Vertex Detectors

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TIDPAN-2026 (IFIC-Valencia)

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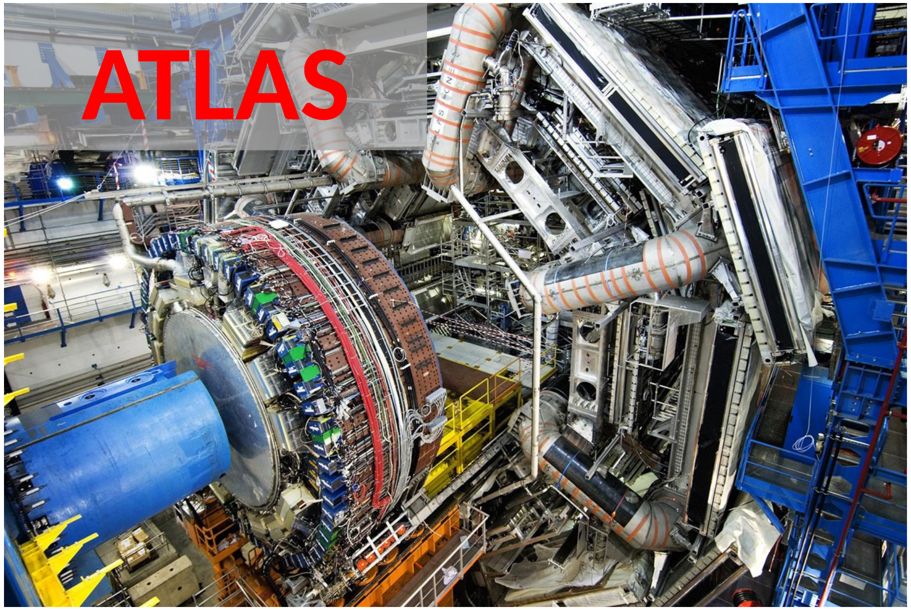
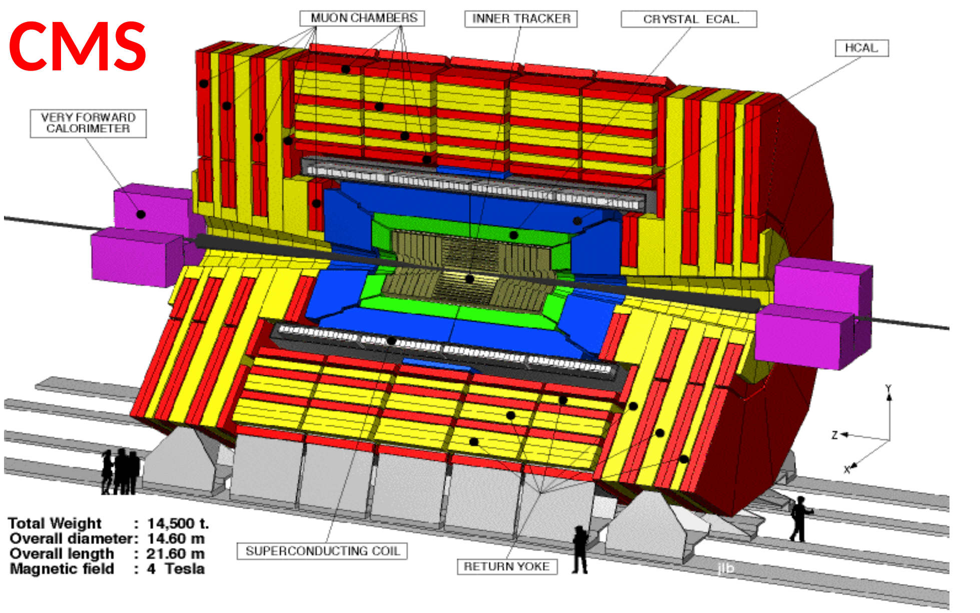
ICREA

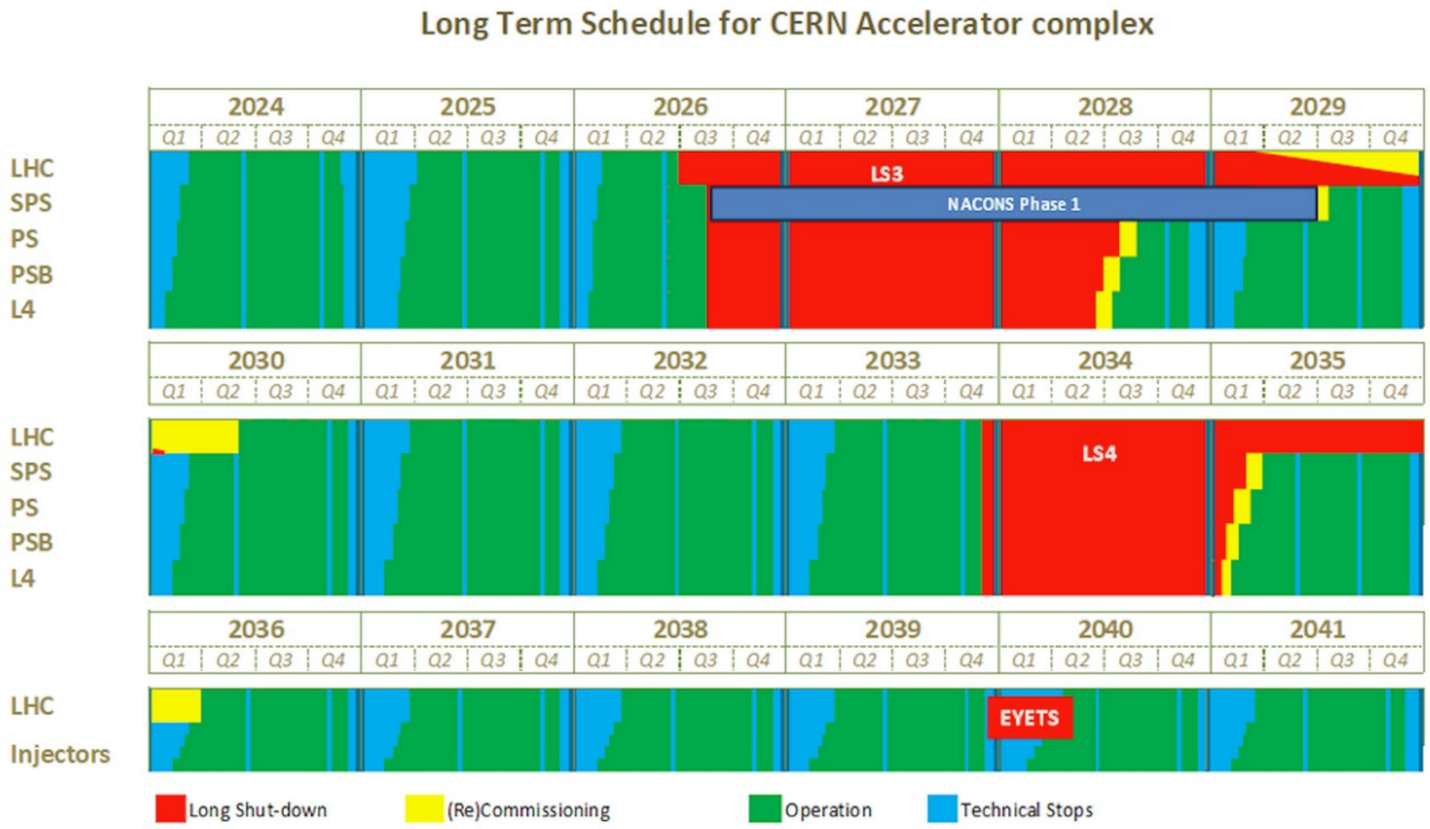
I will focus on vertex detectors in the LHC…



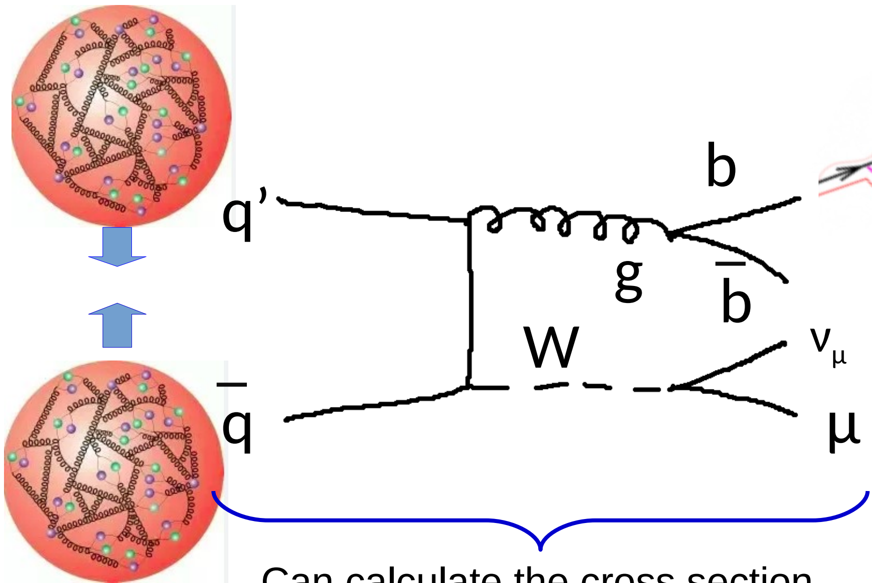


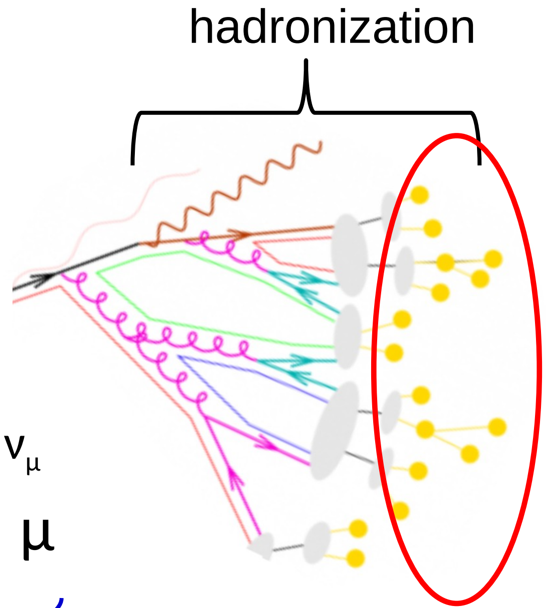
LHC Schedule

Machine and experiment upgrades every 5-10 yrs...



Why **upgrade**? After some time, it becomes more reasonable to improve machine than to wait tens of years to accumulate significant larger sample...

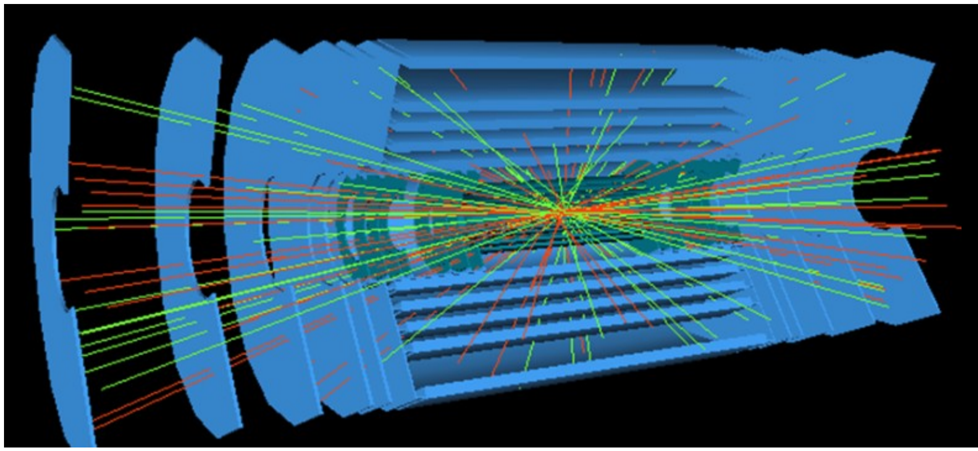




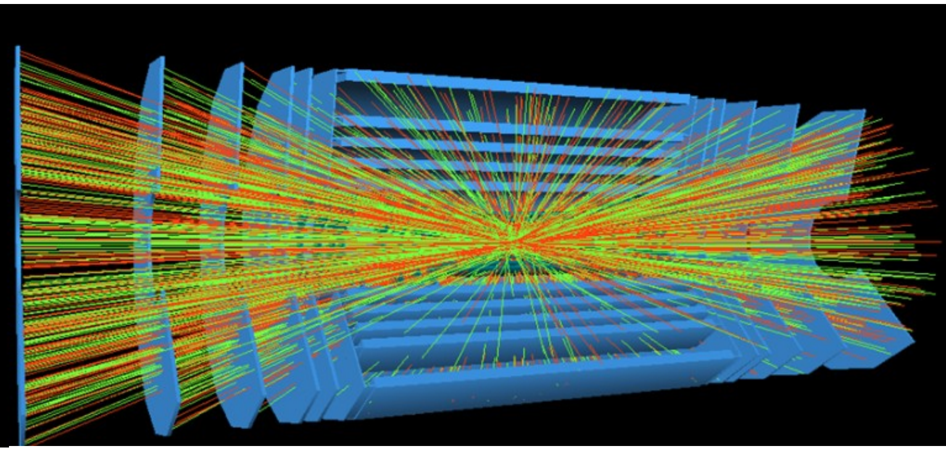
Outgoing particles which are **detected**

Can calculate the cross section (~probability) of this process... (Feynman rules)

And can relate to the measured (“counted”) particles in the detector...

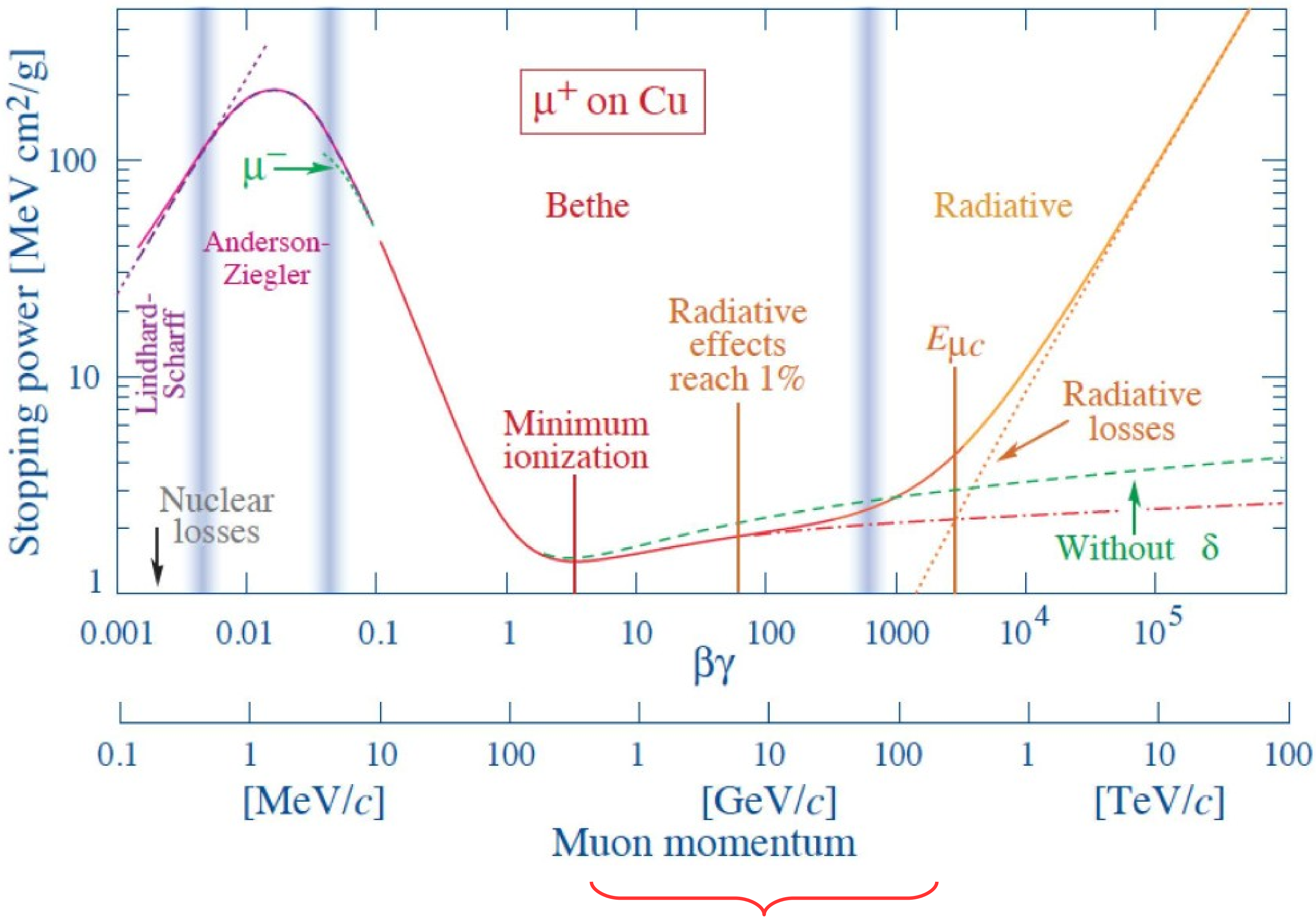


LHC – ATLAS: “now”



