Precision detectors for the flavour (=B)-physics

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External seminar IPNP, Mala Skala 2019

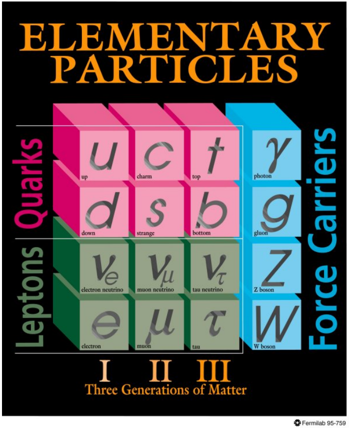
About the Title: B-physics: subset of flavour physics

Why is FP interesting?

- striking pattern of SM
- flavour symmetries
- CP Violation
- matter - antimatter asymmetry
- probing beyond SM physics

Scope of this review

- charm and beauty physics
- little about s quark
- no leptons
- no top



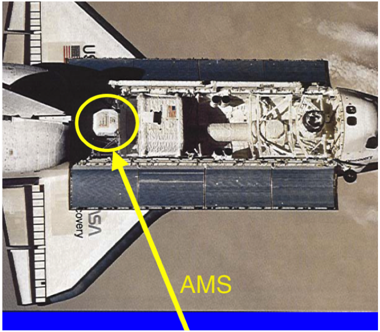
+antimatter

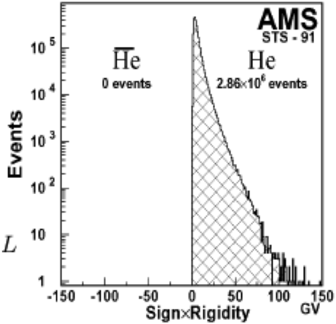
Baryon Asymmetry in Universe (BAU)

At the Big Bang particles and antiparticles created in pairs. Our universe now is composed of matter only (and a lot of photons). Where is the antimatter?

Potential signals:

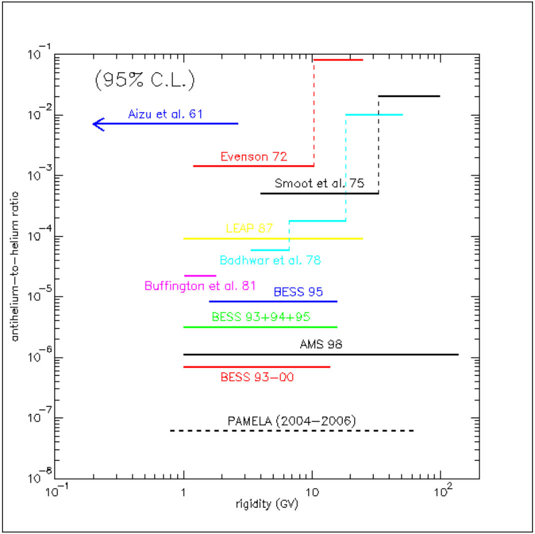
- annihilation photons
- anti ^{4}He nuclei in the cosmic rays (AMS, PAMELA,...)





Baryon Asymmetry in Universe (BAU)

Summary of results:



Baryon Asymmetry in Universe (BAU)

Summary of results:

Baryon Asymmetry in Universe (BAU): possible mechanism

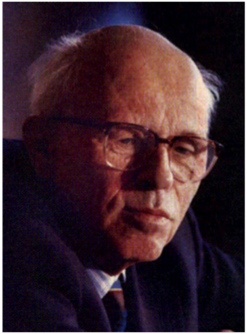
Observed number

$$\frac{\Delta N_B}{N_\gamma} = \frac{N_{bar} - N_{\bar{bar}}}{N_\gamma} = 10^{-10}$$

Sakharov (1967)

3 conditions necessary to get the matter-dominated universe:

1. baryon number violation
2. C & CP Violation
3. thermal inequilibrium



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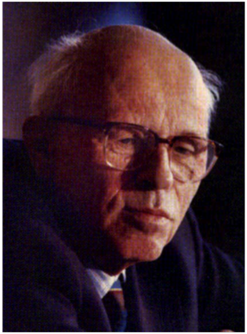
Nobel Peace Prize 1975
Internal exile in Gorky



Precision Measurement: Swedish Coffee Experiment

King Gustav III of Sweden (1746-1792) wanted to ban coffee, because he believed in its toxicity. He wanted to prove it scientifically, so he (reportedly) realized a *S*wedish coffee experiment.

