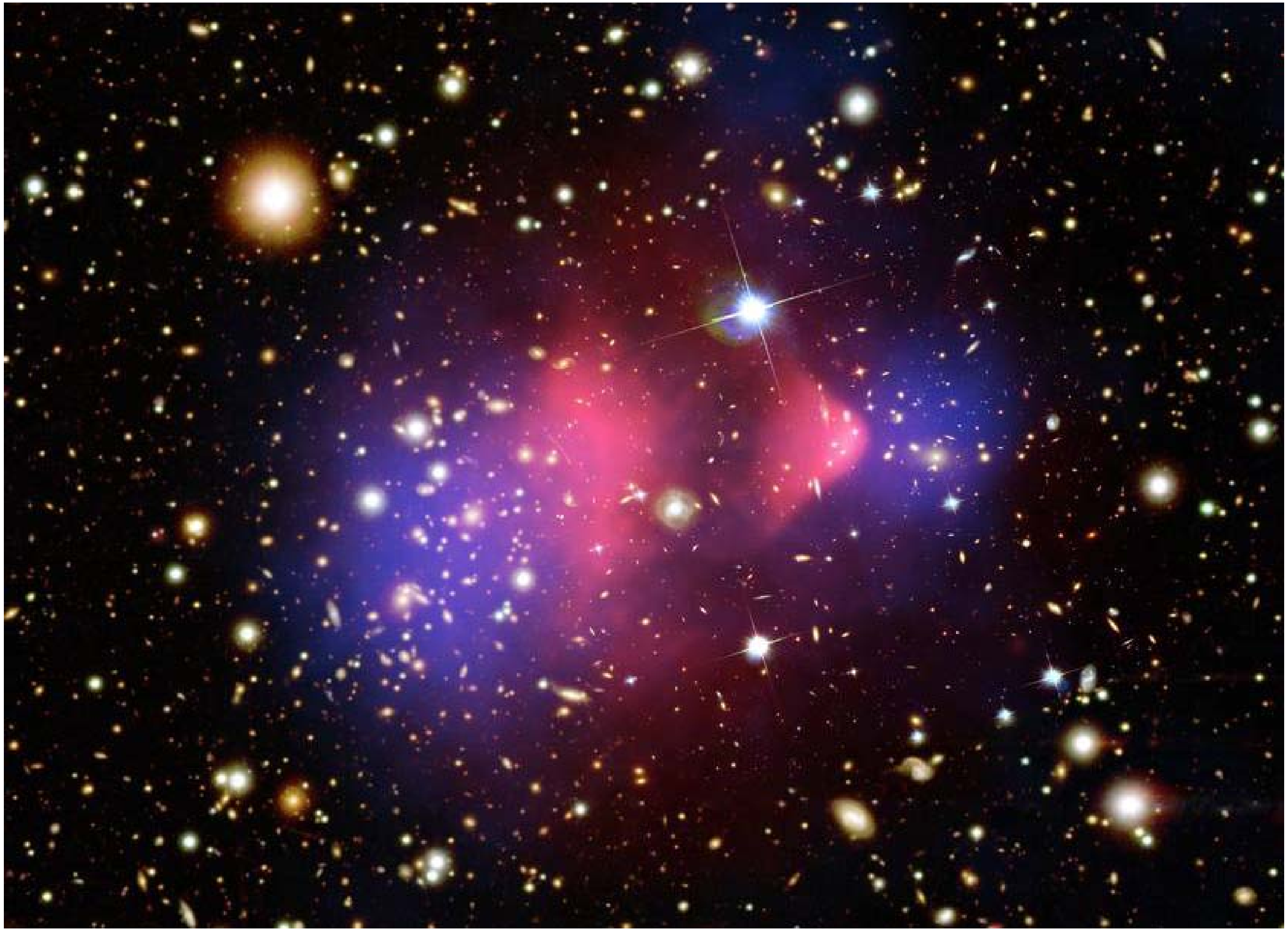
# The International Linear Collider

- Why build new colliders?
- Why build the ILC when we have the LHC?
- Detector performance requirements for the ILC.
- Four detector concepts.
- Detector research:
  - Calorimetry.
  - Tracking.
  - Vertex detectors.
- Summary.

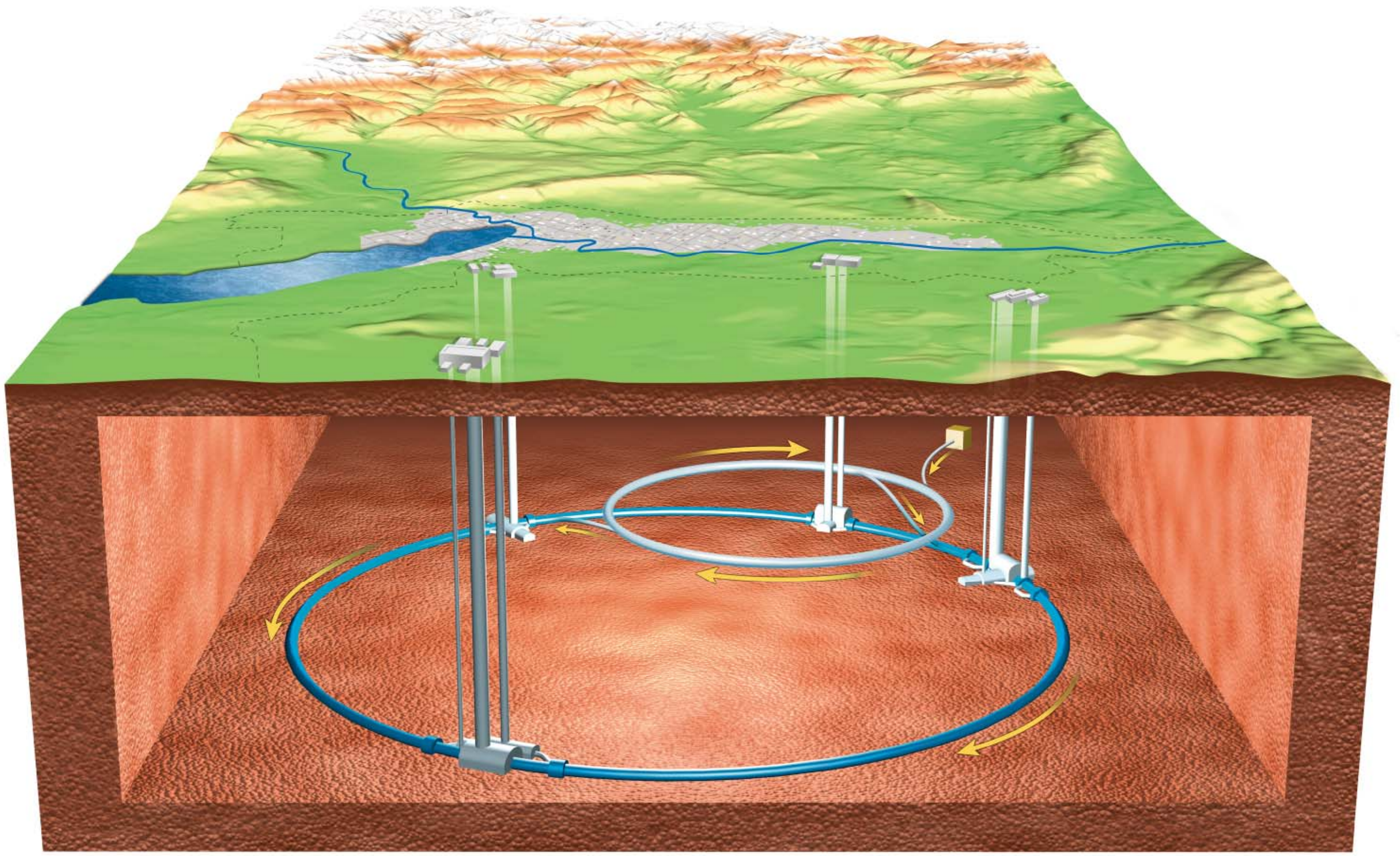
# Why new colliders?
# There is more to heaven and earth...

- Collision of two galaxy clusters seen using the Chandra X-ray Observatory, Hubble, ESO's Very Large Telescope and the Magellan optical telescopes.
- “Direct empirical proof of the existence of dark matter.”
- Now we must study dark matter in the laboratory.



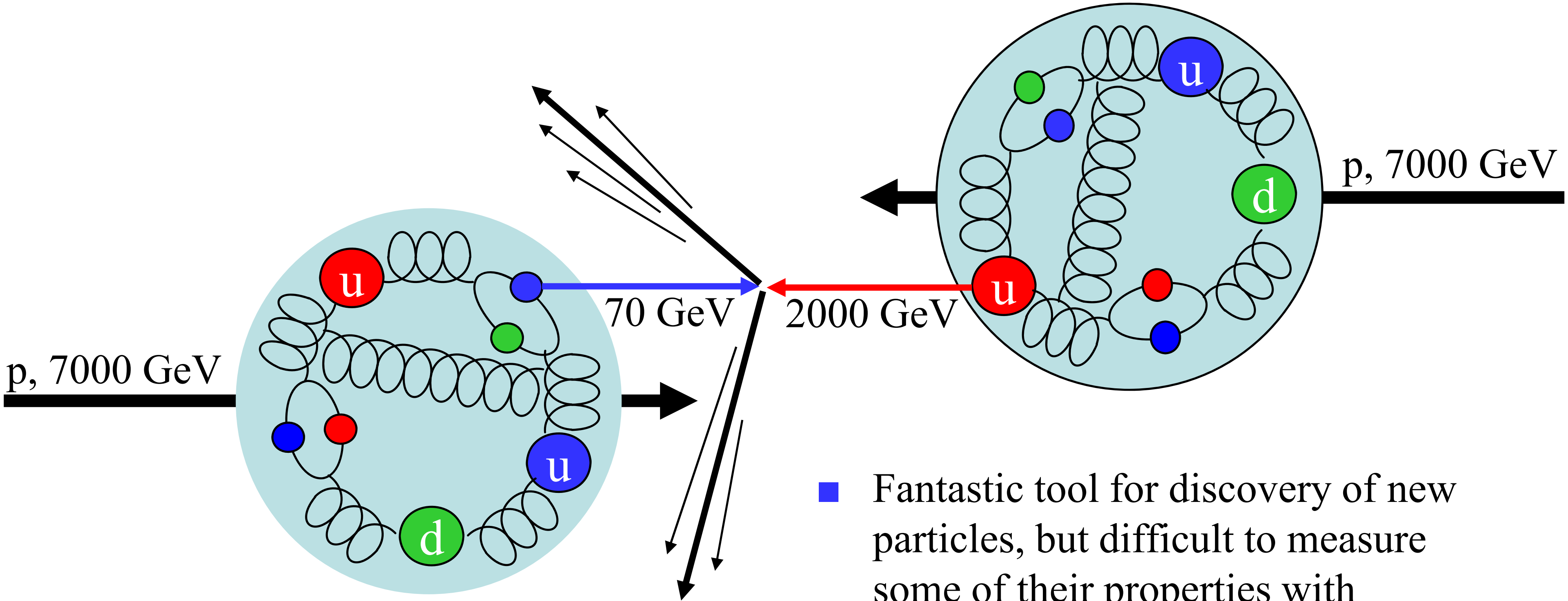
# The Large Hadron Collider

- The LHC will be colliding 7000 GeV protons with 7000 GeV protons in 2008.



# The LHC

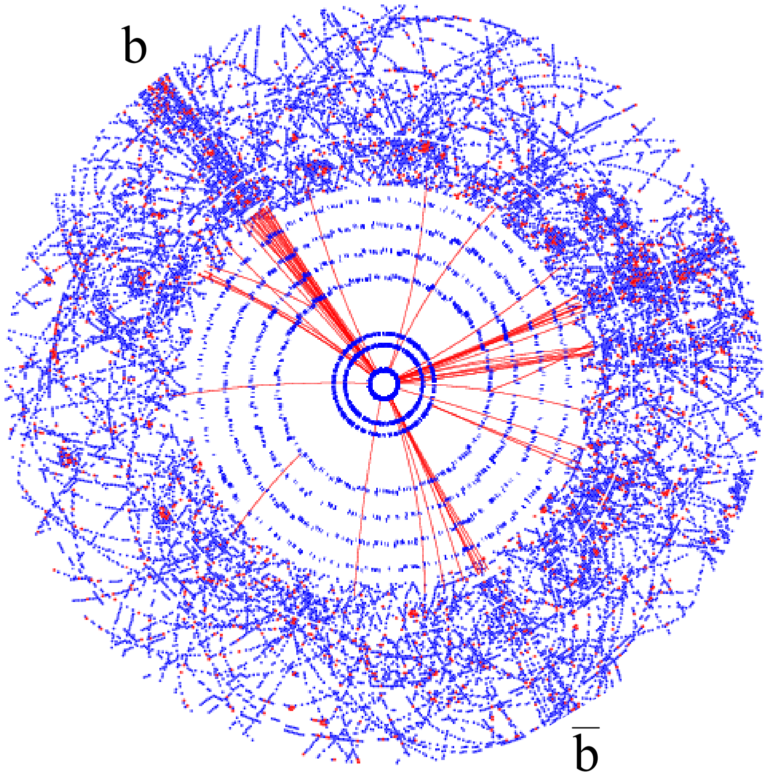
- Each of the quarks and gluons which make up the proton carry a fraction of the proton's energy.
- Interactions take place between these constituents.



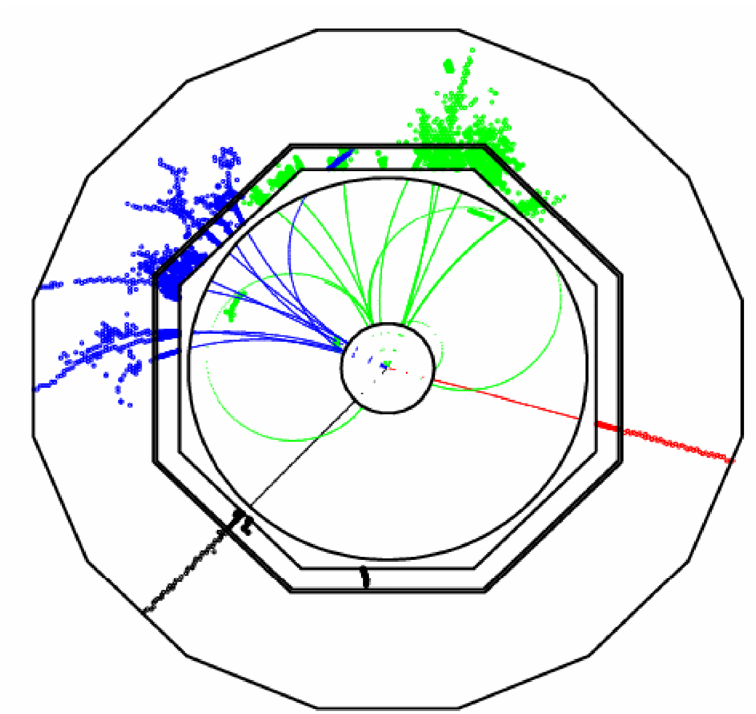

- Fantastic tool for discovery of new particles, but difficult to measure some of their properties with precision.

