Les expériences du future: détecteurs

École de GIF 2019, 2-6 Septembre 2019

École polytechnique - Palaiseau

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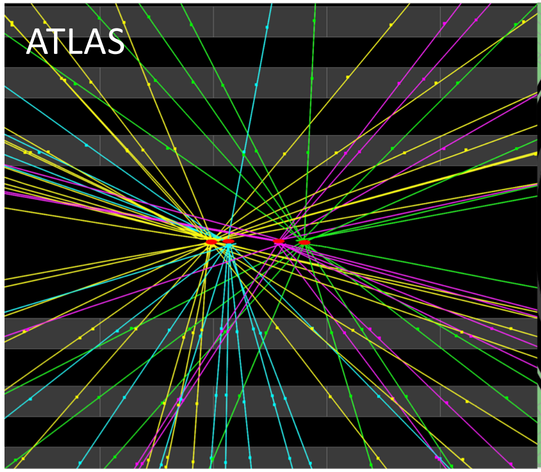
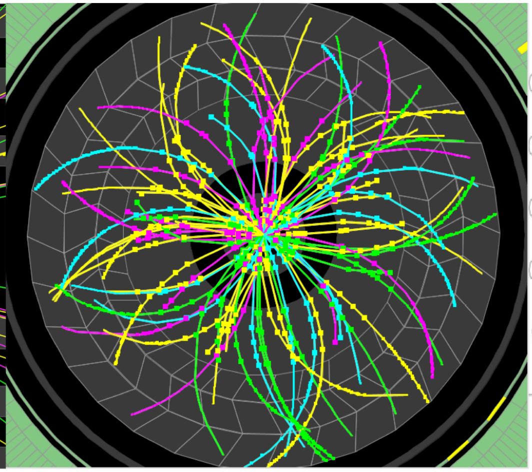
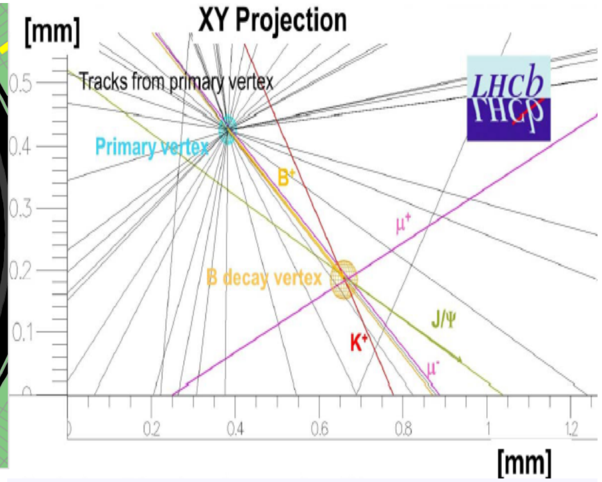
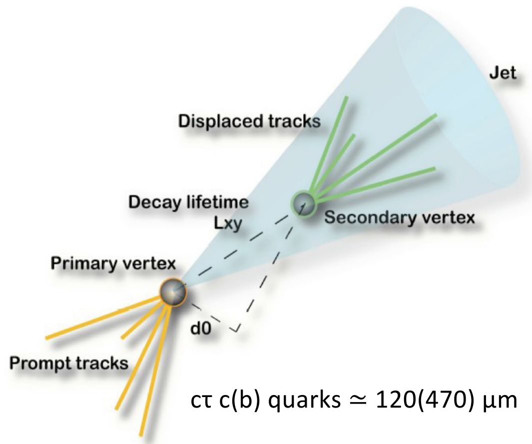
Tracking systems

Provide most precise measurement of charged particle trajectories
to form primary (interaction) and secondary (decay) vertices,
to estimate momentum from curvature in magnetic field







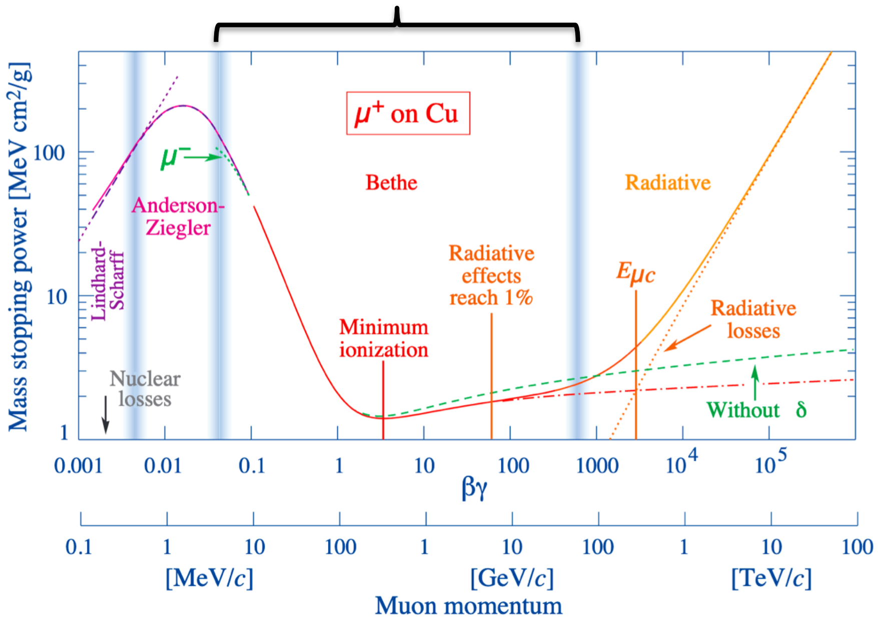


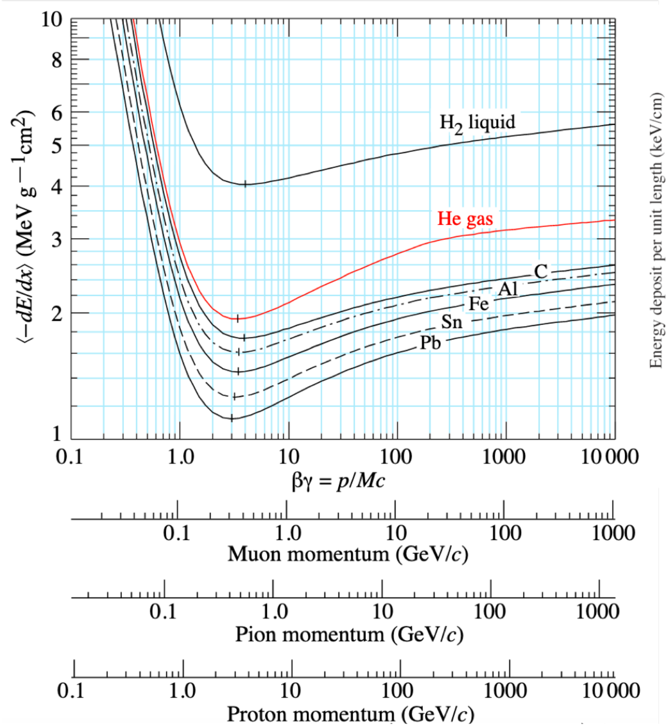
Charged particle energy loss in matter

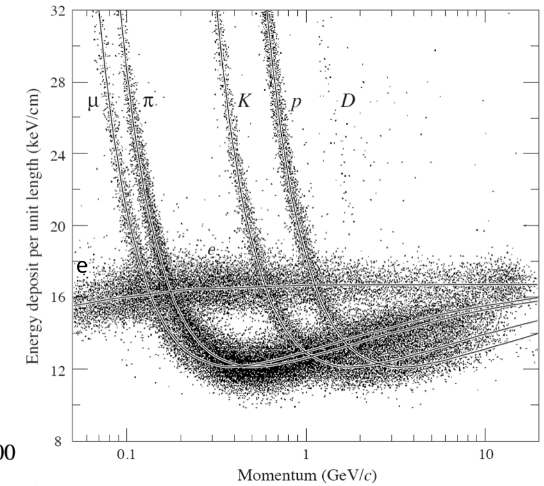
Bethe & Bloch formula (MeV g^{-1} cm^{2}), M $\gg$ m$_e$

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

- Detectors are in the range 0.1 GeV to TeV
- Trackers are measuring ionization





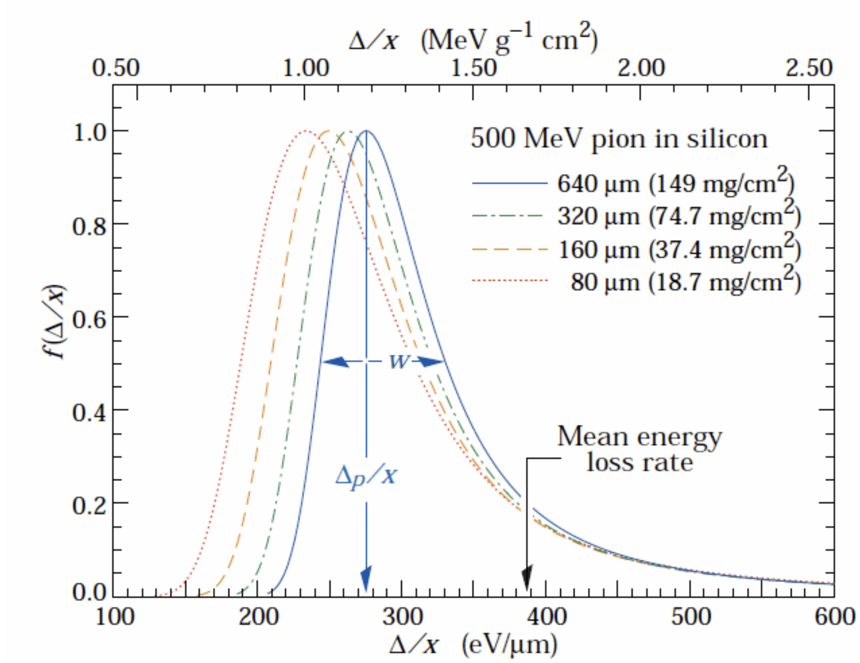


In composite material $\left\langle \frac{dE}{dx} \right\rangle = \sum w_j \left\langle \frac{dE}{dx} \right\rangle_j$

* *Particle Data Booklet http://pdg.lbl.gov/2019/reviews/rpp2018-rev-passage-particles-matter.pdf and https://arxiv.org/pdf/1804.11246.pdf*

Charged particle energy loss in matter: signal

Signal in thin material layers is described by Landau-Vavilov-Bichsel distribution



In Silicon dE/dx = 3.88 MeV/cm and average e-h pair pair energy is 36 eV/
→ S $\simeq$ 106(70) e-h pairs/µm average(maximum probability)

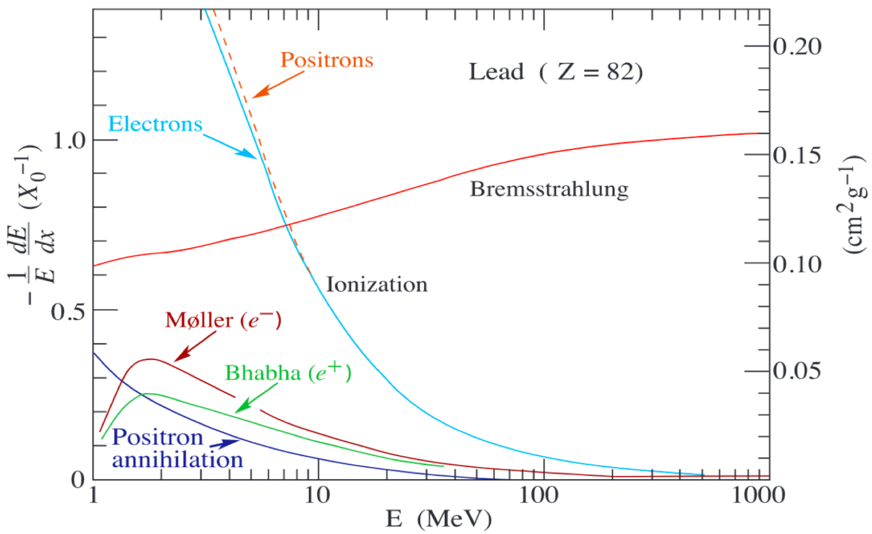
* *Particle Data Booklet http://pdg.lbl.gov/2019/reviews/rpp2018-rev-passage-particles-matter.pdf and https://arxiv.org/pdf/1804.11246.pdf*

Charged particle energy loss in matter: Bremsstrahlung

$$\frac{dE}{dx} = 4\,\alpha N_A \frac{z^2 Z^2}{A}\left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{\frac{1}{3}}} \propto \frac{E}{m^2}$$

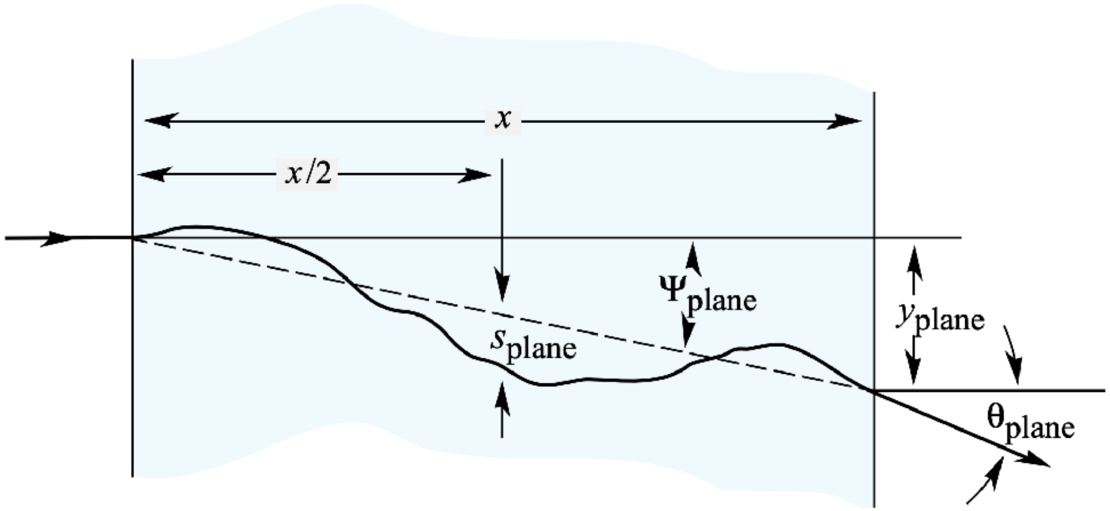
For electrons Bremsstrahlung dominates for E ≥ 8 MeV: $\frac{dE}{dx} = \frac{E}{X_0}$, $E(x) = E_0 e^{-\frac{x}{X_0}}$

Where the radiation length $X_0 = \frac{A}{4\,\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{\frac{1}{3}}}}$ g cm^{-2} $\propto$ A/Z^2 , for composite: $1/X_0 = \Sigma_j\, w_j/X_j$



* *Particle Data Booklet* *http://pdg.lbl.gov/2019/reviews/rpp2018-rev-passage-particles-matter.pdf* *and* *https://arxiv.org/pdf/1804.11246.pdf*

Charged particle passage in matter: multiple scattering (MS)



$$\theta_0 = \theta_{plane}^{rms} = \frac{1}{\sqrt{2}}\theta_{space}^{rms}$$

$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p}\, z\,\sqrt{x/X_0}\,\left[1 + 0.038\ln(x/X_0)\right]$$

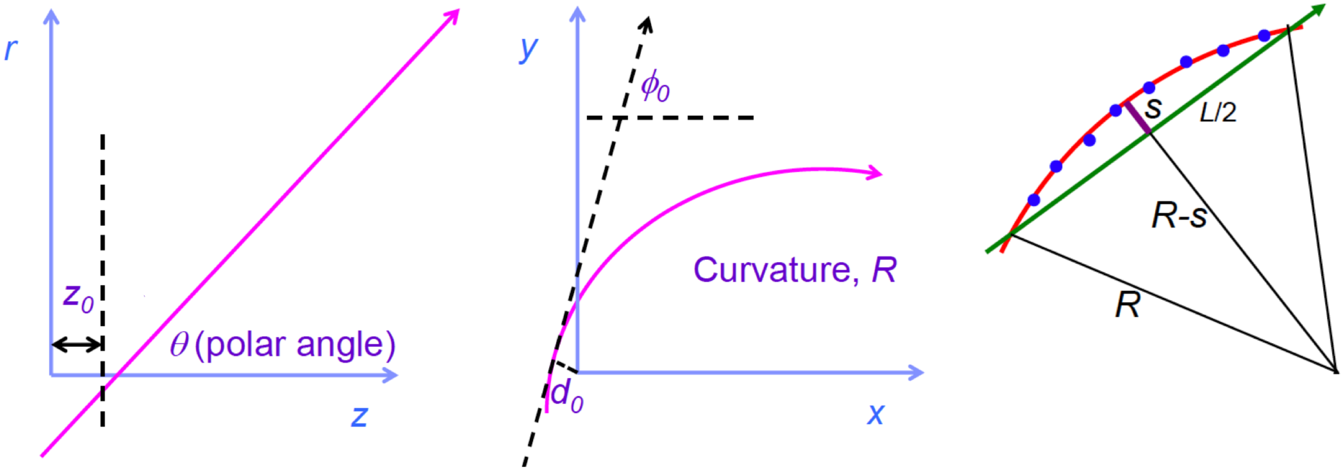
Multiple scattering is a limitation to trajectory measurement precision

Gaussian approximation sufficient for most application

Tracking systems design: momentum measurement in B-field

- Track parameters

  Transverse (xy) and longitudinal (rz) projections, Impact Parameters (IP) d_0 and z_0



