Vertex detectors at e^+e^- and high energy pp colliders

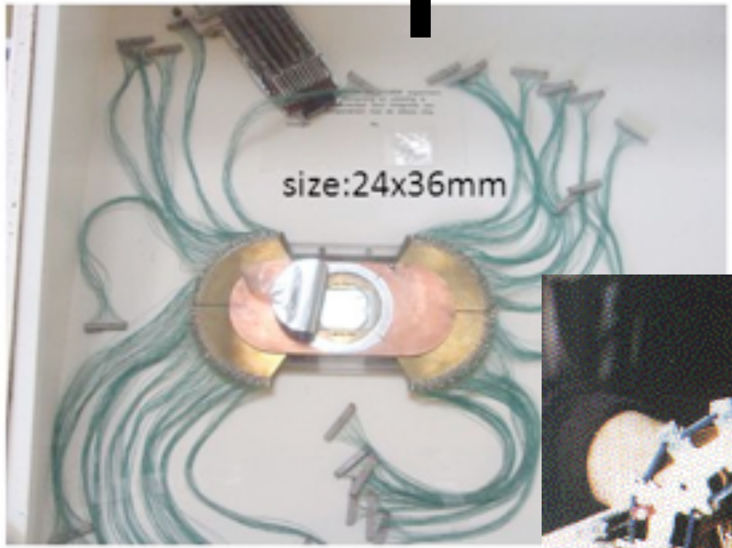
Alberto Cervelli

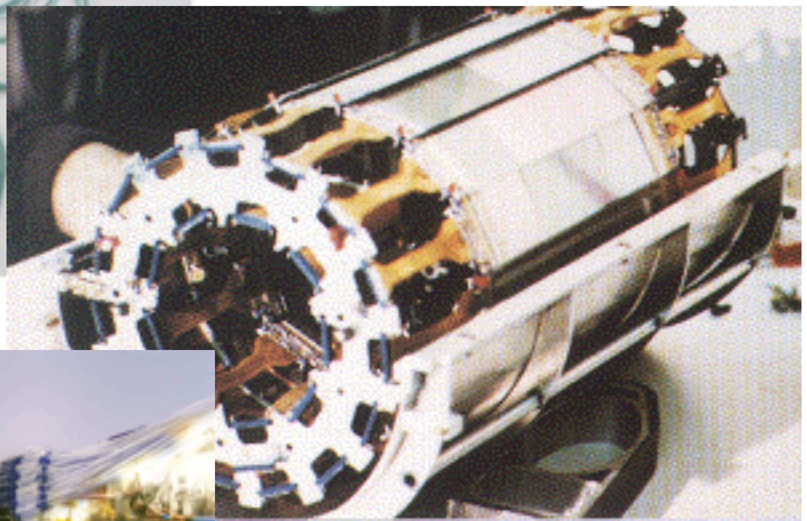
My Experience so far

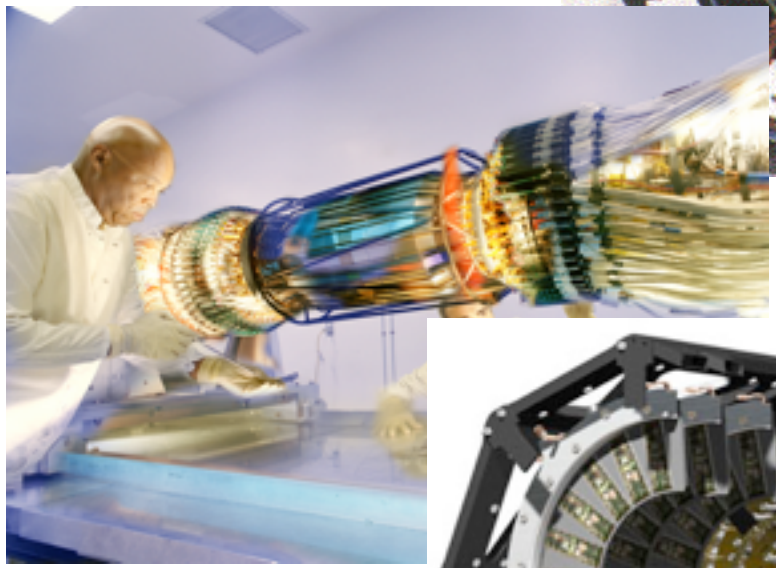
- 2005 Graduated in Univesità di Pisa: tau decays in strange final states
- 2006-2009: PhD in Univesità di Pisa: BaBar experiment, SVT operations and LFV in tau sector
- 2009-2011: Assegno di ricerca at Univesità di Pisa: Development of new silicon detectors for super flavor factories, studies for g-2 measurement in tau decays, impact of polarized beams in LFV searches in tau decays
- 2012-ongoing: PostDoc Universität Bern:
  - Atlas experiment: IBL construction and readout, SUSY searches in EWK production, R&D for ITK (LR HV-CMOS)
  - PET-TT (ToF PET project)
  - Space applications of HEP detectors (collaboration with JUICE mission)

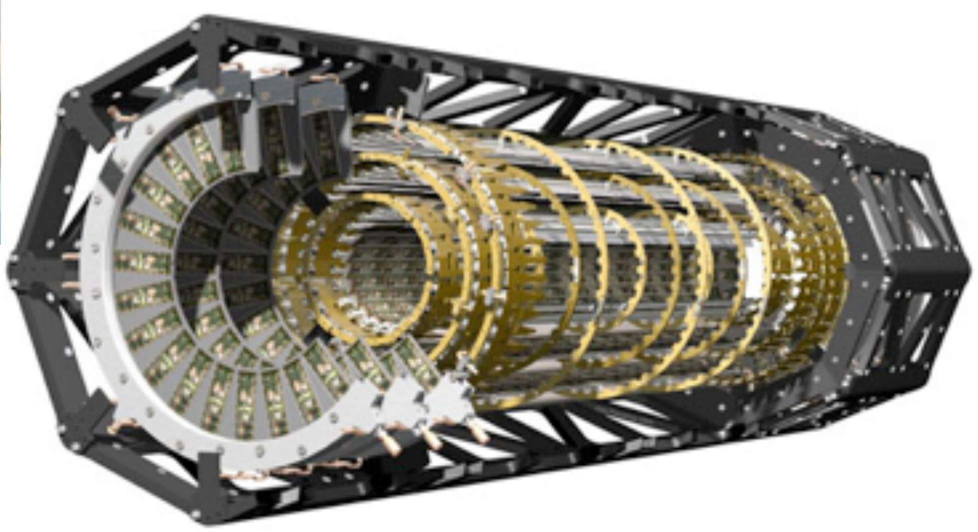
Silicon Vertexes: Historic Perspective

- ‘70s : first Silicon Vertex detectors
- First use: coherent production in fixed target experiment
- ‘80s: micro strips reached few μm resolution
- now: Pixel detectors
- Breakthroughs in HEP: top discovery, direct CPV in B observation, physics at high energy pp colliders

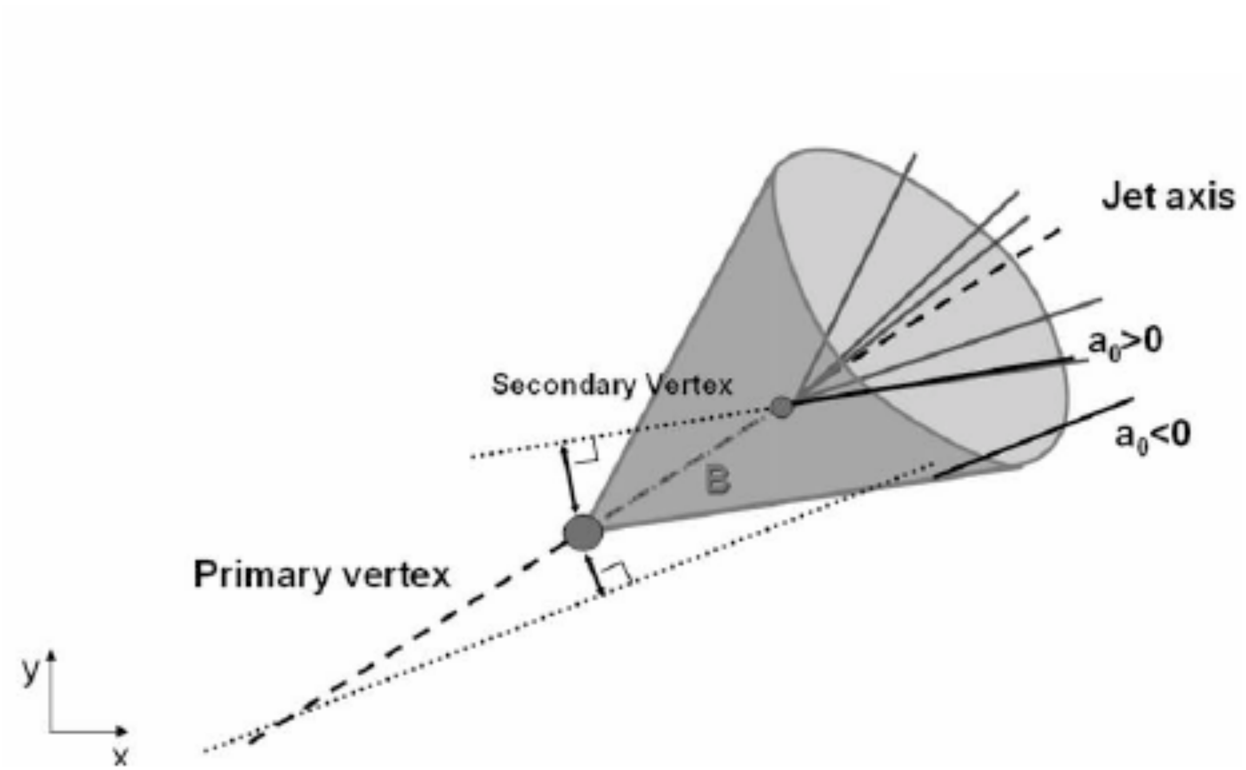








Vertexing



- Aim of a vertex detector: resolve both primary and decay vertices and those from secondary particles
- Require: 3D hit reconstruction, high granularity, proximity to the Interaction Point
- Strongly dependent on resolution of innermost layer and detector lever arm

- Silicon detectors: small size, high channel density, good electric properties at room temperature, high rate capabilities.
- Different physics case need different approaches in detector development

Tracking

Particle P_T in a B field is measured through tracking.

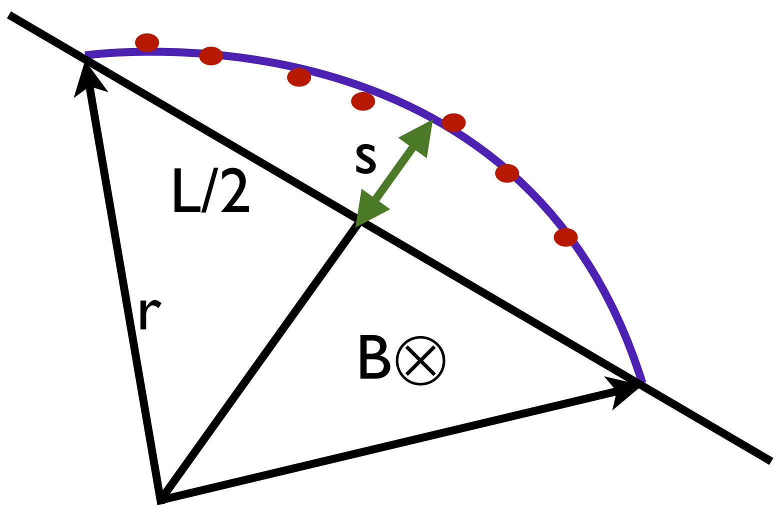
P_T is function of the sagitta:

$$\sigma_s = \sqrt{\frac{A_N}{N+4}} \cdot \frac{\sigma_{r_\phi}}{8}$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{8 p_T}{0.3 B L^2} \cdot \sigma_s$$

Resolution is worsened by other contributions: e.g. Multiple Scattering, constant for given P_T:

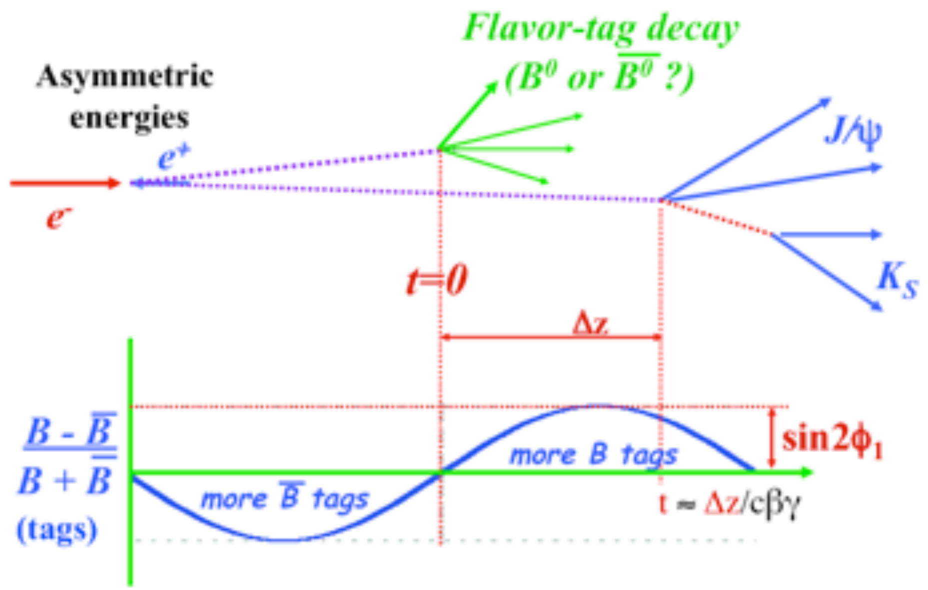
$$\left.\frac{\sigma P_T}{P_T}\right|_{MS} = 0.045 \frac{1}{B\sqrt{t X_0}}$$



Tracking resolution:

- is inversely proportional to P_T
- increases linearly with the B field intensity
- increases quadratically with the dimension of tracking volume
- increase with the square root of tracking points
- decrease with square root of budget material

Vertexing for Flavor Physics: BaBar



BaBar designed to measure B meson mixing

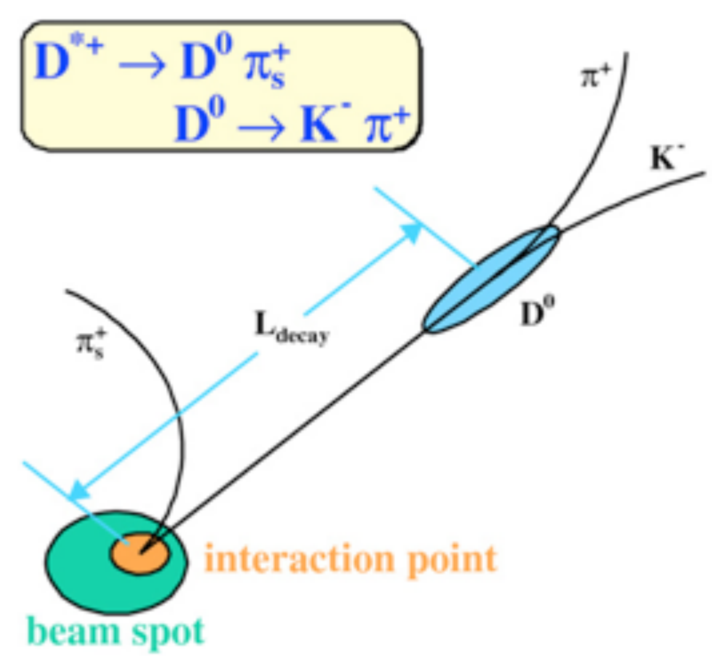
BaBar operated at asymmetric machine: ϒ(4S) produced at rest in CM, decay time proportional to the decay length of the B in lab frame

Resolution <80μm, and the σ(Δz)<125μm to resolve B Vertices.

Other goal: understanding up-sector CPV:

D mesons not produced coherently at ϒ(4S) energy, D tagging made by measuring P and charge of soft pion emitted by the D*.

Soft pion: low P_T tracked only by the Silicon tracker, standalone tracking for P_T<100 MeV

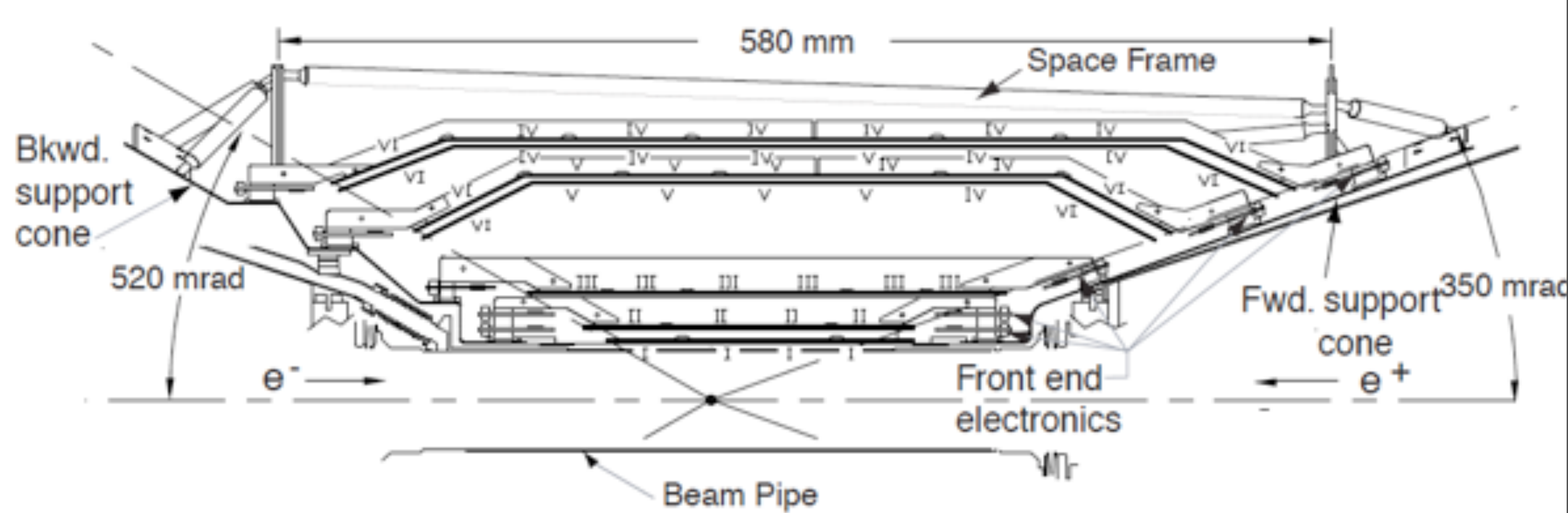


BaBar SVT

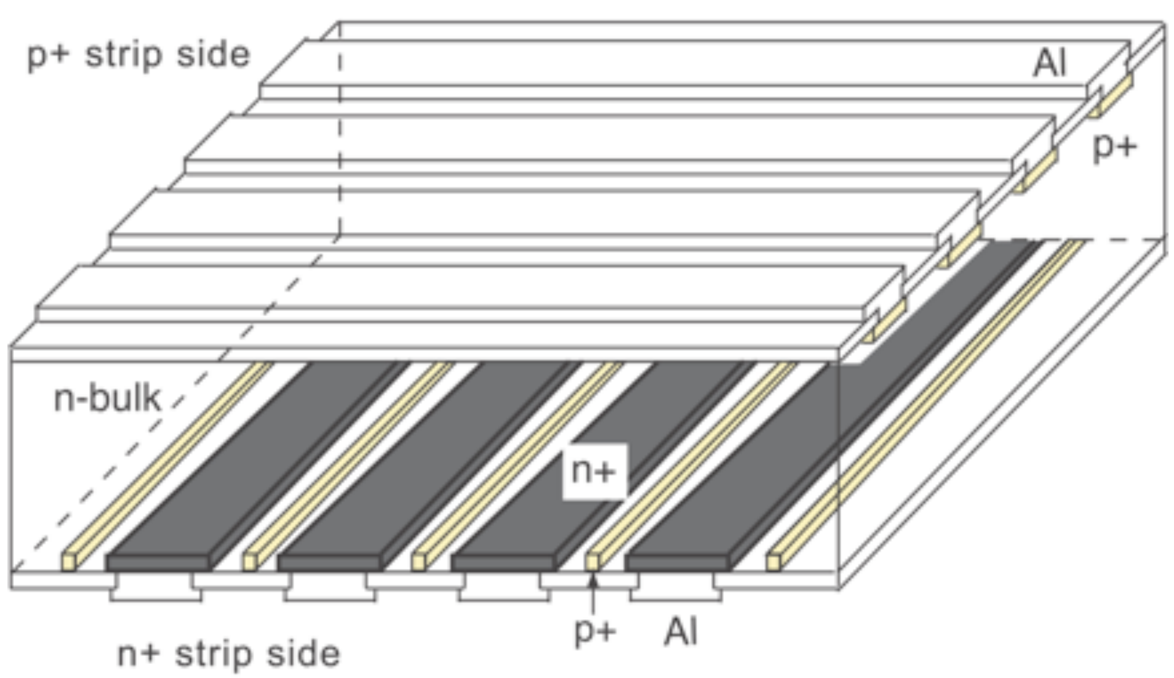
Asymmetric design, but uniform performance for all polar angles.

Low P particles: budget material kept at minimum.

