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

Ph. D. defense

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Strasbourg

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Outlines

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
  $\Rightarrow$ 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

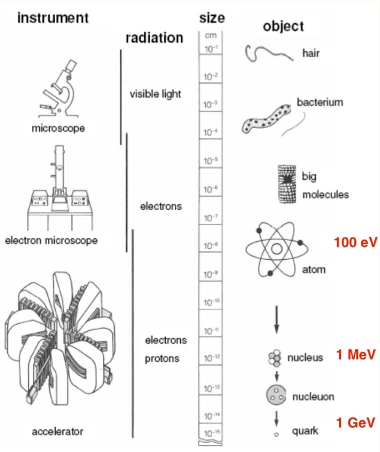
$\Rightarrow$ Complete spectrum of the Standard Model that could be correct up to very high energies

Open questions

Limitations

- Why the electroweak symmetry is broken?
- Is there only one Higgs boson as defined in the SM?
- Why are they 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?



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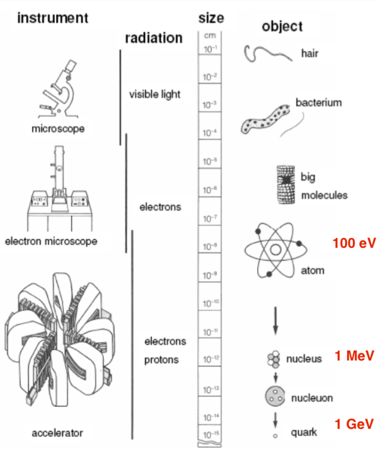
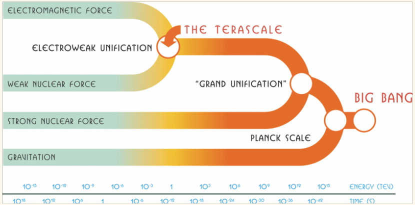
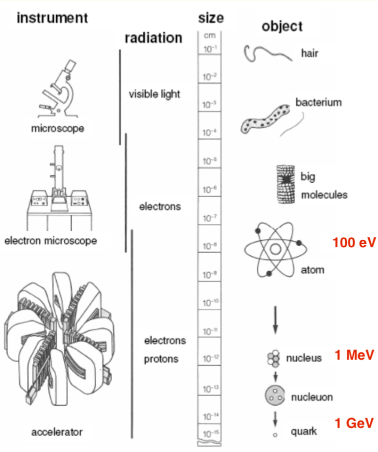
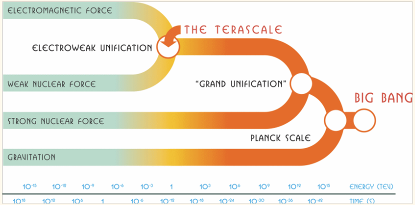




Electroweak symmetry breaking and physics beyond the Standard Model: from 100 GeV to TeV scale

How to study particle physics?

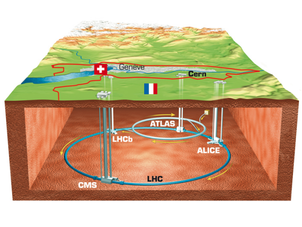




Electroweak symmetry breaking and physics beyond the Standard Model: from 100 GeV to TeV scale

What tools do we have to reach this energy scale?

Large Hadron Collider (LHC)



LHC: a discovery machine

- Centre-of-mass energy $\sqrt{s} = 14$ 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

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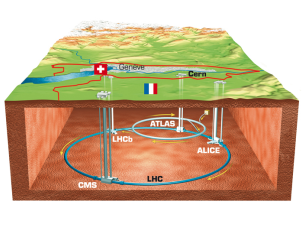

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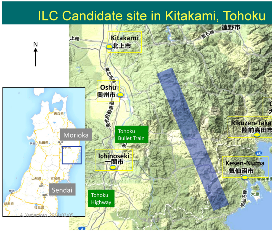
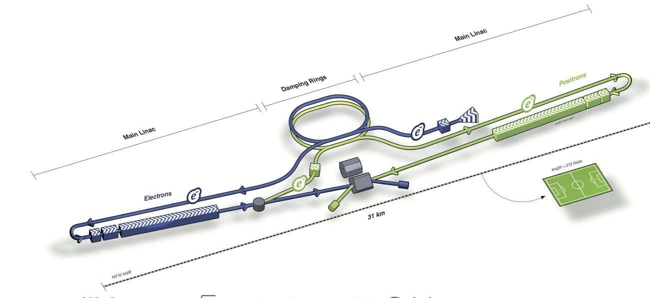
$\Rightarrow$ **Need a complementary experimental program**

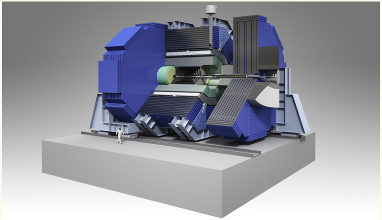
International Linear Collider (ILC)

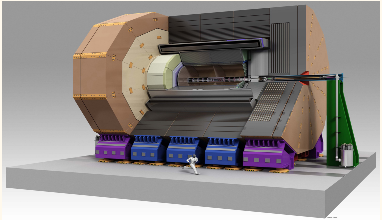




- Future e^+e^- linear collider at $\sqrt{s} = 250 - 500$ GeV (upgrade up to $\sqrt{s} = 1$ TeV)
- Polarised beam
- Luminosity $\simeq 2 \times 10^{34}$ cm^{-2}s^{-1}
- Candidate site: Kitakami in nothern Japan
- To study properties of the Higgs boson, top physics and discovery potential new physics

SiD and ILD





Silicon Detector (SiD)

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

International Large Detector (ILD)

