Detector Technologies for LC

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LCWS, Paris, April 19, 2004

1. Requirements
2. Vertexing
3. Central tracking
4. Calorimeters
5. Other systems

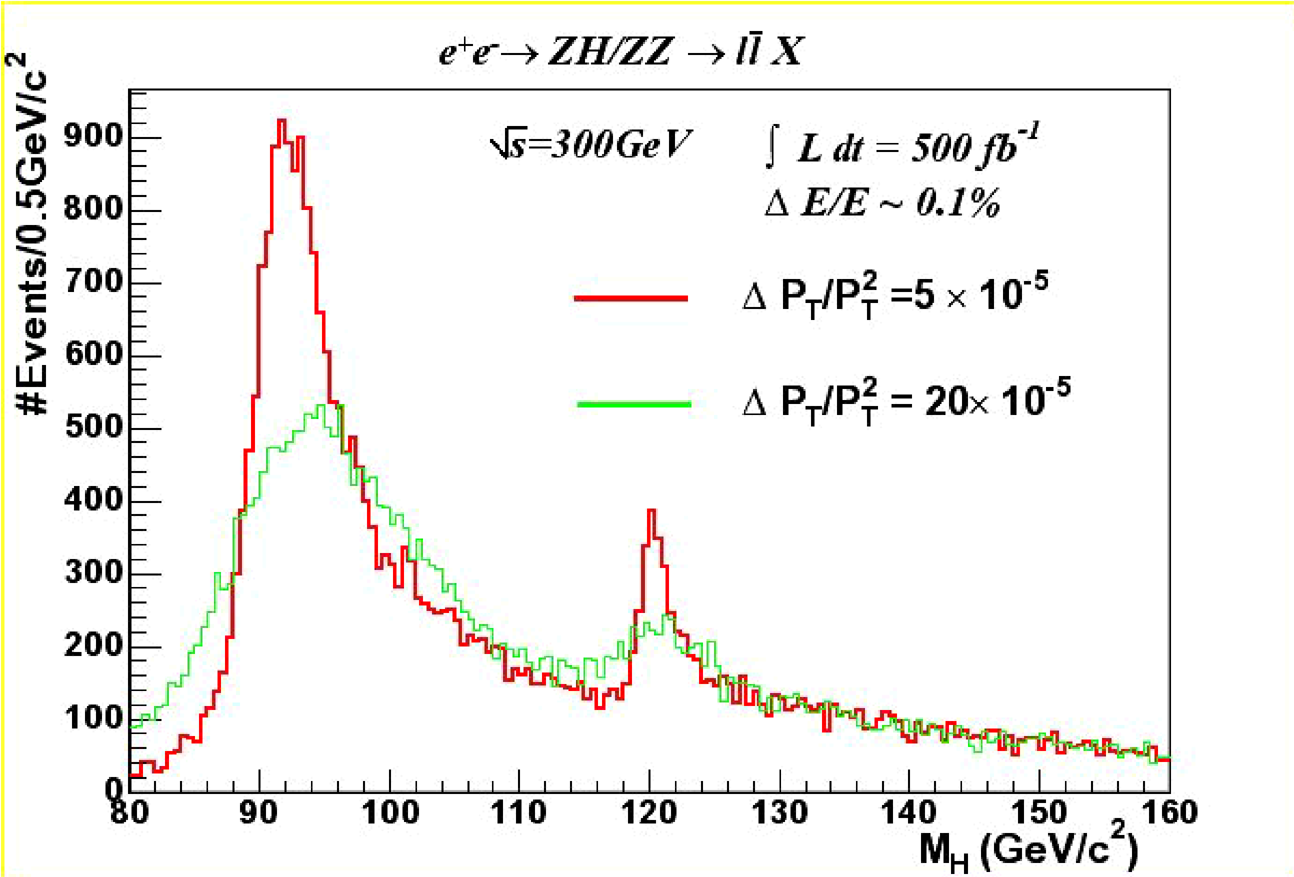
Detector performance goals (Int'l R&D review)

- central tracking: $\sigma(\frac{1}{p_t}) \leq 5 \times 10^{-5}(\mathrm{GeV/c})^{-1}$
  ($\sim 1/10$ LHC. 1/6 material in tracking volume.)
- Jet energy: $\dfrac{\sigma_E}{E} \simeq 0.30 \dfrac{1}{\sqrt{E(\mathrm{GeV})}}$
  (1/200 calorimeter granularity w.r.t. LHC)
- vertexing: $\sigma_{r\phi,z}(ip) \leq 5\,\mu\mathrm{m} \oplus \dfrac{10\,\mu\mathrm{m\,GeV/c}}{p\sin^{3/2}\theta}$,
  ($1/5\ r_{\mathrm{beampipe}}$, 1/30 pixel size, 1/30 thin w.r.t LHC)

Exploits the clean environments of LC.
Not a luxuary, but needed for LC to do its physics.

e.g: The Higgs tagging mode

$$e^+e^- \to ZH, \quad Z \to \ell^+\ell^-$$

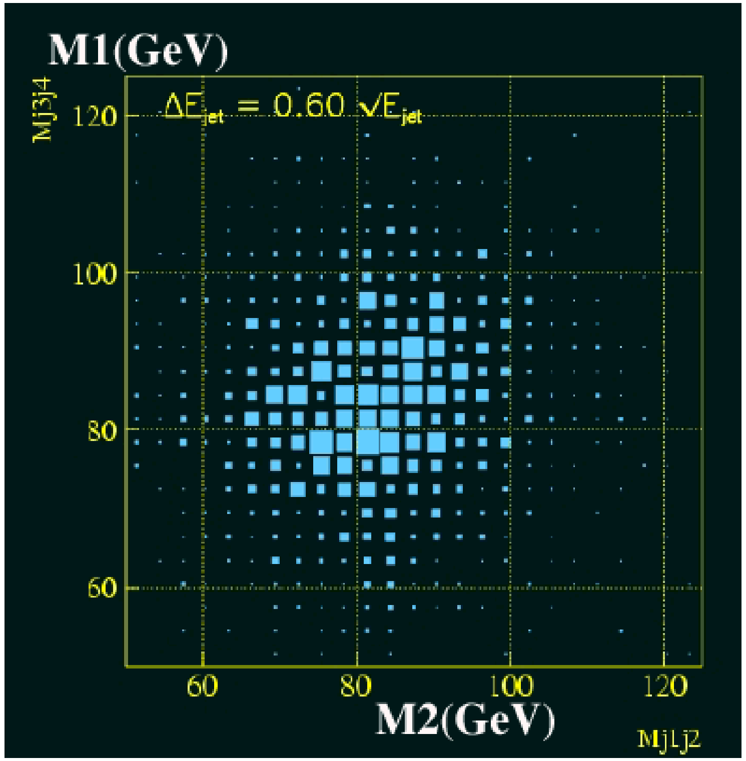


$$\frac{\sigma_p}{p^2} \sim 5 \times 10^{-5}$$ is 'necessay'.

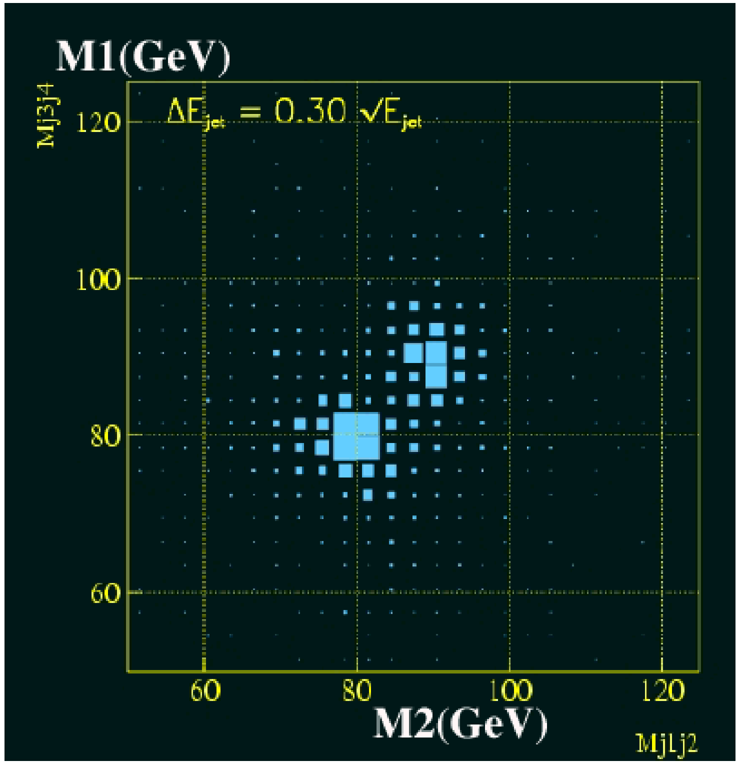
e.g: Separation of WW and ZZ

$$e^+e^- \to \nu\bar{\nu}W^+W^-, \nu\bar{\nu}ZZ\,, \quad W, Z \to 2\text{jets}$$

$$\frac{\sigma_E}{E} = \frac{0.6}{\sqrt{E}}$$



$$\frac{\sigma_E}{E} = \frac{0.3}{\sqrt{E}}$$



$\frac{\sigma_E}{E} \sim \frac{0.3}{\sqrt{E}}$ **is 'needed'.**

Beam Structures

	warm (GLC/NLC)	cold (Tesla)
#bunch/train	192	2820
#train/s	150/120 Hz	5 Hz
bunch sp.	1.4 ns	337 ns
train length	269 ns	950 μs
gap/train	6.6 ms	199 ms

