R&D for future detectors

31st International conference on High Energy Physics

Amsterdam

31st July 2002

Silicon based detectors

Vertexing for Linear Collider	Silicon Pixel sensors – MAPs, HAPs, CCD, Depfet
Tracking for Linear Collider	Silicon drift
High radiation environments	Lazarus, 3d detectors

Micropattern gas detectors

Tracking, Calorimetry	MSGC,GEM, Micromegas

Calorimetry

Jet reconstruction at LC	Digital calorimeters

Photodetectors

LHCb, b factory upgrades	HPD, HAPD

RPCs, Dark Matter searches, Large systems

Paula Collins, CERN

LEP vs LC by Rembrandt

At LC:

"x sections are tiny"

"No radiation issues" → Why not use a LEP/SLD detector?

"Triggerless operation possible"

"Modest rates"

LC physics demands
Excellent
Vertexing (b,c,t)
and Tracking
⇨ in a high B field
⇨ with energy flow

Silicon for vertexing @ the LC

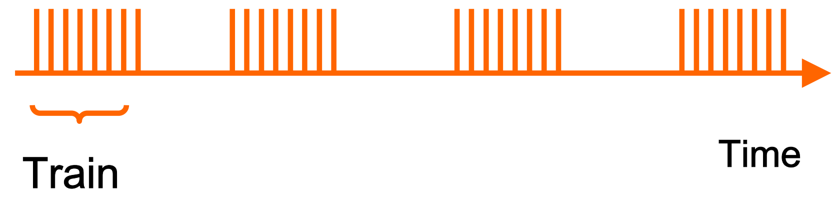
required performance

disentangle complex events $e^+e^- \to t\bar{t} \to b\bar{q}q\bar{b}\bar{q}q$

discriminate b from c and from background $H \to b\bar{b}, c\bar{c}, gg, \tau\bar{\tau}$

δ (IP) < 5 μm $\oplus$ 10 μm/(p sin$^{3/2}$ θ)

(best SLD 8 μm $\oplus$ 33 μm/(p sin$^{3/2}$ θ))



	LEP 0.2 TeV	NLC/ JLC	TESLA 0.5 TeV
bunches perTrain	4	190	2820
Rep rate, Hz	45500	100	5

- Use a silicon based pixel detector
- Confine the e^+e^- background with a high solenoidal field
- Keep occupancy reasonable by reading inner layer in 50 μsec

Vertex detector characteristics

point resolution 1-5 μm

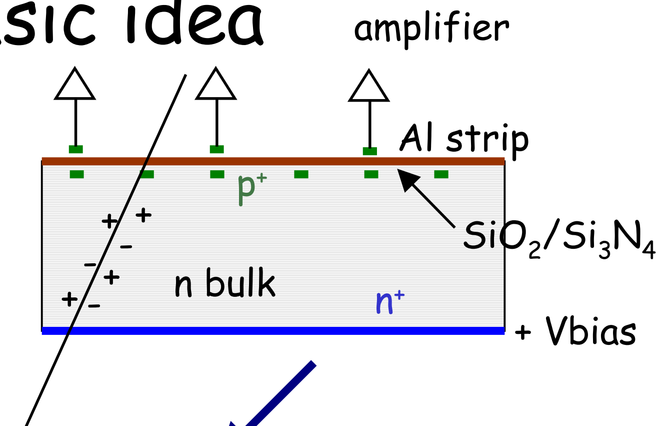
Thickness ~ 0.1 % X_0

5 layers

Inner radius ~ 1.5 cm

Silicon Trends

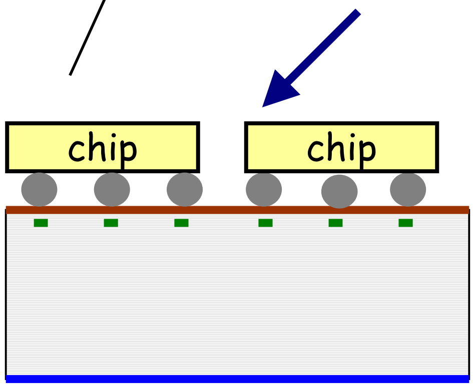
Basic idea



Start with high resistivity silicon

More elaborate ideas:

- n+ side strips – 2d readout
- Integrate routing lines on detector
- Floating strips for precision

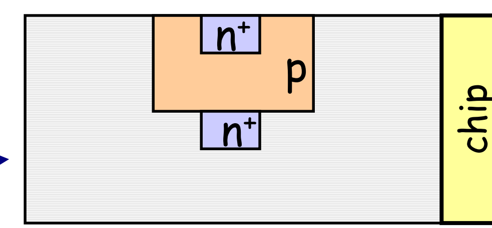


Hybrid Active Pixel Sensors

Chip (low resistivity silicon)

bump bonded to sensor

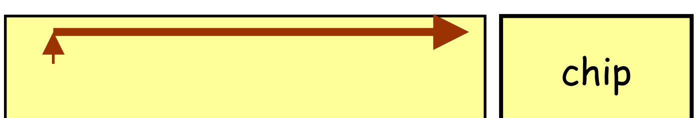
Floating pixels for precision



DEPFET:

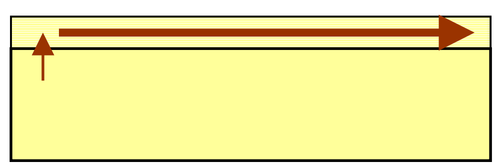
Fully depleted sensor

with integrated preamp



CCD: charge collected in thin layer

and transferred through silicon



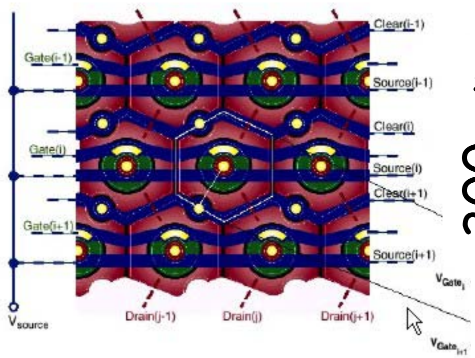
MAPS: standard CMOS wafer

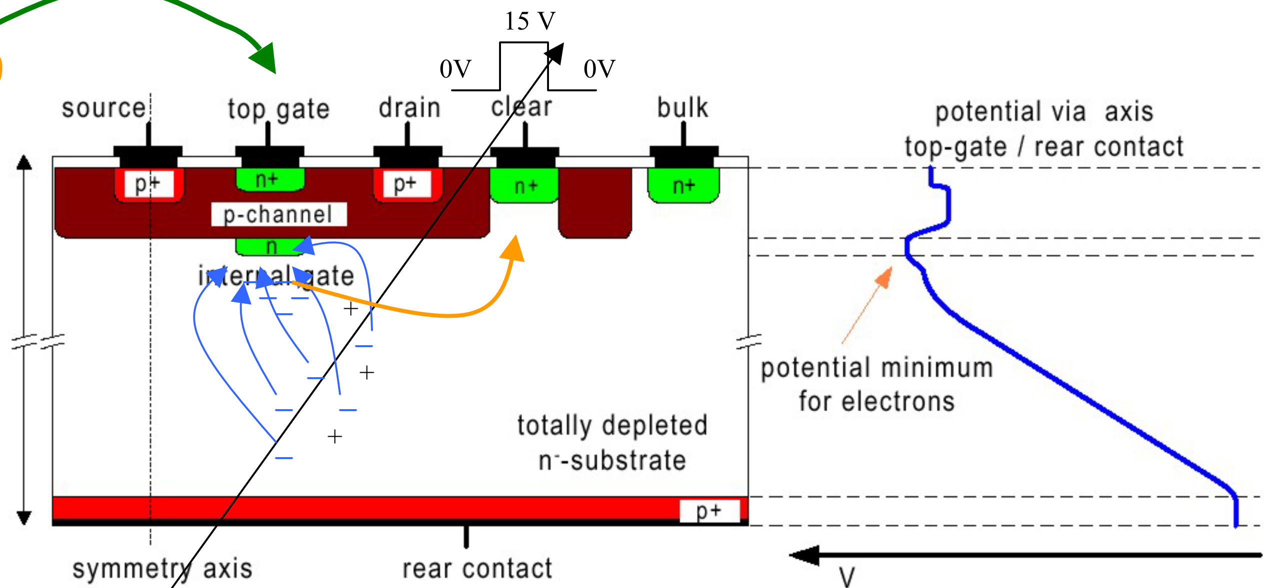
Integrates all functions

DEPFET sensors

Kemmer, Lutz, 1987

R&D for tracking ~ 2000





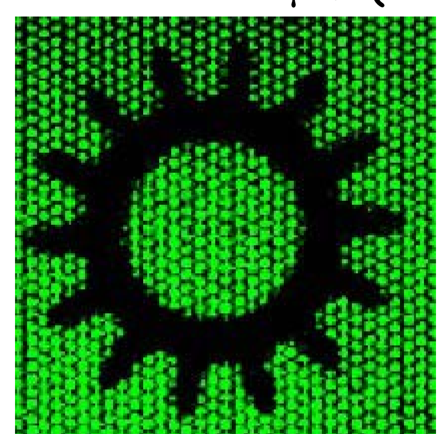
- Amplifying transistor integrated into high resistivity silicon detector
- Low noise operation possible at room temperature
- Thinning possible to 50 µm

R&D: pixel size, power, thinning, speed

End 2002: 128x128 30µmx30µm prototypes

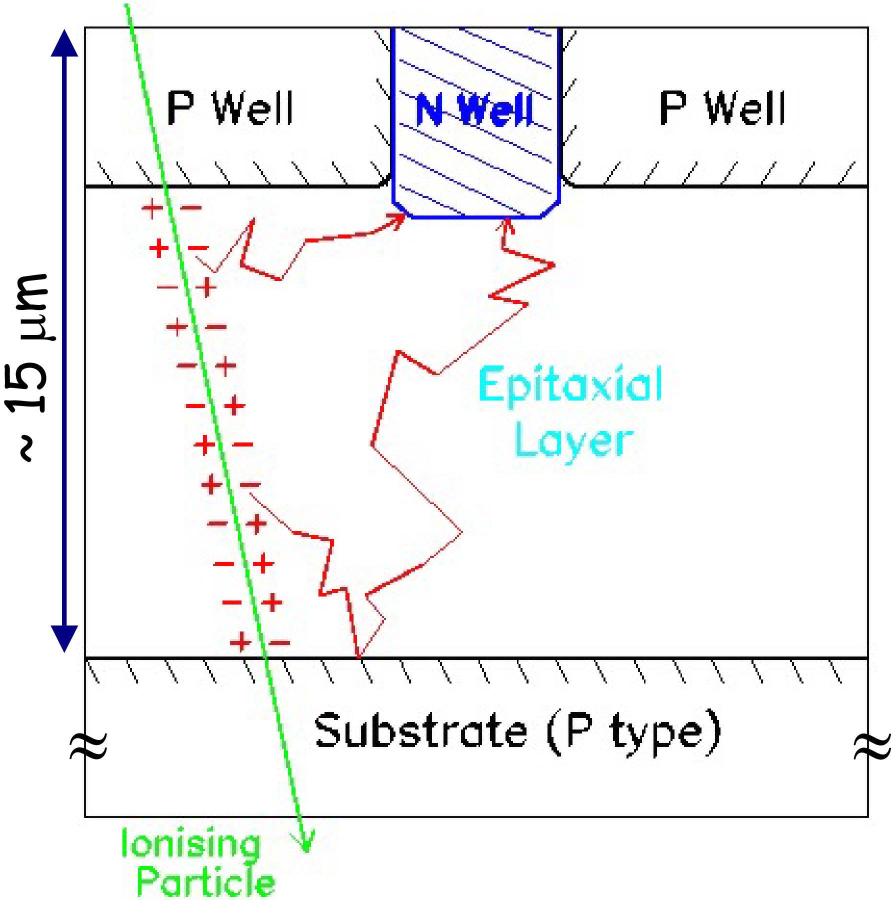
Image of toothed watch wheel

Resolution: 9 µm (50 µm pixels)



NIMA 465 (2001) 247-252

Monolithic Active Pixel Sensors (MAPS)



1999 – R&D on CMOS MAPS

1999 – small scale prototypes

1999-2000 first beam tests

2001 – large prototypes

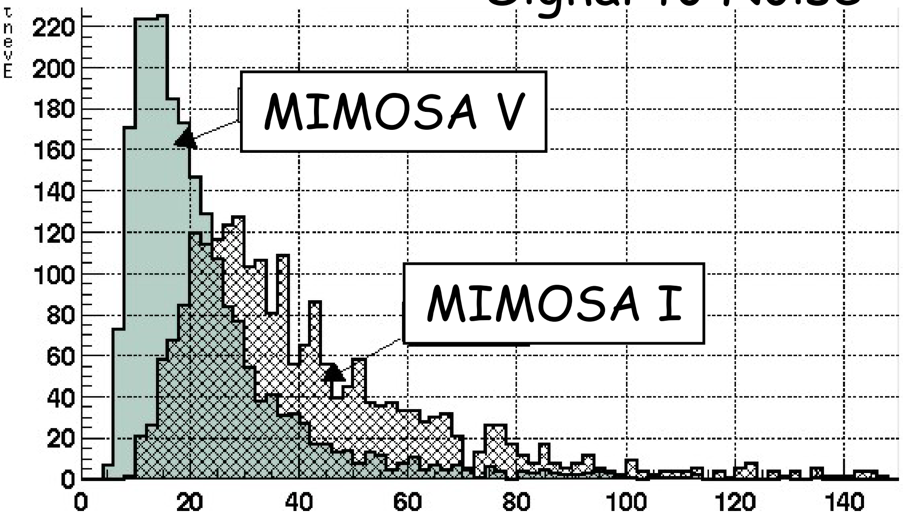
Same unique substrate for detector and electronics

- No connections (e.g. bumps)
- Radiation hardness (no bulk charge transfer)
- Advantages of CMOS process: Easy Design/good yield/low power/Rad hard
- Very small pixel sizes achieveable

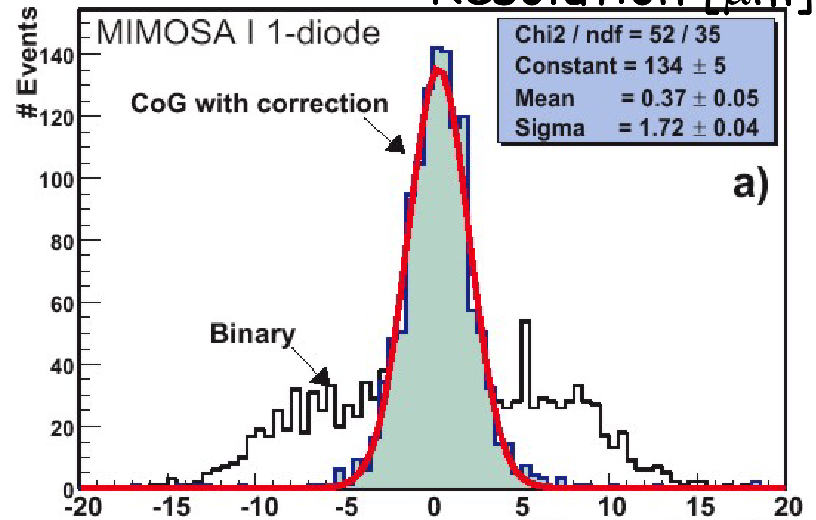
Mimosa	I	II	III	IV	V	VI
Process	0.6 µm	0.35 µm	0.25 µm	0.35 µm	0.6 µm	0.35 µm
Epi layer	14 µm	4.2 µm	2.3 µm	0 (!!!)	14 µm	4.2 µm
# pixels	64x64x4	64x64x6	128x128x2	64x64x4	1,000,000x7	24x128x..

MAPS Beam Test Results

Signal to Noise



Resolution [μm]



	MIMOSA I	MIMOSA II	MIMOSA V
Resolution	1.4 μm	2.2 μm	1.7 μm
Efficiency at S/N > 5	99.5 %	98.5 %	99.3%

Irradiation of MIMOSA I & II up to 10^{13} 1 MeV/c neutrons

Gain ⇨ constant

Noise ⇨ constant

Leakage current ⇨ moderate rise

collected charge ⇨ 50-70% of initial value

(smooth decrease after 10^{12} or few x 10^{11})

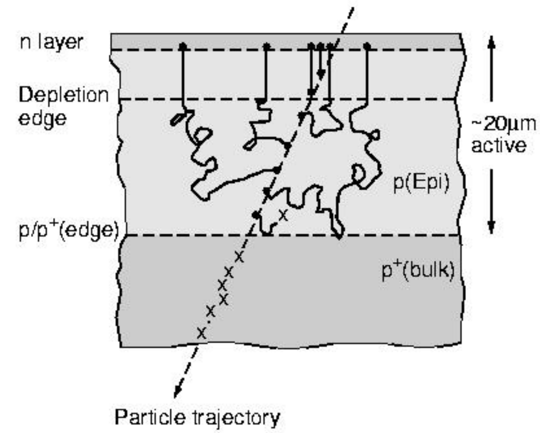
NIMA 478 (2002) 311-315

Charged Coupled Devices - CCDs

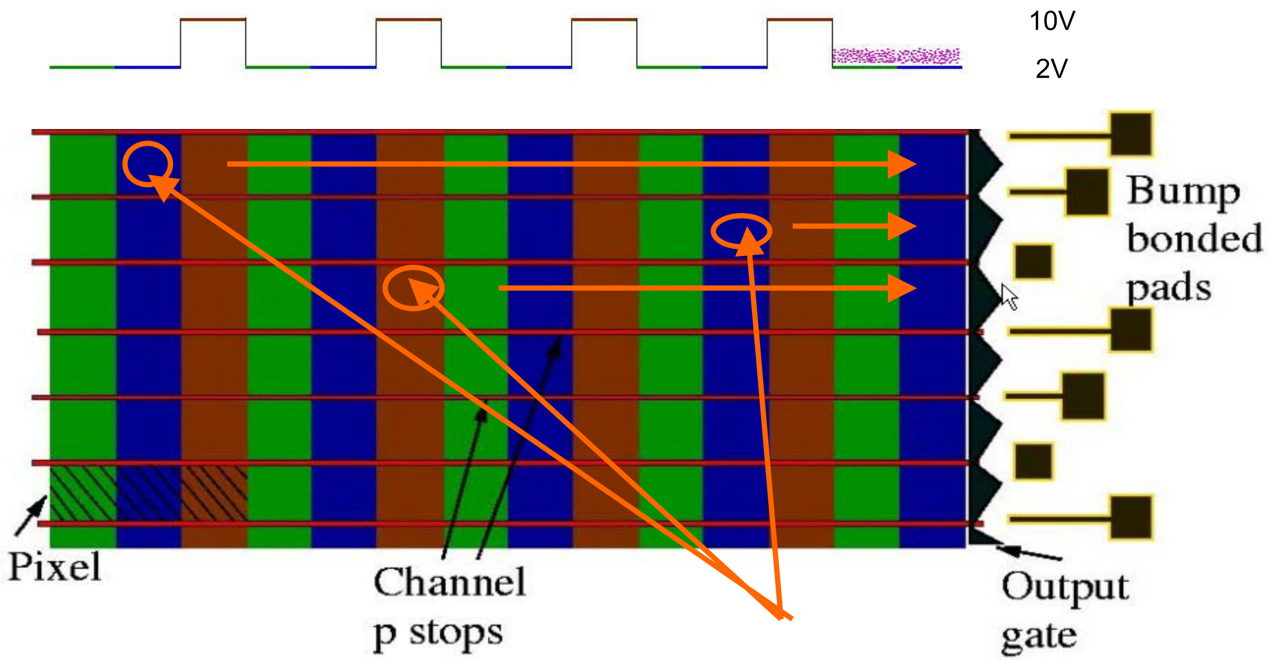
CCDs invented in 1970 – widely used in cameras, telescopes etc.

Tracking applications for HEP:

1980-1985	NA32	120 kpixels
1992-1995	SLD	120 Mpixels
1996-1998	SLD upgrade	307 Mpixels
	TESLA	799 Mpixels



~1000 signal electrons are collected by a combination of drift and diffusion over a ~20μm region just below surface



• Small pixel size – 20 x 20 μm

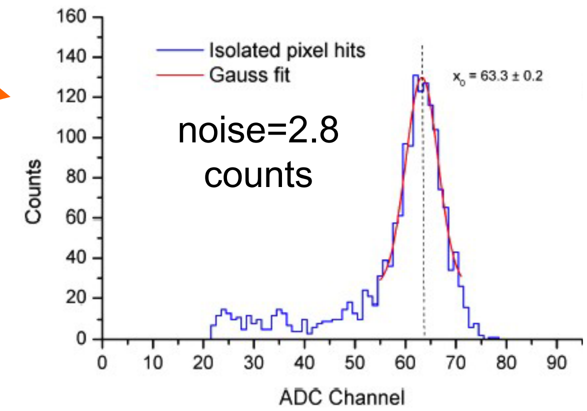
• Possibility of very thin detectors

•Column parallel readout: serial register -> direct bump bonding to chip

CCD R&D for LC requirements

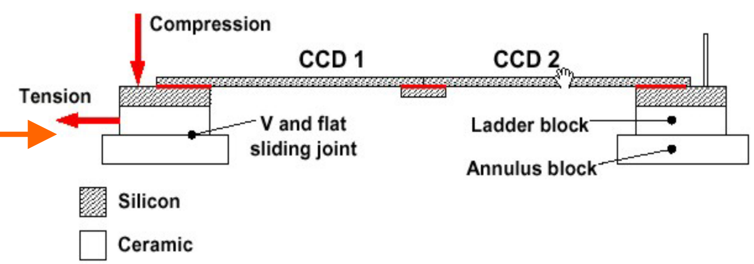
- Speed up readout
  - 5 MHz readout -> 50 MHz
  - Reduce clock amplitudes 10V->3V
  - Build with high resistivity epitaxial material

CCD ^{55}Fe spectrum: 50MHz 3V clocks



- Study radiation resistance to LC doses of 100Krad ionising radiation + 5 x 10^9 neutrons
  - Temperature dependence

- Minimise material in fiducial volume
  - Highly thinned silicon glued to substrate
  - Unsupported "stretched silicon" option



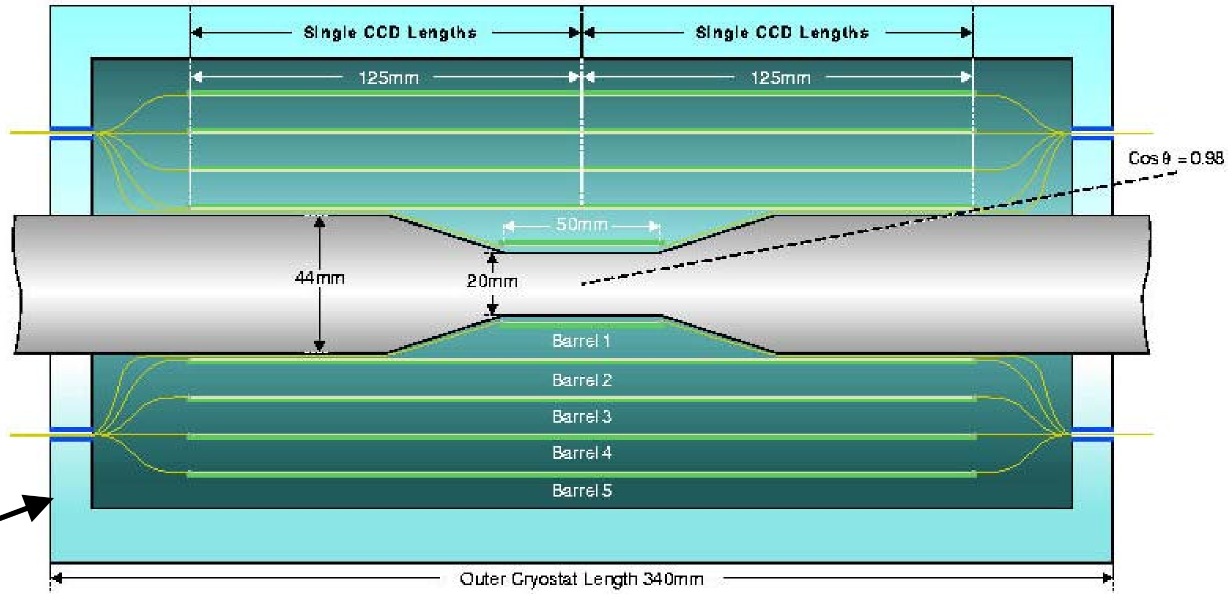
Layer	Radius (mm)	CCD lxw (mm x mm)	CCD Size (Mpix)	Clock / readout time	Background (Hits/mm^2)	Integrated background (kHits/train)
1	15	100 x 13	3.3	50 MHz/50 ms	4.3	761
5	60	125 x 22	6.9	25 MHz/250 ms	0.1	28

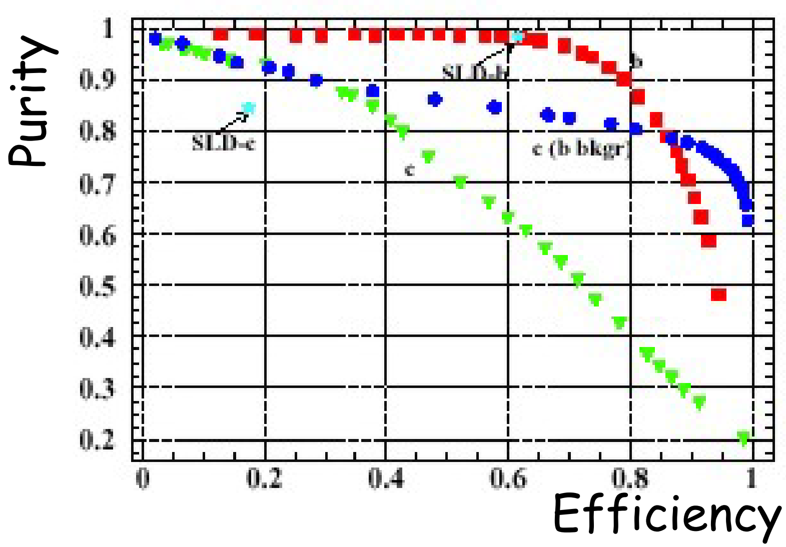
lcfi proposal: April 2002

Integration into LC design

- Baseline design
  - ➢ 5 layers
  - ➢ R_min=15 mm
  - ➢ 3 layer coverage to |cos θ|=0.96
  - ➢ 5 layer coverage to |cos θ|=0.9

Cryostat for CCD option





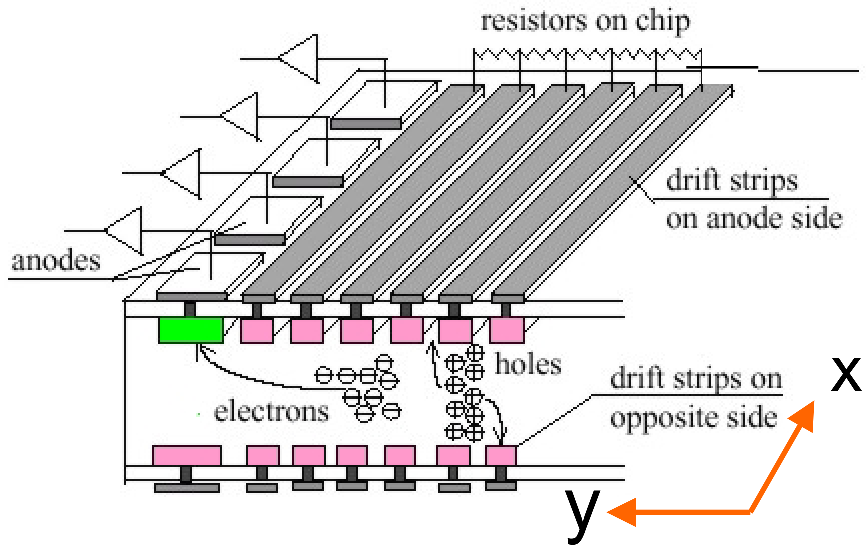
flavour tagging performance at √s=91 GeV

