

Development of a double-sided ladder for tracking in high energy physics

Ph. D. defense

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Strasbourg

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- 1 Introduction
- 2 Higgs boson study at the ILC
- 3 Double-sided layers development
- 4 Mechanical deformation
- 5 Material budget measurement
- 6 Conclusion and outlook

Standard Model

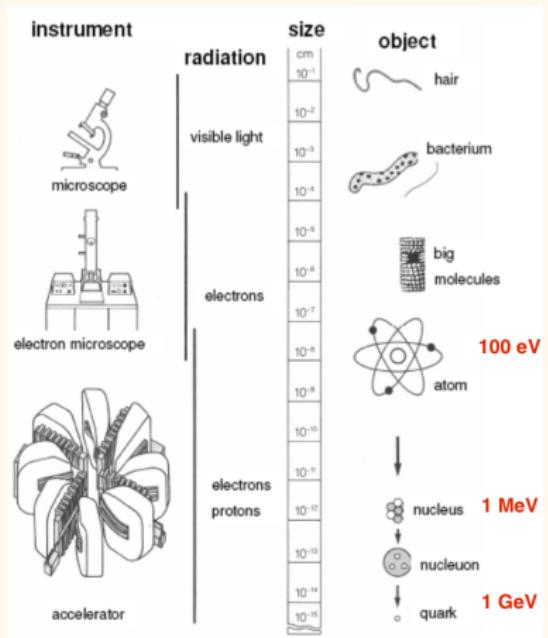
- Well-tested physics theory: predicts precisely a wide variety of phenomena with elementary particles
 - Predicts a mechanism which breaks the electroweak symmetry (EWSB) and generates mass of particles
 - ⇒ Higgs mechanism: one gauge boson is expected in the SM (the Higgs boson)
 - Last milestone: discovery of a particle compatible with the Higgs Boson, which would confirm the EWSB
- ⇒ Complete spectrum of Standard Model that could be correct up to very high energies

Open questions

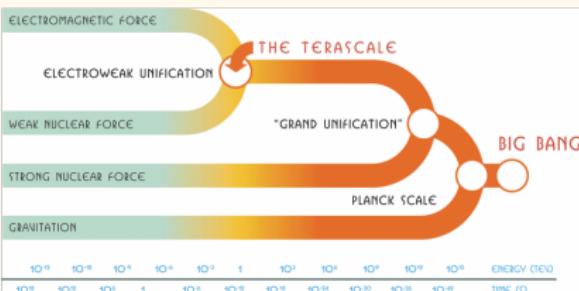
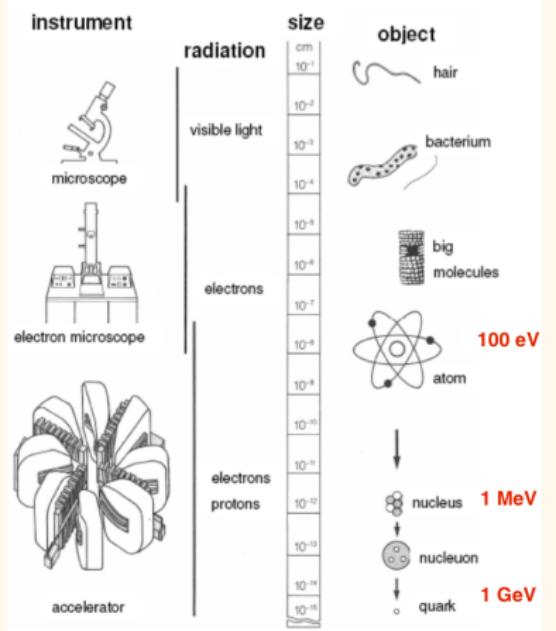
Limitations

- Why electroweak symmetry is broken?
- Is there only one Higgs boson as defined in SM?
- Why are there 3 generations of leptons and quarks?
- Neutrino oscillation (theory does not predict mass of neutrino)
- What are the dark matter and the dark energy?

How to study particle physics?

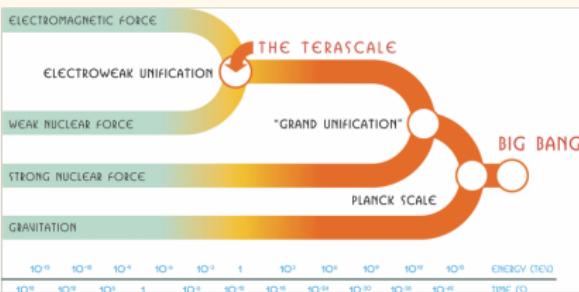
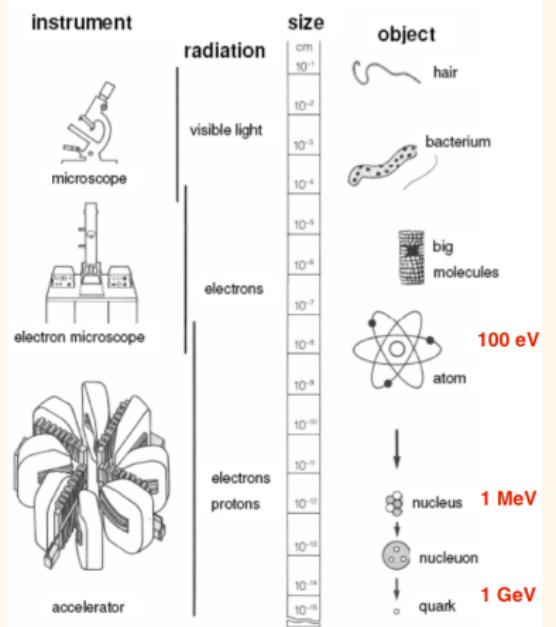


How to study particle physics?



EWSB and physics beyond
SM: from 100 GeV to TeV
scale

How to study particle physics?



EWSB and physics beyond
SM: from 100 GeV to TeV
scale

What tools do we have to reach this energy scale?

Large Hadron Collider (LHC)



LHC: a discovery machine

- Centre-of-mass energy
 $\sqrt{s} = 14 \text{ TeV}$
- Collision with composites particles (protons or Pb)
 - Unknown momentum distribution of partons
 - Unknown polarisation of colliding partons
 - Trigger needed
 - Background made of complex Standard Model reactions

Large Hadron Collider (LHC)

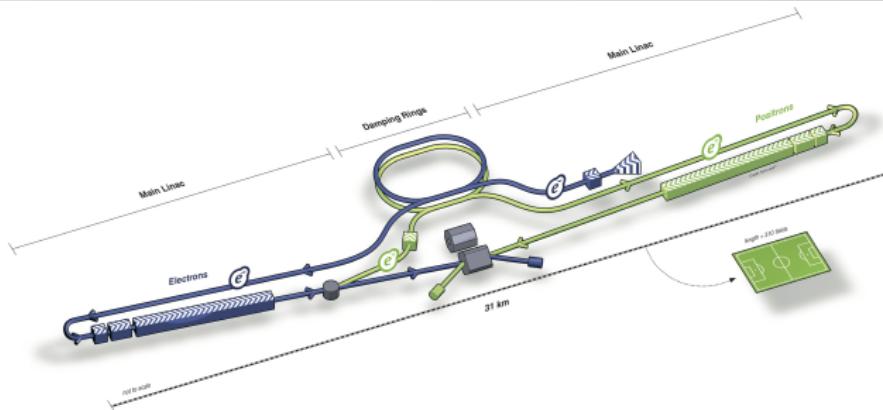


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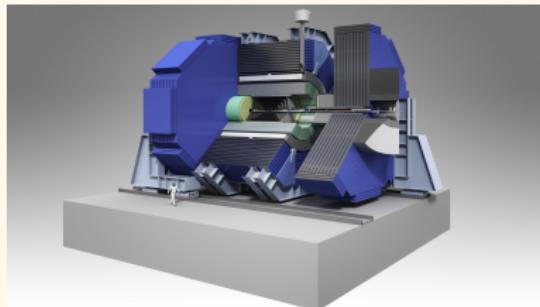
⇒ Need complementary experimental program

International Linear Collider



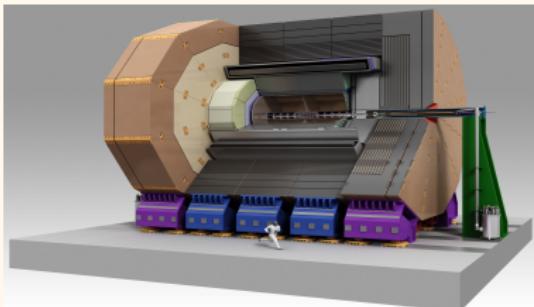
- Future e^+e^- linear collider at $\sqrt{s} = 250 - 500$ GeV (upgrade up to $\sqrt{s} = 1$ TeV)
- Polarised beam
- Luminosity $\simeq 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Candidate site: Kitakami in nothern Japan
- To study properties of the Higgs boson, top physics and discovery potential new physics

SiD and ILD



Silicon Detector

- Silicon tracking
(radius = 1.2 m)
- $B_{field} = 5\text{ T}$



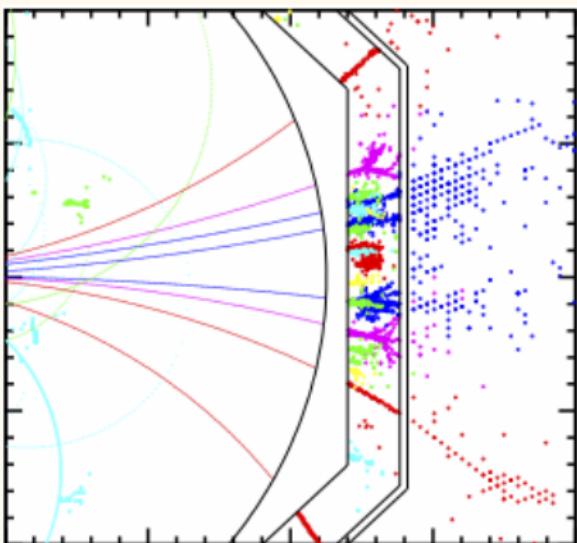
International Large Detector

- TPC + silicon envelope
(radius = 1.8 m)
- $B_{field} = 3.5\text{ T}$

Both detectors designed for Particle Flow Calorimetry

- High granularity calorimeters (ECAL and HCAL) inside solenoid
- Low mass tracker to reduce interactions and conversions

Particle Flow Algorithm



Outlines

1 Introduction

2 Higgs boson study at the ILC

- Motivation
- Study of the $H\nu\nu$ final state
- Reduction of the background

3 Double-sided layers development

4 Mechanical deformation

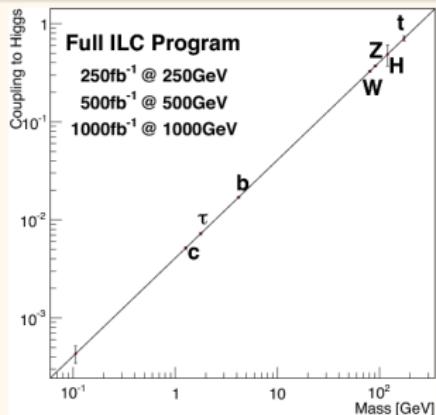
5 Material budget measurement

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Higgs boson study

Measurements @ LHC

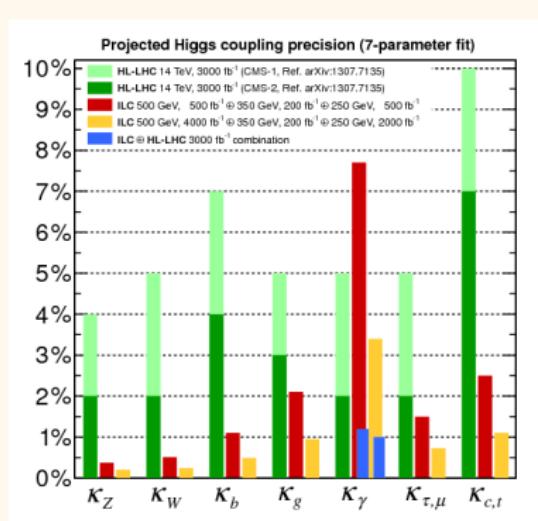
- Higgs boson discovered in 2012 (ATLAS and CMS collaborations)
- Mass: 125.7 ± 0.4 GeV
- Spin: 0



Missing measurements

- Couplings of Higgs boson to c-quarks and gluons
 - Higgs self-coupling
- ⇒ Is the boson discovery compatible with the Higgs boson defined in the SM?

