ILD vertex detector & CMOS sensors studies

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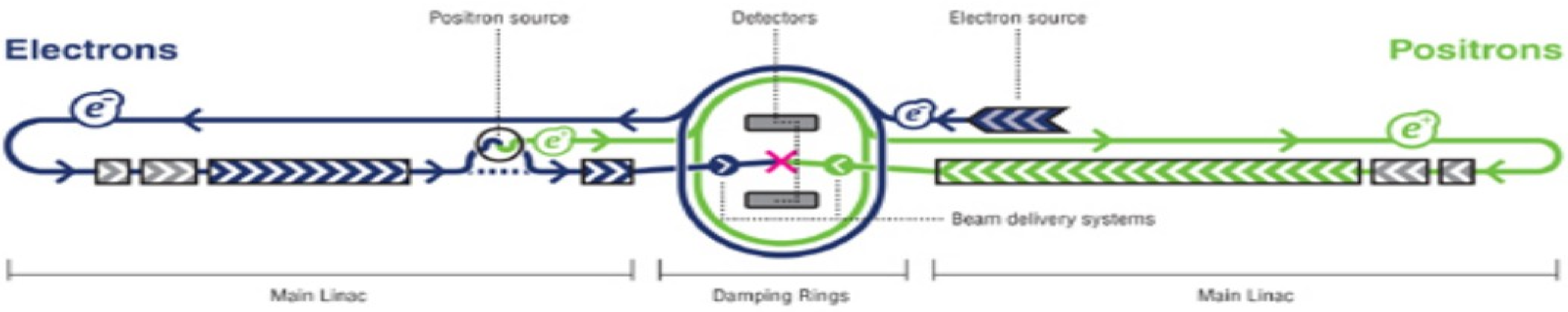
on behalf of IPHC Strasbourg

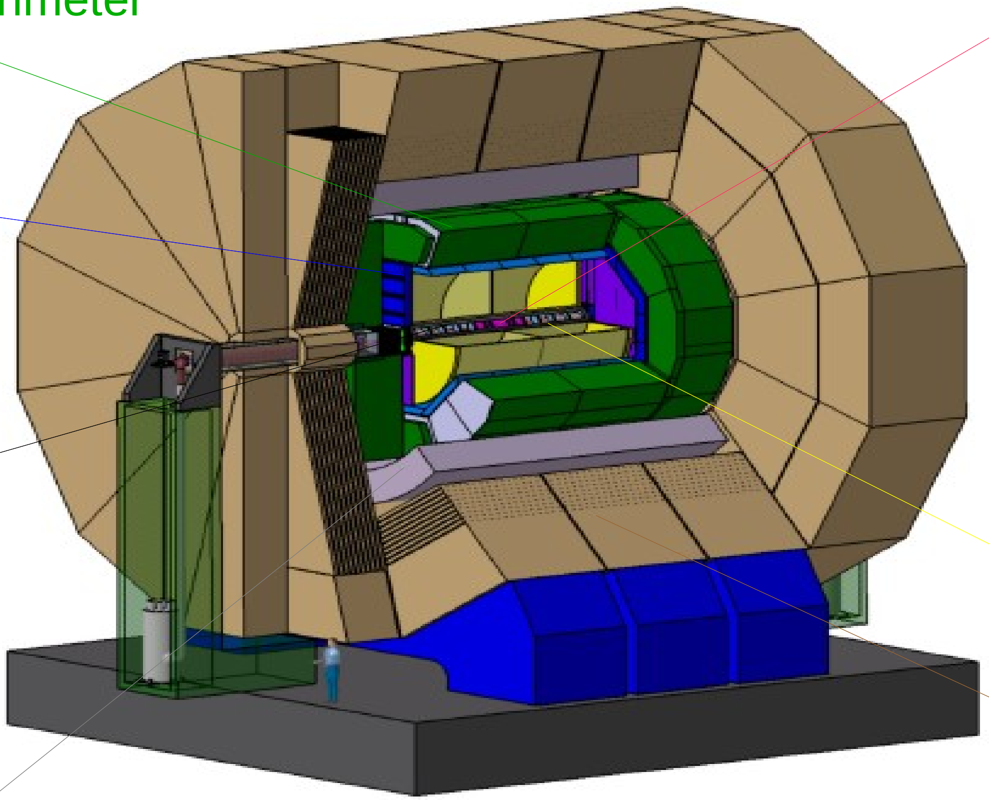
- International Linear Collider
- ILD vertex detector
- CMOS sensors
  - Beam test data analysis
  - CMOS based vertex detector for ILC
- Vertex detector optimisation studies

International Linear Collider



- Future linear electron – positron collider
  - √s = 500GeV, option for 1TeV
  - High precision machine
    - Well defined initial state
    - Clean final state
    - Triggerless
  - Complementary to LHC
- 2 general purpose detectors
  - SiD
  - ILD