- ➢ b jets roughly equal SLD performance
- ➢ c jets improved by factor 2-3 in efficiency

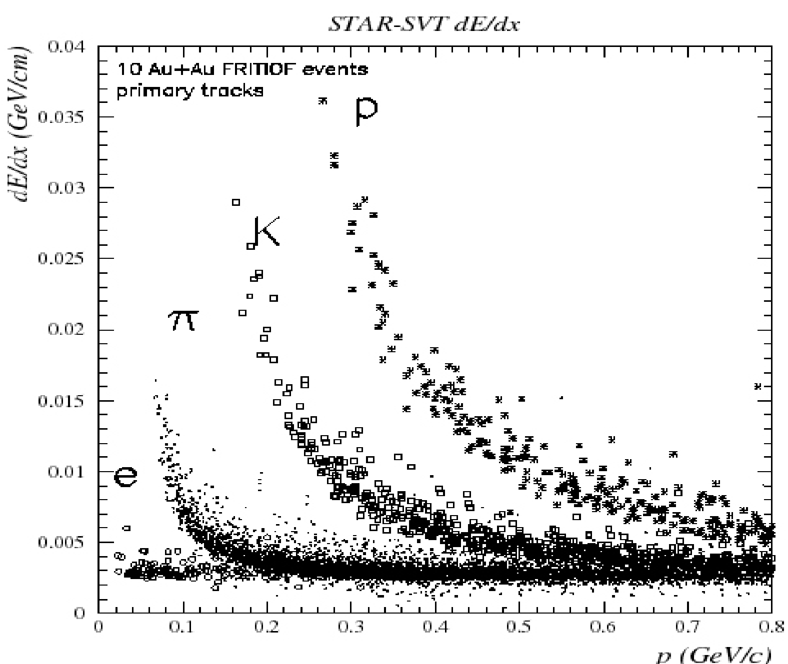
Silicon for tracking: Silicon Drift Detectors

- Principle of sideways depletion – as for DEPFET sensors
- p^+ segmentation on both sides of silicon
- Complete depletion of wafer from segmented n^+ anodes on one side

!! Drift velocity must be predictable
  - → Temperature control
  - → resistivity control
  - → Calibration techniques

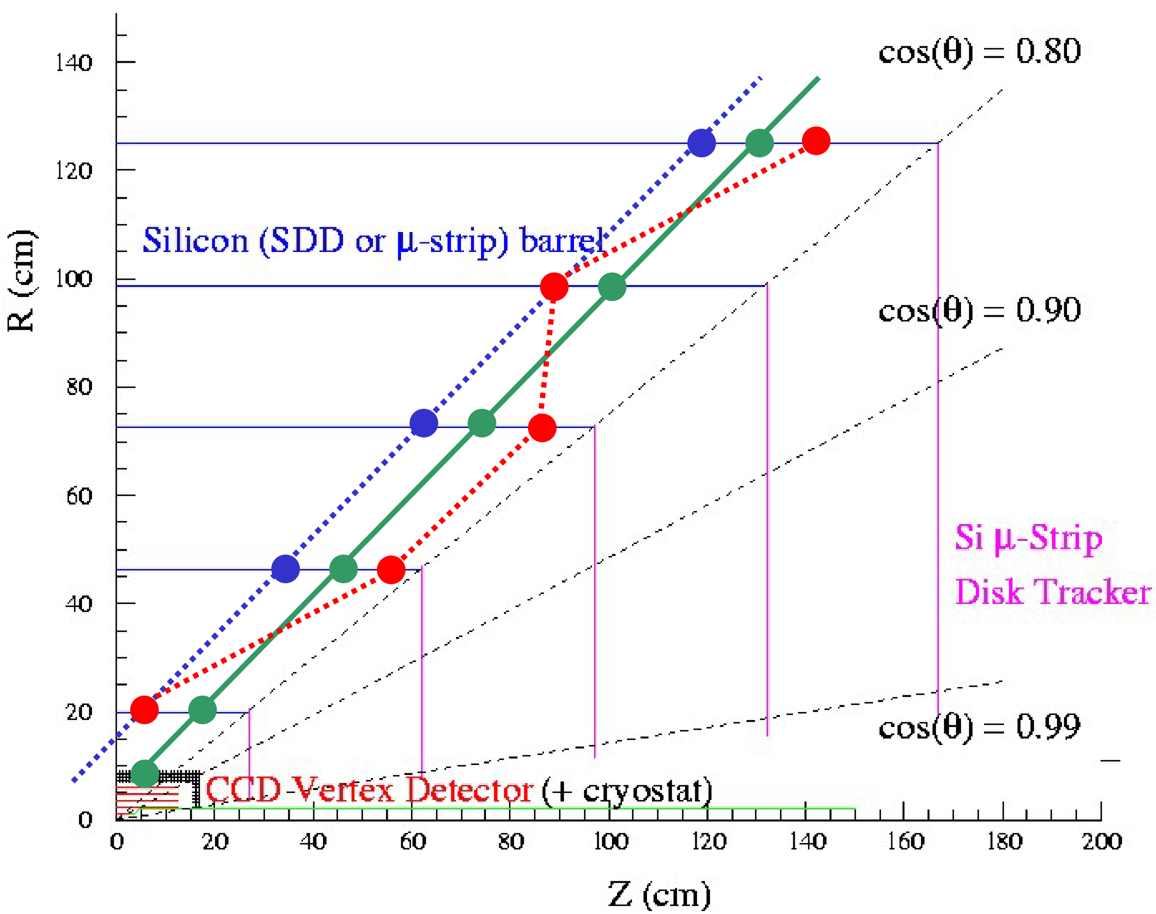


- SDD fully functioning in STAR SVT since 2001
- 216 wafers, 0.7 m^2
- 10 mm in anode direction
- 20 mm in drift direction
- Particle ID



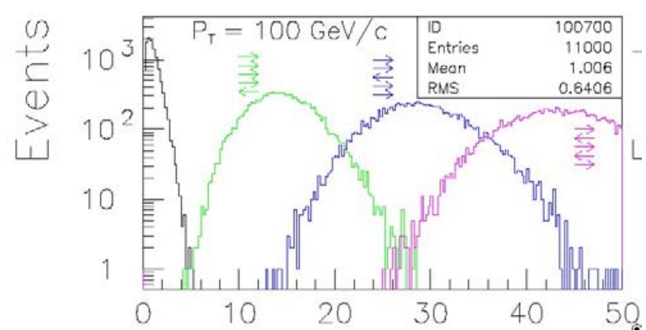
Silicon for tracking: Drift detectors

- SDD are a mature technology – attractive for LC

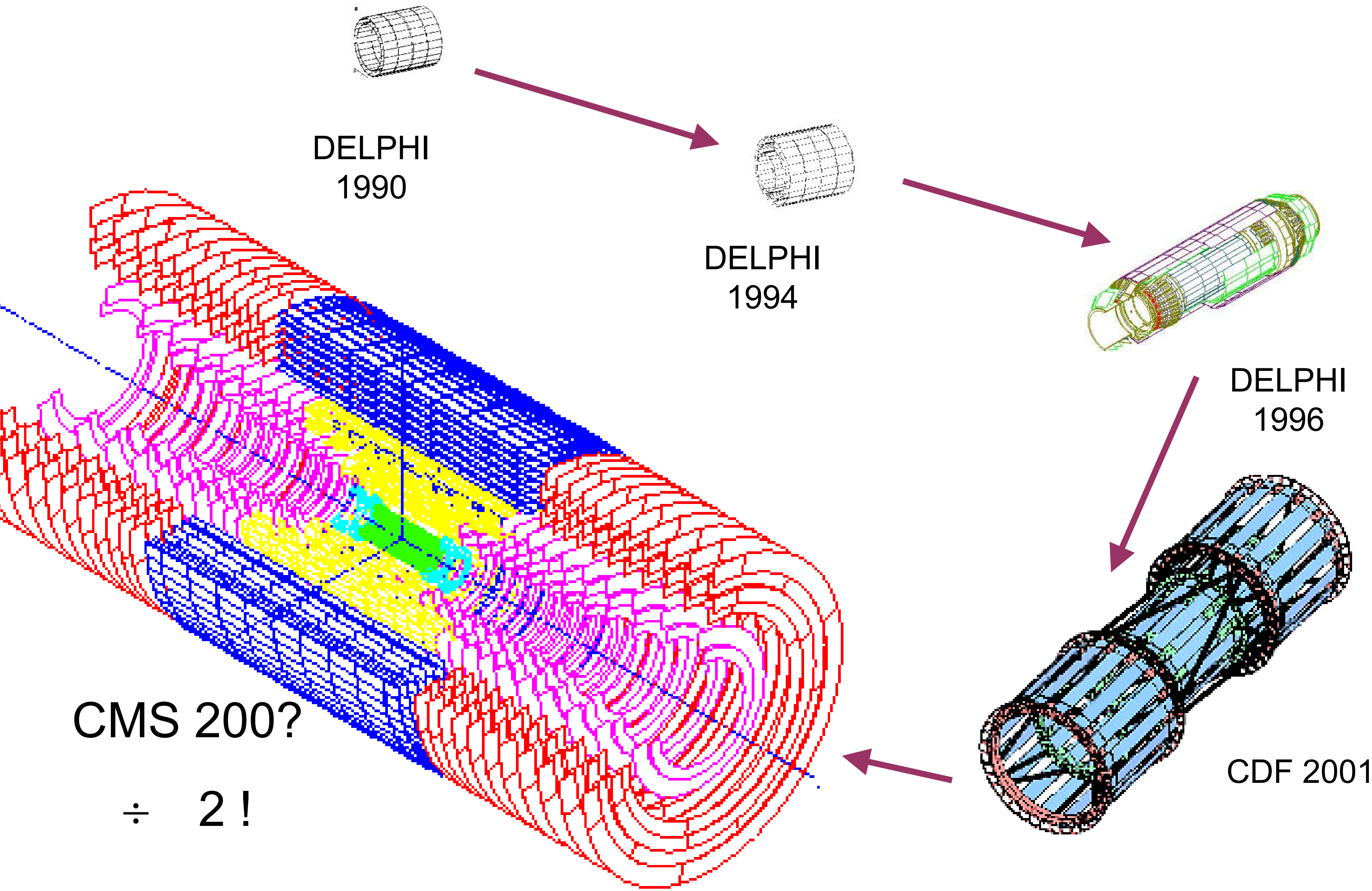


- 5 precise silicon layers to replace TPC
- 56 m^2 silicon
- R&D needed:
  - Improve resolution to 5 μm
  - Improve radiation length
  - Improve rad hardness
- Track stamping possible at nanosecond level

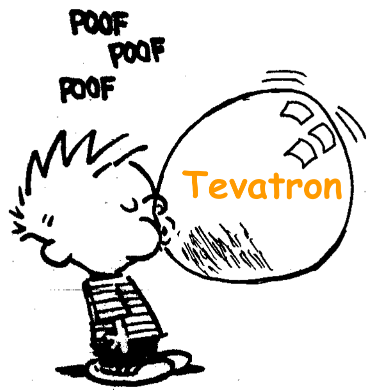
χ^2 separation for out-of-time tracks for different drift direction configurations

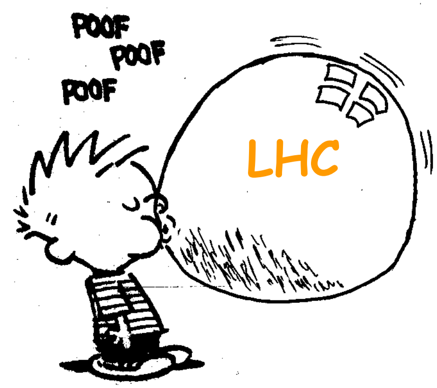


Silicon for tracking: Large Systems



Silicon for tracking: Large Systems

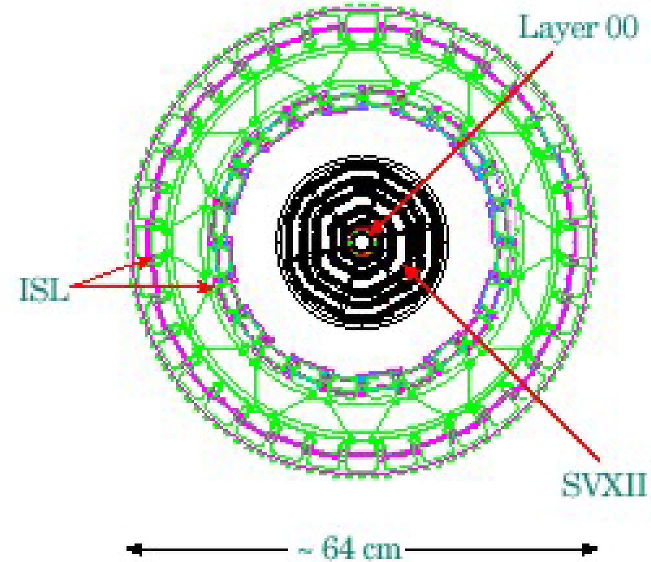




Whoops…

CDF & D0 are demonstrating the possible

CDF	Layer 00	SVX II	ISL	Totals
Layers	1	5	2	8
Length	0.9 m	0.9 m	1.9 m	
Channels	13824	405504	303104	722432
Modules	48 SS	360 DS	296 DS	704
Readout Length	14.8 cm	14.5 cm	21.5 cm	
Inner Radius	1.35 cm	2.5 cm	20 cm	1.35 cm
Outer Radius	1.65 cm	10.6 cm	28 cm	28 cm
Power	~100 W	1.4 kW	1.0 kW	2.5 kW



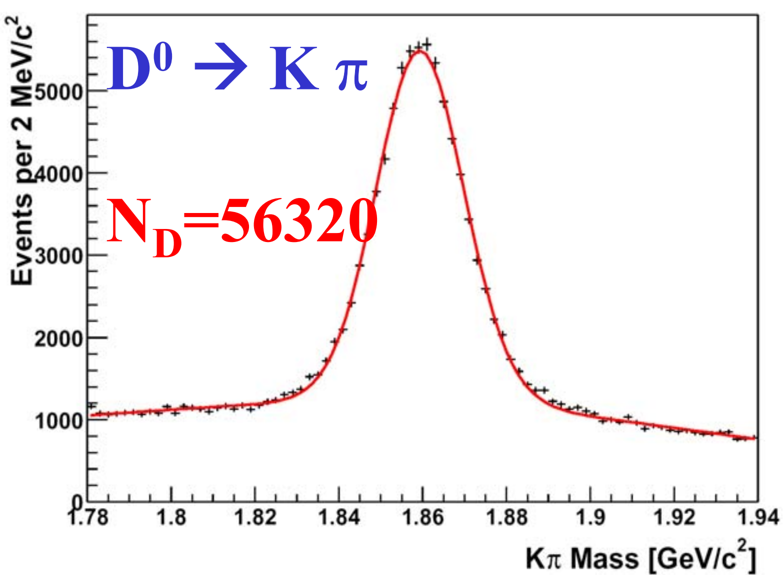
A huge system is up and running:

19 micron resolution (before alignment)

S/N as expected

Silicon participating in trigger

Silicon is used for physics!



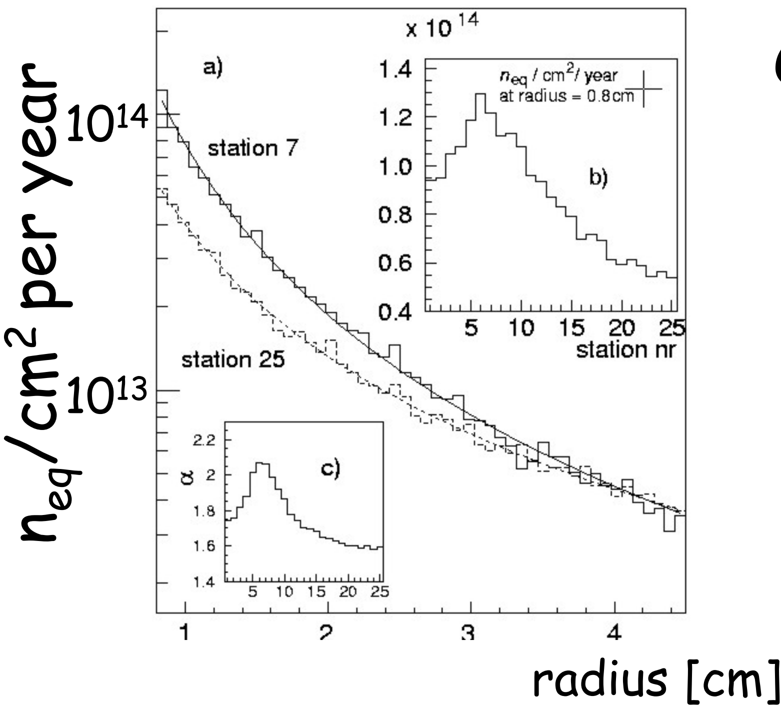
Irradiation

The LHC environment will be FIERCE

LHC upgrade/VLHC will be WORSE!

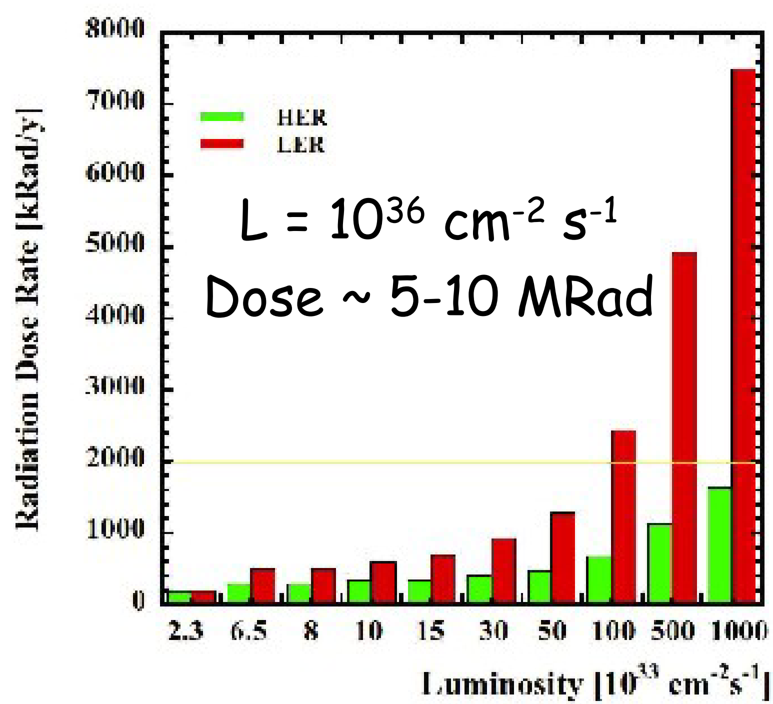
- $L = 10^{34}$ cm^{-2} s^{-1}
- 8×10^8 pp collisions / s
- Hadron fluences to 10^{15} cm^{-2}

LHCb vertex detector



Other collider upgrades are hot too

e.g. Super Belle/Babar



Improved semiconductor designs/materials are well worth considering

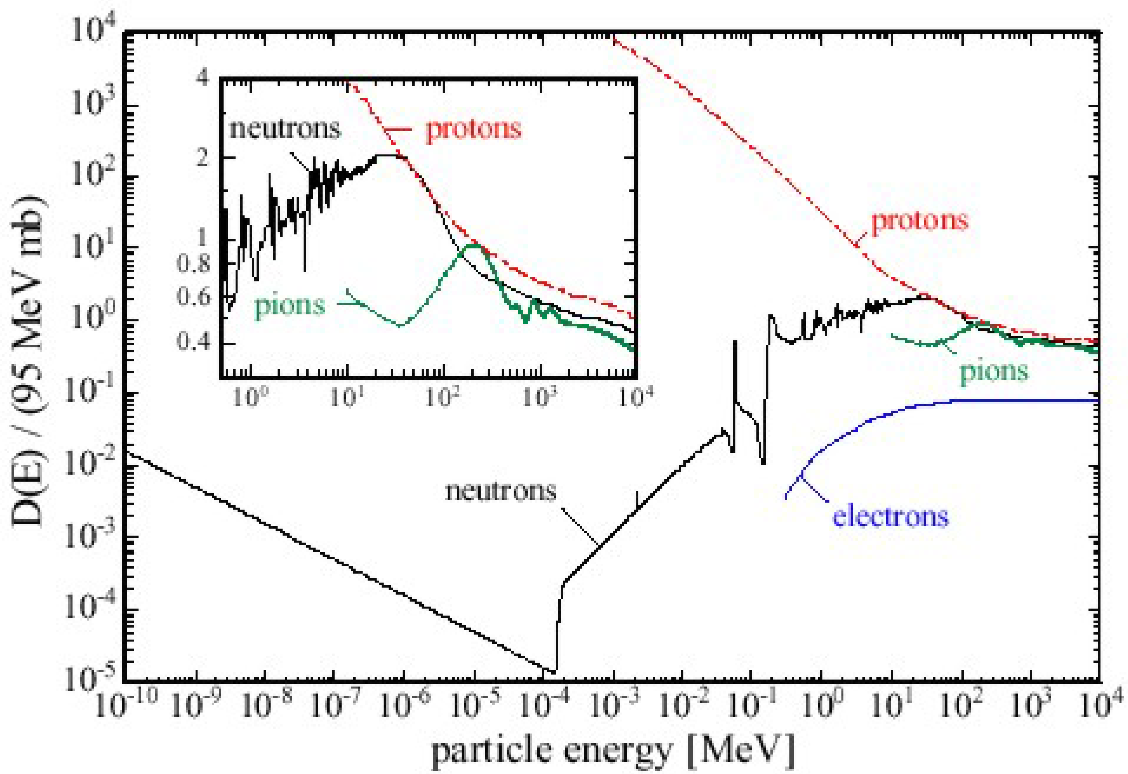
Irradiation

A common language:

"1 MeV neutron equivalent"

Use the NIEL scaling factors

Displacement damage functions



NIEL allows us to look into the future and predict what will happen in complex environments

(!) Has been known to fail for neutrons/charged hadrons in some cases

Irradiation

Bulk Damage Effects in Silicon

Increased Leakage Current

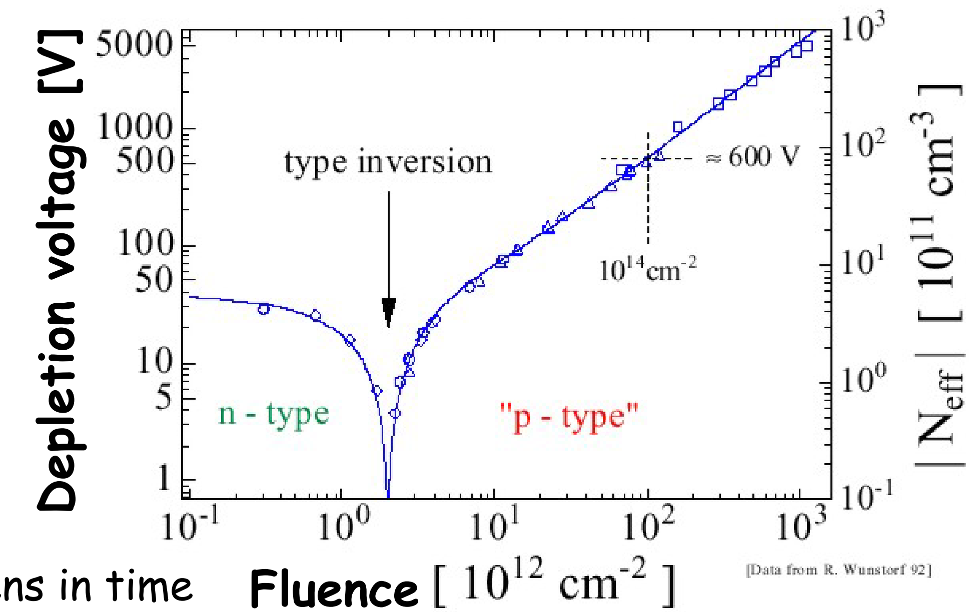
- Noise
- Hard to bias

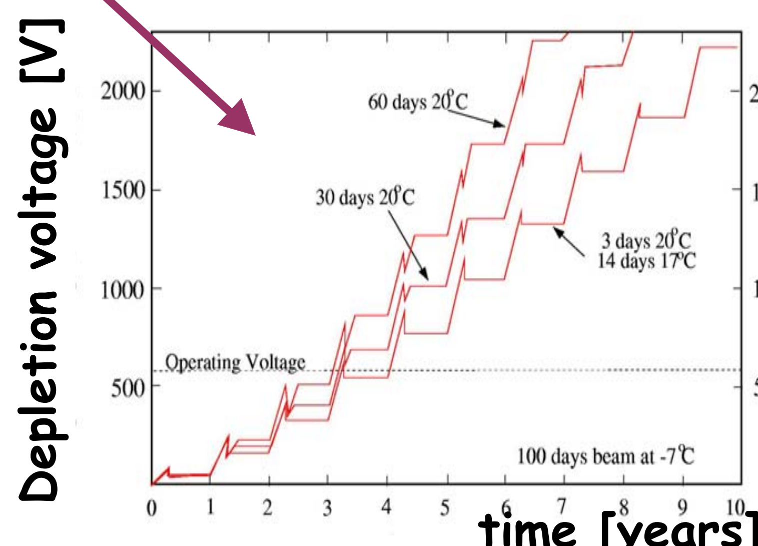
Effective Doping Changes

- Depletion grows from n^+ side

Annealing effects

- Buildup of negative space charge worsens in time
- Strongly temperature dependent



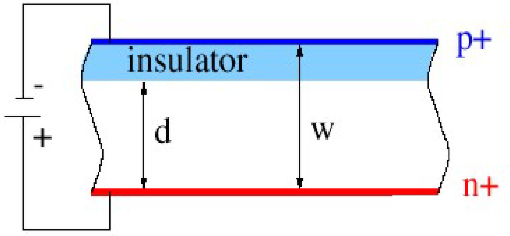


- R&D focusing on:
  - Defect engineering
  - New detector materials
  - Cryo/forward operation
  - 3d and thin devices

will cover these points

Irradiation: strips for LHCb

Irradiated detectors



•Reminder from Ramo (1939)

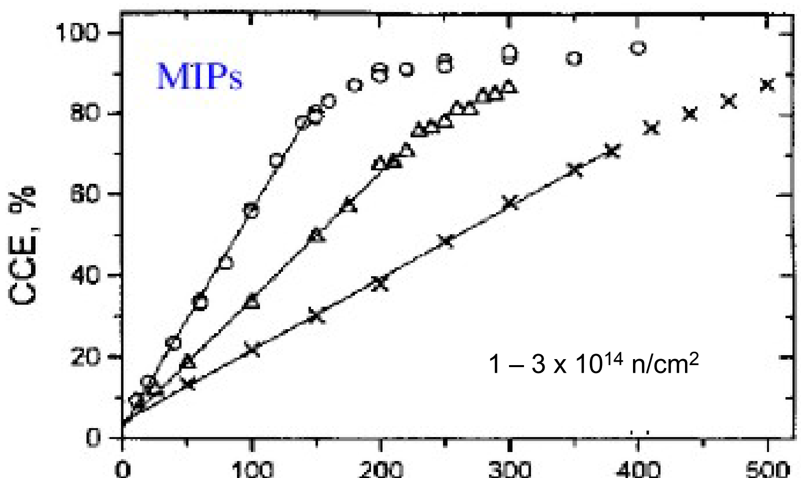
$$Q = e * d/w \propto \quad V_{bias}$$

Underdepletion has two bad consequences

Charge loss

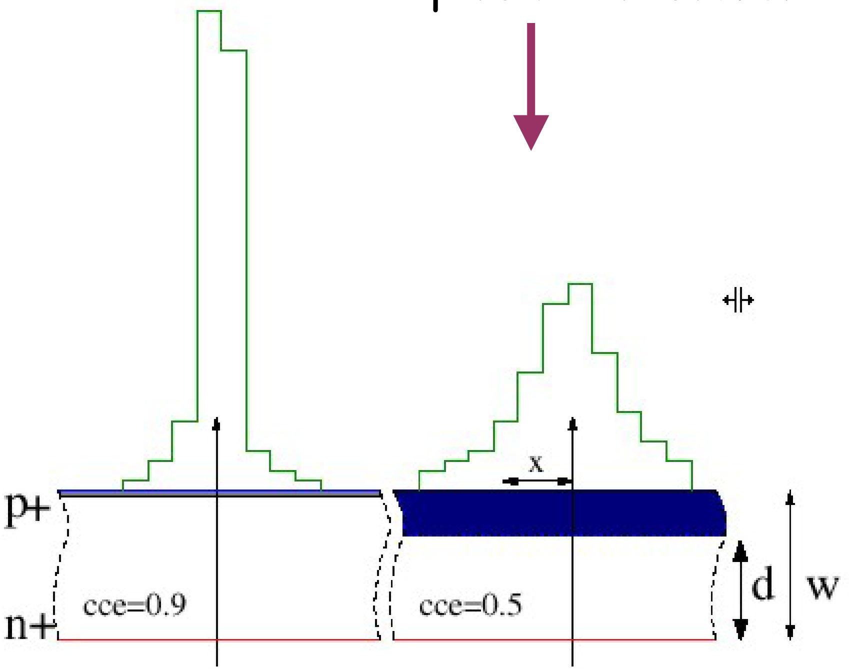
Charge spread:

A killer for fine pitch detectors!



