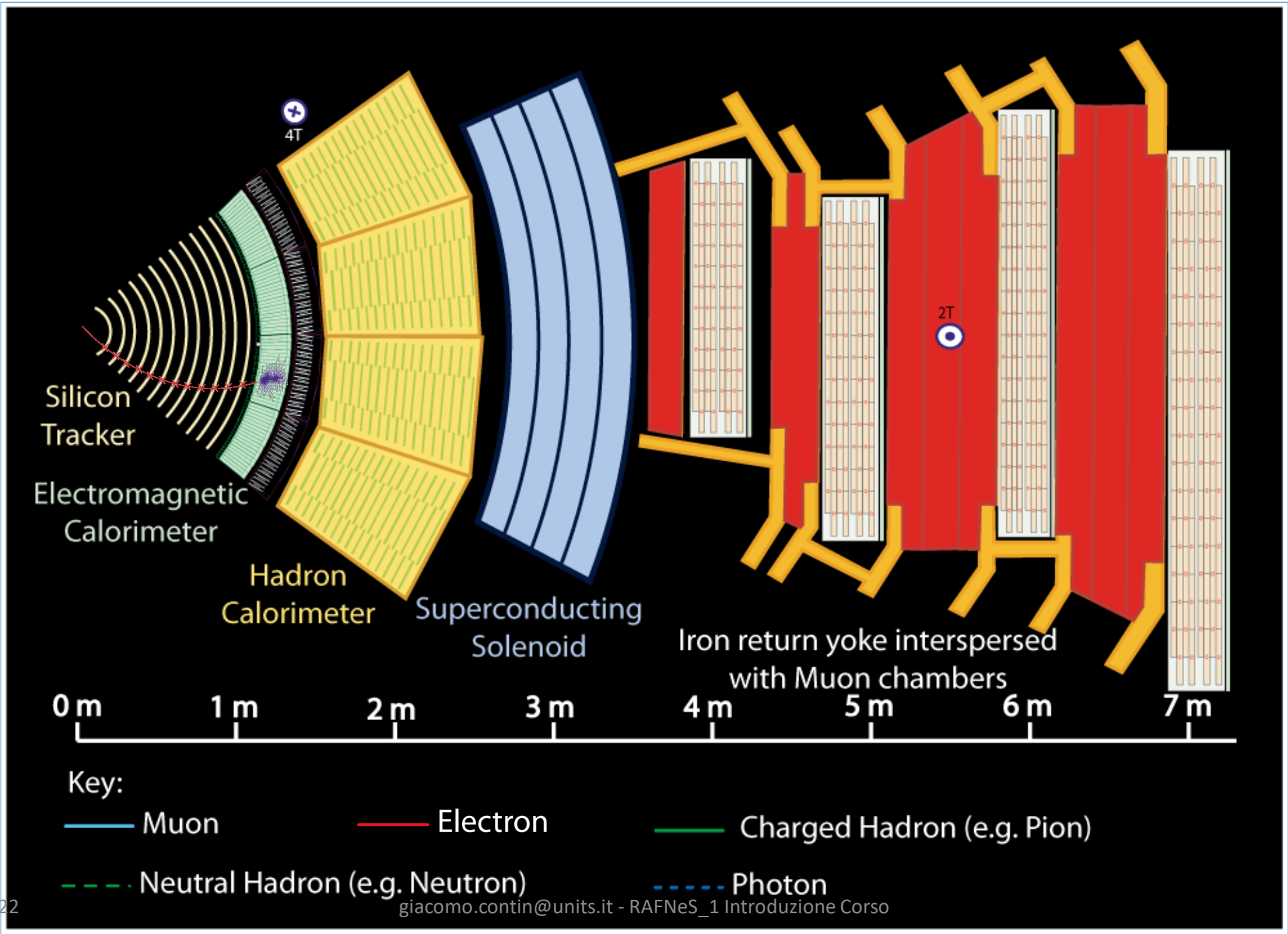


- Key:
- Muon
 - Electron
 - Charged Hadron (e.g. Pion)
 - - - Neutral Hadron (e.g. Neutron)
 - - - Photon

