

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

Ph. D. defense

Benjamin BOITRELLE

Supervisors: Jérôme Baudot, Ingrid Maria Gregor

Strasbourg

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- 1 Introduction
- 2 Higgs boson study
- 3 Detector development
- 4 Mechanical deformation
- 5 Radiation length measurement
- 6 Conclusion and outlook

# Standard Model

- Well-tested physics theory: predict precisely a wide variety of phenomena
- Mass generation mechanism of particles: Higgs mechanism and electroweak symmetry breaking (EWSB)
- Last milestone: discovery of the Higgs Boson that confirms the EWSB

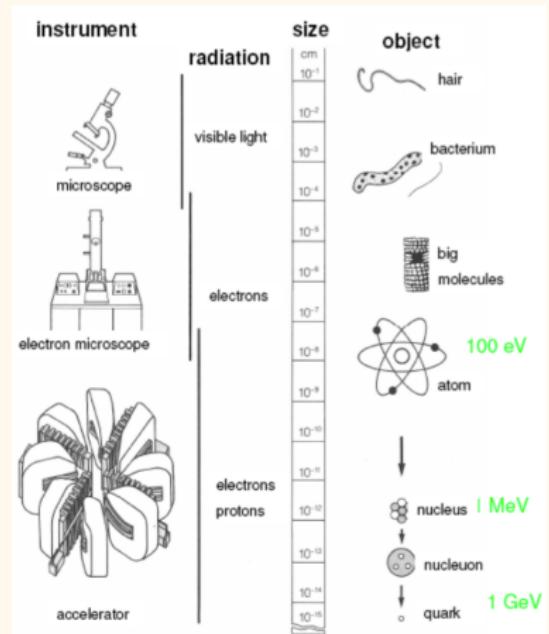
⇒ Complete spectrum of Standard Model that could be correct up to very high energies

# Open questions

## Limitations:

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

# How to study particle physics?

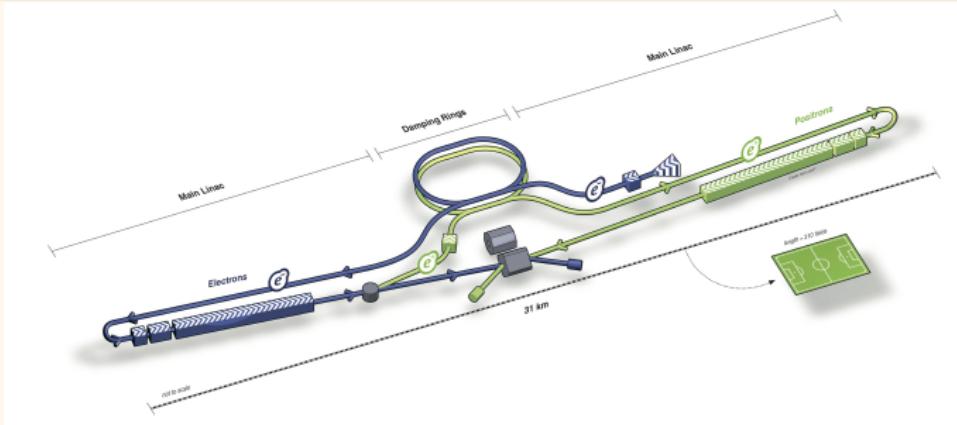


## LHC: a discovery machine

- 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

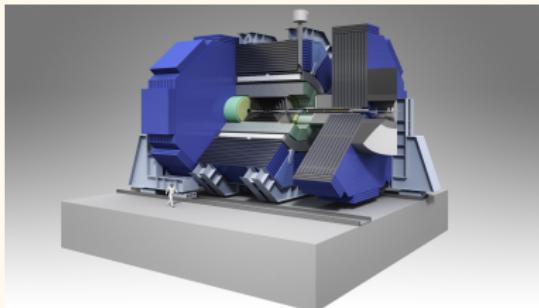
⇒ Need new experimental program

# International Linear Collider



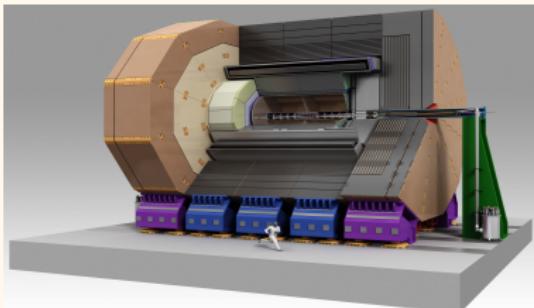
- Future  $e^+e^-$  linear collider at  $\sqrt{s} = 250 - 500$  GeV (upgrade up to  $\sqrt{s} = 1$  TeV)
- Polarised beam
- Luminosity  $\simeq 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Candidate site: Kitakami in northern Japan
- To study properties of the Higgs boson, top physics...

# SiD and ILD



## Silicon Detector

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



## International Linear Detector

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

## Both detectors designed for Particle Flow Calorimetry

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

# Outlines

- 1 Introduction
- 2 Higgs boson study
  - Motivation
  - Study of the  $H\nu\nu$  final state
  - Reduction of the background
- 3 Detector development
- 4 Mechanical deformation
- 5 Radiation length measurement
- 6 Conclusion and outlook

# Higgs boson study

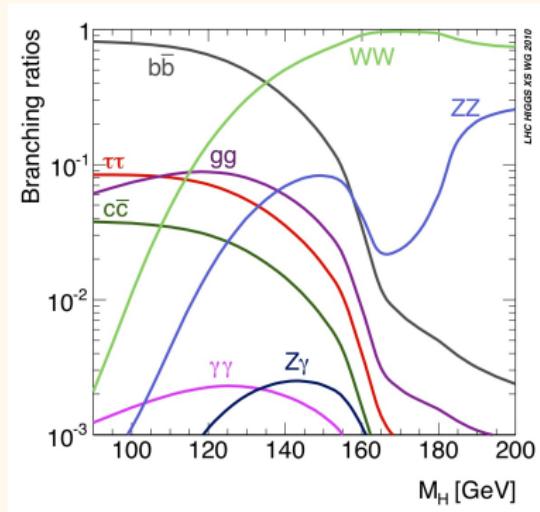
## Measurements @ LHC:

- Higgs boson discovered in 2012 (ATLAS and CMS collaborations)
- Mass:  $125.7 \pm 0.4$  GeV
- Spin: 0
- Only a subset of Higgs decays can be observed (with uncertainties of 5 %)

## Missing measurements

- Couplings of Higgs boson to c-quarks and gluons
- Higgs self-coupling
- Precision required  $\sim 1\%$

# Higgs boson study



## At 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 ILC

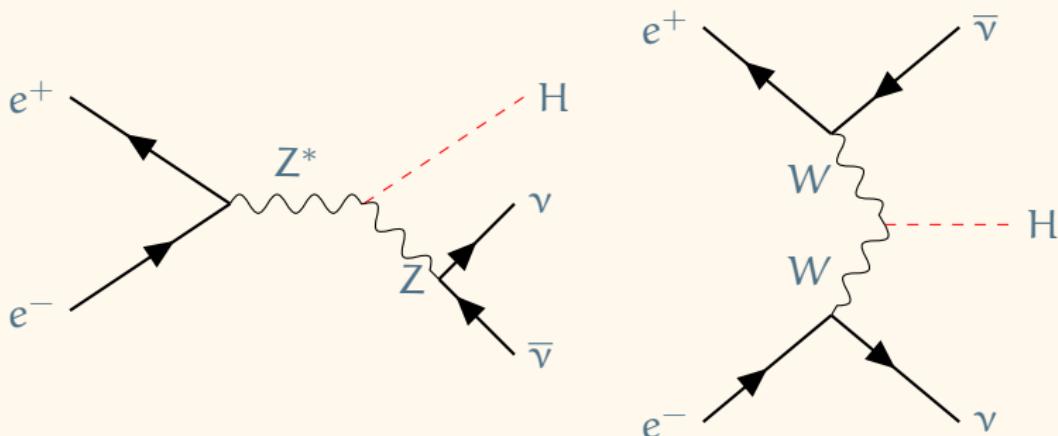
- $H \rightarrow b\bar{b}, c\bar{c}, WW^*, \tau\tau$  and  $gg$  able to be separately identified with high efficiency

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

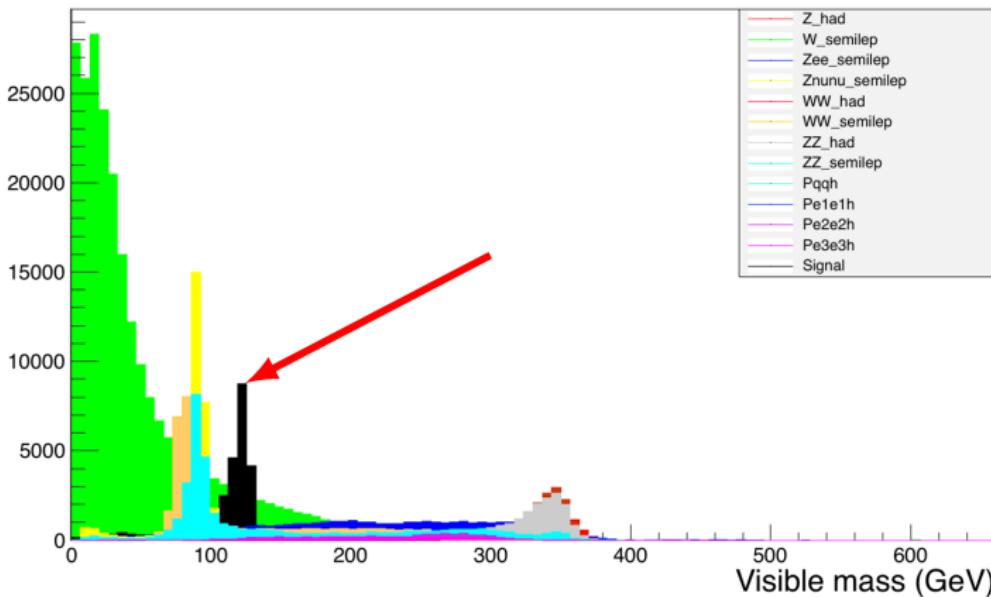
- W-boson pair production
  - Semi-leptonic decay:  $e^+e^- \rightarrow W^+W^- \rightarrow \nu_l l^\pm q\bar{q}$
  - Hadronic decay:  $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$
- Z-boson pair production
  - $e^+e^- \rightarrow ZZ \rightarrow \nu_l \bar{\nu}_l q\bar{q}$
  - $e^+e^- \rightarrow ZZ \rightarrow l^+l^- q\bar{q}$
  - $e^+e^- \rightarrow ZZ \rightarrow q\bar{q}q\bar{q}$
- 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:  $250 \text{ fb}^{-1}$  and polarisation:  $e_L^-, e_R^+$