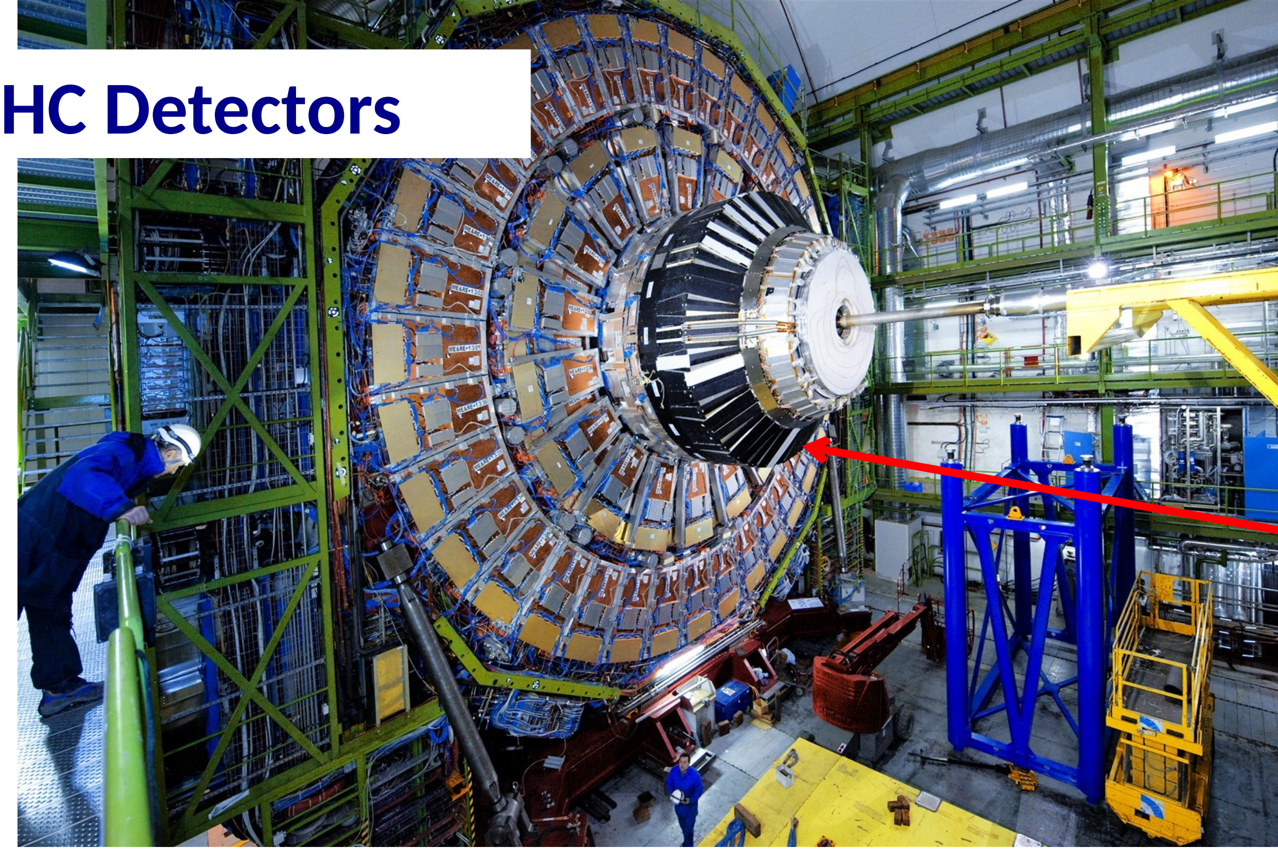
HL-LHC – ATLAS: ~2030

Typical Particles Produced in ATLAS/CMS

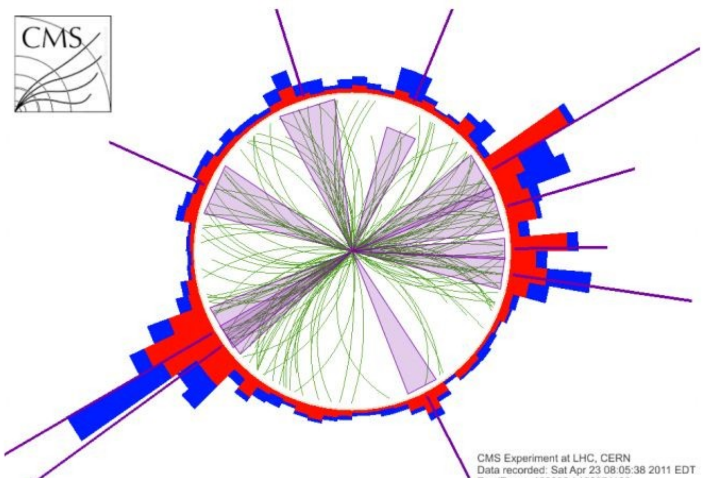


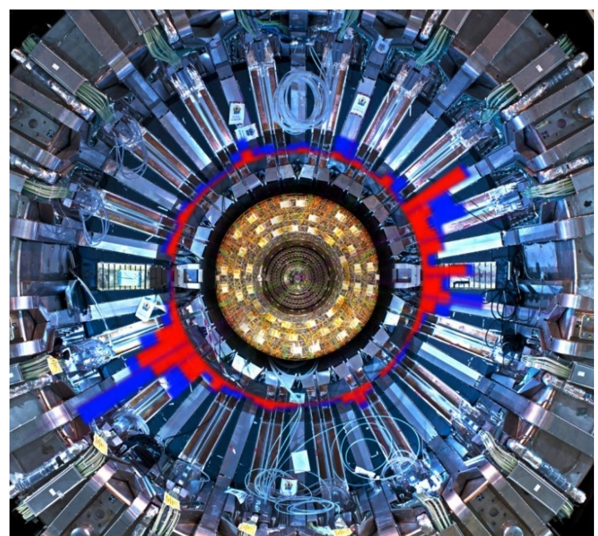
Range at LHC

LHC Detectors



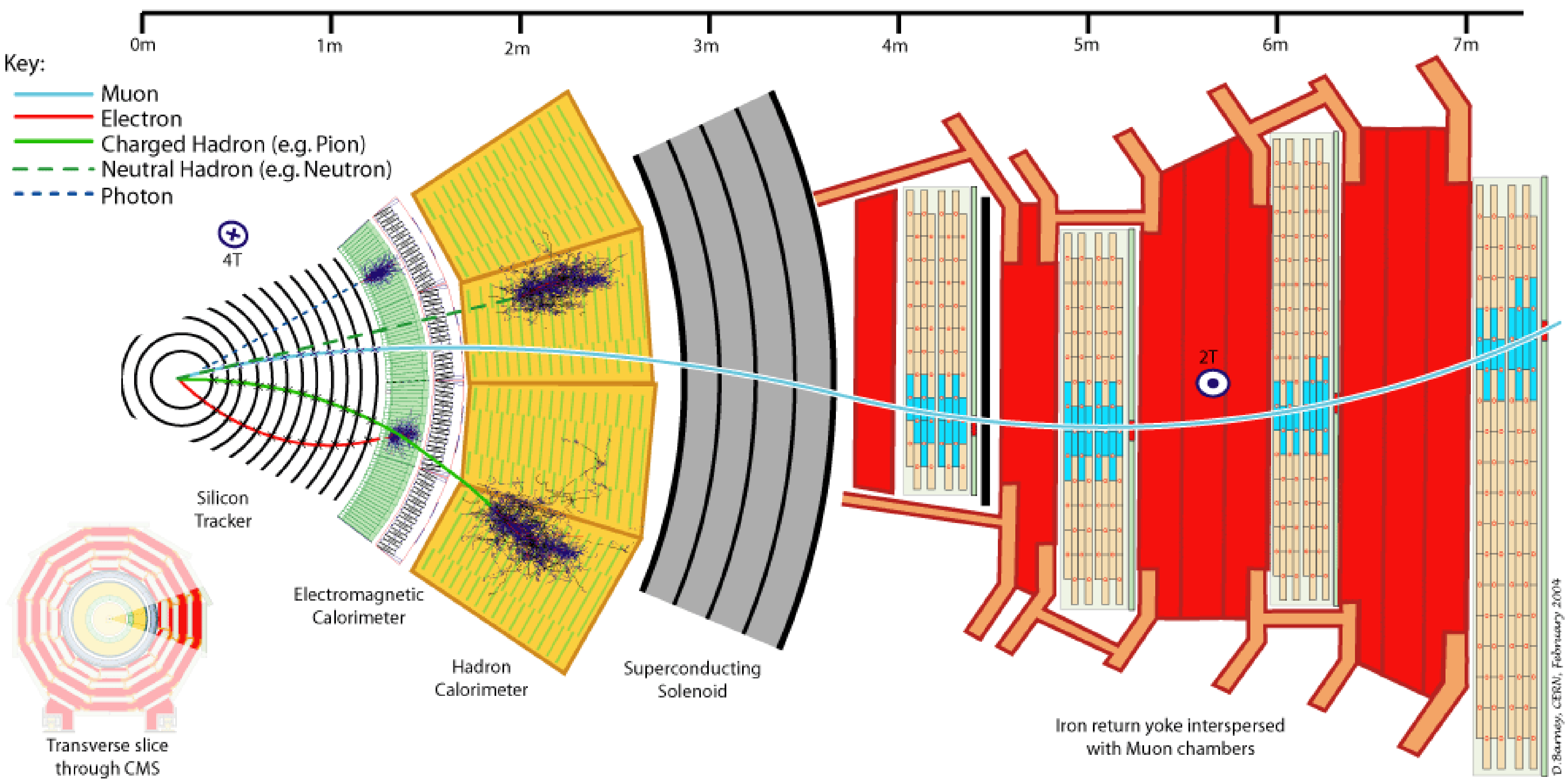
Cylindrical detector surrounds the collision region





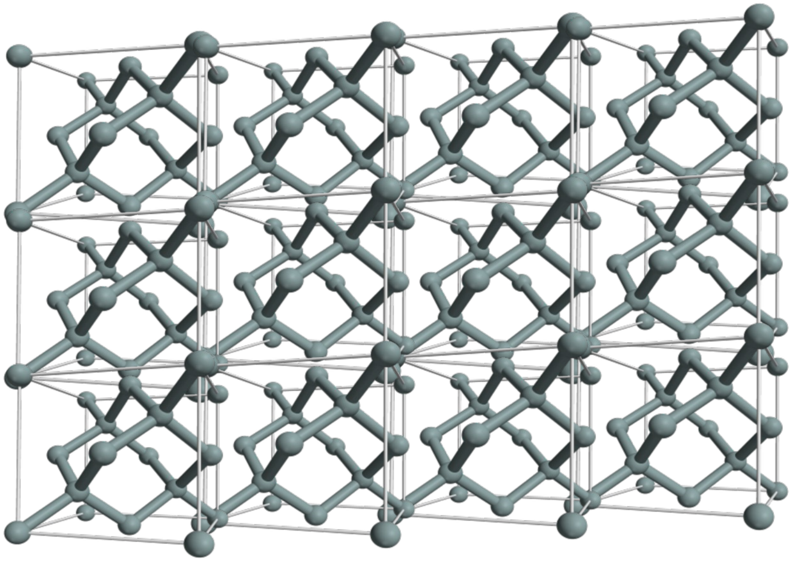
ATLAS is
46 m long,
25 m diameter, 7000 t

The objective of ATLAS and CMS is to measure "everything" that results of the LHC collisions (every 25ns)