- two identical twins sentenced to death kept alive in prison
- one had to drink three pots of coffee everyday
- second had to drink three pots of tea everyday
- two doctors appointed to supervise and report

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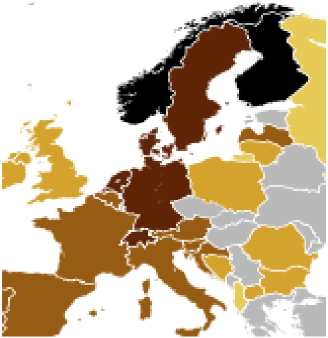
Outcome of Swedish Coffee Experiment

- first of all, both doctors died
- king Gustav was assasinated in 1792
- tea drinker died first, at the age of 83
- the date of death of the surviving coffee drinker unknown



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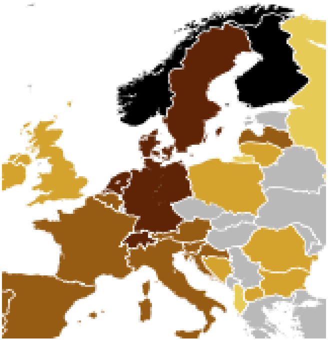


Lessons

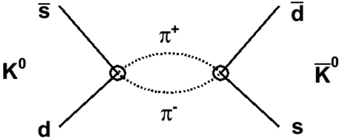
- build the control sample (another twin)
- study aging/hardness of your detectors
- time your experiment reasonably (theorists, funding agencies might not wait/live)
- be prepared for the unexpected

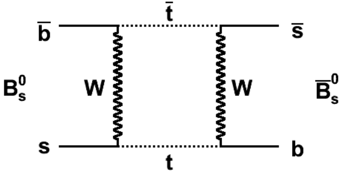
Neutral meson (K^0, D^0, B_d^0, B_s^0) oscillations

Flavour eigenstates M^0 and $\bar{M}^0$ can mix into each other
This is described by the Schrödinger equation (coherent state)

$$\frac{\partial}{\partial t}\begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix} = H \begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix}$$

$M_{S,L} = pM^0 \pm q\bar{M}^0$ physical states
$\Delta m = m_L - m_S$: oscillation frequency
$\Delta\Gamma = \Gamma_S - \Gamma_L$ decay width/lifetime difference





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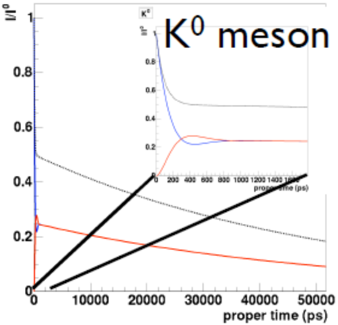
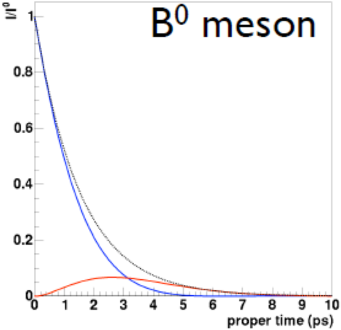
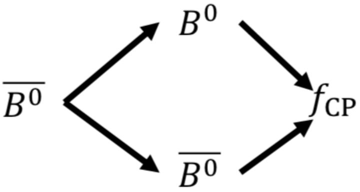
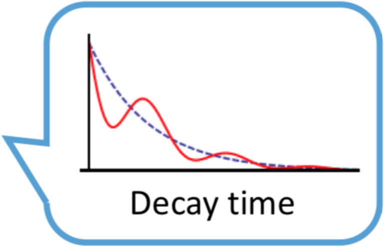




Neutral mesons: perfect lab to study CPV

If neutral meson decays into a CP eigenstate f_{CP}, the decay can go directly or via a coherent state.





