第一届粒子探测技术基础与前沿讲习班

半导体顶点探测器

欧阳群
中国科学院高能物理研究所

第一届粒子探测基础与前沿讲习班，广西大学
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Lecture - 半导体顶点探测器

a) Silicon vertex detectors (硅顶点探测器) 欧阳群 **(IHEP)**

- Vertexing in particle physics experiments
- Silicon detectors
- Radiation Damage in Silicon Detectors
- Examples: silicon vertex detectors in particle physics experiments
- Outlook: future development

b) 高能物理中的像素探测器技术 卢云鹏 **(IHEP)**

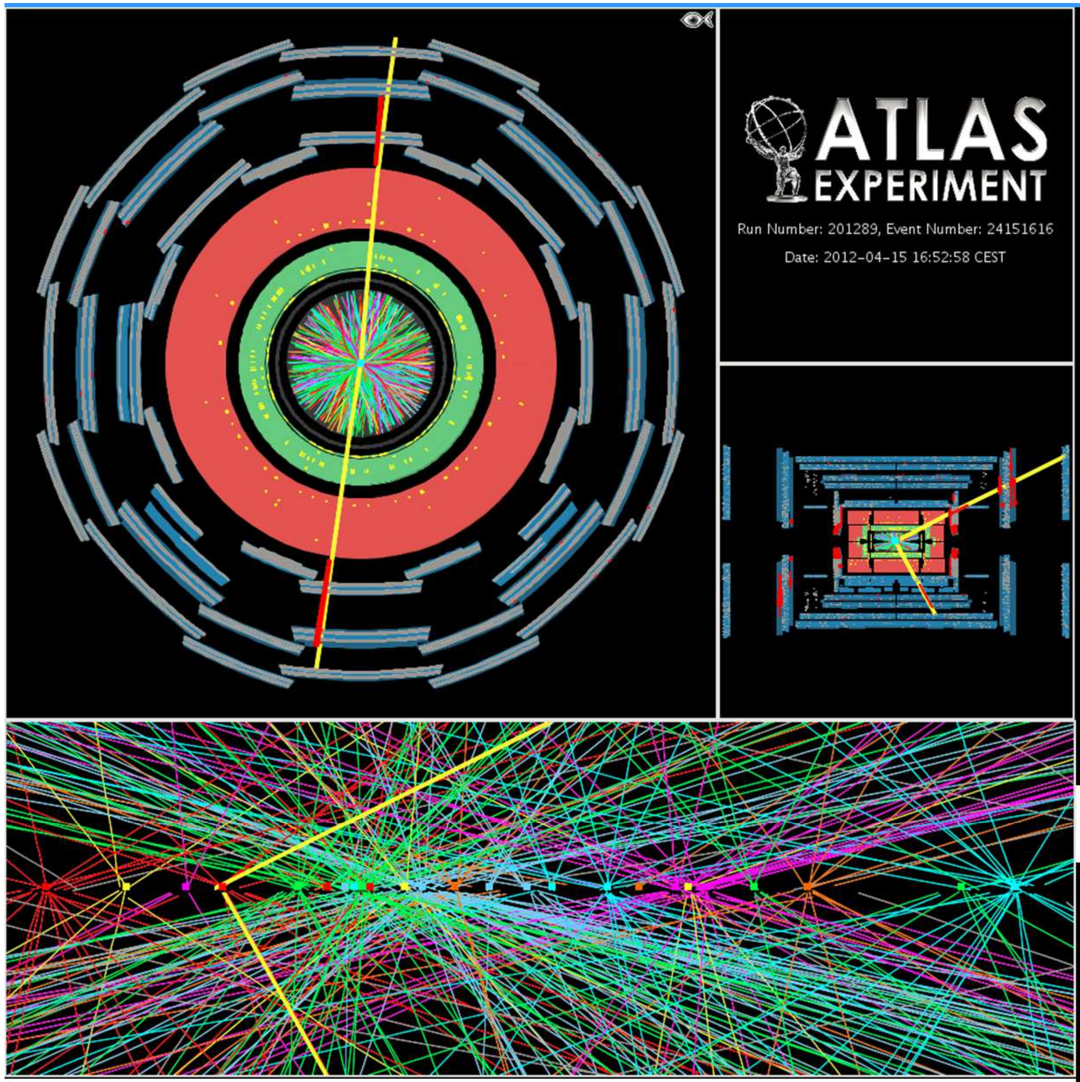
- 相关的几个概念
- 混合型像素探测器（Hybrid）
- 单片集成式像素探测器（Monolithic）
    - DEPFET
    - CPS
    - SOI
- CEPC pixel sensor R&D
- 总结

* 不包括锗、化合物半导体、CCD探测器等

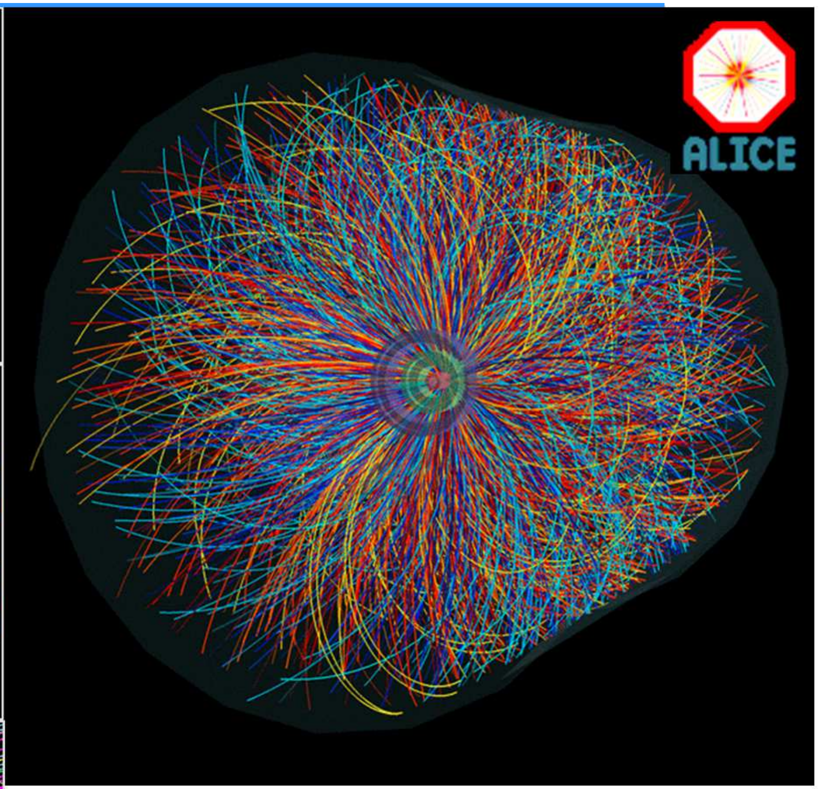
Note： most material (figures and plots, et al) collected from

- Evolution of Silicon Sensor Technology in Particle Physics, *F. Hartmann, Springer Tracts in Modern Physics Volume 231*
- Tracking at Collider Experiments, *L.Musa, CCNU,Wuhan,3 July 2015*
- Tracking, *D. Bortoletto, CERN Academic Training 2016*
- An Introduction to Charged Particles Tracking, *Francesco Ragusa, May 28-29 2014, Scuola Normale Superiore - Pisa*
- Tracking with Solid State Detectors, *Michael Moll, http://cern.ch/ph-dep-dt2/lectures_PD_2005.htm*
- 半导体探测器，胡涛，中科院大学课件
- And others…

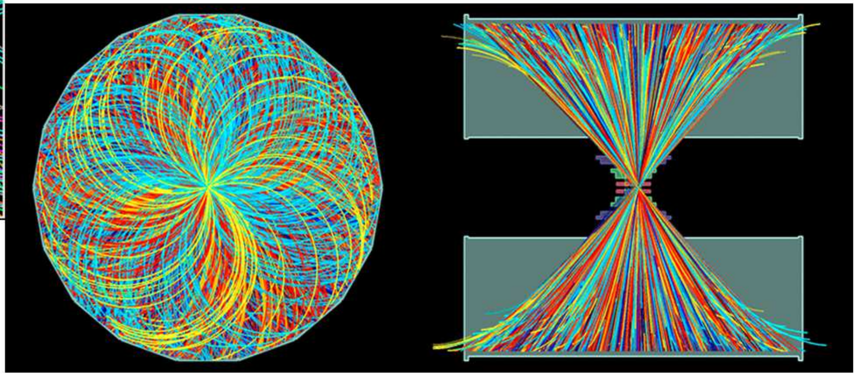
Vertexing in particle physics experiments



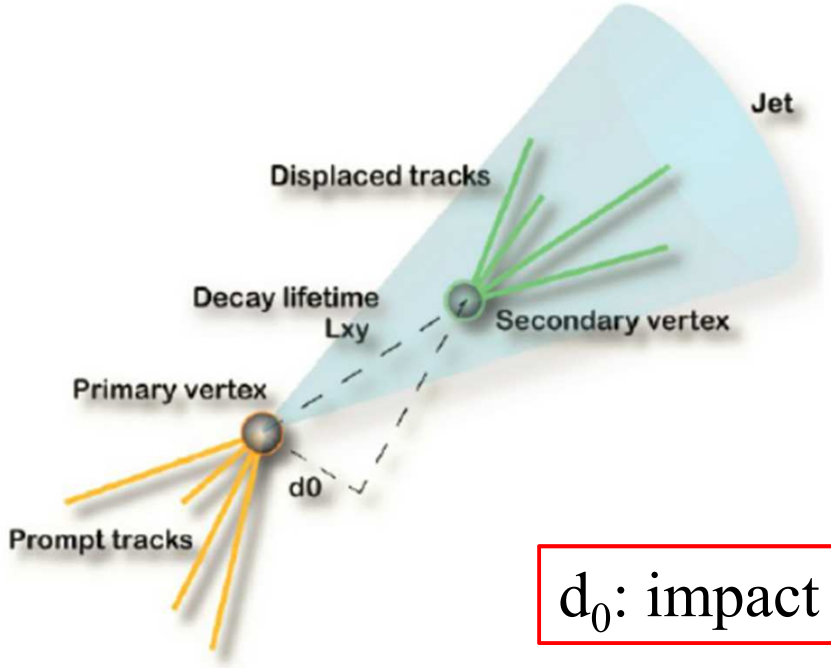
LHC pp collisions: a candidate Z boson event in the dimuon decay with 25 reconstructed vertices. (ATLAS, April 2012)