Higgs boson study at the ILC



At the LHC

- Higgs boson to quarks difficult to observe
- $H \rightarrow b\bar{b}$ observed in special kinematics
- $H \rightarrow c\bar{c}$ and $H \rightarrow gg$ are challenging to observe

At the ILC

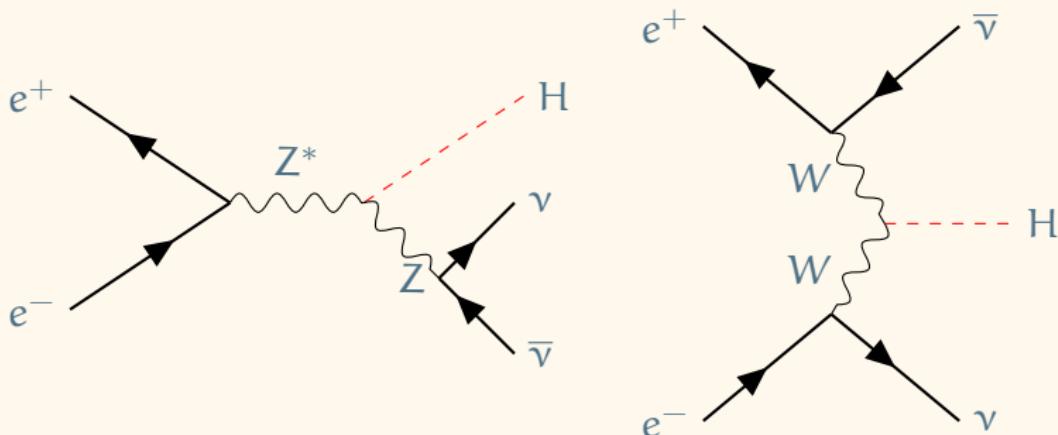
- $H \rightarrow b\bar{b}$, $c\bar{c}$, WW^* , $\tau\tau$ and gg able to be separately identified with high efficiency

Analysis of simulated data at the ILC @ 350 GeV with different polarisations:

- $e_L^+ e_R^-$
- $e_R^+ e_L^-$

Study of $H\nu\nu$ final state

- Study final state leading to $H\nu\nu$ channel where the Higgs boson decays into a pair of quarks or gluons
- Focus on Higgs Strahlung and WW fusion:
 $m_H \simeq 125$ GeV and $\sqrt{s} = 350$ GeV \Rightarrow Higgs Strahlung and WW-fusion have comparable cross sections.



Using polarised beam to separate the processes.

Reconstruction of the $H\nu\nu$ channel

Final state signature

- 2 jets coming from the Higgs boson decay
- Missing energy

Events selection

- ➊ Reject events with isolated leptons
- ➋ Remove $\gamma\gamma$ overlay interactions
- ➌ Look for jets
- ➍ Find displaced vertices of the jets
- ➎ Tag 2 jets coming from Higgs boson decay

Background processes

Events which give same detector response or same final state

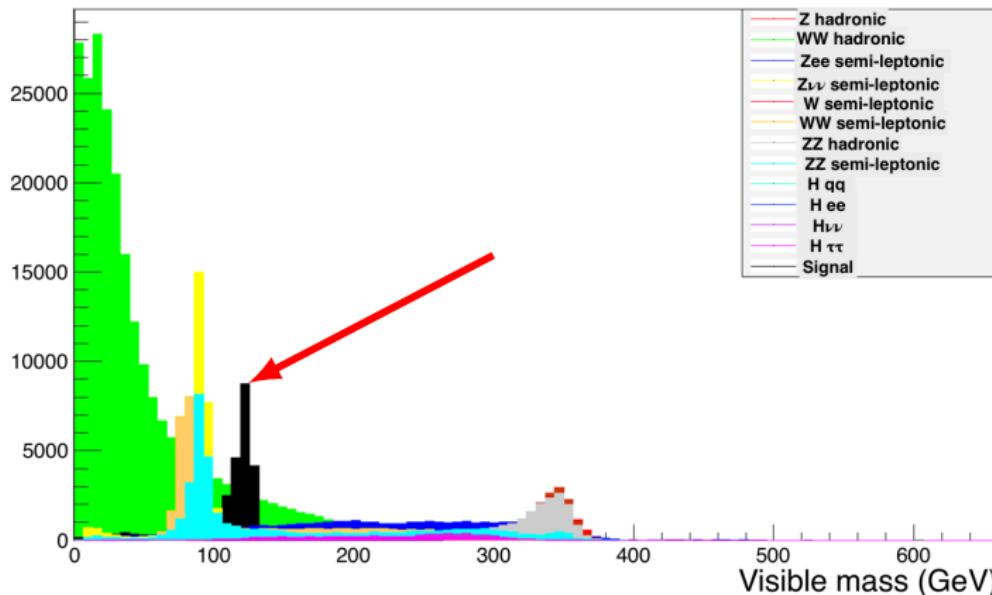
- W-boson pair production
 - Semi-leptonic decay: $e^+e^- \rightarrow W^+W^- \rightarrow \nu_l l^\pm q\bar{q}$
 - Hadronic decay: $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$
- Z-boson pair production
 - $e^+e^- \rightarrow ZZ \rightarrow \nu_l \bar{\nu}_l q\bar{q}$
 - $e^+e^- \rightarrow ZZ \rightarrow l^+l^- q\bar{q}$
 - $e^+e^- \rightarrow ZZ \rightarrow q\bar{q}q\bar{q}$
- Single W-boson production
 - $e^+e^- \rightarrow W^\pm e^\pm \nu_e \rightarrow \nu_e e^\pm q\bar{q}$
- Single Z-boson production
 - $e^+e^- \rightarrow Ze^-e^+ \rightarrow q\bar{q}e^-e^+$
 - $e^+e^- \rightarrow Z q\bar{q} \rightarrow q\bar{q}q\bar{q}$
- Higgsstrahlung:
 - $e^+e^- \rightarrow ZH \rightarrow q\bar{q}q\bar{q}$
 - $e^+e^- \rightarrow ZH \rightarrow l^+l^- q\bar{q}$



Distribution of the visible invariant mass with background

$\sqrt{s} = 350 \text{ GeV}$, luminosity: 250 fb^{-1} and polarisation: e_L^-, e_R^+

Distribution of the visible mass



Reducing the background

Find optimized cuts

- For each cut, try to find the one which reduces the signal the least

$$\text{significance} = \frac{\text{signal}}{\sqrt{\text{signal} + \text{background}}}$$

- Apply the cuts from the one which gives best significance to the one gives the worst

Sequential cuts strategy

cut0 Number of isolated lepton (niso): $\text{niso} = 0$

cut1 Transverse Momentum visible (P_t^{vis}): $35 < P_t^{\text{vis}} < 155 \text{ GeV}$

cut2 Visible mass (m_{vis}): $95 < m_{\text{vis}} < 140 \text{ GeV}$

cut3 Angle between the momentum axis of both jets ($\cos \alpha$):

$-1 < \cos \alpha < 0.22$

...



Reduction table after applying cuts

Process	Background	Signal	Significance
Cross-section (fb)	$5.69 \cdot 10^4$	$6.82 \cdot 10^2$	
Expected event number	$1.88 \cdot 10^7$	$2.25 \cdot 10^4$	5.2
No isolated leptons	$1.65 \cdot 10^7$	$2.23 \cdot 10^4$	5.5
$35 < P_t^{\text{vis}} < 155 \text{ GeV}$	$9.31 \cdot 10^5$	$1.82 \cdot 10^4$	18.7
$95 < m_{\text{vis}} < 140 \text{ GeV}$	$1.50 \cdot 10^5$	$1.66 \cdot 10^4$	40.6
$-1 < \cos \theta < 0.22$	$8.76 \cdot 10^4$	$1.57 \cdot 10^4$	48.8
$26 < (\text{N.R.C} > 1\text{GeV}) < 99$	$2.25 \cdot 10^4$	$1.19 \cdot 10^4$	56.3
$0.11 < \text{DurhamjD2ym} < 1$	$1.78 \cdot 10^4$	$1.05 \cdot 10^4$	62.3
$0 < \text{abs}(P_z^{\text{vis}}) < 113 \text{ GeV}$	$1.51 \cdot 10^4$	$1.01 \cdot 10^4$	63.5
$156 < E_{\text{miss}} < 230 \text{ GeV}$	$1.37 \cdot 10^4$	$9.85 \cdot 10^3$	64.1

Outlook

- Relative uncertainty on branching ratio is impacted by significance to measure signal
- Higher significance is needed to study Higgs decay (TMVA solution)
- Focus on Higgs boson decay mode, especially $H \rightarrow c\bar{c}$
⇒ determine vertex detector geometry for c-tagging ability



Outlines

1 Introduction

2 Higgs boson study at the ILC

3 Double-sided layers development

- ILD vertex detector
- Design
- Test beam

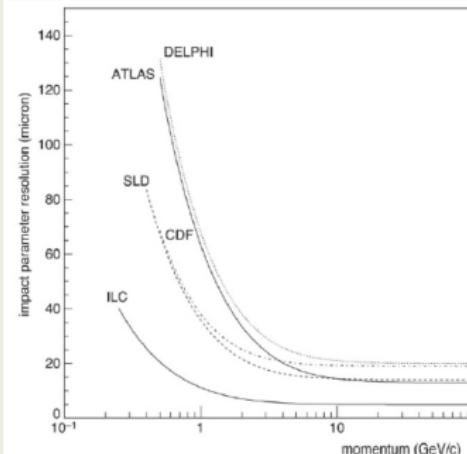
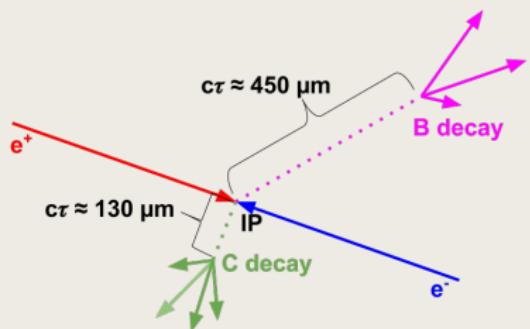
4 Mechanical deformation

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The ILD Vertex Detector

Vertex detector



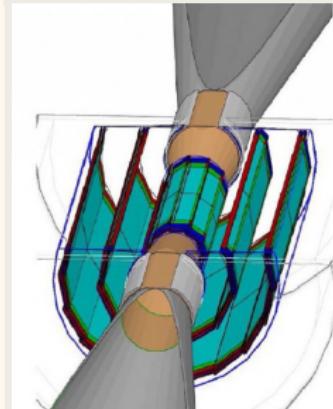
ILD vertex detector

Impact parameter resolution

$$\sigma_{r\phi} \simeq \sigma_{rz} \simeq a \oplus \frac{b}{p \cdot \sin^{2/2}\theta}$$

- Hit resolution: $a \simeq 4 \text{ }\mu\text{m} \Rightarrow \sigma_{\text{spatial}} < 3 \text{ }\mu\text{m}$
- Multiple scattering: $b \simeq 9 - 15 \text{ }\mu\text{m} \Rightarrow \text{material budget per measurement point} \simeq 0.15 \% X_0$

Double-sided layer concept



- 1 mechanical structure for 2 measurement points
- Alignment
- Possibility to use 2 different technologies



Double-sided VXD: PLUME



PLUME = Pixelated Ladder with Ultra-low Material Embedding



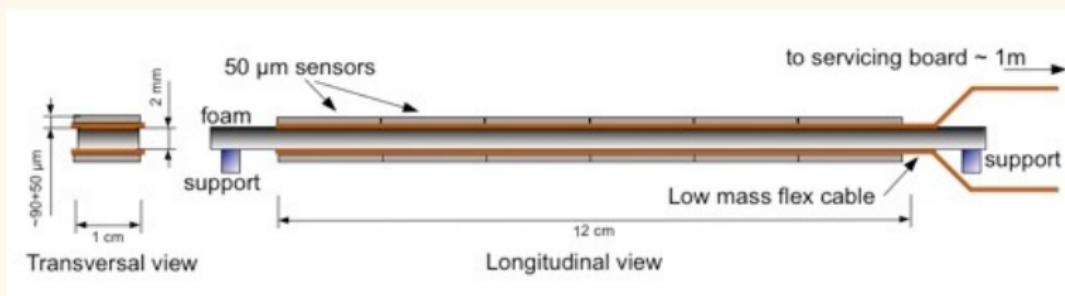
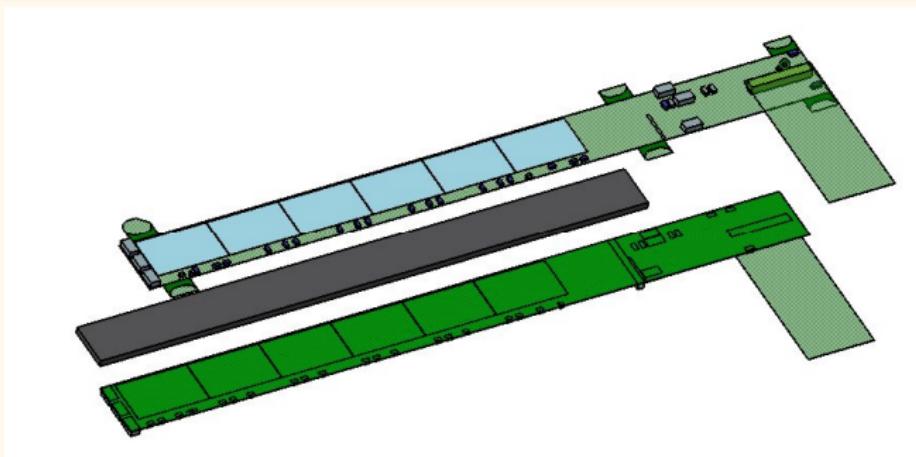
Motivation

To build double-sided ladder with a geometry adapted for the ILD vertex detector at the ILC

Goals

- Reach a constraint material budget $< 0.3 \% X_0$
- Study the added values of double-sided measurement
- Study the mechanical structure and its impact on sensors' performance

What does it look like?