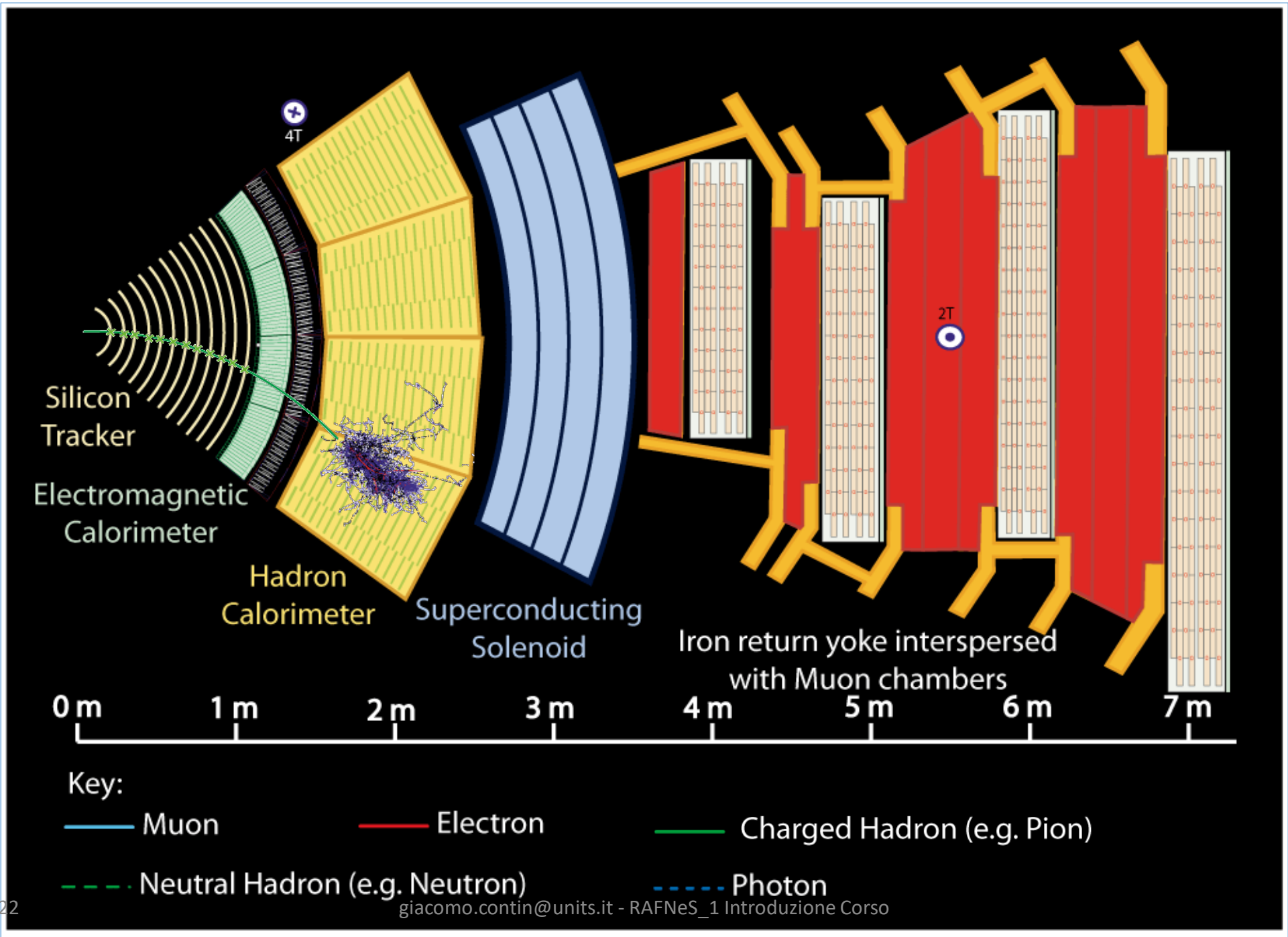
CMS slice



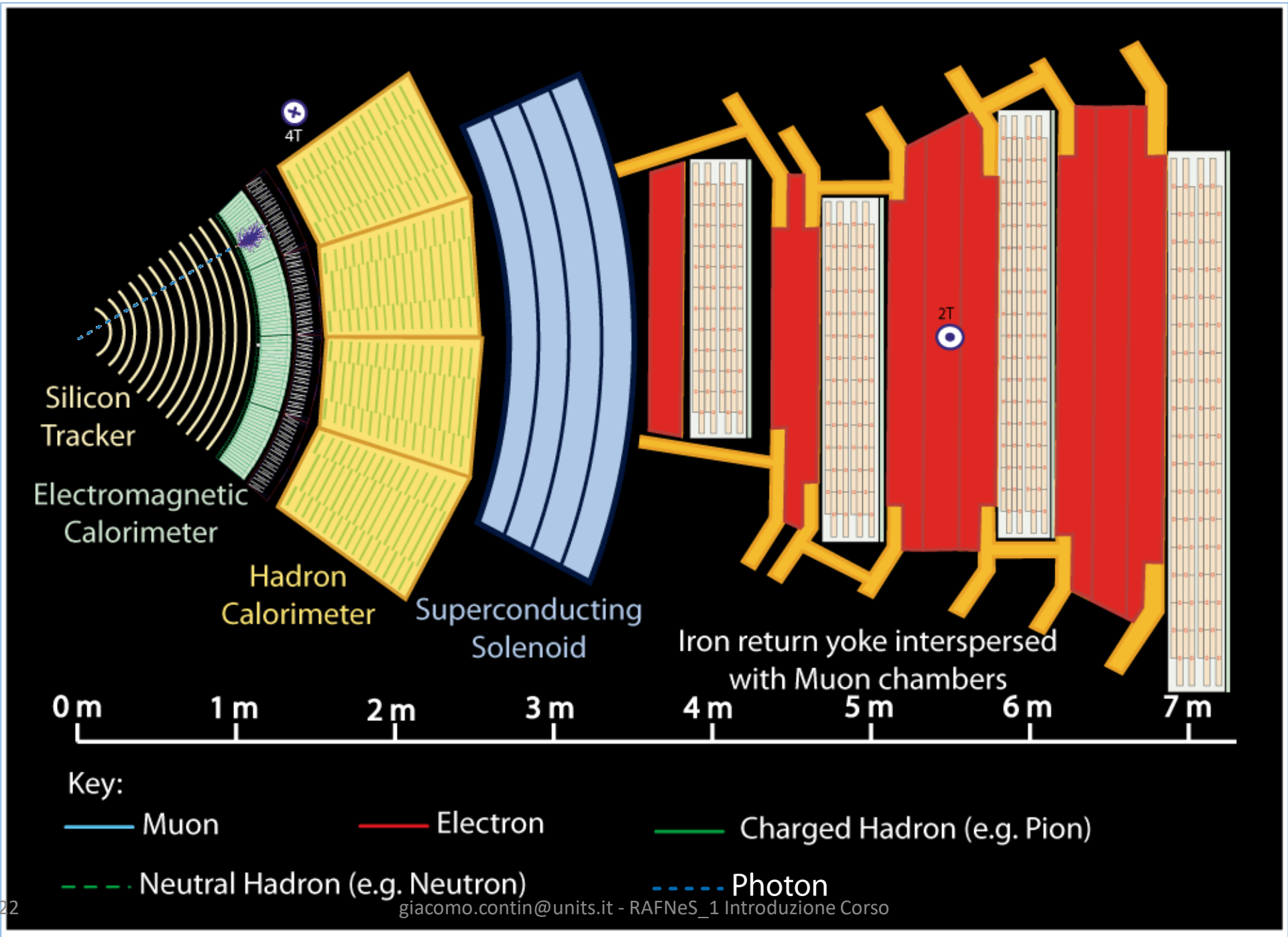
CMS
slice



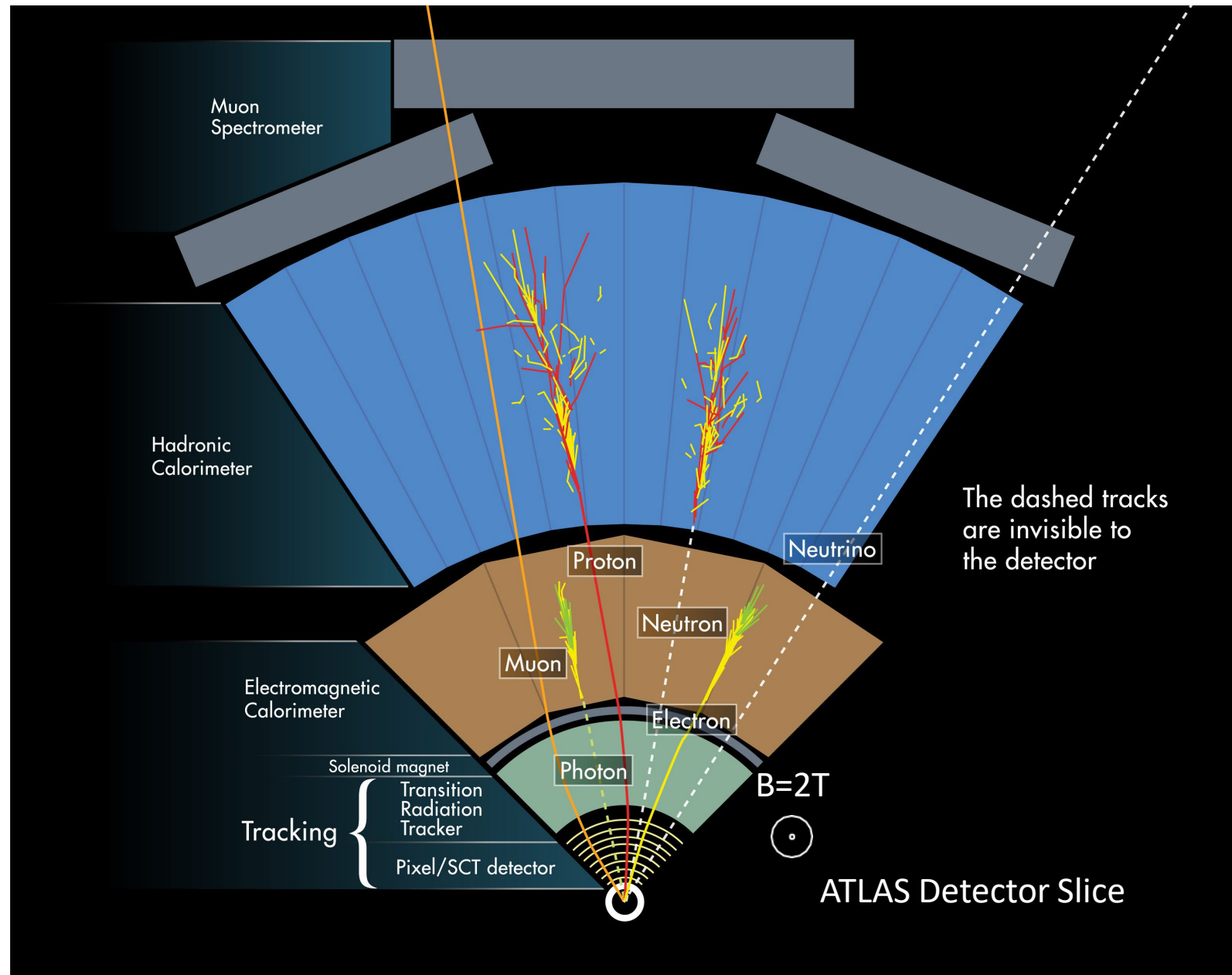
CMS slice



CMS slice

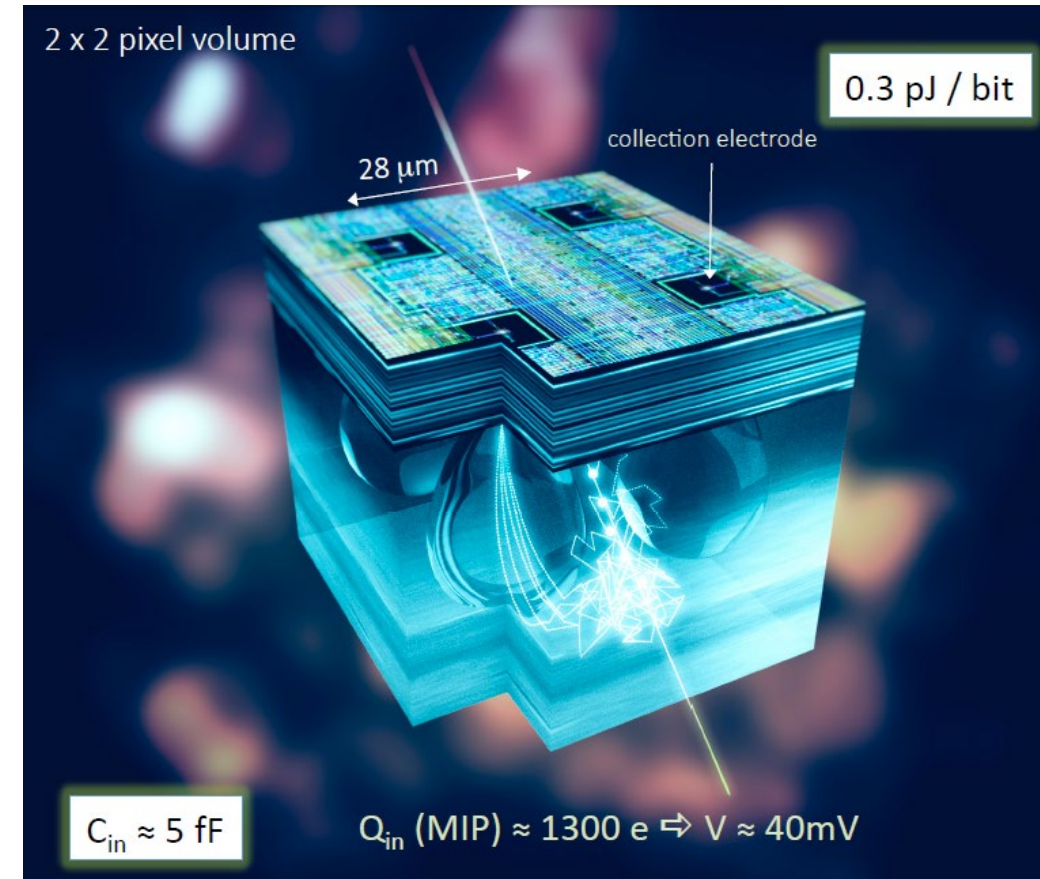


ATLAS slice



Caso esemplare: Sensore a Pixel Monolitici di Silicio

- Nello stesso blocco di silicio:
 - Volume sensibile per la raccolta del segnale
 - +
 - Logica di trattamento del segnale
- Rivela il passaggio di particelle cariche
- Può essere realizzato in uno spessore minimo, dell'ordine di $50\ \mu\text{m}$
- Sviluppato per soddisfare la necessità di ridurre la quantità di materiale attraversata dalla particella:
 - Non perturbare la traiettoria della particella
 - Misurare la traiettoria delle particelle con bassa quantità di moto
 - Mantenere una quantità di segnale necessaria per misurare il passaggio
- Inizialmente sviluppato per applicazioni alle alte energie, ora in fase di test per applicazioni in campo medico e spaziale