CP Violation classification

- CPV in decay (direct)
- CPV in mixing
- CPV in interference between mixing and decay

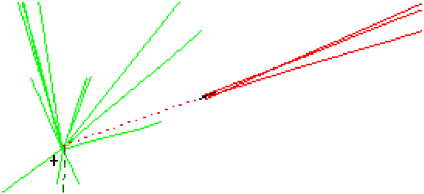
Need to measure CP violation as a function of time!

Experiment

Ideal production process:
$\Upsilon(4S) \rightarrow B_0 \bar{B}_0$
How to measure time with picosecond precision?
Convert to distance measurements?

$\beta \approx 0.1, v\tau \approx 45\mu\text{m}$

Out of reach as well
Trick: high-energy B-meson is relativistic: lives longer, gets further
Production: High-energy collisions (LEP, Tevatron, LHC):
Observing e.g. $pp \rightarrow B_0 \rightarrow X$ as a function of B-displacement between creation and decay position
Second B-meson tells us flavour (B_0 vs $\bar{B}_0$

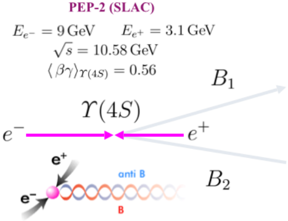


Alternative: Asymmetric B-factories: P. Oddone (1987)

PEP-2 (SLAC)

$$E_{e^-} = 9\,\text{GeV} \qquad E_{e^+} = 3.1\,\text{GeV}$$
$$\sqrt{s} = 10.58\,\text{GeV}$$
$$\langle \beta\gamma \rangle_{\Upsilon(4S)} = 0.56$$

Alternative: Asymmetric B-factories: P. Oddone (1987)



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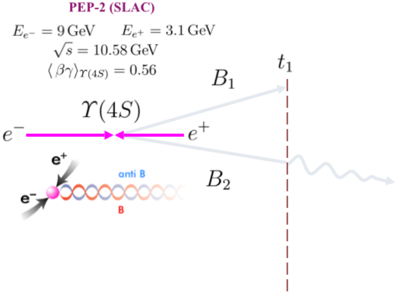

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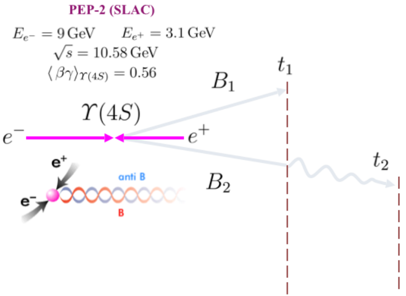

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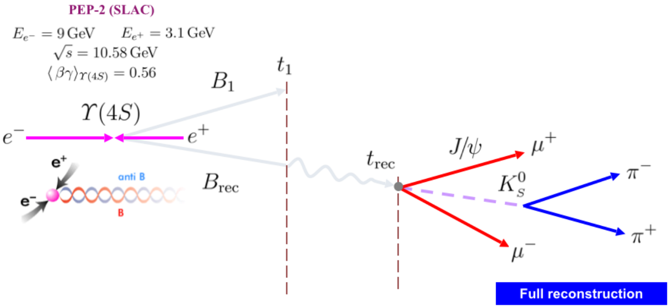