ILD



Hadronic calorimeter

Vertex detector

EM calorimeter

Forward tracking

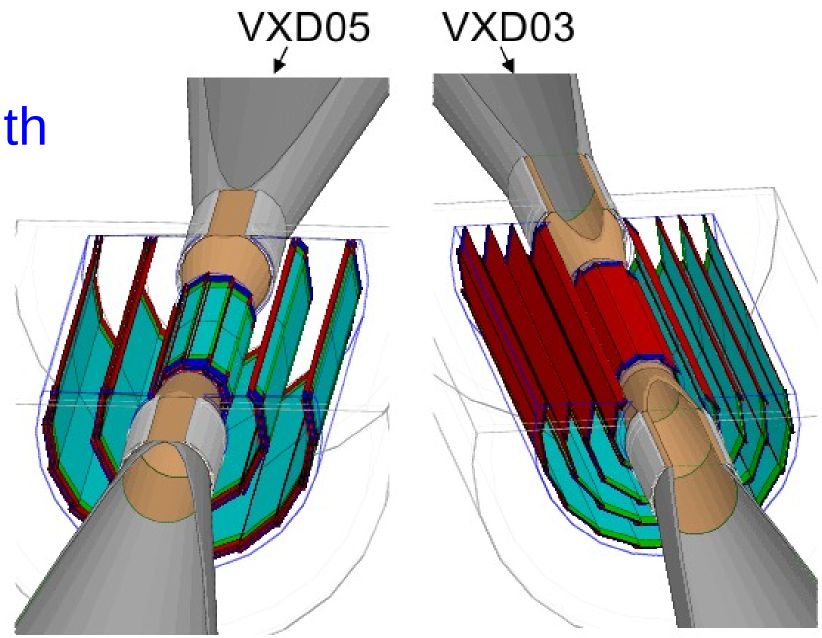
TPC

coil

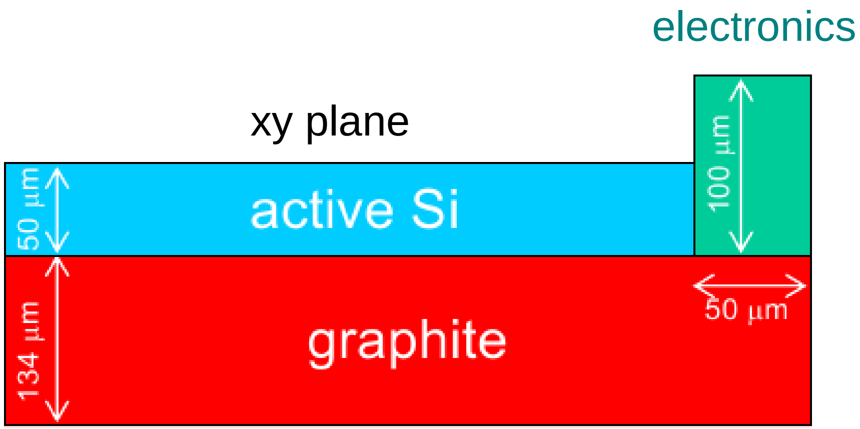
Yoke

ILD vertex detector

- 2 main candidate geometries for ILD VXD
    - VXD05: with 3 double layers equipped with silicon pixel sensors
    - VXD03: 5 single layers

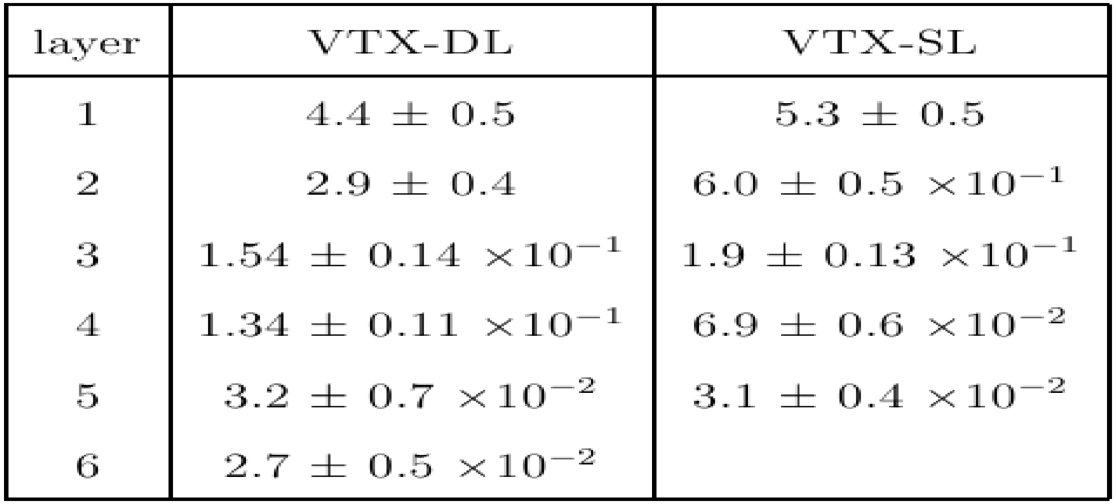


	VXD03	VXD05
layers	5	3 x 2
sensitive length (mm)	62.5	125
sensitive width (mm)	11-15-22	11-22
radii (mm)	15-60	16–60
sensitive thickness (µm/ladder)	50	50
graphite insensitive thickness (µm/ladder)	134	134



Beam induced background

- Background induced due to beam-beam interaction
  - When the beams approaching, exert force to each other
  - Particle's trajectories are bent – beam spot is reduced (pinch effect)
    - Luminosity enhancement by a factor ~ 2
    - Emission of hard beamstrahlung γ
      - beam energy degradation
      - A part of γ is converted to low energy e^+e^- pairs (~10^5 per BX)
- Pairs main source of background to ILC detectors
- Vast majority of pairs are low momentum particles emitted at the very forward direction
- Still some with higher P_T or other backscattered at beamcal can reach VXD



layer	VTX-DL	VTX-SL
1	4.4 ± 0.5	5.3 ± 0.5
2	2.9 ± 0.4	$6.0 \pm 0.5 \times 10^{-1}$
3	$1.54 \pm 0.14 \times 10^{-1}$	$1.9 \pm 0.13 \times 10^{-1}$
4	$1.34 \pm 0.11 \times 10^{-1}$	$6.9 \pm 0.6 \times 10^{-2}$
5	$3.2 \pm 0.7 \times 10^{-2}$	$3.1 \pm 0.4 \times 10^{-2}$
6	$2.7 \pm 0.5 \times 10^{-2}$	

Hit densities from pair background / BX cm^2
from R. DeMasi ILC note

ILD vertex detector requirements

- Figure of merit Impact parameter resolution

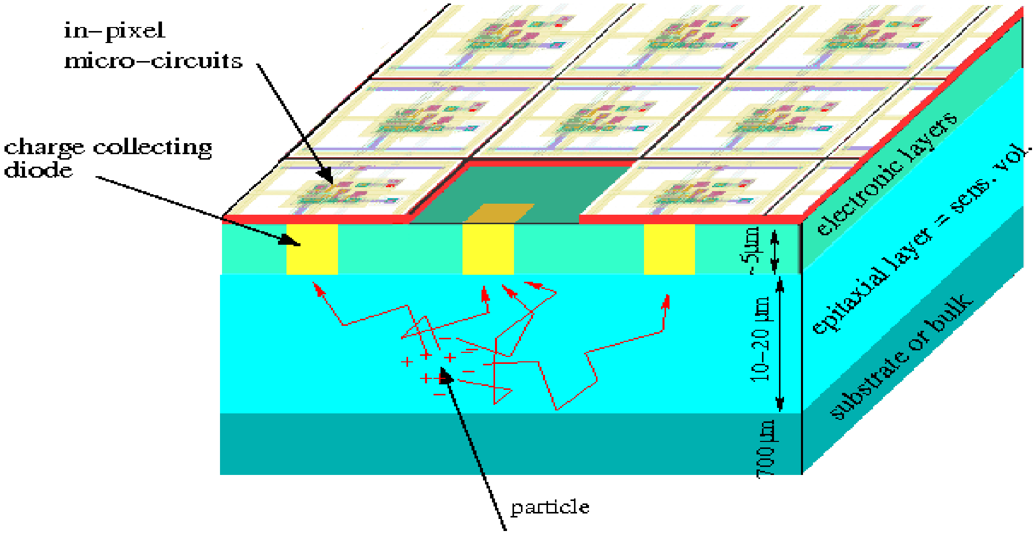
$$\sigma_{IP} = a \oplus b/p\sin^{3/2}\theta$$

$$a \leq 5\mu m,\ b \leq 10\mu m\ \mathrm{GeV}$$

  - Sensor's single point resolution ~ 3μm
  - Material budget > 0.2%X_0 per layer
  - Power dissipation < 100W
- Running constraints mostly defined from beam induced e^-e^+ pair background
  - Determines pixel occupancy
    - Require a relative fast readout
    - 25μs for inner layers, 100μs for outer
  - Moderate radiation tolerance
    - 0.3MRad/y, few $10^{11} n_{eq}/cm^2$ y
- CMOS sensors is a promising candidate technology