# Why build the ILC?
## Electron-positron collisions complement pp

- pp → HX as expected in ATLAS detector at LHC:

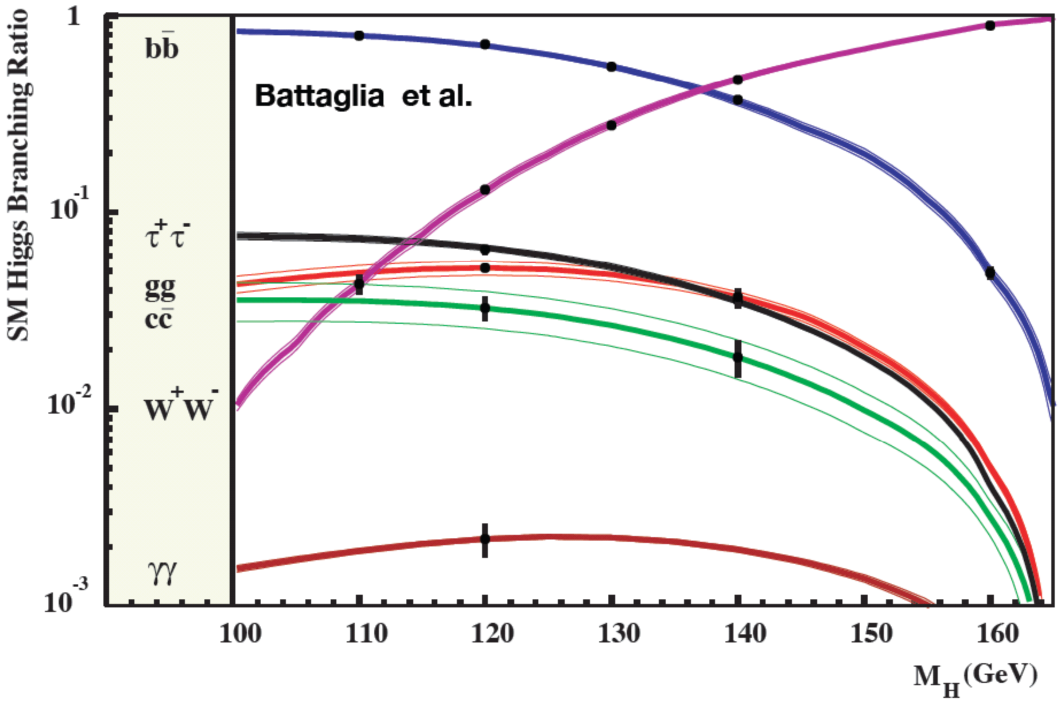



- $e^+e^-$ → HZ as expected in LDC detector at ILC:



# Why build the ILC?

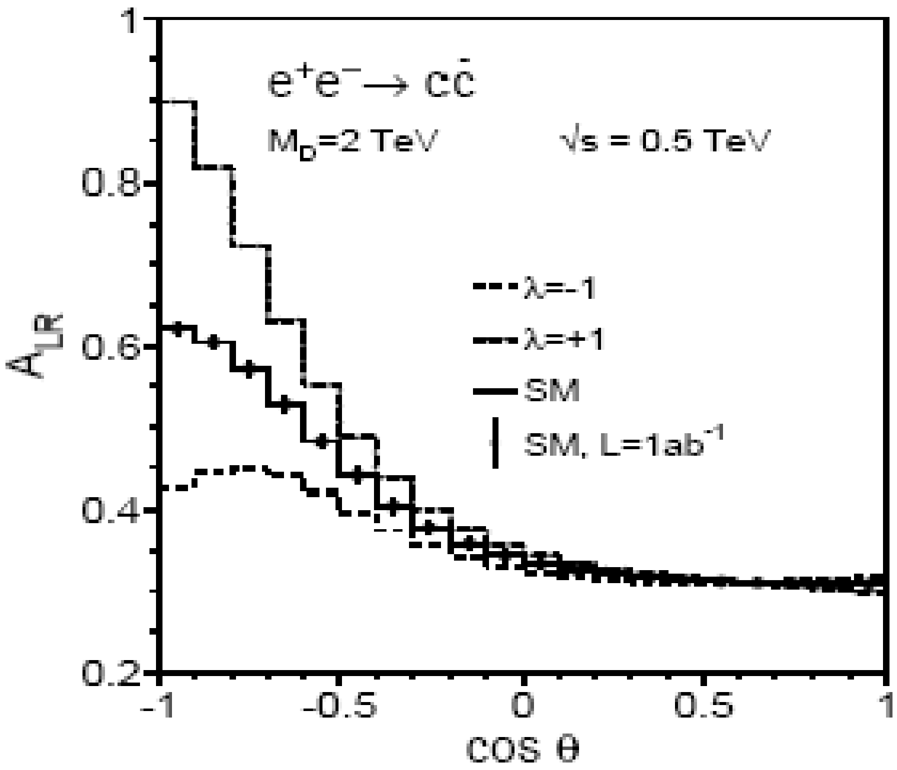
- Discover a Higgs boson at the LHC.
- Is it the particle expected in the Standard Model, or is it the first evidence for Supersymmetry?




- Measure Branching Ratios to b, τ, c...
- Are these as expected in the SM?
- ...or are “d-type” couplings enhanced and “u-type” suppressed as is typical of SUSY?
- Such precision measurements very difficult at the LHC, but possible in cleaner environment of an $e^+e^-$ Linear Collider.
- Tunability of LC allows precision studies of top at $t\,\bar{t}$ threshold.

# Why build the ILC?

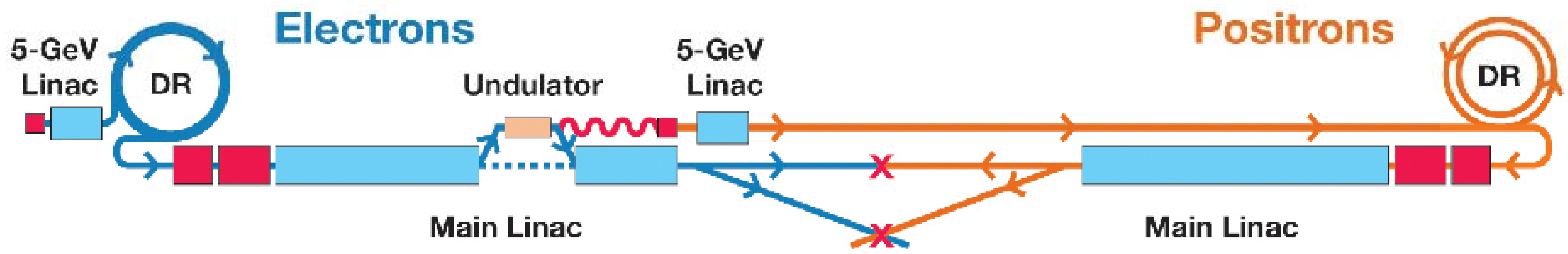
- Electron and positron polarisation powerful tool for physics studies.
- Searches for new physics beyond kinematic limits through precision measurements.
- E.g. influence of large extra dimensions on $A_{LR} = (\sigma_L - \sigma_R)/\sigma_{tot}$ as a function of cos θ in process $e^+e^- \to f\,\overline{f}$.
- Effect small in lepton production, but larger for quarks.
- Requires identification of flavour and charge of quark.
- Sensitivity to $M_D \sim 5$ TeV.



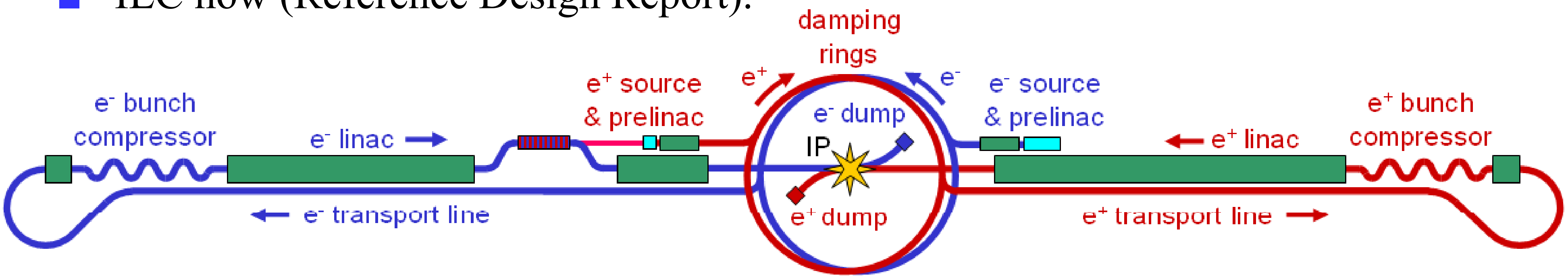

(Sabine Riemann)

# The International Linear Collider

- ILC design July 2006 (Vancouver LCWS)

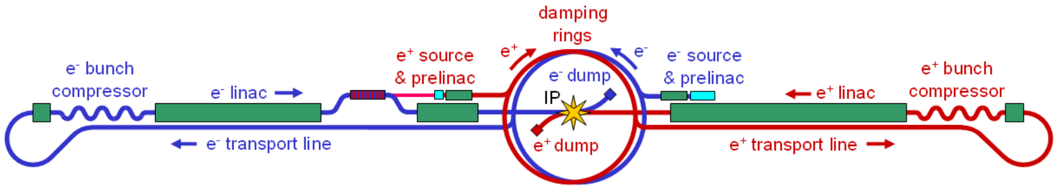


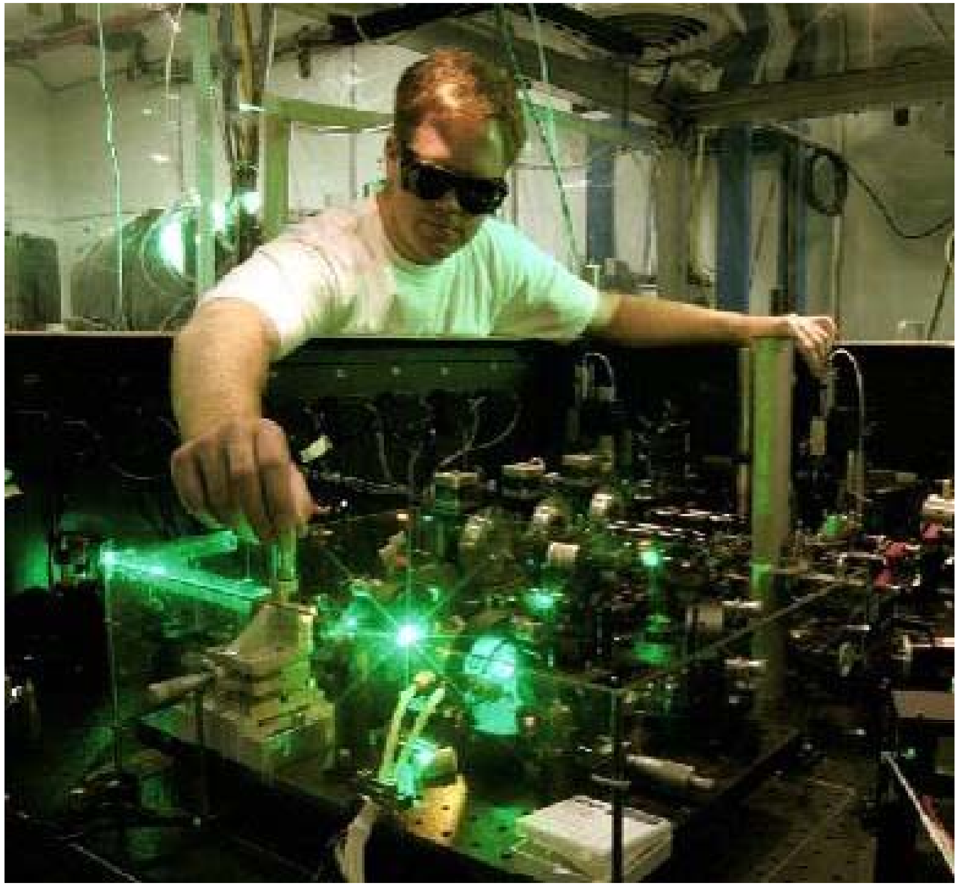

- ILC now (Reference Design Report).




- $\sqrt{s}$ = 200...500 GeV, upgrade to 1 TeV.
- $\mathcal{L} \sim 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, i.e. 500 fb$^{-1}$ in first 4 years.
- Energy stability better than 0.1%.
- Electron polarisation 80% ($e^{+}$ 30%).
- Cost \$4.9B + \$1.8B + 13k person-years.

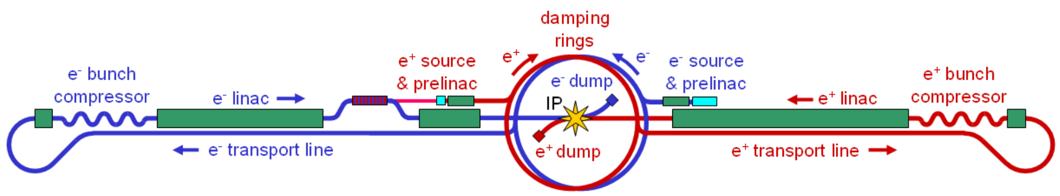
# Electron Source
# and Damping Ring



- Electron source is a DC photocathode gun.
- Produces trains of ~ 3000 bunches.
- Inter-bunch spacing ~ 340 ns.
- $2 \times 10^{10}$ electrons per bunch.
- Bunch train rate 5 Hz.
- Vertical beam size about 1 mm.
- Damping Ring is 6.7 km synchrotron storage ring.
- Stores bunch train for 200 ms.
- Size of each bunch reduced by radiation damping.
- After DR, vertical beam size typically 5 μm.

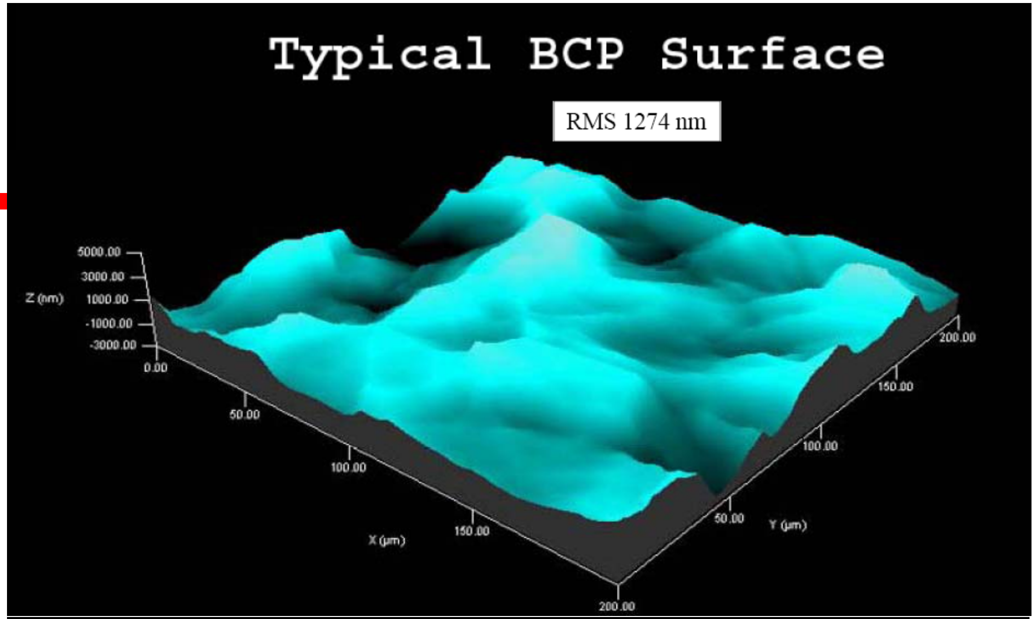
# Bunch Compressor and Main Linac

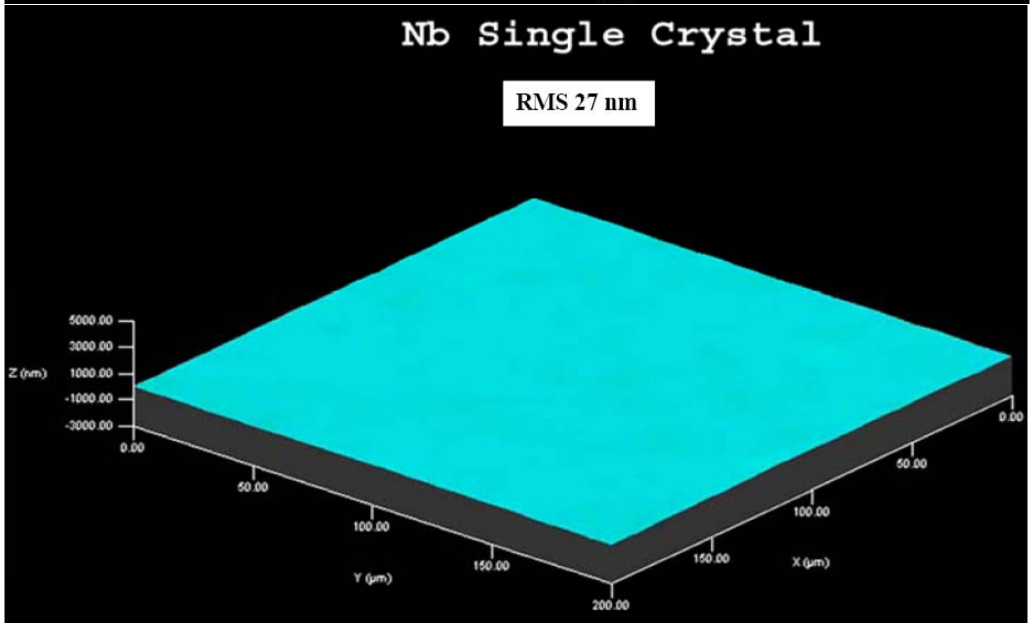



- Bunch compressor reduces the length of each bunch from 6 mm to 300 μm.
- Main Linac accelerates electrons up to 250 GeV.
- Energy in one bunch train 2.4 MJ, average beam power is 12 MW.
- Vertical beam size now 2.5 μm.
- Each of the two Main Linacs is constructed from ~ 10 000 superconducting niobium RF cavities (1.3 GHz).

