Do we need a pixel upgrade?

Hitoshi Yamamolto
The Univeristy of Hawaii

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A proposal for systematic simulation study for vertexing upgrade.

+ A status report on pixel technology

♠: items needing MC study

Physics benefits of better vertex resolution (apart from the obvious improvement in $\sigma_{\Delta z}$)

- Combinatorics
  - Inclusive (e.g. $K^{*0} \to K^- \pi^+$) ♠
  - $B \to D^0 D^-, D^+ D^-, D^0 K^-$ etc. ♠

- Charm vertex → tag-side z resolution. ♠

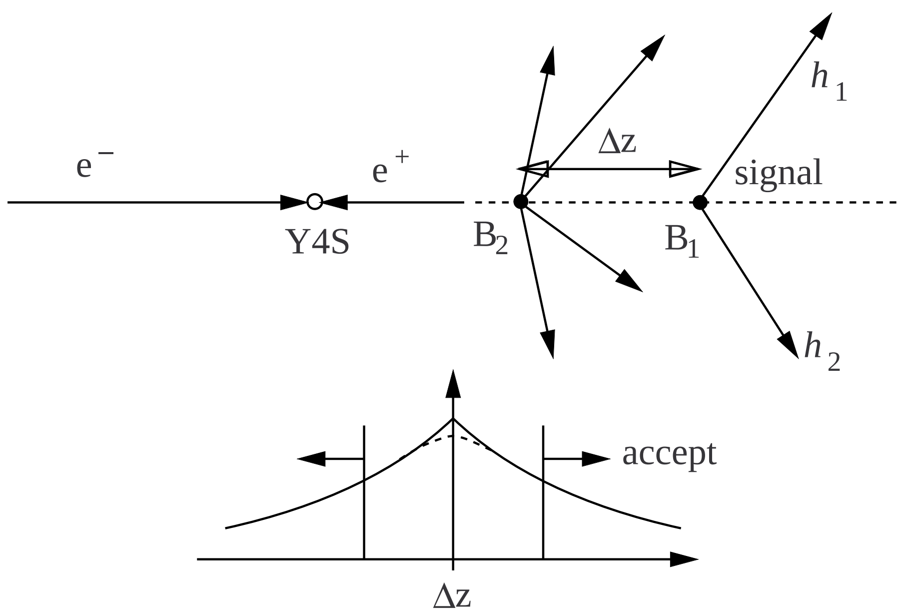
- Vertical B travel: $\to \Delta z \to \Delta t$

  Currently, the correction makes the resolution worse (crude calculation). ♠

- Continuum suppression by Δz ♠

Continuum suppression by z vertex separation

$$e^+e^- \longrightarrow B_1 B_2$$

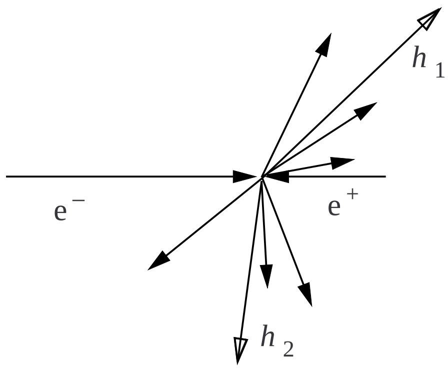


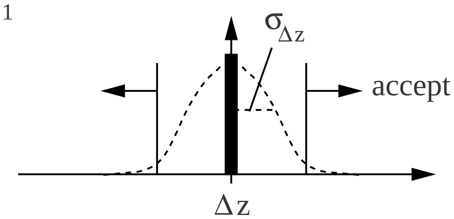
Δz distribution:

$$\propto \exp\left(-\frac{|\Delta z|}{L_0}\right)$$

$L_O(B$ mean decay length$) \sim 211\mu(Belle)$

$e^+e^- \to q\bar{q}$ (continuum)





Δz distribution (assume gaussian):

$$\propto \exp\left(-\frac{\Delta z^2}{2\sigma_{\Delta z}^2}\right)$$

$$\sigma_{\Delta z} \sim 125\mu$$

Discovery sensitivity improvement:

$\#\sigma$ probability of background fluctuate up to the signal.

$$\#\sigma = \frac{N_{\text{sig}}}{\sqrt{N_{\text{bkg}}}}$$

The improvement factor for $\#\sigma$ is then

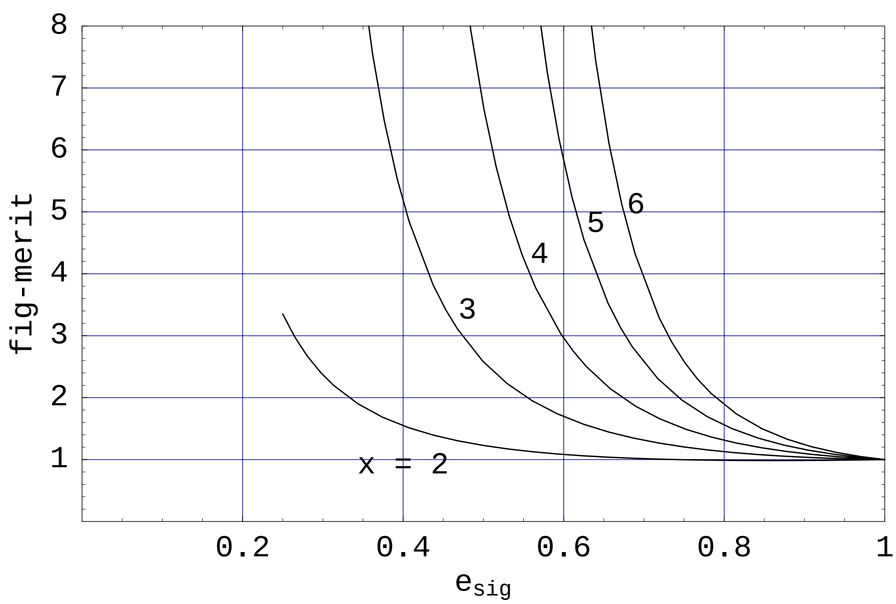
$$\boxed{\text{fig. merit} = \frac{\epsilon_{\text{sig}}}{\sqrt{\epsilon_{\text{bkg}}}}} \quad \text{(discovery)}$$

Does not depend on $N_{\text{sig}}/N_{\text{bkg}}$ before the vertex separation cut.

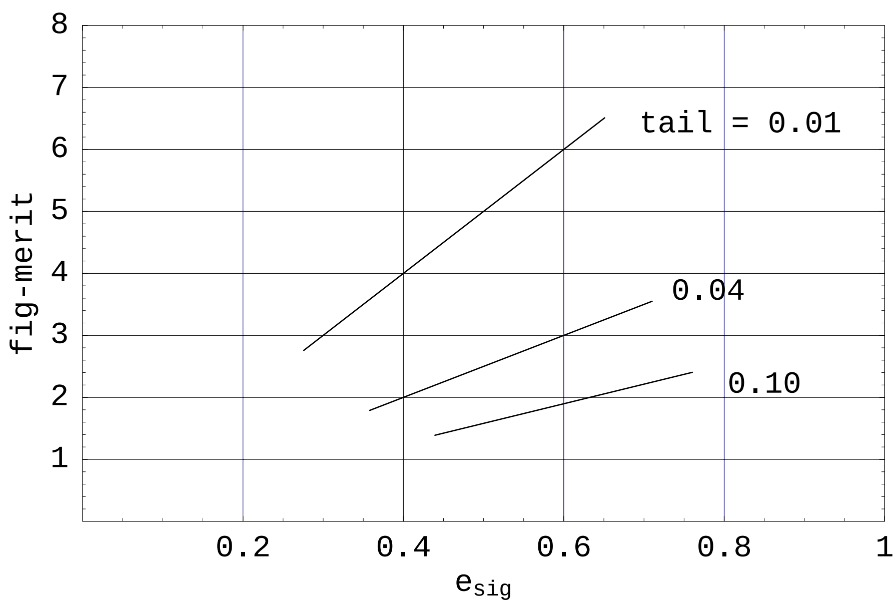
Discovery sensitivity improvement:

$$x \equiv \frac{L_0}{\sigma_{\Delta z}} \quad \sim 2 \text{ for Belle, BaBar}$$

L_0: B mean decay length (211 μ for Belle)



Tail: fraction of non-gaussian ($\sim$ flat) tail of the Δz resolution.



