The WA82 & WA92 experiments and their legacy in Genova (un'eredità di silicio)

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(INFN Genova)

Outline

- Overview of the WA82 and WA92 experiments (Leo)
- The WA92 contiguity trigger (Nanni)
- The WA82&WA92 main physics results (Dario)
- Legacy in Genova (Claudia)

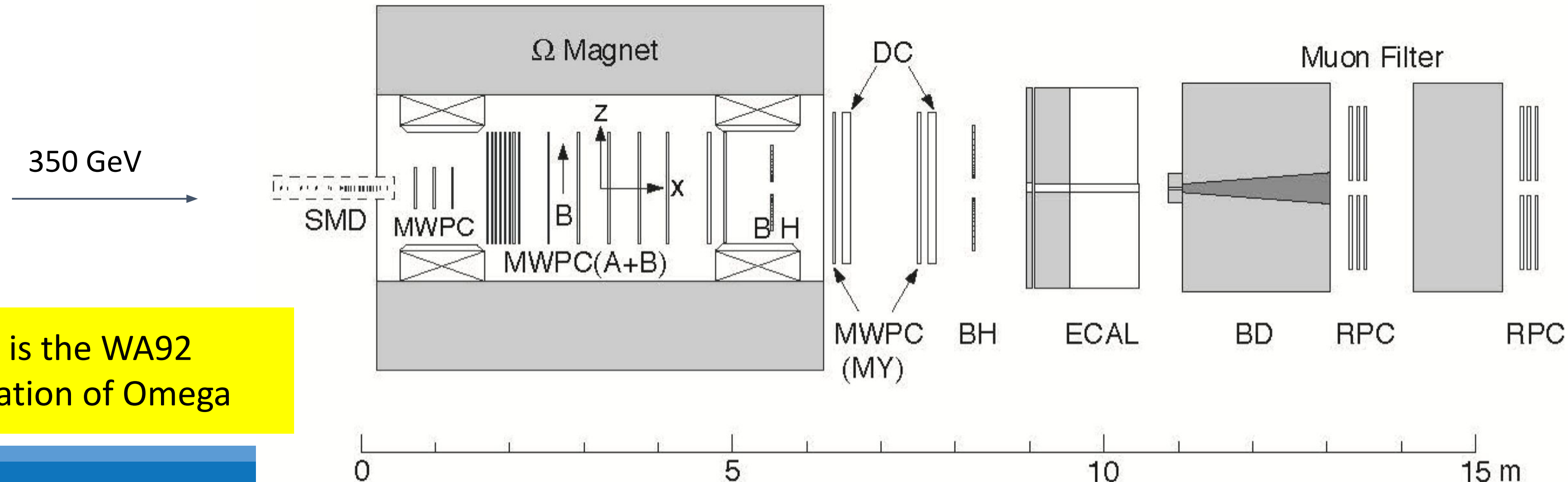
Preamble

- After the 1970's (the decade of the discovery of c & b quarks) there was a lot of interest for the study of particles carrying these heavy quarks.
- The fractional production x-section in hadronic interactions make this possible for charm (10^{-3}) and possible-but-hard (10^{-6}) for beauty in hadronic collisions at SPS momenta (~350 GeV/c).
- c&b hadrons have lifetimes of [0.1-1] ps. The advantage of using a fixed target configuration is the Lorentz boost given to c&b hadrons making their decay vertex displaced from the primary collision and their decay products with an impact parameter (h) of $c\tau$ [30-300] µm.
- The emerging new technique of highly segmented silicon detector allowed measurement of h with the required accuracy (10 µm) at very high speed.
- The "only" remaining problem was the extraction of the signal from the high (or very high) background. This is what has been proposed by WA82 (1985) and WA92 (1990) at the Omega spectrometer.
- Let's begin with briefly illustrate the Omega spectrometer.

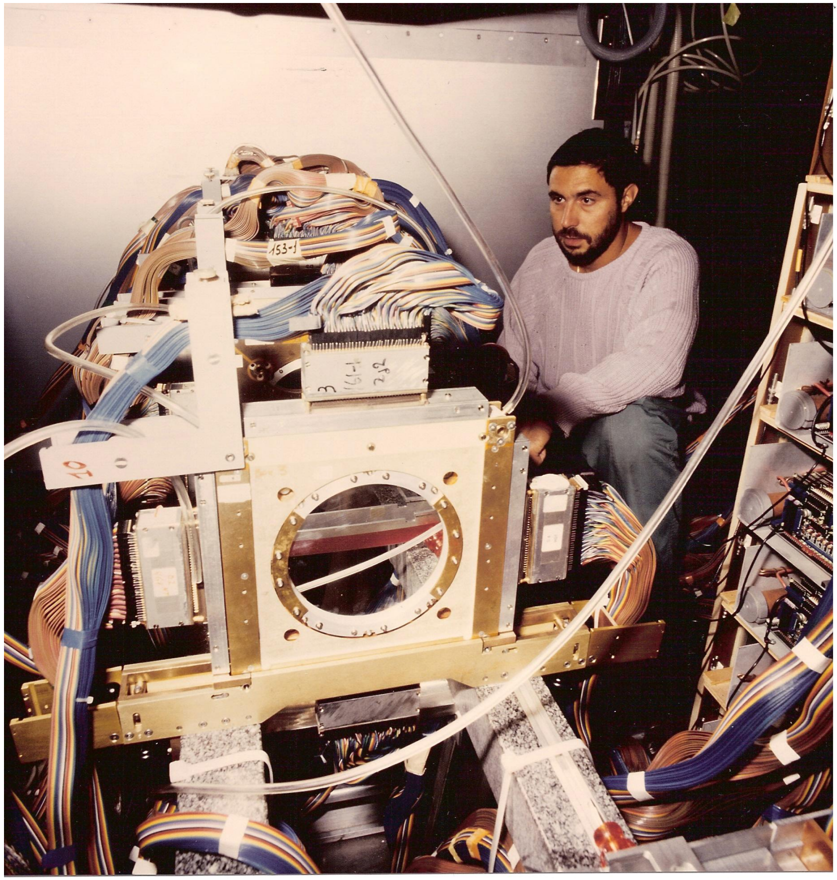
The Omega spectrometer (LEGO experiments)

- The Omega spectrometer was a general purpose facility in the SPS West Area, with a superconducting magnetic field, MWPCs, drift chambers, calorimeters, particle ID, trigger, DAQ, reconstruction software…
- All you need is to come with a good idea (+ some related hardware) and configure your LEGO with the parts you need. Easy! You can do your experiment in 3 to 5 years and with (only) one dozen of motivated colleagues!
- You may then leave your hardware for future use (WA82 and WA89 used the RICH built by WA69, WA82 and WA92 used the calorimeter built by WA70, and in turn WA89 used the WA82 microstrips)

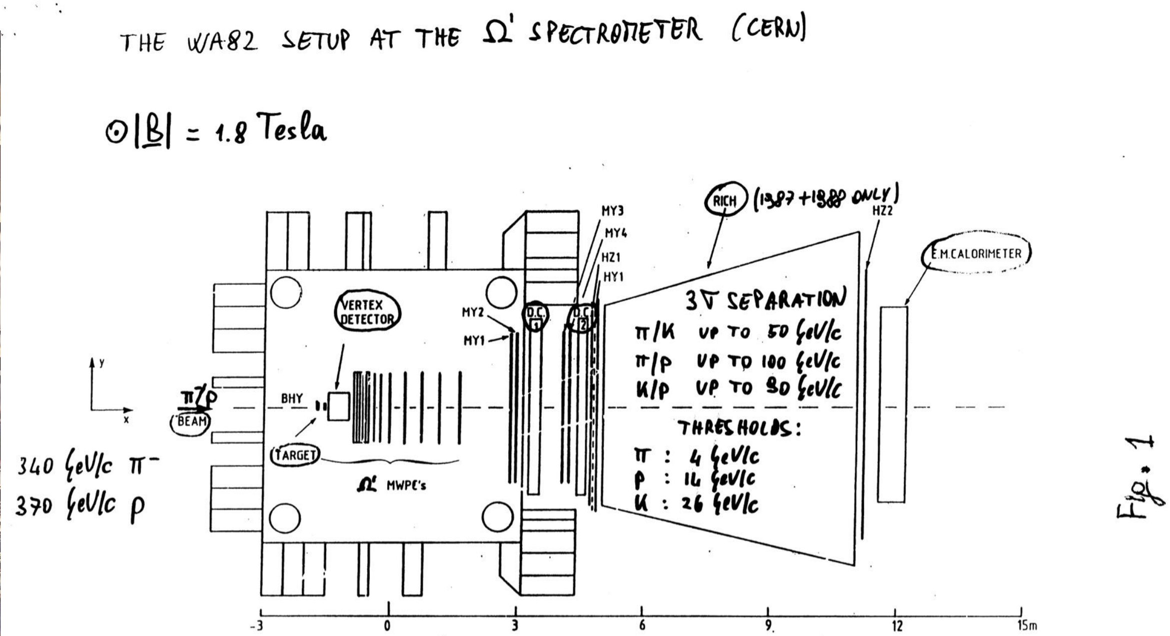
350 GeV



This is the WA92 incarnation of Omega



1987 - WA82 inside Omega



This is the WA82 incarnation of Omega

A Microstrip vertex detector for studying charm hadroproduction
M. Adamovich et al., Nucl.Instrum.Meth.A 309 (1991), 401-410
DOI: 10.1016/0168-9002(91)90243-J

Doing LEGO experiments requires a small crew

CERN/SPSC 85-62
SPSC/P218
16 October 1985

PROPOSAL FOR A TEST OF AN IMPACT PARAMETER TRIGGER

AIMED AT A HIGH STATISTICS HEAVY QUARK STUDY

W. Beusch[1], L. Bravo[4], M. Dameri[2], M. Fernandez[4], B.R. French[1],
J.J. Garcia[4], K. Knudson[1], D. Marioli[3(*)], C. Meroni[3], F. Muller[1],
R. Niembro[4], M.L. Quelle[4], N. Redaelli[1], L. Rossi[1], D. Torretta[3],
G. Vegni[3], E. Villar[4]

Spokesman: L. Rossi
Contactman: F. Muller

WA82: 17 physicists

SCP
CERN-SPSC
90-10

PROPOSAL TO SPSC(*)

MEASUREMENT OF BEAUTY PARTICLE LIFETIMES AND HADROPRODUCTION CROSS-SECTION

M. Adamovich[7], Y. Alexandrov[7], C. Angelini[8], F. Antinori[3], W. Beusch[3], A. Buys[6],
A. Cardini[8], C. Da Viá[3], M. Dameri[4], G. Darbo[4], M. De Vincenzi[9], A. Duane[5], J.P. Dufey[3],
J.P. Fabre[3], V. Flaminio[8], A. Forino[1], B.R. French[3], A. Frenkel[9], S. Gerasimov[7],
R. Gessaroli[1], F. Grard[6], K. Harrison[5], R. Hurst[4], A. Jacholkowski[3], A. Kirk[3],
S. Kharlamov[7], E. Lamanna[9], J.C. Lassalle[3], P. Legros[6], L. Malinina[7], G. Martellotti[9],
P. Mazzanti[1], J.G. McEwen[10], D.R.O. Morrison[3], F. Muller[3], B. Osculati[4], G. Penso[9],
A. Quareni[1], C. Roda[8], L. Rossi[4], G. Schuler[3], G. Tomasini[4], F. Viaggi[1],
D.M. Websdale[5], G. Wilquet[2] and M. Zavertyaev[7]

Spokesman: L. Rossi, **Contactman**: J.P. Fabre

WA92 : 46 physicists

WA82 (a geometric trick to select charm)

- Added to Omega a vertex detector made of microstrips and able to trigger on charm
- Microstrip silicon detectors are pattern of diodes implanted through a lithographic process on a thin (~200 µm) silicon layer. The pitch of these detectors (and in general their geometry) is very precisely defined.
- Typical pitch are of 50 µm (down to the extreme case of 10 µm) and WA82 used different pitches to set-up an "impact parameter trigger".

- 3 detectors of 20, 50 and 100 µm pitch are placed along x such that (once normalized to the incoming beam z-position) the hits due to the tracks coming from the origin have equal value (non bending plane projection).
- A processor cancels all "equal-hits" and uses those remaining to find 3-hit tracks with 0.1<h<1.0 mm
- Events with those offset tracks are accepted.

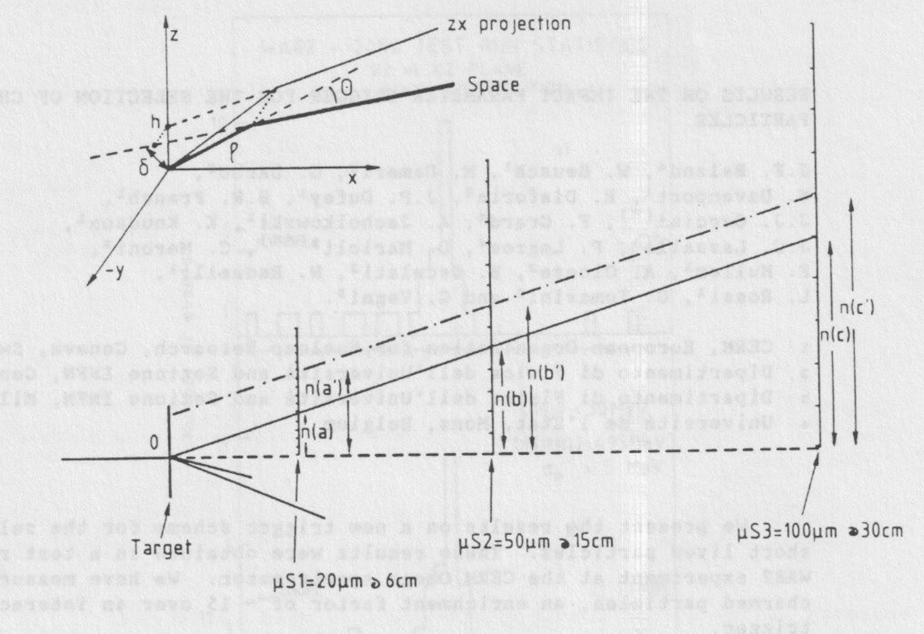


Fig. 1 Sketch of the trigger microstrip in the vertex region.

WA82 (proof of satisfactory operation)

- The enrichment of the charm sample has been measured comparing the D invariant mass signal in a sample triggered and in an unbiased sample.
- The weighted ratio of the D signals gives an enrichment of ~15 and allowed measurements on D-hadroproduction (see Dario)
- WA82 has also been the playground to develop new silicon microstrips and start the technology transfer to Genoa.
- The 10 μm pitch detectors has been pivotal for the follow-up experiment (WA92) that allowed to move the silicon detector activity definitely to Genoa.

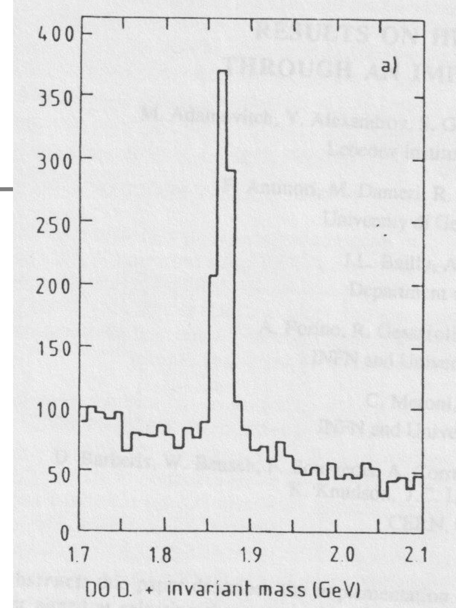


Fig. 4 - (a) D's extracted from a set of IPT events

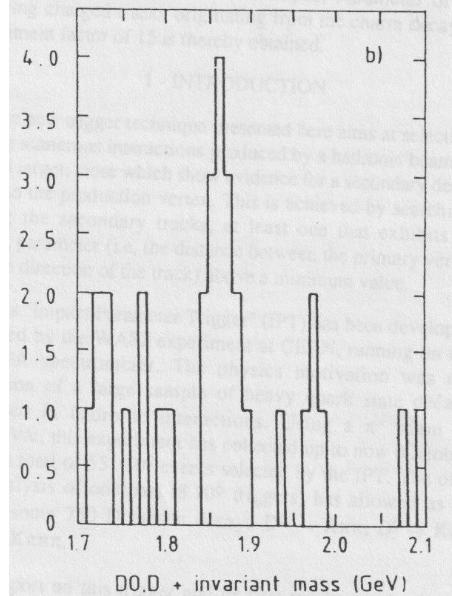


Fig. 4 - (b) D's identified in the raw data

82 Nuclear Instruments and Methods in Physics Research A288 (1990) 82-86
North-Holland

Section II. New detector types

RESULTS ON A 10 MICRON PITCH DETECTOR WITH INDIVIDUAL STRIP READOUT

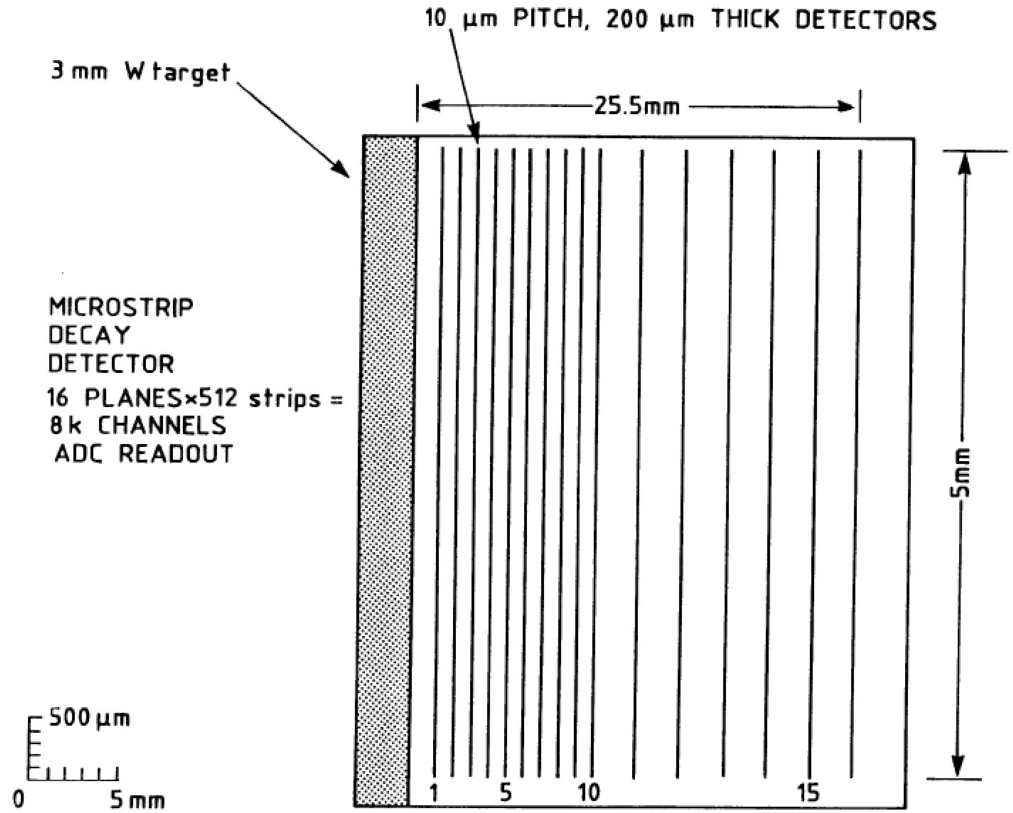
F. ANTINORI [3], D. BARBERIS [2], W. BEUSCH [2], M. DAMERI [3], J.P. DUFEY [2], B.R. FRENCH [2], A. FORINO [1], E.H.M. HEIJNE [2], A. JACHOLKOWSKI [2], P. JARRON [2], P. LEGROS [5], D. MARIOLI [4], C. MERONI [4], F. MULLER [2], A. OLCESE [3], B. OSCULATI [3], N. REDAELLI [4], L. ROSSI [3] and D. TORRETTA [4]*

[1] *Istituto Nazionale di Fisica Nucleare and Dipartimento di Fisica dell'Università, Bologna, Italy*
[2] *CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[3] *Istituto Nazionale di Fisica Nucleare and Dipartimento di Fisica dell'Università, Genova, Italy*
[4] *Istituto Nazionale di Fisica Nucleare and Dipartimento di Fisica dell'Università, Milano, Politecnico di Brescia, Italy*
[5] *Université de l'Etat, Mons, Belgium*

A 10 μm pitch silicon microstrip detector with individual strip readout via hybrid electronics has been produced and operated. Connections to digital and analog electronics is realized through an insensitive fan-out structure on the detector itself. The detector has been used in the WA82 experiment at the CERN Ω' spectrometer.