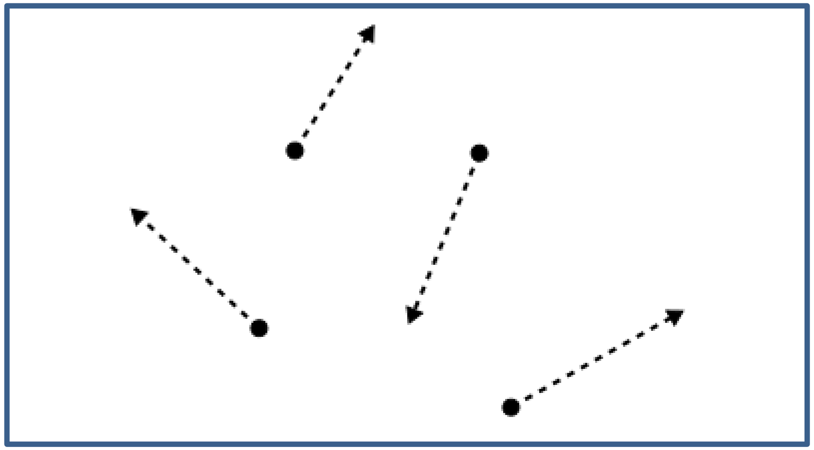


CMS: 21 m long, 15 m Φ, *14 ktons*

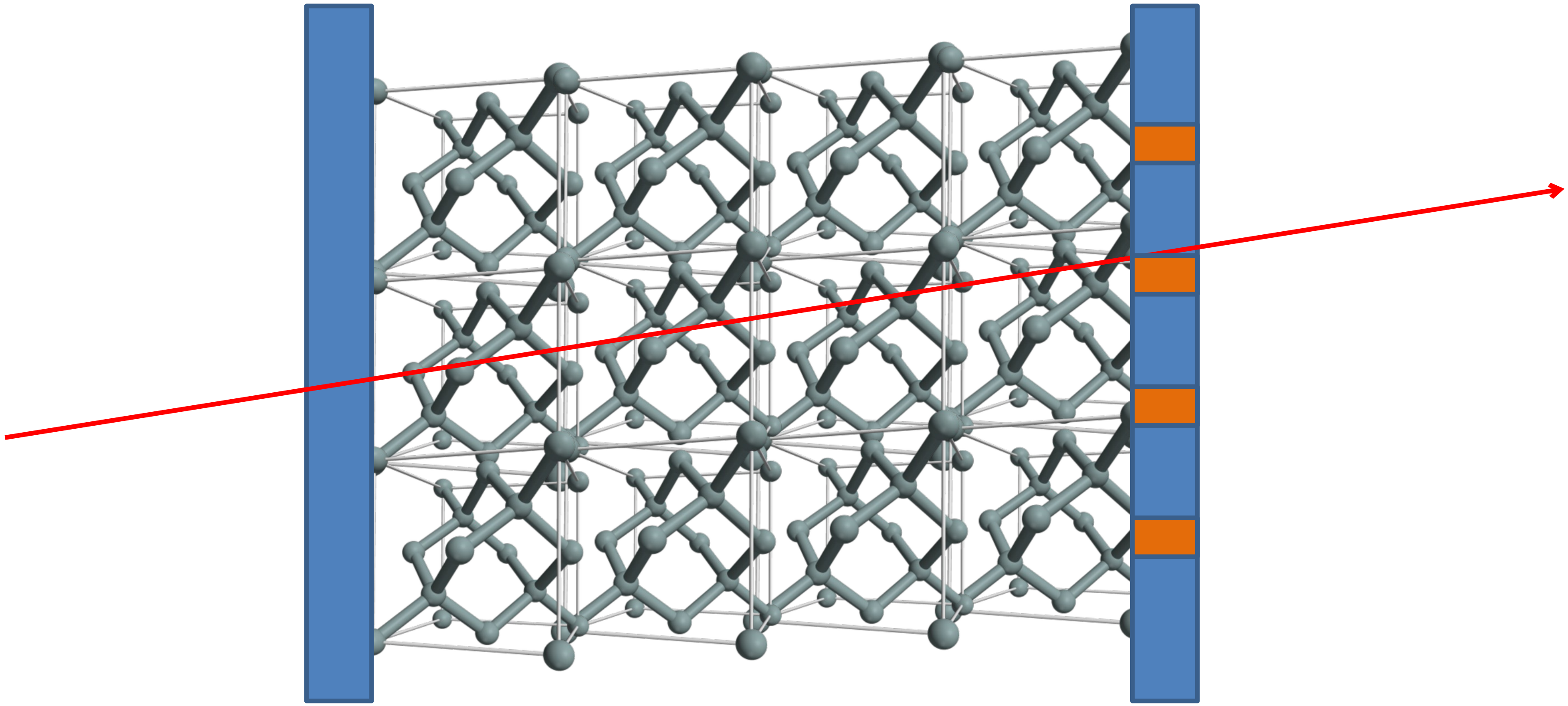
Detector Material/Type

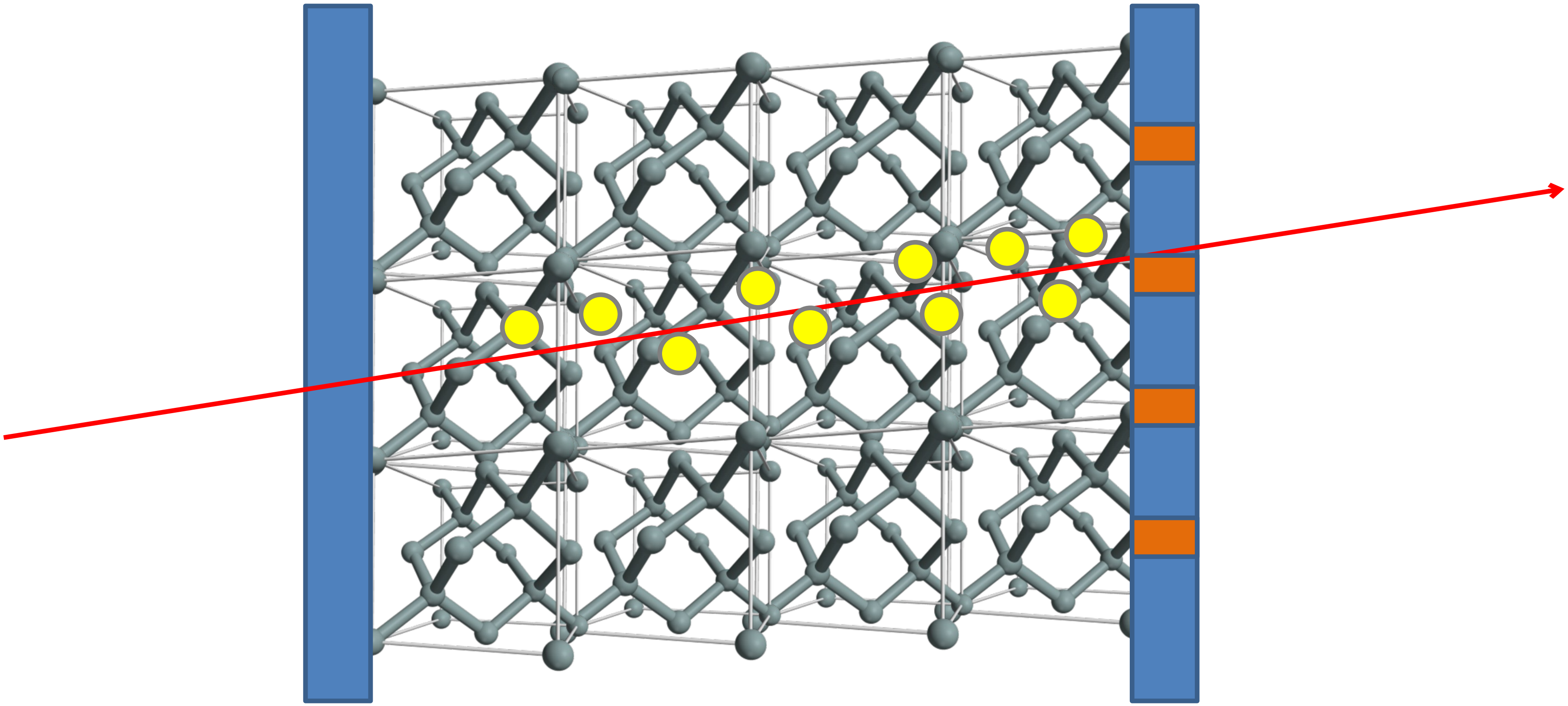


Solid

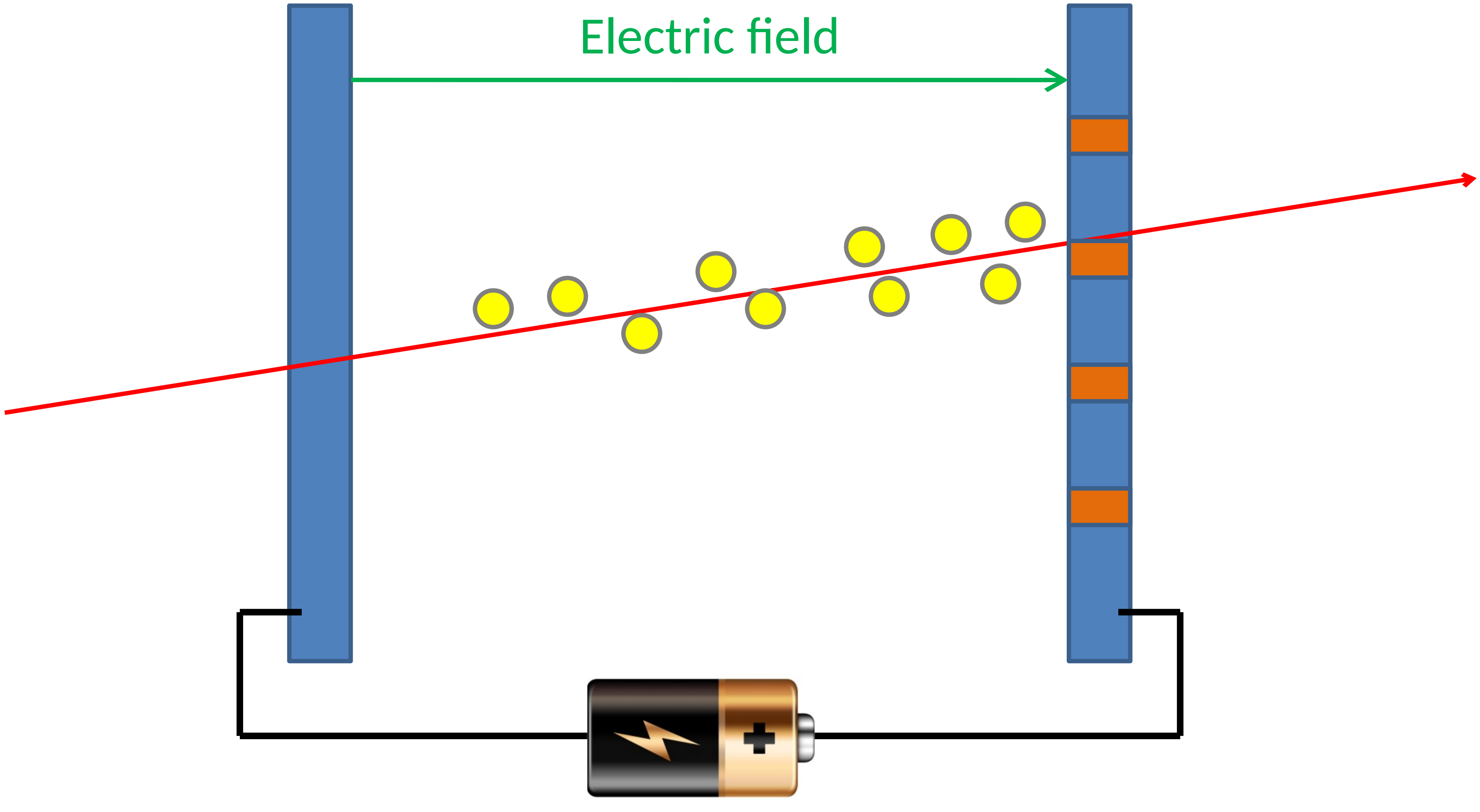


Gas

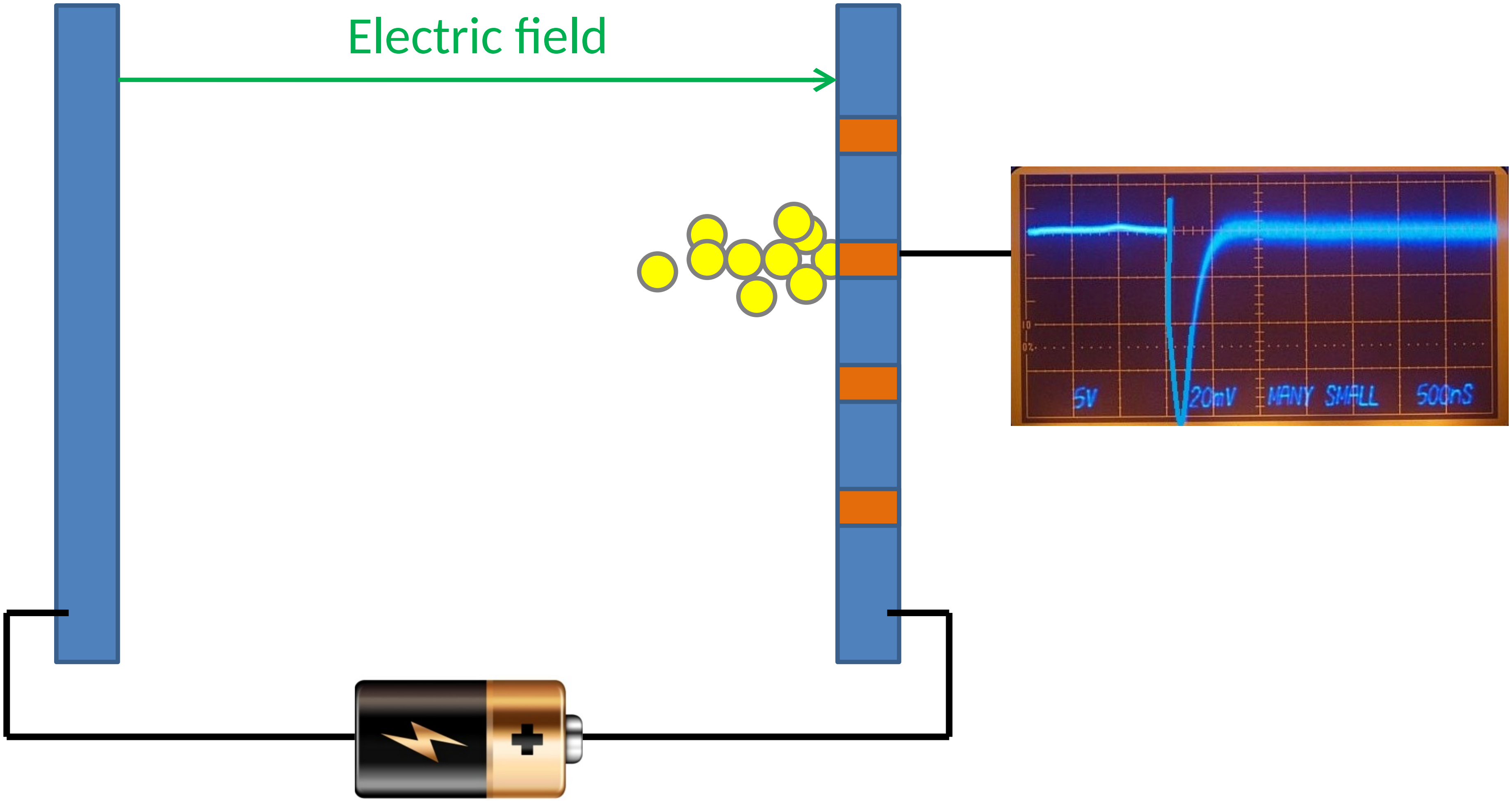




Signal Formation



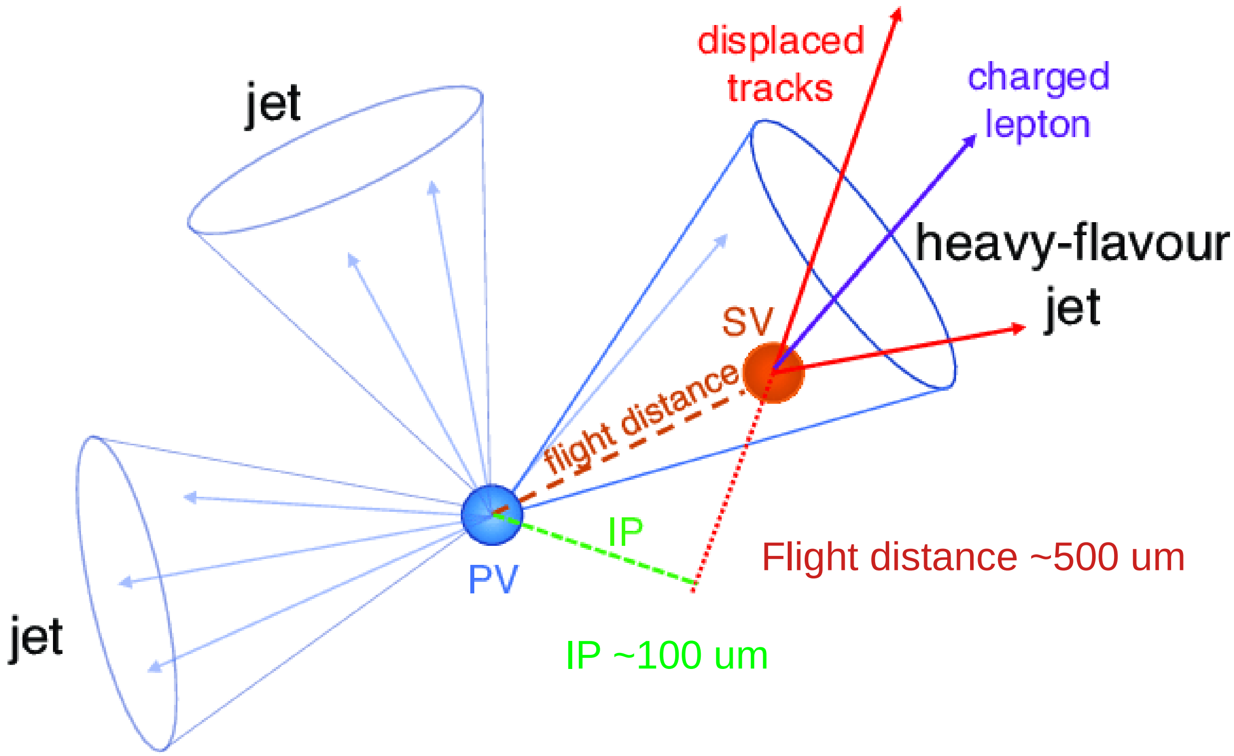
Signal Formation

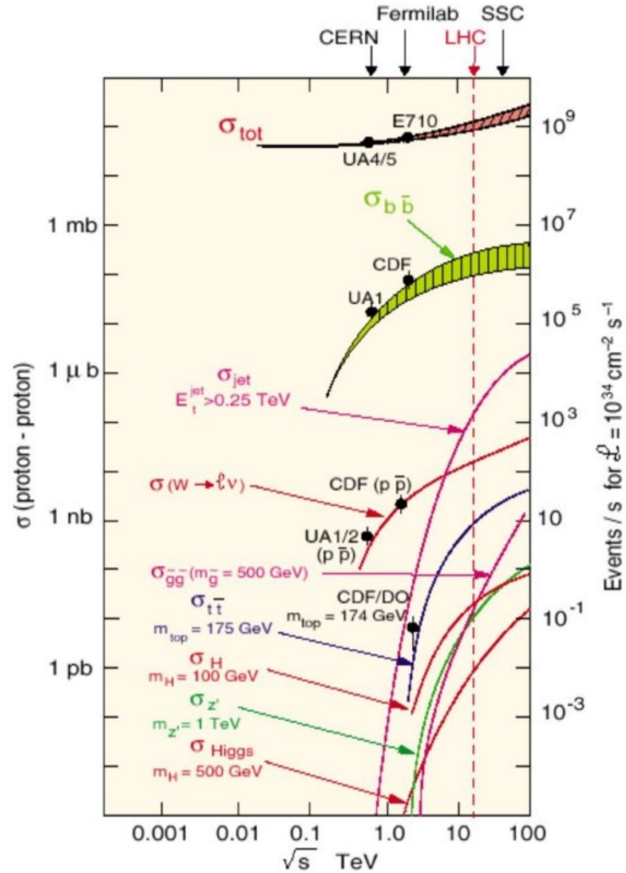


Electrical signal indicates path and energy lost of particle

Vertex Detectors

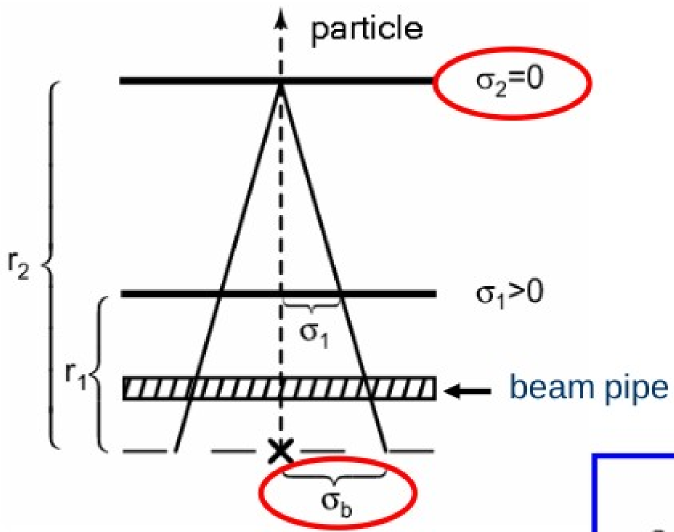
- Background processes in hadron colliders is huge!
- Need a handle to identify potential interesting events...

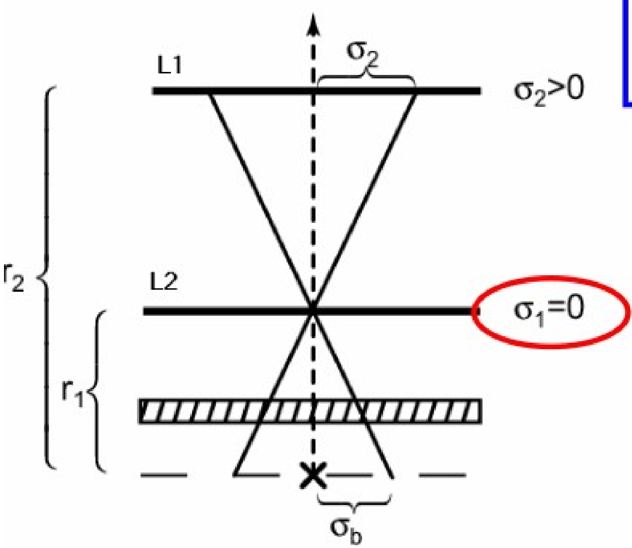




- Identifying heavy flavor jets allows to “remove background”
- Need ~50-10 um impact parameter resolution

Position Resolution





$$\frac{\sigma_b}{\sigma_1} = \frac{r_2}{r_2 - r_1}$$

small ! small !

$$\sigma^2 = \left(\frac{r_1}{r_2 - r_1}\,\sigma_2\right)^2 + \left(\frac{r_2}{r_2 - r_1}\,\sigma_1\right)^2 + \sigma_{MS}^2$$

small x/X_0

$$\frac{\sigma_b}{\sigma_2} = \frac{r_1}{r_2 - r_1}$$

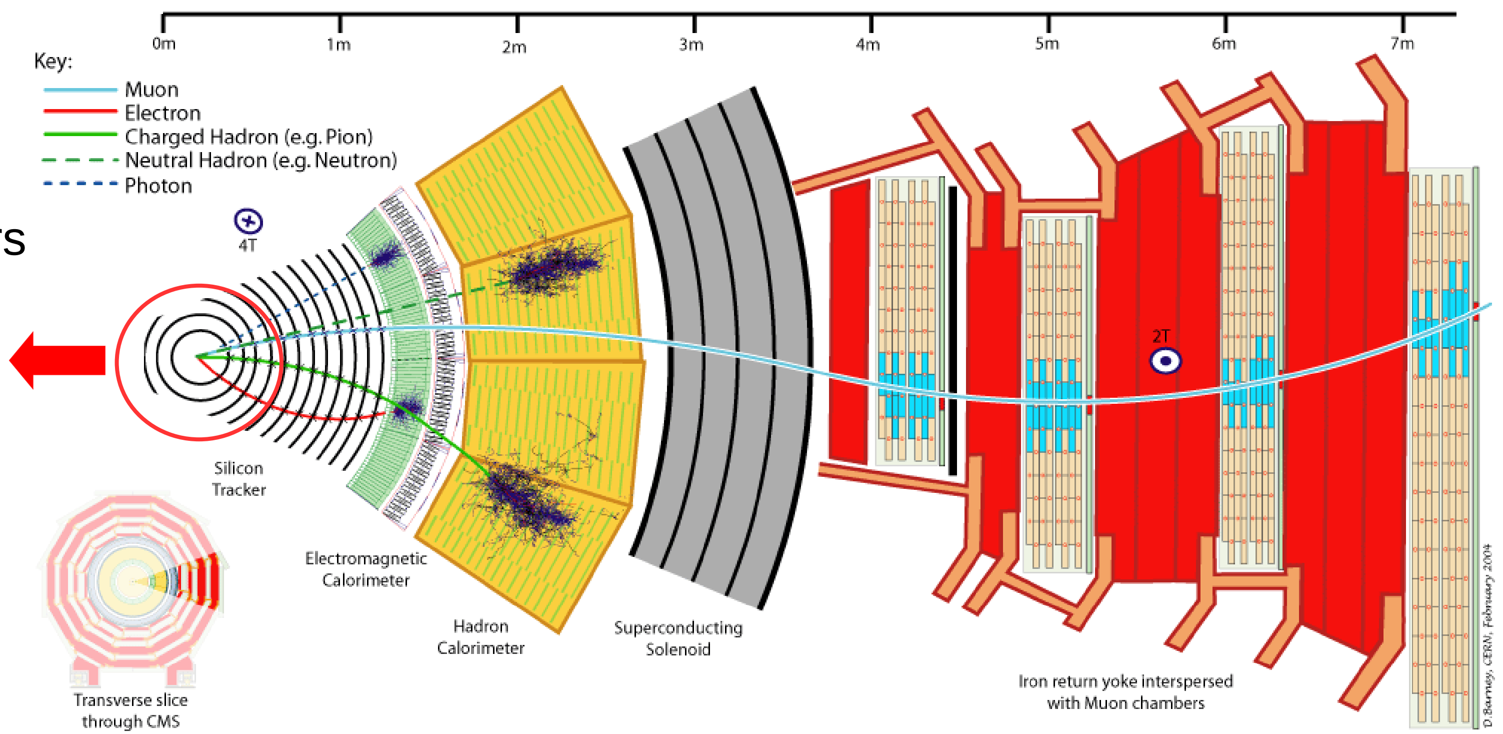
$$\sigma_{MS} \sim \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

N. Wermes

Vertex and Tracking Detectors

- Tracking: reconstruction of trajectory (or track) of electrically charged particles in a detector (tracker), (mostly) from patterns of measured hits (get measurement of particle properties)
- Vertex: identify primary and secondary vertices (eg, key for *heavy flavor identification), part of "tracking"...*

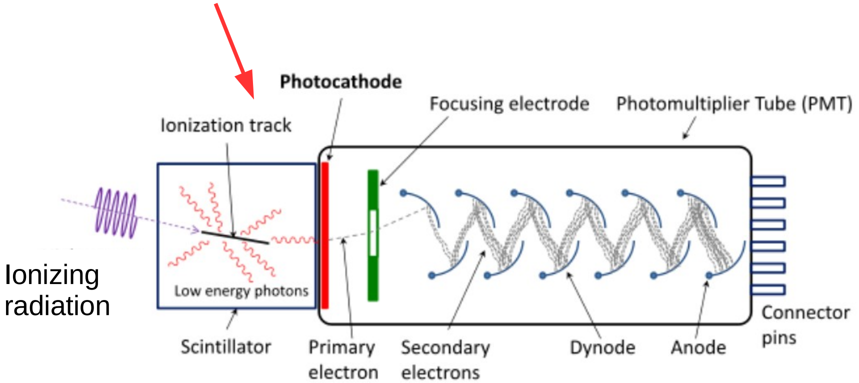
Inner layers critical for vertex position resolution