Example: Can we find $B^- \to K^{*0}K^-$
if Br is 1/20 of $\rho^0\pi^-$? ♠

CLEO 2.5: $\rho^0\pi^-$ S/N $\sim$ 20/20 @ 5 fb^{-1}

Assume factor of 4 reduction in bkg by a loose particle ID cut.

$\to K^{*0}K^-$ S/N $\sim$ 1/5 @ 5 fb^{-1}
$\to K^{*0}K^-$ S/N $\sim$ 10/50 @ 50 fb^{-1}

Significance $= 10/\sqrt{50} = 1.4\sigma$: Not a signal.

With $\sigma_{\Delta z} -> 1/2$ and 1% tail,

Significance $\to 1.4 \times 5.2 = 7.3\sigma$: Clear signal.

$K^{*0}K^-$ is an important mode to understand FSI, annihilation diagram, and $b \to d$ penguin.

There are many important modes at this Br level: D^+K_S, D^0K^+, $K^*\eta'$ ... Many of them play critical roles in direct CP studies. ♠

Factor of 2 improvement in $\sigma\Delta z$ resolution can be achieved by (rough calculation)

- R_{beampipe} 2cm $\rightarrow$ 1cm.
- 1/2 reduction of material (Si, support, beampipe).
- Keeping the same $\sigma_{\text{measurement}}$.

In general,

- σ_{measure} counts for high-P tracks ($P > 2$ GeV).
- Material reduction is important.
- R_{beampipe} reduction is essential.

Full MC study needed. ♠

Studies needed:

- Beam background control and IR design (incl. beampipe). ♠
- Detector thin and tolerant of radiation/noise hits

Possible detector candidates for inner layers:
(e.g. 2 inner layers out of 5 total for vertexing)

1. Silicon strip
2. Pixel

Pros and cons of the pixel solution

Cons:

1. Requires substantial R& D to apply to Belle
   (A few pixel detectors working in HEP experiments)

2. Readout electronics adds to the material budget
   (could be as thin as a few 10's of μ; will see)

Pros:

1. Measures true 3D points $\rightarrow$ noise hit tolerance

   Assume 40 real hits on a 1×3 cm^2 sensor.
   (pitch: 50μ)

occupancy	point hit	3 pitches/hit
pixel:	3×10^{-4}	3×10^{-3}
strip:	20%	60%

   Needs realistic track finding simulation. ♠

2. Low capacitance per channel ($\ll$ 1 pF) $\rightarrow$ low noise

3. Low leakage current per channel ($\sim$ fA) $\rightarrow$ low noise

   Low noise partially translates to radiation tolerance.

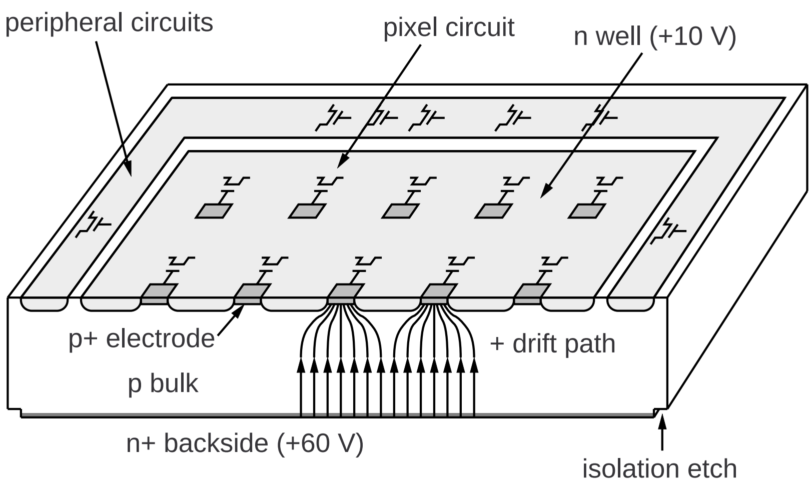
   A study on silicon strip detectors:
   (1cm$\times$1.3cm, shaping time 0.7μsec, ^{90}Sr)