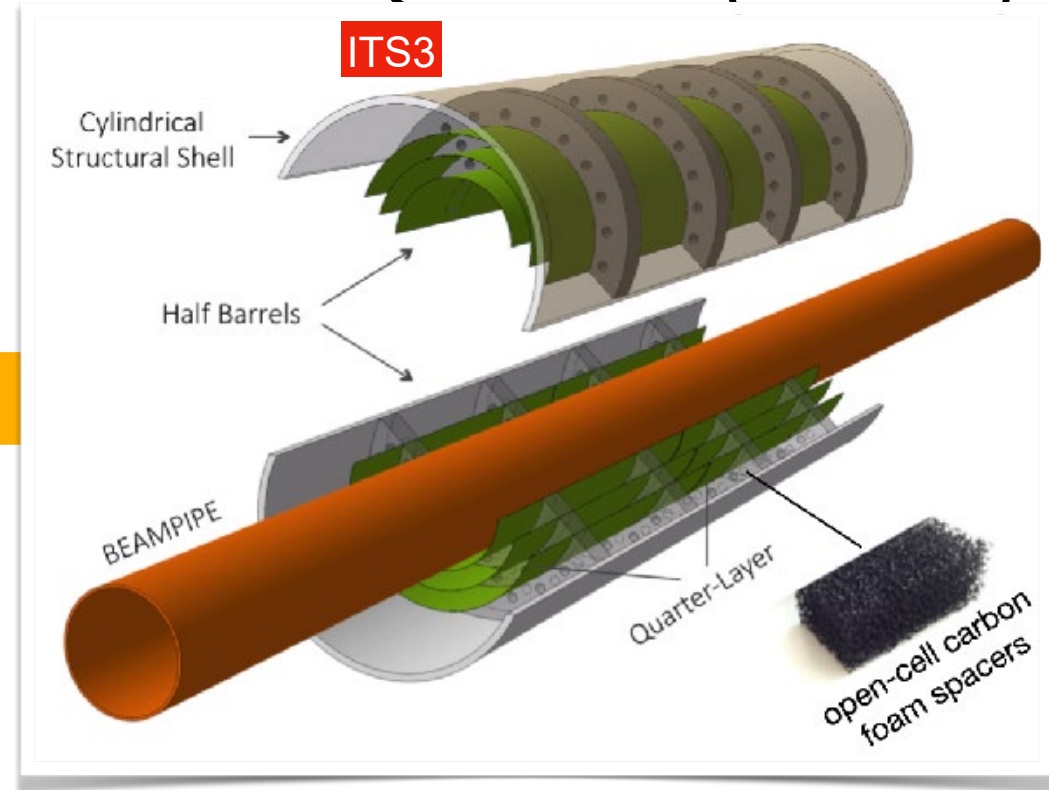


Apparati del futuro: ALICE-ITS3 @ LHC (2027)

replace



by



in LS3

key improvements:

- ▶ closer to beam pipe: 23 → 18 mm
- ▶ less material: 0.3 → ~0.03 % X_0

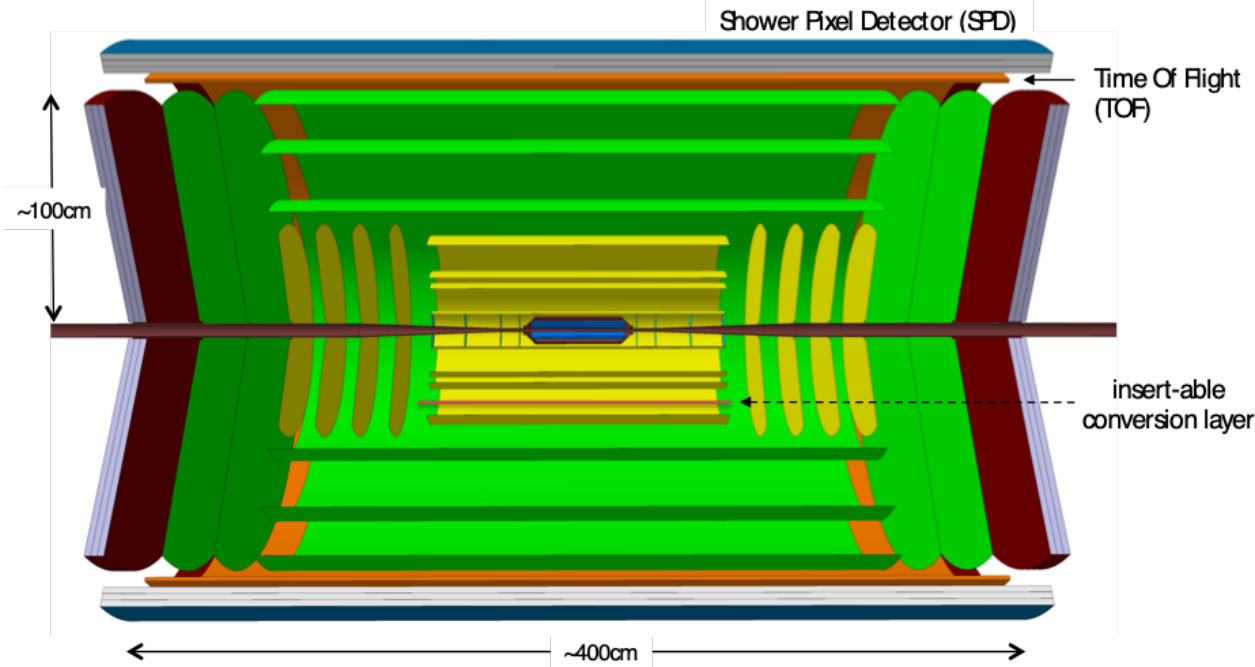
main benefit:

- ▶ better tracking performance
- ▶ especially at low p_T

based on:

- ▶ wafer-scale (up to ~28x10 cm),
 - ▶ ultra-thin (20-40 μm),
 - ▶ bent ($R=18, 24, 30$ mm)
- Si sensors (MAPS)**

Apparati del futuro: ALICE 3 @ LHC (2032)



• tracking

- ~10 layers (blue, yellow, green) of barrels and disks based on **monolithic pixel silicon sensors** (MAPS)

• particle identification

- time-of-flight layers (orange) in central barrel based on **silicon timing sensors**
- Pre-Shower Detector (outermost blue) based on dense material and **MAPS**

key requirements

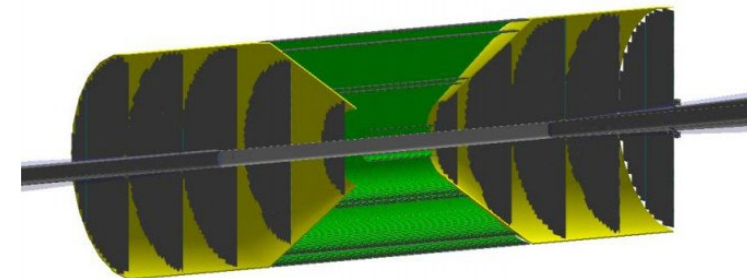
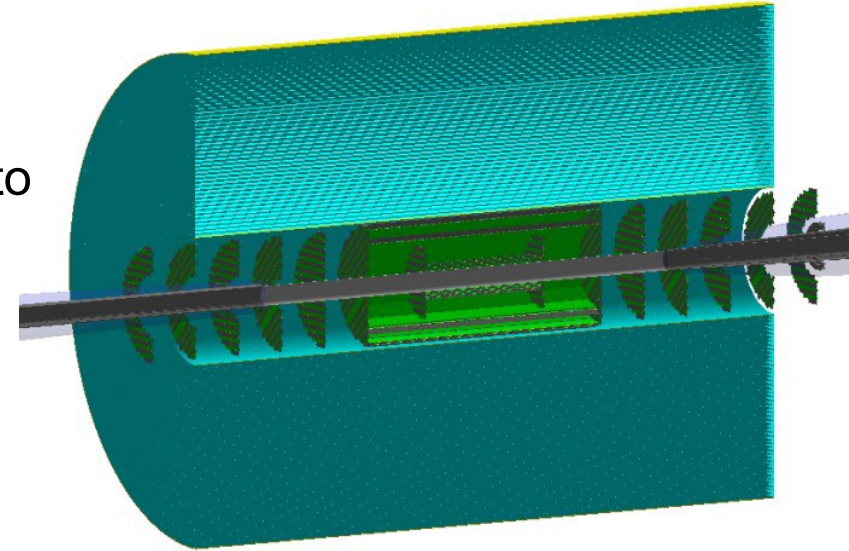
- **ultra-low material budget** for low p_T tracking
 - $X/X_0 \sim 0.05\%$ / layer
- **fast** to sample large luminosity
 - 50 - 100x Run 3/4
- **large acceptance**
 - $|\eta| < 4 \Rightarrow \Delta\eta = 8$ (total)
 - $|\eta| < \sim 1.4$ (central barrel)
- **excellent spatial resolution** for tracking and vertexing
 - innermost layers: $\sigma < 3 \mu\text{m}$
 - outer layers: $\sigma \sim 5 \mu\text{m}$
- **precise time measurement** for particle identification
 - $\sigma \sim 20 \text{ ps}$

Apparati del futuro: Electron Ion Collider (2030 - 2035)

Requirements for an EIC tracker according to the [EIC detector handbook](#):

- Hermetic
 - * ($11 < 4, 0 : s \phi < 2n$ coverage)
- Compact
- Low-material-budget tracker
 - * (3-5% of X_0)
- Excellent momentum, angular, and vertex resolutions
 - * ($dp/p \sim \text{few } \%$)
- Aid in particle identification (PID).

Hybrid tracker



All-Si tracker

SDD DESIGN OPTIMIZATION FOR X-RAY SPECTROSCOPY AND IMAGING

Detector development activity performed in the framework of the XDXL and ReDSOX R&D INFN programs

Prototypes designed, manufactured and tested in collaboration between INFN, INAF and FBK.

