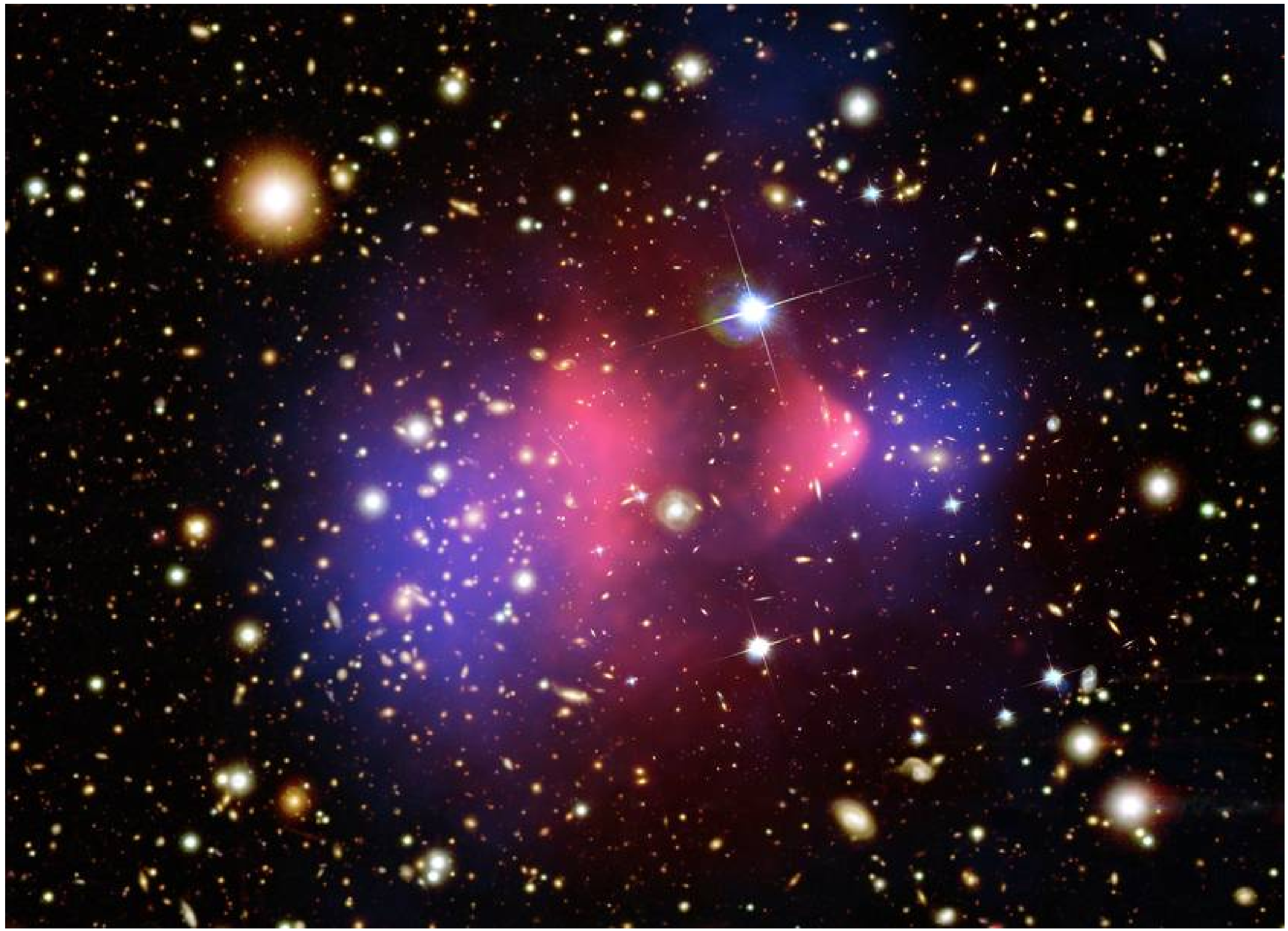
# Physics with Flavour at the International Linear Collider

- Introduction
- Progress with the ILC
- ILC detectors
- Flavour identification at the ILC
- Some physics of, and with, flavour
- Summary

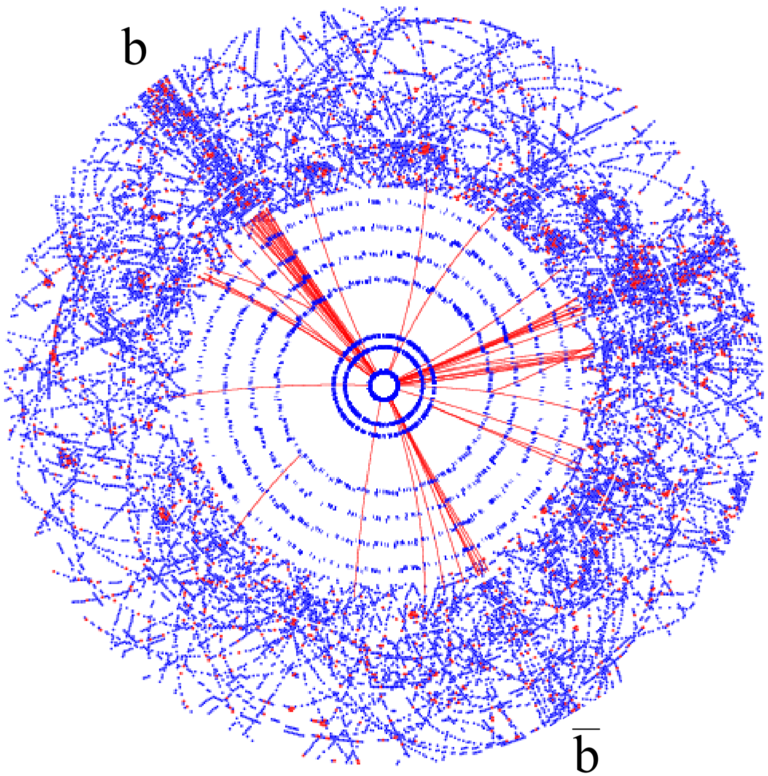
# Why new colliders?
# There is more to heaven and earth...

- 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.

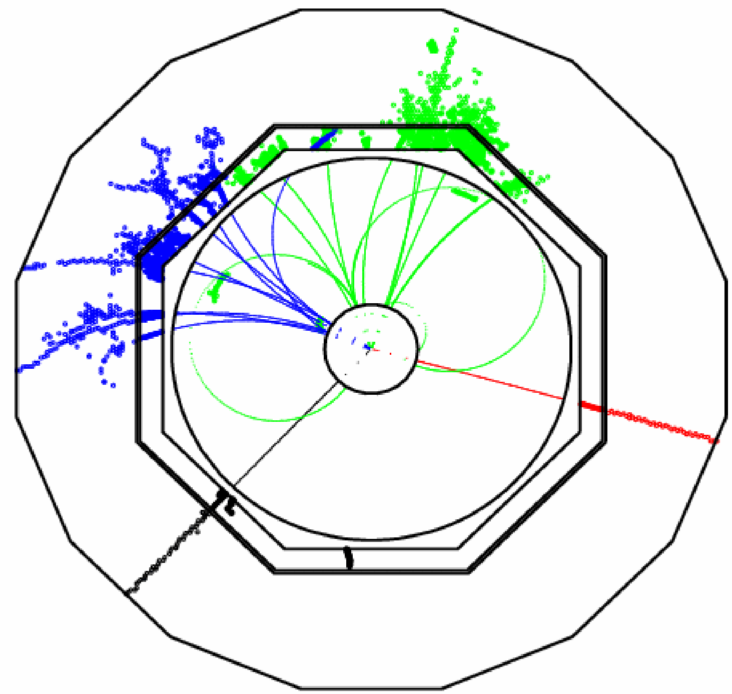


# Why the ILC? Electron-positron collisions complement pp

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

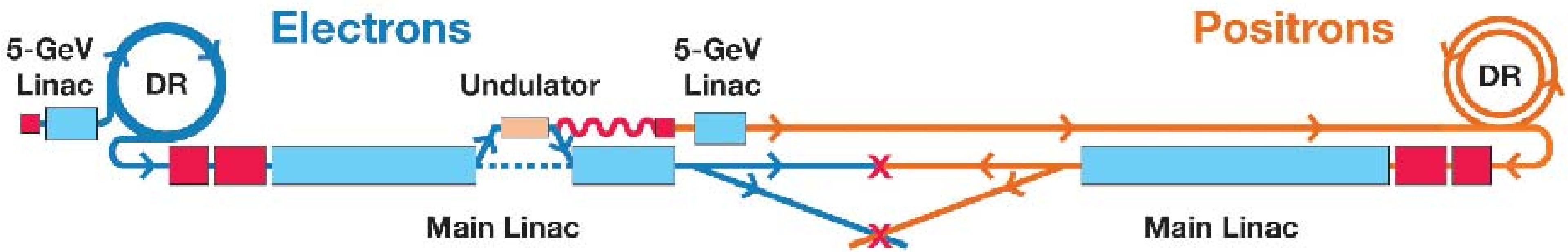



- $e^+e^- \rightarrow HZ$ as expected in LDC detector at ILC:

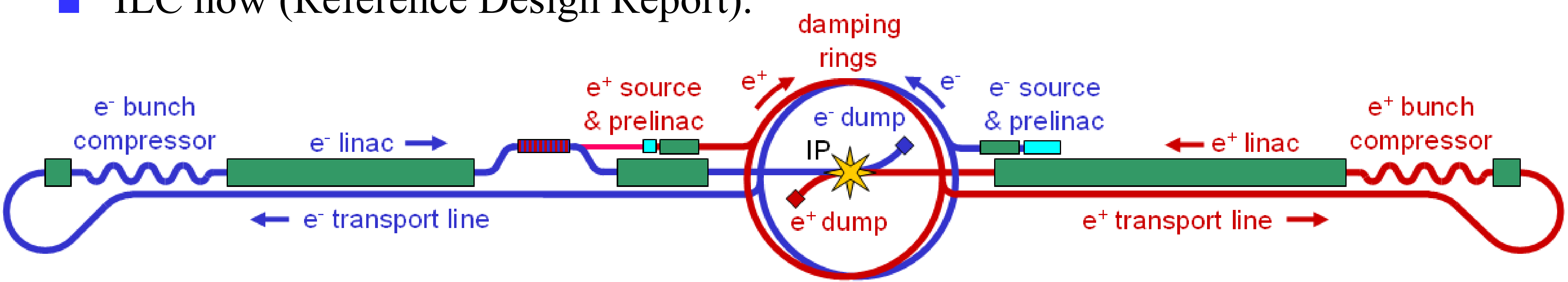


# The International Linear Collider

- ILC design July 2006 (Vancouver LCWS)

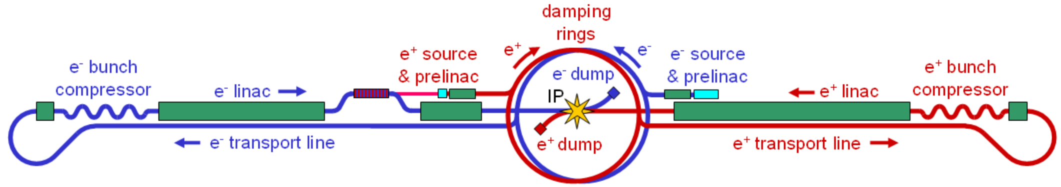



- ILC now (Reference Design Report).

