A new era of pixel detectors for future High Energy Physics experiments

Sonia Fernandez-Perez

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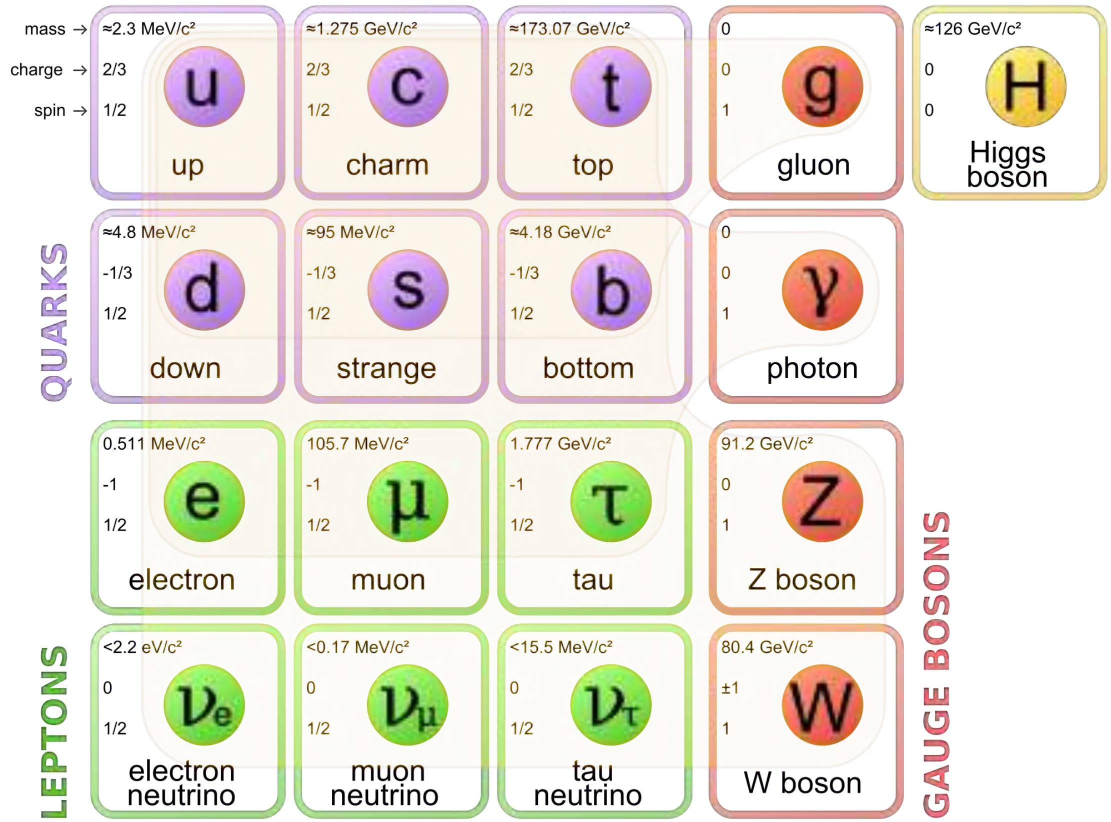
Outline

- The Large Hadron Collider (LHC)
- The ATLAS detector
- The HL- LHC program
- Basic working principle and challenges of pixel detectors
- Pixel detectors developments for ATLAS at HL-LHC

The Large Hadron Collider

- The Standard Model describes all elementary particles and their interactions
- It is incomplete (no explanation to gravitational interactions, dark matter, asymmetry matter-antimatter, etc)



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- proton-proton collider
- 27 km circumference
- 100 m underground
- During the first data taking period Run 1 (2009-2012) luminosity of 10^{34} $cm^{-2}s^{-1}$, collision energy of 7-8 TeV, and 50 ns bunch crossing.
- 4 main experiments: ALICE, ATLAS, CMS, LHCb

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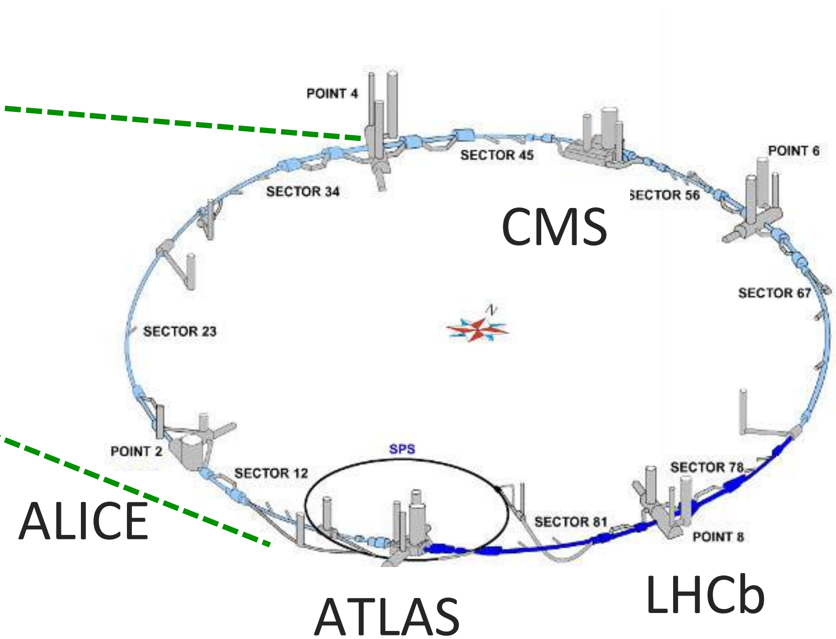

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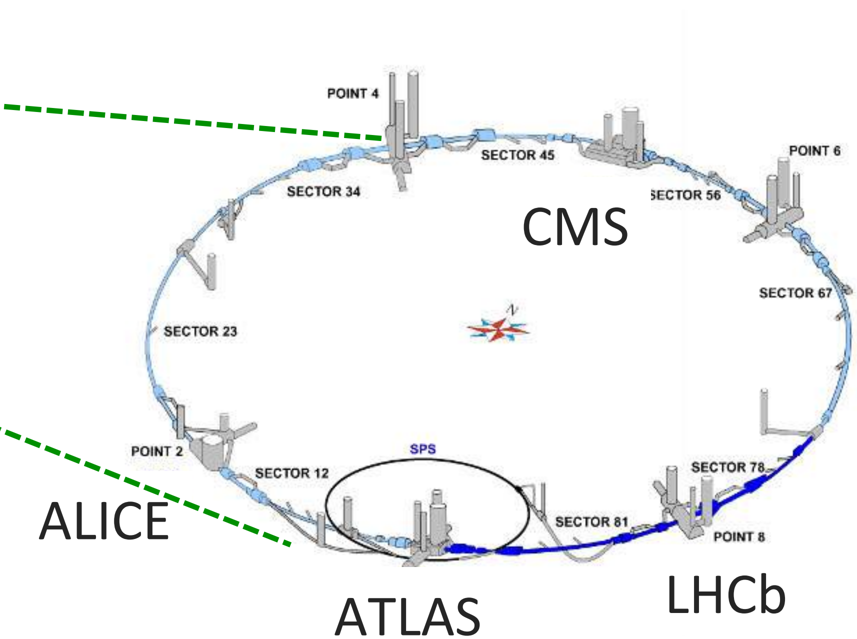
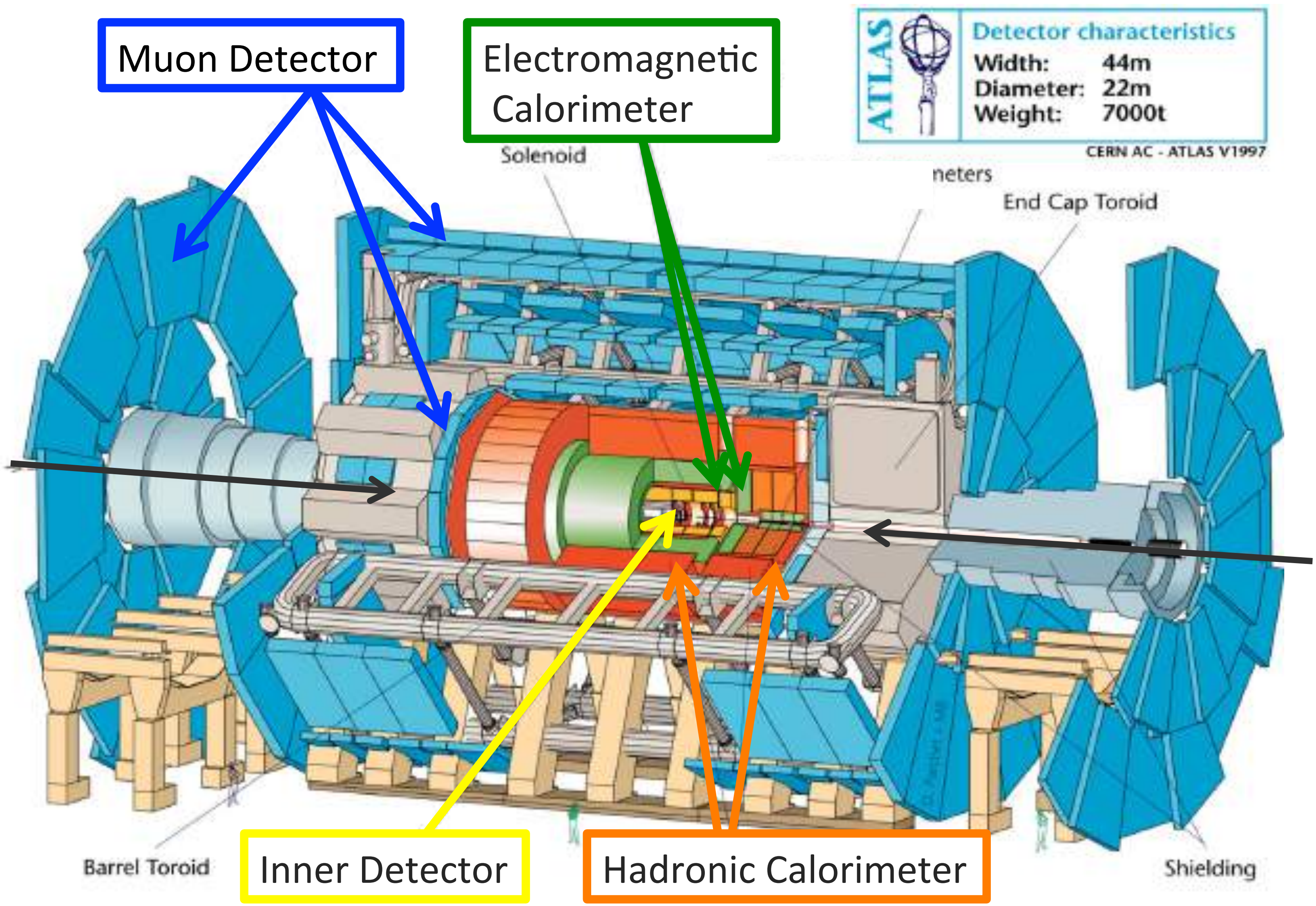
Higgs discovery (2012)