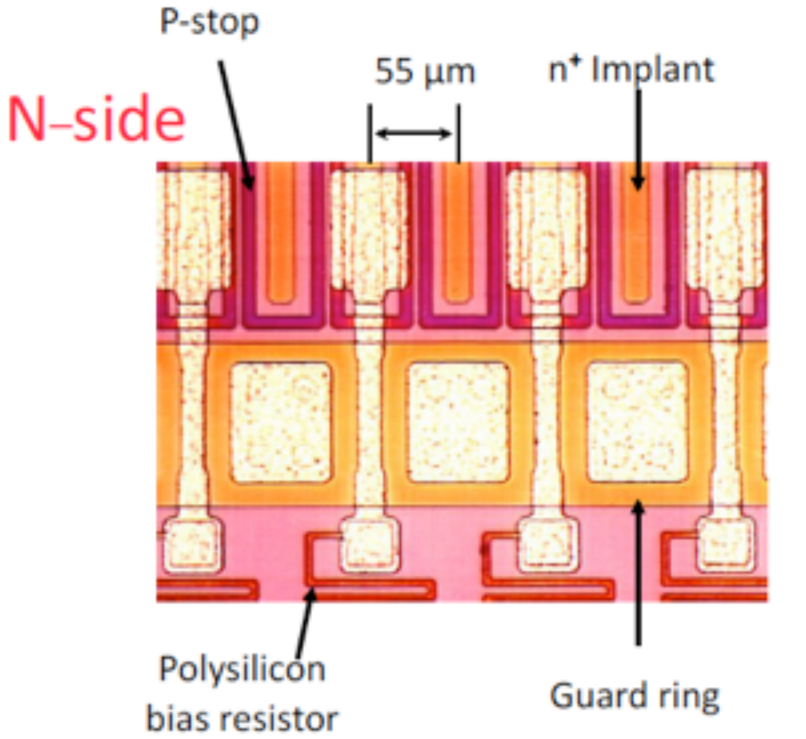
High radiation environment: high luminosity ($10^{34} cm^{-2} s^{-1}$) requires operation to be stable for >2MRad

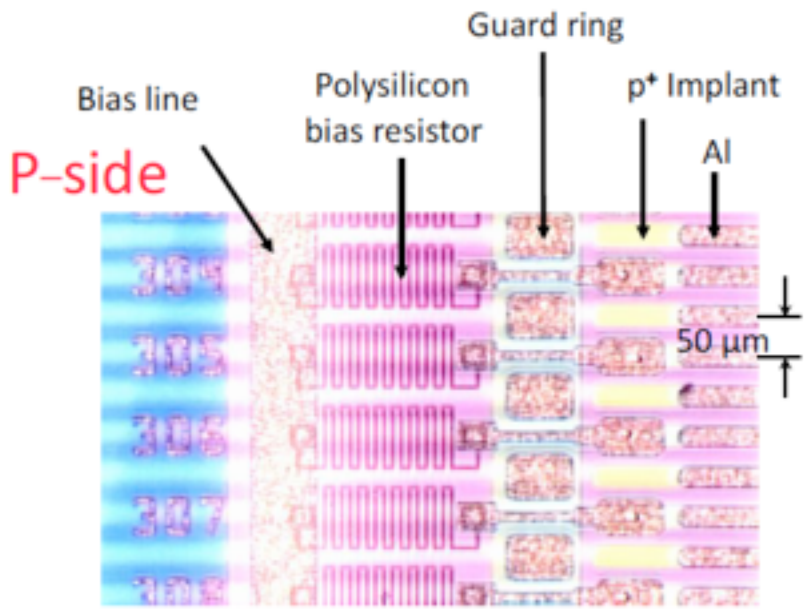


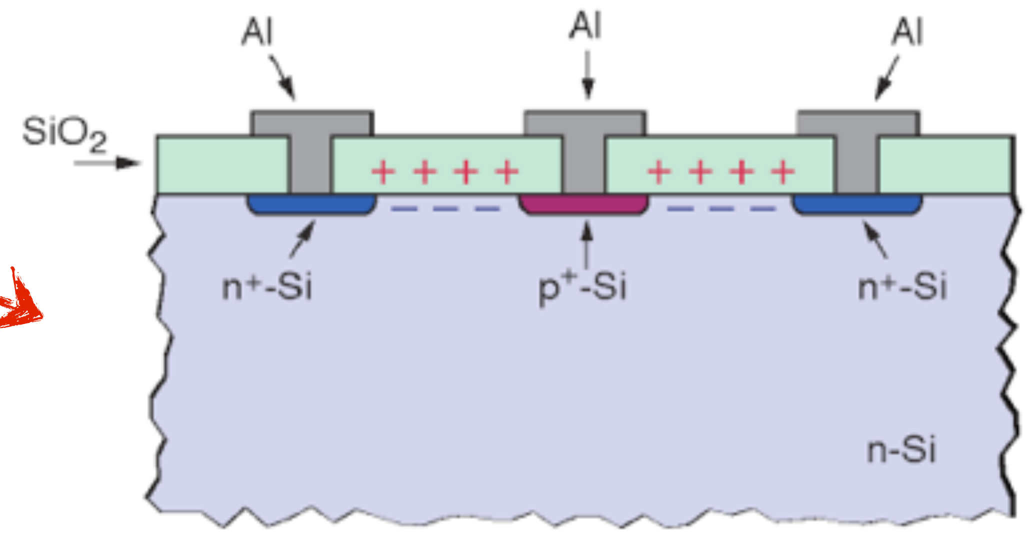
- 300 μm Silicon wafer thickness
- 5 Layers of double sided lecture silicon, with stereo strips.
- 1556 readout chips, 140K channels
- 50 μm pitch for p,n strips in inner layers, and p-side on outer layers, 100μm pitch on n-side outer layers
- Six different module geometries
- Bias Voltage applied 10-40V
- Maximum trigger rate 10KHz
- Maximum hit rate/channel 150KHz
- Budget material 5% X_0



BaBar SVT

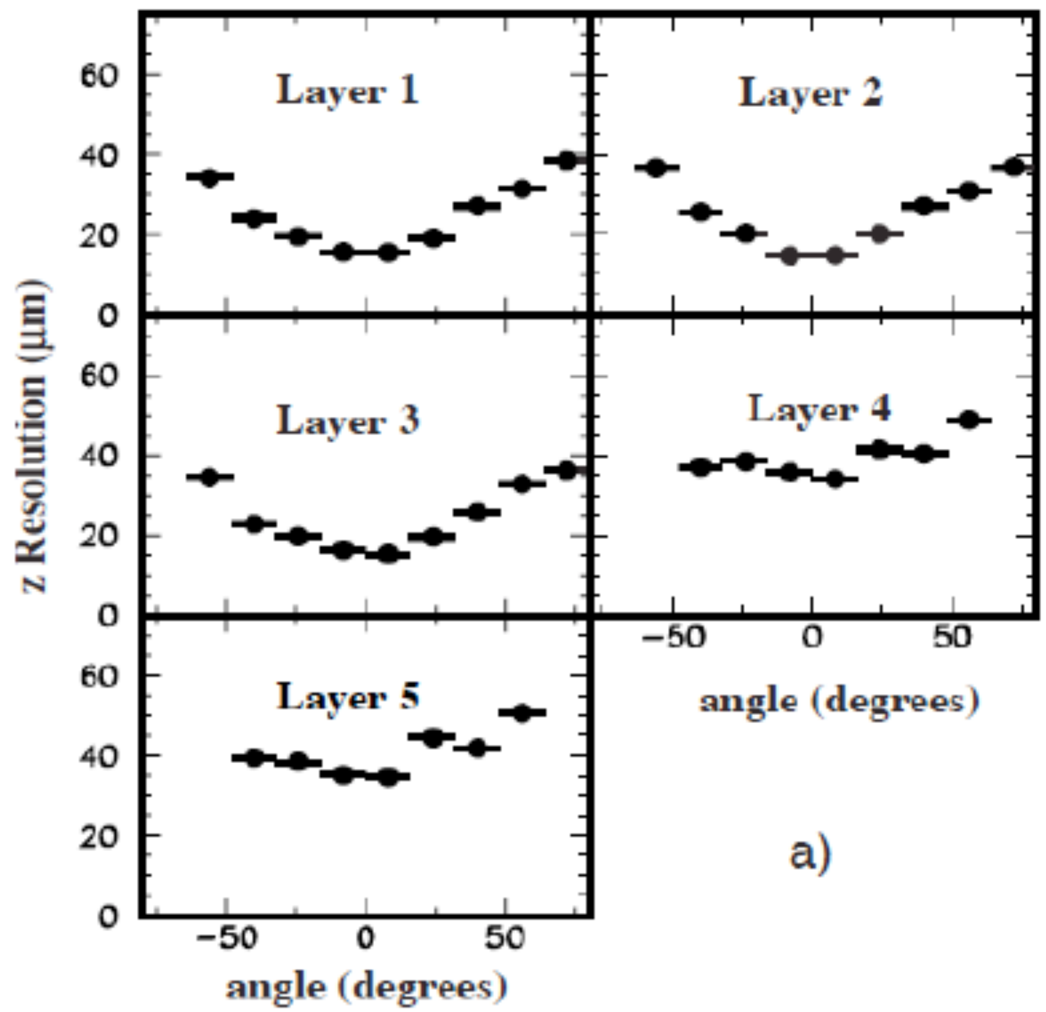


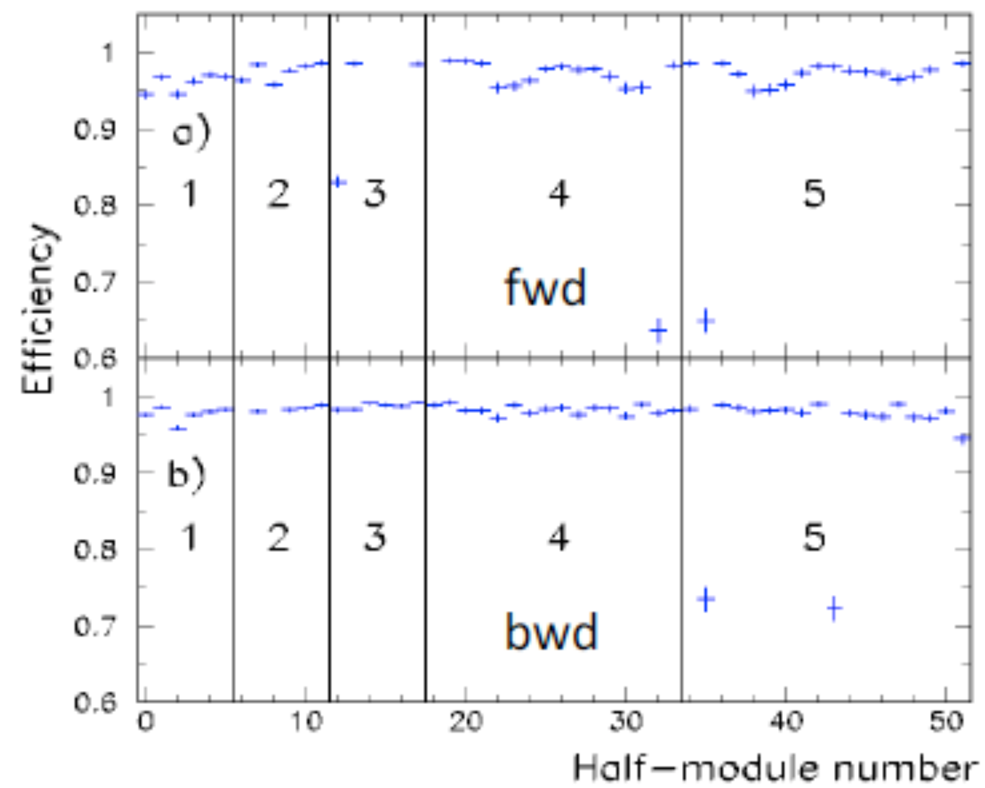




To avoid shortening of the n^+ strips on the n-side a p^+ implant is added (p-stop)

SVT Performances



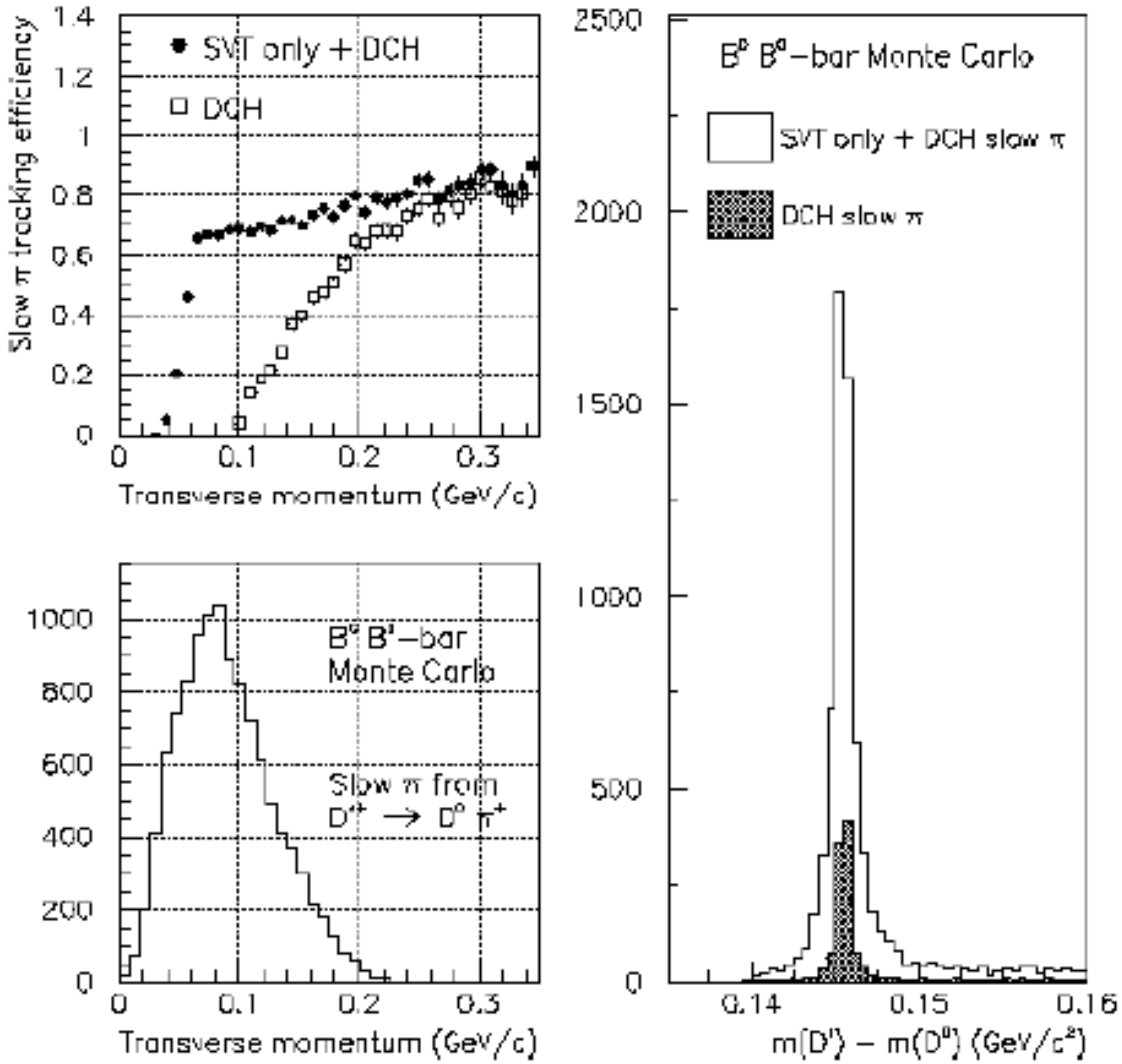


TDR target for perpendicular tracks:
Layer 1-3 10-15µm
Layer 4-5 30-40µm

Average efficiency ~98% per track

The BABAR Detector: Upgrades, Operation and Performance NIM A729 (2013) 615-701

Physics Results



Soft pion reconstruction from
$D^{\star +} \to \pi^+ D^0$
mostly done by Silicon Vertex tracker alone
First evidence of D^0 mixing

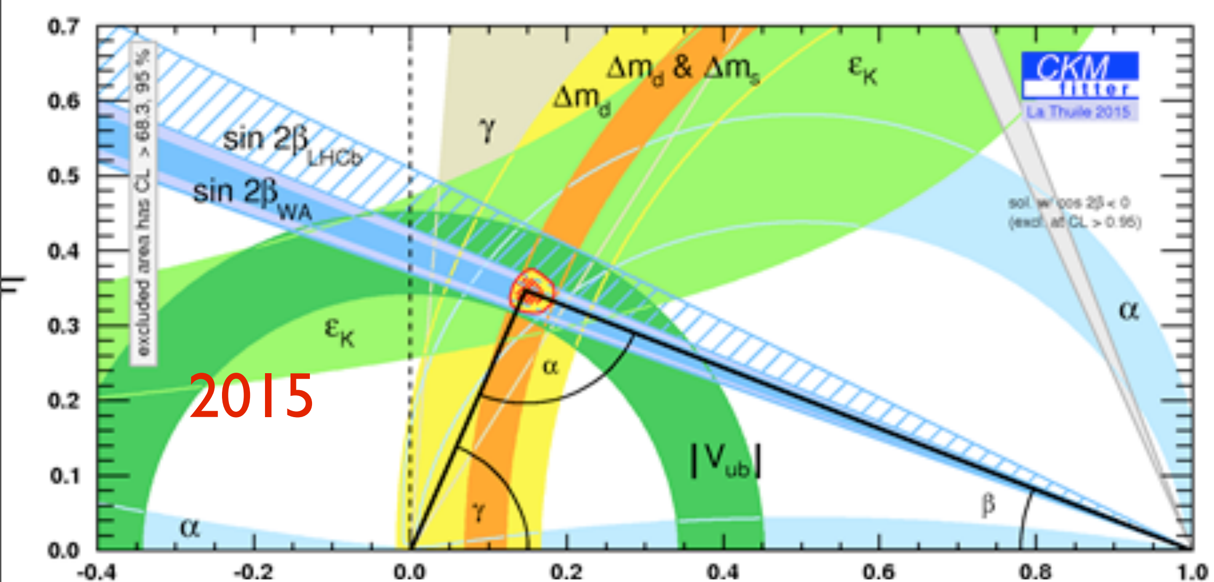
Resolution in z allowed for precise B meson mixing measurements

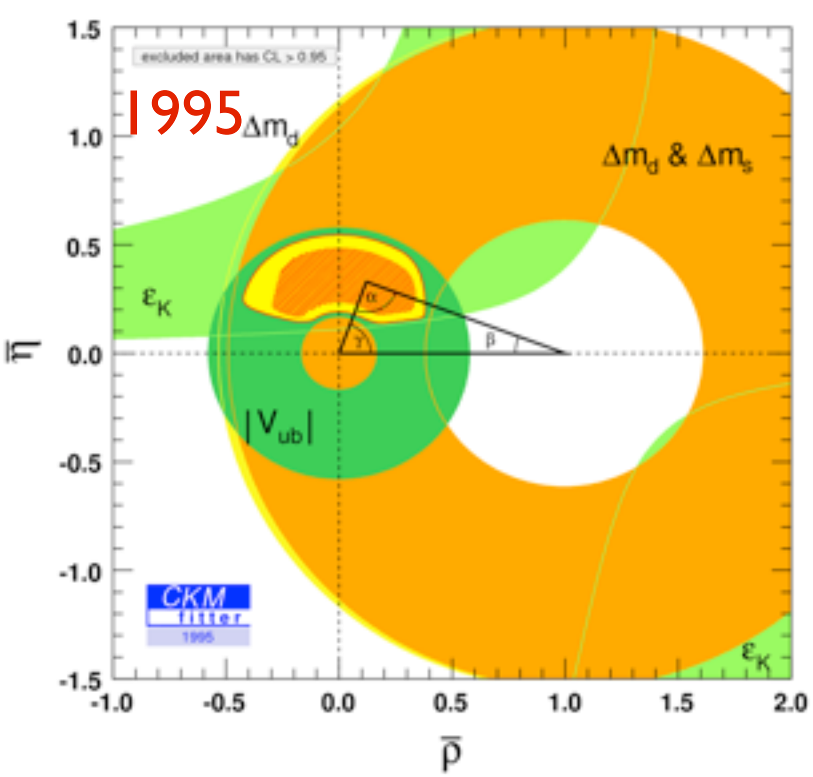
Neutral Mesons

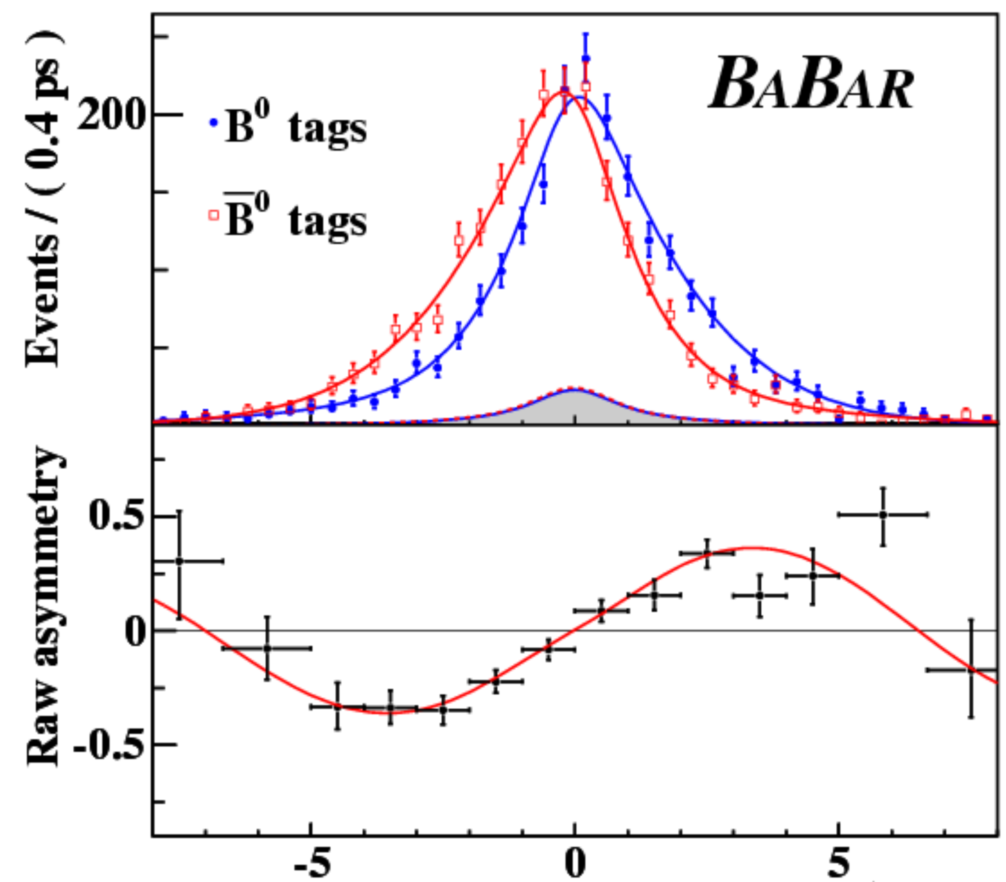
BaBar and Belle managed to measure the flavor property of the SM at unprecedented precision.

This effort was made possible by the use of a precise and efficient Silicon vertex tracker.

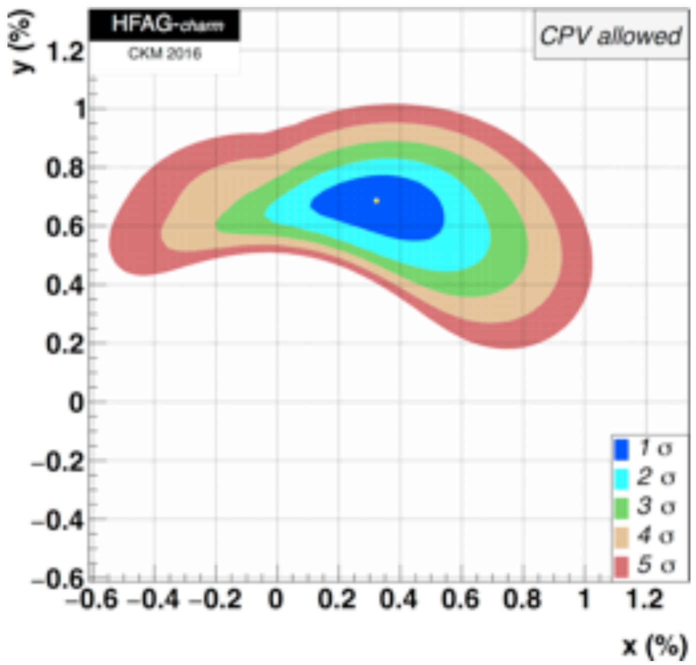
Resolution in z allowed for precise B meson mixing measurements