WA92 (the electronic bubble chamber)

- Identification of B-hadrons through invariant mass peaks was not possible at SPS because of the smallness of the x-section and the smallness of the branching ratio in “reconstructable” modes.
- Added to Omega an “electronic bubble chamber”+ vertex detector + better trigger
- The proposed way out was to extract the signal using its very peculiar topology of associated production and subsequent decay chains (b-->c).
- For this purpose a set of 10 µm microstrip detectors packed in a small volume was built just in front of a 3 mm W/Cu target.
- This Decay Detector (DD) has allowed to “see” the decay topology.



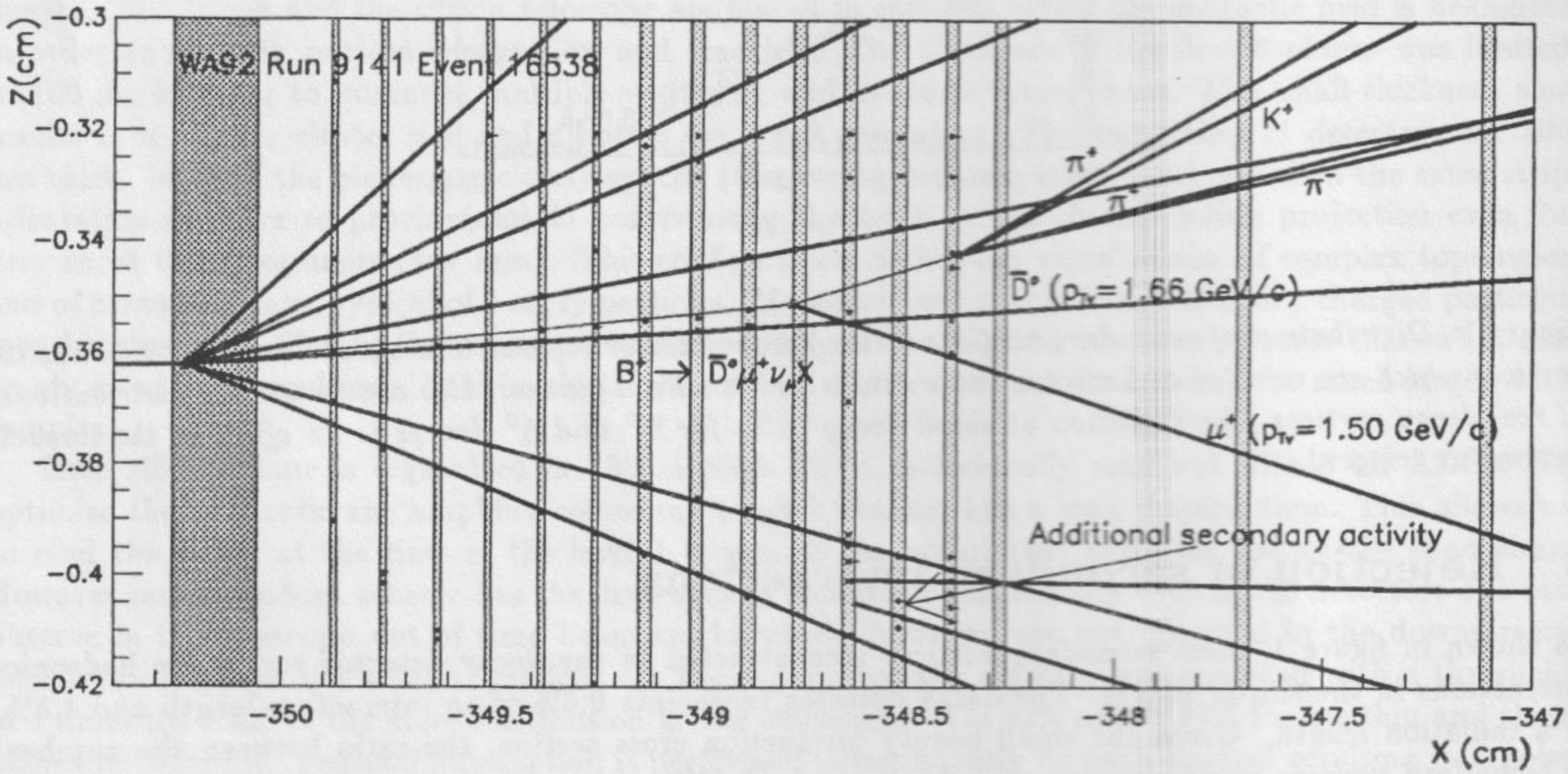
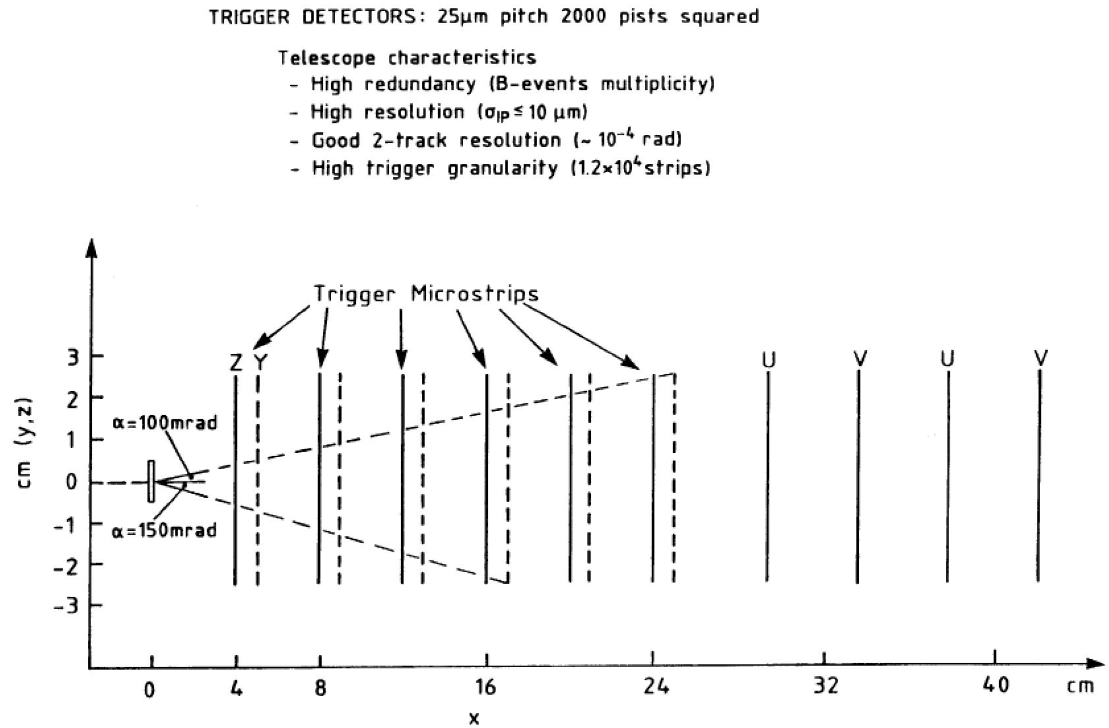


Figure 2: *Display of an event reconstructed in the decay detector where the decay chain* $B^+ \rightarrow \overline{D^0}\mu^+\nu_\mu X$ *is clearly visible, together with additional secondary activity (two tracks not pointing to the primary vertex). Both the* $\overline{D^0}$ *and the* μ^+ *have a large transverse momentum relative to the line of flight* p_{Tv}. *The hits left by the* B^+ *meson itself are visible in 5 layers of the decay detector (the* B^+ *and* $\overline{D^0}$ *lines of flight are shown as thin lines).*

WA92 (seeing is not enough)

- Topology as the one just shown are visible in 1 collision out of ~10^8, which makes the selection problem even more important than in WA82.
- The trigger was then based not just on one track with large impact parameter, but on the existence of a primary vertex in target + an intersection downstream of the target.
- This was implemented using 6 25 µm pitch microstrips and with a much more powerful processor (see Nanni: Beauty Contiguity Trigger) than the old and by then slow MICE(*) processor used for WA82



(*) MICE

WA92 (seeing is not enough)

- As expected crossing which are triggered are mostly interactions in the DD (many rejected by a pulse height cut), but also K, Lambda or D.
- Still there are random crossing or crossing that do not show an invariant mass peak.
- A “many vertex topology search” is then necessary (complemented with some kinematic and identification cuts) to identify B hadrons.

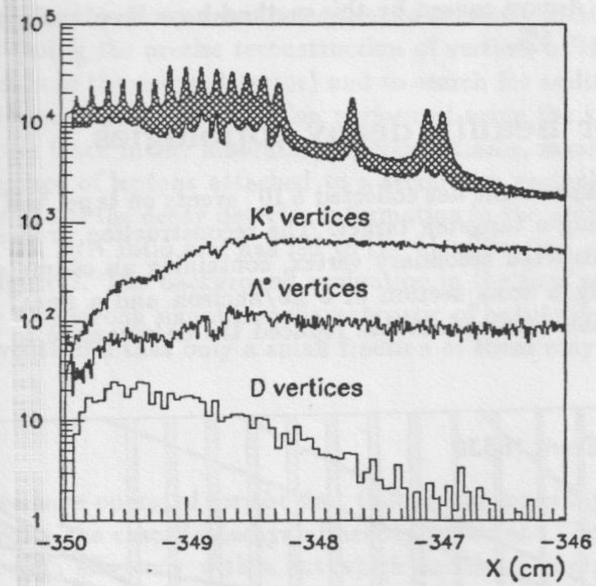


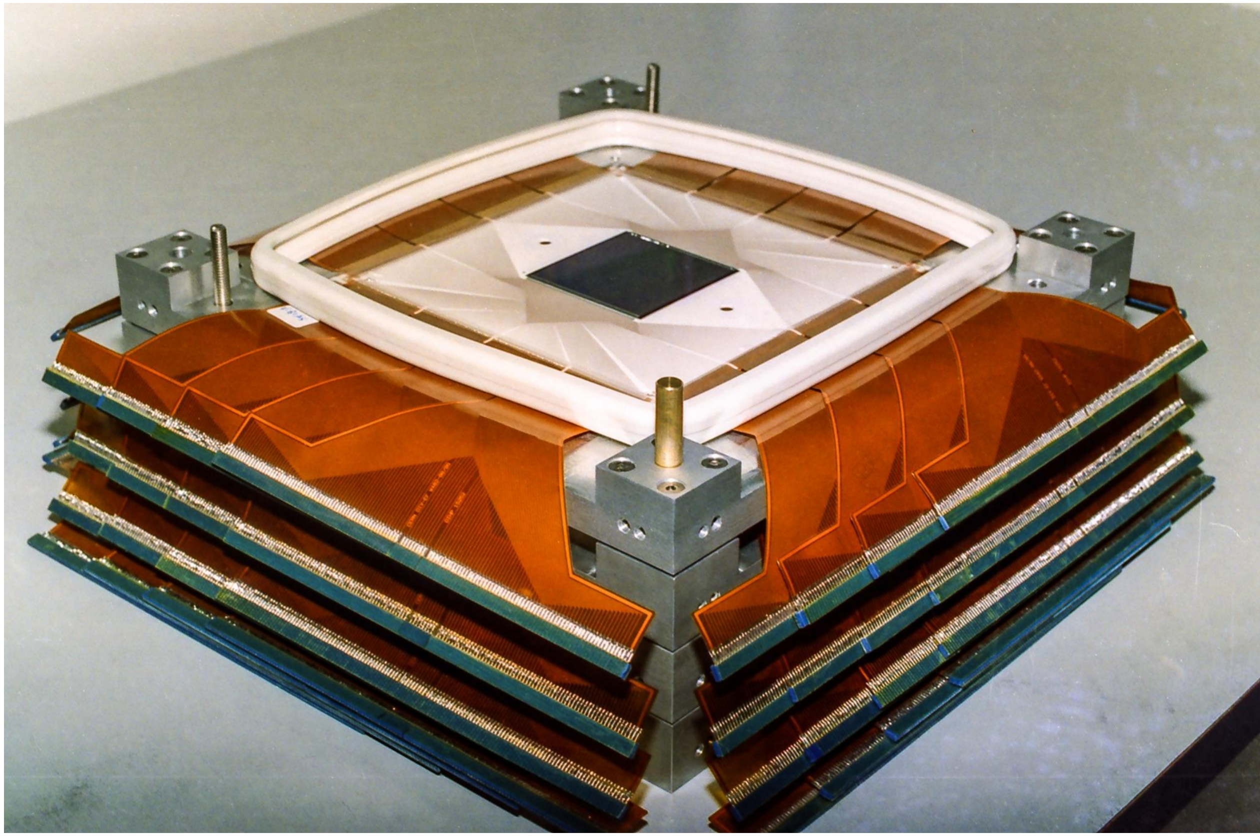
Figure 1: *Distribution of secondary vertices in the decay detector region. The shaded area corresponds to vertices which are rejected as hadronic interactions in the silicon planes. Also shown are the distributions of real decay vertices (the depletion at small decay paths for* K^0 *and* Λ^0 *decays is an effect of the impact parameter trigger).*

WA92 (silicon lab in Genoa)

- Building of the many WA92 detectors took place in Genoa where a lab was built following the WA82 experience. This later evolved in a Pixel lab (and still evolving…see Claudia).

- This is one of the quadruplets (X,Y,U,V) of 25 µm strips 5x5 cm^2 which were used in the WA92 vertex detector.

- The support is quite massive (Fixed Target geometry) and the electronics is still "plug-in" and hybrid (not ASIC).



WA92 (way forward)

- New kind of detectors (high resolution segmented silicon) and new approach to electronics (ASIC) have paved the way to the next step (pixel detectors) where both these techniques are pivotal.

- International links to groups active in the same domains favoured this transition

Beauty Contiguity Trigger - BCT

Algorithm and its implementation in a custom hardware processor

Contiguity Mask - CM

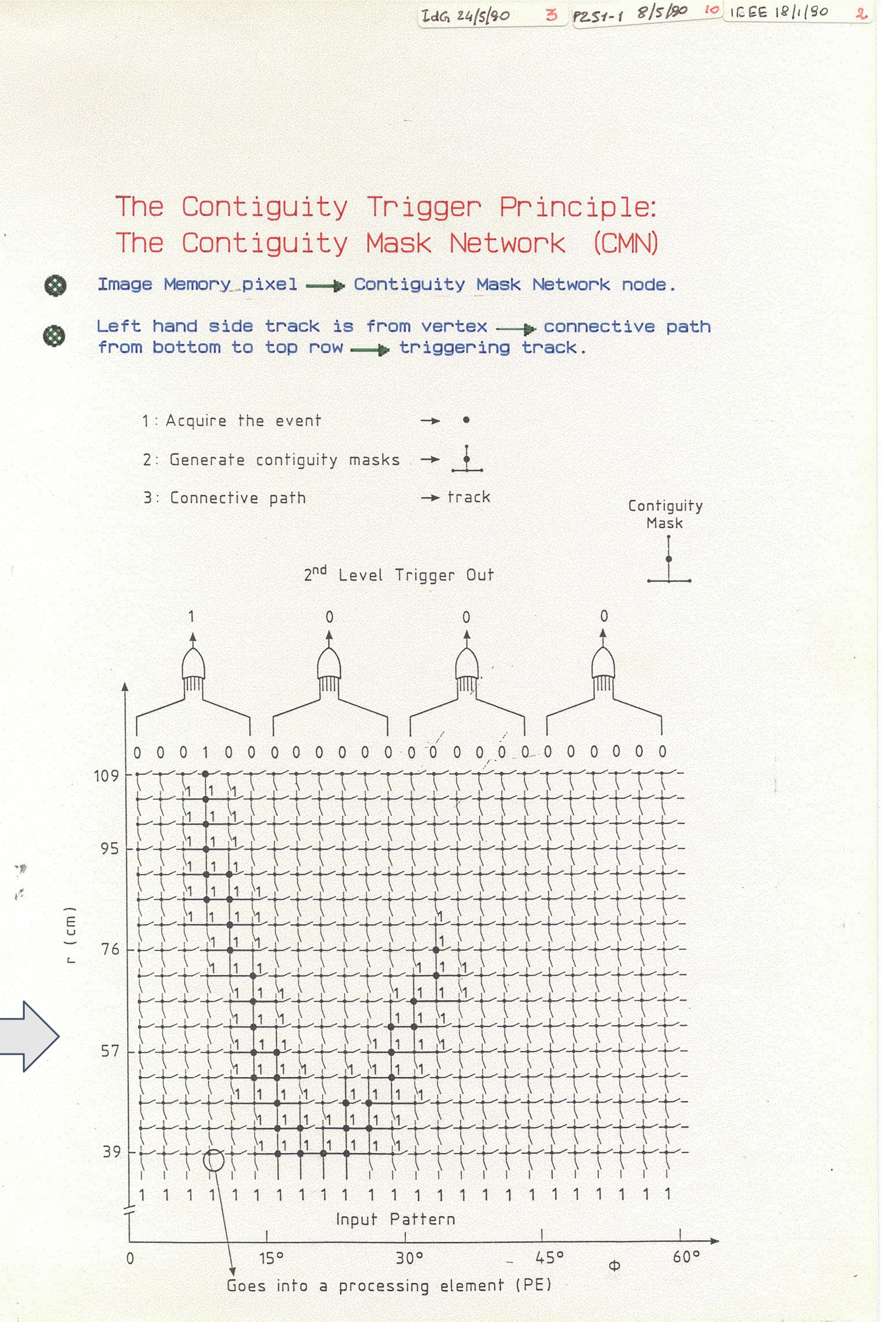
Algorithm and hardware implementation

Algorithm: *look at the brain that first searches for connected patterns in space and then evaluate metrics*

1) map track points into nodes of a square mesh
2) for each point build a Contiguity Mask closing the neighboring connection (*switches*) with the predefined rule
3) a track is found by searching connected paths

Processor: mesh of processing elements executing the same instruction stream - so-called Single Instruction Multiple Data (SIMD) Architecture.

<u>*On the right*</u>: example of the image mapped from a time slice of the DELPHI TPC into the Contiguity Trigger (1989).