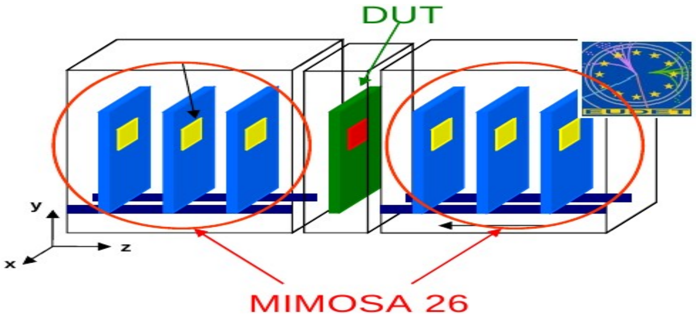
CMOS sensors principle of operation – main features

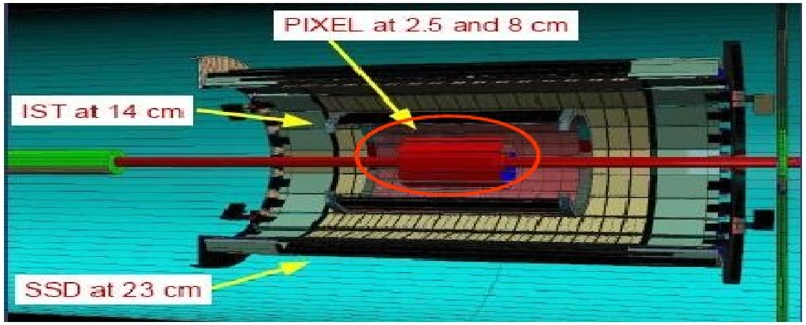
- CMOS sensors: Appropriate technology for high precision tracking devices like vertex detectors and beam telescopes
- Signal created by mips: ~80e^--h pairs/μm
- Electrons diffuse thermally at epi layer collected by an Nwell-p-epi junction - - - - -
- Advantages
  - High granularity O(10μm)
  - Low material budget (<50μm)
  - Signal processing on substrate
  - Cost
- Limitations
  - Small signal O(1000e^-) calls for low noise electronics
  - Use of only NMOS transistors for on pixel signal processing
  - Undepleted sensitive volume → non ionising radiation tolerance, charge collection

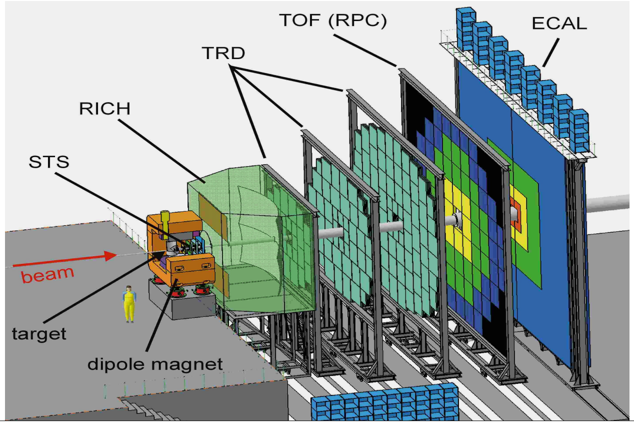


CMOS sensors HEP applications

- MIMOSA26 first real scale digital sensor of this series with on chip data sparsification
- MIMOSA 26 equips reference planes of EUDET beam telesc
  - EUDET FP6 project - infrastructure for ILC detectors R&D
  - Commissioned at CERN SPS at 2009
  - Extrapolated resolution ~ 2µm
  - Upto 10^6particles/cm^2/s beam intensity
- Baseline sensor for heavy ion collider experiments
  - STAR HFT
    - 1M pixels
    - 200µs integration time
    - First data expected at 2013
  - CBM MVD
    - More severe radiation tolerance requirements
    - Double sided ro (20µs int. time)
    - Prototyping 2012
- ILD vertex detector (option)
- ALICE upgrade (option)

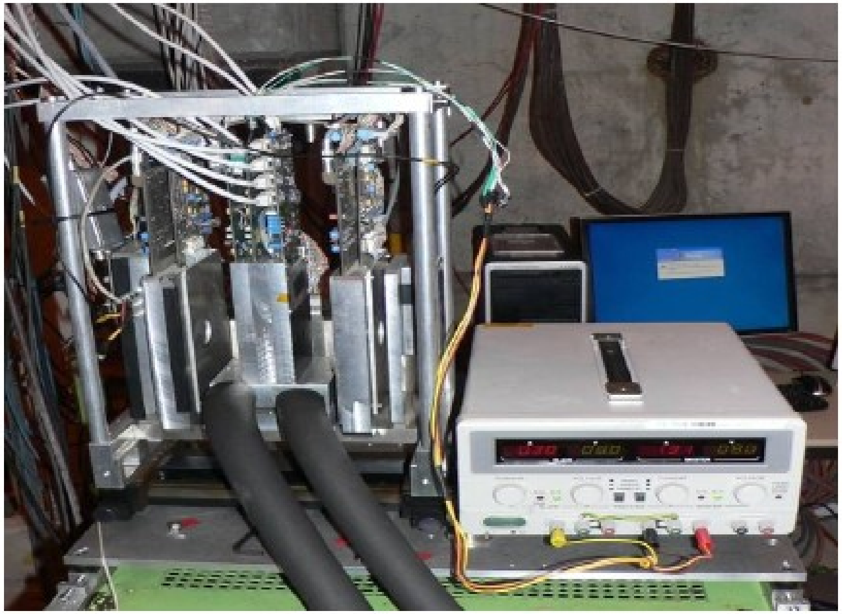






CMOS sensors test beam data analysis

- Main goals of a beam test
  - ➔ Analog part: measure charge collection, noise, signal/noise ratio
  - ➔ Digital part: calculate efficiency, resolution, fake hit rate, cluster multiplicity
  - ➔ Radiation tolerance studies with sensors irradiated with ionising or/and non ionising radiation
- Use of a beam telescope for track reconstruction