LHC Pb-Pb collision (ALICE,Sep2011)



Lifetime tagging

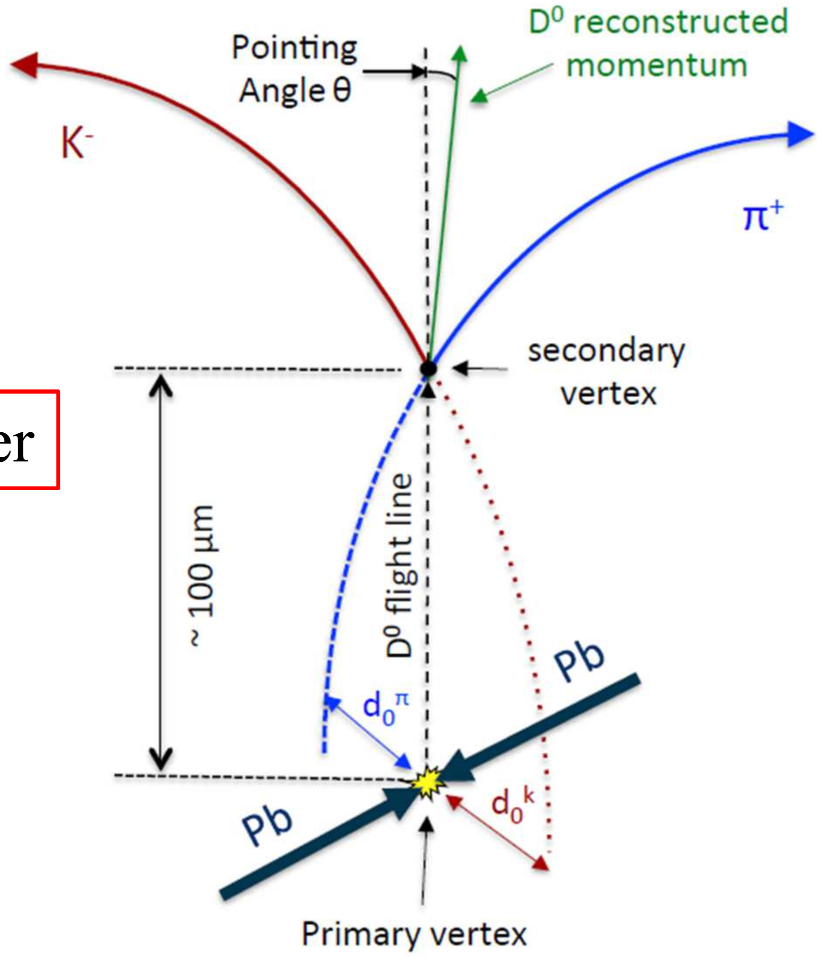


d_0: impact parameter

Open charm

Particle	Decay Channel	cτ (μm)
D^0	$K^- \pi^+$ (3.8%)	123
D^+	$K^- \pi^+ \pi^+$ (9.5%)	312
D_s^+	$K^+ K^- \pi^+$ (5.2%)	150
Λ_c^+	$p K^- \pi^+$ (5.0%)	60

Example: D^0 meson



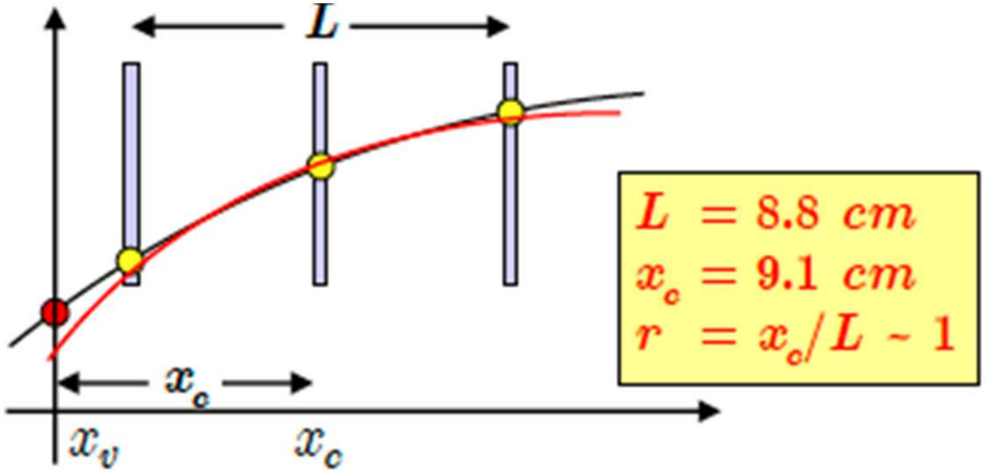
Extrapolation to vertex (impact parameter resolution)

Extrapolation of track to the vertex

$B\neq 0$

Parameters *a*, *b* and *c* measured at the center of the track

$$y_{ip} = a + bx_v + cx_v^2$$



$L = 8.8\ cm$
$x_c = 9.1\ cm$
$r = x_c/L \sim 1$

Error propagation gives

$$\sigma_{ip}^2 = \sigma_a^2 + x_v^2\sigma_b^2 + x_v^4\sigma_c^2 + 2x_v^2\sigma_{ac}$$

The calculation gives [*W.Blum, W.Riegler, L.Rolandi Particle Detection with Drift Chamber 2008*]

$$\sigma_{ip} = \frac{\sigma}{\sqrt{N+1}} B_{aa}(r,N) \qquad r = \frac{Xc}{L}$$

$B_{aa}(r,N)$

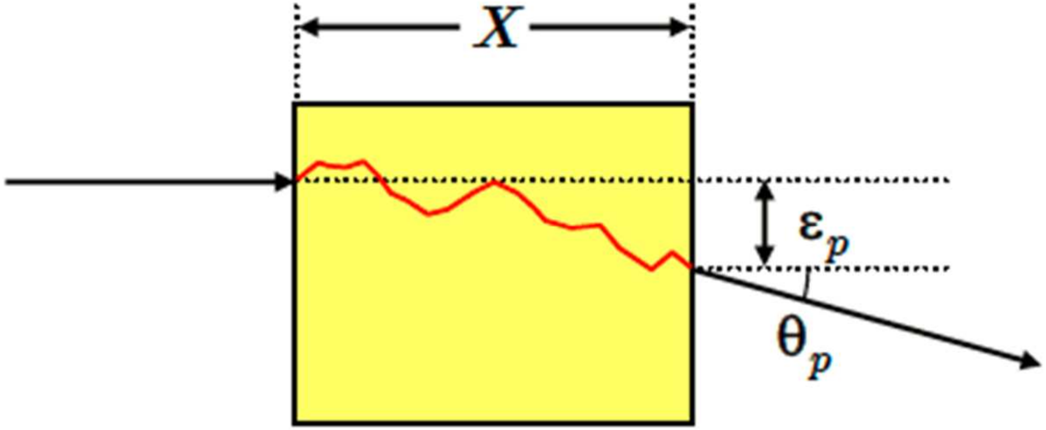
N \ r	5.0	3.0	2.0	1.5	1.0	0.75	0.60	0.50
2	211	75/3	32.9	18.1	7.63	4.10	2.65	2.05
3	224	80.2	35.2	19.5	8.29	4.48	2.84	2.07
5	250	89.5	39.4	21.9	9.39	5.10	3.20	2.26
10	282	101	44.6	24.8	10.7	5.84	3.65	2.54
19	304	109	48.1	26.8	11.6	6.32	3.95	2.72
∞	335	120	53.0	29.5	12.8	7.00	4.37	3.00

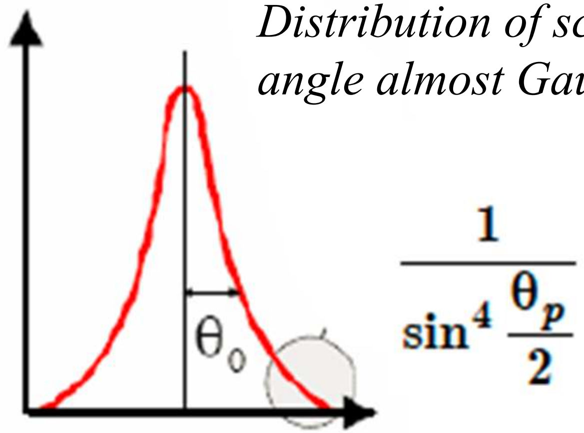
* ATLAS PIXEL Detector (only an exercise!!!)

- r_{min}=47mm, r_{max}=135mm, N+1=3, σ=10μm
- L=88mm, x_c=91mm, r~1
- B_{aa}(r=1,N=2)=7.63→ **σ_{ip}=44μm**

Multiple scattering

Particles moving trough the detector material suffer innumerable EM collisions which alter the trajectory in a random fashion





Distribution of scattering angle almost Gaussian

$$\langle\theta_p\rangle = z\frac{0.0136}{p\beta}\sqrt{\frac{x}{X_0}}$$

- Higher momentum p → less scattering
- Smaller x/X_0 → less scattering (but only as sqrt)
- Lateral displacement ε_p displacement is proportional to the thickness of the detector

$$\sigma_{ip} = \frac{B_{aa}(r,N)}{\sqrt{N+1}}\frac{L}{N}\frac{0.0136}{p\beta}\sqrt{\frac{X}{X_0}}$$

Vertex precision

- Impact parameter resolution

$$\sigma_{r\phi} = a \oplus \frac{b}{p(GeV)\sin^{3/2}\theta}\ (\mu m)$$

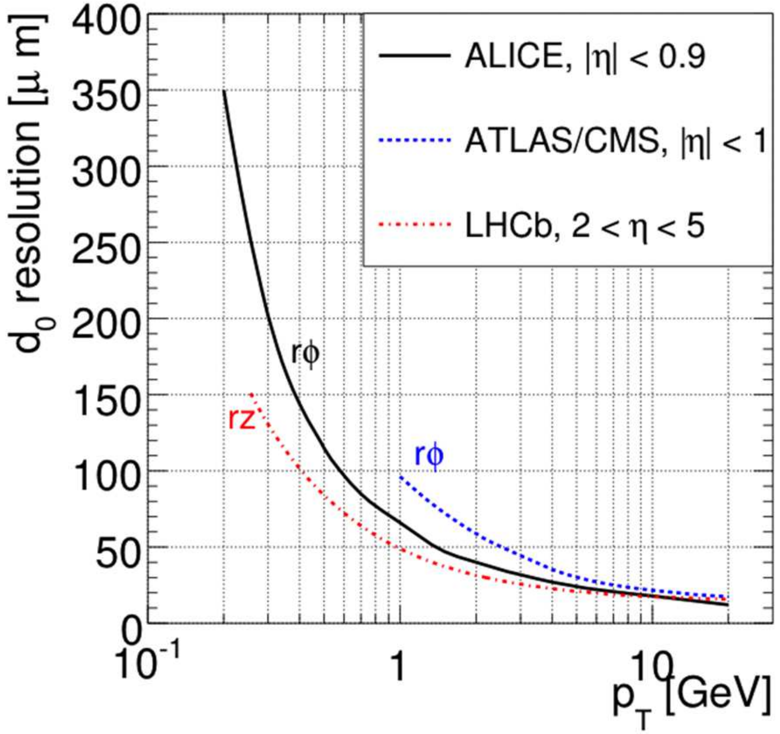
a depends on detector resolution σ & on the lever arm