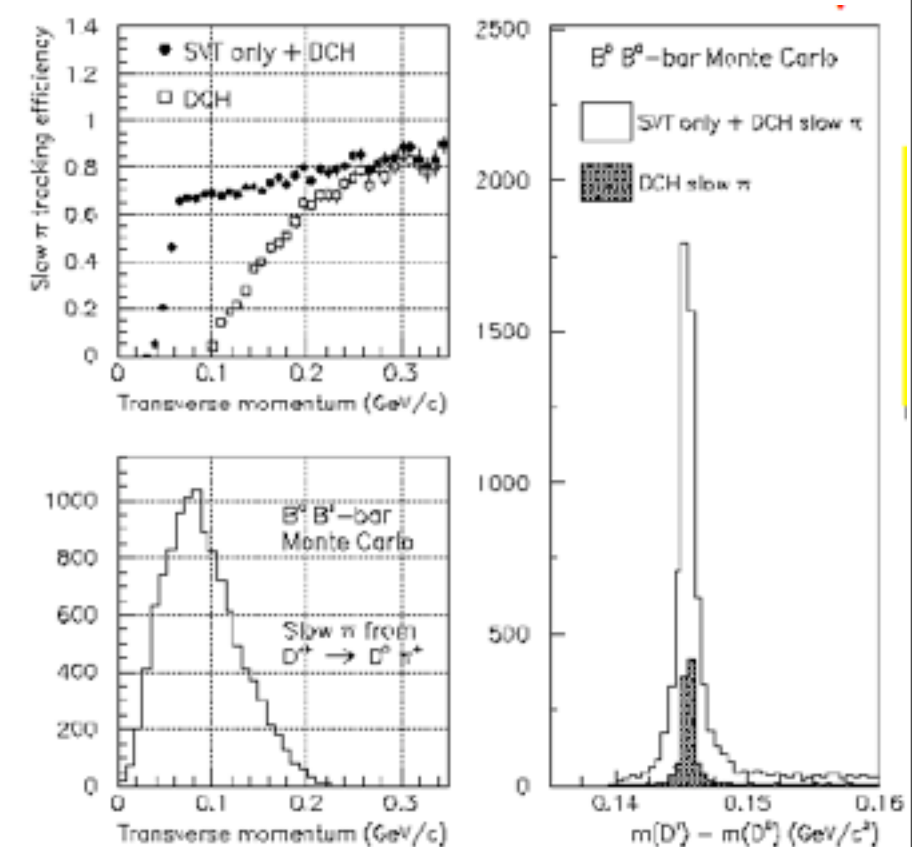
charm physics

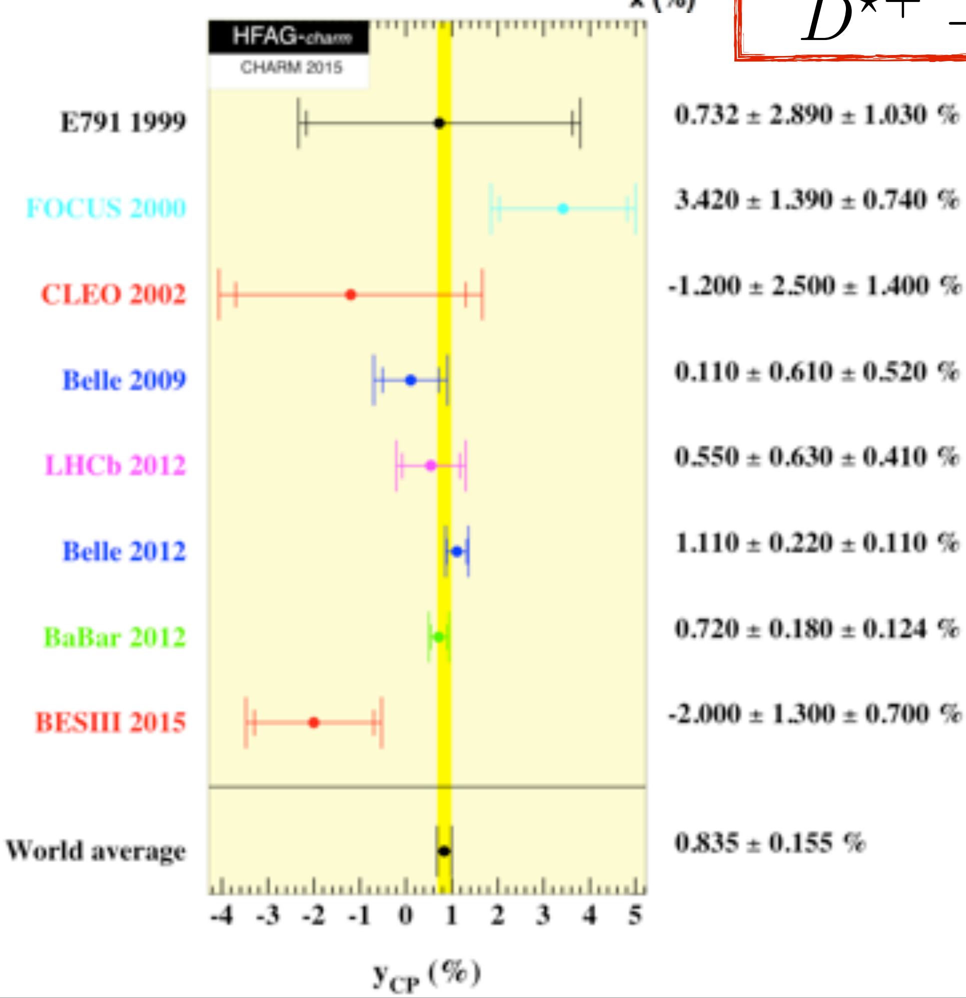


CPV if x, y not zero

Mixing in Up sector observed
CPV to be investigated

Possible with soft pion reconstruction from SVT in
$D^{\star +} \to \pi^+ D^0$





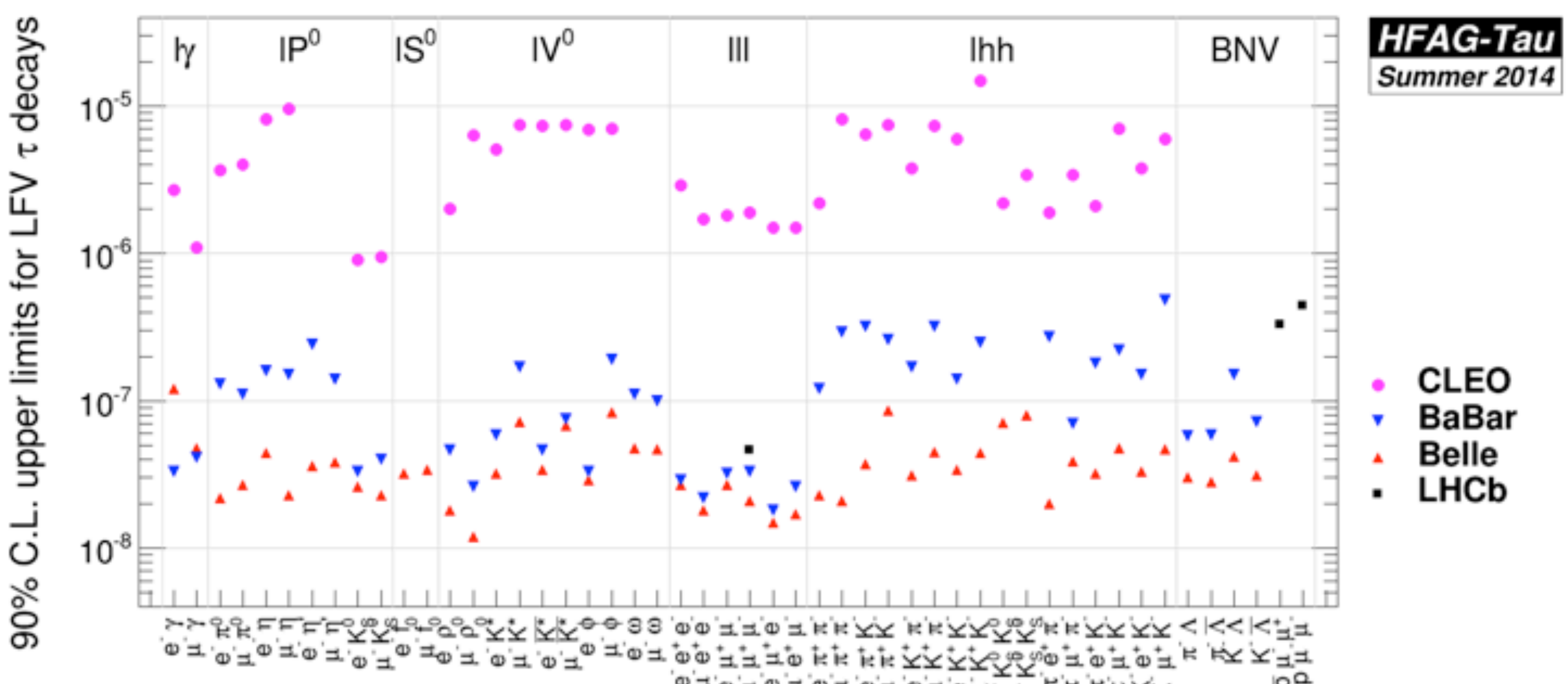
$$x = \frac{M_1 - M_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

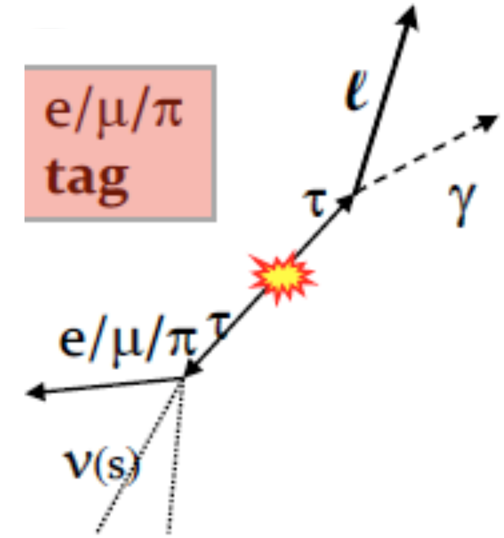
$$\frac{d\Gamma}{dt}[|D^0(t)\rangle \to f] \propto e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS decay}} + \underbrace{\sqrt{R_D}\,y'\,\Gamma t}_{\text{Interference between DCS and mixing}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$

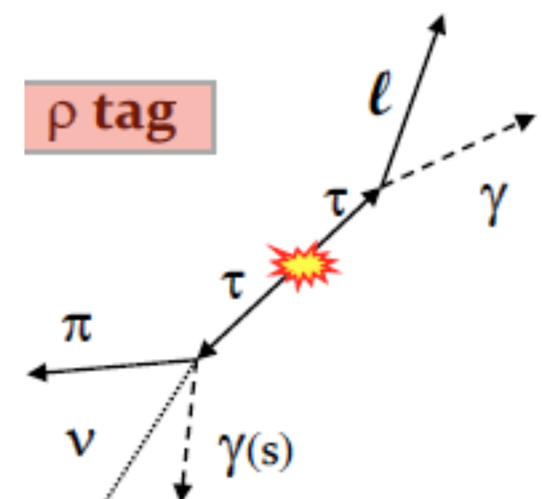
τ physics

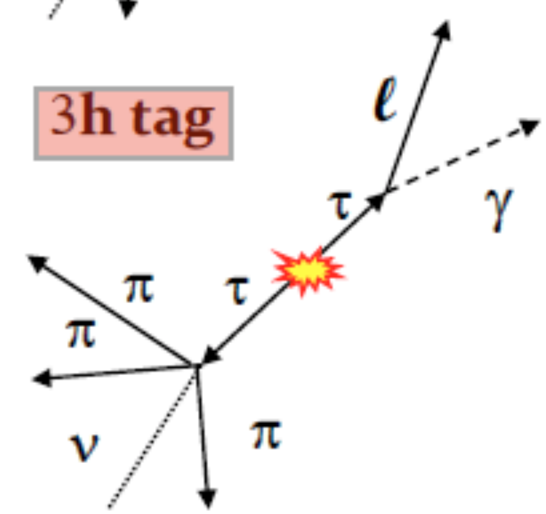
Silicon vertex detector allowed for precise reconstruction of tau decay products

A large array of decay state were tested to unprecedented level, still best results w.r.t. LHC experiments

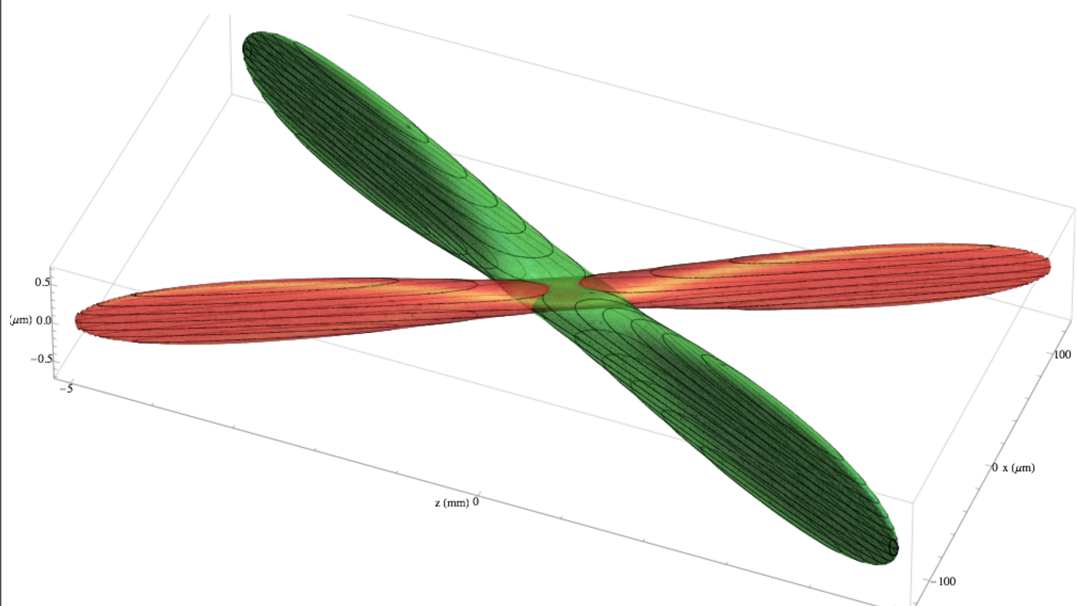


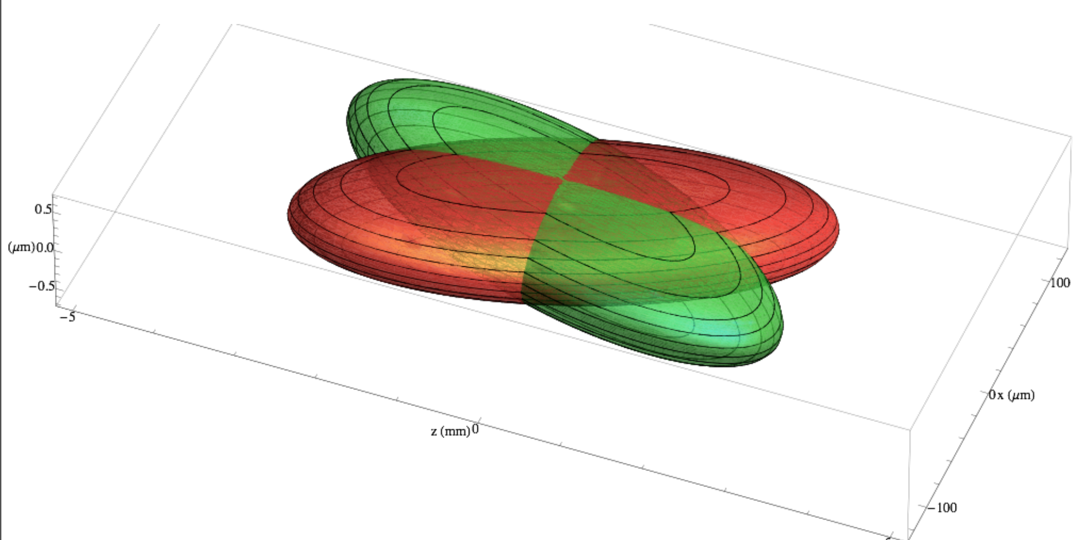






Super Flavor Factories





At the end of their lifetime BaBar and Belle were limited by statistics.

SuperFlavor factories: luminosities of up to $10^{36} cm^{-2}s^{-1}$

SuperB: nano beams and polarized e^-.

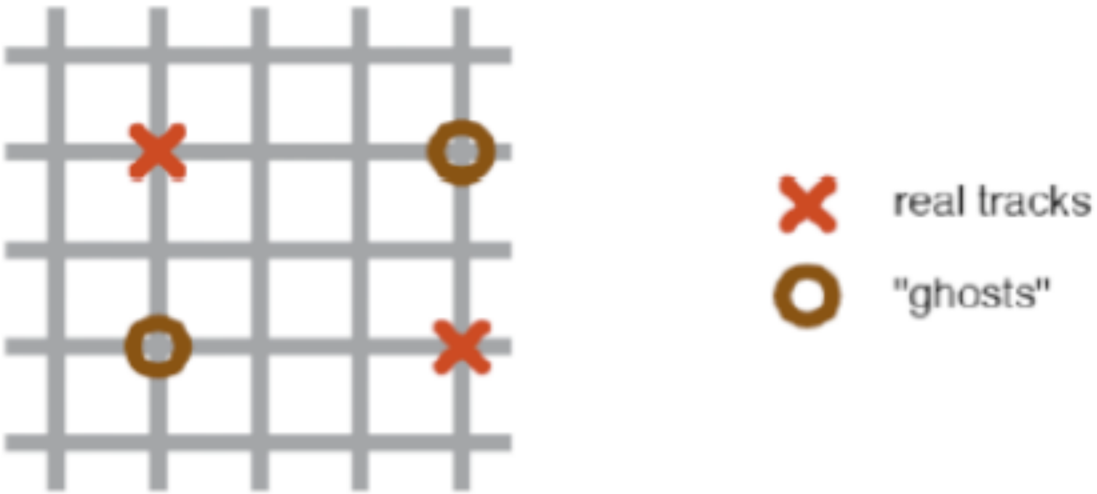
Tracking tau decay and D^* vertices for LFV studies, D CPV

Rates too high for Double Sided Strip Detectors.

Impact parameter resolution improvement needed for D^* tau physics

Moving from DSSD to Pixel

From Strips to Pixels

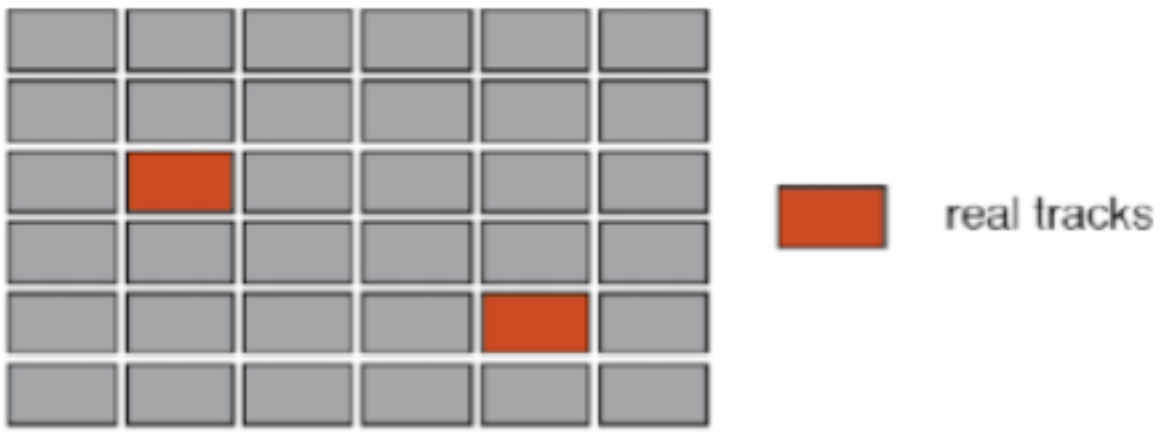


Double sided silicon detectors limitation: ghost tracks.

Tracking of two tracks hitting at the same time is ambiguous

Becomes main problem in high track density environment (i.e. LHC).

Pixel do not have ambiguities: multiple tracks passing through sensor have unambiguous hits



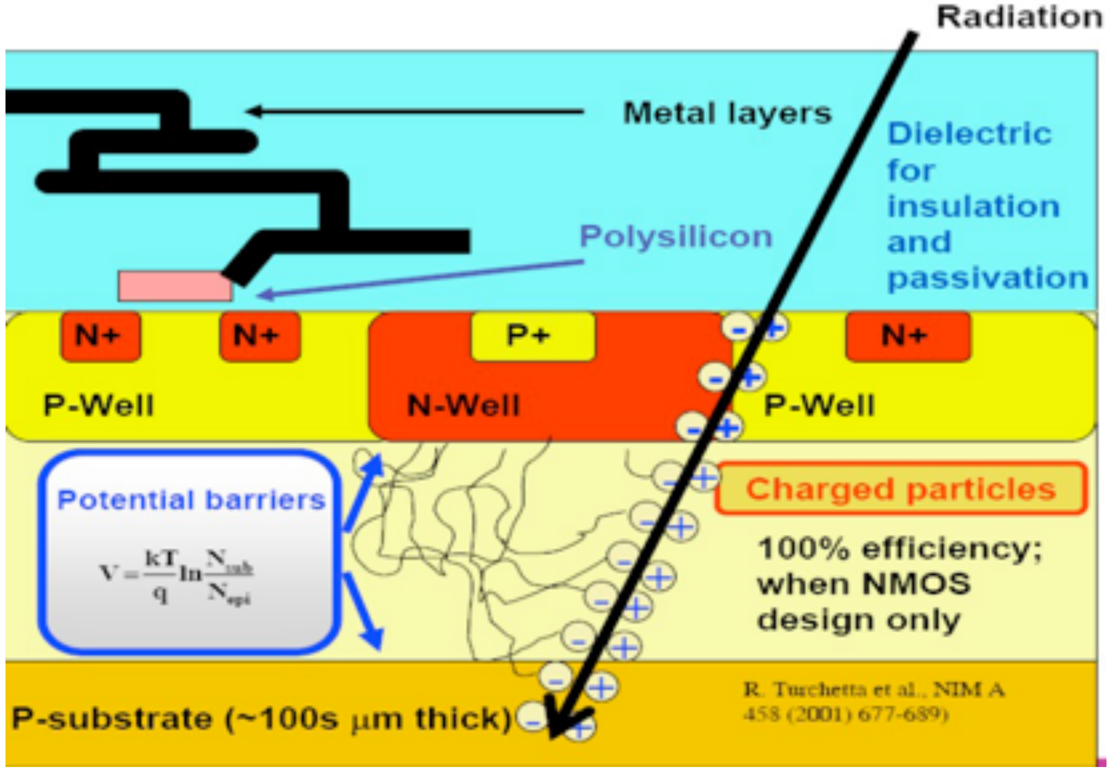
Monolithic Active Pixels

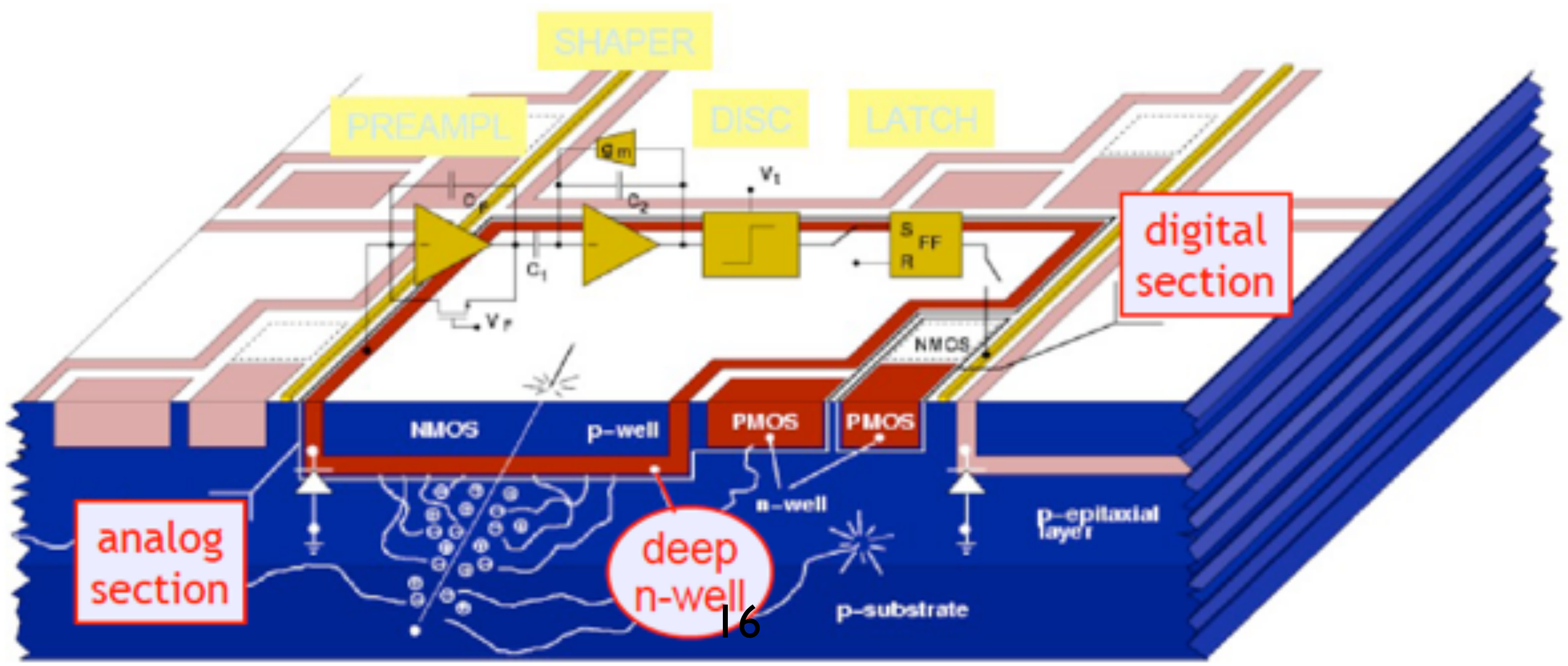
MAPs integrate sensor and electronics in the same substrate.