V_{bias}

NIM A 412 (1998) 238



Similar story for trapping…

Mr. Ramo

I co-invented the electron microscope

I pioneered microwave technology

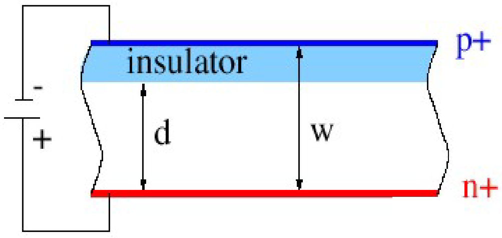
I founded TRW

I had a theorem

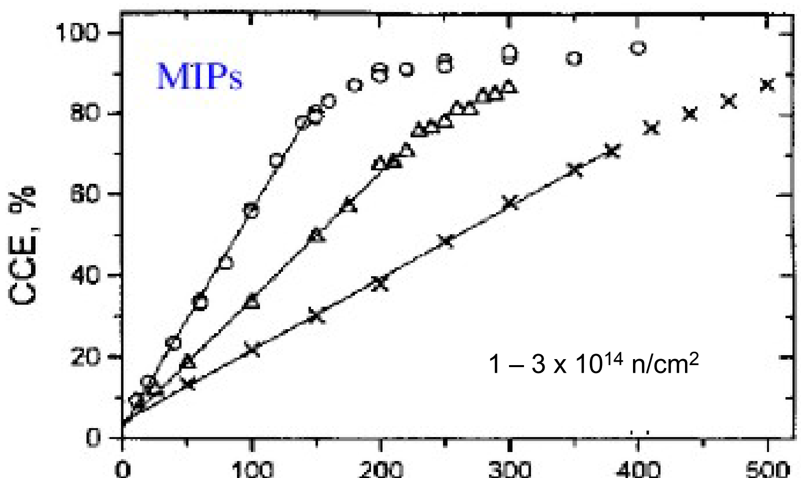
Irradiation: strips for LHCb

- Reminder from Ramo (1939)

Irradiated detectors



$Q = e * d/w \propto \quad V_{bias}$



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NIM A 412 (1998) 238

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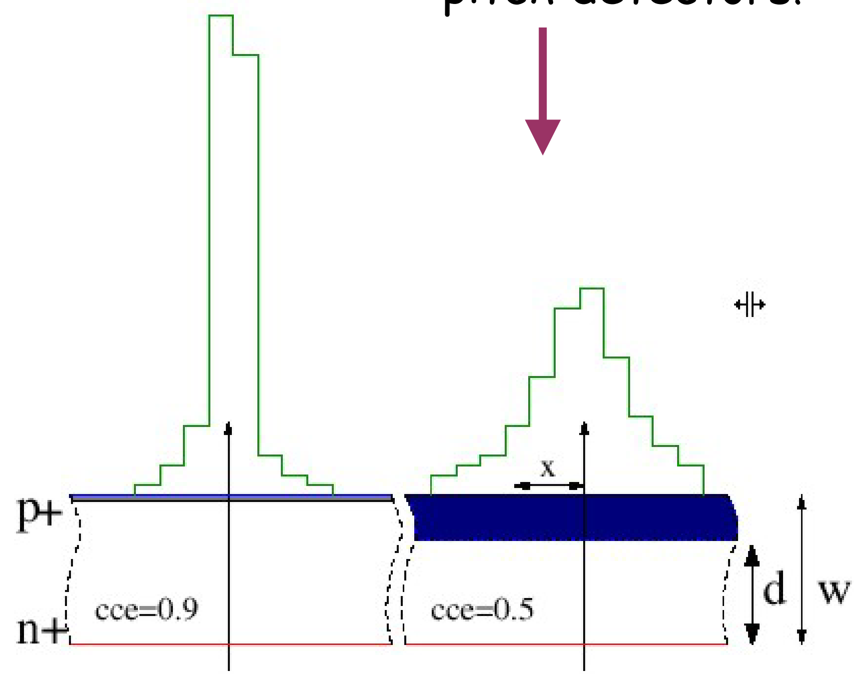
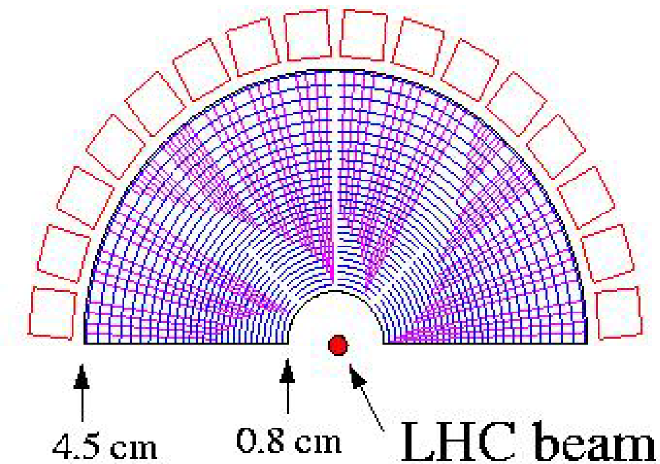


Similar story for trapping…

Irradiation: strips for LHCb

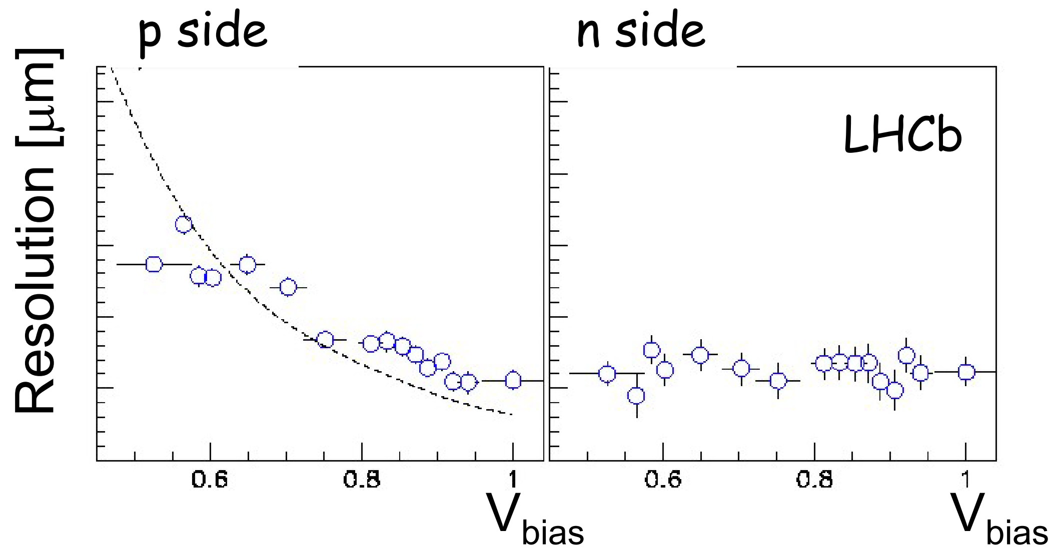
Charge spread causes problems on the p side only

Up to ~10^{14} underdepletion is still more important than trapping

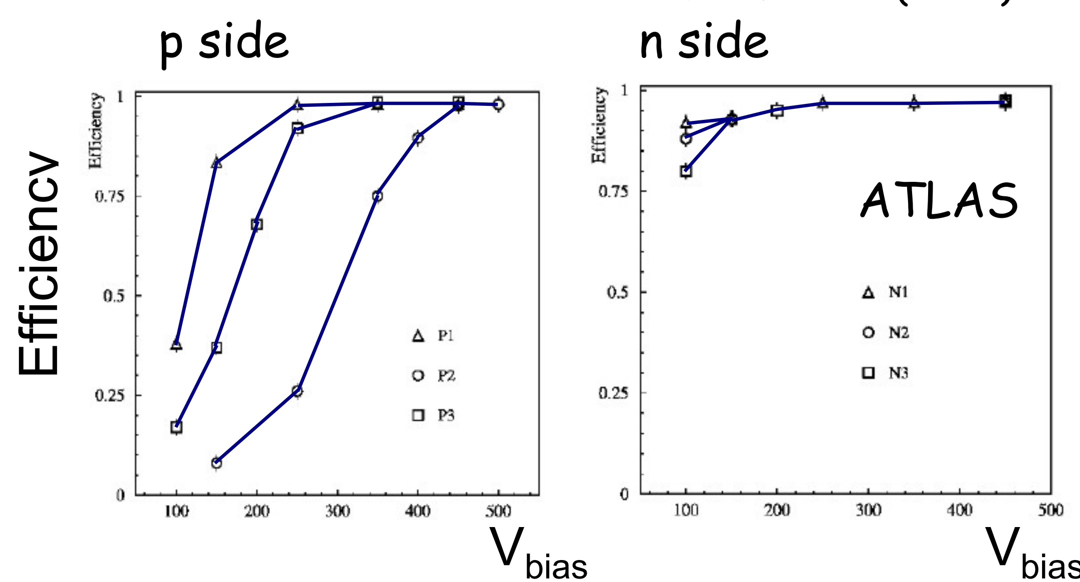


For LHCb

n-on-n detectors are the technology choice



NIM A 440 (2000) 17

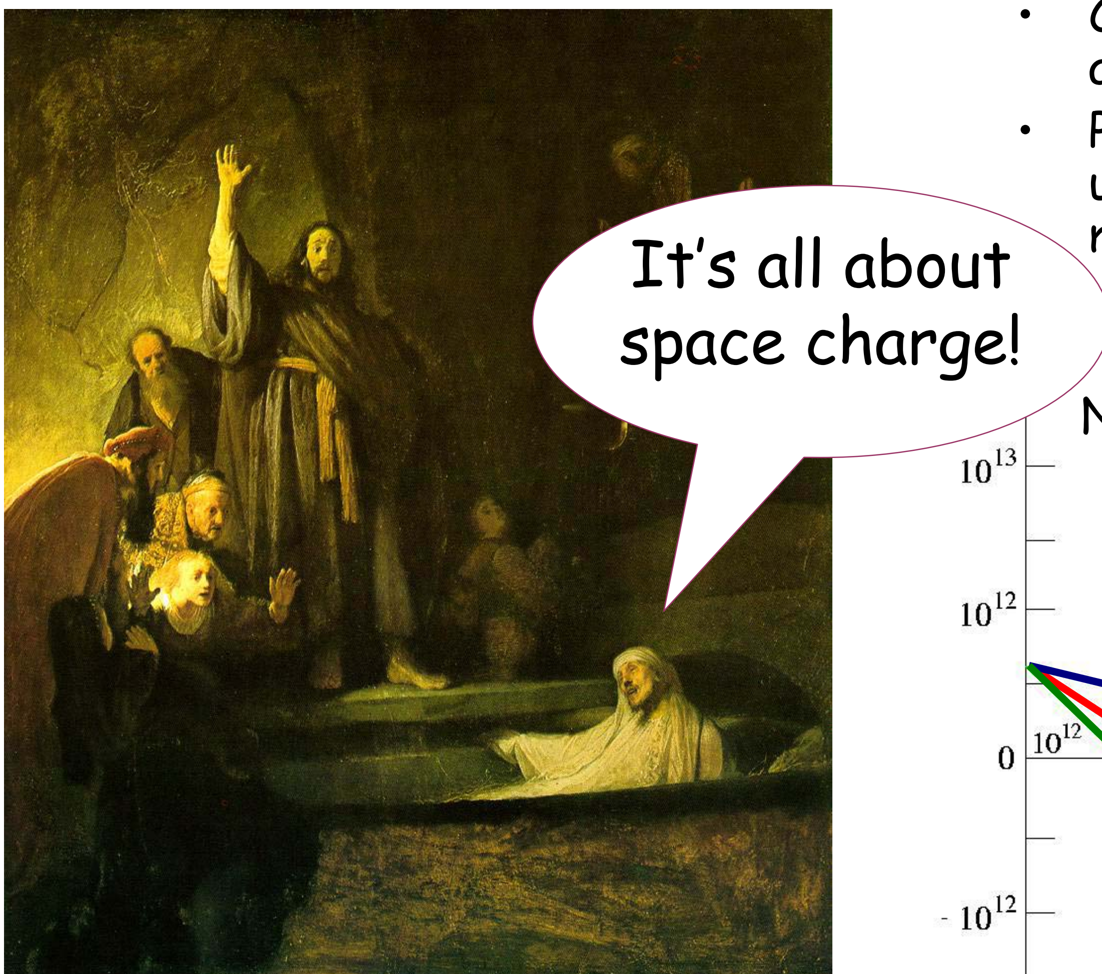


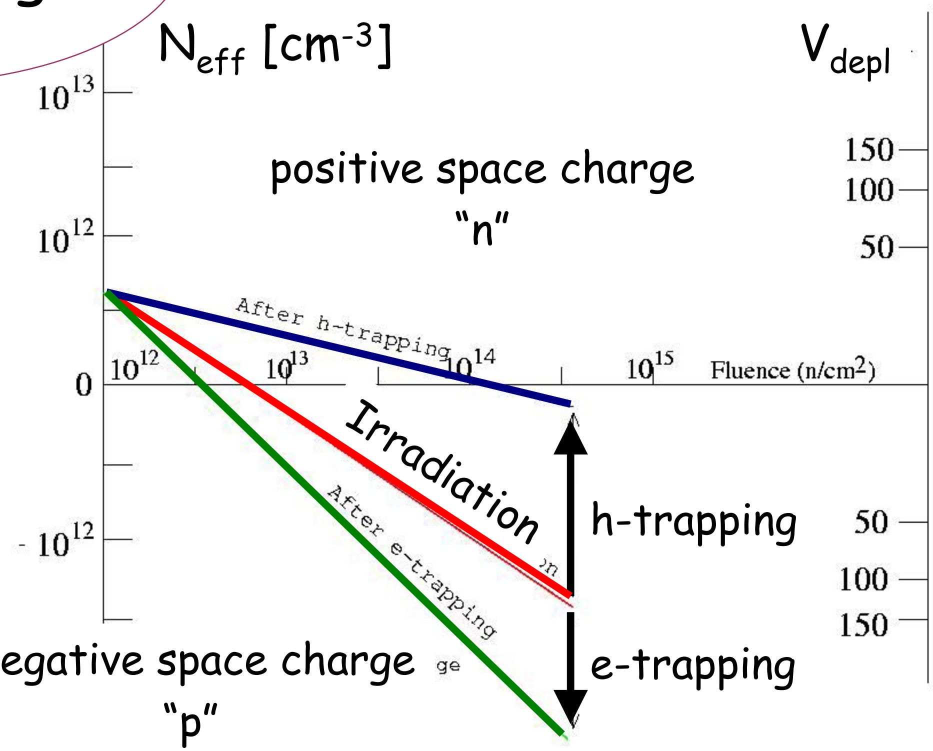
NIM A 450 (2000) 297

Irradiation: the Lazarus effect

COLD is COOL – as Rembrandt knew

- Cool detectors have little leakage current
- Cool detectors don't reverse anneal
- Possible to control doping – hence underdepleted detectors magically become depleted



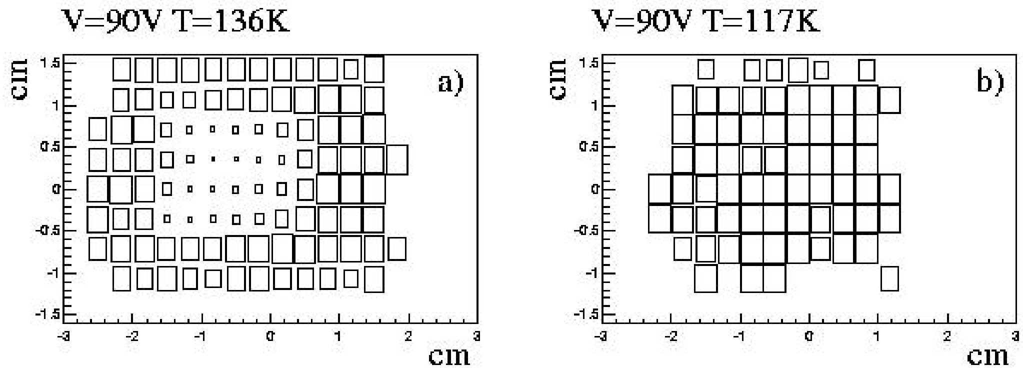


$V_{depl} \propto |$ space charge (N_{eff}) $|$

Irradiation: the Lazarus efect

Resurrection of a microstrip detector

Efficiency
HOT



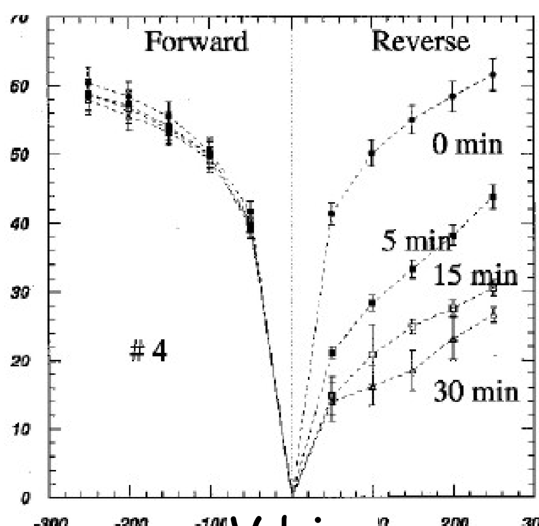
Efficiency
COLD

NIM A 440 (2000) 17

Recovery is temporary – but this can be solved

Forward bias Reverse bias

charge collection

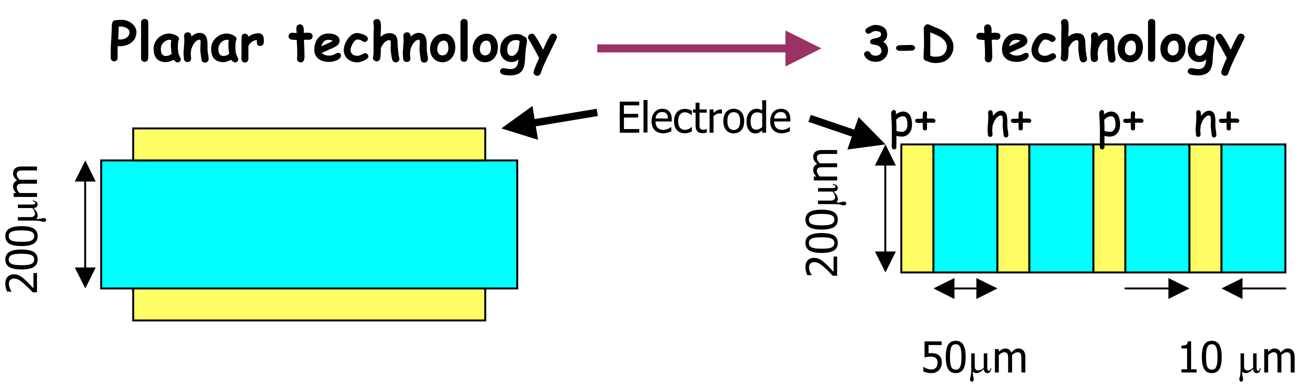


V bias

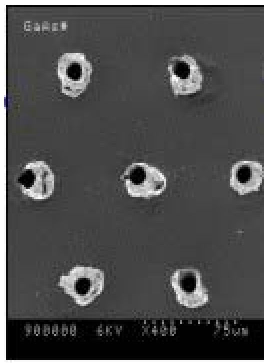
0 min
5 min
15 min
30 min

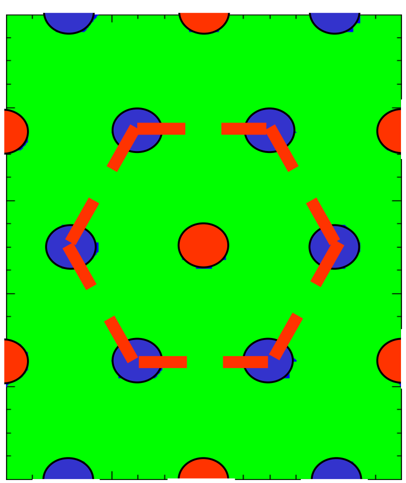
NIM A 440 (2000) 5

Irradiation: 3d detectors



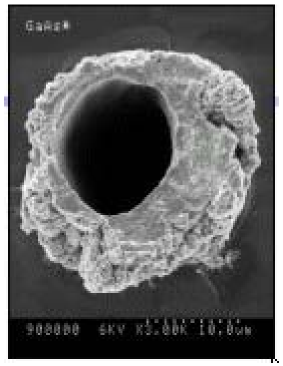
Proposed by Parker, Kenney 1995





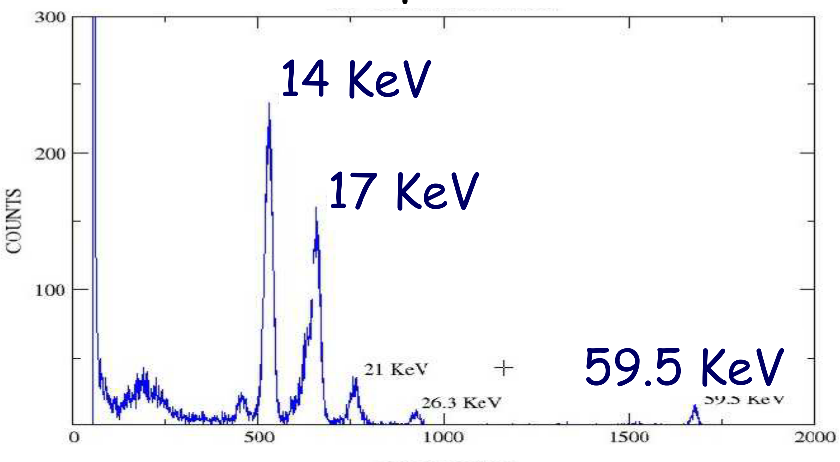
Unit cell defined by e.g. hexagonal array of electrodes

- Maximum drift and depletion distance governed by electrode spacing
  - Lower depletion voltages
  - Radiation hardness
  - Fast response
  - At the price of more complex processing
  - Narrow dead regions on edges



3d detectors: characteristics

Am^{241} spectrum



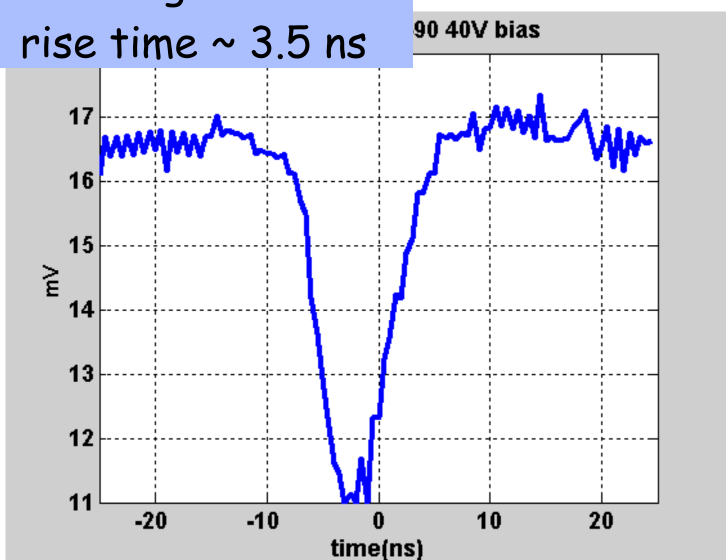
- Low leakage currents
- Low depletion voltages
- Gaussian X ray lines
- fast charge collection