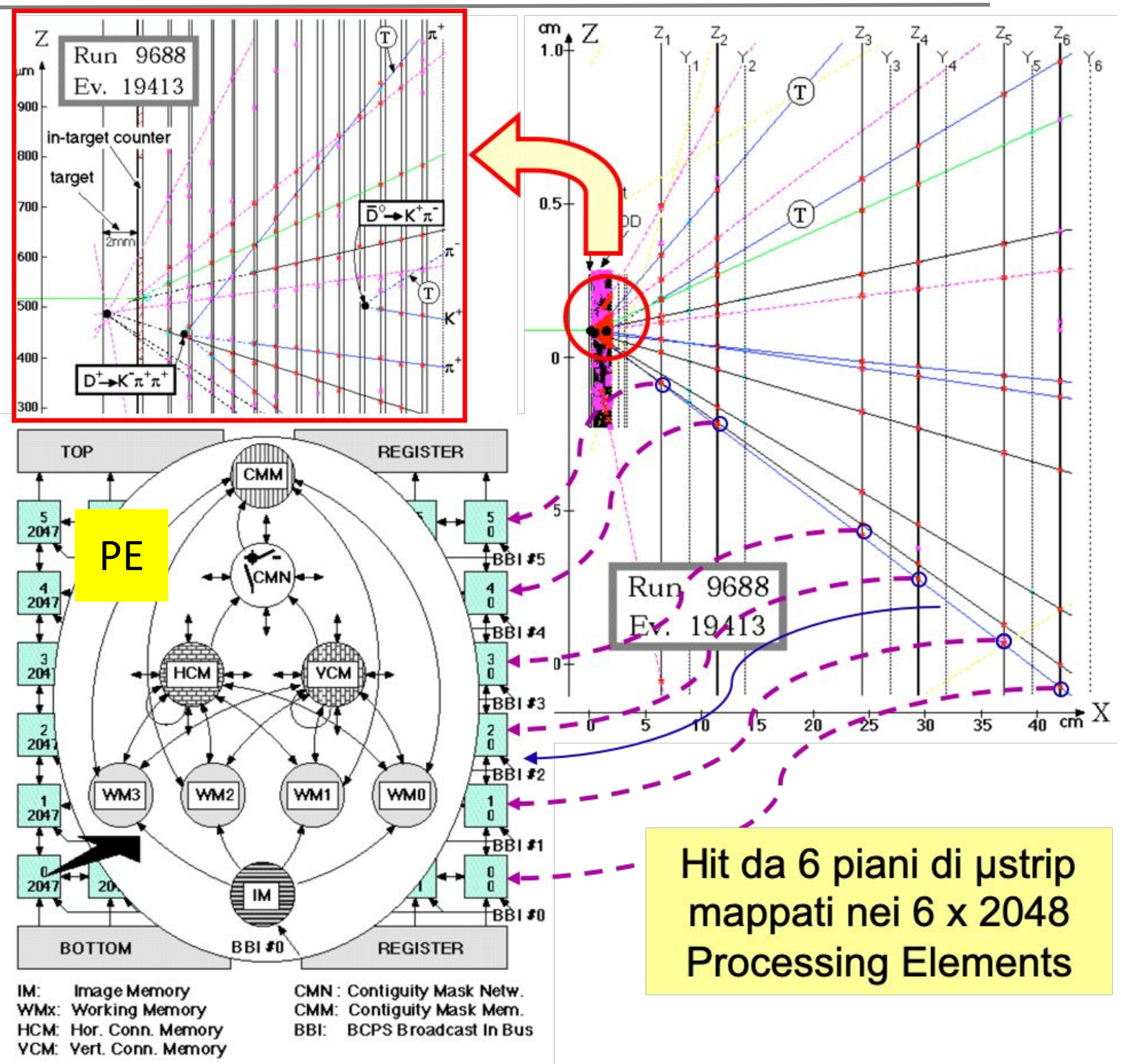


Hits from Six μ-strips Planes to BCT

Data R/O from the 6 VXD and two-beam Z-planes each of 2048 μ-strips.

Hits from the Z-planes of vertex strips transformed by a “*look-up table*” and sent to 2048-columns times 6-row processing elements (PE).

The PEs are 1-bit processors connected to four neighbors and all run the same instruction stream - with differentiation by row.



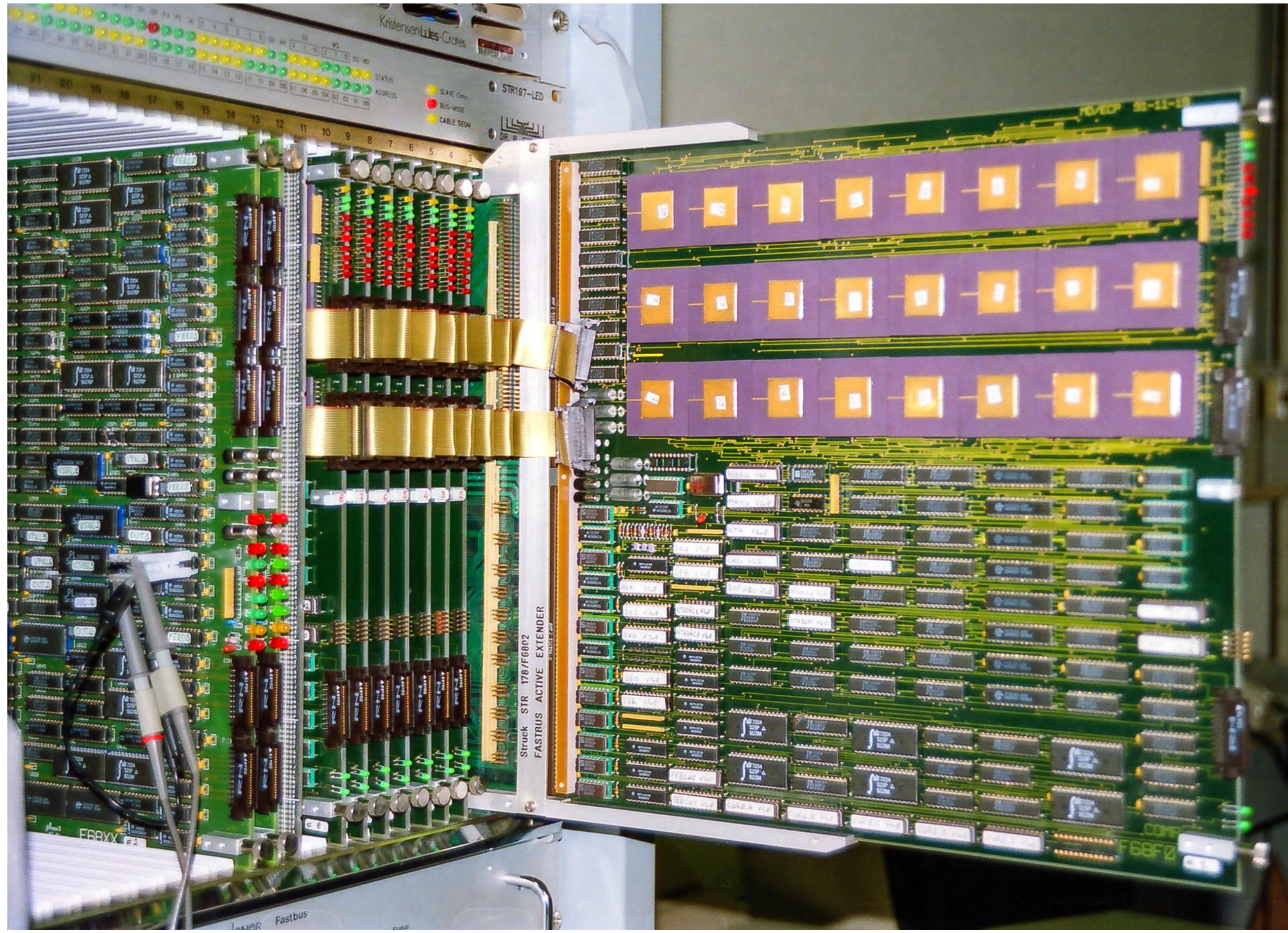
BCT - Beauty Contiguity Trigger

SIMD - Single Instruction Multiple Data architecture

2048 x 6 processing elements

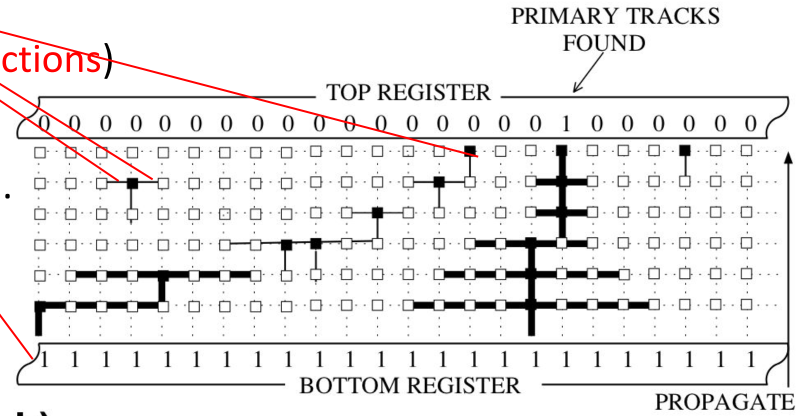
8 Fastbus Cards + Controller

192 ASIC chips

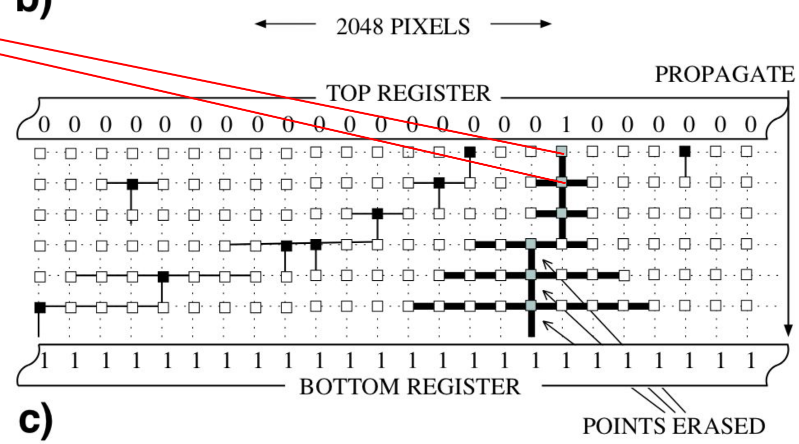


Algorithm - Primary Tracks Finding & Counting

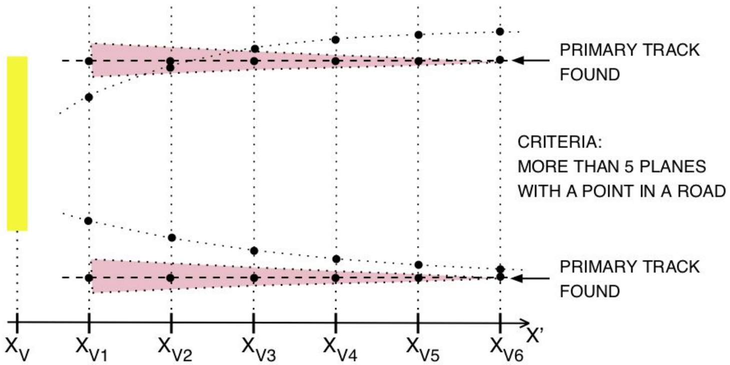
1. Z-beam in the target (z_V) is extrapolated from the two beam planes
2. the points in the 6 Z-planes of the VXD are converted by a linear transformation using Z_V: converted primary tracks become parallel lines and secondary hiperbola (a).
   Converted hits loaded into the PE of the BCT (b - full dots).
   A CM is generated as a function of hits and rows (b - connections)
3. Signal is applied to the "BOTTOM REG" and connected paths from bottom to top identify primary (b - "111...111").
4. Starting from "TOP REG" pixel connected to "1" are erased from PE's (c).



b)



c)



a)

Algorithm - Impact Parameter Tracks

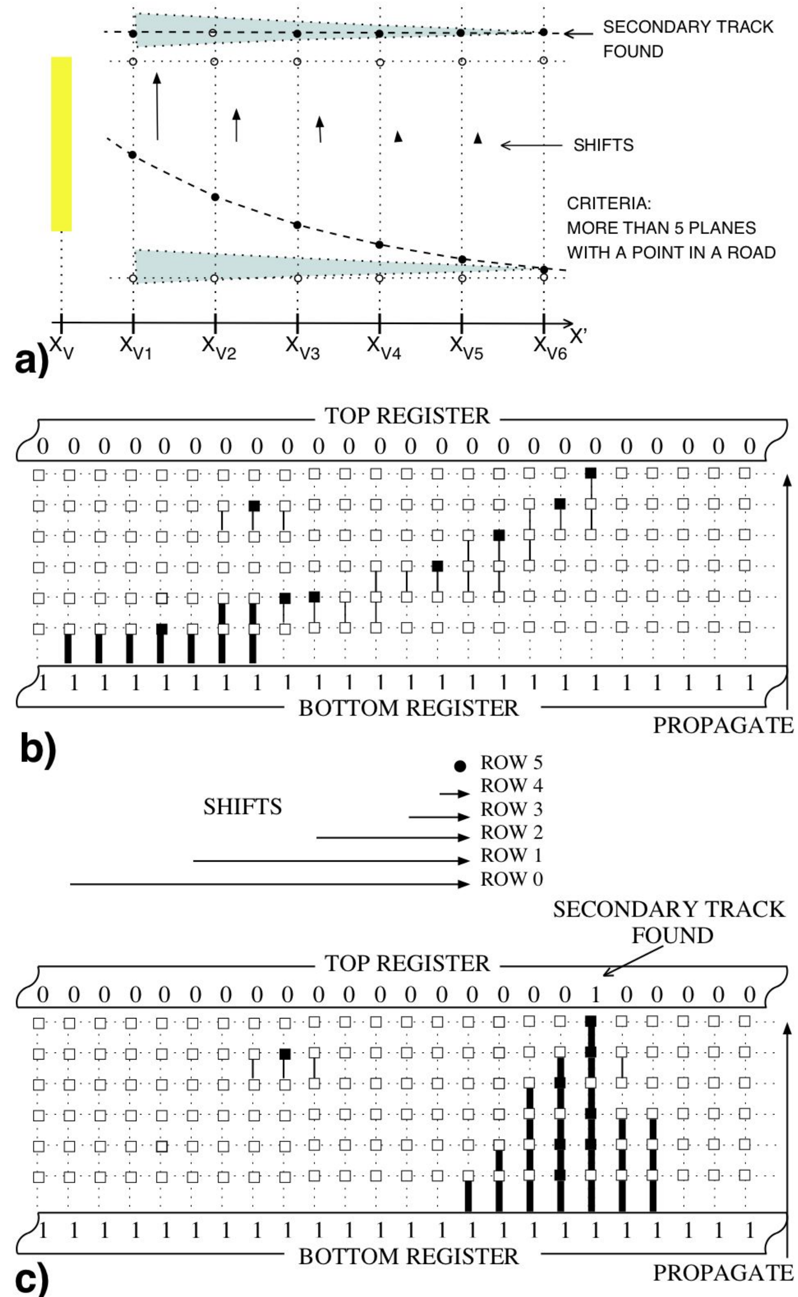
1. Tracks with the same Impact Parameter (IP) have the same curvature (hyperbole).

2. A set of shifts bring all secondary with the same IP into an acceptance window (a).

3. Example of a secondary track (b) that after row shifts bring hits “almost aligned” and found by contiguity masks (c).

4. BCT counts primary and secondary track with preselected IP. The algorithm needs 5 out of 6 planes having track hits (tolerant for inefficiencies).

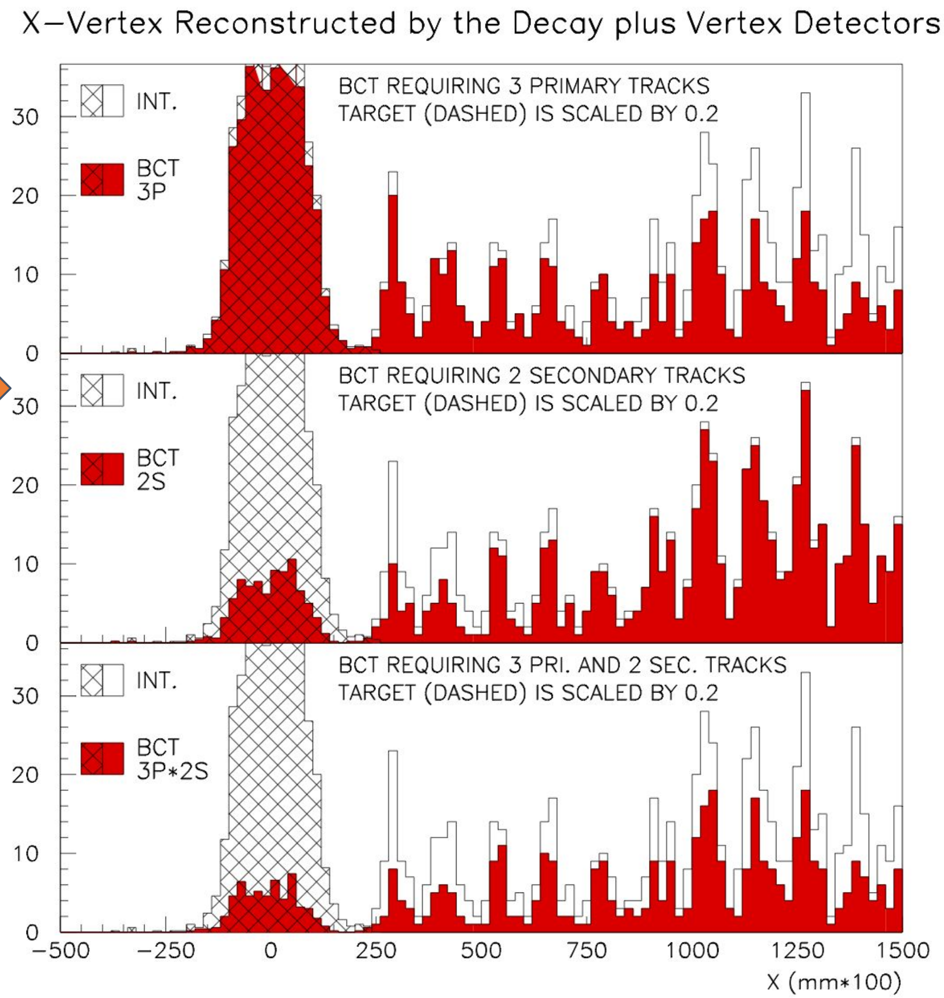
A programming language and a software emulator (HELEN) was implemented to optimize the trigger algorithm (Credits C.Salvo & C.Bruschini)



Triggers in WA92

In addition to the BCT, a PT (transverse momentum) trigger has also been implemented which uses a butterfly-shaped scintillator and a muon trigger.

Enrichment in primary + secondary events given by **BCT**



WA92 Trigger: Level-2 acceptances (% of interaction triggers). BCT required 3 primary and 2 secondary tracks, 1PT required one particle of $p_T \geq 0.6$ GeV/c, while 1 MU and 2 MU required at least one or two muons

	Minimum bias		$c\bar{c}$	$b\bar{b}$
Trigger	Data (%)	— Simulation —		
BCT	5.4	5.4%	13.5%	49.3%
1PT	41.0	41.0%	45.0%	62.7%
1MU	2.7	2.5%	8.0%	18.3%
2MU	0.08	0.06%	0.1%	1.6%

Last century emphasis on hardware processors for trigger purposes

Specifically for the vertex trigger there were two approaches:

- Contiguity Trigger in DELPHI and in WA92 using special multiprocessor architecture running a program

- Associative Memory (AM) in CDF using parallel pattern matching based on Content Addressable Memory

Exp.	Year	Input rate	Latency	Processor
WA82	1987	700 Hz	470 μs	CPU MICE
WA92	1992	6.6 kHz	45 μs	Beauty Contiguity Trigger
CDF	2000	40 kHz	15 μs	Associative Memories + FPGA
D0	2001	10 kHz	50 μs	DSP's, Processor farm
ATLAS	2005	75 kHz	10 ms	Processor Farm, RoI
LHCb	2005	1 MHz	256 μs	Processor farm
BTeV	2005?	7.6 MHz	n/a	DSP + Processor farm

Comparison of Vertex Trigger as at year 1999 - ref. G. Darbo, NIMA 447 2000 210-217

One of the first experiences in HEP on ASIC design

bulletin

WEEK MONDAY 22 SEPTEMBER — n° 39/86 — SEMAINE DU LUNDI 22 SEPTEMBRE

Microphotograph of a multipurpose silicon chip (6 mm × 3.6 mm) showing at the left a 34 MHz encoder/decoder for digital networking, in the middle (top) a quad line receiver/comparator with ECL output operating in excess of 100 MHz and (bottom) a contiguity processor chip for the DELPHI TPC, and at the right (top) a digital bus arbiter for FASTBUS modules for the ALEPH event builder and (bottom) a low-noise preamplifier for large capacitance detector elements.

Microphotographie d'une multipuce en silicium (6 mm x 3,6 mm) montrant à gauche un encodeur/décodeur de 34 MHz pour réseau numérique, au milieu (en haut) un récepteur-comparateur à quatre voies et à sortie ECL fonctionnant à plus de 100 MHz et (en bas) un processeur de contiguïté pour la TPC de DELPHI, ensuite à droite (en haut) un contrôleur de bus numérique pour module FASTBUS destiné au formateur d'événements d'ALEPH et (en bas) un préamplificateur à faible bruit pour des éléments de détecteur à capacité élevée.