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

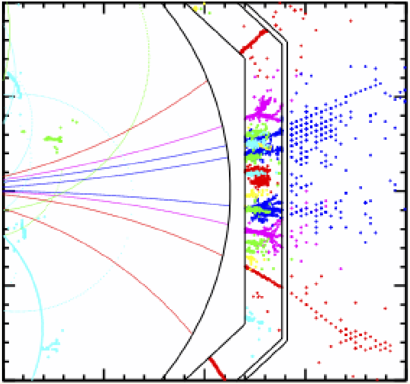
Both detectors designed for Particle Flow Calorimetry

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

Particle Flow Algorithm

Tracking system

Calorimeters

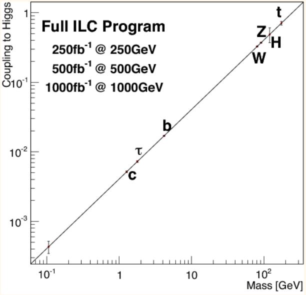


Outlines

Higgs boson study

Measurements @ LHC

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

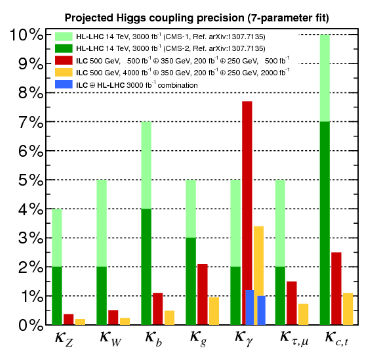


Recall the footprint of SM-Higgs

- Couplings of Higgs boson to c-quarks and gluons
- Higgs self-coupling

$\Rightarrow$ Is the boson discover 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
- $\mathrm{H} \to \mathrm{b\bar{b}}$ observed in special kinematics
- $\mathrm{H} \to \mathrm{c\bar{c}}$ and $\mathrm{H} \to gg$ are challenging to observe

At the ILC

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

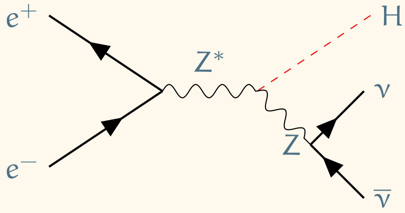
Analysis of simulated data at the ILC @ 350 GeV with different polarisations:

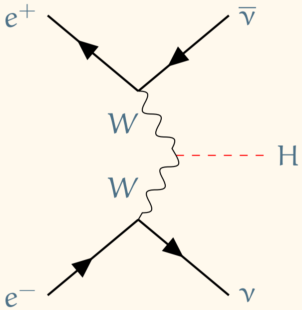
- $e^+_L e^-_R$
- $e^+_R e^-_L$

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

1. Reject events with isolated leptons
2. Remove $\gamma\gamma$ overlay interactions
3. Look for jets
4. Find displaced vertices of these jets
5. Tag 2 jets coming from the Higgs boson decay

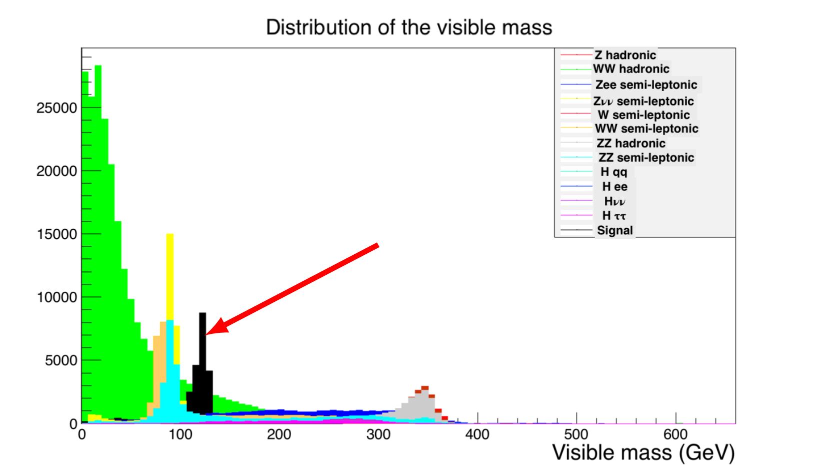
Background processes

Events which give same detector response or same final state

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

Distribution of the visible invariant mass with background

$\sqrt{s} = 350$ GeV, luminosity: 250 fb^{-1} and polarisation: e^-_L, e^+_R



Background: $1.88 \cdot 10^7$ events; signal: $2.25 \cdot 10^4$ events

Reducing the background

Find optimised cuts

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

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

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

Sequential cuts strategy

cut0 Number of isolated lepton (niso): niso = 0

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

cut2 Visible mass (m_{vis}): $95 < m_{vis} < 140$ 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
$35 < P_t^{vis} < 155$ GeV	$9.31 \cdot 10^5$	$1.82 \cdot 10^4$	18.7
$95 < m_{vis} < 140$ GeV	$1.50 \cdot 10^5$	$1.66 \cdot 10^4$	40.6
$-1 < \cos , < 0.22$	$8.76 \cdot 10^4$	$1.57 \cdot 10^4$	48.8
$26 < (N.R.C > 1GeV) < 99$	$2.25 \cdot 10^4$	$1.19 \cdot 10^4$	56.3
$0.11 < DurhamjD2ym < 1$	$1.78 \cdot 10^4$	$1.05 \cdot 10^4$	62.3
$0 < abs(P_z^{vis}) < 113$ GeV	$1.51 \cdot 10^4$	$1.01 \cdot 10^4$	63.5
$156 < E_{miss} < 230$ GeV	$1.37 \cdot 10^4$	$9.85 \cdot 10^3$	64.1

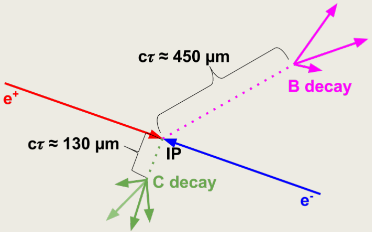
Outlook

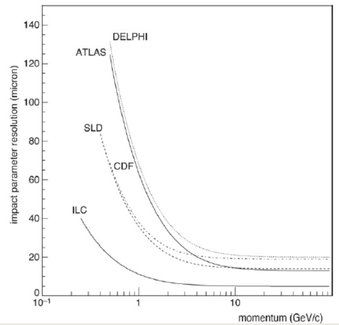
- Relative uncertainty on branching ratio is impacted by significance of the measured signal
- Higher significance is needed to study Higgs decay (TMVA solution)
- Focus on Higgs boson decay mode, especially $H \to c\bar{c}$
  $\Rightarrow$ determine vertex detector geometry for c-tagging