	300μ	100μ
S/N	29.7	7.88

   A large common-mode noise seen for 100μ sensor.

Monolithic Pixel Detector

Readout electronics and sensor on the same chip



Hawaii-Stanford monolithic pixel detectors
Fabricated at CIS, Stanford

- Thickness 300μm

Collection electrode:	p^+ (i.e. collects holes)
Bulk:	p
Backside:	n^+-diffusion

- One PMOS readout circuit in n-well for each pixel.

- Operated with full depletion at $\sim$60 V.

Two versions of monolithic pixel detector succesfully tested:

V1. 1993. Pitch $34 \times 125\mu\text{m}^2$
1.02mm$\times$1.02mm active area
Full readout

Tested at Fermilab (muon beam)
$\rightarrow \sigma = 2.0\mu$m ($34\mu$m pitch direction)

V2. 1996. Pitch $65 \times 67\mu\text{m}^2$
32$\times$32 array ($\sim$ 1mm^2 active area)
Sparse readout
Tested by ^{241}Am

Challenges for the monolithic pixel design:

1. **Larger array**

   Using the same sparse readout scheme, 320×320 array (1 cm^2), 0.5% pixel occupancy
   $\rightarrow \sim 300\mu s$ readout.

   But, at this size most of the rows are hit (the sparse readout operates on rows) $\rightarrow$ might as well read all rows (future)

2. **Foundry**

   Difficult to find a foundry who is

   - willing to closely collaborate,
   - has deep-submicron technology,
   - can respond to non-standard facbrications: rad-hard design, high-purity bulk silicon.

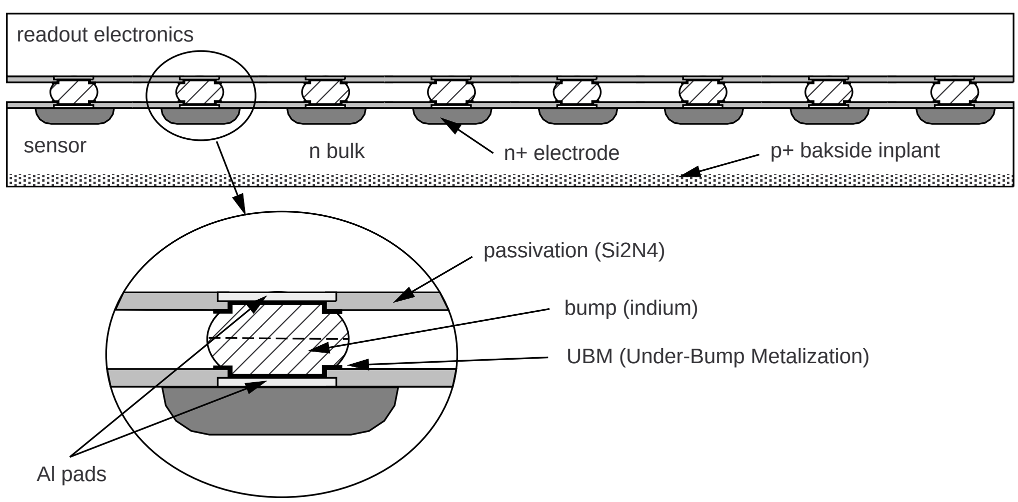
   $\rightarrow$ keep looking for a foundry,
   but pursue hybrid design meanshile.