Front page of CERN weekly bulletin of September 1986

Print your project on silicon

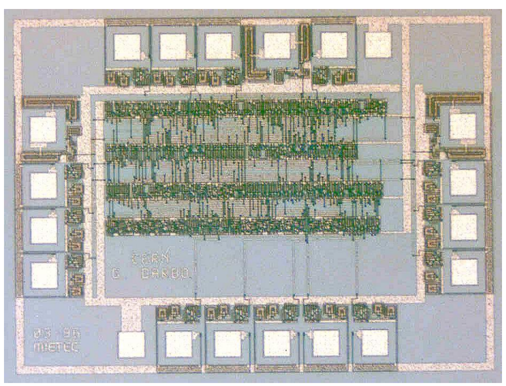
In a project between CERN and the Belgian Inter-University Micro-Electronics Center (IMEC) in Leuven, eight electronics engineers from four CERN divisions followed last November a 10-day course in silicon chip design. Afterwards they worked using a graphics terminal at CERN connected to the Leuven-based standard cell software via a permanent telephone line connection. Five circuits were selected for this practical training, and by the end of March all designs were finalized and put together with other IMEC designs on a so-called multi-project wafer. After mask making and silicon chip productiou in Belgium, the test samples were received at CERN at the beginning of June, just six months after the end of the course. All five circuits were found to function as designed and simulated. Integrated circuit technology, once the monopoly of Silicon Valley, is now finding its way around the world. Software and hardware are becoming available for economical production of small series of Application Specific Integrated Circuits (ASICs). This rapid development resembles in many respects the 'worldwide' introduction of the bookprinting technique in the fifteenth century. The CERN-IMEC practical training showed how to get (electronic) ideas printed on silicon.

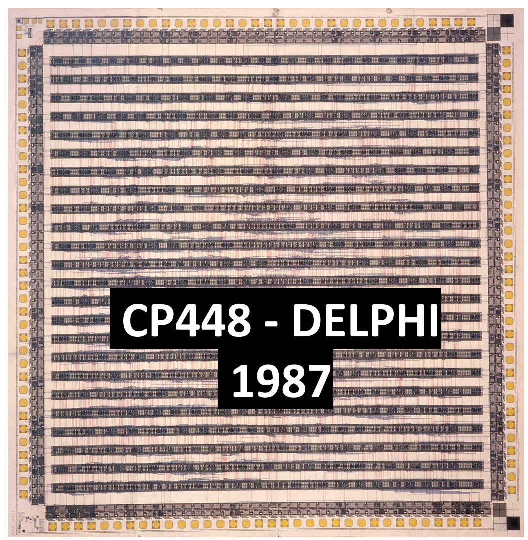
ASIC's for Contiguity Trigger

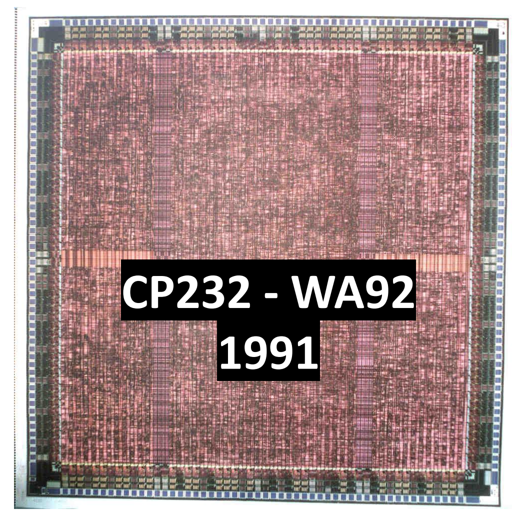
	IMEC MPW	**CP448**	**CP232**
Tecnologia CMOS (*)	3µm, SC	2µm, GA	1.2 µm, SG
Routing layers	1M/1P	2M	2M
No. Cells (AND, OR, FF)	80	1469	6817
No. Transistors	1 k	14.5 k	70 k
Area (mm^2)	4.5	70	67

(*): *SC = Standard Cells, GA = Channeled Gate Array, SG = Sea of Gates*

IMEC Multi-Project Chip 1986







Physics Results

WA82: Charm Production and Decays

WA92: Charm and Beauty Production and Decays

WA82 Physics: Charm production

Nuclear dependence of charm production by a 340-GeV pi- beam

M. Adamovich (Lebedev Inst.) et al.,
Phys.Lett.B 284 (1992), 453-456

DOI: 10.1016/0370-2693(92)90460-L

$$\sigma(A) = \sigma_0 A^{\alpha}$$

$$\alpha(K^0_S) = 0.72 \pm 0.02$$

$$\alpha(D) = 0.92 \pm 0.06$$

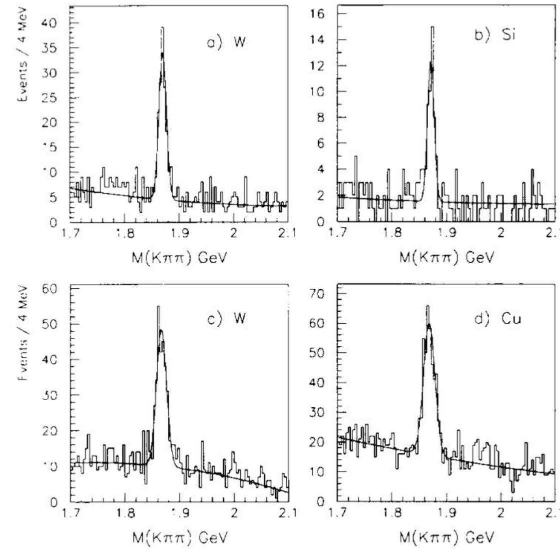


Fig. 3. Invariant mass distributions of $D^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$ and their fits (see text for details) for interactions in the target made of (a) tungsten and (b) silicon and in the target made of (c) tungsten and (d) copper.

Study of D+ and D- Feynman's x distributions in pi- nucleus interactions at the SPS

M. Adamovich (Lebedev Inst.) et al.,
Phys.Lett.B 305 (1993), 402-406

DOI: 10.1016/0370-2693(93)91074-W

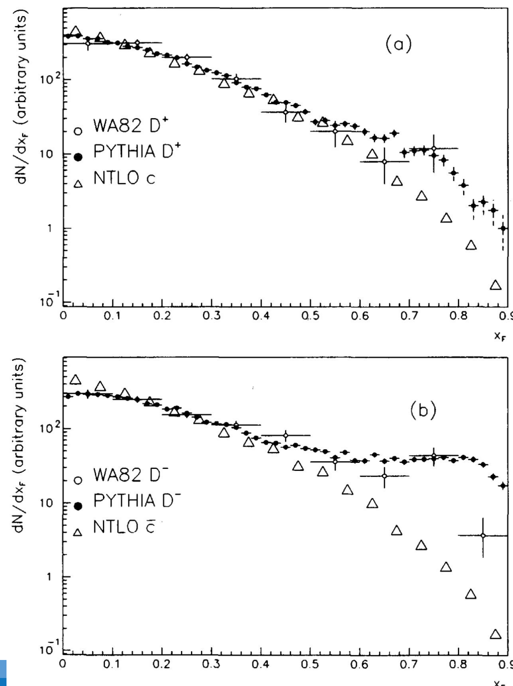


Fig. 3. x_F distributions from π^- interactions, (a) D^+, (b) D^-.

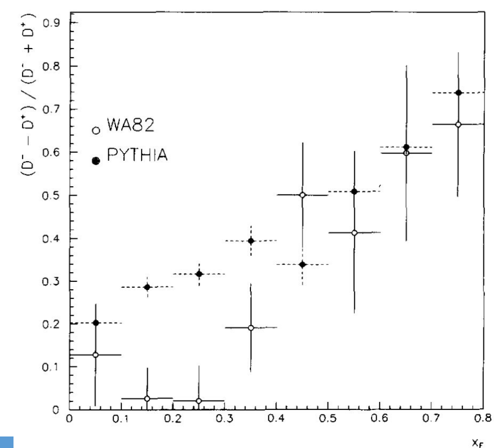


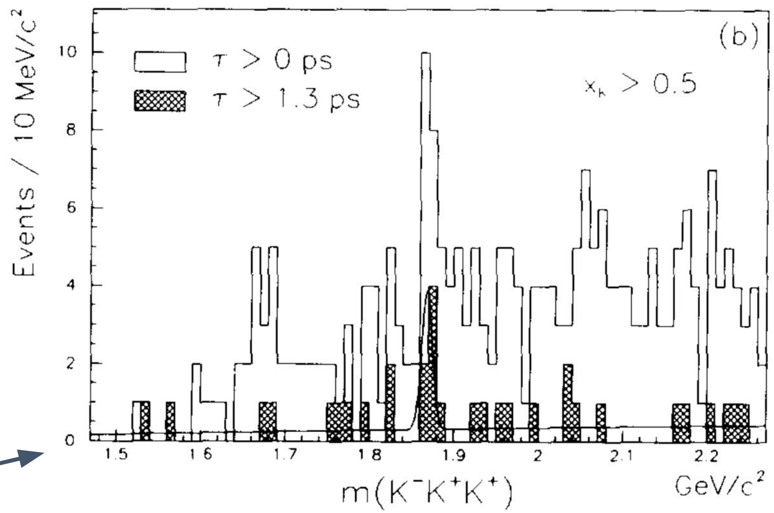
Fig. 2. $(D^- - D^+)/(D^- + D^+)$ asymmetry (π^- data).

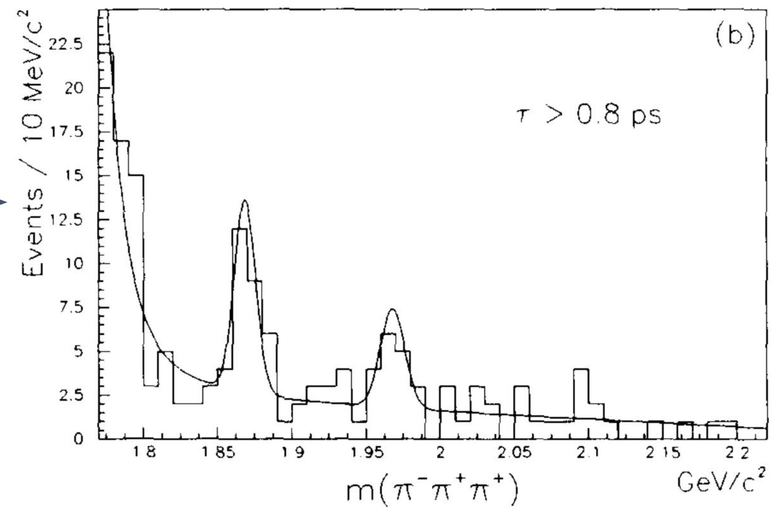
WA82 Physics: Charm decays

A Study of the semileptonic decay D+ ---> anti-K*0 e+ electron-neutrino
M. Adamovich et al., Phys.Lett.B 268 (1991), 142-144
DOI: 10.1016/0370-2693(91)90936-K

Measurement of relative branching fractions of D0 Cabibbo suppressed decays
M. Adamovich et al., Phys.Lett.B 280 (1992), 163-168
DOI: 10.1016/0370-2693(92)90791-2

Measurement of relative branching fractions for D+ ---> K- K+ K+ and D(S)+ ---> pi- pi+ pi+ decays
M. Adamovich et al., Phys.Lett.B 305 (1993), 177-181
DOI: 10.1016/0370-2693(93)91125-7





WA92 Physics: Data

Data taking was performed at the CERN Ω' spectrometer in 1992 and 1993, with a 350 GeV/c π^- beam incident on a 2 mm copper or tungsten target.

Target	Cu	W
Events	100×10^6	40×10^6
Int. lumi $(\text{nb/nucleus})^{-1}$	8.1	1.3

The trigger acceptance was ~30% for beauty events, ~25% for J/ψ and ψ′ events, ~10% for open charm events and ~2% for inelastic interactions.

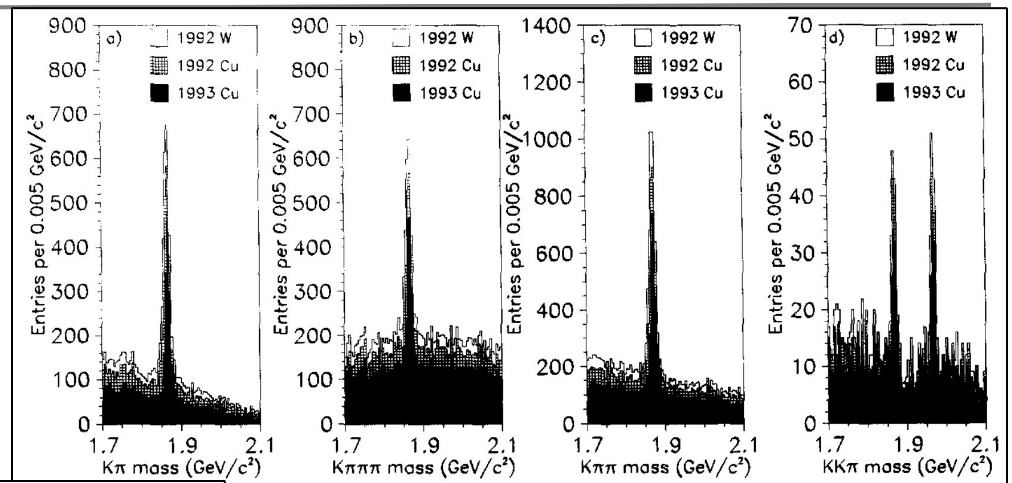
WA92 was built to study b-physics, but an important byproduct was the study of charm meson production with high statistics.

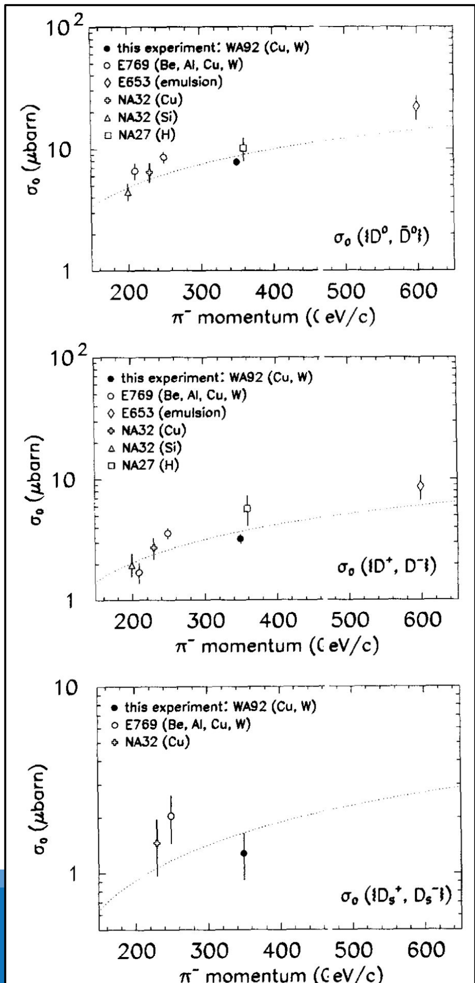
All results were very relevant at the time they were performed and several of them remain unsurpassed.

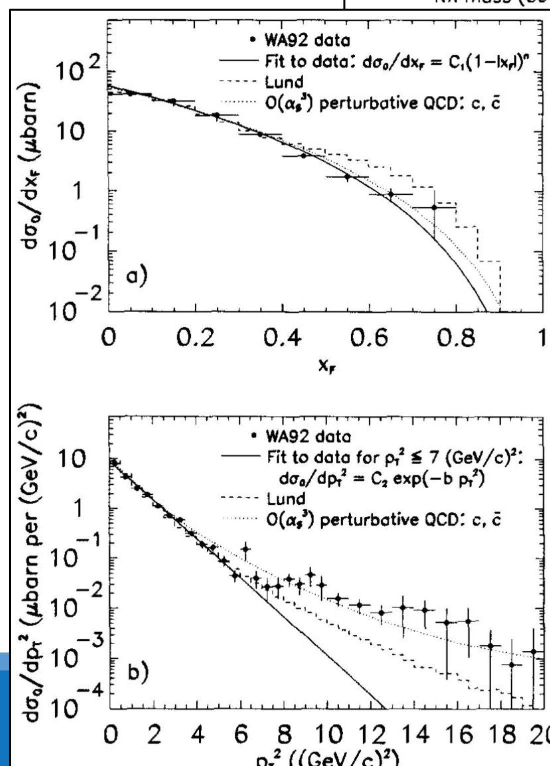
WA92 Physics: Open charm production

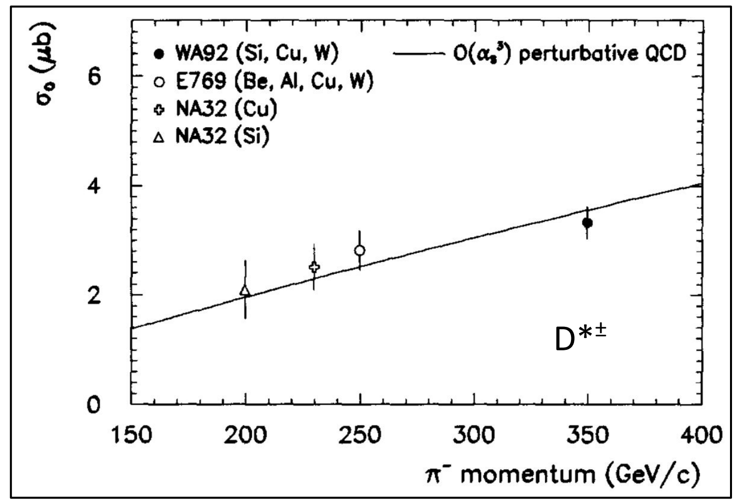
Fully reconstructed 7k $D^0/D^{\pm}/D_s$ hadronic Cabibbo-favoured decays, plus 600 $D^{*\pm} \to D^0\pi$.

Measured total and differential cross-sections; also production asymmetries.

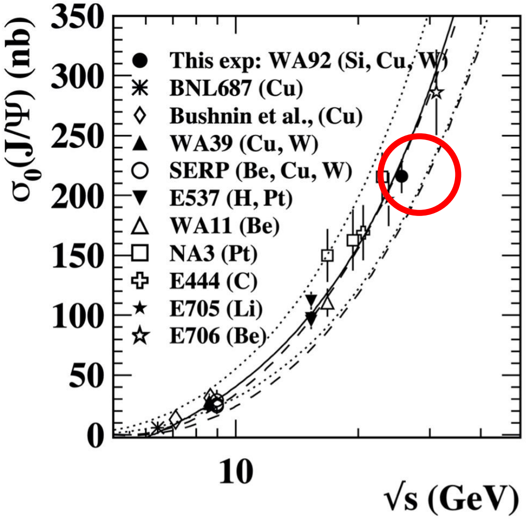


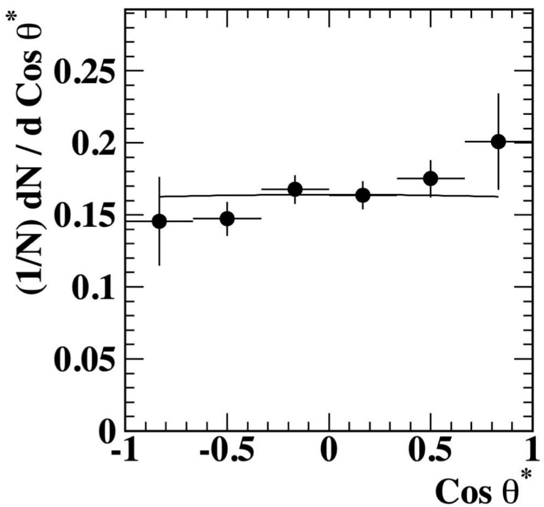


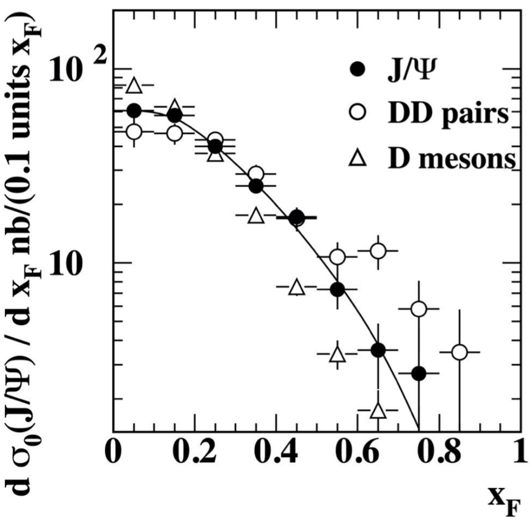


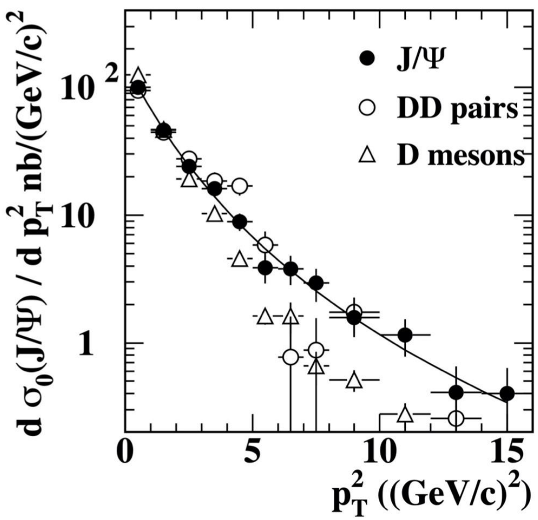


WA92 Physics: Hidden charm production









Prompt J/ψ and ψ′ events produced in interactions with Cu, W and Si were selected requiring a $\mu^+\mu^-$ pair with the production vertex compatible with the position of the Cu or W target, or one of the Si planes of the Decay Detector.