Outlines

The ILD Vertex Detector

Vertex detector





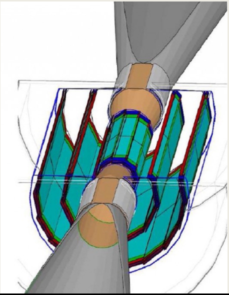
ILD vertex detector

Impact parameter resolution

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

- Hit resolution: $a \simeq 5\ \mu m \Rightarrow\ \sigma_{spatial} < 3\ \mu m$
- Multiple scattering: $b \simeq 9 - 15\ \mu m \Rightarrow$ material budget per measurement point $\simeq 0.15\ \%\ X_0$

Double-sided layer concept



- 1 mechanical structure for 2 measurement points
- Pattern recognition and alignment
- Possibility to use 2 different technologies
- Air cooling system

Double-sided VXD: PLUME

PLUME = **P**ixelated **L**adder with **U**ltra-low **M**aterial **E**mbedding

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG — DESY — University of BRISTOL

Motivation

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

Goals

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

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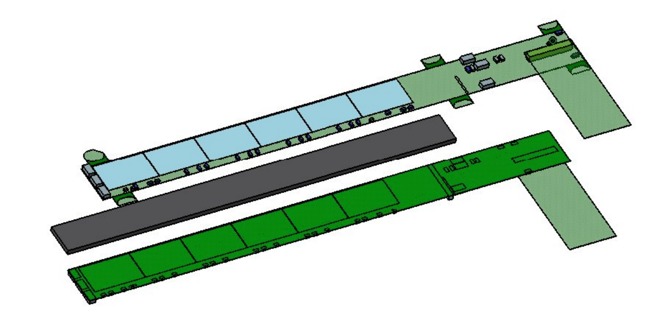
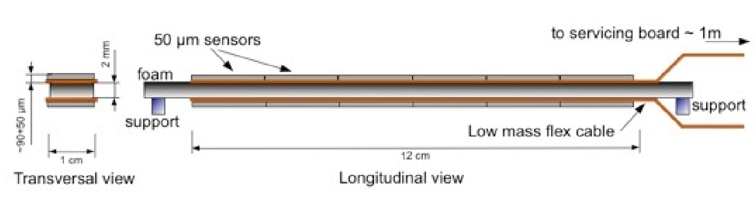
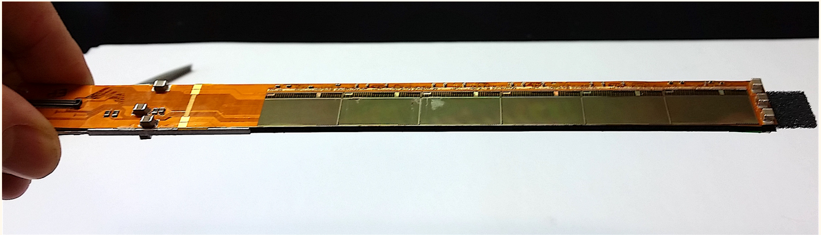
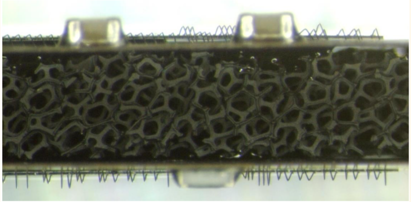
What does it look like?





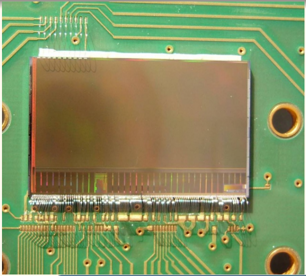
PLUME in real

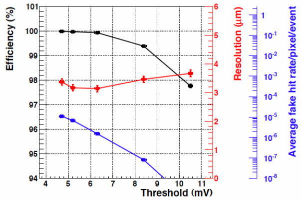


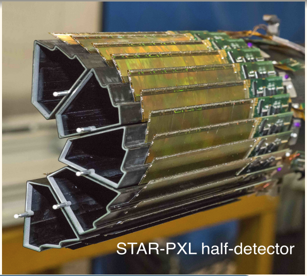


- 50 µm CMOS pixel sensor
- 100 µm flex-cable
- 2 mm SiC foam (4 - 8 %)
- Air-flow cooling system

MIMOSA-26 sensor







Monolithic Active Pixels Sensor (MAPS)

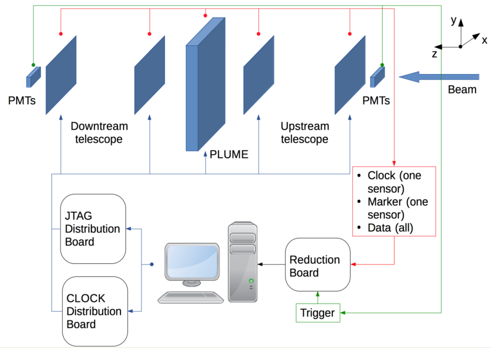
- Well known sensors $\Rightarrow$ used for EUDET telescope
- Extended to MIMOSA-28 exploited in STAR-PXL vertex detector @ RHIC-BNL since 2014
- Thickness: 50 μm
- Pitch: 18.4 μm (square pixels)
- Active area: 10.6×21.2mm^2 (576 rows x 1152 columns)
- Integration time: 115.2 $\mu(s)$ (200 ns per line)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