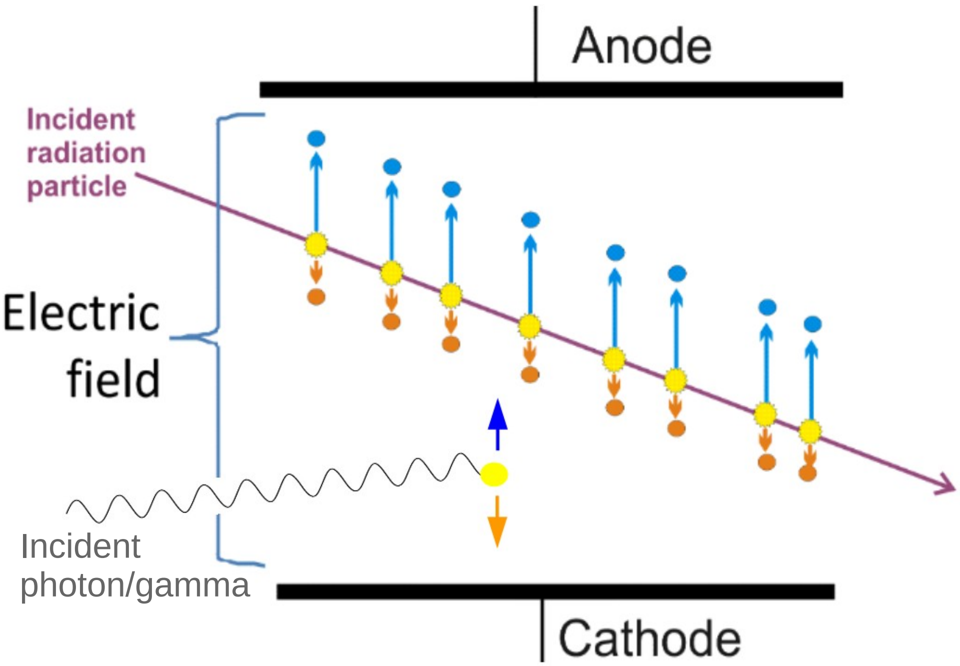


Tracking Detectors

Two basic detector types:

- **Gaseous** (liquid) detectors
  - Ionization, proportional or Geiger mode operation
- **Solid-state** detector
  - Semiconductor-based
  - Scintillators





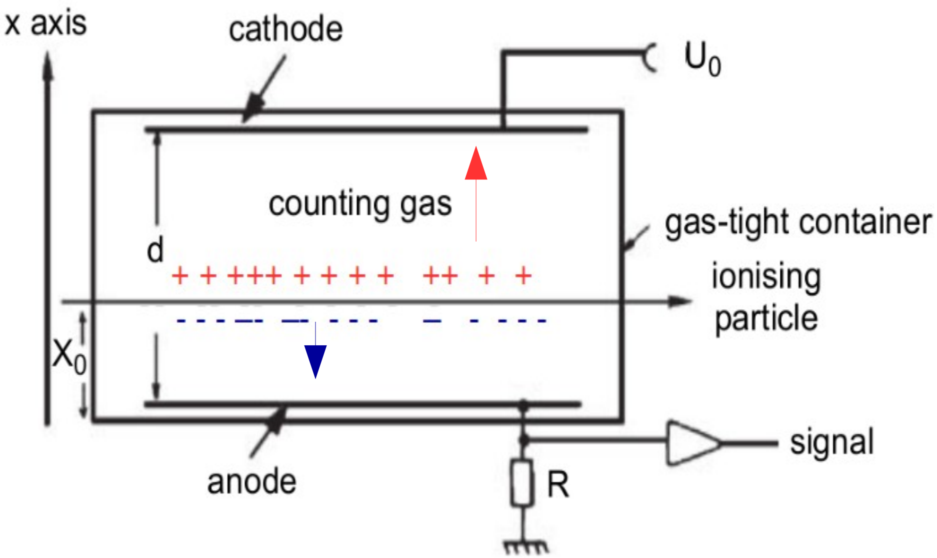
Ionization detectors

Ideal detector:

- High/good: **efficiency** and position **resolution**
- Low: fake rate, material budget, operational requirements and cost

Gaseous Detectors

"Simplest" detector:



Ionization counter

- Measures the amount of (primary) ionization produced by charged particle

Collected charge:

- Parallel plate capacitor: Q = N e → V = N e / C (C: capacitance of detector)
- Typical signal (for a ~few cm size detector)
  - 5 MeV α-particle in Ar (e-ion energy W=26 eV) with C = 10 pF → V = 3 mV
  - But: MIP in 4 cm or Ar → V=7 μV (too small! → will need to address this)

Signal formation:

- How does the signal look like?
- Ramo theorem… (back up slides...)

1 e → 1.6E-19 C

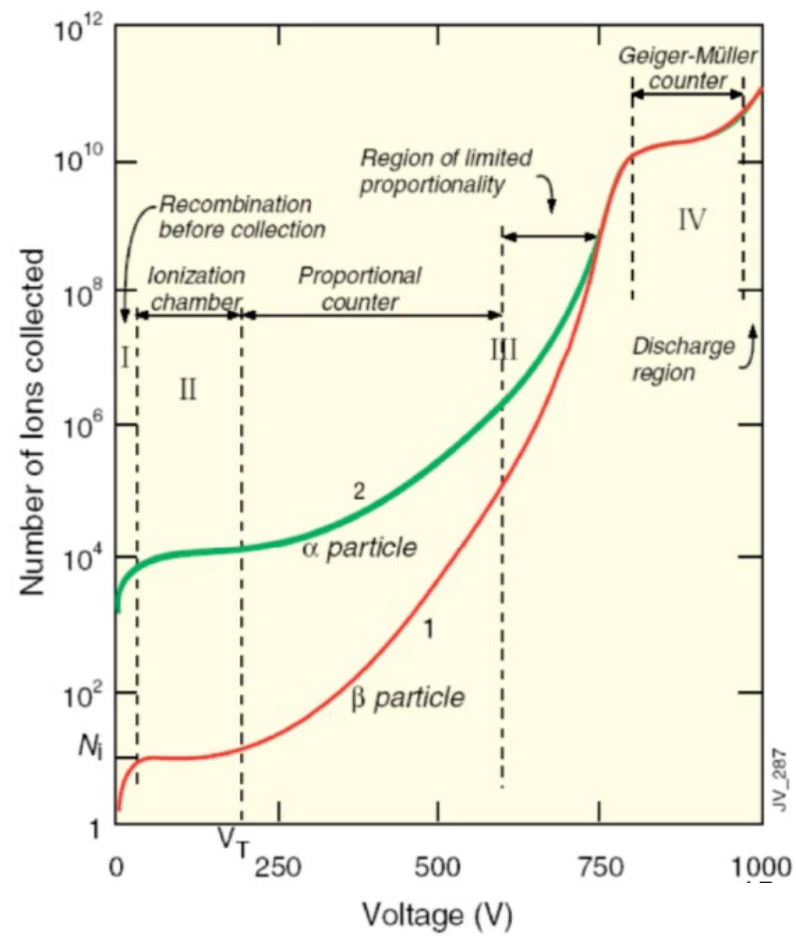
Gaseous Detectors

- Ionization chambers do not yield enough signal for mip detection...
- How to improve?
  - Reduce capacitance or, better, get more charge! (V = Q / C)
  - **Increase HV to obtain signal gain**

If field strength in some region of the counter volume is high, an electron can gain enough energy between two collisions to ionize another atom.

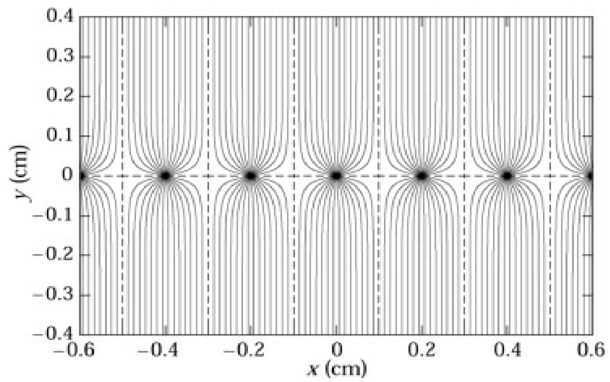
Increase HV

- Recombination before collection
- Ionization range
  - Collect ionization
- Proportional regime
  - Signal is amplified
  - Signal is proportional to primary ionization
- Geiger-Müller region
  - Photo-electron production dominates, loss of proportionality



Multi-Wire Proportional Chambers (MWPC)

► Back to “tracking”, reconstructing trajectory of particles...

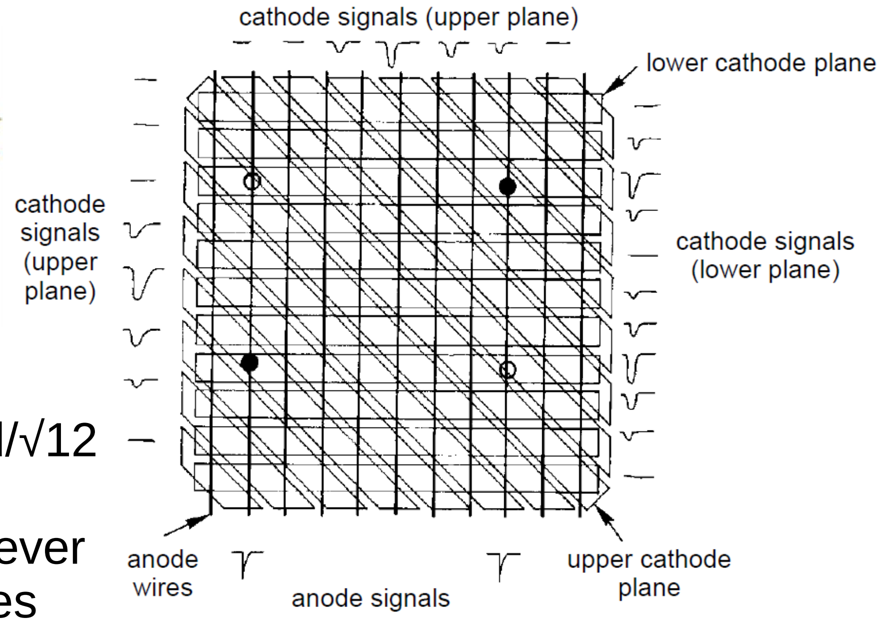


- Two cathodes planes with series of anode wires between the planes
- E field and gas properties chosen so that chamber operates in proportional mode (avalanche near wires, signal collected from wires and corresponding strips)
- The electric field geometry close to the anode wires is very similar to the field in a proportional counter → each individual anode wire behaves as a proportional counter
- Anode wires: 20 μm thick Au-plated W, Al; 2 mm spacing

  Counting gas: Ar, Kr, or Xe with admixture of CO_2 , CH_4 , isobutane, … (high electron mobility)

  Amplification: 10^5 ; efficiency: ~100%

Multi-Wire Proportional Chambers (MWPC)



Position resolution

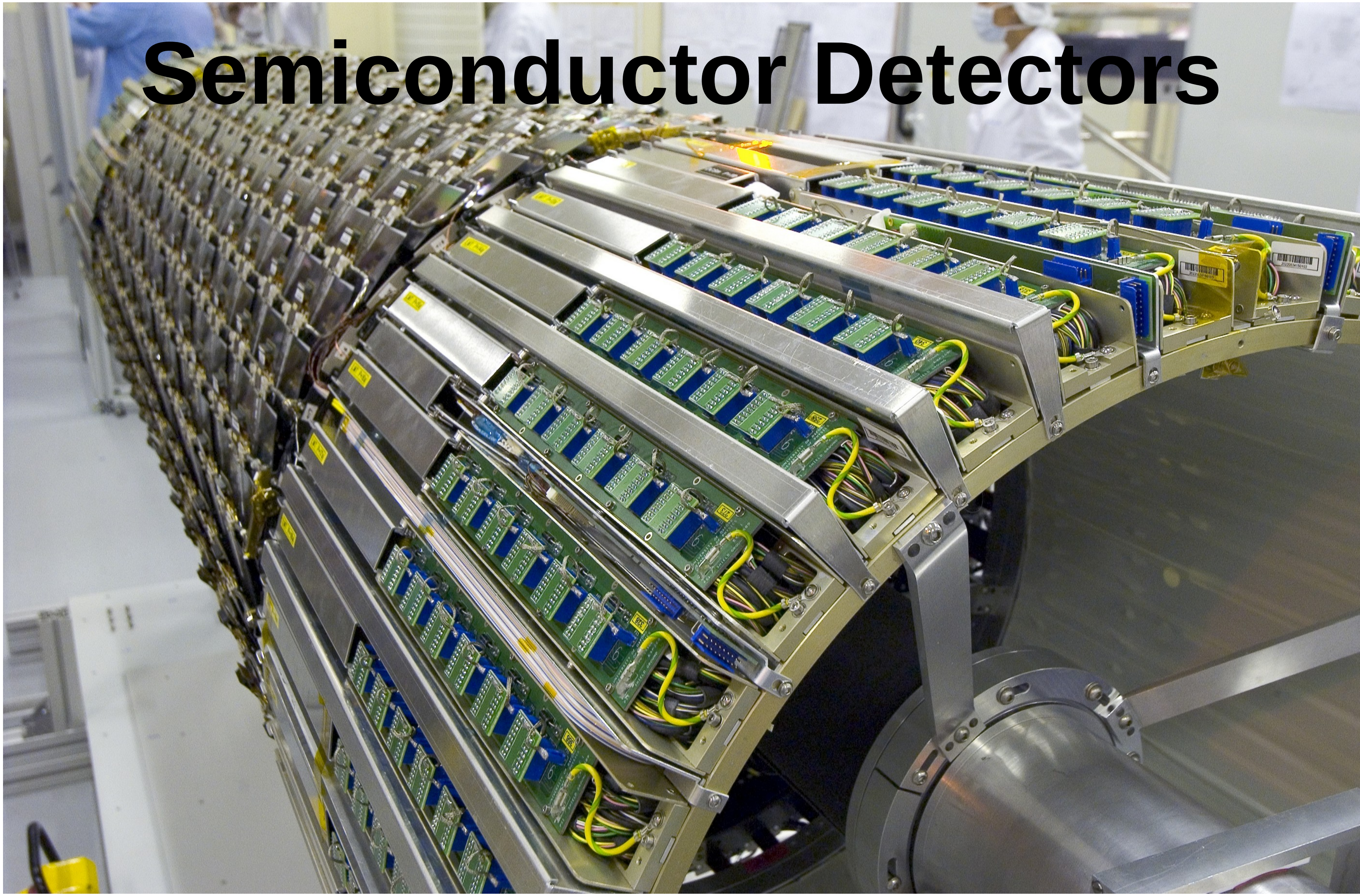
- Given by pitch, inter-wire distance, d: $\sigma(x) = d/\sqrt{12}$
  - $\sigma(x)$ = 577 μm for d = 2 mm
- To improve resolution one can reduce d, however limited by electrostatic repulsion between wires
- Charge division to determine other coordinate (use wire resistivity, needs readout from both sides)

Further improve position resolution

- Segment cathode planes into strips; strips run perpendicular (on one cathode) and at an angle or parallel (in the other) to the anode wires
  - Signal spread into several strips, use center of gravity to obtain position
  - Can achieve $\sigma(x)$ = ~100 μm (depending on chamber size)
  - Improve further…: 2D cathode segmentation!
  - Typical voltages: ~1000 V or more

But **not** enough for b-tagging...

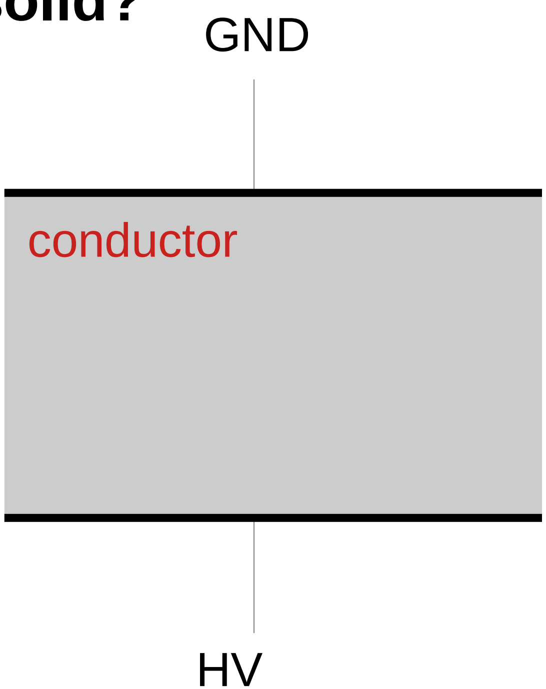
Semiconductor Detectors

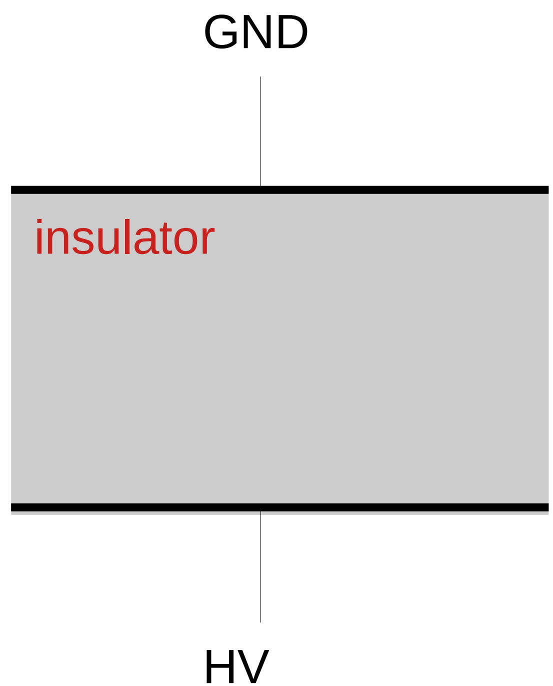


ATLAS Silicon Tracker – CERN

Solid State Detectors

What solid?





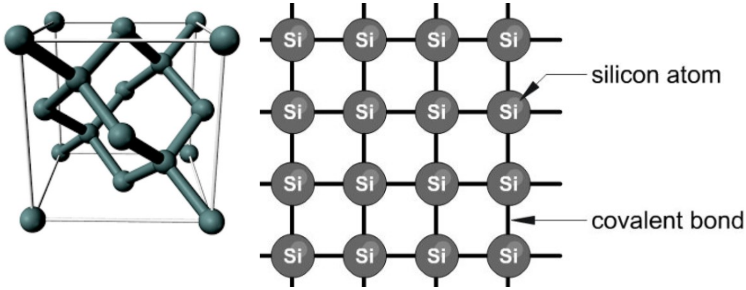
- Too much current as soon as one applies voltage
- Can not see signal...

- No current flow, but also no signal induced!
- Can not see signal...

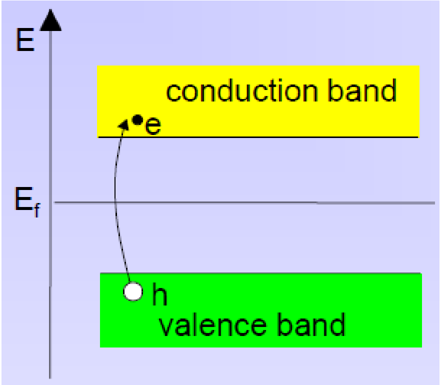
Solid State Detectors

What solid?