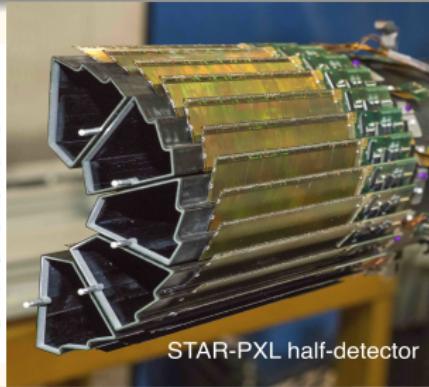
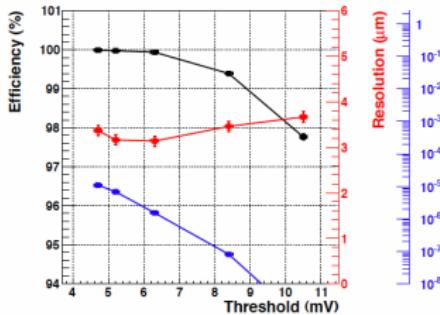
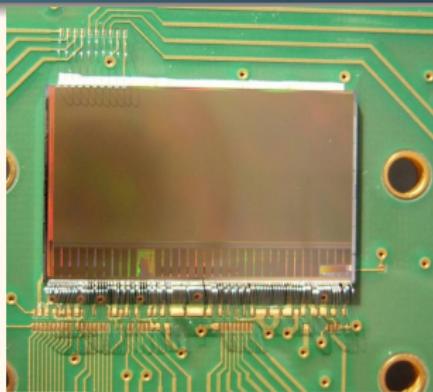


PLUME in real



- 2 mm SiC foam
- 50 μm CMOS pixel sensor
- 100 μm flex-cable
- Air-flow cooling system

MIMOSA-26 sensor



STAR-PXL half-detector

Monolithic Active Pixels Sensor (MAPS)

- Well known sensors ⇒ used for EUDET telescope
- Extended to MIMOSA-28 exploited in STAR-PXL vertex detector @ RHIC-BNL since 2014
- Thickness: 50 μm
- Pitch: 18.4 μm (square pixels)
- Active area: $10.6 \times 21.2\text{mm}^2$ (576 rows x 1152 columns)
- Integration time: 115.2 μ(s) (200 ns per line)
- Binary output with Zero suppression

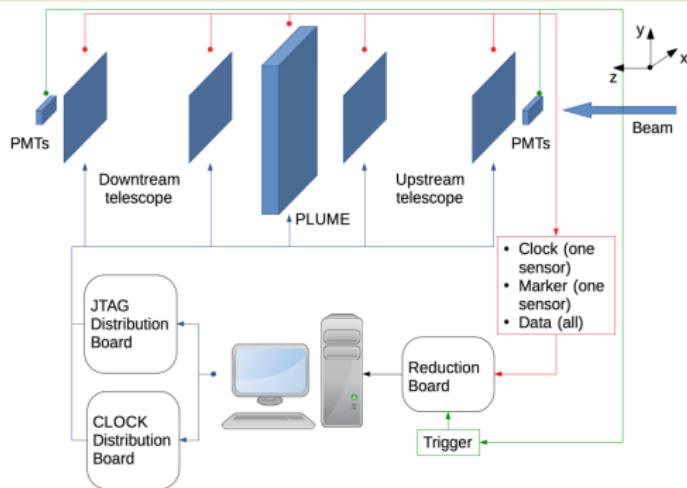


Test beam

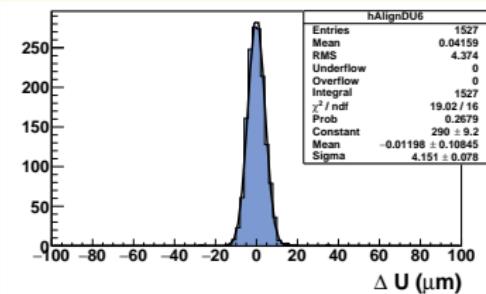
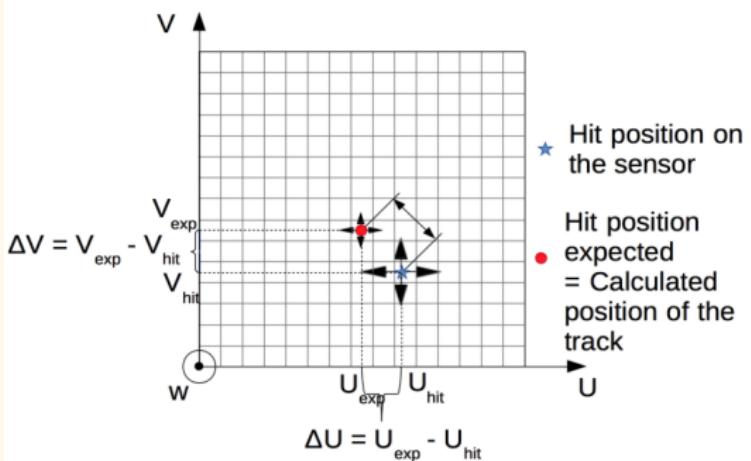
Motivation

Test detector under real conditions to determine its performance

Set-up



Track-hit residual



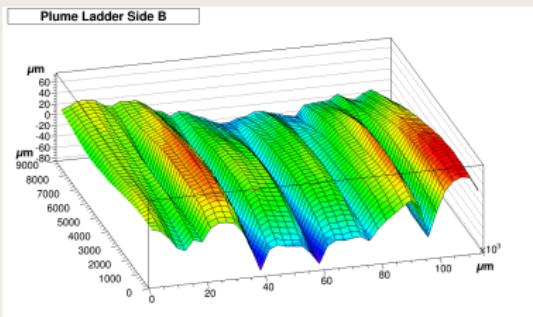
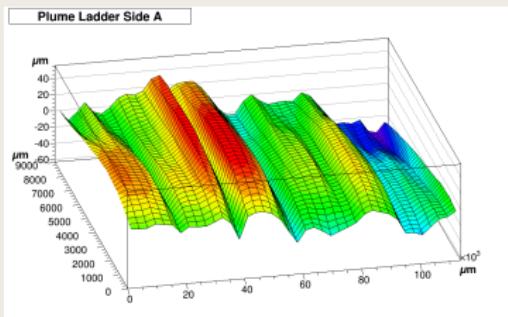
Outlines

- 1 Introduction
- 2 Higgs boson study at the ILC
- 3 Double-sided layers development
- 4 Mechanical deformation
 - Surface's survey
 - Origin of deviations and how to take them into account
 - Results on the correction of deviations
- 5 Material budget measurement
- 6 Conclusion and outlook

Metrology of module's surface

Are our ladders completely flat?

Peak-to-peak flatness $\sim 100 \mu\text{m}$



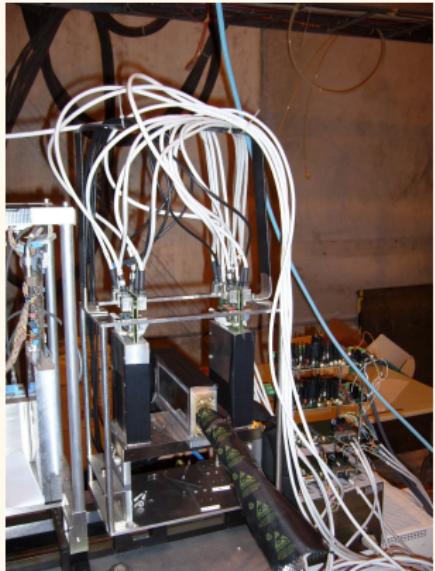
Test performed at Bristol with a dummy ladder

Question

What is the impact of such deformations on ladder's performance?



Test of the first fully functional prototype



Test beam 2011

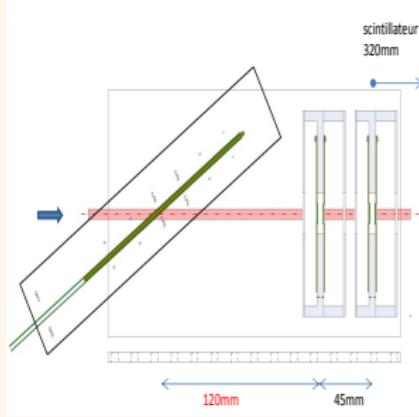
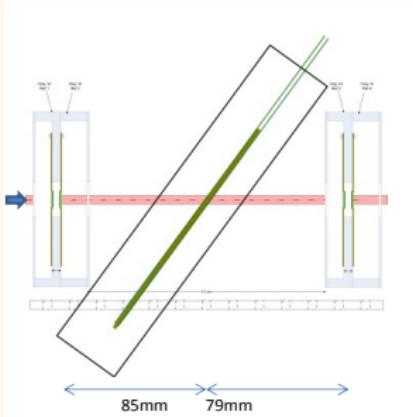
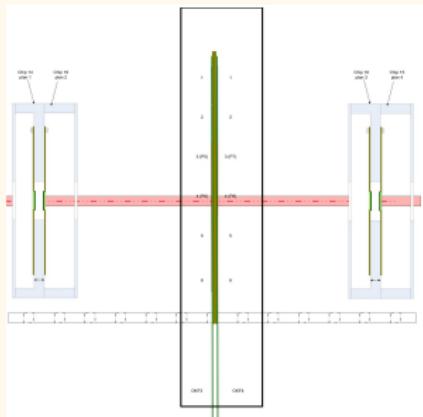
- CERN-SPS with 120 GeV π^-
- Reference plane: 4 MIMOSA-26
- DUT: first double-sided ladder equipped with 12 MIMOSA-26 sensors
- Ladder performance studies with different configurations

Impact of deformations

- Already observed and studied by 2 Ph. D. students
- Method to correct manually and locally these deviations

Is it possible to include the deformations observed during the offline analysis?

Geometrical configurations studied

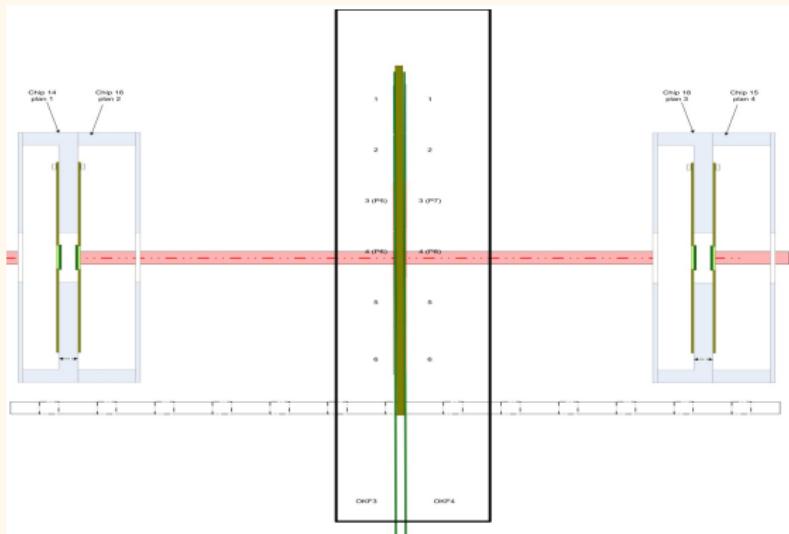


Module perpendicular to the beam.