- Transverse momentum
  - p_T (GeV/c) = 0.3 B(T) R(m)
  - $R = L^2/8s + s/2 \simeq L^2/8s$
  - L = path in B-field

Resolution[1)]: $\sigma(p_T)/p_T = 8p_T\sigma(s)/0.3BL^2$

With N equally spaced points of resolution $\sigma(r\Phi)$: $\sigma(s) = \sqrt{(720/(N+4))} \cdot \sigma(r\Phi)/8$ (Gluckstem formula)

$\sigma(r\Phi)$ has a constant term from intrinsic precision + a multiple scattering term $\propto 1/(p_T \sin^{1/2}(\theta)) \sqrt{(L/X0)}$

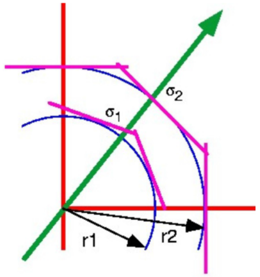
$$\sigma(p_T)/p_T = ap_T \oplus b/\sin^{1/2}(\theta)$$

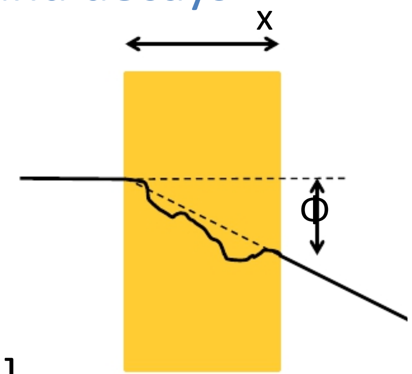
Where a depends on $1/BL^2$, number of layers & intrinsic resolution and b depends on B, L number of X_0

1) *Detectors are aligned with muons (from collisions and cosmic) and measured field MAP is corrected from mass measurements (ex. J/Ψ)*

Tracking systems design: transverse (longitudinal) IP resolution

- Track origin resolution determines quality of association to collision vertex and decays





  - Geometry term: $\sigma^2_{geom.}(d_0) = [(r_1\sigma_1)^2 + (r_2\sigma_2)^2]/(r_2 - r_1)^2$
    - r_1 - r_2 and σ_1/σ_2 inner/outer radii and hit resolutions
  - MS term: $\sigma^2_{MS}(d_0) = \Sigma^n_j (r_j\,\sigma(\Phi))^2$, n number of layers
    - $\sigma_j(d_0) = r_j\sigma(\Phi) = (r/\sin(\theta)p)13.6(MeV)\sqrt{(x/\sin(\theta)\,X_0)}\,[1 + 0.38 \log (x/\sin(\theta)X_0)]$
      - x layer thickness, X_0 radiation length θ track polar angle, Φ scattering angle

Transverse IP resolution: $\sigma(d_0) \simeq a \oplus b/p_T \sin^{1/2}(\theta)$

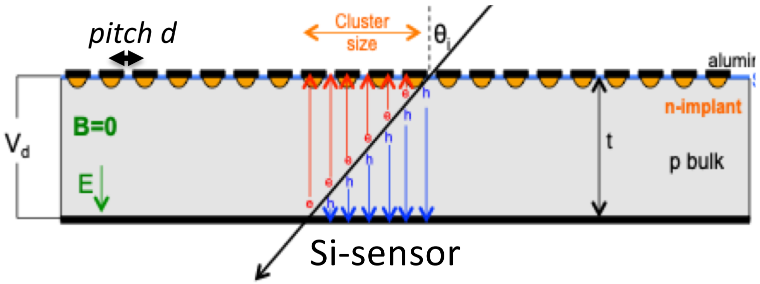
Constant term depends only on geometry, multiple scattering term depends on material, transverse momentum and pseudo-rapidity η[1)]

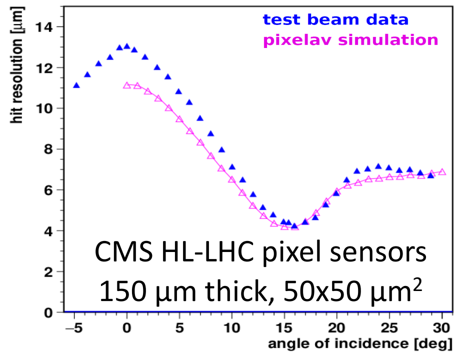
σ(d_0) is driven by the vertex detector performance (Si-pixel detector)

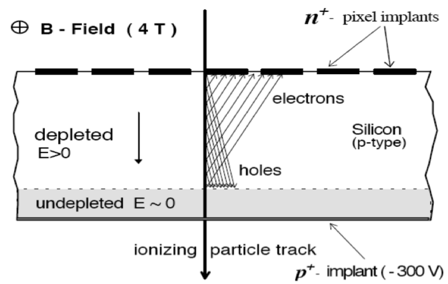
1) η = -log [tan(θ/2)]

Tracking systems design: hit position resolution

- Intrinsic resolution is driven by channel pitch, charge sharing across channels, and Signal to Noise ratio (S/N)
  - In binary readout (no amplitude measurement) position is given by the center of the channel or 1/2 depending on cluster size, eg number of channels with S/N above threshold: $\sigma(x) = d/\sqrt{12}$ to $d/2\sqrt{12}$
  - In digital readout position can be weighted with signal amplitude: $\sigma(x) \propto 1/(S/N)$





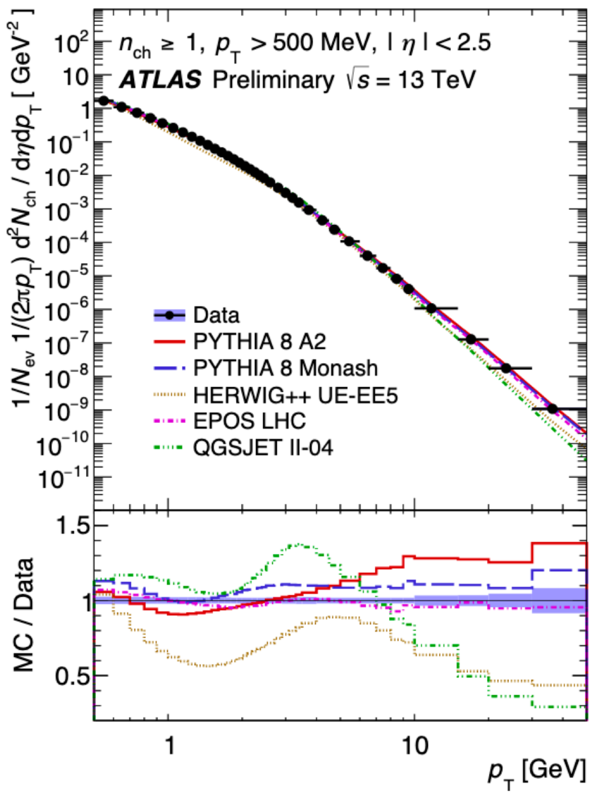


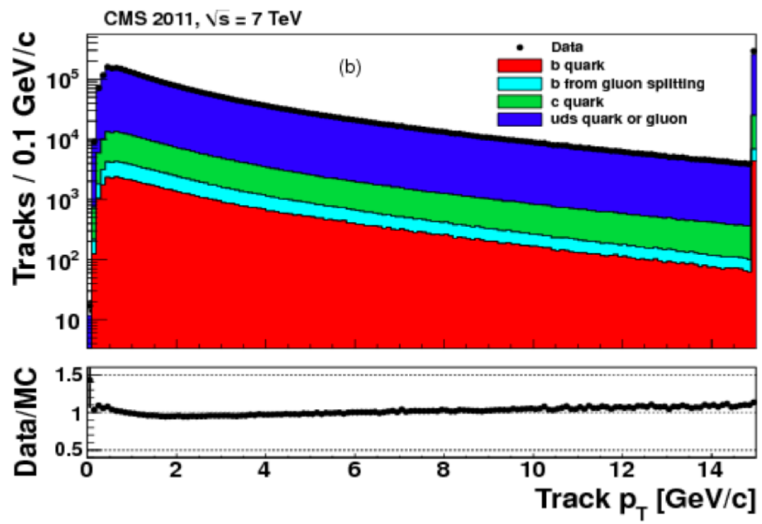
Charge sharing depends on diffusion1) in sensitive element, S/N2), incident angle and B-field,
Resolution3) optimization is a compromise in layer thickness, pitch and configuration parameters4)
It should also consider 2-tracks separation, requiring thorough simulation and measurements

1) Diffusion $\sigma = \sqrt{(2Dt_d)}$, t_d drift time, $D = \mu\, kT/q$ → $\sigma \simeq 8$ μm for 300 μm thickness
2) *S/N degrades with irradiation and cross-talk effect should be considered*
3) *Ultimate resolution is also limited by δ-rays emission that shift center of gravity (favoring small thickness but allowing lower diffusion),*
4) *Compensating or not Lorentz angle in B-field and/or tilting modules compared to ⊥ incidence*

Tracking system design: physics parameters

Measuring low momentum tracks is important for hard scatter vertex and for pile-up mitigation

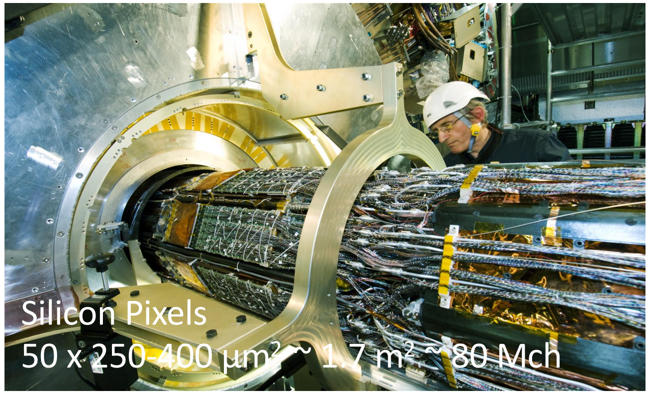


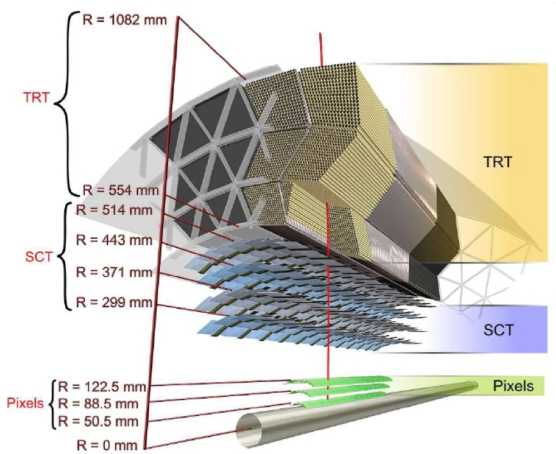


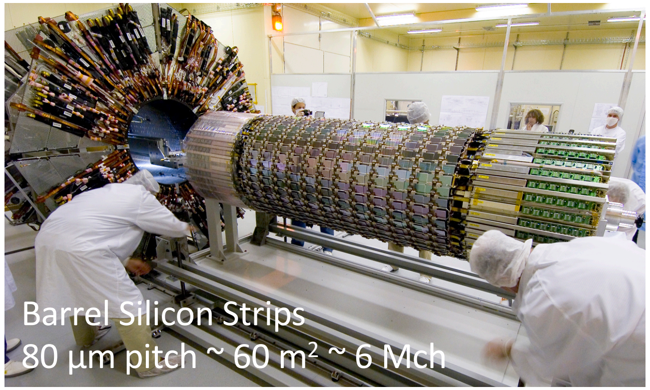
Current trackers: ATLAS and CMS examples

ATLAS

36 TRT 4 mm straws precision ≃ 120 - 140 μm, 4x2 Si strips layers precision ≃ 120 - 140 μm



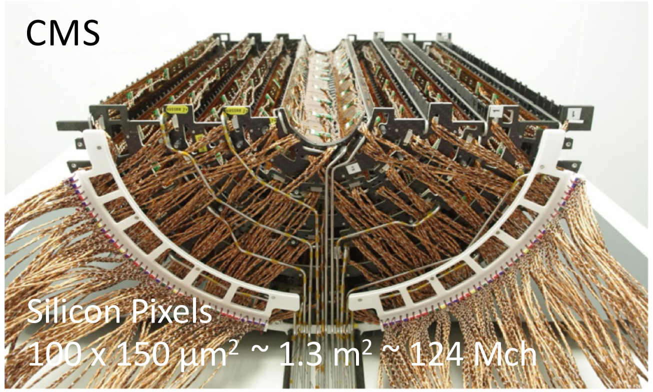


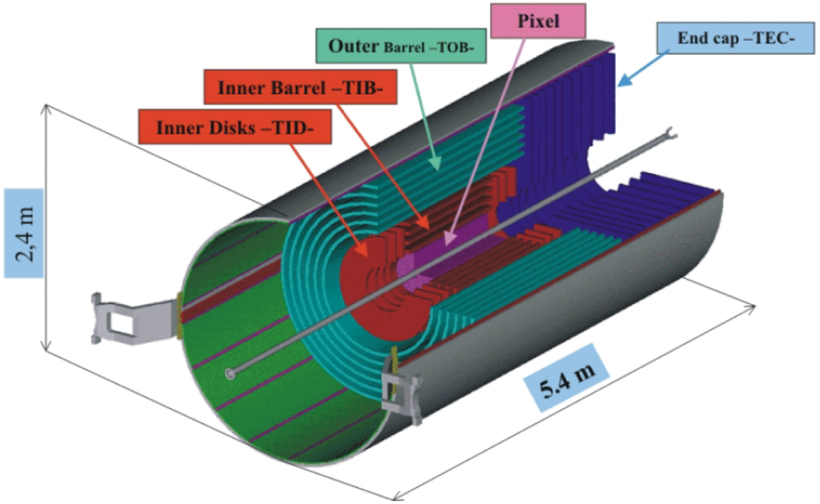


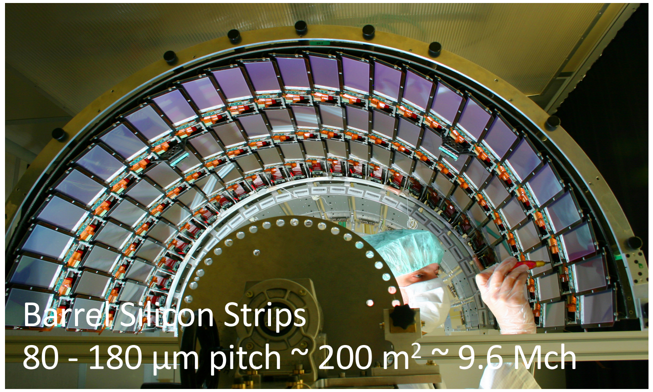
4 barrel layers and 3 disks
precision ≃ 10 -15 μm

10 x 2 barrel layers and 9 disks
precision ≃ 20 - 30 μm

CMS



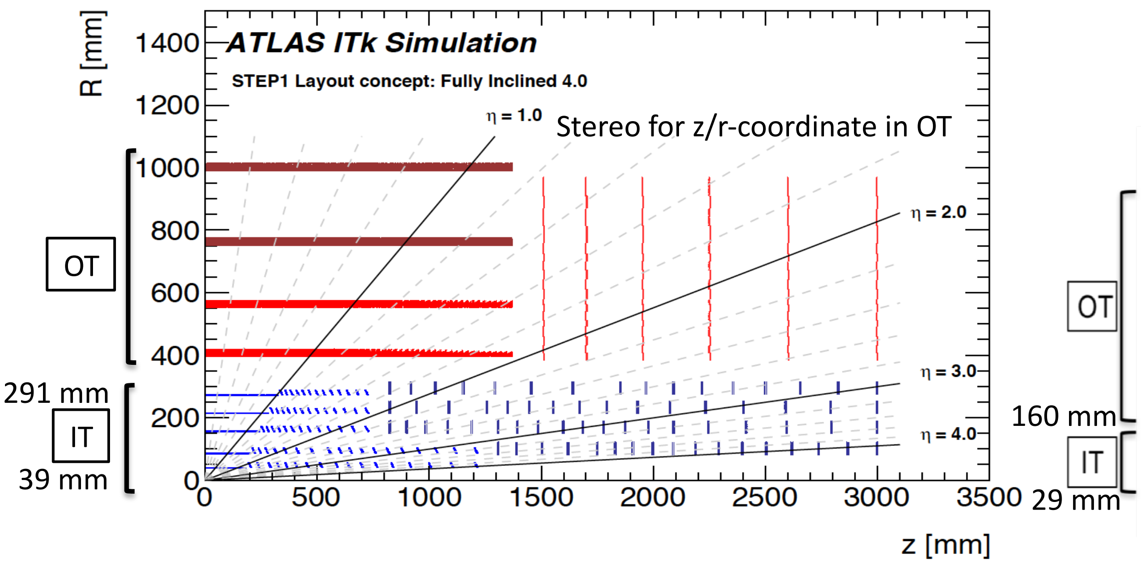


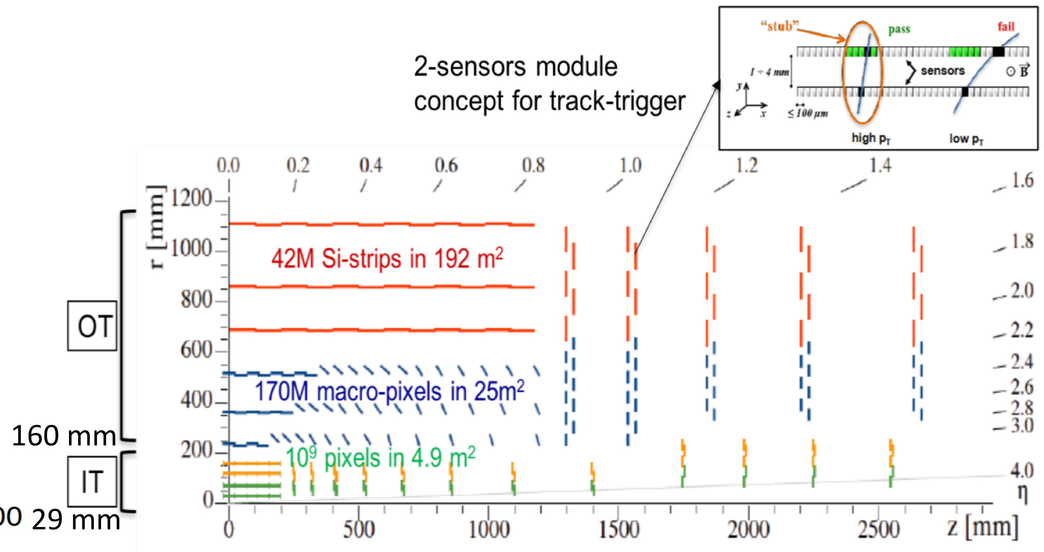


Future Silicon trackers: ATLAS and CMS optimizations at HL-LHC

Overall configuration drivers

- Both trackers extend Inner Tracker pixel (IT) coverage up to η ≃ 4 for VBF-H and VBS physics
- ATLAS has a 5 layers barrel pixel detector
  - Should optimize IP resolution (depending on MS), and also improve two track separation
- CMS has a design to provide Outer Tracker (OT) track parameters in hardware trigger at 40 MHz
  - Possible thanks to the high B-field, requires a pixelated layer close enough to the beam for z-coordinate measurement, but prevents a 5th pixel barrel layer
- Inner pixel layers are replaceable both in ATLAS and CMS