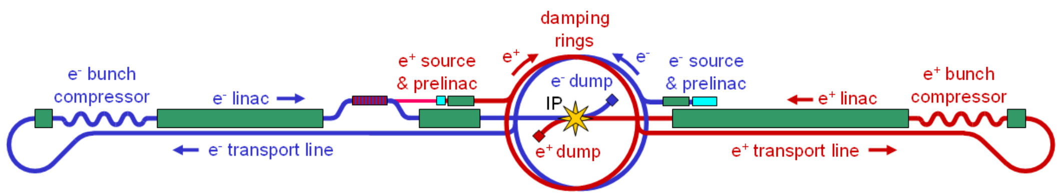
# Superconducting cavities

- Construction of ILC relies on industrial production of high gradient SC cavities.
- Material of choice niobium.
- Smoothness critical, compare surface of BCP etched polycrystalline cavities with cavities manufactured from single:
  - BCP RMS 1274 nm.
  - Single crystal RMS 27 nm.
- (Buffered chemical polish = phosphoric acid + nitric acid + hydrofluoric acid.)

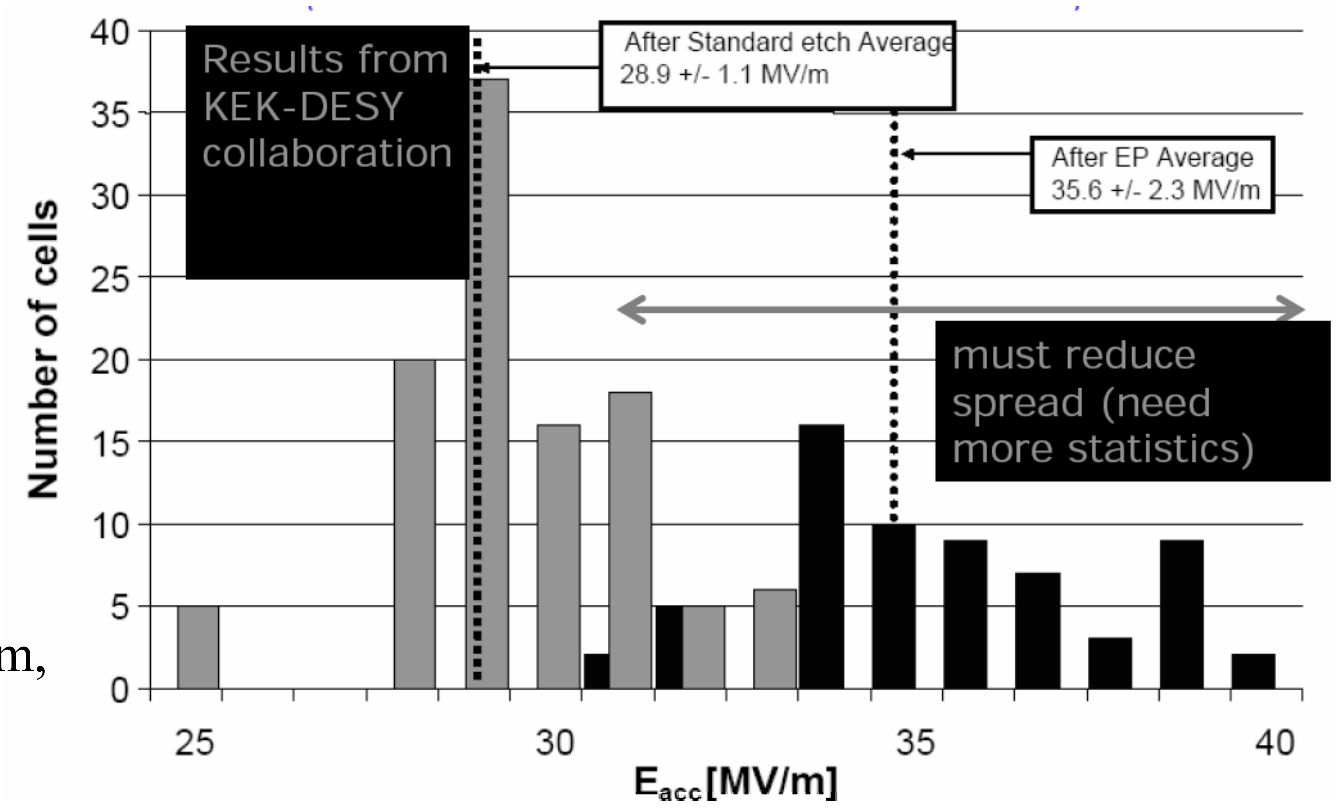


# Superconducting cavities

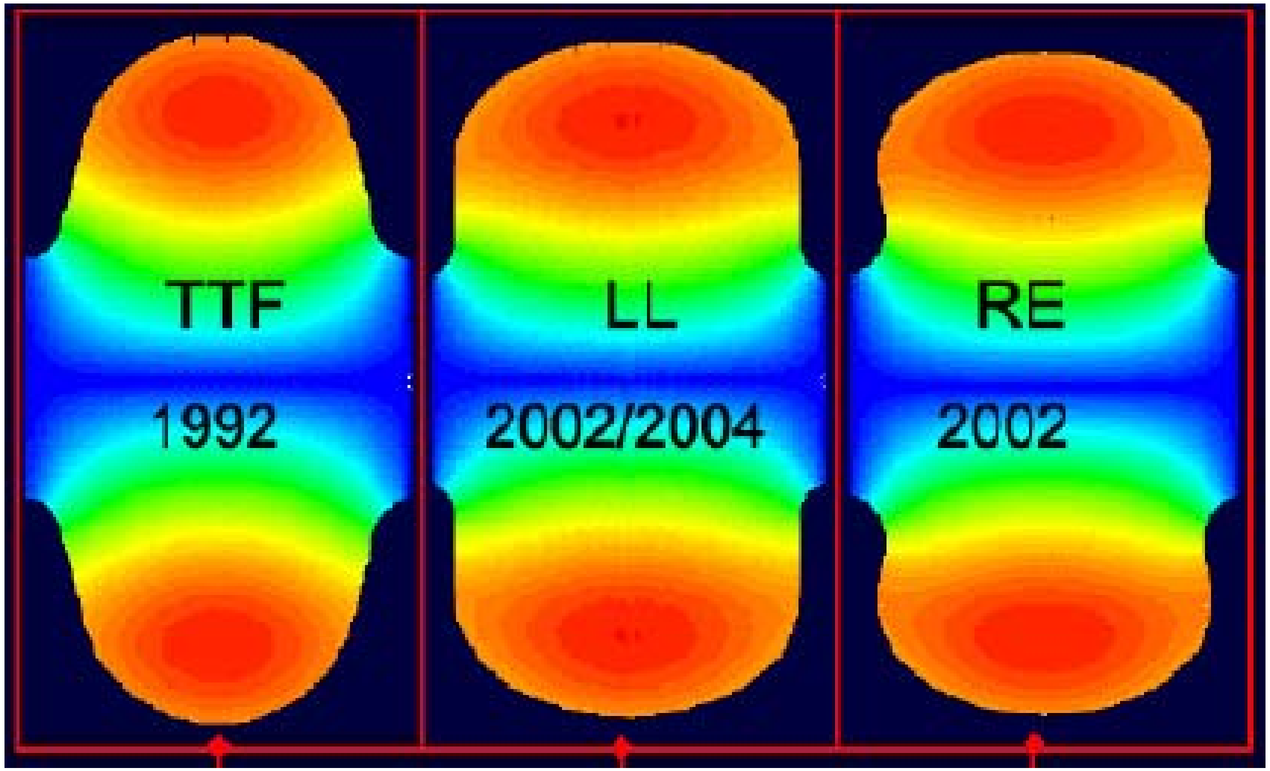



- ILC relies on industrial production of high gradient SC cavities.
- Need peak gradient of 35 MV/m for $\sqrt{s}$ = 500 GeV.
- Material of choice niobium.
- Surface smoothness critical.
- Average gradient after standard etch ~ 29 MV/m, after electro-polishing ~ 36 MV/m.
- Single crystal cavity up to 45 MV/m.

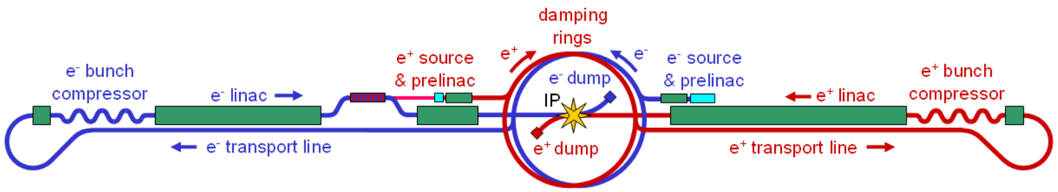


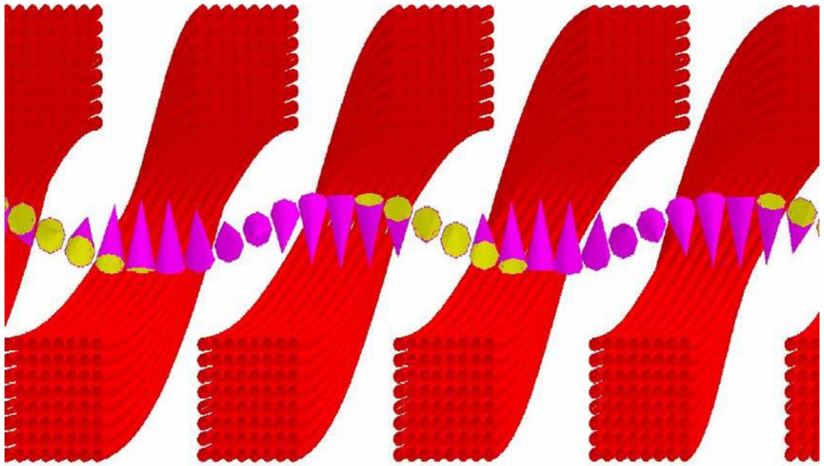
# Superconducting cavities

- Cavity shape mod.s investigated.
- Limitations given by field emission ($E_{peak}$) or "quench" ($H_{peak}$).
- "Low Loss" and "Re-Entrant" shapes reduce $B_{peak}/E_{acc}$, i.e. inc. $E_{acc}$ for given "quench" field.
- Unfortunately inc. surface E field: better contamination control needed.

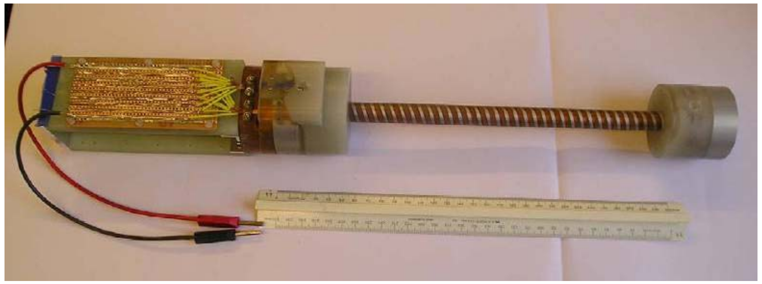


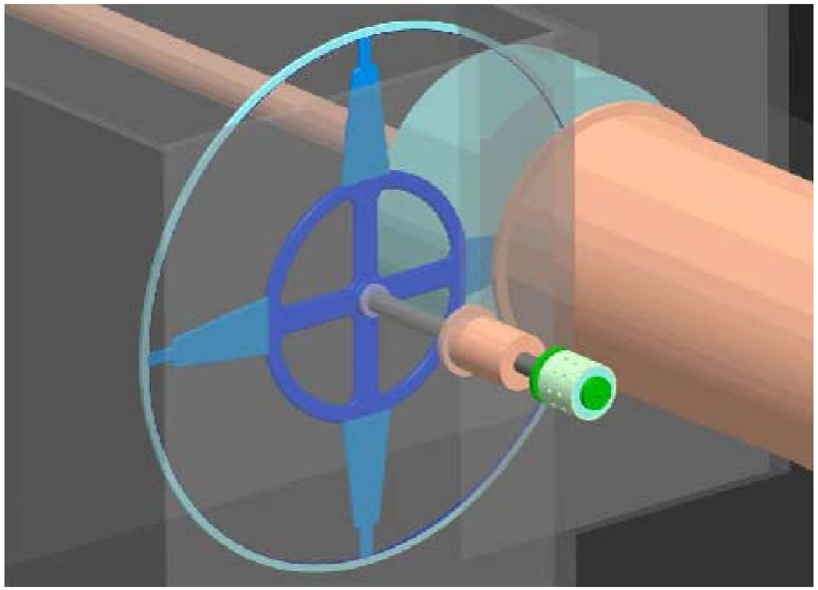
# Helical Undulator and positron production



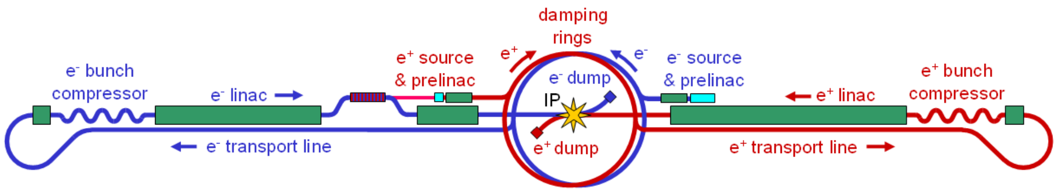
- High energy circularly polarised photons produced in ~ 100 m, 1 T superconducting helical undulator, 1 cm period, 4 mm bore.



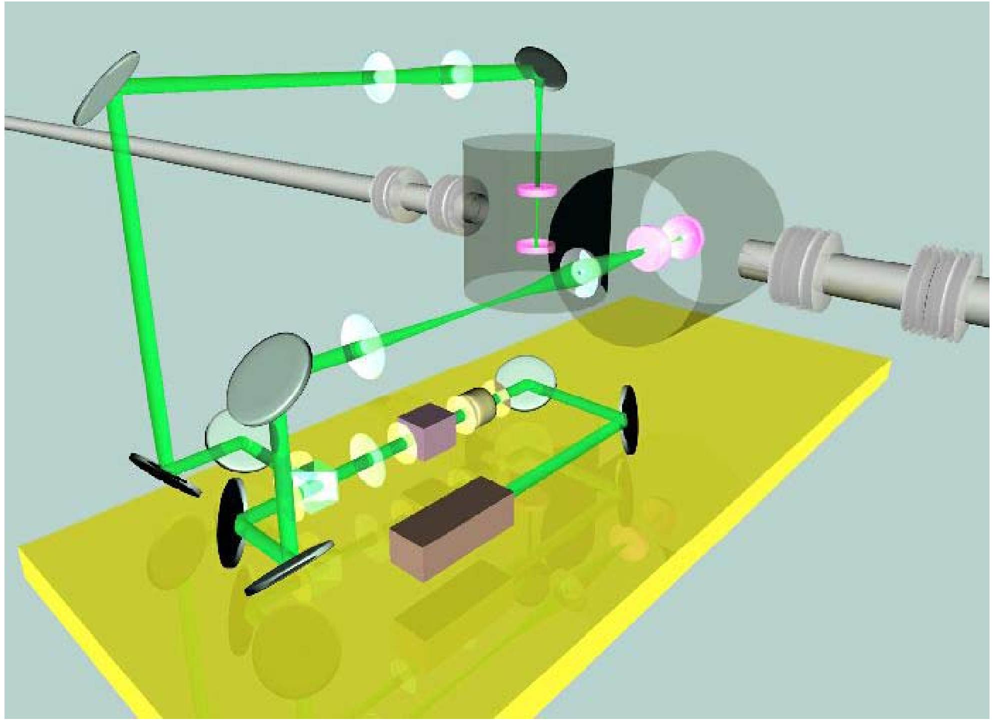


- Photons impinge on target and generate polarised $e^+e^-$ pairs.
- Target is 2 m diameter Ti Al V wheel spinning at 3 400 rpm.
- Polarised positrons are captured and accelerated through chain similar to that for electrons.