Charge is collected via thermal diffusion on the n-well. No depletion

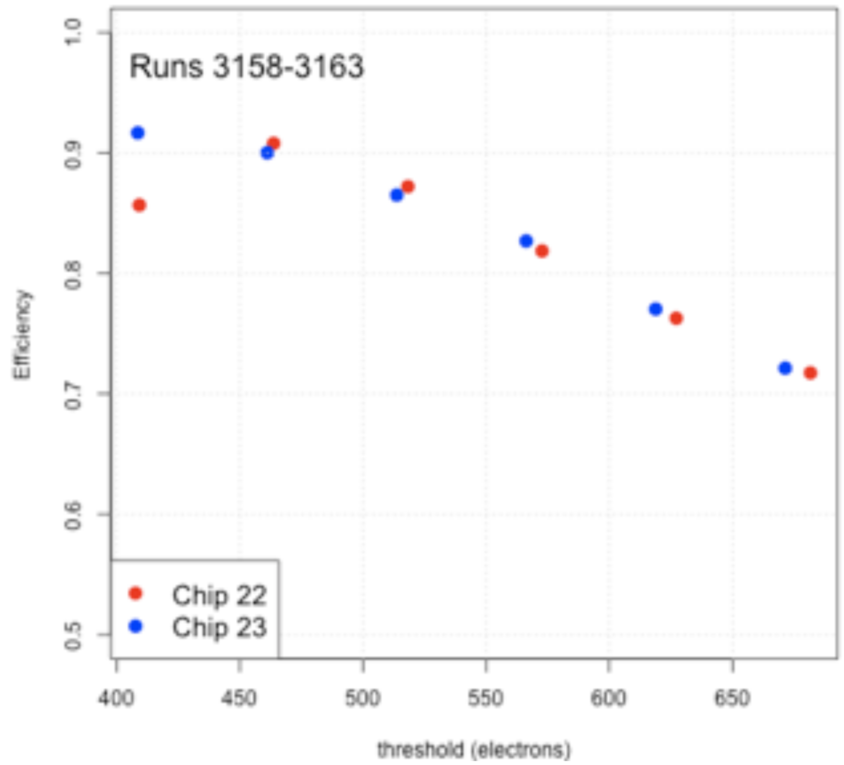
Active layer is very thin ~10μm. Substrate thinning possible down to 50μm

Full signal processing chain implemented at pixel level





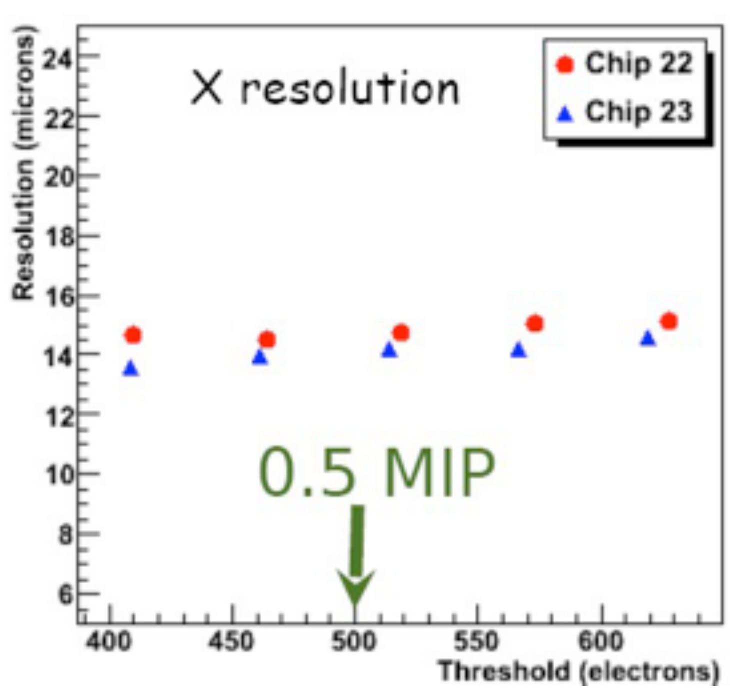
MAPS performances

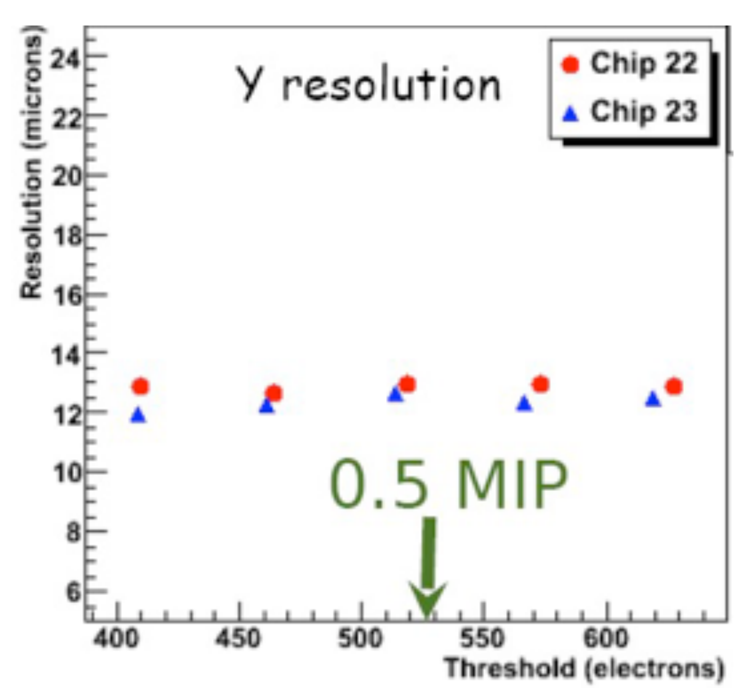


A 4K (32x128) matrix of 50x50μm^2 tested on beam with both irradiated (10MRad) and non irradiated chips, with different thinnings (100μm and 300μm).

Efficiency of ~92% with 400e$^-$ threshold. Uniform over the pixel matrix.

Resolution measured from track fit residual after multiple scattering correction agrees with $50/\sqrt{12}$=14.4μm.





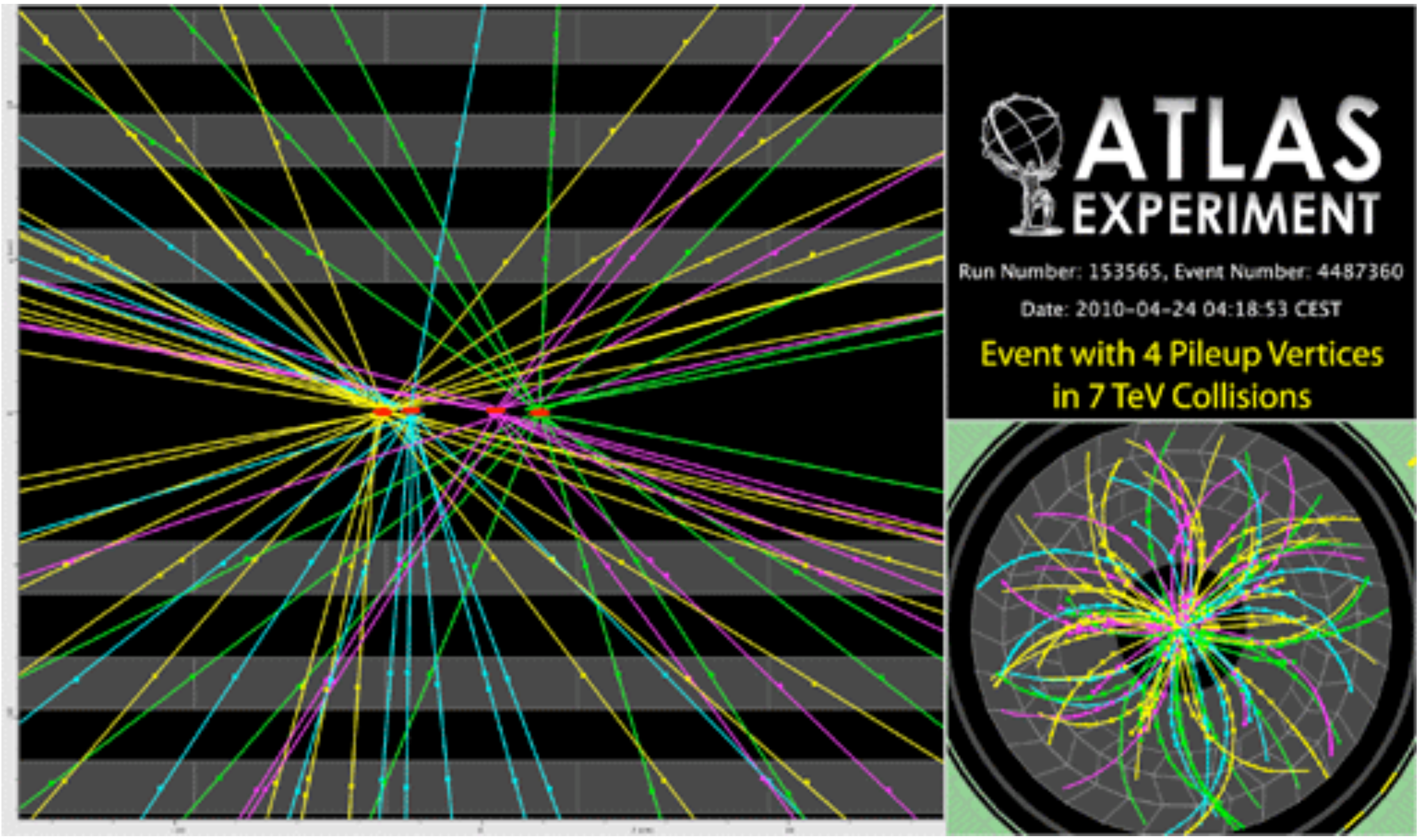
Physics at LHC

Needs for Vertex detector at LHC:

•High radiation: large amount of damage to Si from non ionizing radiation
•High interaction rate: Pile-Up (i.e. more than one interaction during a single bunch crossing)

Needs:

•Radiation Hard, stable in operation through the aging process
•High granularity
•Fast to cope with interaction rate

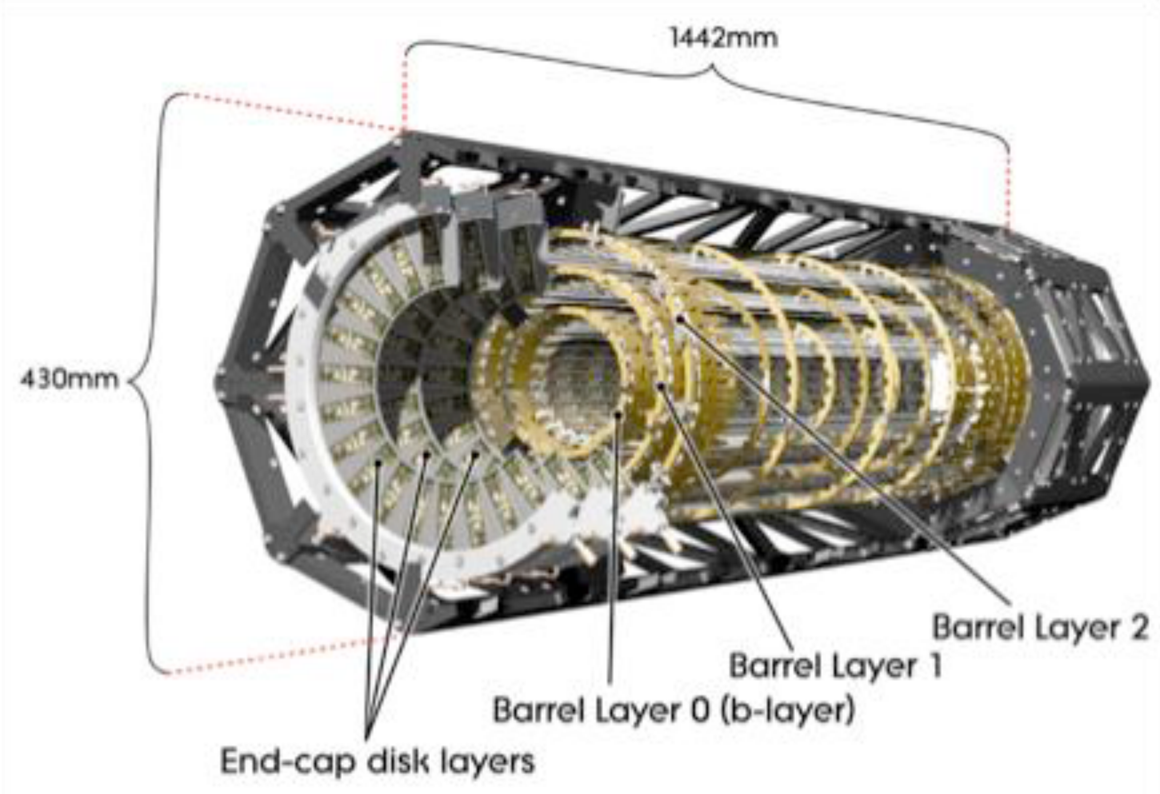


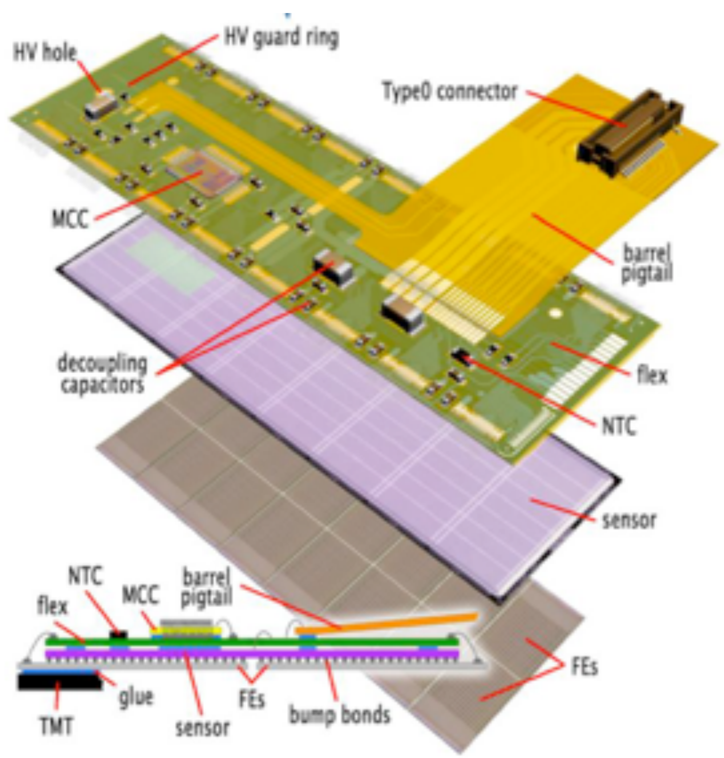
Solution: Pixels
Small capacitance, large signal: Rad damage

Small size: high granularity and spatial resolution.

Short drifts: Faster than strips

ATLAS Pixel detector





- 3 Layers + 6 Disk endcap
- ATLAS Pixel detector has 1744 Hybrid modules with 80M readout channels
- Pixel size 50x400μm^2
- 300μm thickness
- 0.1X_0 material budget
- High resolution: 8μm rφ, 75 μm in z
- Read out speed of 40Mb/s-160Mb/s depending on Layer.

Performance in Run1:

- 98% average efficiency
- 3500 e$^-$ threshold with ~160e$^-$ noise (i.e. 20 S/N ratio)

ATLAS IBL

Motivation: better performances in Run2

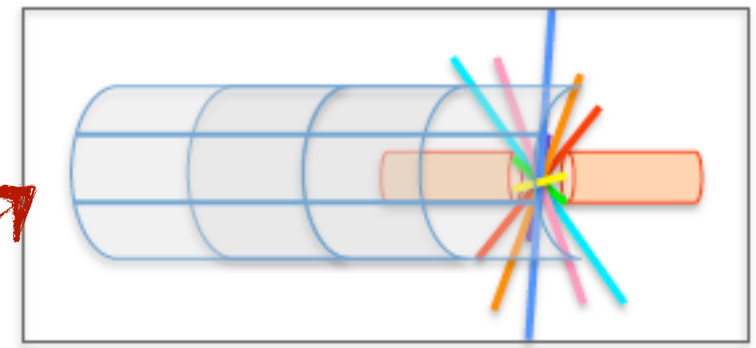
Solution: new Pixel layer ➜ Insertable B-Layer (IBL)

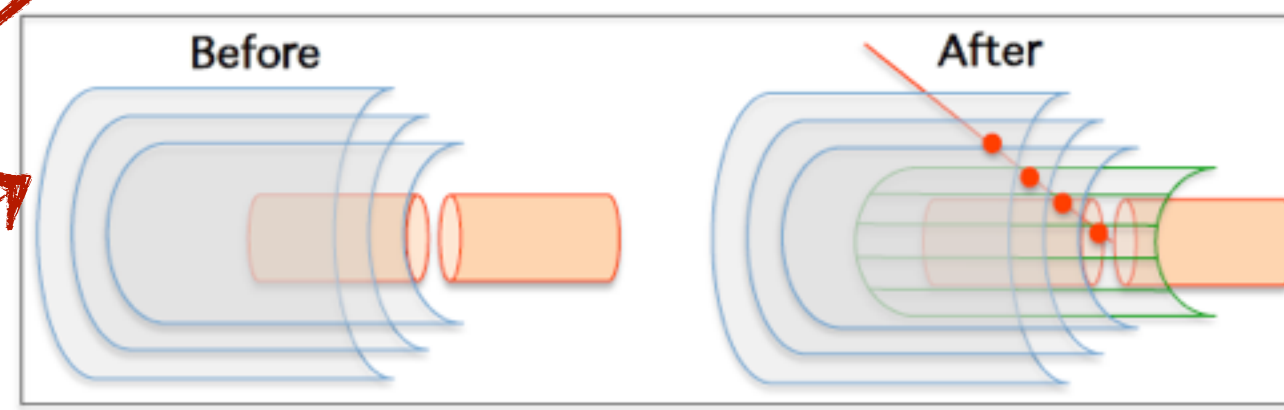
Vertex reconstruction depends mainly on resolution of the first hit

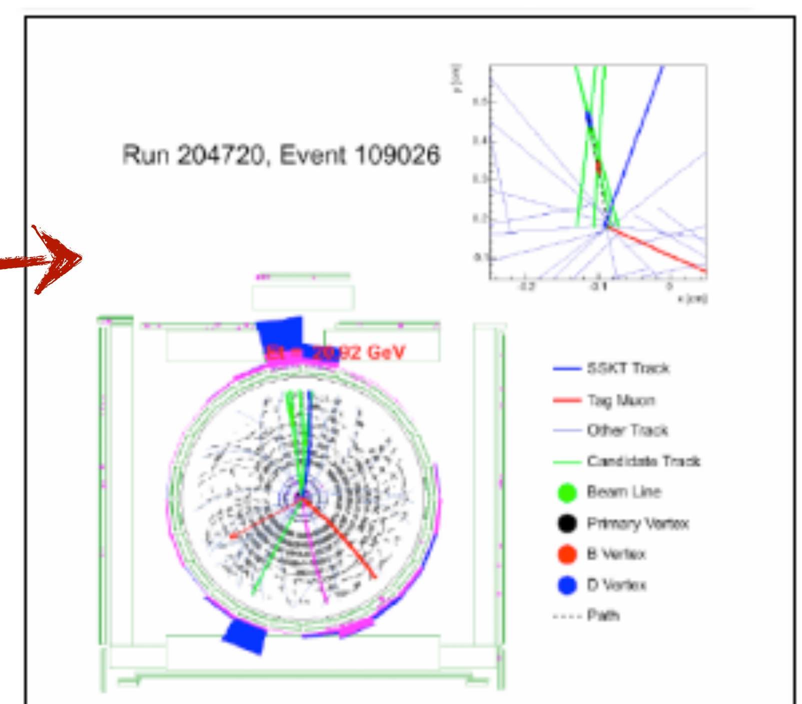
Highly segmented: $50 \times 250 \mu m^2$

Adds another tracking point: $\sigma(p)/p \propto 1/\sqrt{N}$

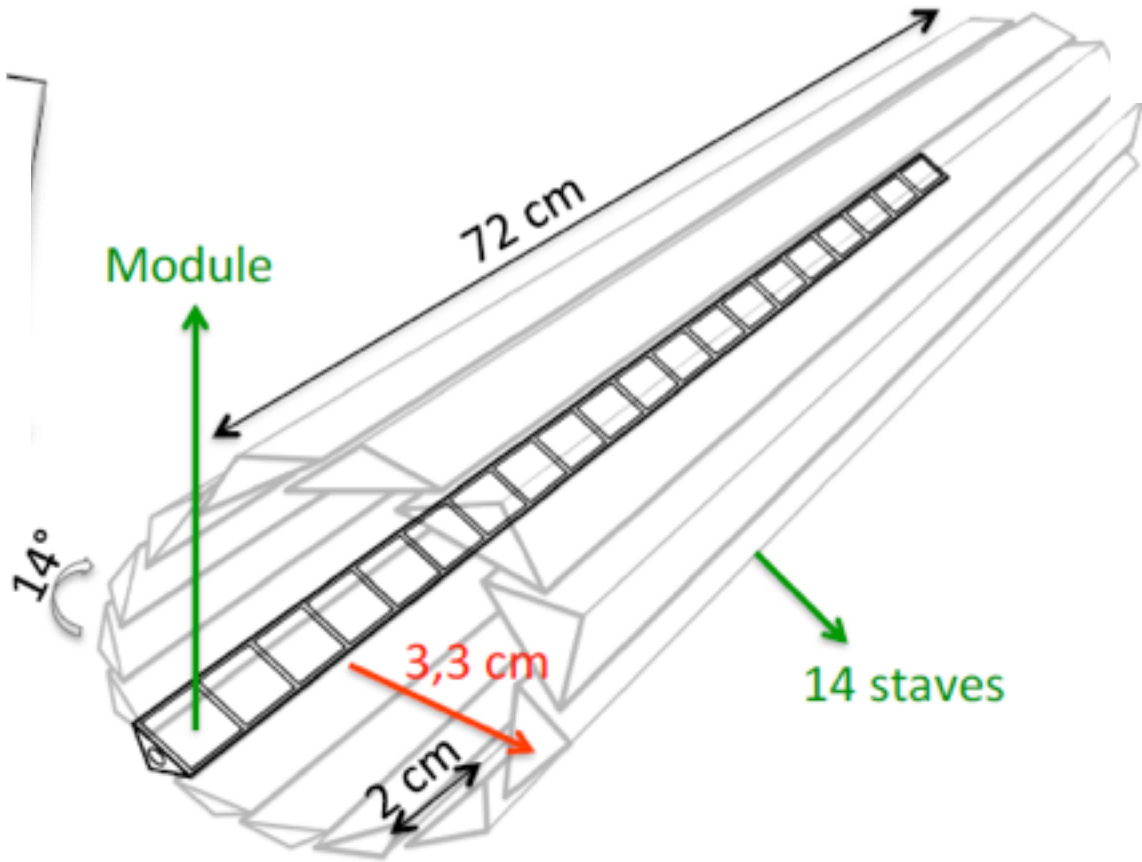
Closer to the interaction region: secondary vertex resolution improves, better b-jet tagging performances







ATLAS IBL



IBL composed of 14 staves, each with 32 modules, read by 16 front end chips.

It has 24 double planar sensors (central sensors, and 8 3D (at the edges)

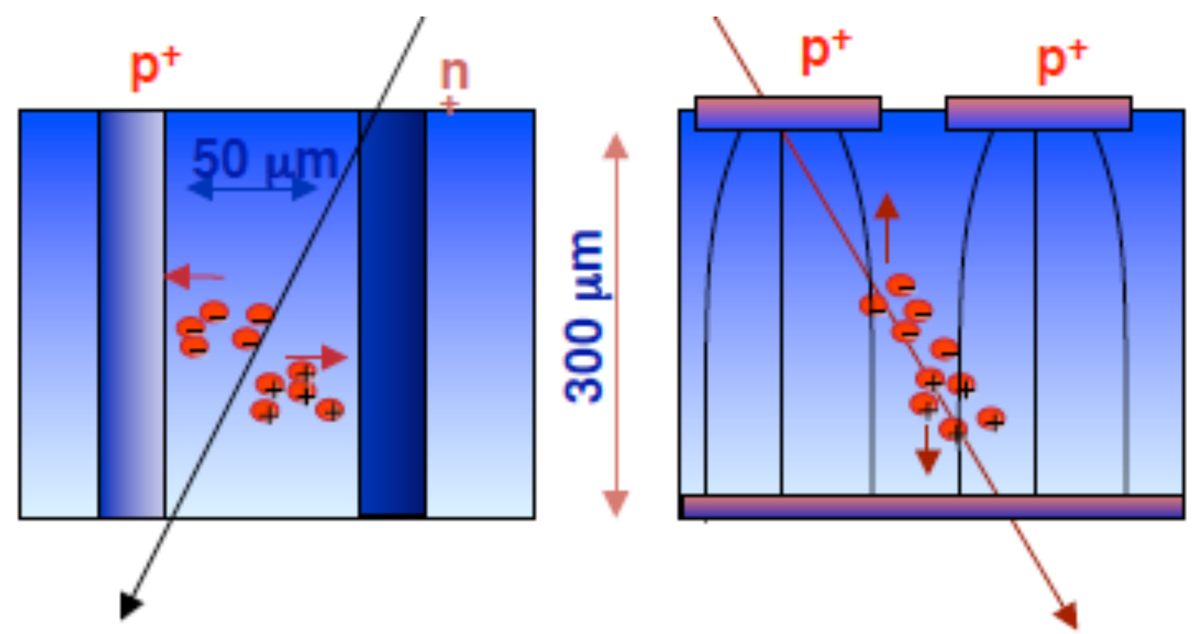
The IBL readout speed: 160Mb/s.