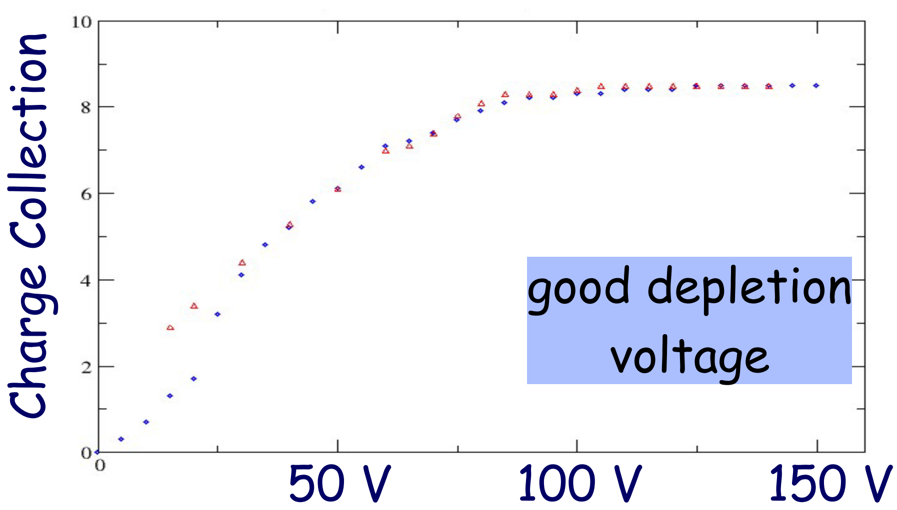
Performance after irradiation

~10^{15} p/cm^2

Fast charge collection

rise time ~ 3.5 ns

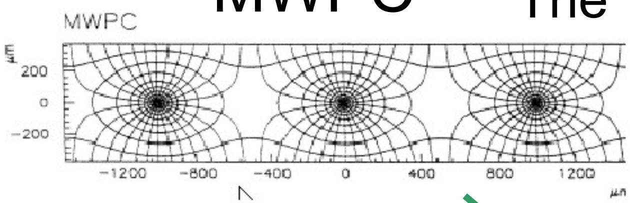




MPGDs: Micro-Pattern Gas Detectors

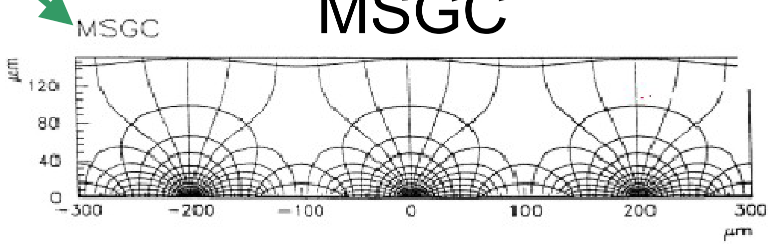
MWPC

The “daddy” of proportional counters



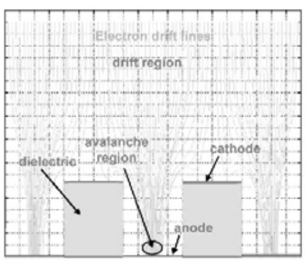
Photolithographic techniques

MSGC



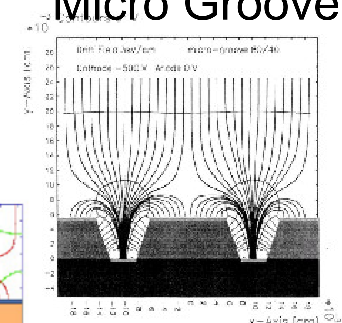
- Spatial resolution
- Rate capability

Micro WELL

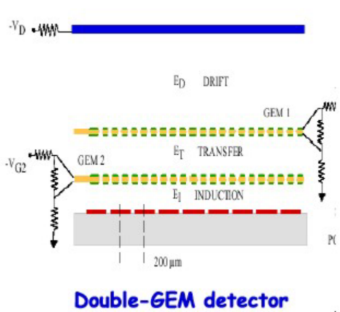


advanced PCB technology

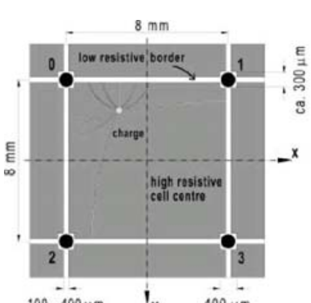
Micro Groove



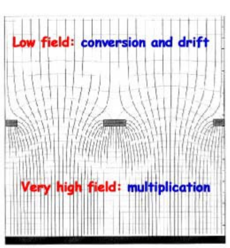
Hybrid devices



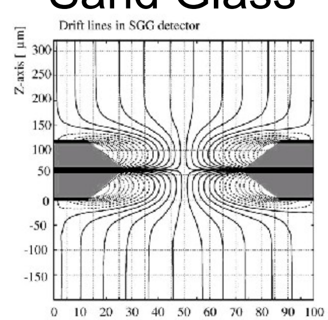
MicroCAT



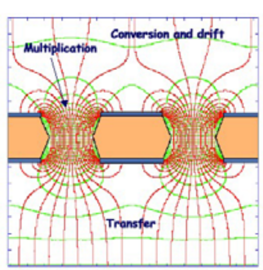
MicroMega



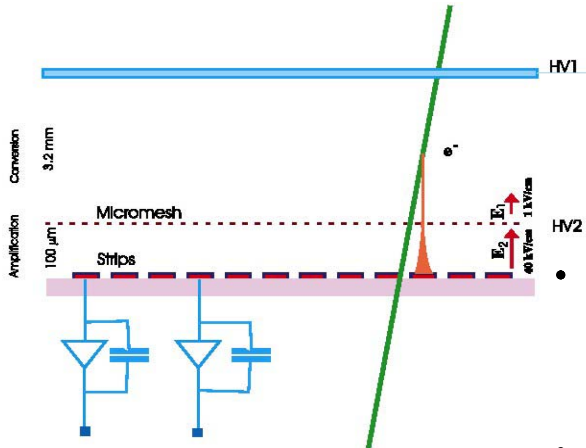
Sand Glass



GEM

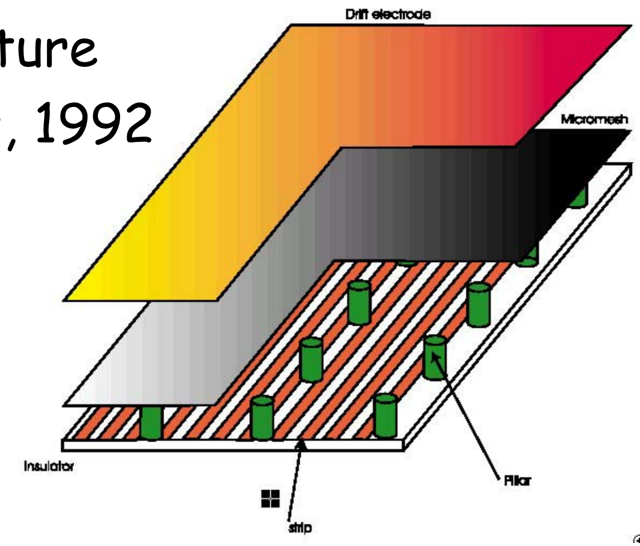


MPGDs: MicroMegas

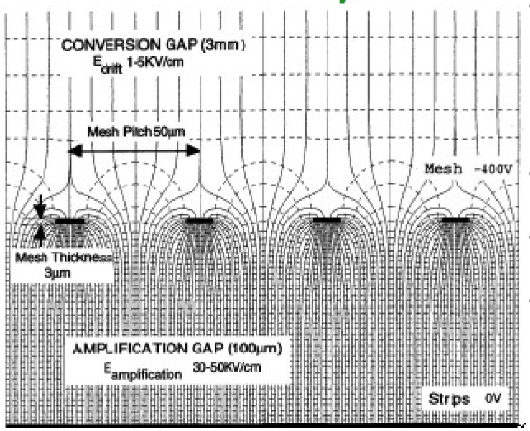


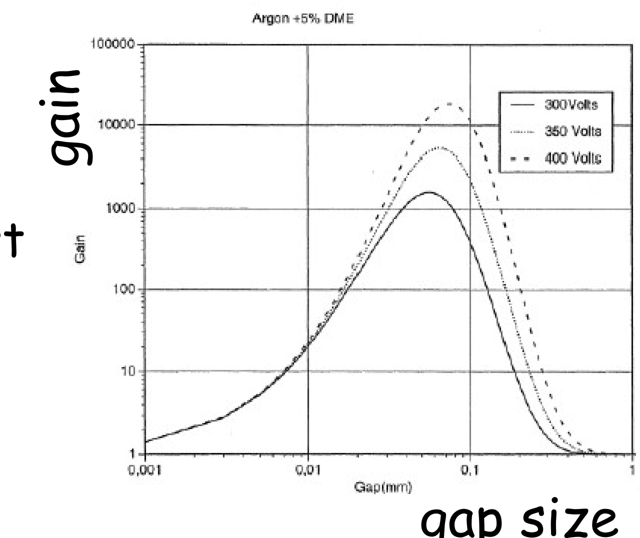
Micromesh gaseous structure

G. Charpak, Y. Giomatraris, 1992

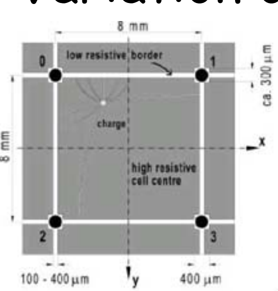


- Thin gap || plate structure
  - Good energy resolution
  - High rate capability
- Conversion space separated from amplification gap by micromesh
- Ion feedback suppressed
- ΔU~500V -> 50 kV/cm
- Saturation of Townsend coefficient ⇨ stable against gap variations





Variation on a theme: MicroCompteurATrous

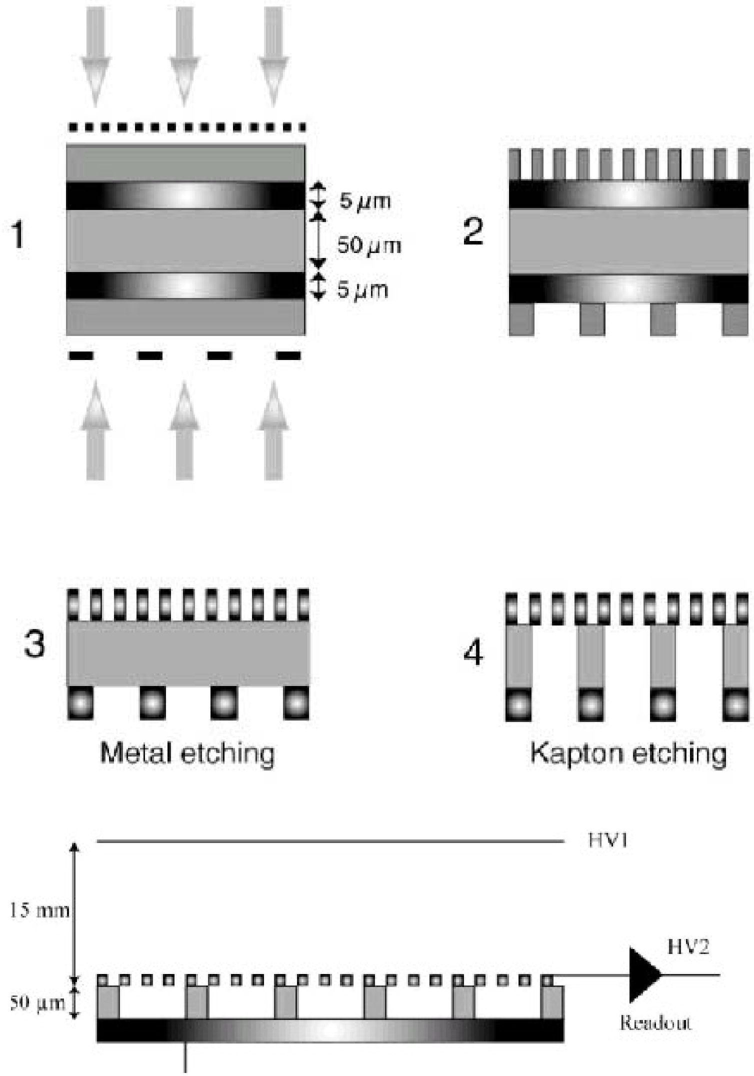


Two dimensional interpolating readout

Structure

Large active area with new spacer concept (e.g. Wagner, 2002)

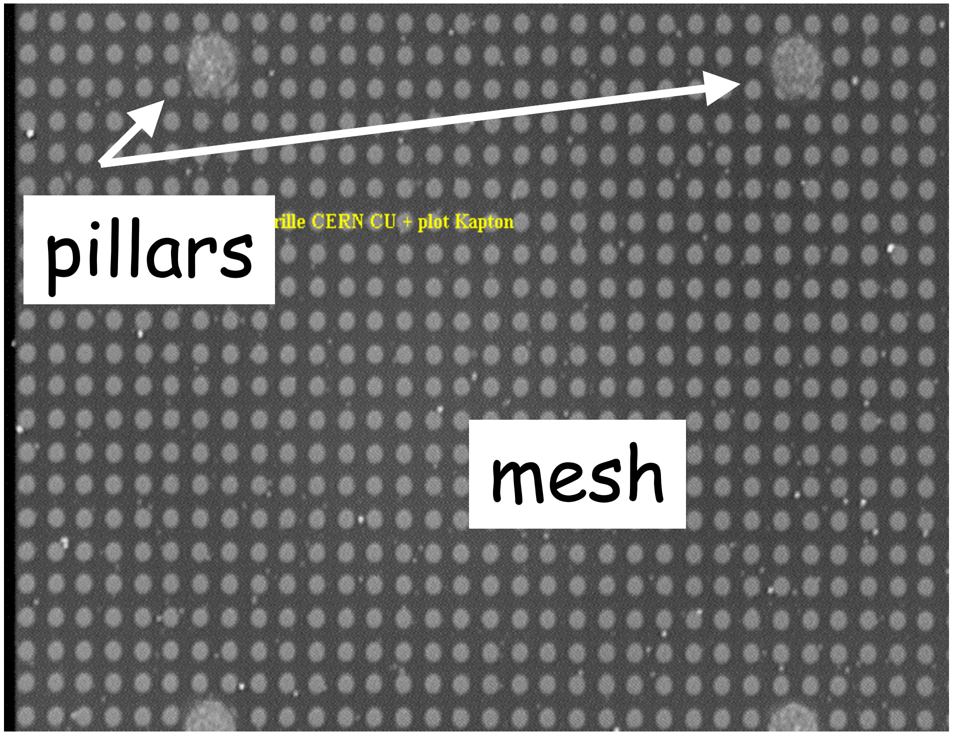
Micromegas



•NIMA 461 (2001) 84

New fabrication technique

•Integrate manufacture of mesh and spacers

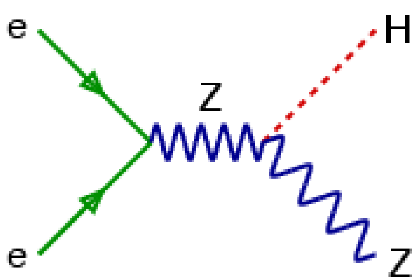


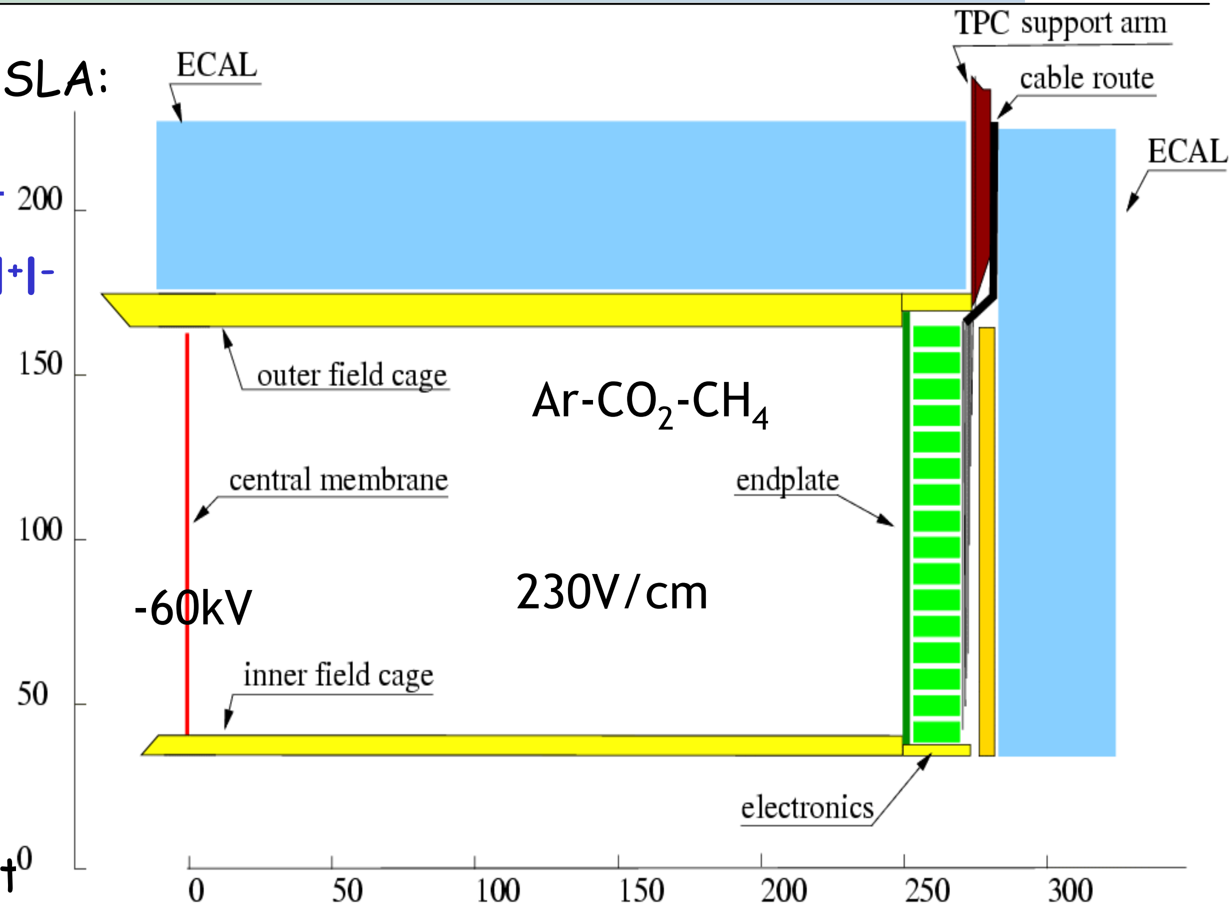
MPGD's for TESLA TPC

Tracking requirements for TESLA:

$\delta(1/p_T) < 5\times10^{-5}$ GeV^{-1}

Precision on M_H from $Z \Rightarrow l^+l^-$





TPC design

- 200 3d points per track wit $\sigma_{r\phi}$~150 μm
- d $(1/p_T) = 1.4\times10^{-4}$ GeV^{-1} (barrel)
- Drift time 50 μs ⇨150 bx
- 20 MHz readout

R&D focus:

new gas amplification system

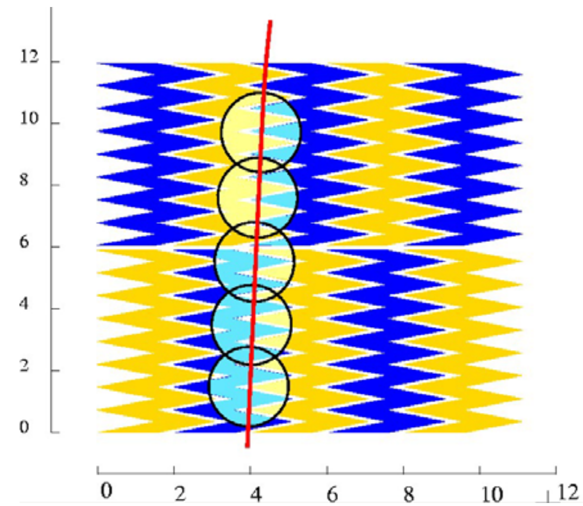
MGPD readout (GEM/Micromega)

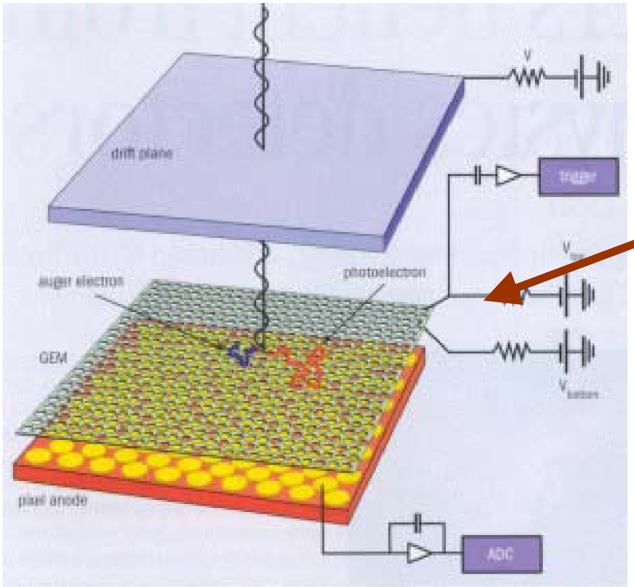
MPGD's for TESLA TPC

new gas amplification system

MGPD readout (GEM/Micromega)

- Ion feedback suppressed to 2% level
- Good dE/dx
- E x B effect reduced to 50 μm
- Gating @ 2cm possible between trains
- Chevron pads compensate low induction signals





Another option: use silicon pixel readout a la "x ray polarimeter"

- Each GEM hole has its own pixel(s)
- GEM gain 1000-3000 + pixel noise (200 e)
  = single electron detection
- 1.7 Gpixels

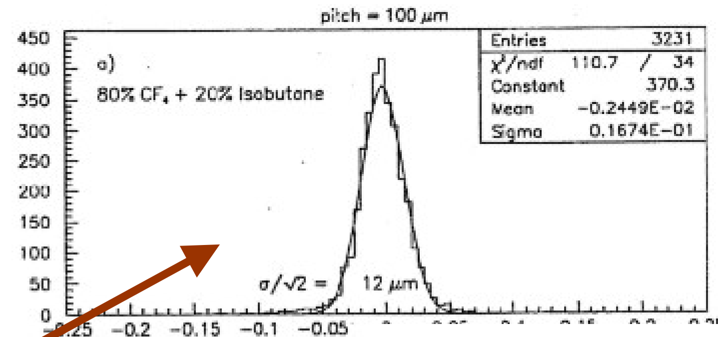
A digital TPC limited only by diffusion

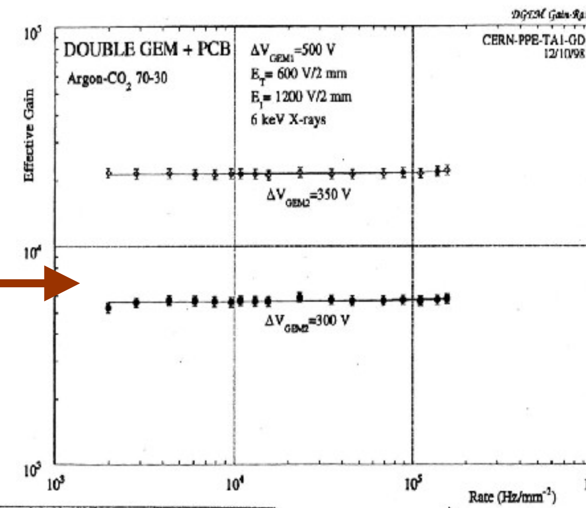
MGPDs : Advantages

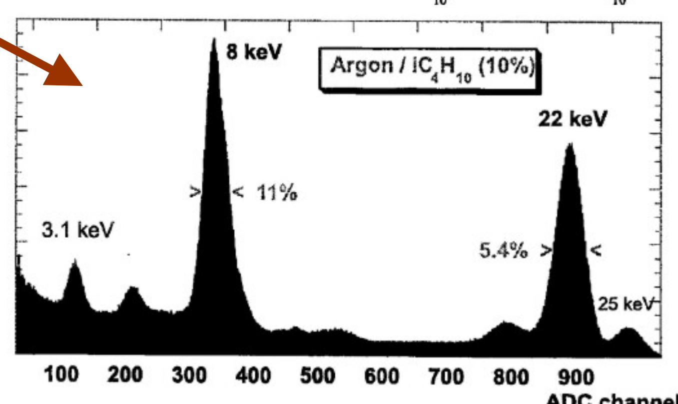
- Common advantages of MGPD family:
  - Efficiency ⇨ 99% plateau at G=6500 in COMPASS
  - Spatial resolution ⇨ micromega best 12 μm
  - Rate capability

    Double GEM 10^5 Hz/mm^2
  - Energy resolution and gain stability
  - Time resolution

    ~10 ns for micromega
  - Adaptable gain



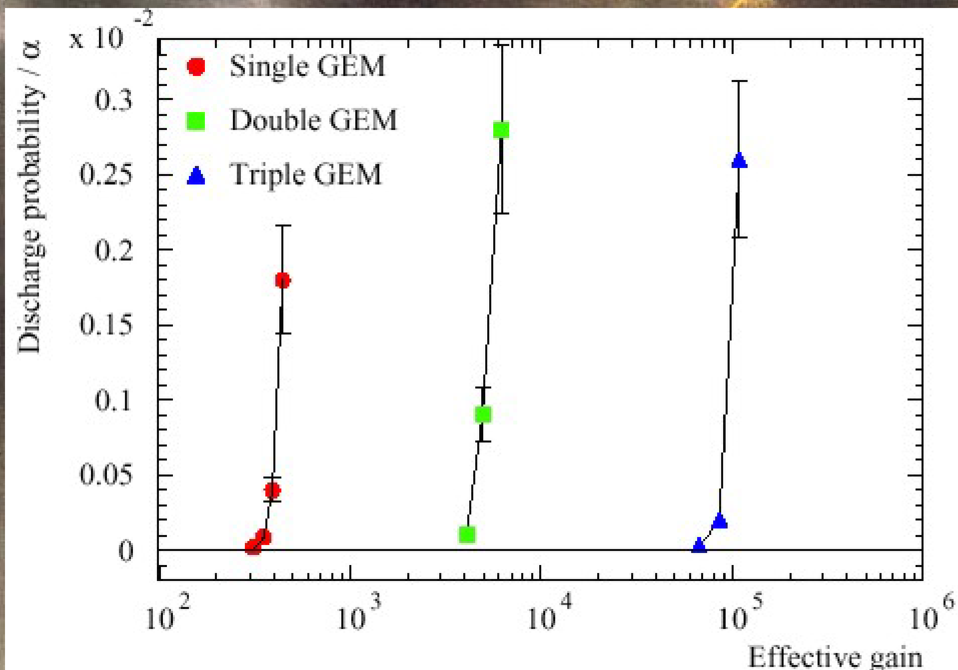


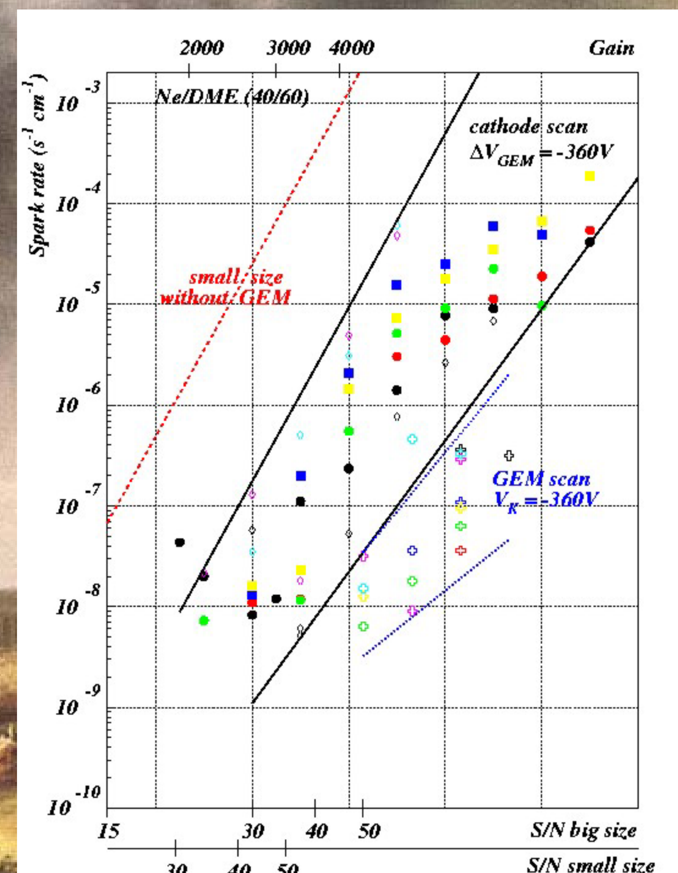


MPGD's by Albert Cuyp

MPGD's by Albert Cuyp

- Triple GEM solution:
- Reduced spark probability for equal gain





GEM + SGC:

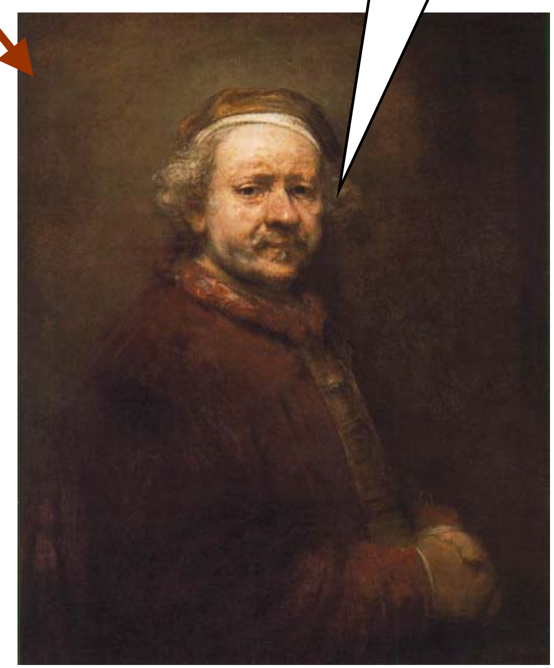
Tune the voltages to optimise discharge rate -> factor 100