Distribution of the visible mass



# Distribution of each processes

Process	Expected events
Z hadronic decay	$1.3 \cdot 10^7$
WW hadronic decay	$2.2 \cdot 10^6$
WW semi-leptonic decay	$3.7 \cdot 10^6$
ZZ hadronic decay	$2.0 \cdot 10^5$
ZZ semi-leptonic decay	$1.9 \cdot 10^5$
W semi-leptonic decay	$5.4 \cdot 10^5$
Zee semi-leptonic decay	$1.0 \cdot 10^5$
Zvv semi-leptonic decay	$1.2 \cdot 10^5$
Higgs BG	$5.3 \cdot 10^4$
Other Higgs boson decay	$1.0 \cdot 10^4$
Background	$1.9 \cdot 10^7$
Signal	$2.2 \cdot 10^4$

# 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):  $niso = 0$

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

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

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

- Higher significance is needed to study Higgs decay (TMVA solution)
- Focus on Higgs boson decay mode, especially  $H \rightarrow c\bar{c}$

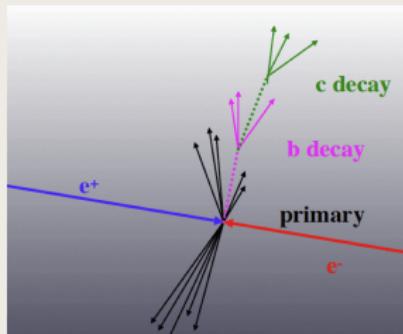
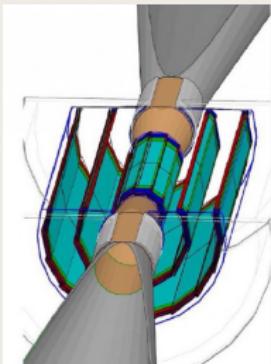
⇒ determine vertex detector geometry

# Outlines

- 1 Introduction
- 2 Higgs boson study
- 3 Detector development
  - ILD vertex detector
  - Design
  - Test beam
- 4 Mechanical deformation
- 5 Radiation length measurement
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# The ILD Vertex Detector

## Vertex detector



## Impact parameter resolution

- $\sigma_{r\phi} \simeq \sigma_{rz} \simeq a \oplus \frac{b}{p \cdot \sin^{3/2}\theta}$
- Hit resolution:  $a \simeq 5\mu\text{m} \Rightarrow \sigma_{\text{spatial}} < 3\mu\text{m}$
- Multiple scattering:  $b \simeq 10 - 15\mu\text{m} \Rightarrow \text{material budget per layer} \simeq 0.15 \% X_0$



# Main aims

- Constraint material budget  $\Rightarrow < 0.3 \% X_0$
- Study impact of the mechanical structure on sensor performance
- Study the added value of double-sided measurement (mini vectors)

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# Double-sided VXD: PLUME



PLUME = Pixelated Ladder with Ultra-low  
Material Embedding



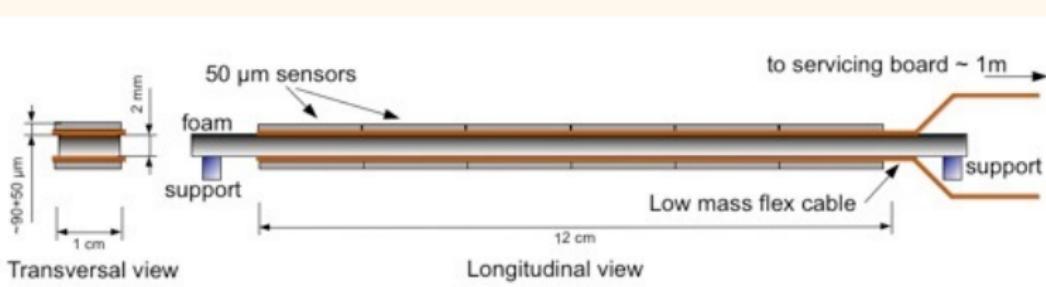
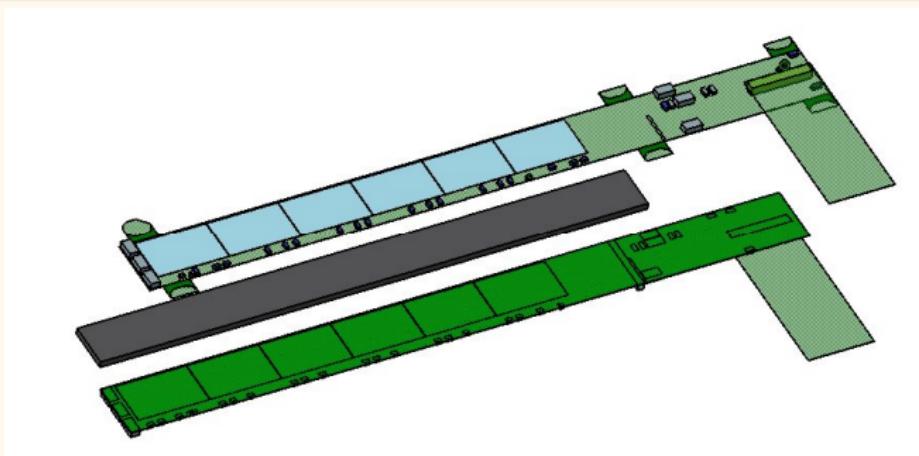
## Motivation

## ILD Vertex detector at ILC

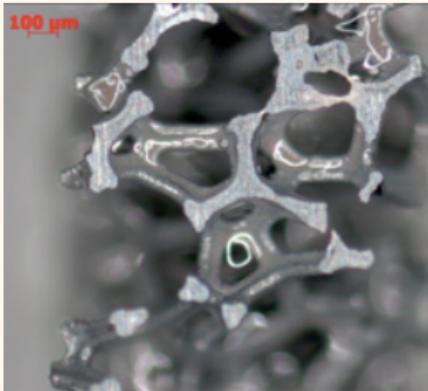
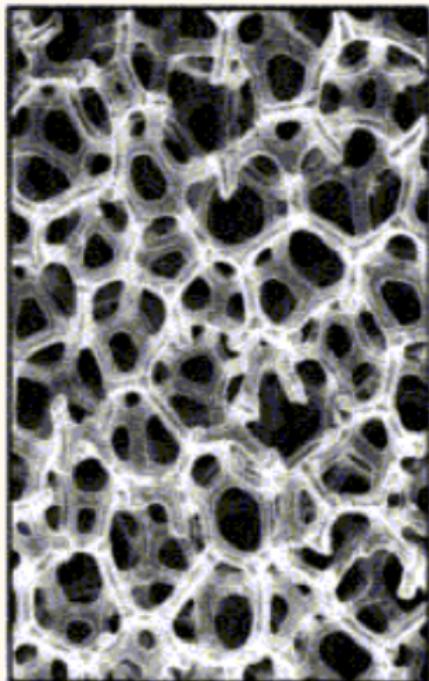
## Design

- Double-sided ladder with an active area of  $1 \times 12\text{cm}^2$
- On each side: six MIMOSA-26 CMOS sensors thinned down to  $\sim 50\text{ }\mu\text{m}$  on a kapton-metal flex cable
- 2 mm of silicon carbide foam as mechanical support and spacer between two modules

# What does it look like?



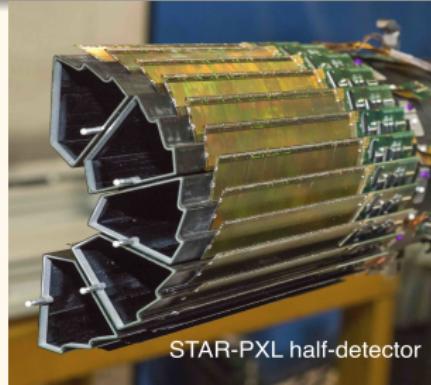
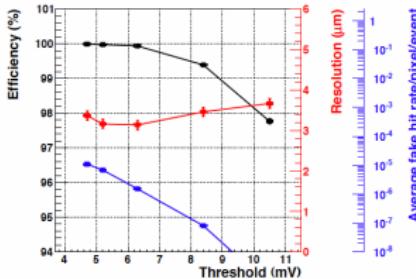
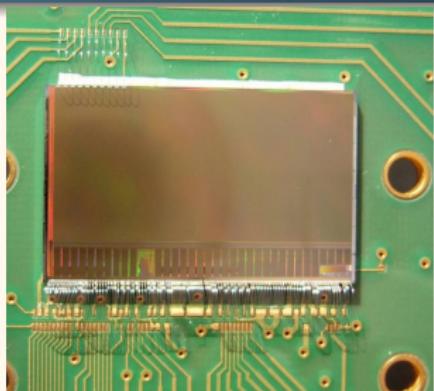
# Silicon-Carbide foam support structure