Material Budget 1.5% X_0

Two different technologies:

Planar: usual Pixel configuration, slim edges to reduce the non sensitive area

3D: Horizontal depletion, small depletion space (Rad-Hard), BUT columns are not sensitive

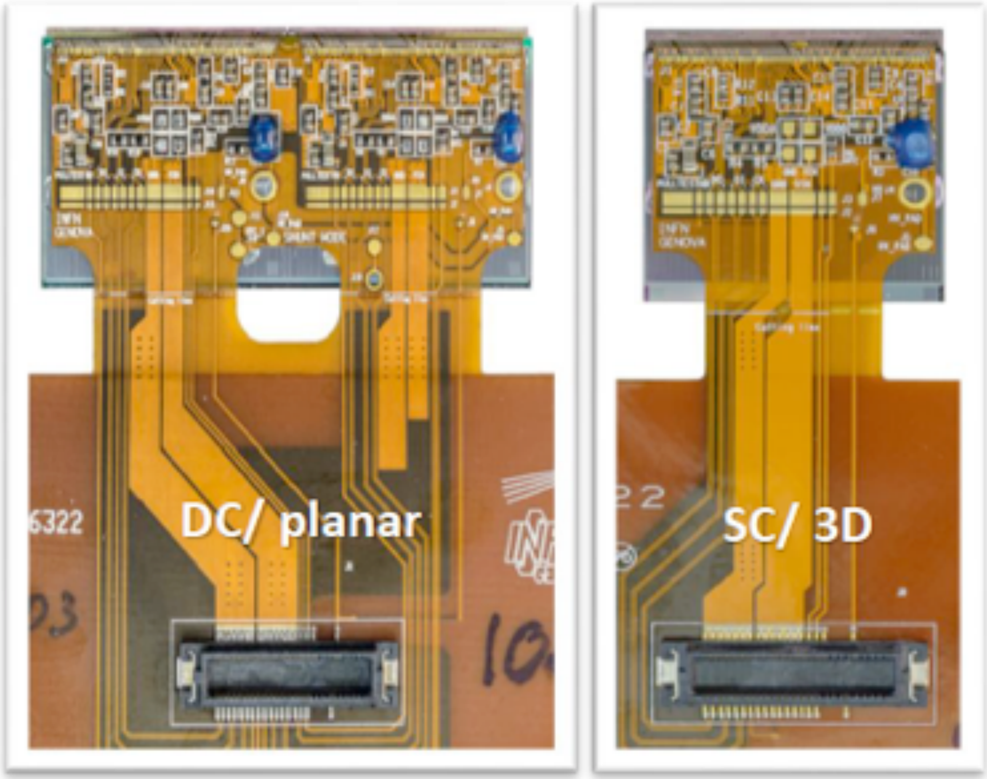


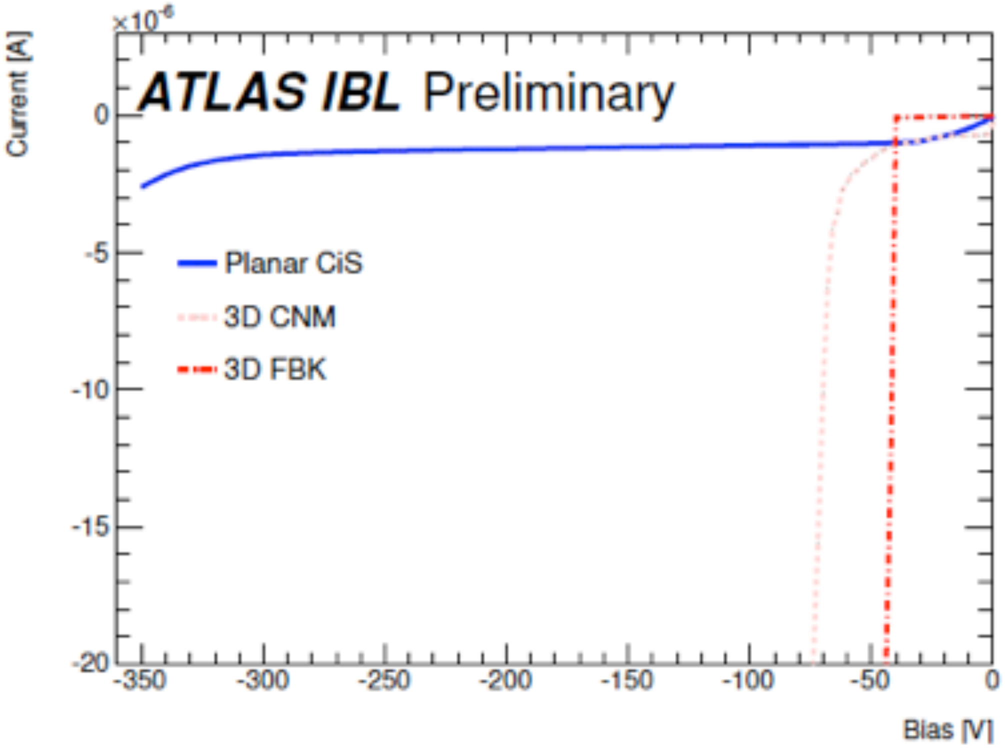
IBL Construction

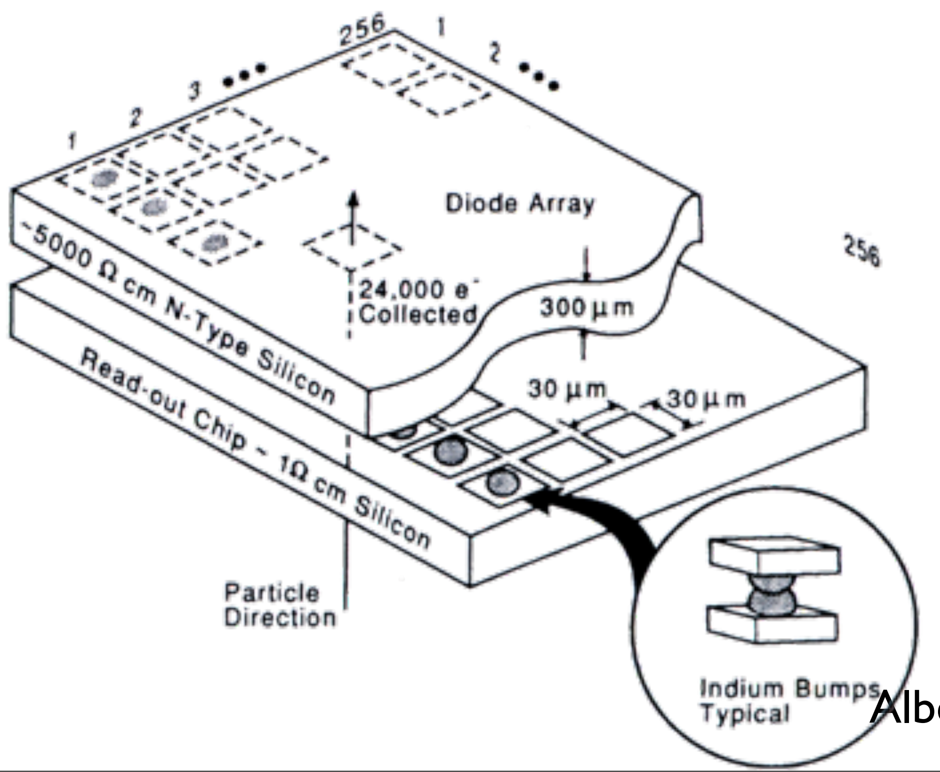
Hybrid detector: Sensors are bump bonded to the FE chip.
Bonding is a critical and expensive process.
After FE bonding to sensors, sensors tested for their Electrical properties.

Junction tested through I-V measurements

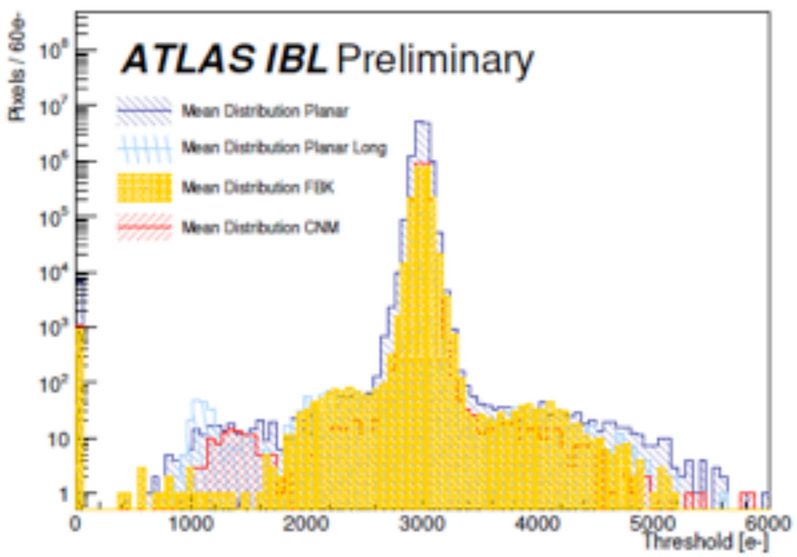
Very high voltages to allow for operations with high radiation damage

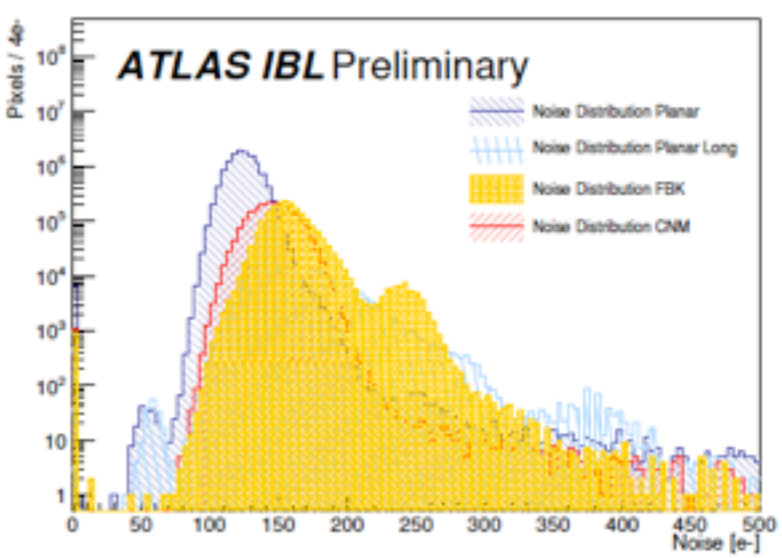






IBL Modules performance





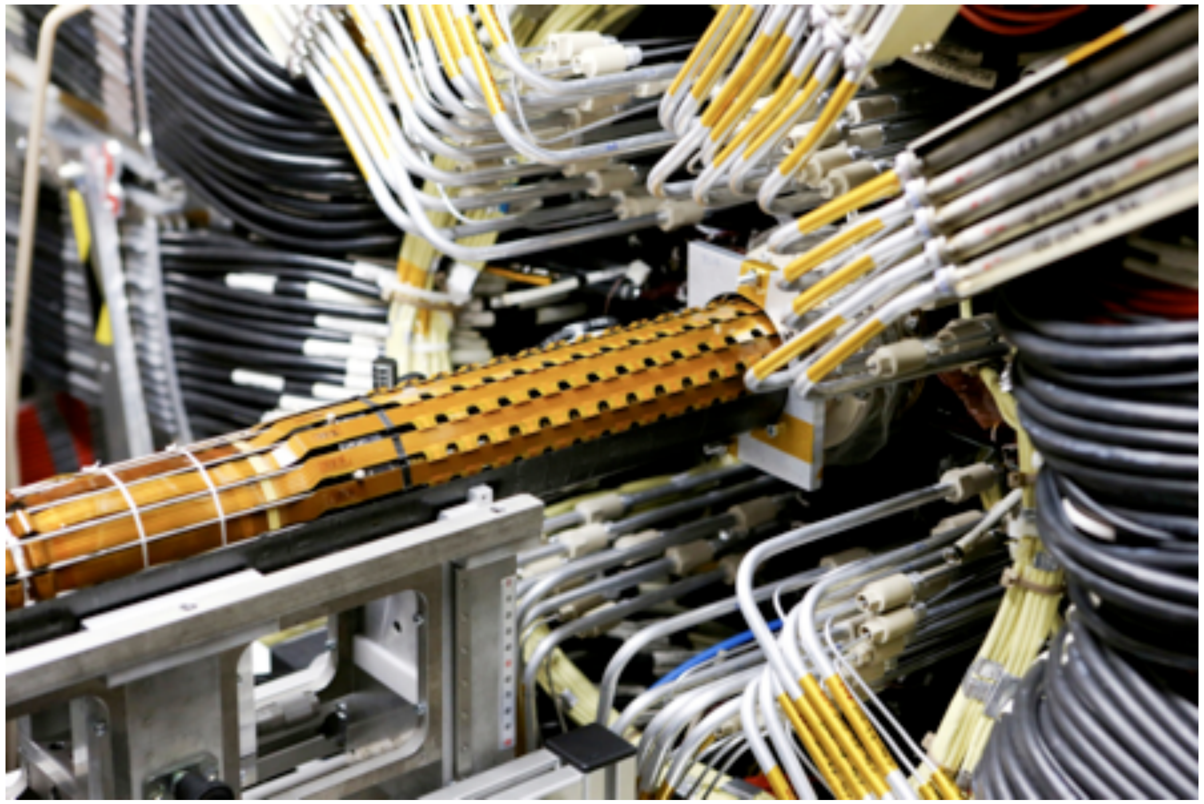
Before glueing sensors to support and connect readout modules were tested:

the digital components were tested injecting pulses through the front-end.

The analog component by injecting pulses in the pre-amplifier stage of the sensor: ENC characterized for each sensor.

Scan with radiation sources and cross talk measurement to check damaged bump bonds

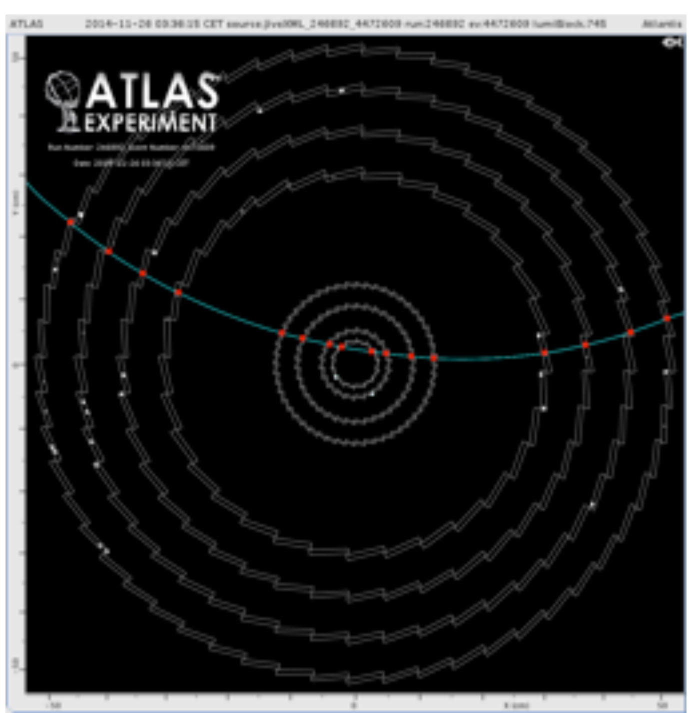
IBL

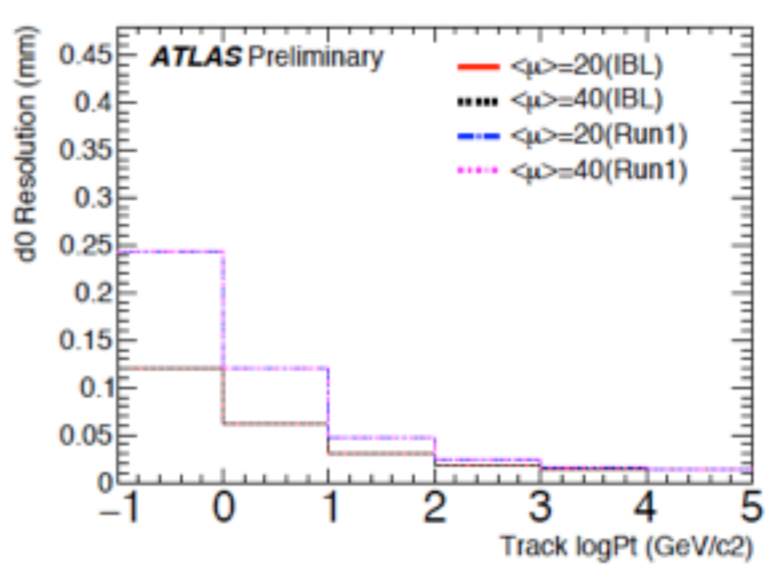


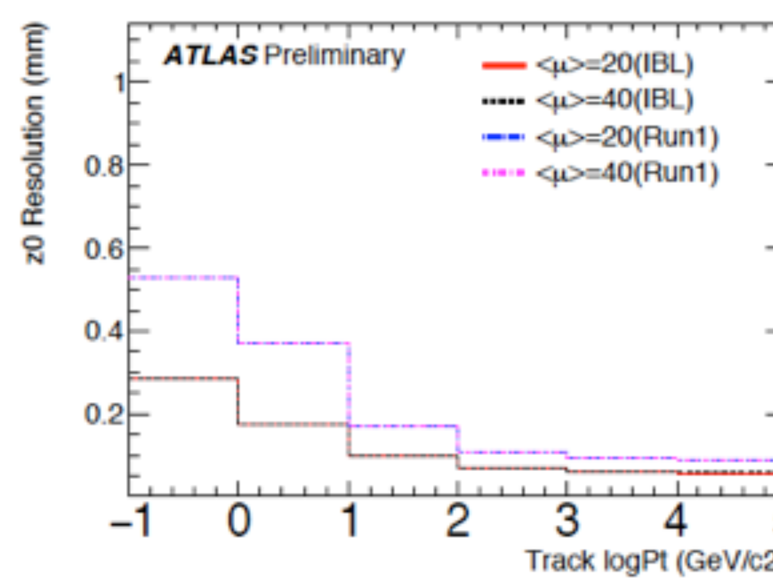
IBL successfully installed in May 2014, started taking data in LHC Run2.

Stable performance during Run2.

b-jet tagging and tracking capabilities of the inner tracker improved







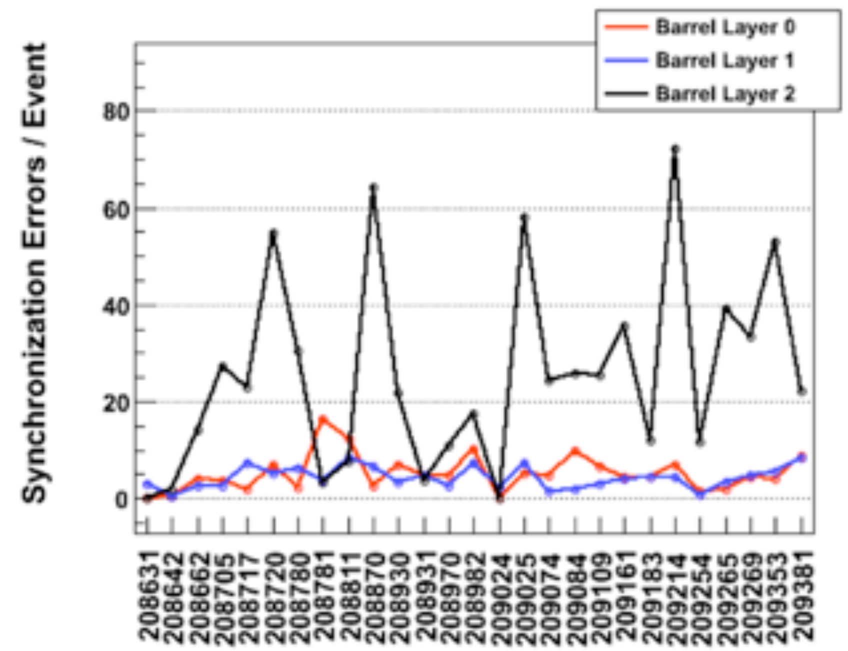
Pixel Readout Upgrade

End of Run1: innermost Pixel layers suffered from high occupancy.

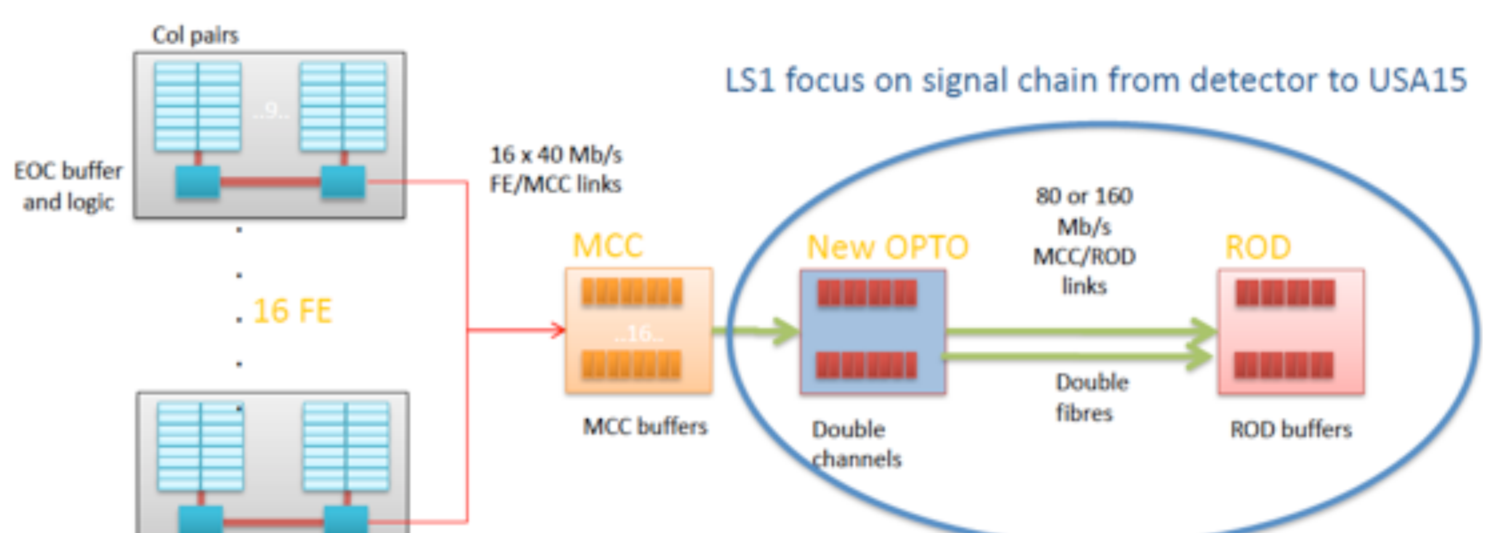
Problem expected to worsen in Run2.

Faster readout is needed.

Solution: use the IBL readout system designed for 160 Mb/s operation



Link occupancy at 100 kHz L1 Trigger					
	µ	B-Layer	Layer 1	Layer 2	Disks
50 ns	37	51%	45%	69%	40%
25 ns; 13 TeV	25	47%	42%	65%	37%
	51	71%	67%	88%	52%
	76	95%	97%	148%	75%



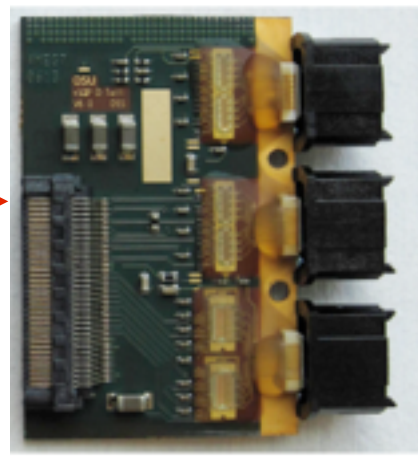
L2 increase speed from 40Mb/s to 80Mb/s on single optical fibre, L1 from 80Mb/s to 160Mb/s on double optical fibre.

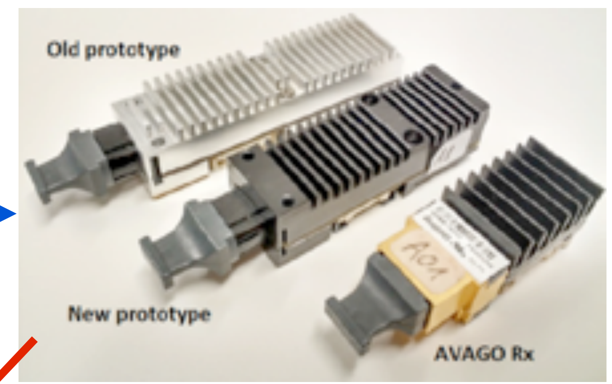
Optical components used in IBL not usable in Pixel operation due to different data encoding.