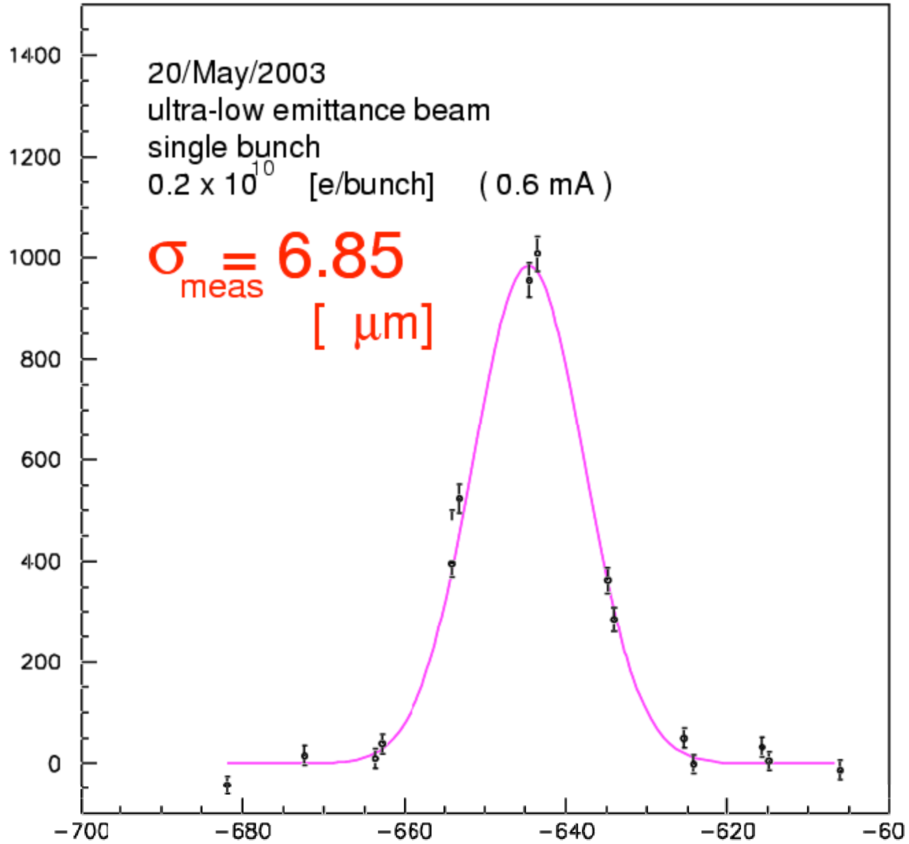
# Beam Delivery System



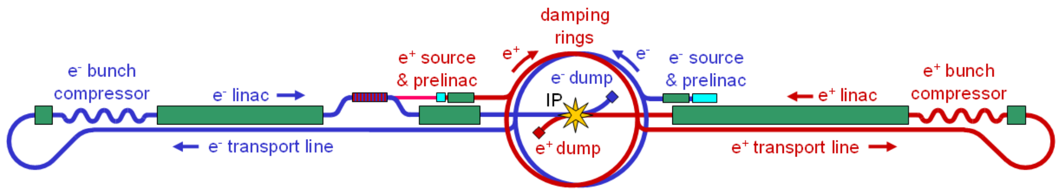

- Collimation – remove "halo".
- Diagnostics – laser wire monitors...



- ...measure beam size with resolution of ~ few μm.



# Beam Delivery System




- Final focus.
- Luminosity given by:

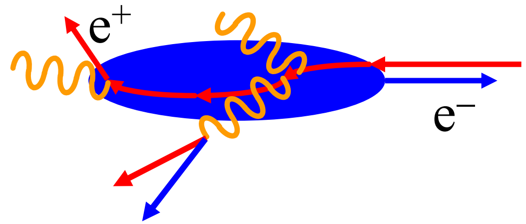
$$\mathcal{L} = \frac{n_b N^2 f_{rep}}{A} H_D,$$

where:

  - $n_b$, number of bunches in train.
  - N, number of particles per bunch.
  - $f_{rep}$, bunch train frequency.
  - A, area of bunch at IP.
  - $H_D$, beam-beam enhancement factor.

- Need smallest possible cross-sectional beam areas.

- Particles pass through intense field of opposing beam, radiate photons.

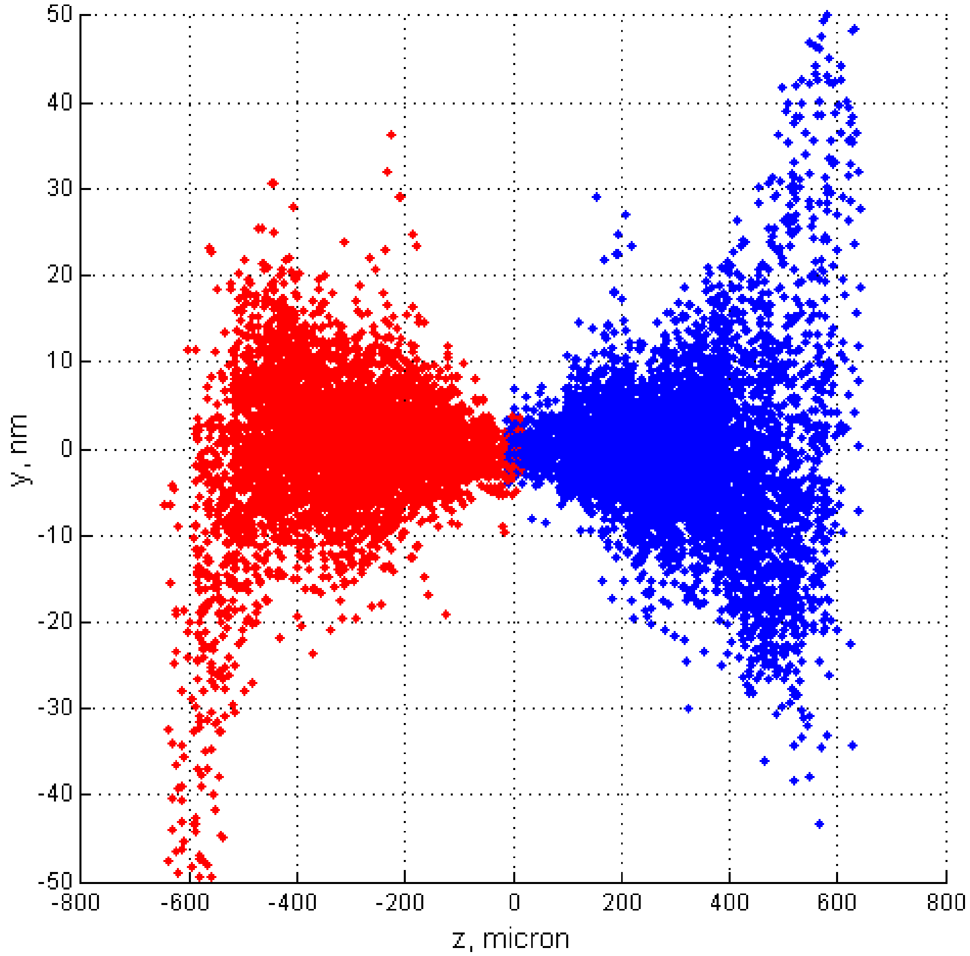



- These beamstrahlung photons interact with field of bunches, and generate $e^+e^-$ pairs.
- Beam-beam effects characterized by disruption parameter:

$$D_{x,y} = \frac{2 r_e N \sigma_z}{\gamma \sigma_{x,y}(\sigma_x + \sigma_y)}.$$

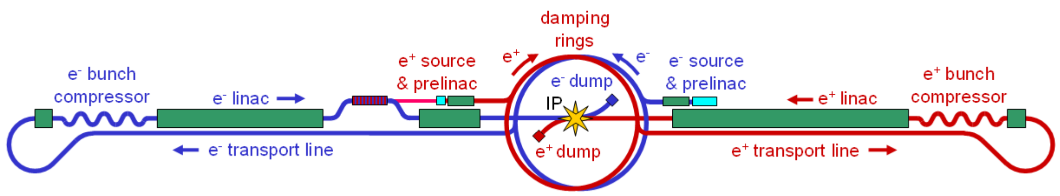
- Flat beam, $\sigma_y < \sigma_x$, better than round: beam height ~ 5 nm, width ~ 500 nm.

# Beam-beam interactions

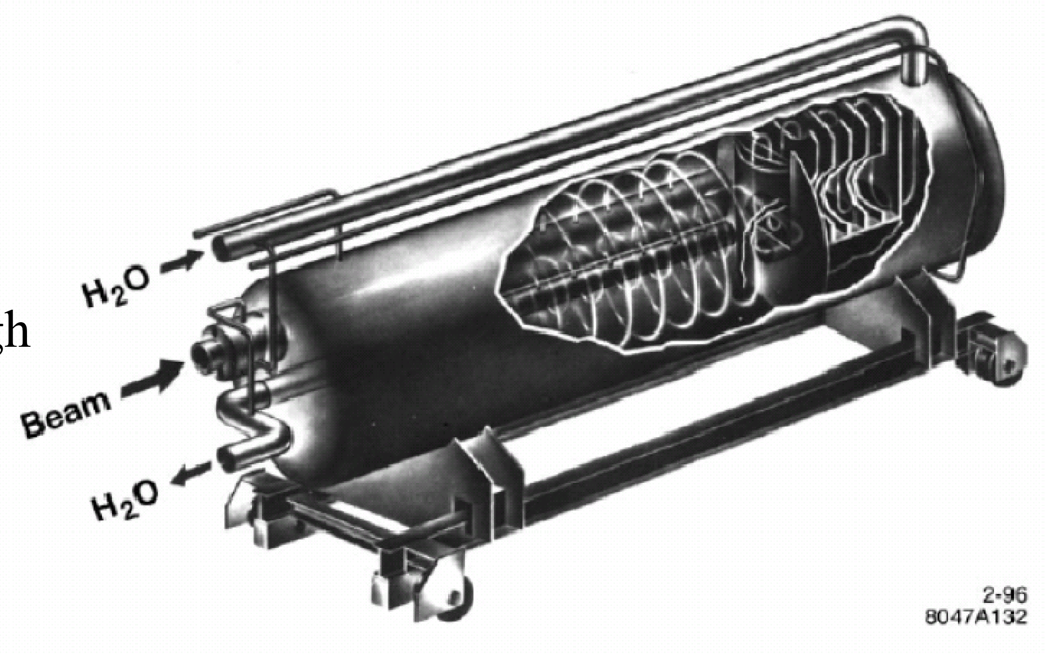


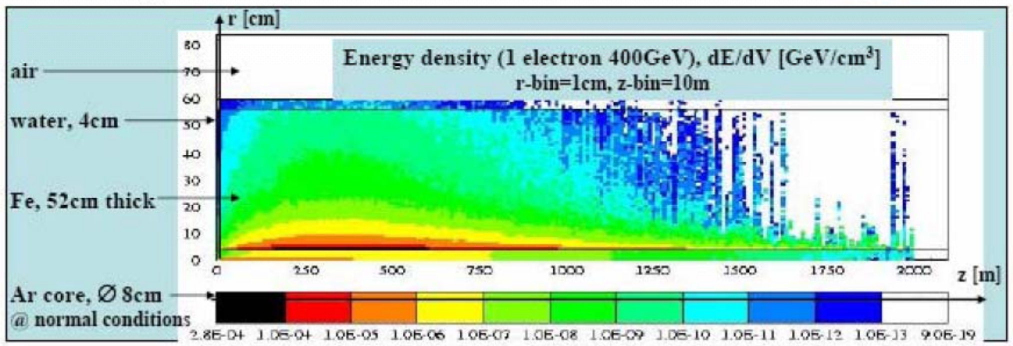

Simulations by Andrei Seryi, using GuineaPig by Daniel Schulte.

# Beam Dumps




- Must allow safe deposition of 12 MW beam power.
- Baseline design is high pressure, high velocity water dump:

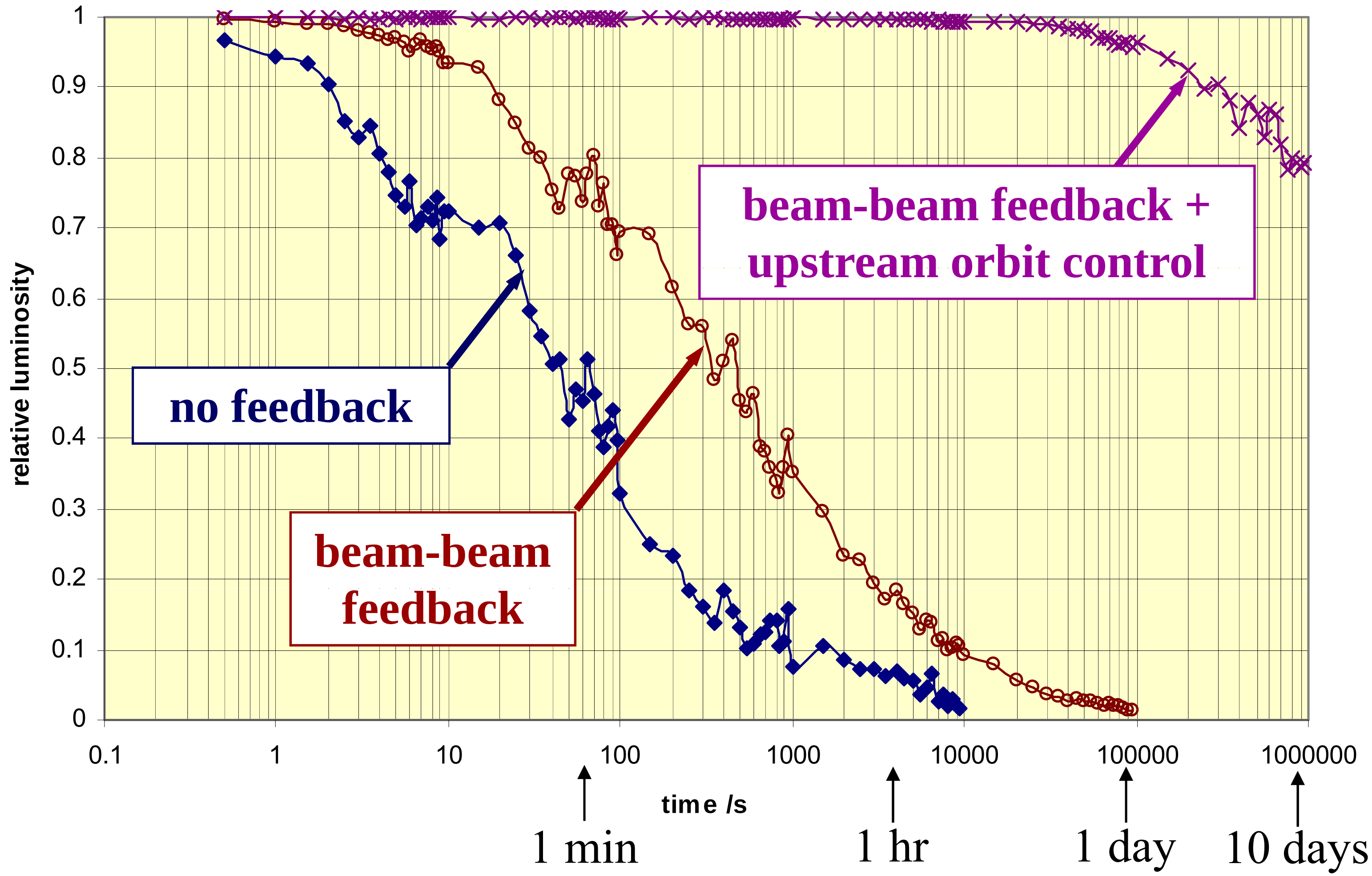



- Possible alternative is gas (Ar or Xe) surrounded by iron.