## 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 sensor



STAR-PXL half-detector

## Monolithic Active Pixels Sensor (MAPS)

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

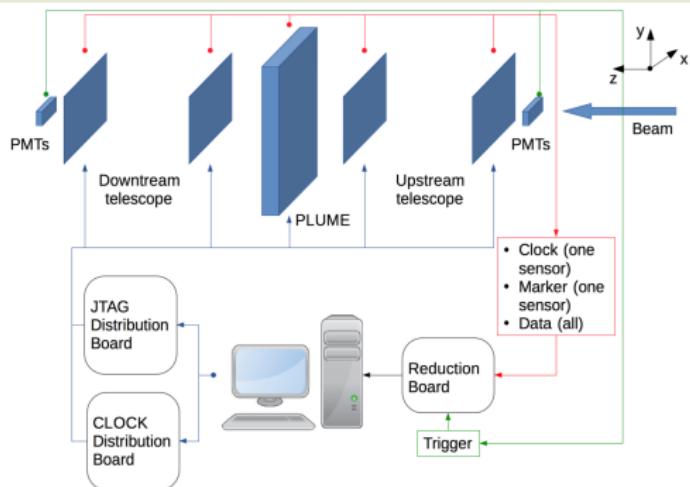


# Test beam

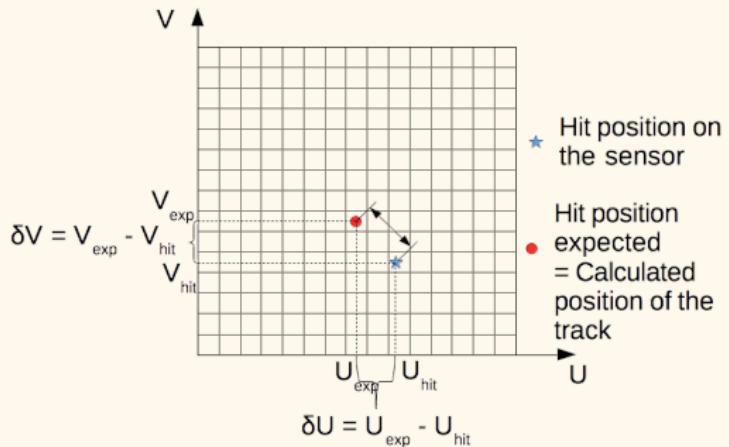
## Motivation

Test detector under real conditions to determine its performance

## Set-up



# Track-hit residual



Device Under Test (DUT) alignment:

- Telescope planes defined particle's track
- Alignment of DUT in local coordinate system:
  - Define a maximal range in which a hit can be associated to a track
  - Find the best tilt and position to minimise the distance between a hit and its associated track.

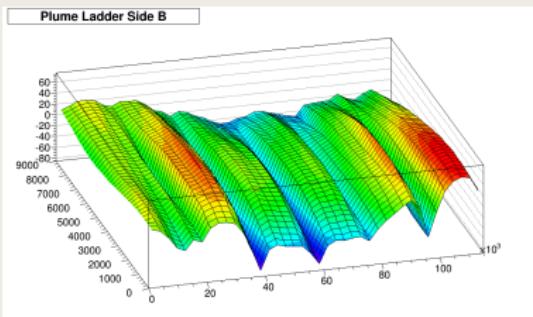
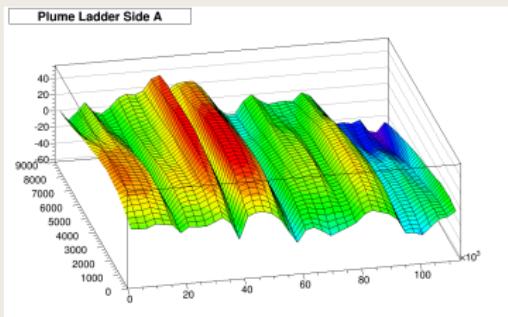
# Outlines

- 1 Introduction
- 2 Higgs boson study
- 3 Detector development
- 4 Mechanical deformation
  - Surface's survey
  - Origin of deviations and how to take them into account
  - Results on the correction of deviations
- 5 Radiation length measurement
- 6 Conclusion and outlook

# Metrology of module's surface

Are our ladders completely flat?

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



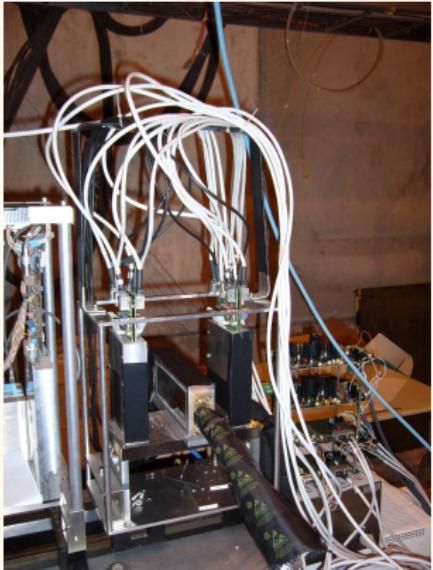
Test performed at Bristol with a dummy ladder

Question

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



# Test of the first fully functional prototype



## Test beam 2011

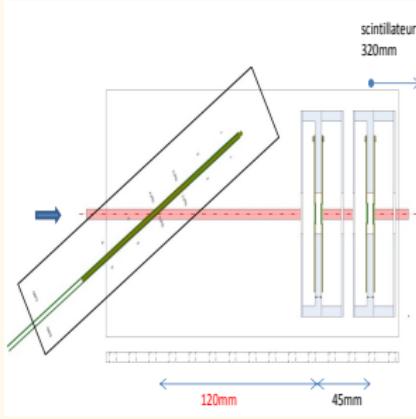
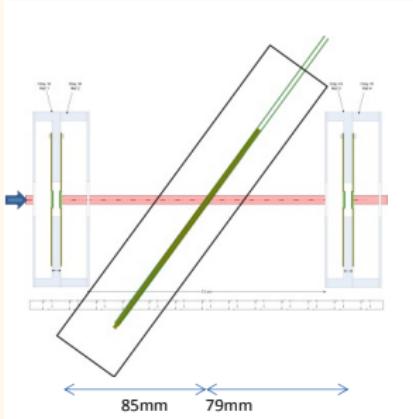
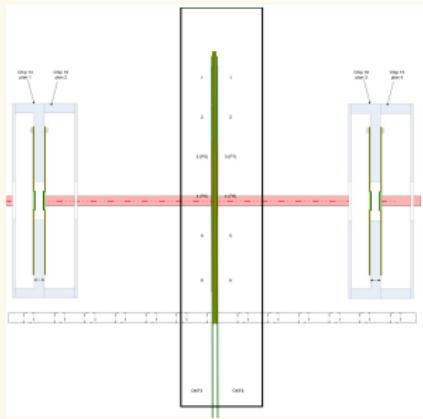
- CERN-SPS with 120 GeV  $\pi^-$
- Reference plane: 4 MIMOSA-26
- DUT: first double-sided ladder equipped with 12 MIMOSA-26 sensors
- Ladder performance studies with different configurations

## 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



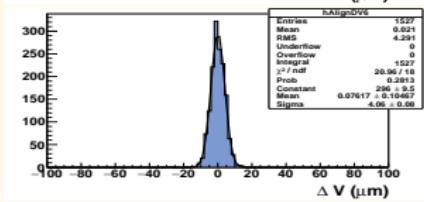
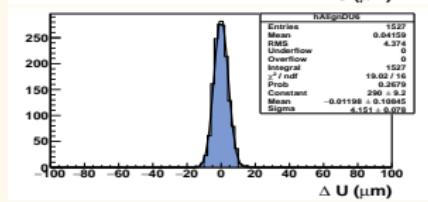
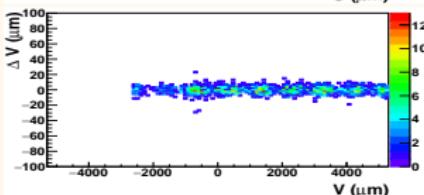
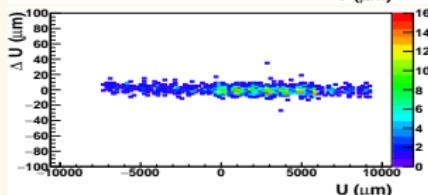
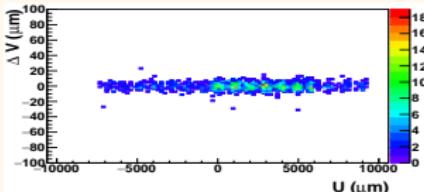
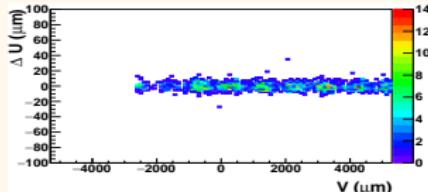
**Module perpendicular to the beam.**

⇒ 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

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

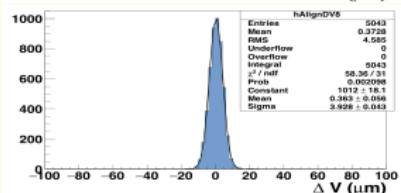
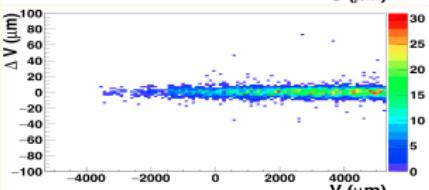
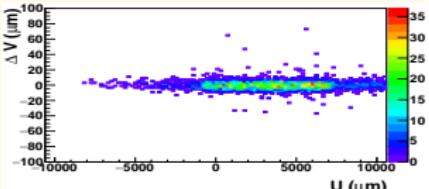
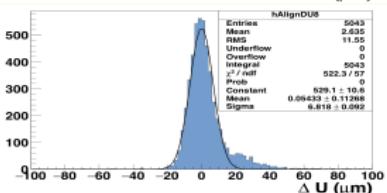
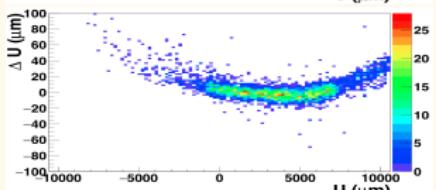
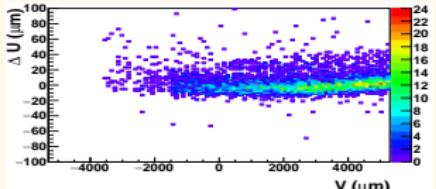