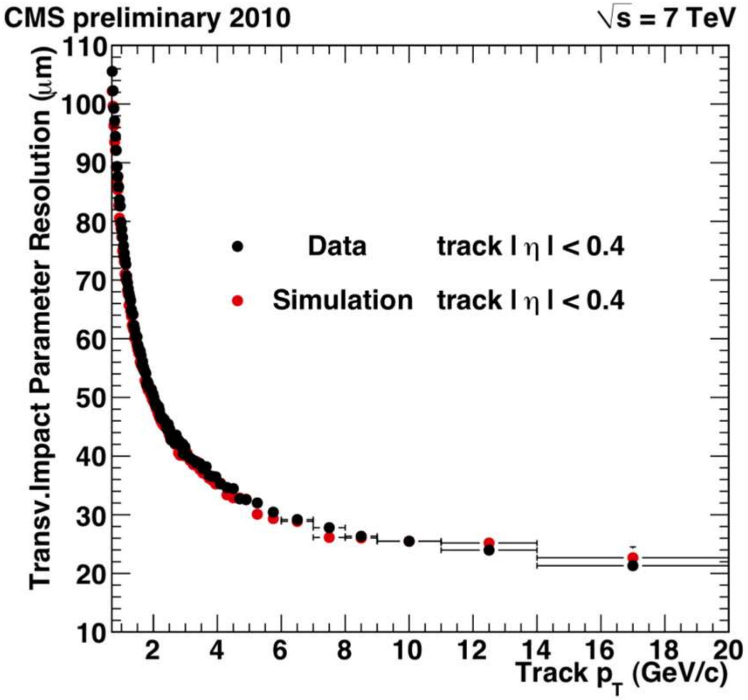
b depends on the distance between the innermost layer to IP and on the material budget

- Detector system requirements:
  - Small σ
  - Small material budget
  - First detector layer located small radius

Vertex precision

IP resolutions



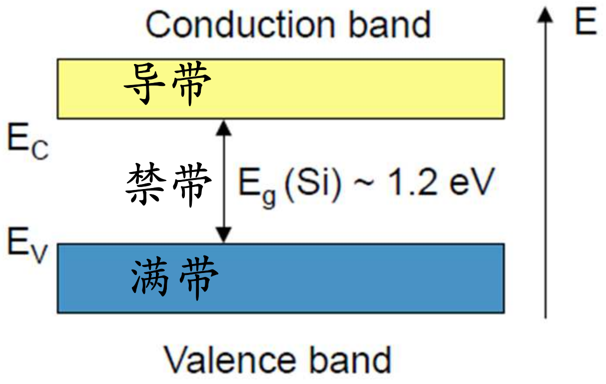


ATLAS/CMS expect:
100 μm @ 1 GeV,
20 μm @ 20 GeV

CMS Observed:
100 μm @ 1 GeV,
20 μm @ 20 GeV

Silicon properties

Si	1.12eV
Ge	0.67eV
GaAs	1.42eV
Diamond	5.5eV



- 一般情况下，半导体的满带完全被电子占满，导带中没有电子。
- 载流子：电子、空穴
- 外加电场时，电子和空穴都运动，方向相反。

✓若电场不高，漂移速度正比于外加电场E　　v=μE，μ为迁移率
气体探测器，电子的迁移率远大于正离子；
半导体中，电子和空穴的迁移率差别不大。

✓硅密度2.33g/cm3, MIPs在硅中能损dE/dx=3.9MeV/cm
→平均电离能 ~3.6eV (MIPs 产生80-100 e-h pairs/μm)
→ 能量分辨好

✓半导体探测器一般都工作在非常高的电场条件下，以得到电荷载流子的饱和速度，~10^7cm/s。
当硅厚度为0.1cm时，收集时间~10ns。
具有非常快的时间响应。

Silicon properties

本征半导体与掺杂

- 理想的不含杂质的半导体称为本征半导体，导带上的电子数目严格等于满带上的空穴数目，n=p 。
- 掺杂：在本征硅（四价元素）半导体内掺入
  - 五价元素（P(磷)、As(砷)、 Sb(锑)、 Li(锂) 等）

    → N型（电子型）半导体：导带内电子运动。
  - 三价元素（B(硼)、Al(铝)、Ga(镓)、In(铟) 等）

    → P型（空穴型）半导体：满带内空穴运动。

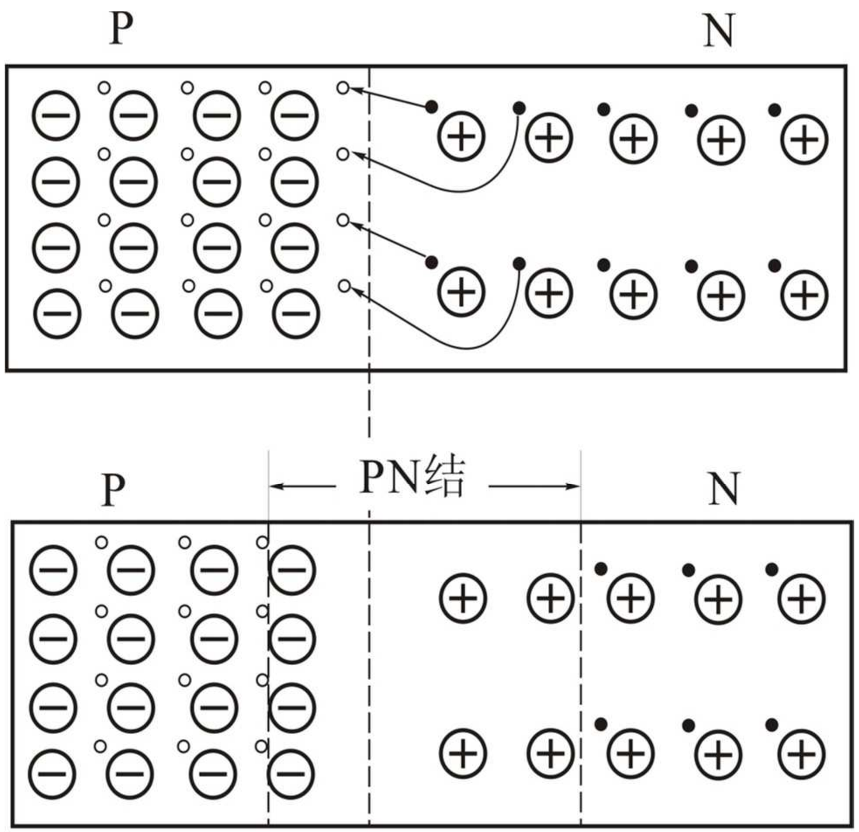
- 参杂半导体电子和空穴的浓度不相等

  N型半导体 $n=n_{\text{施}}$，$p=n_i^2/n_{\text{施}}$

  P型半导体 $p=p_{\text{受}}$，$n=n_i^2/p_{\text{受}}$

\>> resistivity of intrinsic silicon ~235kΩcm
\>> silicon for pixel detectors ~1- 6kΩcm
\>> silicon substrate for CMOS ICs ~0.1-10Ωcm

Silicon properties



Pn结的形成及各物理量的分布

结合前，N区的电子比P区多，P区的空穴比N区多。

结合后，电子由N区向P区扩散与空穴复合；空穴由P区向N区扩散与电子复合。扩散的结果形成PN结。

在PN结区，电子空穴很少，剩下的杂质正负离子形成空间电荷区，其内建电场方向由N区指向P区，阻止电子、空穴继续扩散，并造成少数载流子的反向漂移运动。当扩散运动和反向漂移运动达到平衡时，P区或N区的电子空穴浓度就不再变化。

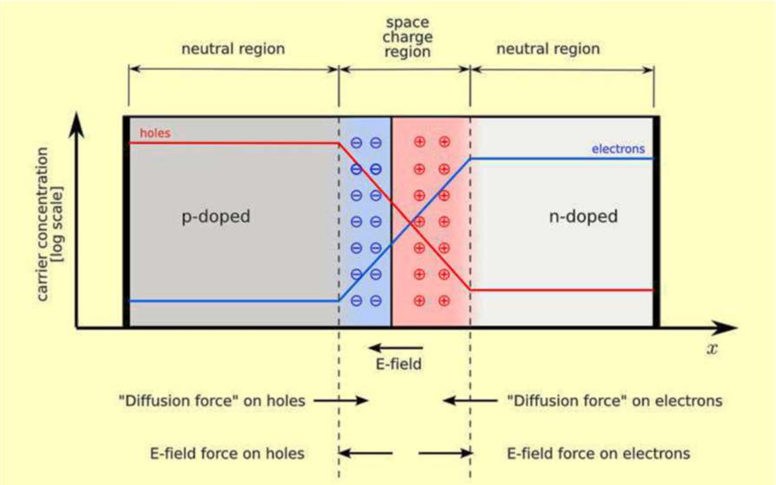
这个由不可移动的杂质离子组成的空间电荷区，即PN结区，对电导率没有贡献，而载流子的密度非常低，亦称耗尽区，阻挡层，势垒区。