The ATLAS detector



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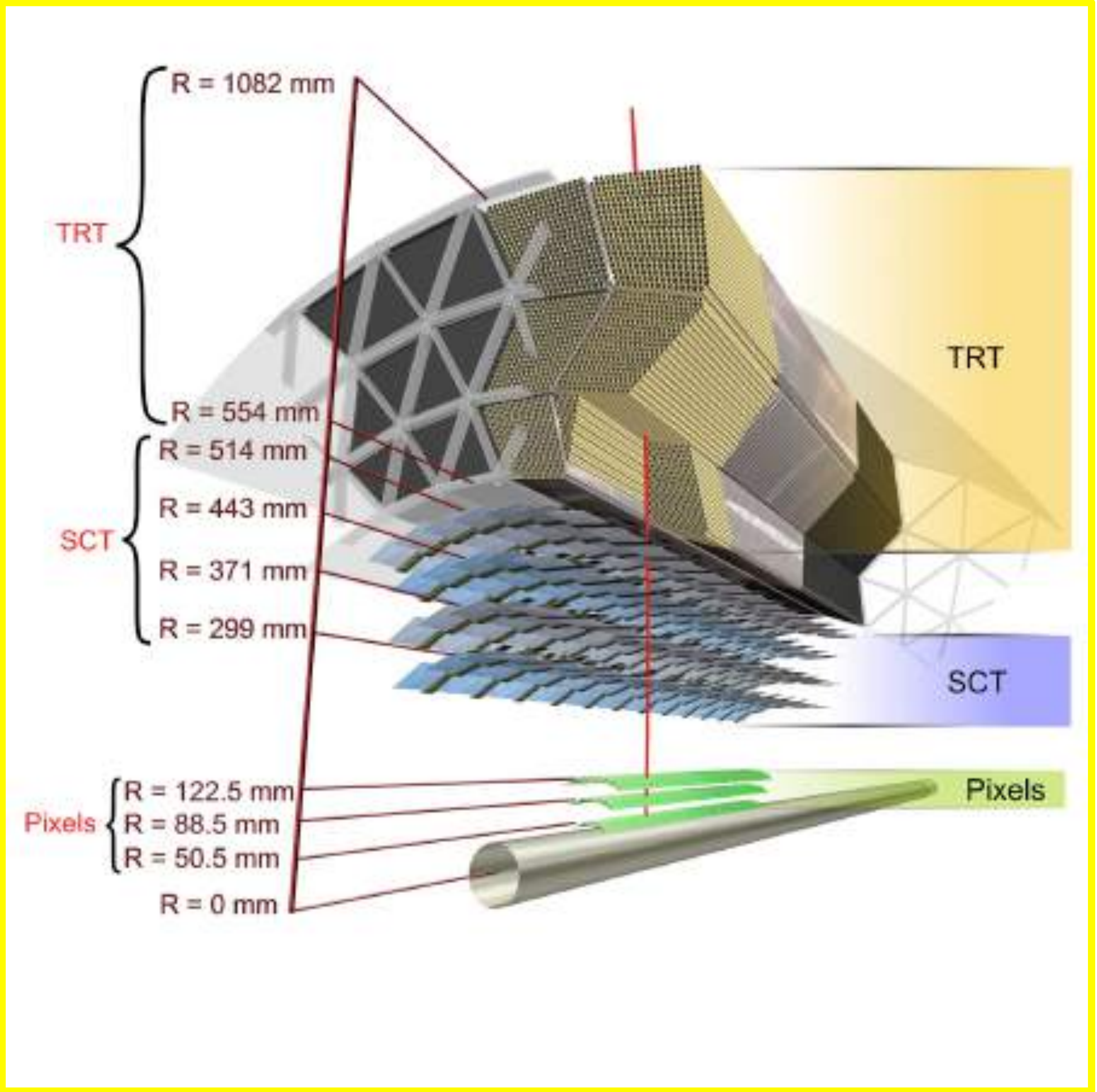
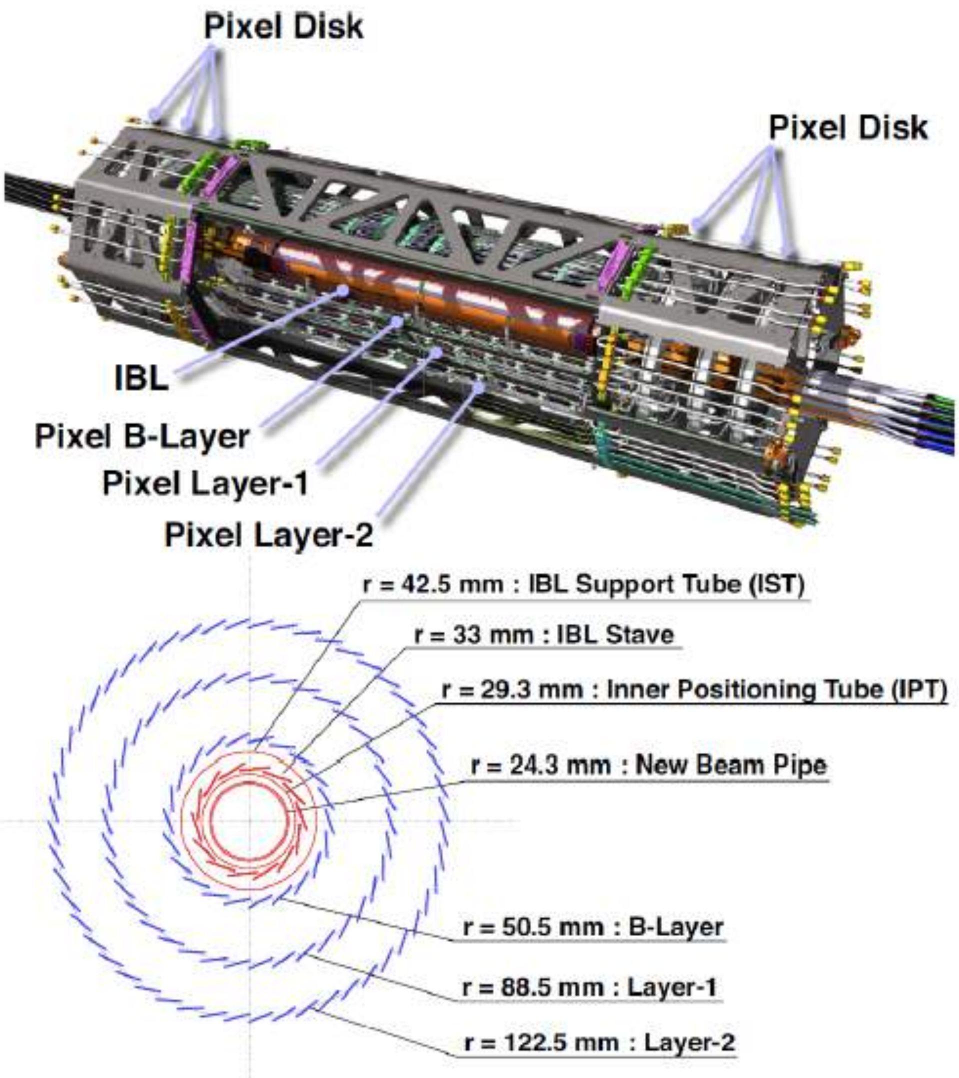


Inner Detector

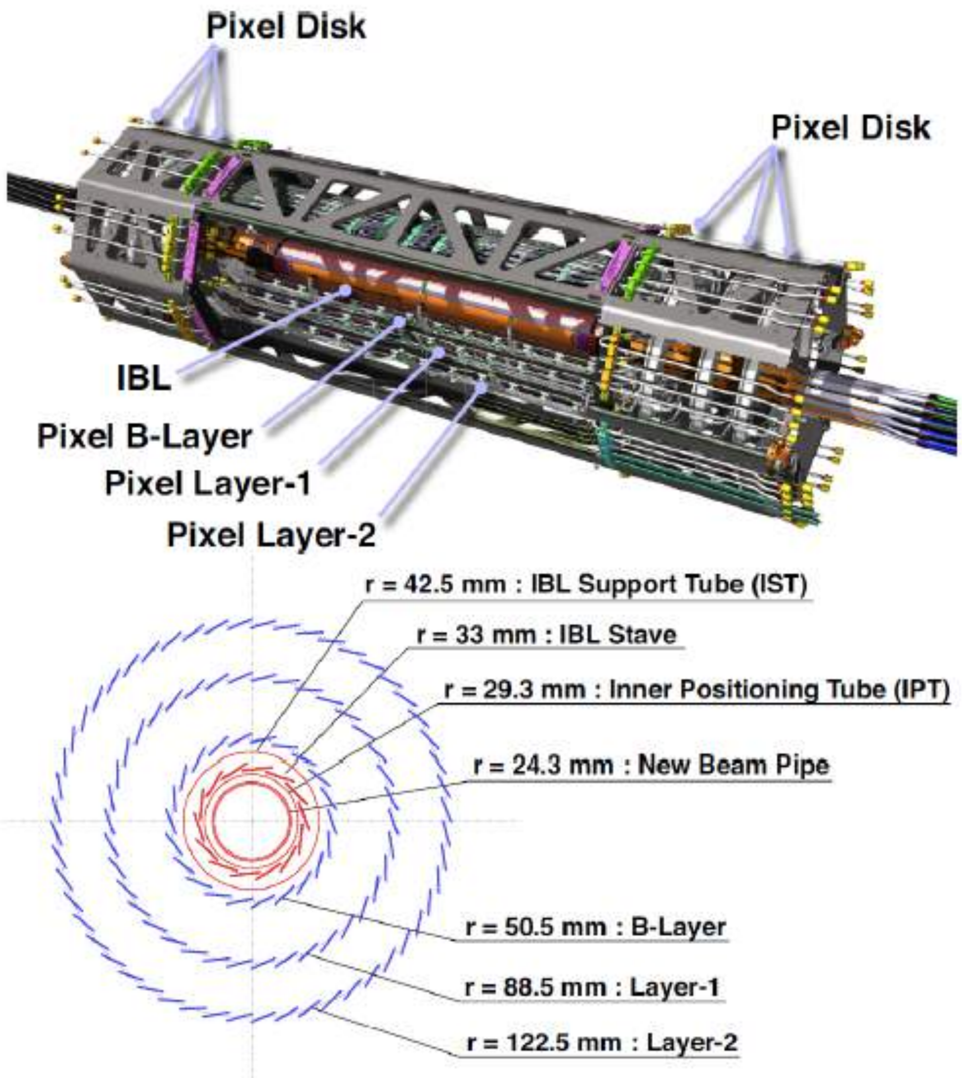
The Pixel Detector



- The Pixel Detector is exposed to the harshest conditions
- 4 silicon detector layers

Insertable B-Layer (IBL) installed in 2014

The Pixel Detector



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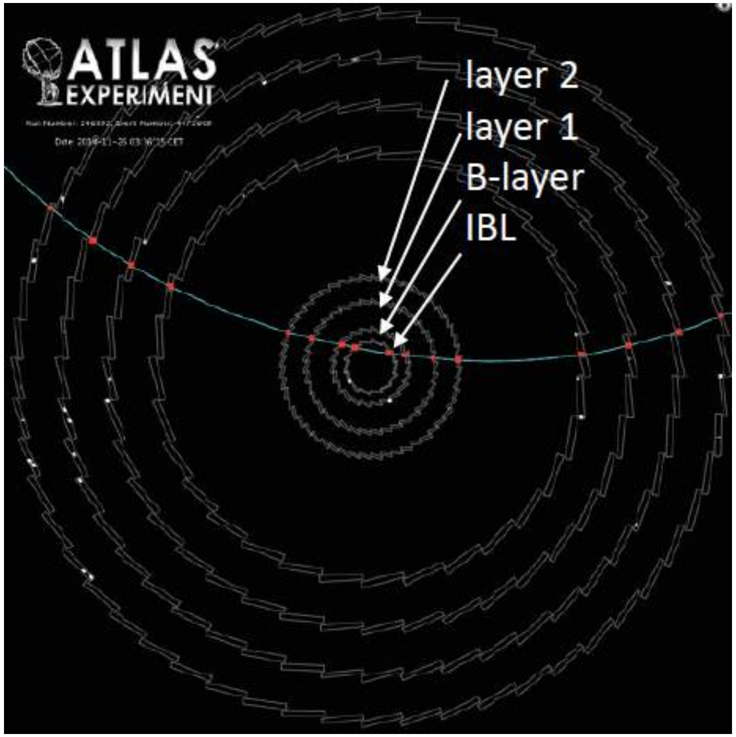
A true 4-hit pixel system!



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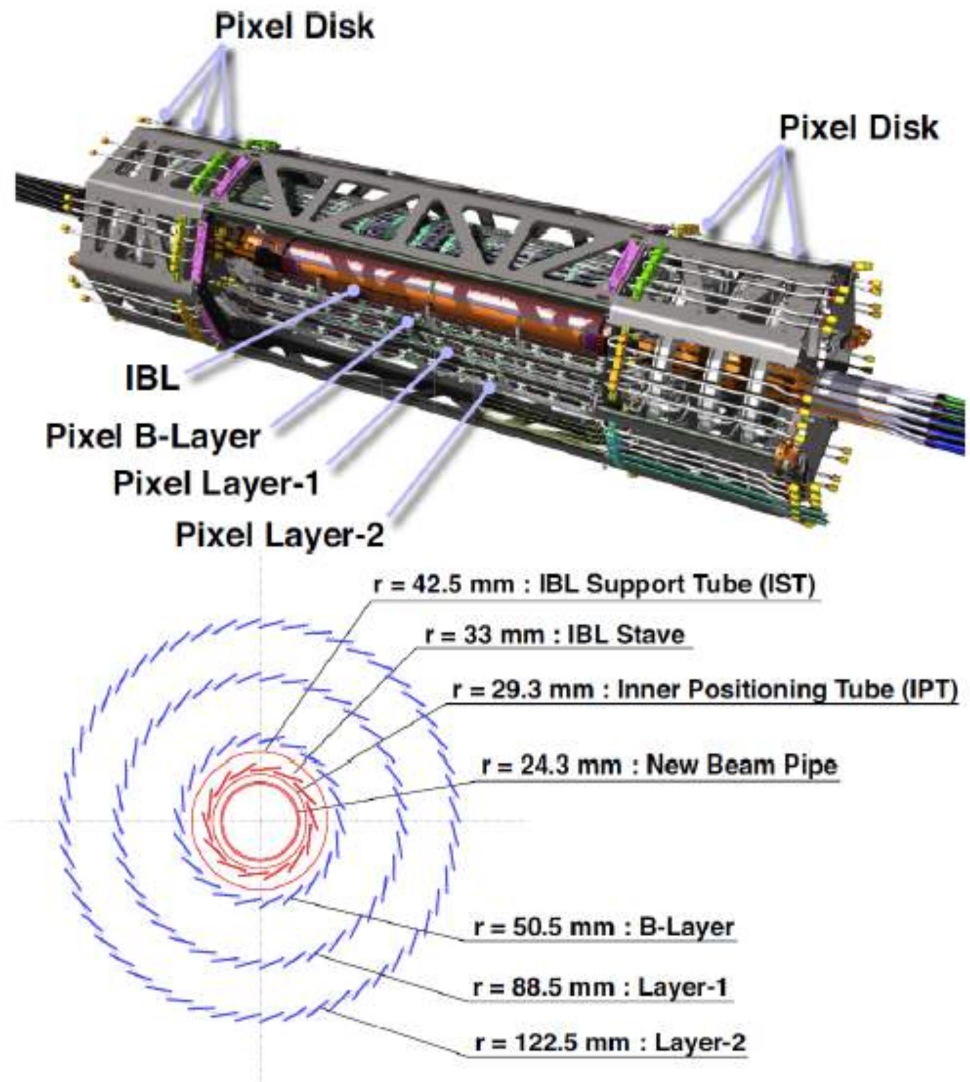
Introduction The Pixel Detector