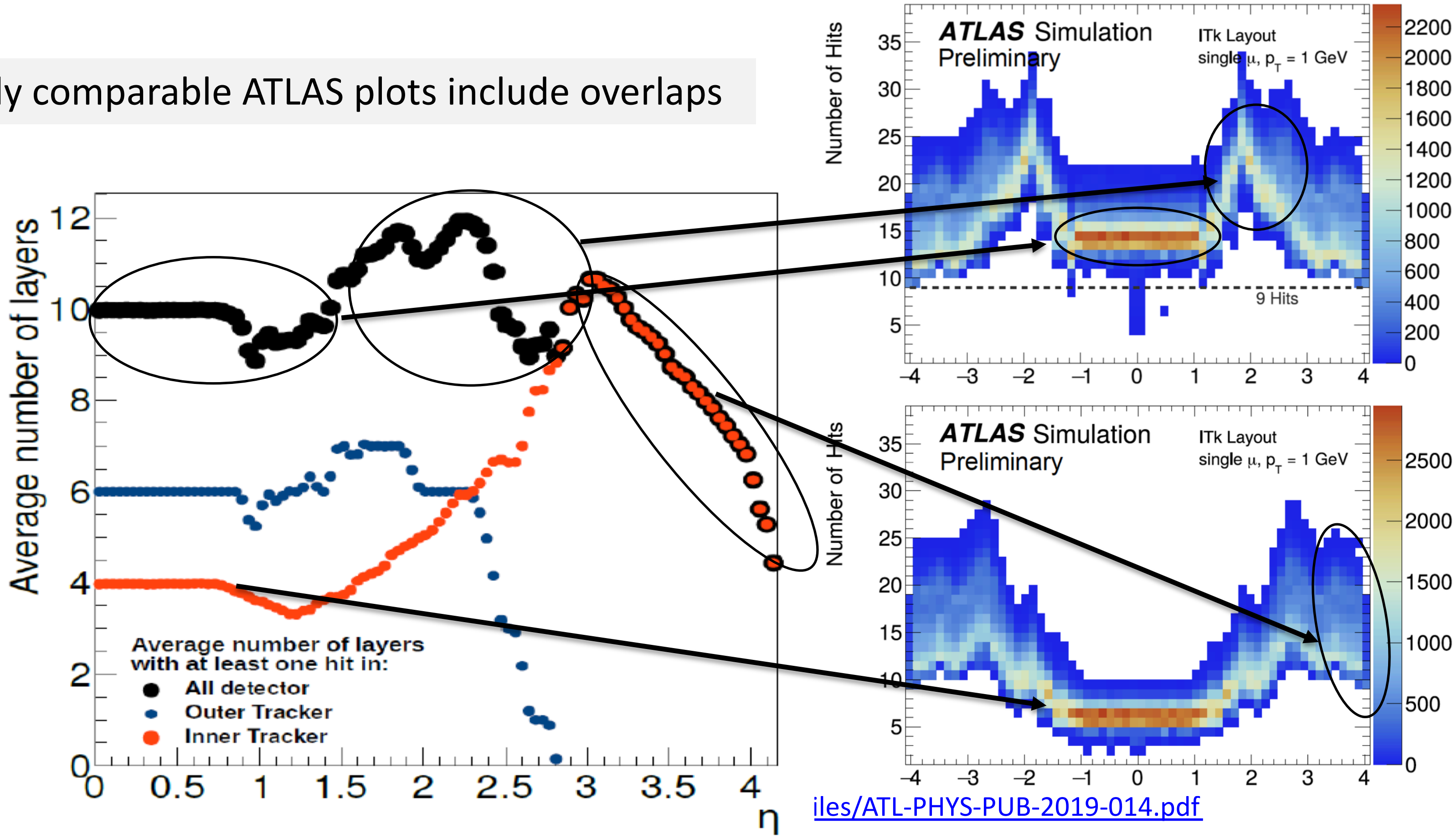


Future Silicon trackers: ATLAS and CMS optimizations at HL-LHC

Main configuration parameters

- Number of hits per track: the figure of merit is the efficiency, including redundancy

Not fully comparable ATLAS plots include overlaps



total

Pixels only

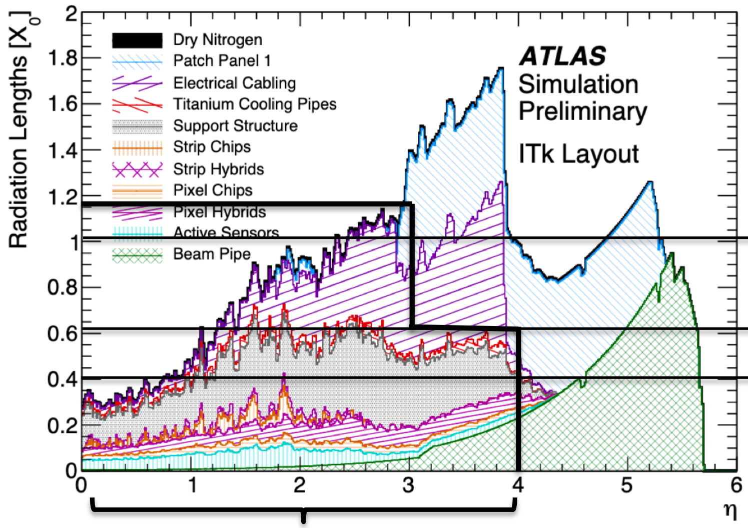
iles/ATL-PHYS-PUB-2019-014.pdf

Future Silicon trackers: ATLAS and CMS optimizations at HL-LHC

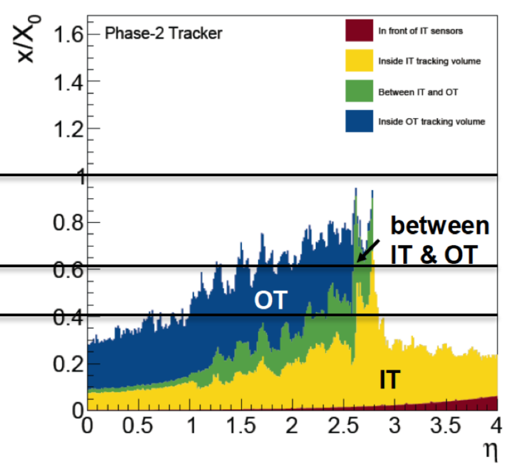
Main configuration parameters

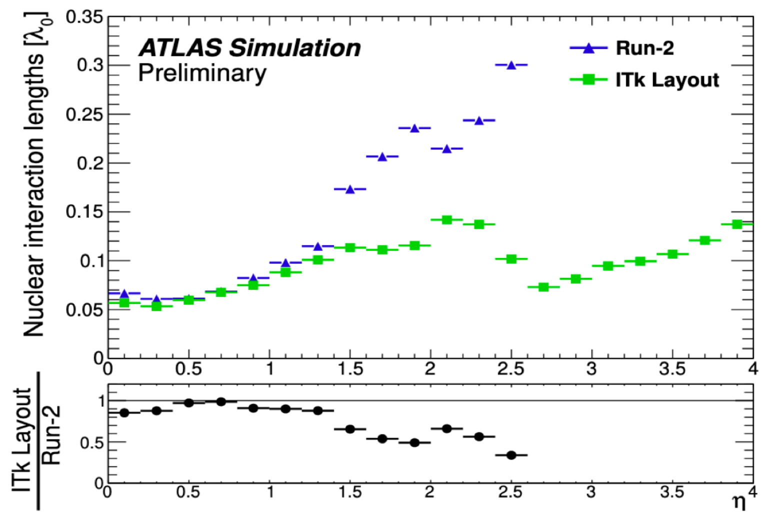
- Detector weight: divided by 2, with less layers, lighter mechanics, tilted modules in forward regions, new CO_2 cooling, DC-DC powering to reduce cable material and better arrangement of services, figures of merit:
  - Low fraction of radiation length reduce MS, γ-conversion and e-bremsstrahlung
  - Large interaction length reduce hadron interaction rates

CMS seems to have slightly lower X/X_0 (particularly in endcaps)



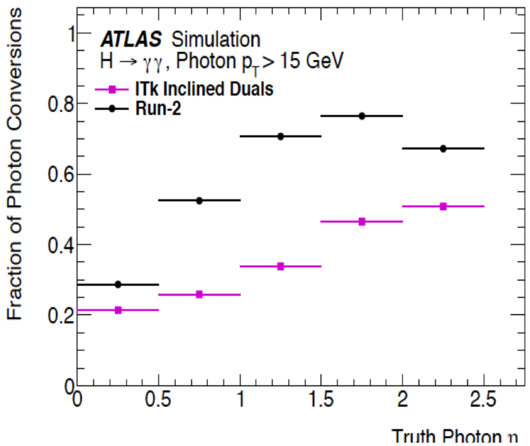
Tracker acceptance volume

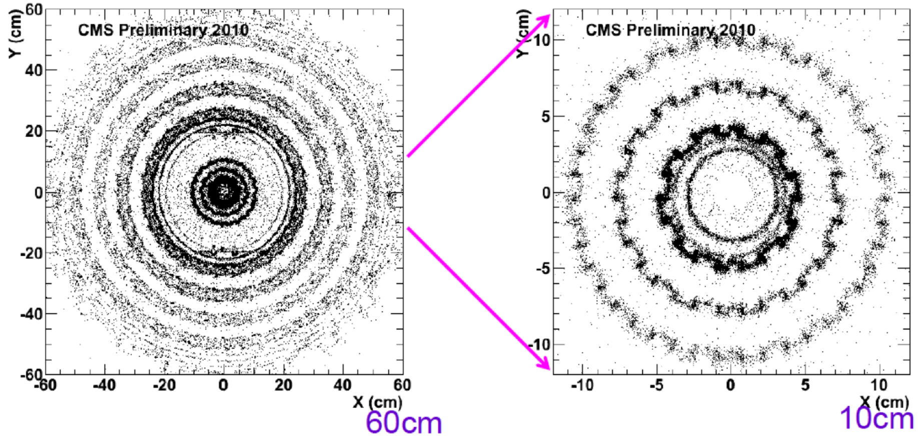


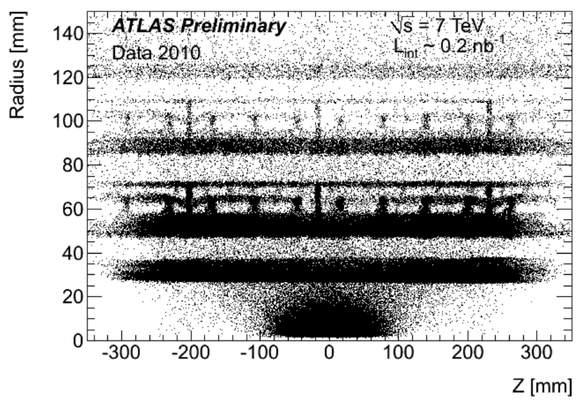


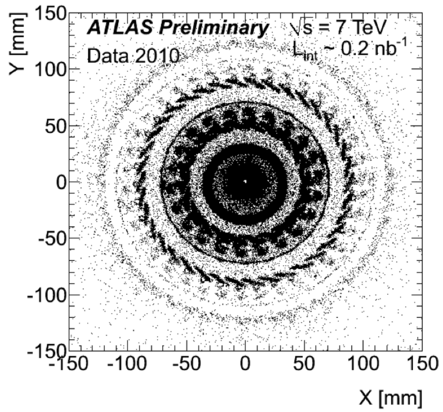
Future Silicon trackers: ATLAS and CMS optimizations at HL-LHC

- Detector weight:
  - Thorough weighting of parts and registration of material at construction needed for simulation
  - Photon conversion and hadron interaction radiographies from data allow to correct description



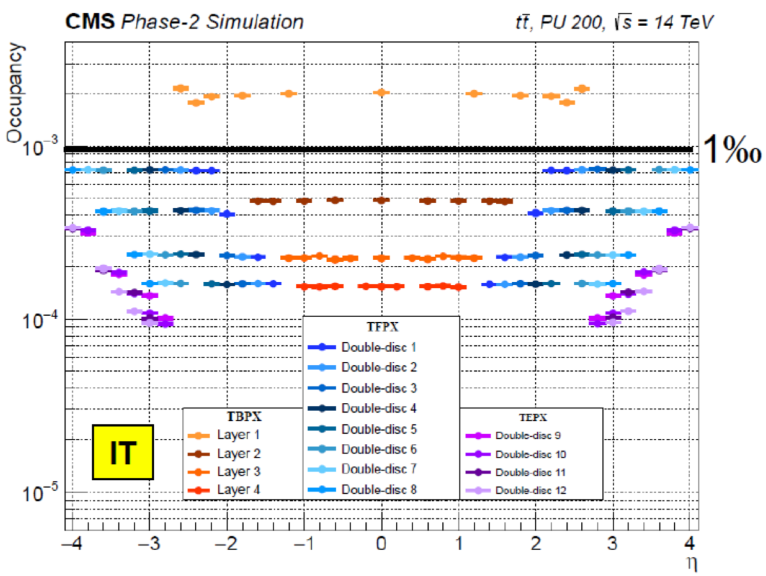


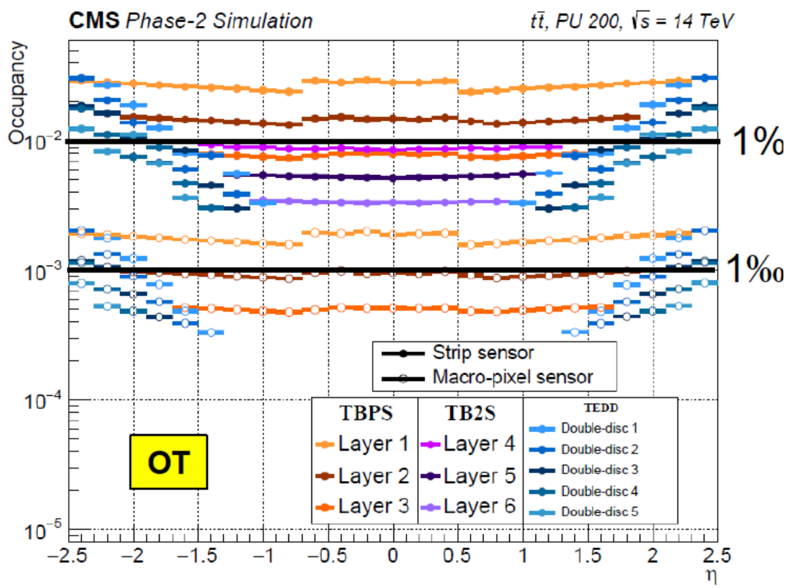




Future Silicon trackers: ATLAS and CMS optimizations at HL-LHC

- Sensor parameters: the figure of merits are hit occupancies and resolutions
  - Number of channels has been increase by ≃ 4 to 6 x present trackers[1)]
    - Pixel sizes ≃ 25 x 100 μm², 100 - 150 μm thickness
    - Strip pitch ≃ 75 to 90 μm and length ≃ 2.5 to 5 cm length (likely 290 μm thickness)
    - n-in-p and 3D sensors, radiation tolerance up to NIEL ≃ 2 x 10^{16} 1 MeV neq/cm² and TID of 1 Grad