Hybrid Pixel Detectors

Hybrid = Bump-bonded

Sensor:high-resistivity silicon (typically float-zone)
Readout chip: Commercial CMOS OK

→ Fabricate separately and bond them
(flip-chip technology)



Most current and proposed HEP pixel detectors uses hybrid design.
(DELPHI, WA97, ATLAS, CMS., ALICE, BTeV...)

	pixel size	# pixel (total)	sensor thickness	heat/cell
DELPHI	$330\times330\mu^2$	1.2 M	300μ	40μW
WA97	$50\times500\mu^2$ $75\times500\mu^2$	1.2 M	300μ	
ATLAS	$50\times300\mu^2$	105 M	200-250μ	50μW
CMS	$150\times150\mu^2$	56 M	200-250μ	60μW
ALICE	$50\times300\mu^2$	15.7 M	150μ	30μW
BTeV	$50\times300\mu^2$	60 M	300μ	$<40\mu$W

Issues for a Belle pixel detector:

(a) Readout electronics (that fits in $50 \times 50\mu^2$)

(b) Thinning of sensor and readout chips

(c) Bump bonding

(d) Radiation hardening

(a) Proposed readout electronics

(Conceptual design by G. Varner)

- Avoid sending analog signal by digitizing on each pixel.
- V_{ramp}+Comparator and 5-line counting bus. LVDS driver at the end of sensor.
- 1cm$\times$3cm, $50 \times 50\mu$m^2 pixel. 2% occupancy $\rightarrow$ 200μs read out time.

Expected heat generation

- Most of the time the MOS transistors do not dissipate heat, namely static.
  (much easier situation than LHC)

- Needs a completed design of the circuit,
  but roughly, $\sim$0.4μW/pixel
  $\rightarrow \Delta T \sim$ 0.1°K (side cooing)

- LVDS driver generates lots of heat, but it is at the end of sensor.

(b) Thinning of the sensor and readout chip

- Wafer thinning is a routine commercial process (for heat dissipation)

  $$\begin{cases} \text{Grinding-polishing-etching} \\ \text{Plasma etching} \end{cases}$$

- Readout electronics:
  Thinned after fabrication using a commercial process (e.g. MOSIS).

- Sensors may be thinned first.
  (needs a dedicated foundry)

  Or, thinned after fabrication
  (still needs some processing of the thinned side)

- Thin before or after the bump bonding?

  If thinned after bonding, the read-out electronics may be made quite thin ($\sim 20\mu$?).

  $\rightarrow$ **more R& D needed.**

(c) Bump bonding

- Bump bonding defects $< 10^{-4}$ (dummy tests). But some problems reported for the real ATLAS detector.

- Bump diameter can be $< 10\mu$, pitch can be $< 20\mu$ (e.g. GEC Marconi)

Two types of bumps

	Indium	Solder
UBM *	simple	complicated
bump deposition	both sides	one side
connection	pressure	fused
Strength (4K bumps) (tension& sheer)	2.5 lb	10-14 lb (strong)
alignment required	1-2μ	$\sim 10\mu$ (self-slinging)
resistance/bump	1-2 Ω (poor)	2-3 $\mu\Omega$ (good)

* UBM = Under Bump Metalization

(d) Radiation Hardening

Radition damage effects

a) Effective dopant creation
b) Leakage current increase
c) Threshold shift of MOS transistors

a) Effective dopant creation

Mostly p type

- Change in $V_{\text{depletion}}$ (e.g. increase)
  $\rightarrow$ high voltage breakdown, partial depletion
- Type conversion ($n \rightarrow p$) at high dose
  (OK for Belle)