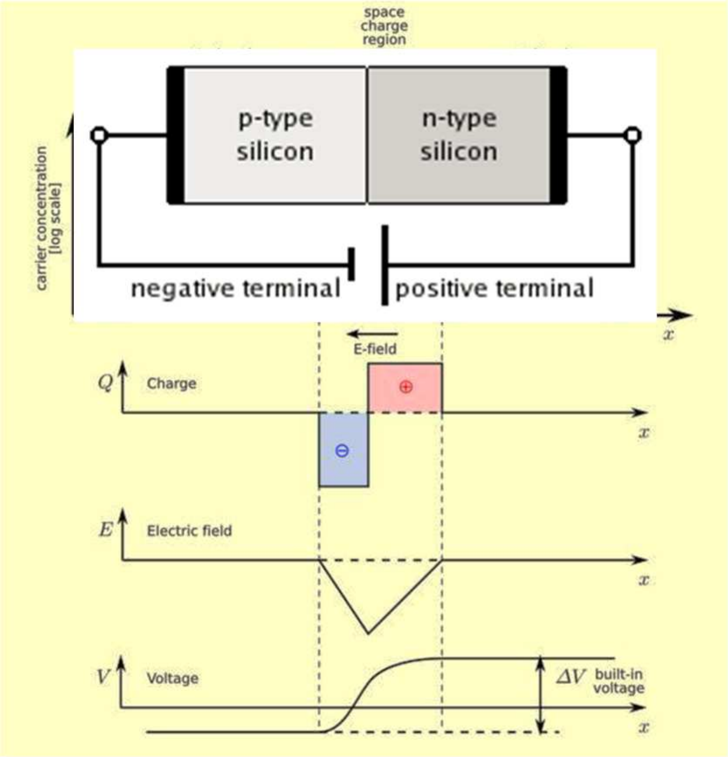
Silicon Detectors

- A silicon detector is a p-n diode

– n-type (P, As, Sb doping ➠ more electrons)
– p-type (B, Al, Ga doping ➠ more holes)

P-n junction without external voltage
– Free charges move until equilibrium is reached and create the built-in potential





The space charge (depletion) region can be made bigger by applying a reverse bias voltage

$$W \sim \sqrt{2\varepsilon_0 \varepsilon_r \mu \rho |V|}$$

$$\rho = \frac{1}{e\mu N_{eff}}$$

V … External voltage
ρ….. resistivity
μ … mobility of majority charge carriers
N_{eff}..effective doping concentration

小结：硅探测器优点

1）非常好的位置分辨
  - 硅微条可达1-2μm
  - 现代半导体技术工艺的飞速发展，每个探测单元可对应一路读出电子学，有利于空间分辨率的提高。

2）很高的能量分辨率
  - 半导体探测器的能量分辨率比气体探测器大约高一个数量级，比闪烁计数器高得更多。
  - 在硅半导体中电离产生一对电子-空穴对只需要3eV左右的能量，同样能量的带电粒子在半导体中产生的电子-空穴对数要比气体中产生的离子对高一个数量级以上。这样电荷数的相对统计涨落也比气体小很多。
  - 法诺因子F也小 硅 F≈0.10，锗 F≈0.06，气体 F≈0.4，闪烁体 F=1

3）能量线性很好：平均电离功与入射粒子的能量和种类以及探测器的类型无关，探测器输出脉冲与入射粒子能量成正比。

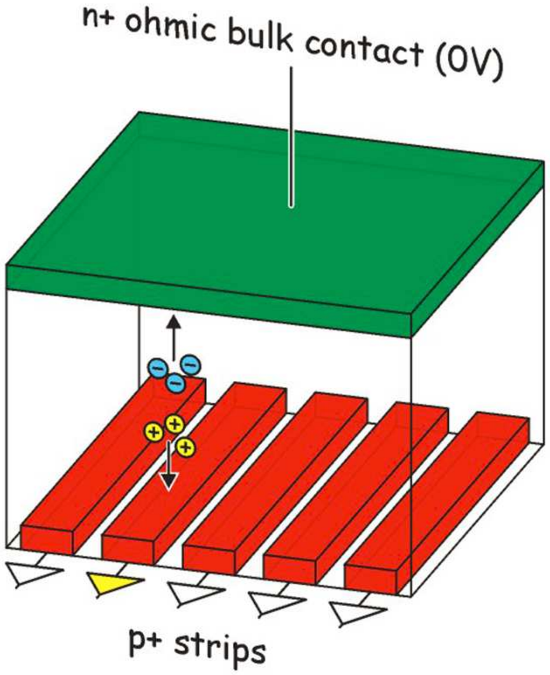
4）非常快的响应时间

5）体积可做得很小：厚度是300μm左右，当带电粒子穿过时，大约可产生3.2×10^4 电子-空穴对。

6）抗磁场性能好：对磁场(B<10KG)不灵敏。

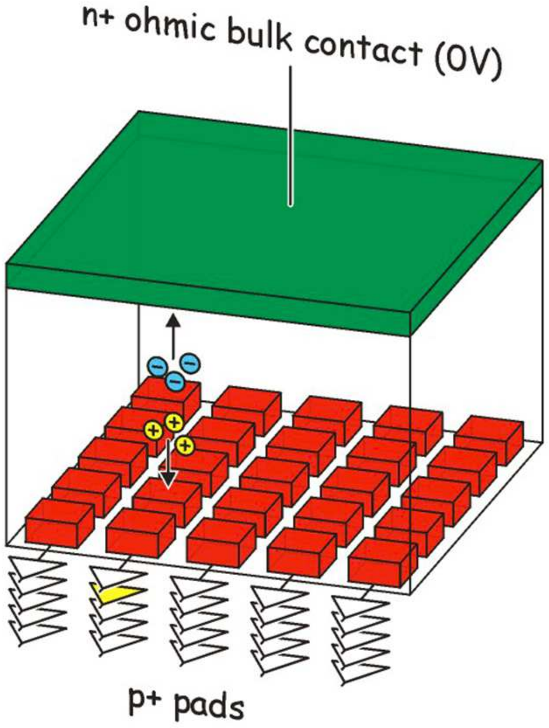
But…

Strip Detector vs Pixel Detectors



$$\sigma_X = \frac{p}{\sqrt{12}}$$

$$\sigma_X \propto \frac{p}{SNR}$$



- Each strip is connected to one electronic readout channel
- First prototypes: ~1980
- Strip pitch: ~10—100µm
- Position resolution: ~few µm due to charge sharing between neighboring strips (determine MPI centroid of charge)

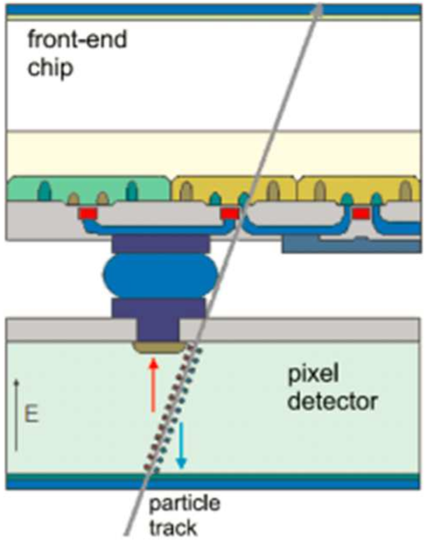
- 2D resolution
- First prototypes ~1990
- Can be used for tracking or imaging:

\- particle tracking = detection of individual charged particles

\- imaging = count/integrate particles or photons

The world of Silicon Pixel Detectors

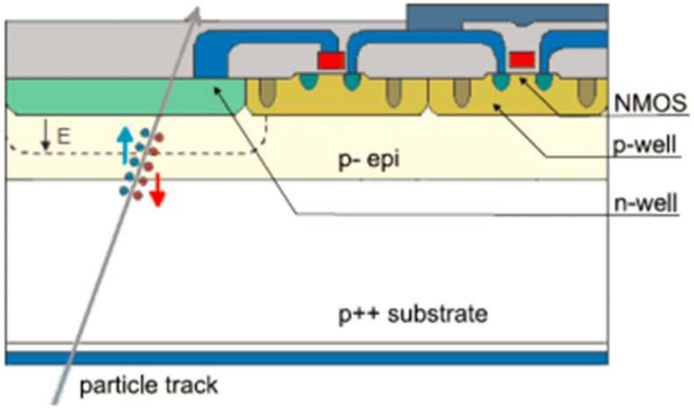
Hybrid Pixel Detector



- Sensor based on silicon junction detectors produced in a planar process
- High resistivity wafers (few kΩ·cm) with diameters of 4”–6”
- Specialized producers (~10 world wide)
- Readout Chip: ASIC-CMOS sub-micron technology
- Interconnect technology based on flip-chip bonding

高计数率、抗辐照能力强→强子对撞机实验

Monolithic Pixel Detector



- Charge generation volume integrated into the ASIC
- Exist in many different flavours: CCDs, CMOS MAPS, HV/HR CMOS, DEPFET, SOI, …

高分辨、低物质量→正负电子对撞机实验

详细内容由卢云鹏介绍

Radiation Damage in Silicon Detectors

➢ **Two general types of radiation damage:**

• **Bulk (Crystal) damage** due to **Non Ionizing Energy Loss (NIEL)**

- Displacement Damage –

I. Change of **depletion voltage** (higher operation voltage, underdepletion)

⇒ constant cooling needed to avoid reverse annealing

II. Increase of **leakage current** (increase of shot noise, thermal runaway)

⇒ needs cooling of sensors during operation

III. Decrease of **charge collection efficiency**
due to underdepletion and increased trapping

• **Surface damage** due to **Ionizing Energy Loss (IEL)**

- accumulation of positive in the oxide (SiO2) and the Si/SiO2 interface –

affects: inter-strip capacitance (noise factor), breakdown behavior and other structures depending on near-surface effects