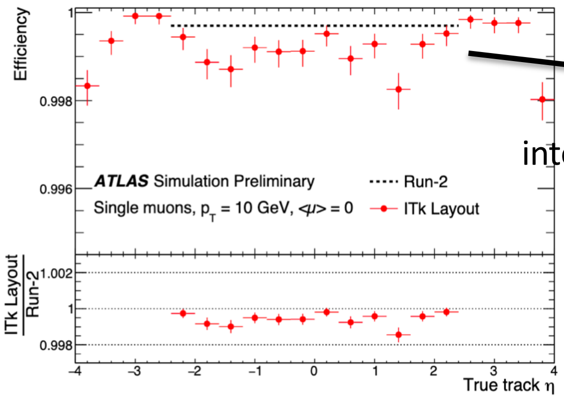


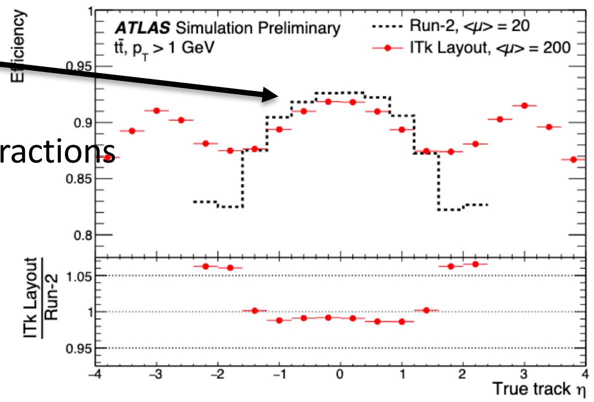
1) High # of channel is more a density and power issue in FE electronics than a data bandwidth issues with zero suppression in FE

Future Silicon trackers: ATLAS and CMS optimizations at HL-LHC

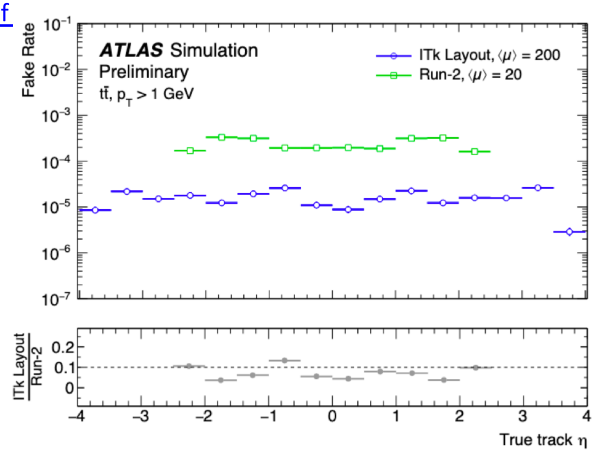
- Performance criteria: efficiency and fake rate

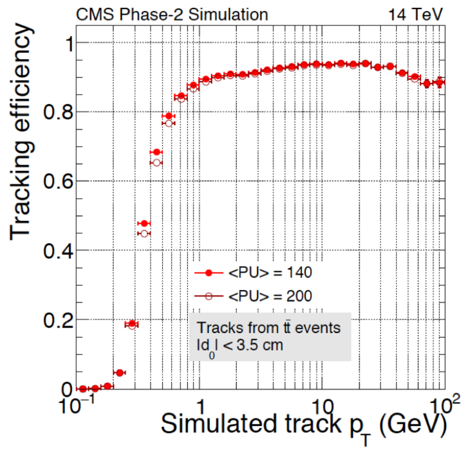
https://cds.cern.ch/record/2669540/files/ATL-PHYS-PUB-2019-014.pdf

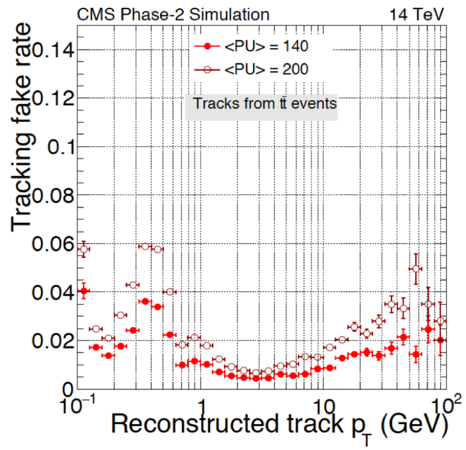




interactions



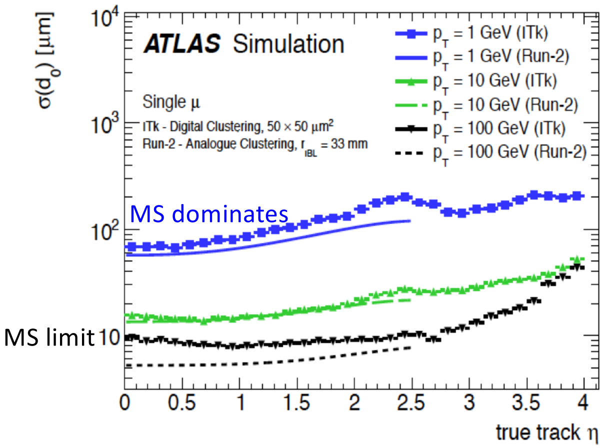


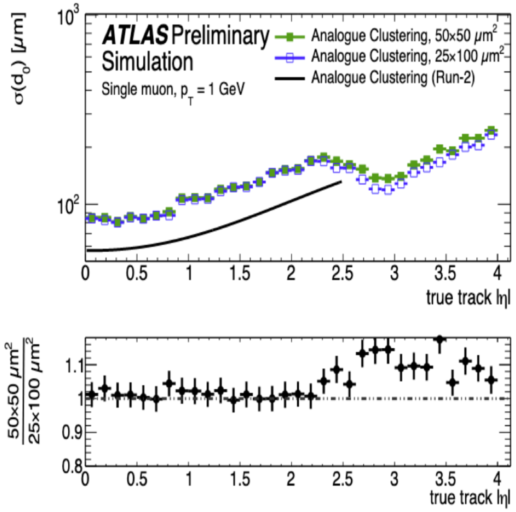


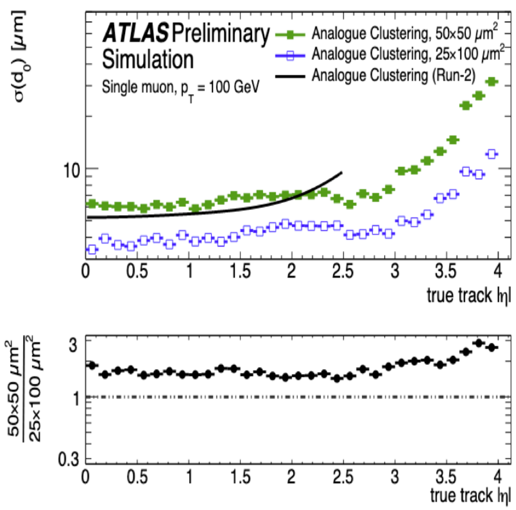
https://cds.cern.ch/record/2272264/files/CMS-TDR-014.pdf

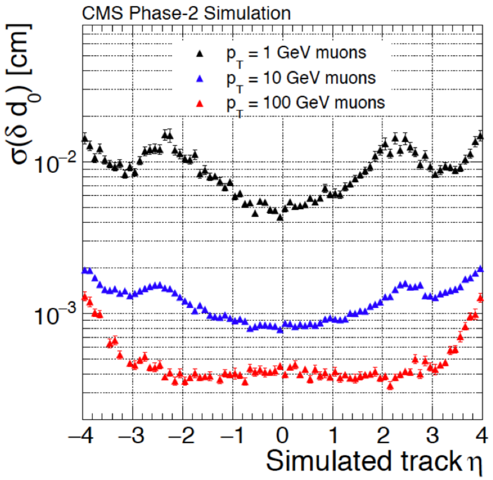
Future Silicon trackers: ATLAS and CMS optimizations at HL-LHC

- Performance criteria: transverse Impact Parameter resolution
  - ATLAS studies:
    - Smaller radius of first layer dominates geometry factor compared to benefit of 5th layer
    - ≃ GeV track resolution is dominated by MS[1)]
    - Digital clustering is beneficial compared to binary mostly at high p_T
    - 25 x 100 μm² form factor is better than 50 x 50 μm²





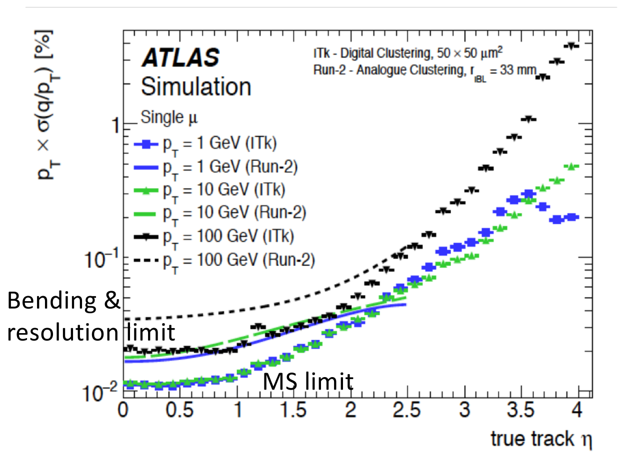


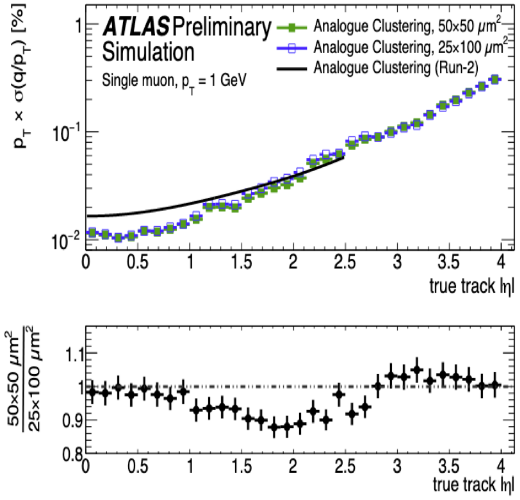


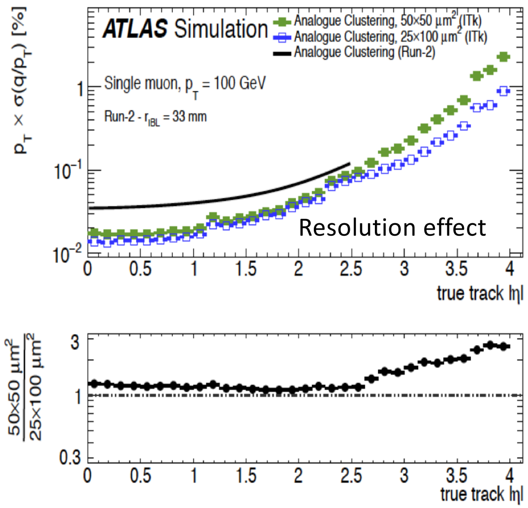
1) *Jet tracks are in the range 1 -10 GeV, similar behavior in longitudinal direction with slightly smaller performance due to angle and MS*

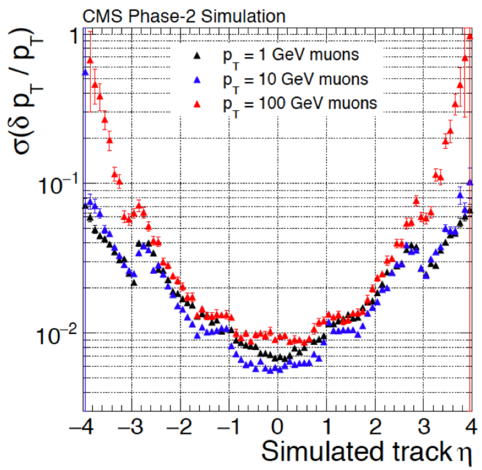
Future Silicon trackers: ATLAS and CMS optimizations at HL-LHC

- Performance criteria: p_T resolution
  - ATLAS studies:
    - $\sigma(p_T)$ up to > 10 GeV dominated by MS
    - $\sigma(p_T)$ 100 GeV sensitive to resolution





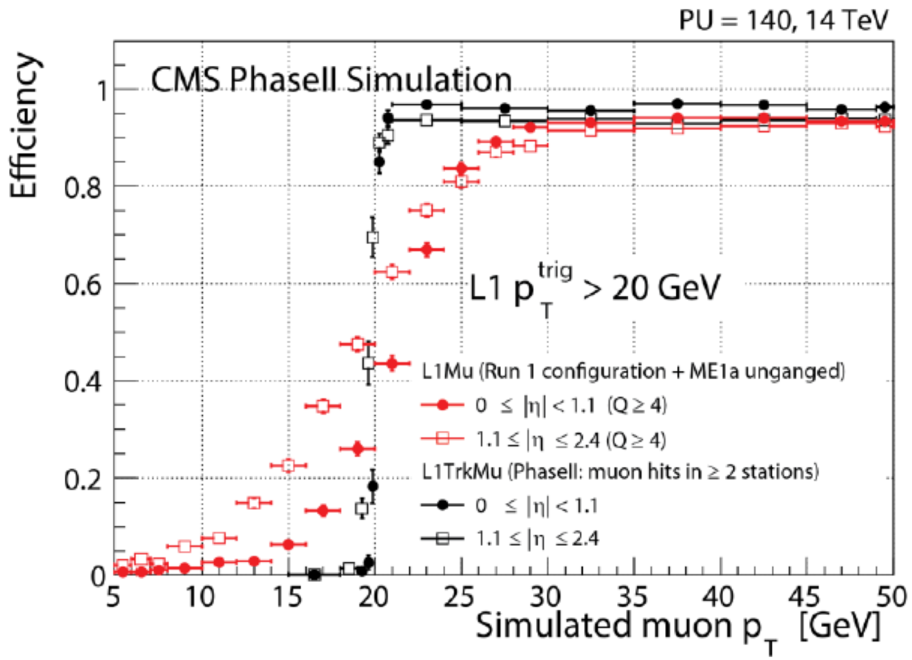


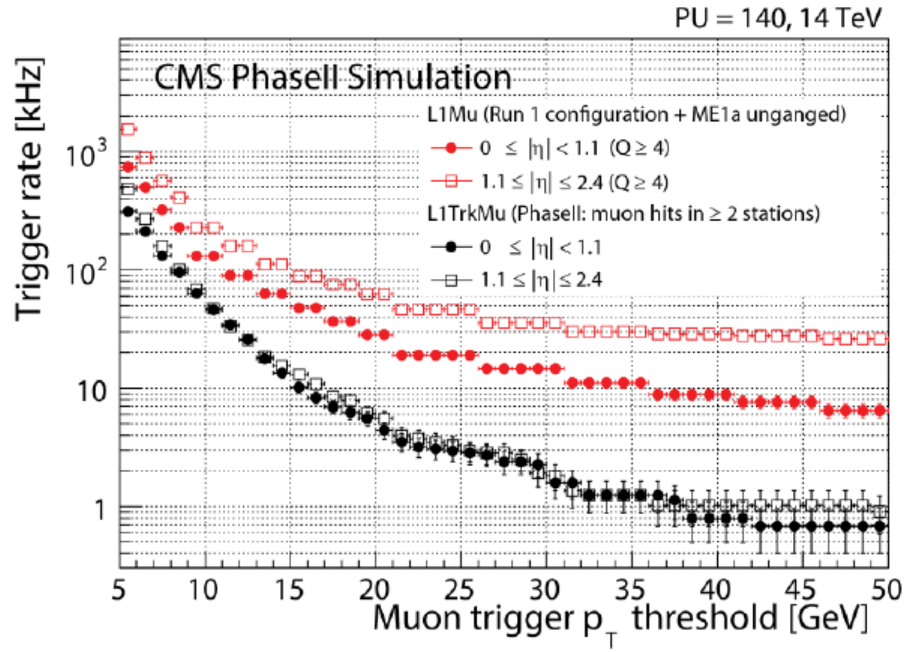


CMS has a better $\sigma(p_T)$ due to higher B-field

Future Silicon trackers: CMS Track Trigger

Example of efficiency and background rate reduction for a muon trigger threshold at 20 GeV

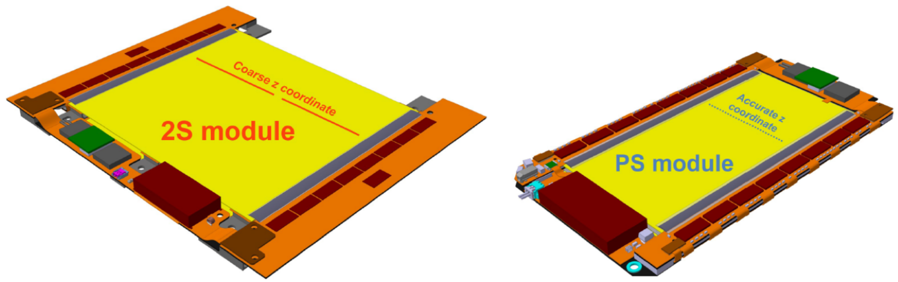




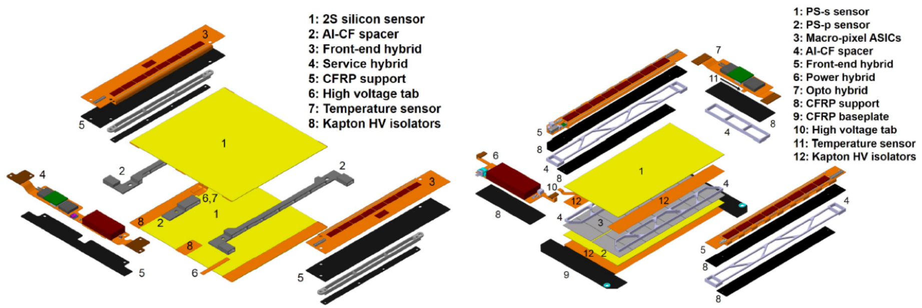
Future Silicon trackers: CMS HL-LHC OT modules example