⇒ Study track-hit residual and the distribution of this residual as a function of the relative position of the beam on the sensor.

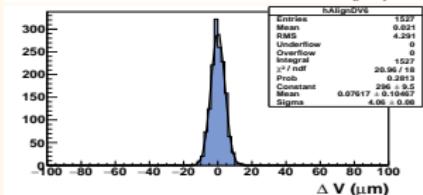
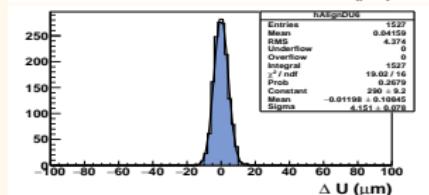
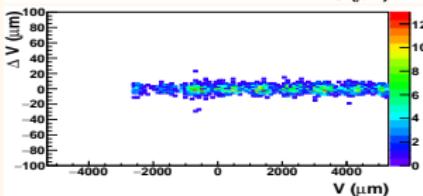
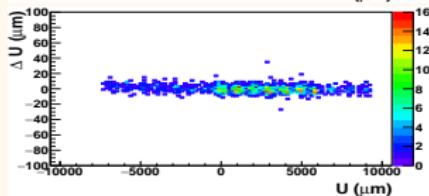
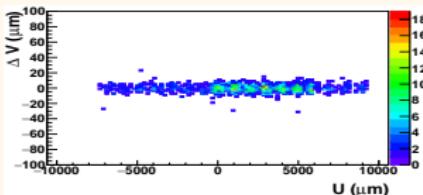
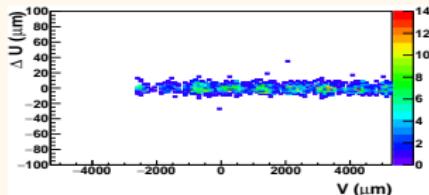
Analysis performed with TAF (TAPI Analysis Framework).

Module perpendicular to the beam



Module perpendicular to the beam

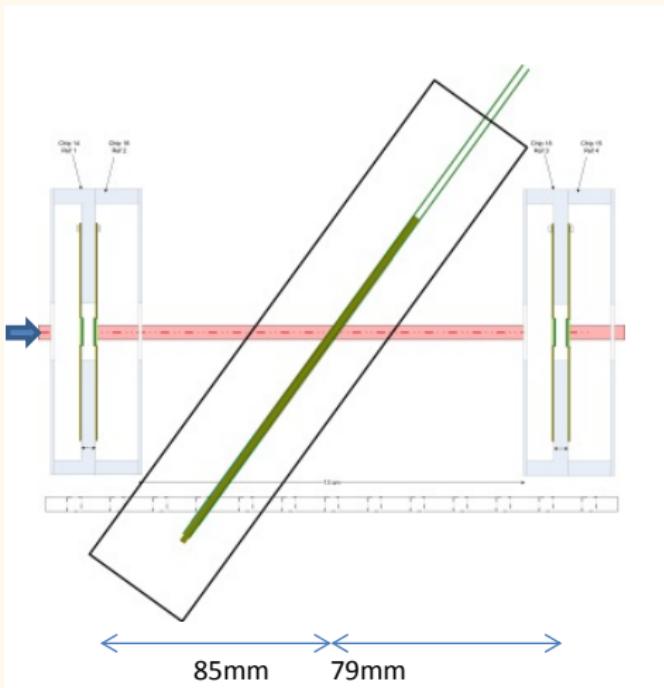
Threshold 6σ , air flow speed $< 5\text{m/s}$ and 1.8M events.



Spatial residual obtained after alignment:

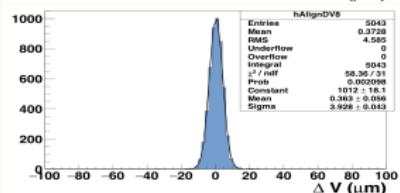
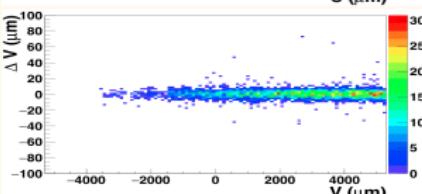
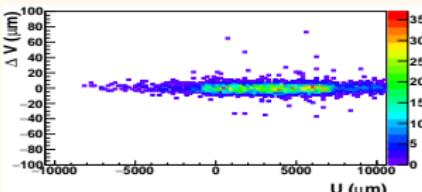
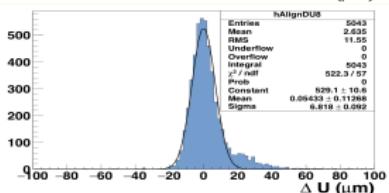
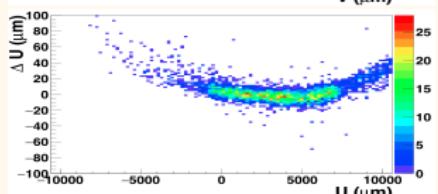
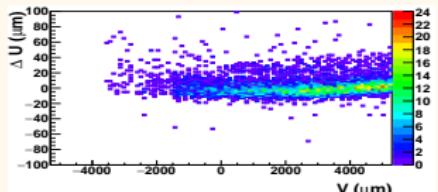
$$\sigma_U \simeq 4.2 \mu\text{m} \text{ and } \sigma_V \simeq 4.1 \mu\text{m}$$

Module tilted in one direction (36°)



Module tilted in one direction (w.r.t. to the beam axis)

Threshold 6σ , air flow speed $< 5\text{m/s}$, 720k events and 36° tilt.



Spatial residual obtained after alignment:

$$\sigma_U \simeq 6.8 \text{ } \mu\text{m} \text{ and } \sigma_V \simeq 4.0 \text{ } \mu\text{m}$$

Origin of deviations

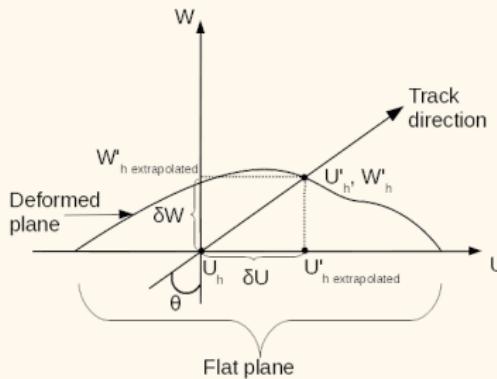
Consequence of the ladder's characteristics

- Use of ultra-thin ($50 \mu\text{m}$) and precise sensors (spatial resolution less than $4 \mu\text{m}$)
- Mechanical constraints induce permanent deformations ($\simeq 100 \mu\text{m}$) which can not be flattened during the ladder assembly

Origin of the deviations

Artefacts from the modelling of our sensors during the analysis

- Sensors modeled as completely flat planes
- The track extrapolation is sensitive to the exact position of the hit on the plane and the angle of incidence



Deviations of the residual

$$\delta W = \frac{\delta U}{\tan \theta}$$

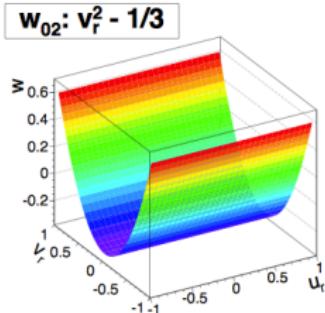
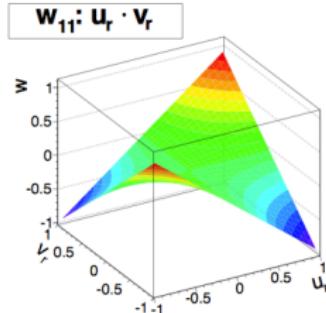
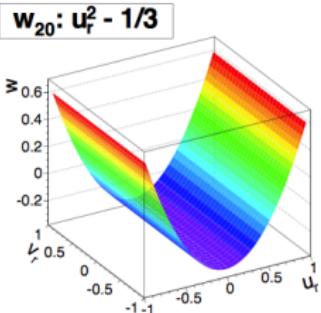
How to describe deviations from the flat plane?

arXiv:1403.2286 [physics.ins-det] CMS paper

- Sensor shape parametrised as a sum of products of modified Legendre polynomials:

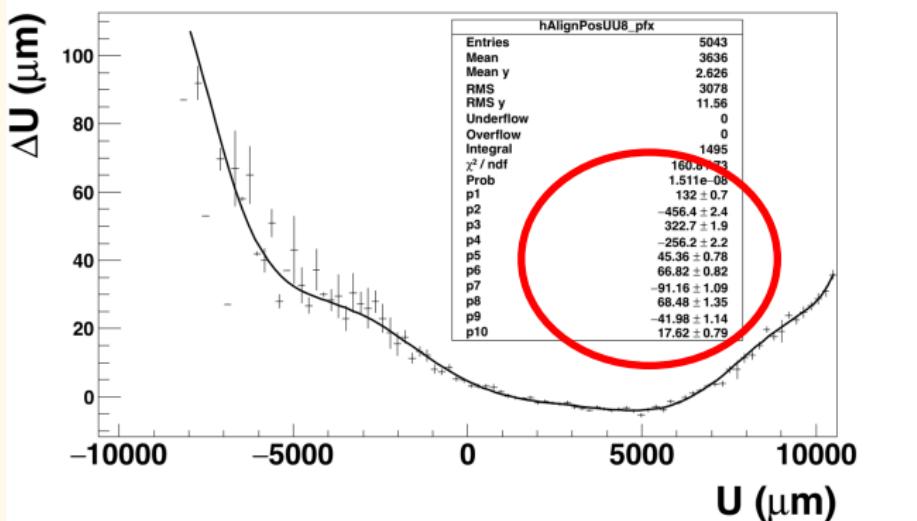
$$w(u_r, v_r) = w + w_{10} \cdot u_r + w_{01} \cdot v_r + w_{20} \cdot (u_r^2 - 1/3) + w_{11} \cdot (u_r \cdot v_r) + w_{02} \cdot (v_r^2 - 1/3)$$

- In our case, we used Legendre polynomials of the 11th order only in the direction of the deformation.



Deformation's parametrisation for 36°

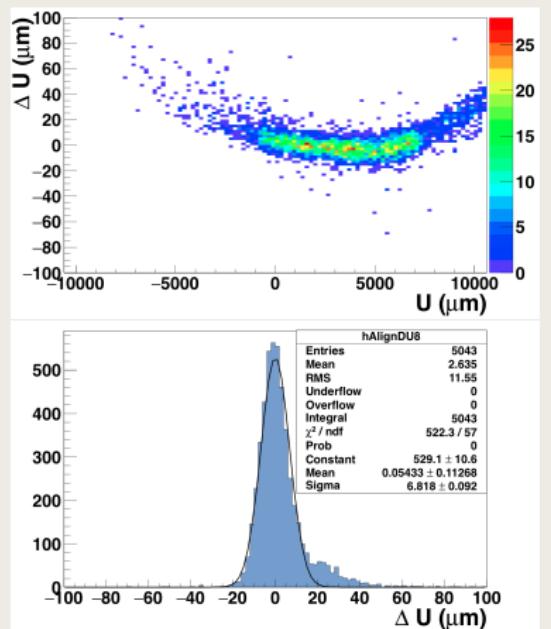
Possibility to parametrise the deformation with Legendre polynomials of the 11th order .



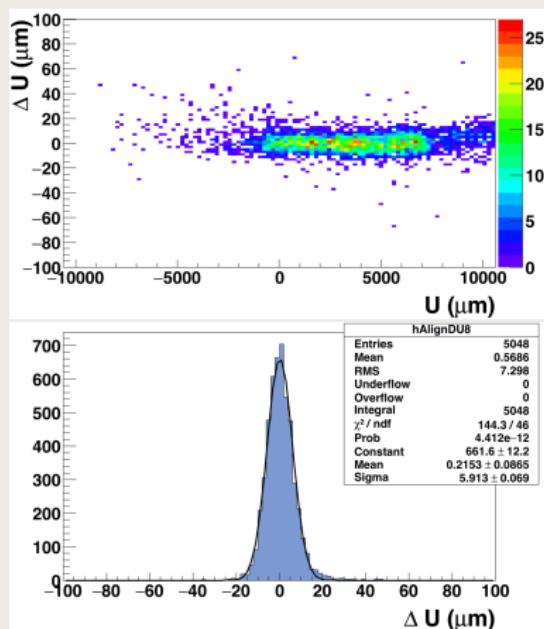
$$\delta W = \frac{\delta U}{\tan \theta}$$

Summary before/after correction at 36°

Before correction



After correction



Summary of correction for different angles and same planes

Spatial residuals

Side	Tilted angle (°)	$\sigma_u^{\text{Def}} (\mu\text{m})$	$\sigma_u^{\text{Cor}} (\mu\text{m})$	Improvement
Front	28	9.0 ± 0.1	4.9 ± 0.1	46.6 %
Back	28	5.7 ± 0.1	4.7 ± 0.1	17.5 %
Front	36	14.1 ± 0.1	6.1 ± 0.1	56.0 %
Back	36	6.8 ± 0.1	5.9 ± 0.1	13.2 %
Front	60	41.2 ± 0.15	25.8 ± 0.2	37.4 %
Back	60	23.3 ± 0.13	21.7 ± 0.1	6.8 %

$\sigma_{\text{tel}} = 2.2 \mu\text{m}$ for 36° and $\sigma_{\text{tel}} = 18.8 \mu\text{m}$ for 60° .