(Rachevski et al., JINST, 2015)

SUBSTRATE OPTIMIZATION FOR X-RAY DETECTION

MATERIAL: NTD \rightarrow FZ

GEOMETRIC AREA (filling factor): 5" \rightarrow 6" wafer <100>

RESISTIVITY: 4 k Ω cm \rightarrow 9 k Ω cm

THICKNESS (QE): 300 μ m \rightarrow 450 μ m

DESIGN OPTIMIZATION FOR X-RAY DETECTION AND SPACE APP.

VOTLAGE DIVIDER: reduced power

SURFACE CURRENT: minimization

Si-SiO₂ INTERFACE GAP: minimization

FIELD PLATE: optimization for minimal surface current

QUANTUM EFFICIENCY: optimization for low E_{ph}

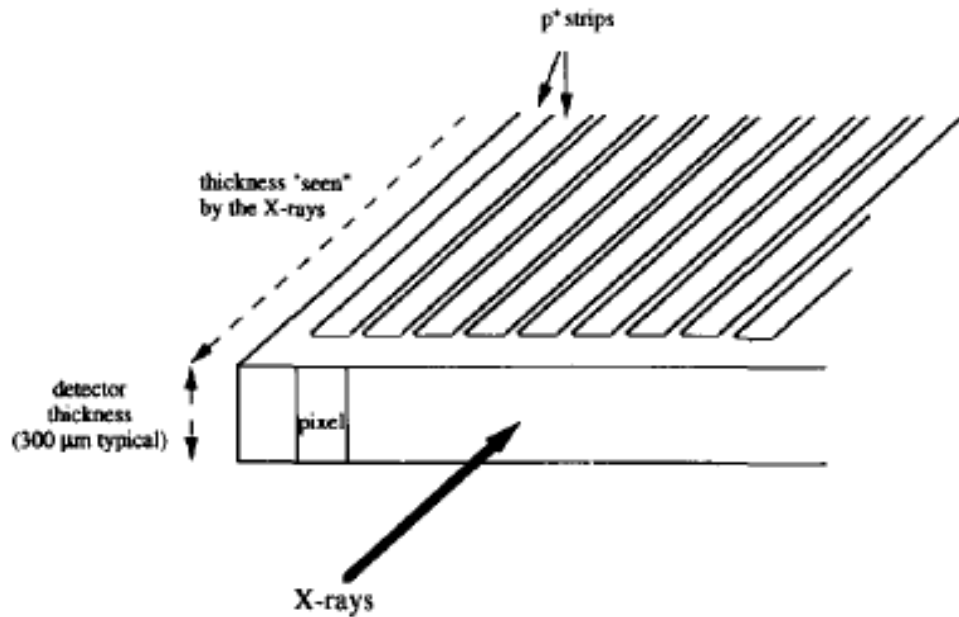
ANODE PITCH: opt. for spectral-timing & imaging



Altre applicazioni delle Silicon Drift Detector

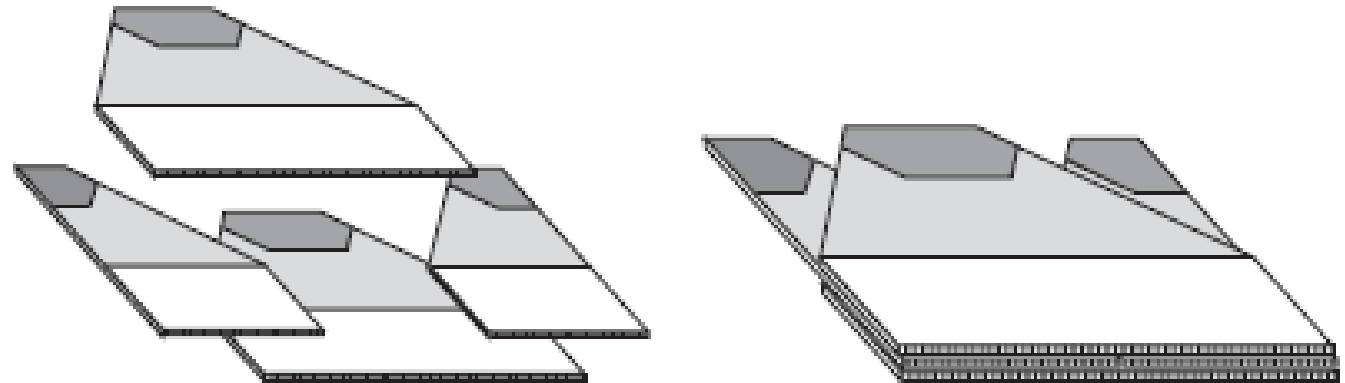
- Spettroscopia + ricostruzione posizione 2D
 - Risoluzione all'anodo di decine di μm per X-rays con 2 keV
 - Lunghezza di deriva piu' grossolana: non c'e' rivelazione di tempo zero (6 mm per $E > 3.5$ keV)
- ⇒ Medical field: Compton camera
- ⇒ Nuclear physics precision spectroscopy
- ⇒ X-ray astronomy/astrophysics
- ⇒ X-ray imaging for Advanced Light Sources (SR and FEL)

Applicazione medica delle Silicon Strip Detector: SYRMEP @ ELETTRA: mammografia digitale



- Orientazione edge-on

- Struttura che ammetta connessione di tutti i canali in 3D, ma anche eviti una spaccatura al centro del volume sensibile



Riassumendo...

- C'è una crescente richiesta ed espansione nel campo dei rivelatori a semiconduzione
- Applicazioni in tutti i campi della fisica
 - Sviluppo spesso trainato dalla fisica delle alte energie
 - Applicazioni negli altri campi con specifiche ottimizzazioni
- E' importante:
 - Capire la fisica che si vuole osservare
 - Definire i requisiti che i rivelatori devono soddisfare
 - Analizzare le proprietà e le prestazioni dei rivelatori esistenti
 - Sviluppare ulteriormente rivelatori e infrastrutture per soddisfare i requisiti
- Proviamoci!



Grazie dell'attenzione!

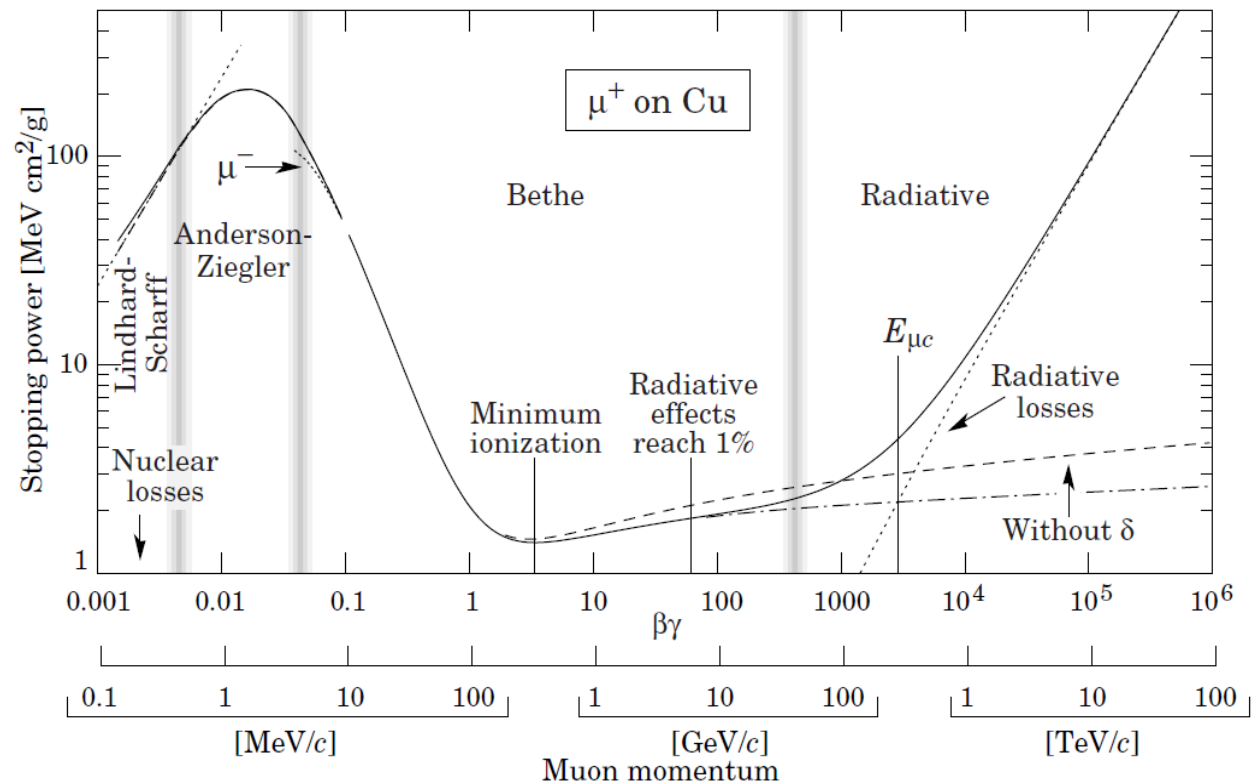


Fig. 27.1: Stopping power ($= \langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Data below the break at $\beta\gamma \approx 0.1$ are taken from ICRU 49 [4], and data at higher energies are from Ref. 5. Vertical bands indicate boundaries between different approximations discussed in the text. The short dotted lines labeled “ μ^- ” illustrate the “Barkas effect,” the dependence of stopping power on projectile charge at very low energies [6].