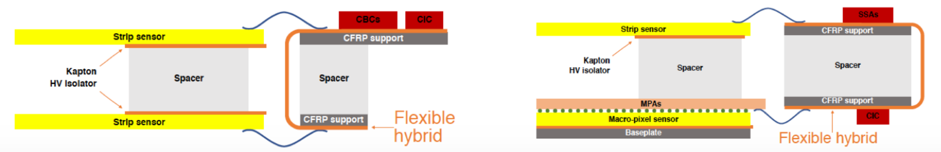
Two types of modules: < 50 g, power consumption
FE 20(50) ns peaking(full) time, 0.5 mW/channel
Total cooling power (-35°): 100(50) kW Outer(Inner) Tracker

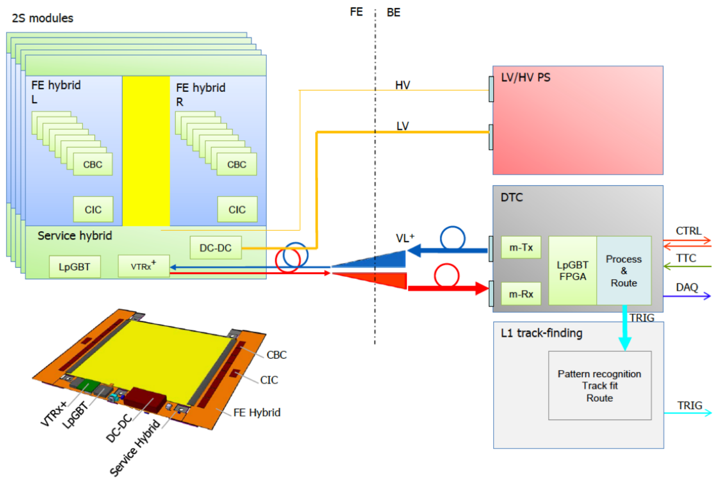
Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	7680
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	5616
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		**2872**	**4464**	**5960**	**13296**	



2S module		PS module	
$\sim 2 \times 90$ cm^2 active area		$\sim 2 \times 45$ cm^2 active area	
2×1016 strips:	~ 5 cm $\times$ 90 μm	2×960 strips:	~ 2.4 cm $\times$ 100 μm
2×1016 strips:	~ 5 cm $\times$ 90 μm	32×960 macro-pixels:	~ 1.5 mm $\times$ 100 μm
Front-end power ~ 5 W		Front-end power ~ 8 W	
Sensor power ($-20\,°$C) ~ 1.0 W		Sensor power ($-20\,°$C) ~ 1.4 W	







Future Silicon trackers: next colliders performance target

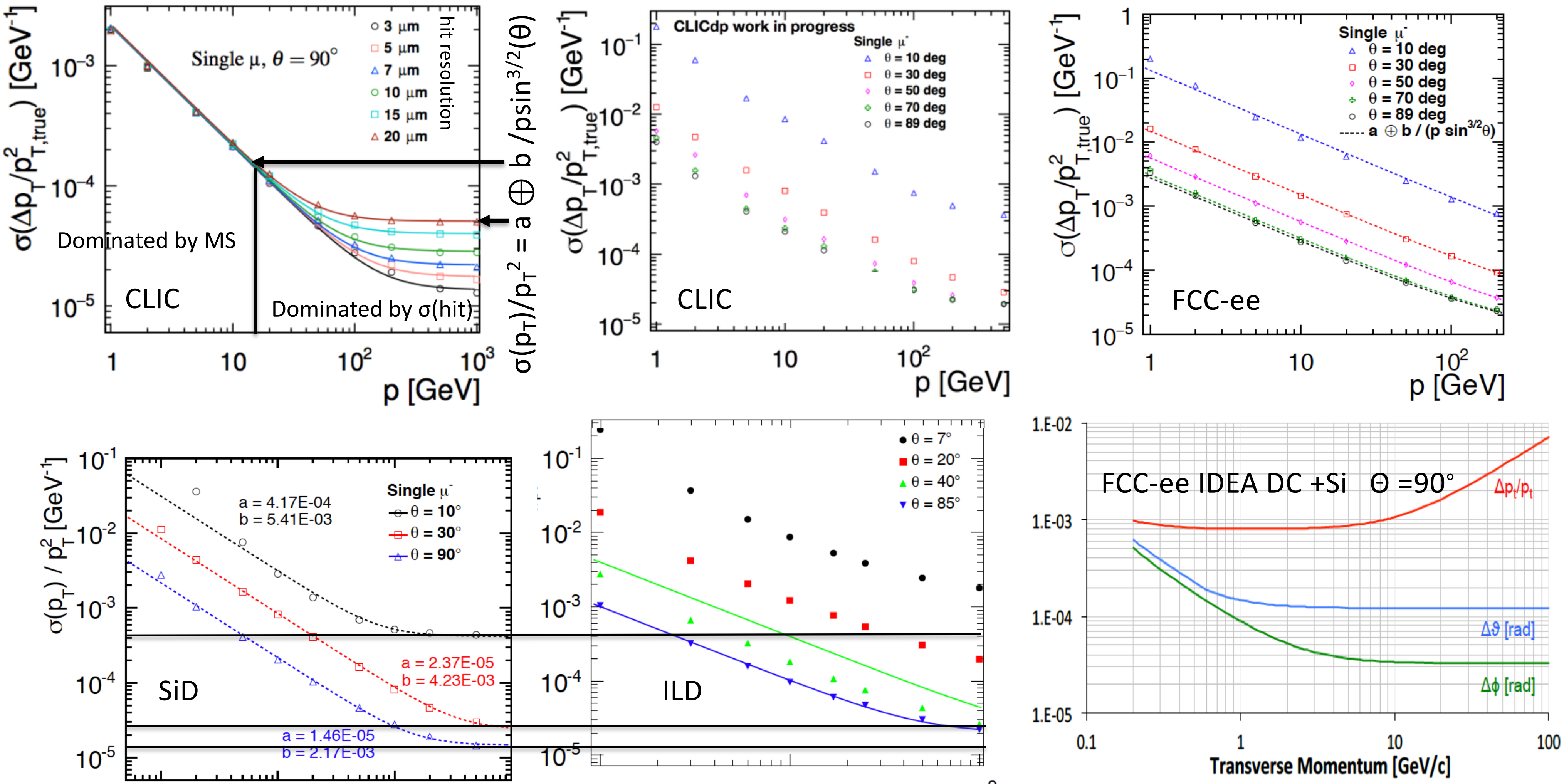
- e-e experiments (ILC/CLIC/FCC-ee/CepC): track P_T and Impact Parameter resolutions ≃ /5 LHC
    - $\sigma(p_T)/p_T^2 \simeq 3 \times 10^{-5}\ GeV^{-1}$ ($p \leq 100$ GeV)
    - $\sigma(d_0)/d_0 \simeq$ 2/3-5/10-20 μm (100/10/1 GeV at 90°)
  - R&D challenge
    - ≃ 3 μm hit resolution with ≃ 0.2 % X_0 per layer in pixel vertex detector
- h-h experiments FCC-hh/SppC need similar detectors
    - Resolutions ≃ x 2 e-e (due to larger inner layer radius (rates/radiation) and mass (power/cooling))
  - Additional R&D challenge
    - Hit rate readout capability ≃ 30 GHz/cm² in inner pixel layer
    - Current technology would not survive R ≤ 30 cm for radiation tolerance

Future Silicon trackers: next colliders concepts

	Tracker parameters / experiments	ILD-ILC	SiD-ILC	CLICdet-CLIC	CLD-FCC-ee	IDEA FCC-ee/CepC	Baseline-CepC	FCC-hh (SppC)
Vertex pixel detector	Silicon: Planar, 3D sensors, HR/HV CMOS, hybrid/3D/SoI interconnection or monolithic readout							
	In/Out layer radius (mm)	16/60	14/60	30/60	17/60			25/200
	Number of layers/disks	3 x double layers	5/4	3x double-layers	Same as CLICdet			
	Thickness (µm)	50 to 100 (depending on elctronics)				Same as CLD	Same as ILD	50 to 100
	Pitch/cell size (µm x µm)	≤ 25 x 25						25 x 50 - 33 x 400
	Hit resolution (µm)	3						7
	(X0)/layer (%)	0.2			0.3			1
	$\sigma(\Delta d_0)$ (µm) (1/10/100 GeV)	10/3/2		20/5/2	20/5/2			30/10/5
	Max NIEL (1 MeV neq/cm^2)/TID (Mrad)	10^{11}/0.1	10^{11}/0.1	10^{11}/0.1	2 x 12^{12}/1			6 x 10^{17} / 30 x 10^{3}
Outer Tracker	Outer Tracker technologies	TPC[1)] + Si	Si	Si	Si	DC[2)] + Si	Si	Si
	Layer/Outer radius (mm)	153/300/1800	1200	1500	2100	2000		200/1600
	Number of layers/disks (IT/OT)	2/1 double Si inner/outer TPC	5/4	3+3/7+4	same as CLICdet	12 layers 1 cm^2 x 1.2 m	Same as ILD	
	Transverse pitch (µm)	50						33
	Transvers hit resolution (µm)	7				100		10
	X0/layer (%) (Barrel)	1				1.6 (total)		2/2.5
	$\sigma(\Delta p_T)/p_T^2$ (GeV^{-1}) (< 100 GeV, 90°)	2-3 x 10^{-5}						5 x 10^{-5}
	Min NIEL (1 MeV neq/cm^2)/TID (Mrad)							5 x 10^{15} / 10
	Time integration window	0.5 - 5 µs	0.5 - 5 µs	5 ns	1 µs	1 µs	1 µs	25 ns

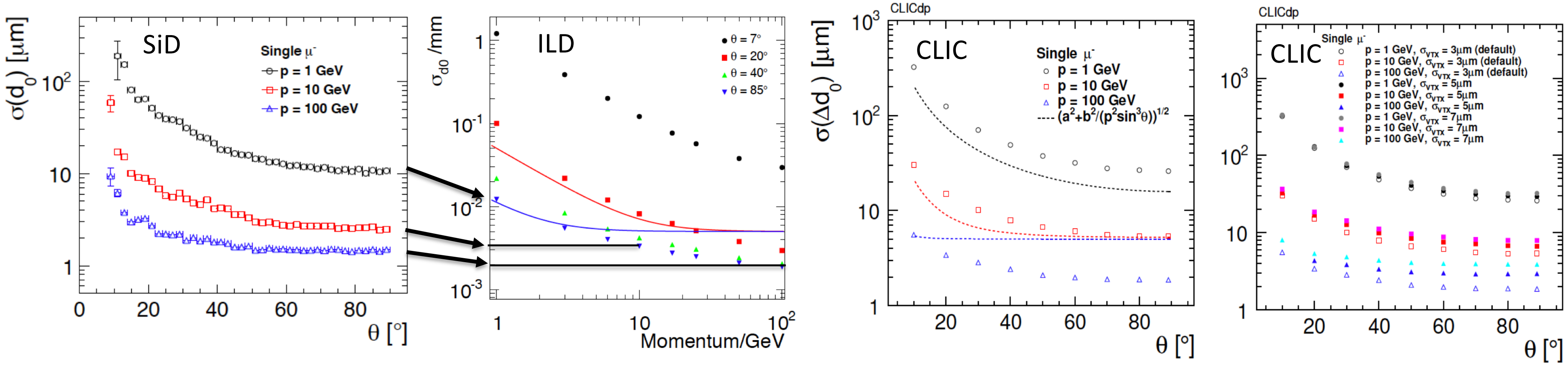
1) *Number of hits in TPC ≃ 225 with expected resolution of ≃ 150 µm*
2) *Number of hits in DC ≃ 122 with expected resolution of ≃ 100 µm*

Future Silicon trackers: e-e collider performance simulations



TPC(DC) + Si seems to do slightly better than full Si for MS (small p_T)

Future Silicon trackers: e-e collider performance simulations



Impact parameter resolution is more sensitive to multiple scattering than intrinsic resolution

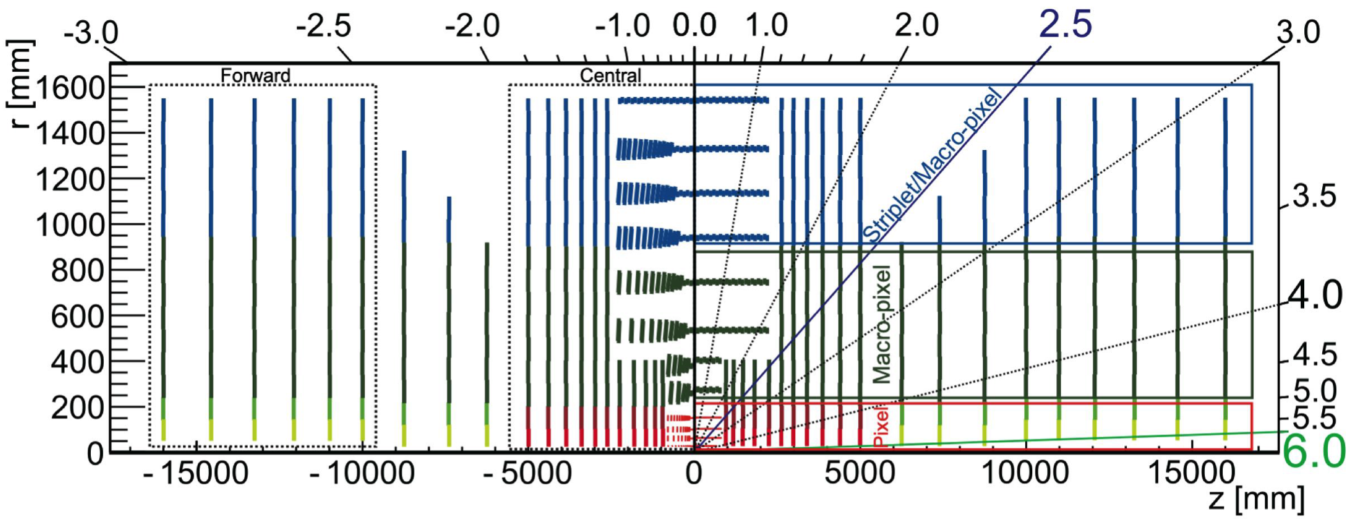
CLIC, ILD and SiD designs provide similar precision

At high momentum resolution seems better than expected from parametrization

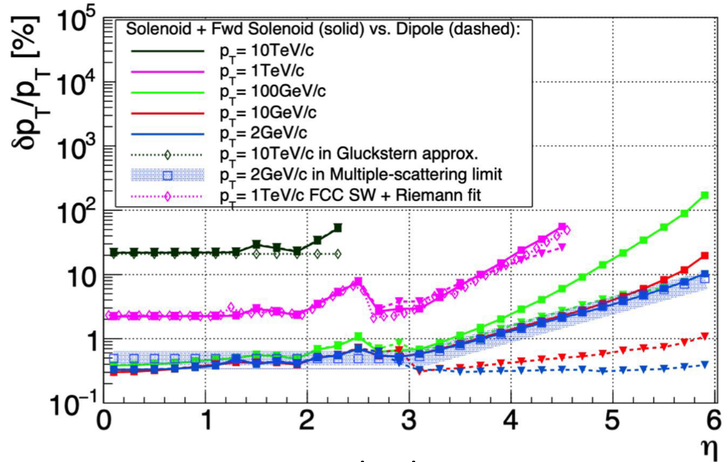
$$\sigma(d_0) \simeq a \oplus b/p_T \sin^{1/2}(\theta) = a \oplus b/p\sin^{3/2}(\theta)$$

Future Silicon trackers: FCC-hh design proposal

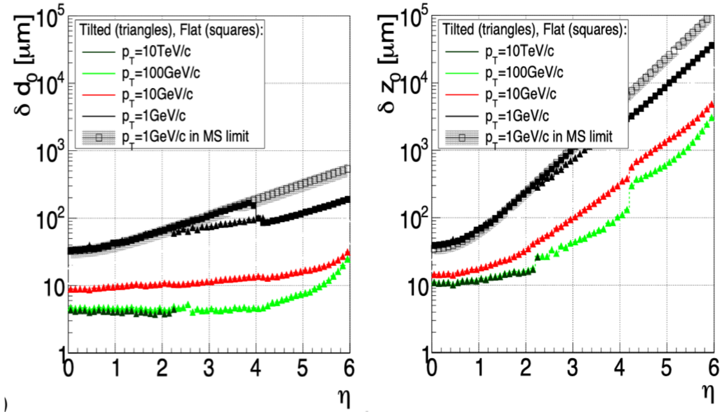
Φ = 3 m, L=2 x 16, $\eta_{max} \simeq 6$, $\simeq$ 400 m^2, 16 x 10^9 channels*, cell size 25 µm x 50 µm - 33 µm x 400 µm - 33 µm x 2-50 mm



$\delta p_T/p_T \simeq 0.5(2)\%$ at 0.1(1) TeV (η<2)



d_0 resolution of 5/10/30 µm at η= 0 for p_T = 100/10/1 GeV/c at 90°



- Cell size down to 25 x 50 µm in inner layers for low occupancy and $\simeq$ 5-10 µm hit resolution for 2-track separation in boosted objects
- Tilted design to minimize MS, conversions, interactions
- 10 GHz/cm^2, fluence $\simeq 10^{18}$ 1 MeV neq /cm^2 and $\simeq$ 30 GRad for 30 ab^{-1} at inner layer radius 2.5 cm