Assuming the same luminosity for warm and cold,

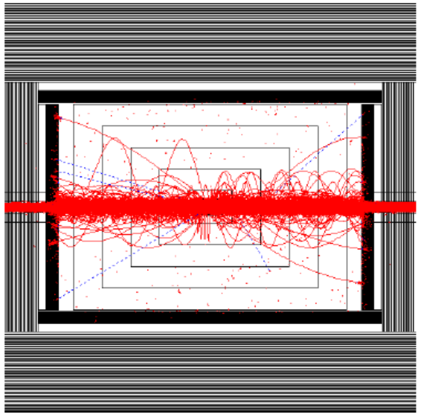
- Luminosity per train: warm/cold $\sim$ 5/150 = 1/30

If beam background $\propto$ luminosity ($\sim$ expected),

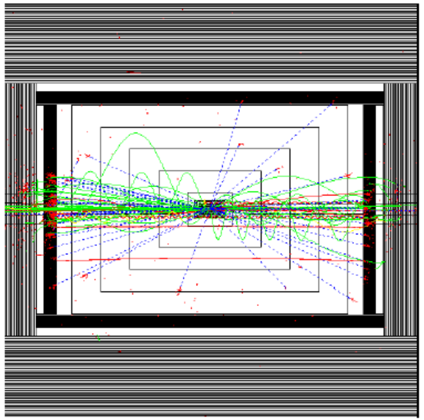
- Background per train(warm)
  $\sim$ Background in 950/30=30μs(cold)

Beam Backgrounds/train Hitting Detctor (warm) (T. Barklow)

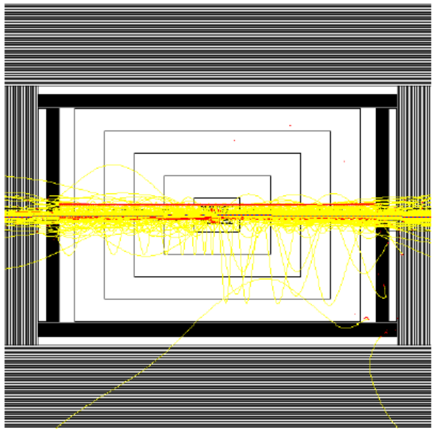
e pairs: 9Ktrks



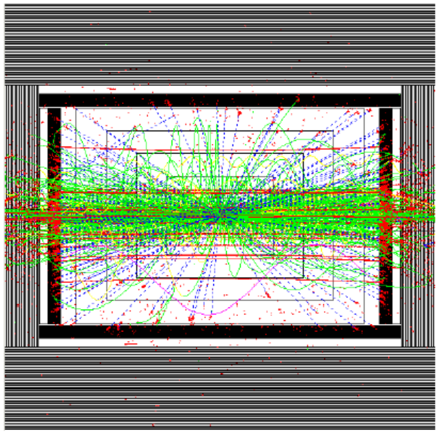
'hadrons': 50trks,80GeV



μ pairs: 20trks,60GeV



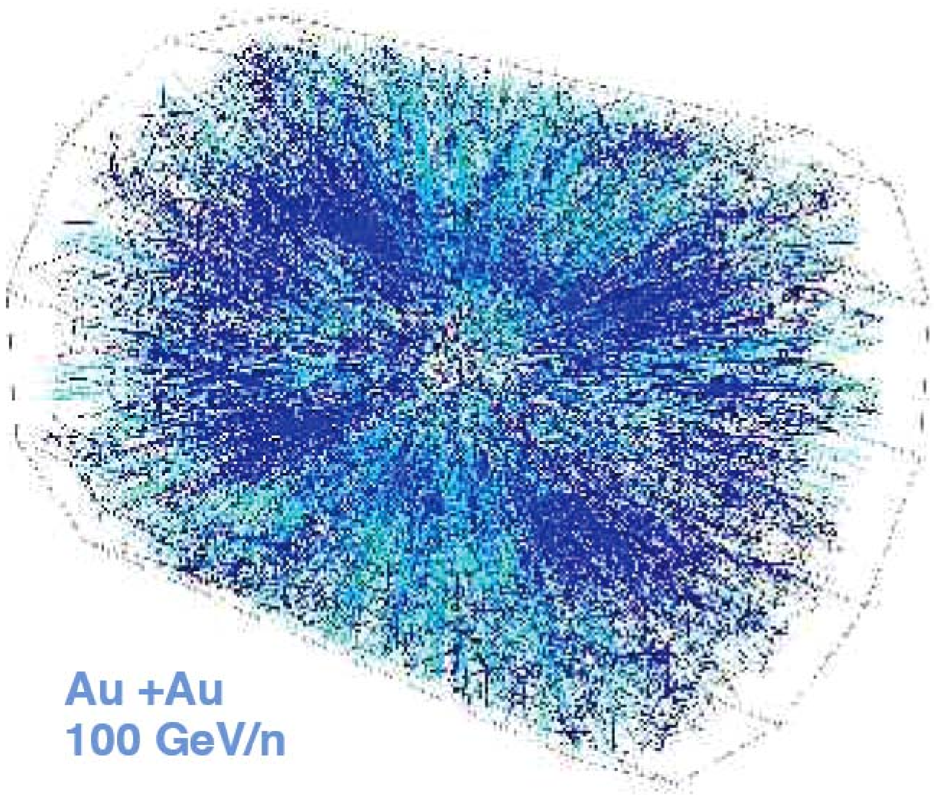
$\gamma\gamma$hadrons: 100trks,450GeV



- Overlay of these ($+\alpha$) is what we have after 1 train passing.
- Hits in vertexing are dominated by e pairs.
- Trks in central tracker dominated by $\gamma\gamma$ events.
- Physics event (if any) would be on top of it.

- Occupancy (w/o time) needs to be manageable.
- bunch id., time stamp highly desirable. (trkers and cals, esp. fwd regions)

A ‘typical’ STAR event (H. Wieman)



1. Vertex Detector

Occupancy $\rightarrow$ pixel devices needed.

- Pixel size $\sim 20 \times 20 \mu\text{m}^2$.
- Occuancy $\sim$ 0.3% for track matching.
- One should be able to read it out
  (non-trivial, as it turns out).

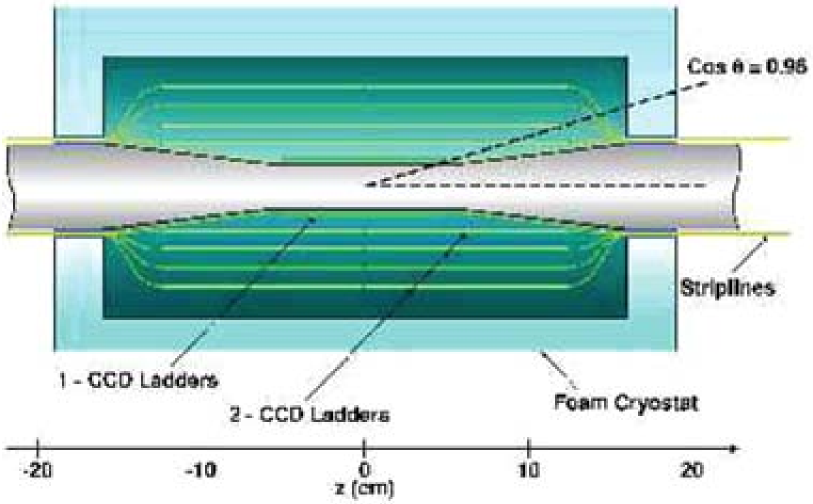
Candidates :

- CCD (Charge-Coupled Device)
- HAPS (Hybrid Pixel Sensors)
- MAPS (Monolithic Active Pixel Sensor),
  FAPS (Flexible -), Small-pixel MAPS ($5 \times 5\mu\text{m}^2$)
- DEPFET (DEPleted Feild-Effect Transistor)
  SOI (Silicon On Insulator)
- ISIS (Image Sensor with In-situ Storage)

CCD

- LCFI (LC Flavour Identification) collaboration:
  UK (Bristol,Glasgow,Lancaster,Liverpool,Oxford,RAL)
- US collaboration (Oregon, Yale, SLAC)
- Japanese collaboration (KEK, Niigata, Tohoku, Toyama)

LCFI CCD (gas-cooled)



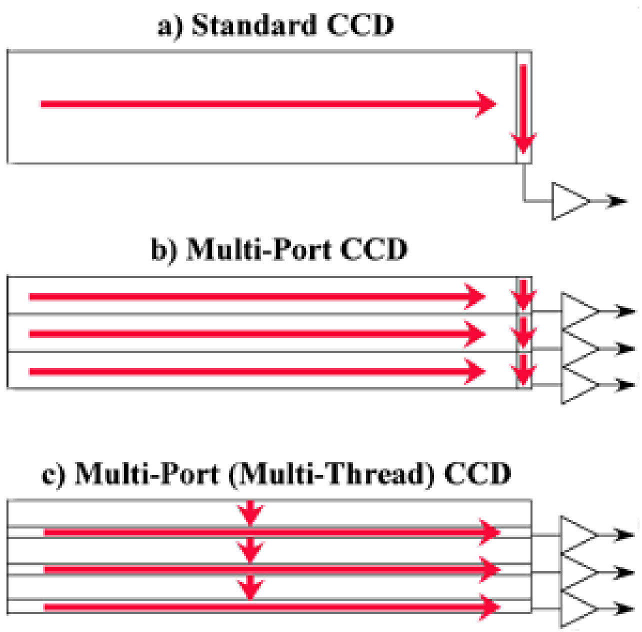
- proven performance at SLD
- Good spacial resolution ($< 5\mu$m)
- slow readout
- modest radhardness
- needs to be cooled(?)