Test beam

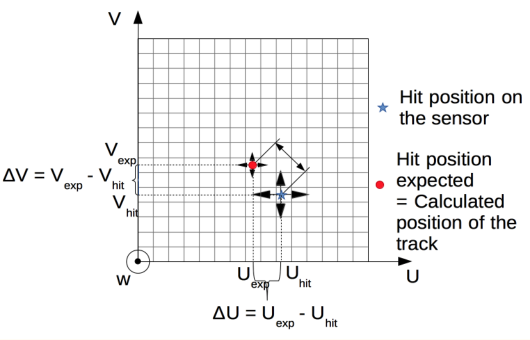
Motivation

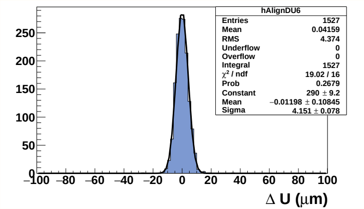
Test detector under real conditions to determine its performance

Set-up



Track-hit residual



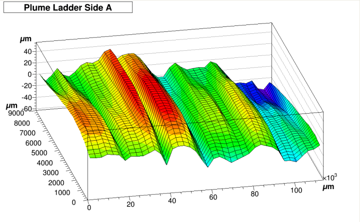


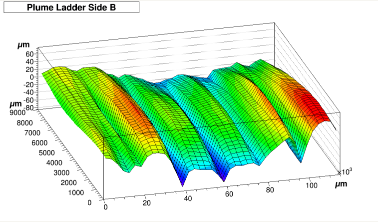
Outlines

Metrology of module's surface

Are our ladders completely flat?

Peak-to-peak flatness $\sim$ 100 μm



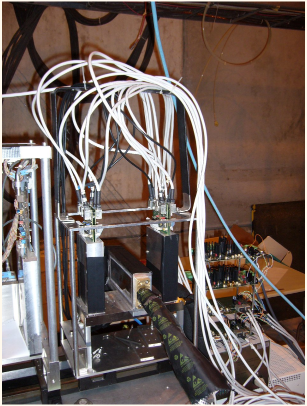


Test performed at Bristol with a dummy ladder

Question

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

Test of PLUME-1



Test beam 2011

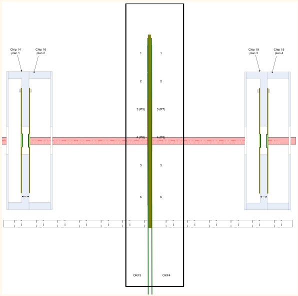
- CERN-SPS with 120 GeV π^-
- Reference plane: 4 MIMOSA-26
- DUT: PLUME-1 first fully functional double-sided ladder equipped with 12 MIMOSA-26 sensors (0.65 % X_0)
- Ladder performance studies with different configurations

Impact of deformations

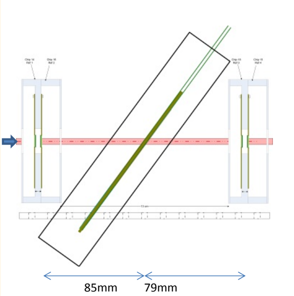
- Already observed and studied by 2 Ph. D. students
- Method to correct manually and locally these deviations

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

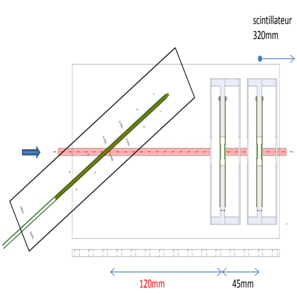
Geometrical configurations studied



Module in normal incidence to the beam



Module tilted (between 28°and 40°)

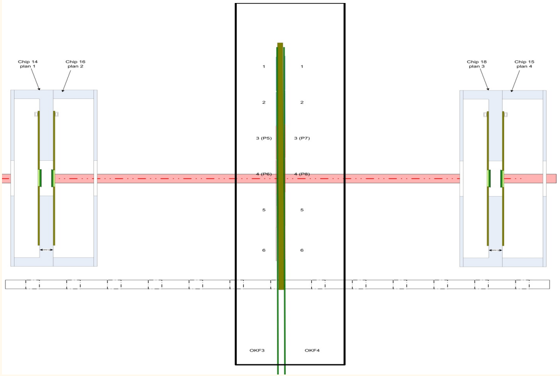


Module tilted ($\simeq 60°$)

$\Rightarrow$ Study track-hit residual and the distribution of this residual as a function of the relative position of the beam on the sensor

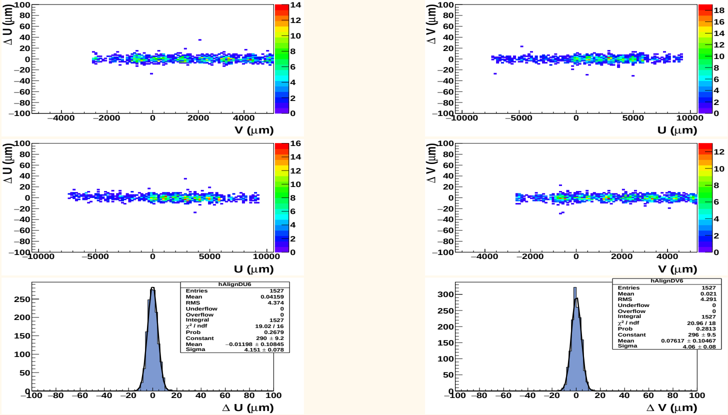
Analysis performed with TAF (TAPI Analysis Framework)

Module in normal incidence to the beam



Module in normal incidence to the beam

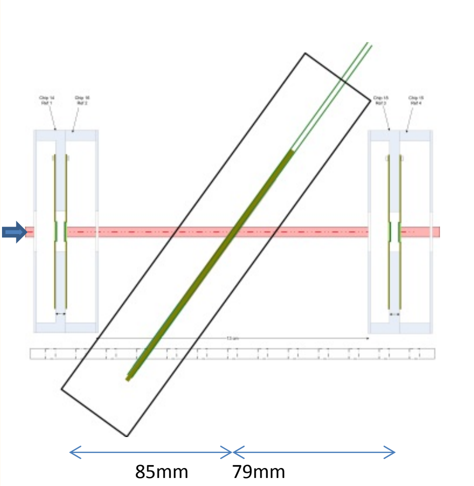
Threshold 6 σ, air flow speed < 5m/s and 1.8M events.