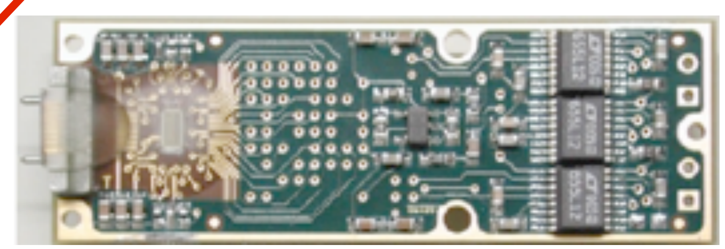
IBL readout cards reused

Pixel readout upgrade

Pixel





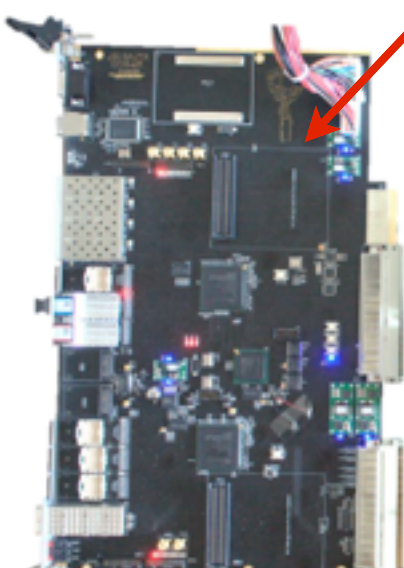


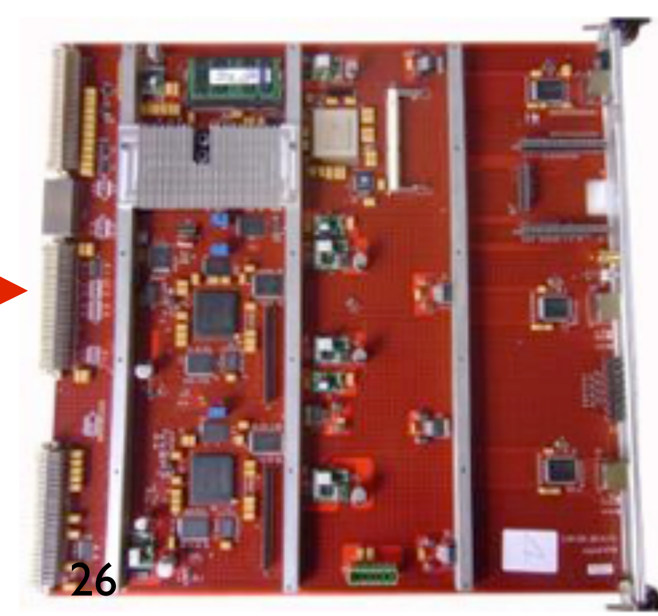
Plug ins: receive optical transform in electrical signal.

Commercial plugins not working for Pixel operations: encoding problem

IBL plugins could not be used

Optoboard: Electrical signal encoded and sent through optical links





ReadOut Card (ROD) And Back Of Crate Card: Control Data acquisition/trigger

Output is sent to ATLAS offline system

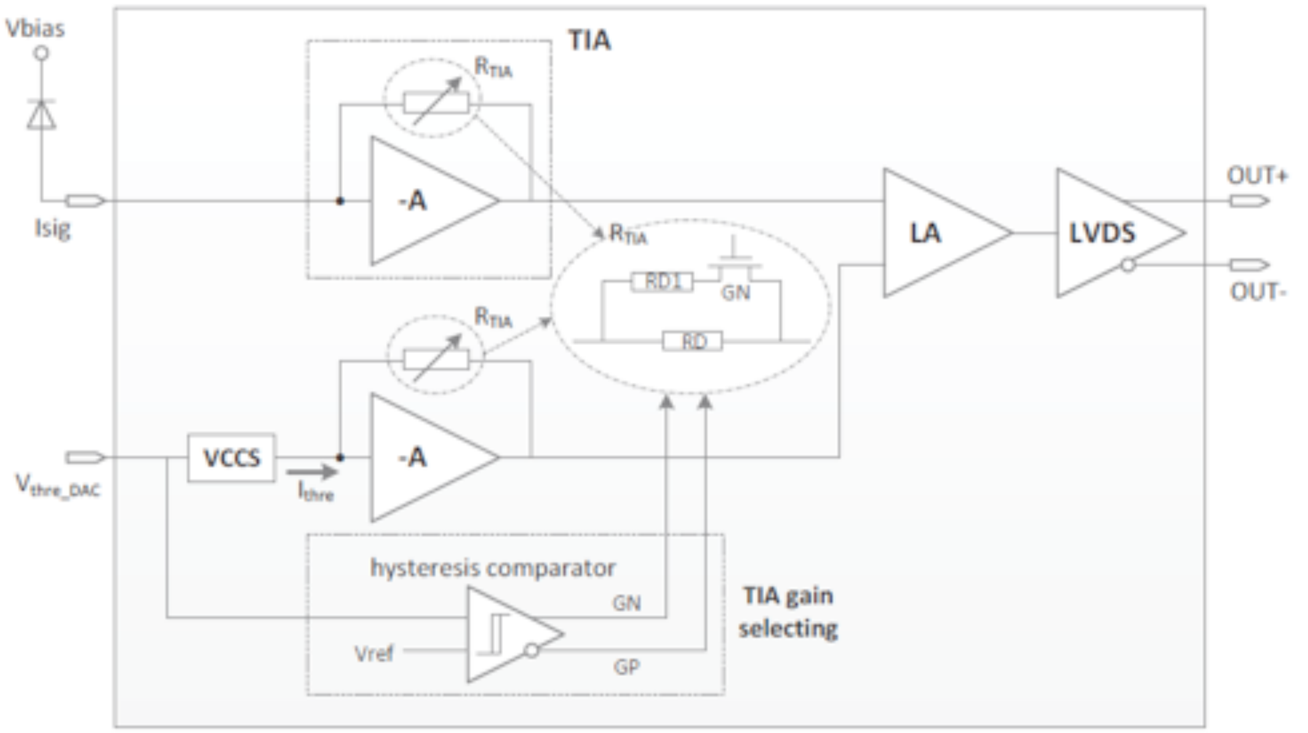
New Optical Plugins

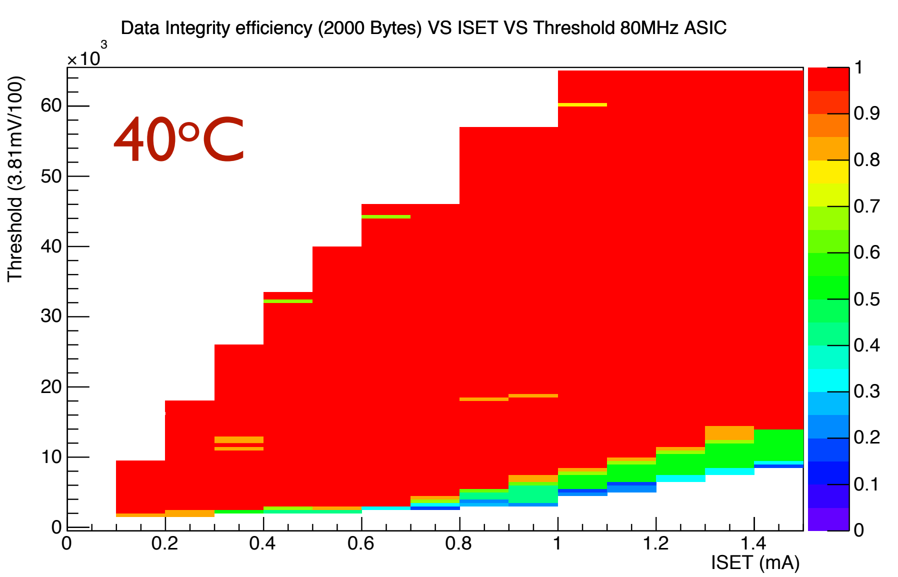
New optical components needed for upgrade

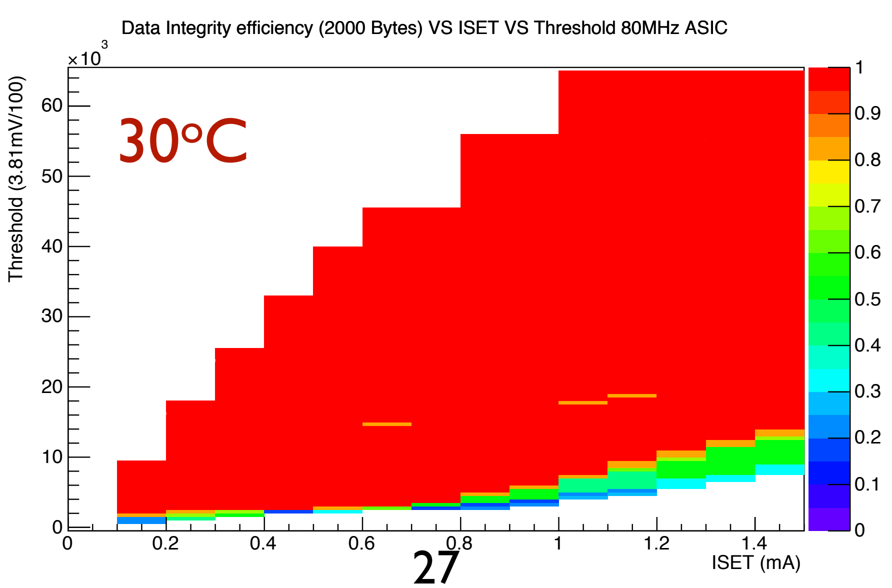
Provide a switching gain: can operate after rad damage on detector side transmitters.

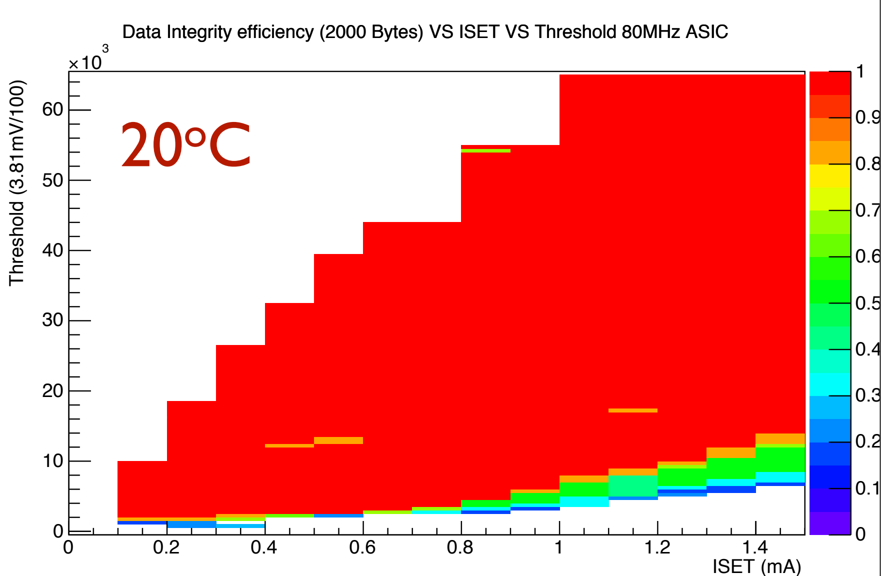
Tested to be stable and able to adjust single channel threshold.

Installed in Dec2015, now being commissioned









ATLAS physics results

ATLAS object definition depends for almost all objects on Tracking:

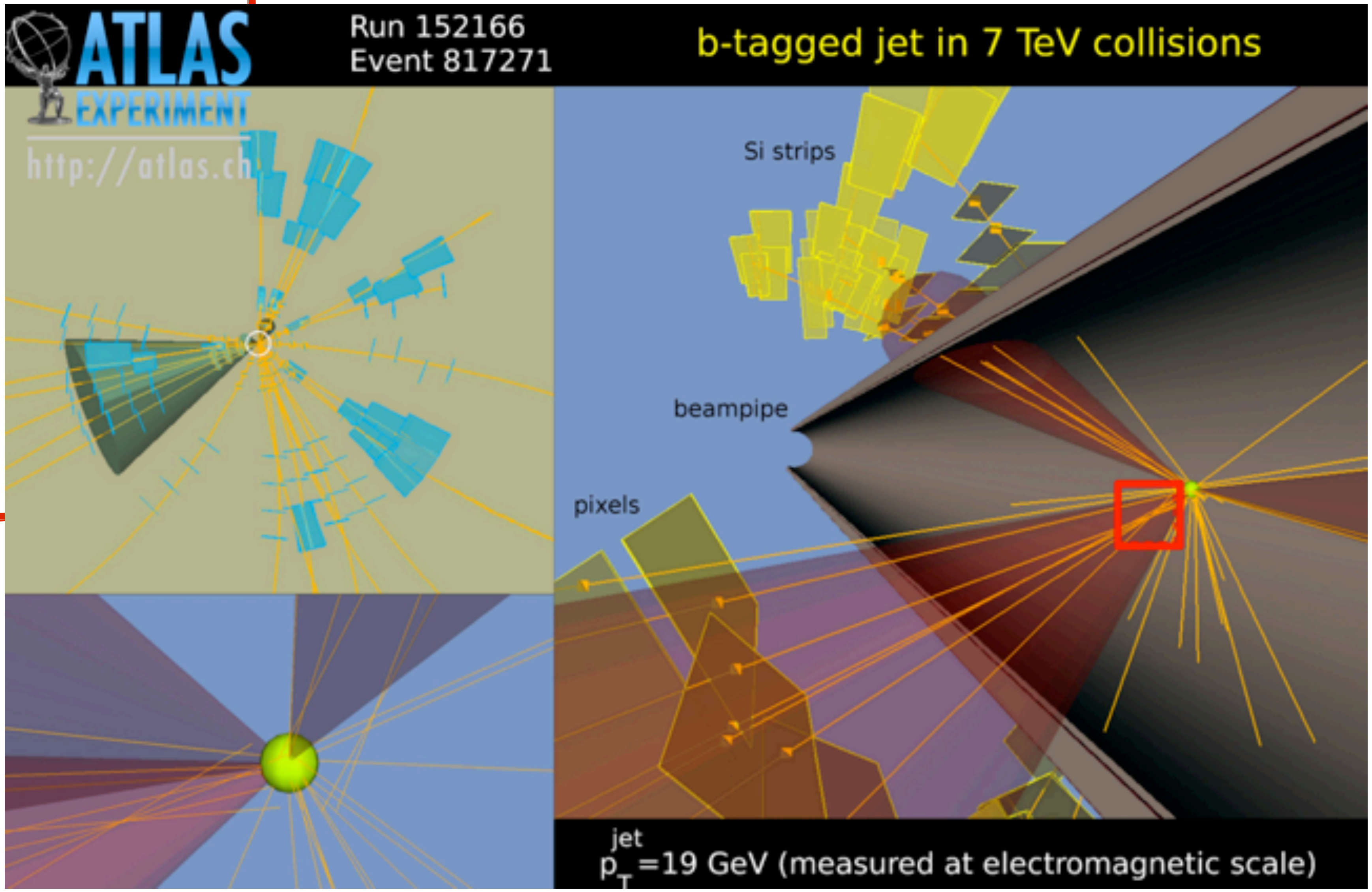
lepton/photon isolation

JFV for jet objects

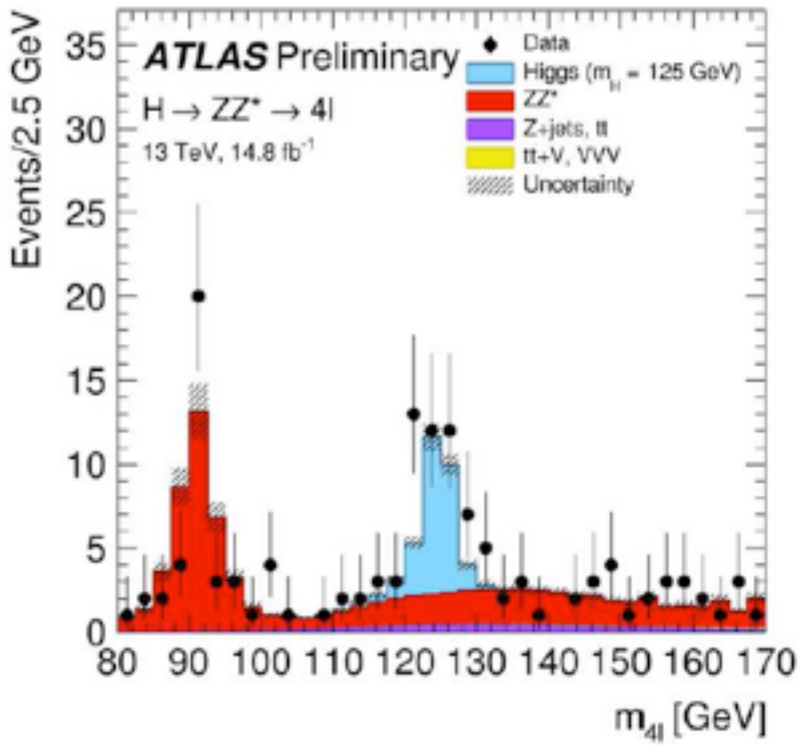
B-tagging

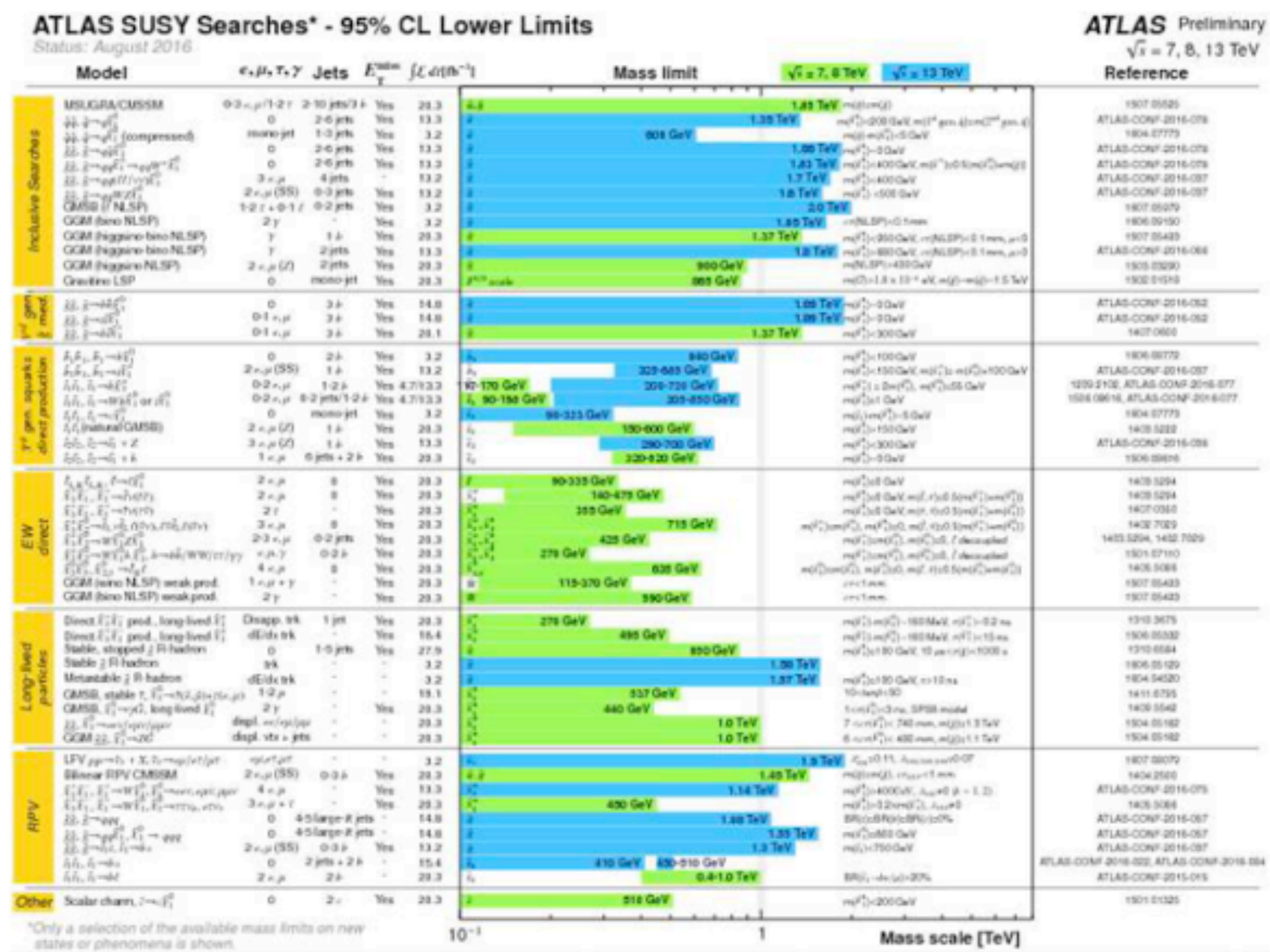
Tau reconstruction

Missing transverse Energy reconstruction

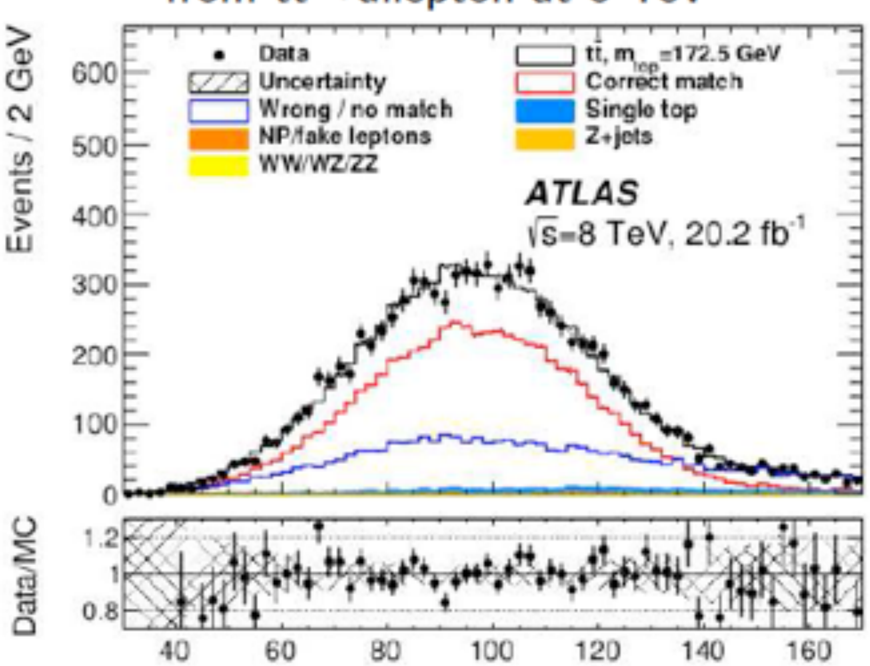


Atlas results





Recent direct measurement from tt→dilepton at 8 TeV



Alberto Cervelli

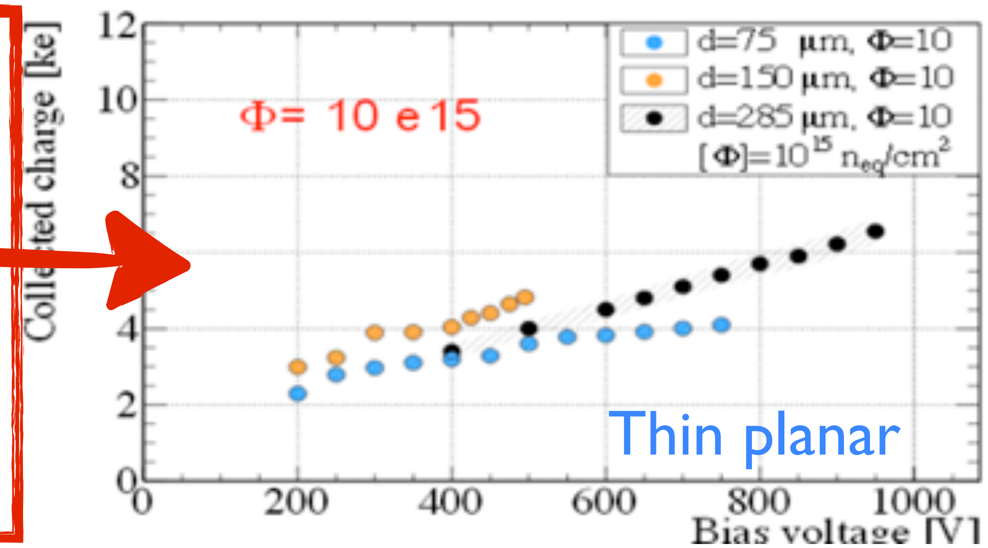
Future of Vertex Trackers

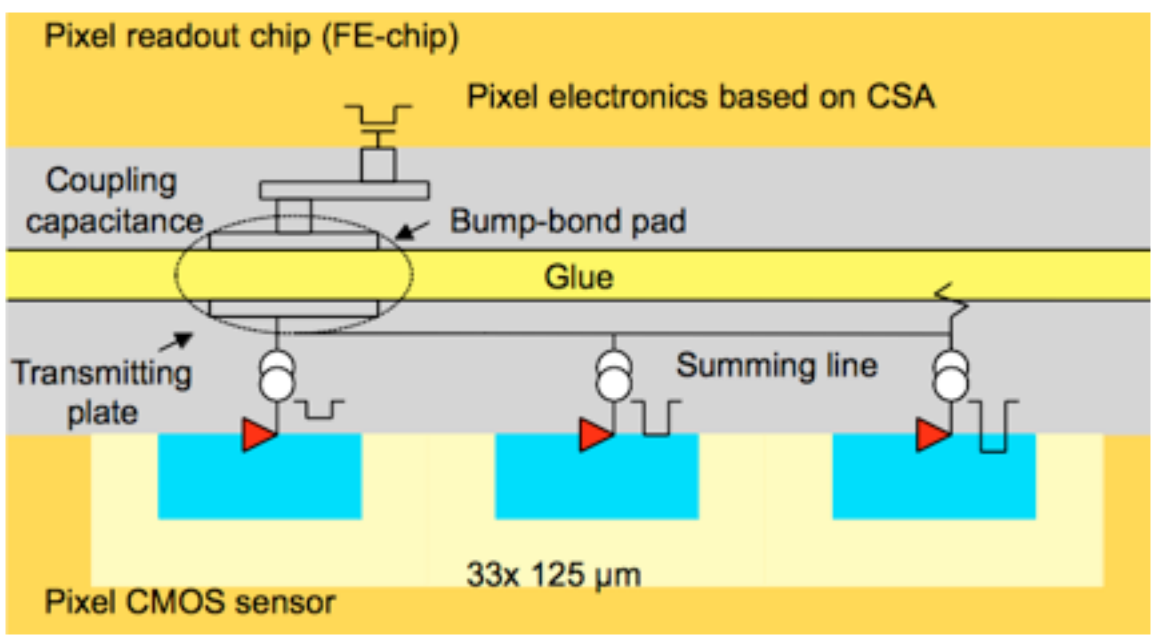
Future Pixel detector for HL-LHC need many improvements:

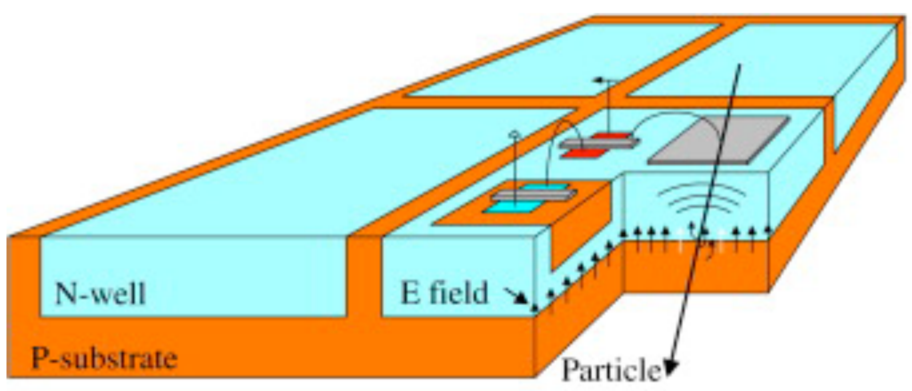
Increased radiation hardness

Smaller sizes

Cheaper interconnection technologies

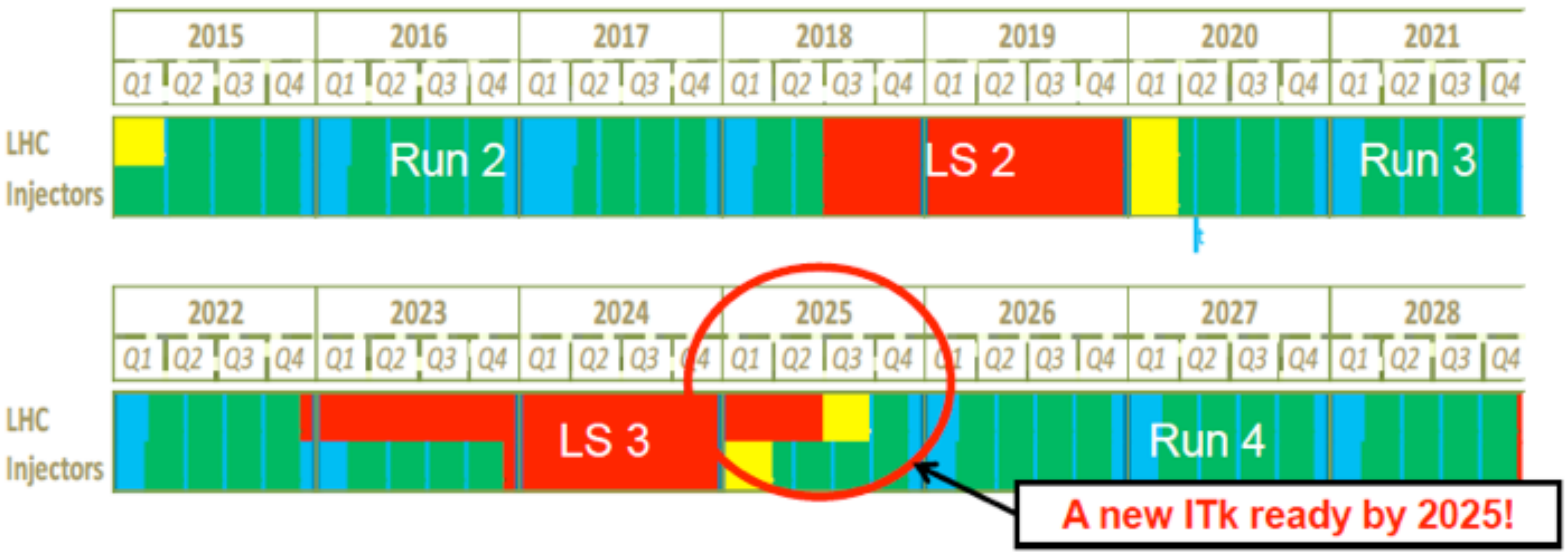






HV-CMOS

Towards LHC phase 2

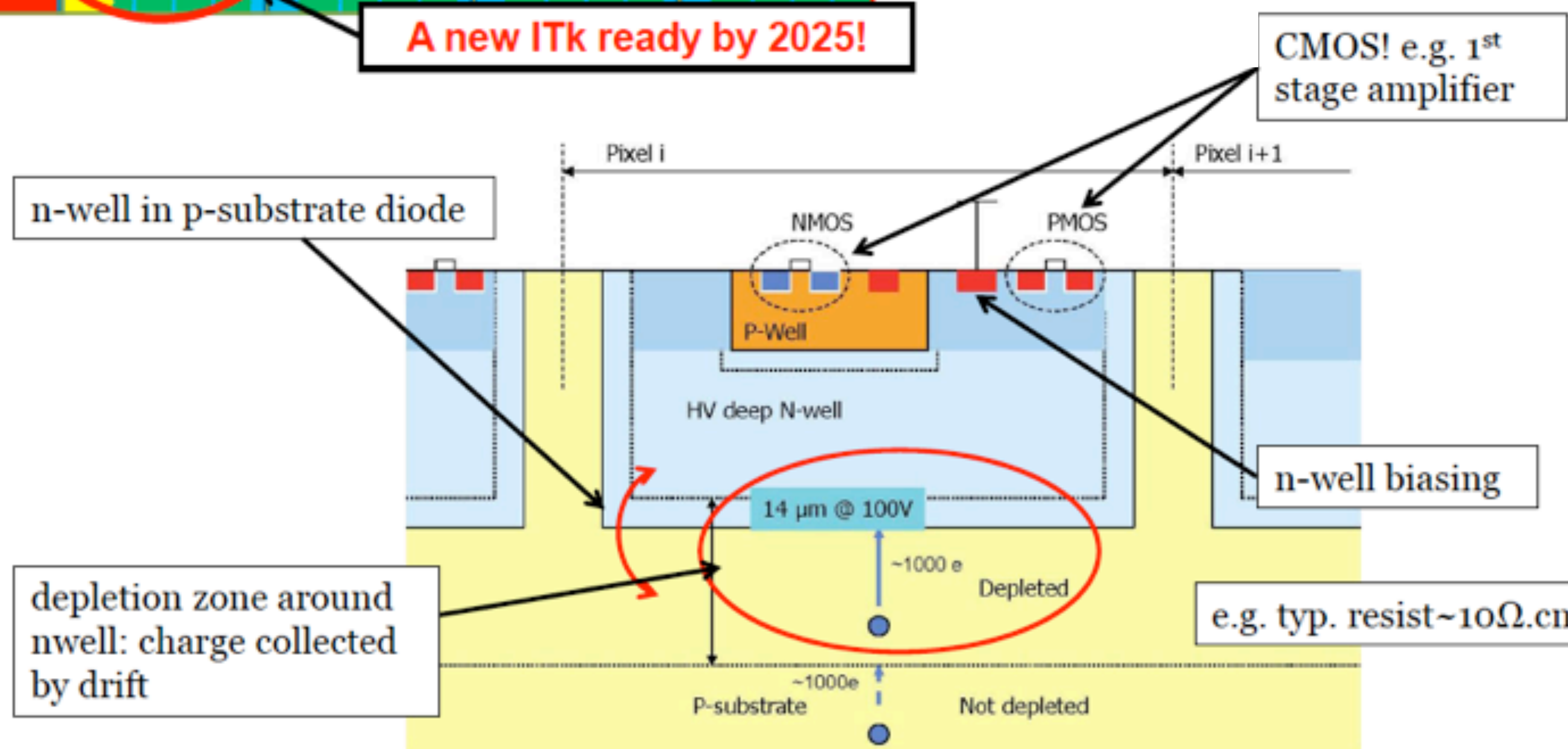


HV-Cmos allow for monolithic design with charge drift.

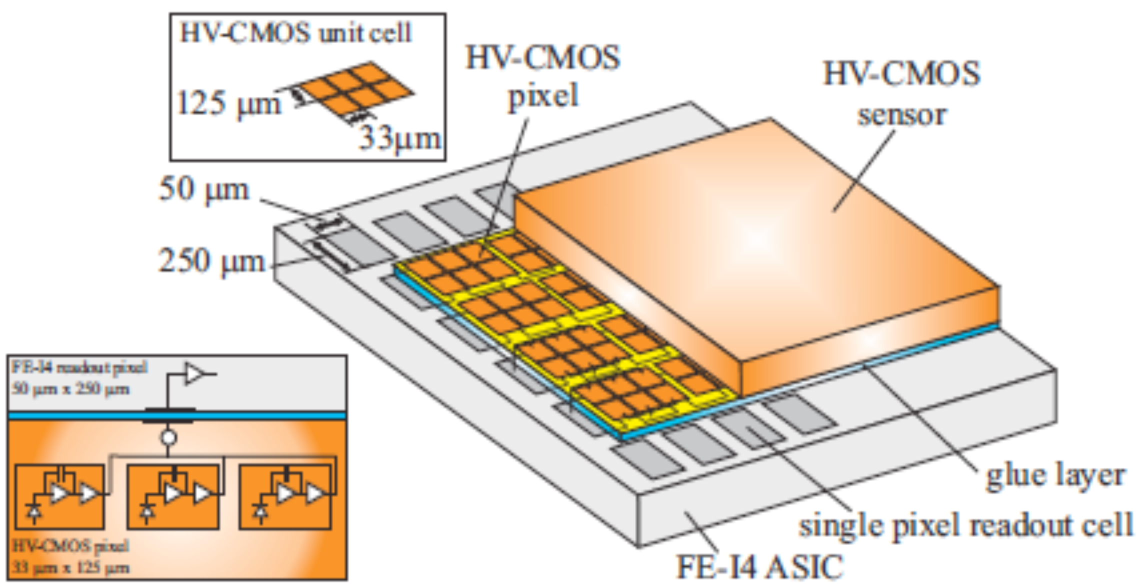
Different approaches possible:

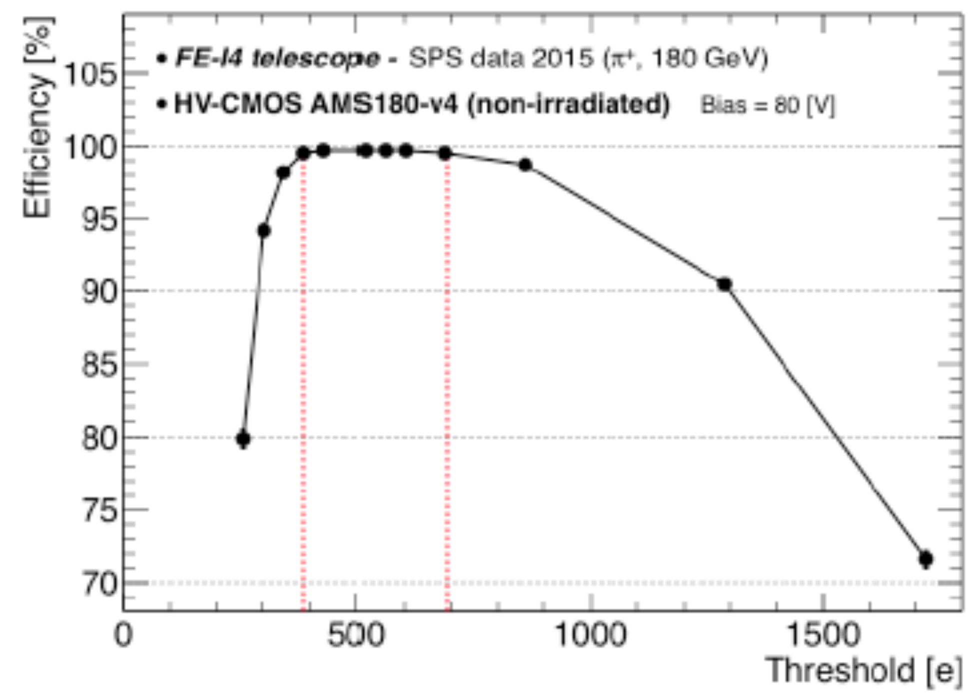
HR: large depletion region higher signal but Larger noise

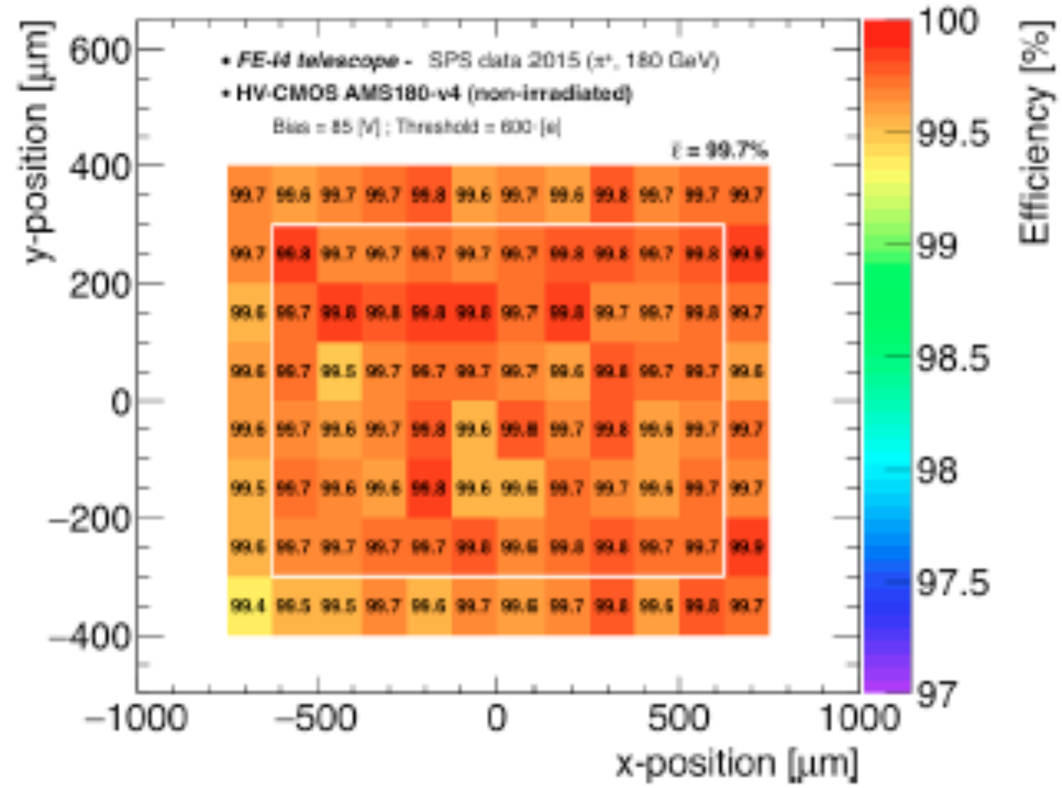
LR: small depletion region, small signal but lower noise



LR HV-CMOS







2015 test beam.

No need for bump bonding, AC coupling through glue

Efficiency map obtained from track reconstructed with Atlas-pixel sensor telescope

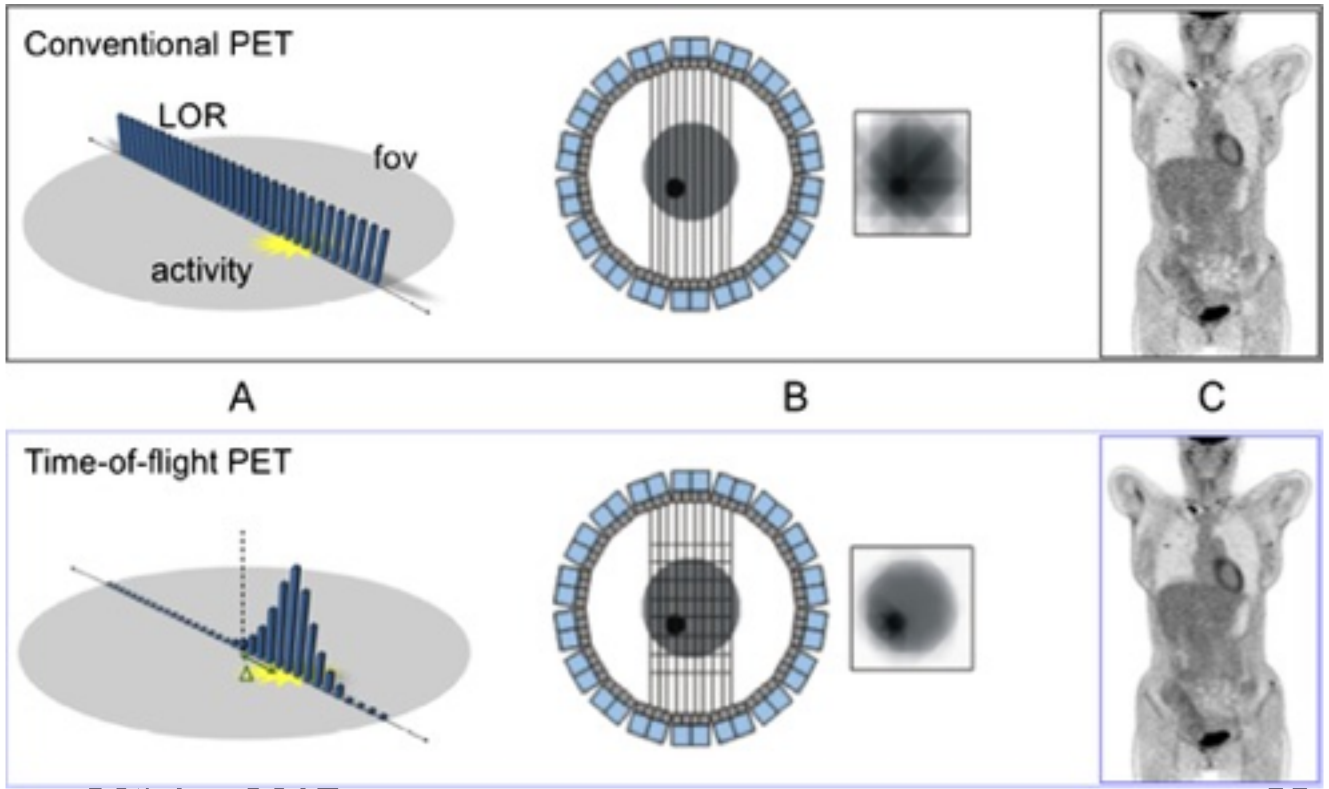
New test beam in 2016 with irradiated samples provided good results in radiation hardness

Application: PET-ToF

TOF PET provide a great spatial resolution with small bore holes.

Now a 600ps resolution TOF has been achieved, corresponding to 9cm resolution.

Goal for a <100ps (30ps) resolution which would match PET resolutions



A PET-TOF offers an intrinsic 3D imaging of the body.

The main requirements for the detector are:

•High detector Granularity, Si detector pixel 1x1.2x0.2mm Vs LYSO 4x4x20mm

•High photon conversion detection to reduce statistical backgrounds

•Small readout time to reduce fake coincidences and increase the time resolution of the single hits

Conclusion

- Silicon vertex trackers were and are of crucial importance for modern detectors at colliders but...

- To build the optimal detector for our purposes we need to understand the underlying physics, both in terms of discovery goals and machine performances

- Different conditions need different detectors, sometimes we can chose, some times the boundary conditions force the choice to a specific of detector

- Sometimes it is not possible to completely redesign or substitute a detector, but it is possible to act on readout electronics and off detector components to make an older design cope with newerer, and unforeseen problematics

- The next phases of LHC upgrades will have to deal with both a change of physics goals and new machine conditions (higher pile up, more radiation) and it is one of the most interesting time for developing new silicon detector technologies!