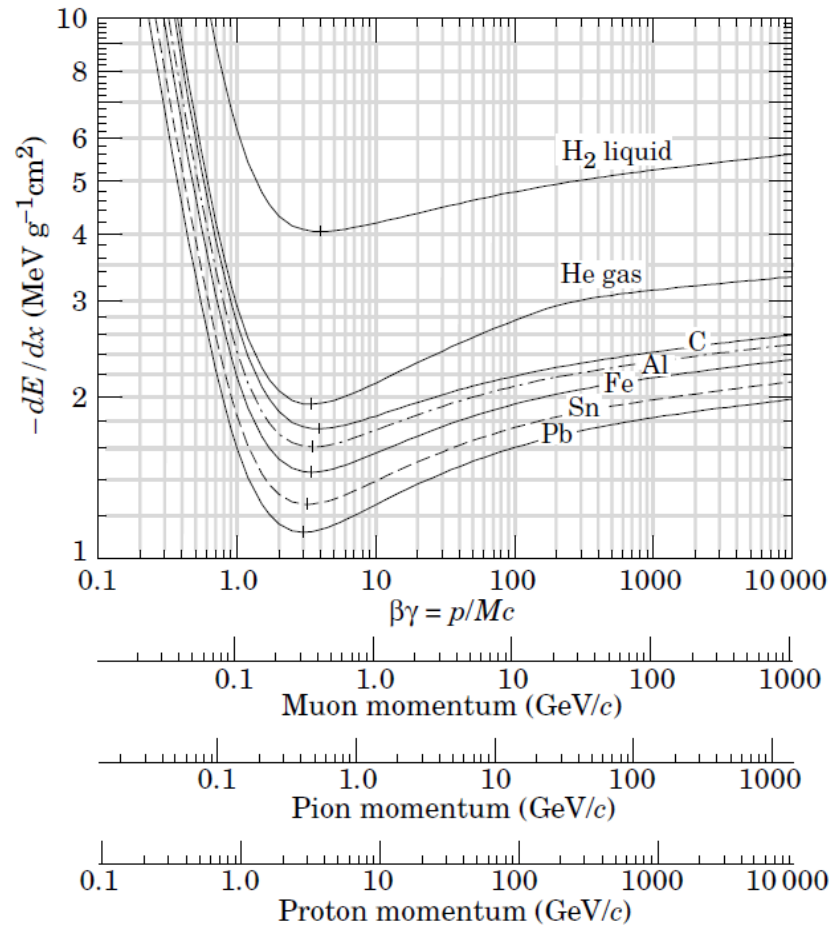


Figure 27.2: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher- Z absorbers. See Fig. 27.23.

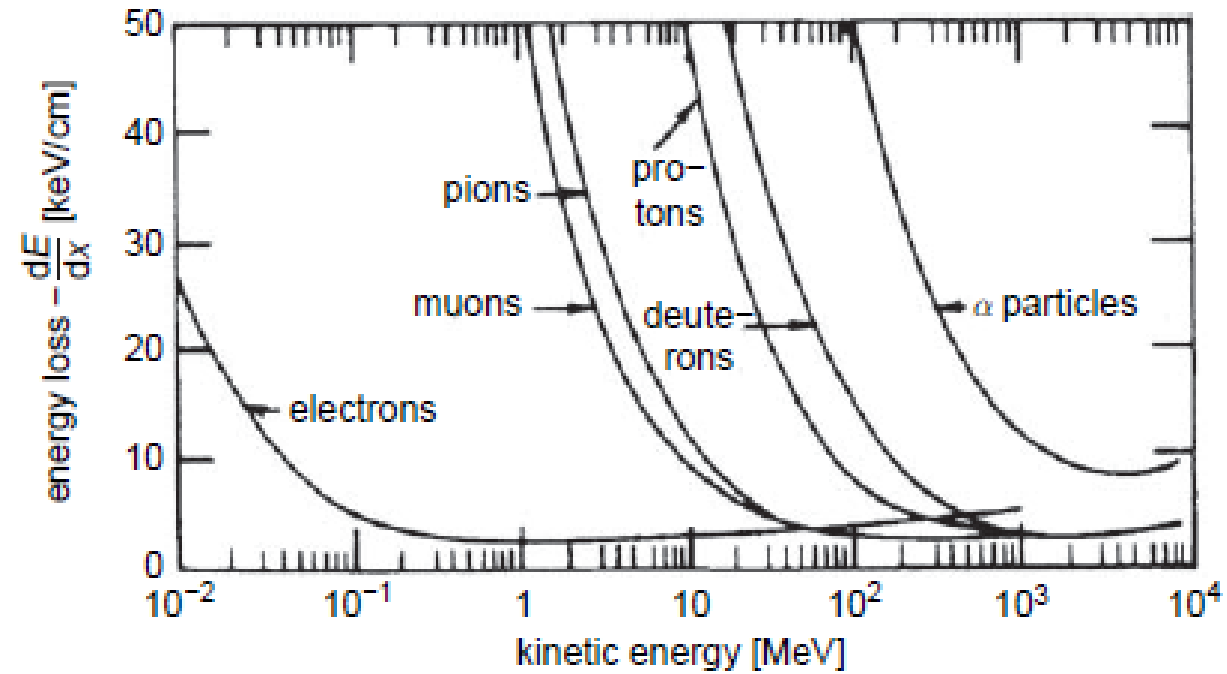


Fig. 1.2. Energy loss for electrons, muons, pions, protons, deuterons and α particles in air [14].

Grafici dE/dx

continuation of Eq. (1.04)

Material	Z	A	X_0 [g/cm ²]	X_0 [cm]	E_c [MeV]
Hydrogen	1	1.01	61.3	731 000	350
Helium	2	4.00	94	530 000	250
Lithium	3	6.94	83	156	180
Carbon	6	12.01	43	18.8	90
Nitrogen	7	14.01	38	30 500	85
Oxygen	8	16.00	34	24 000	75
Aluminium	13	26.98	24	8.9	40
Silicon	14	28.09	22	9.4	39
Iron	26	55.85	13.9	1.76	20.7
Copper	29	63.55	12.9	1.43	18.8
Silver	47	109.9	9.3	0.89	11.9
Tungsten	74	183.9	6.8	0.35	8.0
Lead	82	207.2	6.4	0.56	7.40
Air	7.3	14.4	37	30 000	84
SiO ₂	11.2	21.7	27	12	57
Water	7.5	14.2	36	36	83

Table 1.1. Average energy loss of minimum-ionising particles in various materials [10–12]; gases for standard pressure and temperature

Absorber	$\frac{dE}{dx} \Big _{\min}$ [$\frac{\text{MeV}}{\text{g/cm}^2}$]	$\frac{dE}{dx} \Big _{\min}$ [$\frac{\text{MeV}}{\text{cm}}$]
Hydrogen (H ₂)	4.10	$0.37 \cdot 10^{-3}$
Helium	1.94	$0.35 \cdot 10^{-3}$
Lithium	1.64	0.87
Beryllium	1.59	2.94
Carbon (Graphite)	1.75	3.96
Nitrogen	1.82	$2.28 \cdot 10^{-3}$
Oxygen	1.80	$2.57 \cdot 10^{-3}$
Air	1.82	$2.35 \cdot 10^{-3}$
Carbon dioxide	1.82	$3.60 \cdot 10^{-3}$
Neon	1.73	$1.56 \cdot 10^{-3}$
Aluminium	1.62	4.37
Silicon	1.66	3.87
Argon	1.52	$2.71 \cdot 10^{-3}$
Titanium	1.48	6.72
Iron	1.45	11.41
Copper	1.40	12.54
Germanium	1.37	7.29
Tin	1.26	9.21
Xenon	1.25	$7.32 \cdot 10^{-3}$
Tungsten	1.15	22.20
Platinum	1.13	24.24
Lead	1.13	12.83
Uranium	1.09	20.66
Water	1.99	1.99
Lucite	1.95	2.30
Shielding concrete	1.70	4.25
Quartz (SiO ₂)	1.70	3.74

Table 2.1 Values of Z , Z/A , I , ρ , $h\nu_p$ and density-effect parameters S_0 , S_1 , a , md , and δ_0 for some elemental substances.

El.	Z	Z/A	I eV	ρ g/cm ³	$h\nu_p$ eV	S_0	S_1	a	md	δ_0
He	2	0.500	41.8	1.66×10^{-4}	0.26	2.202	3.612	0.134	5.835	0.00
Li	3	0.432	40.0	0.53	13.84	0.130	1.640	0.951	2.500	0.14
O	8	0.500	95.0	1.33×10^{-3}	0.74	1.754	4.321	0.118	3.291	0.00
Ne	10	0.496	137.0	8.36×10^{-4}	0.59	2.074	4.642	0.081	3.577	0.00
Al	13	0.482	166.0	2.70	32.86	0.171	3.013	0.080	3.635	0.12
Si	14	0.498	173.0	2.33	31.06	0.201	2.872	0.149	3.255	0.14
Ar	18	0.451	188.0	1.66×10^{-3}	0.79	1.764	4.486	0.197	2.962	0.00
Fe	26	0.466	286.0	7.87	55.17	-0.001	3.153	0.147	2.963	0.12
Cu	29	0.456	322.0	8.96	58.27	-0.025	3.279	0.143	2.904	0.08
Ge	32	0.441	350.0	5.32	44.14	0.338	3.610	0.072	3.331	0.14
Kr	36	0.430	352.0	3.48×10^{-3}	1.11	1.716	5.075	0.074	3.405	0.00
Ag	47	0.436	470.0	10.50	61.64	0.066	3.107	0.246	2.690	0.14
Xe	54	0.411	482.0	5.49×10^{-3}	1.37	1.563	4.737	0.233	2.741	0.0
Ta	73	0.403	718.0	16.65	74.69	0.212	3.481	0.178	2.762	0.14
W	74	0.403	727.0	19.30	80.32	0.217	3.496	0.155	2.845	0.14
Au	79	0.401	790.0	19.32	80.22	0.202	3.698	0.098	3.110	0.14
Pb	82	0.396	823.0	11.35	61.07	0.378	3.807	0.094	3.161	0.14
U	92	0.387	890.0	18.95	77.99	0.226	3.372	0.197	2.817	0.14