Semiconductors...

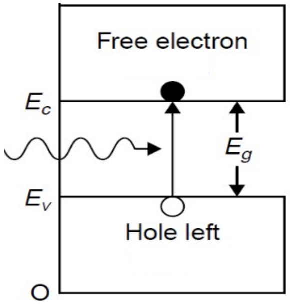


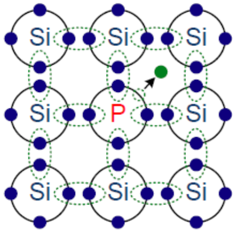
- **Silicon** specially attractive for many HEP applications:
  - Silicon semiconductor that has 4 valence electrons
  - **Small band gap:** Eg = 1.12 eV; E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
  - **High specific density**: 2.33 g/cm^3 ; dE/dx (mip) = 3.8 MeV/cm → 100 e-h/µm (average)
  - **High carrier mobility**: μ_e=1450 cm^2/Vs, μ_h = 450 cm^2/Vs → fast charge collection (<10 ns)
  - **Very pure** < 1ppm impurities and < 0.1ppb electrical active impurities
  - **Rigidity** of silicon allows thin self supporting structures
  - Detector production by **microelectronic techniques**
    - **Si abundant, Industrial technology, small structures...**



	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

Silicon Detectors





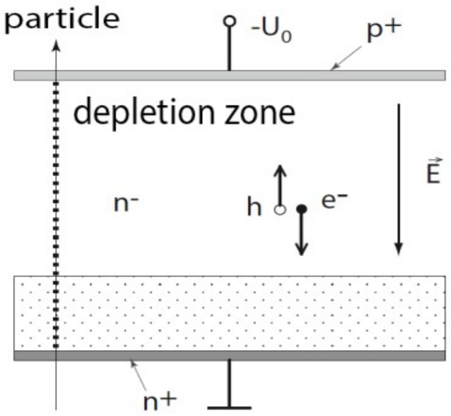
$$n = 2\left(\frac{2\pi m_n k_B T}{h^2}\right)^{3/2} e^{-(E_C - E_F)/(k_B T)}$$

Electron concentration in conduction band

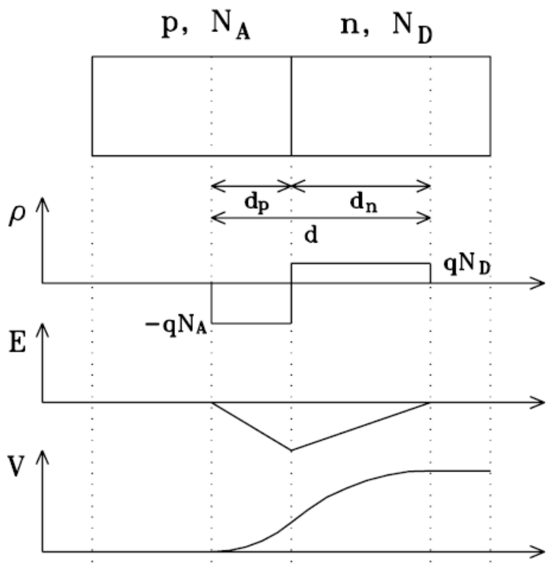
- Incident radiation generates e-h pairs that are collected by electric field
- However, **in pure intrinsic silicon** electron (n) and hole (p) densities are too large, n = p = 1.45E10 /cm^3 (at room temp.)
  - While **expected signal** in typical (200 µm thick) sensor is much smaller, 20000 e-h pairs
  - **Solution**: dope Si to form a p–n junction → zone that is free of charge carriers (depleted), enlarged by applying a voltage
    - Elements with 3 valence e- (p-type, B)
    - Elements with 5 valence e- (n-type, P)

- **Silicon detector is basically a reverse biased p-n junction**
- Depleted region (ionization collection region) depends on external voltage

- *Key to sensor sensitivity is depletion depth, which can be adjusted with reverse bias and resistivity (both technology dependent)*



Silicon Detectors



$d = x_p + x_n$ (1) $\quad N_A x_p = N_D x_n$ (2) charge neutrality

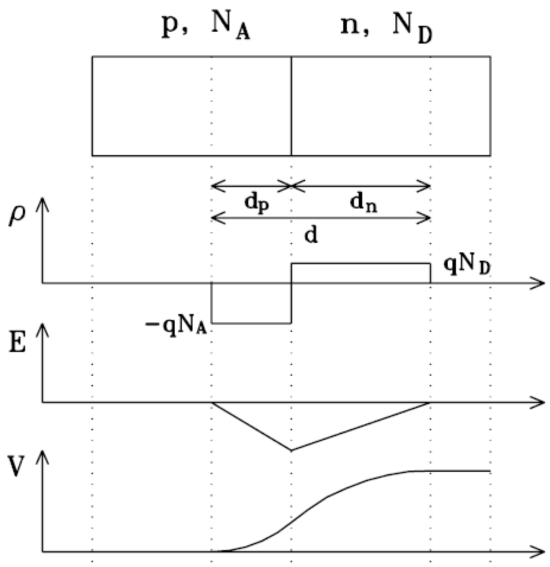
$$\rho(x) = \begin{cases} -eN_A, & -x_p < x < 0 \\ eN_D, & 0 < x < x_n, \\ 0 \end{cases} \qquad \frac{dE}{dx} = \frac{\rho(x)}{\varepsilon}$$

$$E(x) = \begin{cases} -eN_A(x + x_p)/\varepsilon, & -x_p < x < 0 \\ eN_D(x - x_n)/\varepsilon, & 0 < x < x_n, \\ 0 \end{cases}$$

$$V_{bi} = -\int_{-x_p}^{x_n} E(x)\, dx = \frac{e}{2\varepsilon}(N_A x_p^2 + N_D x_n^2) \quad (3)$$

→ using (1), (2) and (3): $d = \sqrt{\frac{N_A + N_D}{N_A N_D} \frac{2\varepsilon}{e} V_{bi}}$

Silicon Detectors



$$d = \sqrt{\frac{N_A + N_D}{N_A N_D} \frac{2\varepsilon}{e} V_{bi}}$$

Usually, Na >> Nd or Nd >> Na:

$$d = \sqrt{2\epsilon V_{bi}/(eN_{eff})} \approx \sqrt{V\,\rho}$$

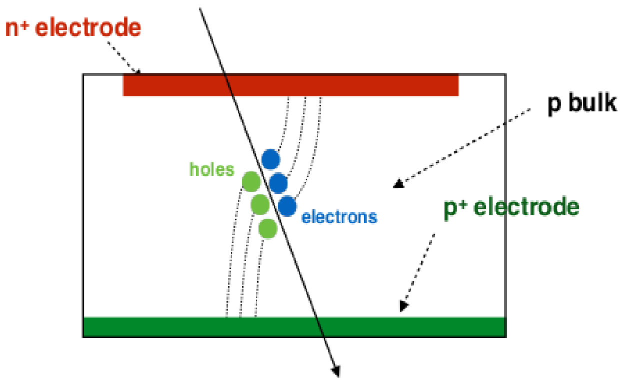
ρ is resistivity [Ω cm]

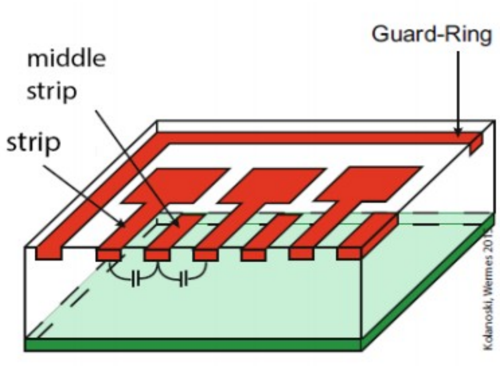
- For some typical values (Neff ~ 10^{12} cm^{-3}, Vbi~0.5V) → d ~ 20 µm
- Apply external voltage to increase depletion region into the low (high) doped (resistivity) substrate
- **Example**:
  - d = 300 µm
  - Neff = 1.5 10^{12} cm^{-3} *(ρ=1/(µeN)=3kΩcm)*
  - **Vdep = 100V**

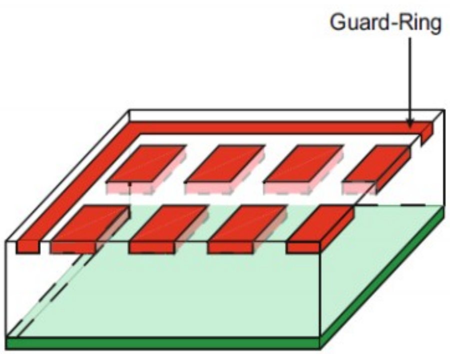
$$V_{dep} = \frac{e}{2\,\epsilon} N_{eff}\, d^2$$

Types of Silicon Detectors

- Ideal silicon detector:
  - Provides excellent position resolution (~10 µm or better)
  - Has ~100% efficiency
  - Sustain large radiation doses (both ionizing and non-ionizing radiation)
  - Maintain low fake trigger rate
  - Fast operation (fast charge collection, can operate at 25 ns, fast electronics...)





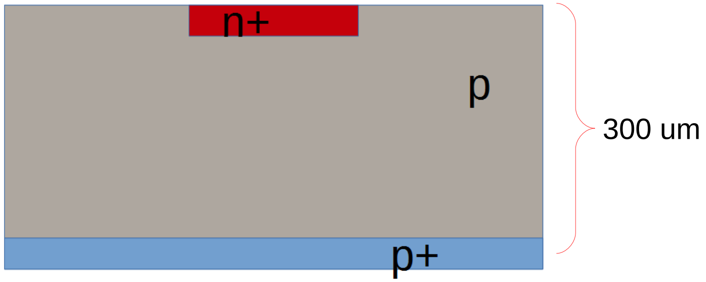


Pad detectors: easiest to fabricate but poor position resolution

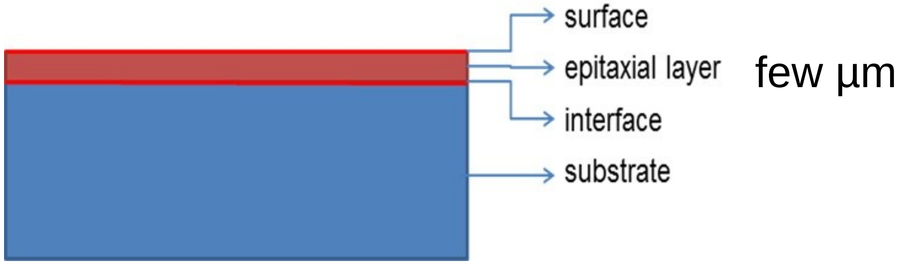
Strip detectors: Pitch ~ 80 µm, but difficult to provide excellent 2D resolution

Pixel detectors: Best position resolution, but: large power consumption & assembly cost

Types of Silicon Detectors: Substrates

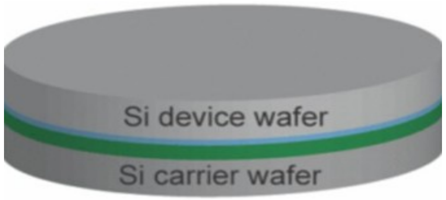


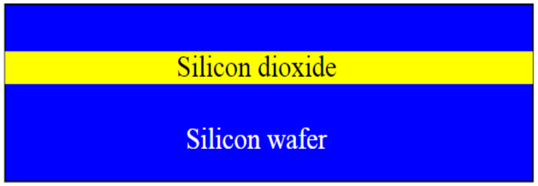
- Standard HEP detector on **high ρ silicon substrate**
- **n-on-p** for e collection (faster)



- **Epitaxial layer** on silicon bulk
- Usually deposited through CVD
- Used in CMOS processes

- Wafer to wafer bonding



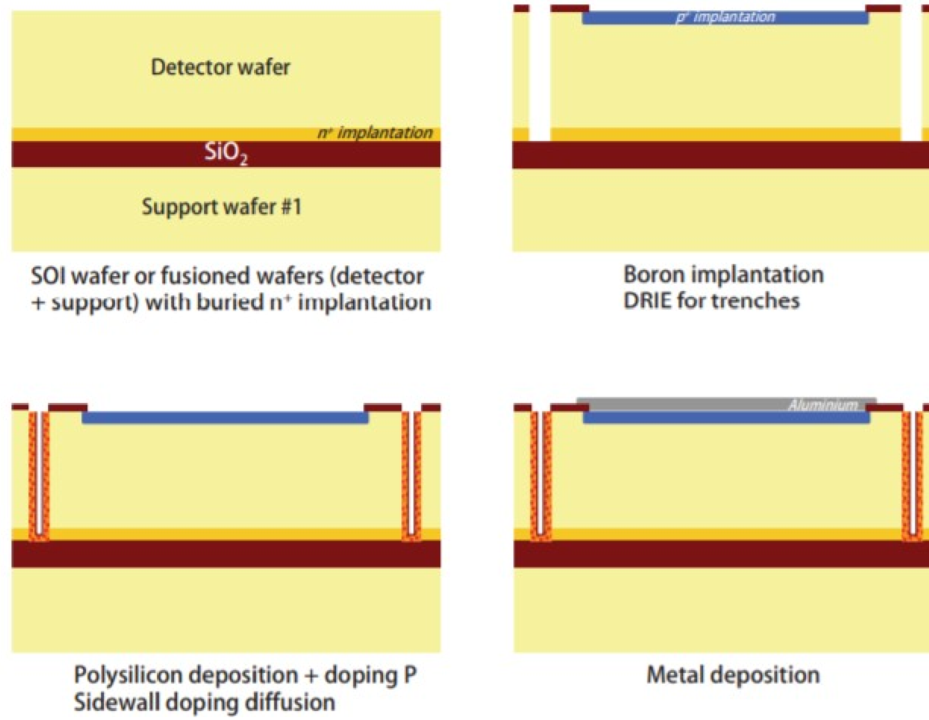


- **Silicon On Insulator** (SOI)
- SiO2 reduces parasitic capacitance
- Top layer varies with application
- Used in specialized processes

- **Technology selection** driven by experimental **conditions & requirements** and sensor fabrication strategies

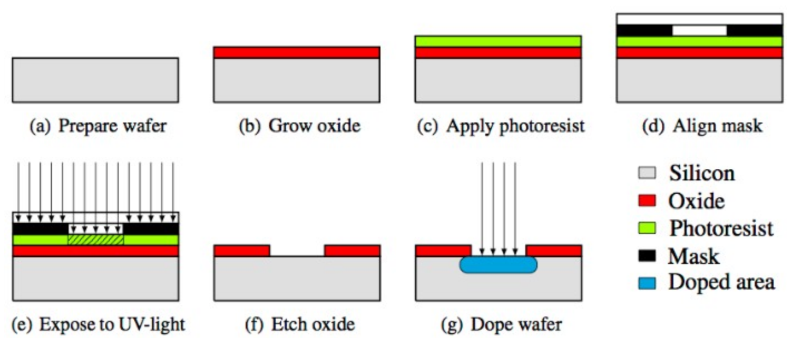
Silicon Detectors: Fabrication

Silicon ingots → wafer starting point

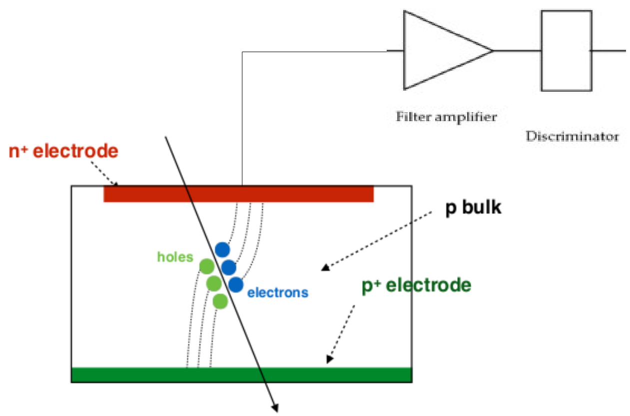


Sensor fabrication takes about ~50-100 steps of processing (pattering, passivation, etching, etc) in dedicated facilities.

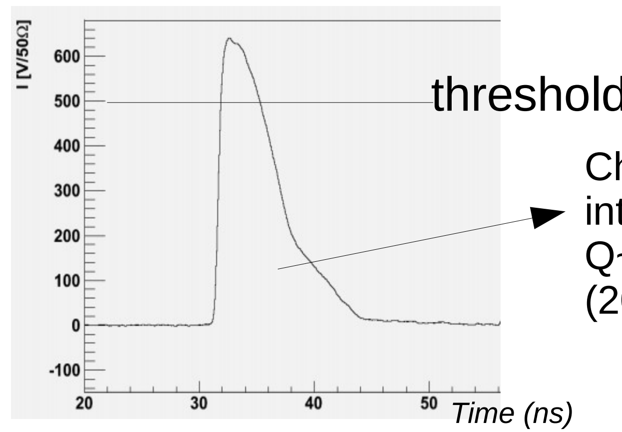
Note: Sensor vs "**Chip**" fabrication: similar...