Spatial residual obtained after alignment:

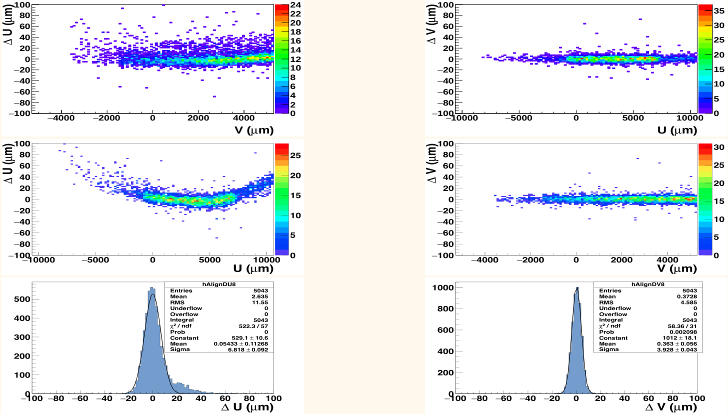
$\sigma_U \simeq 4.2$ μm and $\sigma_V \simeq 4.1$ μm

Module tilted in one direction (36°)



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

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



Spatial residual obtained after alignment:

$\sigma_U \simeq 6.8\ \mu m$ and $\sigma_V \simeq 4.0\ \mu m$

Origin of deviations

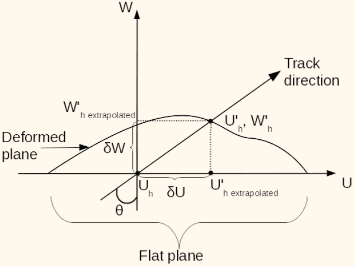
Consequence of the ladder's characteristics

- Use of ultra-thin (50 μm) and precise sensors (spatial resolution less than 4 μm)
- Mechanical constraints induce permanent deformations ($\simeq$ 100 μm) 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

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

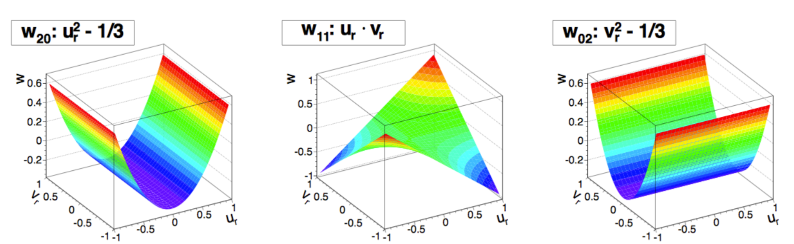
How to describe deviations from the flat plane?

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

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

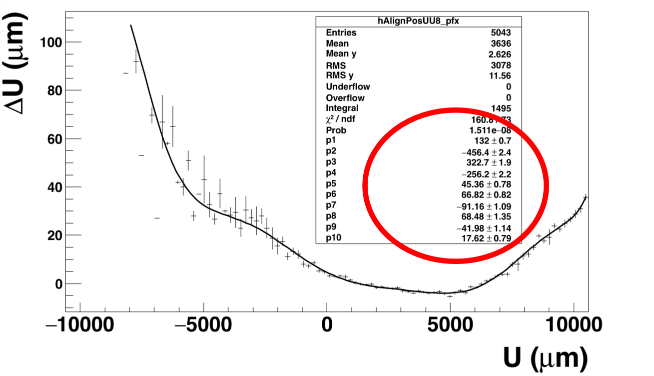
$$\begin{aligned} w(u_r, v_r) &= w \\ &+ w_{10} \cdot u_r + w_{01} \cdot v_r \\ &+ w_{20} \cdot (u_r^2 - 1/3) + w_{11} \cdot (u_r \cdot v_r) + w_{02} \cdot (v_r^2 - 1/3) \end{aligned}$$

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



Deformation's parametrisation for 36°

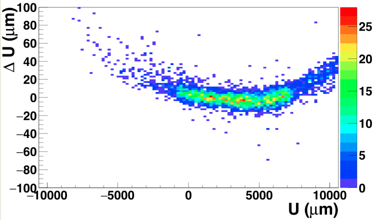
Possibility to parametrise the deformation with Legendre polynomials of the 11^{th} order .

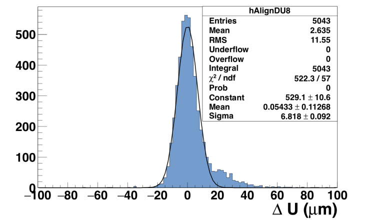


$$\delta W = \frac{\delta U}{\tan\theta}$$

Summary before/after correction at 36°

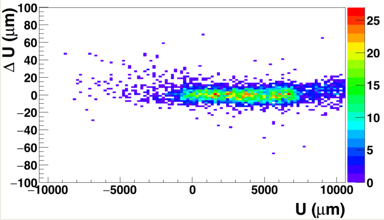
Before correction

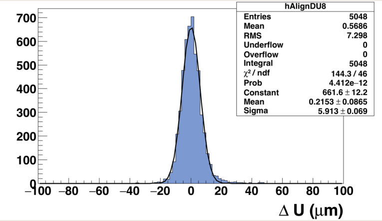




$\sigma_u = 6.8\ \mu m$

After correction





$\sigma_u = 5.9\ \mu m$

Summary of correction for different angles and same planes

Spatial residuals

Side	Tilted angle (°)	σ_U^{Def} (μm)	σ_U^{Cor} (μm)	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 %

$\sigma_{tel} = 2.2$ μm for 36°and $\sigma_{tel} = 18.8$ μm for 60°.