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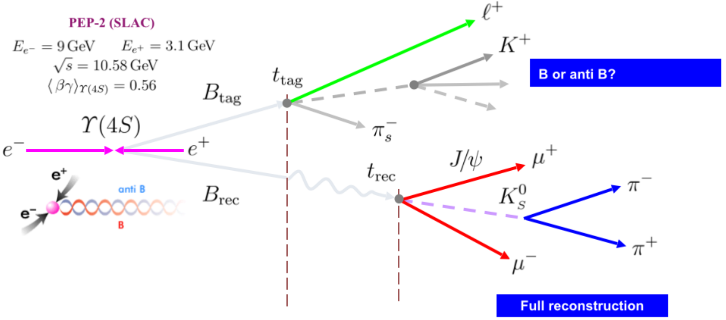

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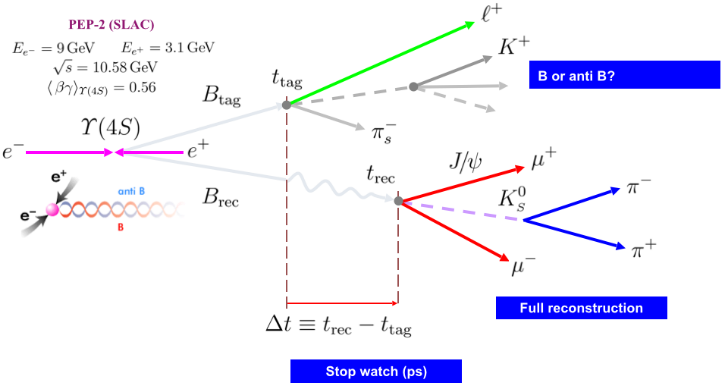


$$\Delta t \approx \Delta z / c \langle\beta\gamma\rangle_{\Upsilon(4S)}$$

$$\langle\Delta z\rangle_{B\bar{B}} \approx 260\,\mu\mathrm{m}$$

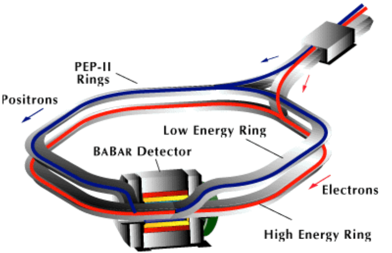
Flavour Physics at the LHC Era

Comparison of experiments at electron and hadron machines

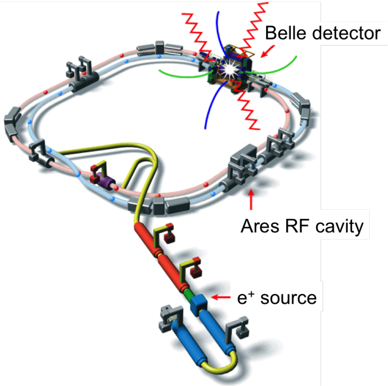
	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ BF/SuperBF	$p\bar{p} \to b\bar{b}X$ Tevatron	$pp \to b\bar{b}X$ LHC
C.M. energy $\sqrt{s}$	10.588 GeV	2 TeV	14 TeV
Luminosity $10^{34}/\text{cm}^2\text{s}$	1/80	0.05	1
Production σ	1.2 nb	100 μb	500 μb
Typical $b\bar{b}$ rate	12 Hz/960 Hz	100 Hz	500 Hz
Pile-up	0	1.7	0.5-20
b hadron mixture	$B^+B^-(50\%)$ $B^0\bar{B}^0(50\%)$	$B^+(40\%)$, $B^0(40\%)$ $B_s^0(10\%)$, $\Lambda_b^0(10\%)$	
b hadron boost	small $\beta\gamma \approx 0.5$	large $\beta\gamma \approx 100$	
Underlying event	$B\bar{B}$ alone	Many add. particles	
Production vertex	Not reconstructed	Reconstructed	
$B^0\bar{B}^0$ pair production	Coherent (from $\Upsilon(4S)$)	Incoherent	
Flavour tagging power	$\varepsilon D^2 \approx 30\%$	$\varepsilon D^2 \approx 5\%$	