Events	W	Cu	Si
J/ψ	320 ± 19 ± 3	719±28±4	57±9±2
ψ′	6.3±3.6±0.7	13.3 ± 5.5 ± 3.3	–

Top-left: total J/ψ production cross-section per nucleon, compared to previous experiments and theoretical models (Color Evaporation and Factorization Approach)*:

$\alpha(J/\psi)$\{Si, Cu, W \} = 0.87 ± 0.05 ± 0.04

$\sigma_0(J/\psi)$ = 216.2 ± 5.4 ± 13.3 nb/nucleon

$\sigma_0(\psi')$ = 28.3 ± 8.1 ± 11.3 nb/nucleon

$\sigma_0(\psi')/\sigma_0(J/\psi)$ = 0.13 ± 0.05 ± 0.01

Top-right: J/ψ polarization.

Bottom: longitudinal and transverse differential cross-sections for J/ψ production compared to DD pairs and events with at least a reconstructed charm meson.

(*) $\sigma = \sigma_0 A^\alpha$

WA92 Physics: Beauty event selection

Event selection: events with secondary vertices between 3 mm and 6 cm downstream of the target, not compatible with interactions in the Si detectors, with at least one of:

1) a high-p_T muon (12 events)
2) 3 secondary vertices with high-p_T tracks (12 events)
3) non-pointing fully reconstructed D decay (5 events)

Some events belonged to more than one class, so we had 26 events in total. The estimated charm background was 0.6 ± 0.6 events.

In 13 events we could reconstruct both B meson decays and study the production correlations.

WA92 Physics: Beauty event

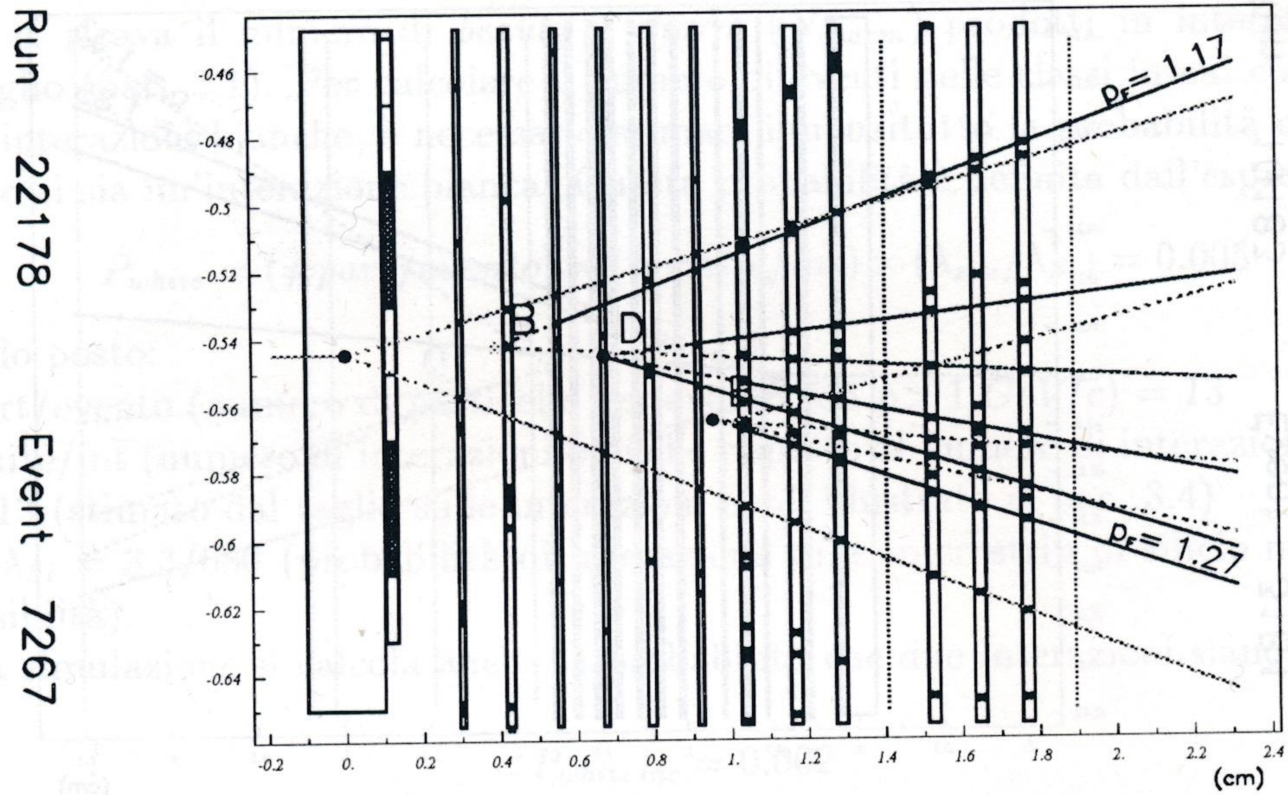


Figura 4.1: *Un evento beauty candidato nel campione Cu93. B e D indicano i vertici beauty e charm.* p_F *indica il valore del momento trasverso rispetto alla linea di volo.*

WA92 Physics: Beauty total cross-section

$$\sigma_{b\bar{b}} = 5.7\ ^{+1.3}_{-1.1}\ (\text{stat.})\ ^{+0.6}_{-0.5}\ (\text{syst.}) = 5.7\ ^{+1.5}_{-1.2}\ \text{nb/N}$$

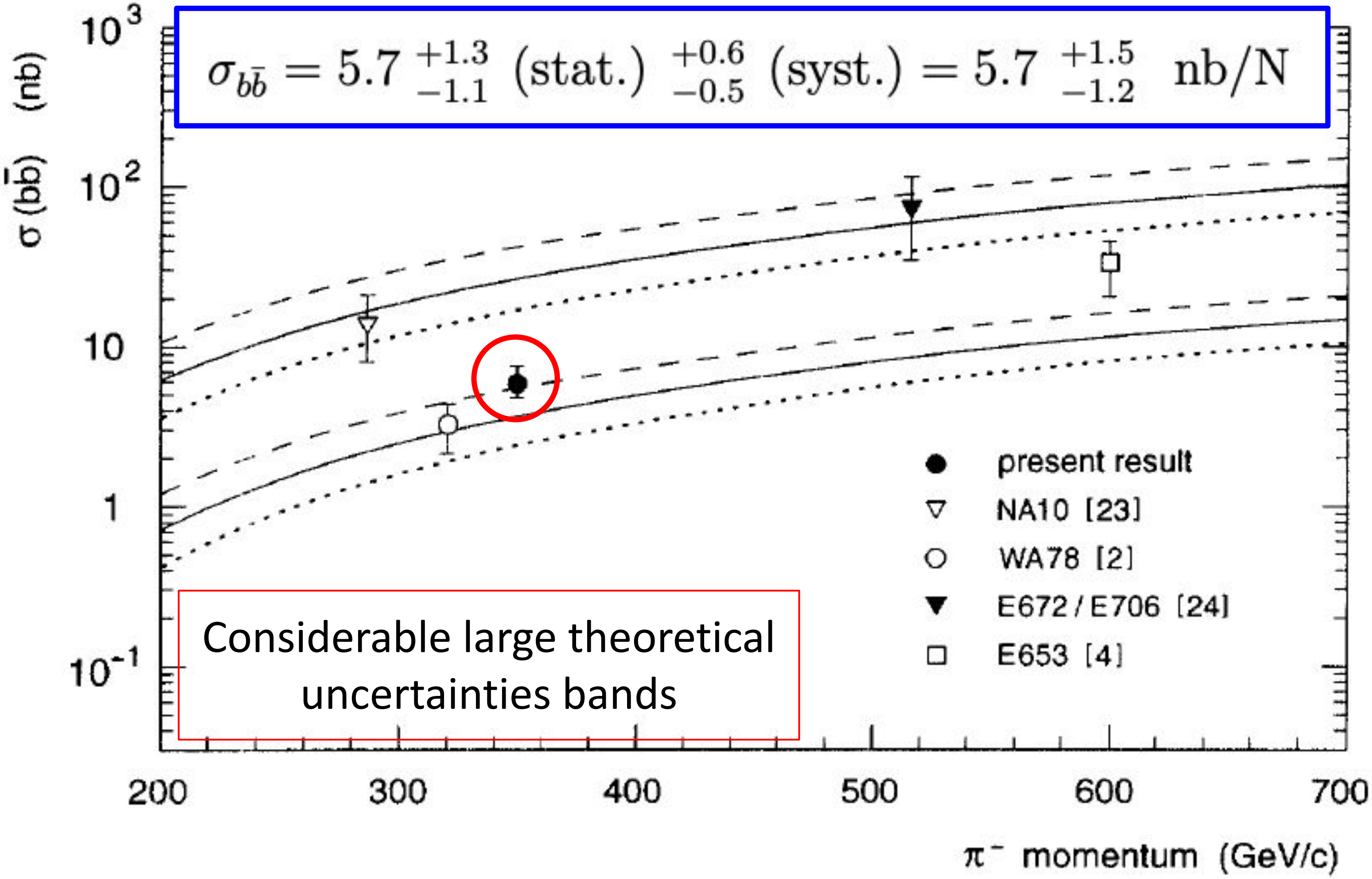
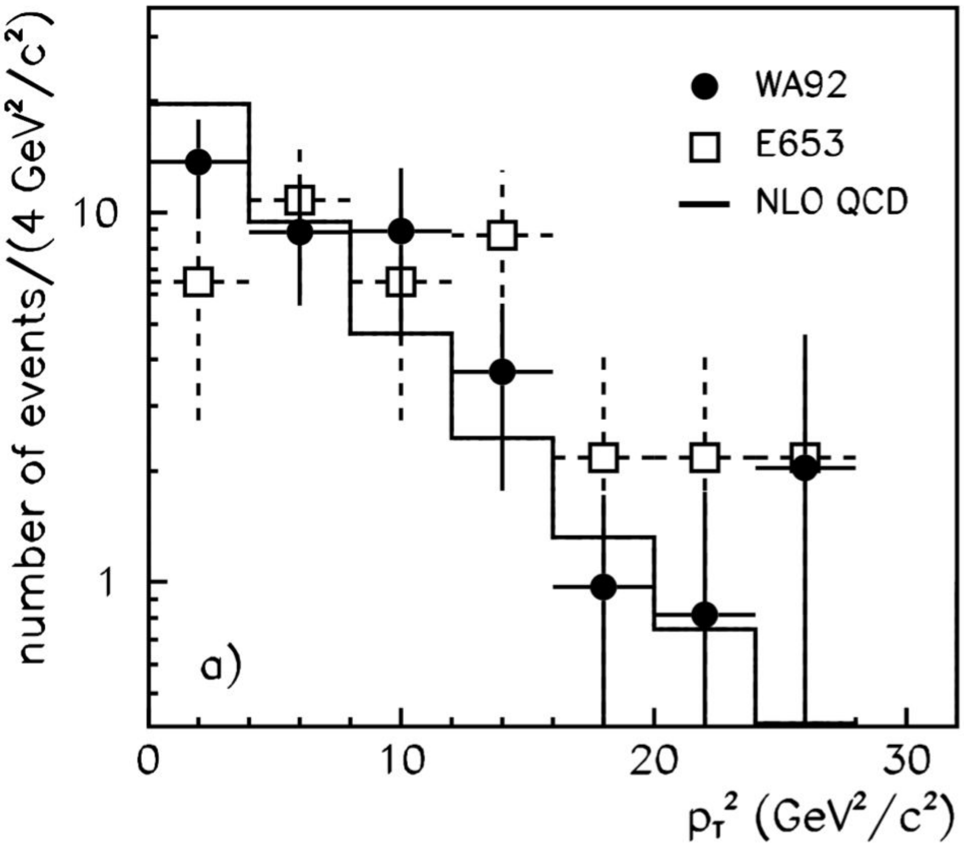
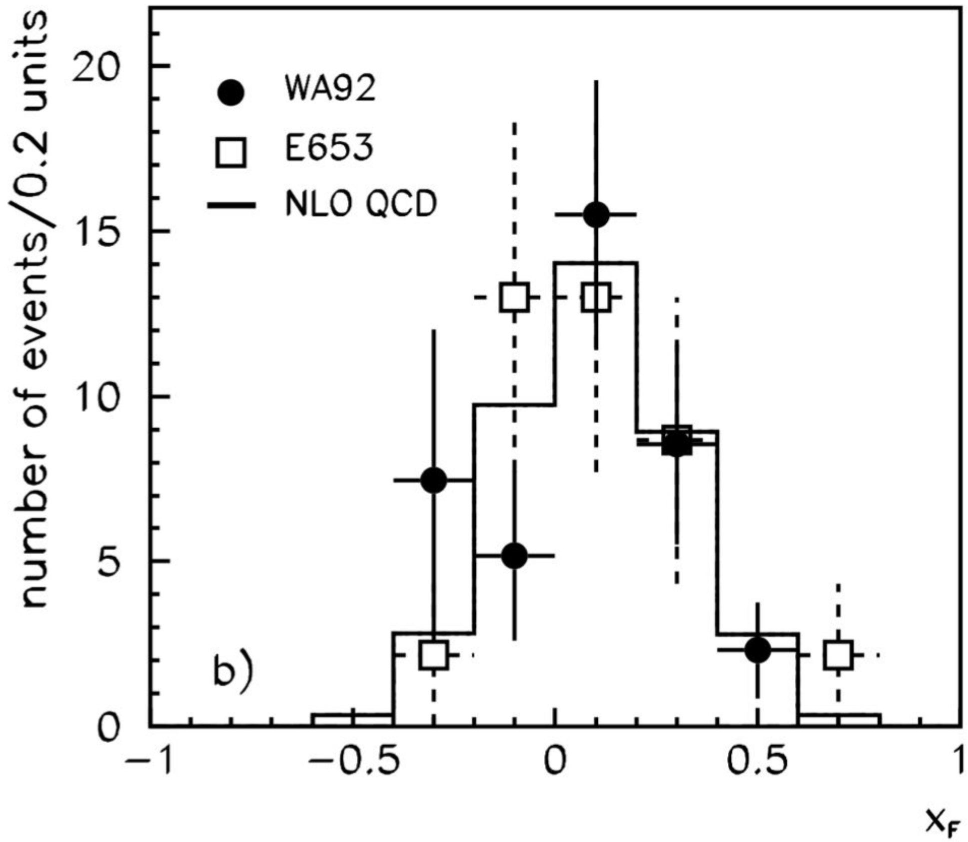


Fig. 9. Beauty cross section measurements in $\pi^- N$ interactions compared with theoretical predictions. Theoretical uncertainty bands are obtained by varying the b-quark mass (m_b), the factorization scale (μ_F), and the renormalization scale (μ_R). Dashed band: $m_b = 4.5$ GeV$/c^2$; solid band: $m_b = 4.75$ GeV$/c^2$; dotted band: $m_b = 5$ GeV$/c^2$. The band widths correspond to a variation of μ_F and μ_R between $m_b/2$ and $2m_b$.

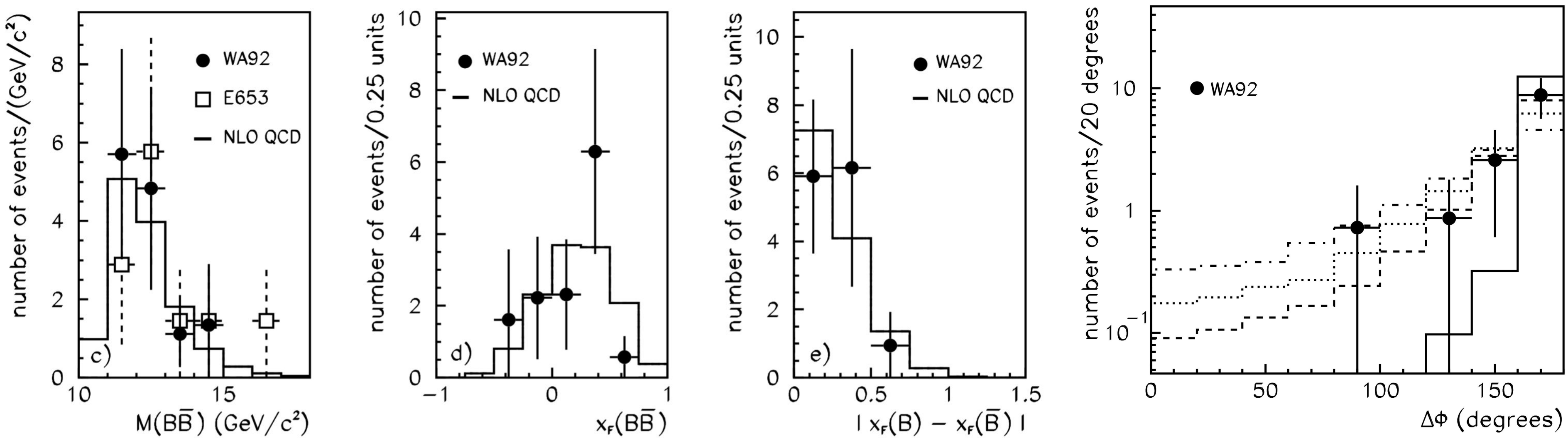
WA92 Physics: Beauty differential cross-sections





Distribution of B-meson cross-sections vs p_T and x_F of the 39 B particles, compared to a previous experiment (E653) and NLO QCD calculations
[C. Gemme, PhD thesis]

WA92 Physics: Beauty pair correlations



Correlations between the two B mesons for the 13 events with both reconstructed decays, compared to experiment E653 and NLO QCD:

- BB invariant mass
- x_F of the BB pair
- difference of x_F between the B and anti-B particle
- azimuthal angle difference between the B and anti-B particle compared to NLO QCD predictions for different values of the average interacting partons transverse momentum squared: $\langle k_T^2 \rangle$ = 0, 0.5, 1 and 2 $(GeV/c)^2$ (from sharper to broader) [Frixione, Mangano, Nason, Ridolfi]

[C. Gemme, PhD thesis]

WA92 Physics: Ds→μν decay selection

The Ds→μν decay is "clean" from QCD effects and can be calculated simply:

$$B(D_s \to \ell\nu_\ell) = \frac{G_F{}^2}{8\pi}|V_{cs}|^2 f_{D_s}^2 \tau_{D_s} M_{D_s} m_\ell^2 \left(1 - \frac{m_\ell^2}{M_{D_s}^2}\right)^2$$

where f_{Ds} is the decay constant, that measures the q-qbar wavefunction overlap at the origin.