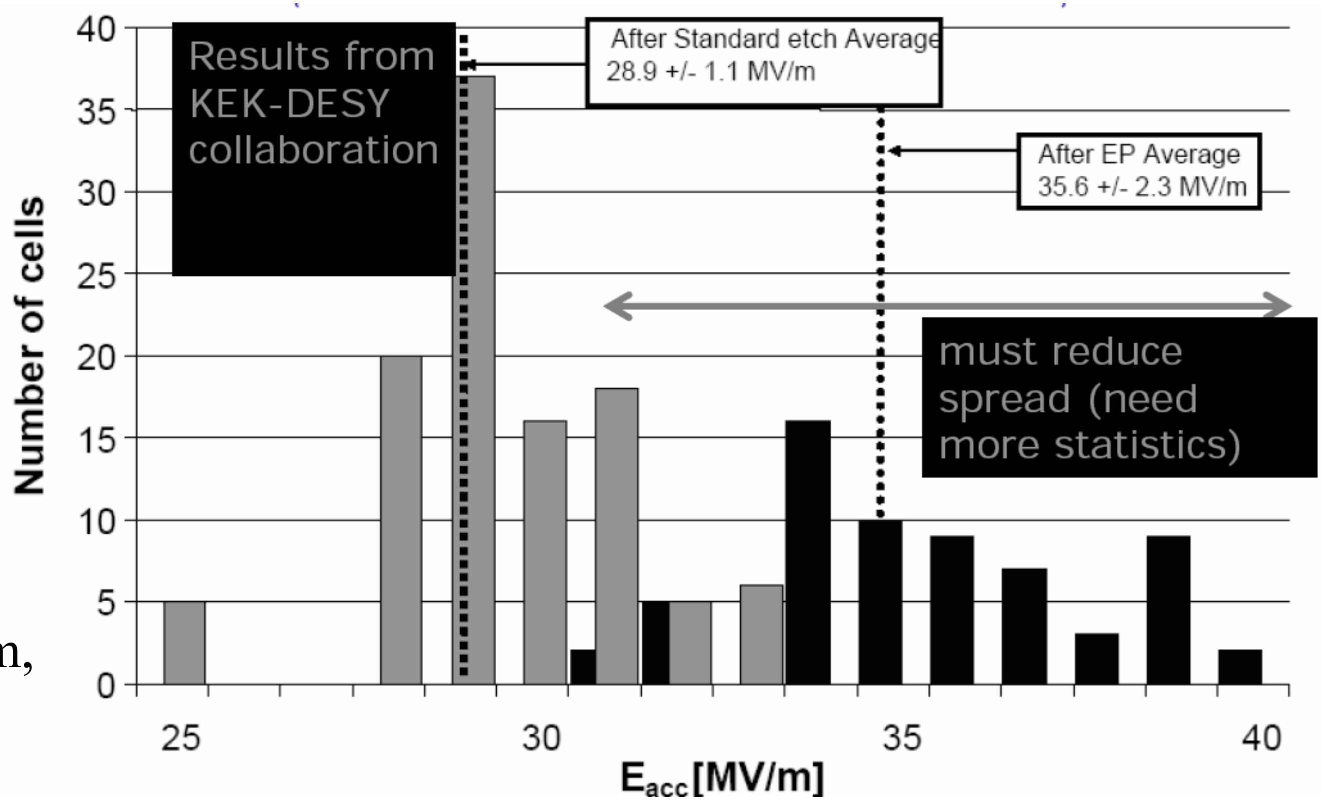



- $\sqrt{s}$ = 200...500 GeV, upgrade to 1 TeV.
- $\mathcal{L} \sim 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, i.e. 500 fb$^{-1}$ in first 4 years.
- Energy stability better than 0.1%.
- Electron polarisation 80% ($e^+$ 30%).
- Cost \$4.9B + \$1.8B + 13k person-years.

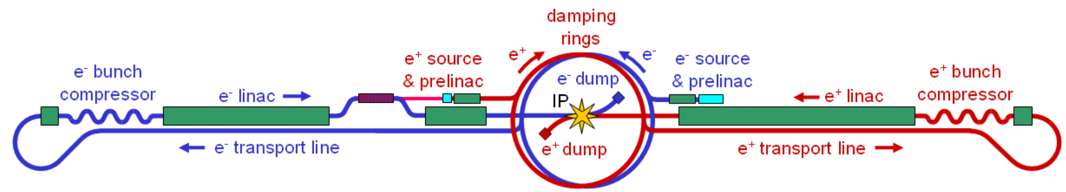
# Superconducting cavities




- 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.



# Beam Delivery System




- Final focus.
- Luminosity given by:

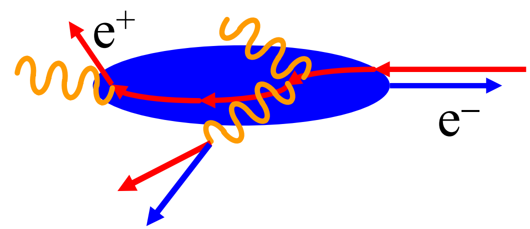
$$\mathcal{L} = \frac{n_b N^2 f_{rep}}{A} H_D,$$

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.



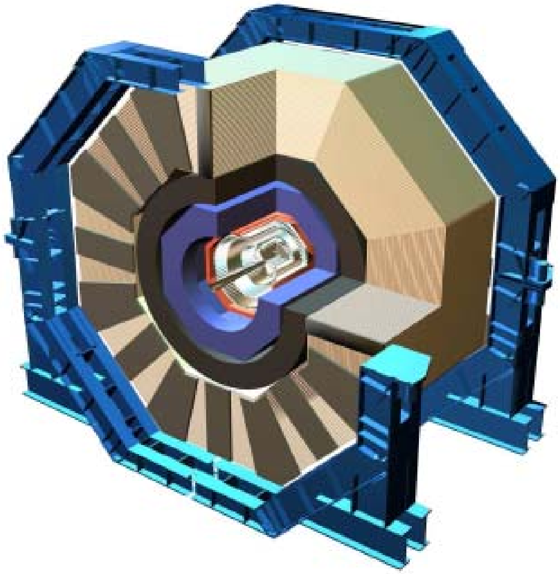

- These beamstrahlung photons interact with field of bunches, and generate $e^+e^-$ pairs.
- Beam-beam effects characterized by disruption parameter:

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

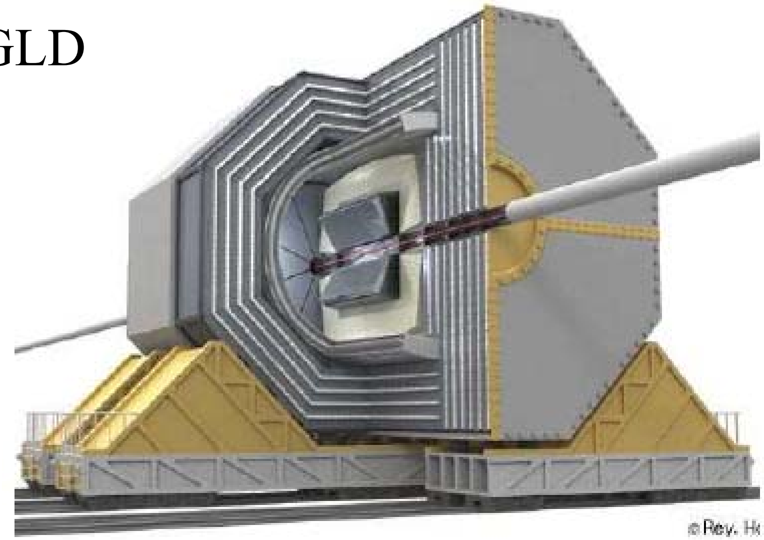
- Flat beam, $\sigma_y < \sigma_x$, better than round: beam height ~5 nm, width ~500 nm.

# Four detector concepts

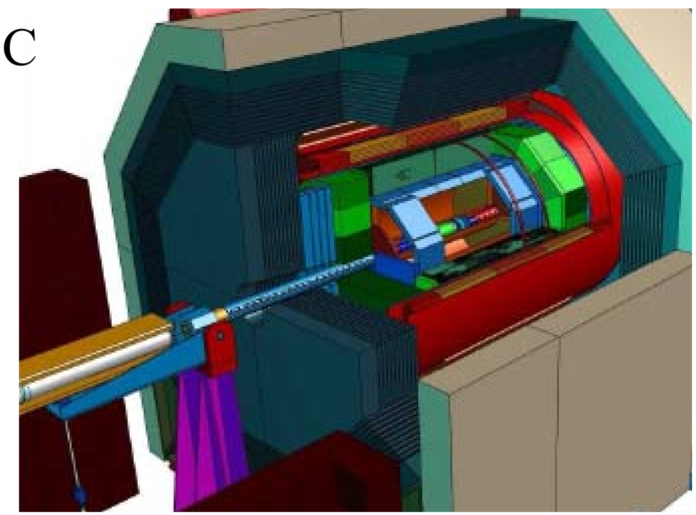
- SiD



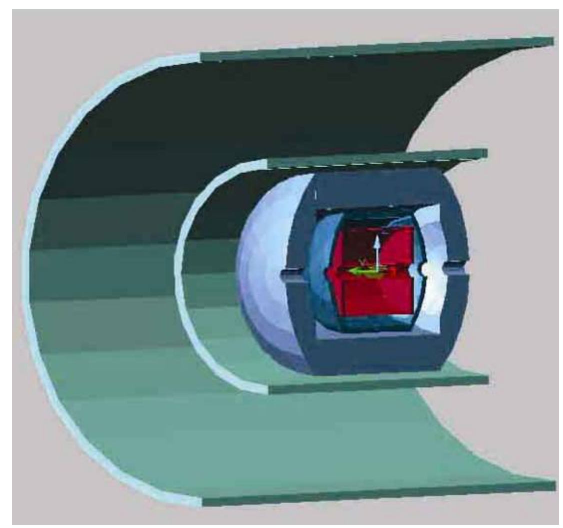
- GLD



- LDC

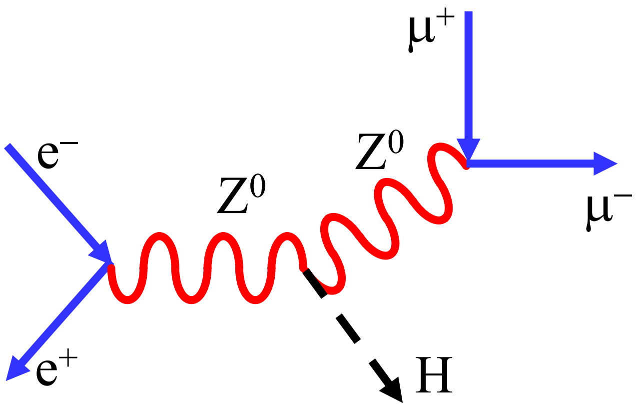


- Fourth

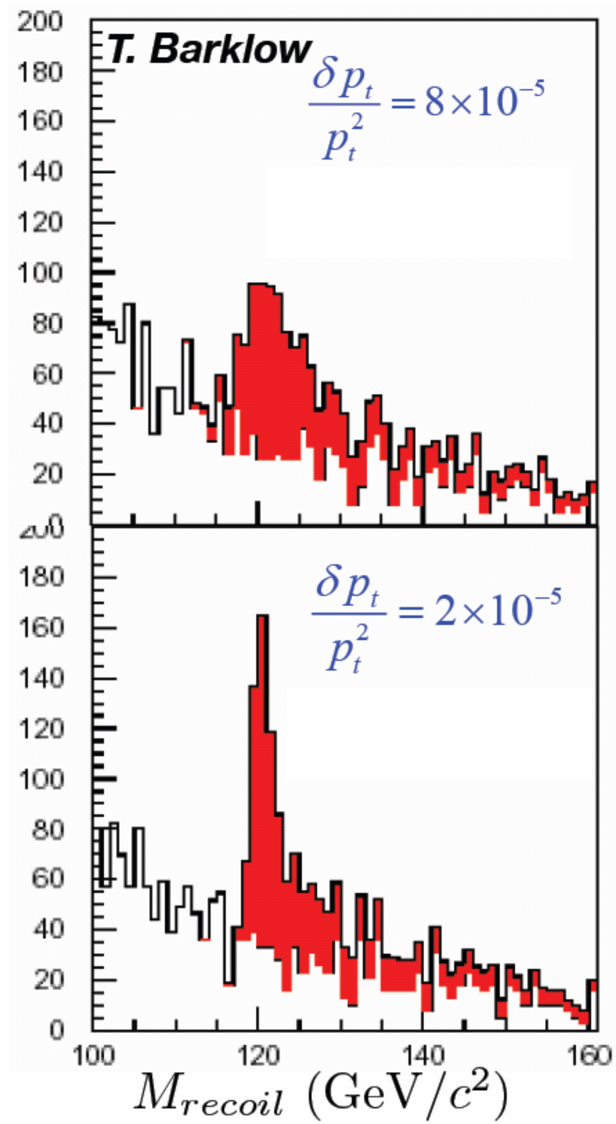


# Detector requirements – tracking

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



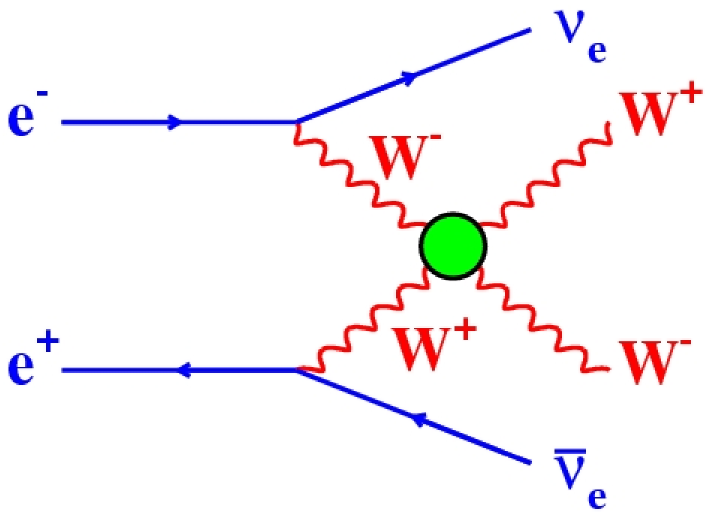

- Must couple with large acceptance and robust pattern recognition capabilities to cope with multi-jet environment, e.g. six jets in $e^+e^- \to t\,\bar{t}$ events.