Adapted from arXiv:1305.4688

B-factories: (Super)KEKB and PEP-II



SLAC, California
1999-2008, 530/fb



(Super)KEKB, Tsukuba, Japan
1999-2010, 1024/fb
2017-2027 50/ab

Detectors and Experiments for the Job

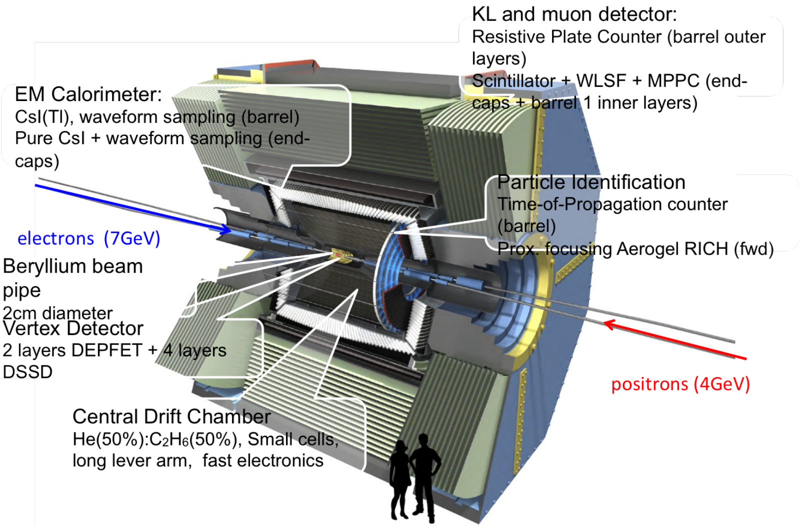
General requirements for the HEP detector

- trajectory and momentum measurements of charged particles
- hadron and γ energy measurement
- muon identification

B-physics experiments at the precision era

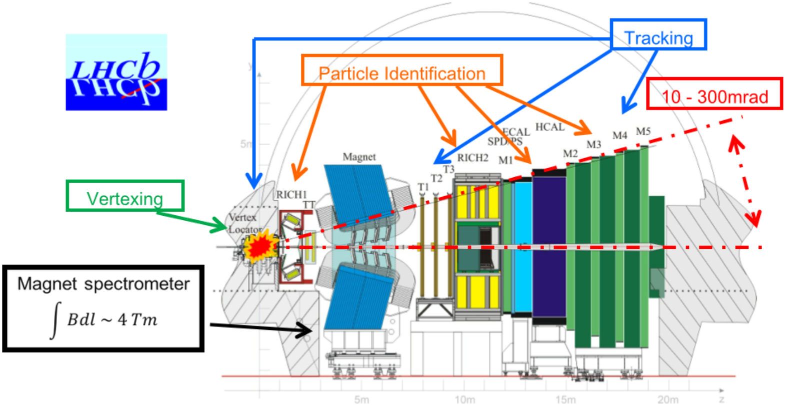
- vertex/timing measurement (tens of microns)
- particle identification (K/π)
- nowadays: missing E_T measurement (hermeticity)
- systematics under control (control samples, background estimates)