CCD for Warm Machine

- Integrate signal over one train
  Expected occupancy $\sim$ 0.3% (OK).
- Shift out during the train gap (7ms), after RF pickups have died down.

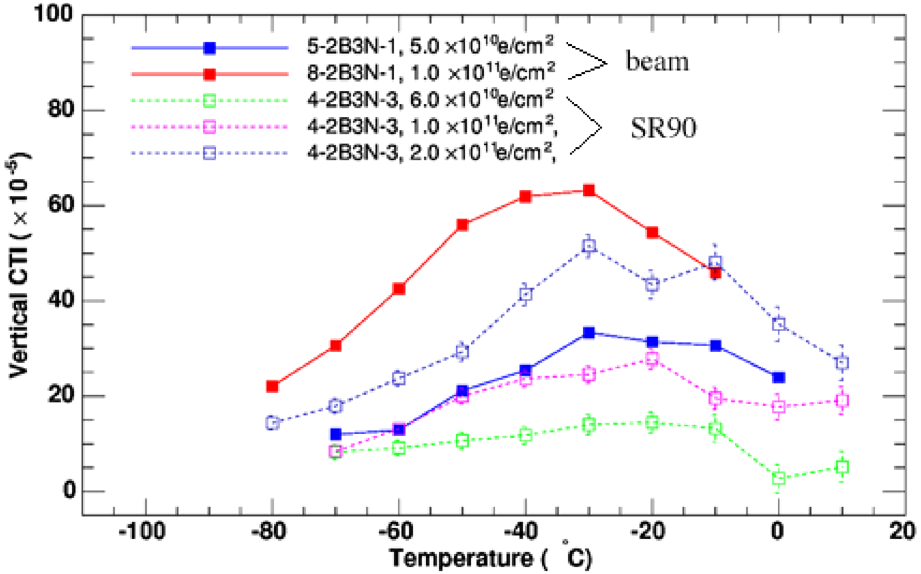
<R&D's on-going>

- Conventional serial readout too slow.
  $\rightarrow$ Multi-port readout.
- e.g. 50 ports for 2×10cm^2-area $(20\mu\text{m})^2$-pixel CCD to be readout in 5ms (20 MHz).
- Thinned sensor ($\sim$50μm).
- Mechanical support.
- Room temperature operation.
- Radiation hardness (acceptable).



Electron irradiations (150 MeV e beam, SR90)

CTI (Charge transfer inefficiency)
vs temperature

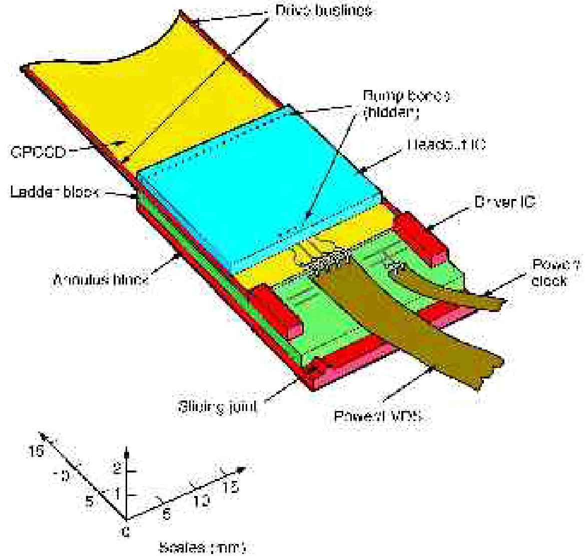


(by Sugimoto)

- 150MeV electrons 2∼ 3 times more damaging than SR90.
- CTI imporves at higher temperature.
  Fat-zero charge injection.

CCD for Cold Machine

- Need to read out every 50μs (20 times) during a train for ~0.5% occupancy.
- → 50 MHz collum-parallel readout (CPCCD, 5cm-long).
- First prototype made and working.
- Clock feedthrough for > 16 MHz.
- Charge collection ~ 100 ns.
  → at 50 MHz, a signal charge is spread over several buckets.
  → Fully-depleted CCD.
  → Charge distribution study.
  Or, need to hold clock during charge collection.
- But very nice for warm machine. (proof of solution)



LCFI CPCCD (exists!)

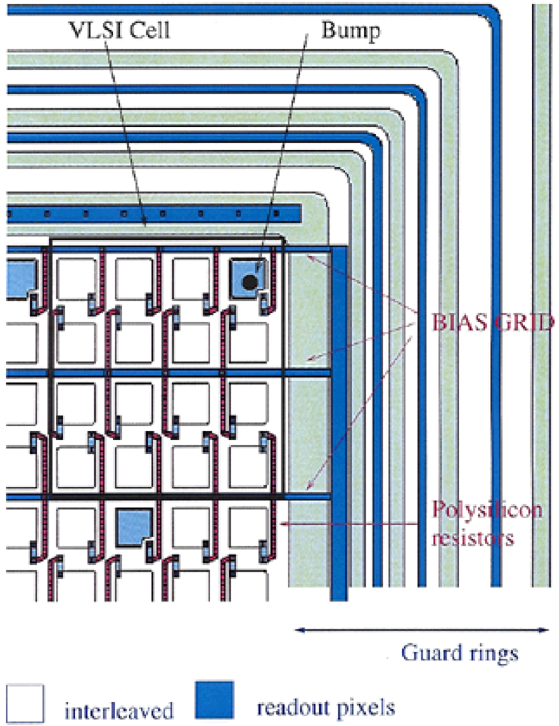
HAPS (Hybrid Active Pixel Sensors)

(CERN, Helsinki, INFN, Krakow, Purdue, Warsow)

A sensor made of high-registivity silicon bump-bonded to readout chip(s) fabricated by a commercial process.
(a la LHC pixel sensors)

R&D items

- material reduction
- smaller pitch
  (typ. 50x400 μm^2 too big)
- capacitively-coupled readout
  to reduce #channel
  Works reasonably well.



MAPS (Monolithic active pixel sensors)

(Strasbourg, RAL, IRES, LEPSI $\rightarrow$ MAPS collaboration)

- Readout/sensor on one chip.
- CMOS image sensor technology (commercial process).
- Pixel size ~CCD.
- (cold) Read out every 50μs.
  Charge sharing OK
  (not coninuously shifted at high rate)

R&D items

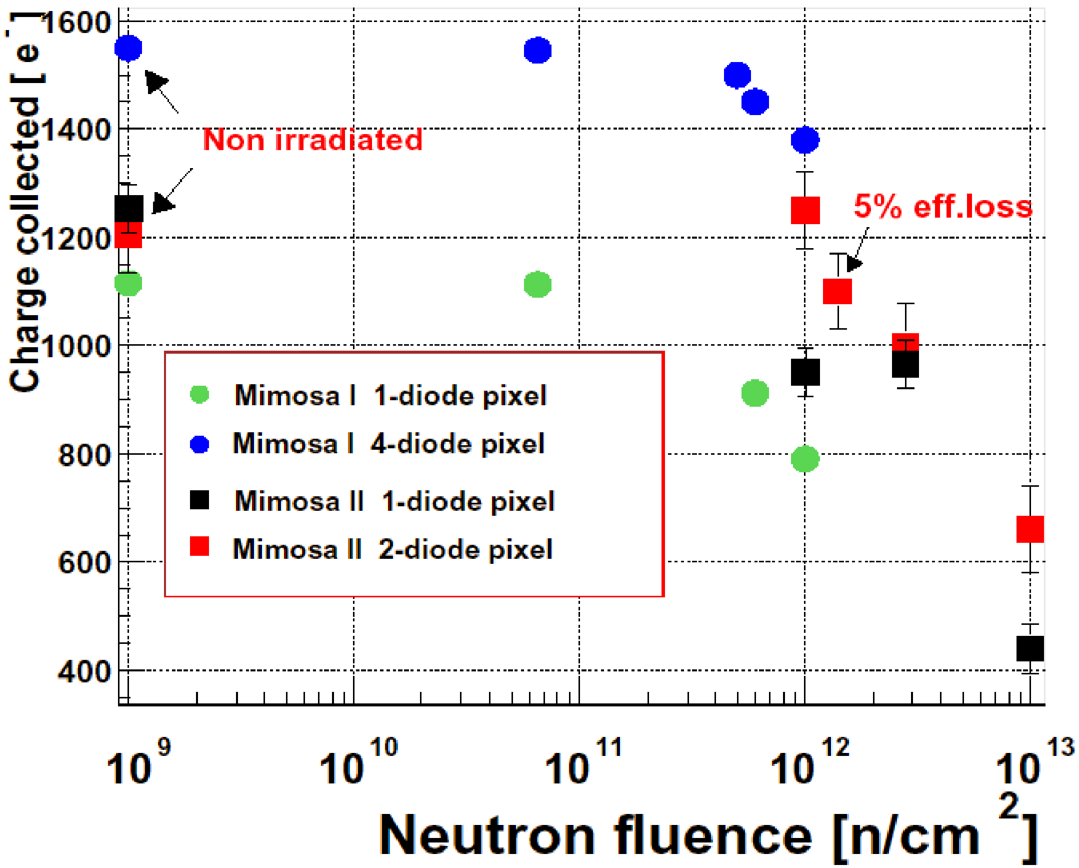
- large-area sensor (3.5 cm^2 - MIMOSA-5 tested OK)
- fast readout (50 MHz possible)
- thinning (120 μm tested OK - MIMOSA-5)
- CP, CDS and fast enough. . . .
  (column-parallel, correlated double sampling)

MIMOSA Chips

v.	MIMOSA-4	MIMOSA-5	MIMOSA-6
year	2001	2001	2002
tech.	AMS 0.35μm	AMS 0.6μm	MIETEC 0.35μm
epi.	0μm	14μm	4.2μm
pitch	(20μm)^2	(17μm)^2	(28μm)^2
array size	64^2	$\sim 1000^2$	64^2
readout BW	40M Hz	40 MHz	30 MHz
feature	no-dope subs.	(1.75 cm)^2	CP, CDS

- $\sigma_{\text{sp}} = 1.5(2.2)\mu$m for 14(4)$\mu$m epi.
- 50 μm readout needs to be demonstrated.
  Currently, CDS takes time,
  and read out transversely.
- Rad-hardness acceptable.