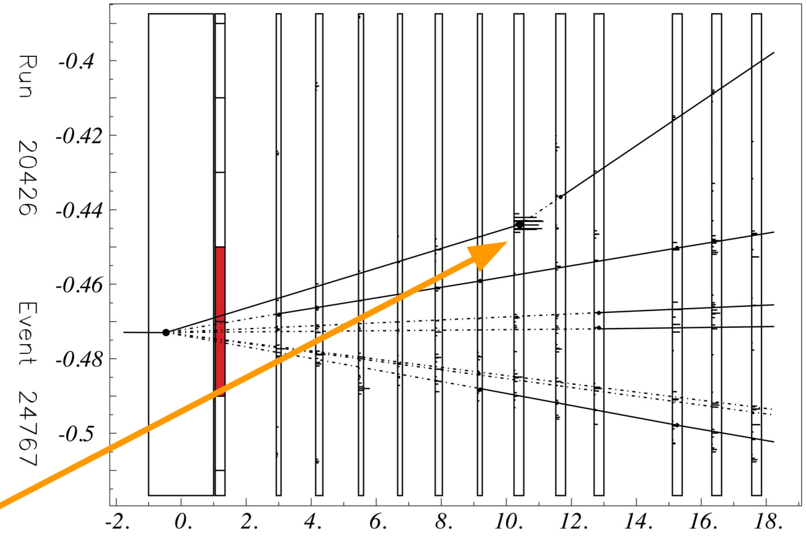
The event selection matched the decay topology:

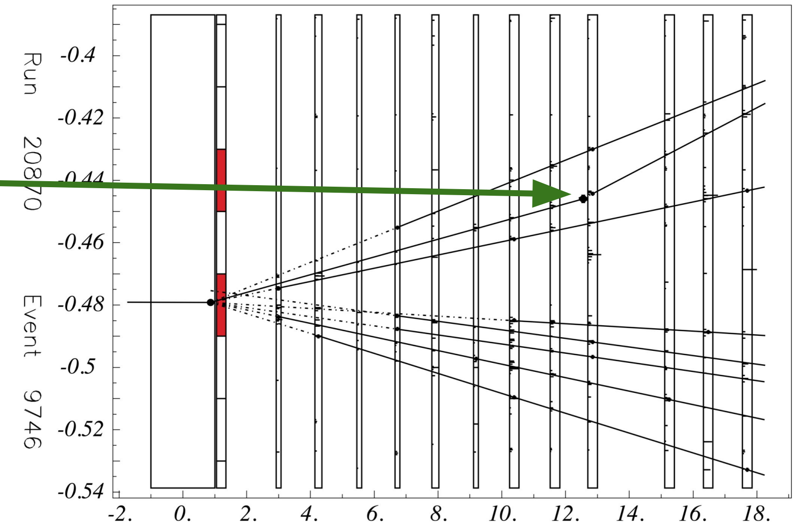
- High-p_T muon (p_T > 500 MeV)
- Impact parameter to primary vertex > 20 μm
- Isolated kink between 3rd and 11th DD plane
- No energy deposit > 5 MIPs near the kink to separate hadronic interactions from decays

Special reconstruction software was developed to reconstruct the short tracks and the kinks in the DD.

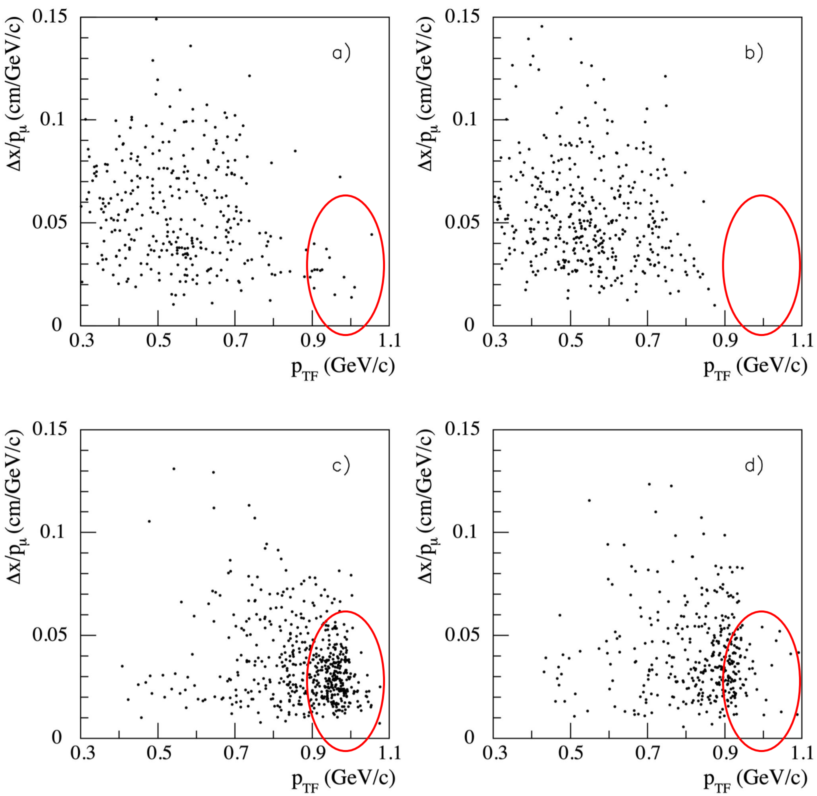
Finally had 82 events in W target and 300 in Cu target.

Efficiencies from simulation 80-90% for Ds→μν decays and also for D→μν decays and generic c-cbar events.





WA92 Physics: Ds→μν branching fraction and decay constant



Plots of $\Delta x/p_\mu$ vs p_{TF} for:

a) all selected real events
b) general c-cbar events
c) simulated Ds→μν decays
d) simulated D→μν decays

The number of detected Ds→μν decays can be found by subtracting the remaining background due to D→μν decays and generic c-cbar events with a maximum likelihood fit. Then it can be combined with the measurement of the Ds→φπ decays in the same experiment:

$$\frac{B(D_s \to \mu\nu_\mu)}{B(D_s \to \varphi_{(K^+K^-)}\pi)} = \frac{N^{obs}_{D_s\to\mu\nu_\mu}}{\varepsilon_{D_s\to\mu\nu_\mu}} \times \frac{1}{N^{prod}_{D_s\to\varphi_{(K^+K^-)}\pi}}$$

to find the ratio of branching fractions:

$$\frac{B(D_s \to \mu\nu_\mu)}{B(D_s \to \varphi_{(K^+K^-)}\pi)} = 0.47 \pm 0.13 \pm 0.04 \pm 0.06$$

and finally the leptonic branching fraction and the decay constant:

$$B(D_s \to \mu\nu_\mu) = (0.83 \pm 0.23 \pm 0.06 \pm 0.18)\%,$$

$$f_{D_s} = 323 \pm 44 \pm 12 \pm 34 \text{ MeV},$$

[errors are statistical, syst(WA92), syst(B(Ds→φπ)]

WA92: Publications

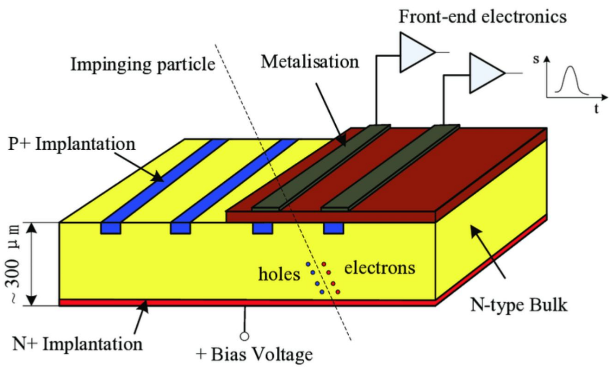
- Study of charm correlations in pi- - N interactions at s**(1/2) approximately = 26-GeV
  BEATRICE Collaboration • M. Adamovich (LPI, Moscow (main)) et al.
  DOI: 10.1016/0370-2693(95)00205-Y
  Published in: Phys.Lett.B 348 (1995), 256-262
- Search for the decay D0 ---> mu+ mu-
  BEATRICE Collaboration • M. Adamovich (Lebedev Inst.) et al.
  DOI: 10.1016/0370-2693(95)00593-A
  Published in: Phys.Lett.B 353 (1995), 563-570
- WA92: A Fixed target experiment to trigger on and identify beauty particle decays
  BEATRICE Collaboration • M Adamovich (Lebedev Inst.) et al.
  DOI: 10.1016/0168-9002(96)00480-9
  Published in: Nucl.Instrum.Meth.A 379 (1996), 252-270
- A Study of kinematical correlations between charmed particles produced in pi - Cu interactions at s**(1/2) = 26-GeV
  BEATRICE Collaboration • M. Adamovich (Lebedev Inst.) et al.
  DOI: 10.1016/0370-2693(96)01024-6
  Published in: Phys.Lett.B 385 (1996), 487-492
- Measurements of charmed meson production in interactions between 350-GeV/c pi- particles and nuclei
  BEATRICE Collaboration • M. Adamovich (Lebedev Inst.) et al.
  DOI: 10.1016/S0550-3213(97)00223-X
  Published in: Nucl.Phys.B 495 (1997), 3-34
- Search for the flavor changing neutral current decay D0 ---> mu+ mu-
  BEATRICE Collaboration • M. Adamovich (Lebedev Inst.) et al.
  DOI: 10.1016/S0370-2693(97)00775-2
  Published in: Phys.Lett.B 408 (1997), 469-475
- Measurement of the beauty production cross-section in 350-GeV/c pi- Cu interactions
  BEATRICE Collaboration • M. Adamovich (Lebedev Inst.) et al.
  DOI: 10.1016/S0550-3213(98)00209-0
  Published in: Nucl.Phys.B 519 (1998), 19-36
- Azimuthal correlation between beauty particles produced in 350-GeV/c pi- - Cu interactions
  BEATRICE Collaboration • Y. Alexandrov (Lebedev Inst.) et al.
  DOI: 10.1016/S0370-2693(98)00691-1
  Published in: Phys.Lett.B 433 (1998), 217-222
- A Measurement of the form-factor ratios in the decay D+ ---> anti-K*0 muon+ muon-neutrino
  BEATRICE Collaboration • M. Adamovich et al.
  DOI: 10.1007/s100529801012
  Published in: Eur.Phys.J.C 6 (1999), 35-41
- D*+- production in 350-GeV/c pi- - N interactions
  BEATRICE Collaboration • M. Adinolfi (INFN, Pisa and Pisa U.) et al.
  DOI: 10.1016/S0550-3213(99)00173-X
  Published in: Nucl.Phys.B 547 (1999), 3-18
- Inclusive J/ψ and $\psi^\prime$ production in π^{-} - nucleus interactions at $S^{(1/2)}$ approximately equals 26-GeV
  BEATRICE Collaboration • Y. Alexandrov (Lebedev Inst.) et al.
  DOI: 10.1016/S0550-3213(99)00412-5
  Published in: Nucl.Phys.B 557 (1999), 3-21
- Measurement of the kinematic variables of beauty particles produced in 350 GeV/ c pi- Cu interactions
  BEATRICE Collaboration • Y Alexandrov (Lebedev Inst.) et al.
  DOI: 10.1016/S0370-2693(99)00647-4
  Published in: Phys.Lett.B 459 (1999), 417-422
- Measurement of the D(s) ---> muon neutrino(muon) branching fraction and of the D(s) decay constant
  BEATRICE Collaboration • Y. Alexandrov (Lebedev Inst.) et al.
  DOI: 10.1016/S0370-2693(00)00266-5
  Published in: Phys.Lett.B 478 (2000), 31-38

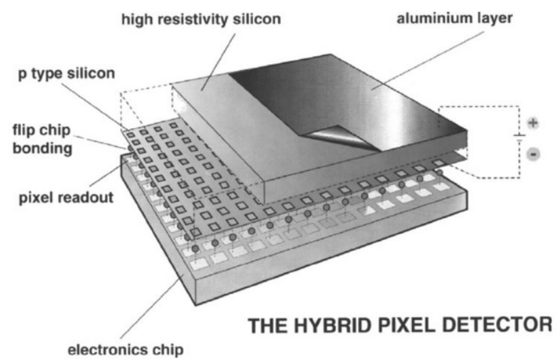
Legacy in Genova

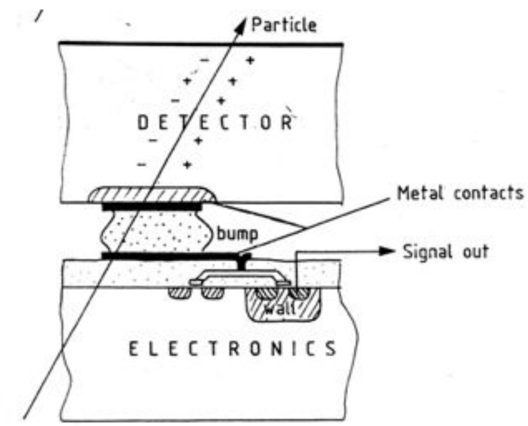
Pixel technology in HEP → Hybrid Pixel detectors

- Pixel detectors have their roots in photography, where they have in the decades revolutionized the camera market. CCDs pioneered the use of Pixel in tracking (ACCMOR at CERN PS, SLD at SLAC Linear Collider, DELPHI at CERN LEP). But their use had two important limitations:
  - Poor radiation tolerance and long readout time

- Hybrid Pixel detectors could solve these limitations and fully exploit all the progress done in the microstrips technologies
  - Reduce the strip length closer to its width → Pixel
  - The ASIC has to face the sensor channel rather than lying at the surface edge.







RD19

- While the idea was simple, its implementation involved a long R&D program, begun by early 90s by Erik Heijne and colleagues at CERN (RD19).
  - This was one of the several R&D projects launched at CERN to develop detectors able to cope with the LHC program.

- The Genova group had got significant expertise in silicon microstrip detectors and ASICs with WAxx experiments. Transition to Pixel detectors happened within the framework of RD19.

- RD19 over a decade and with up to 150 members produced detectors for three experiments: WA97, NA57 and the DELPHI forward tracking.
  - Initially starting from a feature size of 3 µm, pixels were originally pretty large and reduced in local electronics. But the pixel technology could profit of the steady reduction of the feature size in electronics chips, thus allowing for always smaller pitch pixels.

	Year	Pitch [μm^2]	Channels	Area [m^2]
WA97	1994	75x500	288 k	0.01

The first tracking systems and a big challenge

First Results from the 1994 Lead Beam Run of WA97

Presented by:
Federico Antinori / CERN and Genoa
for the WA97 Collaboration:

G. Alexeev[p], E. Andersen[c], A. Andrighetto[j], F. Antinori[e,f], N. Armenise[b], J. Ban[g], D. Barberis[f], A.C. Bayes[d], H. Beker[n], M. Benayoun[k], W. Beusch[e], R. Blaes[q], J. Bohm[l], J.M. Brom[q], M. Campbell[e], E. Cantatore[e], J.N. Carney[d], N. Carrer[j], M.G. Catanesi[b], E. Chesi[e], M. Dameri[f], G. Darbo[f], J.P. Davies[d], A. Diaczek[k], D. Di Bari[b], S. Di Liberto[n], A. Di Mauro[b], J.P. Dufey[e], D. Elia[b], D. Evans[d], K. Fanebust[c], R. Fang[q], Ph. Farthouat[e], R. Fini[b], B.R. French[e], W. Geist[q], C. Gemme[f], B. Ghidini[b], G. Grella[o], M. Guida[o], E.H.M. Heijne[e], H. Helstrup[e], A.K. Holme[c], A. Inyakin[p], A. Jacholkowski[e], P. Jovanovic[d], A. Jusko[g], V.A. Kachanov[p], T. Kachelhoffer[q], J. Kahane[k], V. Khodyrev[p], J.B Kinson[d], A. Kirk[e], W. Klempt[e], K. Knudson[e], I. Kralik[g], J.C. Lassalle[e], V. Lenti[b], Ph. Leruste[k], J. Lien[i], R. Lietava[g], L. Lopez[e], G. Lovhoiden[i], M. Luptak[g], I. Macha[m], V. Manzari[b], P. Martinengo[e], M.A. Mazzoni[n], F. Meddi[n], A. Michalon[q], M.E. Michalon-Mentzer[q], P. Middelkamp[e], M. Morando[j], M.T. Muciaccia[b], E. Nappi[b], J.L. Narjoux[k], F. Navach[b], K. Norman[d], B. Osculati[f], M. Pairat[k], A. Pallares[q], B. Pastircak[g], F. Pellegrini[j], K. Piska[l], F. Posa[b], E. Quercigh[e], J.L Reister[q], T. Reitan[i], R.A. Ricci[h], G. Romano[o], G. Rosa[n], L. Rossi[f], H. Rotscheidt[e], K. Safarik[e], J. Sahagun Pareja[e], S. Saladino[b], L. Sandor[g], S. Sclmane[k], T. Scognetti[b], G. Segato[j], M. Sené[k], R. Sené[k], P. Sennels[i], P. Shagin[p], S. Simone[b], A. Singovski[p], B. Sopko[m], P. Staroba[l], J. Stastny[l], T. Storaas[i], S. Szafran[k], T.F. Thorsteinsen[c], G. Tomasicchio[b], J. Urban[g], M. Vanickova[l], G. Vassiliadis[a], H. Vettunen[q], O. Villalobos Baillie[d], T. Virgili[n], A. Volte[k], C Voltolini[q], M.F. Votruba[d] and P. Zavada[l].

[a] Nuclear Physics Department, Athens University, GR-15771 Athens, Greece
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[e] CERN, European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland
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[l] Institute of Physics, Czech Academy of Sciences, CZ-18040 Prague, Czech Republic
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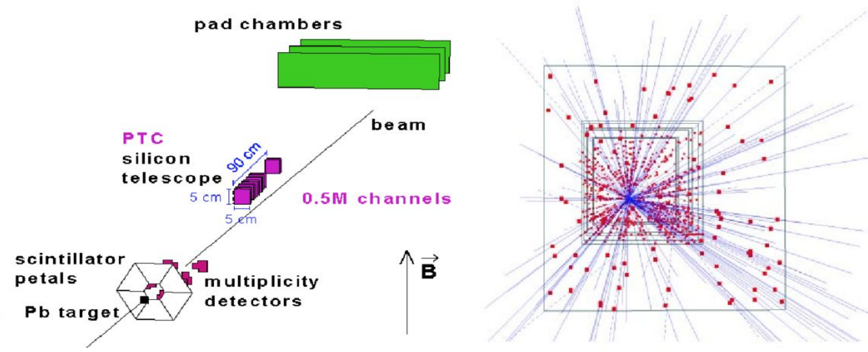
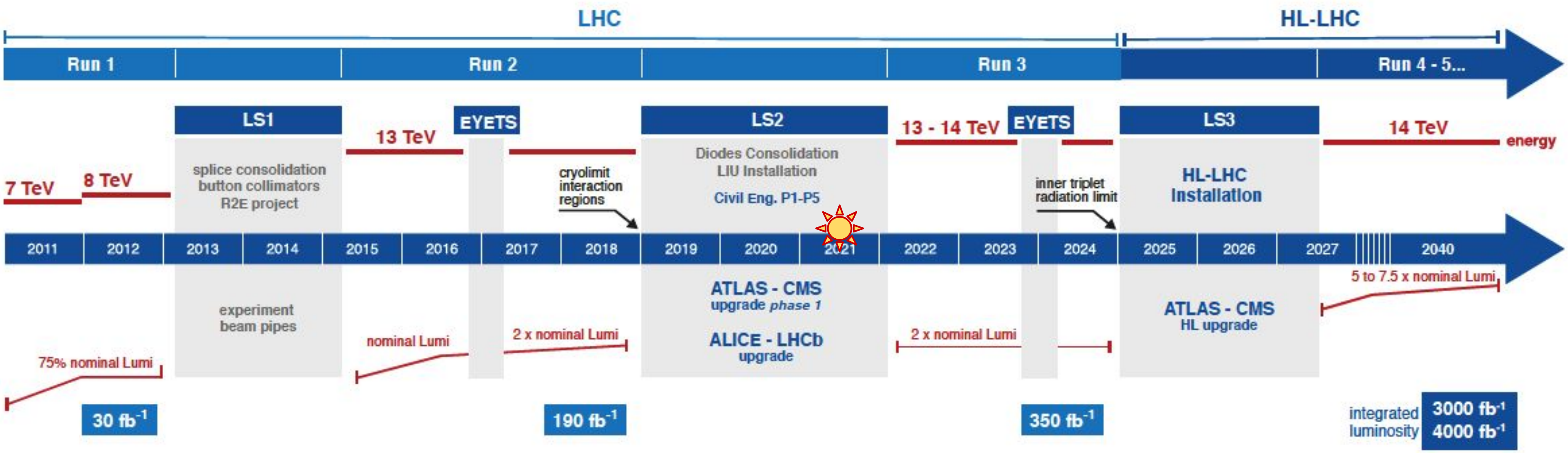


Figure 2. WA97 experiment setup (left). In the right, perspective view of fixed target Pb-Pb event reconstruction with 153 tracks using a 7-plane telescope in WA97 (Setup 1995 using 'Omega2' arrays). Each window represents a $5 \times 5\,\text{cm}^2$ with 72000 pixel cells. The red dots represent hits in the silicon detectors after which the tracks have been reconstructed. Every dot is associated with one track. The image was taken without magnetic field [13].