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

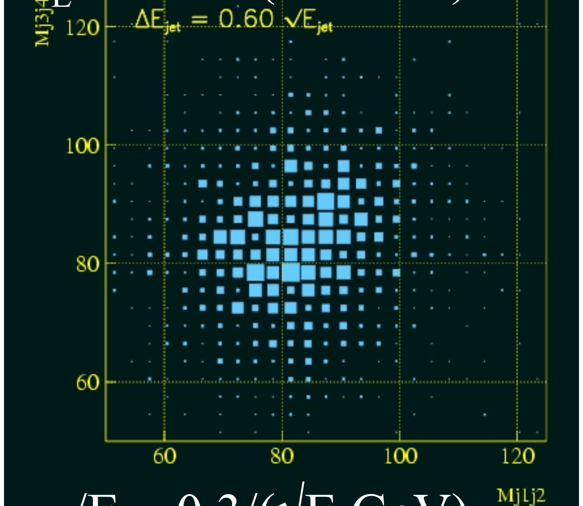
# Detector requirements – calorimetry

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

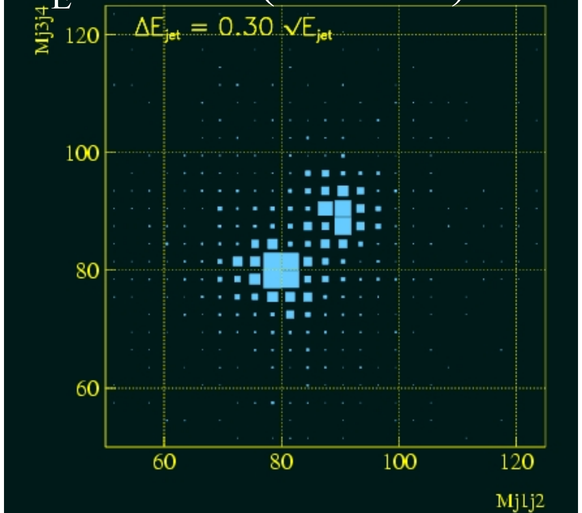



- Good jet energy resolution required.

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

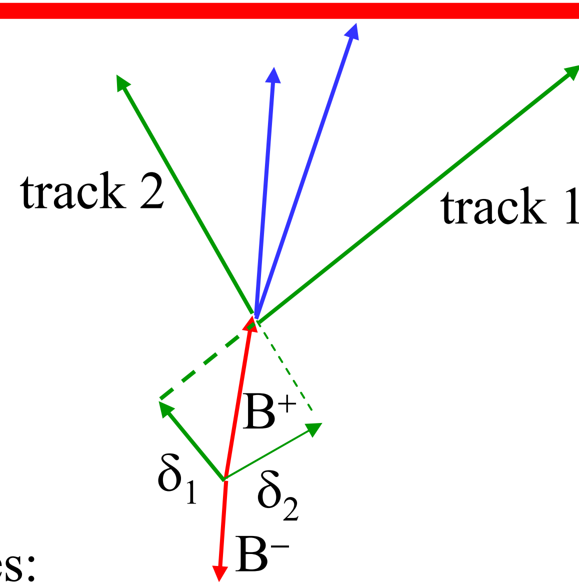



- $\sigma_E/E = 0.3/(\sqrt{E}\ \text{GeV})$



# Detector requirements – vertexing

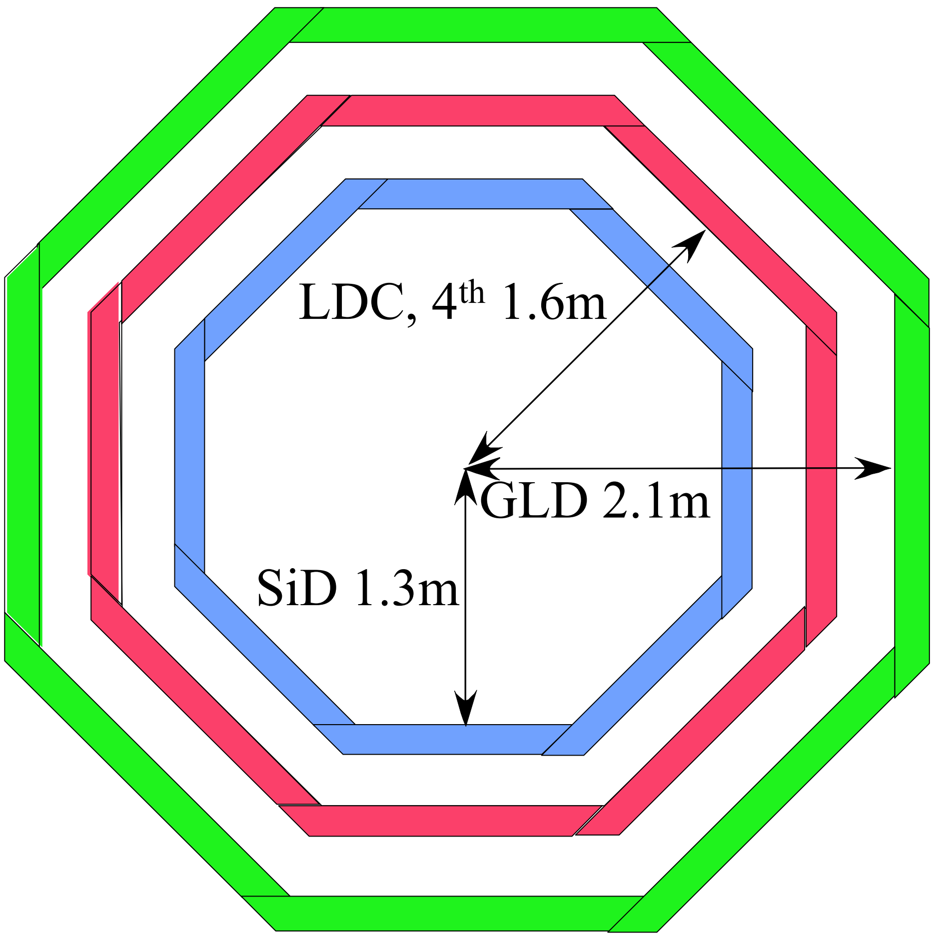
- Efficient identification required for $\tau$ leptons, c and b quarks.
- Average impact parameter $\delta$ of B decay products ~ 300 μm, of charmed particles less than 100 μm.
- Must resolve all tracks in dense jets.
- Cover large solid angle: forward/backward events are of particular significance for 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 $|\cos \theta| < 0.96$.

# The four detector concepts

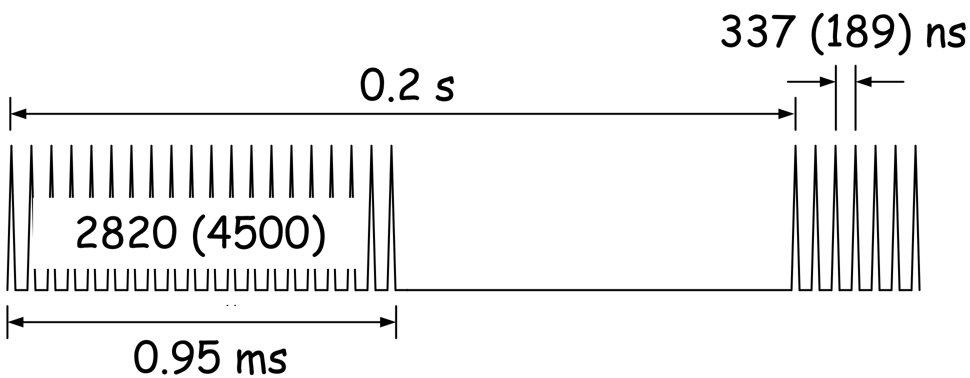
- Approximate relative sizes:




- ECal and HCal inside coil.
- SiD:
  - W/Si ECal, Fe/RPC HCal.
  - All silicon tracking + VXD.
- LDC:
  - W/Si ECal, Fe/Scint or Fe/RPC HCal.
  - TPC + silicon tracking + VXD.
- GLD:
  - W/Scint Ecal, Pb/Scint Hcal.
  - TPC + silicon tracking +VXD.
- Fourth:
  - Cystal ECal, W/multi-fibre HCal.
  - TPC + silicon tracking +VXD.

# Vertex detectors – constraints due to machine

- Minimum beam pipe radius ~14 mm.
- Pair background at this radius in ~4T field causes ~0.03 (0.05) hits per BC and $mm^2$ at $\sqrt{s}$ = 500 (800) GeV.
- Bunch train structure:

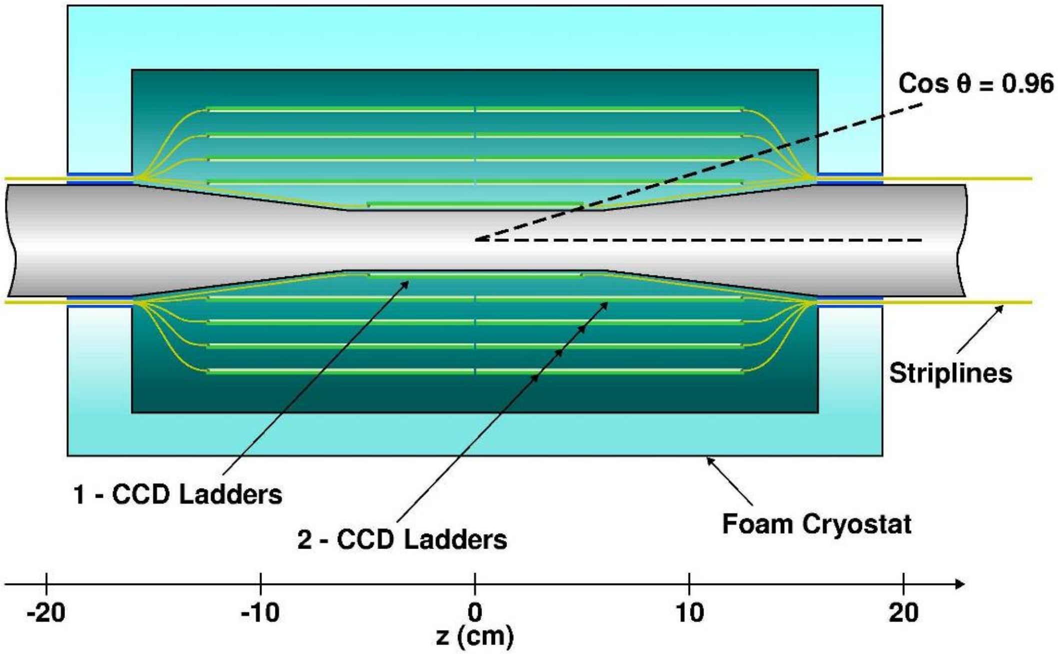



- For $10^9$ pixels of size 20 x 20 $\mu m^2$, implies readout or storage of signals ~20 times during bunch train to obtain occupancy less than ~ 0.3% (0.9%).

- Must withstand:
  - Radiation dose of ~50 krad p.a.
  - Annual dose of neutrons from beam and beamstrahlung dumps ~1 x $10^9$ 1 MeV equiv. n/$cm^2$.
- Must cope with operation in magnetic field of up to 5 T.
- Must be robust against beam-related RF pickup and noise from other detectors.
- None of available sensor technologies yet satisfies all these requirements.