MIMOSA Radiation Hardness

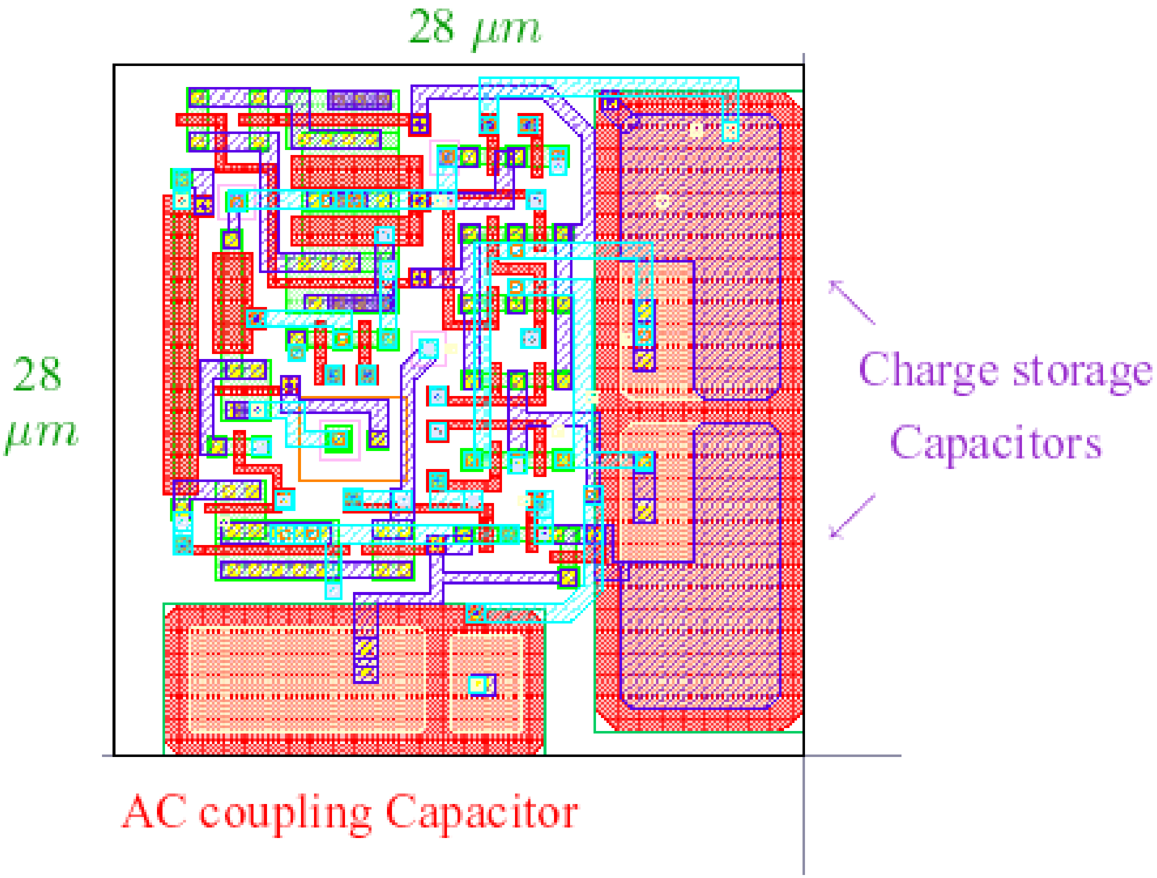


5% drop in charge at 1.5E12 n/cm^2
Acceptable for linear collider.

MIMOSA-6

CP (Column-parallel readout, 128ch/line)
CDS (Correlated double sampling)

Pixel electronics

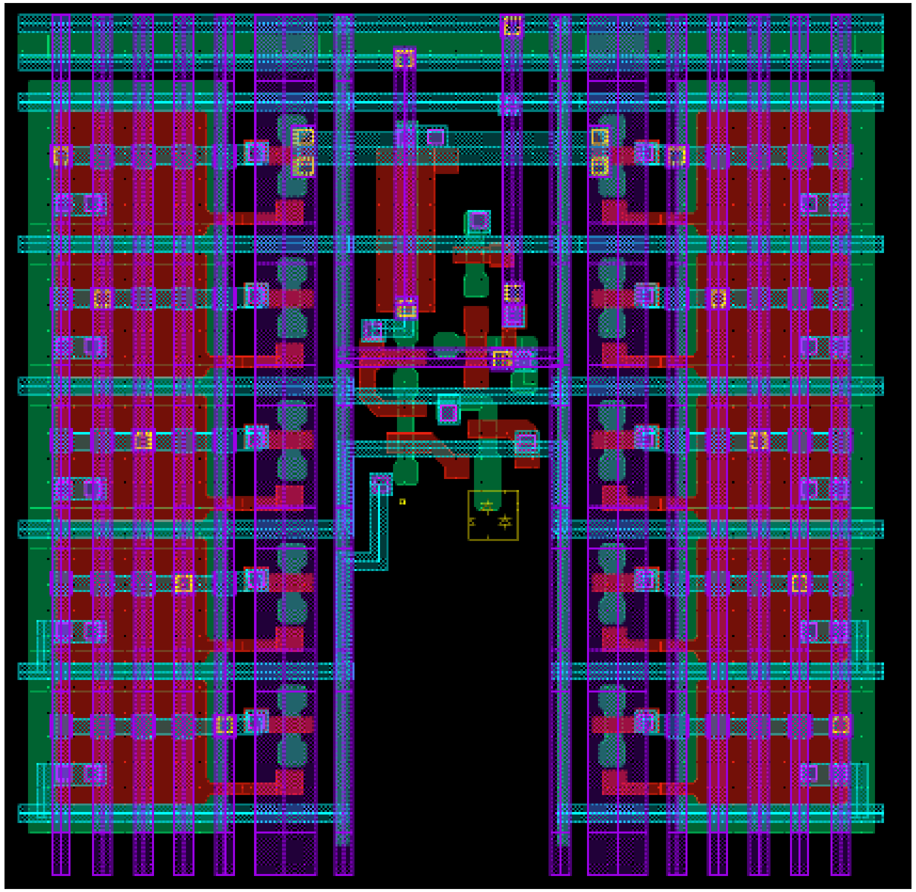


- 2 storage capacitors for CDS.
- Shrinking of size expected.
- Fabricated.
  Currently under test.

FAPS (Flexible APS) (RAL)

Extension of MIMOSA-6 CDS (applicable also to HAPS)

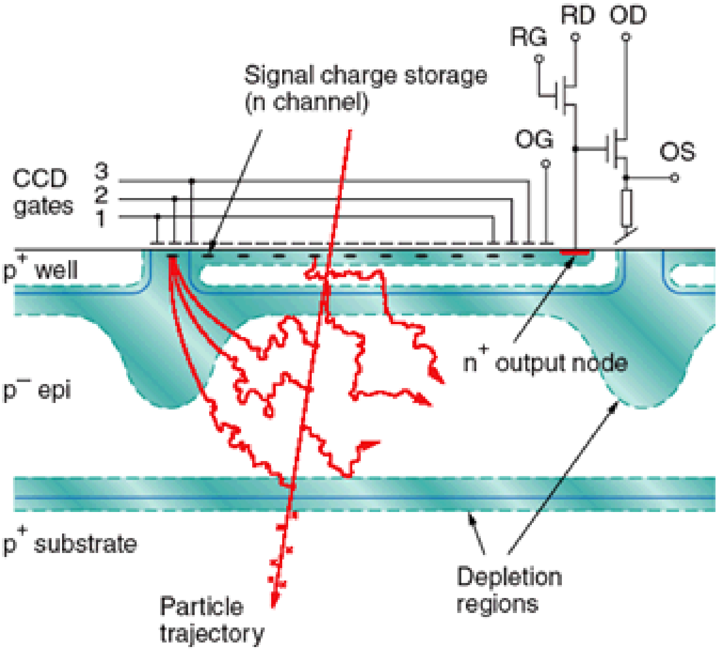
Pixel electronics



- 10 storage capacitors/pixel.
  20 should be possible.
  20 frames / train (cold)
- Useful for GLC/NLC also
  (if bkg is too large)

ISIS (Image Sensor with In-situ Storage)

(RAL)



- 20 burried-channel storages/pixel.
- Each storage stores 50μs time slice.
- Immune to RF pickup.
- Similar device commercially exist.
  Ultra high-speed camera :
  (up-to 1Mfps)
- Modification for LC is manageable.