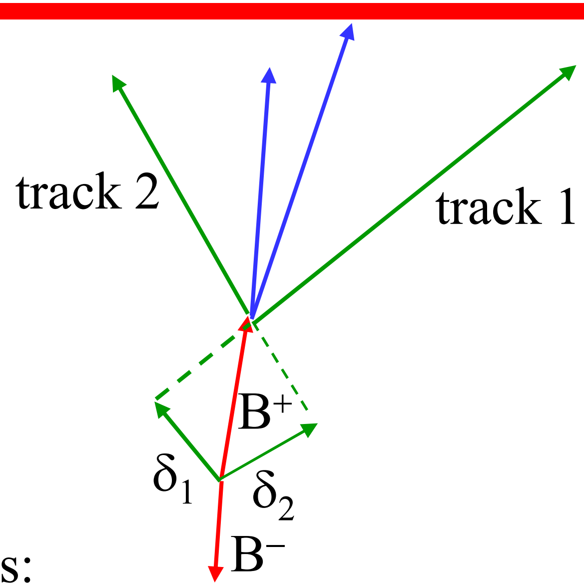
# Ground motion

- Feedback systems needed to ensure collisions of tiny (5 μm) beams maintained:



# Detector requirements – vertexing

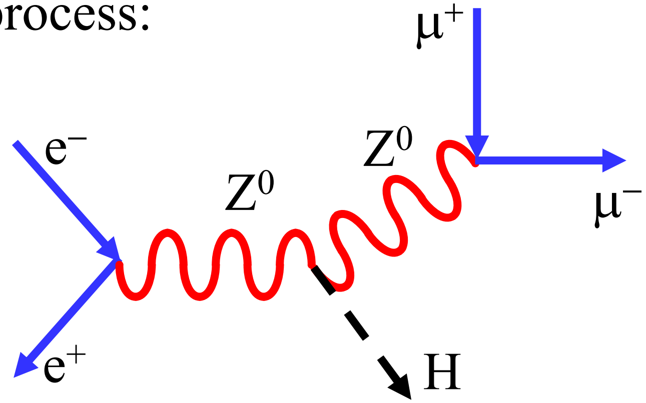
- Efficient identification required for $\tau$ leptons, c and b quarks.
- Average impact parameter $\delta$ of B decay products ~ 300 μm, of charmed particles less than 100 μm.
- Must resolve all tracks in dense jets.
- Cover large solid angle: forward/backward events are of particular significance for studies with polarised beams.
- Stand-alone reconstruction desirable.



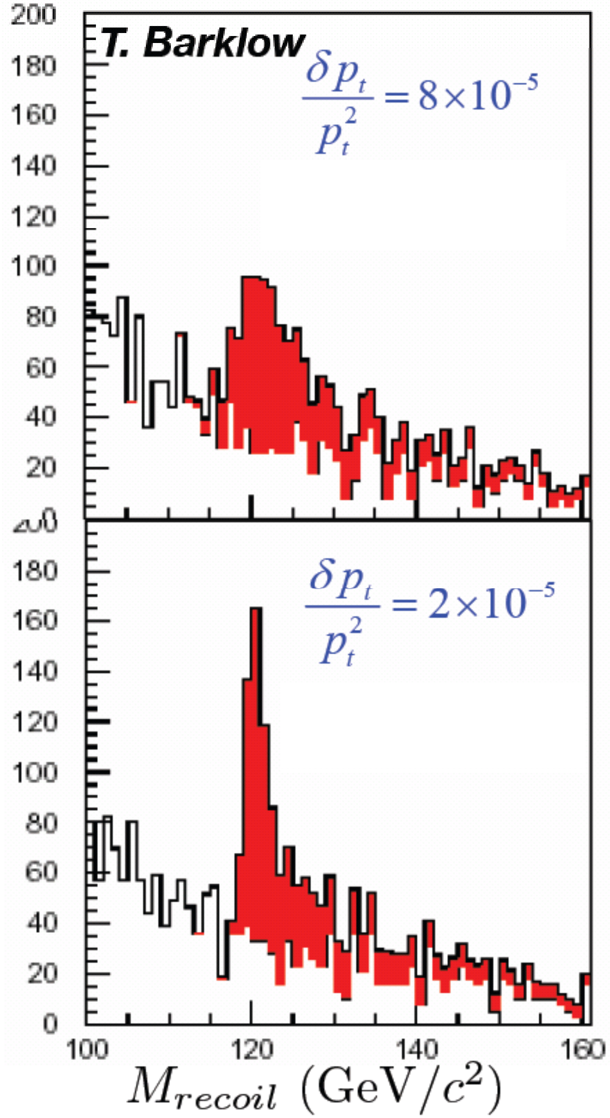

- Implies:
  - Si pixels ~ 20 x 20 $\mu m^2$ or smaller.
  - Hit resolution better than 5 μm.
  - First measurement at r ~ 15 mm.
  - Five layers out to radius of about 60 mm, i.e. total ~ $10^9$ pixels
  - Material ~ 0.1% $X_0$ per layer.
  - Detector covers $|\cos\theta| < 0.96$.

# Detector requirements – tracking

- Excellent momentum resolution needed to reconstruct "recoil" mass, e.g. when Higgs decays invisible in process:



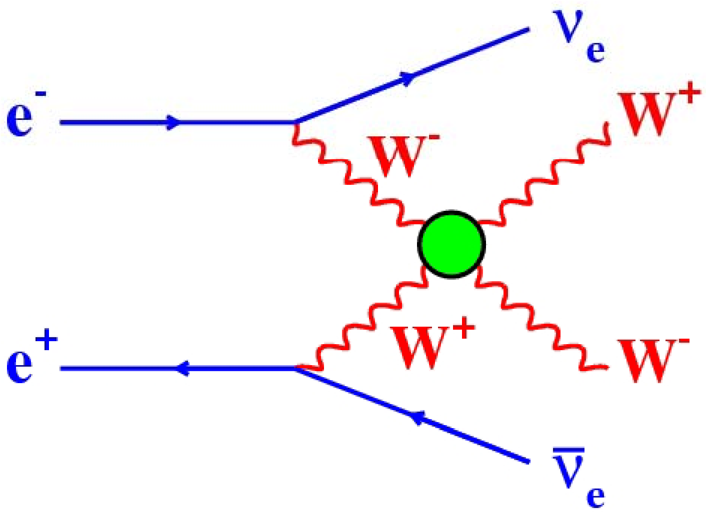

- Must be coupled with large acceptance and robust pattern recognition capabilities to cope with multi-jet environment, e.g. six jets in $e^+e^- \to t\,\bar{t}$ events.




Target resolution:
$$\frac{\delta p_T}{p_T^{\ 2}} \sim 5\times10^{-5}\ \mathrm{GeV}^{-1}.$$

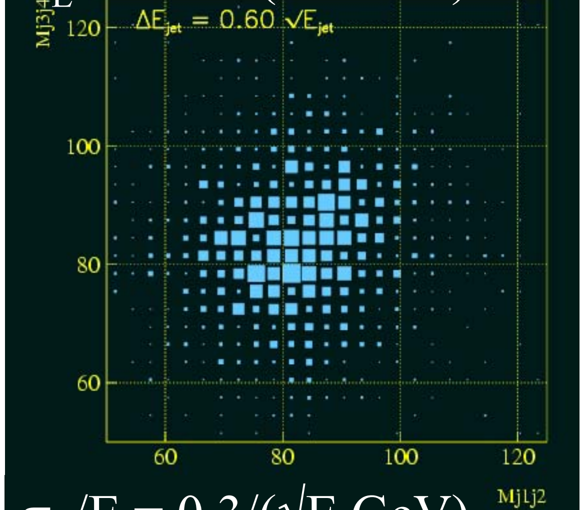
# Detector requirements – calorimetry

- Want to be able to separate final states $W \rightarrow q\,\bar{q}'$ and $Z \rightarrow q\,\bar{q}$.
- Allows e.g. study of processes:

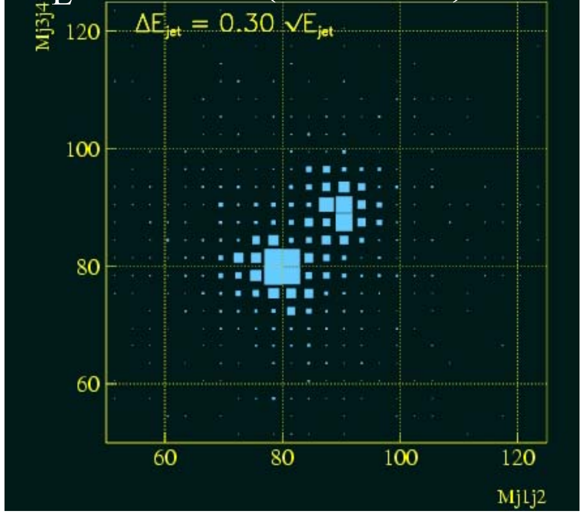



- Good jet energy resolution required.

- $\sigma_E/E = 0.6/(\sqrt{E}\ \mathrm{GeV})$

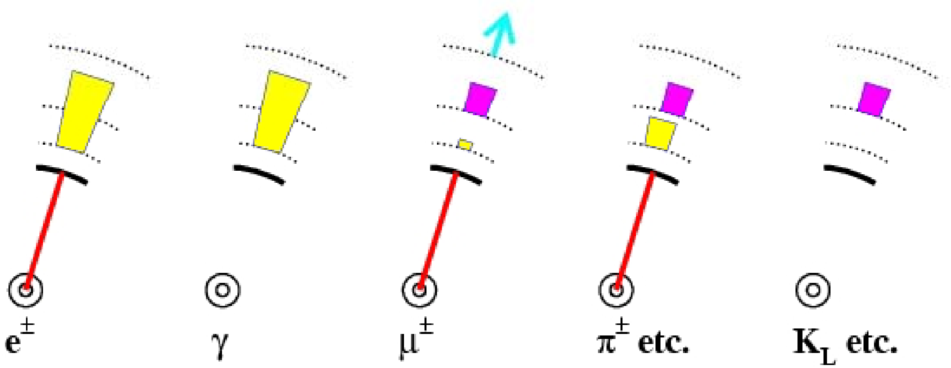



- $\sigma_E/E = 0.3/(\sqrt{E}\ \mathrm{GeV})$



# Detector concepts and particle flow

- Majority of detector designers agree, get jet energy resolutions of $\sigma_E/E = 0.3/(\sqrt{E}\ \text{GeV})$ through particle flow measurements.
- Reconstruct momenta of individual particles, avoid double counting:



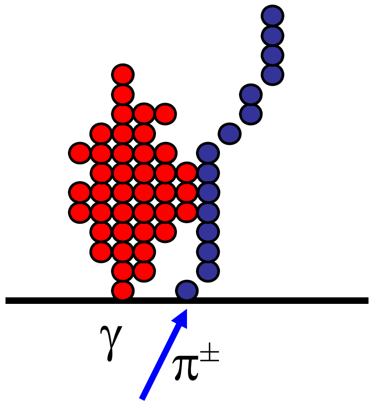

- For 45 GeV jet, can achieve:

| | Detector | $E_{jet}$ frac. | $\sigma_E$ | $\sigma_{Ejet}$ |
|---|---|---|---|---|
| $\pi^{\pm}$... | Tracker | 0.6 | $10^{-4}\ E_{\pi\pm}$ | $\sim 0$ |
| $\gamma$ | ECAL | 0.3 | $0.11\sqrt{E_\gamma}$ | $0.06\sqrt{E_{jet}}$ |
| $K_L$... | HCAL | 0.1 | $0.4\sqrt{E_{KL}}$ | $0.13\sqrt{E_{jet}}$ |

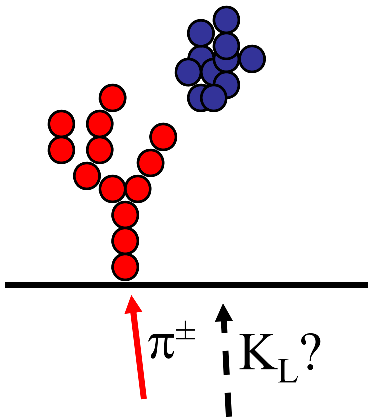
- Expect resolution $\sigma_{Ejet} = 0.14\sqrt{E_{jet}}$, dominated by HCal contribution.
- But also have contributions to resolution from "confusion", assigning energy deposits to wrong particles, double-counting etc.
- Single particle resolutions not dominant contribution, $\sigma_{Ejet} \sim 0.30\sqrt{E_{jet}}$ is a major challenge!

# Detector concepts and particle flow

- Must separate energy deposits from different particles: granularity more important than energy resolution.



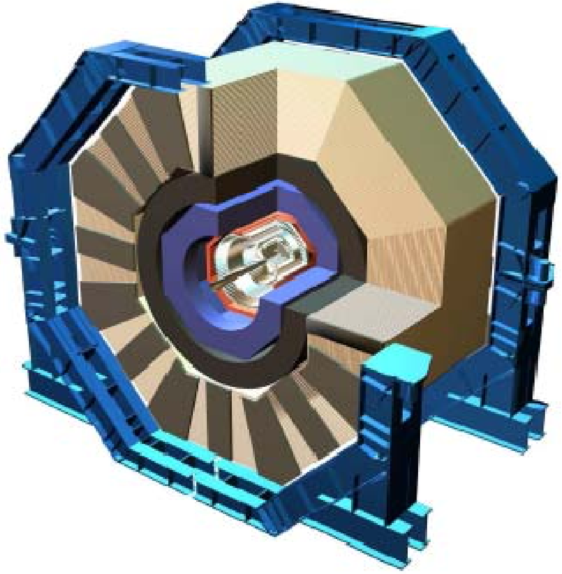

- But even with excellent granularity, this is difficult problem!



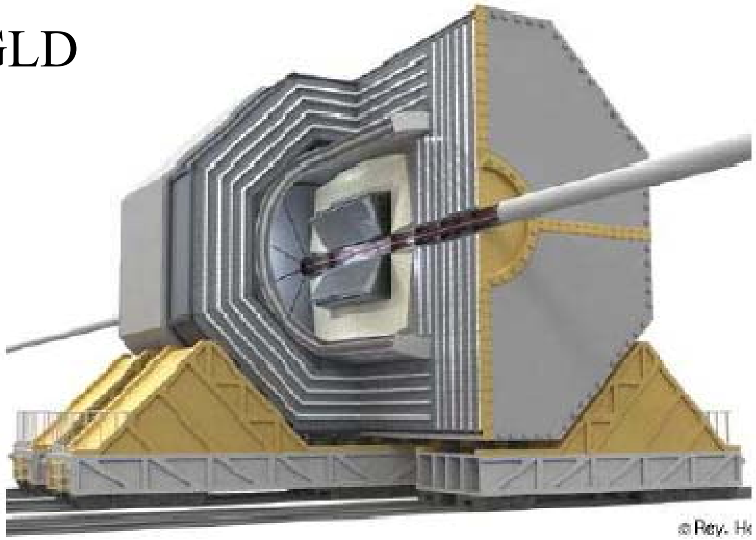

- Separation of particles requires large detector, high B field and high spatial resolution calorimeter.
- Funding agencies require small detectors, inexpensive magnets and cheap calorimeters.
- The tension between these differing views on the optimal ILC detector has led to the three concepts:
  - SiD (small detector, B = 5T).
  - GLD (large detector, B = 3T).
  - LDC (intermediate size, B = 4T).
- Fourth concept, use calorimeter to get required jet energy resolution, size ~ LDC, $B_{in}$ = 3.5T, $B_{out}$ = –1.5T.