➢ **Signal/noise ratio is the quantity to watch**

⇒ **Sensors can fail from radiation damage !**

Radiation tolerant detectors

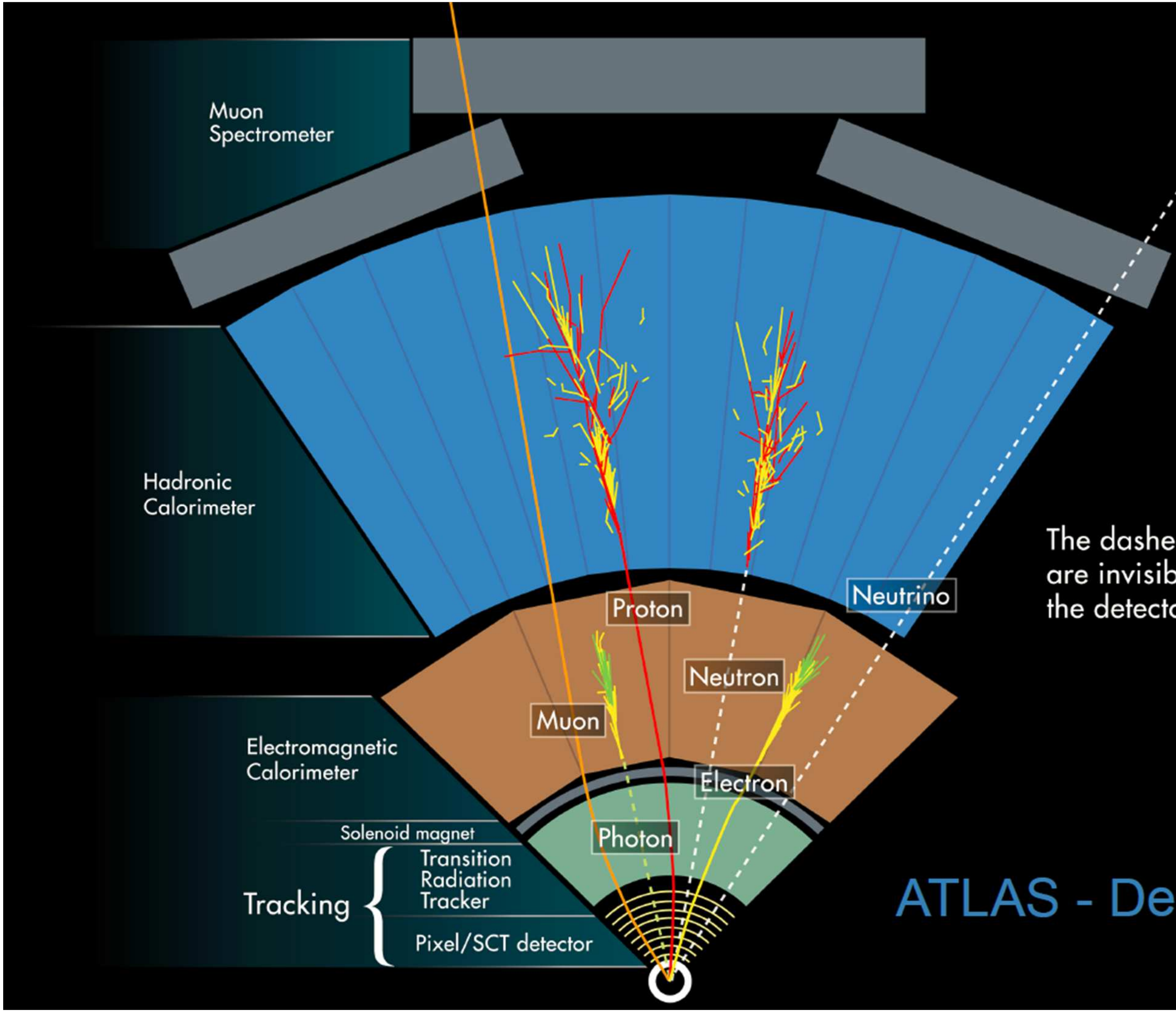
- **New Materials** (other semiconductors than Si)
  – Diamond, Silicon Carbide (SiC), …
- **New detector designs**
  – Examples:
    - p-type silicon detectors (n-in-p)
    - thin detectors, epitaxial detectors
    - 3D and Semi 3D detectors
- **Cryogenic operation of detectors**

Operate detectors at 100-200K to reduce the charge loss

Active CERN R&D collaborations:

- *RD50 "Radiation hard semiconductor devices for very high luminosity colliders"*
- *RD42 "CVD Diamond Radiation Detectors"*
- *RD39 "Cryogenic Tracking Detectors"*

ATLAS - Detector



The dashed tracks are invisible to the detector

Pixel Detectors in HEP–Short historical excursus

First use in HEP Experiments: CCDs used early 1980s in SLD/SLAC and NA11/32 CERN

“The silicon micropanern detector: a dream?”
E.H.M Heijine, P. Jarron, A. Olsen and N.Redaelli,
Nucl.Instrum.Meth.A273(1988)615

“Development of silicon micropanern detectors”
CERN RD19 collabora1on, *Nucl.Instrum.Meth.A348(1994)399*

1995 – First Hybrid Pixel detector installed in WA97 (CERN,Omega facility)

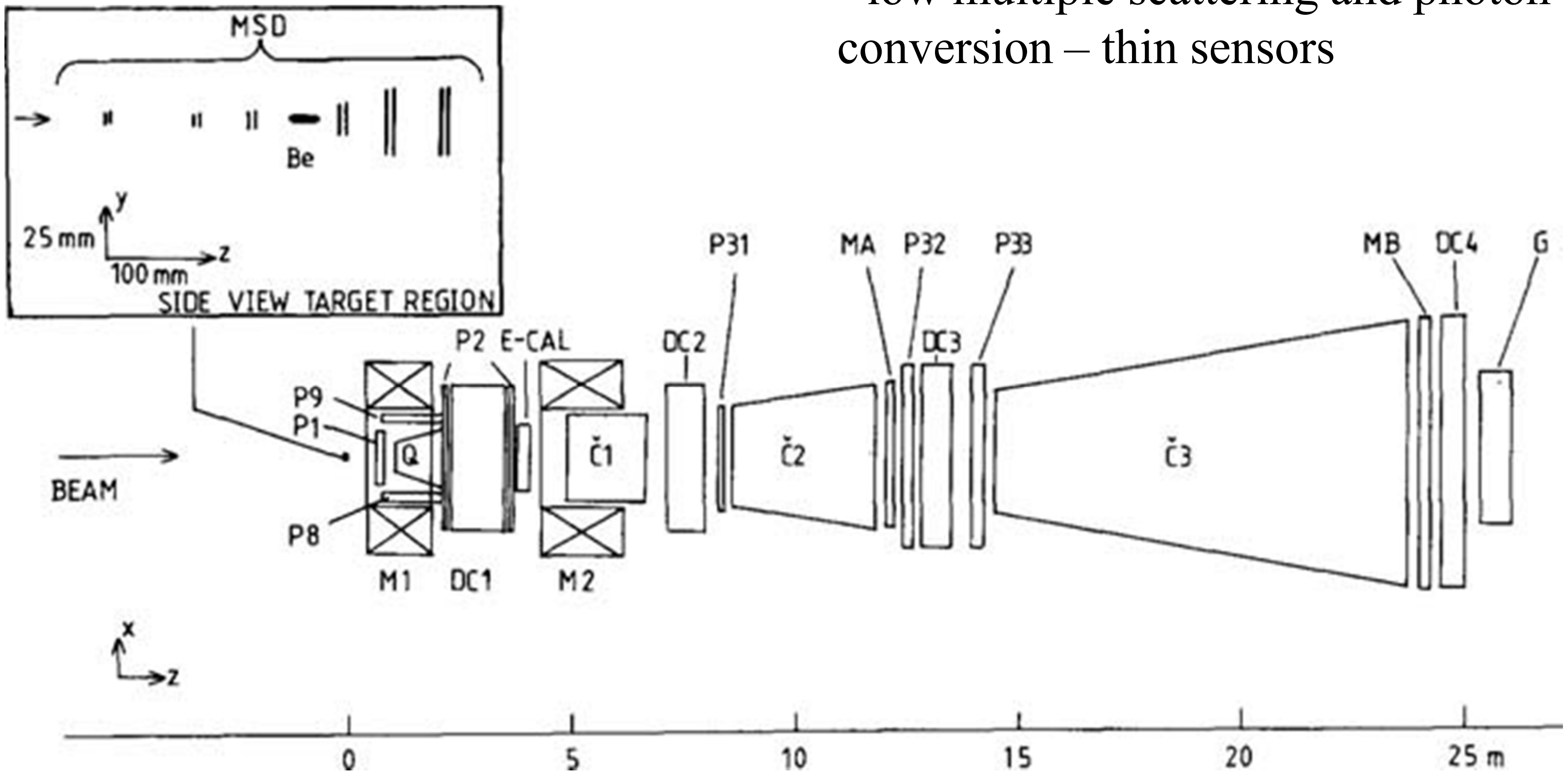
1996/97 – First Collider Hybrid Pixel Detector installed in DELPHI (CERN, LEP)

First Silicon Strip Detector in NA11 and NA32

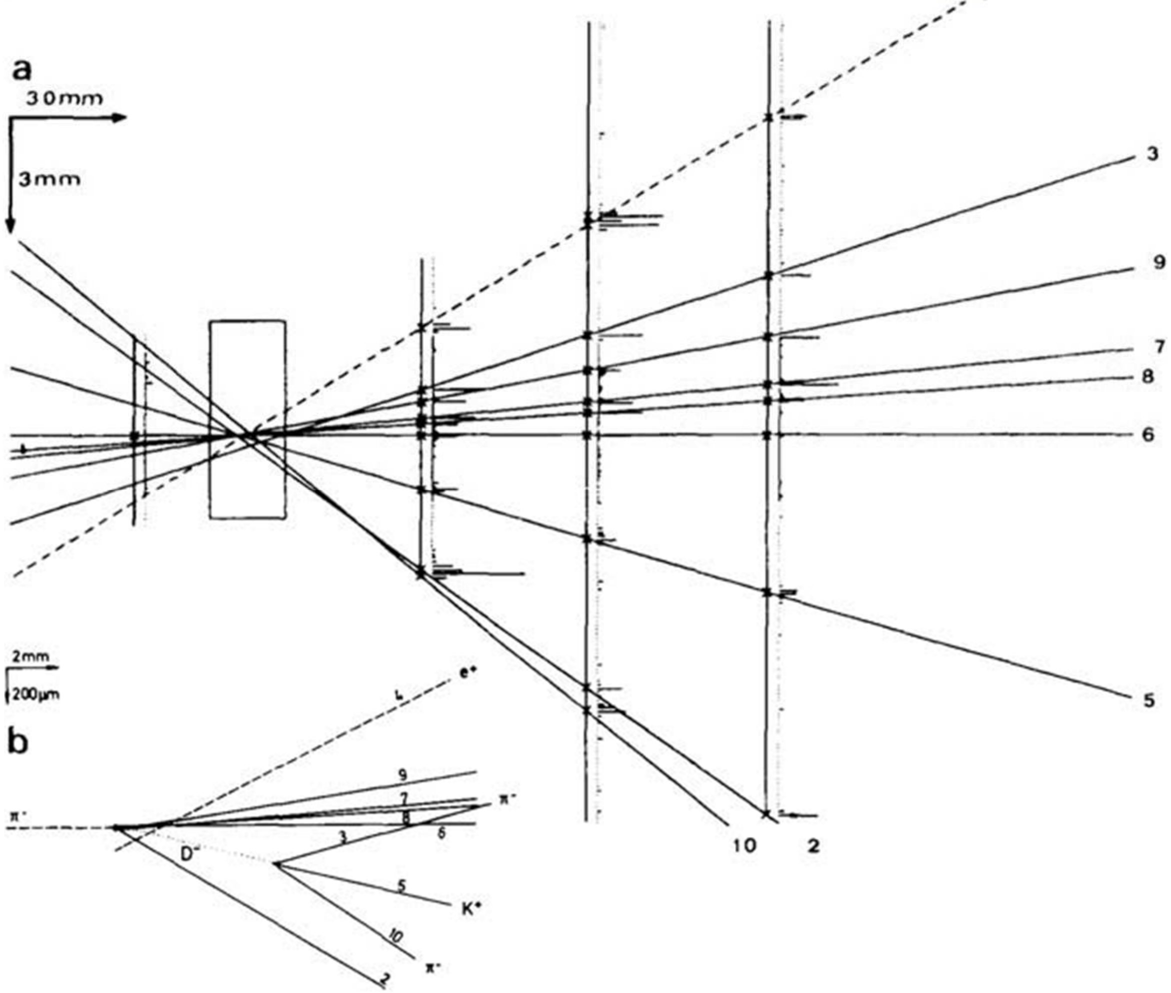
for lifetimes of the lowest mass charm states were of the order of 0.1 ps corresponding to $c\tau \sim 30\mu\text{m}$