"WA97 has developed a practical silicon pixel device in close collaboration with the CERN-RD19 effort. We like to stress that WA97 ***is the first and so far still the only experiment successfully employing silicon pixel devices****."*

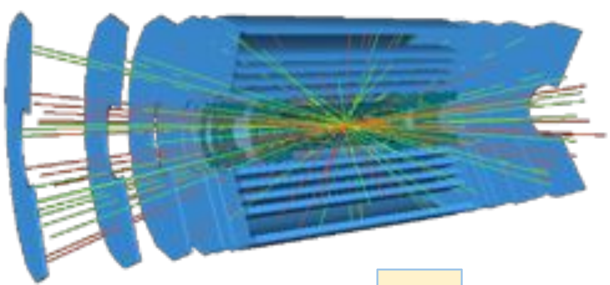
- Given the maturity of the technology and the experience in RD19-WA97, Genova was ready to sustain at all levels (locally, within INFN and internationally) the project for a Pixel detector in the ATLAS Experiment at the LHC.
  - unprecedented challenges for surface, radiation damage, data transmission.

LHC programme



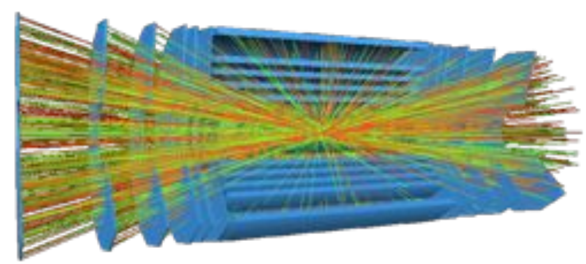
	PIXEL	IBL	ITk
Min . Bias	19-55		140-200
Data Taking	2009 -	2015 -	Exp 2027
Pitch [µm^2]	50x400	50x250	50x50
FE tech. [nm]	250	130	65
Area [m^2]	1.73	0.15	**13**
Modules	1.7 k	0.28 k	**9.2 k**
Channels	80 M	12 M	**5100 M**
Rad. Hard. [neq/cm^2]	1 10^{15}	5 10^{15}	**2 10^{16}**

Inner Detector (ID): installed in 2007, upgraded with IBL in 2014



LHC

"Phase II": full Si Inner detector ITk (Pixel+Strip)

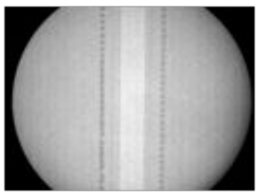


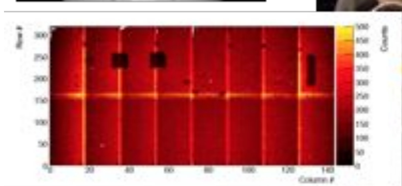
HL-LHC

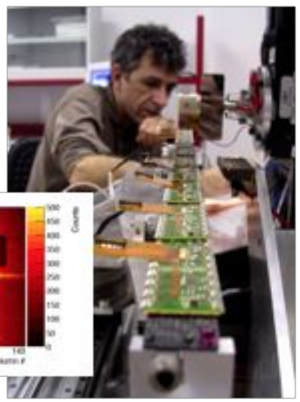
ATLAS Pixel

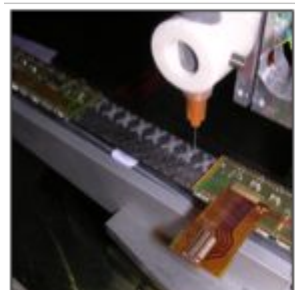
- The construction of the Pixel detector (PIXEL), with activities in several areas, represents the real step for the Genova's ATLAS group. The team grew significantly in personpower, instrumentation and space.
- Thanks to that experience Genova has gained a recognized international leading role, that has allowed for playing a significant role in IBL first and now in ITk.

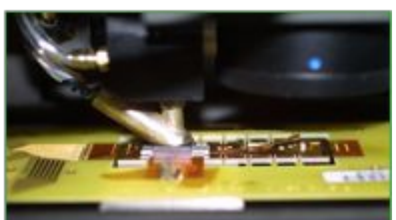
1998-2003

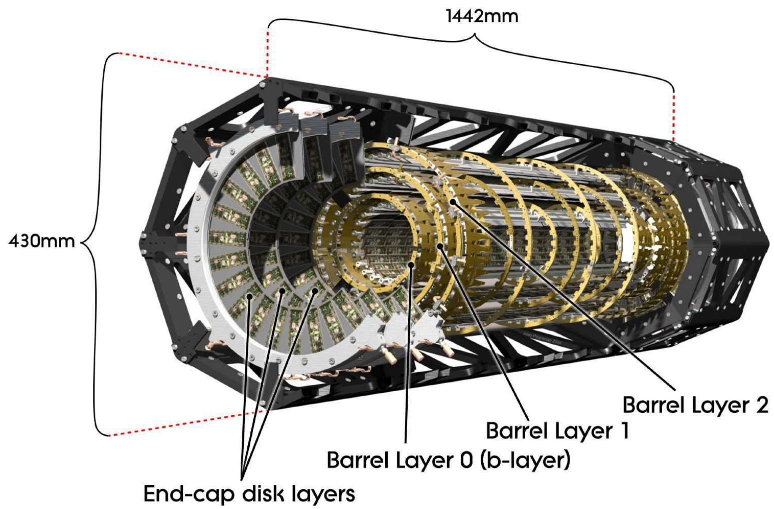


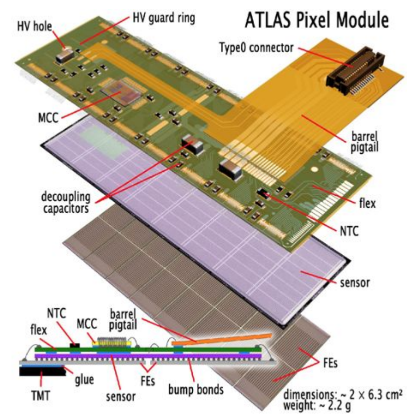


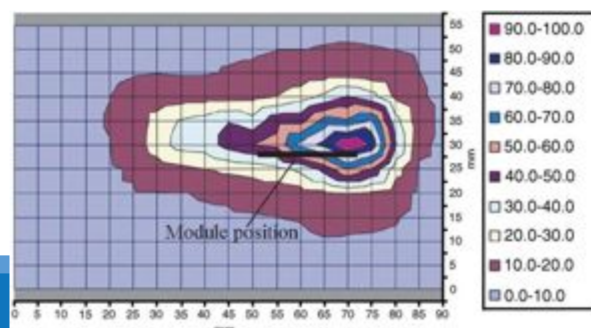






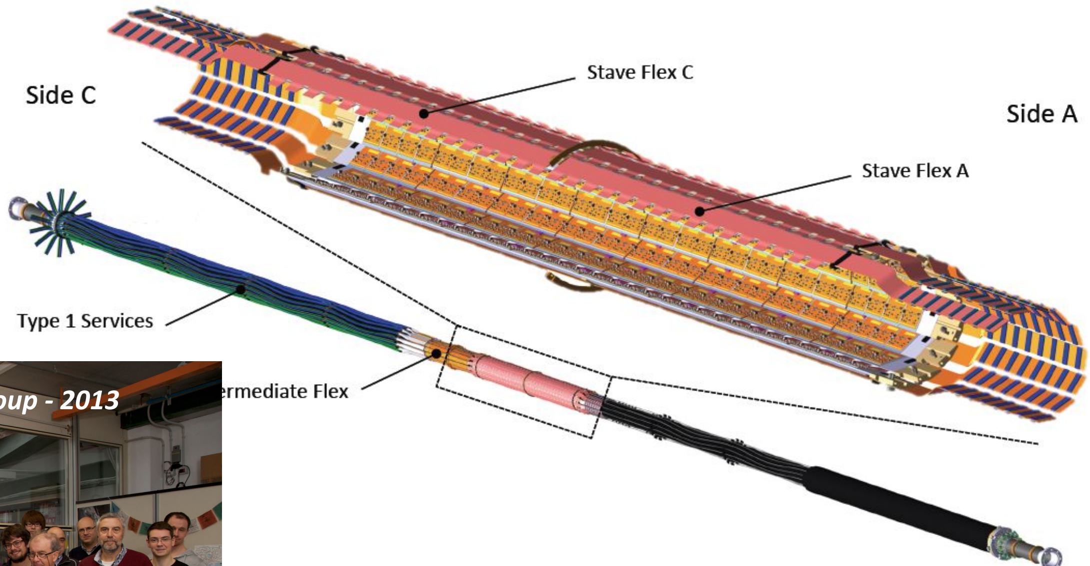


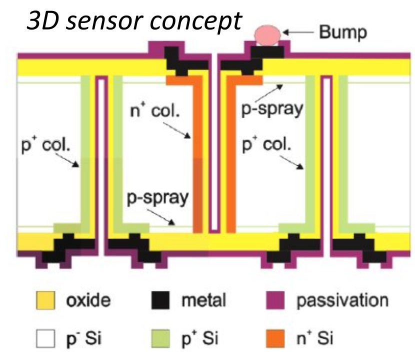


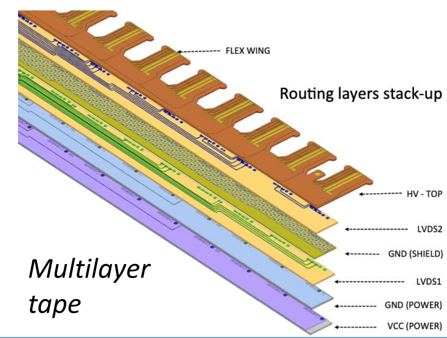


ATLAS Pixel upgrade: IBL

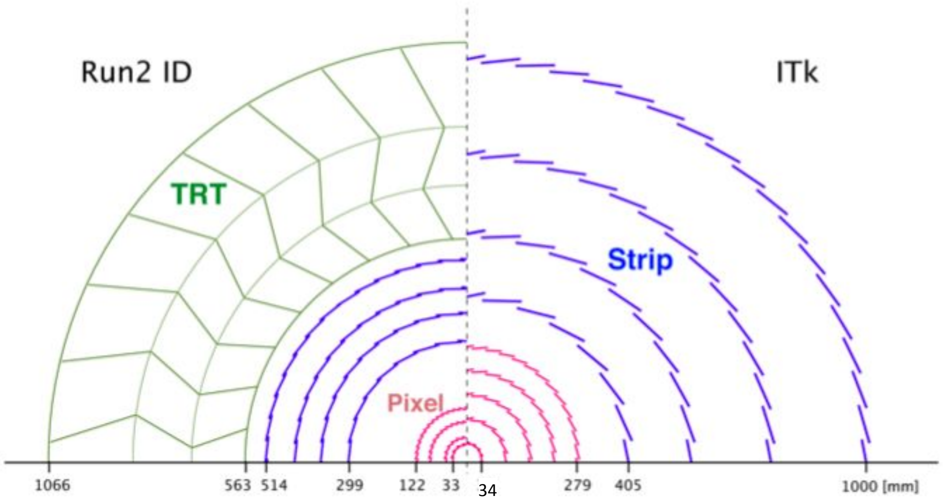
- In the first shutdown of LHC, a new layer has been added to the pixel detector. The Insertable B Layer (IBL) has been built around the beam pipe and slided into the existing 3-layers detector.
- Beside consideringly enhancing the tracking performance thanks to the proximity to the primary vertex, it represents an intermediate step towards the upgrades for HL-LHC. Indeed several new technologies have been first tested there: 3D sensors, CO_2 cooling, 130 nm ASIC technology, etc ..

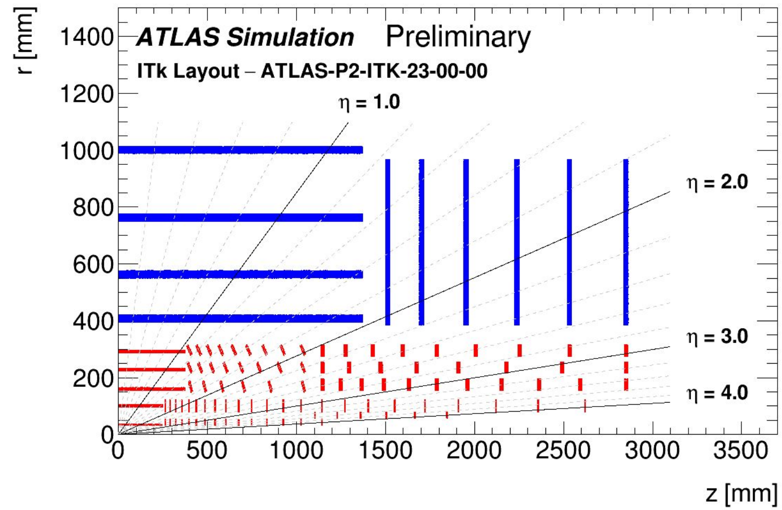


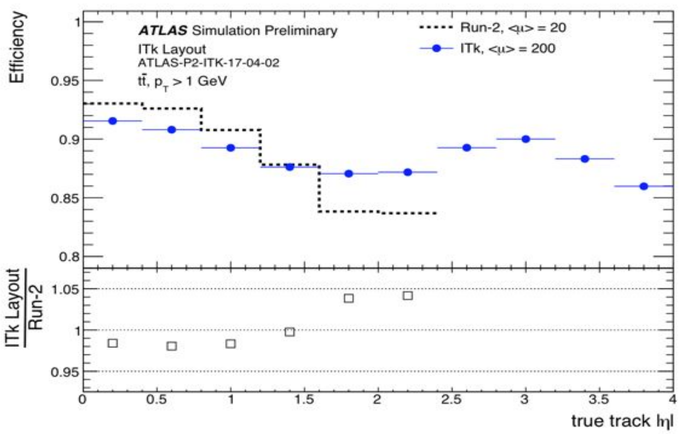


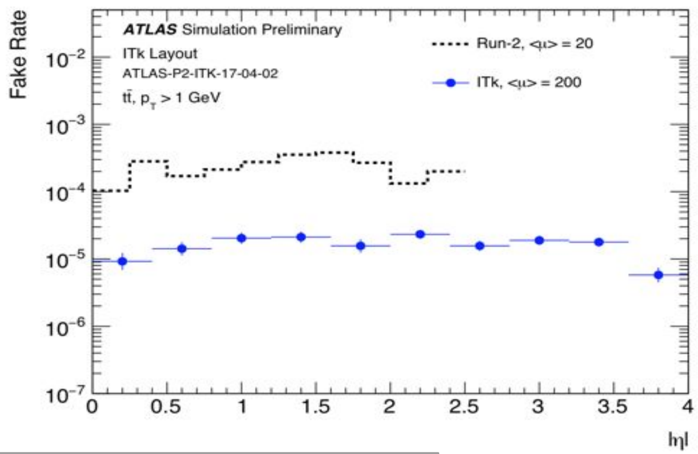


ATLAS Pixel @ HL-LHC









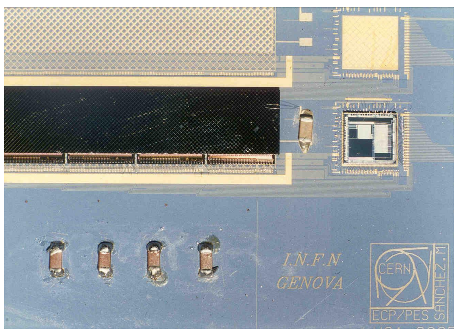
Overall significant improvement of ITk vs ID thanks to

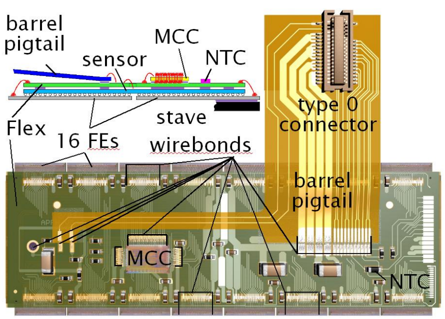
- Reduced material budget → minimize material interactions
- Increase in overall hit counts → tighter track selection
- Improved hermeticity → more hits, fewer holes

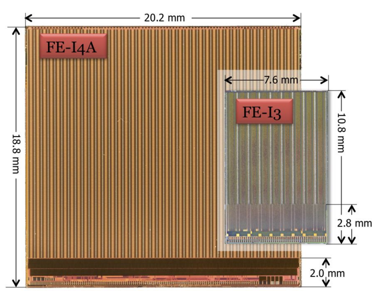
Example: Electronics

Experience in digital chip design has found application in the design of:

- RD19/WA97 - Pixel Ladder Controller (COOP)
- ATLAS - Pixel Module Chip Controller (MCC)
- FE-I4A/B - 26k pixel (~80M transistors/125nm IBM tech.) for ATLAS IBL
  - Contribution: development of command decoder (porting and extending MCC design), chip verification, test vectors

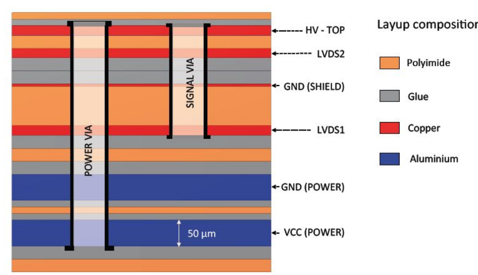


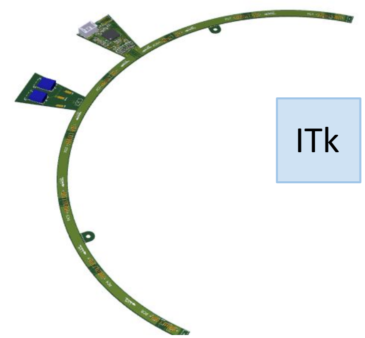




Experience in circuits design growing as well

- In PIXEL test of flex hybrid with MCC
- For IBL: Flex Modules and bus tape with Al-Cu vias (produced at CERN)
- in ITk LV/DCS bus tape



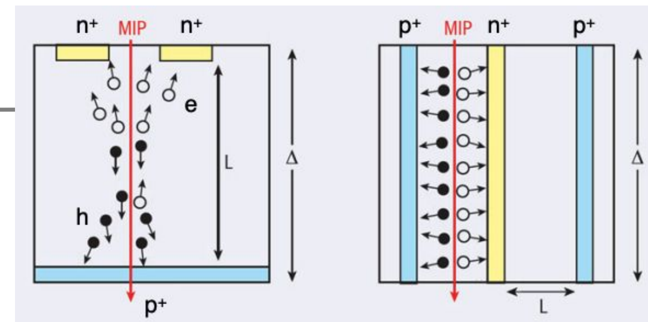


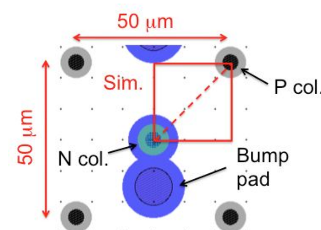
Example: Modules

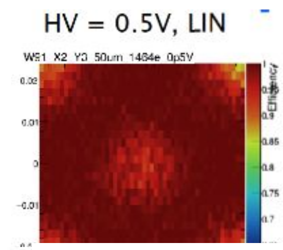
In Pixel Genova played the key role to qualify the large scale hybridization sensor-ASIC in Leonardo. Moreover we have assembled ⅓ of the detector modules. This expertise has continued in IBL (half detector build in Ge) and now in ITk.

R&D on 3D sensors with FBK has led to their use in HEP exp for the first time in IBL, and have been chosen for the innermost layer in ITk.