Belle II detector

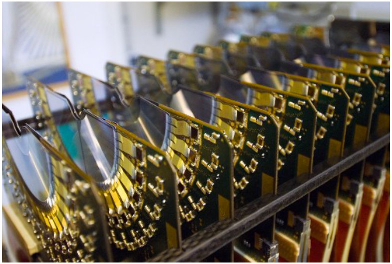


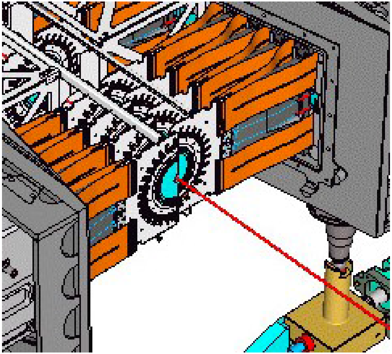
LHCb: forward precision spectrometer

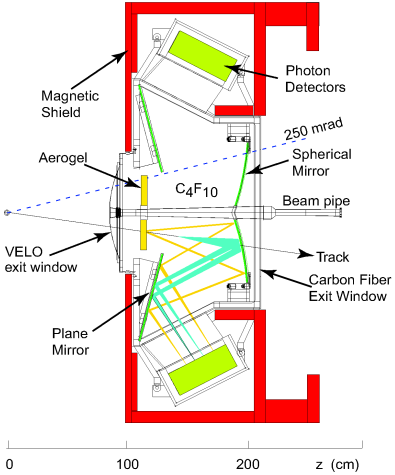
Dedicated flavour physics experiment at the LHC



LHCb: VELO, RICH

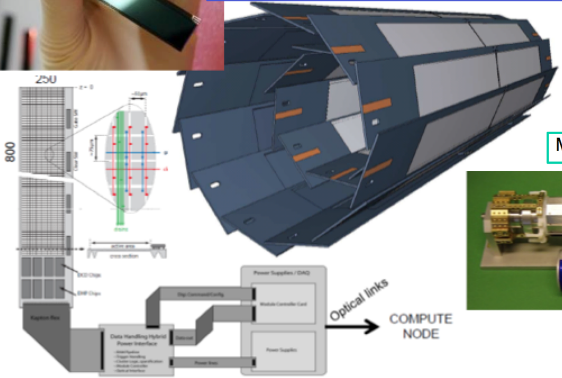






	radius	pixel	thickness
Layer 1	r = 14mm	$50\times50\mu m^2$	$75\mu m$(0.18%X0)
Layer 2	r = 22mm	$50\times75\mu m^2$	$75\mu m$

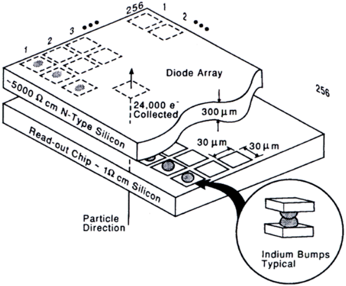
total of 8 M pixels

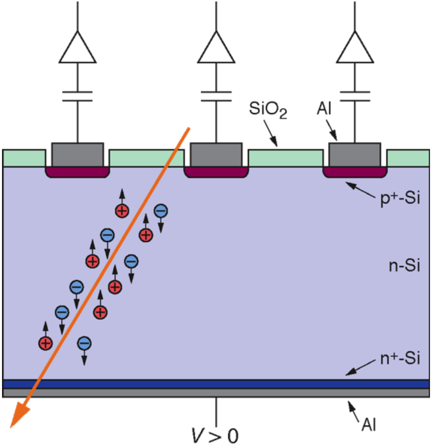


Mechanical mockup

Vertex reconstruction: Si strips or pixels

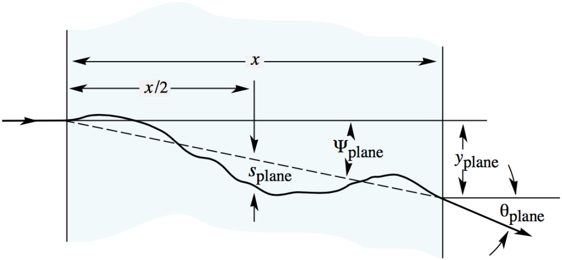
ATLAS:
Silicon detektors, pitch ca 80 μm
80 milion cells
Radiation hardness is eseential
(10^{15-16}neutrons cm^{-2})





Multiple scattering

Scattering by Coulomb potential of nucleus
Affects particle track, crucial for tracking detectors



RMS of scattering-angle distribution:

2D-projected: $\Theta_{\text{rms}}^{\text{proj.}} = \sqrt{\langle\Theta^2\rangle} \approx \frac{13.6\,\text{MeV}}{\beta cp}\sqrt{\frac{x}{X_0}}$