2. Central Tracker

Two basic types:

- Gaseous
  large, many samplings/trk
  dE/dx π/K separation promising.
  - Jet chamber
  - TPC

- Silicon
  small, $\sim$5 samplings/trk
  No dE/dx π/K separation.
  (may be useful for new long-life heavy particles)

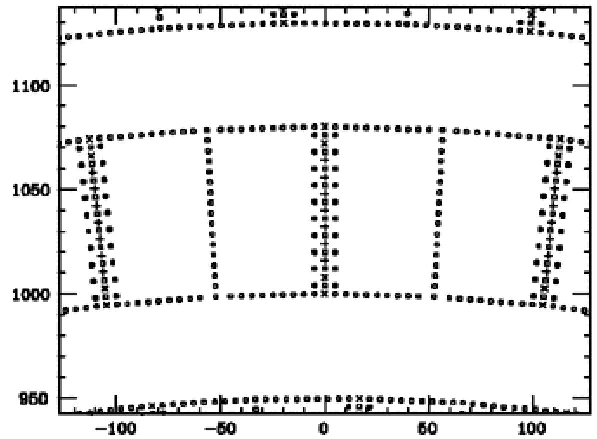
Jet Chamber

(Hiroshima, KEK, Kinki, Kogakuin,
MSU, Nagoya, Saga, Tsukuba, TUAT)

- Sag of 4.6m-long wires under control.
- $\sigma_{\mathrm{hit}} = 90\mu$m.
- 2-trk separation 2mm.
- Time stamp: $\sigma_t = 2$ns.
- $\sigma(1/p) < 10^{-4}$.

CO_2, isobutane (90/10)
sense : W D=30μm
field : Al D=150μm

Jet chamberis a viable option for the warm machine with B=3T.



- Neutron: 2khits/train.
- Positive ion problem
  for the cold technology

Needs further R&D for cold, or for B>3T.

TPC

LC-TPC: Aachen, DESY/Hamburg, Karlsruhe, Krakow, MPI-Munich, NIKHEF, Novosibirsk, Orsay/Sacley, Rostok, St. Petersburg, Carleton/Montreal/Victoria, LBNL, MIT, Chicago/Purdue/3M, BNL, Temple/Wayne St, Yale,

+ KEK

(Pros): Works at high B field (>3 T)
Good 2-trk resolution, dE/dx, No thick endplates.

(Cons): probably needs new charge readout system.
Bunch identification.

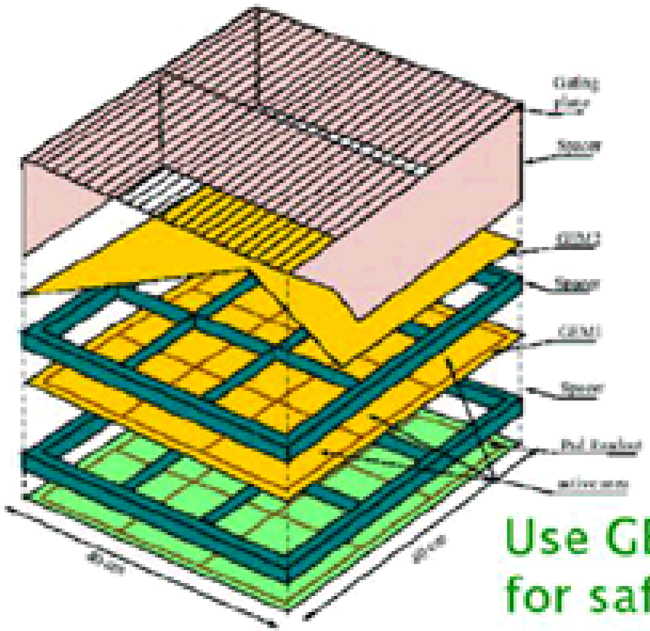
TPC readout devices

- Conventional: MWPC + pads.
  Positive ion feedback.
  Resolution limited by the MWPC response.

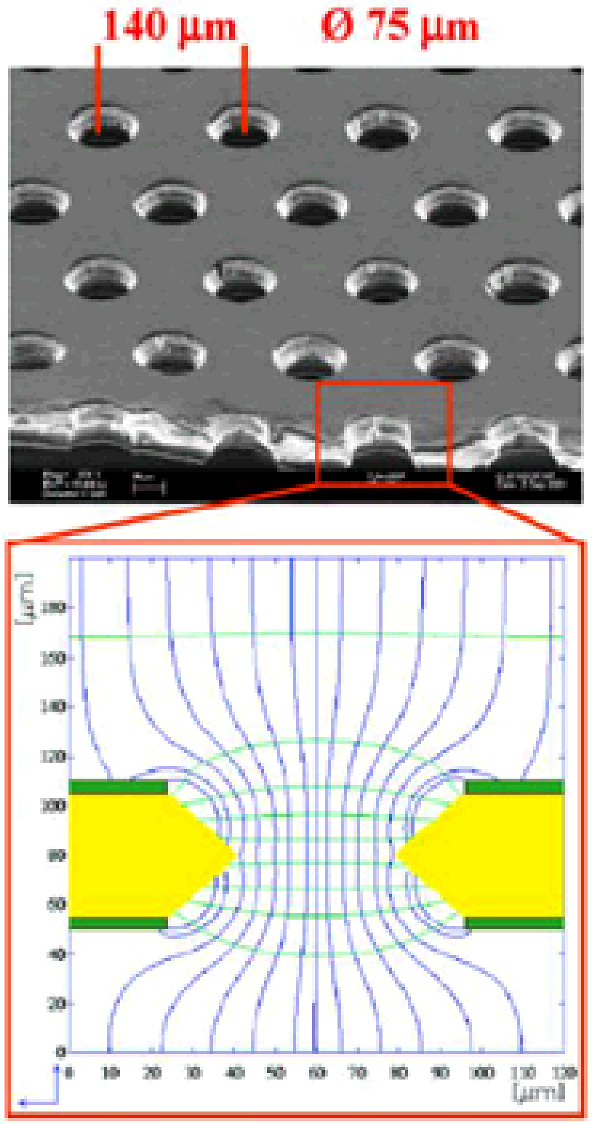
- MPGD's (Micro Pattern Gas Detectors)
  - GEM (Gas Electron Multiplier)
  - MicroMEGAS (Micro Mesh GAS detector)

Gas Electron Multiplier – GEM (F. Sauli 1996)

- 50 µm capton foil,
  double sided copper coated
- 75 µm holes, 140 µm pitch
- GEM voltages up to 500 V
  yield 10^4 gas amplification



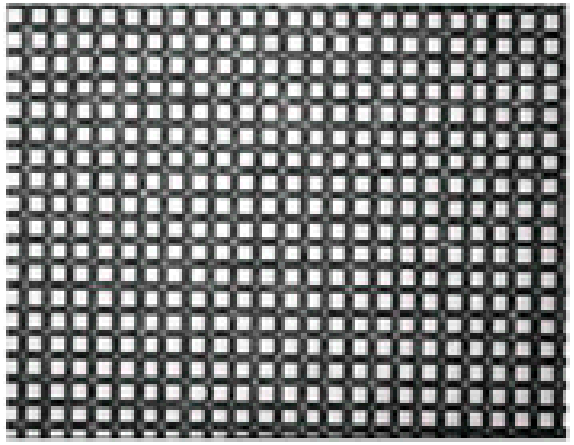
Use GEM towers
for safe operation
(COMPASS)

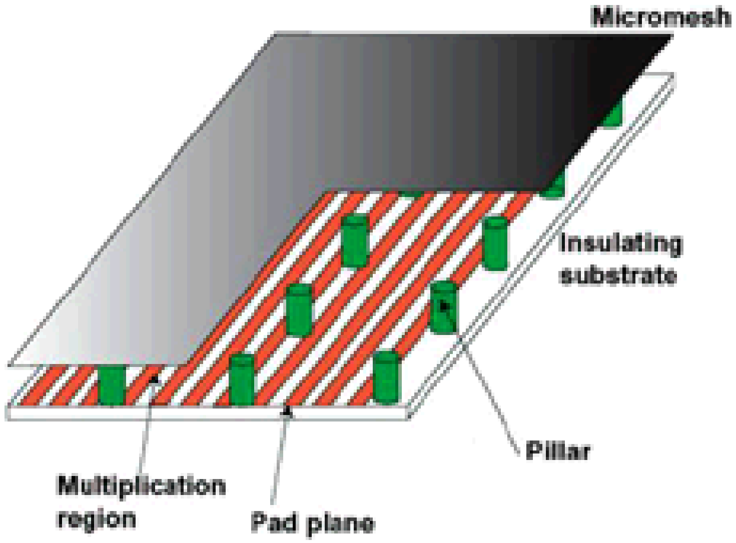


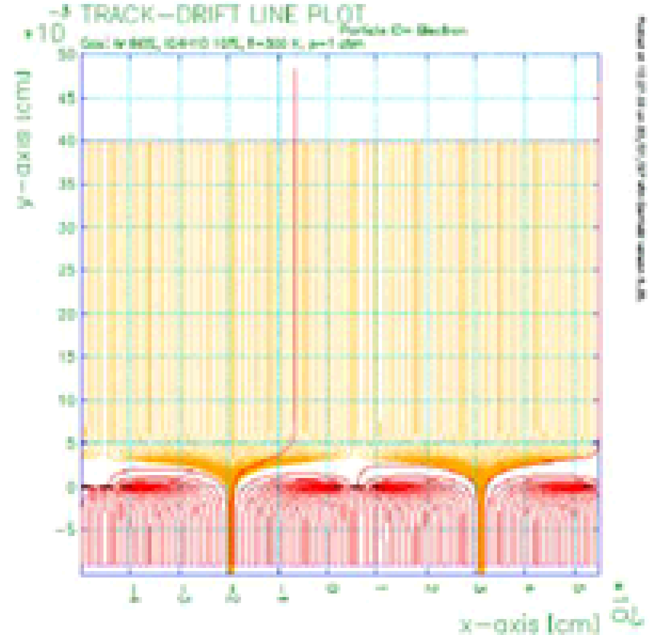
Micromegas (Y. Giomataris 1996)