The requirements:

- spatial resolution: better than 10µm and good particle separation
- rate capability about 10^6 Hz
- low multiple scattering and photon conversion – thin sensors



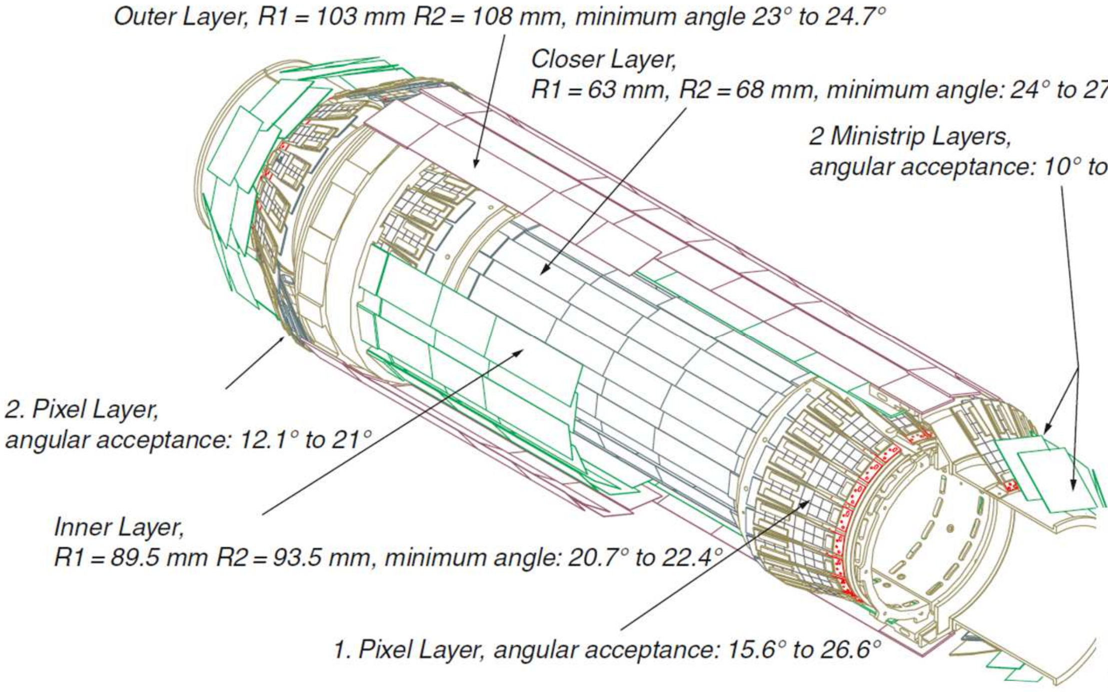
NA11 experiment



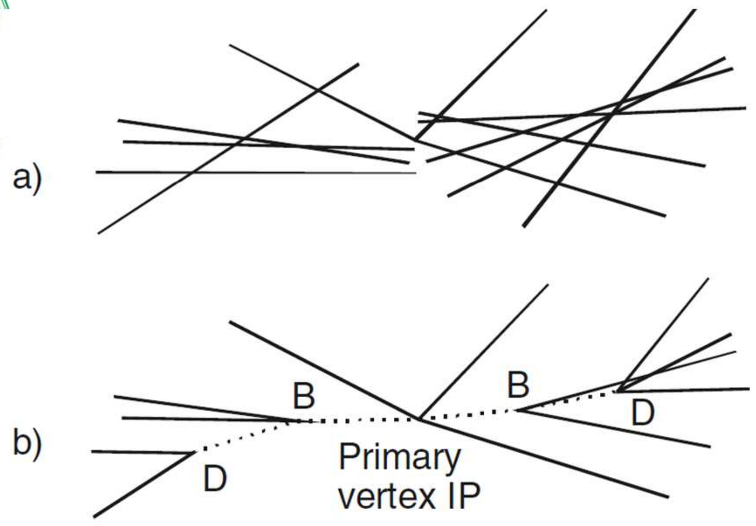
Reconstruction of the production and decay of a D^- → $K^+\pi^-\pi^-$ as measured in the NA11 experiment in 200 GeV/c π^- Be interactions

- the measured pulse height in the silicon sensors.
- The connecting lines represent the reconstructed particle paths.
- trajectories 3, 5, 10 are not originating from the same decay point as the others. They are not starting from the primary vertex, but from a secondary vertex.

The DELPHI Microvertex Detector (MVD)



- identify heavy quarks and τ
- lifetimes are around 0.2 – 1.5ps

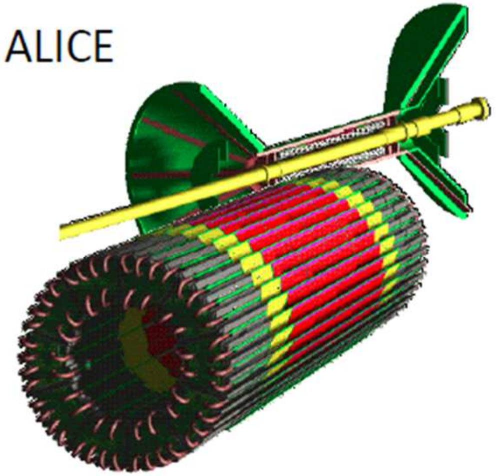


Hybrid Active Pixel Sensor (HAPS) module

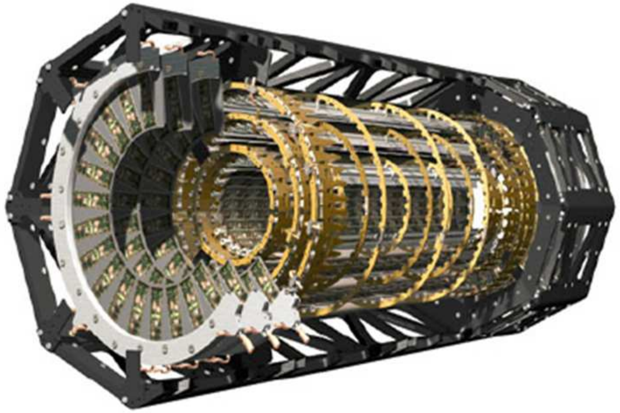
- **Sensor**
  - 8064 pixels
  - 320μm (Rφ)×320μm (z)
  - DC coupled readout
- **16 FE chips**
  - bump bonded to sensor