Outlines

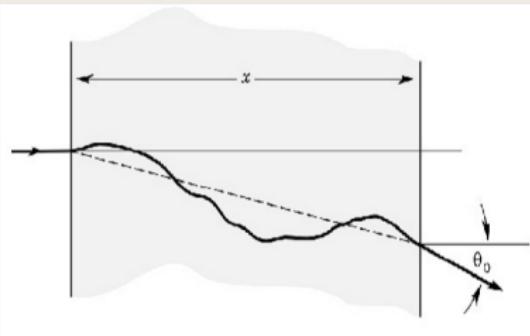
- 1 Introduction
- 2 Higgs boson study at the ILC
- 3 Double-sided layers development
- 4 Mechanical deformation
- 5 Material budget measurement
 - Motivation
 - Test beam @ DESY
 - Theoretical estimation
 - Results
- 6 Conclusion and outlook

Multiple scattering

Charged particles traveling through matter

- Lose energy via inelastic collisions with atomic electrons
- Deflection by many small angles (Coulomb scattering from nuclei)
- Standard deviation of the scattering angle distribution described by Highland formula

$$\theta_0 = \frac{13.6(\text{MeV})}{p} \left(\frac{x}{X_0} \right)^{0.555}$$



Motivation of measuring the material budget

- Key parameter for tracking algorithm: has to take into account multiple scattering and energy degradation
- Compare material budget prediction to its result after construction
- Goal: mapping in uv of X_0

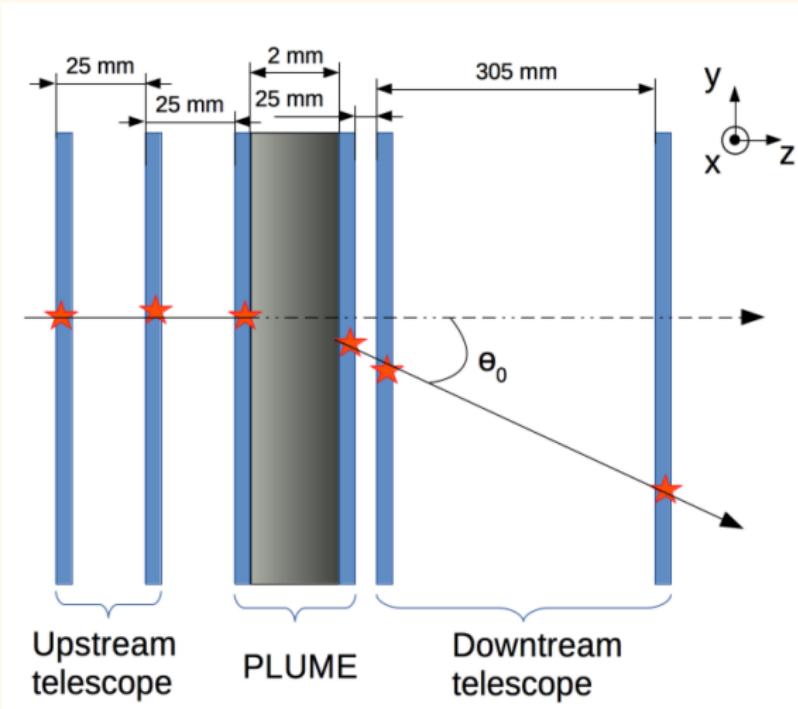


Test beam @ DESY with 5 GeV e^- (April 2016)

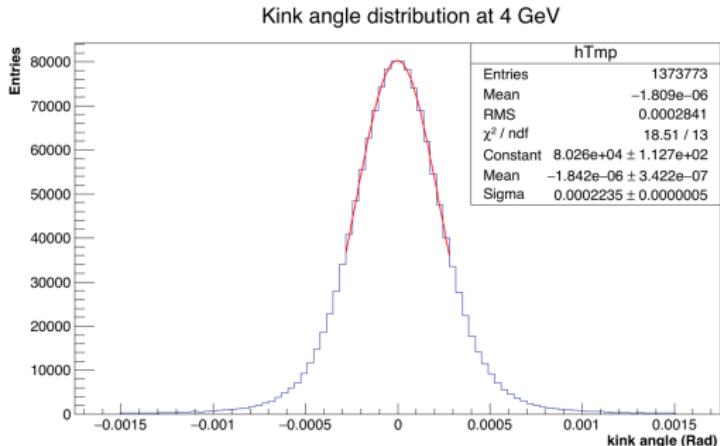


- Test Beam 21
- Reference plane: 4 EUDET telescope planes
- Goal: material budget measurement

Kink angle measurement



Kink angle measurement at 4 GeV



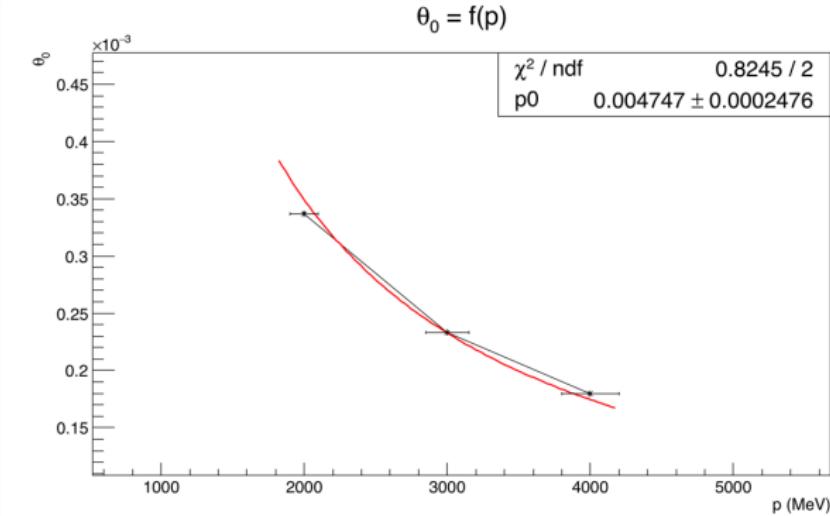
Determination of projected scattering angle θ_0

$$\theta_0 = \sqrt{\sigma^2 - F}$$

- σ = sigma of the kink angle distribution fit
- F = Offset parameter from the GBL track fitting algorithm



Material budget



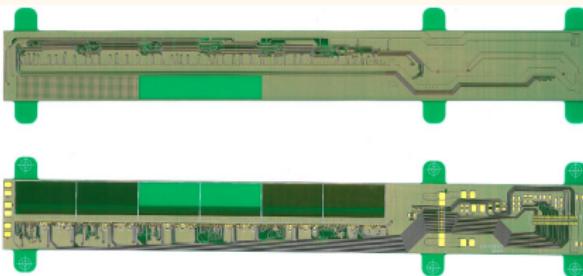
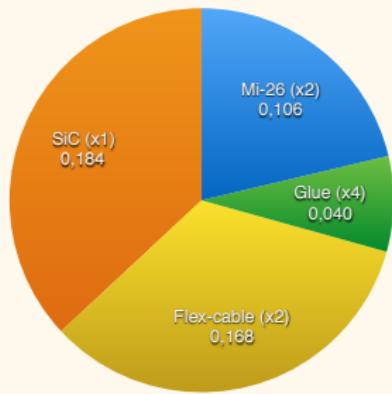
Measurement

Highland formula: $\theta_0 = \frac{13.6(\text{MeV})}{p} \left(\frac{x}{X_0} \right)^{0.555}$

$$\frac{x}{X_0} |_{\text{measured}} \simeq 0.47 \pm 0.02 \% X_0$$



Estimation of the radiation length

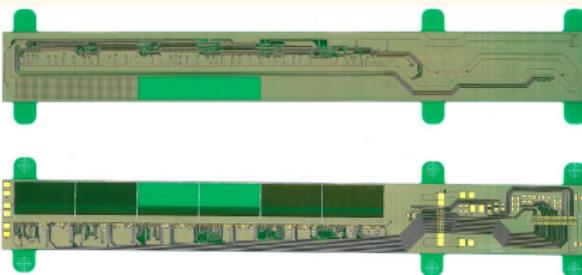
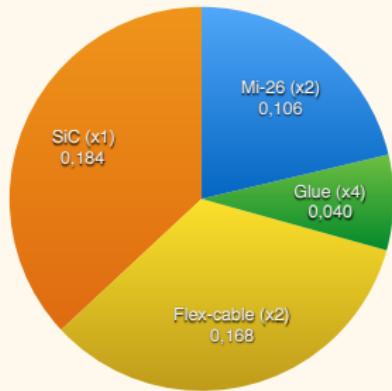


Total material budget

Depends on flex-cable fill factor (25 % or 30 %)

$$\Rightarrow \frac{x}{X_0} \simeq 0.498 - 0.515 \% X_0$$

Estimation of the radiation length

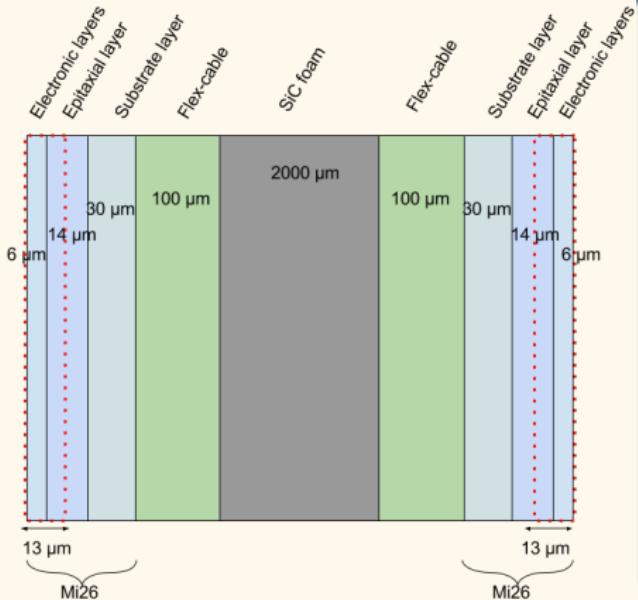


Total material budget

Depends on flex-cable fill factor (25 % or 30 %)

$$\Rightarrow \frac{x}{X_0} \simeq 0.498 - 0.515 \% X_0$$
$$\frac{x}{X_0} |_{\text{measured}} \simeq 0.47 \pm 0.02 \% X_0$$

Lower estimation of X_0



Possible explanation

- During analysis, hit position is located in middle of the epitaxial layer
- Missing 6 μm of the electronic layers and 7 μm of epitaxial layer
- For 2 sensors ⇒ ~ 0.028 % X_0 not included in the calculation

Outlines

- 1 Introduction
- 2 Higgs boson study at the ILC
- 3 Double-sided layers development
- 4 Mechanical deformation
- 5 Material budget measurement
- 6 Conclusion and outlook

Conclusion 1/2

Context

- The ILC is the next colliding machine to study precisely EWSB (and other physics scenarios)
- The Higgs boson will be more precisely characterised
- Physics performance to achieve requires a new R&D detector development

Higgs boson study

To achieve a precision of $\sim 1\%$ in the Higgs boson branching ratio measurement a simple sequential cuts is not the best option

Conclusion 2/2

PLUME development

PLUME is the first double-sided layers developed according to the ILD requirements

- Impact of the mechanical structure
 - Mechanical structure induces permanent deformations which have an impact on ladder's performance
 - Algorithm based on Legendre polynomials is able to reduce the impact of these deformations on ladder's performance
- Material budget
 - Material budget is predicted from construction
 - Measurement of this material budget for PLUME-1 gives:

$$\frac{x}{X_0} \mid_{\text{measured}} \simeq 0.47 \pm 0.02 \% X_0$$
$$\frac{x}{X_0} \mid_{\text{estimated}} \simeq 0.498 - 0.515 \% X_0$$