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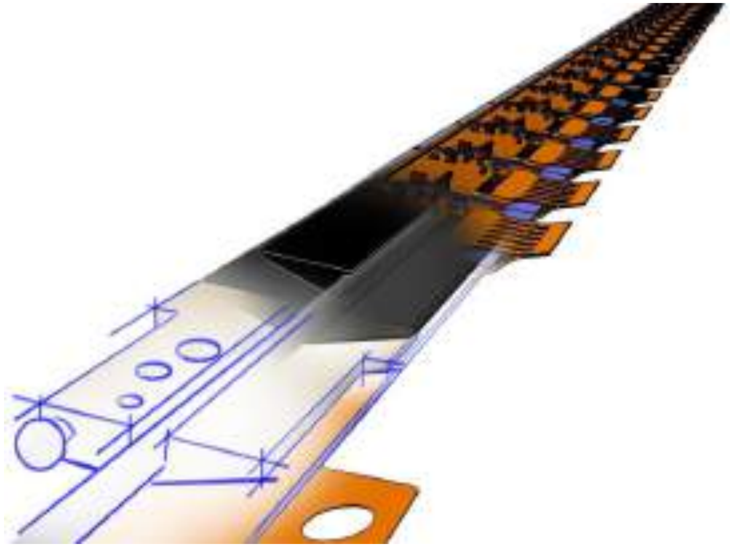
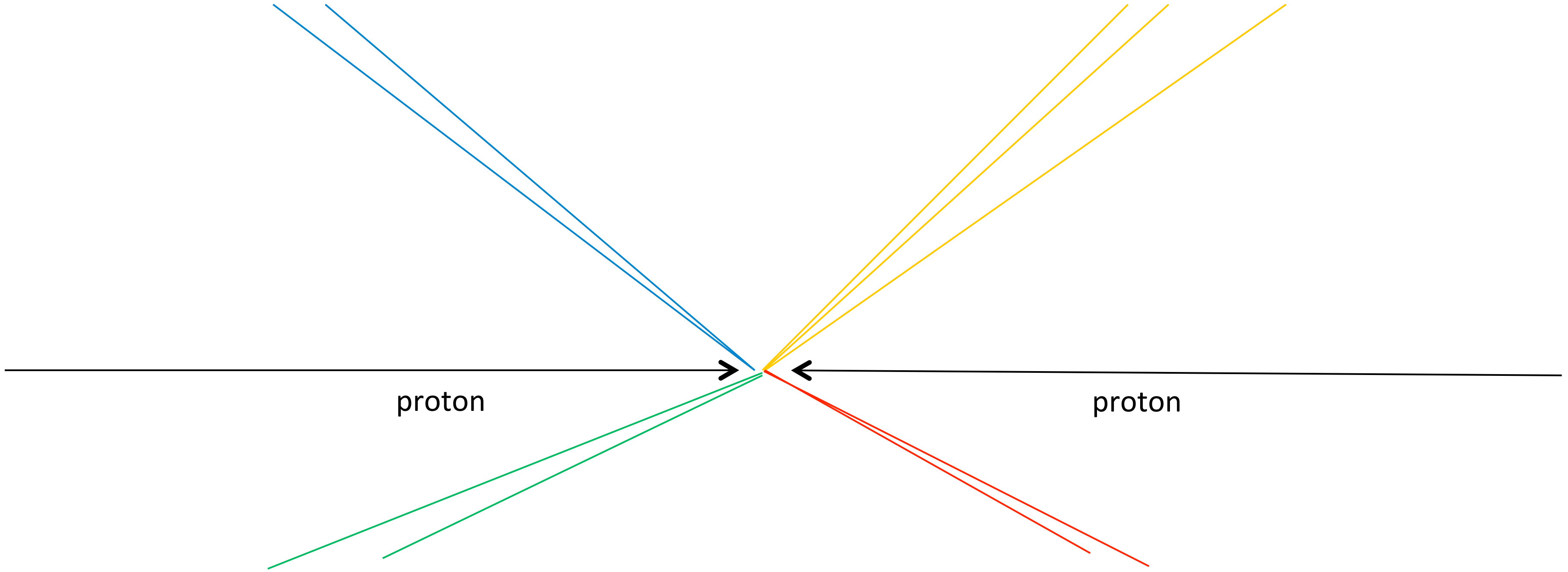
- 4 silicon detector layers
- Each layer is composed of 2D segmented silicon detectors



Particle's tracking detectors

- Layers of segmented silicon detectors
- The energy loss by the particle while traversing the detector → electrical signal



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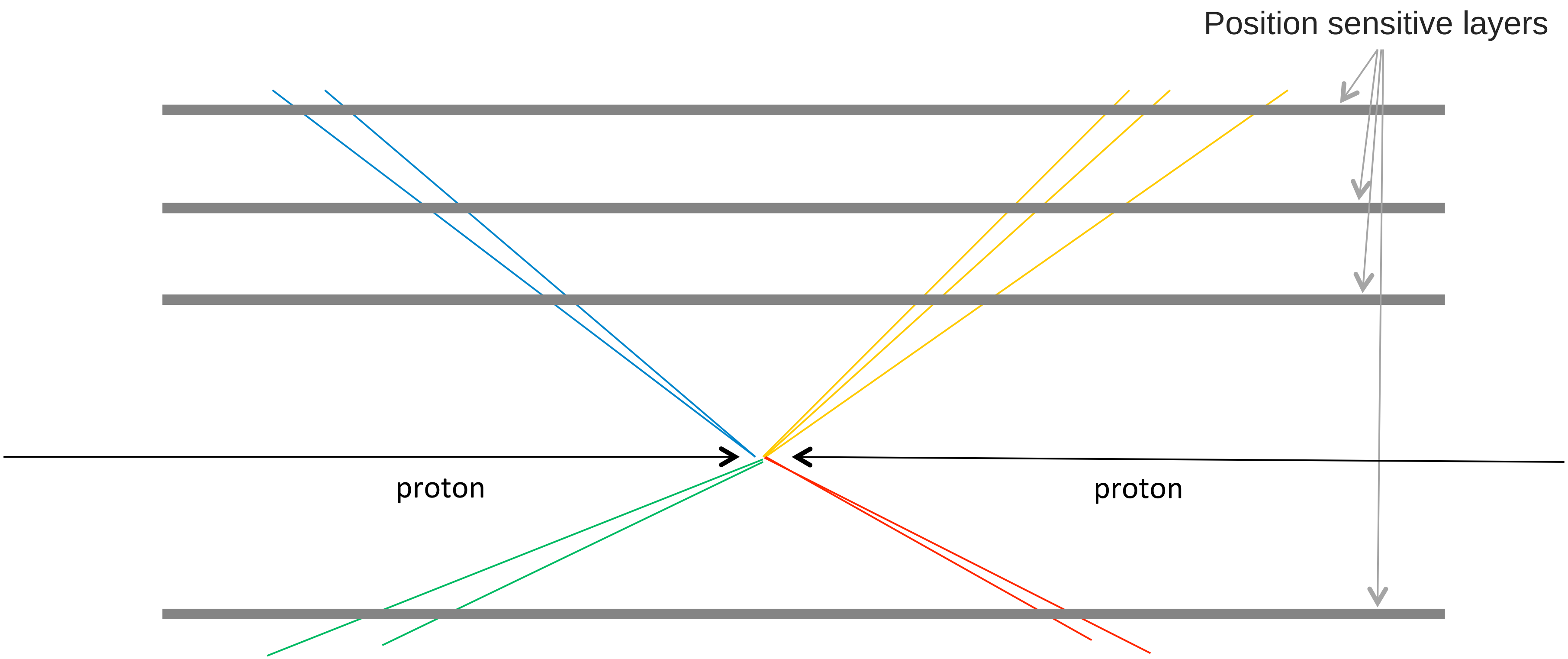

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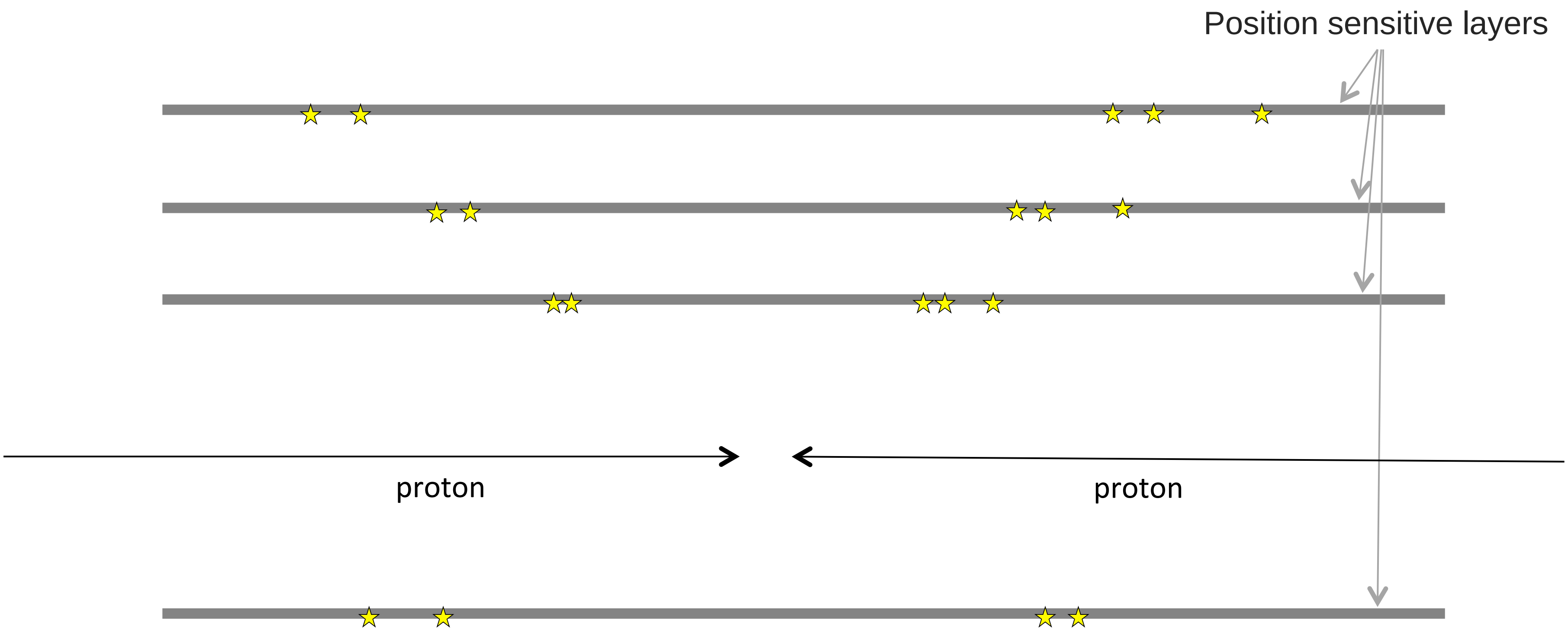

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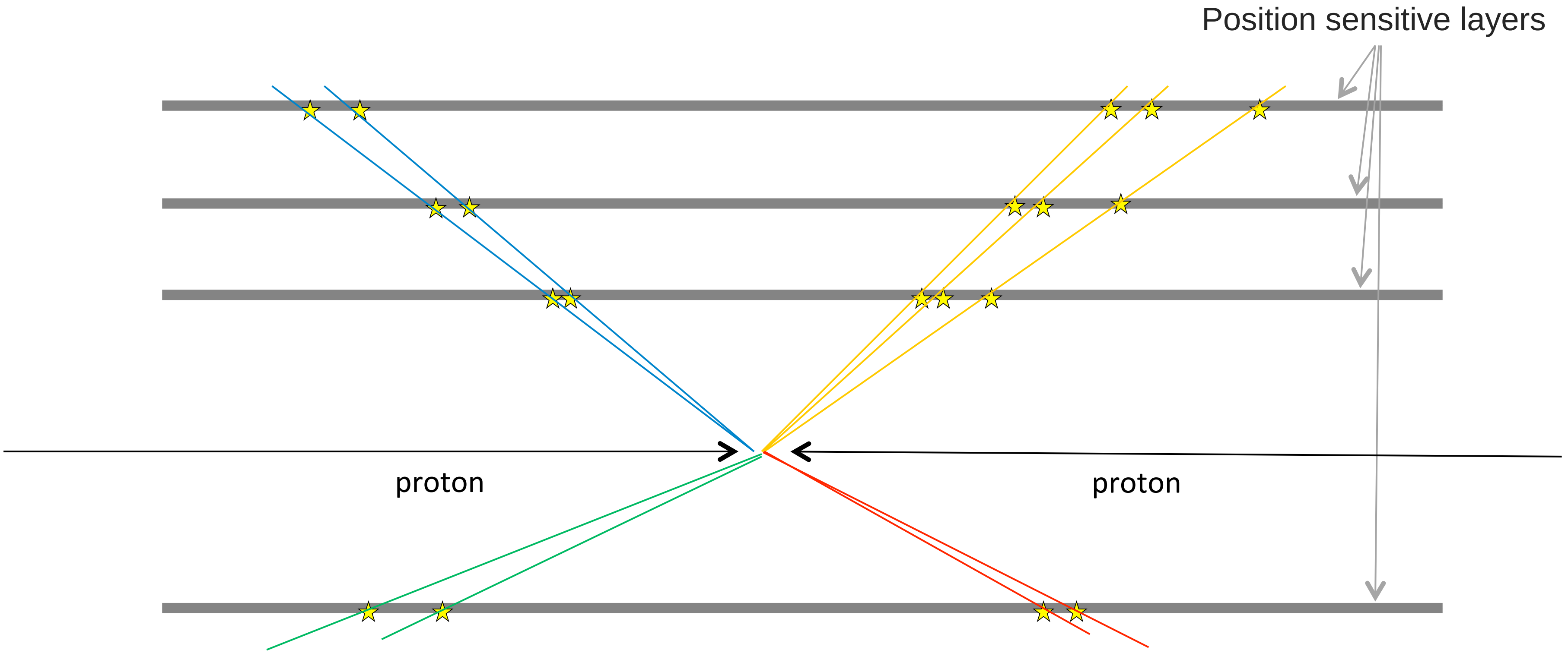
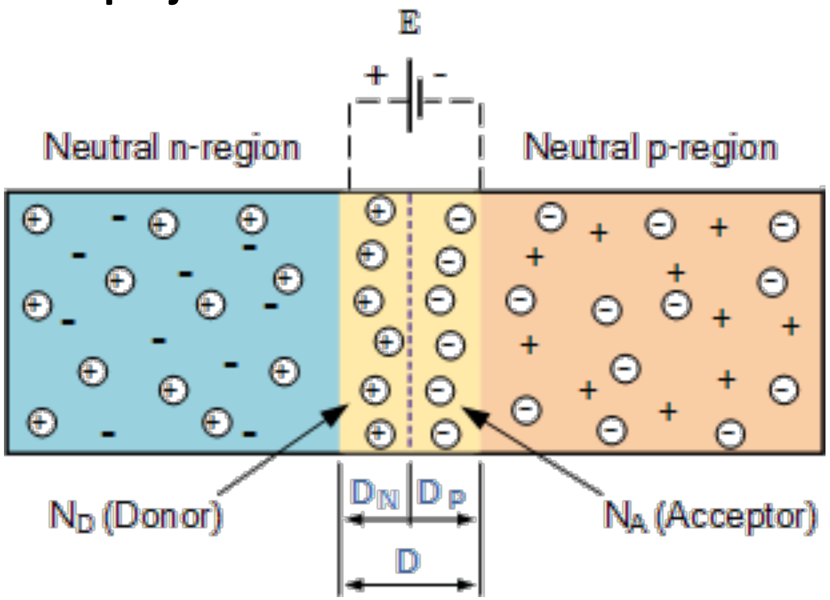