Pixel Detectors in LHC experiments — Hybrid

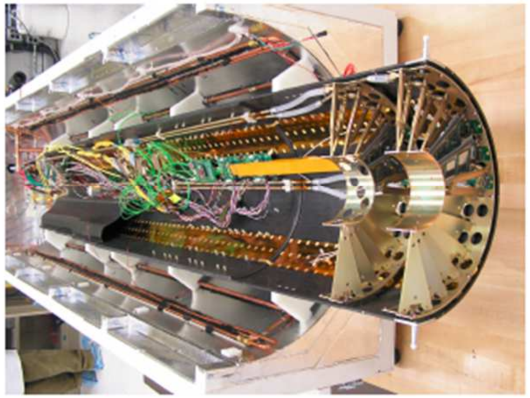
ALICE



ATLAS



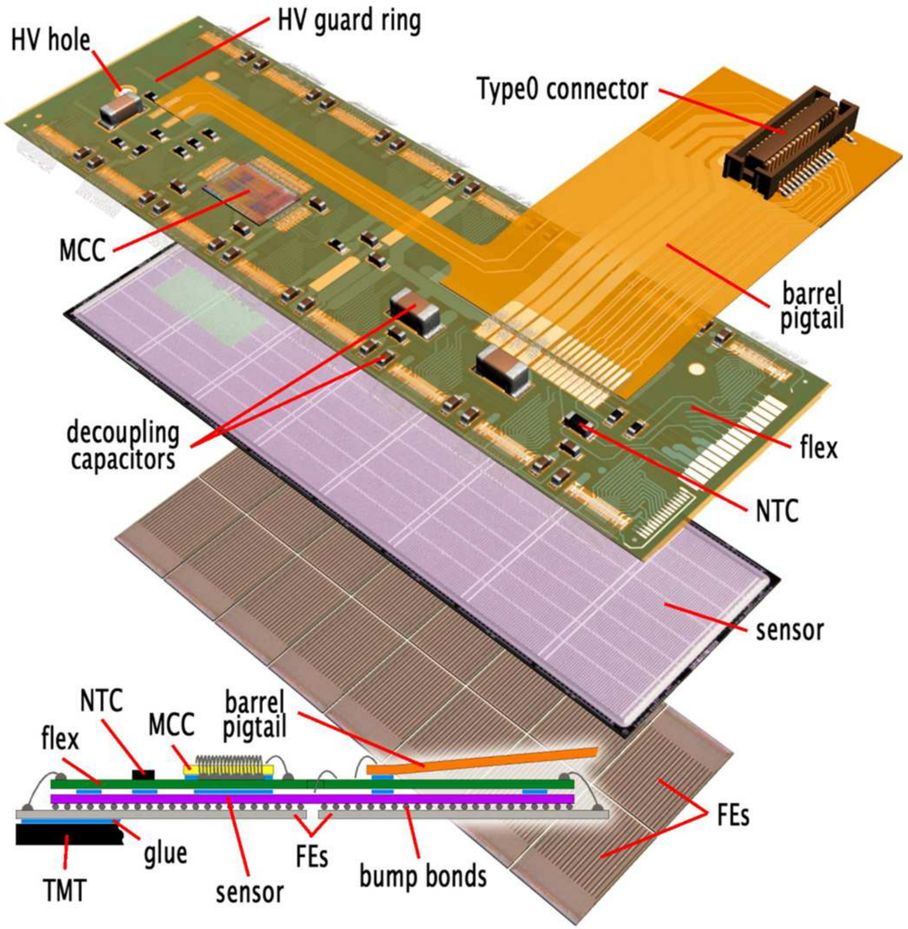
CMS



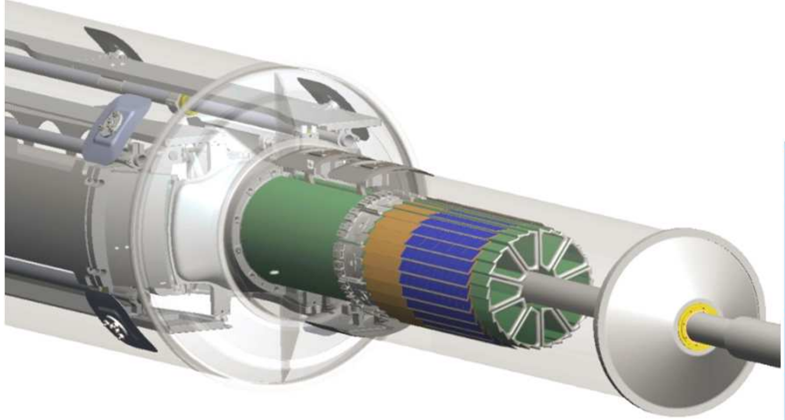
Parameters	**ALICE**	**ATLAS**	**CMS**
Nr. layers	2	3	3
Radial coverage [mm]	**39** - 76	**50** - 120	**44** – 102
Nr of pixels	9.8 M	80 M	66 M
Surface [m^2]	0.21	1.7	1
Cell size (rϕ x z) [μm^2]	50 x 425	50 x 400	100 x 150
Silicon thickness (sens. + ASIC) - x/X_0 [%]	0.21 + 0.16	0.27 + 0.19	0.30 + 0.19

ATLAS Pixel Module

- **Sensor**
  - 47232 pixels
  - 250μm thickness
  - 50μm (Rφ)×400μm (z)
  - 328 rows (x_{local})×144 columns (y_{local})
- **16 FE chips**
  - bump bonded to sensor
- **Flex Hybrid**
  - passive components
  - Module Controller Chip to perform distribution of commands and event building
- **Radiation-hard design:**
  - Dose >500 Gy
  - NIEL >1015 neq/cm2 fluence

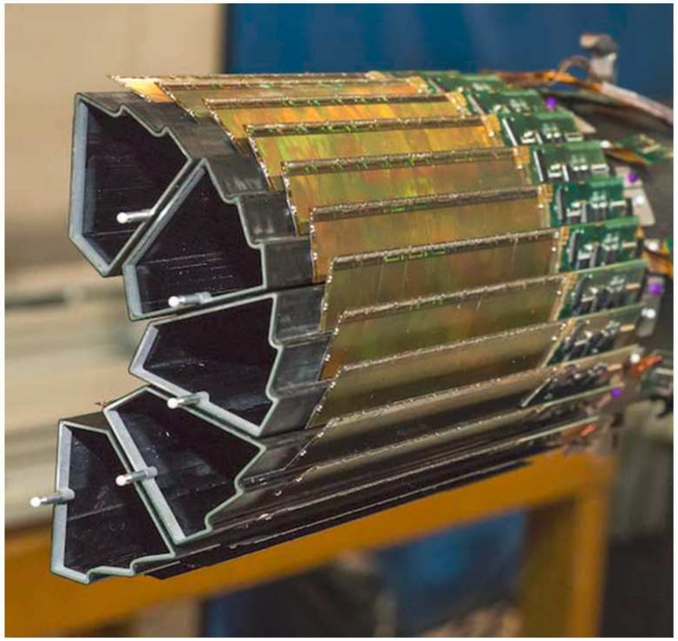


STAR Pixel Detector (PXD) — Monolithic

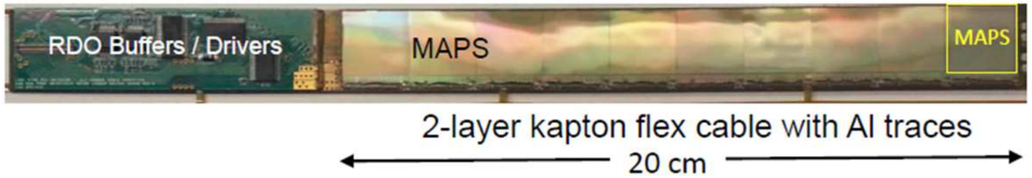


L. Greiner (LBL) / CPIX-2014

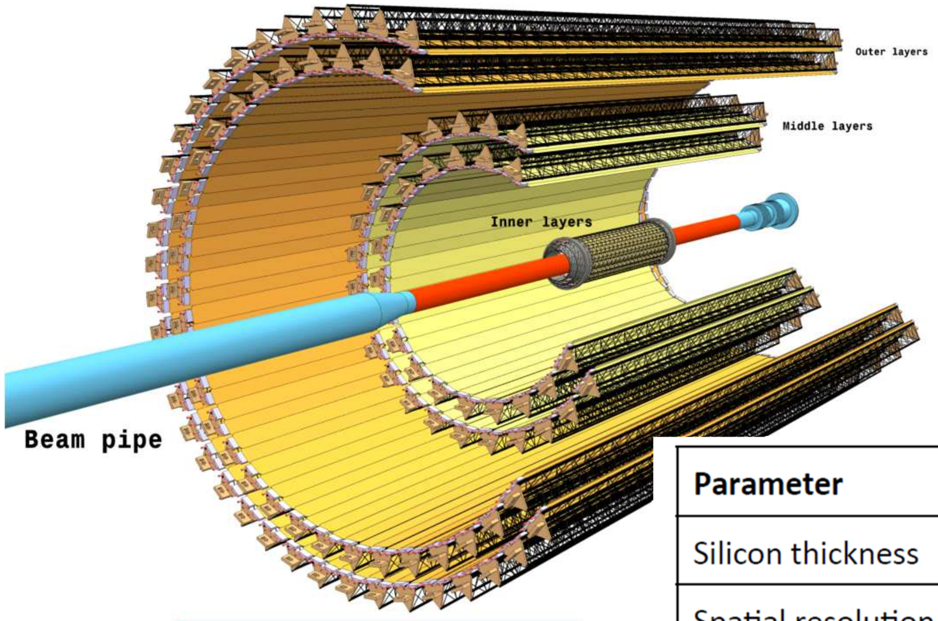
DCA Pointing resolution	$(12^{(*)} \oplus 24\ \text{GeV}/p\cdot c)\ \mu\text{m}$
Layers	Layer 1 at 2.8 cm radius Layer 2 at 8 cm radius
Pixel size	20.7 μm X 20.7 μm
Hit resolution	3.7 $\mu\text{m}^{(*)}$ (6 μm geometric)
Position stability	6 μm rms (20 μm envelope)
Radiation length first layer	x/X_0 = 0.39% (Al conductor cable)
Number of pixels	356 M
Integration time (affects pileup)	185.6 μs
Radiation environment	20 to 90 kRad / year $2*10^{11}$ to 10^{12} 1MeV n eq/cm^2
Rapid detector replacement	~ 1 day



Ladder with 10 MAPS sensors (~2cm×2cm each)



ALICE ITS upgrade — Monolithic



12.5 G-pixel camera
(~10 m^2)

Improve impact parameter resolution by a factor of ~3

- Get closer to IP : 39mm → 23mm
- Reduce x/X0/layer: ~1.14% → ~0.3% (for inner layers)
- Reduce pixel size: currently 50µmx425µm → O(30µmx30µm)

- Material/layer: 0.3%X0(IB), 1%X0(OB)
- CMOS Pixel Sensor using TowerJazz 0.18µm CMOS Imaging Process

Parameter	**Inner Barrel**	**Outer Barrel**
Silicon thickness	50 µm	
Spatial resolution	5 µm	10 µm
chip dimensions	15 mm x 30 mm	
Power density	< 300 mW/cm^2	< 100 mW/cm^2
Event time resolution	< 30 µs	
Detection efficiency	$> 99\%$	
Fake hit rate	$< 10^{-5}$ per readout frame	
TID radiation hardness (*)	2700 krad	100 krad
NIEL radiation hardness (*)	1.7×10^{13} 1MeV n_{eq}/cm^2	10^{12} 1MeV n_{eq} / cm^2