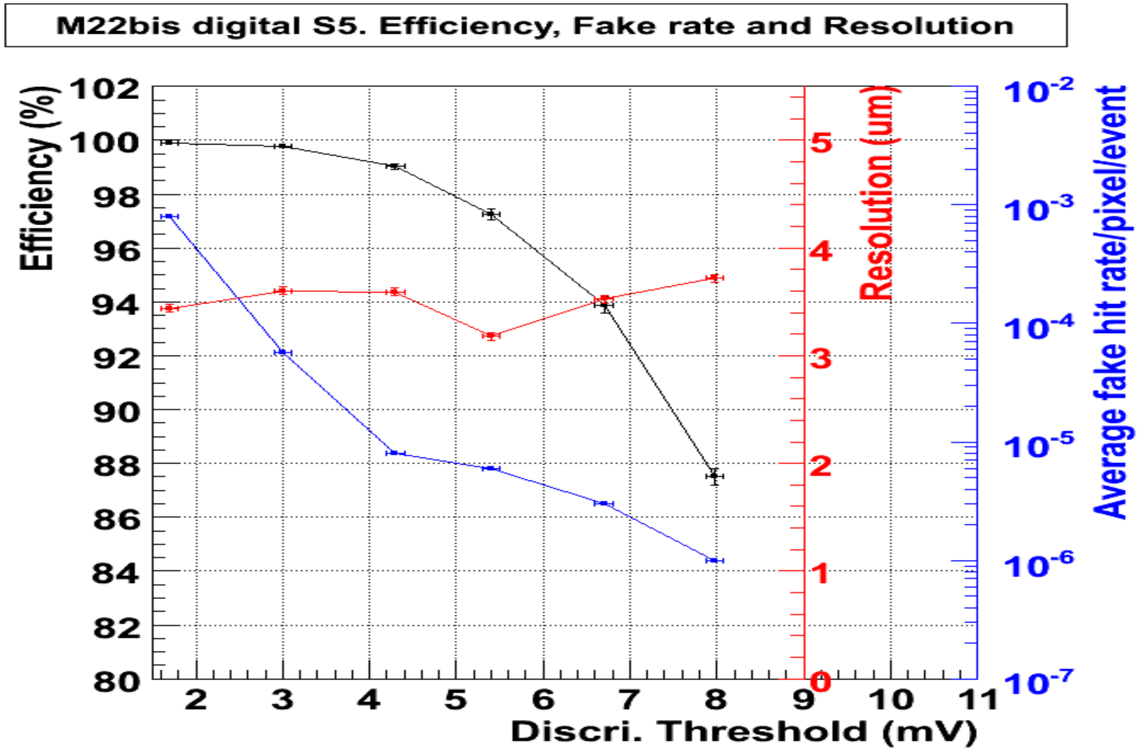


- Following results are from beam tests at CERN SPS
- 120GeV pion beam – multiple scattering negligible

MIMOSA 22/22bis beam test analysis

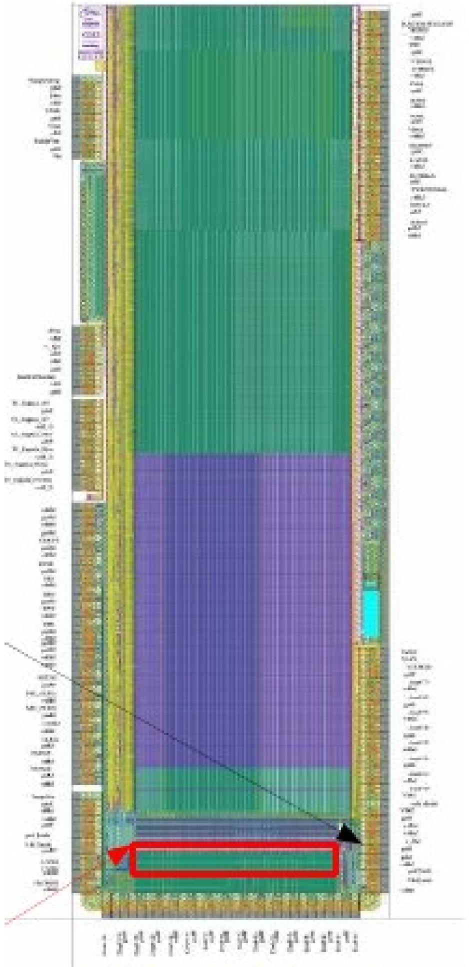
- Intermediate digital sensor for EUDET beam telescope
  - Column parallel readout mode at a real scale sensor
  - Optimization of pixel architecture for EUDET BT sensor
  - Radiation tolerance studies

Mimosa 22bis non irr.	2.48M
Mimosa 22bis 150krad(20 & 35°C)	2.17M
Mimosa 22bis 300krad	660k
Mimosa 22 10^{12} n_{eq}	1M



Analog part

Discriminators – digital part

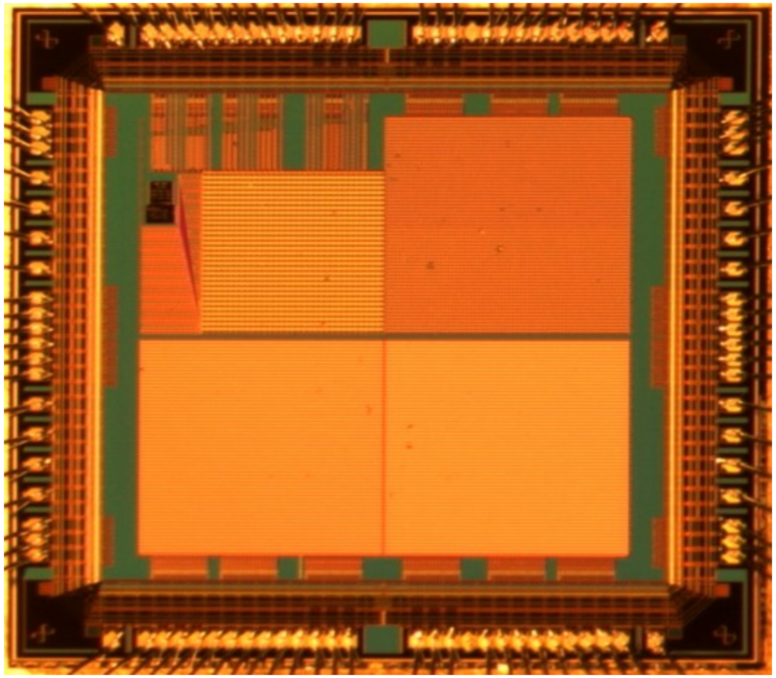


Mimosa 22 layout

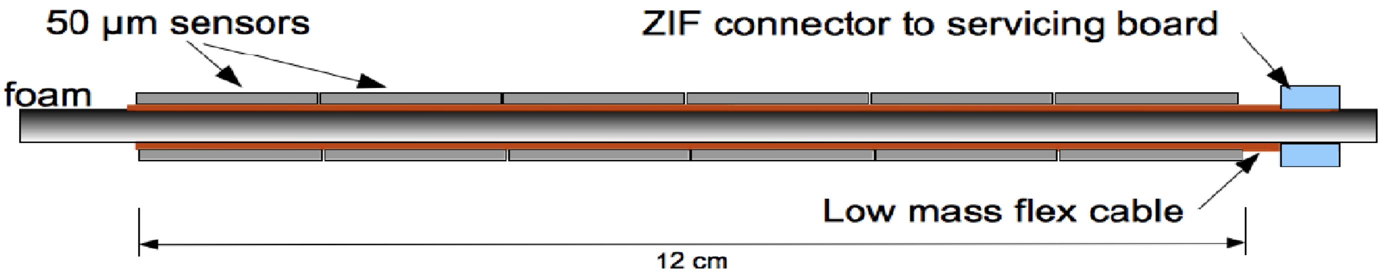
- For not irradiated chips @ 20°C
  - Efficiency ~ 99.8% for fake rate per pixel O(10^{-5}) - Resolution between 3.5 - 4µm
- Reference pixel design exhibits satisfactory results in both sensors / EUDET