Backup

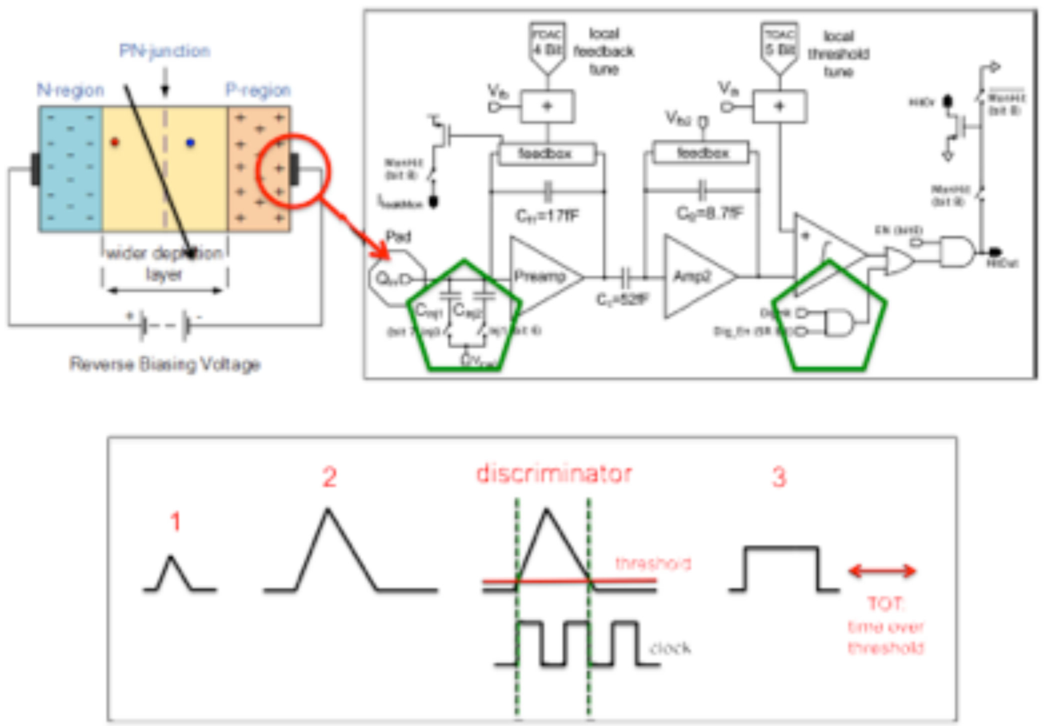
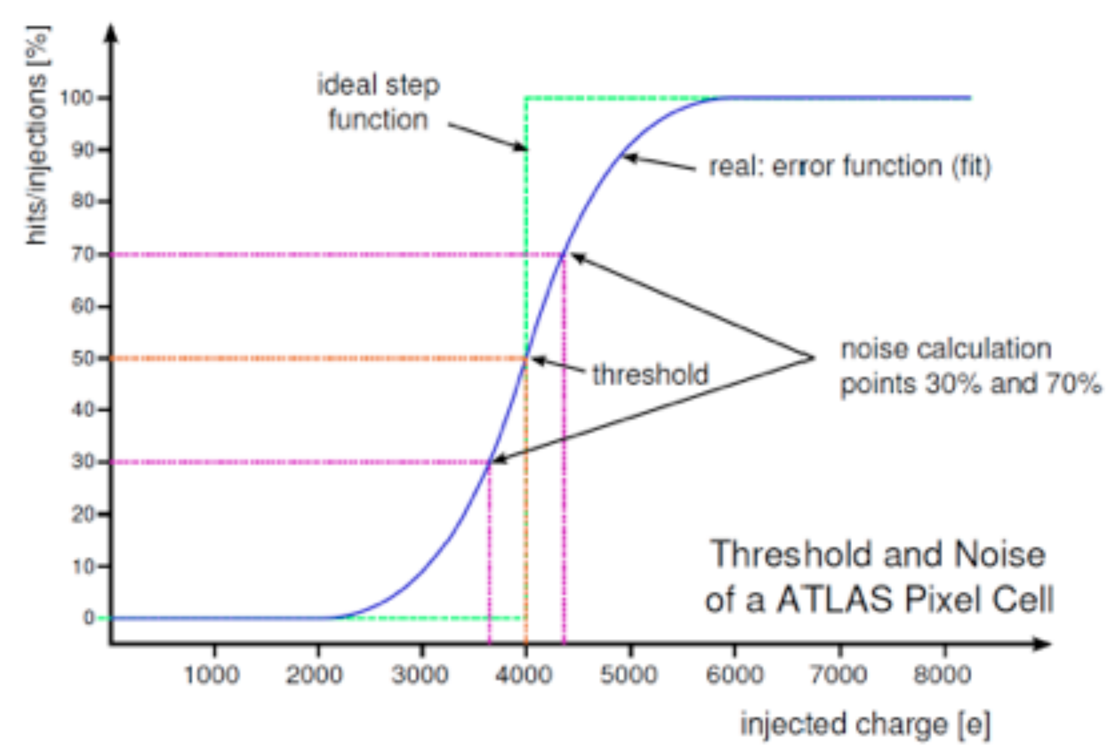
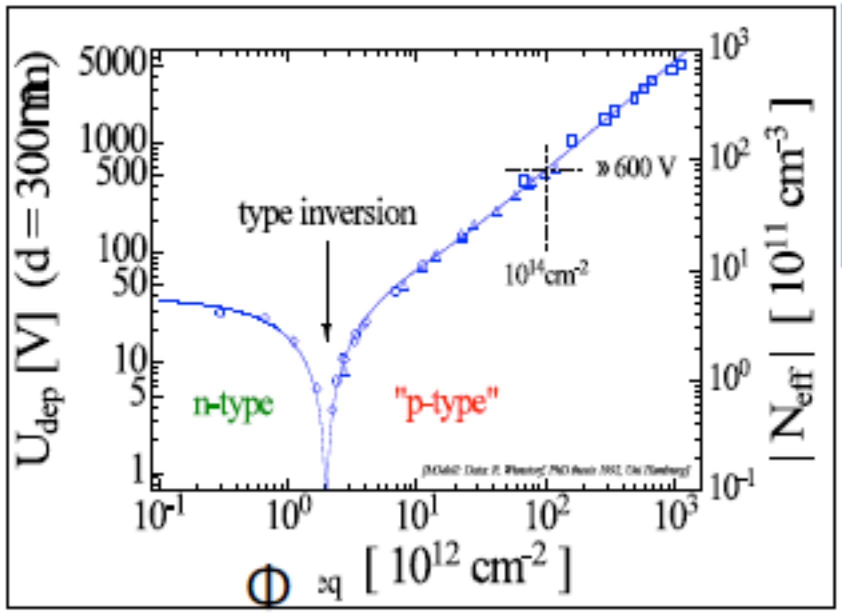
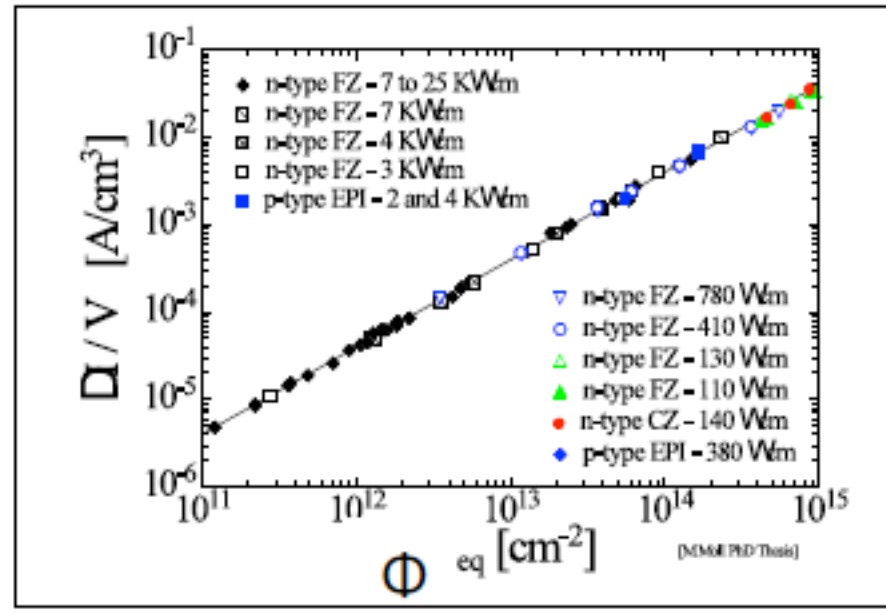


Figure 1: FE-I4 layout and scheme of the signal processing.

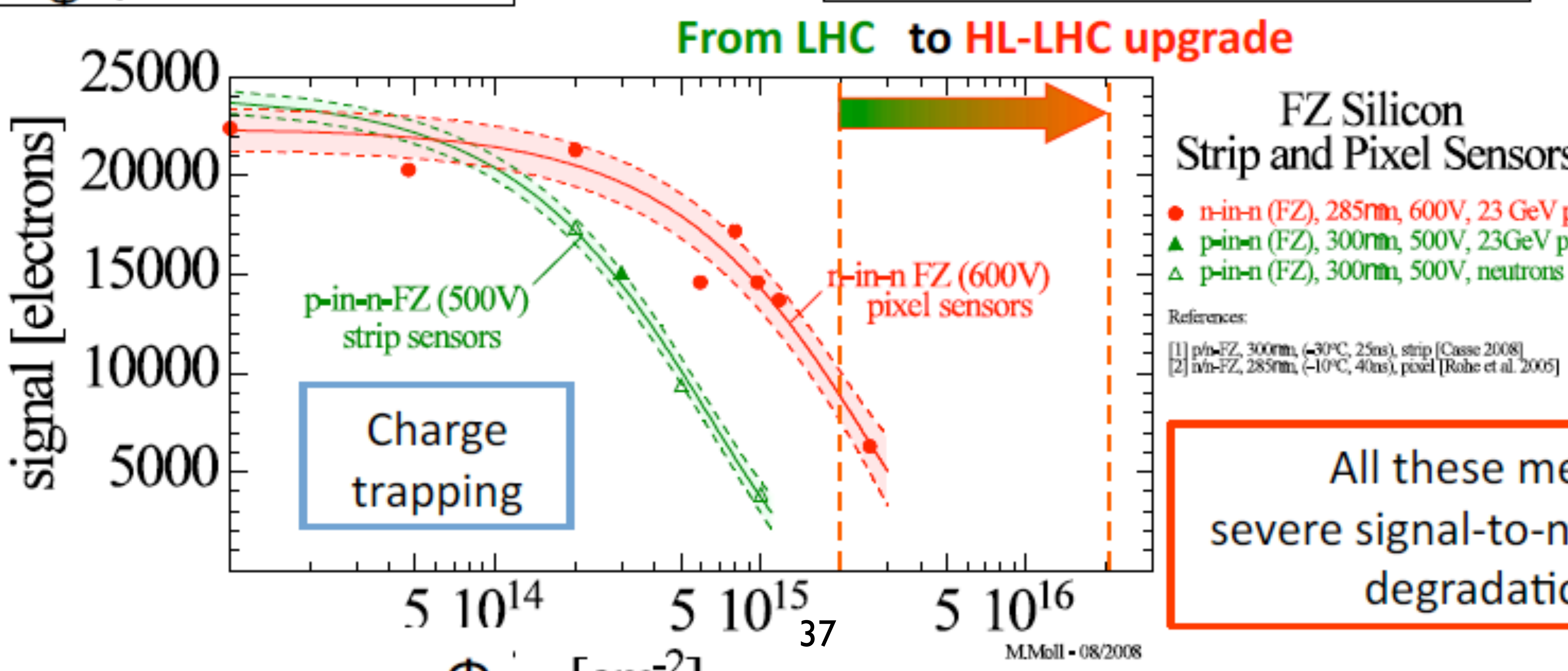




Depletion voltage increase



Leakage current increase



Charge trapping

All these mean:
severe signal-to-noise-ratio degradation

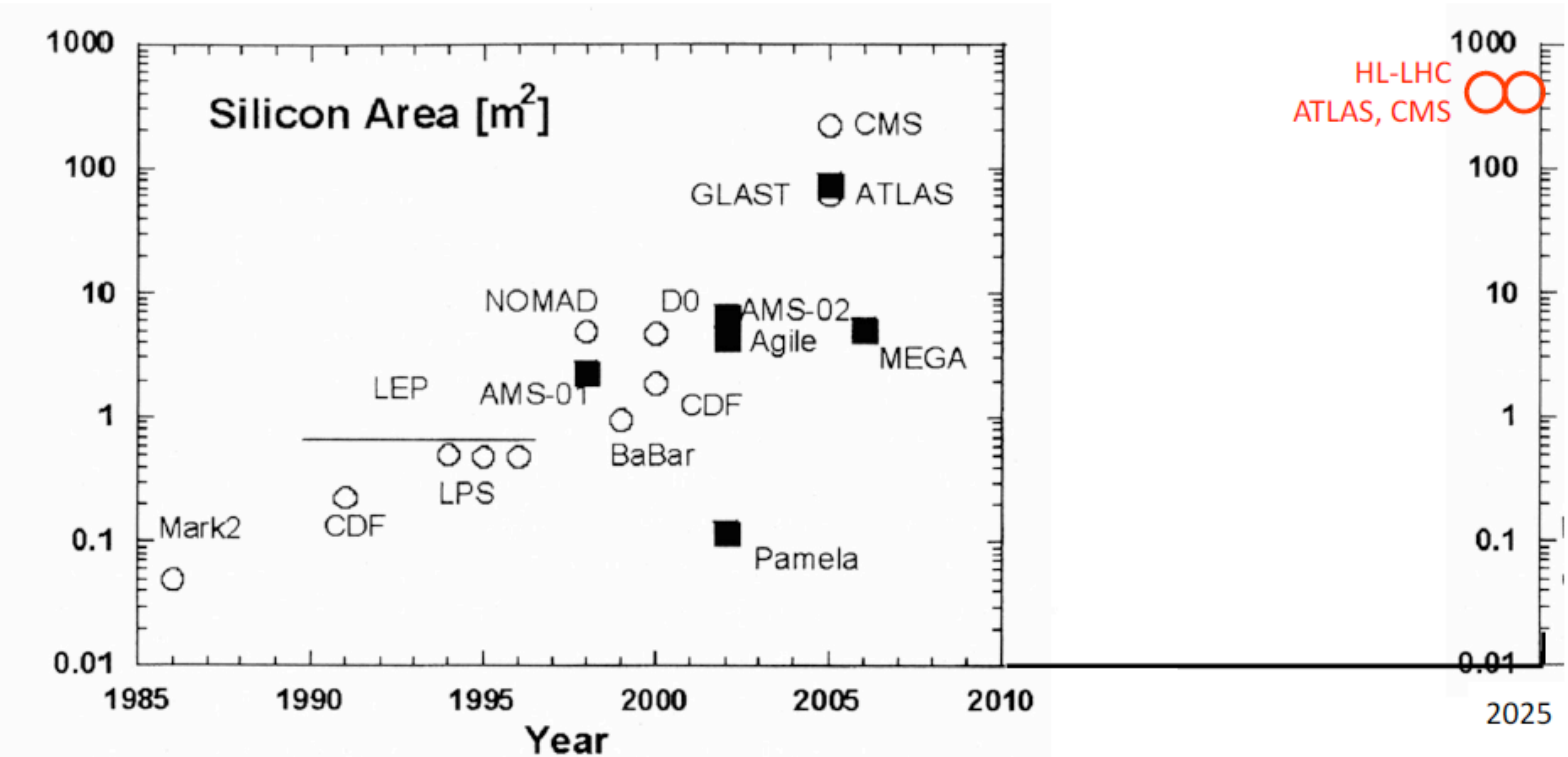
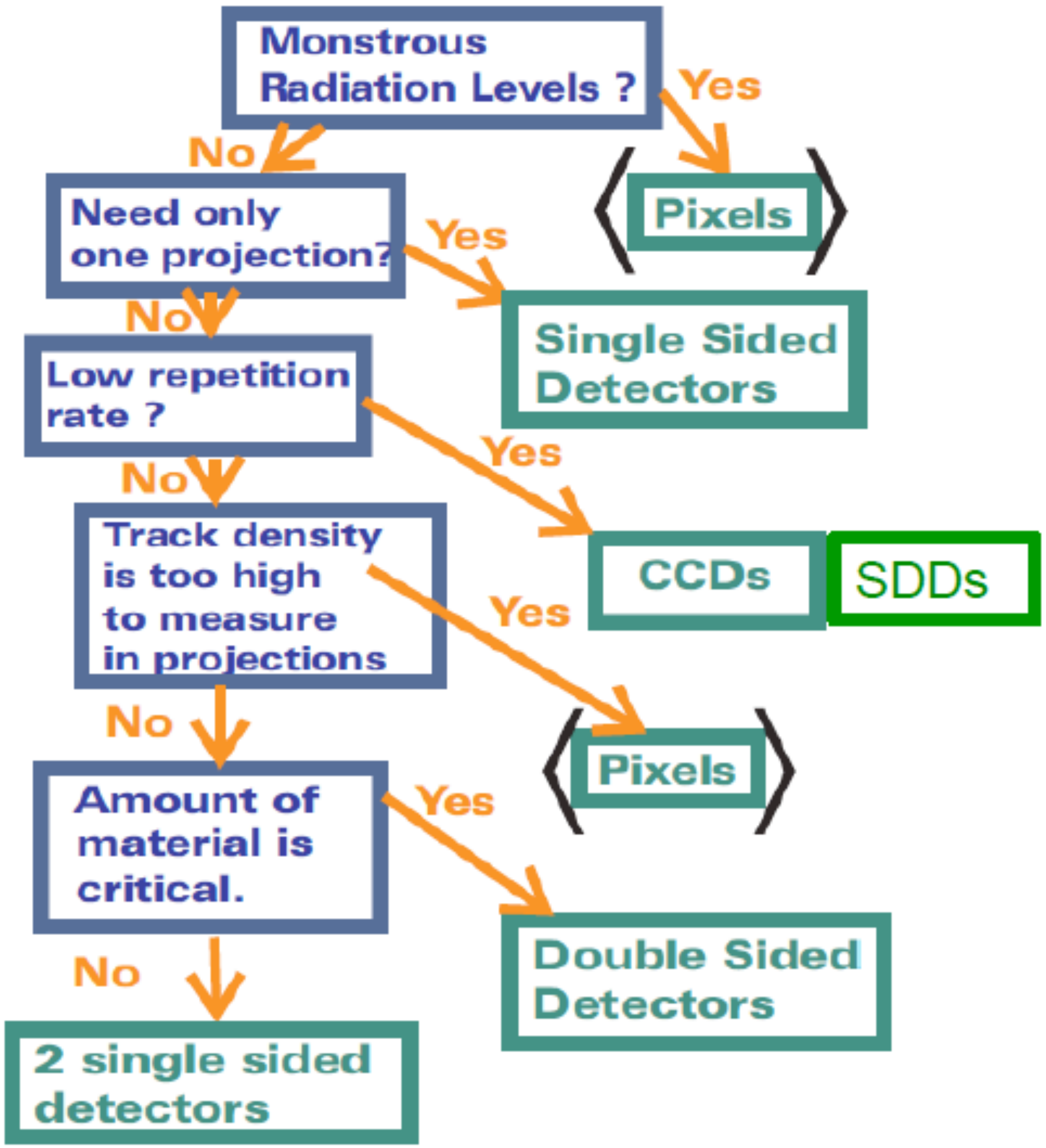


Fig. 4. The rise of the silicon detector: area of silicon detectors in experiments as a function of time. The full squares denote space-based instruments. The exponential growth of the area with time is an expression of Moore's law.

Extreme simplification



$\sigma(\text{point})^2 = \sigma(\text{mult.scatt.})^2 + \sigma(\text{detector})^2$

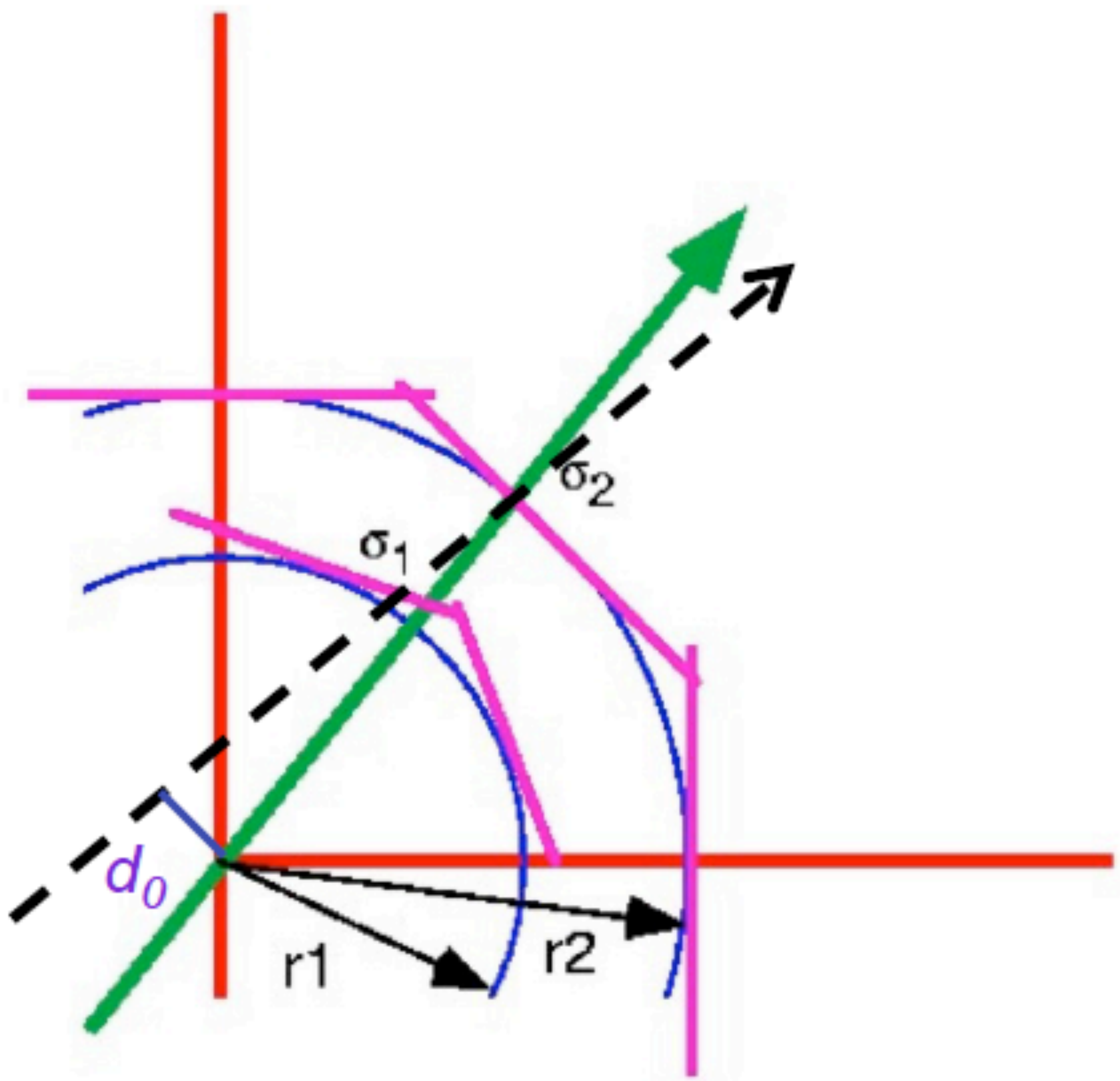
$$\sigma(\text{mult. scatt.}) \approx \frac{0.014R\sqrt{X/X_0}}{\sin^{5/2}\vartheta\,\beta c p}$$

For p=1 GeV/c, for R=3 cm,
X(beampipe+1st layer) = 1.4% X_0
σ(mult. scatt.) = 50 μm at 90°

Typical SVT detector resolution at BaBar is
σ = 12 - 14 μm at 90°

Impact parameter resolution is dominated by resolution on first hit

14

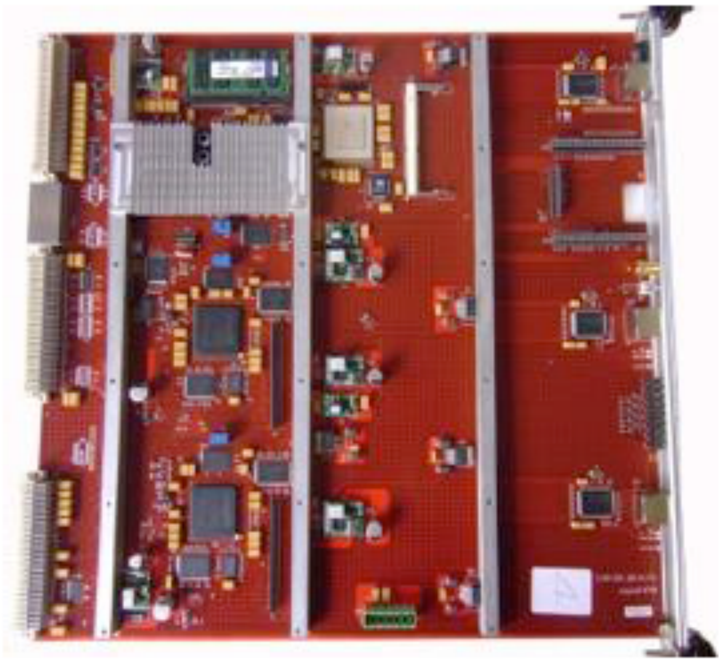


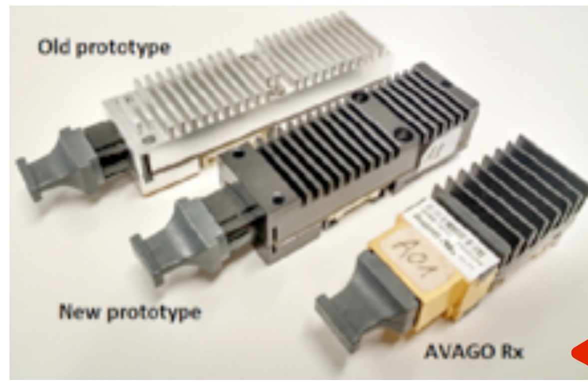
$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

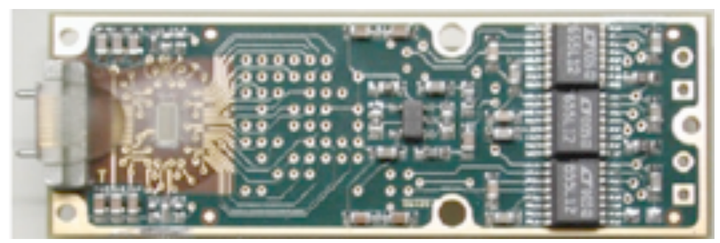
Suggests small r_1, large r_2, small σ_1, σ_2

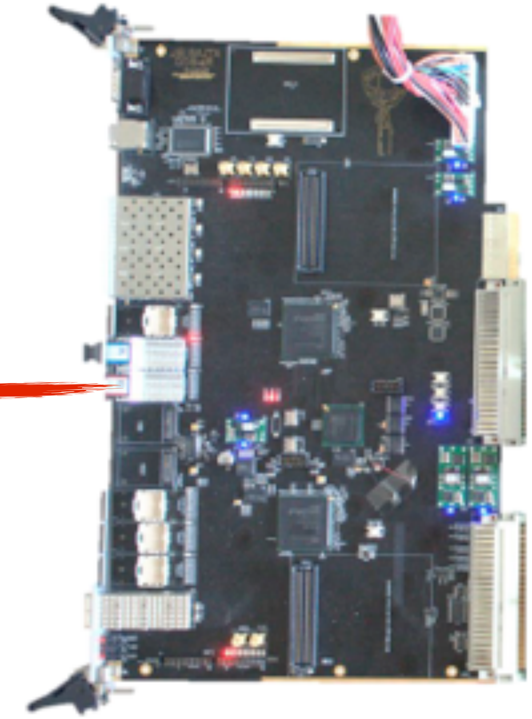
But precision is degraded by multiple scattering…

Pixel readout upgrade









Readout driver (ROD) controls data acquisition and is used as a master for the Back of crate Card(BOC)

connected to BOC through VME bus and to ATLAS readout with ethernet

Controls hystogramming of data, and calibration control

Data from/to detector are transmitted through optical connections.

IBL has a 8b/10b encoding which could use commercial optical transceiver

Pixel uses a protocol which is not supported by commercial transceivers

BOC provide connection between the ROD and the detector.

Is has 2 FPGAs one to connect to half a stave of modules, and is controlled through a microprocessor.

Data is received and decoded from detector, and clock and triggers are issued to detector