 Signal generation on silicon detectors

- pixel sensor: a 2D segmented pn-diode (reversely bias → depletion zone)

pn-junction



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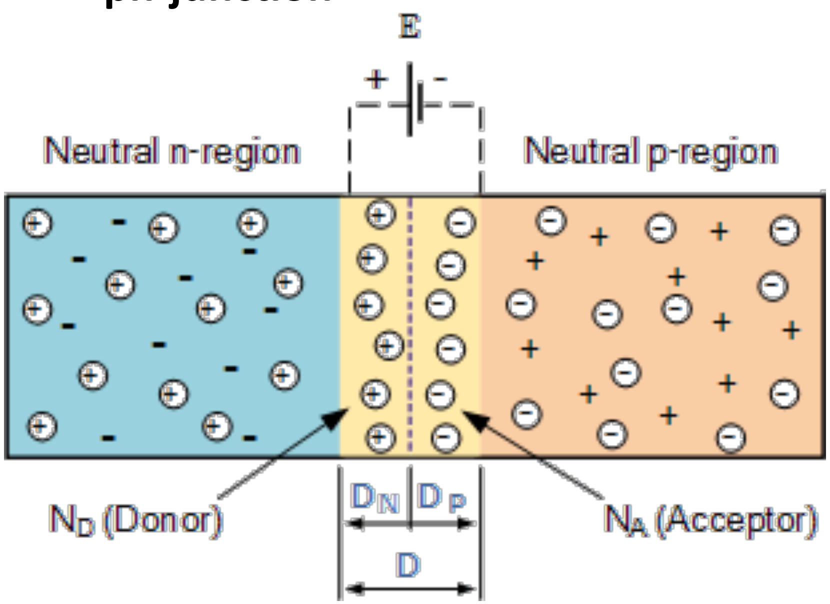
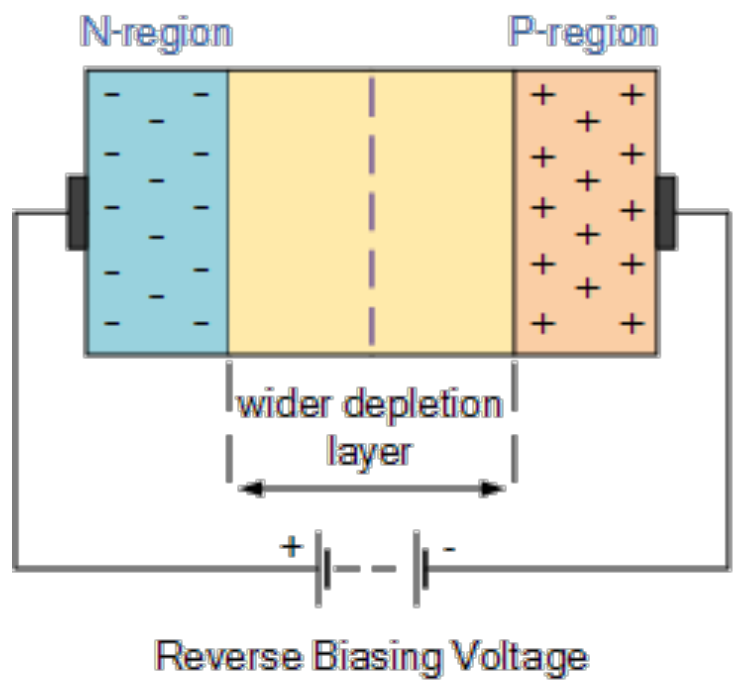


Reversely bias pn-junction



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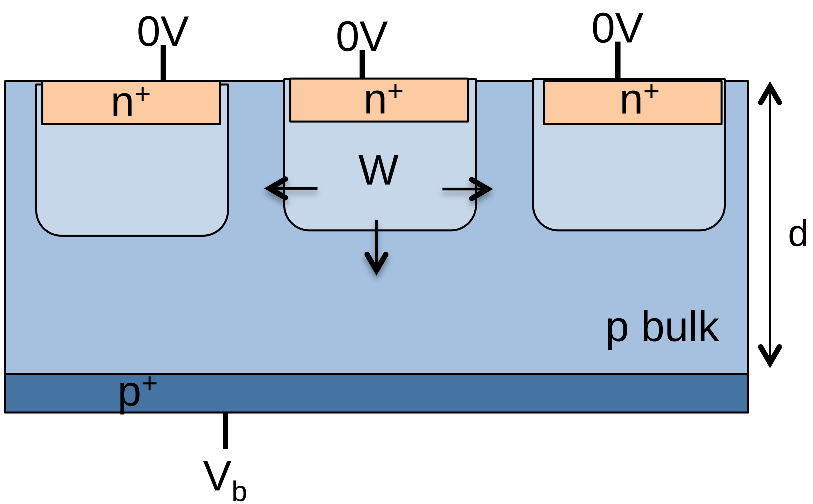

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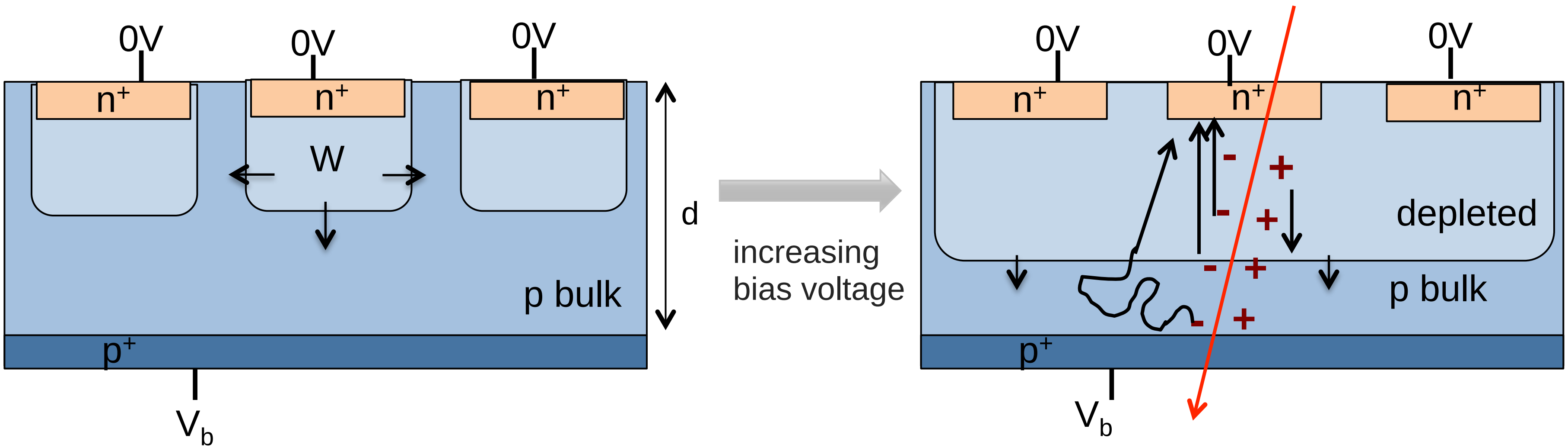

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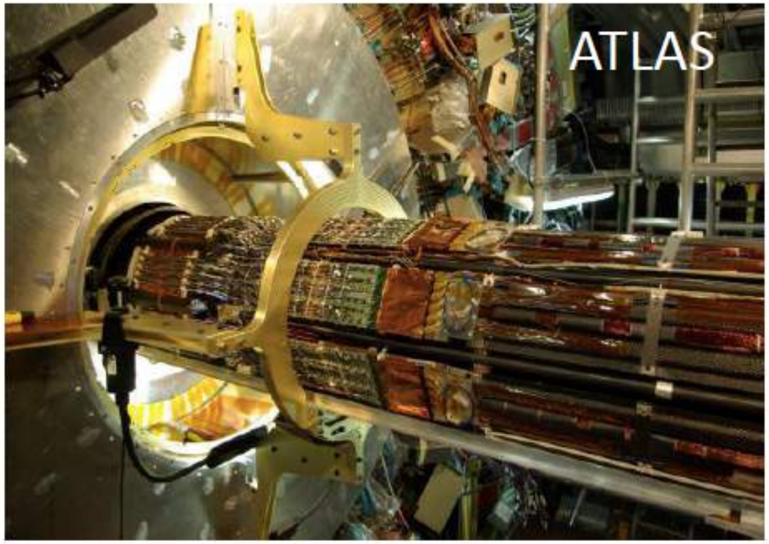
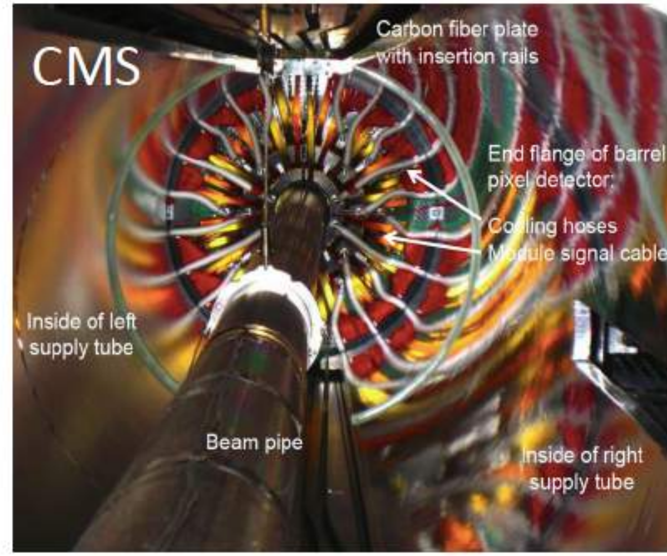
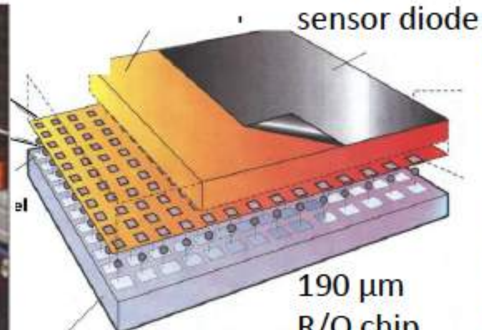
- A particle traversing the sensor generates electron-hole pairs
- Signal generation → drift and diffusion
- ATLAS requirements: drift
- The signal is amplified and digitized in a R/O chip

LHC pixel detectors



all based on
"Hybrid Pixels"





- Very good performance and reliability since 2009
- Not sufficient for long term LHC plans of luminosity increase

High Luminosity LHC

- Why do we need high luminosity?

frequency to obtain an specific event:

$$N_{event} = Luminosity \times \sigma_{event}$$

σ (pp) = 10^{11} pb
σ (W/Z) = 10^{4} pb
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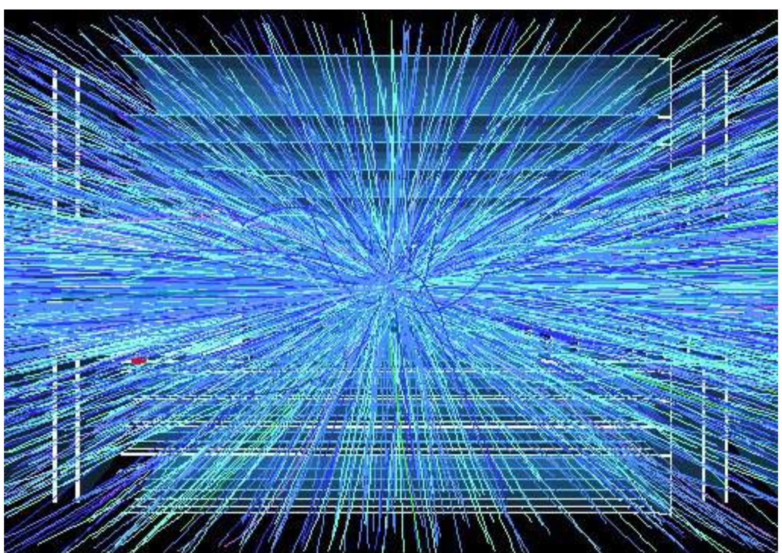
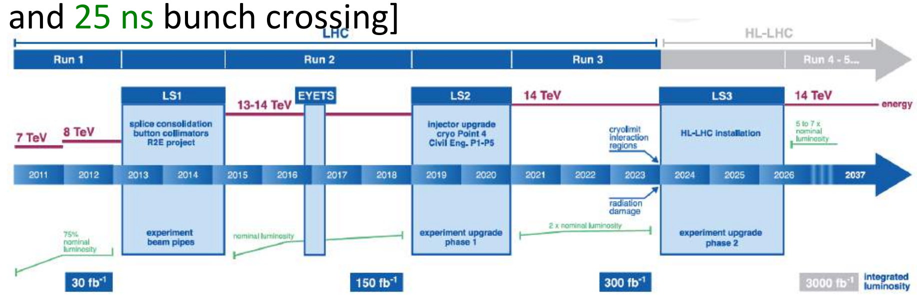
- The LHC plans to increase by a factor of 7 the luminosity in 2026 → **HL-LHC program**

[luminosity of 7* 10^{34} $cm^{-2}s^{-1}$, collision energy of 14 TeV, and 25 ns bunch crossing]





Detector implications:

- Radiation hard detectors
- High rate
- Fast detectors

Introduction The ATLAS Inner TracKer (ITk)

- The full Inner Detector of ATLAS will be replaced by a new all-silicon detector
  - Pixels and Strips
- The Pixel Detector layout is under discussion (4-6 layers)
- The requirements are at least one order of magnitude higher

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	Pixels LHC	IBL	Pixels HL-LHC (inner layers)	Pixels HL-LHC (outer layers)
Particle rate	1 MHz/mm^2	5 MHz/mm^2	10 MHz/mm^2	1 MHz/mm^2
Total Ionizing Dose (TID)	50 Mrad	250 Mrad	1 Grad	50 Mrad
Non Ionizing Energy Loss (NIEL)	$10^{15}\ n_{eq}cm^{-2}$	$5\times10^{15}\ n_{eq}cm^{-2}$	$2\times10^{16}\ n_{eq}cm^{-2}$	$1\times10^{15}\ n_{eq}cm^{-2}$
Silicon Area	$\approx$1.73 m^2	$\approx$0.15 m^2	$\approx$1 m^2	$\approx$10 - 20 m^2
Pile-up	23	23	200	-