# Conceptual vertex detector design

- Example using CCDs:

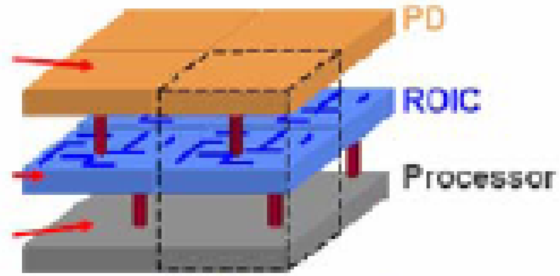



- Surrounded by ~2 mm thick Be support cylinder.
- Allows Be beam pipe to be of thickness of ~0.25 mm.
- Pixel size 20 x 20 $\mu m^2$, 8 x $10^8$ pixels in total.
- 50 MHz readout of inner layer.
- Standalone tracking using outer 4 layers.
- Hits in first layer improve extrapolation of tracks to IP.
- Sensor operation at ~220 K, gas cooling, additional evaporative cooling for electronics if needed.
- Readout and drive connections routed along BP.
- Important that access to vertex detector possible, "roll" outer tracker along BP as done at SLD.

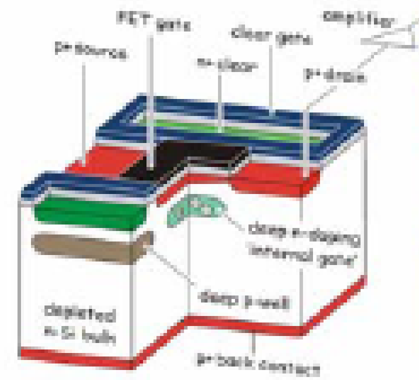
# Sensors for the vertex detector

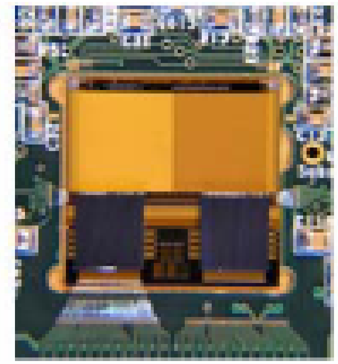
**Many different technologies**

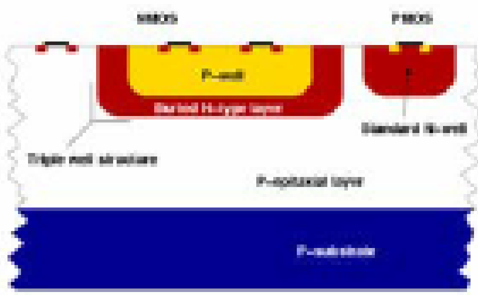
- CP-CCD
- DEPFET
- FAPS
- FP-CCD
- MAPS
- MAPS (tripple well)
- SOI
- 3D

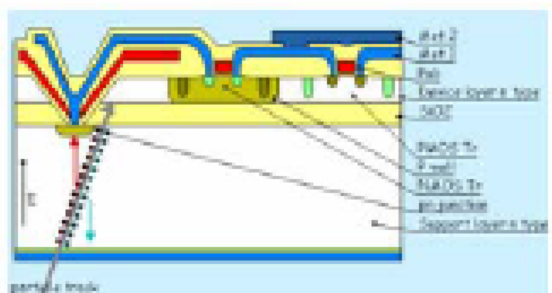


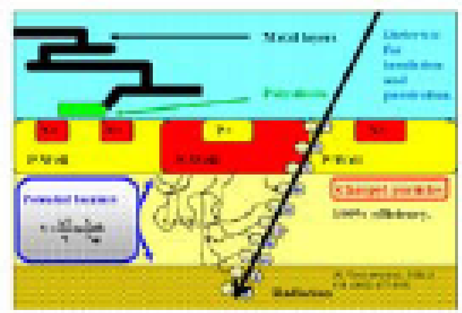

3D Pixel Layout[9]





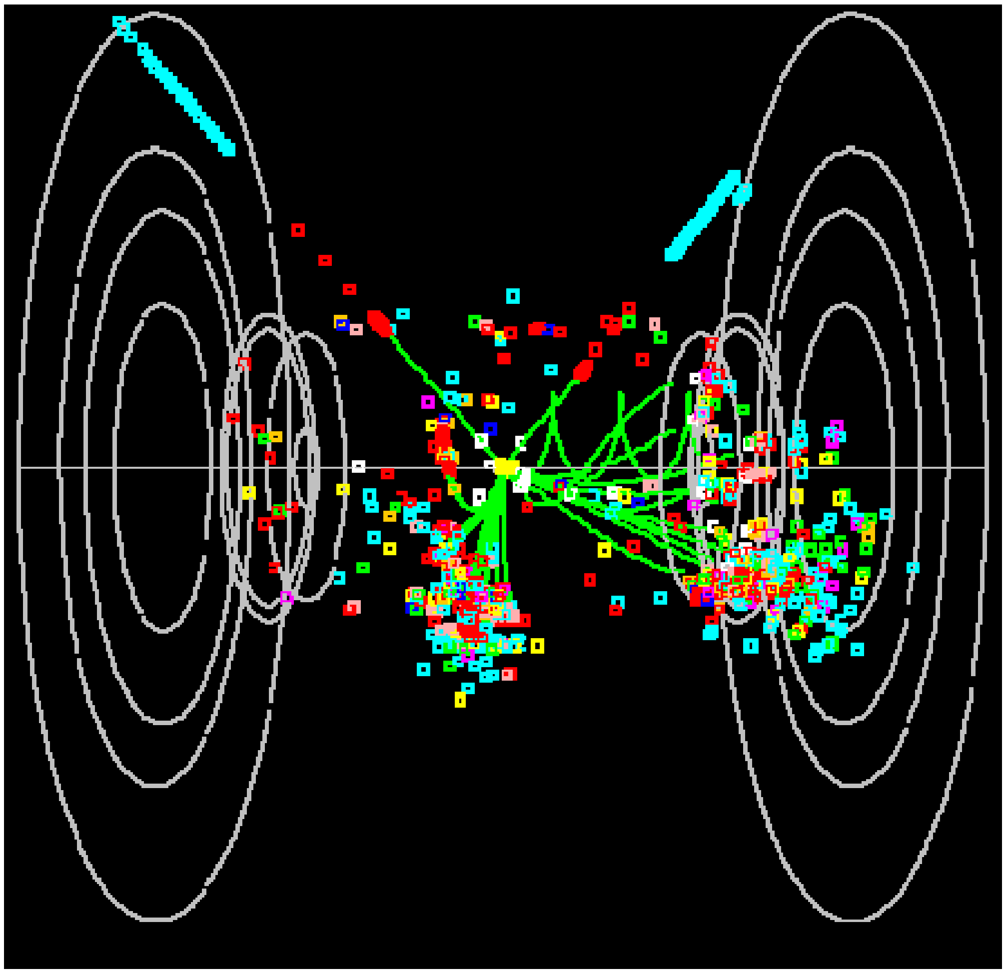




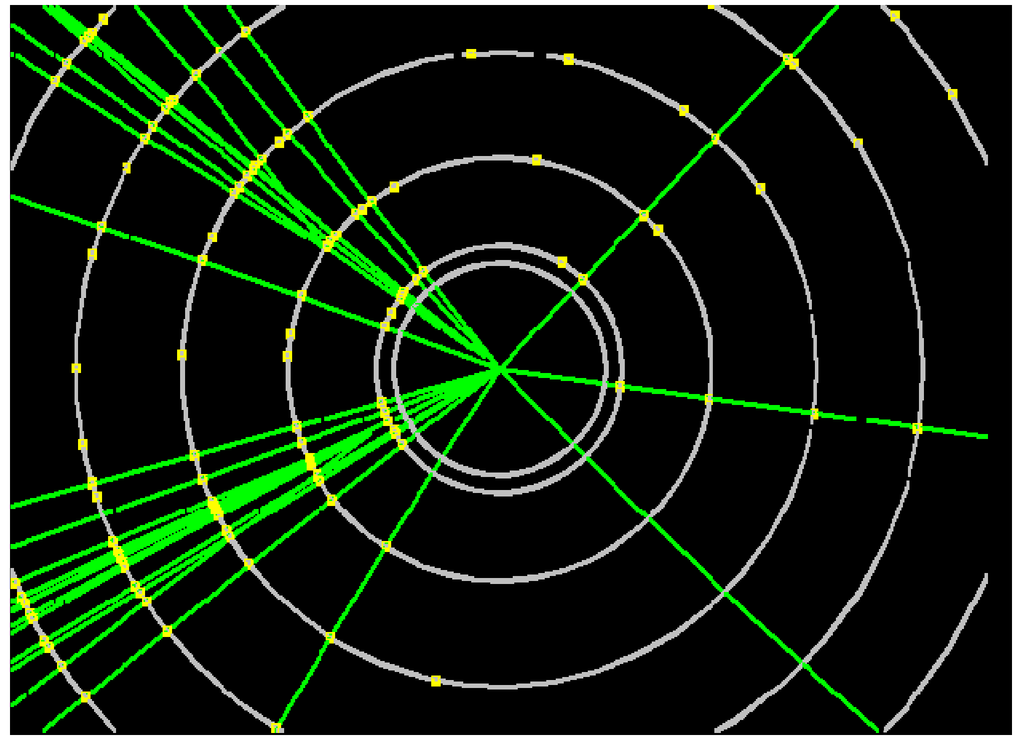
Excellent reviews by Konstantin Stefanov, Joel Goldstein, Rainer Richter, Hans Krueger, Marc Winter, Devis Contarato, Valerio Re, Tadashi Nagamine, Ray Yarema, Wojciech Kucewicz

# Finding decay vertices using the vertex detector

- E.g. $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-$ jet jet.



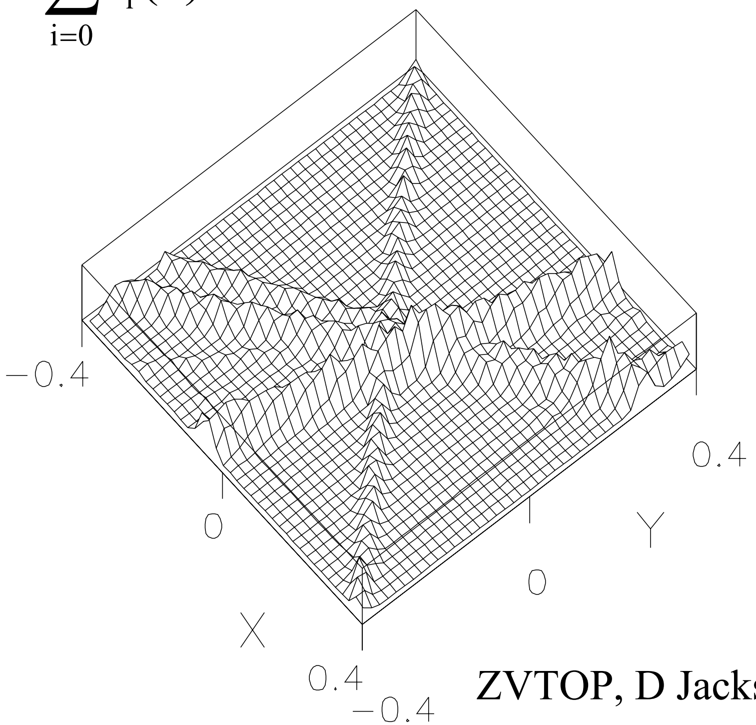
- Vertex region:



- Challenge is to associate all charged tracks with correct vertex in high track density environment.