MIMOSA 24 beam test analysis

- Exploration of fabrication processes is an important R&D line
- Epitaxial layer thickness often not known reliably
- MIMOSA 24 motivation: exploration of XFAB 0.35µm process
- Sensor description
    - Analog sensor with 8 different pixel designs
- Main objective
    - Comparison with MIMOSA9
    - Similar sensor but fabricated in a different process
- Results
    - Indicate similar performance with MIMOSA 9

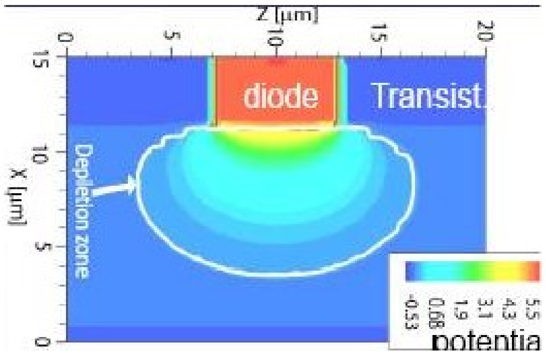


Towards a CMOS based vertex detector for ILD (1)



- Sensor integration studies
  - PLUME project – collaboration of Bristol - DESY - Oxford – Strasbourg
  - Double sided ladder equipped with 2x6 thinned down to 50 µm MIMOSA-26 (material budget 2012 target: 0.3 % X_0)
  - Explore feasibility, performances and added value of double-sided ladders

- High resistivity epitaxial layers
  - Partially depleted sensitive volume
  - More tolerant to non-ionising radiation
  - Faster and enhanced charge collection

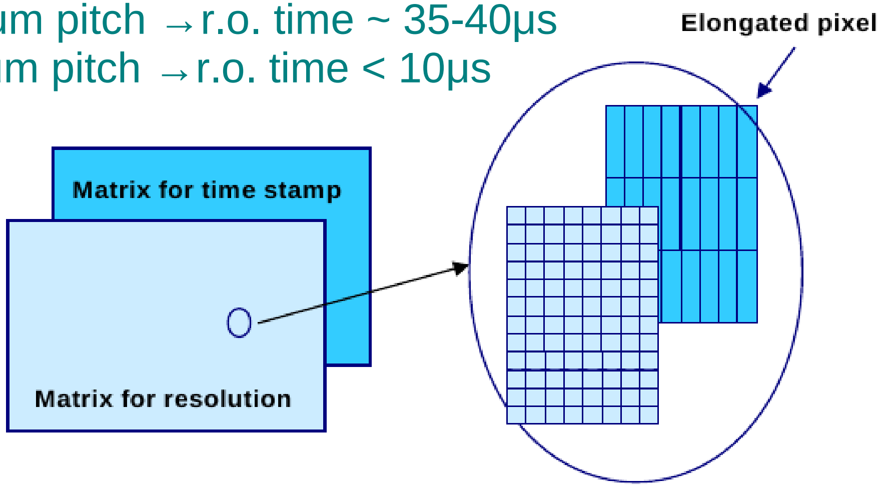


A.Dorokhov high res. simulation studies

Towards a CMOS based vertex detector for ILD (2)

- Double layers geometry option
  - ➔ Inner superlayer
    - ➢ Binary sensors
    - ➢ First layer ~ 15µm pitch
      - ✓ High spatial resolution ~ 3µm
    - ➢ Second layer ~ 60µm pitch
      - ✓ Column parallel r/o → r/o time proportional to # pixels/column
      - ✓ Time stamping

✓ 15µm pitch → r.o. time ~ 35-40µs
✓ 60µm pitch → r.o. time < 10µs



Depleted epi layer → allows for larger sensing diode spacing

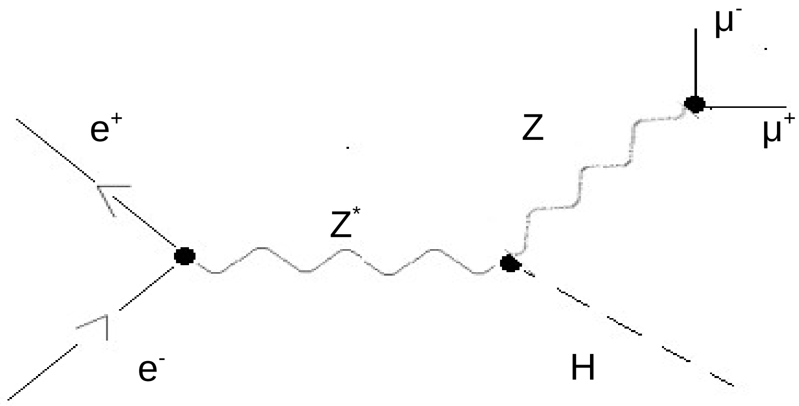
- ➔ Outer Layers
  - ➢ Less severe requirements @ readout speed
  - ➢ Pixel pitch ~ 35µm
  - ➢ 4-5 bits ADC
    - ✓ Single point resolution < 3.5µm
  - ➢ Aim mainly for low power dissipation

ILD vertex detector optimisation

- ILD VXD goals
  - High precision flavour tagging
  - Track reconstruction (especially for low momentum tracks)
- Crucial for
  - Extraction of branching ratios – study of Higgs couplings
  - Vertex charge reconstruction
- Optimisation will be mostly based on
  - Performance of the 2 main candidate VXD geometries on
    - Heavy flavour tagging performance
    - Extraction of Higgs hadronic branching ratios
    - Reconstruction of vertex charge
  - Study of VXD performance in the presence of pair beam background