Outlook 1/2

Test beam 2016

- Mapping in uv of X_0
- Study ladder performance at low energy

PLUME-2

New prototype with a material budget of 0.35 % X_0 has been built and tested in the laboratory but not yet in real conditions

Next PLUME ladder

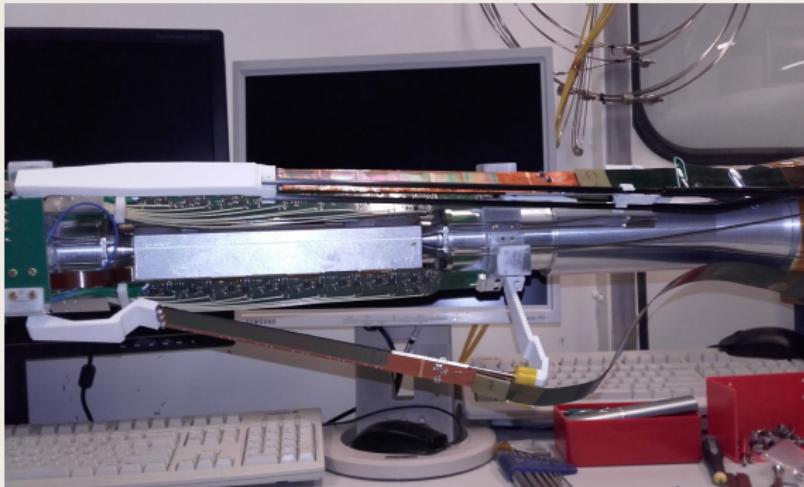
- Higher constraint on material budget (0.3 % X_0)
- Enriching double-sided layer concept with sensors having different characteristics (fast integration time VS good spatial resolution)
- Adapt sensor technology and cooling system to the ILC beam structure



Outlook 2/2

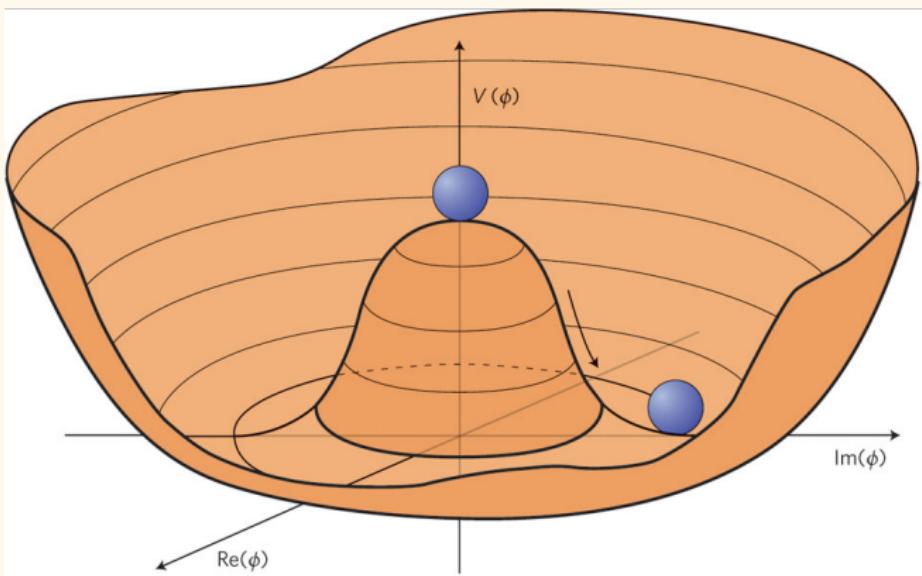
BEAST project

PLUME-2 will be used in the BEAST project at SuperKEKB



Thanks for your attention !!!

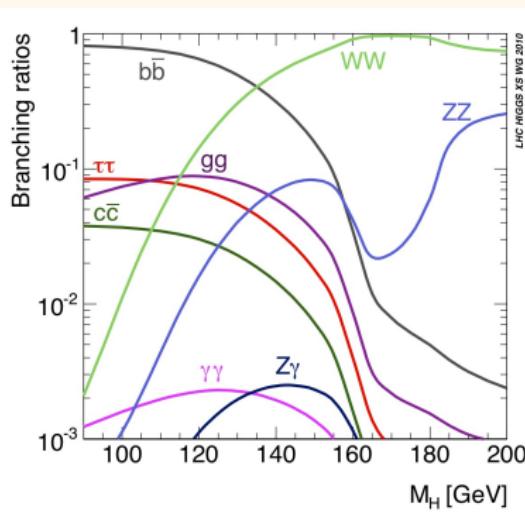
Higgs boson potential



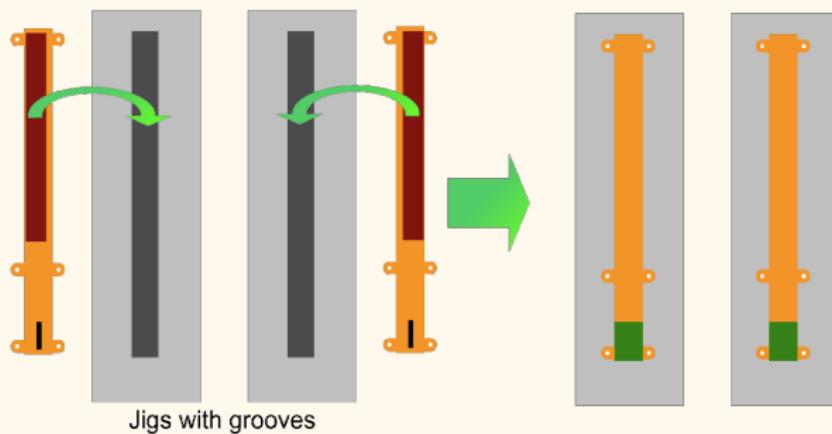
Higgs boson physics at the ILC

- Same measurements as LHC: couplings, mass and spin
- Model independent measurement: no dependence on theory
- Total Higgs width
- $H \rightarrow c\bar{c}/gg$
- Higgs self couplings

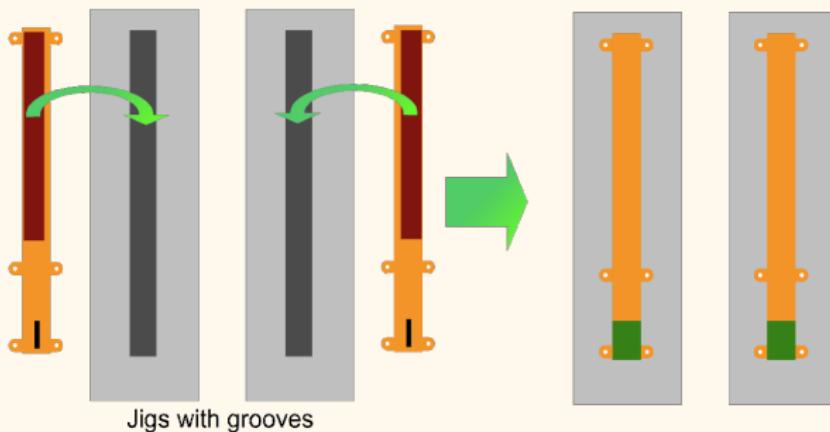
Higgs branching ratio



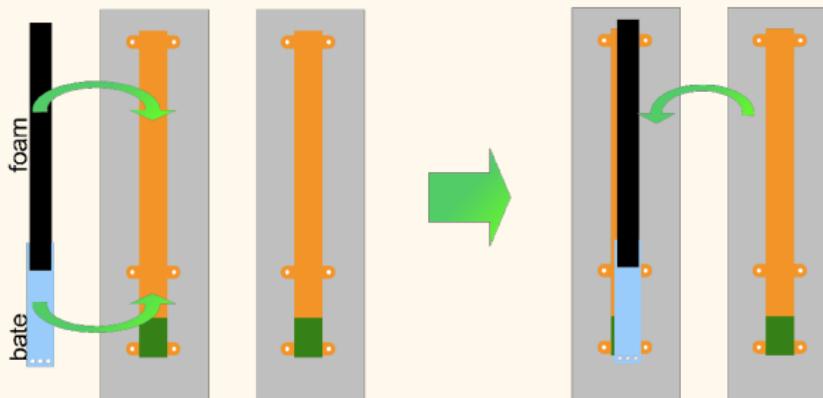
Ladder assembly



Ladder assembly

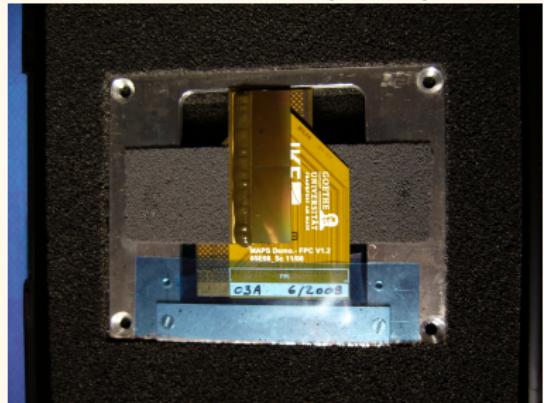


Jigs with grooves



PLUME history

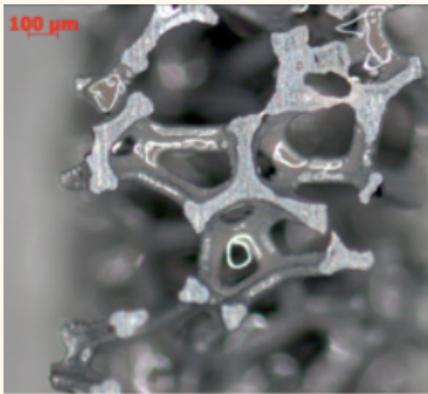
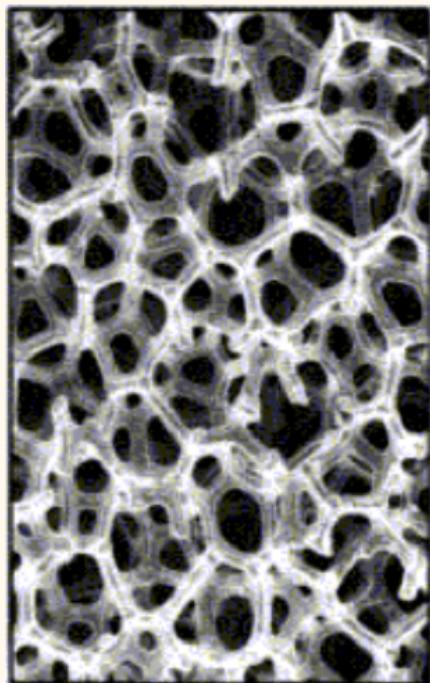
PLUME-V0 (2009)



PLUME-V1 (2010)



Silicon-Carbide foam support structure



Properties

- Open-cell foam
- Macroscopically uniform
- No tensioning needed
- Density: 4 to 8 % (2-3 % possible)
- Low thermal and electrical conductivity (50 W/m/K)