3D space: $\Theta_{\text{rms}}^{\text{space}} \approx \frac{19.2\,\text{MeV}}{\beta cp}\sqrt{\frac{x}{X_0}}$

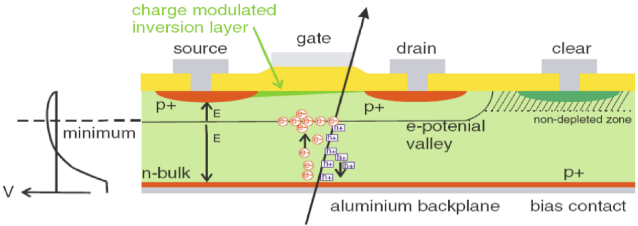
X_0: radiation length (material characteristics)

Monolithic active pixels

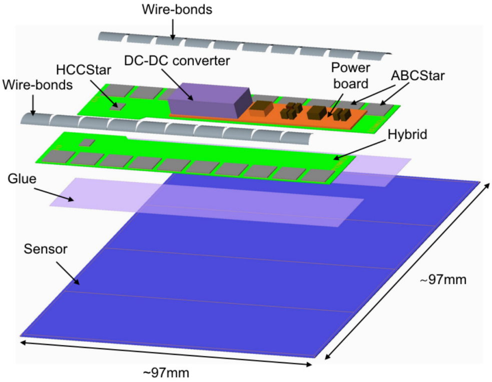
Silicon used both in a detector and in processing electronics
Why not integrated? Using the same wafer/substrate?
This is not so easy:
Electronics needs high conductivity Si
Detectors need high-resistivity Si (to achieve depletion)
Several approaches to match these contradictions:

- Monolithic Active Pixels (CMOS)
- Monolithic Active Pixels (SOI)
- DEPFET Pixels

Minimizing material (thinning to 50 μm)



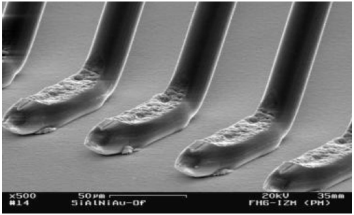
How to make a detector: module



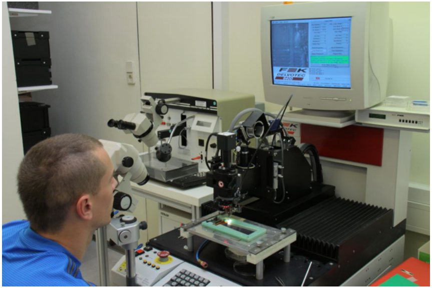
- Low mass (multiple scattering)
- Rigid, strong
- Low coefficient of thermal expansion (CTE)
- Good thermal conduction
- Restricted space
- Low cost (!)
- Radiation hard
- Works at low temperatures

Wire bond connection

Ultrasonic welding technique
typically 25 μm bond wire of Al-Si-alloy
Fully-automized system with automatic pattern recognition



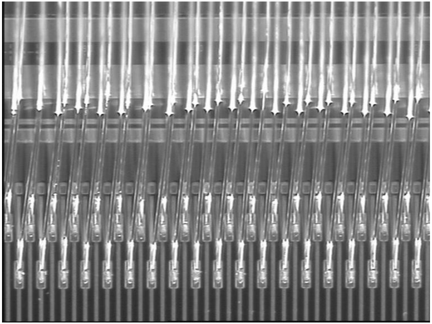
Automatic wirebonder



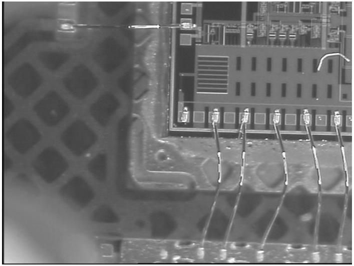
Wire bond connection: quality control

Pull test (> 7 g)