# Topological vertex reconstruction

- Using VXD hits, tracks approximated as probability tubes, $f_i(\vec{r})$, beam spot as ellipsoid, $f_0(\vec{r})$.
- E.g. N tracks, integrating over z, $\sum_{i=0}^{N} f_i(\vec{r})$:

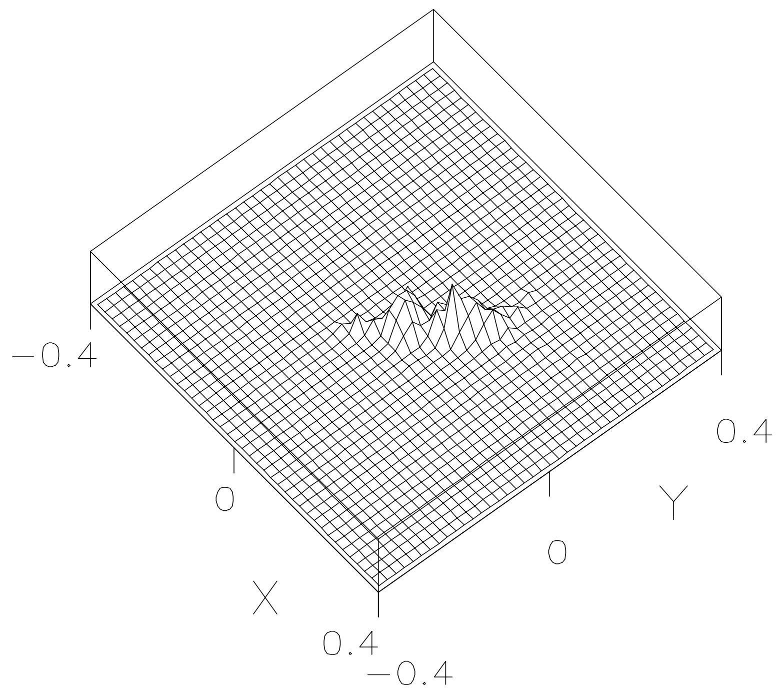



ZVTOP, D Jackson

- From these define vertex function:

$$V(\vec{r}) = \sum_{i=0}^{N} f_i(\vec{r}) - \frac{\sum_{i=0}^{N} f_i^2(\vec{r})}{\sum_{i=0}^{N} f_i(\vec{r})}$$

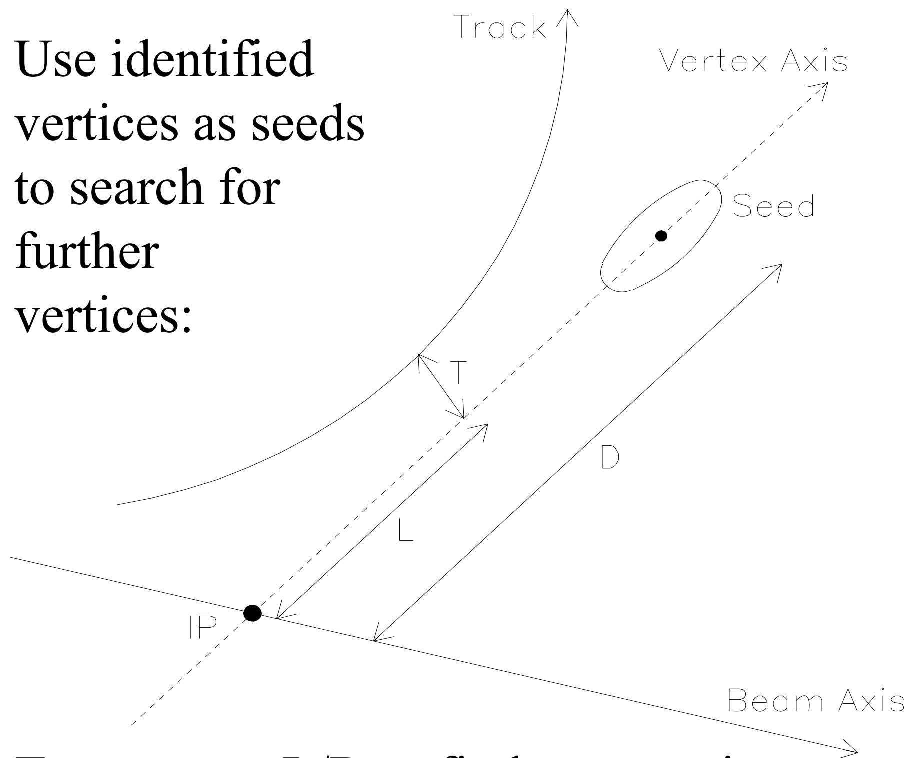
- Returning to e.g.:



# Topological vertex reconstruction

- Find "seed" maxima in $V(\vec{r})$ for track-track and vertex-track pairs which are "resolvable" and for which $\chi^2$ good.
- Search around seeds for true maxima in $V(\vec{r})$, including all tracks and vertex.
- Spatially resolved maxima form candidate vertices if associated with 2 or more tracks.
- Track/vertex association ambiguities are decided according to largest $V(\vec{r})$ after quality cuts.
- Vertex that includes the IP ellipsoid is primary vertex.

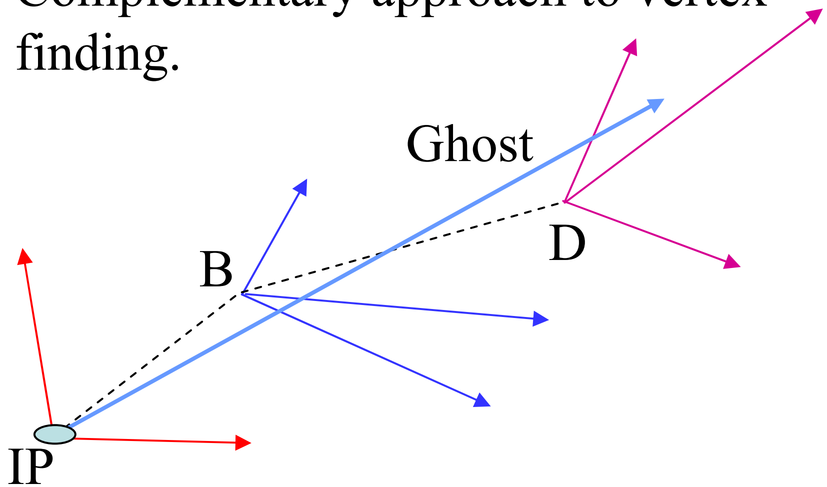
- Use identified vertices as seeds to search for further vertices:




- Tune cut on L/D to find new vertices, possibly "one prong".
- (Additional weighting factors can be applied to favour vertices near jet core, to suppress vertices v. close to IP etc.)

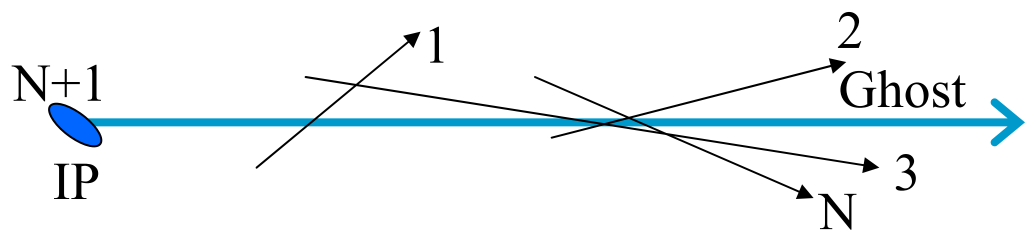
# Ghost track algorithm

- Complementary approach to vertex finding.

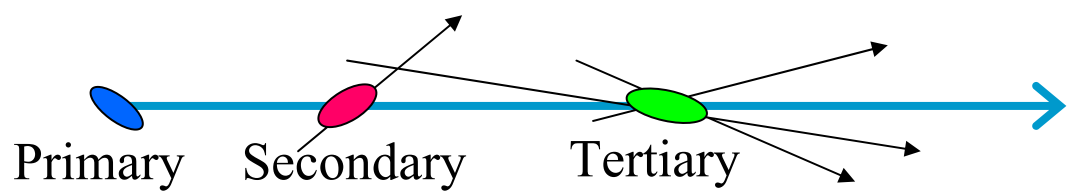



- Start with straight "ghost" track at IP along jet axis direction.
- Calculate $\chi^2$ of DCA each track in jet to ghost track.
- Swivel ghost track in $\theta$ and $\varphi$ to minimise $\sum\chi^2$ for all tracks in jet.

- Now have N (tracks) + 1 (IP) initial vertex candidates.



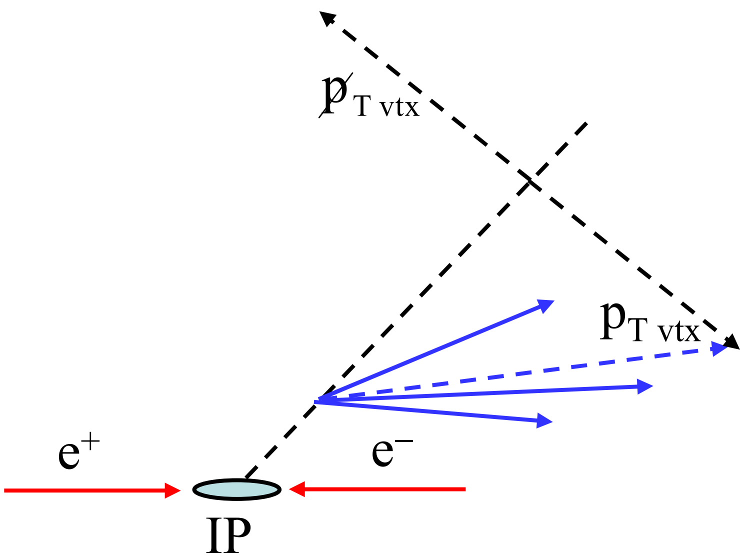

- Calculate fit probability for all track-ghost track or track-IP combinations.
- If prob. high, combine objects to form vertex.
- Iterate.



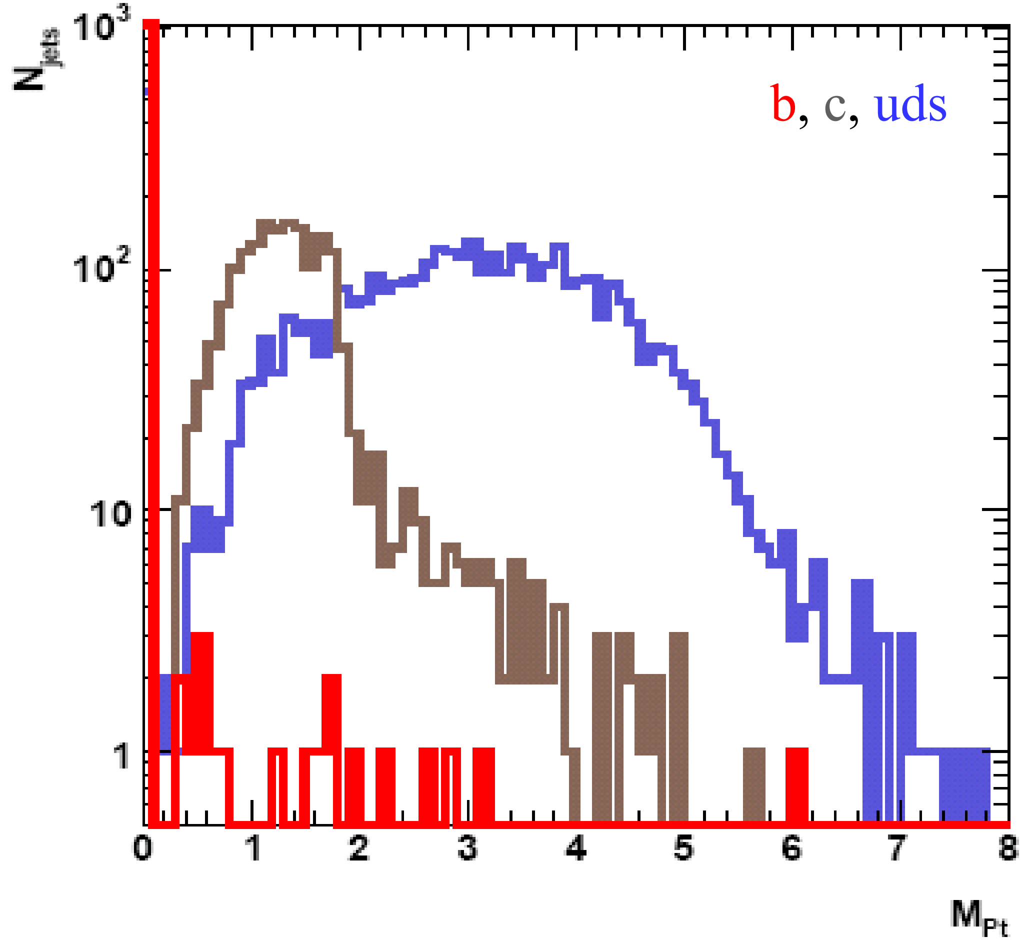
# Flavour identification

- Identify variables that provide discrimination between uds/gluon and c and b jets.
- E.g., if vertex found, $p_T$ corrected mass, $m_{pT}$, is useful variable,