Spatial residual obtained after alignment:

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

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

Threshold  $6\sigma$ , air flow speed  $< 5\text{m/s}$ , 720k events and  $36^\circ$  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

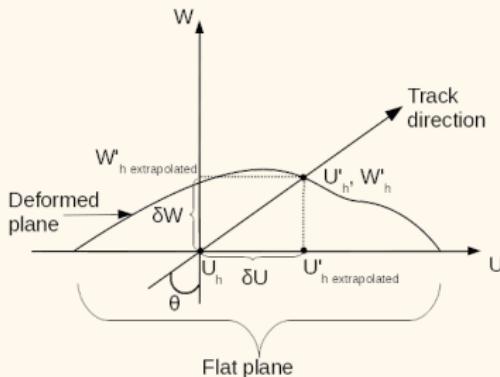
## Consequence of the ladder's characteristics

- 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

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

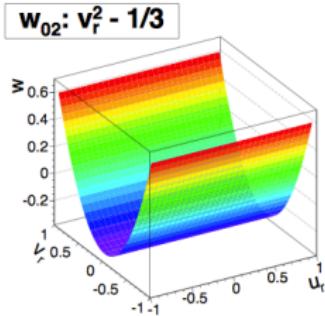
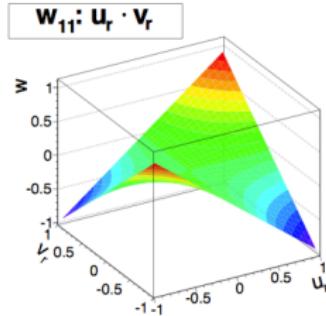
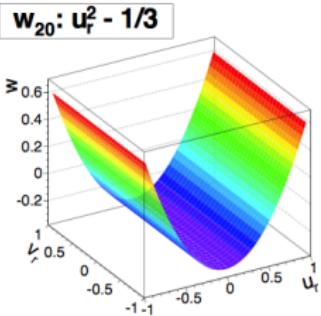
# How to describe deviations from the flat plane?

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

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

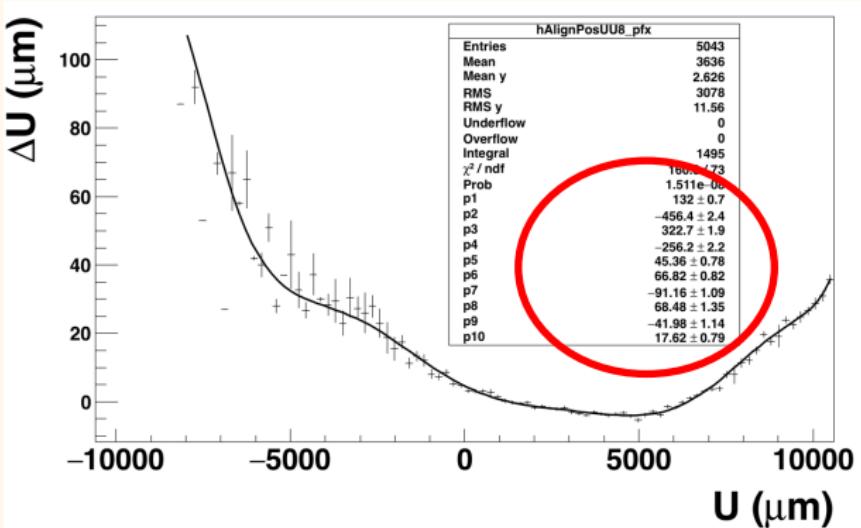
$$\begin{aligned} w(u_r, v_r) &= w \\ &+ w_{10} \cdot u_r + w_{01} \cdot v_r \\ &+ w_{20} \cdot (u_r^2 - 1/3) + w_{11} \cdot (u_r \cdot v_r) + w_{02} \cdot (v_r^2 - 1/3) \end{aligned}$$

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



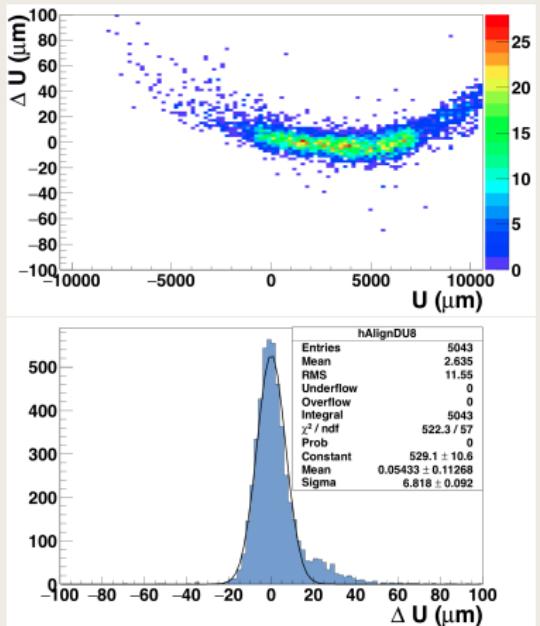
# Deformation's parametrisation

Possibility to parametrise the deformation with Legendre polynomials of the 11<sup>th</sup> order .



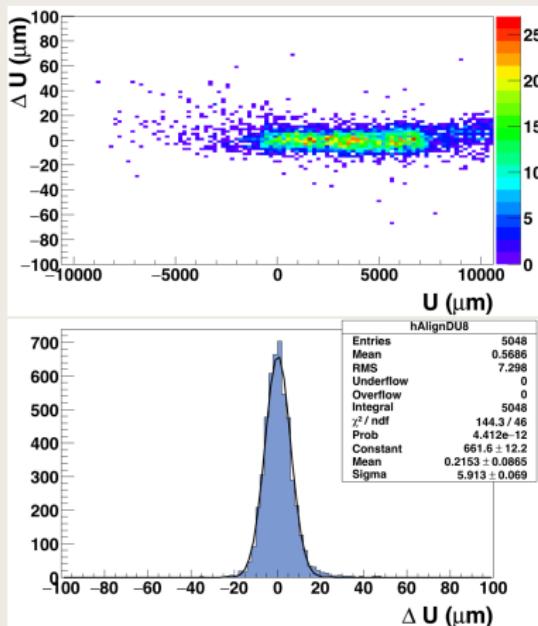
# Summary before/after correction

Before correction



$$\sigma_u = 6.8 \mu\text{m}$$

After correction



$$\sigma_u = 5.9 \mu\text{m}$$

# 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	$9.0 \pm 0.1$	$4.9 \pm 0.1$	46.6 %
Back	28	$5.7 \pm 0.1$	$4.7 \pm 0.1$	17.5 %
Front	36	$14.1 \pm 0.1$	$6.1 \pm 0.1$	56.0 %
Back	36	$6.8 \pm 0.1$	$5.9 \pm 0.1$	13.2 %
Front	60	$41.2 \pm 0.15$	$25.8 \pm 0.2$	37.4 %
Back	60	$23.3 \pm 0.13$	$21.7 \pm 0.1$	6.8 %

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

# Outlines

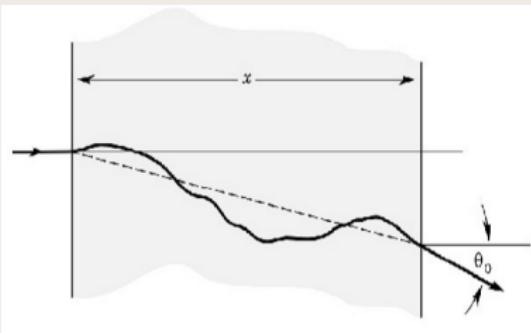
- 1 Introduction
- 2 Higgs boson study
- 3 Detector development
- 4 Mechanical deformation
- 5 Radiation length measurement
  - Motivation
  - Test beam @ DESY
  - Theoretical estimation
  - Results
- 6 Conclusion and outlook

# 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 radiation length:

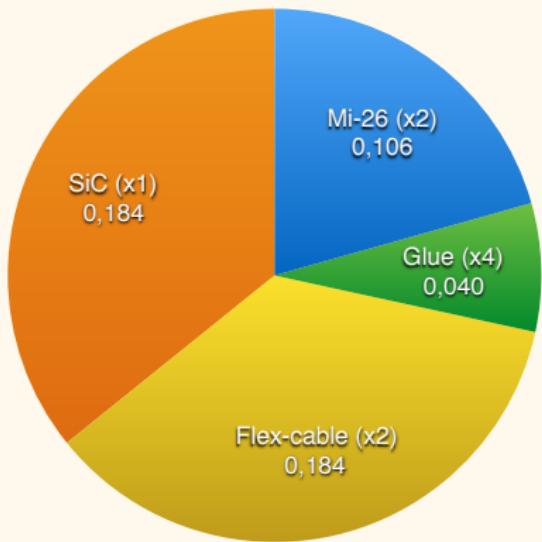
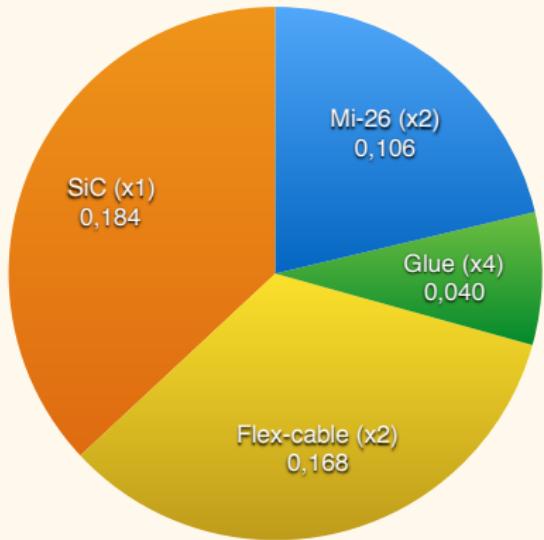
- Tracking system has to detect particle's path and minimise its energy degradation
- Physics analysis: reconstruction of events depends strongly on the energy loss inside the different part of detectors