- asymmetric parallel plate chamber with micromesh
- saturation of Townsend coefficient
  mild dependence of amplification on gap variations
- ion feedback suppression

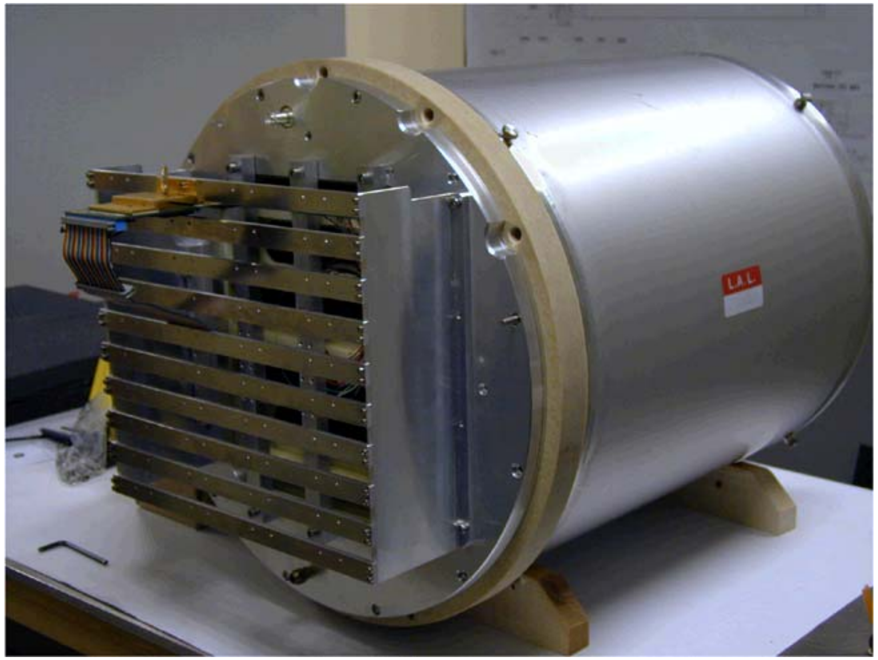
50 μm pitch







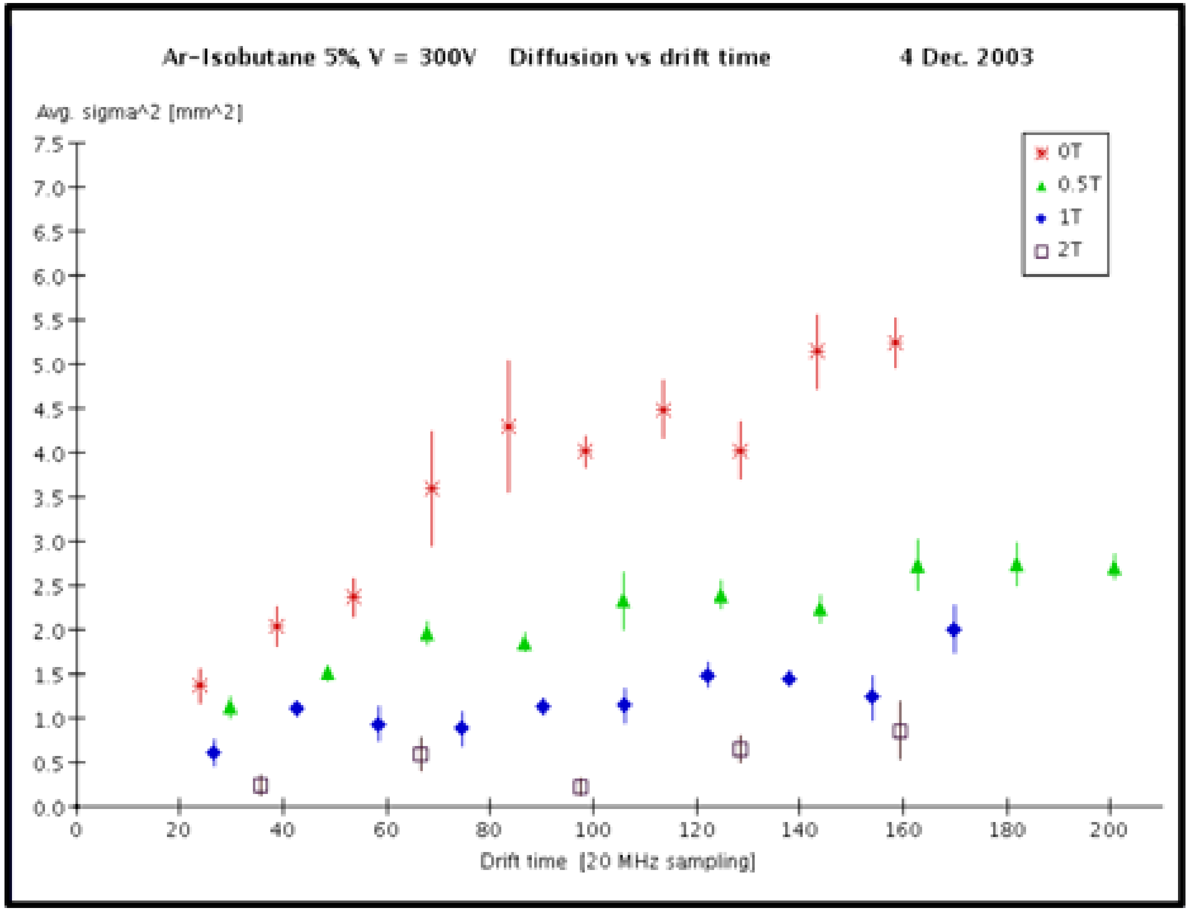
e.g. MicroMEGAS-TPC



- LBNL, Berkley, LAL Orsay, DAPNIA Saclay.
- 50cm-drft, 1000 channels.
- Tested up to 2T at Saclay (15cm-drft version) No gain drop with Fe55.

MicroMEGAS-TPC up to 2T

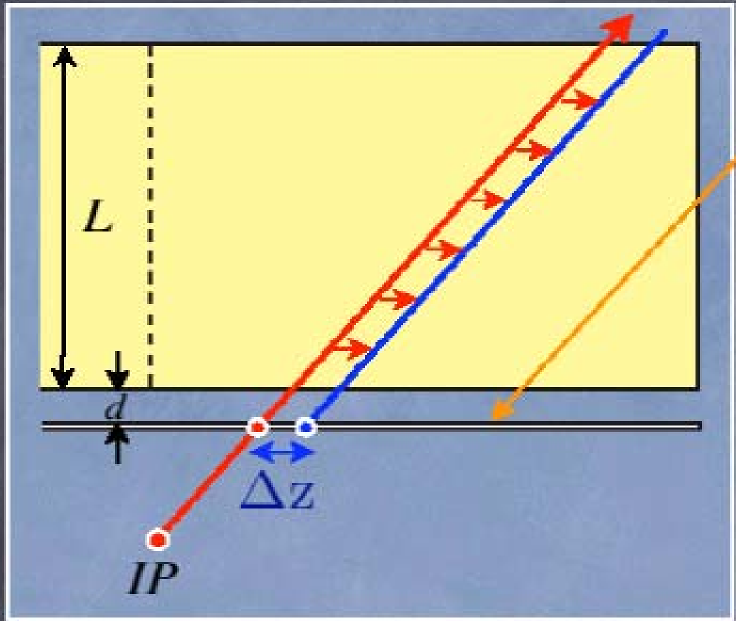
Diffusion vs drift time



TPC R&D Items

- Operation of GEM, MicroMEGAS (robustness)
- Gas studies. Ar + (CH_4 or CO_2 or CF_4). . . .
  neutron bkg, drift velocity, chimical features. . .
- Positive ion feedback.
  $\sim 0.3\%$ seems possible. Good enough?
- Electronics.
  Massive integration (2M ch). Faster sampling (>20MHz)
- Pad geometry. Size, shape.
- Charge spreading for better resolution.
  (Charge sharing over multiple pads)
- Time stamping.
- Beam backgrounds.