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Pixels LHC: Hybrid technology, Planar Pixel Sensor (PPS)

IBL: Hybrid technology, Planar Pixel Sensor (PPS), 3D Silicon sensor (3D)

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Hybrid technology
Planar Pixel Sensor (PPS)

Hybrid technology
Planar Pixel Sensor (PPS)
3D Silicon sensor (3D)

<u>Inner layers</u>

1. **Radiation hardness**
2. **Low power consumption**
3. Low material
4. Occupancy

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International R&D effort for the new pixel detectors generation

...Sensor (PPS)

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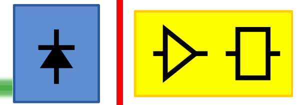
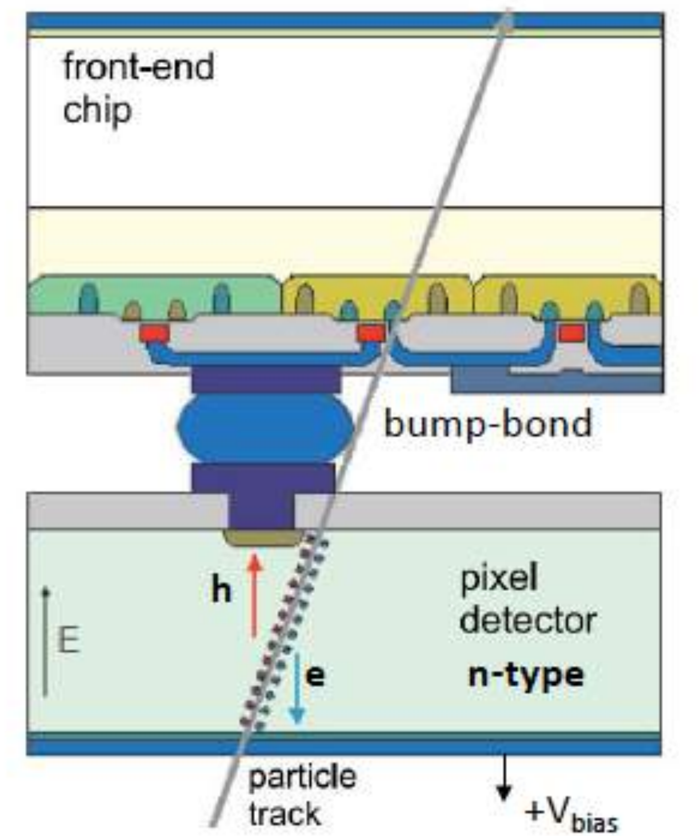
Pixel developments for ATLAS at HL-LHC. From Hybrid detectors to depleted Monolithic detectors

Hybrid detector technologies



Hybrid pixels

- Sensor + front-end chip separated entities
- Signal collected by drift
- Mature technology (in use since LEP 1996)



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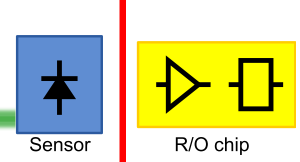

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- Complex signal processing already in pixel cell possible
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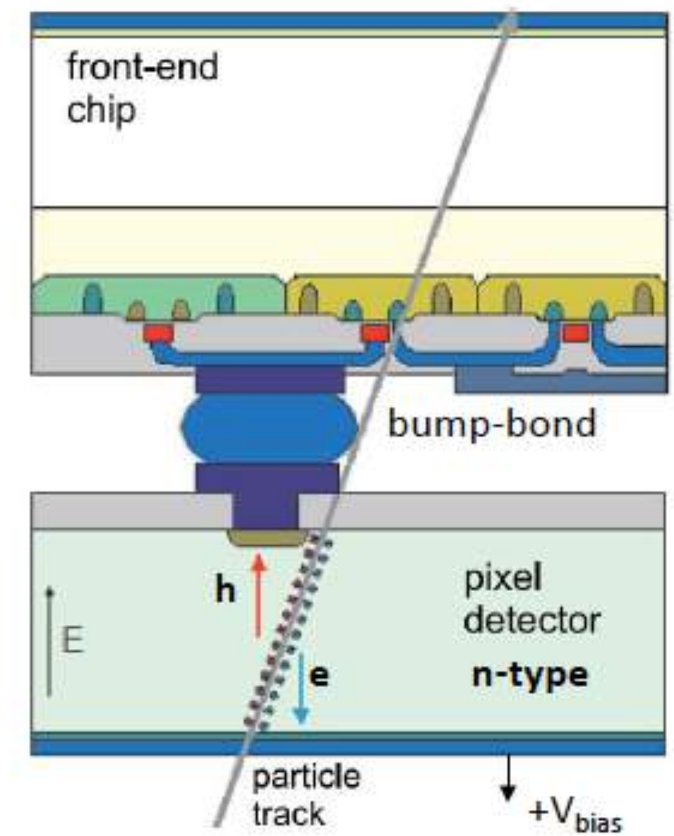
- High rate capability (~MHz/mm^2)



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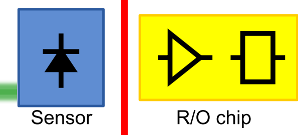

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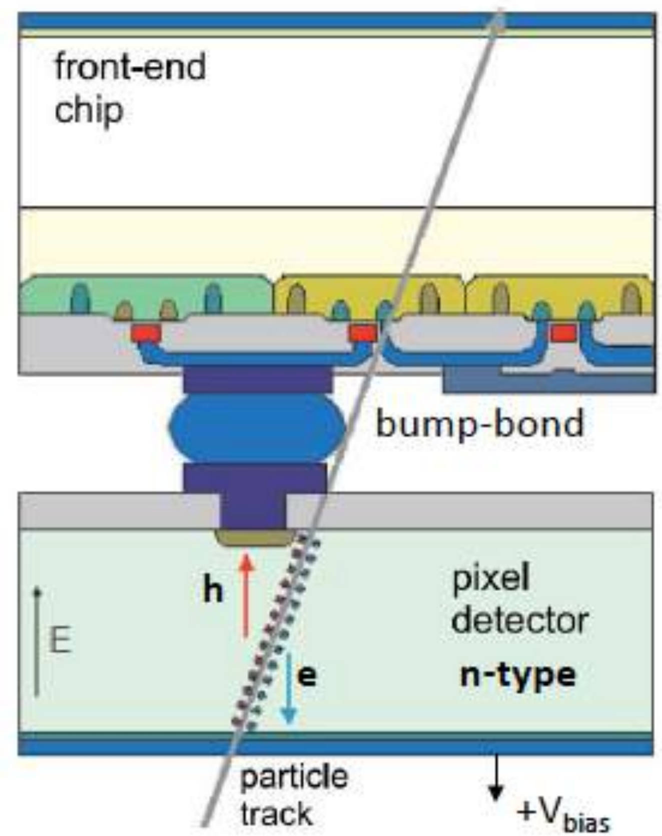
Disadvantages

- Complex and laborious module production
  - Many production steps → low production yield
  - Bump-bonding / flip-chipping → limiting pixel size
  - Expensive
- Relatively large material budget ~3% X_o per layer
  - sensor + chip + flex kapton + passive components
  - support, cooling, services



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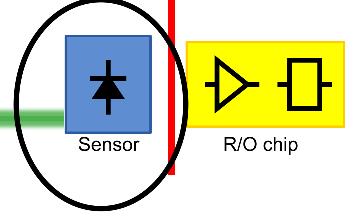
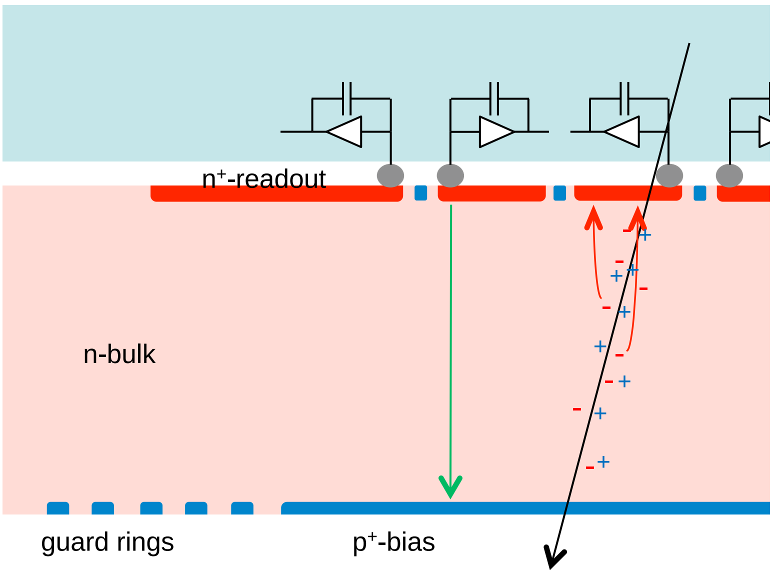
Hybrid sensors technologies



Planar Pixel Sensor (PPS)

- Technology used in present Pixel Detector
- Collection distance = drift distance
- High production yield (%)
  - Large area sensors



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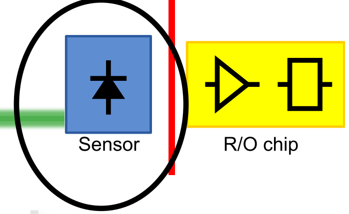

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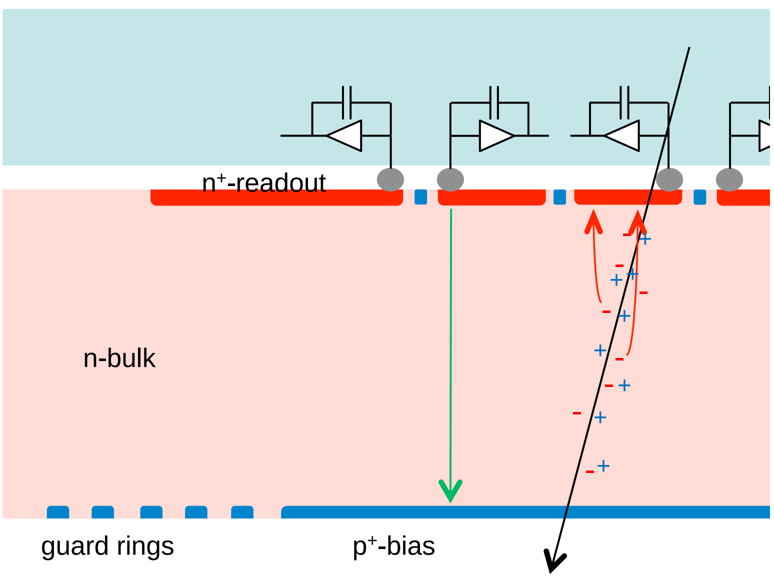
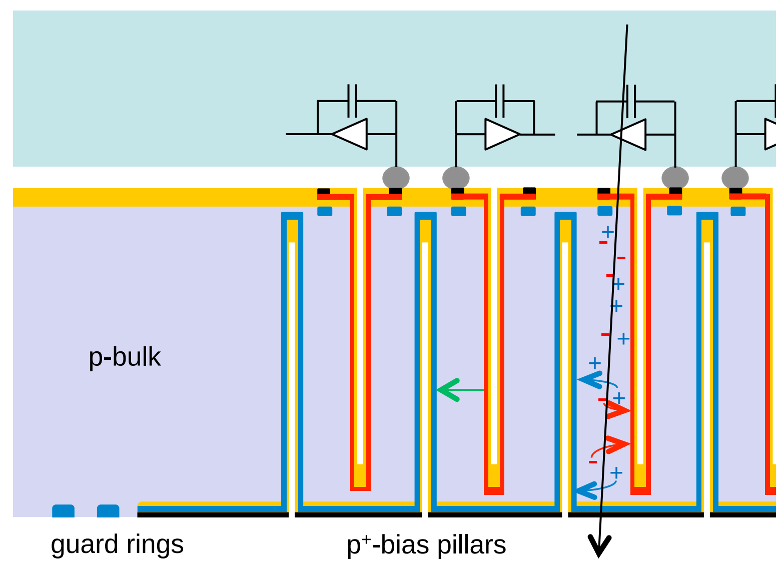


3D Silicon Sensor (3D)

- Technology installed for the first time IBL
- Collection- and drift distance disconnected
- More difficult production, lower yield
  - Smaller area sensors



CMOS Pixel Technologies

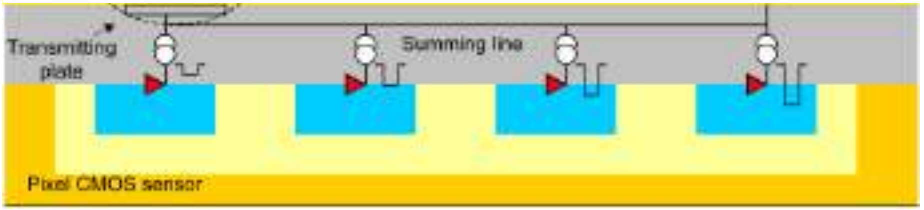
CMOS-based pixels

- Industrial process
  - higher production yield
  - cheaper sensors
- Collecting electrode inside →logic implementation in same silicon tile
  → capacitive coupled connections, monolithic …
  - smaller cost
  - smaller material budget
  - smaller pixel size

- There are two approaches

$$W = \sqrt{2\,\epsilon\,\mu\,\rho\,V_b}$$

→ HV-CMOS
→ HR-CMOS



- Both technologies are developed so far as hybrid approach

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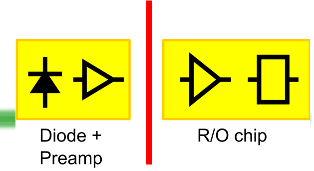