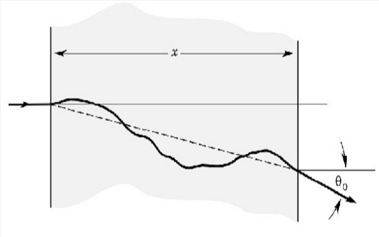
Outlines

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

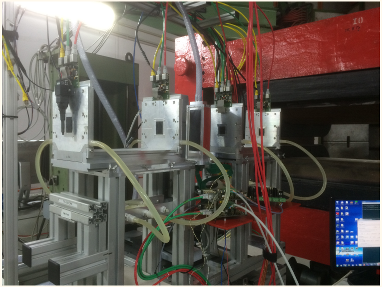
$$\sigma_{\theta_0} = \frac{13.6(MeV)}{p}\left(\frac{x}{X_0}\right)^{0.555}$$



Motivation of measuring the material budget

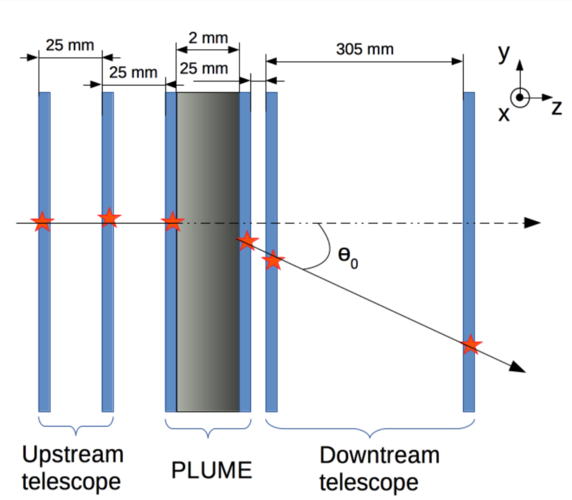
- Key parameter for tracking algorithm: has to take into account multiple scattering and energy degradation
- Compare material budget prediction to its result after construction
- Goal: surface mapping of $\frac{x}{X_0}$

Test beam @ DESY with low energy e^- (April 2016)

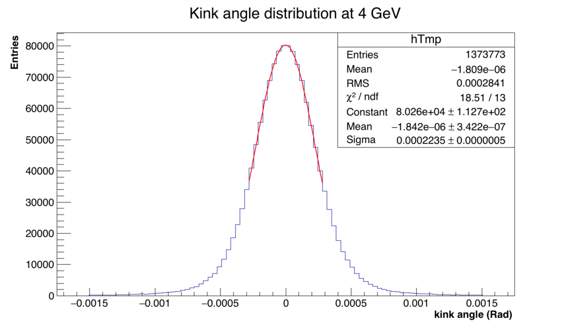


- Test Beam 21
- Reference plane: 4 EUDET telescope planes
- DUT: PLUME-1 with a weighted material budget of 0.65 % X_0
- Energy: [1;5] GeV $\Rightarrow$ well suited for material budget measurement
- Goal: material budget measurement

Kink angle measurement



Kink angle measurement at 4 GeV

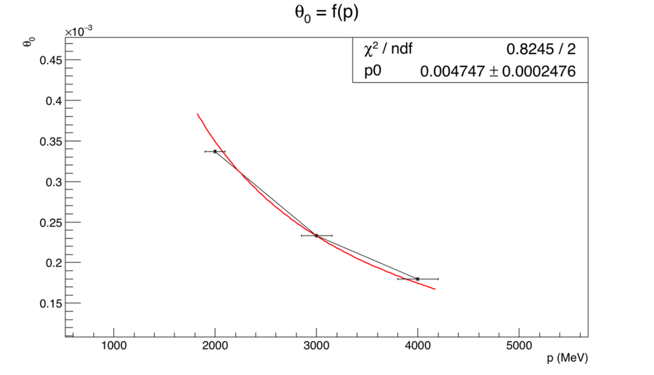


Determination of projected scattering angle θ_0

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

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

Material budget

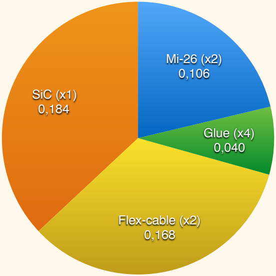


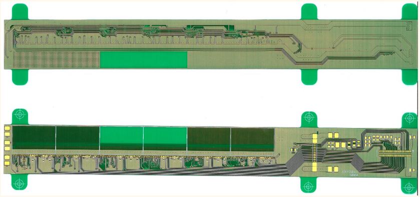
Measurement

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

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

Estimation of the radiation length

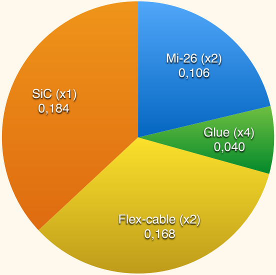


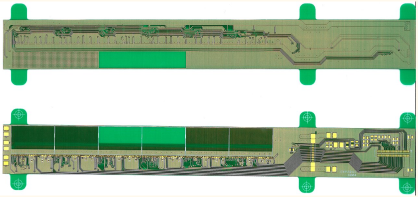


Total material budget

Depends on flex-cable metallic fill factor w.r.t. kapton (25 % or 30 %) $\Rightarrow \frac{x}{X_0} \simeq 0.498 - 0.515\ \%\ X_0$