# The four detector concepts

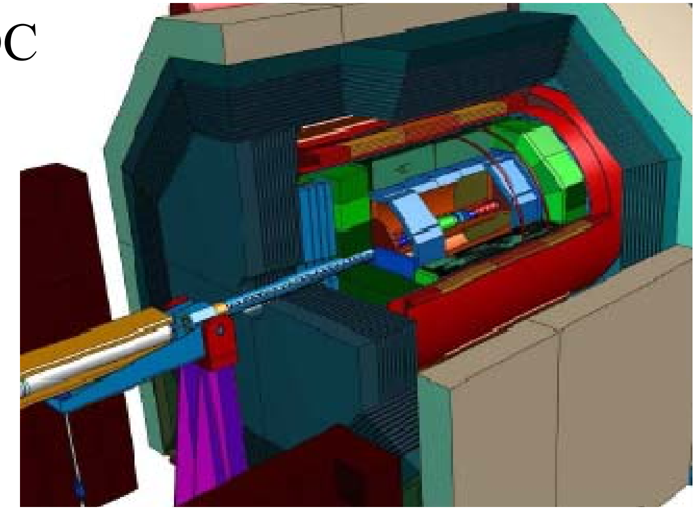
- SiD



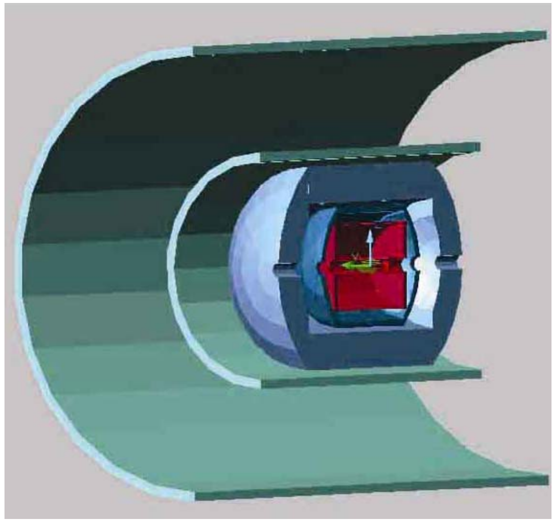
- GLD



- LDC

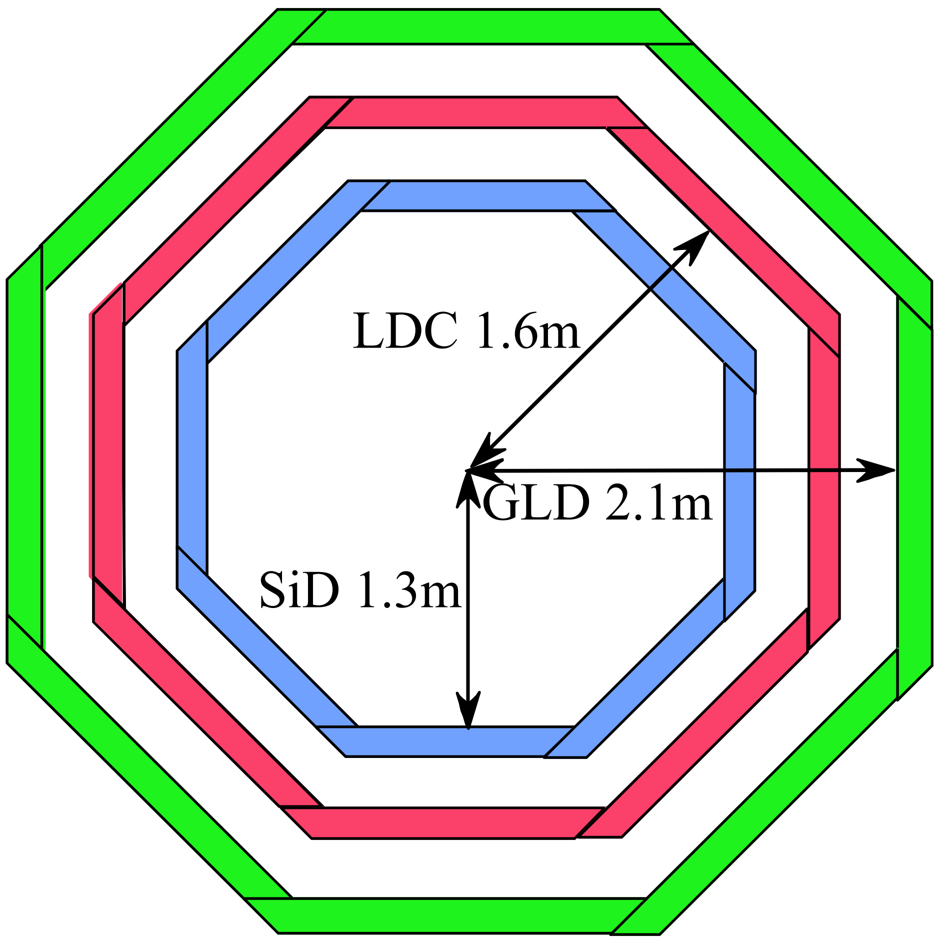


- Fourth



# The four detector concepts

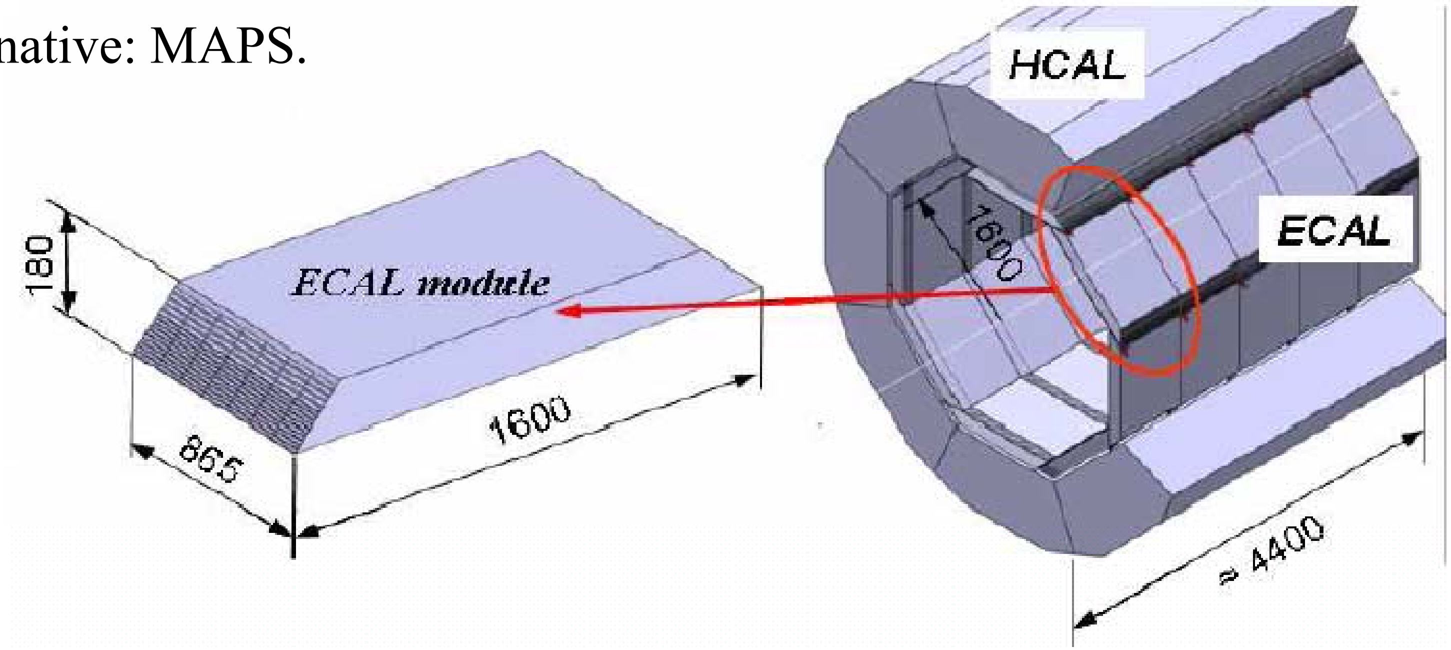
- Approximate relative sizes:




- All four detectors have ECal and HCal inside coil.
- SiD:
  - W/Si ECal.
  - Fe/RPC HCal.
  - All silicon tracking.
- LDC:
  - W/Si ECal.
  - Fe/Scint or Fe/RPC HCal.
  - TPC + silicon tracking.
- GLD
  - W/Scint Ecal.
  - Pb/Scint Hcal.
  - TPC + silicon tracking

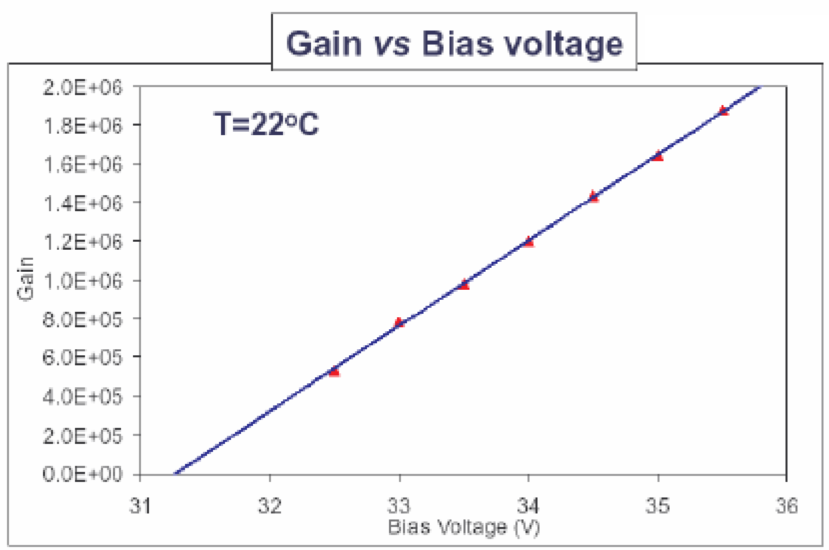
# Calorimetry – SiD/LDC

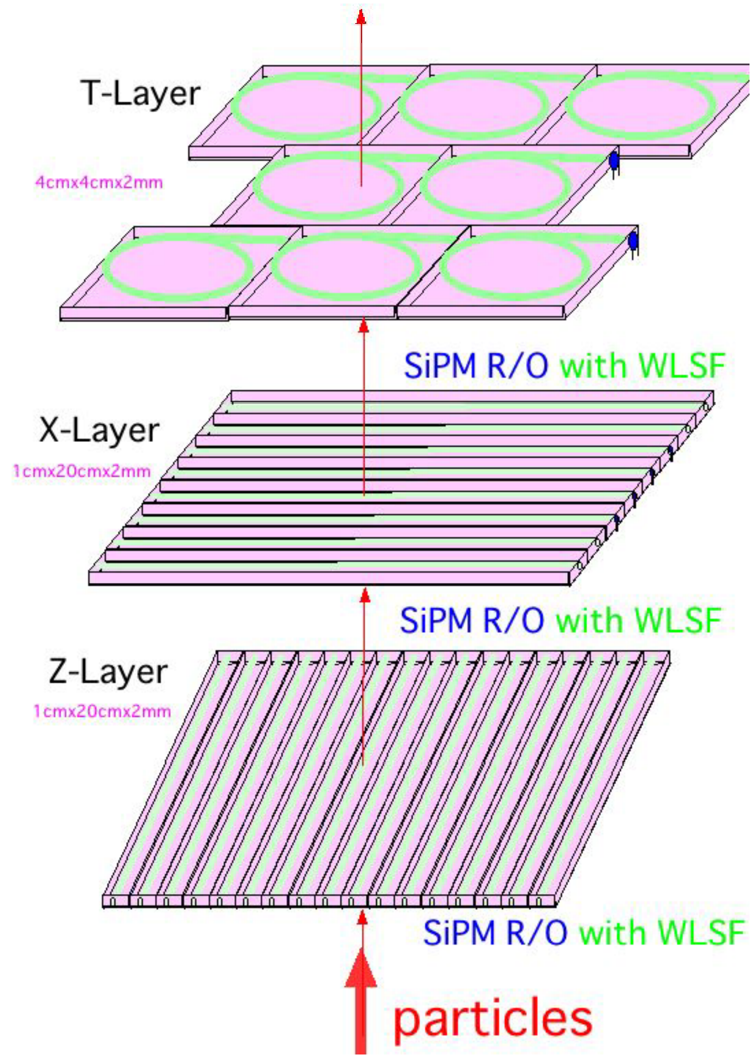
- ECal, tungsten absorber with readout granularity matched to $R_M \sim 1$ cm, 40 layers (24$X_0$, 0.9$\lambda_{had}$).
- Minimise gap between plates to maintain small $R_M$, use silicon pad detectors with low power readout, e.g. KPix chip.
- Alternative: MAPS.
- Tile HCal, analogue scintillator readout, 5 x 5 cm$^2$ granularity or...
- Digital HCal, RPC (or GEM...) readout, 1 x 1 cm$^2$ granularity.
- Longitudinal segmentation ~ 40 samples, 4...5 $\lambda_{had.}$



# Calorimetry – GLD

- ECal, achieve effective 1 x 1 $cm^2$ granularity using combination of orthogonal strips and pads.
- Strips 1 x 20 x 0.2 $cm^3$.
- Pads 4 x 4 x 0.2 $cm^3$.
- Silicon PM readout.

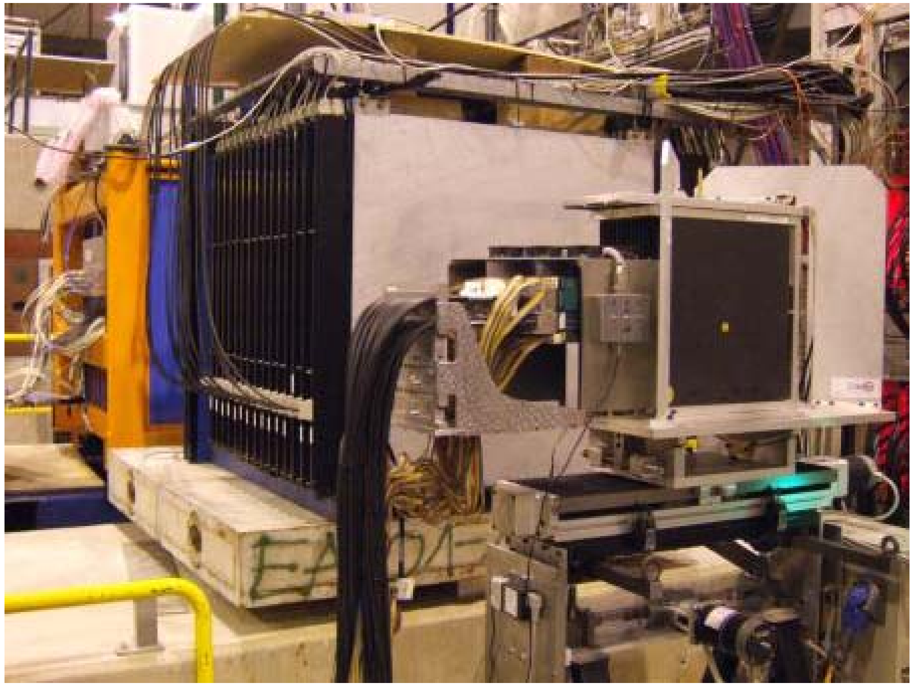


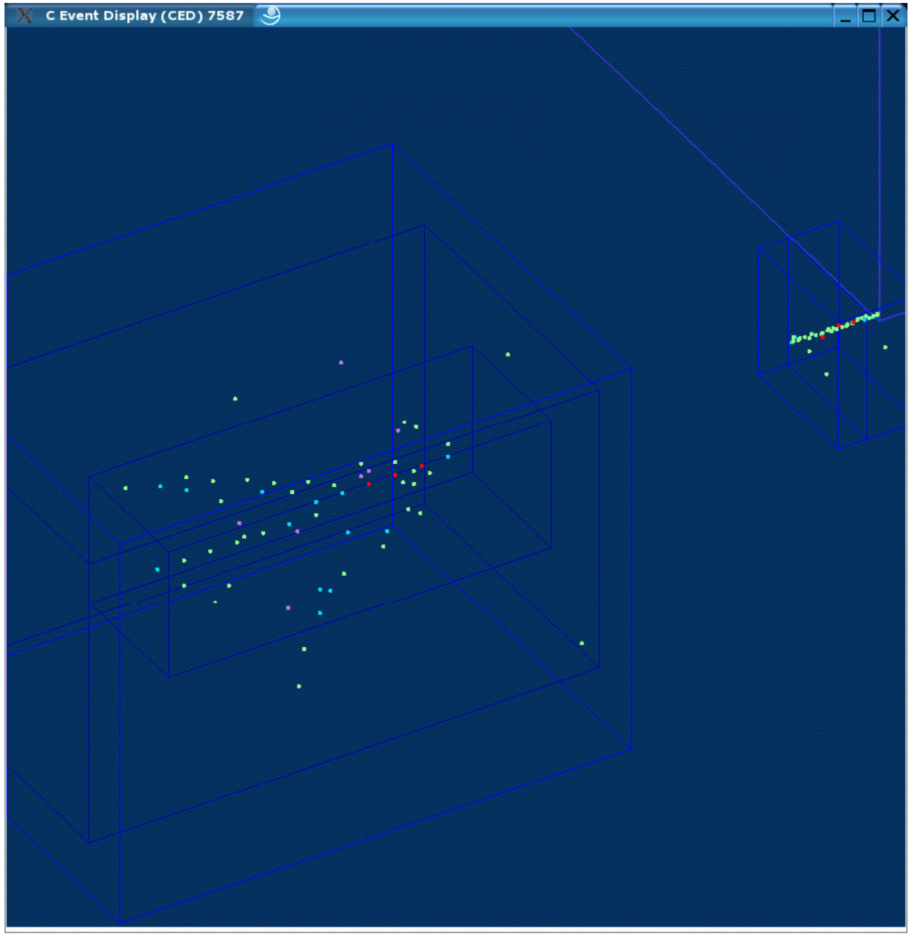

G Pauletta (Udine)

# Calorimetry

- Extensive programme to investigate technologies for fine grained calorimeters and validate simulations – CALICE Collaboration.
- CERN beam test (ongoing).