3D sensors concept vs planar

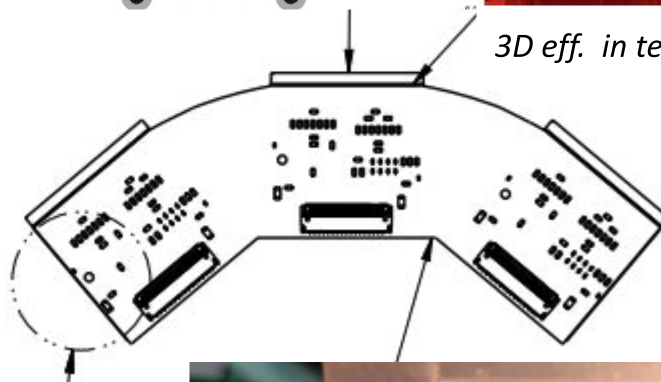




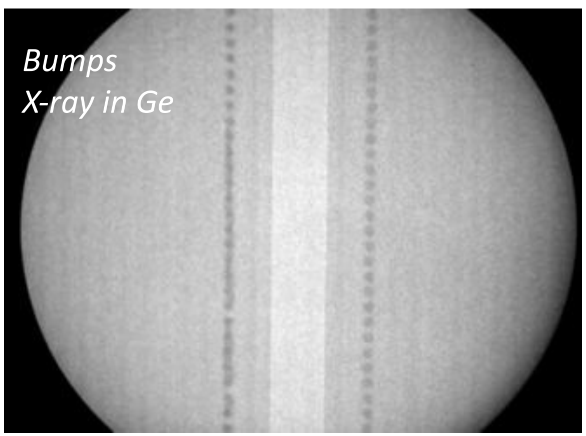


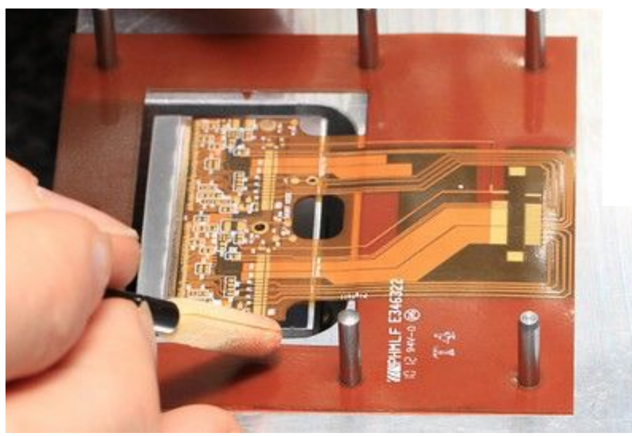
ITk

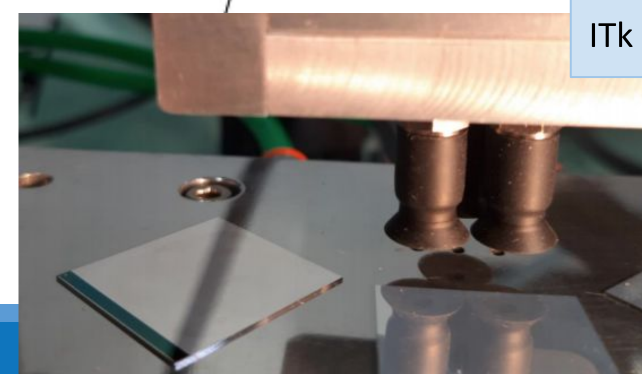
3D eff. in test beam



Module hybridization and assembly





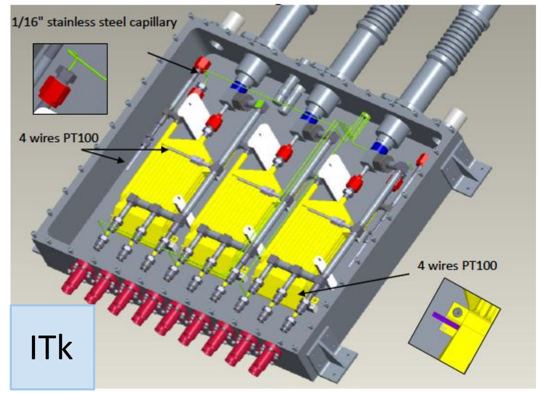


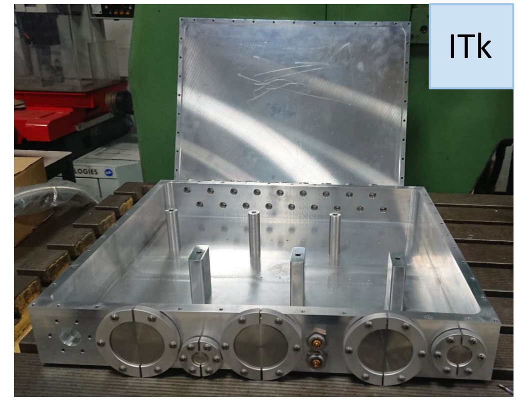
ITk

Example: Mechanics & Cooling

Experience in mechanics has been applied for the local supports for Pixel Staves and now in ITk for the half rings (~100): large commitment in our workshop for construction and metrology.
An additional important commitment in the CO2 system, as Genova is in charge of building ~60 splitter boxes for the full ITk detector.

Splitter boxes and heat Exchanger for the CO2 cooling system.





Ultra-light and stable composite structure to support and cool the ATLAS pixel detector barrel electronics modules

M. Olcese[a,*], C. Caso[a,e], G. Castiglioni[b], R. Cereseto[a], S. Cuneo[a], M. Dameri[a], C. Gemme[a,e], K.-W. Glitza[c], G. Lenzen[c], F. Mora[a], P. Netchaeva[a], W. Ockenfels[d], E. Piano[e], C. Pizzorno[a], R. Puppo[a], A. Rebora[f], L. Rossi[a], J. Thadome[c], F. Vernocchi[a], E. Vigeolas[g], A. Vinci[a]

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[b] *PLYFORM, I-20020 Bienate di Magnago (MI), Italy*
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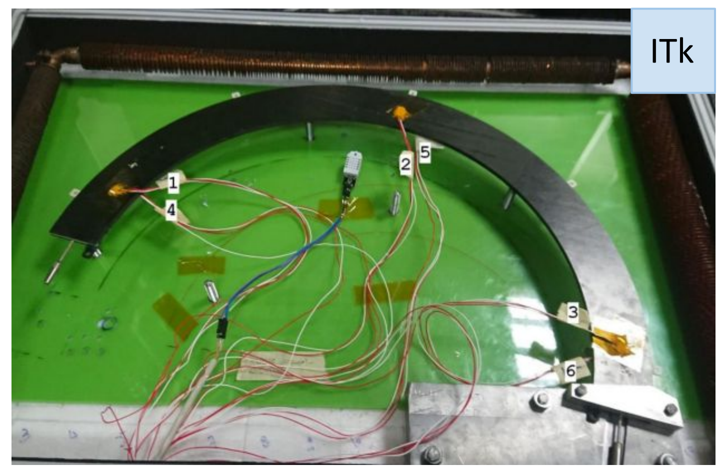
[e] *Department of Physics, Università degli Studi di Genova, I-16146 Genova, Italy*
[f] *Mechanics and Machine Design Department, Università degli Studi di Genova, I-16145 Genova, Italy*
[g] *CPPM, Centre de Physique des Particules de Marseille, F-13288 Marseille, France*

Pixel: Staves machined and surveyed in Genova

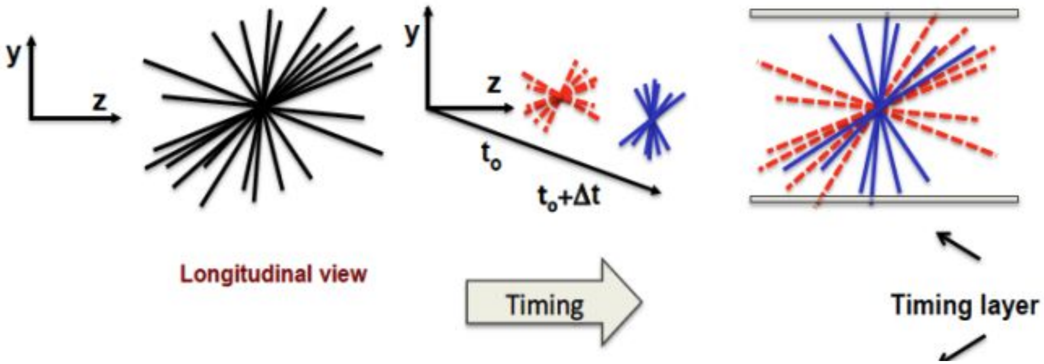
Survey of Half Ring Local Supports

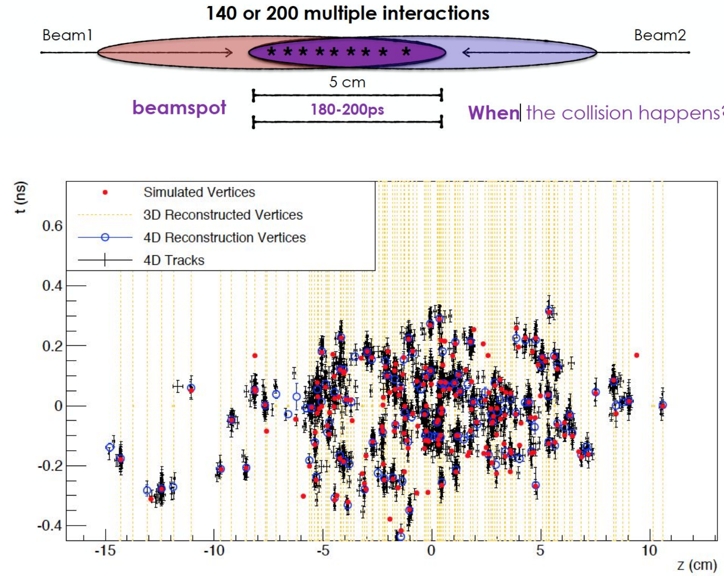


A glance in the future...

While focus is construction of the Pixel detector for HL-LHC, interests in new technologies. Primarily within the AIDAInnova European call framework

- Sensors (3D and LGAD) with improved timing performance (tens of ps) to provide 4D space-time points.





- ASICs in 28nm technology
- more evolved hybridization techniques to avoid bump bonding and flip-chip.

Conclusions

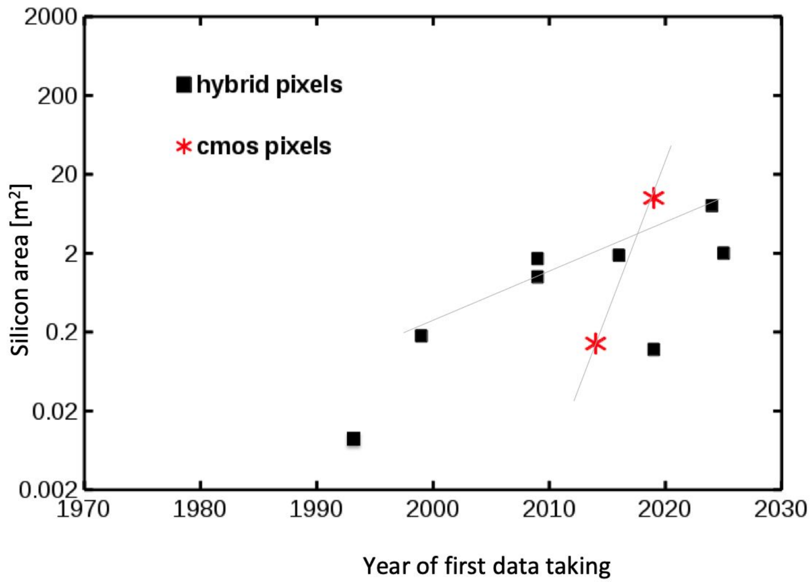
- High resolution segmented silicon detector technology (and related electronics) has been transferred to INFN-Genova thanks to the successful operation of the WAxx Omega experiments.
- This has happened when the R&D effort for the preparation of the LHC experiments was just beginning.
- The proposal for the ATLAS vertex detector based on silicon Pixel sensors was the natural follow-up of the experience accumulated by the group in Genova (and increased in RD19).
- The proposal was accepted after a hard competition and allowed the Genoa group to grow up and to play key roles since then.

Disclaimer

- Precision vertexing means heavy quark selection and tagging. This remains our main thrust in physics measurements also in ATLAS (even if we had no time to treat this issue now).

Backup

pixel evolution vs time



Hybrid Pixels

1994 RD19/WA97
1999 DELPHI
2009 ATLAS
2010 CMS
2015 CMS
2019 Velopix
2024 ATLAS
2025 CMS

CMOS Pixels

2014 STAR
2019 ALICE

Plot credits: M. Garcia-Sciveres [2015] + RD19/WA97 point from:

Construction and characterization of a 117 cm/sup 2/ silicon pixel detector,

Authors: H.Heine + [D.Barberis, G.Darbo, P.Musico, L.Rossi /Genova]+ al., Published on IEEE Trans. NS, **DOI:** 10.1109/23.467810

	year	pixel pitch	Canali	area
WA97	1994	75x500	288 k	4 x 25 cm2
NA57	1999	75x500 and 50x500	1.1 M	
DELPHI FW	1996	330x330	1.2 M	1300 cm2

Contiguity Trigger Bibliography

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11. E. Ruscino et al., "Design of hv-cmos detectors in bcd technology with noise and crosstalk measurements," in 2019 26th IEEE International Conference on Electronics, Circuits and Systems (ICECS), pp. 398–401, Nov 2019. **DOI:** 10.1109/ICECS46596.2019.8965094.

Old Photos: Ω-spectrometer and WA92 Detector

WA71 - WEST HALL and Ω-spectrometer in 1984: https://www.flickr.com/photos/giovannidarbo/albums/72157647873628947

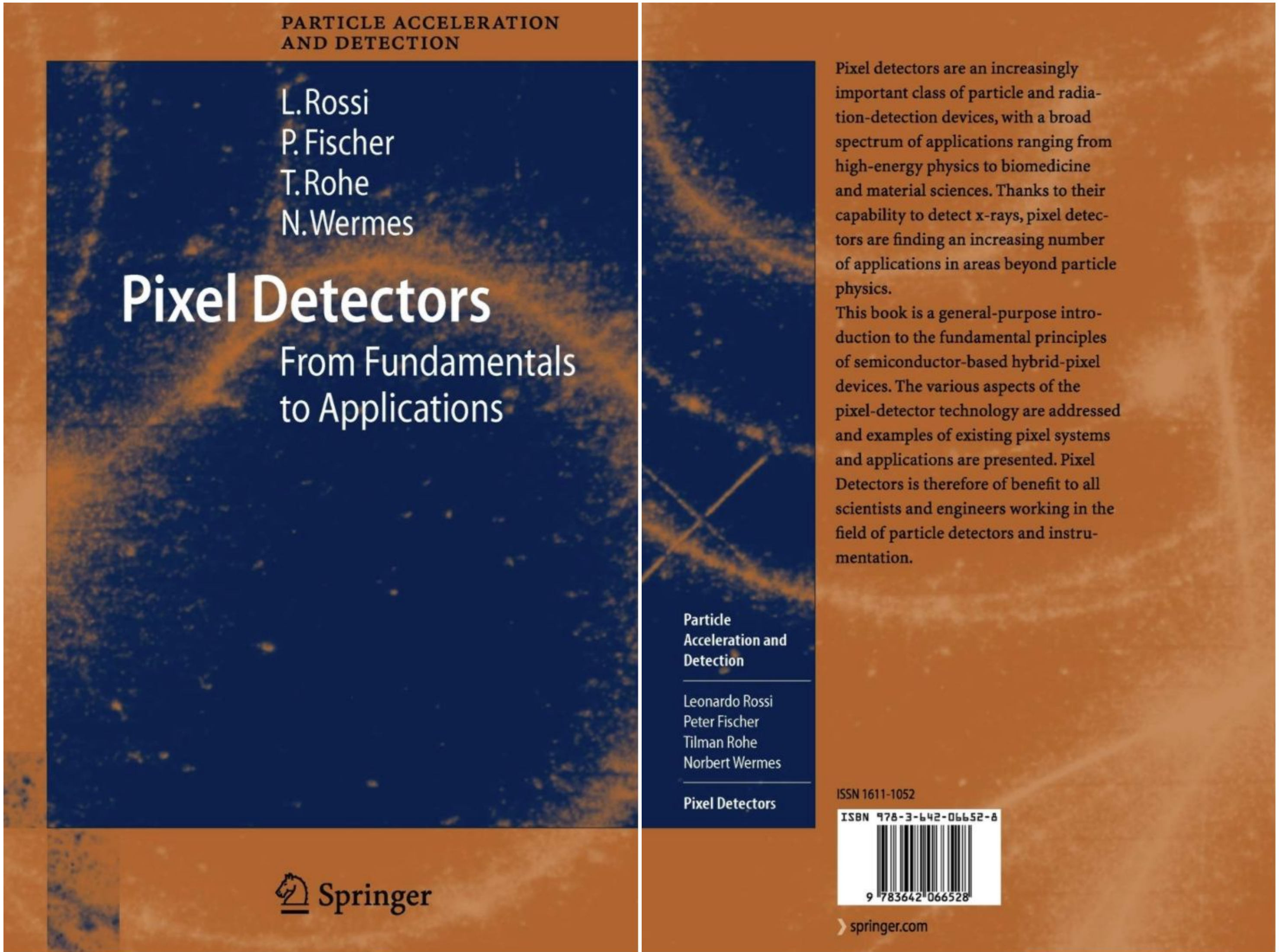
WA92 - Vertex Detector and Beauty Contiguity Trigger in Genova: https://www.flickr.com/photos/giovannidarbo/albums/72157718482925113

RD19: Status report and Addendum Development of hybrid and monolithic silicon micropattern detectors

Spokesman: Erik H.M. Heijne

CERN[1], Collège de France[2], CPPM Marseille[3], EPFLausanne[4], ETH Zurich[5], IMEC Leuven[6], INFN and University of Bari[7], Bologna[8], Genova[9], Milano[10], Modena[11], Padova[12], Pisa[13], Roma[14], University GHS Wuppertal[15], Technical University Athens[16‡], Inst. Jozef Stefan Ljubljana[17‡], Group Praha[18‡], Canberra Semiconductor NV[19¶], GEC-Marconi (Caswell)[20¶] and Smart Silicon Systems SA[21¶]

F. Anghinolfi[1], F. Antinori[1], H. Beker[14], K. Bass[20¶], G. Batignani[13], W. Beusch[1], V. Bonvicini[10], L. Bosisio[13], B. Bostjancic[17‡], C. Boutonnet[2], P. Burger[19¶], M. Campbell[1], P. Cantoni[11], M.G. Catanesi[7], E. Chesi[1], V. Cindro[17‡], C. Claeys[6], J.C. Clemens[3], M. Cohen Solal[3], G. Darbo[9], C. Da Via[1], I. Debusschere[6], P. Delpierre[2,3], D. Di Bari[7], S. Di Liberto[14], B. Dierickx[6], C.C. Enz[4], E. Focardi[13], F. Forti[13], Y. Gally[3], M. Glaser[1], T. Gys[1], M.-C. Habrard[3], G. Hallewell[3], E.H.M. Heijne[1], L. Hermans[6], J. Heuser[15], R. Hurst[9], P. Inzani[10], J.J. Jæger[2], P. Jarron[1], T. Karttaavi[1+], S. Kersten[15], F. Krummenacher[21*], R. Leitner[18‡], F. Lemeilleur[1], V. Lenti[7], M. Lokajicek[18‡], D. Loukas[16‡], M. Macdermott[5], G. Maggi[7], V. Manzari[7], P. Martinengo[9], G. Meddeler[1], F. Meddi[14], A. Mekkaoui[3], A. Menetrey[1], P. Middelkamp[15], M. Morando[12], A. Munns[20¶], P. Musico[9], P. Nava[11], F. Navach[7], C. Neyer[5], F. Pellegrini[12], F. Pengg[1†], R. Perego[10], M. Pindo[10], S. Pospisil[18‡], R. Potheau[3], E. Quercigh[1], N. Redaelli[10], J. Ridky[18‡], L. Rossi[9], D. Sauvage[3], G. Segato[12], S. Simone[7], B. Sopko[18‡], G. Stefanini[1], V. Strakos[18‡], P. Tempesta[7], G. Tonelli[13], G. Vegni[10], H. Verweij[1], G.M. Viertel[5], V. Vrba[18‡], and J. Waisbard[2]


PARTICLE ACCELERATION AND DETECTION
L. Rossi
P. Fischer
T. Rohe
N. Wermes
Pixel Detectors
From Fundamentals to Applications
Springer
Pixel detectors are an increasingly important class of particle and radiation-detection devices, with a broad spectrum of applications ranging from high-energy physics to biomedicine and material sciences. Thanks to their capability to detect x-rays, pixel detectors are finding an increasing number of applications in areas beyond particle physics.
This book is a general-purpose introduction to the fundamental principles of semiconductor-based hybrid-pixel devices. The various aspects of the pixel-detector technology are addressed and examples of existing pixel systems and applications are presented. Pixel Detectors is therefore of benefit to all scientists and engineers working in the field of particle detectors and instrumentation.
Particle Acceleration and Detection
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