Signal Processing



DC (or AC) coupling



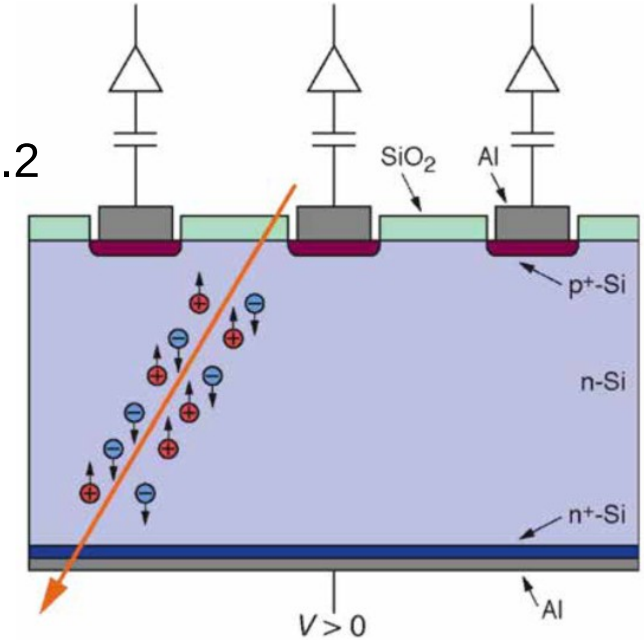
$$I_i(t) = q\vec{v}_{dr}(\vec{E}(\vec{r}(t))) \cdot \vec{E}_{i,w}(\vec{r}(t))$$

- Relatively small signals (20ke)
- Current induced in readout electrode as charge drift towards electrodes (Ramo)
- Need to amplify and discriminate signal

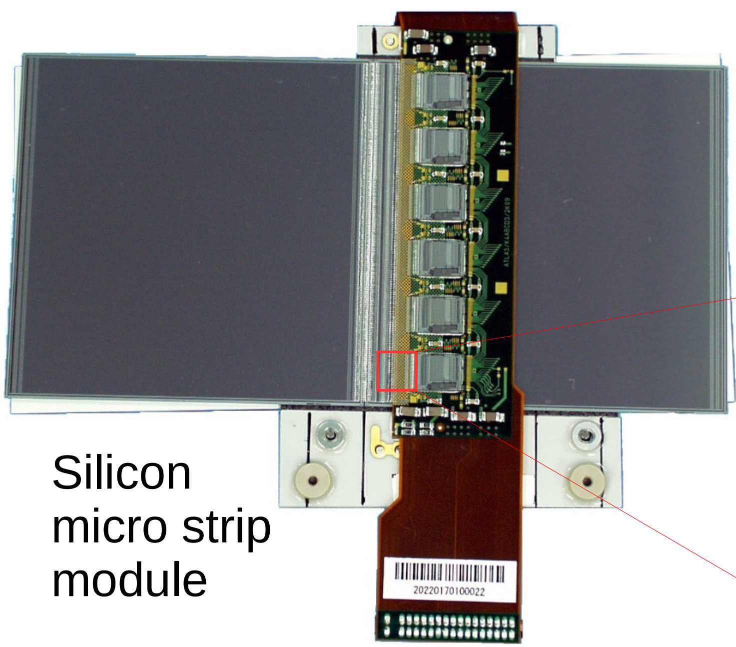
  - Signal processing done by electronics next to sensor ("front end", chip or Application-Specific IC: ASIC)
  - Noise is an important factor to determine detector performance
    - For silicon detectors most important contribution driven by C_{det}
  - Signal-to-Noise: typical values >10-15, Radiation damage degrades the S/N

Silicon Micro-Strip Detectors

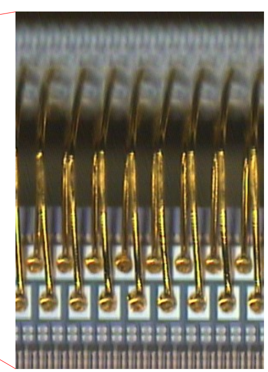
- Segmented electrode into strips on one side
- Using n type silicon with a resistivity of 2 kΩcm (N_D ~2.2 10^{12} cm^{-3}) results in a depletion voltage ~ 150 V
- Typical pitch about ~80 µm
  - For a position resolution σ ~ p/√12 ~ 20 µm
  - Better for cluster size > 1 with cog method



- Silicon strip detectors are frequently the core of the **tracking** detectors in hadron colliders
- 1000s of modules, covering are of many m^2

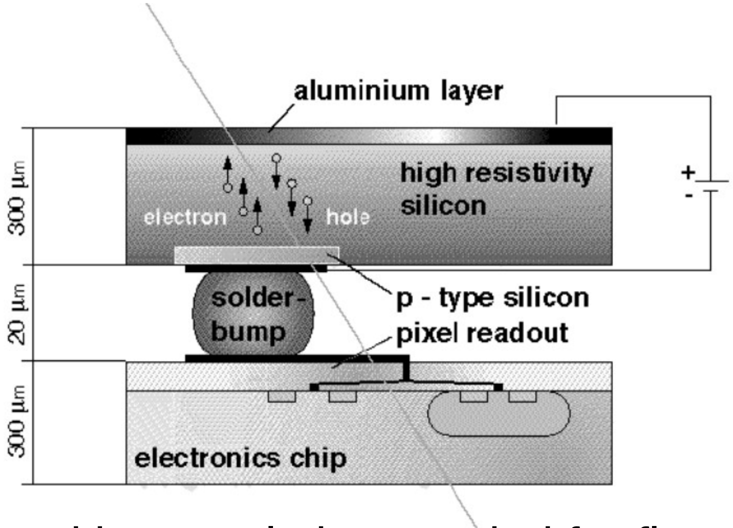


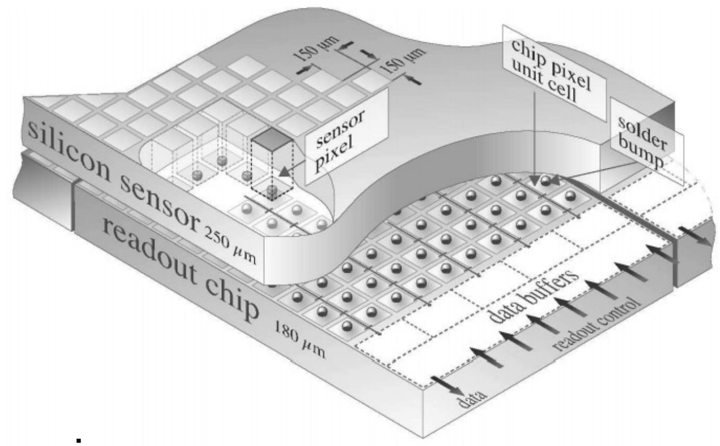
Silicon micro strip module



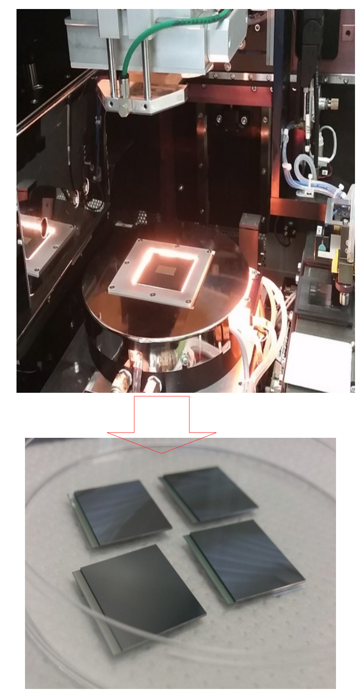
Wire-bonding connects sensor to readout chip

Pixel Detectors





- Best position resolution needed for flavor tagging
  - Innermost layers critical for impact parameter resolution
- Typical (current) pixel size ~50x50 µm^2
- Need to connect each pixel to a readout channel
  - Hybrid pixel module
    - Allows optimization of design of ASIC and sensor (radiation hardness)
  - Usually done through a solder ball (~25 µm diameter)
  - Complicated process, cost ~same as (ASIC+sensor)/cm^2
    - *Can we avoid hybridization?*



Flip-chip process

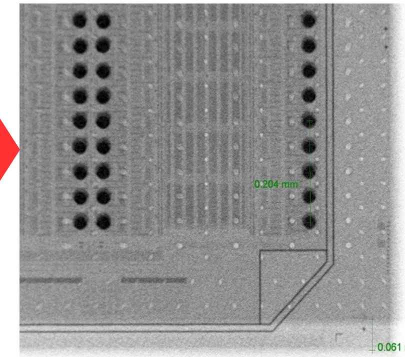
Hybridization and Module Assembly

FEI4 readout chip and 3D sensor

I. Lopez, F. Forster
J. Garcia, E. Peregrina
M. Chmeissani

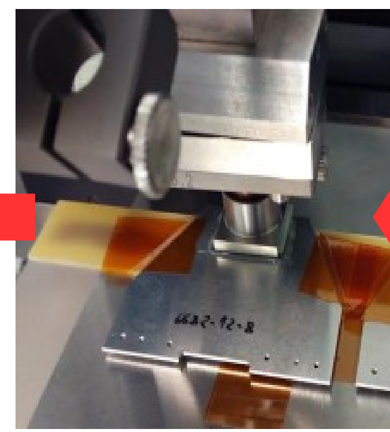
Flip-chip

Reflow

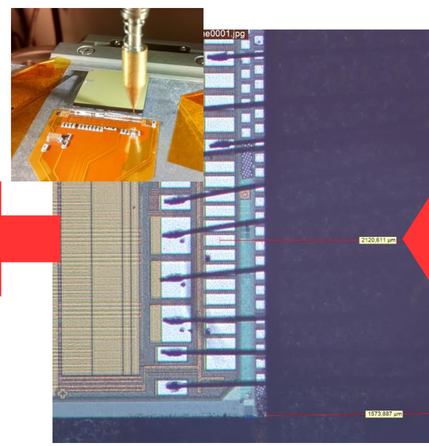


X-ray inspect

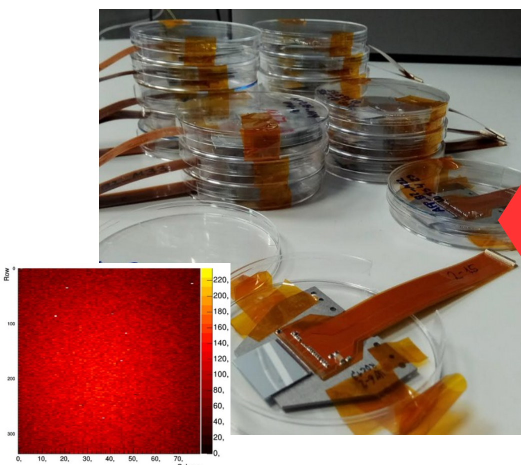
Probe



Glue



Wire-bond and pull test

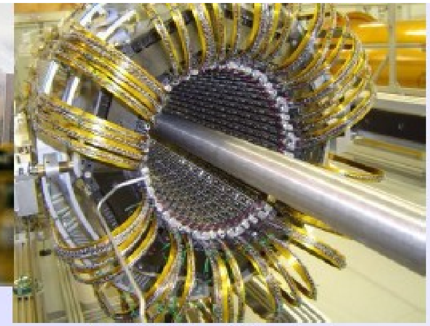


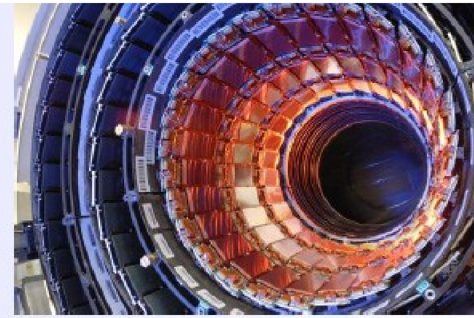
QA of final modules!

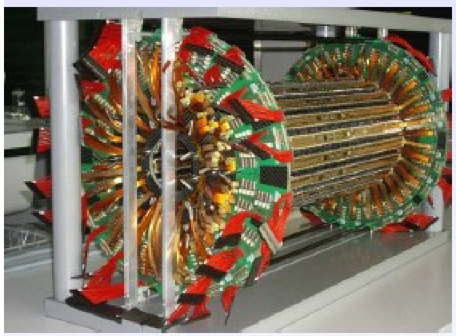
(Some) Vertex Detectors in Operation

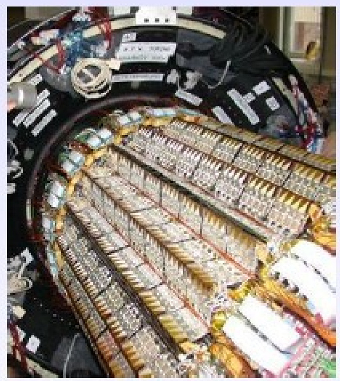

ALICE Pixel Detector

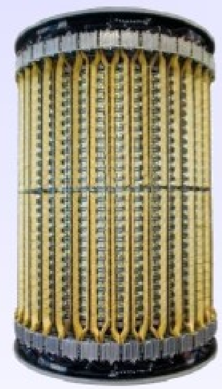

LHCb VELO

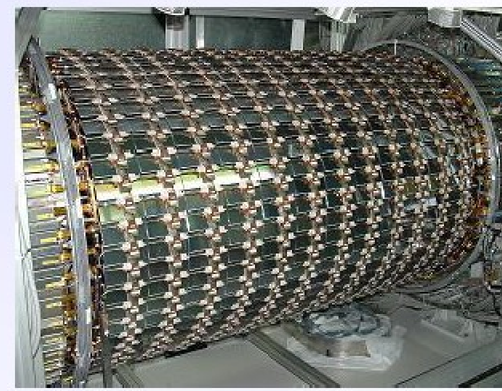

ATLAS Pixel Detector


CMS Strip Tracker IB


CMS Pixel Detector

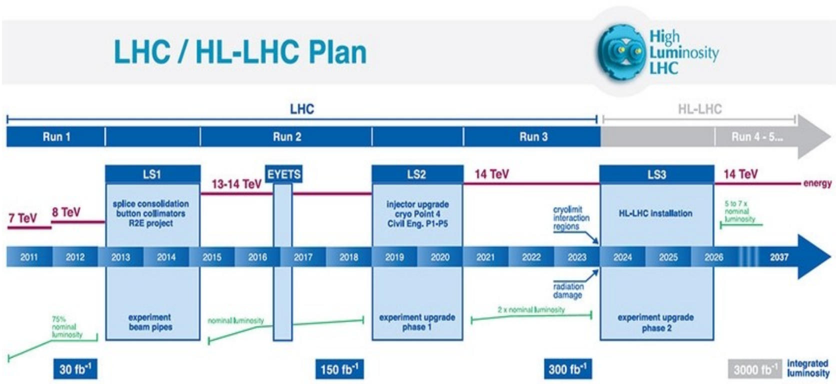

ALICE Drift Detector


ALICE Strip Detector


ATLAS SCT Barrel

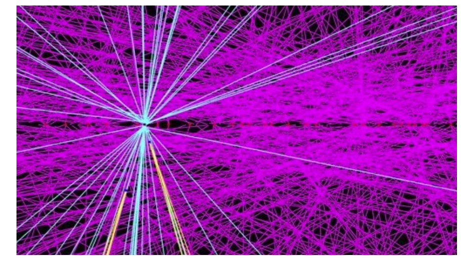
- Silicon tracking detectors are used in all LHC experiments:
- Different sensor technologies, designs, operating conditions,….

Radiation Damage



LHC accelerator upgraded periodically to keep exploring energy frontier

- Thus increase the amount of radiation experiments have to sustain



Two general types of radiation damage to the detector material:

- Bulk (crystal) damage due to Non Ionizing Energy Loss (NIEL)
  - Change of effective doping concentration & acceptor/donor removal (higher depletion voltage, under-depletion)
  - Increase of leakage current (increase of shot noise, thermal runaway)
  - Increase of charge carrier trapping (loss of charge)
- Surface damage due to Ionizing Energy Loss (IEL)
  - Accumulation of positive charge in the oxide (SiO2) and the Si/SiO2 interface
    - Affects: inter-strip/pixel capacitance (noise factor), breakdown behavior, ...

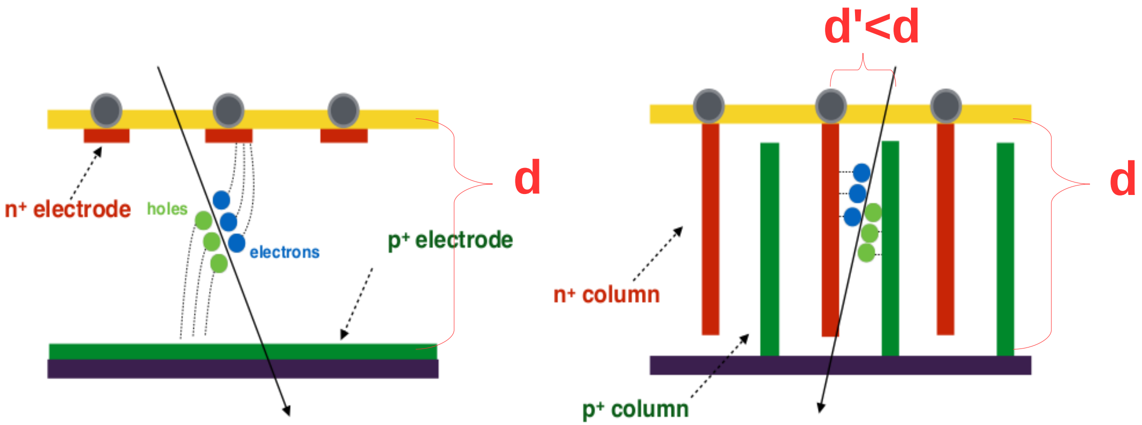
~1E15 1-MeV neutron (equivalent)/year

~100 Mrad/year (1MGy)

Impact on detector performance and charge collection efficiency (depending on detector type and geometry and readout electronics). Radiation damage: usually **critical** factor in hadron colliders.

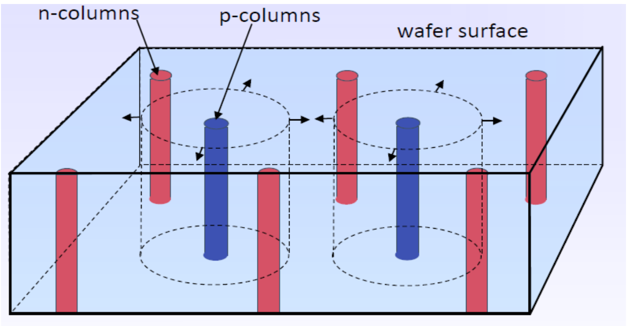
Other detector topologies: 3D sensors

- Irradiation introduces charge trapping, charge loss before can generate signal
- To reduce charge trapping, one should reduce the distance between electrodes
- But in standard planar sensors, this would reduce the amount of change collected
  - One could add a multiplication layer (à la APD), but:
    - Large multiplication is not desirable (no time for quenching, want to maintain E~Qcoll, increase of noise...)