Estimation of the radiation length



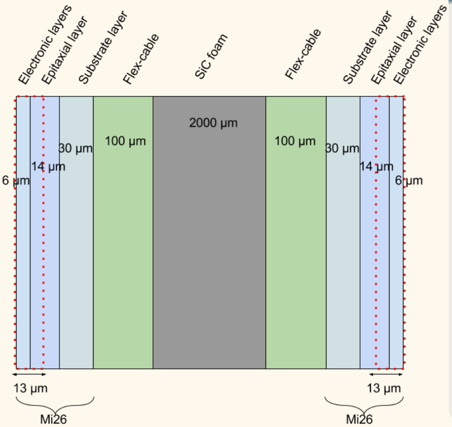


Total material budget

Depends on flex-cable metallic fill factor w.r.t. kapton (25 % or 30 %) $\Rightarrow \frac{x}{X_0} \simeq 0.498 - 0.515\ \%\ X_0$

$$\left.\frac{x}{X_0}\right|_{measured} \simeq 0.47 \pm 0.02\ \%\ X_0$$

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

Conclusion 1/2

Context

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

Higgs boson study

Studying the $H\nu\nu$ final state is possible at the ILC, but to measure more precisely the Higgs boson branching ratio, a simple sequential hard cuts is not adapted

Conclusion 2/2

PLUME development

PLUME is the first double-sided layers developed $\sim$ matching 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
  - Confirmed by measurement for PLUME-1:

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

Outlook 1/2

Test beam 2016

- Surface mapping of $\frac{x}{X_0}$
- 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

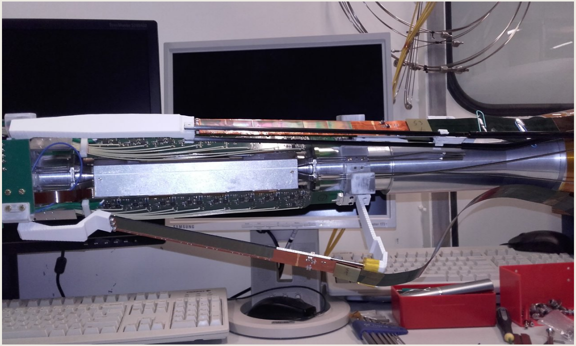
Next PLUME ladder

- Material budget can still be improved: $\lesssim 0.3\ \%\ X_0$
- 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 (power-pulsing)

Outlook 2/2

BEAST project

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



Thanks for your attention !!!

Standard Model Lagrangian

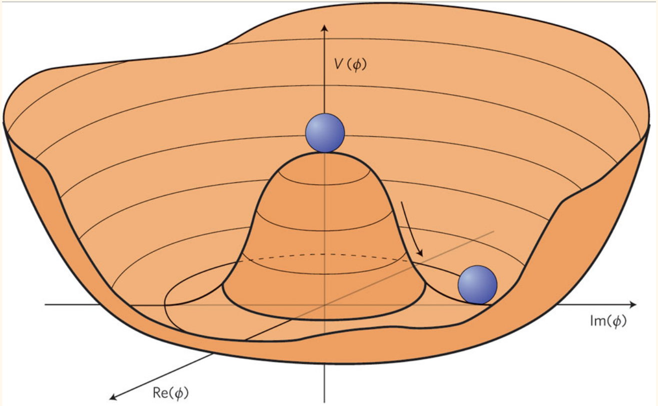
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\Psi} \not{D} \psi + h.c.$$

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

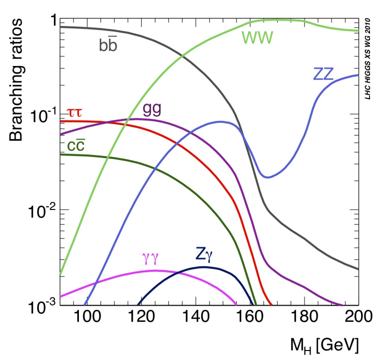
Higgs boson potential



Higgs boson physics at the ILC

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

Higgs branching ratio



Higgs branching ratio

$$\mathrm{BR}(h \to A\bar{A}) = \Gamma(h \to A\bar{A})/\Gamma_h$$

- Γ_h: total rate of Higgs decay or the total width of the Higgs boson as a resonance

Higgs-strahlung kinematics

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

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

$$|\overrightarrow{p_H}| = |\overrightarrow{p_Z}| = \frac{\sqrt{[s - (M_H + M_Z)^2] \cdot [s - (M_H - M_Z)^2]}}{2\sqrt{s}}$$

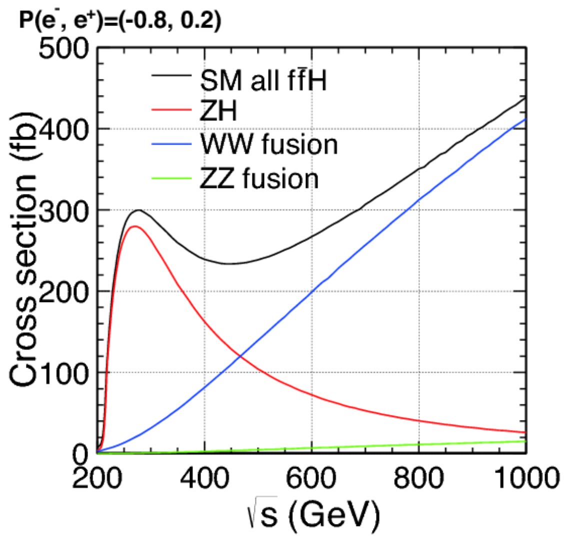
If $M_H = 125$ GeV, $M_Z = 91.2$ GeV and $\sqrt{s} = 350$ GeV, then:

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

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

$$|\overrightarrow{p_H}| = |\overrightarrow{p_Z}| \simeq 68.5 \text{ GeV}$$

Higgs production cross-section



Sequential cuts strategy

cut0: Number of isolated lepton (niso): niso = 0

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

cut2: Visible mass (mvis): $95 < m_{vis} < 140$ 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 longitudial momentum ($\mathrm{abs}(P_z^{vis})$)

cut7: E_{miss}

ZH production

Z boson will decay yo:

- Charged leptons $\simeq 10\%$
- Neutrinos $\simeq 20\%$
- Hadrons $\simeq 70\%$

Hadronic decay channel has large statistics but model dependency and large background