In the Case of TPC



External Z Detector (T0 Device)

Wrong T0 makes a Z-shift!

$$\Delta \mathrm{z} = v_{\mathrm{drift}} \times \Delta T_0$$

Naively we expect

$$\sigma_{\Delta T_0} \simeq \frac{2\sigma_{\mathrm{z}}}{v_{\mathrm{drift}}\sqrt{n}} \left[1 + 3\left(\frac{d}{L}\right) + 3\left(\frac{d}{L}\right)^2 \right]^{-\frac{1}{2}}$$

$$\simeq \frac{2\sigma_{\mathrm{z}}}{v_{\mathrm{drift}}\sqrt{n}} \quad \text{if} \quad \left(\frac{d}{L}\right) \ll 1$$

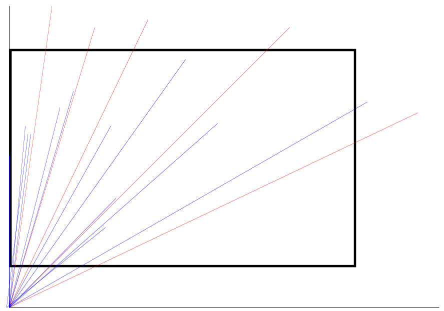
Assuming that Z resolution of the external detector is negligible

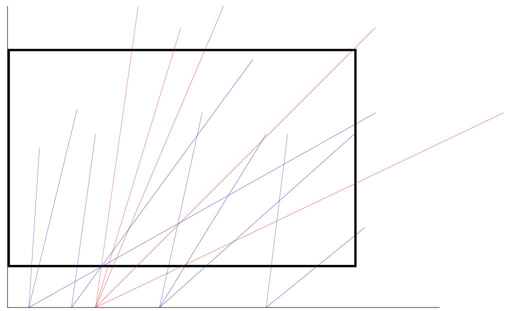
$$\sigma_{\mathrm{z}} = 500\ \mu\mathrm{m}$$
$$v_{\mathrm{drift}} = 5\ \mathrm{cm}/\mu\mathrm{s}$$
$$n = 120$$

$$\Rightarrow \quad \sigma_{\Delta T_0} \simeq 2.0\ \mathrm{ns}$$

Beam background in TPC

- Drift velocity$\sim$ 5cm/μs $\rightarrow$ 40μs to sweep 2.0m.
  During which time cold will have the same integrated beam background as one train of warm.
- Vertex dsitributions are different.
  warm: 70μm per bunch sp., 1.4cm/train
  cold: 1.7cm per bunch sp., 50m/train.





- Elimination of trks from other bunches: easier for cold.

Si Tracker (Small detector option)

A 5-layer Si tracker as the central tracking device
in high-B field (5Tesla)
($r_{\max} = 1.25$m, $L/2 = 1.67$m or a larger version)

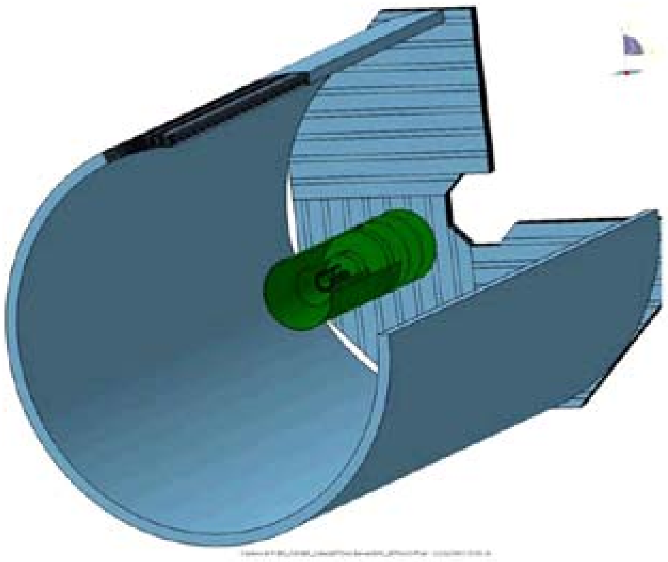
SiLC: CNM Barcelona, DPNG-Geneva, Helsinki, IEKP-Karlsrule, Obninsk,
LPNHE-Paris, INFN-Pisa, Charles U., Rome, Torino, AS Wien
+ Santa Cruz, Wayne St., Michigan, Korea (KNU, SNU, YSU, SKKU)

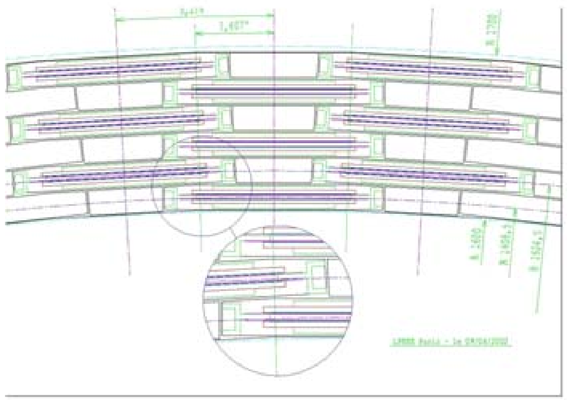
R&D Itmes:

- Thinner substrates/mechanical support.
- Long ladders (longer shaping time for low noise etc.).
- Power switching (to match trains).
- Pulse-height information (time walk, dE/dx)
- Alignment (inteferometer a la ATLAS)

Si tracker design (SiLC)

Serious design studies have begun.
(Also on sensors and electronics)





Forward Tracker

Silicon microstrip disks to cover down to $|\cos\theta| = 0.99$ (8 deg)
First few layers could be pixel sensors (TESLA TDR)

(Santa Cruz, SLAC)
simulation and protyping together with the Si tracker R&D.

Intermediate Tracker

Place between the vertex detector and the central tracker
to aid track matching between them
and to improve momentum resolution.

Relevant R&D's by
(LPNHE-Paris, Santa-Cruz/SLAC, Wayne State, Korea)

Additional Trackers

- Silicon External Tracker (SET)
  Just after TPC (endcap and barrel)
  (LPNHE-Paris)
  R&D: Cost reduction.

- Straw chambers (behind TPC endcap)
  (DESY)
  R&D: spacial resolution, material thickness,
  bunch tagging, calorimeter sprashback.

- Sicintillating fibre tracker
  between Vertexing and TPC
  (Indianna)
  R&D: timing precision, material thickness.

3. Calorimeters

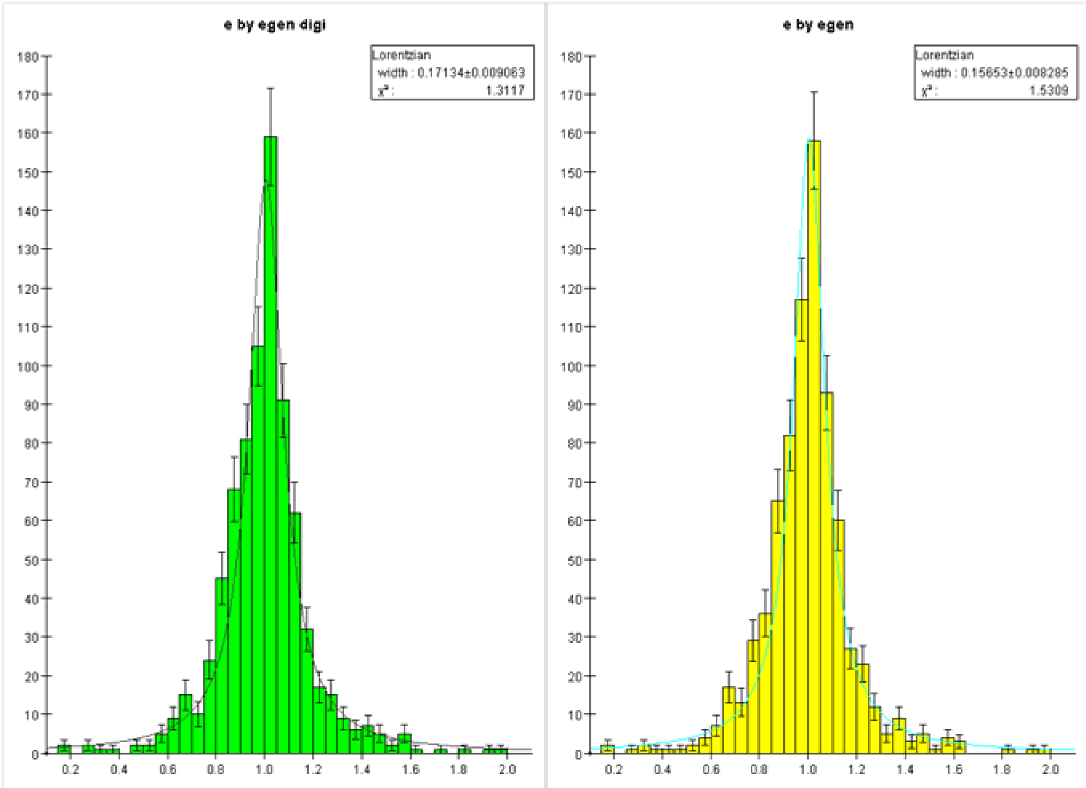
EFA/PFA ('Energy/Particle-flow' algorithm):
Combine information from the trackers,
the calorimeters, and also the muon system,
avoid double counting,
assign approprеate weights
→ jet 4-momentum.
Extensive software effort to begin with.

Granurarity is critical ('Imaging calorimeter')
→ fine granurarity, on/off readout
Try 'Digital HCAL'

CALICE collaboration: (9 coutries, 28 institutions, 164 phycisists)
Looks like an experimantal 'collaboration' itself. . . .
(Maybe it should be called 'Cal-LC'?)
+ others

Digital vs Analog HCAL (NLC S case) (by NIU)

$$dE_{\rm jet}/dE_{\rm jet}$$



Digital∼Analog : No ful sim.
Futher developments are to come.

ECAL

- **Si-W calorimeter**
  High granurarity ($\sim$1cm^2), but expensive:
  \$100M/Si now. How far does it do down?
  (CALICE, Oregon/SLAC)
  R&D items:
  - Segmentation optimization (cost reduction).
  - Prototype construction/test (CALICE 2004).