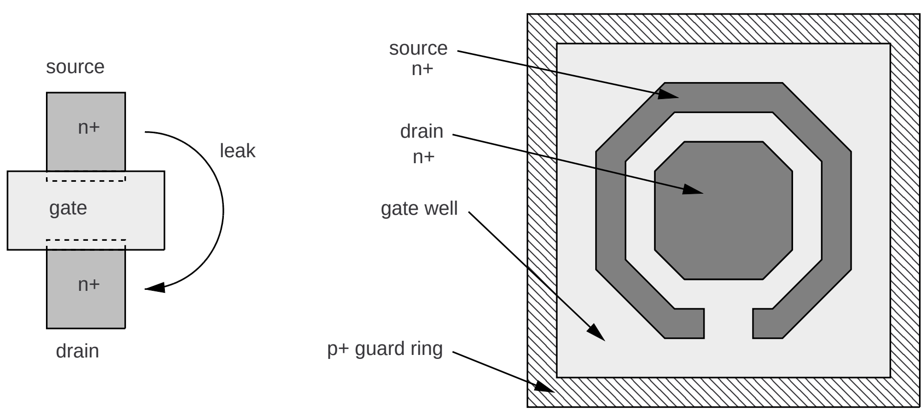
$\rightarrow$ Design the detector such that it can stand high voltage
(e.g. guard rings at the edges of sensor)

b) Leakage current

1. source-drain leakage
2. inter-transistor leakage
3. detector bulk leakage current

Strategy:

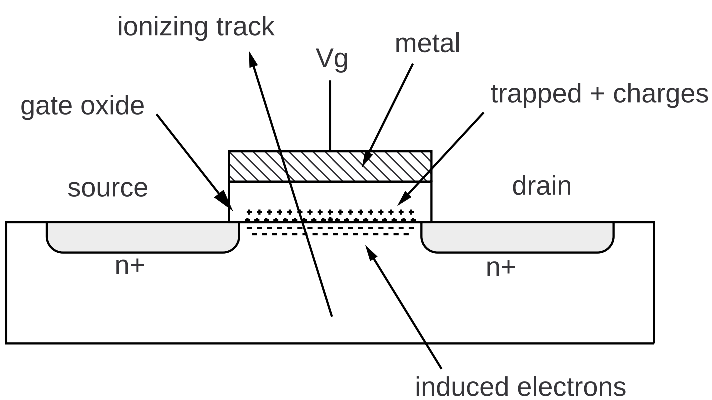
- Rad-hard design rules
  - ∗ Surround-gate design
  - ∗ p-stop around NMOS transistor



- current compensation for detector leakage (read-out electronics design)

c) Threshold shift of MOS transistor

Trapped positive ionization charges at gate-oxide
$\longrightarrow$ induces elctrons just below the gate.



$$\Delta V_{\mathrm{th}} \propto \begin{cases} t^2 & (t < 10\,\mathrm{nm}) \\ t^3 & (t < 10\,\mathrm{nm}) \end{cases}$$

t: gate thickness

Make the gate oxide thin:
$\longleftarrow$ natural result of small scale processes.
(e.g. <u>commercial</u> IBM $0.25\,\mu$ process)

Pixel detector status summary:

1. Monolithic pixel proven to work (32×32 array).

   Challenges:
   - larger detector
   - rad-hardness
   - **foundry !!**

   → try hybrid design.

2. Hybrid pixel design

   - heat $< 50\mu$W/pixel for LHC.
     Less for Belle → probably not a problem.
   - thickness $< 250\mu$ (sensor & read-out)
     being tested. 150μ total seems feasible.
   - bump bonding

     yield $> 99.99\%$:dummy test
     (some problems with real detectors)

     pad size can be $< 10\mu$, pitch can be $< 20\mu$
   - Rad-hardness of readout chip
     Deep subμ + rad.hard rules →
     30 MRad : IBM 0.25μ (ALICE)
     (Barely fits in $50 \times 300\mu^2$)

R& D Items Summary:

1. Readout electronics that fits in pixel and rad-hard.

2. Thinning of sensor ($\sim 100\mu$)
   and readout chip ($\sim 50\mu$).

3. Bump bonding for our specifics.

On-going efforts:

Prototype design

2mm$\times$2mm
pixel: $50\mu \times 100\mu$

- Readout electronics design by G. Varner.
  MOSIS submission in a few months.

- Sensor design by S. Parker and C. Kenney.
  To be fabricated at CIS in the same time scale.

- Bump-bonding test: in contact with GEC Marconi.
  Other companies are to be tested.