Data are from [Sternheimer, Berger and Seltzer (1984)]

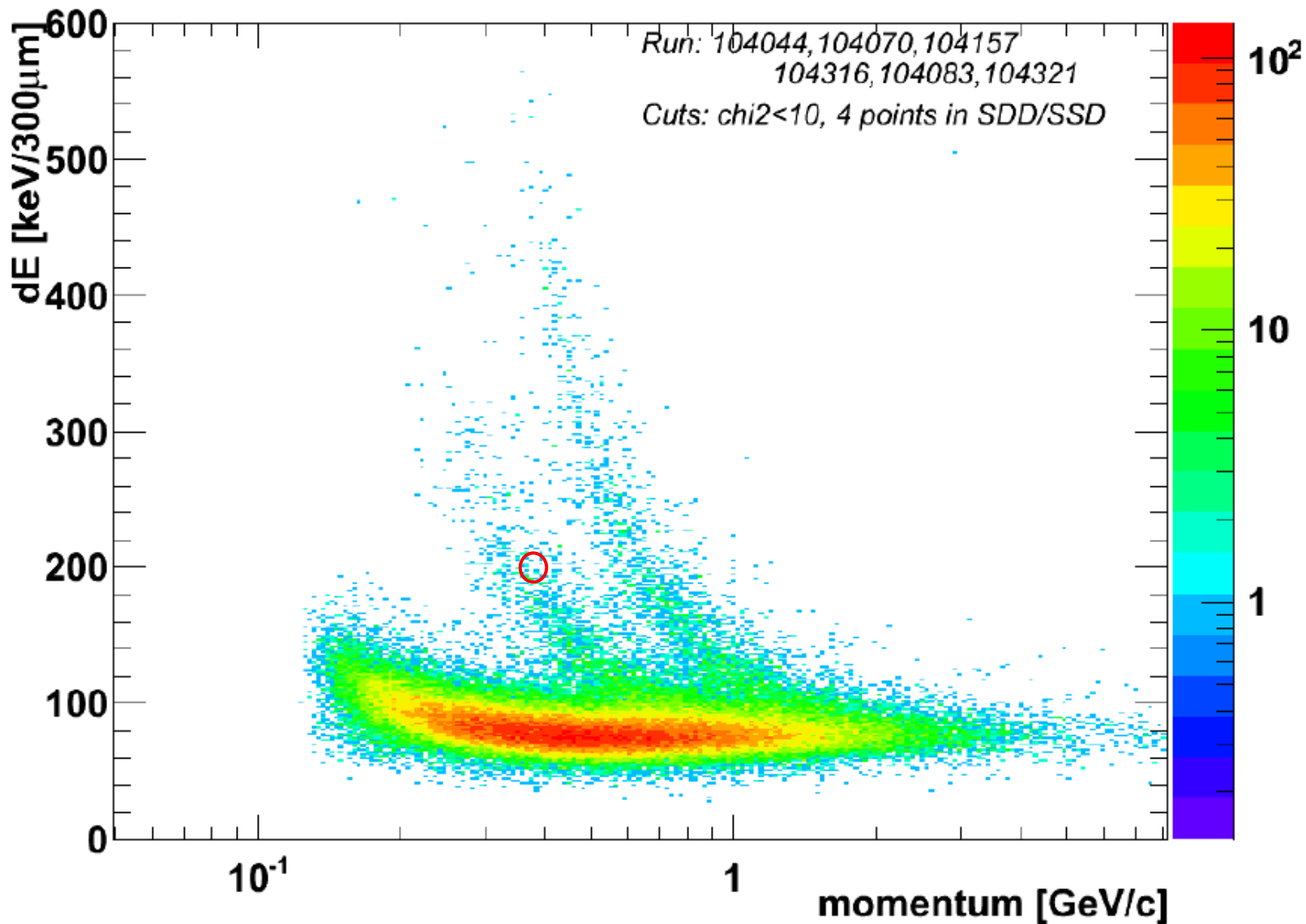
Table 2.2 Values of Z/A , I , ρ , $h\nu_p$ and density-effect parameters S_0 , S_1 , a , and md for some compounds and mixtures.

Material	Z/A	I eV	ρ g/cm ³	$h\nu_p$ eV	S_0	S_1	a	md
(dry) Air at sea level	0.499	85.7	1.21×10^{-3}	0.71	1.742	4.276	0.109	3.399
Anthracene	0.527	69.5	1.28	23.70	0.115	2.521	0.147	3.283
Ethane	0.599	45.4	1.25×10^{-3}	0.79	1.511	3.874	0.096	3.610
Ethyl Alcohol	0.564	62.9	0.79	19.23	0.222	2.705	0.099	3.483
Freon-12	0.480	143.0	1.12	21.12	0.304	3.266	0.080	3.463
(lead) Glass	0.421	526.4	6.22	46.63	0.061	3.815	0.095	3.074
Kapton, polyimide film	0.513	79.6	1.42	24.59	0.151	2.563	0.160	3.192
Lithium carbonate	0.487	87.9	2.11	29.22	0.055	2.660	0.099	3.542
Methane	0.623	41.7	6.67×10^{-4}	0.59	1.626	3.972	0.093	3.626
Methanol	0.562	67.6	0.79	19.21	0.253	2.764	0.090	3.548
Plastic scint., vinyltoluene	0.541	64.7	1.03	21.54	0.146	2.486	0.161	3.239
Polyethylene	0.570	57.4	0.94	21.10	0.137	2.518	0.121	3.429
Propane	0.590	47.1	1.88×10^{-3}	0.96	1.433	3.800	0.099	3.592
Lucite	0.539	74.0	1.19	23.09	0.182	2.668	0.114	3.384
Silicon dioxide	0.499	139.2	2.32	31.01	0.139	3.003	0.084	3.506
Tissue, soft (ICRP)	0.551	72.3	1.00	21.39	0.221	2.780	0.089	3.511
Tissue, soft (ICRP four-comp.)	0.550	74.9	1.00	21.37	0.238	2.791	0.096	3.437
Tissue-equiv., gas (methane base)	0.550	61.2	1.06×10^{-3}	0.70	1.644	4.140	0.099	3.471
Tissue-equiv., gas (propane base)	0.550	59.5	1.83×10^{-3}	0.91	1.514	3.992	0.098	3.516

Data are from [Sternheimer, Berger and Seltzer (1984)]

dEdX distribution (ITS signal, truncated mean)