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



- Test Beam 21
- Reference plane: 4 EUDET telescope planes
- Goal: radiation length measurement

# Estimation of the radiation length

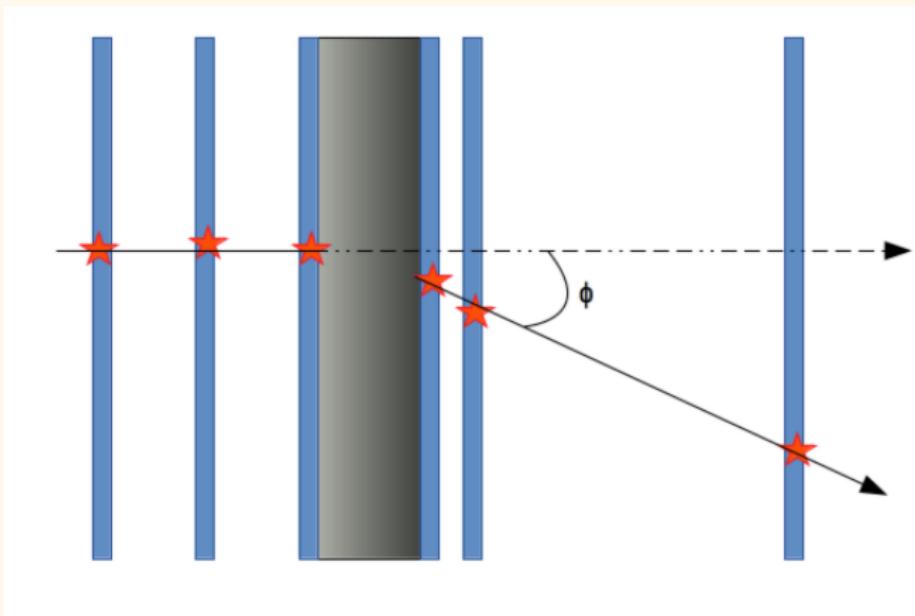


## Total material budget

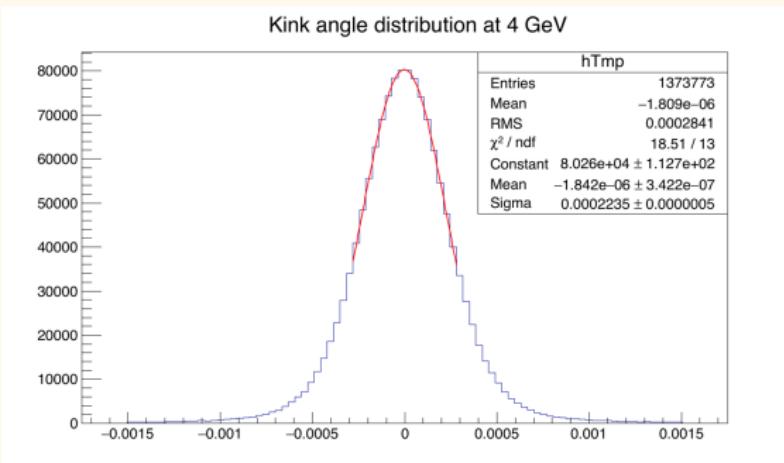
Depends on flex-cable fill factor (25 % or 30 %)

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

# Kink angle measurement



# Kink angle measurement at 4 GeV



## Determination of projected scattering angle $\theta_0$

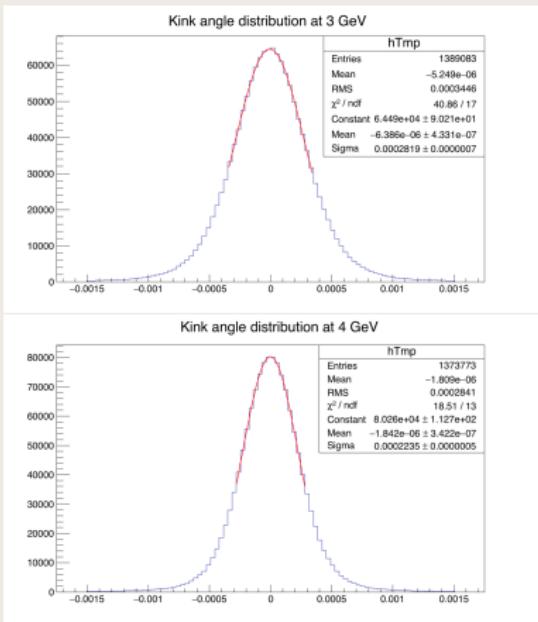
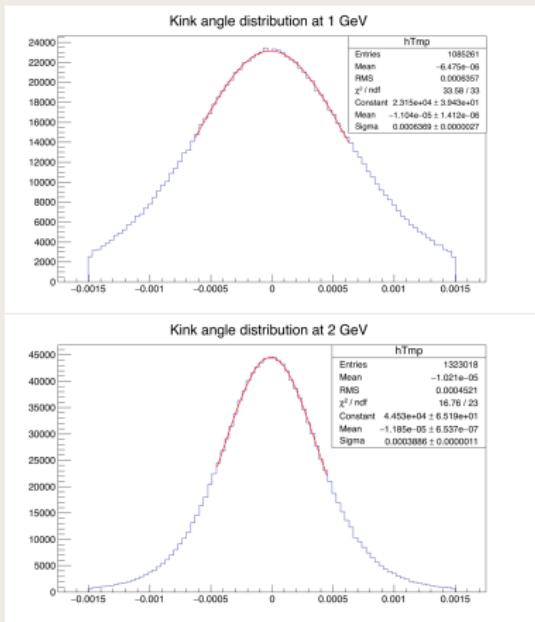
$$\theta_0 = \sqrt{k^2 - F}$$

- $k$  = width of the kink angle distribution fit
- $F$  = Offset parameter from the GBL track fitting algorithm

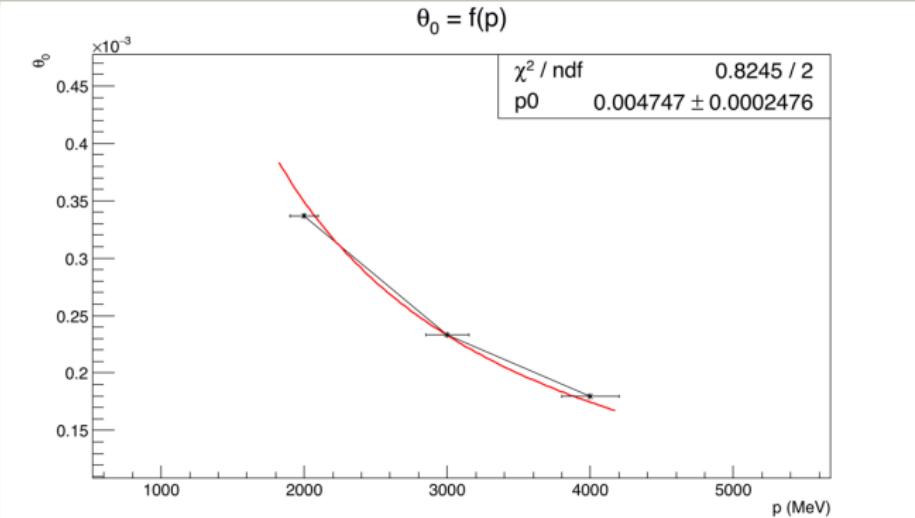


# Kink angle measurement between 1 and 4 GeV

## Fitted kink angle distributions



# Material budget



## Measurement

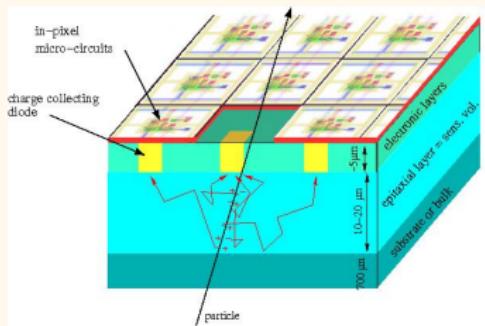
$$\text{Highland formula: } \theta_0 = \frac{13.6(\text{MeV})}{p} \left( \frac{x}{X_0} \right)^{0.555}$$

$$\frac{x}{X_0} |_{\text{estimated}} \simeq 0.498 - 0.515 \% X_0$$

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



# 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

# Conclusion

## Context:

- ILC: next collider to study precisely EWSB (and other physics scenarios)
- Performances to achieve imposes R&D detector development

## blabla

- Mechanical deformations observed are impacting ladder's performance
- Algorithm based on Legendre polynomials reduces impact of these deformations during the analysis
- Radiation length measurement:

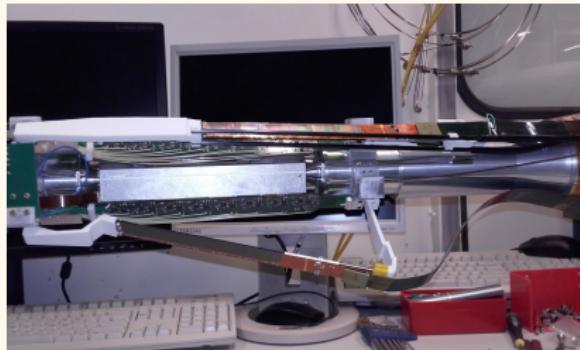
$$\frac{x}{x_0} \mid_{\text{estimated}} \simeq 0.498 - 0.515 \% X_0$$

$$\frac{x}{x_0} \mid_{\text{measured}} \simeq 0.47 \pm 0.02 \% X_0$$



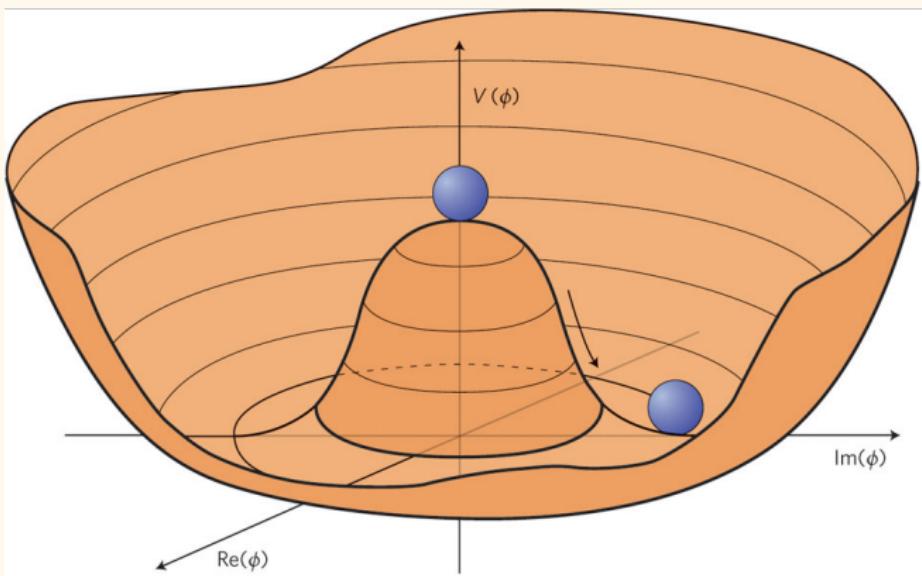
# Outlook

- Study ladder performance for low energy (test beam April 2016)
- New prototype with a material budget of 0.35 %  $X_0$  has been built, tested in laboratory but not yet in real conditions
- Double-sided ladders could be enriched with sensors having different characteristics (fast integration time VS good spatial resolution)
- Using the beam structure to apply a power-pulsing method
- Application of PLUME in SuperKEKB for the BEAST project



# Thanks for your attention !!!

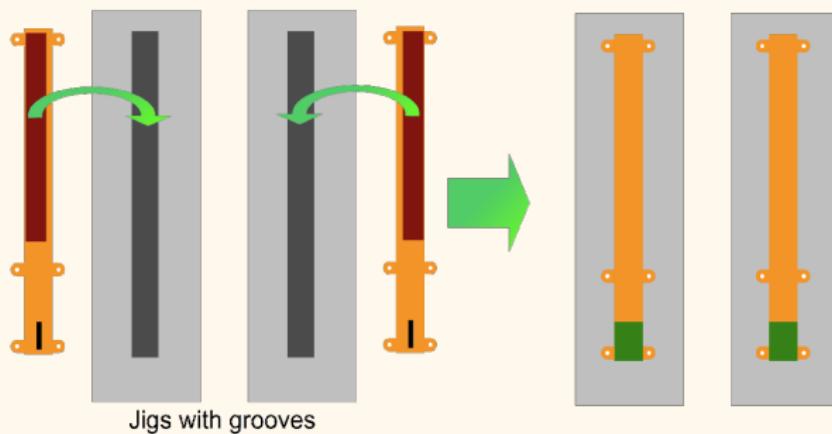
# Higgs boson potential



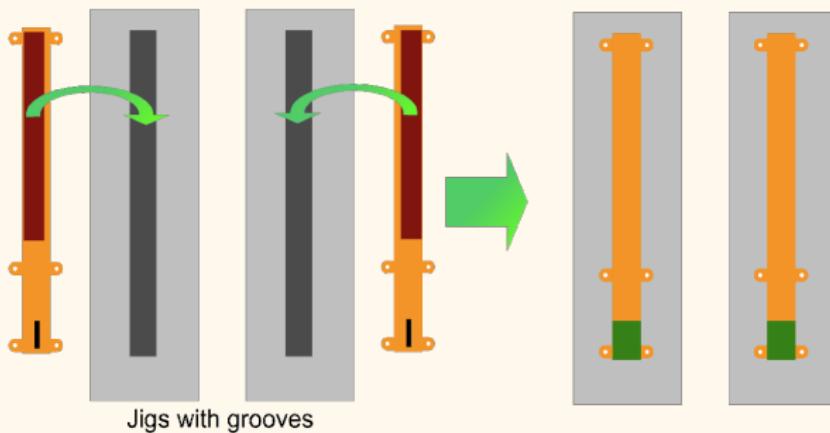
# Higgs boson physics at the ILC

- 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

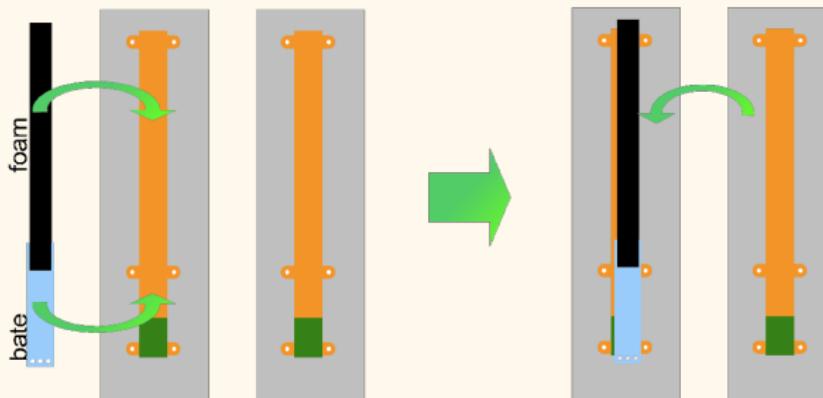
# Ladder assembly



# Ladder assembly

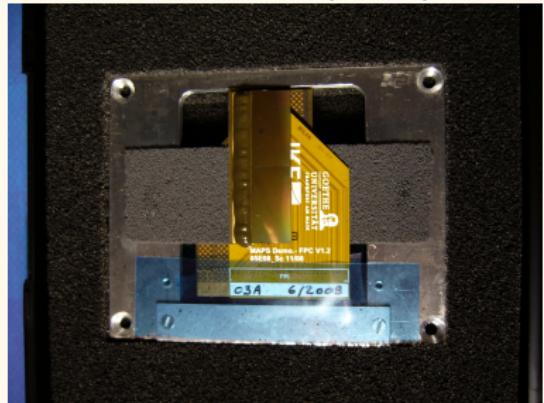


Jigs with grooves



# PLUME history

PLUME-V0 (2009)



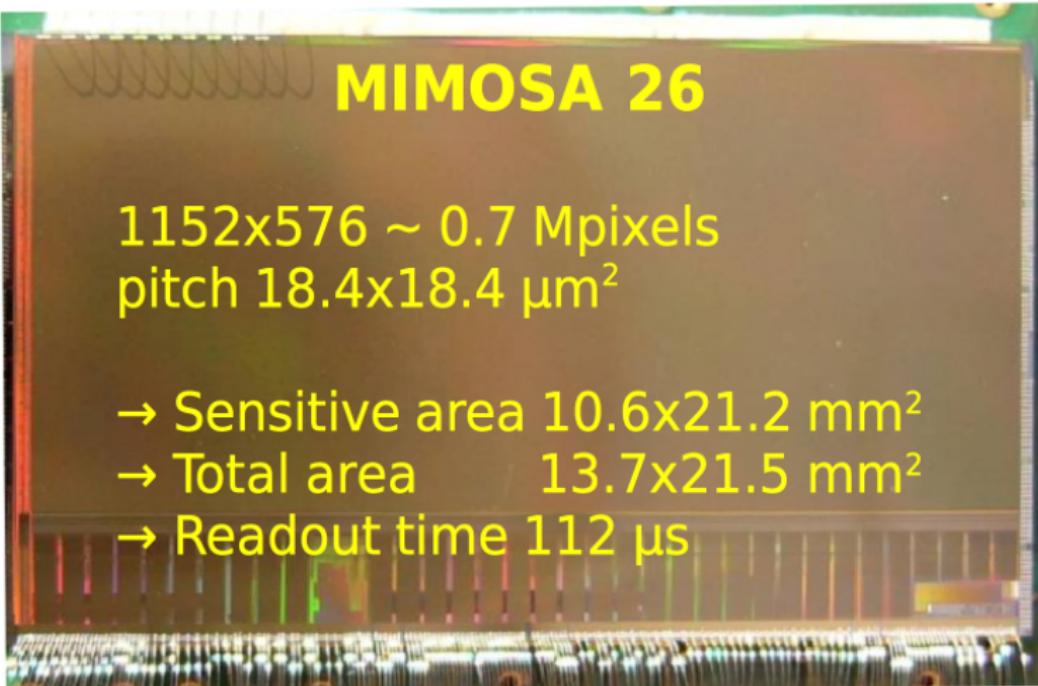
PLUME-V1 (2010)