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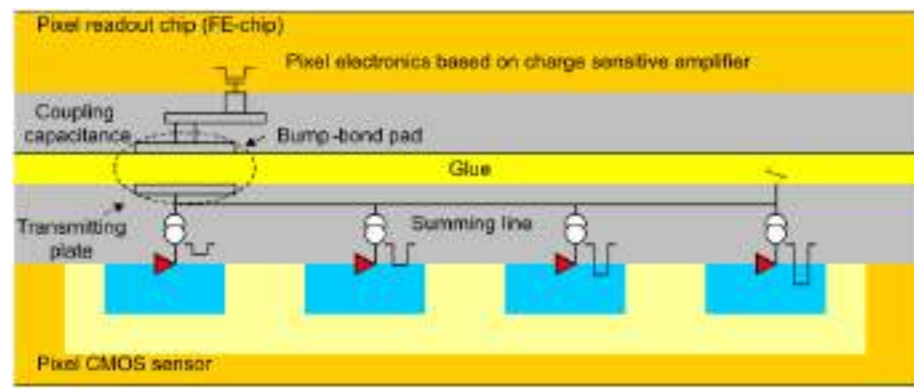

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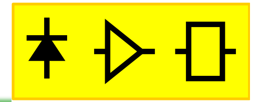
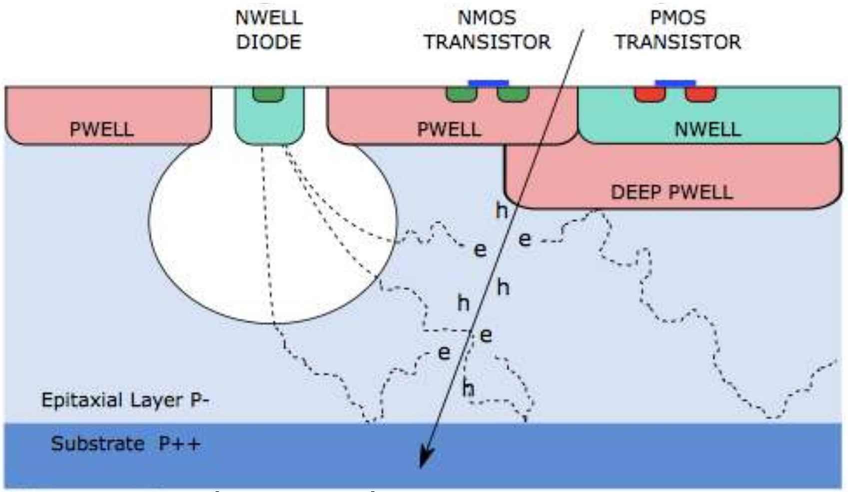


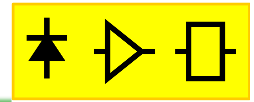
MAPS epitaxial layer



ALICE ITS (L. Mussa)

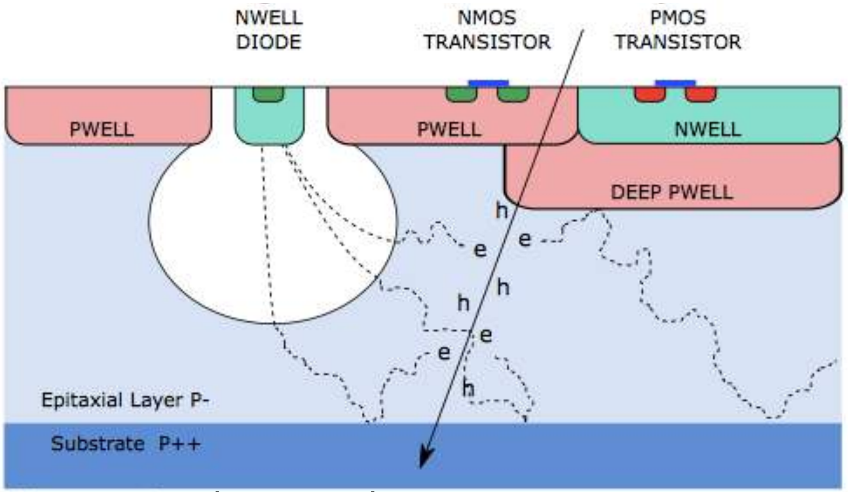
- Complex R/O electronics in sensor layer needed.
- High resistivity epitaxial layer
- Slow charge collection (diffusion)
- "low" radiation hardness
- STAR (2014), ALICE ITS (2018)

Monolithic Active Pixel Sensors



Diode + Amp + Digital

MAPS epitaxial layer



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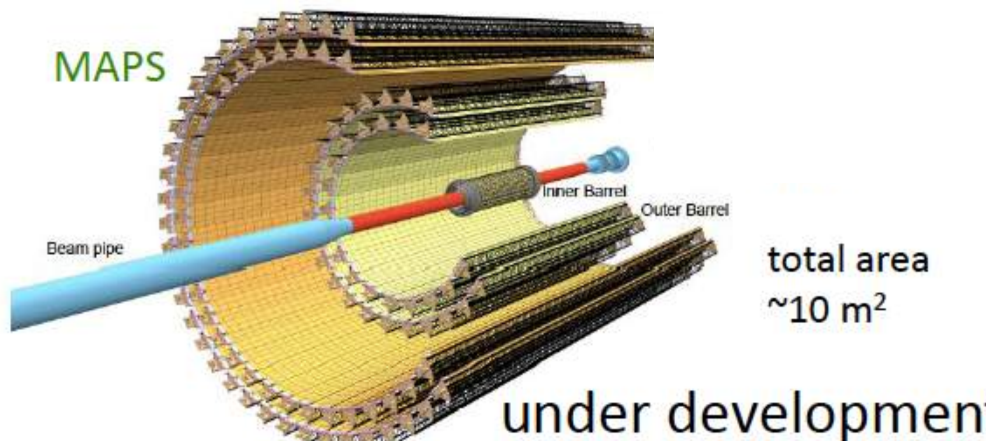
STAR / RHIC

MAPS

in operation since 2014

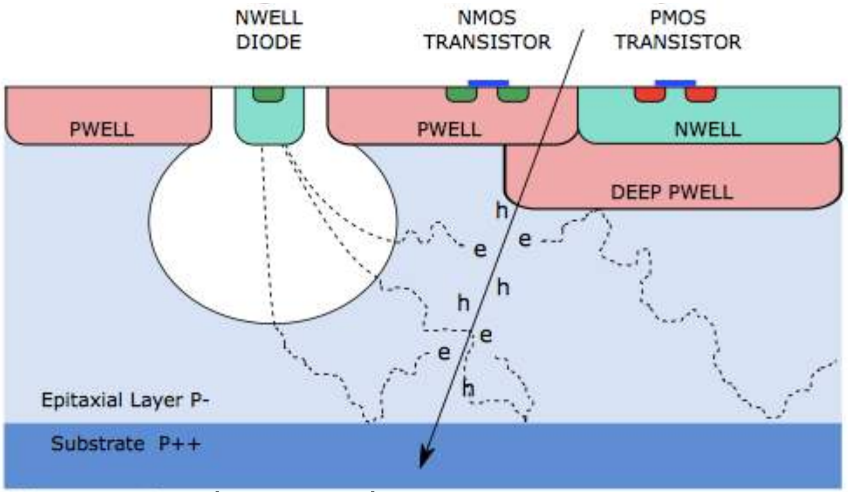
ALICE Upgrade



Monolithic Active Pixel Sensors

Diode + Amp + Digital

MAPS epitaxial layer



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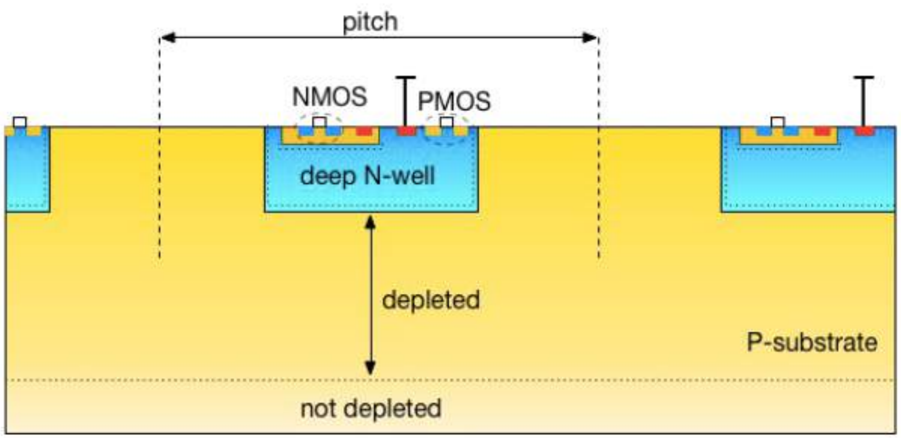
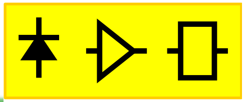
Depleted MAPS



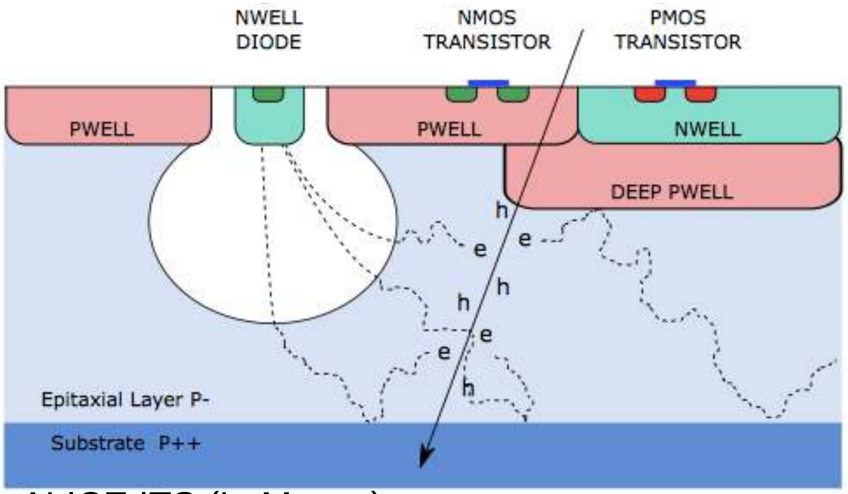
- Complex R/O electronics in sensor layer needed.
- High voltage/high resistivity process
- Fast charge collection (drift)
- [BELLE II DEPFET]

Monolithic Active Pixel Sensors



Diode + Amp + Digital

MAPS epitaxial layer



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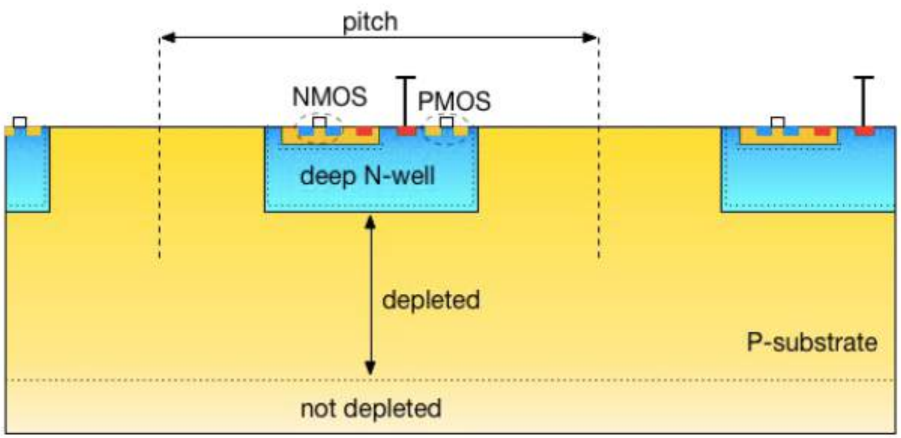
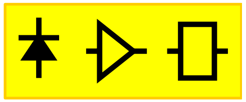


Belle II (SuperKEK) DEPFET

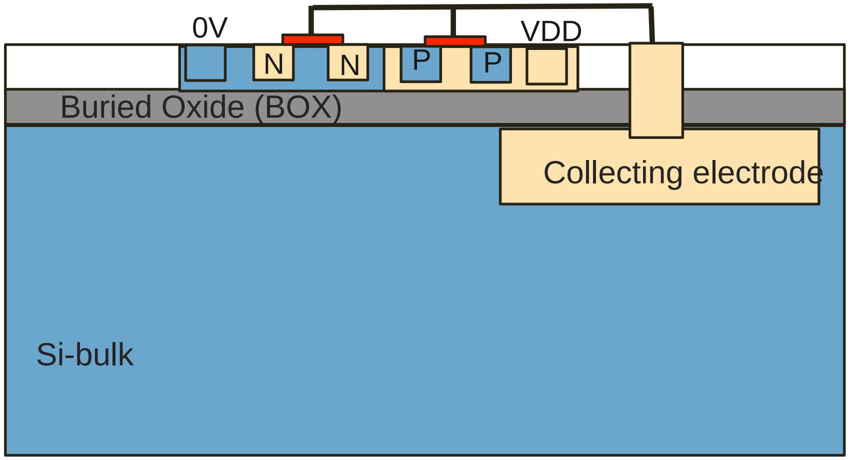
in production for 2017

Depleted Monolithic Active Pixel Sensors

Depleted MAPS Silicon-On-Insulator



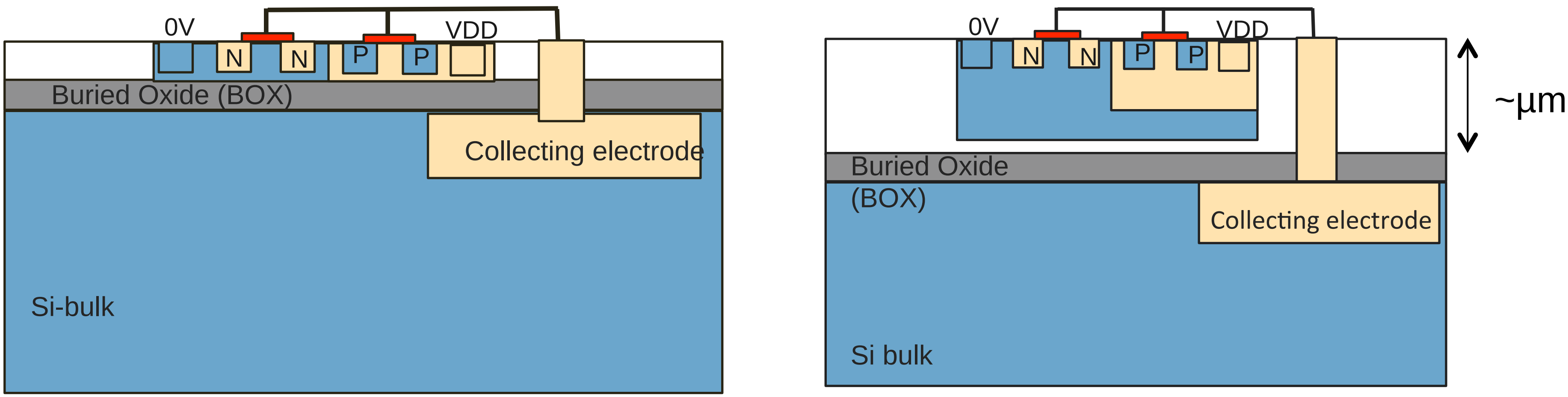
Diode + Amp + Digital



- Silicon-On-Insulator to separate logic from sensor diode. Several advantages:
  - Decoupling of electronics and sensor silicon resistivity
  - No competing NWELL
  - Free choice of fill factor
  - Lower cross-talk
- Charge collection by drift