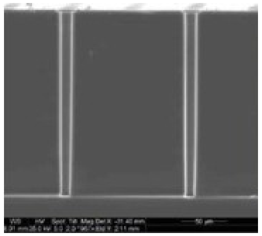


Planar detectors   3D detectors

- **3D sensors** improve radiation hardness through column-like electrodes that penetrate the silicon bulk, decoupling sensor thickness to electrode distance
  - More radiation hard
  - But: more expensive (lower fabrication yield)



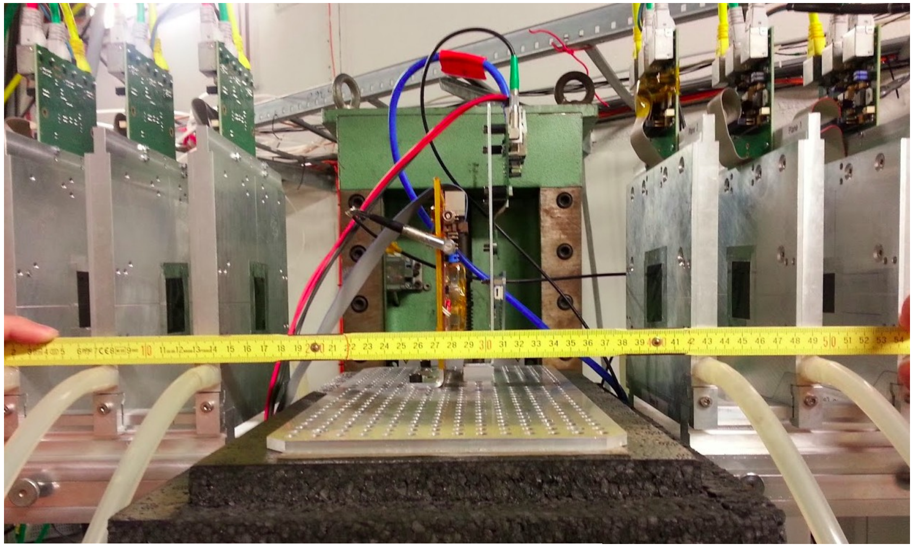
- Column diameter ~10 μm
- Inter column distance ~20 μm



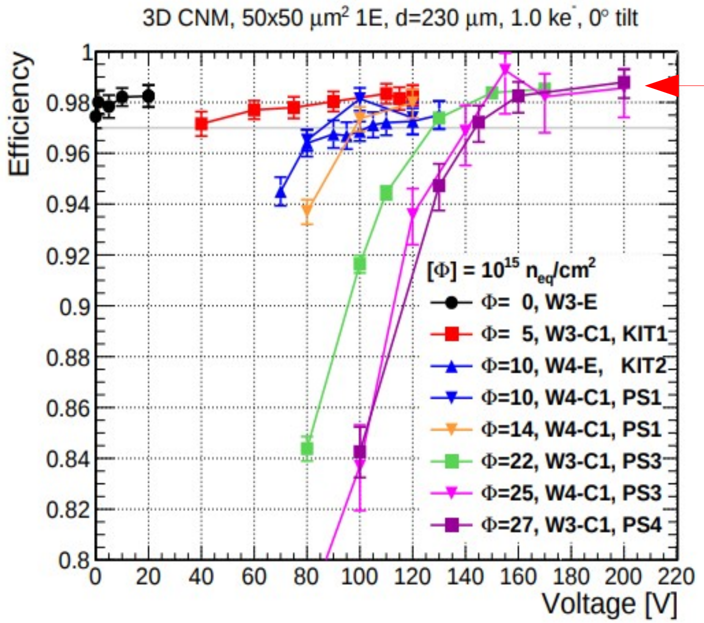
SEM of columns

Detector Evaluation (~R&D phase)

- Fabricate "prototype"
- Test it with beam (or lab...)
- Simulate ~10 yrs in experiment
  - Irradiate samples
- Test it with beam



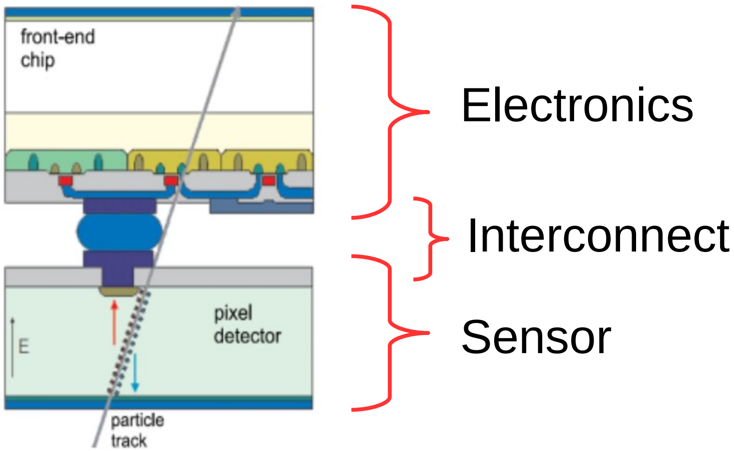
- Most important measurement: **efficiency after irradiation**
- Linked to operational considerations (ie, power dissipation)



Excellent **efficiency** after irradiation (after simulation of many years of operation)

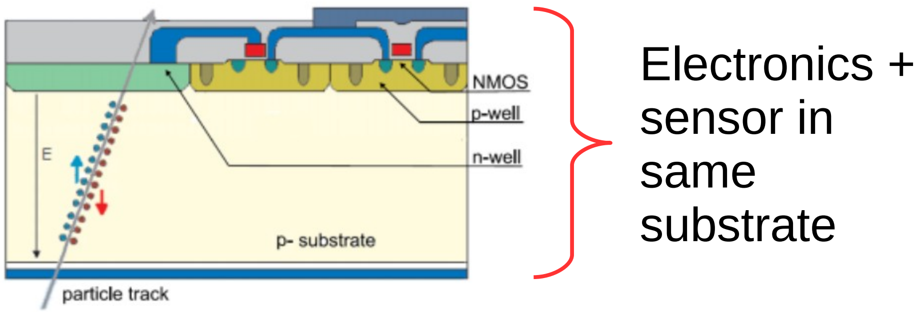
Other detector technologies: monolithic devices

Hybrid detectors



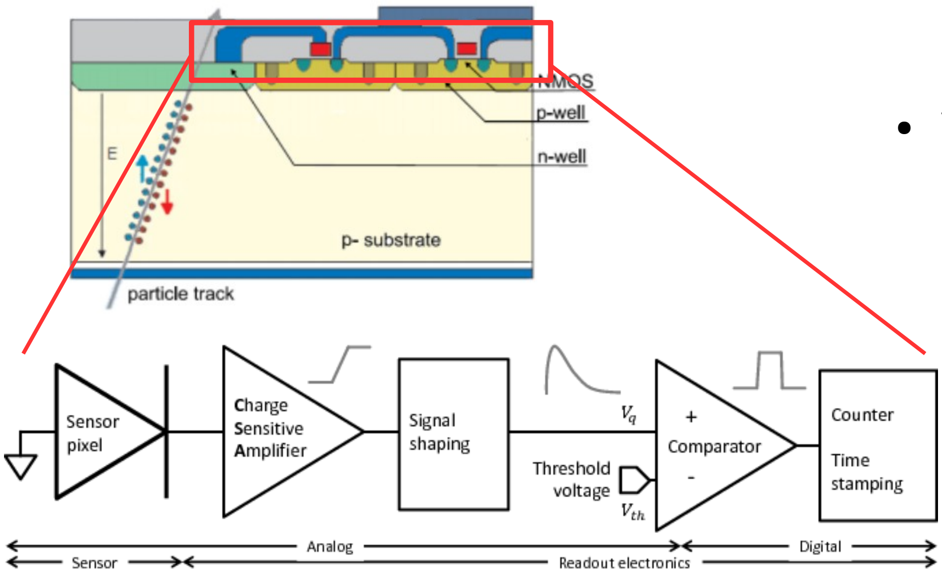
- Standard in current experiments
- Design allows for optimization of electronics and sensor
  - Radiation hardness, rate, power...

Monolithic detectors



- Less material, less complexity
  - And cost...
- Smaller pixel possible
  - No pixel size limitation due to interconnection

Other detector technologies: monolithic devices



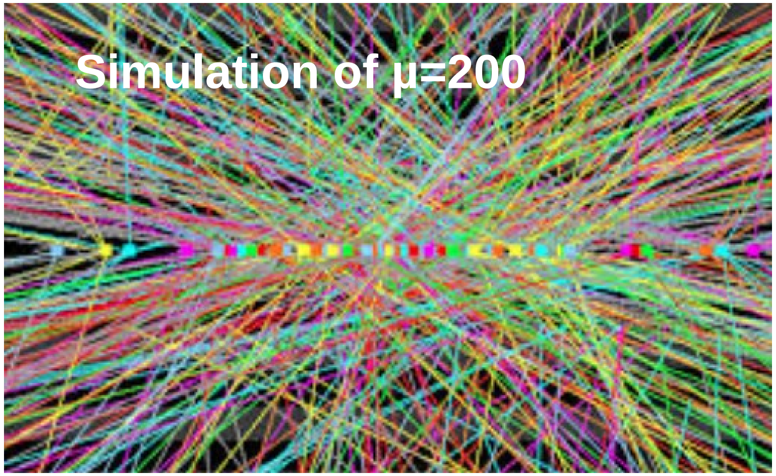
Comparator and digital part can be in periphery of chip

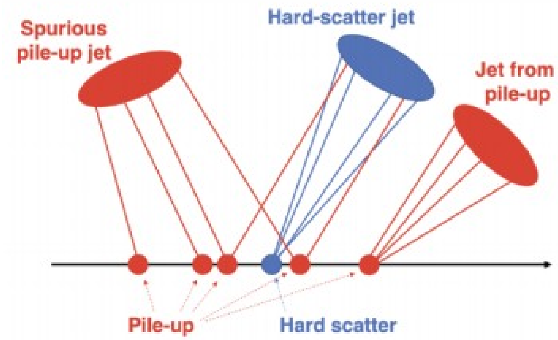
- Why CMOS camera ≠ HEP-CMOS?
  - "CMOS camera" ~ little depletion/mostly diffusion of charge
  - Diffused charge slow and not collected after irradiation
  - Need to increase depletion region for HEP, two approaches
    - Increase V (HV-CMOS)
    - Increase resistivity (HR-CMOS)
    - Common name: Depleted Monolithic Active Pixels (DMAPS)

- Future of silicon detectors at low to intermediate fluences

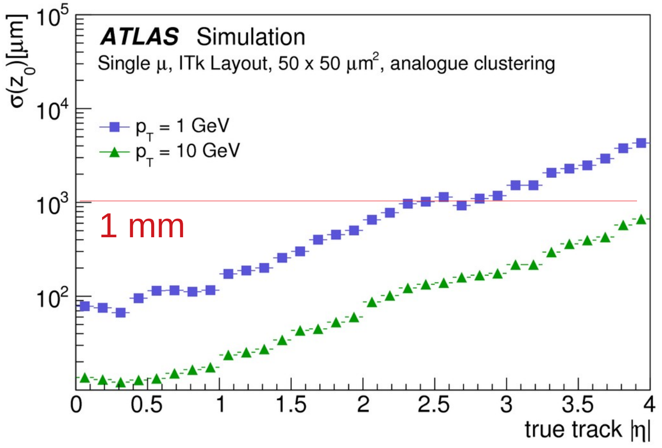
$$d \sim \sqrt{\rho \cdot V}$$

Timing with Silicon in HEP

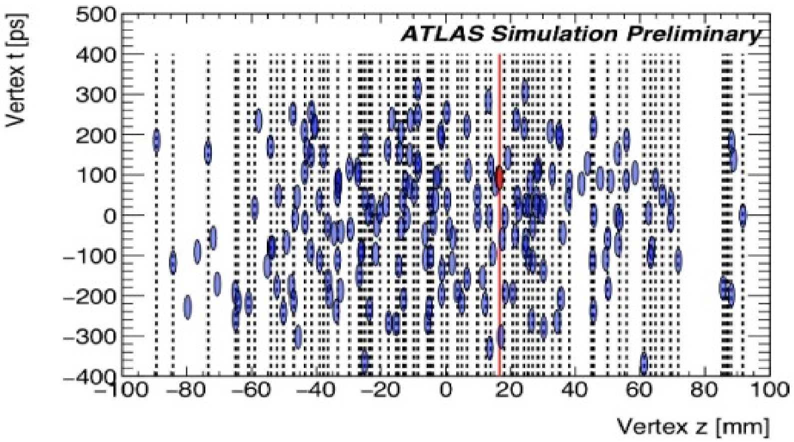




At HL-LHC: average 1.6 collisions/mm. Pile-up can add jets, create spurious jets, alter the properties of hard scattered jets: degrading physics performance

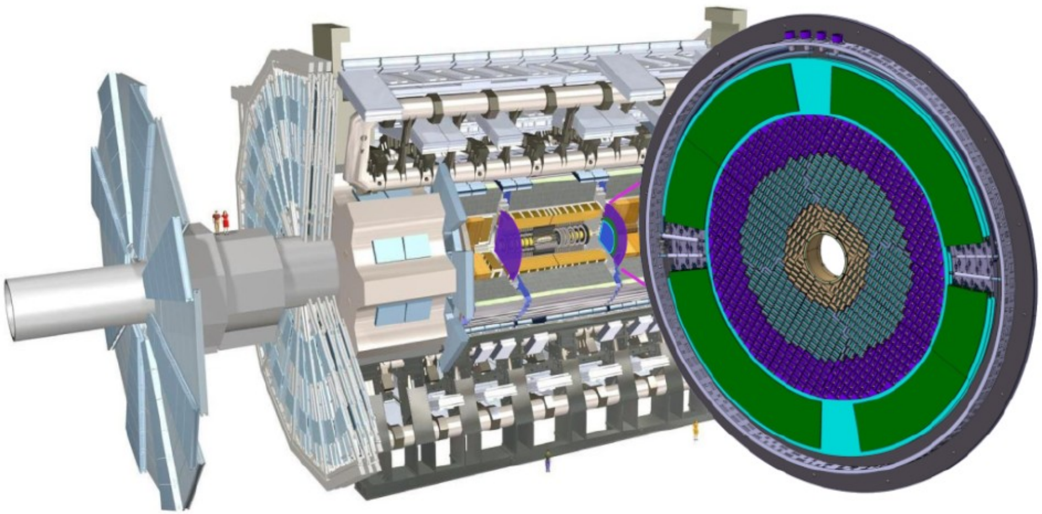


The ITk tracker mostly mitigates the effect of pile-up, but still challenging in the forward region



Timing information (~30 ps) can be used to mitigate the effect of pile-up

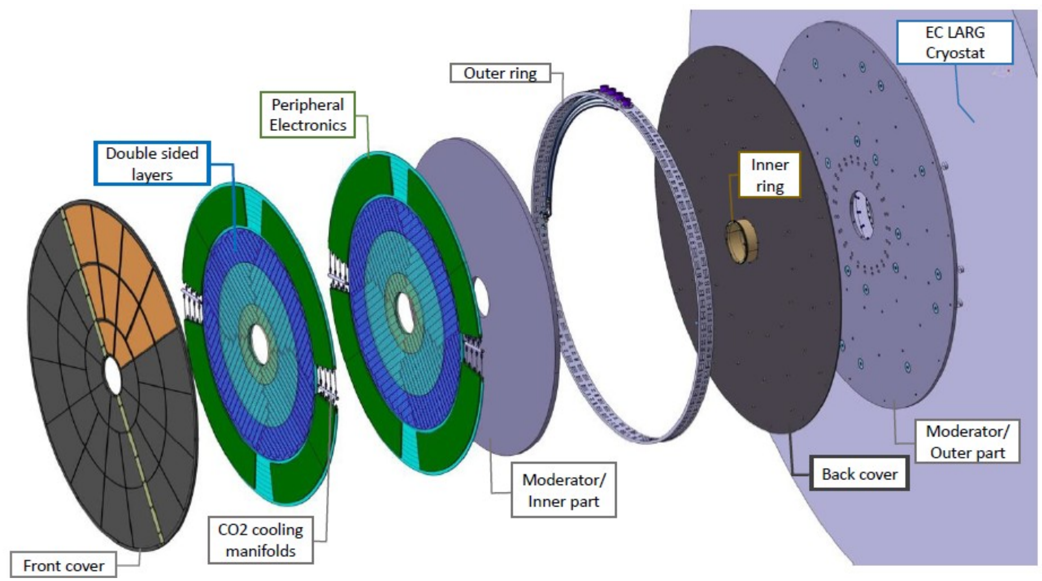
High Granularity Timing Detector



HGTD designed to improve ATLAS performance in the forward region in view of increased pile up in the HL-LHC

Target time resolution:
30-50 ps/track up to 4000/fb

- Located between barrel and end-cap calorimeters (|z|=3.5 m)
- Silicon detector modules mounted on disks
- Two sensor layers/disk
- Two disks/side
- Active area: 12 cm < r < 64 cm
  - **2.4 <|η|< 4.0**



Timing with Silicon in HEP

10.1016/j.nima.2025.170763

- To reduce "pile-up" (effect of secondary interactions) LHC experiments plan to deliver silicon-based timing detectors
    - Timing+rad hardness+compactness
- The target is to achieve about ~50 ps/mip/layer resolution: **beyond standard silicon** devices

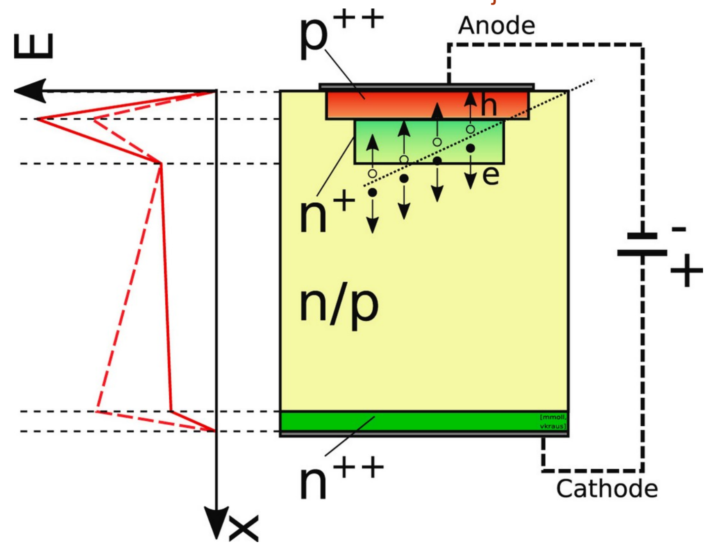
$$\sigma^2_{\text{det}} = \sigma^2_{\text{Landau}} + \sigma^2_{\text{elec}}$$

$$\sigma^2_{elec} = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2$$

Jitter *Time-walk*

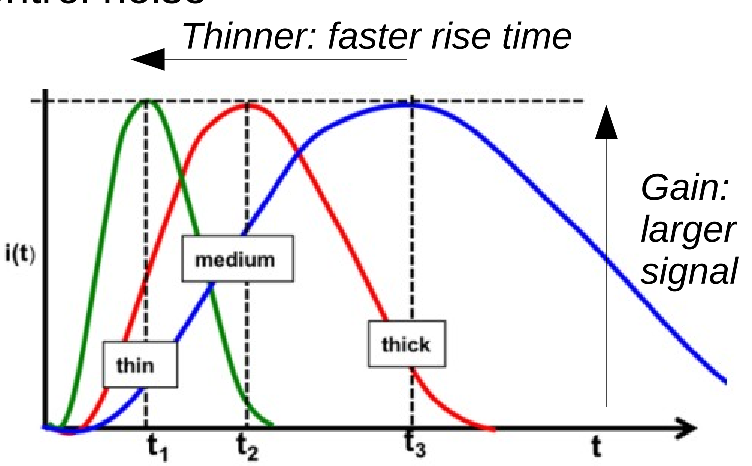
- Need fast signal and excellent S/N
    - A multiplication layer increases signal slope
- Thin sensors (50 μm) to reduce intrinsic Landau contribution to resolution

LGAD achieve 30 ps resolution before irradiation (degrades after...)