MPGD’s by Rembrandt

1629

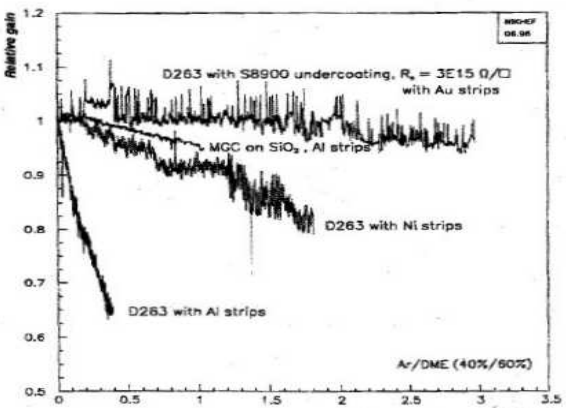
1640

Ageing can be
a problem



1669

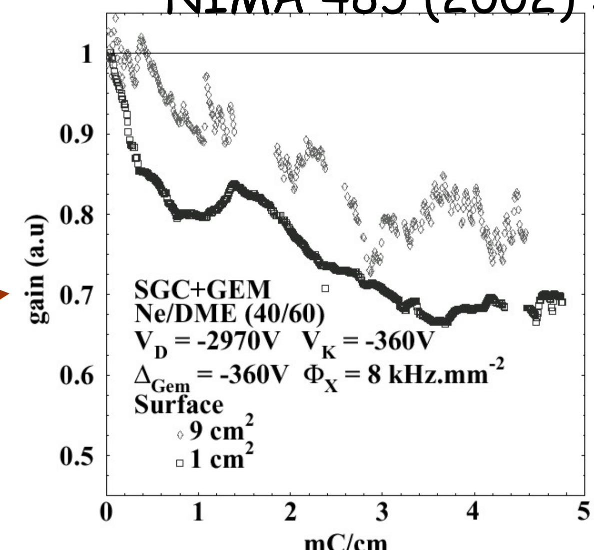
MPGD's: Ageing



MSGC ageing

- Dependence on materials
- Sensitive to pollutants, strip and substrate material

•NIMA 485 (2002) 322

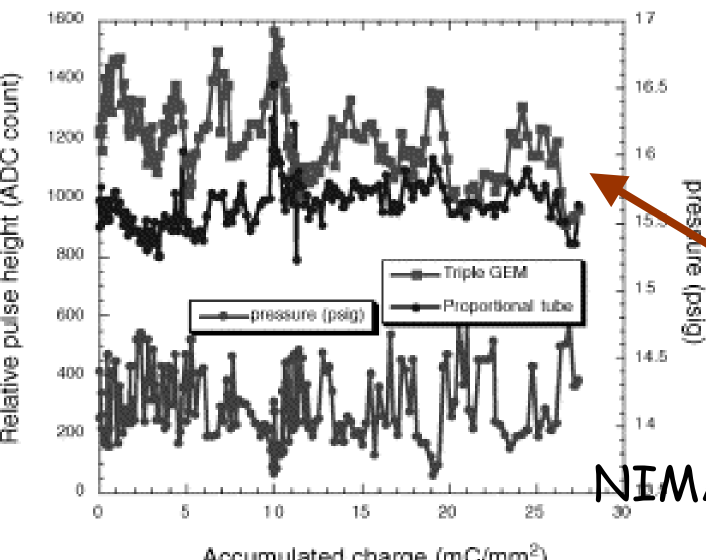


Long term ageing test for GEM+SGC:

After 500 LHC days (5 kHz/mm^2 at gain=2800)

•5% anode loss

•25% gain loss



Long term ageing test for triple GEM

No degradation after 27 mC/mm^2

NIMA 478 (2002) 263

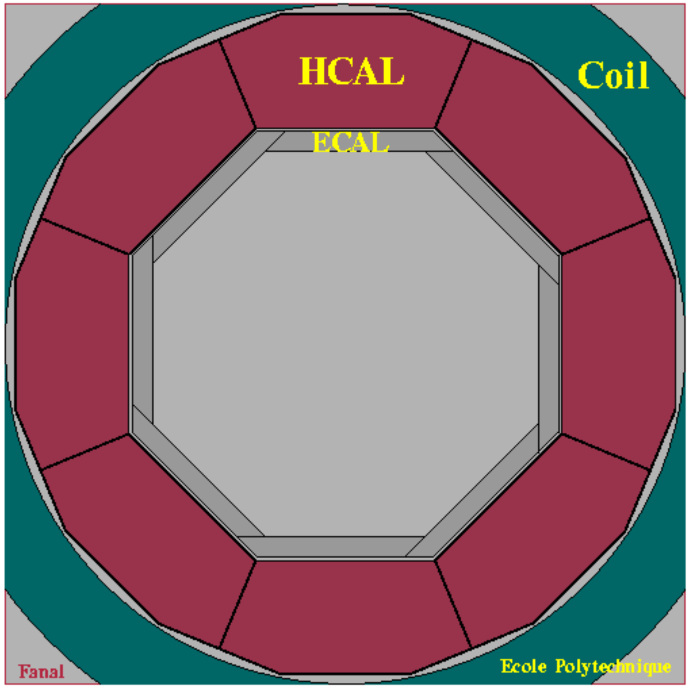
Calorimetry for the LC

- LC physics all about jets:
  - tth ⇨ 8 jets
  - hZ ⇨ 2l + 2 jets, 4 jets
  - hhZ ⇨ 2l + 4 jets, 8 jets

+ SUSY, quark, τ tagging, lepton/hadron id

High magnetic field demands compact design

Calorimetry at the LC will be demanding



ENERGY FLOW is the name of the game

$E_{jet} = \Sigma\, E_{ch} + \Sigma\, E_{\gamma} + \Sigma\, E_{neutrals}$

Identification and reconstruction of all eflow objects

Charged tracks from tracking system

Photons from ECAL

Neutral hadrons from ECAL and HCAL

Calorimetry for the LC

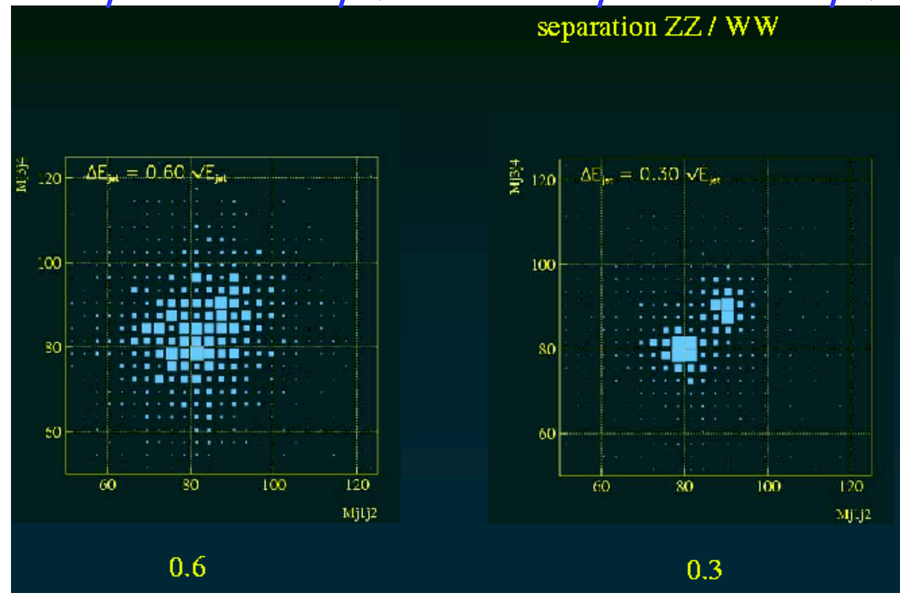
ECAL: silicon-tungsten (Si-W) sampling electromagnetic calorimeter:

- 40 layers, between 0.4 and 1.2X_0 (radiation lengths).
- 24X_0 total thickness.
- 32 million channels.
- 1 x 1 cm^2 pad size

HCAL: digital calorimeter concept

- count 1cm^2 cells
- 16 million channels
- Stainless steel absorber plates
- Readout with RPCs/wire chambers

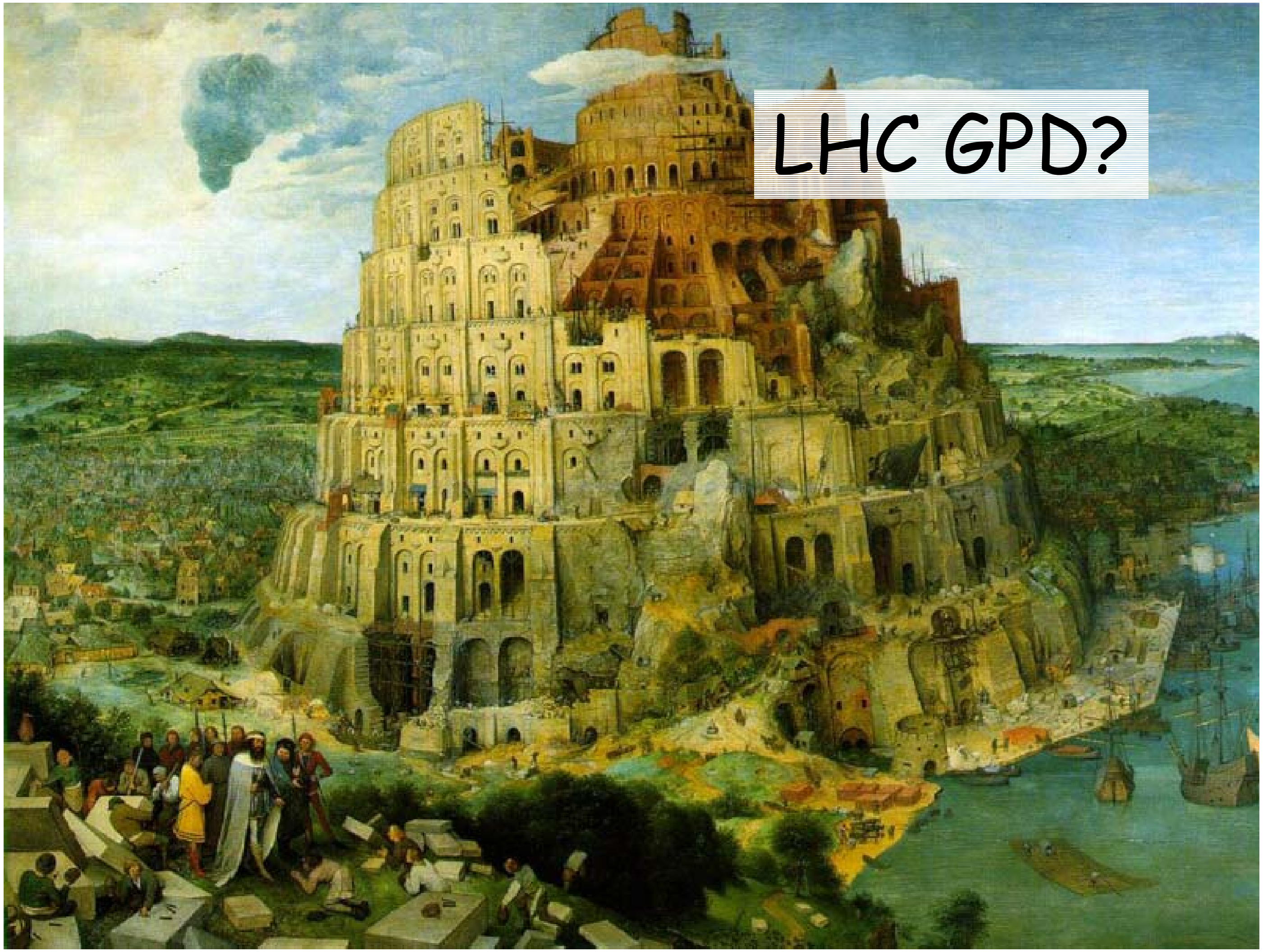
$\Delta E/E = 60\%/\sqrt{E}$ $\Delta E/E = 30\%/\sqrt{E}$



For hadronic jets, TDR calorimeters give $\Delta E/E = 33\%/\sqrt{E}$

- Distinguishes $\nu\nu W^+W^-$ and $\nu\nu ZZ$ final states
- Higgs $\rightarrow \gamma\gamma$ gives $\sigma_m \sim 2$ GeV

Challenges of Large Systems



The Tower of Babel by Pieter Breugel

ack: G. Charpak

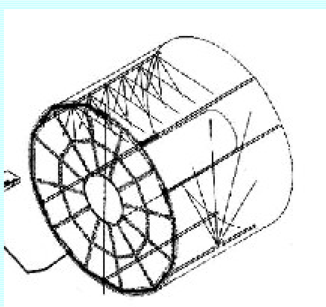
Challenges of Large Systems

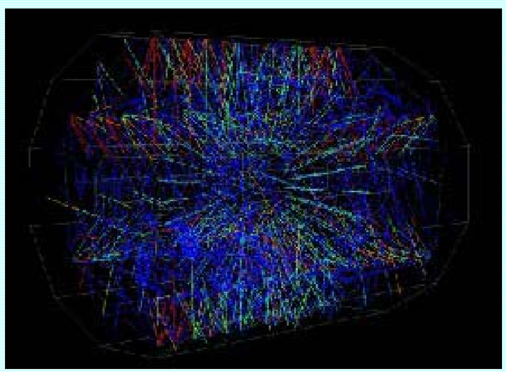
mass production, QA, electronics, computing, long time scales (technology, aging), risk factors, mechanics, etc. etc.

Example: Calibration systems

Will assume huge importance: from cross check to full integration

STAR calibration system





200-400 UV laser beams

Measures drift velocity

Next step: embed in data stream

CMS calorimeter

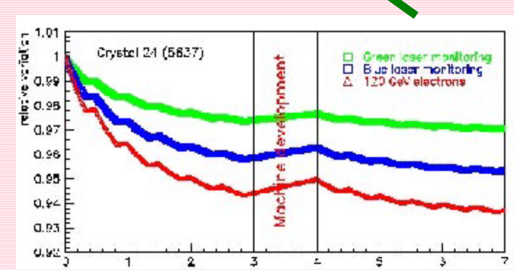
80,000 crystals

Intercalibration 0.1-0.2%

Will use data and monitoring

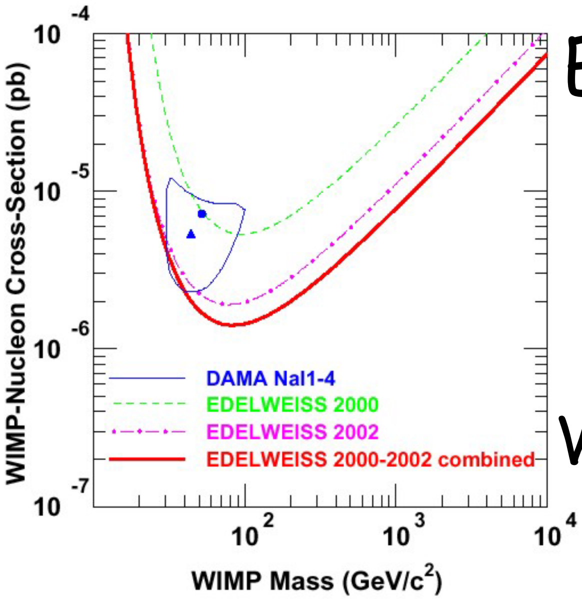
$W \rightarrow e\nu$

$Z \rightarrow ee$



Huge effort for database

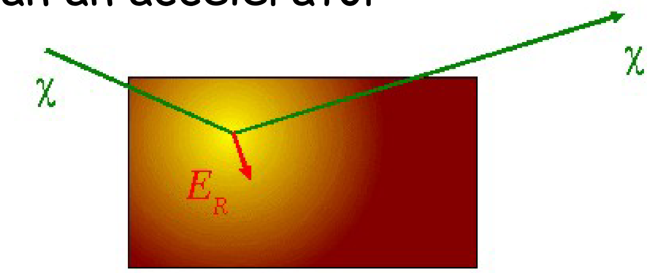
Applications in Dark Matter Searches



Example: Direct detection of WIMPs

formidable challenge to detector technology
from nature rather than an accelerator

Nuclear recoil from
WIMP elastic scatter



Search for a tiny signal with low rates

~ 10 keV

~ 0.1 count/kg/day

CRESST I, ROSEBUD, Tokyo LiF, Milano TeO_2 → phonons

HD Moscow, GENIUS → ionisation

UKDMC NaI, DAMA NaI → scintillation

phonons + ionisation: EDELWEISS, CDMS

ionisation + scintillation: UKDMC Xe

phonons + scintillation: CRESST II $CaWO_2$

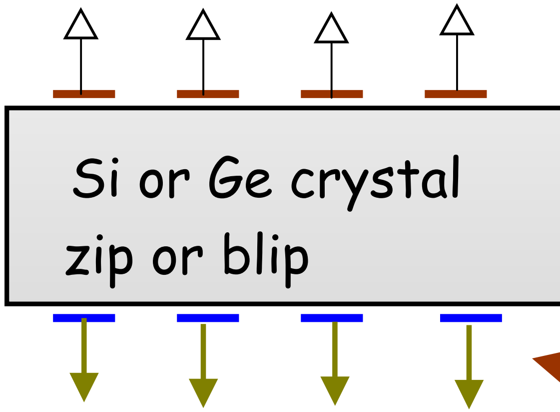
Applications in Dark Matter Searches

next generation detectors ⇨ 10 kg

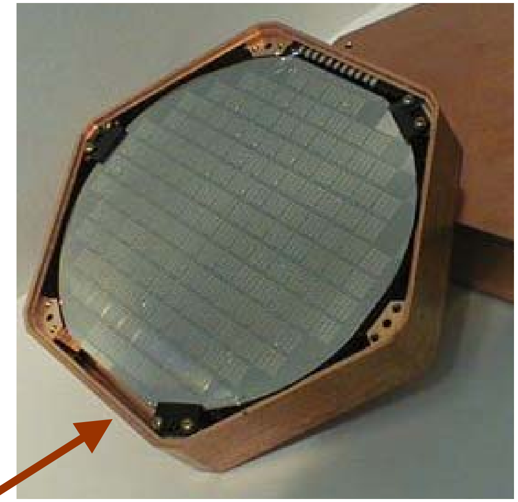
CDMS:

this side collects ionisation energy

this side collects phonon energy



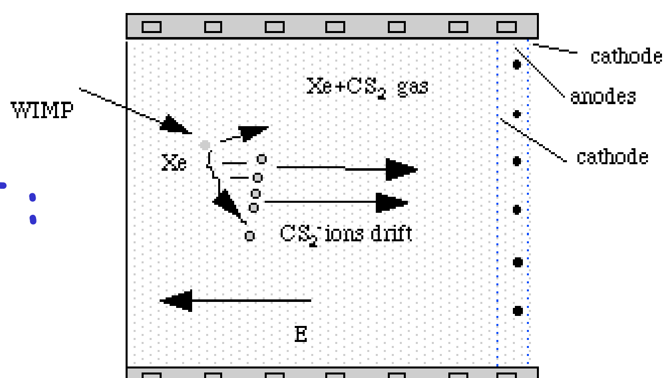
to SQUID array



Array of superconducting Transition Edge Sensors

CRESST II : Simultaneous detection of phonons + scintillation light with $CaWO_4$ crystals

DRIFT :



Low pressure gas Xe TPC

Charge carried by negative ions

Readout with MWPC/CCD/MPGD

Conclusions by Rembrandt

Detector R&D making a huge impact on the future of HEP

The syndics of the referees guild

Acknowledgements

Thanks to all people who provided material, including

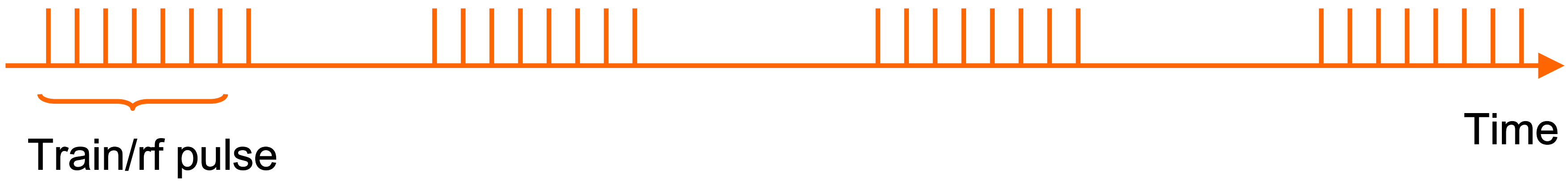
LC Marty Breidenbach, Keith Riles, Paul Dauncey, Ron Settles Silicon Hans Dijkstra MAPS Marc Winter, Grzegorz Deptuch, Wojtek Dulinski, CCD Chris Damerell DEPFET Marcel Trimpl Johannes Ulrici SDD Rene Bellweid, Vladimir Rykov HAPS Massimo Caccia, Wojtek Kucewicz, Peter Chochula, Peter Rosinsky Irradiation Sherwood Parker, Cinzia da Via, Angela Kok, Mahfazur Rahman, Michael Moll, Mika Huhtinen, William Trischuk, Zheng Li Tevatron Alan Sill MPGD Lev Chekhtman, Yannis Giomataris, David Bouvet, Harry van der Graaf RPC Werner Riegler, Crispin Williams photodetectors Roger Forty, Thierry Gys b factory David Leith, David Hitlin Dark Matter Hans Kraus, Fabrice Feinstein, Harry Nelson Calibration Jim Thomas, Alexei Lebedev Overview Tejinder Virdee, Guy Wilkinson

and not forgetting

the painters of the low countries

From now on backup transparencies

Timing @ the LC

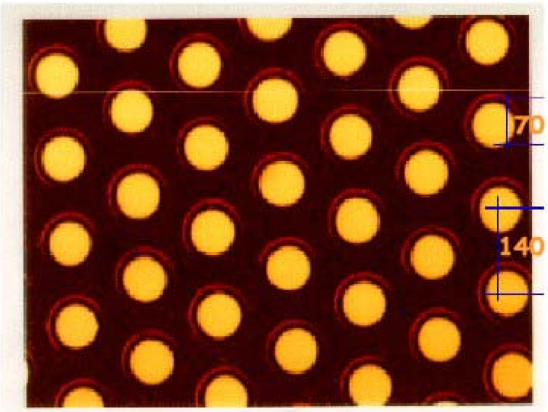


	LEP 0.2 TeV	NLC/JLC	TESLA 0.5 TeV
Train length, μs	0.750	0.265	950
Number of bunches/Train	4	190	2820
Bunch separation, ns	200	1.4	337
Repetition rate, Hz	45500	100	5

⇨ at TESLA, keep occupancy reasonable by reading out innermost layer in 50 μsec

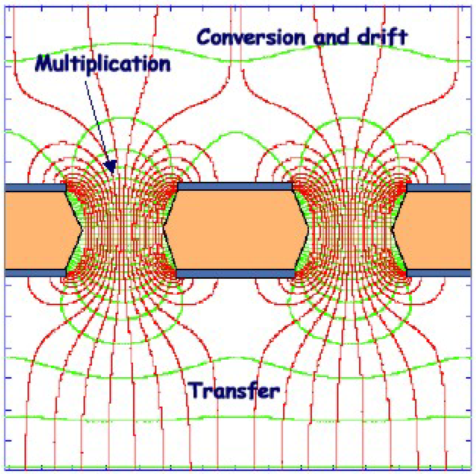
MPGD: GEM detectors

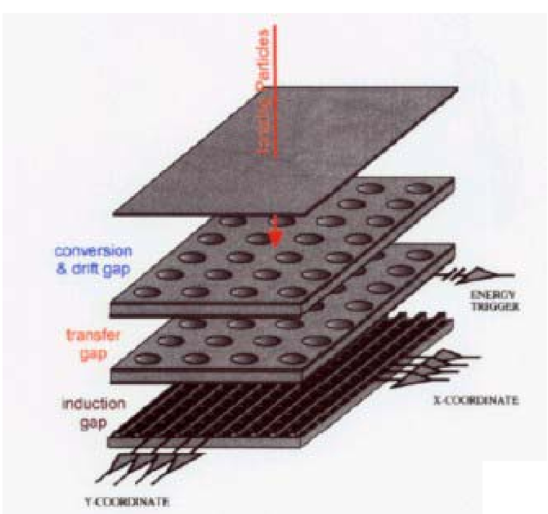
Gas Electron Multiplier – F. Sauli 1996



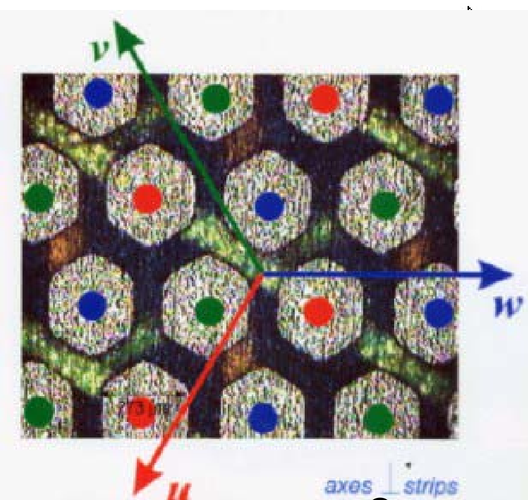
F. Sauli, Nucl. Instr. Meth. A386 (1997) 531

- Copper clad kapton foil
- Perforated by many ($\sim 10^4/cm^2$) holes
- ΔU between electrodes creates amplification region inside holes
- Gain is a property of foil





- Can cascade several GEMS
  - ➢ Higher gain
- Amplification and readout stages are separate
- Many readout schemes possible, e.g. 3d, Sauli 2002



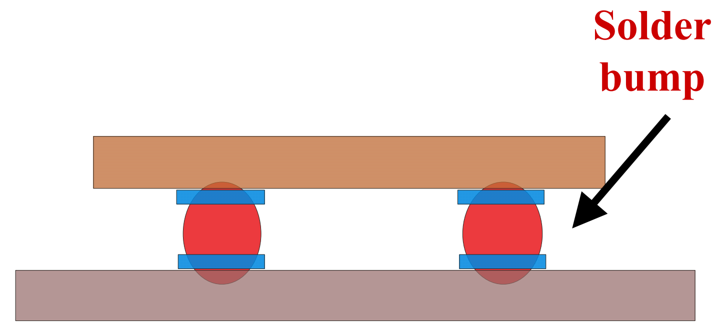
$u + v + w = 0$

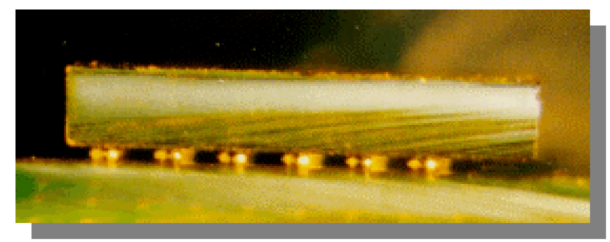
Hybrid Active Pixel Sensors (HAPS)

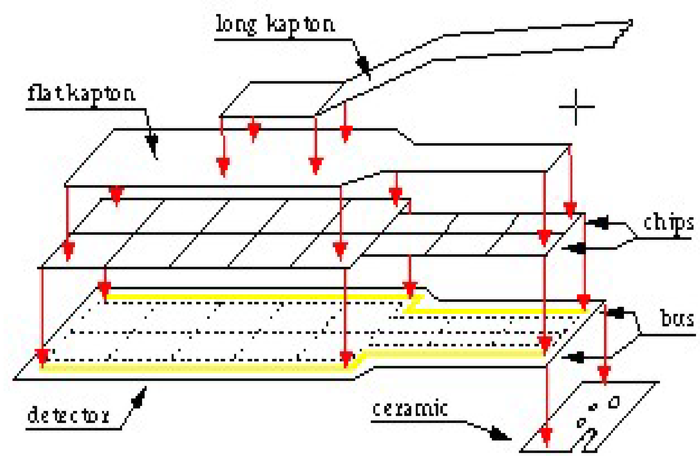
Hybrid pixels

(some) Tracking applications for HEP:

1995	WA97	0.5 Mpixels	75 x 500 μm²
1996	DELPHI	1.2 Mpixels	330 x 330 μm²
	NA60	0.7 Mpixels	50 x 400 μm²
	ATLAS	100 Mpixels	50 x 400 μm²
	CMS	23 Mpixels	150 x 150 μm²
	ALICE	100 Mpixels	50 x 400 μm²
	BTeV	23 Mpixels	50 x 400 μm²