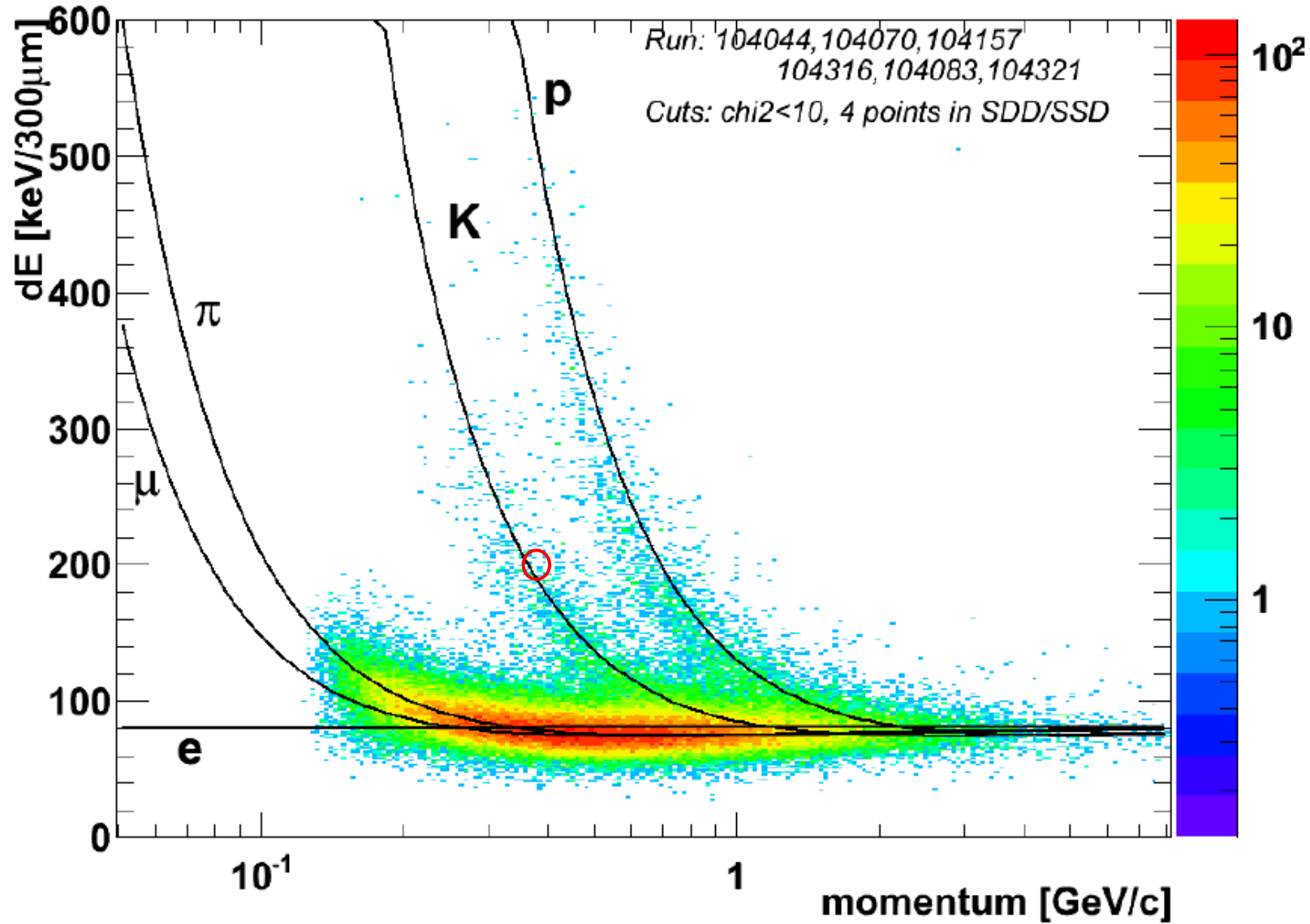
Entries 116536



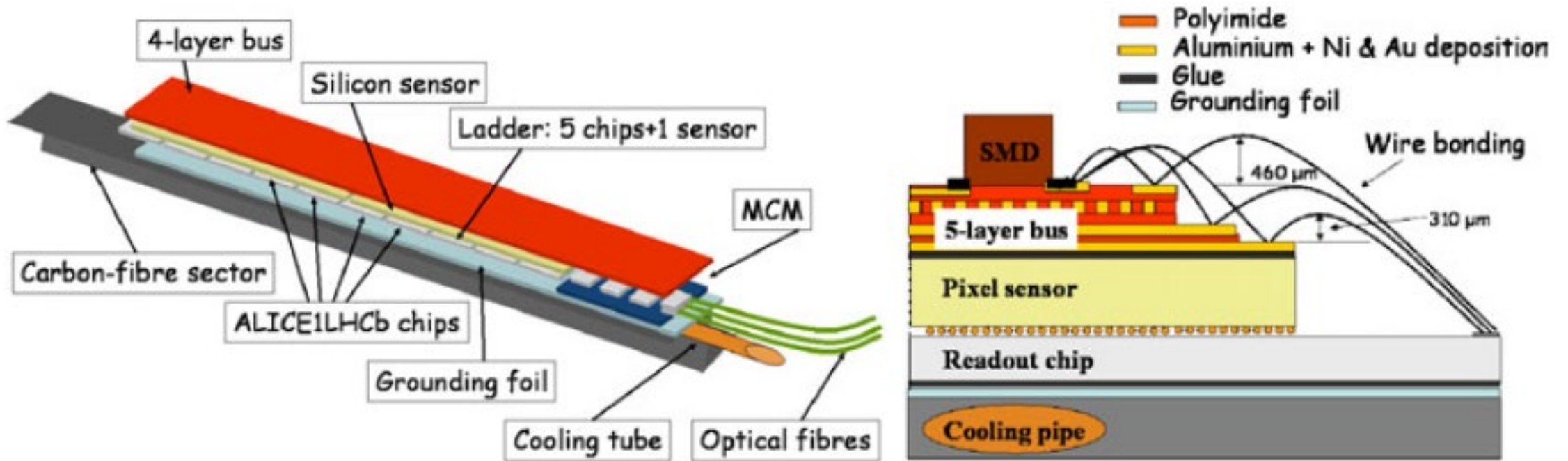
- Istogramma a dispersion carica ricostruita da 4 misure
- Esempio: 200 keV @ quantita' di moto $p=400$ MeV/c
- Che tipo di particella e'?

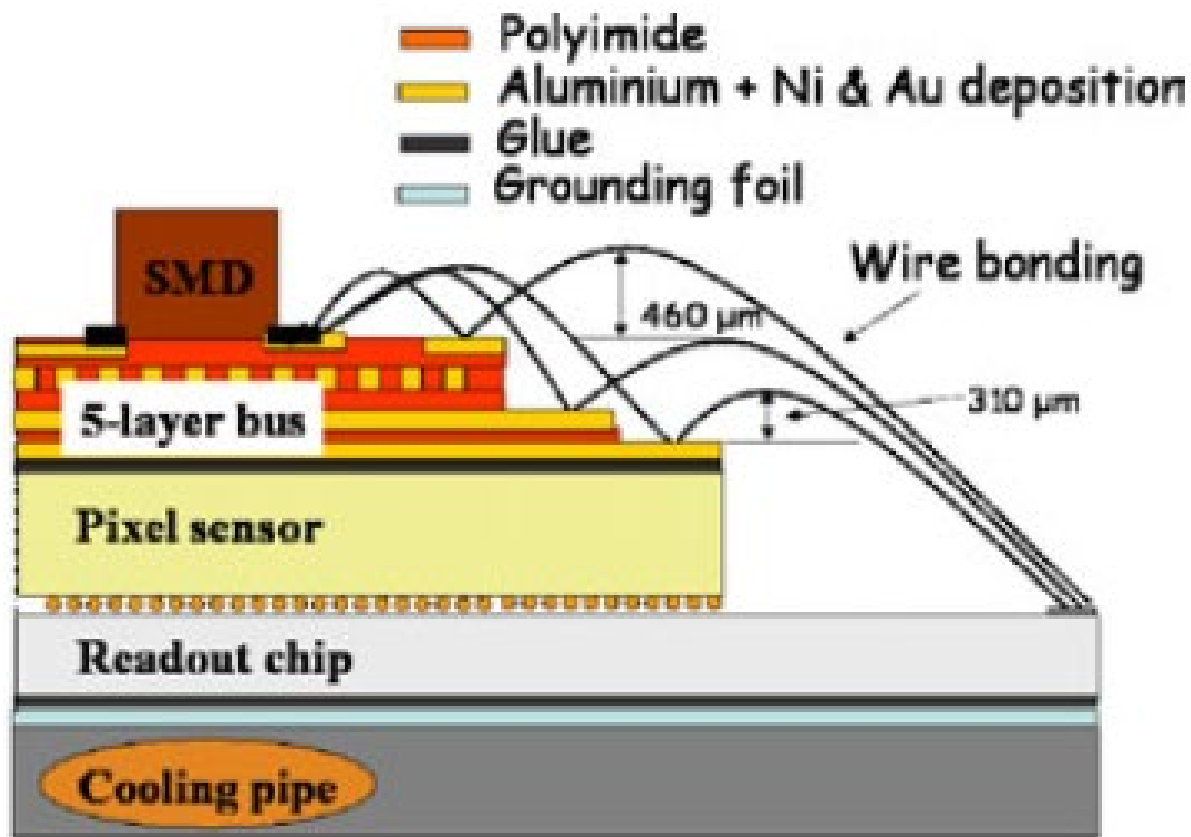
dEdX distribution (ITS signal, truncated mean)

Entries 116536



Silicon Pixel Detector – ALICE (2008 – 2019)

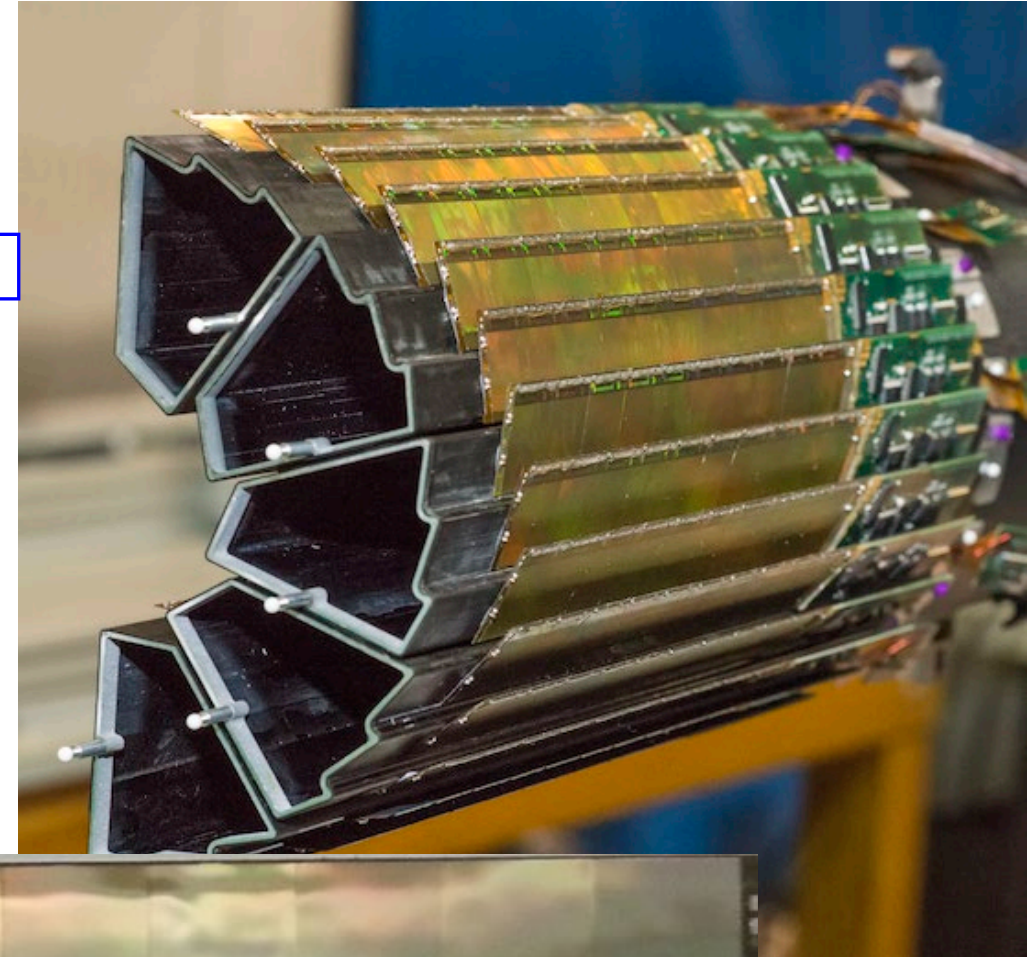
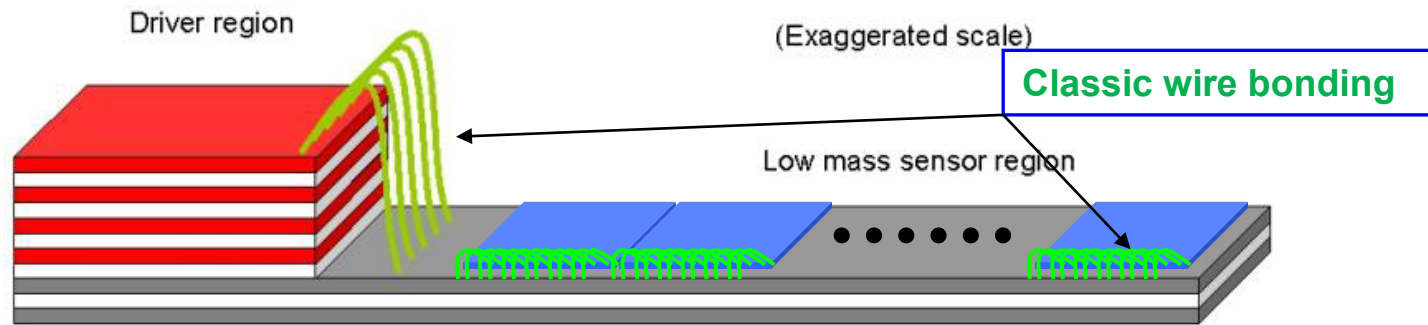