$$m_{pT} = \sqrt{m_{vtx}^2 + p_{T\,vtx}^2} + p_{T\,vtx}.$$

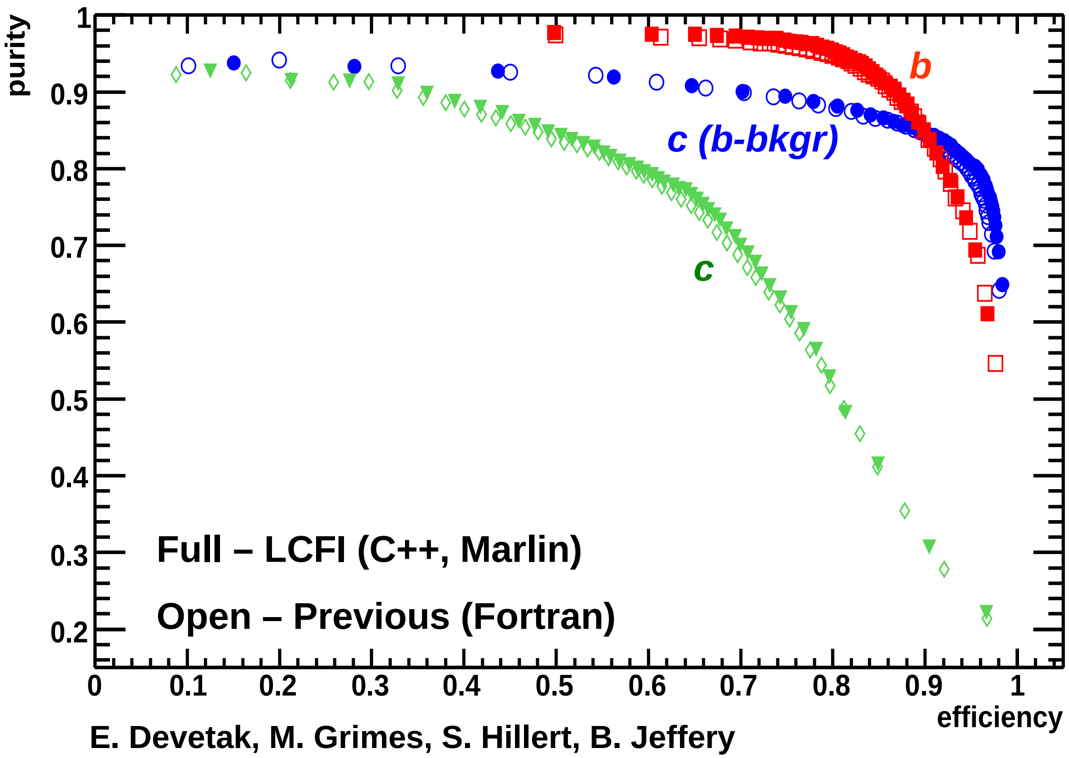



- $m_{pT}$ distributions:

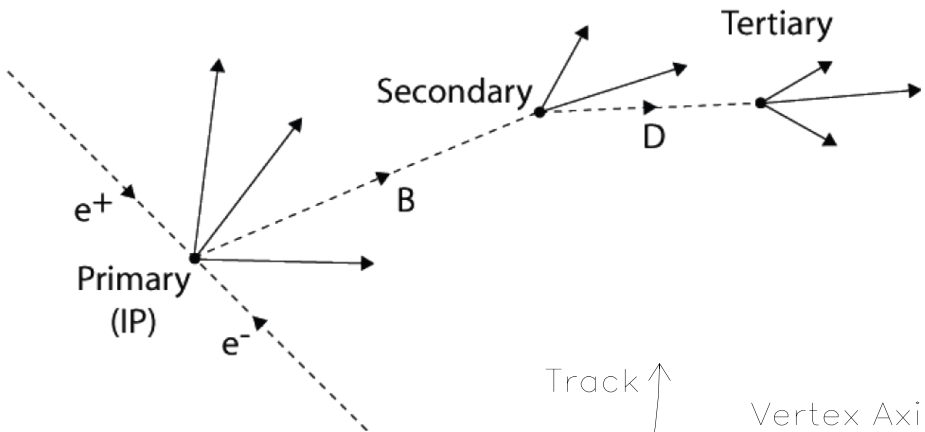


# Flavour identification

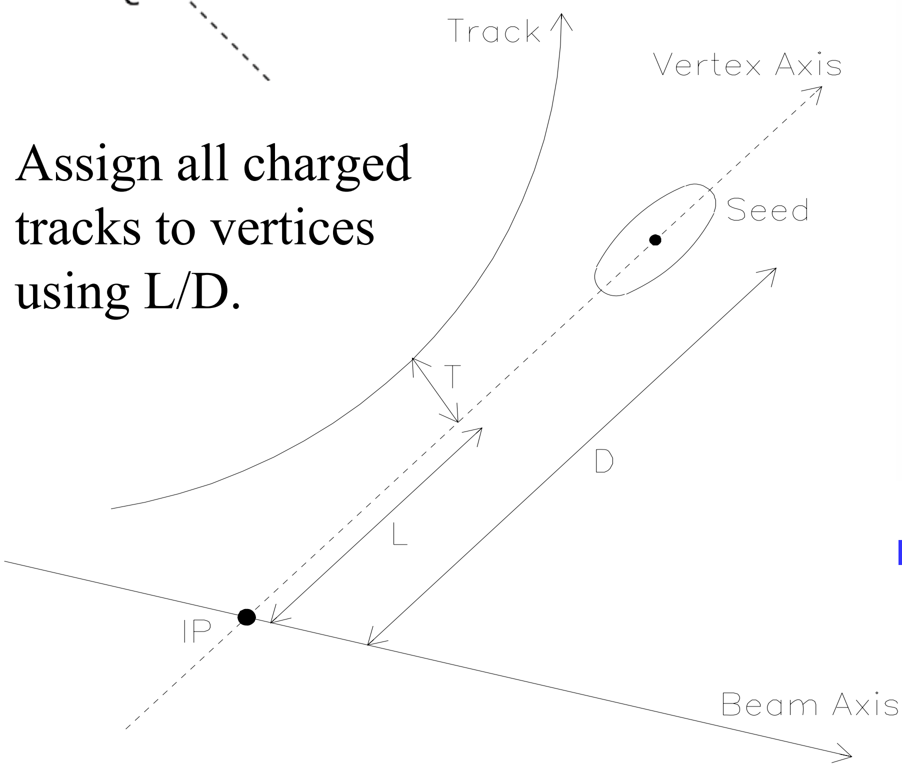
- Combine variables using neural net.
- Input variables:
  - Momentum and impact parameter significance in r-ϕ and z of two most significant tracks.
  - Probability in r-ϕ and z that all tracks originate from IP.
- Additionally, if secondary vertex found:
  - $m_{pT}$.
  - Momentum associated with vertex.
  - Decay length.
  - Decay length significance.
- Resulting flavour identification performance (here at $\sqrt{s} = m_Z$).



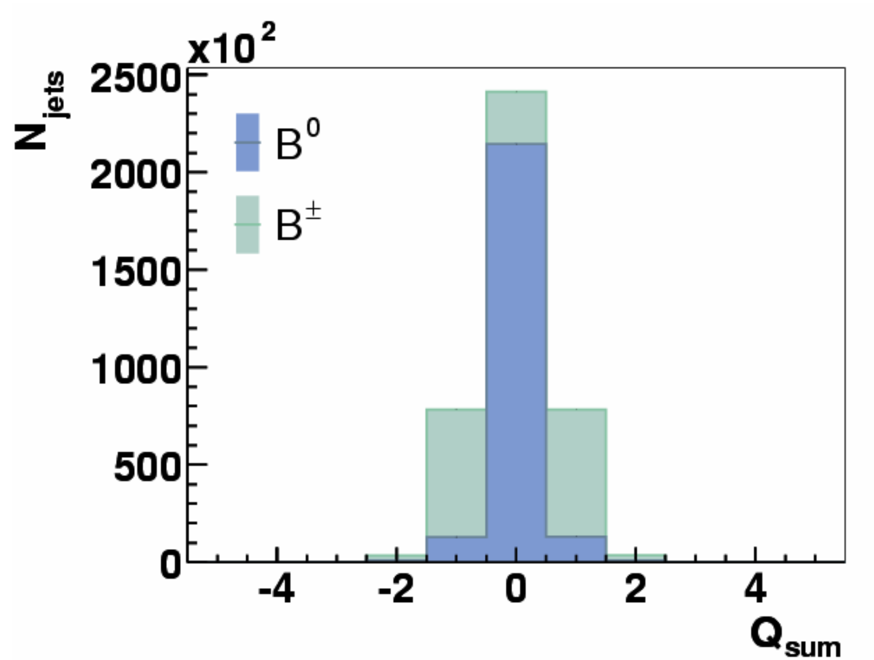
# Quark charge identification




- Assign all charged tracks to vertices using L/D.



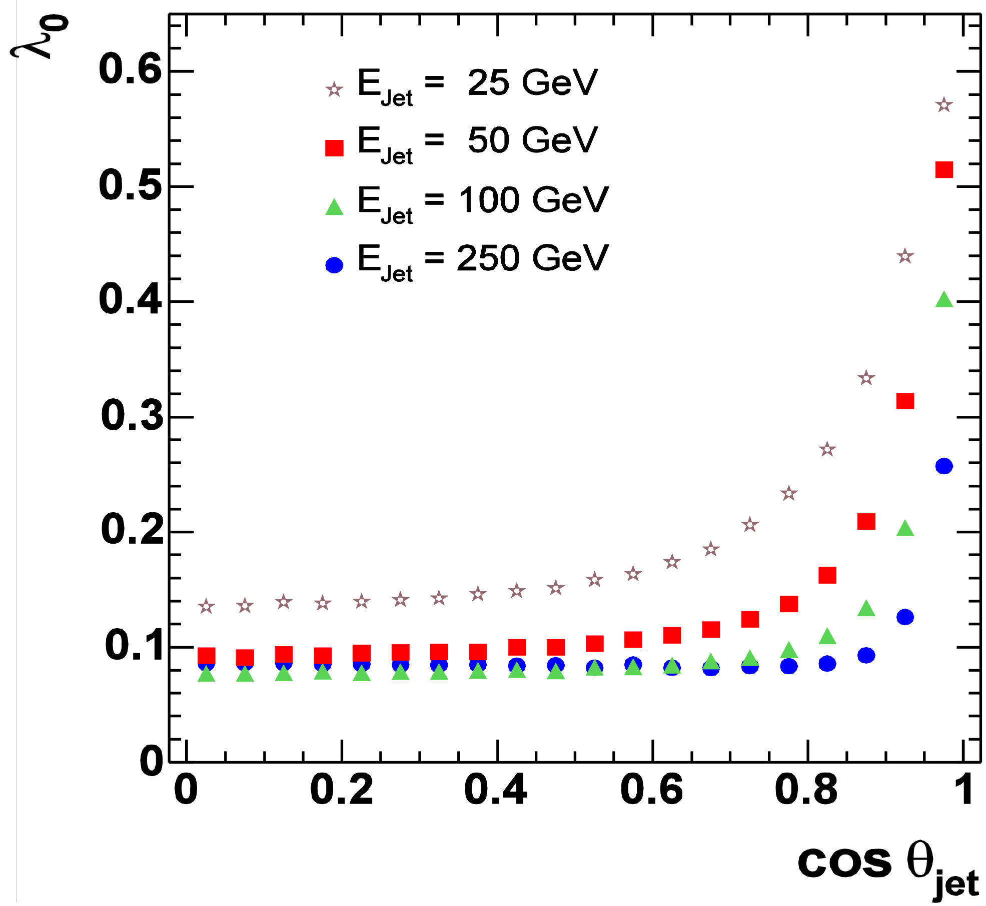

- Sum charge of tracks at secondary vertex to form $Q_{sum}$:




- Define $Q_{vtx} = \mathrm{sgn}(Q_{sum})$.