✯ No specific sensor technology assumed in these studies

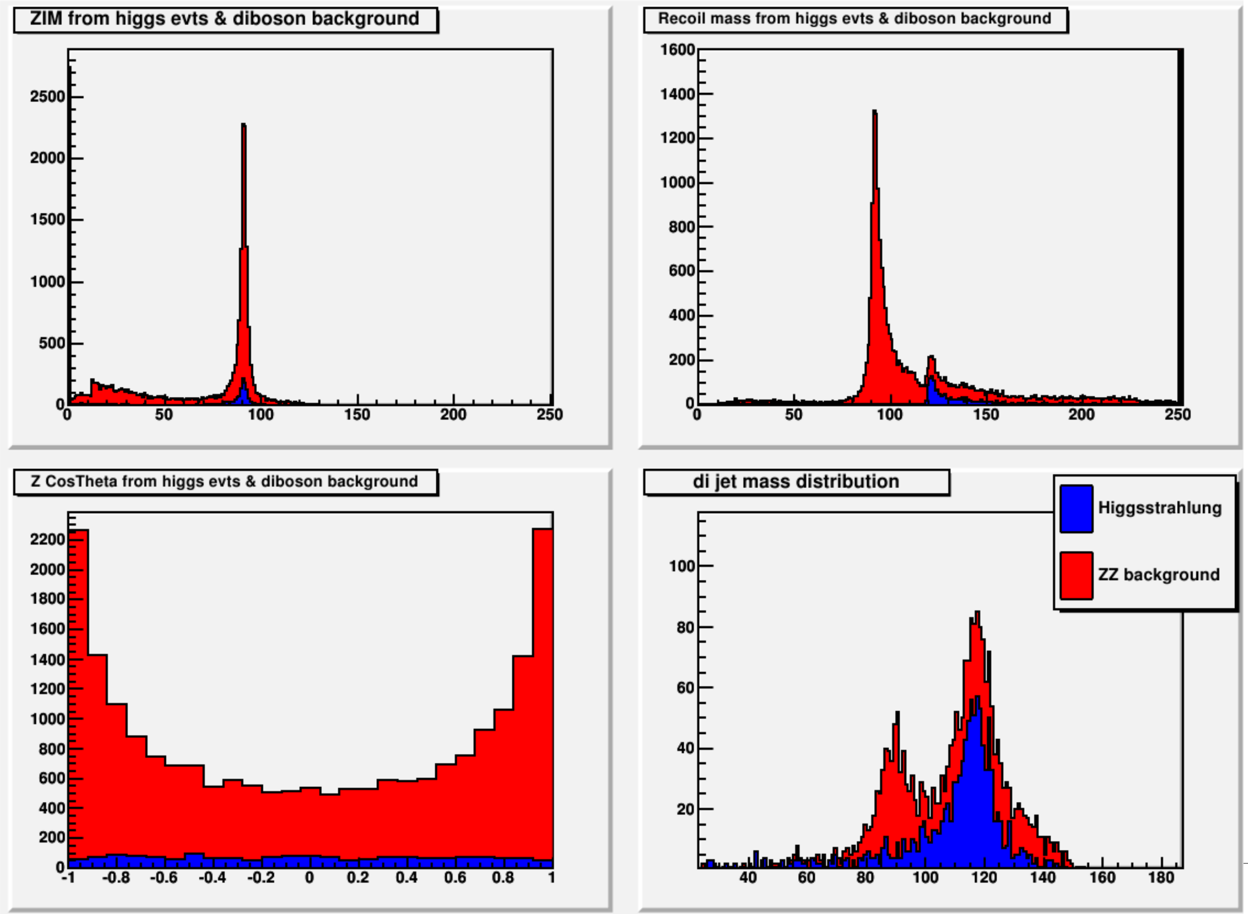
Physics channel – event reconstruction



- Higgsstrahlung channel $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-X$
  - √s 250GeV
  - M_H 120GeV
  - Higgs decaying according to its SM BR – Z decaying to a pair of muons
    - Z recon. out of best candidate pair of muons
    - Rest of particles forced to 2 jets, using Durham jet clustering algorithm
- MC file from ILC data samples – unpolarized beams, cross section ~ 7fb
- Simulated with Mokka (Geant4 based package)
  - Exchange VXD models: VXD03 (single layers) & VXD05 (double layers)
  - s.p. Resolution assumed 2.8μm for all layers
- $250fb^{-1}$ reconstructed with ilcsoft
- An independent sample of $500fb^{-1}$ has been reconstructed to be used at the fit for the BR extraction

Physics background – event selection

- $e^+e^-\to ZZ\to\mu^+\mu^-qq_{bar}$, beam polarization 0, σ = 79.0fb
  - ➢ $250fb^{-1}$ events reconstructed
- $e^+e^-\to WW\to\mu\ \nu_\mu\ qq_{bar}$, beam polarization 0, σ = 2278.55fb
  - ➢ Out of 10k events reconstructed, 1event passes the cuts=> assumed negligible
- 2f-4f background negligible