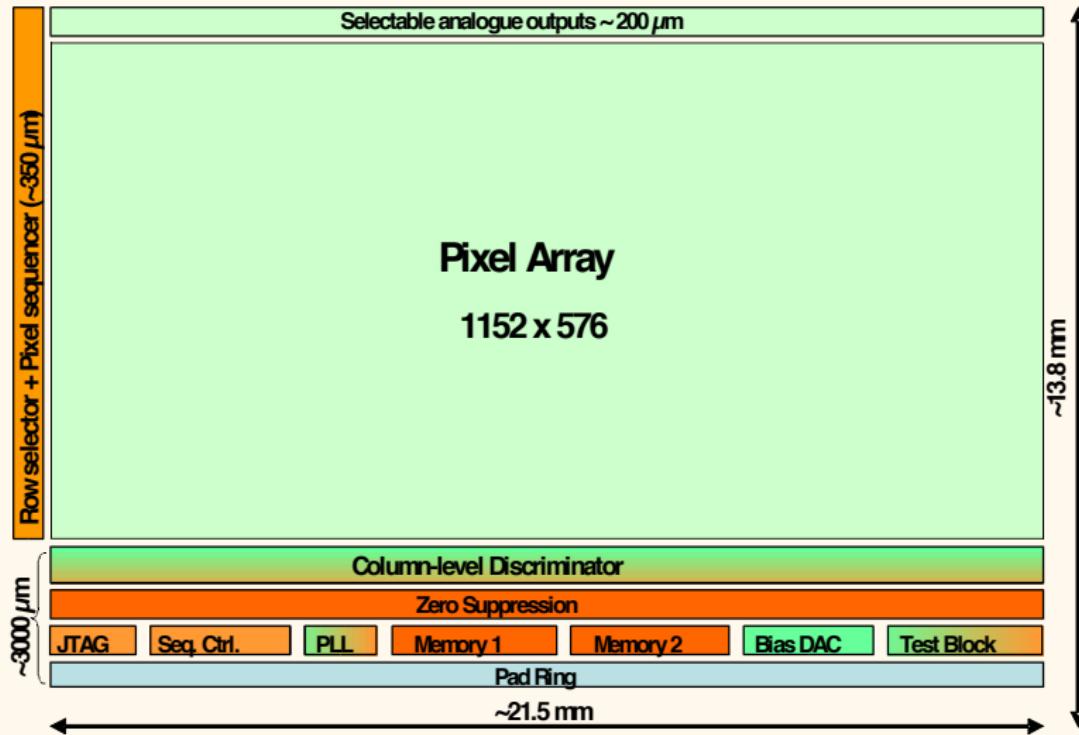
## MIMOSA 26

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

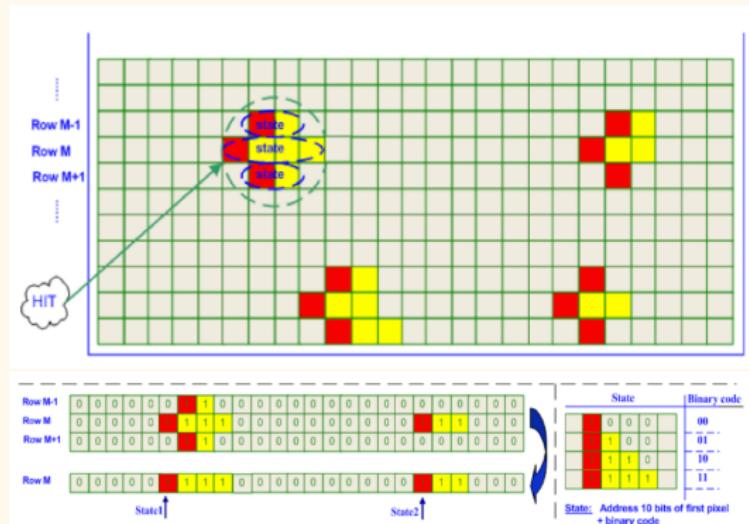
- Sensitive area  $10.6 \times 21.2 \text{ mm}^2$
- Total area  $13.7 \times 21.5 \text{ mm}^2$
- Readout time  $112 \mu\text{s}$



# MIMOSA-26 architecture



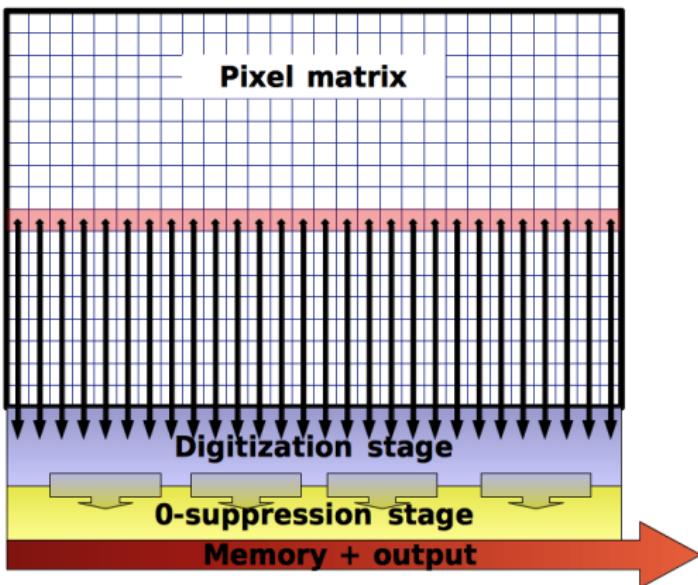
# Zero Suppression logic (SUZE)



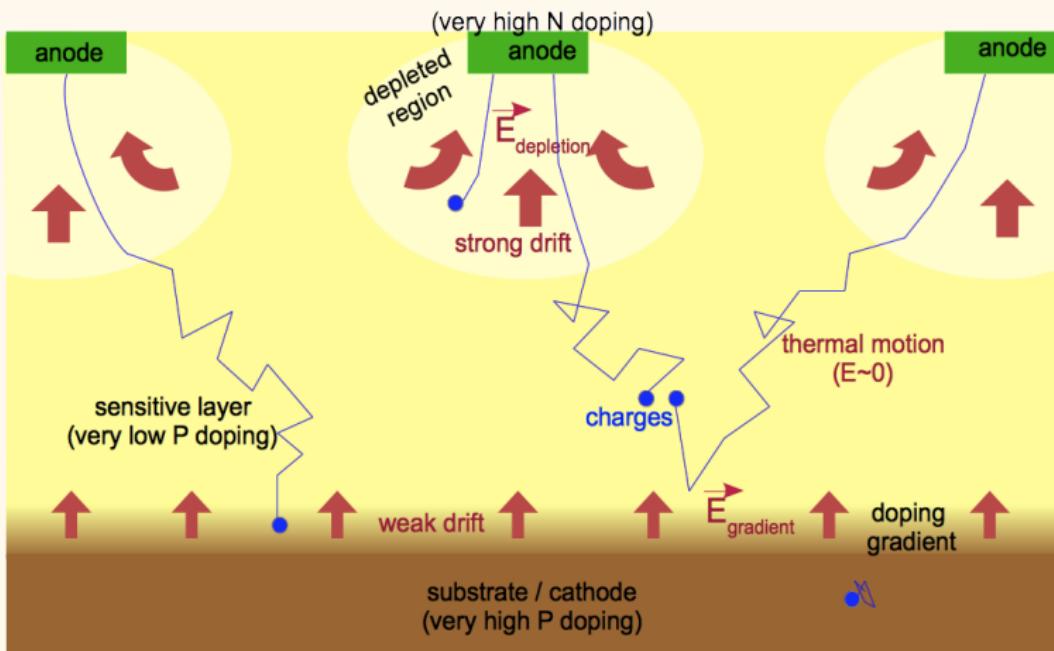
SUZE logic split in 3 blocks:

- **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

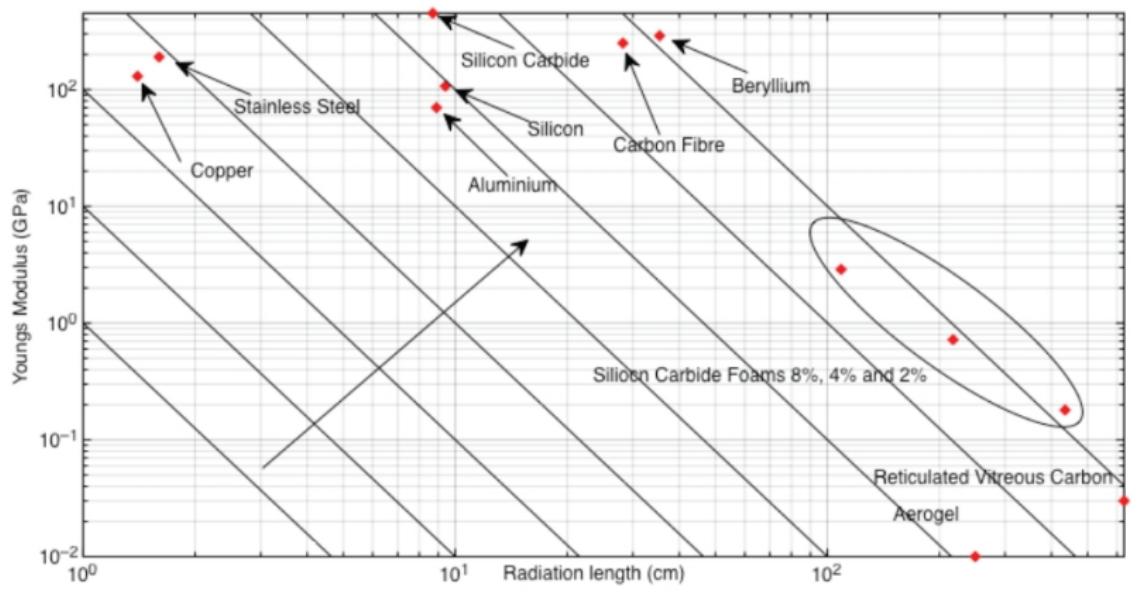


# MAPS principle

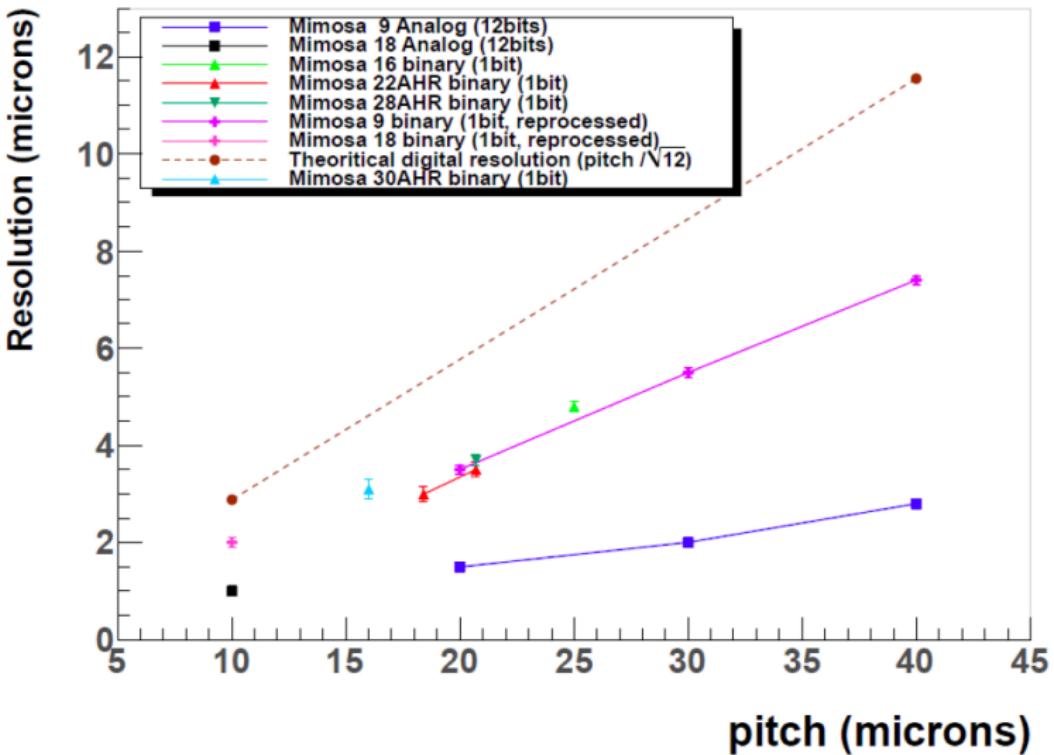


## Young Modulus

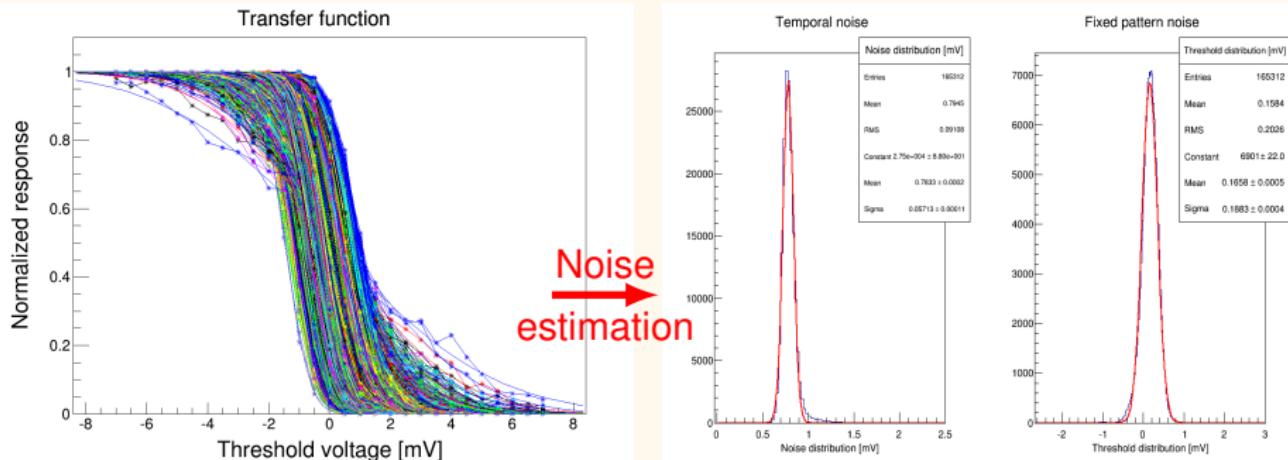
## Material Selection Graphs



# 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

# 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?

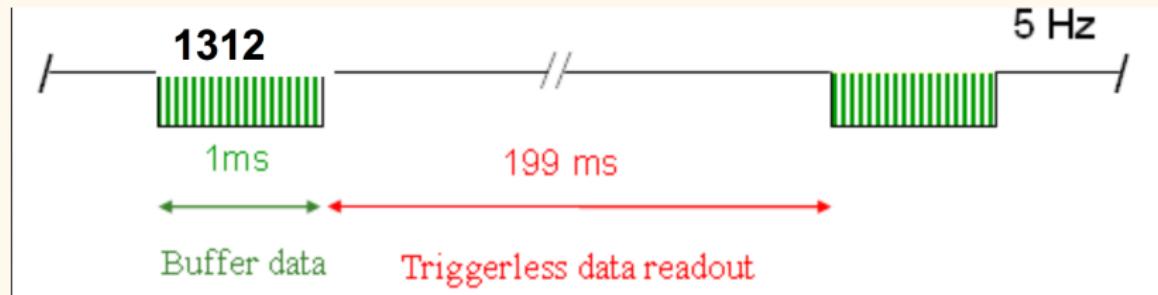
## Limitations of $e^+e^-$ colliders

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

## Advantages of linear colliders

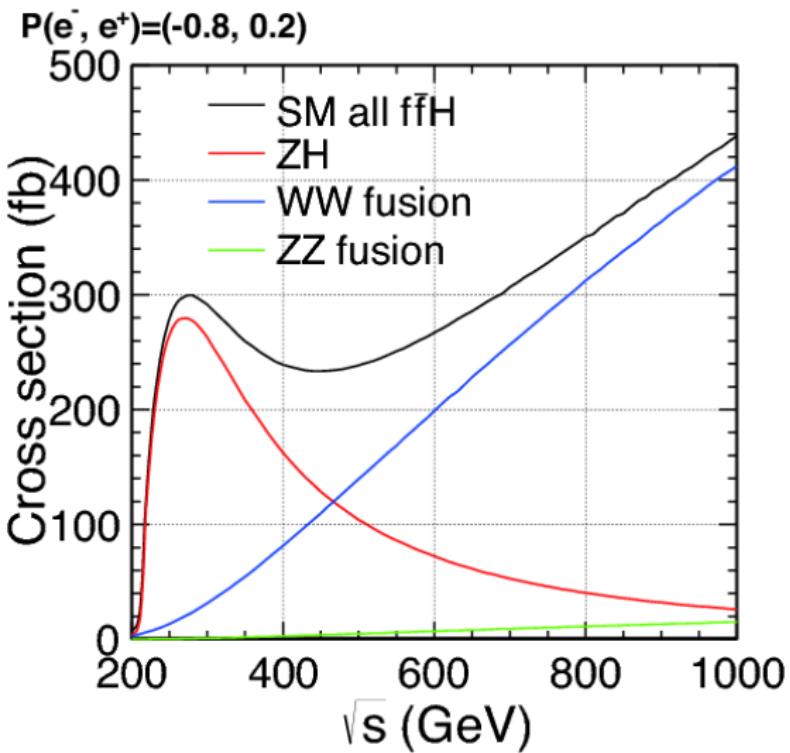
- Not limited by synchrotron radiation
- Cost:  $\sim$  linear with energy
- Polarisation of both beams
- Detectors close to the IP  $\Rightarrow$  optimum for c-tagging

- 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

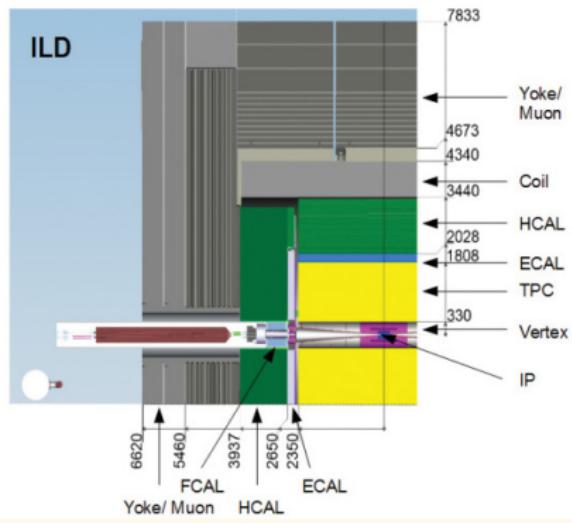
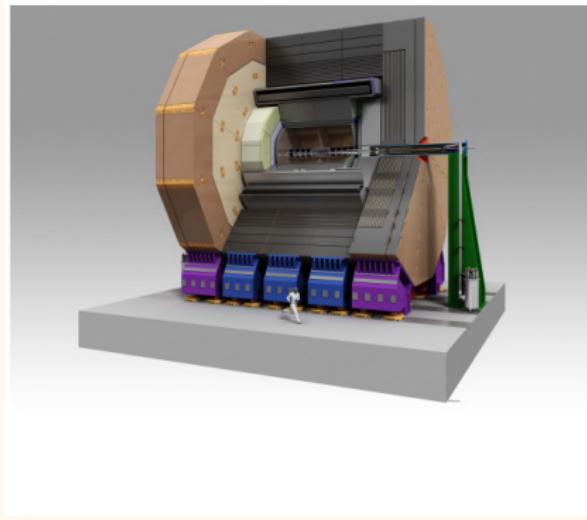


- Bunch spacing of  $\sim 554$  ns
- 1312 bunches in a 1 ms long pulse (train)
- Quiet time: 199 ms
- Occupancy dominated by beam background and noise
- Reading during quiet time possible

# 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 ( $P_t^{\text{vis}}$ ):  $35 < P_t^{\text{vis}} < 155 \text{ GeV}$

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

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:  $E_{\text{miss}}$

# Beam polarisation

Simulated data: 100 % left or right events

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

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