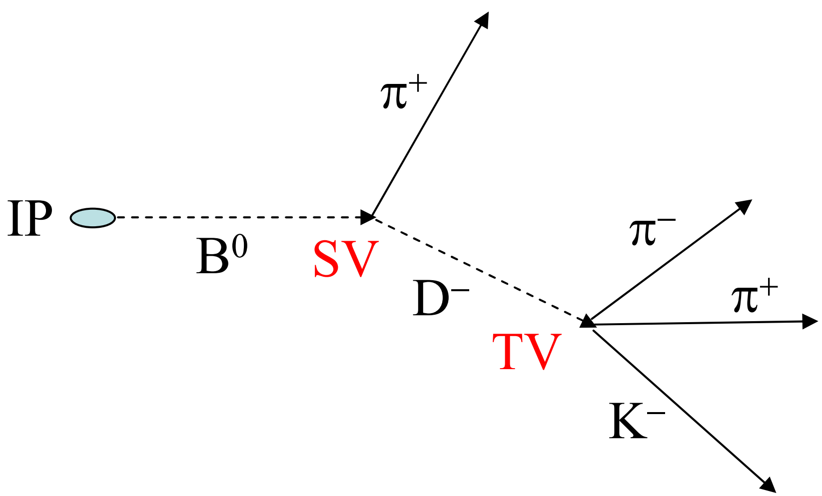
# Quark charge identification

- Quantify performance in terms of $\lambda_0$, probability of reconstructing neutral B hadron as charged.
- Degradation at large cos θ caused by loss of tracks and multiple scattering.
- Effect stronger at lower jet energy (broader jets, lower momenta...)



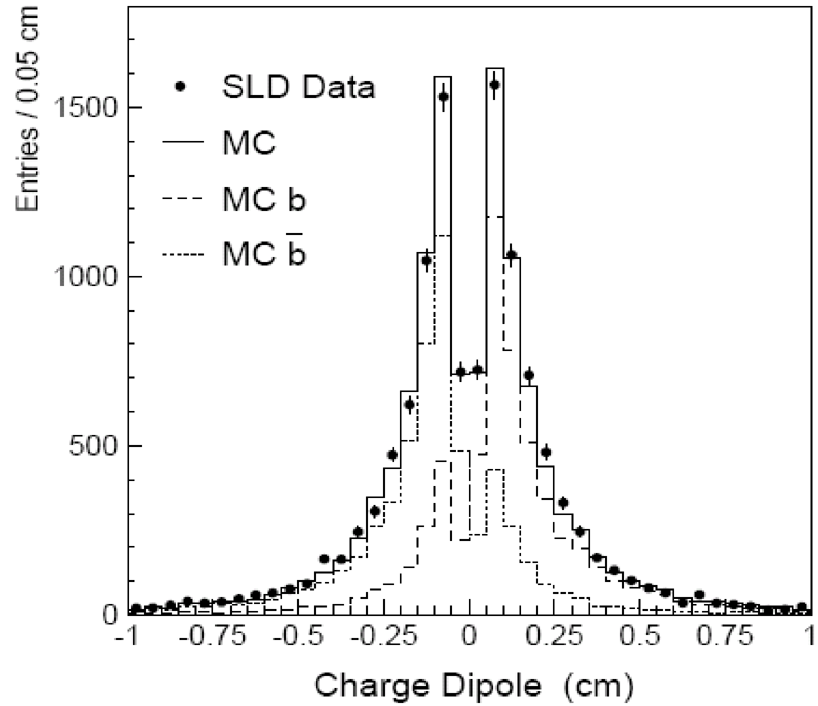
# Identifying quark charge – dipole method

- Applicable when b fragments to $\overline{B}^0$ or $\overline{b}$ to $B^0$.
- Identify secondary and tertiary vertices and measure charge.




- $Q_{SV} = +1, Q_{TV} = -1, \quad \Rightarrow B^0;$
  $Q_{SV} = -1, Q_{TV} = +1, \quad \Rightarrow \overline{B}^0.$

- Charge dipole distribution:

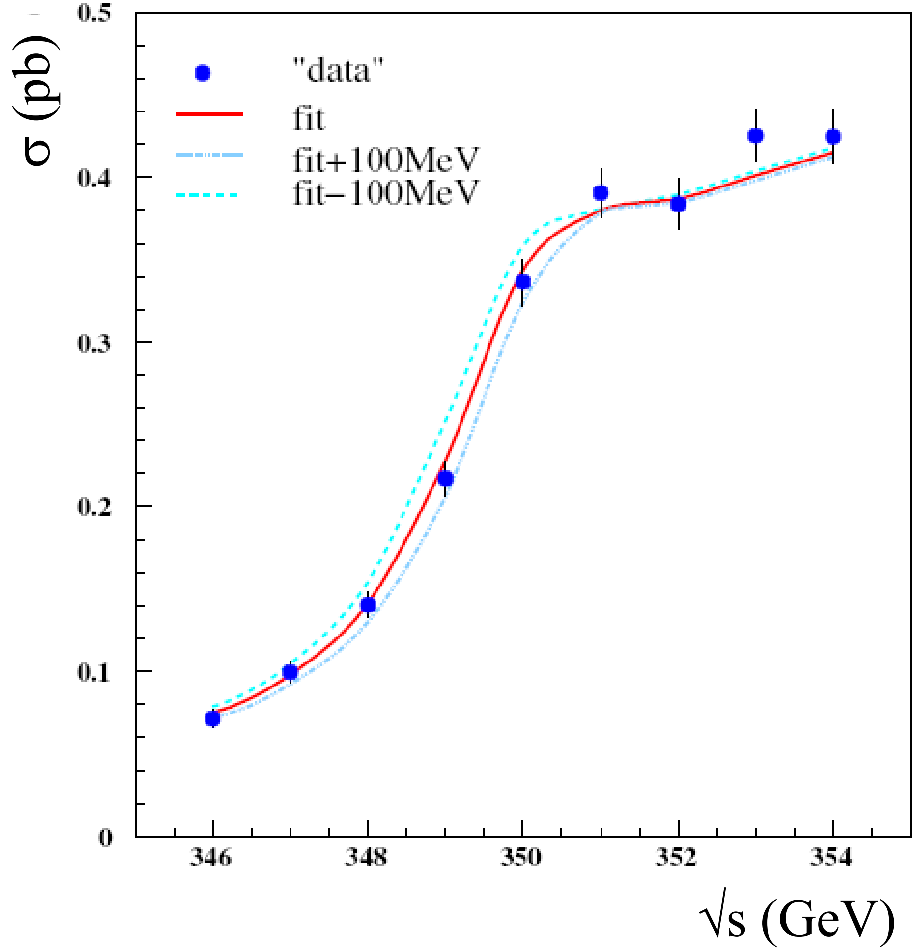



- Here particle ID can help with charge measurement.
- Of course, quark charge determination affected by mixing!

# Flavour physics at the ILC – top mass determination

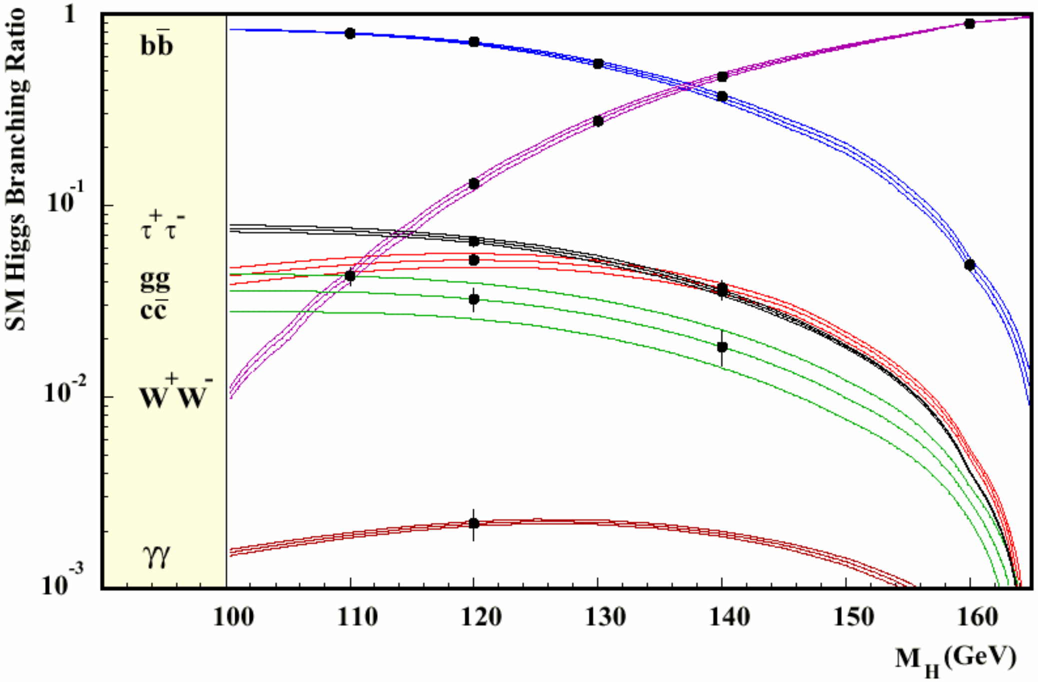
- LHC will provide $m_t$ measurement with precision of ~ 1 GeV.
- Will remain large source of uncertainty for many SM calculations.
- Threshold scan at ILC allows determination of $m_t$ with precision of 50...100 MeV.
- Top width also measured to 3...5%.

- Top production cross section:



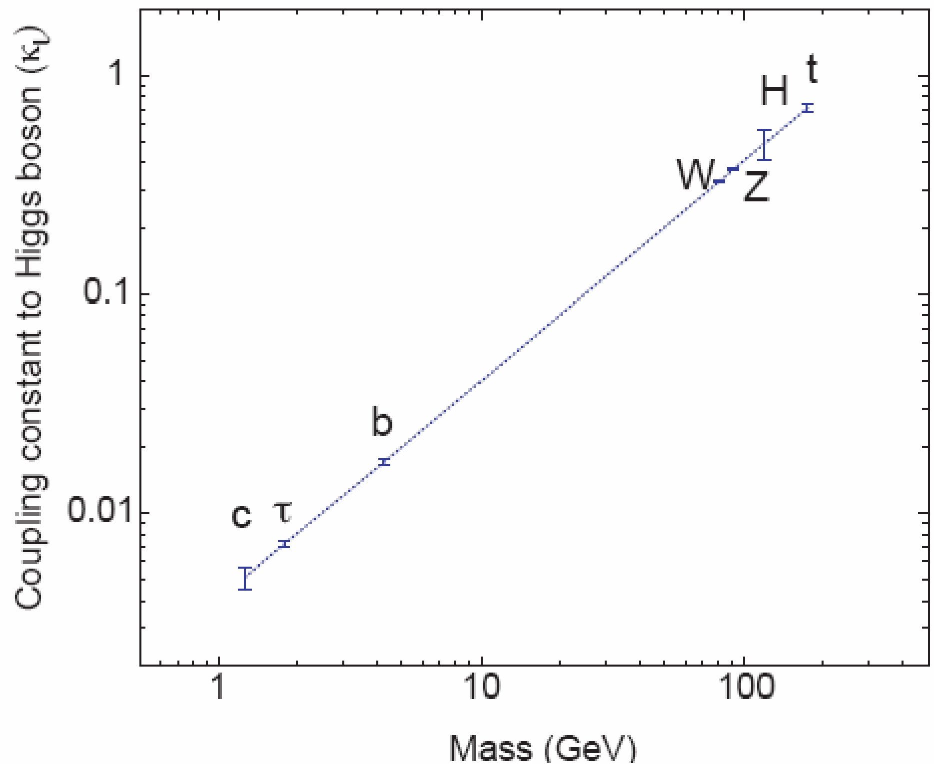
# Higgs branching ratios and couplings

- Crucial to precisely measure branching ratios of Higgs boson.




- Here $\sqrt{s}$ = 350 GeV, integrated luminosity 500 $fb^{-1}$.