- **Tile-fibre calorimeter**
  Modest granurarity (4×4cm^2)
  (KEK, Niigata, Tsukuba)
  R&D items:
  - Segmentation optimization.
  - fibre configuration.
  - Prototype construction/test being done.

- **Si-scintillator hybird**
  (Como, ITE Warsaw, LNF, Padova, Trieste)
  Performance-cost optimization.

ECAL (cont'd)

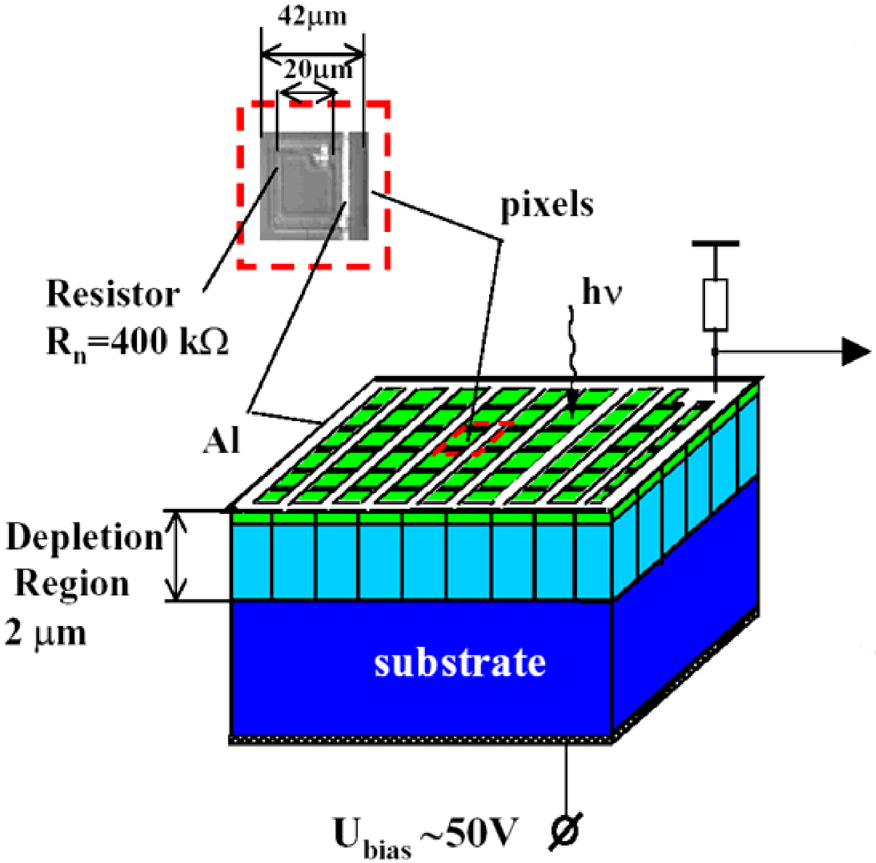
- **Showermax detector (for tile-fibre)**
  Inserted near showermax to aid granurarity.
  - scintillator strips (Shinshu/Kobe)
  - silicon pads.
- **Shashlik calorimeter**
  Fibres run londitudinally.
  Londitudinal segmentation is an issue.
  R&D items:
  - Londitudinal segmentation
    - scintillating fibres of different decay times
    - photodiodes to readout the front part.
- **Scintillator strip calorimeter**
  Orthogonally arranged. (Tsukuba)
  Provides good position and energy resolution.
  (Prototype: $dE/E = 0.129/\sqrt{E}$ obtained)

HCAL

- Tile-fibre calorimeter
  Larger granurarity than the ECAL version.
  Fe: good for effective Moliere radius.
  Pb: hardware compensation at 4mm/1mm sampling.
  (CALICE, KEK, Kobe/Konan)

  R&D items:
  - Granurarity optimization.
  - Optimization of absorber material.
    (e.g. hardware compensation)
  - Prototype construction (also tested with ECAL)
  - Photon detectors in high B field:
    APD, SiPM, HPD, HAPD, EBCCD.

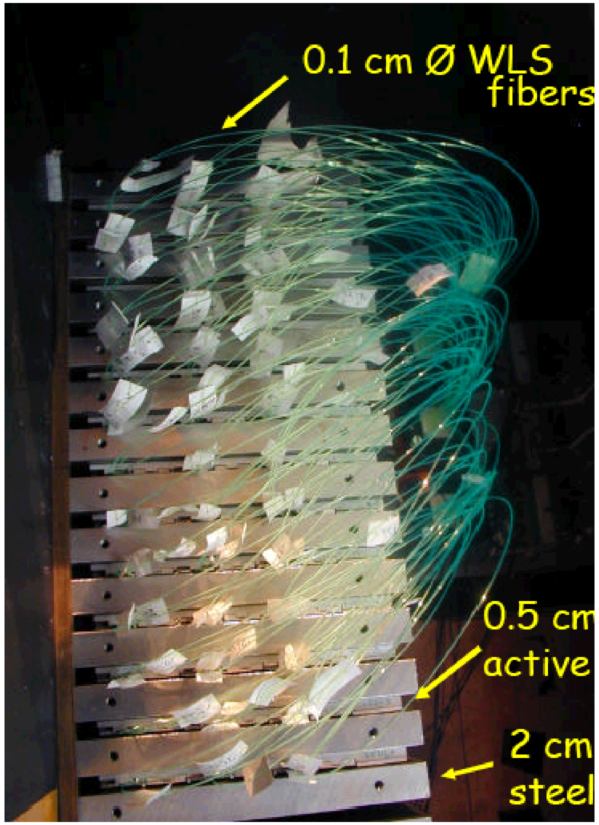
SiPM (Silicon Photomultiplier)



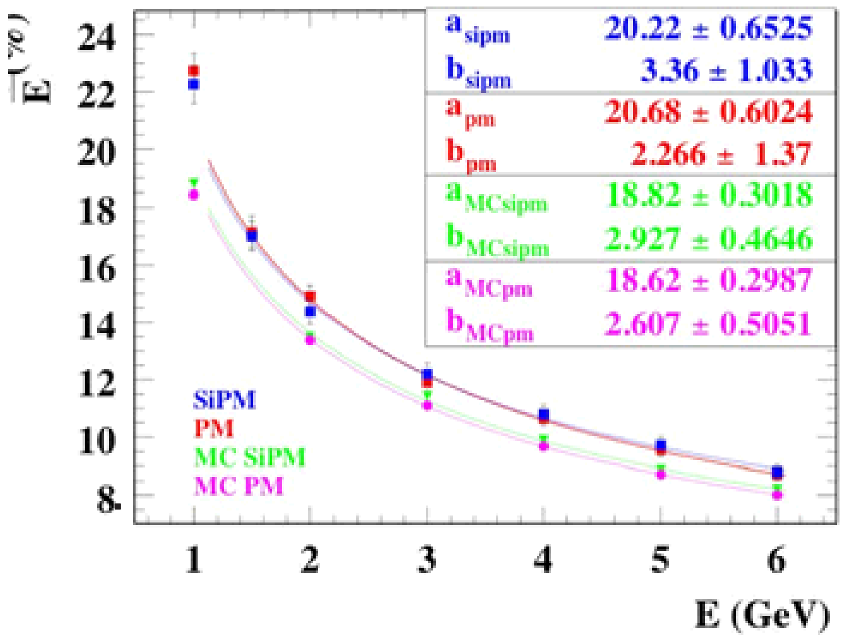
- $(42\mu\text{m})^2$ cell, limitted Geiger. $(1\text{mm})^2$ total/SiPM now.
- $V_{\text{bias}} \sim$ 50 V.
- Works in a high B-field (5T OK).
- Quantum eff.$\sim$ 0.3.
- Fast ($\sigma_{1\gamma} = 50$ ps).
- Quite cheap (a few $/piece).
- Directly attach to a scintillator, fibre, etc. Only electrical wires come out.
- Noisy $\rightarrow$ moderate cooling?

MINICAL Prototype (CALICE)

(G. Eigen)



- Fe-scintillator sandwich.
- 12 layers, 9 sci tiles each.
- 108 SiPM's. (one on each tile)
- Tile: $5 \times 5\text{cm}^2$
- A loop fibre $\rightarrow$ SiPM.
- Obtained similar res. as PMT.



- Digital calorimeter

  Very-high granurarity (~ 1cm^2) with 1-bit readout.
  After lots of software work $\rightarrow$ jet energy.
  (CALICE, U. Texas)

  R&D items:

  - Simulation (Does DHCAL really work as advised?) Also in the context of PFA.
  - Prototype (tile/digital interchangeable)
  - Readout: RPC, scintillator, (wires).
  - New readouts (GEM, VLPC).

4. Muon Detector

Muon ID + hadron shower tail

Fe as flux return/hadron absorber
Readout: RPC, Scintillation counter strips, or wires.
(INFN-Frascati, Kobe, Tohoku, N. Illinois, FNAL)

R&D items needed:

- Mechanical design.
  Support system of the large heavy detector.

- Simulation studies.
  Tracking algorithms as a part of
  PFA (= global particle reconstruction)
  Beam backgrounds (timing)
  Hadron punch-throughs

- Hardware R&D's
  Prototype design and beam tests.

Summary

- In order for LC to be succesful, extending the performance fronteers is a necessity.
- R&D activities to meet the challange are intensively under way.
- The R&D efforts are now truly worldwide. (CALICE, LC-TPC, SiLC. . .)
- Many are common to large and small detectors, or cold and warm technologies.
- We should phase in the design of the actual detectors within a few years.