Event selection

(1) 70GeV < muon pair IM < 110GeV

(2) 1 only Z candidate

(3) 117GeV < Recoil mass < 150GeV

(4) $|\cos\theta_z| < 0.9$

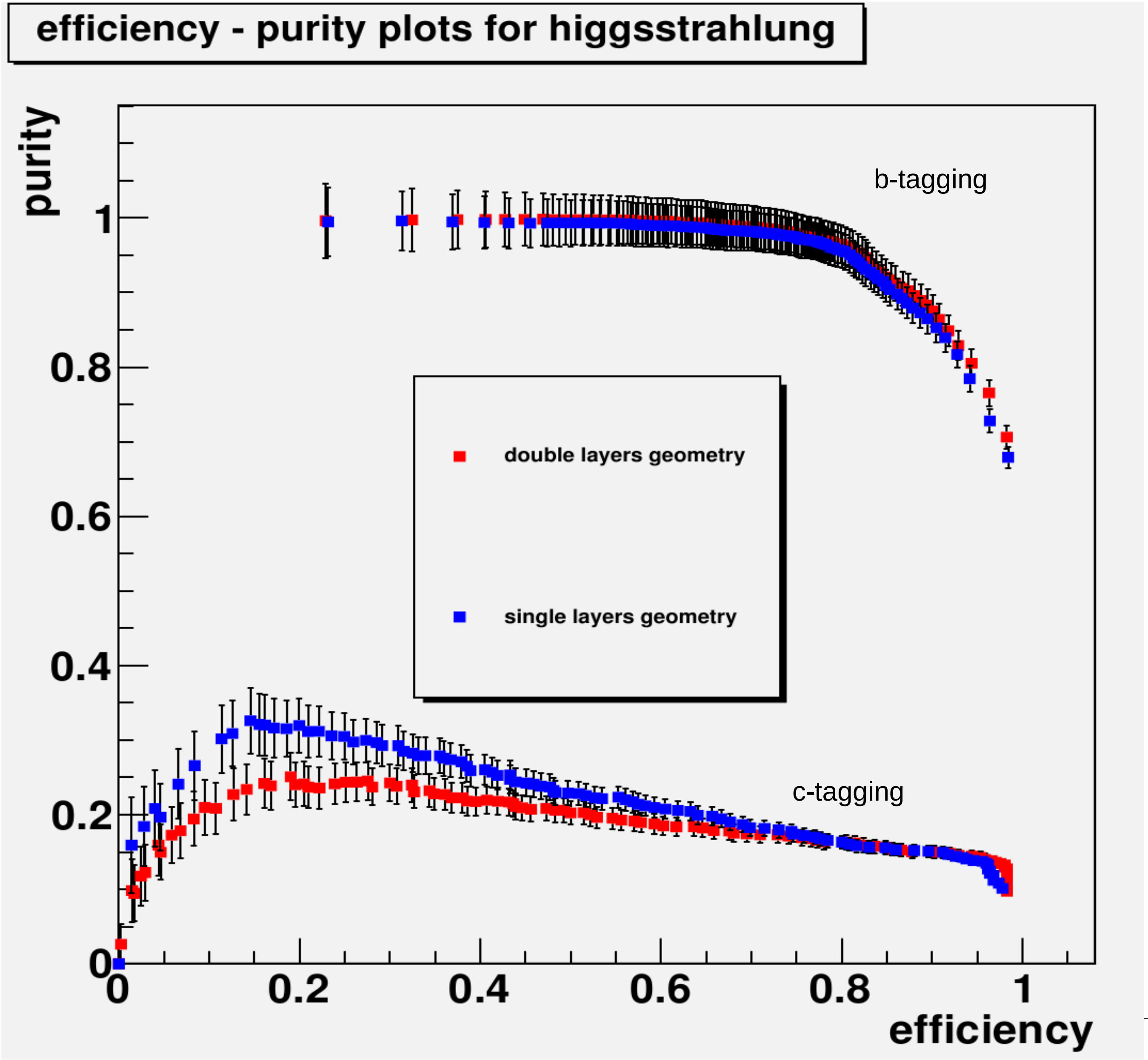
(5) 100GeV < di-jet IM < 140GeV

$S/\sqrt{S+B} = 21.4$

Neural nets based flavour tagging

- Neural nets of LCFI group used for heavy flavour tagging
- Training sample: Z → qqbar @ √s = 91.2GeV, 10k for each different VXD geometry
- 3 different sets of nets for b(c) tagging depending on vertex multiplicity in the jet
- Different set of discriminating variables used for 1 or >1 vertices found
  - Main variables when 1 vertex found inside the jet
    - Impact parameter significance and P_T of the 2 most significant tracks
    - Joint probability that all tracks coming from primary vertex
  - When the jet has 2 or more vertices
    - Mostly use observables from the additional vertices
- Training uncertainties much smaller than statistical
- Neural nets checked for overtraining

Flavour tagging results – no beam bkg



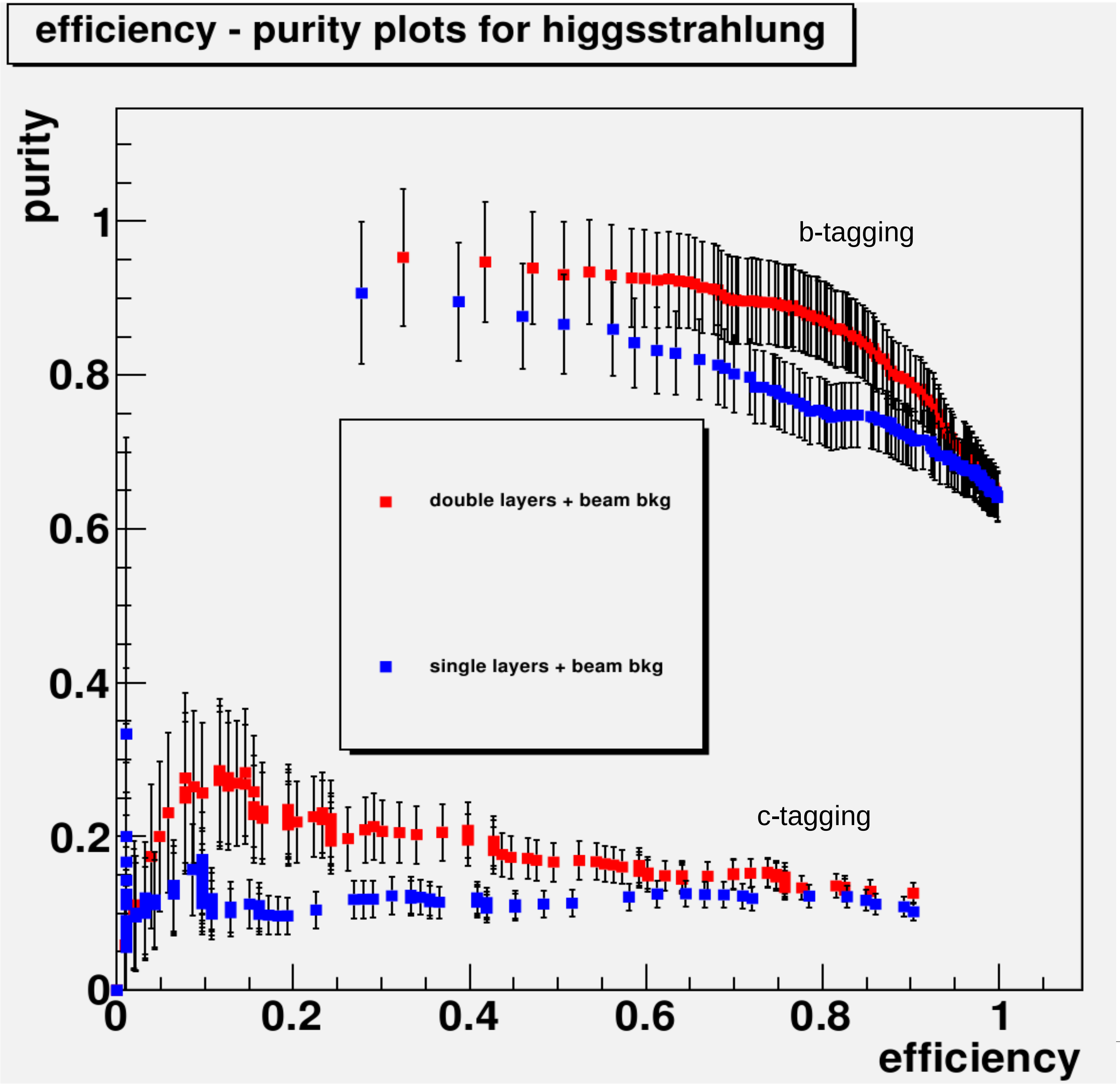
- 700fb^{-1} of Higgsstrahlung analyzed
- No beam bkg superimposed
- Statistical errors shown in plot
- Nets uncertainties ~ 1% - less than statisticals
- B tagging performance almost identical
- C tagging performance : single layer option has a region for low and moderate efficiency with higher purity
  - Mainly due to smaller distance from IP

Beam background

- Random noise clusters superimposed according to expected hit density
- Number of BXs superimposed depending to readout time of each VXD layer
  - ➔ Pixel occupancy
  - ➔ Combinatorial background
  - ➔ Fake tracks

layer	Readout (μs) - (#BXs superimposed)	
	SL	DL
0	25 (68)	25 (68)
1	50 (136)	25 (68)
2	100 (272)	100 (272)
3	100 (272)	100 (272)
4	100 (272)	100 (272)
5		100 (272)