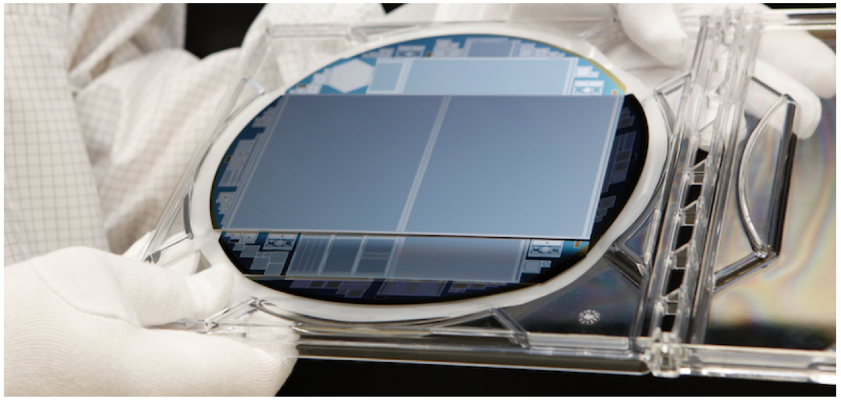
Current sensor and readout technologies would not sustain radiation for R < 40 cm, effective Pile-Up of $\simeq$ 50 would require $\simeq$ 5 ps Time of Flight precision**

** Compared to 6 x 10^9 and 2.2 x 10^9 for ATLAS/CMS Phase-II Trackers; ** Compared to 30-40 ps in ATLAS/CMS HL-LHC MIP Timing Detectors*

Tracking systems: Silicon technology

Si-crystals semiconductor properties:

- Small energy gap 1.2 eV (between valence & conduction band), E (e-h pair creation)[1] $\simeq$ 3.6 eV
- High density 2.33 g/cm^3; dE/dx (MIP) ≈ 3.8 MeV/cm ≈ 106 e-h/μm (average)
- High carrier mobility: $\mu_e(\mu_h)$ =1450(450) cm^2/V.s,
  - v = μE, fast charge collection can go down to O(1) ns
- Material used in industrial process, relatively low cost



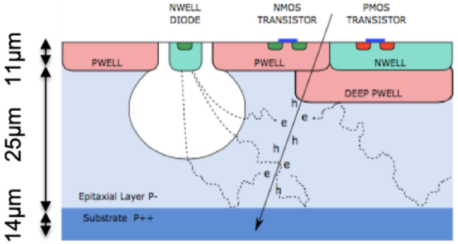
	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

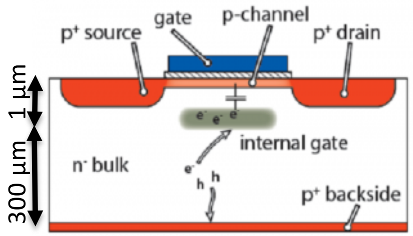
Alternative semi-conductors: Ge need cryogeny with liquid nitrogen at 77k, Diamond less signal and expensive

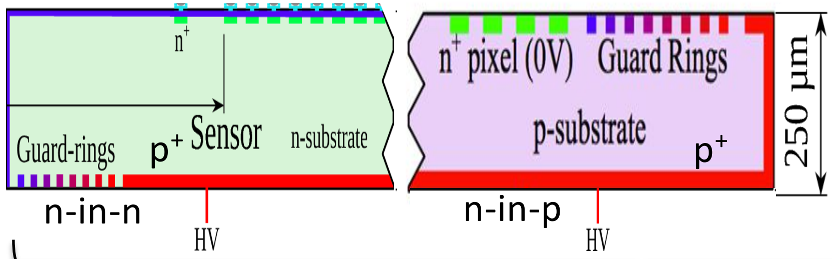
1) *$\simeq$ 30 eV LAr and 100 eV in scintillators*

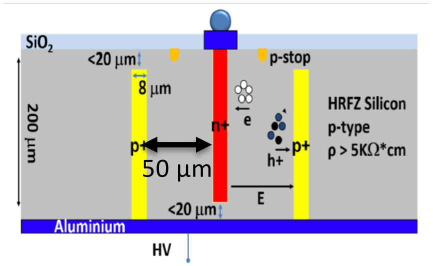
Tracking systems: Silicon sensors

Several Si-sensors types and design, differences are in depletion, electronic readout implementation and eventually in performance, hybrid designs much more radiation tolerant









CMOS and DepFET Monolithic Active Pixel:

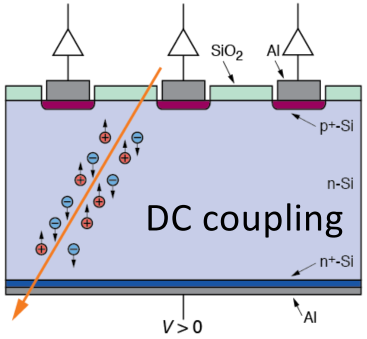
- Microelectronic process, collection electrodes readout with MOS electronics grown on substrate
- CMOS not depleted (no E-field) e^- are collected through diffusion, DepFET has some low voltage depletion
- Works for small pitch, thin sensors slow signal time integration

Hybrid design pixels/strips: planar and 3D

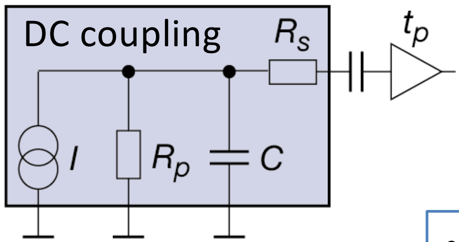
- More complex process (double sided) to allow depletion voltage
  - p/n doping (acceptors (B, …)/donors (P, As, …) allow to work as a p-n junction with reverser bias and full depletion of free carriers (noise)[1)]
- Electrodes connected to electronics through bump(wire) bonding in pixels(strips)

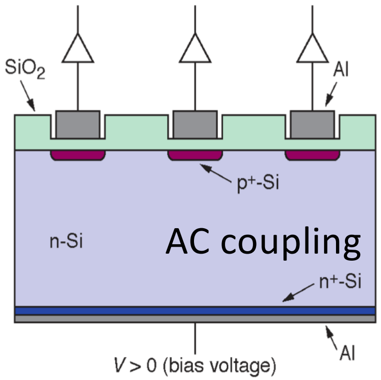
1) *$\simeq 10^4$ more free carriers in Si than MIP signal*

Tracking systems: Si-sensors electronic scheme and noise



Detector equivalent scheme





Noise: $ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$

- $ENC_C = a + b\,.C$ dominates total noise, $b \propto 1/\tau$ (integration time) and C electrode capacitance (proportional to size)
- $ENC_I = (e/2)\sqrt{(I_{leak}\tau/e)}$ leakage current noise becomes important after irradiation
- $ENC_{Rp} = (e/e)\sqrt{[kT\tau/2R_p]}$ (bias resistor)
- $ENC_{Rs} = 0395C\sqrt{(R_s kT/\tau)}$

e euler number, e electron charge

- DC coupling used for small size pixels/mini-strips (small C and I_{leak})
- AC coupling preferred for strips to avoid large I_{leak} (strips have also larger C)

Typical noise for Si-sensors today is ≃ 100(1000) e^- for pixels/strips

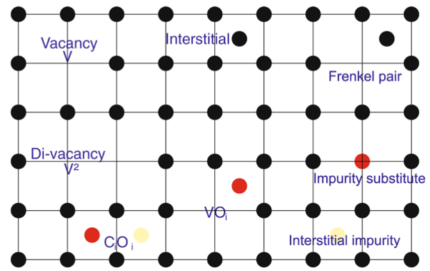
Choice of S/N threshold is an optimization of hit efficiency versus noise occupancy (bandwidth), a minimum of 1/5 of S is considered acceptable[1)2)]

1) *In pixels a higher threshold ≃ 10 x N is needed to contain absolute bandwidth*
2) *Precise timing measurements need higher S/N to reduce noise contribution to resolution*

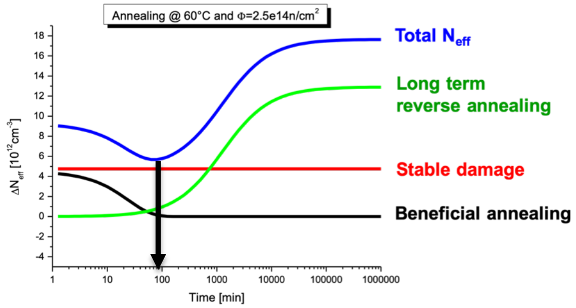
Tracking systems: Si-sensors irradiation effects

Irradiation introduces default in the crystal lattice that reduce signal and/or increase noise

- Mostly displacement of Si-atoms and doping modification (affecting band gap levels) result in:
  - Increased leakage current[1), and therefore noise
  - Modified doping concentration mostly toward p-type, requiring V_d increase
  - Creation of trapping[2) centers that captures electrons and holes, reducing Charge Collection Efficiency, the most critical effect at high irradiation level



- Surface damage (SiO_2 layer) that do not affect CCE but can create operation issues
  - Typically solved with design features
- Annealing decrease I_{leak} and allows diffusion of defaults/change of doping but beneficial annealing is followed is by reverse annealing



Operation optimizations

- Temperature as low as possible, annealing scenarios during maintenance

Sensor optimizations[3)

- n-in-p (p-type bulk) collect electrons (less trapping), avoid some micro discharges creating noise
  - ATLAS, CMS and LHCb choice for LHC upgrade
- Thinner sensors (deep signal is not collected), reduce V_{bias} and I_{leak} and allow higher electric field
- Material and fabrication process details are important

1) *I_{leak} varies exponentially with Temperature x 2 every 7°, hence operation at low temperature for noise and also to avoid thermal runaway*
2) *Trapping is characterized by collection time → prefer electron collection (faster), and higher electric field*
3) *Non-Ionization Energy Loss concept do not fully apply at highest irradiation, requiring thorough testing with all particles (n,p,γ)*

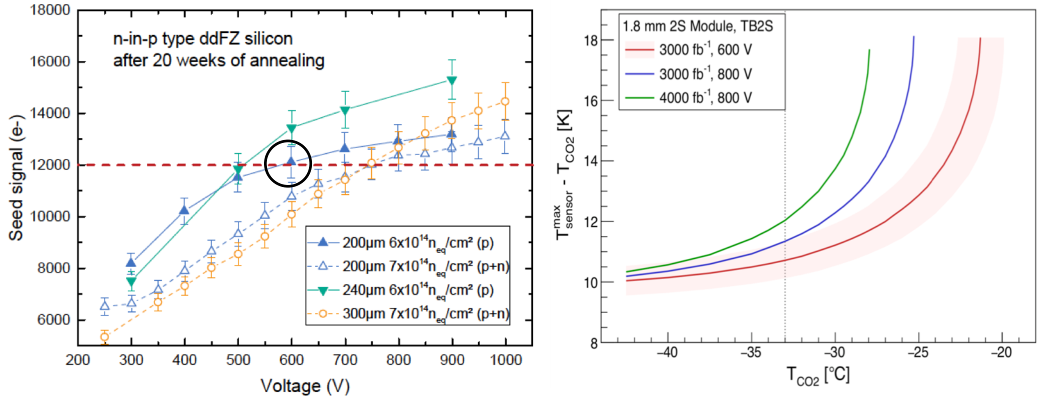
Tracking systems: Si-sensors Outer Tracker S/N (depleted case)

In Si-sensors with full depletion, charge collection efficiency before irradiation is ≃ 100%

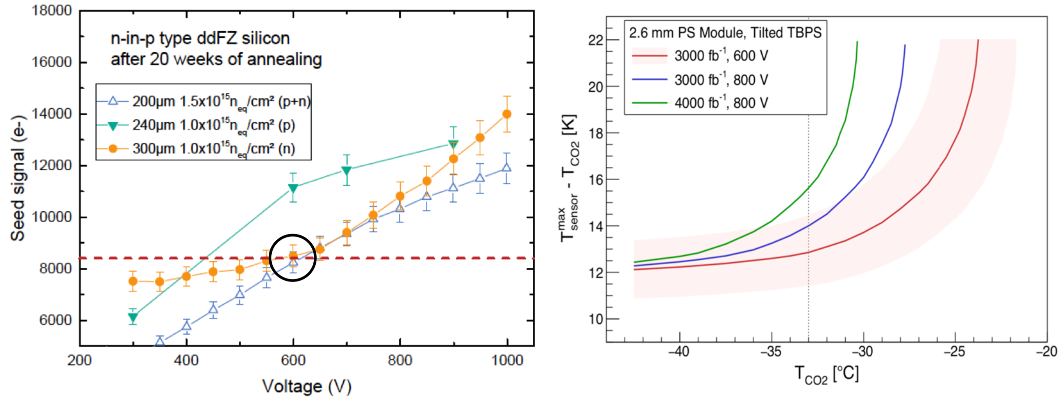
- Ex. 200 µm thickness: max probability(average) charge[1)] number is ≃ 14000(21200) e^-
- This allows comfortable S/N, typically ≥ 15 for all type of designs[2)]

Example of CMS at HL-LHC n-in-p sensors after irradiation

- S/N remains comfortable at 12 with sufficient margin, sensor specification to sustain 800 V to provide further margin, but would approach thermal runaway limit



2S strip sensors, S/N ≃ 12 at 2 x 3000 fb^{-1}



PS strip sensors, S/N ≃ 12 at 1.5 x 3000 fb^{-1}

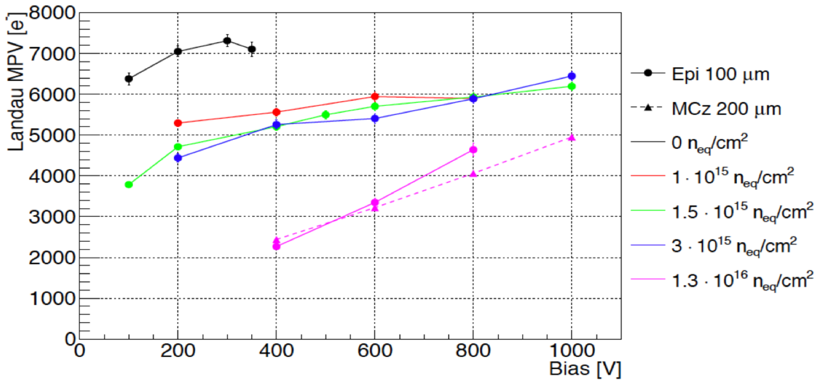
1) *For S/N seed strip signal (after charge sharing) needs to be considered*
2) *S/N referring to the collected charge assumes that the preamplifier-shaper integrate all the charge*

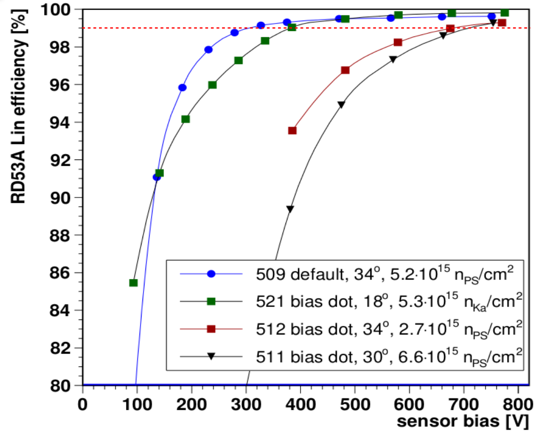
Tracking systems: Si-sensors Inner Tracker S/N (depleted case)

CMS pixels 1st (2nd) layers are exposed to 2(0.5) 10^{16} 1 MeV neq/cm^2 for HL-LHC 3000 fb^{-1}

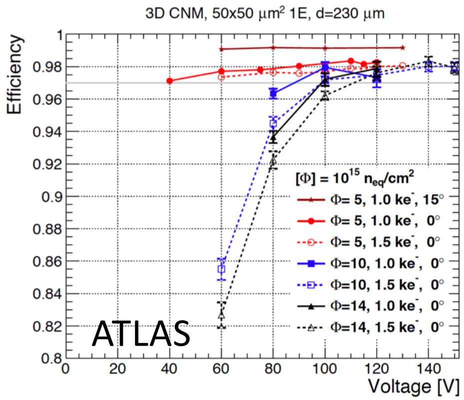
- Efficiencies measured for S/N threshold (RD53) = 1200 (10^{-6} noise occupancy $\simeq$ 1% of hits in layer 4)

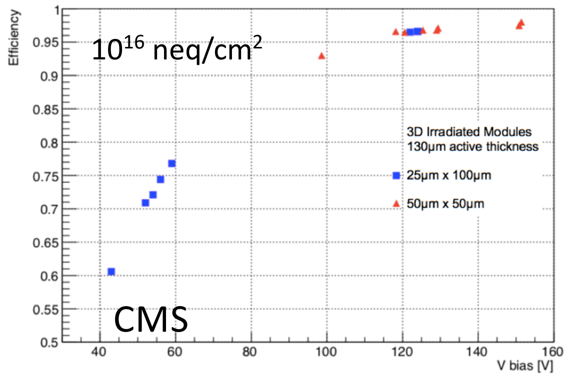
CMS planar pixel sensors ongoing tests: 2nd layer can sustain 3000 fb^{-1} at 600 V