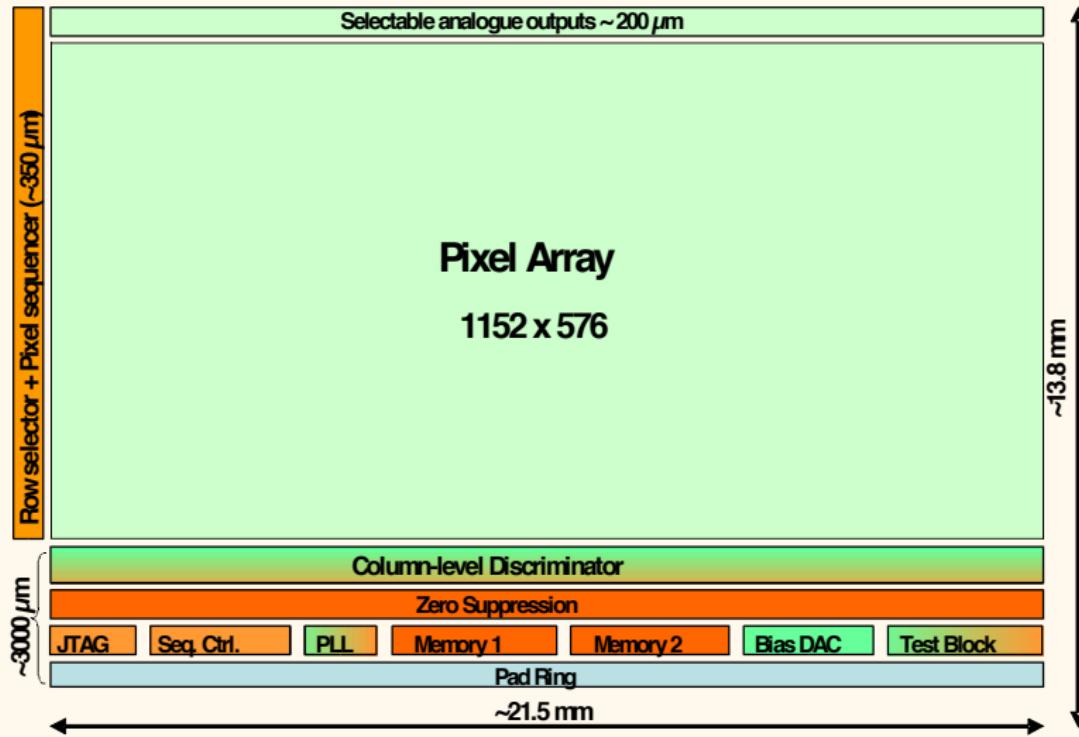
MIMOSA 26

1152x576 ~ 0.7 Mpixels
pitch $18.4 \times 18.4 \mu\text{m}^2$

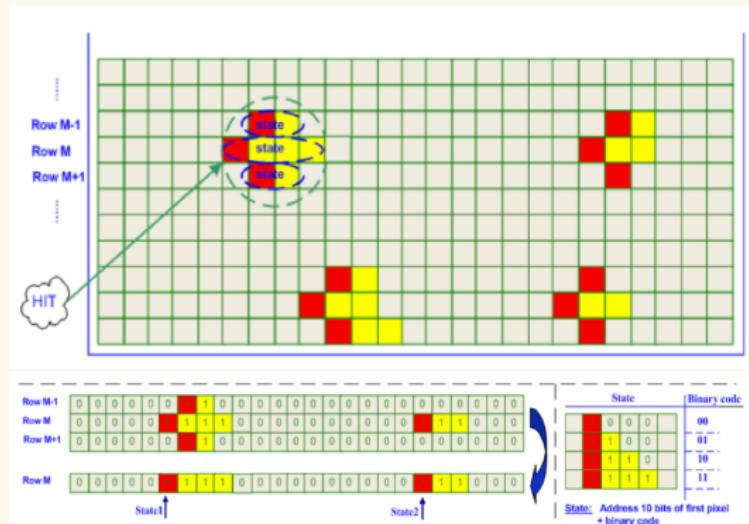
- Sensitive area $10.6 \times 21.2 \text{ mm}^2$
- Total area $13.7 \times 21.5 \text{ mm}^2$
- Readout time $112 \mu\text{s}$



MIMOSA-26 architecture



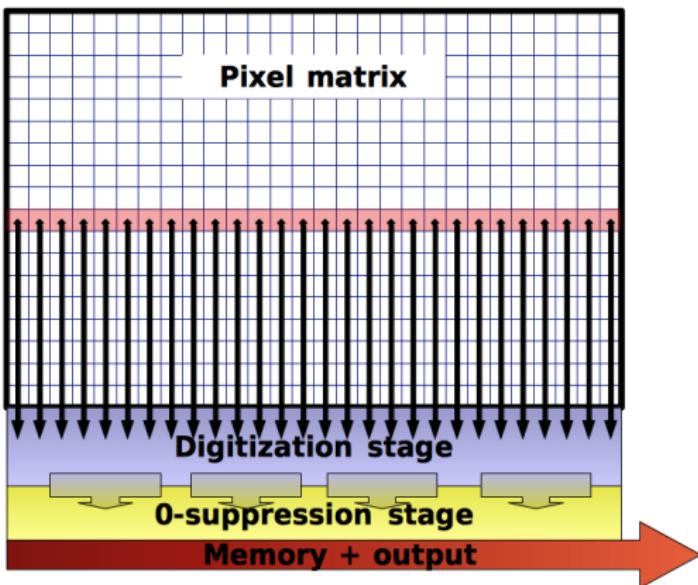
Zero Suppression logic (SUZE)



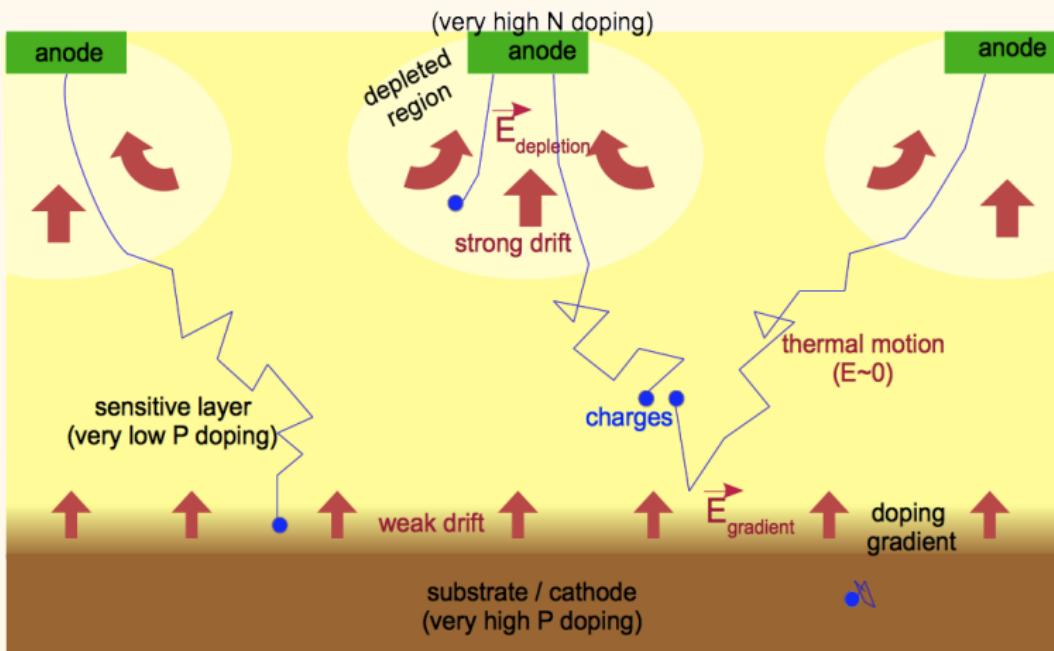
SUZE logic split in 3 blocks:

- **Sparse Data Scan (SDS)** Hit detection per line and data encoding, until 6 states consecutive pixels (1 to 4 pixels) per block of 64 columns;
- **Multiplexing Logic (Mux)** giving up to 9 states;
- **Memory storage** 2 blocks to store the states of the full frame, switching to avoid dead time (during one acquire states of event N, the other one transfer the information of frame N-1).

Column parallel readout

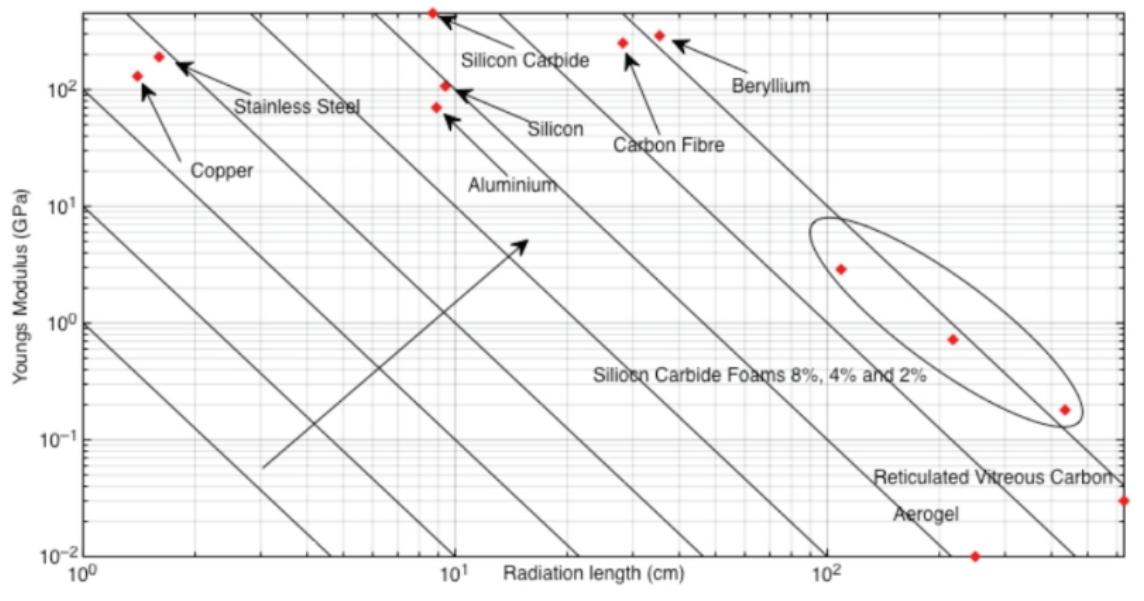


MAPS principle

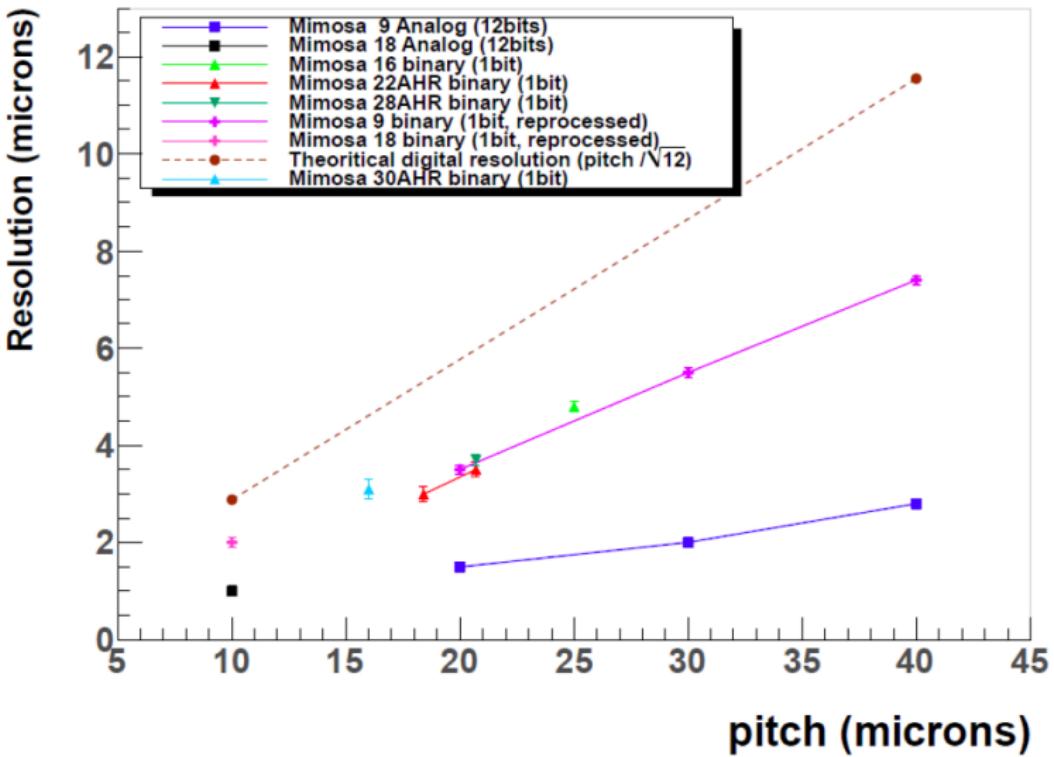


Young Modulus

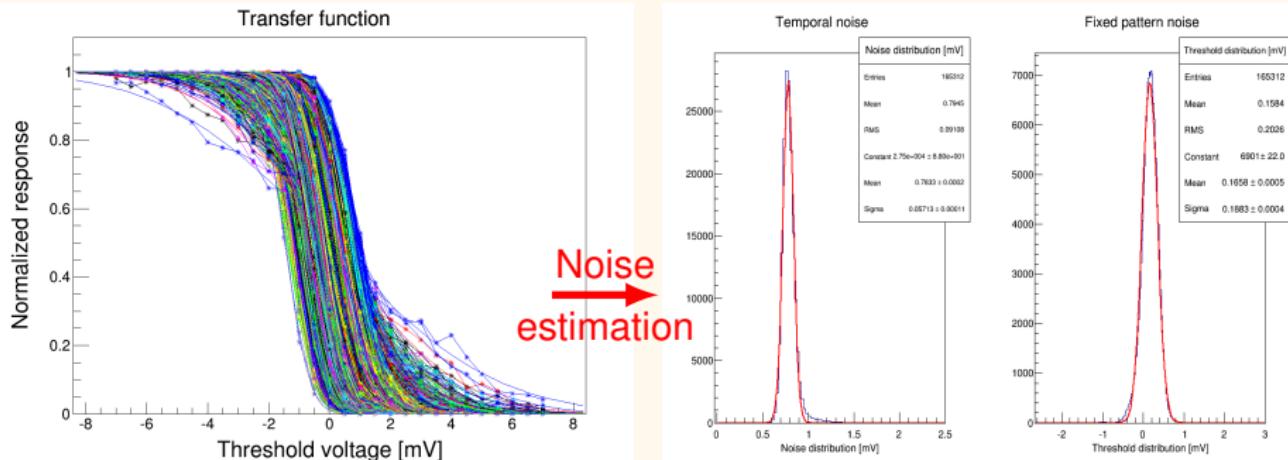
Material Selection Graphs



Spatial resolution for different pitch (IPHC-Strasbourg)



Characterization of one sensor



Threshold scan

Normalised response of pixels in a sub-matrix (288 discriminators) as a function of threshold applied (mV).