Flavour tagging with beamstrahlung

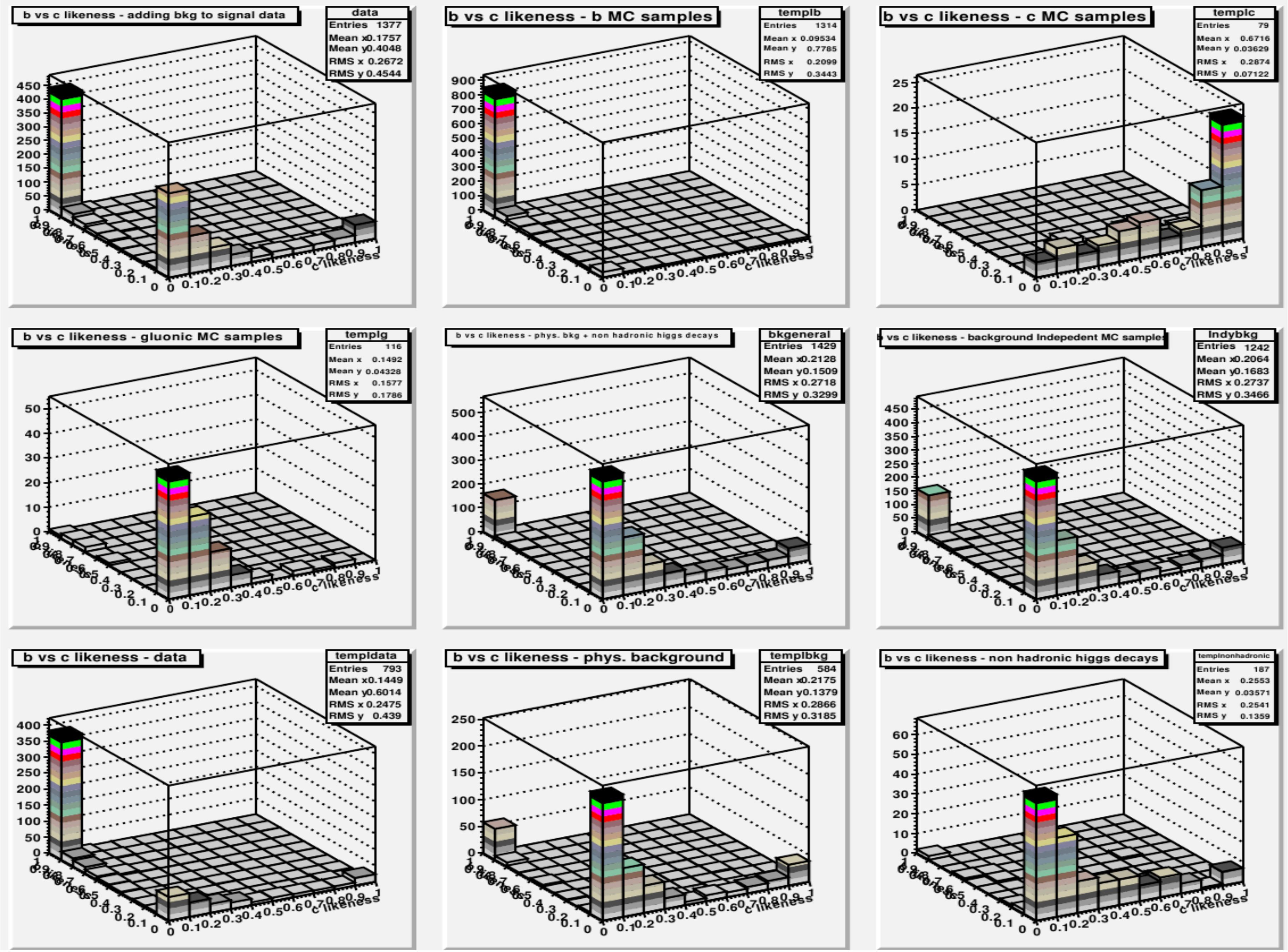


- Similar study but now with salt n' pepper background superimposed according to layer's r.o. time
- ~250fb^{-1} of Higgsstrahlung analyzed
- In order to gain processing time silicon tracking modified
  - ✓ Negligible effect on the performance
- Better performance for double layers geometry
- Maybe consequence of tracking
  - ~1k silicon tracks/evt for DL geometry
  - ~5k silicon tracks /evt for SL geometry
  - ~ 30/evt for both geometries w/o beam background

Higgs branching ratios extraction

- Based on ILD Letter Of Intent ZH→llqq branching ratios analysis
  - ➔ Repeat these studies for different VXD geometries
  - ➔ Include beam background
- b(c) likeness: event wise variable
  - ➔ Likeness = x1x2/(x1x2 + (1-x1)(1-x2)) , where x1,2 are the outputs of the neural nets for first and second jet respectively
- Previous studies shown that a cut based extraction of the flavours does not yield the best sensitivity
- Use of template fitting technique
- There is no analytic distribution function so we use MC samples for the fitting
  - ➔ Split the initial sample to “data” and monte carlo
  - ➔ Split the monte carlo sample to H→bb, H→cc, H→gg, non hadronic higgs decays + physics background
  - ➔ Create 2D templates with b-c likeness and fit the data by changing the normalisations of each sample – fix bkg sample factor to 1
  - ➔ Extract branching ratios from the normalisation factors

MC templates for VXD05 - 500fb^{-1}



Fitting results

- BR(H→xx) = r_{xx} x BR(H→xx)$_{SM}$, where r_{xx} are the fit results for each hadronic decay channel (bb,cc,gg) – these factors expected to be 1 for SM
- Comparison between relative errors for the candidate models – especially for c-tagging

	Double layers	Single layers
r_{bb}	0.93±0.06	0.99±0.06
r_{cc}	0.93±0.59	0.86±0.54
r_{gg}	1.68±0.58	0.88±0.61

Fit Limitations

  - Statistical fluctuation of MC samples
  - Bins with very few events
  - Templates with the majority of events at only 1 bin
- Trying different fitting methods
  - Finally choose χ^2 mostly due to low statistics of MC templates

$$X^2 = \Sigma_{bins} (D_{bins} - (N_D / N_{MC}) \Sigma_s r_s N_s^{bins})^2/\sigma_{bins}^2$$

  - χ^2 (cope with limited data but not with very few evts @ 1 bin) – cut at bins with <5 entries

Conclusions

- A vertex detector for ILC
    - ➔ Extract Higgs branching ratios – measure Higgs couplings
    - ➔ Reconstruct vertex charge: forward – backward assymetry
- Impact parameter resolution figure of merit
    - ➔ Excellent heavy flavour tagging
    - ➔ High tracking capabilities (especially for low P_T tracks)
- Beamstrahlung is a big challenge for ILC VXD
- CMOS is a promising candidate technology for ILC VXD sensors
    - ➔ Exploit feature technology to trade of with the often conflicting ILD VXD requirements