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

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My Experience so far

- 2005 Graduated in Università di Pisa: tau decays in strange final states
- 2006-2009: PhD in Università di Pisa: BaBar experiment, SVT operations and LFV in tau sector
- 2009-2011: Assegno di ricerca at Università 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:

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

$$
\frac{\sigma_{pT}}{p_T} = \frac{8p_T}{0.3BL^2} \cdot \sigma_s
$$

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

$$
\frac{\sigma_{P_T}}{P_T}_{MS} = 0.045 \frac{1}{B\sqrt{tX_0}}
$$

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: \( \Upsilon(4S) \)
produced at rest in CM, decay time
proportional to the decay length of the B in
lab frame

Resolution <80\( \mu \)m, and the \( \sigma(\Delta z) < 125 \mu \)m to
resolve B Vertices.

Other goal: understanding up-sector CPV:

D mesons not produced coherently at \( \Upsilon(4S) \)
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 \( P_T < 100 \text{ MeV} \).
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 10-15 μm
- Layer 4-5 30-40 μm

Average efficiency ~98% per track

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

Soft pion reconstruction from $D^{*+} \rightarrow \pi^+ D^0$
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

$$D^{*+} \rightarrow \pi^+ D^0$$
Siemens 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 $10^{36}\text{cm}^{-2}\text{s}^{-1}$

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 50x50μm² 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/√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 50x400 $\mu$m$^2$
- 300 $\mu$m thickness
- 0.1X0 material budget
- High resolution: 8 $\mu$m r$\varphi$, 75 $\mu$m in $z$
- Read out speed of 40Mb/s-160Mb/s depending on Layer.

Performance in Run1:
- 98% average efficiency
- 3500 e$^-$/threshold with $\sim$160e$^-$ noise (i.e. 20 S/N ratio)
ATLAS IBL

Motivation: better performances in Run2

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

Vertex reconstruction depends mainly on resolution of the first hit

Highly segmented: 50×250\(\mu\)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 Construction Diagram](image_url)
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

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

Optoboard: Electrical signal encoded and sent through optical links

Plug ins: receive optical transform in electrical signal.

Commercial plugins not working for Pixel operations: encoding problem

IBL plugins could not be used

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

40°C

30°C

20°C
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
Future of Vertex Trackers

Future Pixel detector for HL-LHC need many improvements:

- Increased radiation hardness
- Smaller sizes
- Cheaper interconnection technologies
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

30th Jan 2017
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

From LHC to HL-LHC upgrade

FZ Silicon Strip and Pixel Sensors
- p-in-n FZ (500V) strip sensors
- p-in-n FZ (600V) pixel sensors

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

Monstrous Radiation Levels?

Need only one projection?

Low repetition rate?

Track density is too high to measure in projections

Amount of material is critical.

2 single sided detectors

Single Sided Detectors

CCDs SDDs

Pixels

Double Sided Detectors

Bologna
30th Jan 2017

Alberto Cervelli
\[ \sigma(\text{point})^2 = \sigma(\text{mult. scatt.})^2 + \sigma(\text{detector})^2 \]

\[ \sigma(\text{mult. scatt.}) \approx \frac{0.014R\sqrt{X/X_0}}{\sin^{5/2} \beta \rho} \]

Impact parameter resolution is dominated by resolution on first hit.

Typical SVT detector resolution at BaBar is \(\sigma = 12 - 14 \, \text{µm at } 90^\circ\).

For \(p=1 \, \text{GeV/c}\), for \(R=3 \, \text{cm}\),
\(X(\text{beampipe+1st layer}) = 1.4\% \, X_0\)
\(\sigma(\text{mult. scatt.}) = 50 \, \text{µm at } 90^\circ\)
\[ \sigma_{d_0}^2 = \frac{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}{(r_2 - r_1)^2} \]

Suggests small \( r_1 \), large \( r_2 \), small \( \sigma_1, \sigma_2 \)

But precision is degraded by multiple scattering...
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.