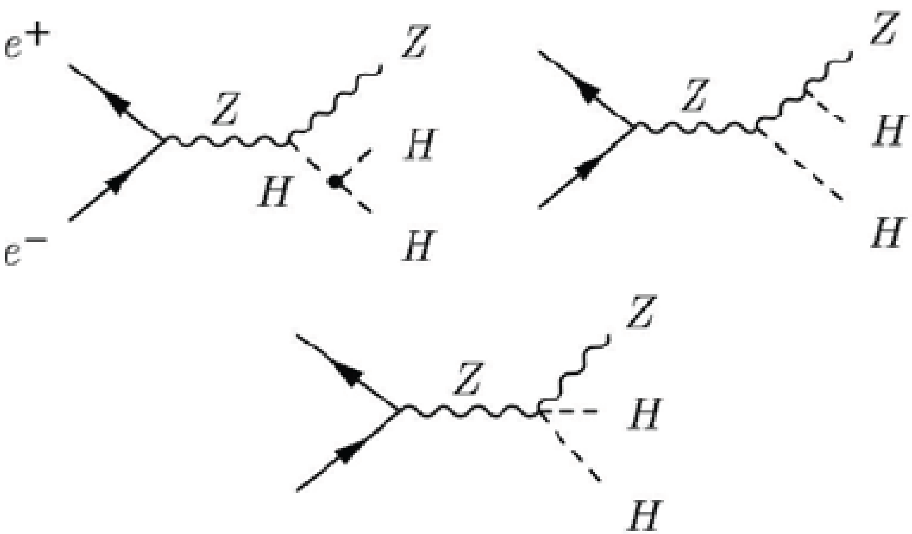
- Extract couplings and check proportional to masses:




- Here $m_H$ = 120 GeV, 500 Gev (700 GeV) running for HHH ($t\bar{t}H$) couplings.

# Determining the Higgs self coupling and the top Yukawa coupling

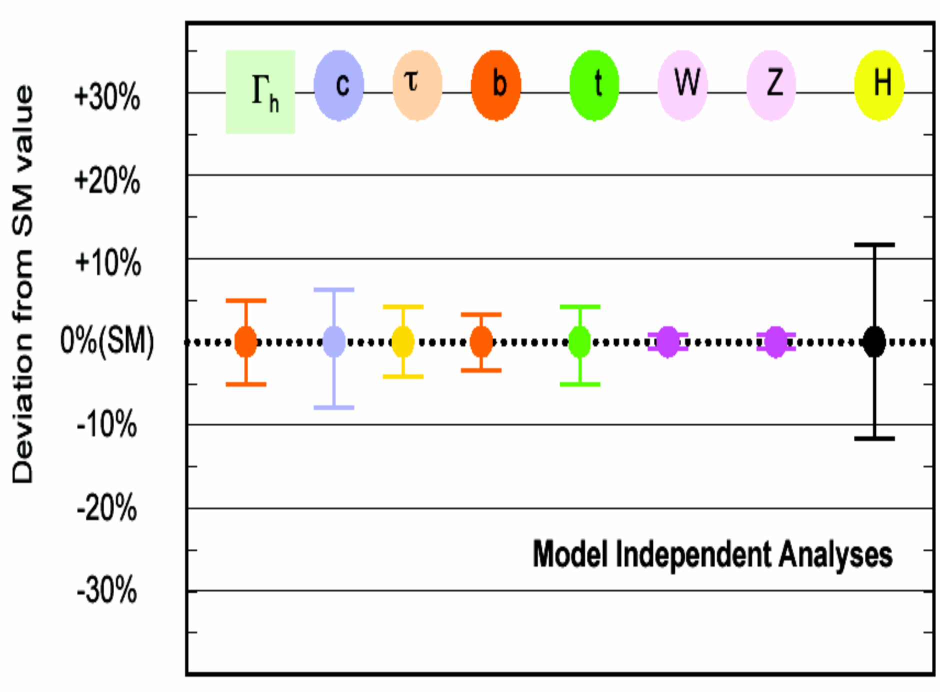
- Quark flavour and charge identification important tool in many measurements.
- E.g. study of $e^+e^- \to HHZ$:



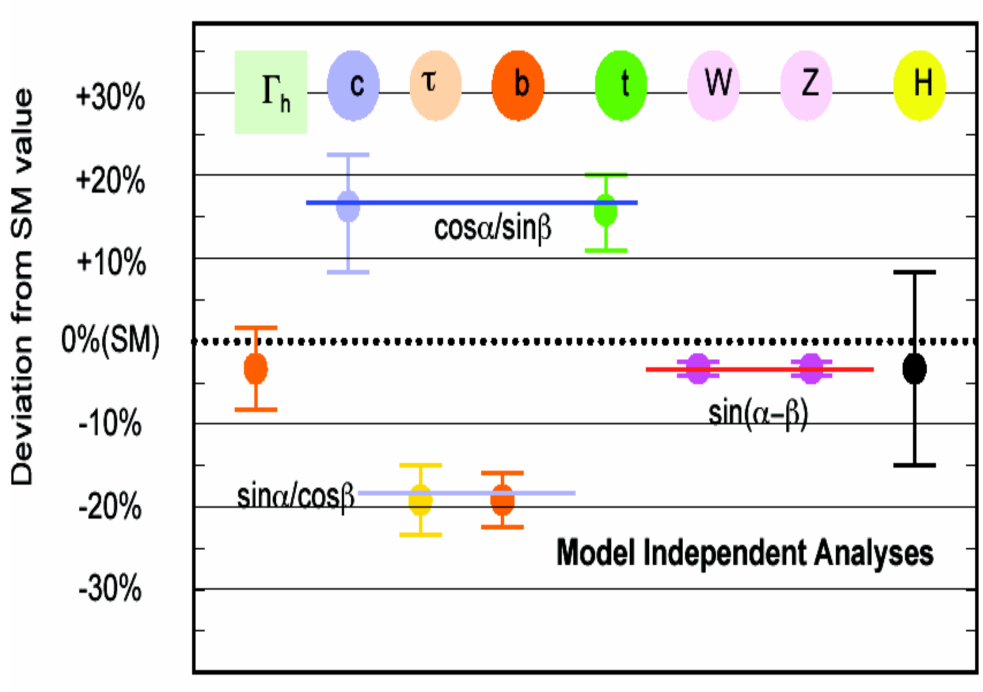

- Identify four b quarks!
- Identification of b quarks and separation of $b$ from $\bar{b}$ reduces significantly combinatorial background.
- Study of this process allows determination of Higgs self-coupling.
- Similarly, b identification aids separation of $e^+e^- \to t\bar{t}H$ from background with typically >1000 times higher rate.
- Charge ID also helps through reduction of combinatorial BG.

# Higgs and SUSY at the ILC

- Such precision studies of Higgs are powerful means of checking whether Higgs properties are as expected in SM...

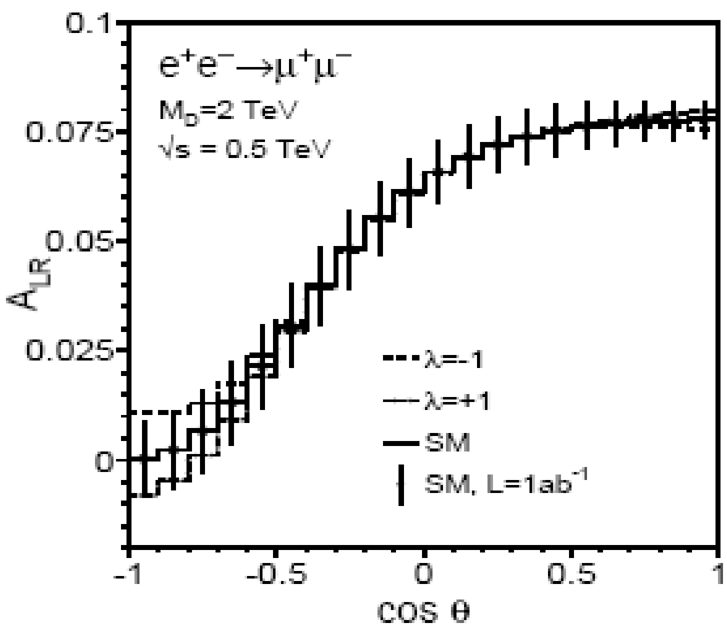



- ...or more like predictions from Minimal SUSY SM:

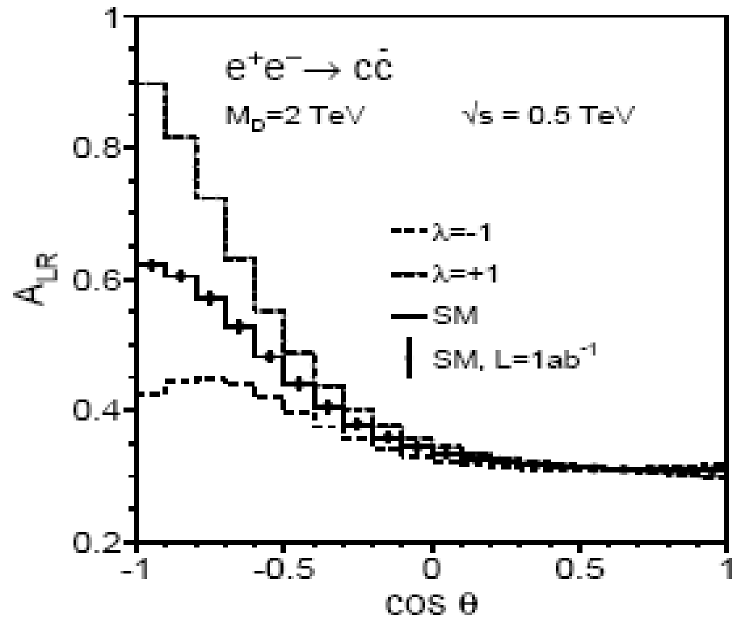


# Quark charge identification

- Increases sensitivity to new physics.
- E.g. effects of large extra dimensions on $e^+e^- \to f\,\bar{f}$.
- Study $A_{LR} = (\sigma_L - \sigma_R)/\sigma_{tot}$ as a function of $\cos\theta$.
- For $\mu^+\mu^-$, effects of ED not visible:




- Changes from SM much more pronounced for c (and b) quarks:

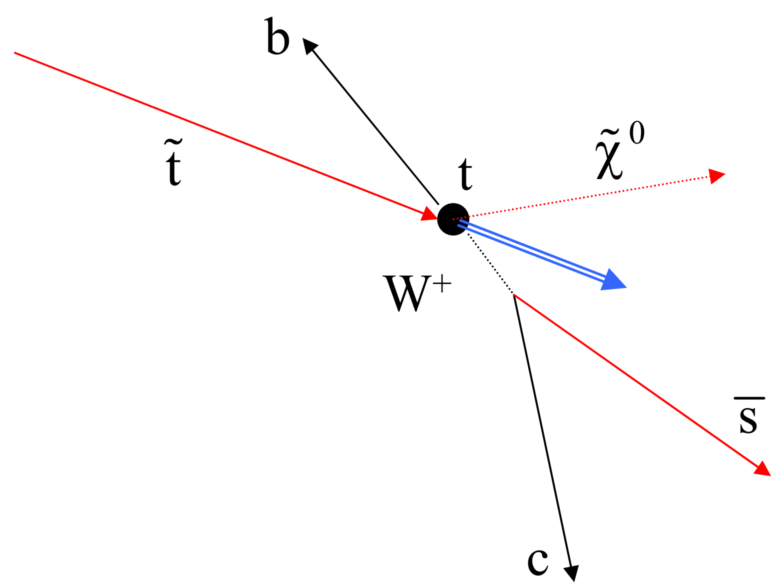



- Efficient flavour identification and charge determination needed out to large $\cos\theta$.

# Quark charge identification

- Provides new tools for physics studies.
- E.g. can measure top polarisation in decay $t \rightarrow W^+ b$, $W^+ \searrow c\bar{s}$
- Top decays before hadronisation.
- Anti-strange jet has $1 - \cos\theta$ distribution w.r.t. top polarisation direction.
- Distinguish between t and $\bar{t}$ by tagging b and c jets.
- Determine quark charge for (at least) one of these jets.

- Example of physics made accessible using this technique:




- Determine $\tan\beta$ and tri-linear coupling $A_t$ and $A_b$ through measurements of top polarisation in $\tilde{t}$ and $\tilde{b}$ decays.

# 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.
- These offer exciting opportunities for studying the physics of heavy flavours and for using heavy flavours as a tool in many investigations.
- Next steps include production of Technical Design Reports for ILC machine and detectors around 2010...
- ...hopefully leading to ILC physics results ~2020.