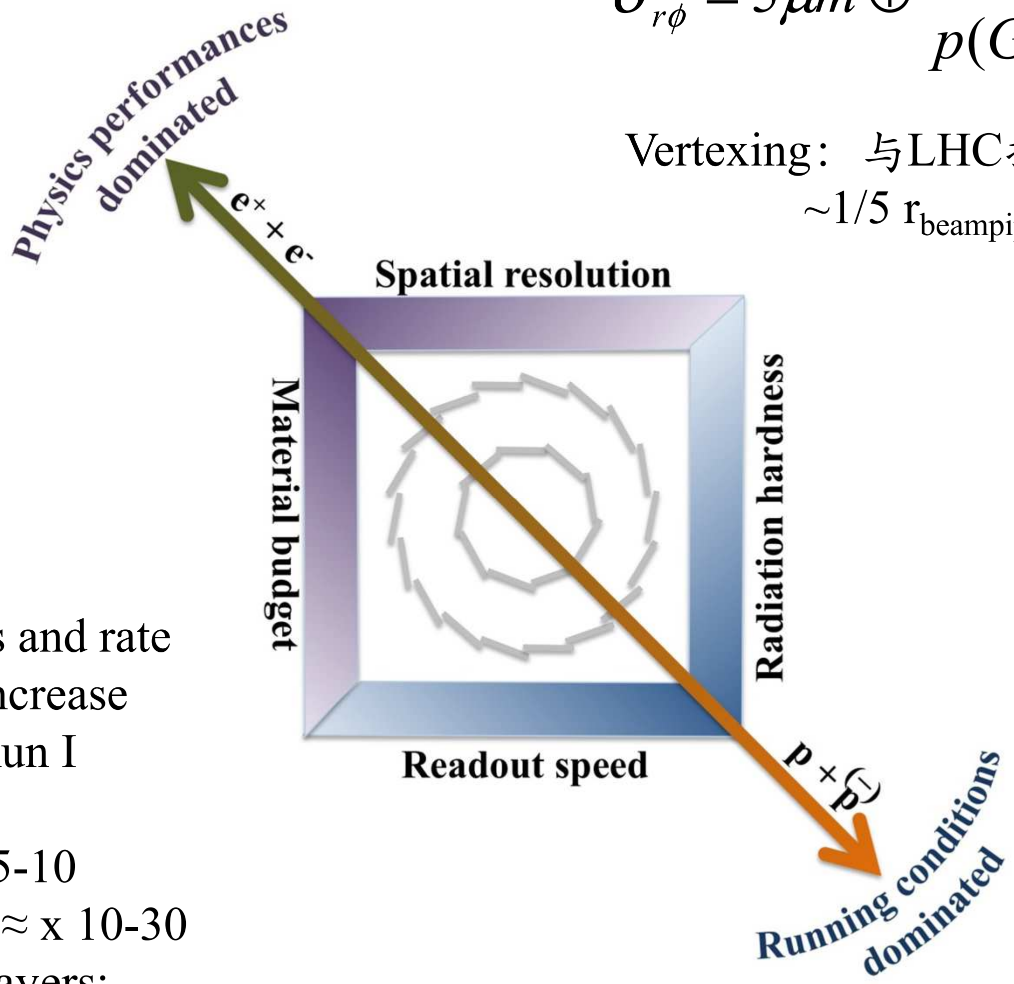
Outlook: future development

正负电子对撞机实验 → ILC、CEPC

$$\sigma_{r\phi} = 5\mu m \oplus \frac{10}{p(GeV)\sin^{3/2}\theta}\mu m$$

Vertexing：与LHC探测器相比

~1/5 $r_{beampipe}$，~1/30 像素面积

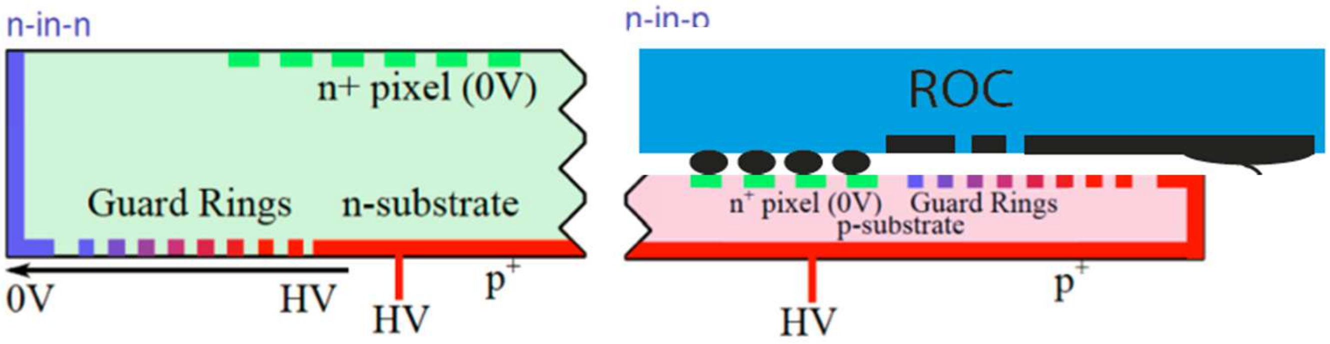


- Radiation hardness and rate performance must increase compared to LHC Run I
  - – Run 2 (2015) ≈ x5
  - – Run 3 (2018) ≈ x 5-10
  - – HL-LHC (>2025) ≈ x 10-30
- In the inner pixel layers:
  - – 10^{16} $n_{eq}cm^{-2}$
  - – TID > 1 Grad

强子对撞机实验 → HL-LHC

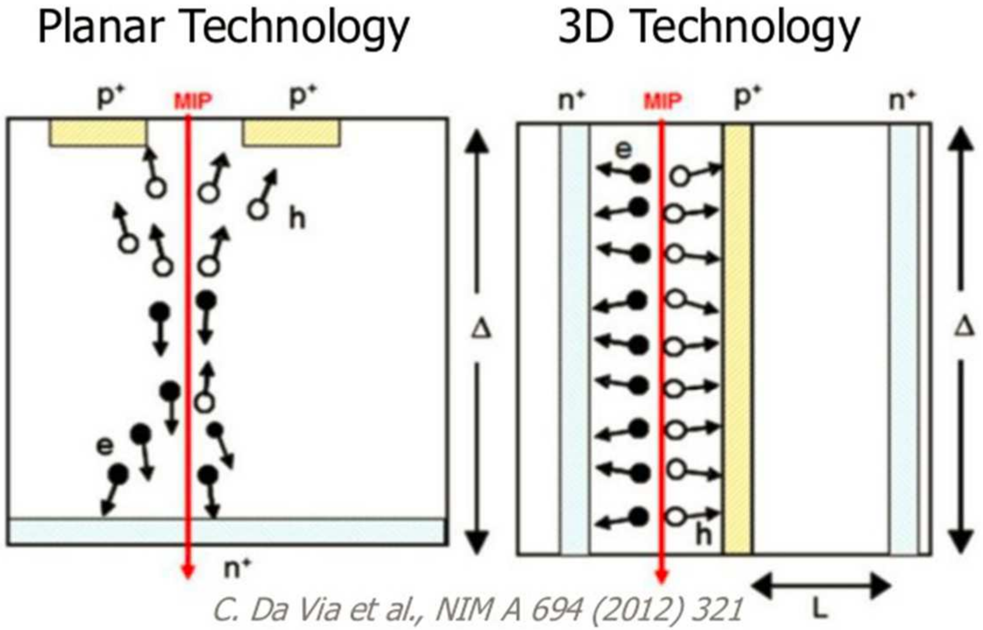
Pixel development for HL-LHC

- Thin planar n^+ in p sensors



Advantages:
– faster charge collection (electrons have higher v_{drift})
– Less signal and CCE degradation

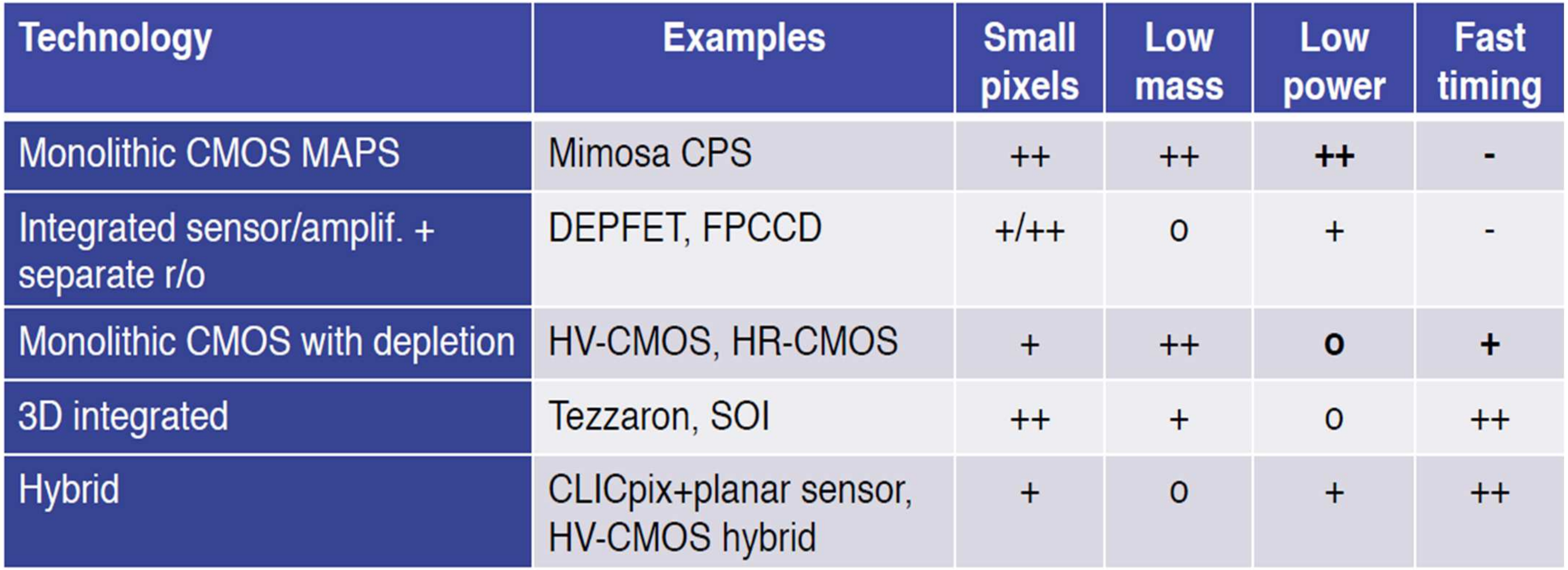
- 3D sensors



C. Da Via et al., NIM A 694 (2012) 321

Advantages
– Decouple thickness from electrode distance
– Lower depletion voltage, less power dissipation
– Smaller drift distance, less trapping

正负电子对撞机实验R&D及性能比较



Technology	Examples	Small pixels	Low mass	Low power	Fast timing
Monolithic CMOS MAPS	Mimosa CPS	++	++	**++**	**-**
Integrated sensor/amplif. + separate r/o	DEPFET, FPCCD	+/++	o	+	-
Monolithic CMOS with depletion	HV-CMOS, HR-CMOS	+	++	**o**	**+**
3D integrated	Tezzaron, SOI	++	+	o	++
Hybrid	CLICpix+planar sensor, HV-CMOS hybrid	+	o	+	++

Recent developments in LC vertex and tracking R&D，Dominik Dannheim，LCWS 2015

详细内容由卢云鹏介绍