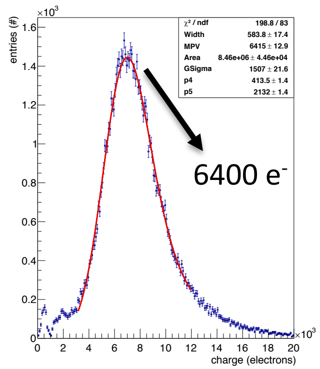




3D pixel sensors ongoing tests with RD53 chip:
1st layer in CMS[1)] should sustain at least ½ of 3000 fb^{-1} with full efficiency at 150





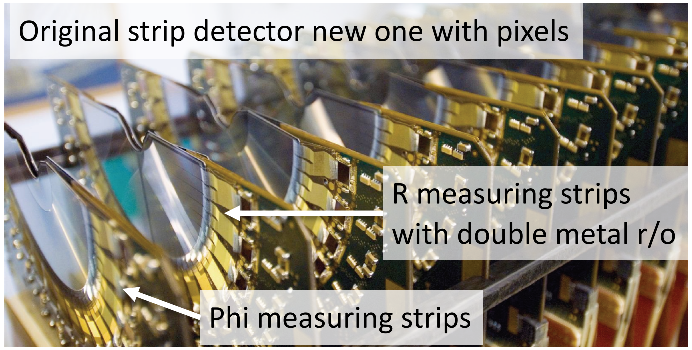


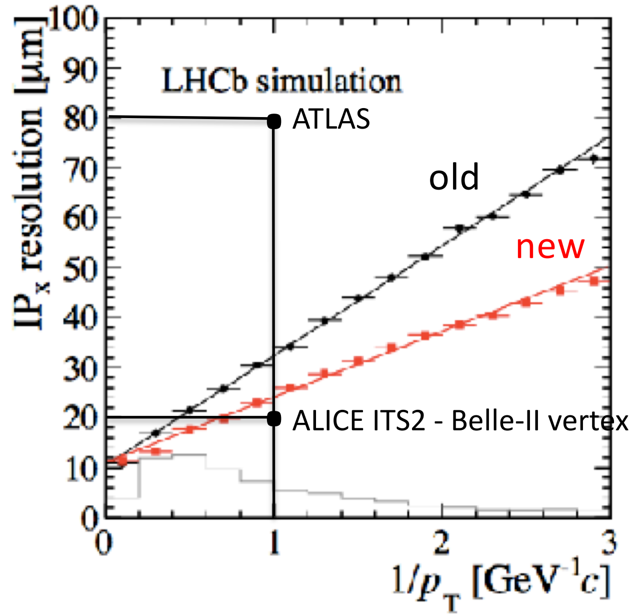
1) 1st layer in CMS is closer to the beam line than in ATLAS with about 1.6 x more fluence

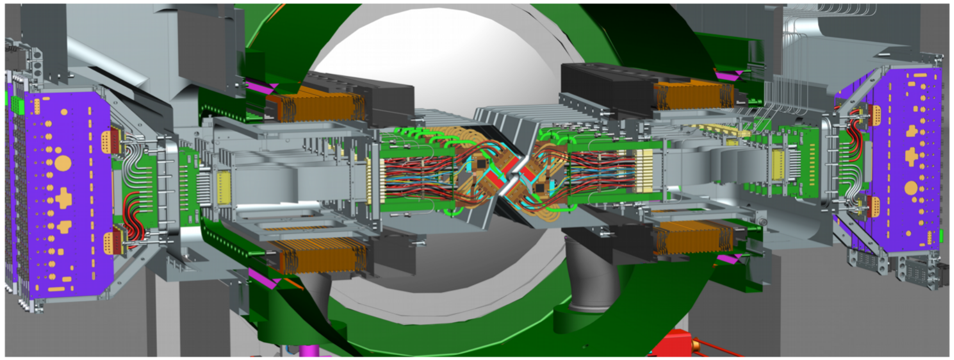
Silicon trackers state of the art: LHCb vertex (pixel) detector

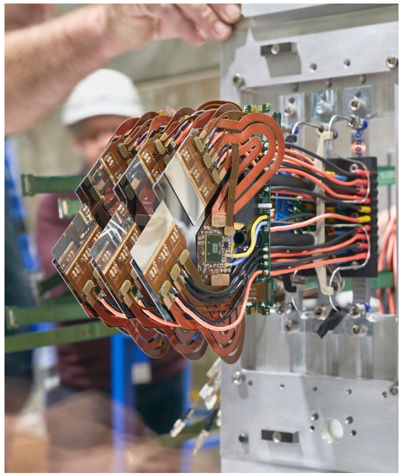
LHCb VELO upgrade for installation during 2020

- 12 disks of 4 modules, inner radius ≃ 4.5 mm
- Planar n-in-p sensors fully depleted up to ≃ kV
- 200 μm thick, 55 x 55 μm^2 pixels, ≃ 10 μm hit resolution
- 120 x 120 μm^2 micro cooling-channel etched in sensor substrate
  - ≃ 1.5% X/X_0 per disk
- Radiation tolerance ≃ 10^{15} 1 MeV neq/cm^2 (T ≃ -20°)





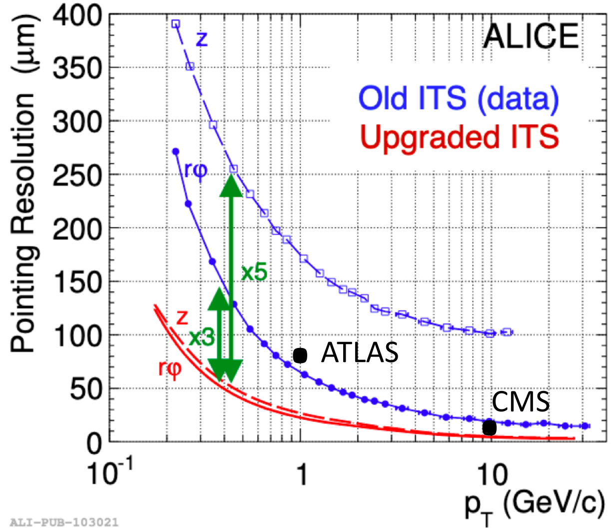


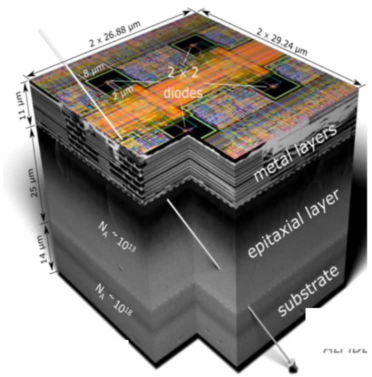


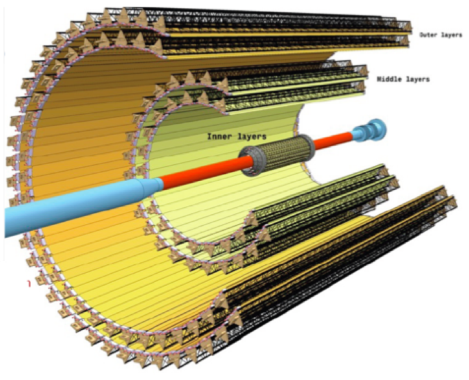
Silicon trackers state of the art: ALICE ITS2 (installation 2020)

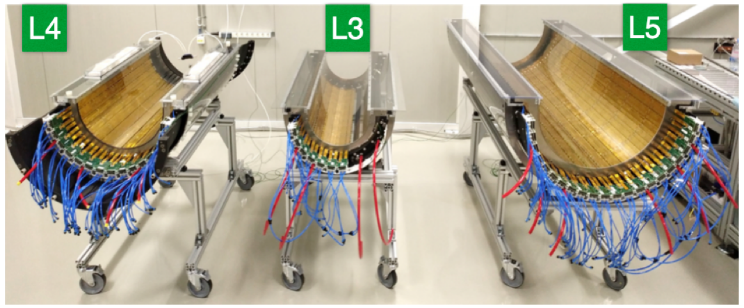
Monolithic Active Pixels (MAPs): CMOS standard process with readout grown on Si-sensors
lightest and most precise designs, relatively slow readout and low radiation tolerance

- 7 layers of MAPs $\simeq$ 10 m^2 with 12.5 Gpix up to η = 1.3
  - 3 inner layer each 0.35% X/X_0 from 22 to 40 mm
  - 4 outer layers of 1% X/X_0 up to 400 mm
- Installation in 2020
  - Sensors CMOS TowerJazz 180 nm technology (no depletion :
    - Epitaxial 50 µm thick, pixels, 29 x 27 μm^2, $\simeq$ 5 µm resolution
  - Binary zero suppressed readout 100 kHz, $\simeq$ 5 µs integration time
  - Radiation tolerance $\simeq$ 2 x 10^{13} neq/cm^2 and $\simeq$ 3 Mrad





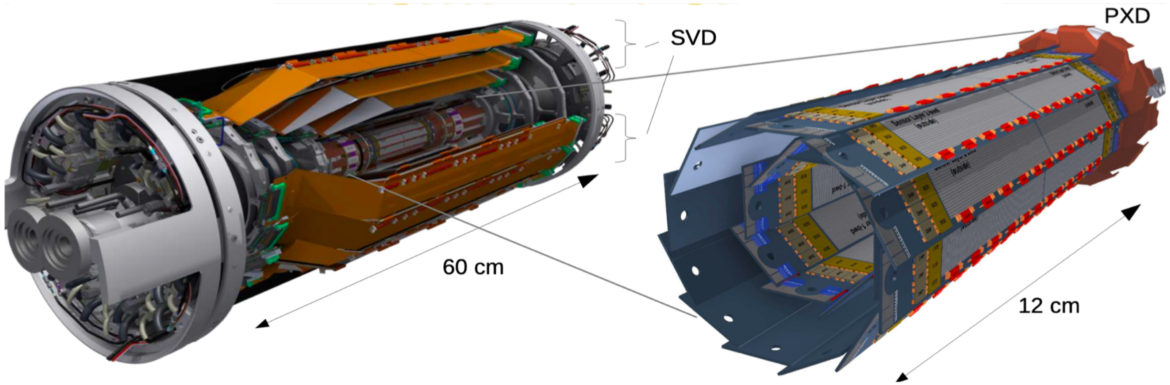


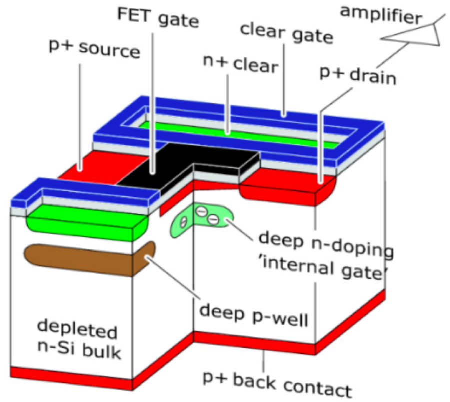


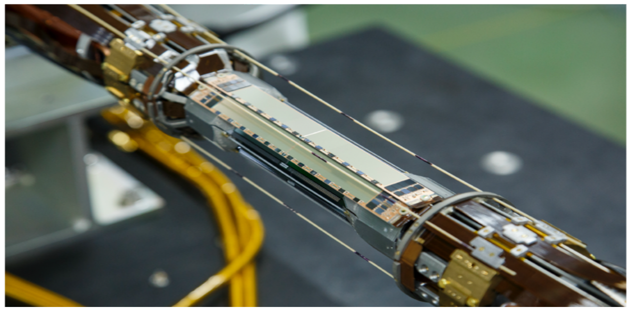
Silicon trackers state of the art: BELLE-II pixel detector

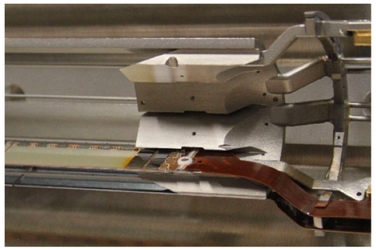
Monolithic Active Pixels (MAPs) in depFET technology

- Pixel detector[1)]: 2 layers at 1.4 cm and 2.2 cm, 0.03 m^2
  - Thickness ≃ 75 µm, pixels ≃ 50 x 50/85 μm^2 , σ(hit) ≃ 15 µm resolution ≃ 0.2% X_0/layer
  - Binary readout continuous row by row, 20 µs integration time
  - Radiation tolerance ≃ 10^{13} neq/cm^2 and ≃ 10 Mrad

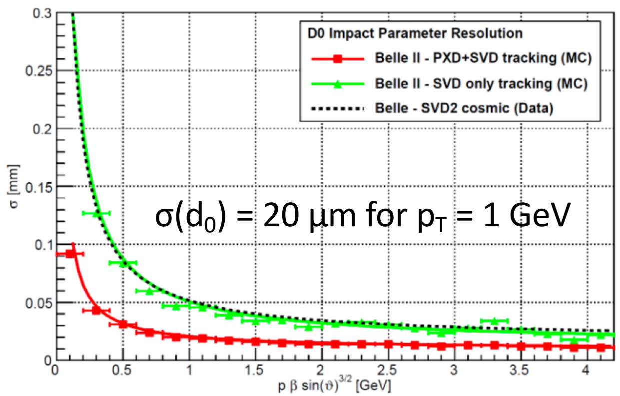








3D-prointed support cooling blocks



1) SVD is ≃1m^2, 4 double side stereo layers at 3.9, 8, 10.4, 13.5 cm,

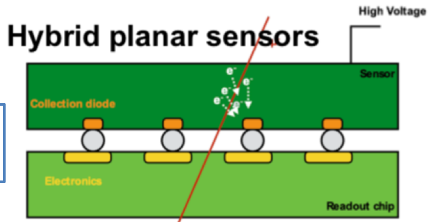
Silicon sensors: R&D goals

An ideal detector would be monolithic with high:
hit and time precision, speed and rate capability, radiation tolerance; and low cost

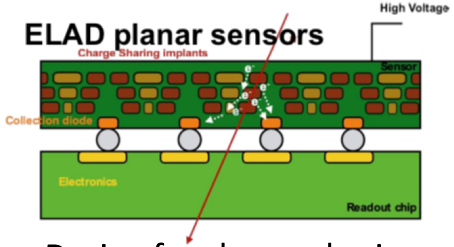
- Improve hit precision → e^+-e^- colliders
  - Smaller pitch and thickness: deeper sub-micron technology
  - Improve charge sharing: new design ex. ELAD
- Improve radiation tolerance → h-h colliders
  - Smaller pitch and thickness, deeper sub-micron technology
    - Planar, 3D to maintain high field and small electron path
  - Work on material and fabrication process to reduce damages
- Improve integration of electronics → e^+-e^- colliders, h-h colliders
  - Monolithic, new connection scheme to electrodes, ASICs interconnection
- Improve cost → e^+-e^- colliders, h-h colliders
  - Develop process as close as possible to standards used in microelectronics and imaging industries

Silicon sensors: R&D examples[1)]

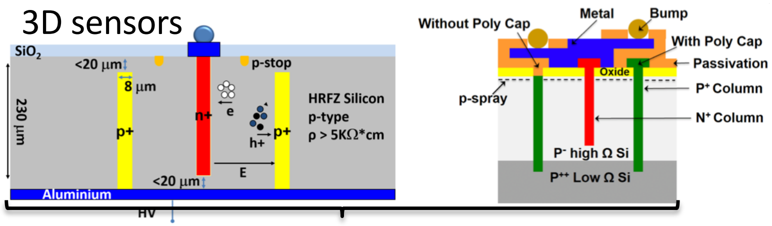
Hybrid design



pixels < 50 x 50 μm^2

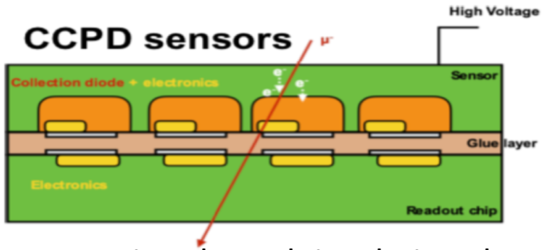


Design for charge sharing

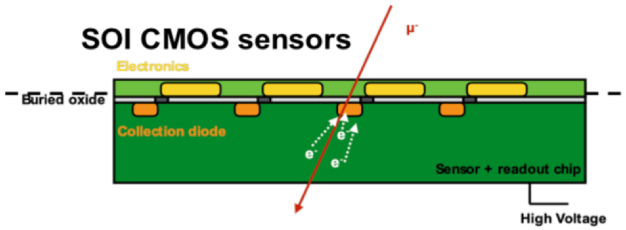


process variants for pitch

Interconnection



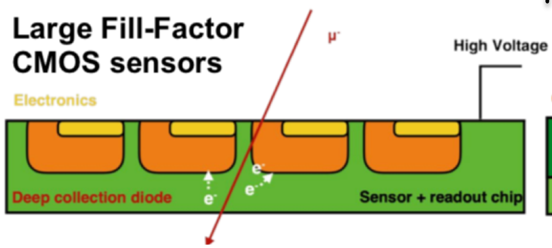
AC connection through insulating glue

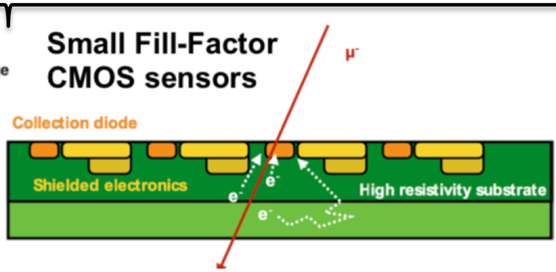


Through SiO_2 via process

can also apply here

Monolithic devices





CMOS modified process for depletion HV-CMOS (left)and HR-CMOS (right)