SPD Element	Thickness μm	% X_0
Al Bus		
Kapton	60	0.021
Al power	100	0.112
Al signals [50% of total surface]	17.5	0.020
Glue Epoxy	70	0.016
SMD components	16.4	0.173
Total bus		0.341
Other Components		
Pixel chip	150	0.160
Sensor	200	0.214
Bump bonds Sn 60%+Pb 40%	0.18+0.12	0.004
Grounding Foil-Kapton/Al	50+10	0.029
Glue Epoxy/thermal grease	200	0.049
Carbon fiber	200	0.106
Total components		0.561
Total bus and components		0.903

MATERIAL BUDGET OF ONE SPD LAYER

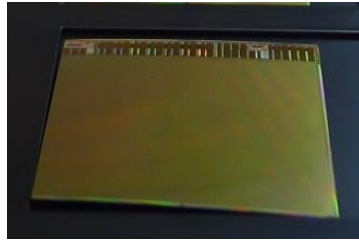
HFT Pixel detector – STAR (BNL) – 2014-2016



PXL Material Budget

- Thinned Sensor

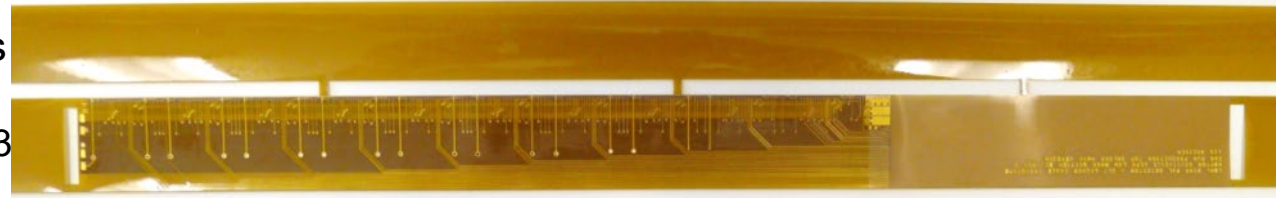
- 50 μm
- 0.068% X_0



- ▶ Curved sensor
- ▶ 40-60% yield after thinning, dicing and probe testing
- ▶ Fully characterized before installation

- Flex Cable

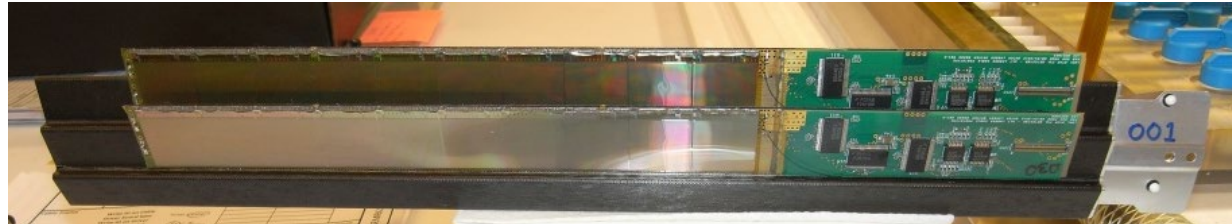
- Aluminum-Kapton
- two 32 μm -thick Al layers
- 0.128% X_0
 - Copper version \rightarrow 0.23



- ▶ Power and signal lines
- ▶ Wire bond encapsulant largest contribution
- ▶ Acrylic adhesive to deal with different CTE

- Carbon fiber supports

- 125 μm stiffener
- 250 μm sector tube
- 0.193% X_0



- Cooling

- Air cooling: negligible contribution

- **Total material budget on inner layer: 0.388% X_0**
(0.492% X_0 for the Cu conductor version)

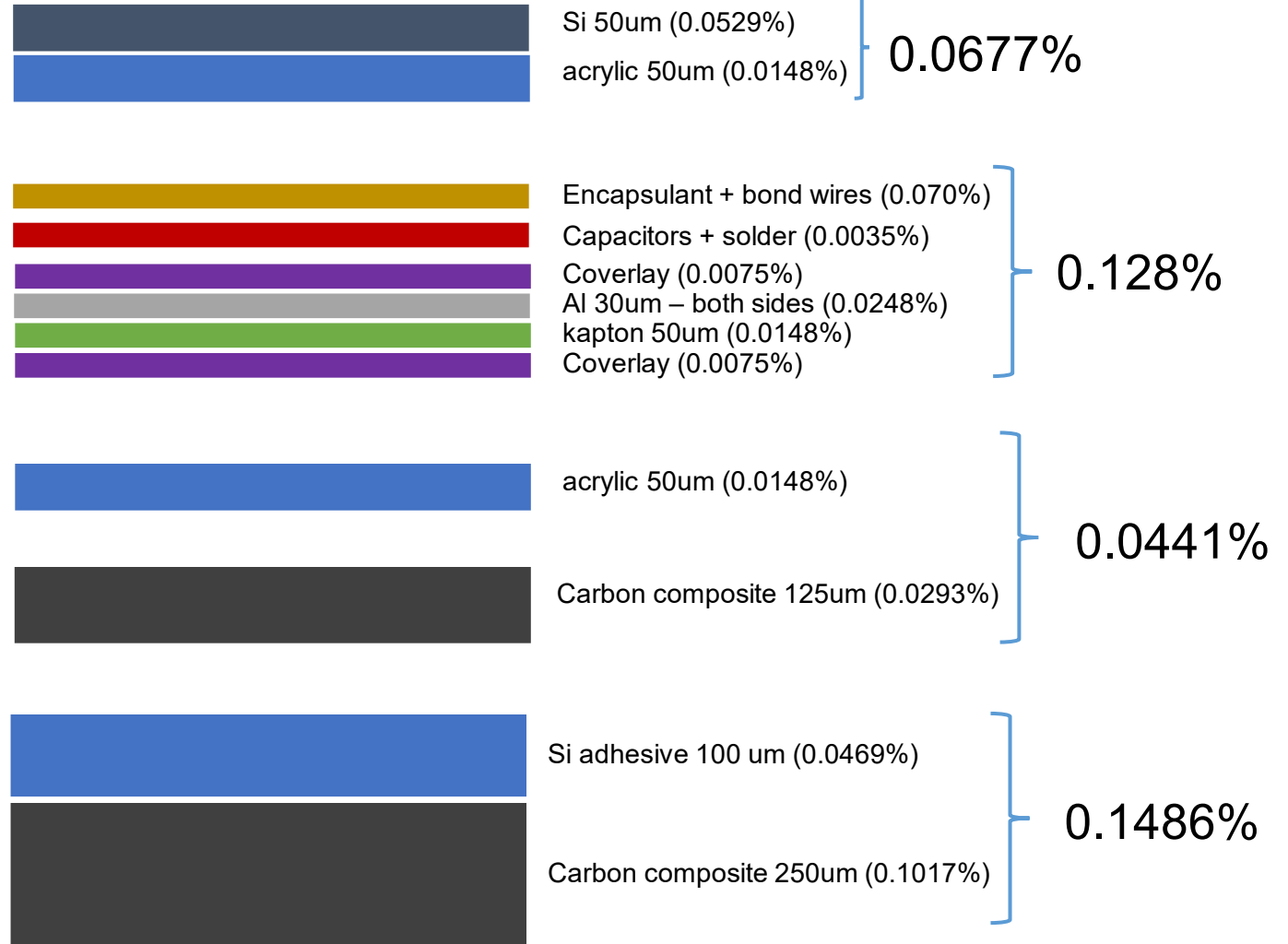
SPD

Material budget comparison

HFT

SPD Element	Thickness μm	% X_0
Al Bus		
Kapton	60	0.021
Al power	100	0.112
Al signals [50% of total surface]	17.5	0.020
Glue Epoxy	70	0.016
SMD components	16.4	0.173
Total bus		0.341
Other Components		
Pixel chip	150	0.160
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Grounding Foil-Kapton/Al	50+10	0.029
Glue Epoxy/thermal grease	200	0.049
Carbon fiber	200	0.106
Total components		0.561
Total bus and components		0.903

MATERIAL BUDGET OF ONE SPD LAYER



Total = 0.388%