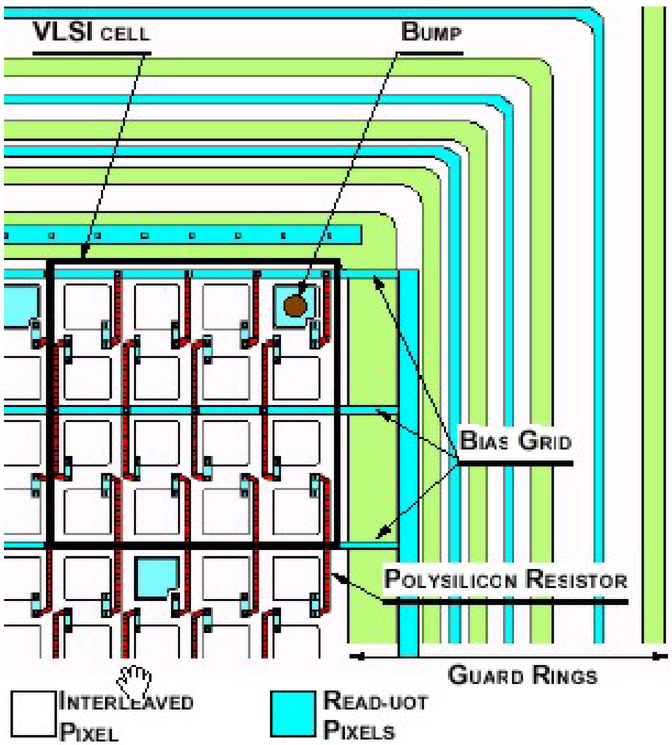
- HAPS are fast and tolerant of LC radiation
- R&D to cover precision and material issues

R&D for HAPS

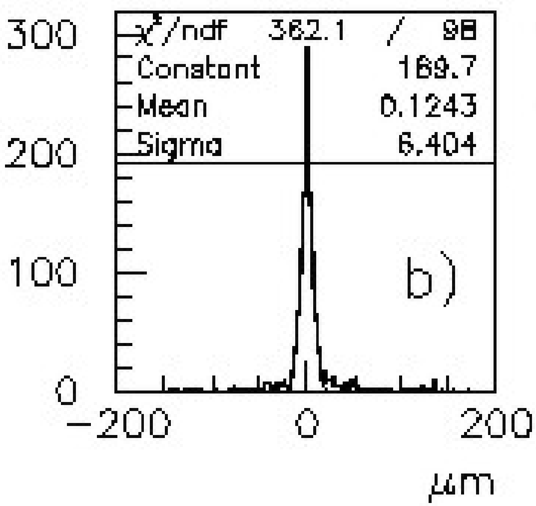
R&D programme

- Fine implant pitch + coarse readout pitch
- Use capacative charge sharing between pixels to improve resolution – use good S/N pixel performance
- Prototype results: 100 μm implant + 200 μm readout gives 3 – 10 μm resolution
- Expected to scale with pitch: 20-25 μm prototypes in production in 2002

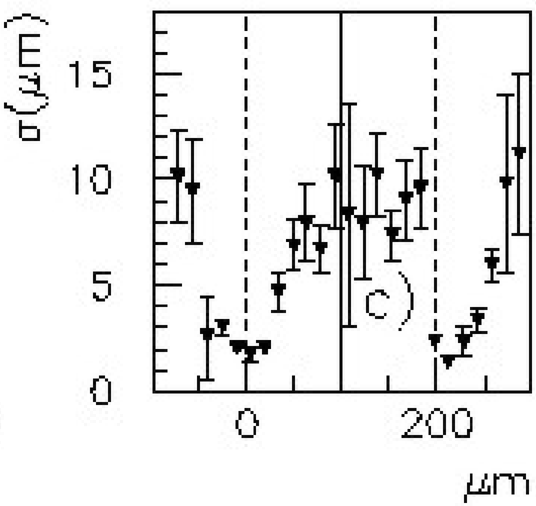
Test structure with interleaved pixels



Resolution



Resolution vs position



hep-ex/0101012

Silicon for vertexing @ the LC

Required Vertexing performance

Flavour tagging: beauty + charm

discriminate b from background $\quad e^+e^- \to t\bar{t} \to b\bar{q}q\bar{b}\bar{q}q$

discriminate b from c $\quad H \to b\bar{b}, c\bar{c}, gg, \tau\bar{\tau}$

disentangle complex events $\quad e^+e^- \to AH \to t\bar{t}t\bar{t}$

↑ 12 jets

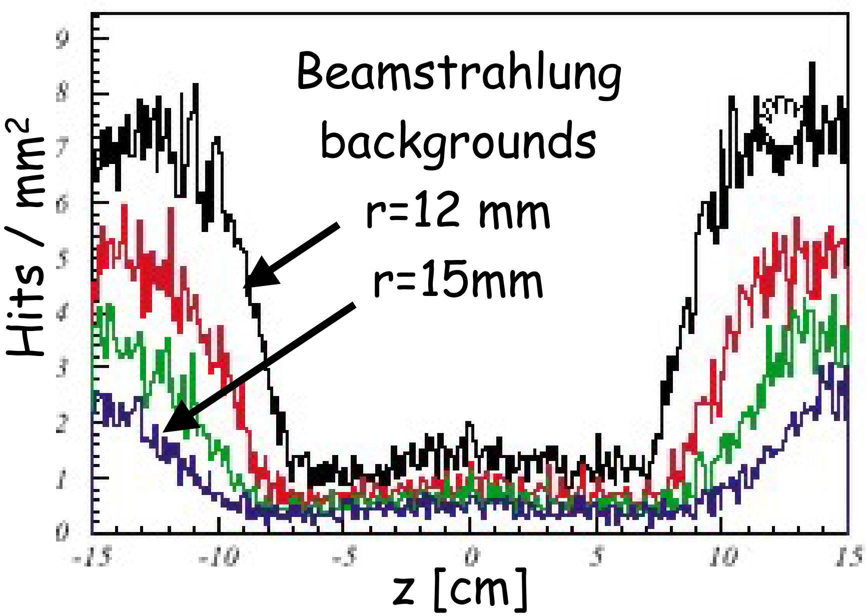
Vertex detector characteristics

point resolution 1-5 μm

Thickness ~ 0.1 % X_0

5 layers

Inner radius ~ 1.5 cm



δ (IP) < 5 μm $\oplus$ 10 μm/(p $\sin^{3/2}\theta$)

(best SLD 8 μm $\oplus$ 33 μm/(p $\sin^{3/2}\theta$))

- Use a silicon based pixel detector
- Confine the background with a big solenoidal field

R&D for photodetectors

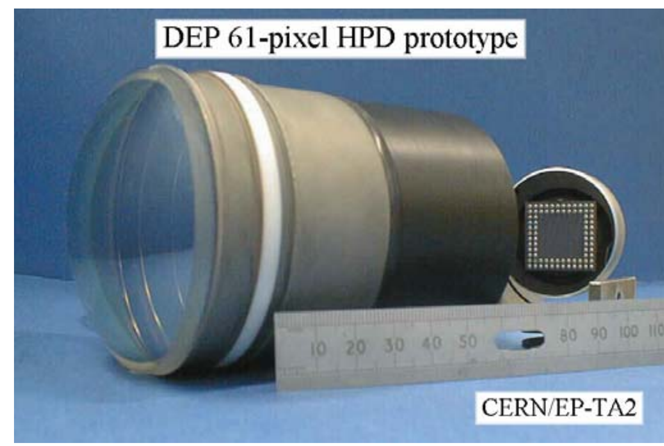
PID is a fundamental requirement for LHCb, BTeV, BaBar, Belle, etc.

LHCb (e.g.) requirements:

- Total image surface ~ 2.6 m^2
- Granularity 2.5 x 2.5 mm^2
- High fill factor
- LHC speed readout

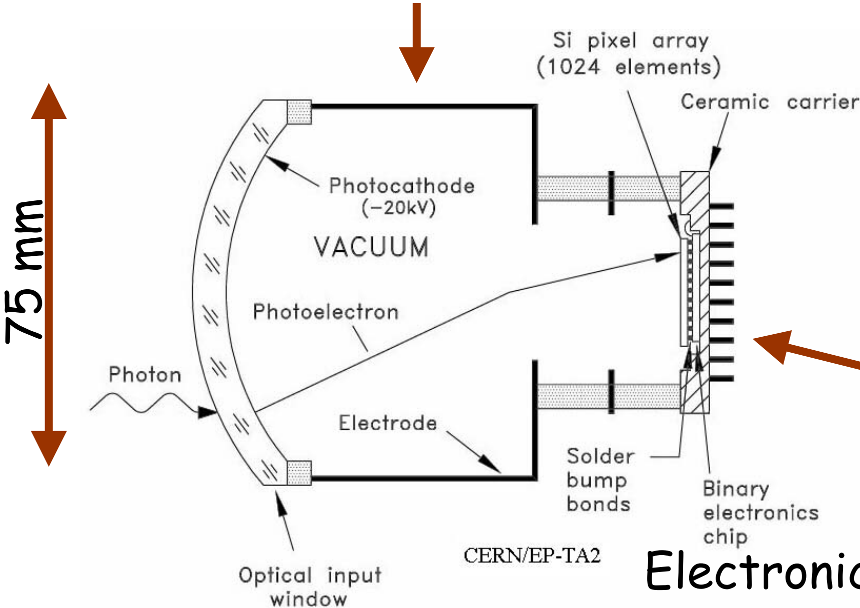
Key R&D effort towards development of suitable photodetector system

- Pixel HPD photodetector developed



Cross focused image intensifier tube

Demagnification x 5

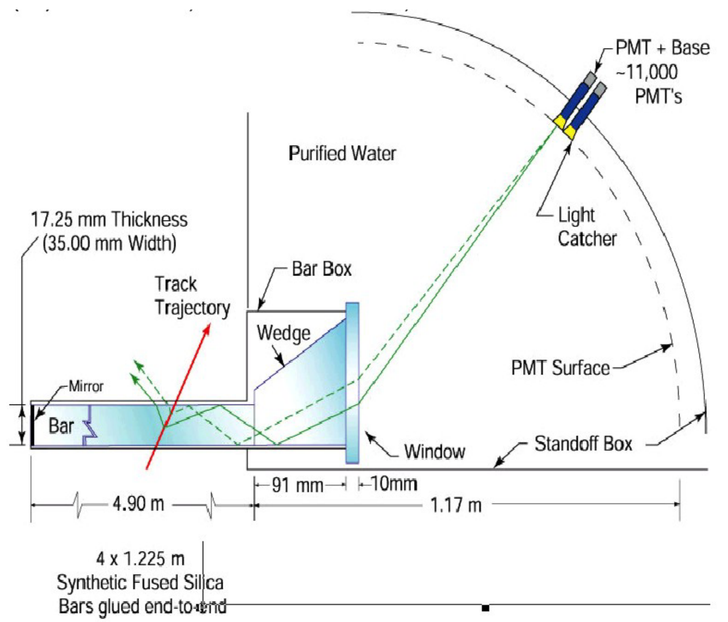


Silicon pixel array bump bonded to binary readout chip pixels 500 μm x 500 μm

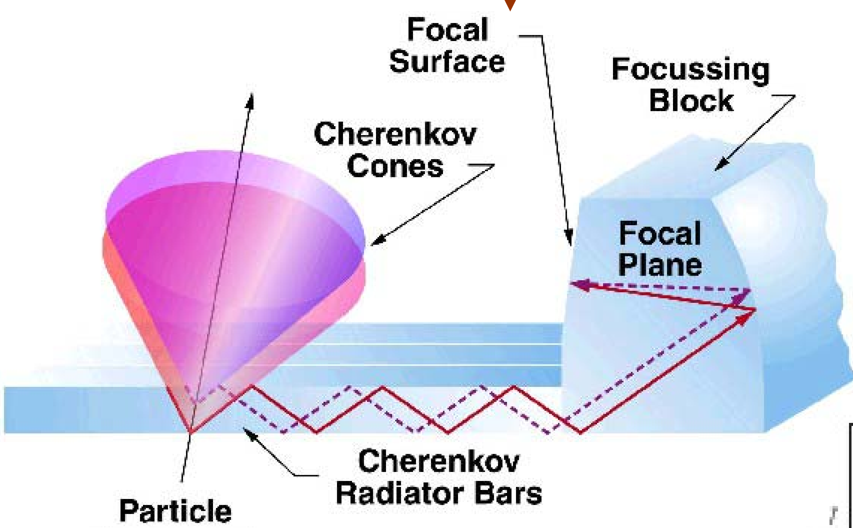
Electronics must be compatible with bakeout cycles!

..and for future DIRC/TOP?

At $L=10^{36}$ cm^{-2} sec^{-1} new readout scheme needed for the BaBar DIRC



Similar ideas in place for Belle TOP

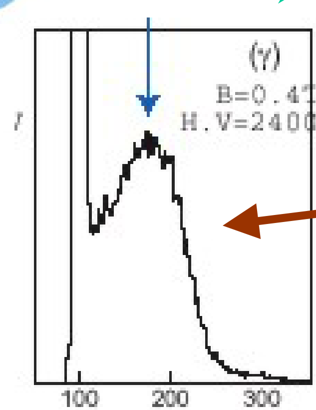


Extra Requirements:

- Time capability ~200ps
- B field operation

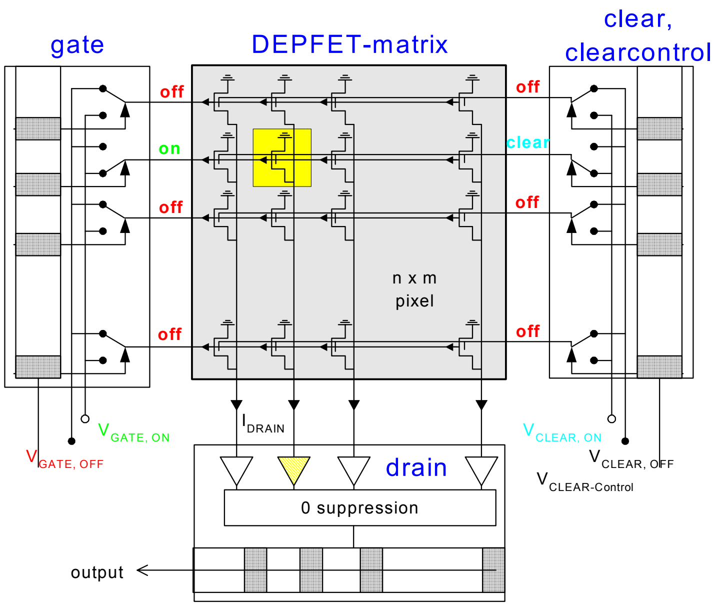
Currently evaluating MaPMTs, Pixel HPDs, Pad HPDs, HAPDs

NIMA 460 p326, 2001, NIMA 463 p220, 2001



Single photon peak obtained with Hybrid Avalanche Photo Diodes

DEPFET readout scheme



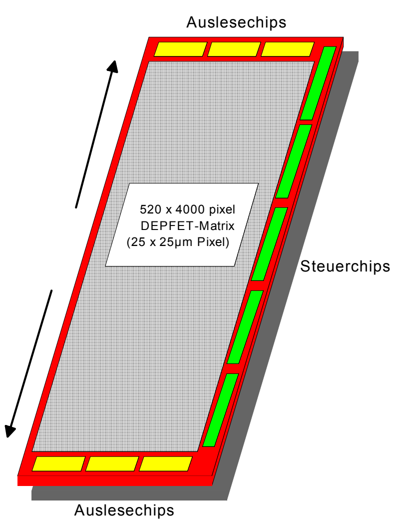
3 steps for each matrix row

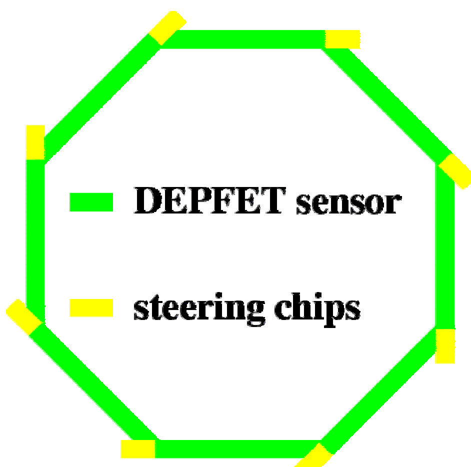
- Read all signal currents
- Reset pixel row via clear contacts
- Read pedestal currents

R&D issues

- Mimimise pixel size
- Thin from backside
- Minimise power consumption
- Speed up readout cycle

Proposed TESLA Layout





R&D steps

1997: 2x2 pixel matrix

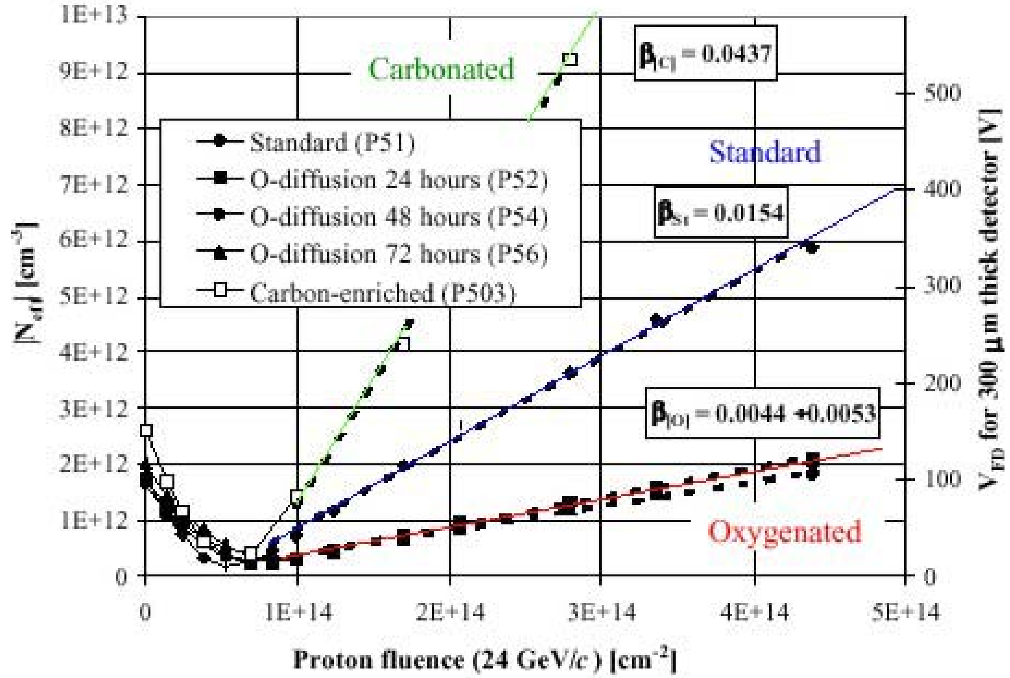
2000: 64x64 matrix

End 2002: 128x128 30µmx30µm prototype

Backup transparency - oxygenation

Influence of Carbon and Oxygen concentration

24 GeV/c proton irradiation



Compared to standard silicon:

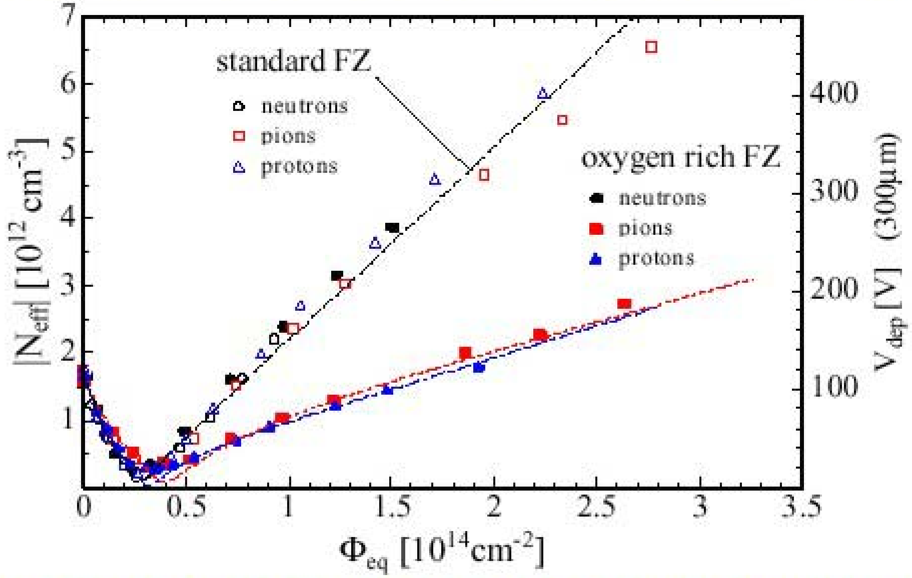
- High Carbon ⇒ less radiation tolerant
- High Oxygen ⇒ more radiation tolerant

M Moll

Backup transparency - oxygenation

Oxygen and standard silicon
- Particle dependence -

23 GeV protons - 192 MeV pions - reactor neutrons

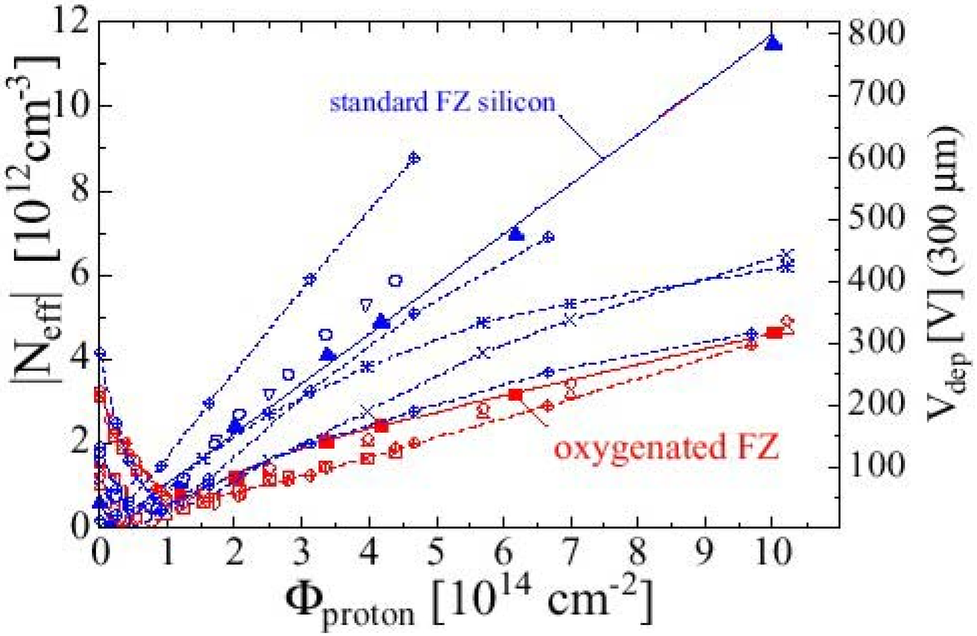


- **Strong improvement for pions and protons**
- **Almost no improvement for neutrons**

Michael Moll - CERN EP-TA1-SD Seminar - 14.2.

Backup transparency - oxygenation

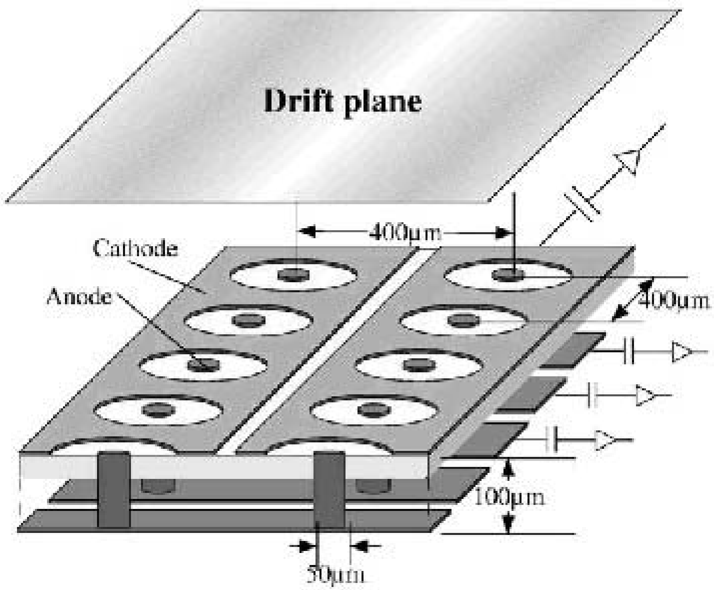
Warning: Variation of “standard material”

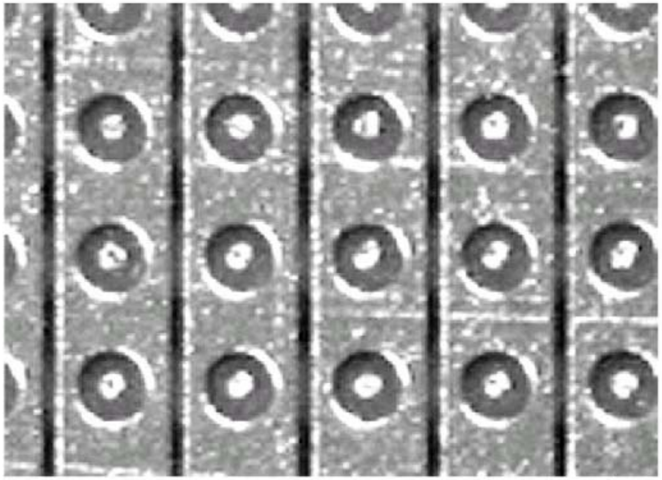


- Strong variation of standard silicon
- Reproducible results for oxygenated silicon

Michael Moll - CERN EP-TA1-SD Seminar - 14.2.2001 - 26 -

MPGDs: micropixels





Towards true gaseous pixel detectors

- Micro-dot chamber (Biagi, 1993)
- Micro-pin structure (Rehak, 1999)
- Micro-pixel chamber (μ-PIC)

  (Ochi *et al, 2001)*

  3 x 3 cm device: Pitch 400 μm

  Anode thickness 50 μm

  5 days continuous operation without discharge at gain=10^3

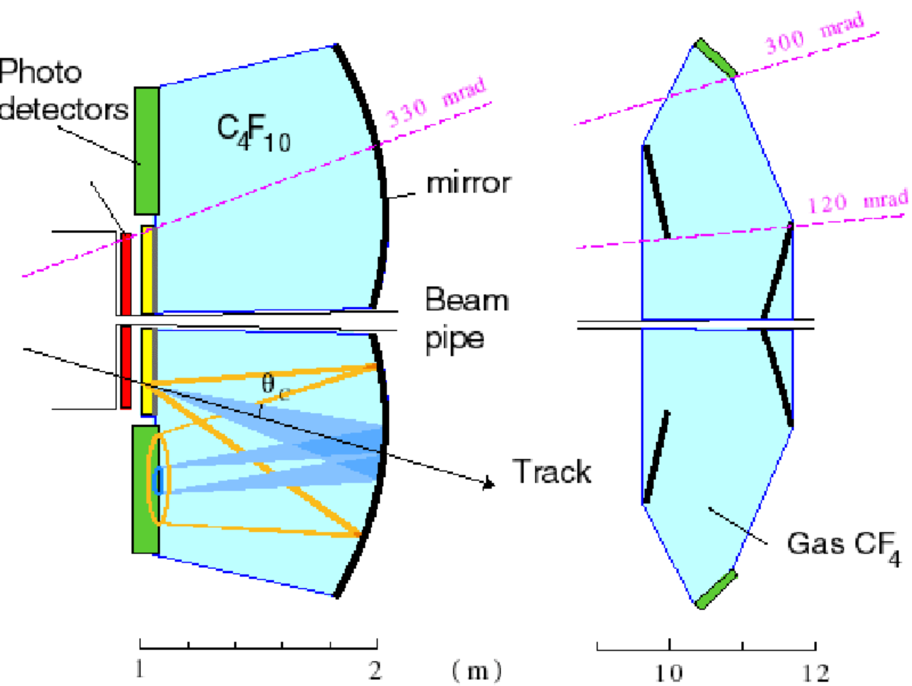
R&D for LHCb RICH

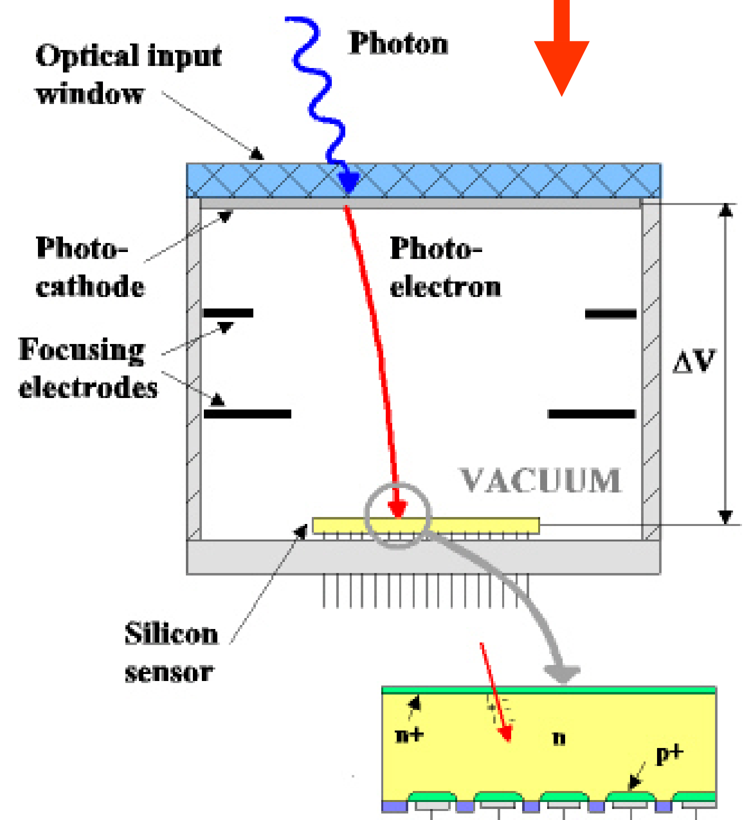
PID is a fundamental requirement for LHCb