1) Design of sensors particularly for field configurations is supported by simulation tools ex. TCAD, it can be interfaced with GEANT to assess signal fluctuation effects, ex CLIC studies

Silicon sensors: R&D demonstrators (not exhaustive)

Connection to high rate capability ASIC planar and CMOS

Planar/3D finer pitch for resolution

CMOS modified process for radiation tolerance
faster and higher rate readout

Smaller pitch and thinner planar and 3D pixels bump bonded

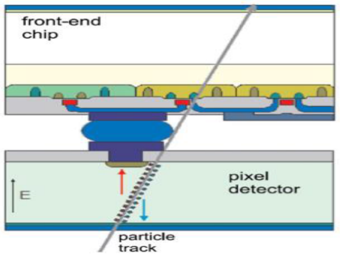
SoI process
Si/ASIC wafers connected through Insulator Oxyde layer

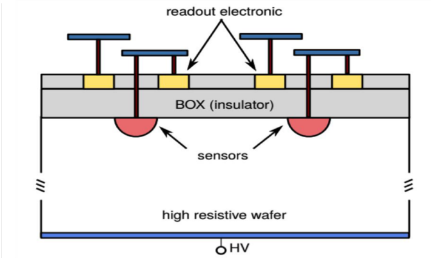
Capacitive Coupling (PD) of HV CMOS design to ASIC through insulating glue

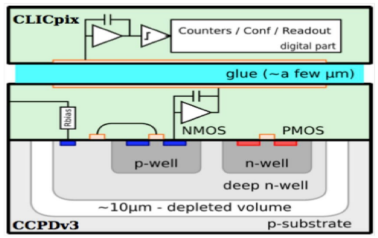
Modified HV-CMOS depletion (< 100 V)

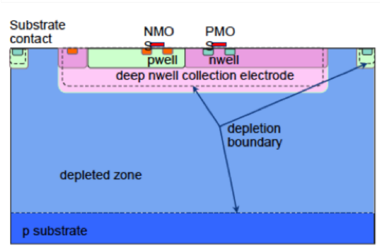
Modified HR-CMOS depletion (6V)

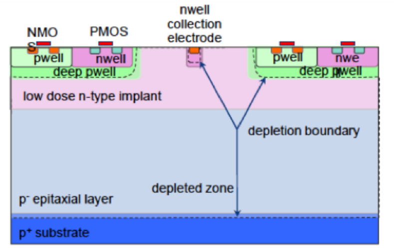
with faster and higher rate readout capabilities

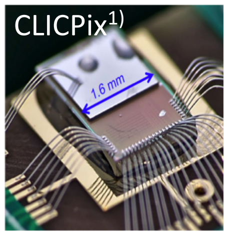


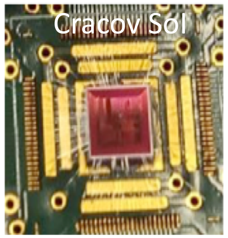


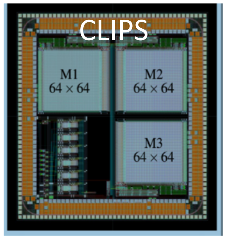


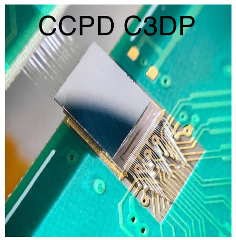


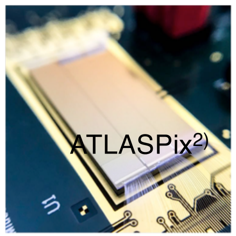


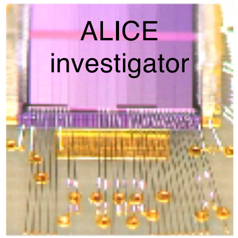


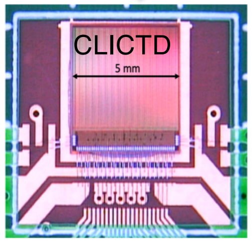


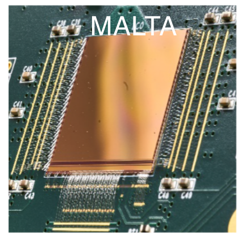












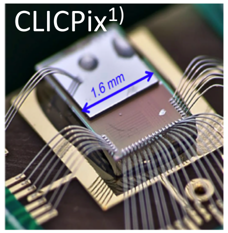
Demonstrators ≃ 2 x 2 cm^2

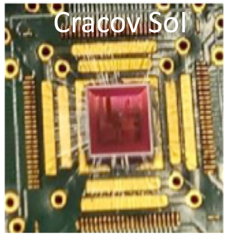
Sinergy with 1) CERN MEDIPIX, 2) Mu3e experiment

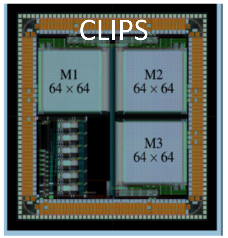
Silicon sensors: R&D demonstrators (not exhaustive)

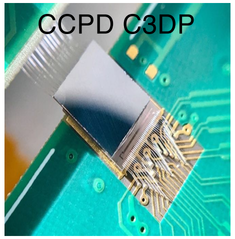
Silicon sensor R&D	Hybrid	SoI		CMOS Monolthitic				CCPD
Demonstrator	CLICpix	Cracov	CLIPS (CLIC)	ALICE investigator	CLICTD*	Malta/Monopix	ATLASpix(Mu3ePix)	C3DP+CLICpix
Sensor	planar	planar	planar	HR-CMOS standard	HR-CMOS modified process		HV-CMOS	
Connection to readout electronics	bump bonding	SoI	SoI	momolithic	monolthitic	monolithic	monolitic	CC with glue
ASIC technology (nm)	65	200	200	180(TJ)	180 (TJ)	180(TJ)/150(LF)	180(AMS)/150(LF)	65
Thickness (µm)	50 / 200	300 / 500	100 / 500	50	50 / 100	100	60	50
Pitch/cell size (µm x µm)	25 x 25	30 x 30	20 x 20	28 x 28	30 x 300	36 x 36	40 x 130	25 x 25
Hit resolution (µm)	9 / 3	5/2		5		4	13	6
Time resolution (ns)	7			6		< 10	7	7
Max NIEL (1 MeV neq/cm2)/TID (Mrad)	$O(10^{16})$/Grad			$O(10^{13})$/300			$O(10^{15})$/100	

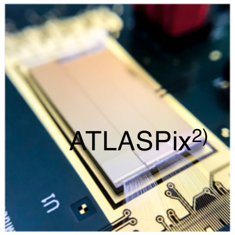
** In production*

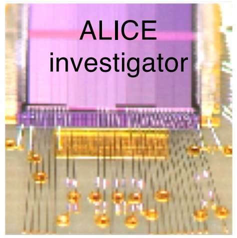


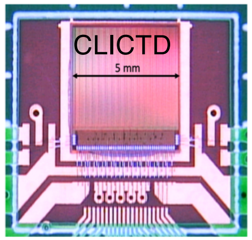


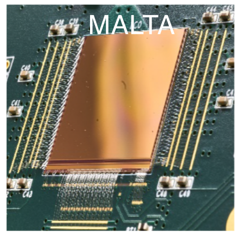












Sinergy with 1) CERN MEDIPIX, 2) Mu3e experiment

Silicon sensors: R&D demonstrators outcome and outlook

- CMOS MAPs suitable for outer trackers and close to fulfil needs for ee- collider vertex detectors
  - 3 µm hit resolution likely needs < 25 x 25 µm^2 pixels (charge sharing[1)] too small with 50 µm thickness)
  - ≃ 200 MHz/cm^2 hit rate capability and ≃ 5 ns time precision (CLIC requirement achieved)
    - However CLIC inner pixel layer hit rate requires 6 GHz/cm^2
  - Enlarged sensor size 15 x 15 cm^2 with stitching process is being investigated
- New ASIC connection techniques still at early stage, bump-bonding difficult with smallest pixels
- O(100) better radiation tolerance achieved in HR/HV CMOS modified process 2 x 10^{15} neq/cm^2
  - Still marginally at the level of requirement for an outer tracker FCC-hh/SppC layer

Deeper sub-micron technologies 65 nm or less can improve in all aspects

- Ex. ALICE ITS3 upgrade proposal: CMOS MAPs in 65 nm technology, 10 x 10 µm^2 pixels, ≃ 20 µm thick sensors for 0.05% X_0

FCC-hh/SppC remains a challenge for hit rate and radiation tolerance

- Also alternative material R&D for radiation tolerance, ex. pCVD diamond CERN RD42

1) Some design studies (ELAD) with implants in depth of sensors to control charge sharing through E-field configuration

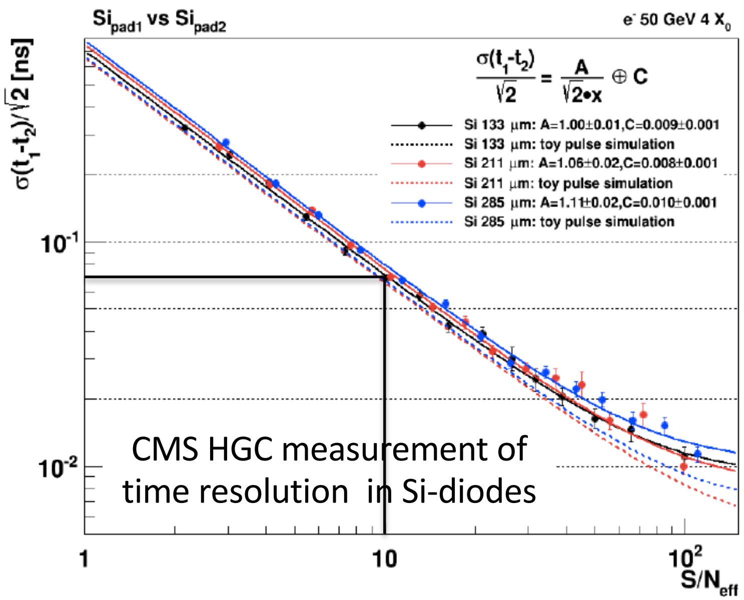
Topics not addressed in this section

- Other tracking technologies
  - TPC, MPGDs in Gas detector section
  - Scintillating devices in calorimeter section
- Si-sensors for other purpose
  - Pad-sensors for High Granularity Calorimeters in calorimetry section
  - Exploitation of precision timing with regular sensors[1)]
  - LGAD technology for precision timing in MIP Timing Detector section
- Other silicon technologies used for photodetection
  - APDs, HPDs, SiPMs, in calorimetry section

1) Regular silicon sensors could provide ultimate timing precision of ≥ 70 ps at S/N ≥ 10

NA62 vertex detector achieve ≃ 115 ps precision

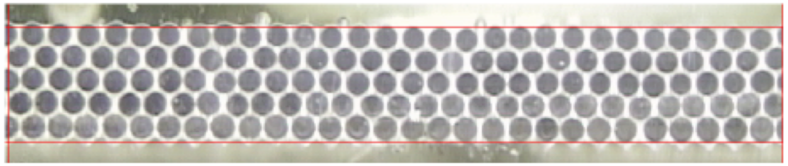
https://indico.cern.ch/event/577856/contributions/3420172/attachments/1878363/3093866/eps2019_na62_kleimenova.pdf



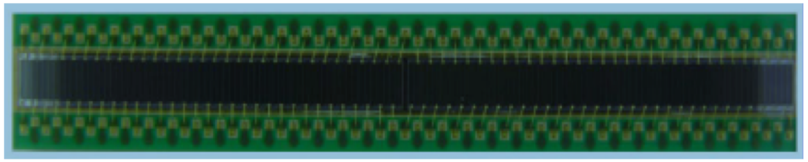
Topics not addressed in this section: LHCb scintillating Fiber Tracker

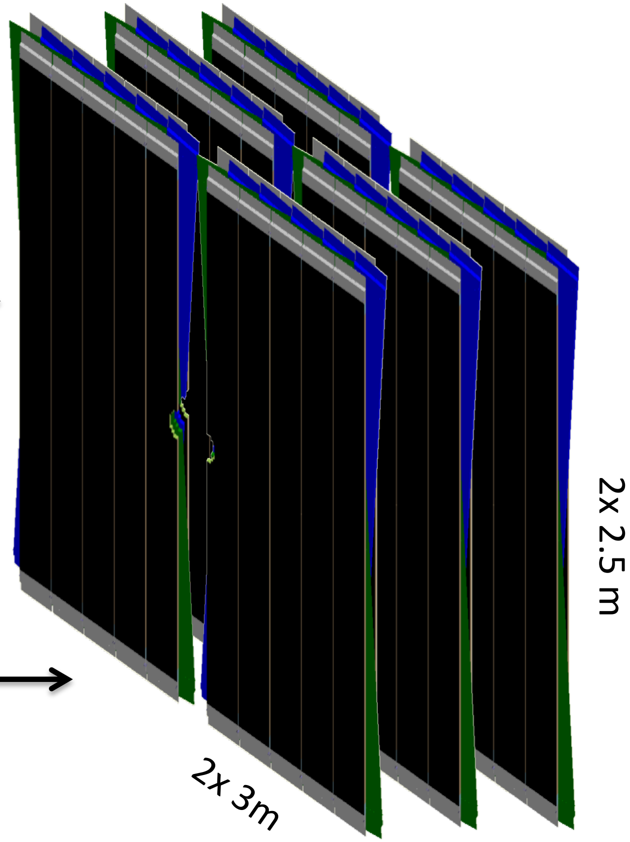
3 stations, each 2.5% X/X0 - 4 plans (X-U-V-X) with ± 5∘ stereo angle - 50-75 µm resolution

- 3 M fibers Φ 250 µm x 2.5 m (10 000 km)
  - 3 Mrad in inner region
  - High precision assembly of fiber mats



- Readout with 128 SiPM array 250 µm pitch
  - 40°C cooling to sustain $1.2 \cdot 10^{12}$ neq. /cm2





Additional information

Charged particle interaction in matter: parameters

Symbol	Definition	Units or Value
α	Fine structure constant $(e^2/4\pi\epsilon_0\hbar c)$	1/137.035 999 11(46)
M	Incident particle mass	MeV/c^2
E	Incident part. energy γMc^2	MeV
T	Kinetic energy	MeV
m_ec^2	Electron mass $\times$ c^2	0.510 998 918(44) MeV
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_ec^2$	2.817 940 325(28) fm
N_A	Avogadro's number	6.022 1415(10) $\times$ 10^{23} mol^{-1}
ze	Charge of incident particle	
Z	Atomic number of absorber	
A	Atomic mass of absorber	g mol^{-1}
K/A	$4\pi N_A r_e^2 m_ec^2/A$	0.307 075 MeV g^{-1} cm^2 for A = 1 g mol^{-1}
I	Mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	Density effect correction to ionization energy loss	
$\hbar\omega_p$	Plasma energy $(\sqrt{4\pi N_e r_e^3}\ m_ec^2/\alpha)$	$\sqrt{\rho\langle Z/A\rangle}\times 28.816$ eV (ρ in g cm^{-3})
N_e	Electron density	(units of r_e)$^{-3}$
w_j	Weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
—	$4\alpha r_e^2 N_A/A$	(716.408 g cm^{-2})$^{-1}$ for $A = 1$ g mol^{-1}
X_0	Radiation length	g cm^{-2}
E_c	Critical energy for electrons	MeV
$E_{\mu c}$	Critical energy for muons	GeV
E_s	Scale energy $\sqrt{4\pi/\alpha}\ m_ec^2$	21.2052 MeV
R_M	Molière radius	g cm^{-2}

Charged particle interaction in matter: Bethe-Bloch terms

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

Table 1: Bethe–Bloche formula terms

$\frac{\mathrm{d}E}{\mathrm{d}x}$	Average energy loss in unit of MeV $\mathrm{g}^{-1}\ \mathrm{cm}^2$
$K = 4\pi N_\mathrm{A} r_\mathrm{e}^2 m_\mathrm{e} c^2 = 0.307$ MeV $\mathrm{g}^{-1}\ \mathrm{cm}^2$	
$W_\mathrm{max} = 2m_\mathrm{e} c^2 \beta^2 \gamma^2 / (1 + 2\gamma m_\mathrm{e}/M + (m_\mathrm{e}/M)^2)$	Maximum energy transfer in a single collision
z	Charge of the incident particle
M	Mass of the incident particle
Z	Charge number of the medium
A	Atomic mass of the medium
I	Mean excitation energy of the medium
δ	Density correction (transverse extension of the electric field)
$N_\mathrm{A} = 6.022 \times 10^{23}$	Avogadro's number
$r_\mathrm{e} = e^2/4\pi\epsilon_0 m_\mathrm{e} c^2 = 2.8$ fm	Classical electron radius
$m_\mathrm{e} = 511$ keV	Electron mass
$\beta = v/c$	Velocity
$\gamma = (1 - \beta^2)^{-1/2}$	Lorenz factor

Charged particle interaction in matter: particle energies

Energy Range	Sources of Radiation
eV	visible light, secondary electrons, thermal neutrons
keV	X-rays, electrons from radioactive β decay
MeV	α particles, photons from excited nuclei, acceleration with cyclotrons, solar neutrinos
GeV	air showers from cosmic rays, acceleration with synchrotrons
TeV	high-energy accelerators (e.g. LHC) TeV gamma rays from galaxy
> TeV	cosmic accelerators: quasars, super-massive black holes, supernova remnants, …