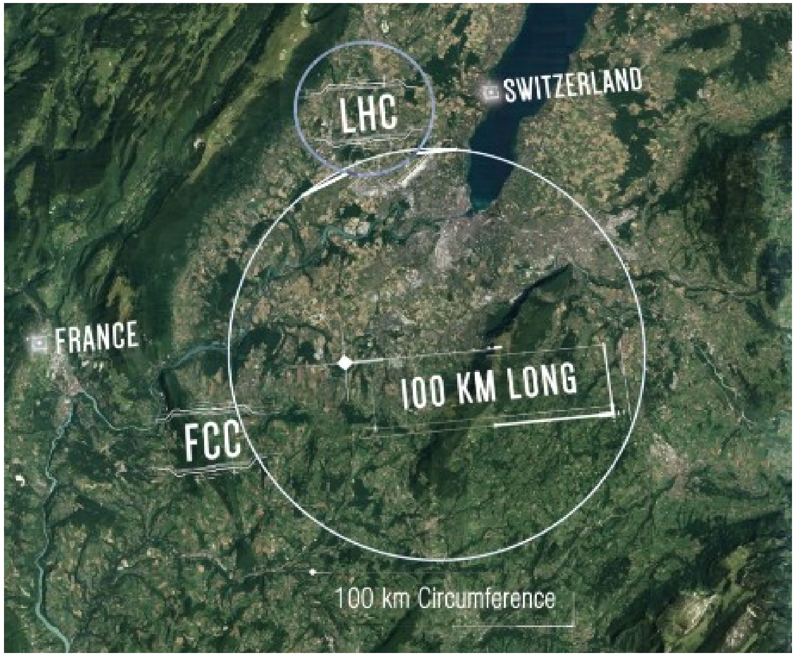


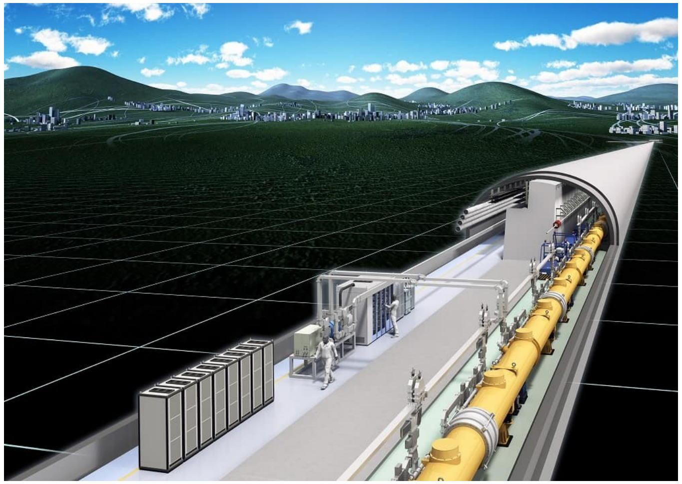
Low Gain Avalanche Detector (LGAD)

- Low gain (G=): improve signal slope but control noise



The Future of HEP

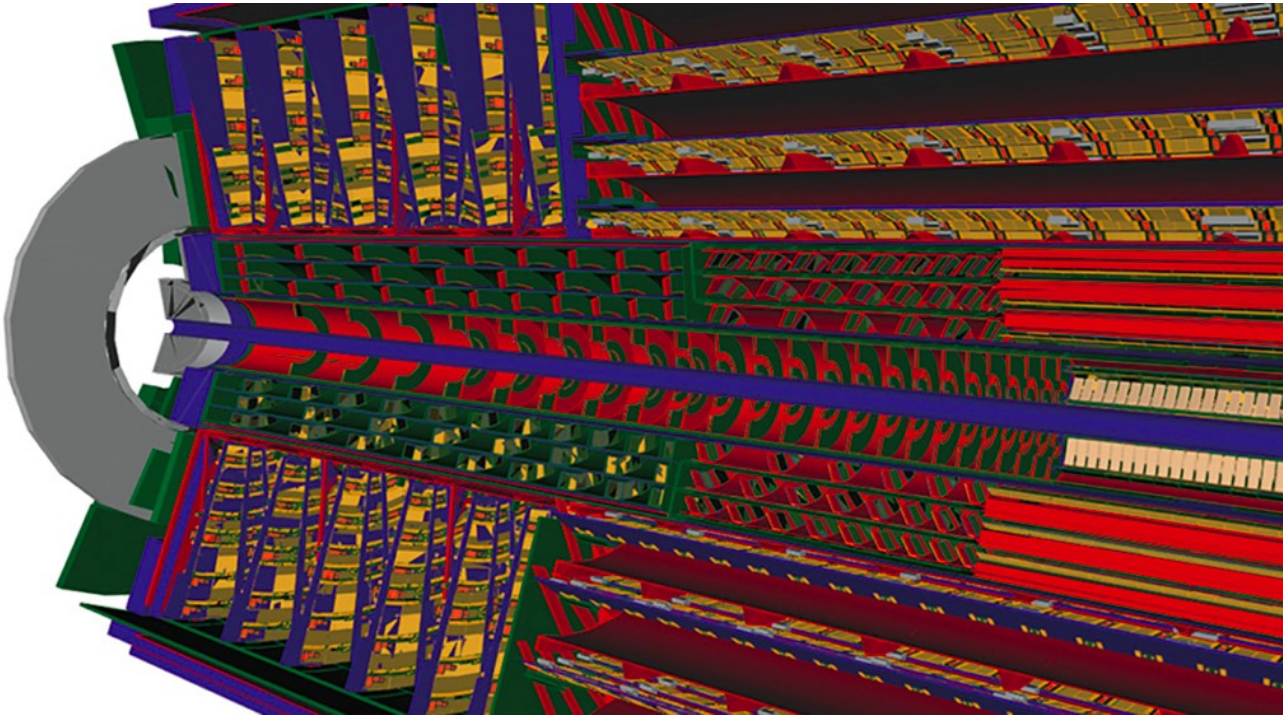




- Several big accelerators being planned
  - Not clear which (if any) will be realized
- Many other HEP experiments being constructed/upgraded
  - Upgrade of current experiments
  - New more specific ones (neutrino, heavy flavor, etc)

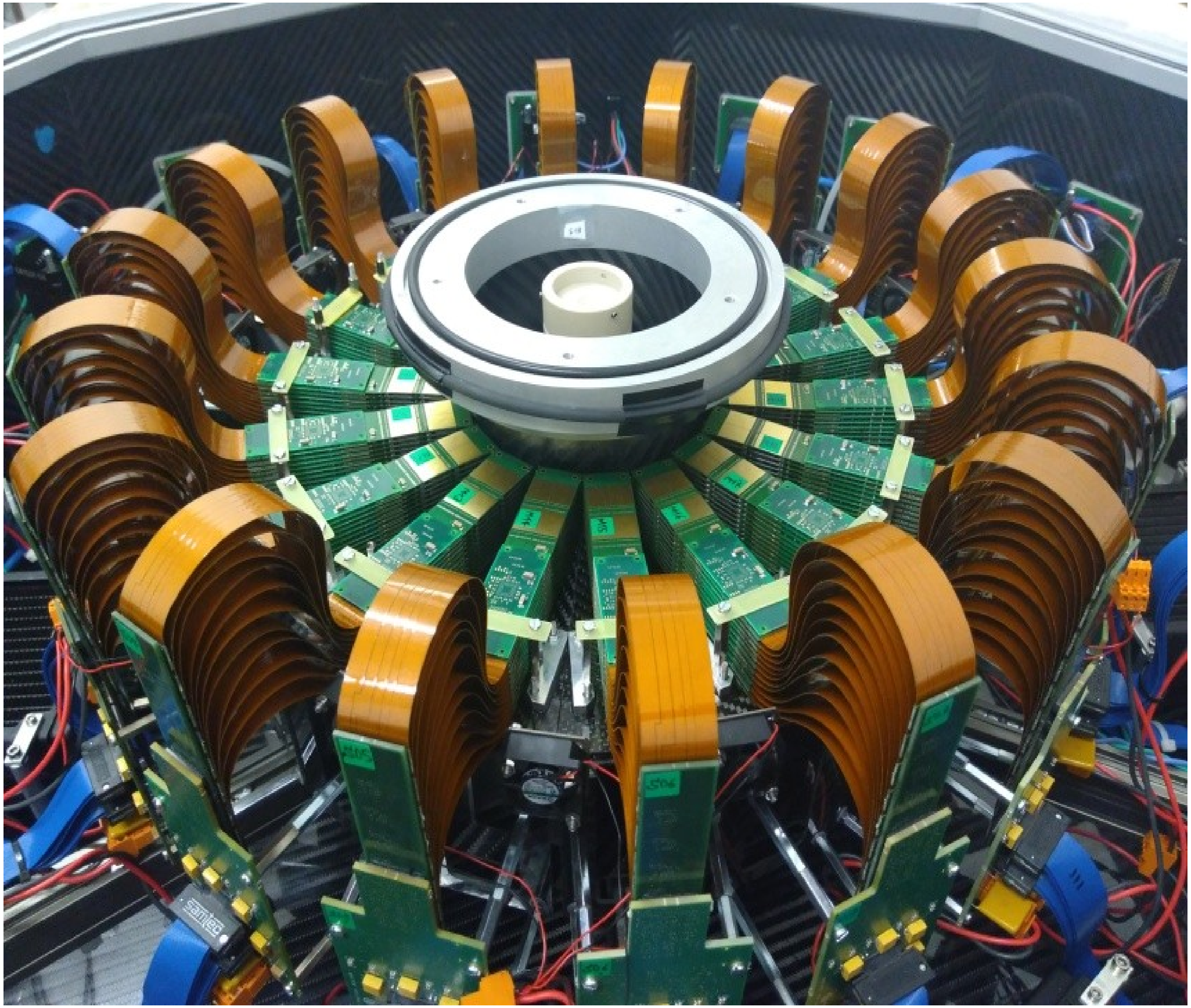
All with silicon detectors!

The Future of HEP



- Silicon detectors, initially limited in size
- Inner layer → inner layers → full trackers → calorimeters (SiPM)…
- Cost: per channel is **very cheap**…!
- ATLAS tracker will have 5000 M channels
- Silicon also used in other radiation detectors (light synchrotron, cosmology cameras, etc)

Beyond HEP



Conclusions

- **Vertex detectors** at the core (literally) of HEP experiments
- Improving since 1980s provide best **performance**
  - **Micro-strip** detectors to cover large areas
  - Hybrid **pixel** detectors to provide the best position resolution
    - Current best option for radiation hardness: **3D** sensors (in fact limited by the performance of the readout/chips)
  - Silicon detectors with excellent **timing** being fabricated
    - LGAD, radiation hardness more limited
  - For moderate fluencies, **monolithic** devices very interesting option
    - One of the most active current R&D areas

- Semiconductor detectors planned in **future accelerators** (FCC, ILC, CEPC)
- Also very active R&D for applications **beyond HEP**

THE END

Signal Formation

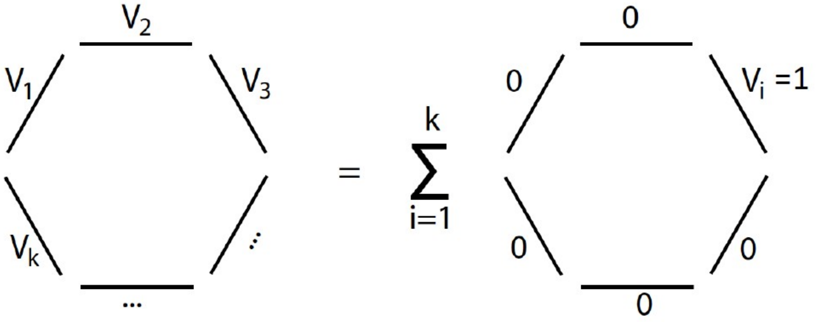
Shockley-Ramo theorem

- Given n electrodes in the detector, one wants to know the current i_k (k = 1, 2, …, n) injected in one of these electrodes by the motion of a charge q somewhere between the electrodes
- The theorem says that current injected in this electrode is $$i_k = \frac{dQ_k}{dt} = q\vec{u_q}\vec{E_k}$$
- Where Q_k is the induced charge on the electrode k, u_q is the velocity of the charge q and E_k is the electric field at the point occupied by charge q when the electrode k is at 1 V potential and all other electrodes are set at zero potential (weighting field)
- Parallel plate capacitor:

$$\vec{E} = -\frac{V_0}{d}\vec{e}_x \quad , \qquad C = \frac{\epsilon\epsilon_0 A}{d}$$

E_k = 1/d, and for low E fields: v = μ E

- *mobility μ*
- *constant E field, ~constant drift velocity*
- *at high E filed, v saturates v=constant*



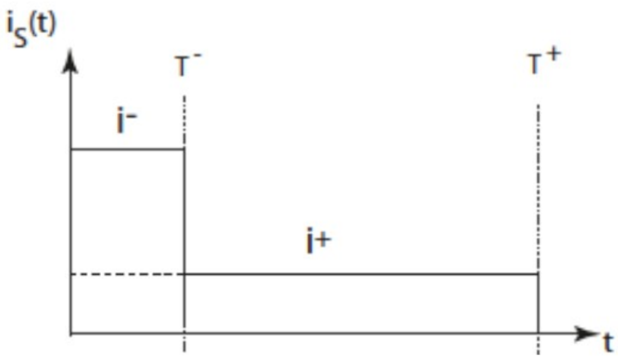
Signal Formation

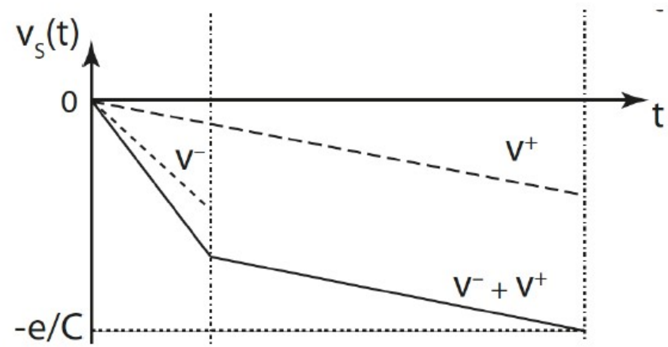
- Using Shockley-Ramo for parallel plate capacitor (with E_a weighting field and u charge velocities)

$$i_- = -e\vec{u}_-\vec{E}_a = e\frac{u_-}{d}$$

$$i_+ = e\vec{u}_+\vec{E}_a = e\frac{u_+}{d}$$

- Electron drift velocity >> ion drift velocity (different mobilities)





$$Q^{tot} = Q^- + Q^+ = -\frac{-Ne}{d}\left(\int_0^{T^-} u_-\,dt + \int_0^{T^+} u_+\,dt\right) = -\frac{-Ne}{d}u_-\left(\frac{d-x_0}{u_-}\right) - \frac{-Ne}{d}u_+\left(\frac{x_0}{u_+}\right) = -Ne$$

As expected, Q=Ne
(note that both electrons and ions contribute to signal)

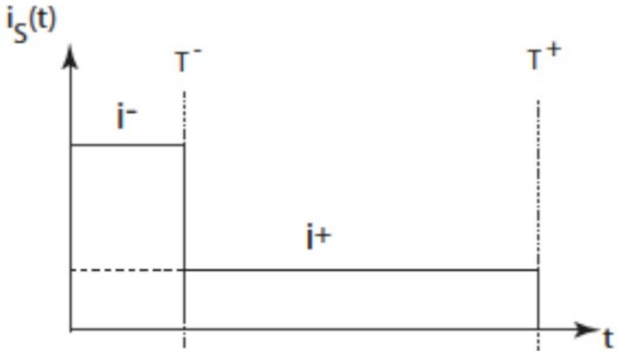
Signal Formation

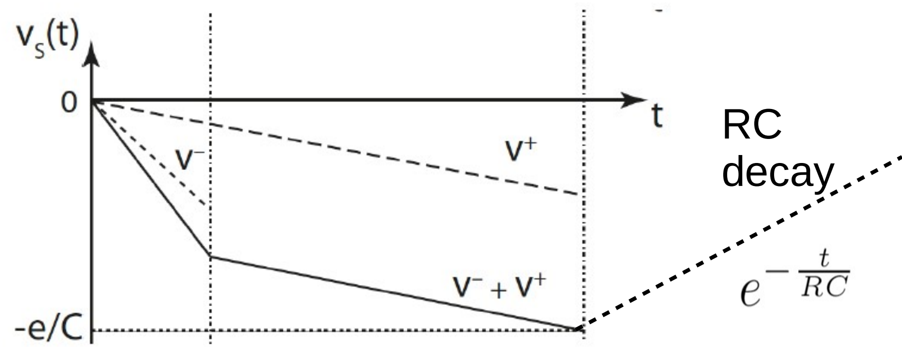
- Using Shockley-Ramo for parallel plate capacitor (with E_a weighting field and u charge velocities)

$$i_- = -e\vec{u}_-\vec{E}_a = e\frac{u_-}{d}$$

$$i_+ = e\vec{u}_+\vec{E}_a = e\frac{u_+}{d}$$

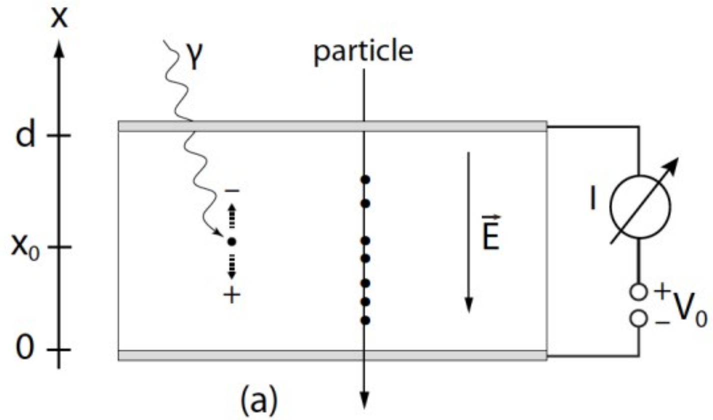
- Electron drift velocity >> ion drift velocity





$$Q^{tot} = Q^- + Q^+ = -\frac{-Ne}{d}\left(\int_0^{T^-} u_-\,dt + \int_0^{T^+} u_+\,dt\right) = -\frac{-Ne}{d} \ldots Ne$$

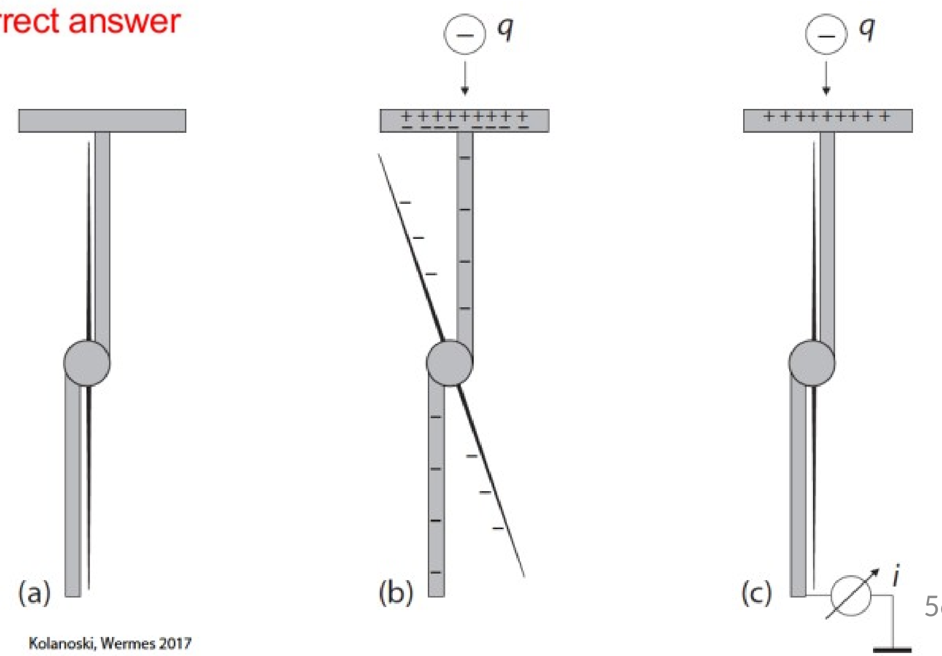
Typical:
$E = 500$V/cm
$u_- = 5$ cm/µs, $u_+ = 5$ cm/ms, d~10cm
$T^- = 2$ µs, while $T^+ = 2$ ms



Q: when does the signal current $i_S(t)$ start?

(a) when charges reach the electrode? → popular answer
(b) when charges begin to move? → correct answer

Effect of charge approaching electrometer



Kolanoski, Wermes 2017