Visual inspection

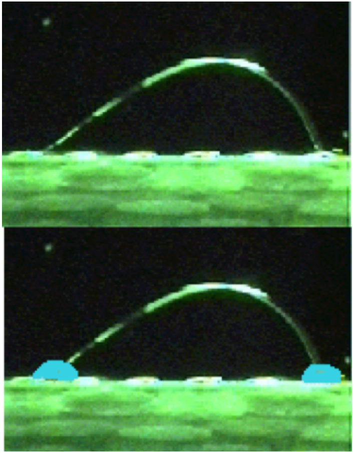


Missing bond

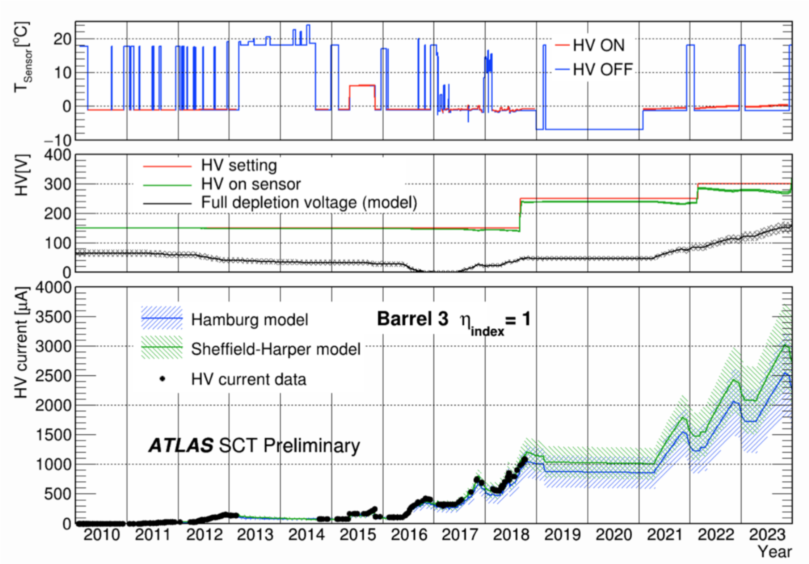


CDF: Resonating Wire Bonds

Pull test (> 7 g)
CDF: Wirebonds orthogonal to 1.4 T magnetic field. If pulsed at the 'right' frequency the tiny Lorentz force (10-50 mg) can excite resonances which fatigue the heel of the wire bond. Eventually cracks are induced and electrical continuity lost.
Possible fix: Potting (encapsulation)

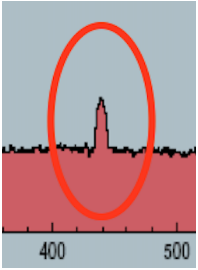


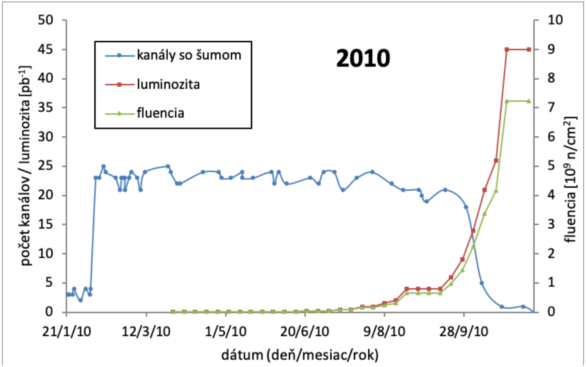
ATLAS strip detector HV current history



ATLAS strip detector: noise bumps

2005: Regions of noisy strips discovered. Tested with laser by Pavel Reznicek and Peter Kodys. Detection performance OK, but problems during testing. Hypothesis: charge stuck in oxide regions (hopefully will be released by radiation)





2013: Further behaviour of these strips studied by Lucia Meszarosova and Ina Carli. They disappeared with first neutrons generated at ATLAS.

Summary

- Great physics needs great detectors
- Great detectors need great people