LHCb requirements:

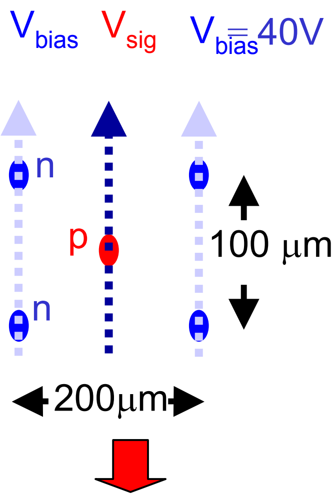
- Total image surface ~ 2.6 m^2
- Granularity 2.5 x 2.5 mm^2
- High fill factor
- LHC speed readout

Key R&D effort towards development of suitable photodetector system

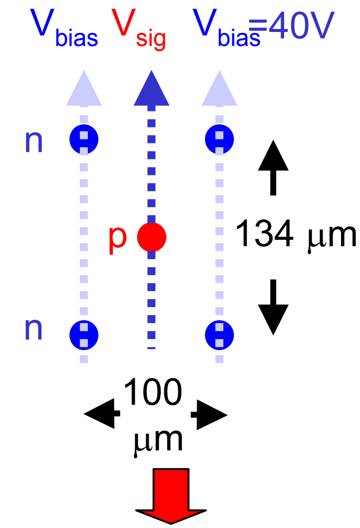


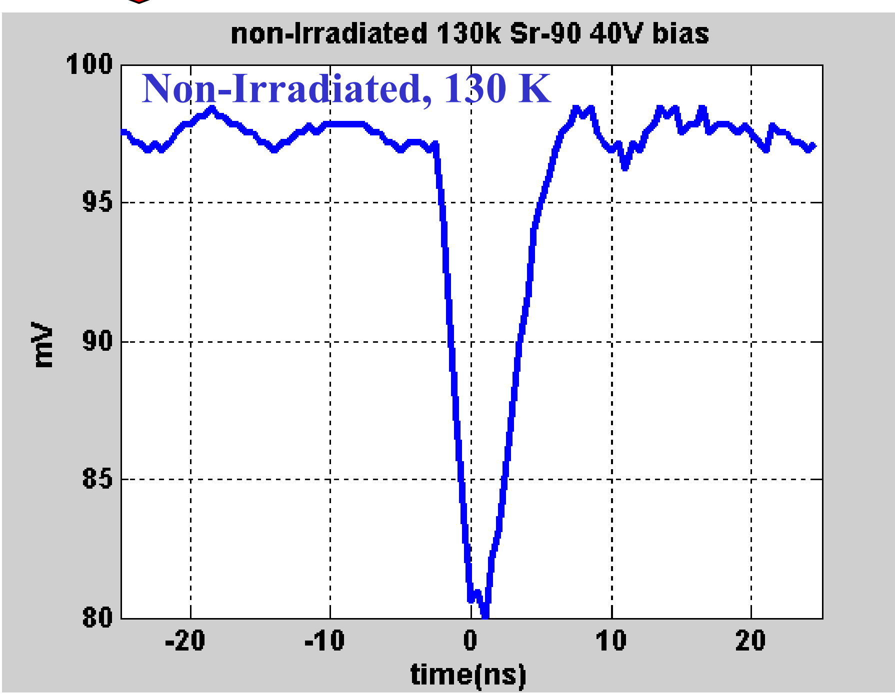


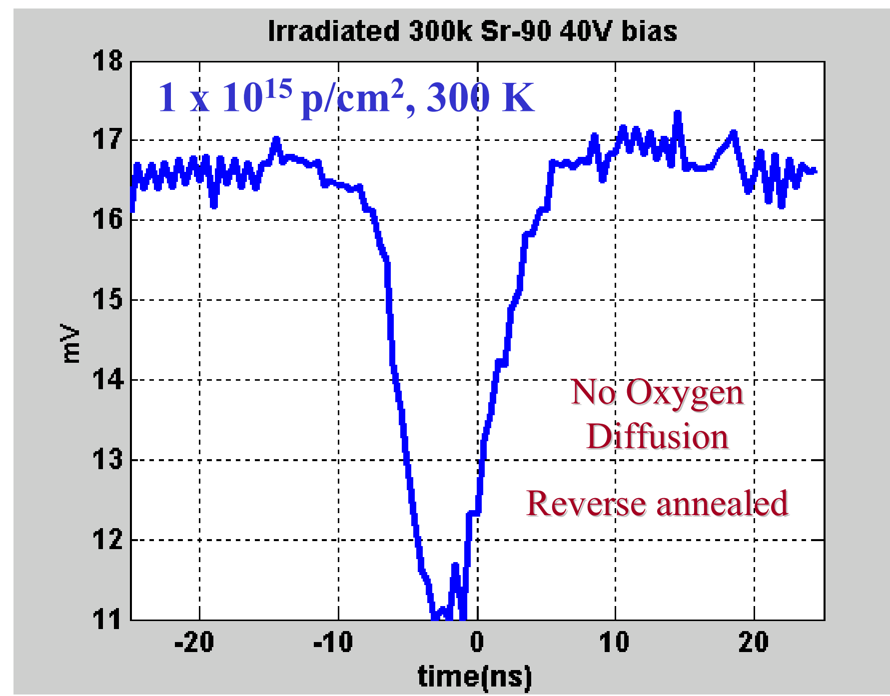
3d Sensors: Speed



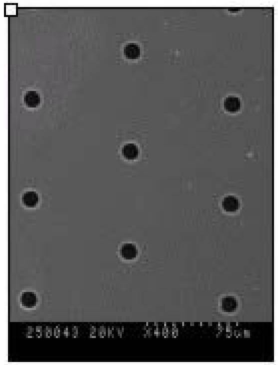
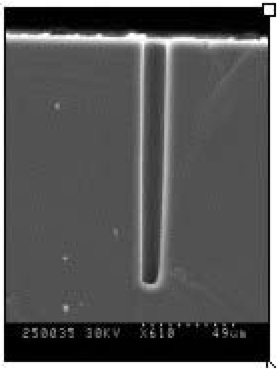
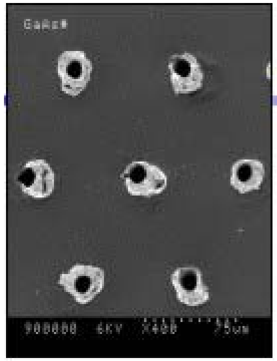
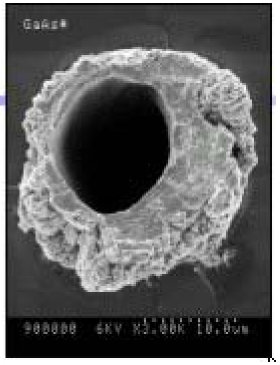
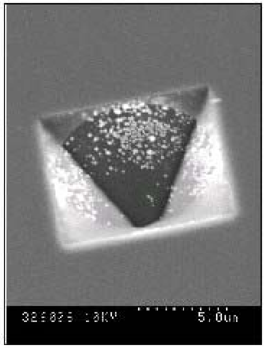
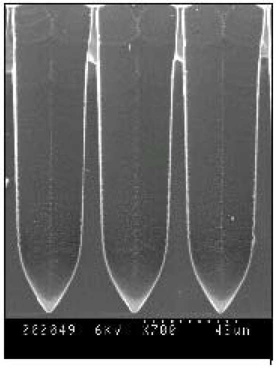
Cell Width	Rise time	T	Fluence
200 μm	1.5 ± 0.25ns	130 K	zero
200 μm	3.5 ± 0.25ns	300 K	zero
100 μm	3.5 ± 0.25ns	300 K	10^{15}p/cm^2







3D detectors: Excavating the holes

Dry Etching	Laser Drilling	Electrochemical etching
 	 	 
➢Standard photolithography process	➢ Any material ➢ No photolithography	➢No sidewall damage
➢Sidewall damage ➢Si and GaAs only	➢Slow process for big arrays ➢Sidewall damage ➢Tapering ➢Repeatability	➢Si only (GaAs and SiC?) ➢Complex photolithography
1µm / min.	1 hole / 3-5sec.	0.6µm / min.
Hole depth/diameter ~ 26	Hole depth/diameter: ~ 40 (but..)	Hole depth/diameter: ~ 25

Lazarus efect: Beamscope for NA60

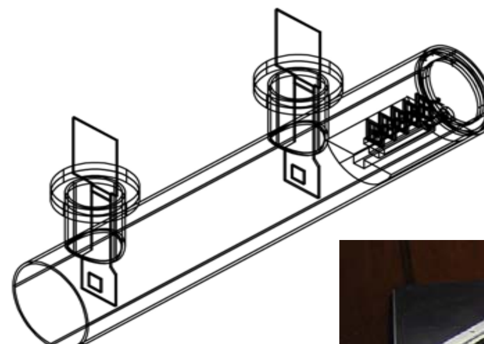
Discovery: 1998 Application: 2001!

Requirements:

- determine primary vertex
- tracking in the beam (p … Pb)
  - high dose - ~Grad per day
  - fast readout (beam intensity)

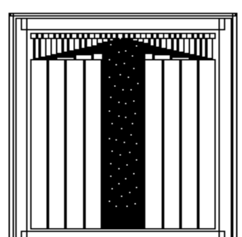
Solution:

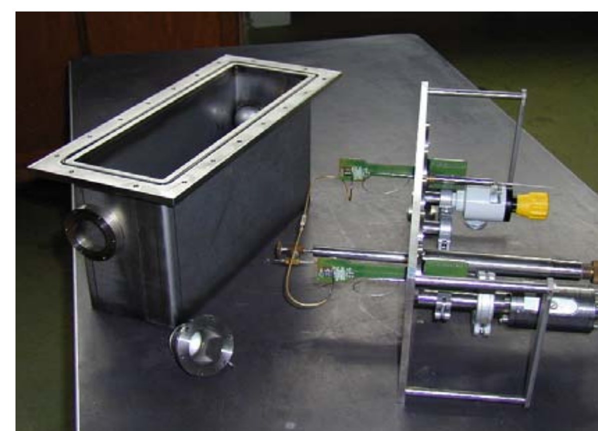
- Lazarus effect (RD39, '98)
  - cryogenic operation
  - CCE restored



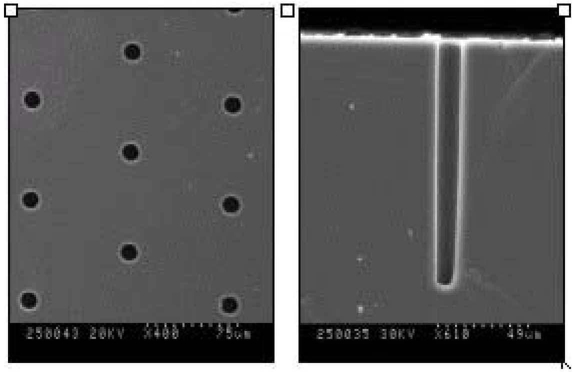
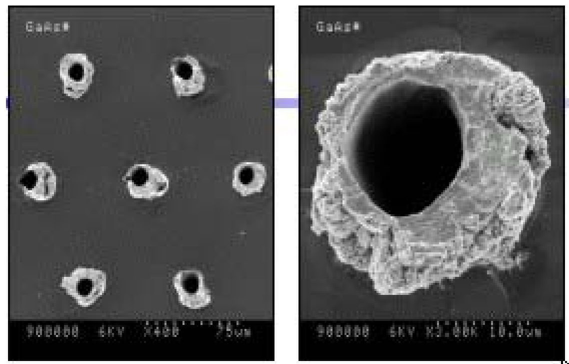
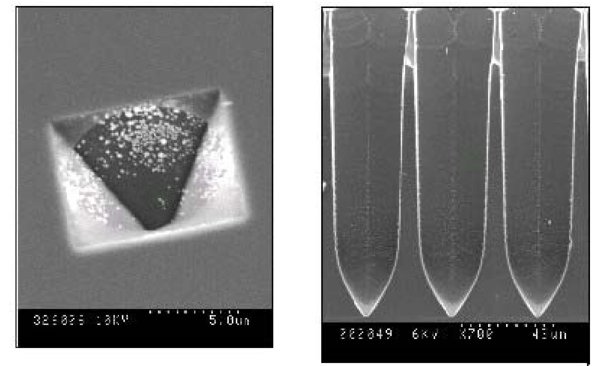
Detector:

- single sided Si strip
- 50 μm pitch, 24 strips
- cryogenic operation ~130 K
  - steel cryostat, LN
  - tens of Grad !
- 2 sensors = 1 space point





3D detectors: Excavating the holes

Dry Etching	Laser Drilling	Electrochemical etching
		
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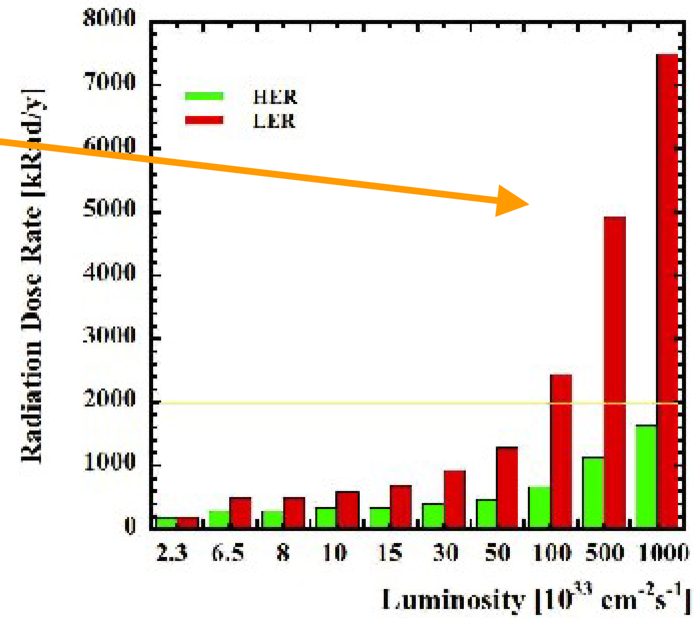
➢Sidewall damage ➢Si and GaAs only	➢Slow process for big arrays ➢Sidewall damage ➢Tapering ➢Repeatability	➢Si only (GaAs and SiC?) ➢Complex photolithography
1µm / min.	1 hole / 3-5sec.	0.6µm / min.
Hole depth/diameter ~ 26	Hole depth/diameter: ~ 40 (but..)	Hole depth/diameter: ~ 25

Irradiation

- Other collider upgrades are hot too
  - e.g. Super Belle/Babar

$L = 10^{36}\ cm^{-2}\ s^{-1}$

Dose ~ 5-10 MRad



- Even an LC is enough to fry an SLD
- LHC detectors will be upgraded where possible
  - LHCb vertex detector
  - Pixel layers of GPDs

→ Improved semiconductor designs/materials are well worth considering

Irradiation: alternative materials

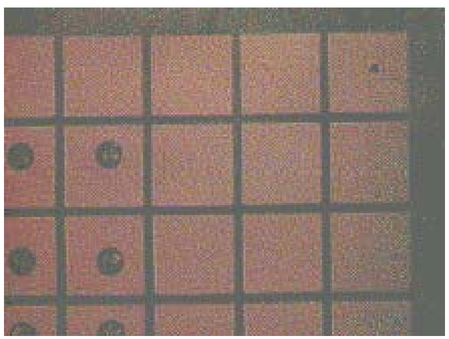
Defect Engineering

- Oxygen enriched silicon
- Oxygen dimer in silicon

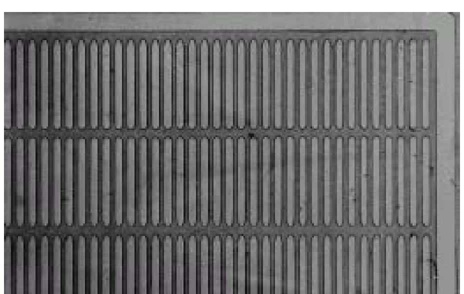
New Sensor Materials

- Silicon Carbide
- Amorphous silicon
- Compound semiconductors
- Diamond

for CMS



for ATLAS

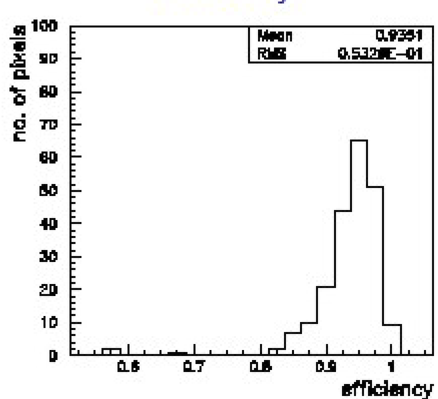


Diamond pixels

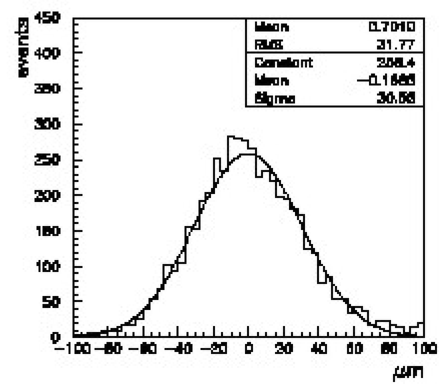
Latest results: $\varepsilon \sim 94\%$, $\sigma \sim 30\ \mu m$

For 125 x 125 μm pixels

Efficiency

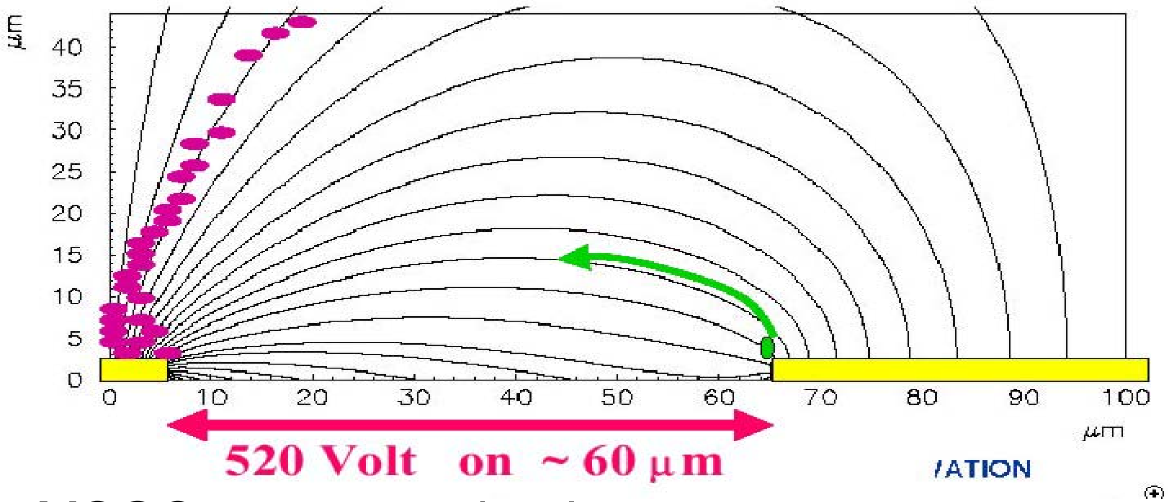


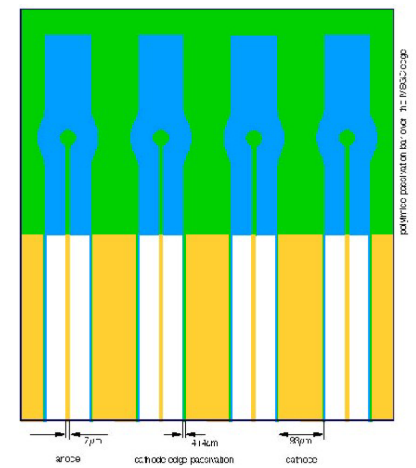
Resolution



MPGDs: Micro Strip Gas Chamber

Proposed by Oed, Bellazini, Udo (1998-89)





MSGC: mature technology

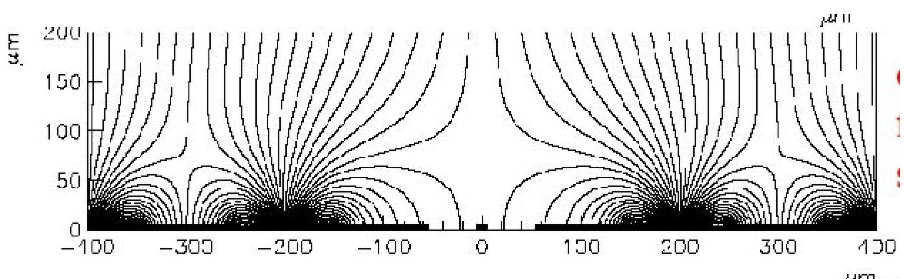
- S/N=31 (98% hit efficiency for CMS)
- Resolution 35 µm
- No aging for an "LHC lifetime"
- Robust for broken strips

HEP applications

- HERA-B

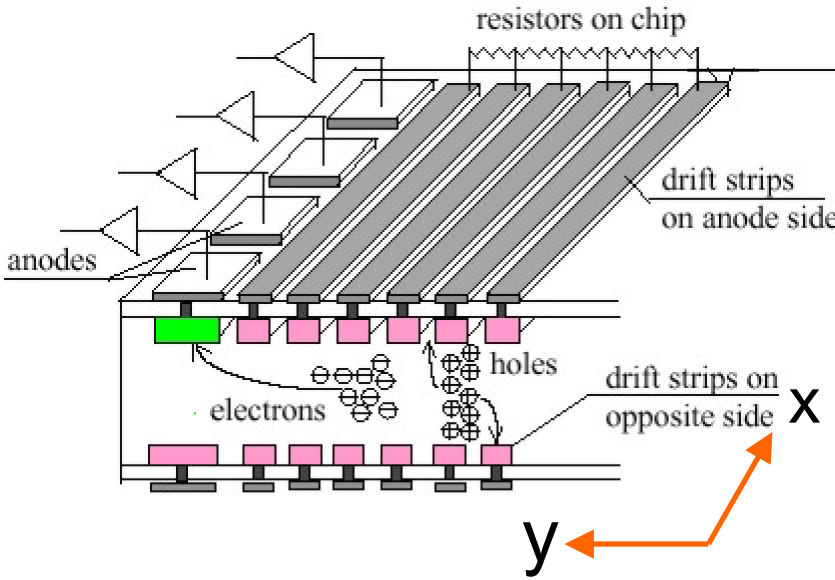
  184 GEM-MSGC ~30*30 cm
- HERMES

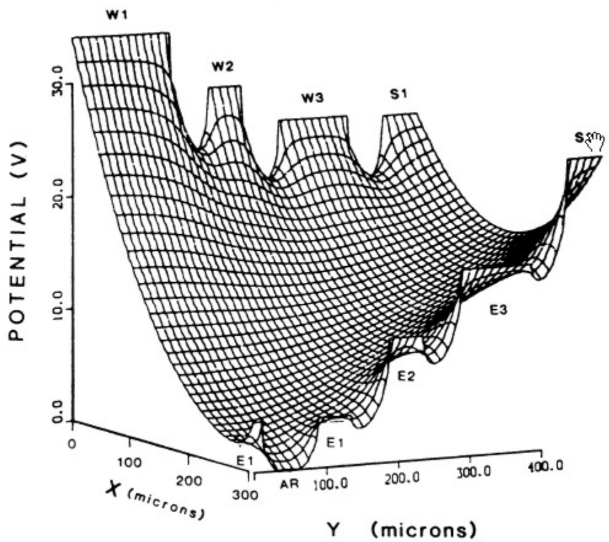
  48 MSGC 14*14 cm



Silicon for tracking: Drift detectors

- Principle of sideways depletion – as for DEPFET sensor
- p^+ segmentation on both sides of silicon
- Complete depletion of wafer from segmented n^+ anodes on one side



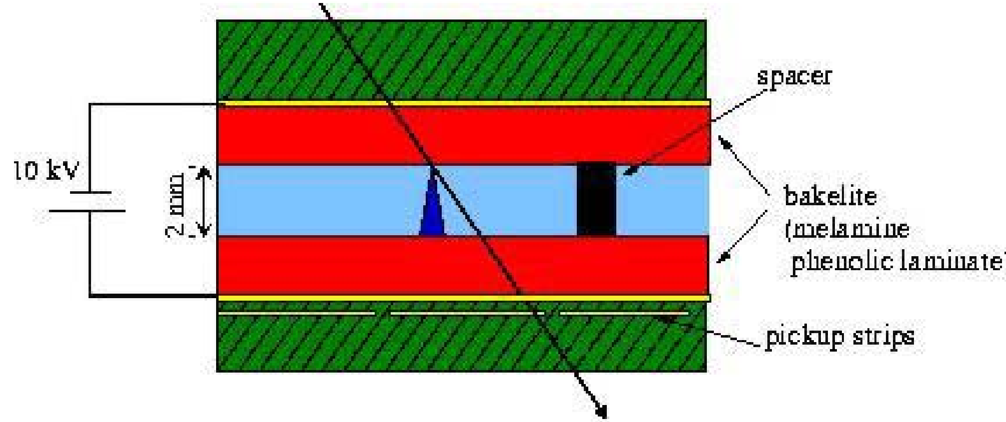


- Electrons drift along potential trough in detector mid plane skewed towards anodes at the end
- X coordinate measured with drift time (~8 μm/ns)
- Y coordinate measured from anode c.o.g.
  - Drift velocity must be predictable
    - → Temperature control
    - → resistivity control
    - → Calibration techniques

- Reduction of channels vs pixel detectors
- Multi track capability
- dE/dx capability
- Small anode capacitance

RPC development

Resistive Plate Chamber:
Parallel plate chamber
with resistive electrodes
Used for TOF, Trigger, Tracker
Streamer mode ⇨ Avalanche mode



- Rate capability ↑ as amplitude ↓
- Lower HV hits time resolution
- Small signal amplitude: noise, x talk issues