Depleted Monolithic Active Pixel Sensors

Depleted MAPS Silicon-On-Insulator



Standard

- Distance transistors-BOX ~nm
- Ultra-thin transistor body ~O(40 nm) FD
- Radiation hardness very challenging
- OKI/LAPIS

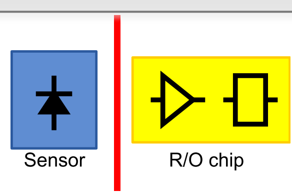
Thick film

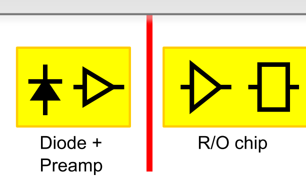
- Distance transistors-BOX ~µm
- Thick transistor body PD
- Multiple "wells" structures

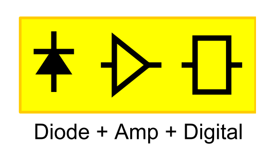
my thesis

Summary of pixel developments features

	Hybrid	CMOS pixels	Monolithic CMOS
Examples	3D, Planar (ATLAS, CMS, LHCvelo,Timepix3)	HV-CMOS HR-CMOS	MAPS (STAR, ALICE ITS) DMAPS SOI
Technology	Industry standard for readout; special high-Ω sensors	R/O and sensors integrated, close to industrial process	R/O and sensor in same piece of silicon; Industrial process
Interconnection	Bump-bonding required	Connectivity facilitated (CCPD) (or monolithic approach)	No needed
Granularity	50 µm x 50 µm	Down to few-micron sizes	Down to few-micron sizes
Timing	Fast	Coarse but improving	Coarse but improving
Radiation hardness	Feasible	To be proven	To be proven







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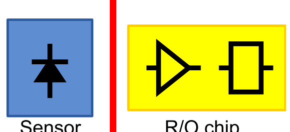
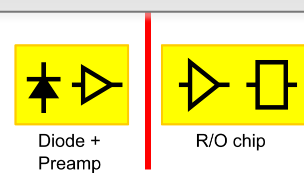
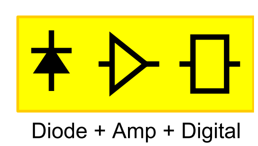
inner pixel layers
ATLAS ITk







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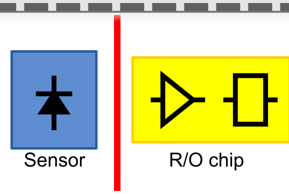
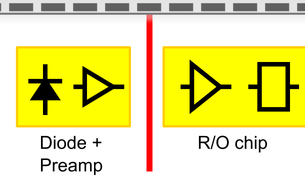
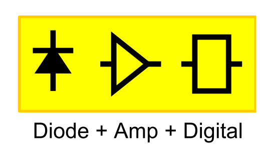
Timing	Fast	Coarse but improving	Coarse but improving
Radiation hardness	Feasible	To be proven	To be proven

inner pixel layers ATLAS ITk

under investigation for outer pixel layers ATLAS ITk

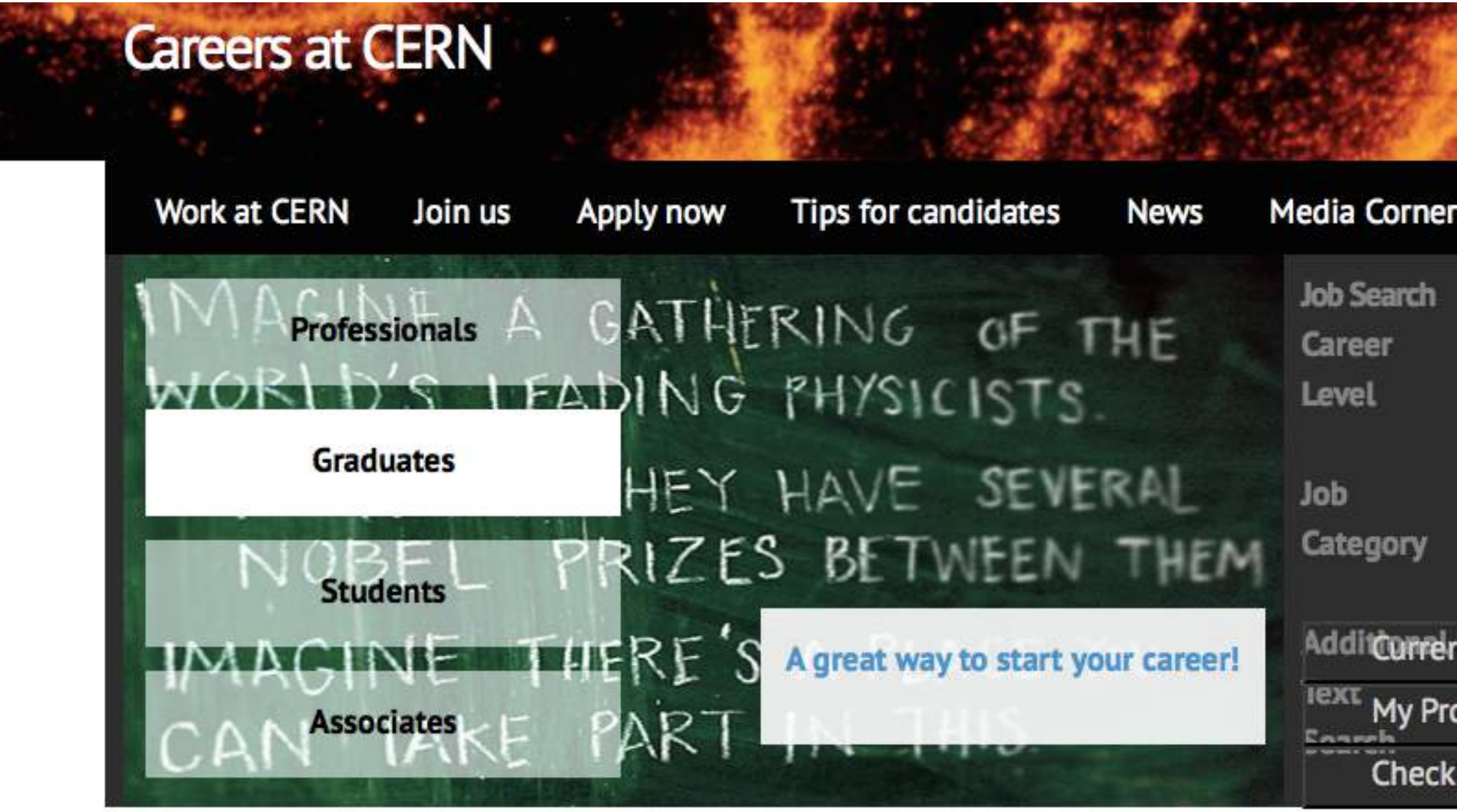






http://visits.web.cern.ch

http://jobs.web.cern.ch



Thank for your attention

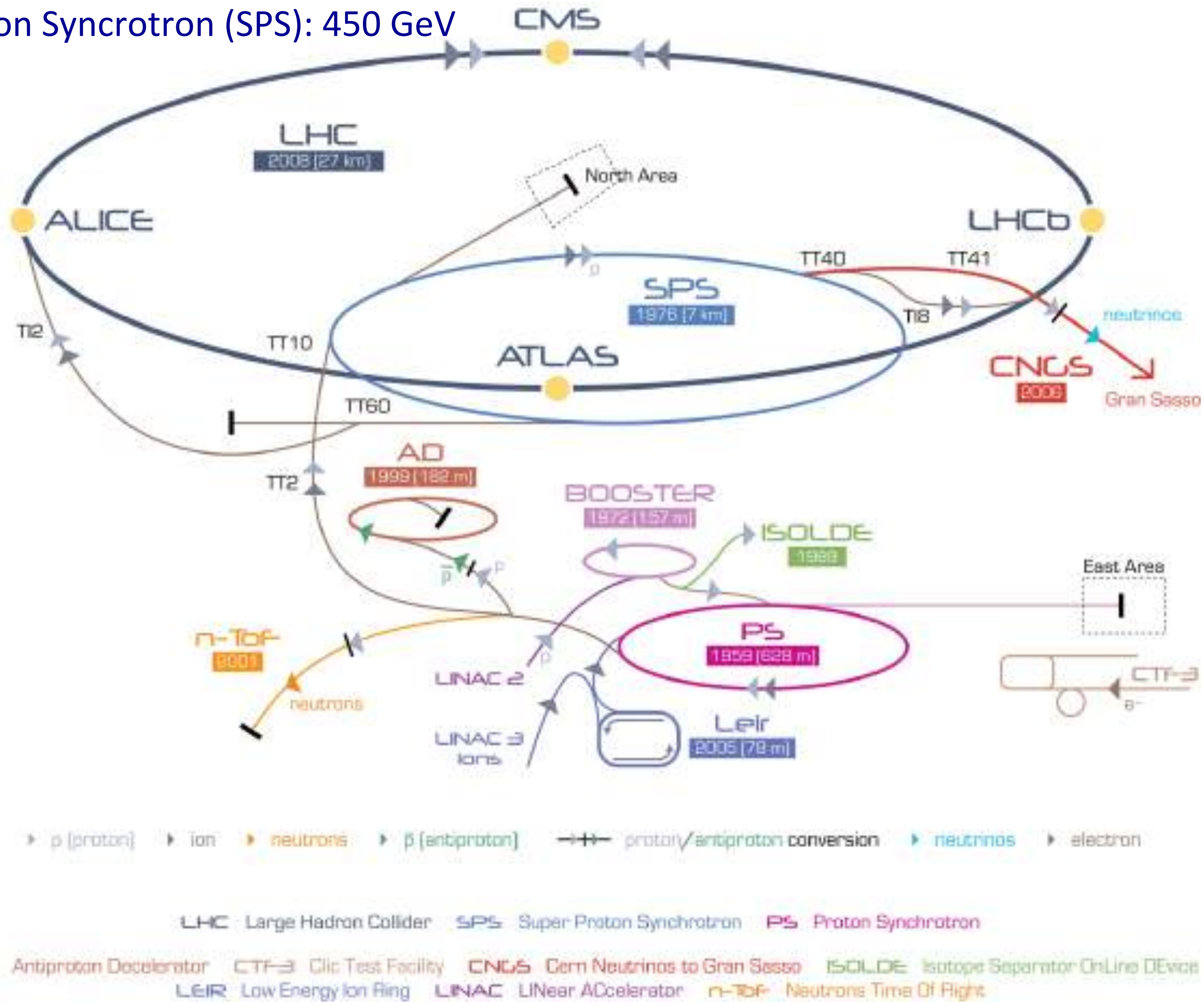
Spare slides

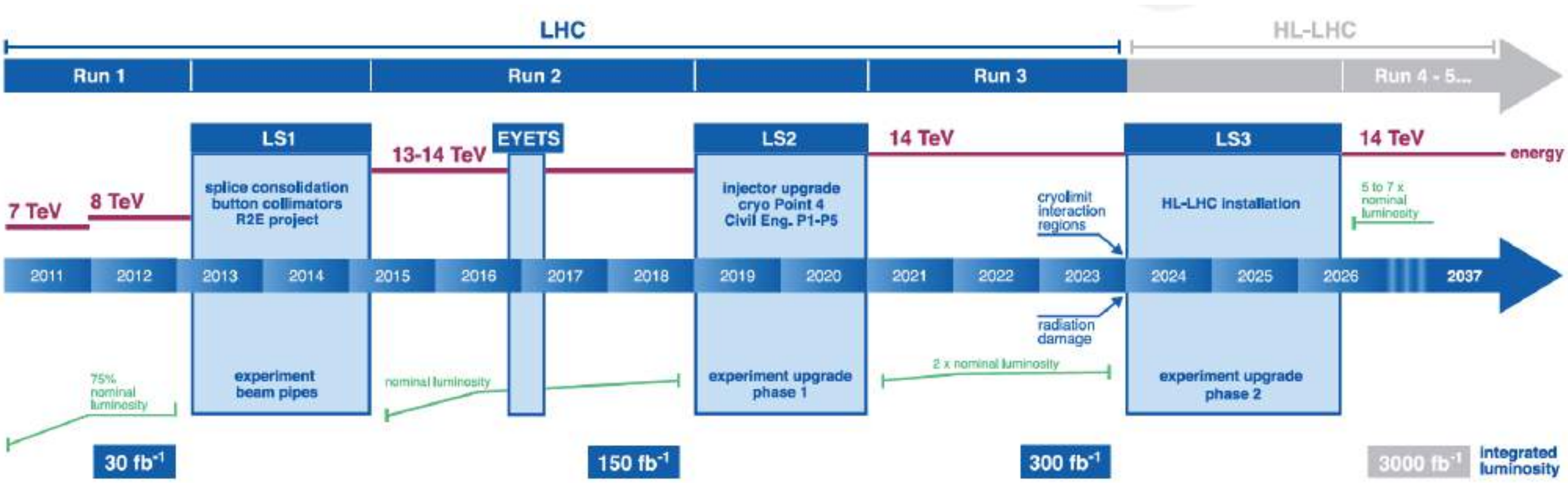
LINAC 2: 50 MeV

Proton Synchrotron Booster (PSB): 1.4 GeV

Proton Syncrotron (PS): 25 GeV

Super Proton Syncrotron (SPS): 450 GeV




LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13-14 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
injector upgrade
cryo Point 4
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC installation
5 to 7 x
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2037
radiation
damage
75%
nominal
luminosity
experiment
beam pipes
nominal luminosity
experiment upgrade
phase 1
2 x nominal luminosity
experiment upgrade
phase 2
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity

Particle colliders requirements

[Slide by N. Wermes, Elba 2015]

	BX time	Particle Rate	NIEL Fluence	Ion. Dose
	ns	kHz/mm^2	n_{eq}/cm^2 per lifetime*	Mrad per lifetime*
LHC (10^{34} cm^{-2}s^{-1})	25	1000	2×10^{15}	79
HL-LHC (10^{35} cm^{-2}s^{-1})	25	10000	2×10^{16}	> 500
LHC Heavy Ions (6×10^{27} cm^{-2} s^{-1})	20.000	10	$>10^{13}$	0.7
RHIC (8×10^{27} cm^{-2}s^{-1})	110	3.8	few 10^{12}	0.2
SuperKEKB (10^{35} cm^{-2}s^{-1})	2	400	~3 x 10^{12}	10
ILC (10^{34} cm^{-2}s^{-1})	350	250	10^{12}	0.4

Monolithic Pixels

- lower rates
- lower radiation
- smaller pixels
- less material
- better resolution

DEPFET: Belle II
MAPS: STAR@RHIC
and future
ALICE ITS

assumed lifetimes:
LHC, HL-LHC: 7 years
ILC: 10 years
others: 5 years

N. Wermes, Elba 2015

5

[Slide by L. Linssen, Final TALENT Conference]

comparison of requirements

weaker ← → very strong

HL-LHC, ALICE upgrade, FCC-hh, CLIC	Position resolution
ALICE upgrade, HL-LHC, CLIC, FCC-hh	Timing accuracy
HL-LHC, ALICE upgrade, FCC-hh, CLIC	Low mass
CLIC, ALICE upgrade, HL-LHC, FCC-hh	Radiation hardness

The 4 listed projects have many individual requirements in common, though their combination is different

Particle's tracking detectors

- Layers of segmented silicon detectors
- The energy loss by the particle while traversing the detector → electrical signal
- The loss of energy by charged particles in matter → inelastic collisions

Charged particles ($m >> m_e$)

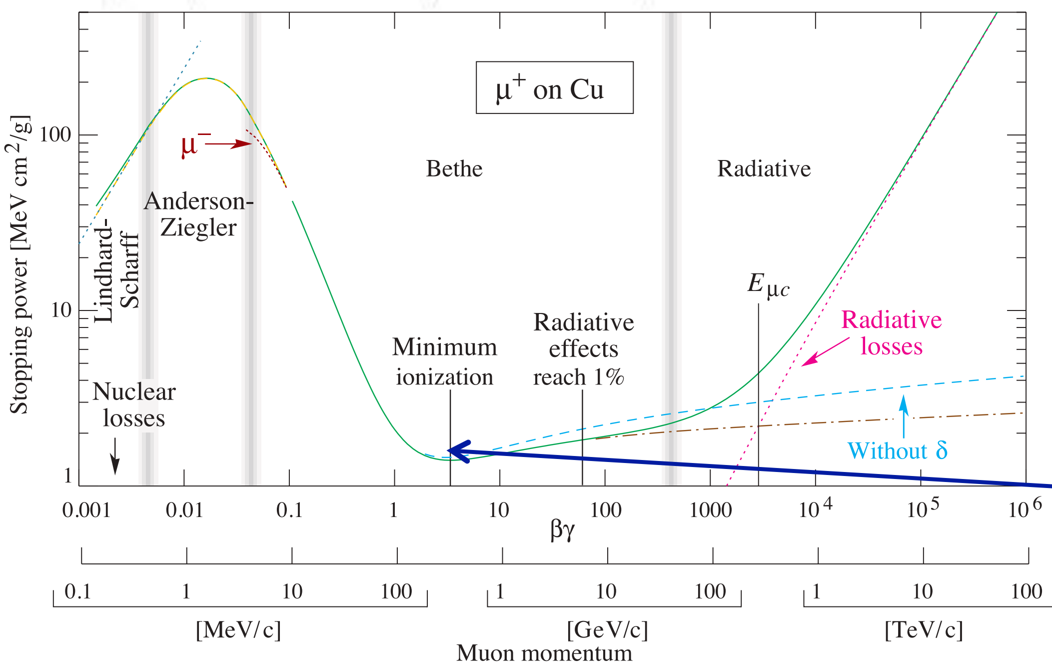
- Excitation and ionization of atoms
- Part of the energy is transferred to the atom
- Bethe-Bloch formula

$$-\frac{dE}{dx} = \frac{4\pi r_e^2 m_e c^2 N_A Z z^2}{A\beta^2} \cdot \left(\frac{1}{2}\ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2}\right) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right)$$

Charged particles ($m \sim m_e$)

- Ionization of atoms + other
- At high energies → Bremsstrahlung dominates

$$-\left(\frac{dE}{dx}\right)_{rad} = \frac{E}{X_o}$$



MIP (Minimum Ionization Particle)

Transverse momentum resolution

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\left(\frac{\sigma_{p_T}}{p_T}\right)^2_{point} + \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{MS}}$$

$$\left.\frac{\sigma_{p_T}}{p_T}\right|_{point} = p_T \cdot \frac{\sigma}{0.3BL^2} \cdot \sqrt{\frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}}$$

$$\left.\frac{\sigma_{p_T}}{p_T}\right|_{MS} = \frac{1}{0.3B}\frac{0.0136}{\beta}\sqrt{\frac{C_N}{X_0 L}}$$

Vertex and Impact Parameter resolution

$$\sigma^2_{vtx} \sim \frac{r_1^2\sigma_1^2 + r_2^2\sigma_2^2}{(r_2 - r_1)^2} + \frac{(2r_1r_2 - r_0(r_1 + r_2))^2}{(r_2 - r_1)^2} \cdot \left(\frac{13.6\,\mathrm{MeV}}{pv} \cdot \sqrt{\frac{d}{X_o}}\right)^2$$

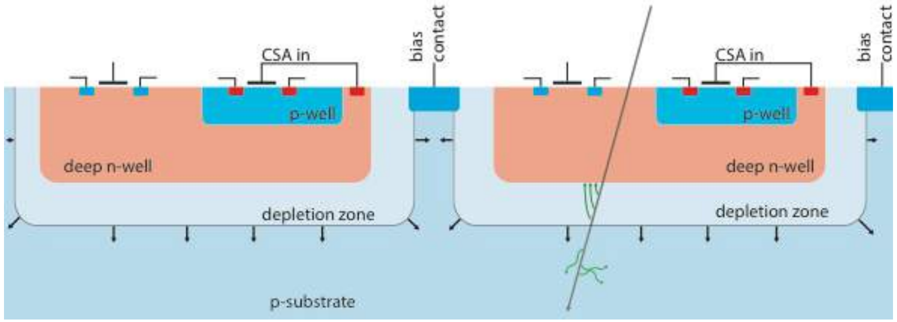
$$\sigma_{d_0} = \sqrt{\frac{\sigma^2}{(N+1)} + \frac{\sigma^2}{(N+1)}\frac{12N}{(N+2)}\frac{z_c^2}{L^2}}; \qquad z_c = (z_N - z_0)/2$$

Requirements to design a tracking detector

- large detector coverage in η
- a trade off between the material budget and the number of tracking layers
- location of the first layer as close as possible to the interaction point
- high magnetic field
- small detector and beam pipe thickness
- fine detector segmentation, specially in the layers close to the interaction point
- detector radiation hardness up to the expected fluences
- excellent detector efficiency which ensures a measurement point per detector layer
- high readout speed (25 ns in-time)

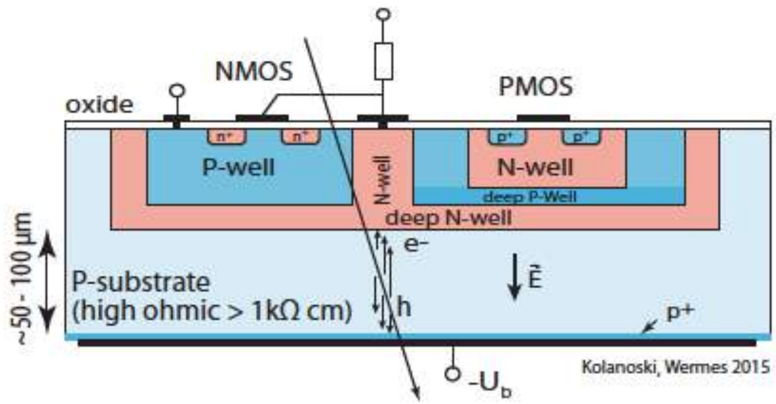
CMOS Pixel Technologies

HV-CMOS



- HV technology (100V)
- Logic in-sensor
- Two approaches
  - Bump-bonded to dedicated R/O chip
  - Capacitive coupling via isolating glue
- Proven up to
  - 1GRad TID, 10^{15} $n_{eq}cm^{-2}$
  - 99% (96%) efficiency before (after) irr
  - depletion depth 10-20µm at 100V
  - signal rise-time 100ns
- A HV-CMOS prototype in 350nm produced in large scale (2x2cm)

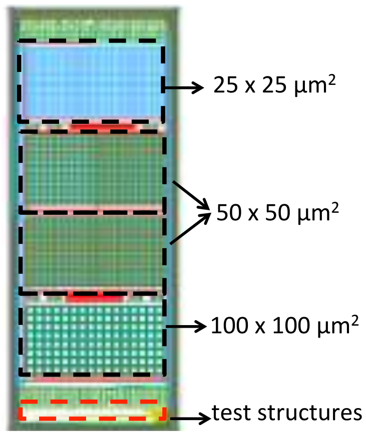
HR-CMOS

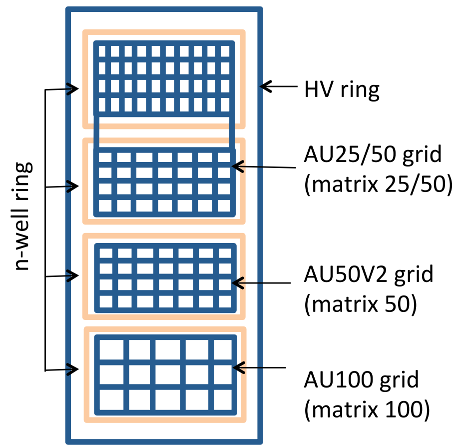


- High resistivity substrate (1-2 KΩ cm)
- Two variants are being investigated
  - different geometries
- Two approaches
  - Bump-bonded to dedicated R/O chip
  - Monolithic
- Proven up to
  - Depletion 60µm at 20V (6200e^{-})
  - Rise-time within 25ns (threshold dependency)
- A HR-CMOS prototype in 150nm selected → production in large scale (2x2cm)

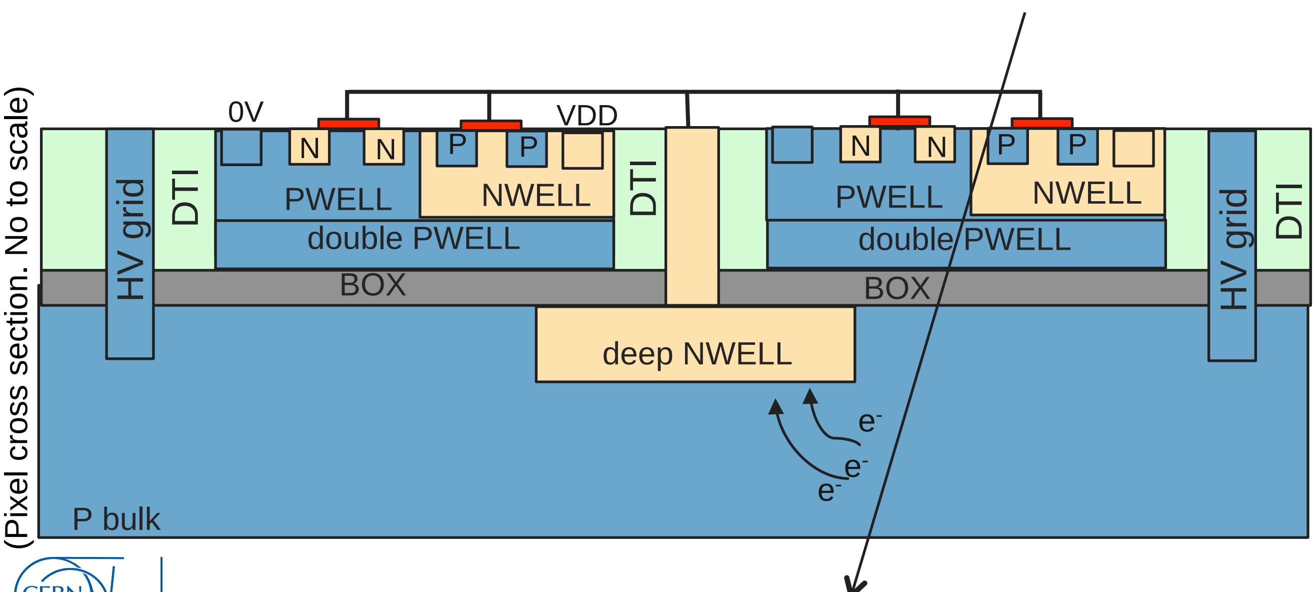
CERN

XTB01 prototype





- 2×5 mm²
- 300 μm thick
- 4 metal layers, wafer size: 8“
- Four matrices with different pixel sizes (25x25 μm², 50x50 μm², 100x100 μm²)
- Transistor test structures
- HV ring, grid rings, n-rings



- thick film DMAPS SOI 0.18 μm
- BOX isolates sensor and electronics
- thick film, double PWELL
- no back-processing (HV applied from front side)
- MIP detection