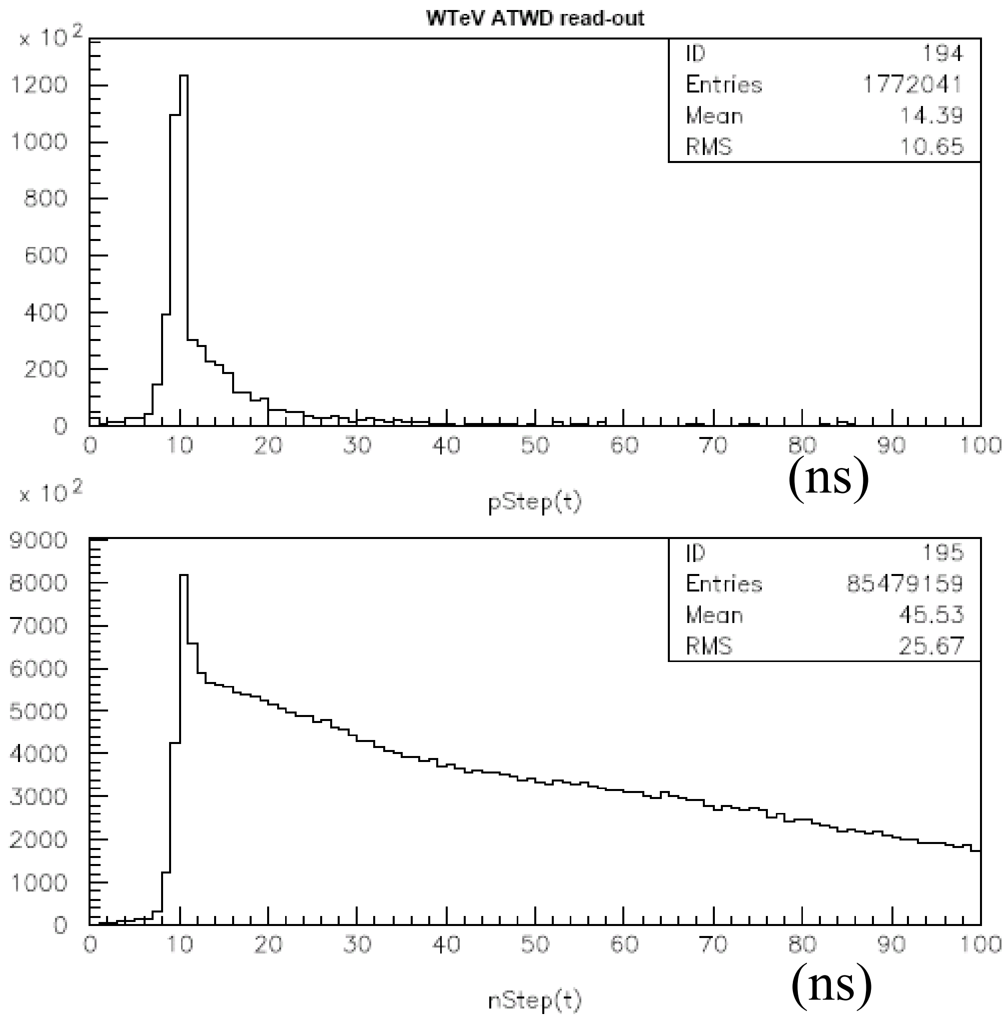


- Fine calorimeter granularity visible in event display.



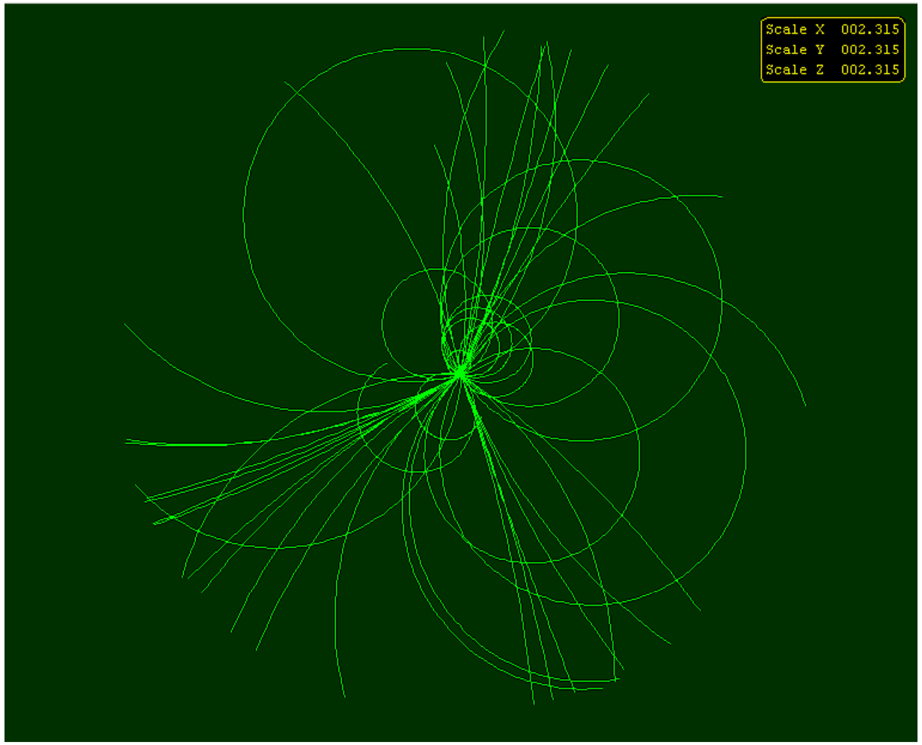
# Calorimetry – Fourth

- Aim to achieve required jet energy resolution using calorimeter alone.
- Tungsten (or brass) absorber.
- Identify fraction of electromagnetic energy using double (triple?) readout:
  - Scintillating fibres, see all charged particles.
  - Čerenkov fibres, primarily sensitive to relativistic electrons.
- Time difference between n and p signals allows n ID (fluc. in BE losses in nuclear break-up largest remaining uncertainty in shower, measure using np → np.)
- Precede with crystal ECal?

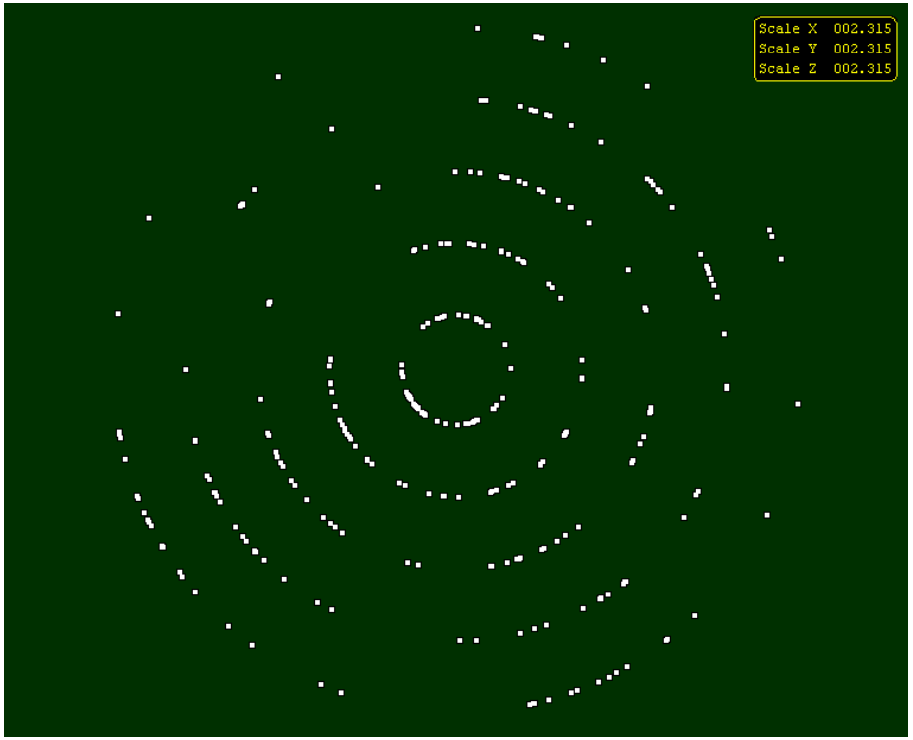


# Central tracking detectors

- Is it better to use a gaseous detector…

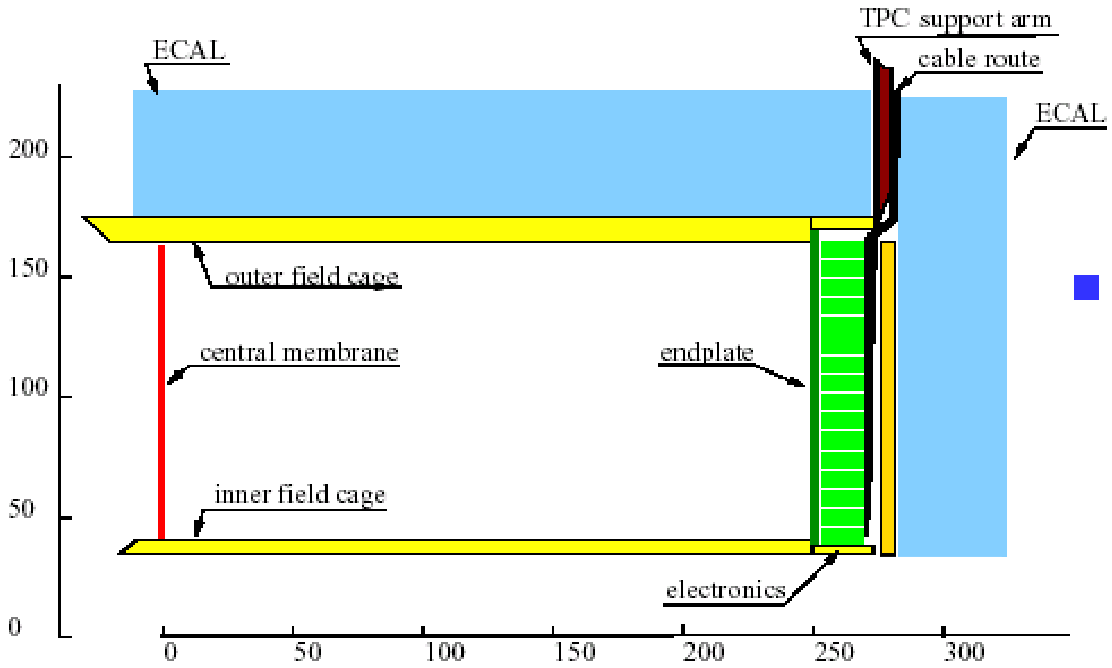



- … or one based on silicon sensors?



# Gaseous central detector

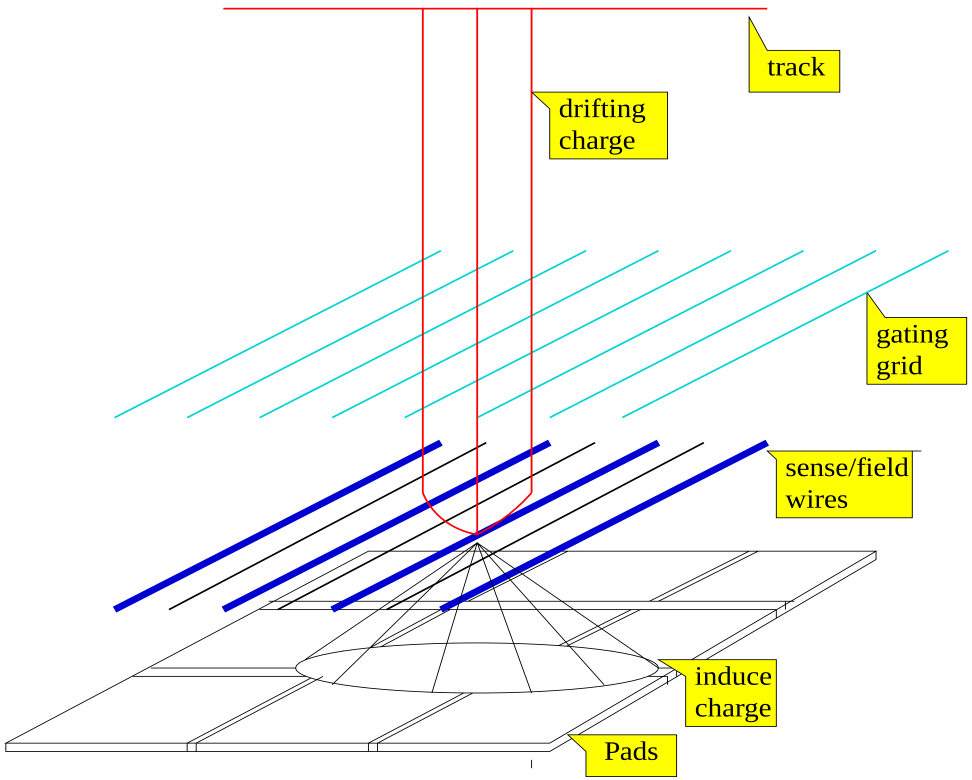
- LDC, GLD and Fourth concept have all opted for a TPC:

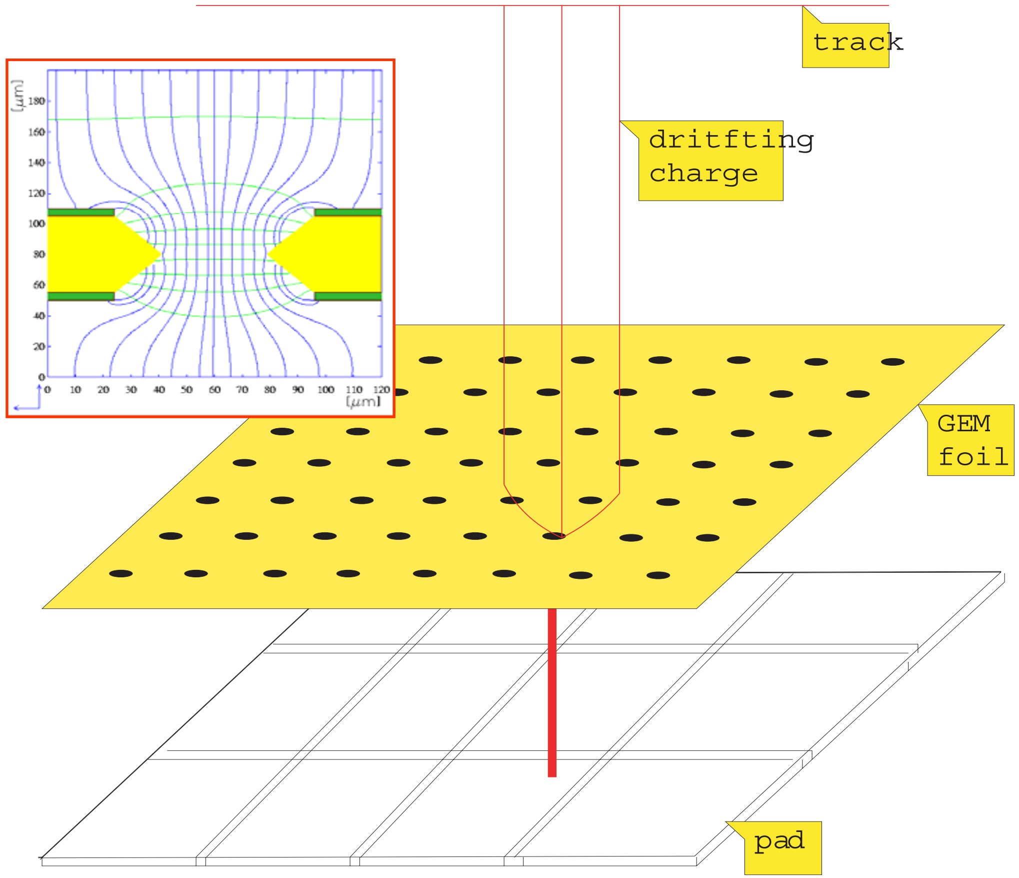



- Pros:
  - Material budget ~ 3%$X_0$.
  - Large sensitive volume.
  - High tracking efficiency (pattern recognition).
  - Particle ID via dE/dx.
- Contras:
  - Point resolution poorer than silicon.
  - Readout slow (~ 55 μs).
  - Material in end plates ~ 30% $X_0$.