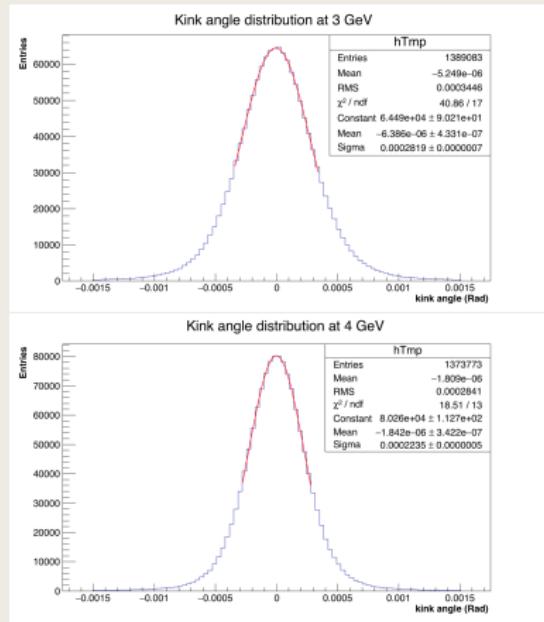
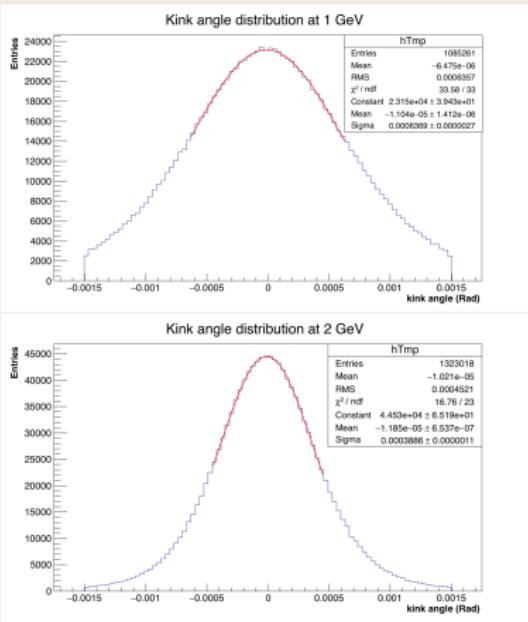
Noise performances

- Temporal noise (derivative of the S-curve): 0.79 mV
- Fixed pattern noise (thresholds' dispersion for a mid-point): 0.2 mV
- Offset: 0.16 mV

⇒ Can now define different thresholds

Kink angle measurement between 1 and 4 GeV

Fitted kink angle distributions



Higgs Strahlung kinematics

$$E_H = \frac{s - M_Z^2 + M_H^2}{2\sqrt{s}}$$

$$E_Z = \frac{s - M_H^2 + M_Z^2}{2\sqrt{s}}$$

$$|\vec{p}_H| = |\vec{p}_Z| = \frac{\sqrt{[s - (M_H + M_Z)^2] \cdot [s - (M_H - M_Z)^2]}}{2\sqrt{s}}$$

If $M_H = 125$ GeV, $M_Z = 91.2$ GeV and $\sqrt{s} = 350$ GeV, then:

$$E_H \simeq 185.4 \text{ GeV}$$

$$E_Z \simeq 164.6 \text{ GeV}$$

$$|\vec{p}_H| = |\vec{p}_Z| \simeq 68.5 \text{ GeV}$$

Detector performances

Vertexing

$$\sigma_{\text{IP}} = 5 \oplus \frac{10}{p \sin^{3/2} \theta} (\mu\text{m})$$

Tracking

$$\sigma(1/p) = 2 \times 10^{-5} (\text{GeV}^{-1})$$

Jet energy

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

Particle Flow Algorithm

- Typical jet:
 - Charged hadrons \simeq 60 %
 - Photons \simeq 30 %
 - Neutral \simeq 10 %
- Standard approach
 - All jet components energy measured in ECAL/HCAL
 - $E_{jet} = E_{ECAL} + E_{HCAL}$
- Particle flow calorimetry
 - Measurement of charged particles in tracker
 - Measurement of photon in ECAL
 - Measurement of hadrons in HCAL
 - $E_{jet} = E_{Track} + E_{\gamma} + E_n$

Why a linear collider?

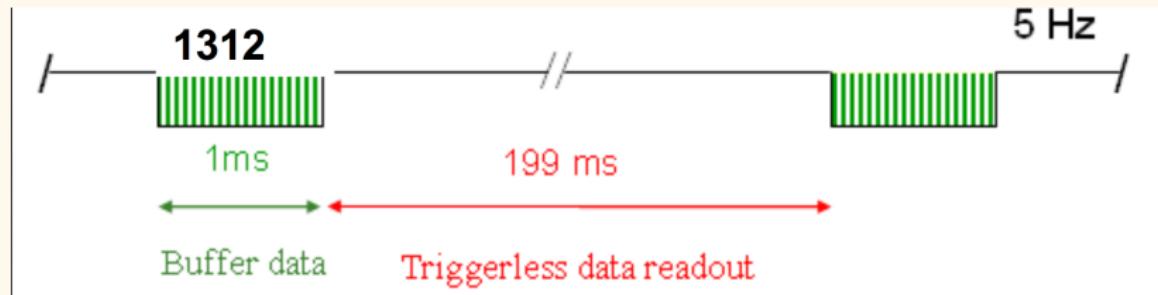
Limitations of e^+e^- colliders

- Synchrotron radiation loss $\sim E^4/r$
- Synchrotron cost: \sim quadratically with energy
- Power consumption

Advantages of linear colliders

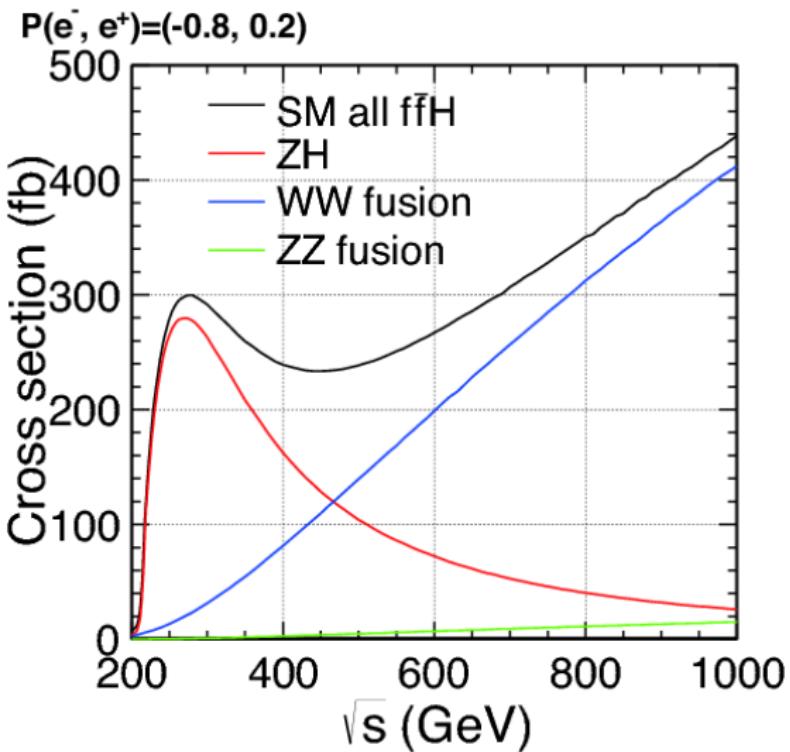
- Not limited by synchrotron radiation
- Cost: \sim linear with energy
- Polarisation of both beams
- Detectors close to the IP \Rightarrow optimum for c-tagging

- 1 interaction region for 2 detectors
- Push-pull:
 - Detectors mounted on movable platforms
 - Sharing of beam time
 - Switching time: 24h to 48h
 - Allow cross-checking

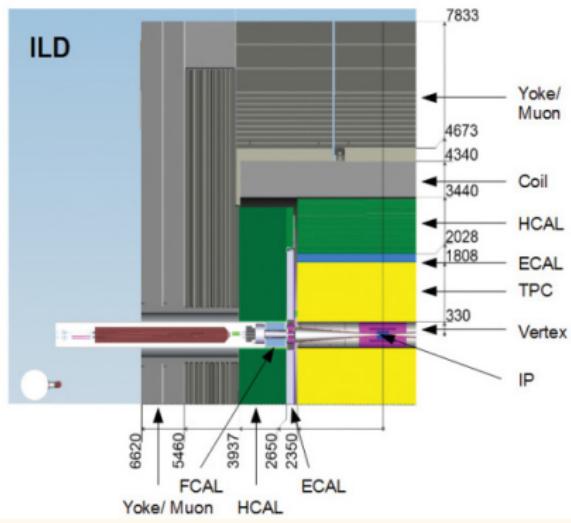
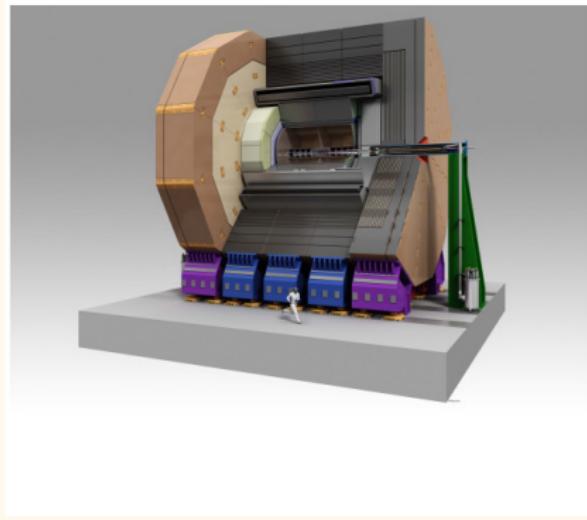


- Bunch spacing of ~ 554 ns
- 1312 bunches in a 1 ms long pulse (train)
- Quiet time: 199 ms
- Occupancy dominated by beam background and noise
- Reading during quiet time possible

Higgs production cross-section



Overview of the ILD



Sequential cuts strategy

cut0: Number of isolated lepton (niso): $n_{\text{iso}} = 0$

cut1: Transverse Momentum visible (P_t^{vis}): $35 < P_t^{\text{vis}} < 155 \text{ GeV}$

cut2: Visible mass (m_{vis}): $95 < m_{\text{vis}} < 140 \text{ GeV}$

cut3: Angle between the momentum axis of both jets ($\cos \alpha$): $-1 < \cos \alpha < 0.22$

cut4: Number of reconstructed particle

cut5: D2YM

cut6: Visible longitudinal momentum ($\text{abs}(P_z^{\text{vis}})$)

cut7: E_{miss}

Beam polarisation

Simulated data: 100 % left or right events

$$\sigma_{P(e^+, e^-)} = \left(\frac{1 - P_{e^-}}{2} \right) \left(\frac{1 + P_{e^+}}{2} \right) \sigma_{RL} + \left(\frac{1 + P_{e^+}}{2} \right) \left(\frac{1 - P_{e^-}}{2} \right) \sigma_{LR}$$

$$\sigma_{P(e^+, e^- = 0.3, -0.8)} = 0.585 \cdot \sigma_{RL} + 0.035 \cdot \sigma_{LR}$$