Trigger-tracker mode

ATLAS ?? m^2
CMS ?? m^2
LHCb ?? m^2

L3	300 m^2
BaBar	2000 m^2
BELLE	2200 m^2
ALICE	144 m^2

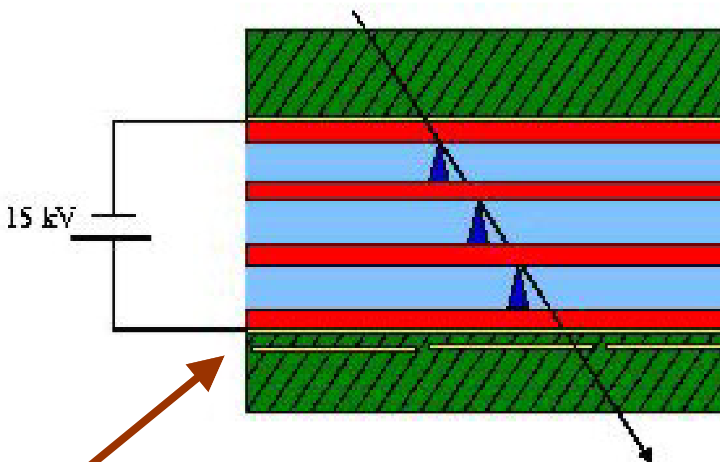
Big worldwide activity
Plenty of accumulated
experience

TOF mode

NA49	0.5 m^2
HARP	8 m^2
STAR	60 m^2
ALICE	144 m^2

RPC development: MRPCs

• Multigap Resistive Plate Chamber : good time resolution



Internal plates electrically floating

Single anode/cathode readout

Recent tests (ALICE,STAR) demonstrate feasibility of

- Large area devices
- Insensitivity to variations in gaps (à la micromega)

Time to Amplitude correction

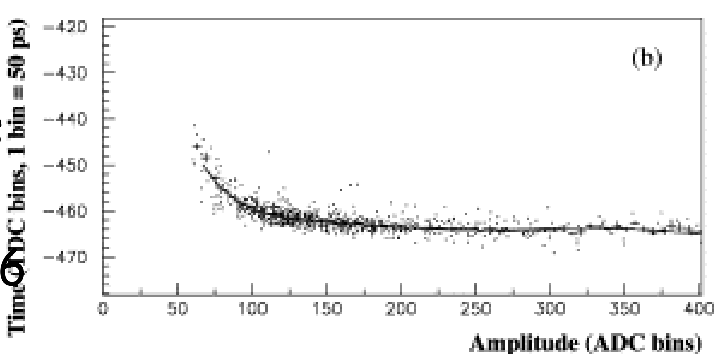
σ_τ = 55 ps Eff=98%

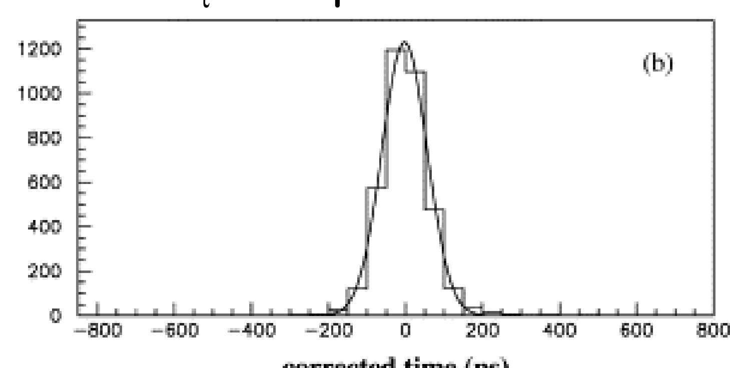
STAR prototype

Six 220 μm gas gaps

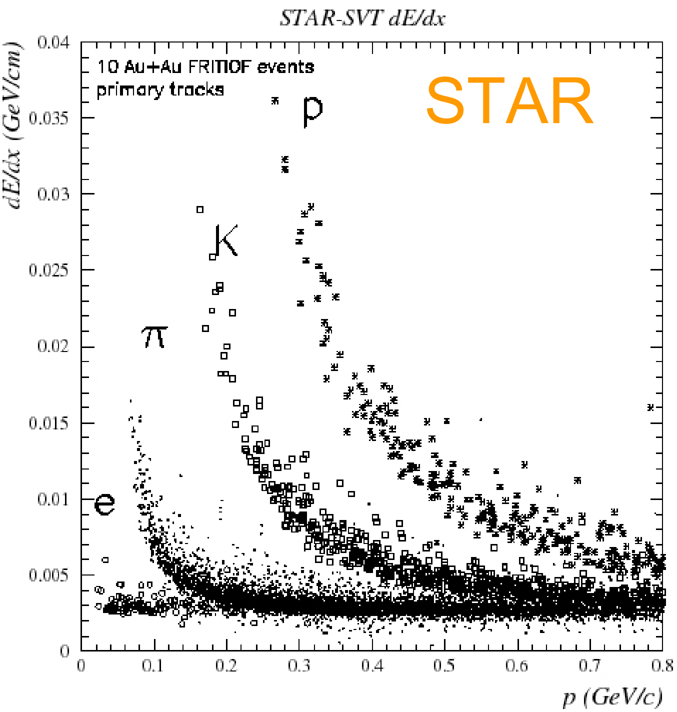
6.5 x 19.5 cm^2

NIMA 478 (2002) 176

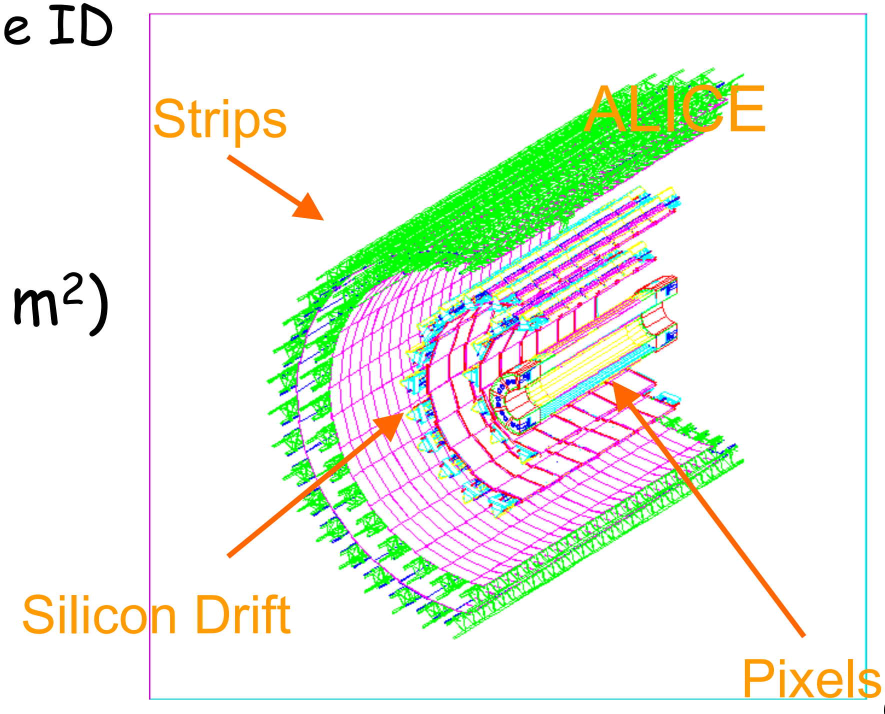




Silicon for tracking: Drift Detectors



- SDD fully functioning in STAR SVT since 2001
- 216 wafers, 0.7 m^2
- 10 mm in anode direction
- 20 mm in drift direction
- Particle ID



SDD also chosen by ALICE (1.3 m^2)

Similar requirements:

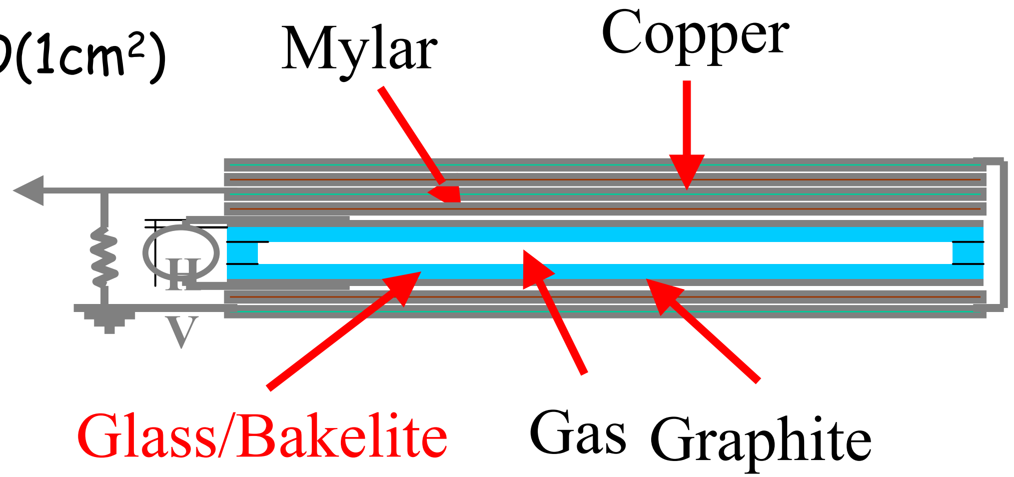
-high multiplicity

-dE/dx

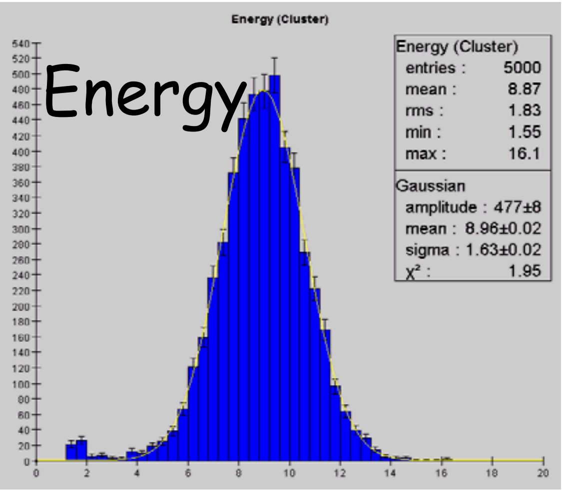
RPCs for the LC HCAL

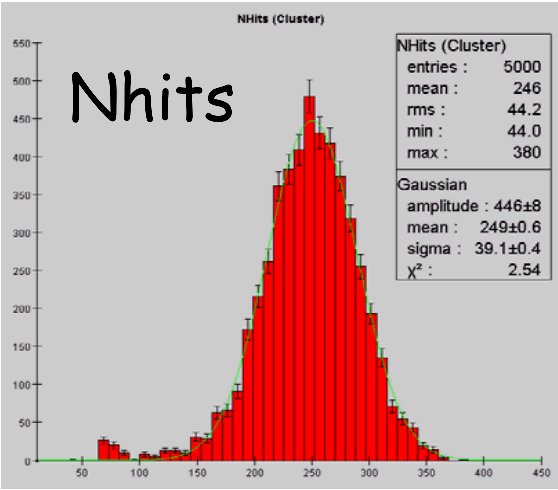
Ability to finely segment: O(1cm^2)
Works in magnetic field
Fits in gap of < 8 mm
Efficient (>95%)
Reliable
Affordable

All requirements met by RPCs



Analog 10 GeV π's Digital



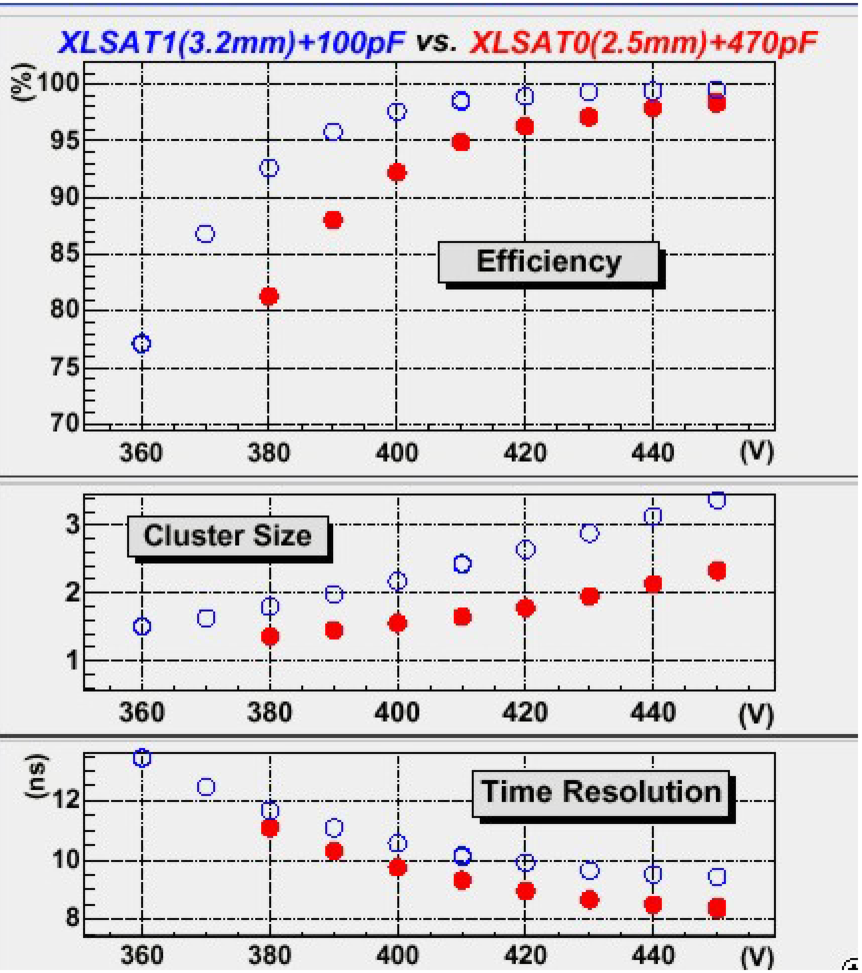


Eflow driven simulations will study detector parameters e.g.

- Transverse segmentation
- Cell depth absorber density
- Layer geometry

Micromegas for COMPASS

- COMPASS: fixed targed experiment at the CERN SPS:
- measure gluon spin contribution to nucleon spin



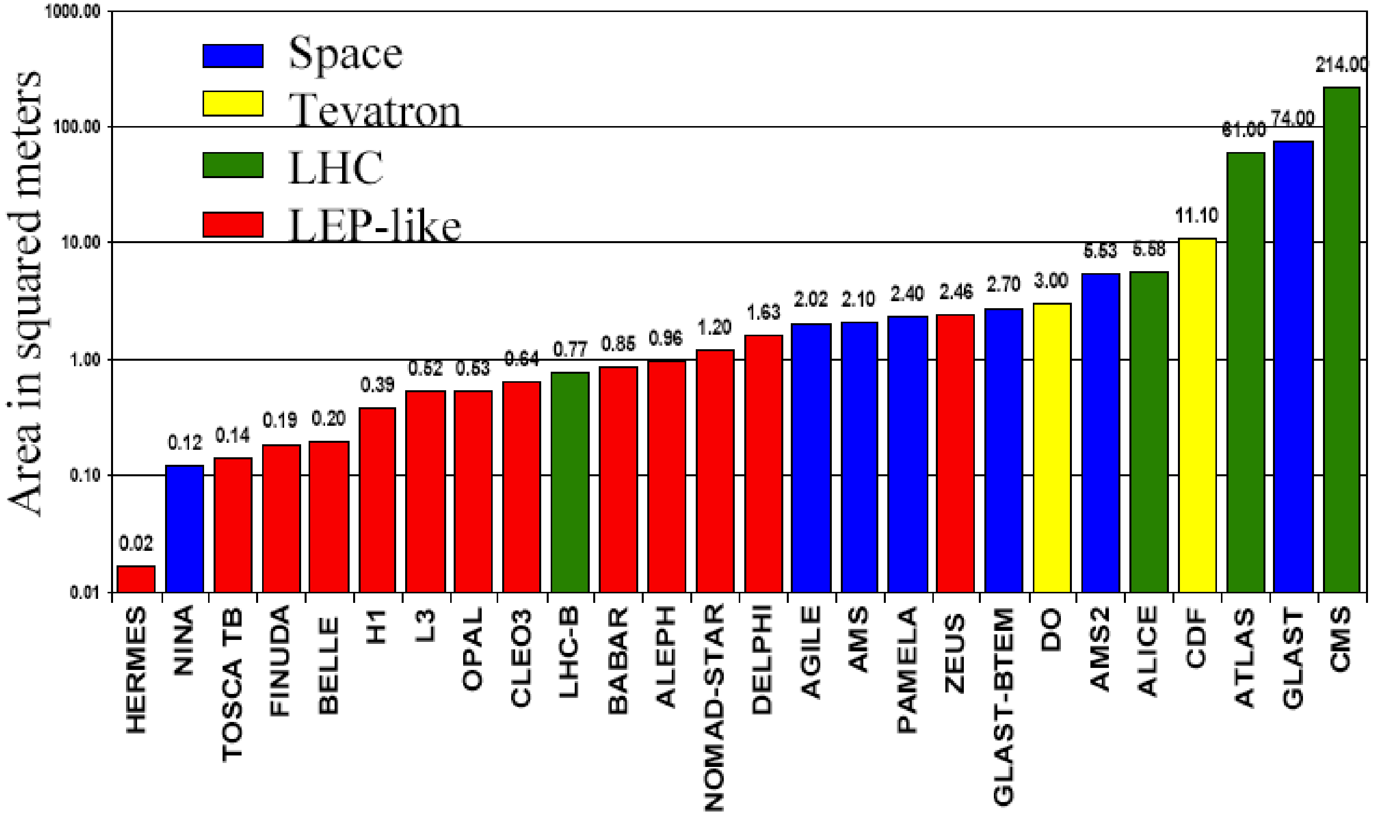
- Compass requirements matched to MPGD performance
  - High rate capability ~100 kHz per strip
  - Good spatial resolution
  - Large active area
  - No aging/discharges

- Compass is largest MGPD application
  - 12 planes, 40 x 40 cm^2
  - Spatial resolution ~ 70 μm
  - Time resolution ~ 10 ns
  - 0.45% radiation length

- PHYSICS DATA WITH FULL DETECTOR SINCE JUNE 24 2002

Size of silicon detectors

Experiments using silicon strip detectors



E. do Couto e Silva – SLAC/Stanford University Vertex 2000, Sept 10-15, National Lakeshore, MI, USA

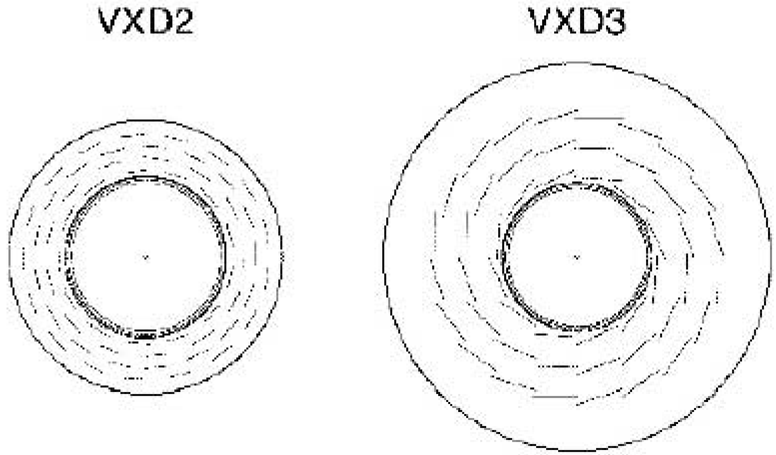
Impact parameter resolution

Some figures of merit

Impact parameter resolution, combination of two contributions:

- single hit precision and lever arm, VXD3: 3.8μm
- multiple scattering: size of beam-pipe, amount of material.

DELPHI R_{pipe}=56mm: $\sigma_{d_0} = \sqrt{28 \bigoplus 71/(p \times sin^{3/2}\theta)}\mu$m



SLD=VXD2 R_{pipe}=25mm: $\sigma_{d_0} = \sqrt{11 \bigoplus 70/(p \times sin^{3/2}\theta)}\mu$m

SLD96=VXD3 R_{pipe}=23mm: $\sigma_{d_0} = \sqrt{8 \bigoplus 33/(p \times sin^{3/2}\theta)}\mu$m

Rubbia (I)

4. Liquid Argon imaging TPC

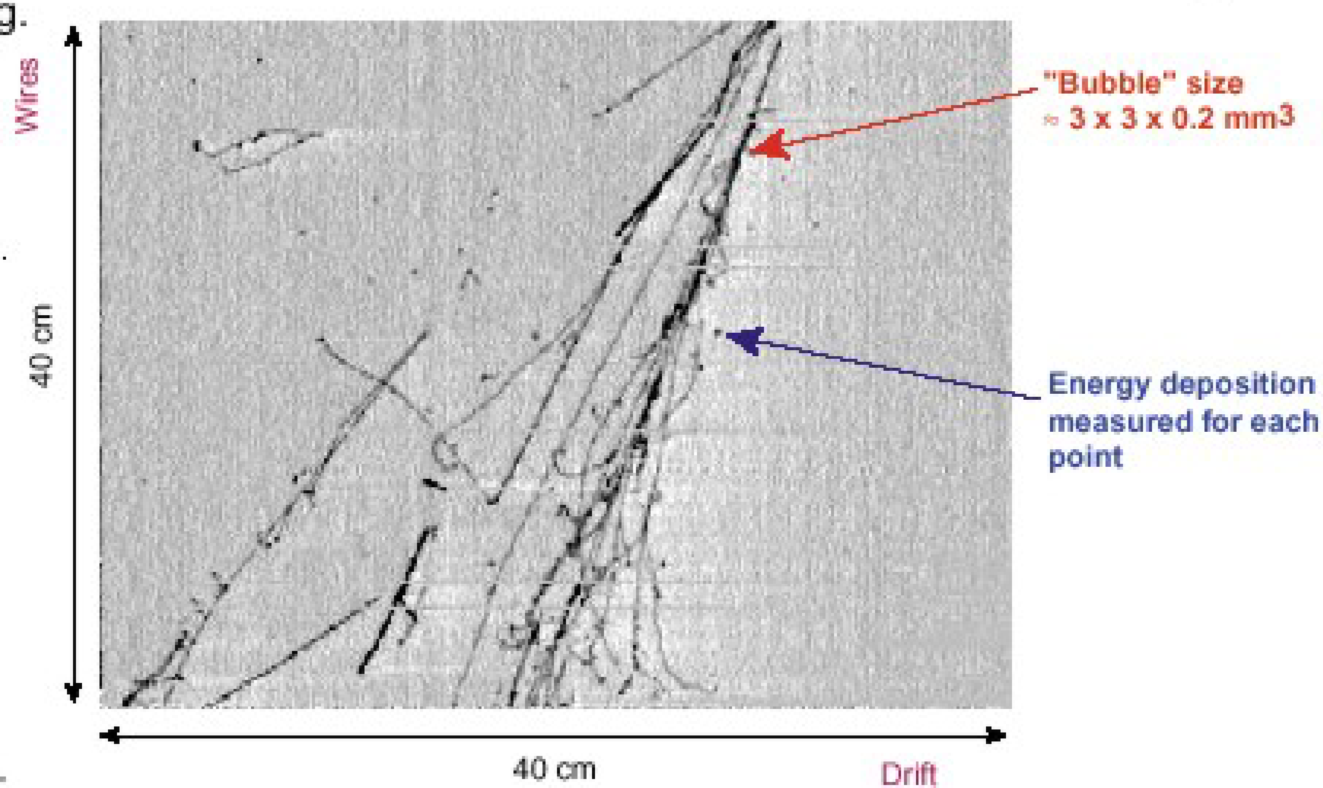
- ***ICARUS***: mature technique, demonstrated up to 15 ton prototype
- Features provided:
  - → Detects: μ^+, μ^-, e, NC, [τ]
  - → Fully homogeneous, continuous, precise ***tracking device*** with high resolution dE/dx ***measurement*** and full sampling ***electromagnetic and hadronic calorimetry***
  - → Excellent ***e identification/measurement*** and ***e/hadron*** separation
  - → Very good hadronic energy resolution
- 600 ton prototype construction ***very advanced***
  - → After the foreseen series of technical tests to be performed in Pavia within the summer 2001, ***the T600 module will be ready to be transported into the LNGS tunnel***
- Disadvantages:
  - → Muon charge discrimination: target cannot be easily magnetized (but...)
  - → Rely on ***down-stream muon spectrometer*** (low threshold since dE/dx ≈ 240 MeV/m)

Idea first implemented in the ICANOE proposal

Rubbia (II)

Liquid Argon technology

- The LAr TPC technique is based on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized (i.e. a set of fine pitch wire grids) it is possible to realize a massive "electronic bubble chamber", with superb 3-D imaging.

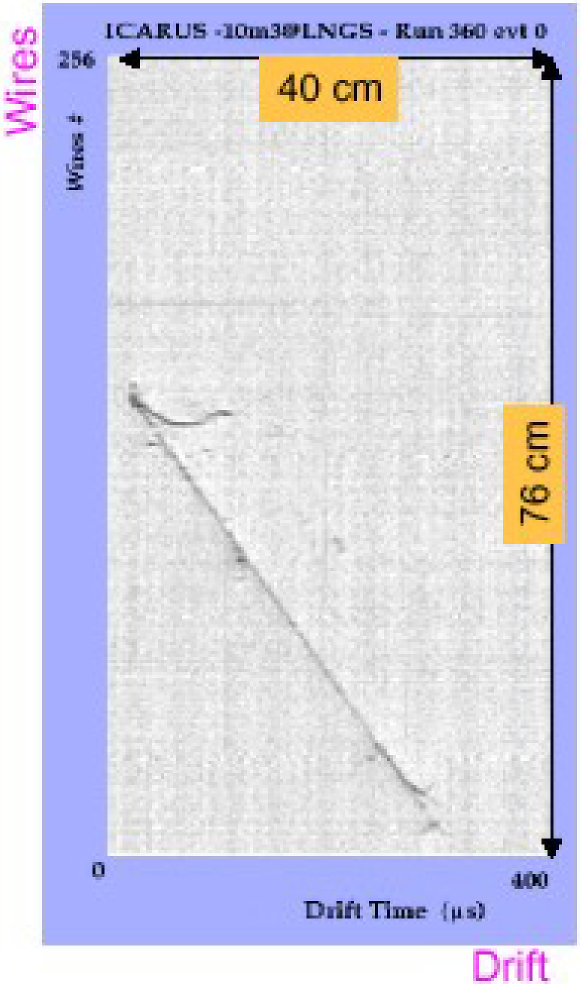


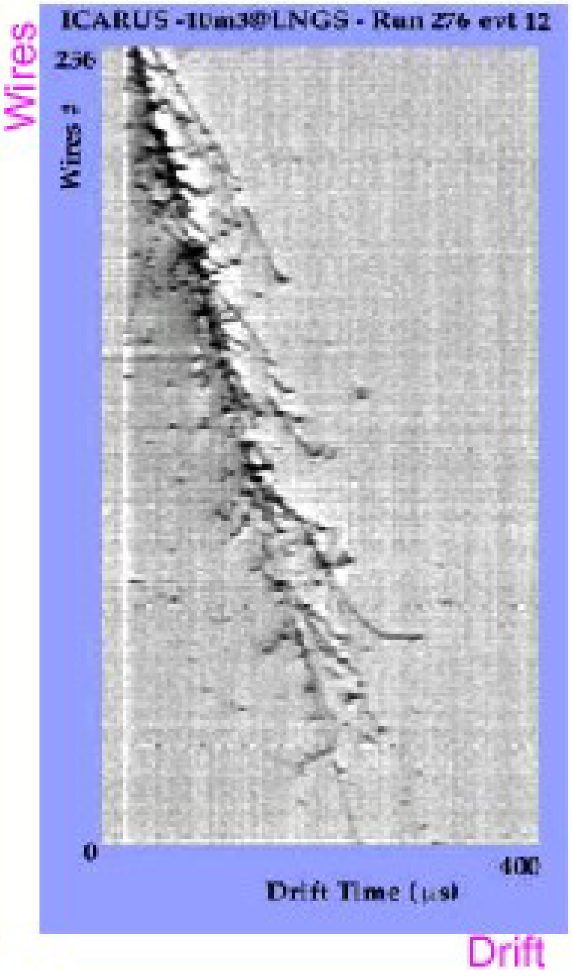
Rubbia (III)

Liquid Argon imaging on large scales

10m³ Module at LNGS

Cosmic Ray tracks recorded during the 10 m³ operation





"Big track" in T600 semimodule expected soon...