# TPC readout

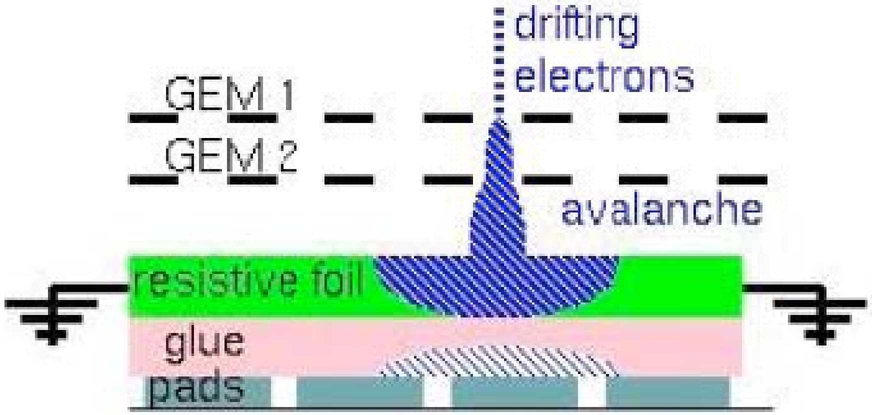
- Baseline design uses MWPC readout, signal induced on pads of approx. 2 x 6 mm$^2$, i.e. ~ 200 hits per track.
- Alternative, readout with MPGDs, e.g. GEM or Micromegas.



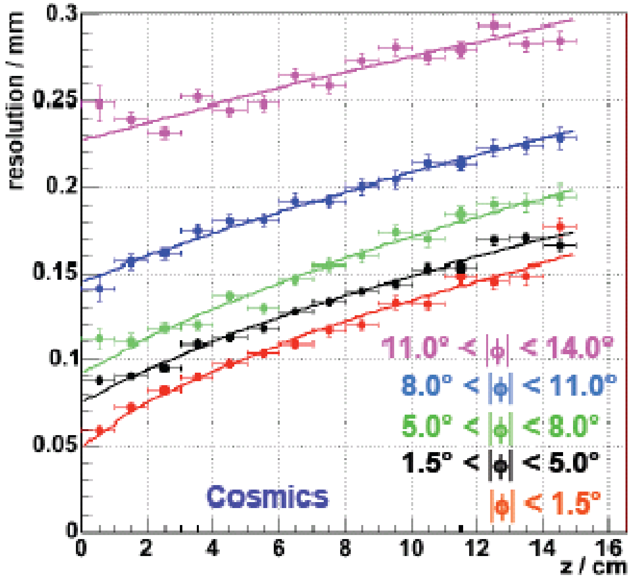



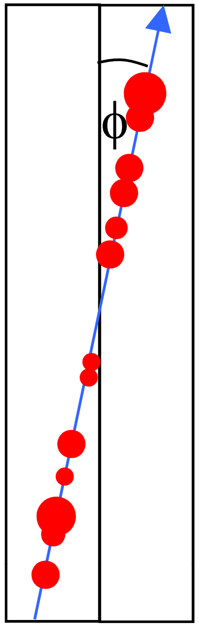
# TPC readout

- Pad width limits resolution with MPGD readout.
- Disperse charge after gas gain to improve centroid determination with large pads.




- Tests show good resolution for radial tracks, extrapolate to σ ~ 100 μm for 2.5 m drift.
- Fluctuations in charge deposition along track cause rapid deterioration with ϕ.

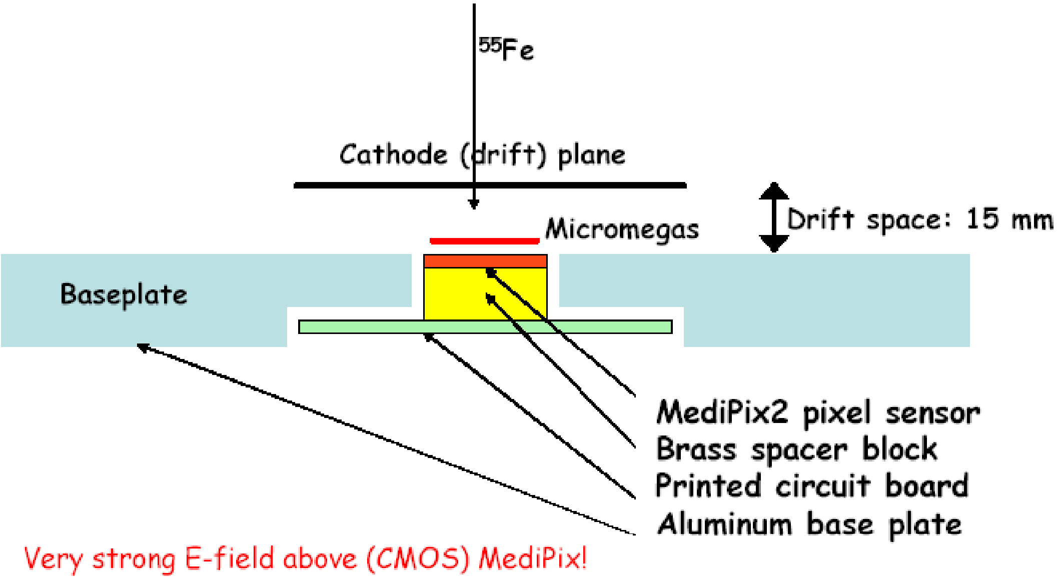



- Shorten pads to counteract?

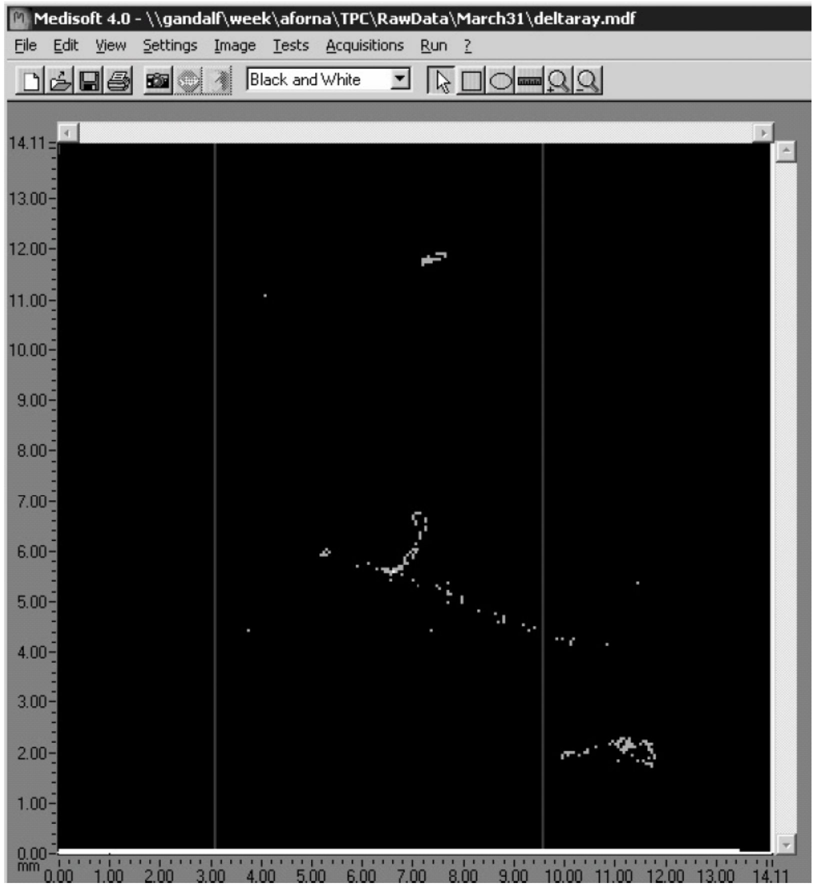
# TPC readout

- Alternative approach, design readout with granularity matching primary ionisation cluster spread.




- Pixel size 55 x 55 $\mu m^2$.
- Count individual ionisation clusters, few primary electrons per cluster.

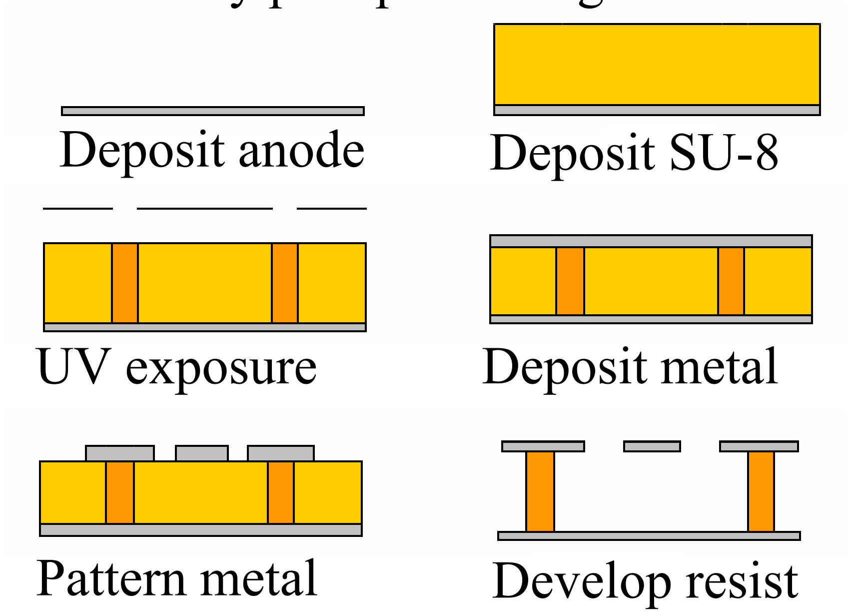
- E.g. δ-ray ejected by cosmic muon:



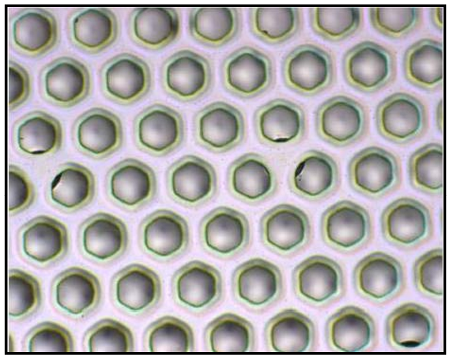

- Fit shows cluster resolution σ ~ 55 μm.

# TPC readout

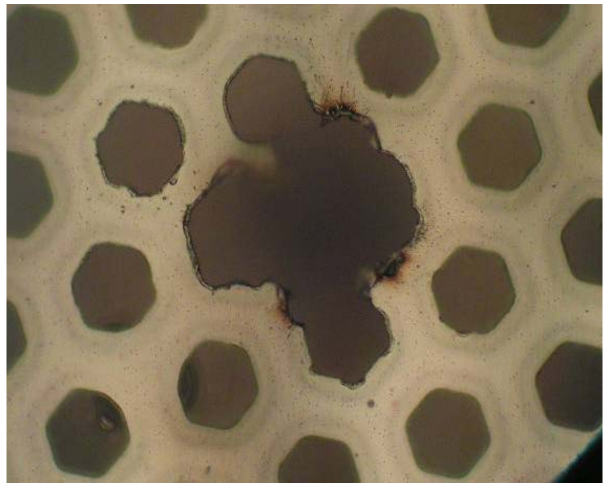
- InGrid: integrate MPGD and pixel sensor by post-processing wafers:




- After some teething problems:



- Measure gas gains up to $10^4$ in 80:20 Ar:$CO_2$ (good aging properties).
- Problem, sparking (80 kV/cm).

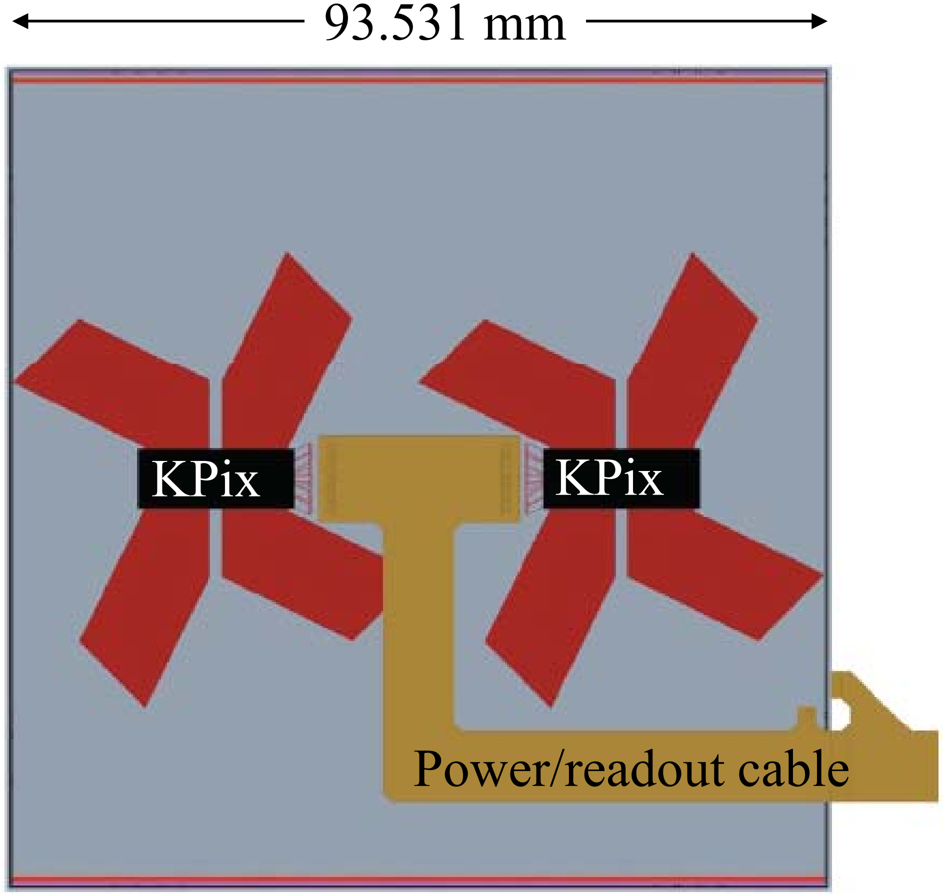


- Studying resistive (few µm amorphous silicon) coating as protection for sensors.

# Silicon central tracking

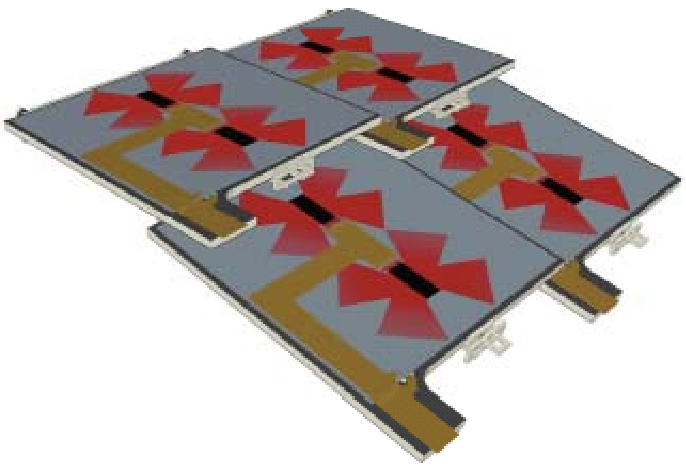
- SiD relies on silicon for tracking, LDC, GLD and Fourth need supplementary silicon tracking to obtain required resolution.
- Challenge is to reduce mass, goal is average of < 1% $X_0$ per layer.
- Exploit duty cycle of ILC.
- Turn off digital functions of chip during collisions (0.5% of time), amplify and buffer signals.
- Turn off analogue front end during readout (99.5% of time).
- KPix chip: readout 1024 pixels/strips, power < 20 mW.
- Hence avoid need for cooling.

- SiD design, single-sided p+/n Si, AC coupled, poly-biased, 50 µm readout/ 25 µm sense pitch, 1840 channels:



# Silicon central and supplementary tracking

- Mount on carbon fibre/rohacell, 50% void, to make module.
- Carbon fibre filled Torlon and $Si_3N_4$ ceramic mounting for precise and repeatable positioning:



- Material budget ~ 0.8% $X_0$ per layer.
- Prototyping underway.

- To supplement the TPC, LDC propose:
  - Few x $10^6$ strips, 10...60 cm long.
  - Strip pitch 50...200 µm, single-sided AC coupled.
  - (CMS: DC 10 to 20% cheaper, more reliable).
- Readout with two time ranges:
  - Shaping time ~ 1 µs, tag bunch crossing, few micron spatial resolution.
  - Shaping time ~ 40 ns, coordinate along strip to ~ 1 cm (1 ns).
- Use 180...130 nm CMOS, future move to SiGe, 90 nm?

# Summary

- The precision of the International Linear Collider provides an excellent complement to the discovery potential of the LHC.
- A feasible baseline ILC design has been produced.
- The challenges for experiments at the ILC are different to those at the LHC and are leading to novel approaches to detector design.
- Window of opportunity for detector development of a few years.
- Technical Design Reports for ILC machine and detectors around 2010...
- ...hopefully leading to ILC physics results before 2020.