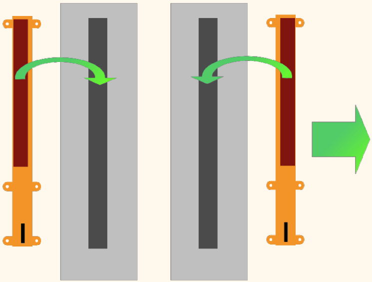
Beam polarisation

Simulated data: 100 % left or right events

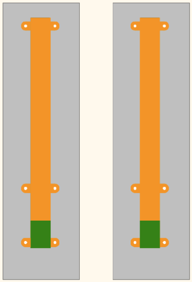
$$\sigma_{P_{(e+,e-)}} = \left(\frac{1-P_{e-}}{2}\right)\left(\frac{1+P_{e+}}{2}\right)\sigma_{RL} + \left(\frac{1+P_{e+}}{2}\right)\left(\frac{1-P_{e-}}{2}\right)\sigma_{LR}$$

$$\sigma_{P_{(e+,e-=\mathbf{0.3},-\mathbf{0.8})}} = 0.585 \cdot \sigma RL + 0.035 \cdot \sigma_{LR}$$

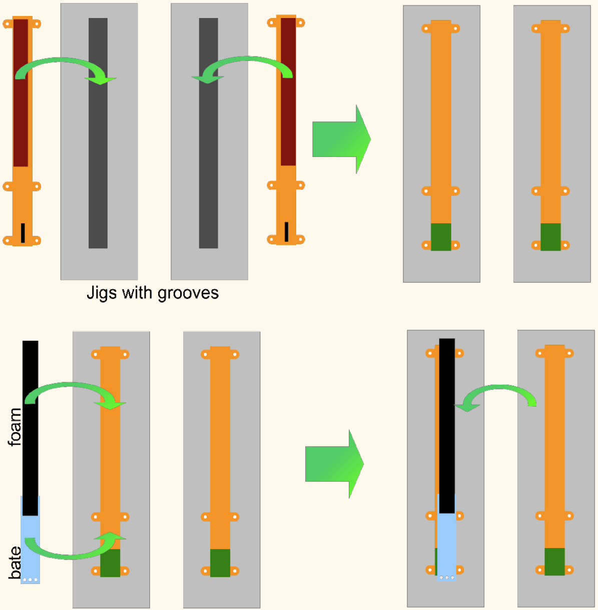
Ladder assembly



Jigs with grooves

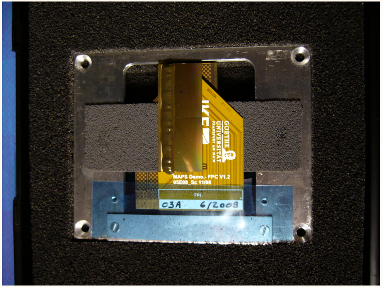


Ladder assembly

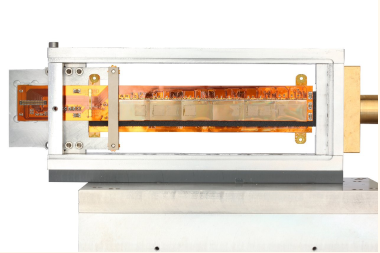


PLUME history

PLUME-V0 (2009)



PLUME-V1 (2010)



PLUME-2 material budget

- Mi26 (x2): 0.106 % X_0
- Glue (x4): 0.04 % X_0
- Flex (4 %) (x2): 0.112 % X_0
- SiC (x1): 0.092 % X_0

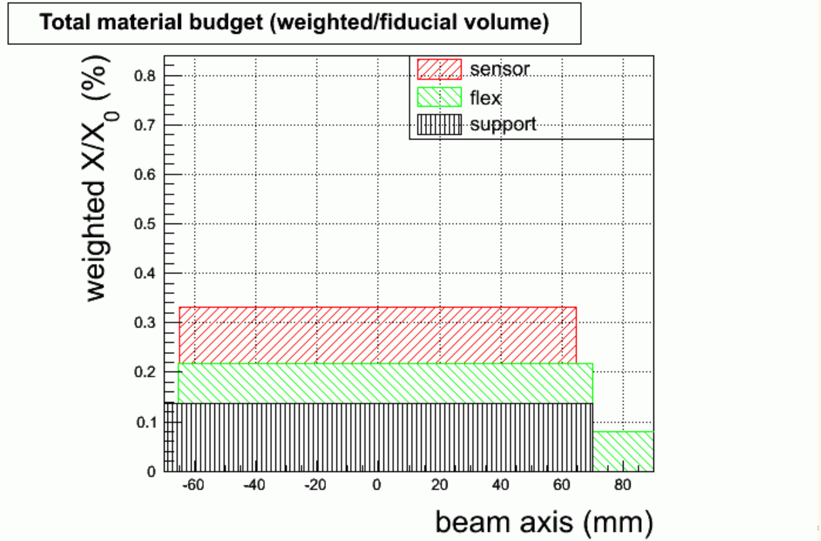
Weigthed material budget

Ladder is made of sensitive and dead areas:

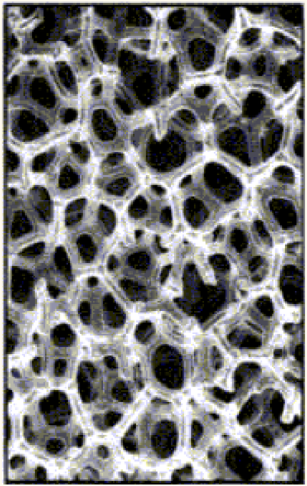
$$\frac{x}{X_0}\Big|_{weighted} = \frac{x}{X_0} \cdot \text{area ponderation}$$

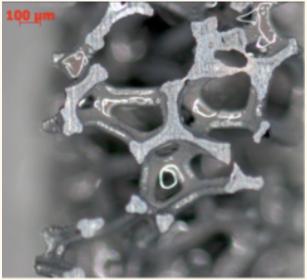
area ponderation = sensitive surface $\times$ number of component + area of layer

PLUME material budget goal



Silicon-Carbide foam support structure

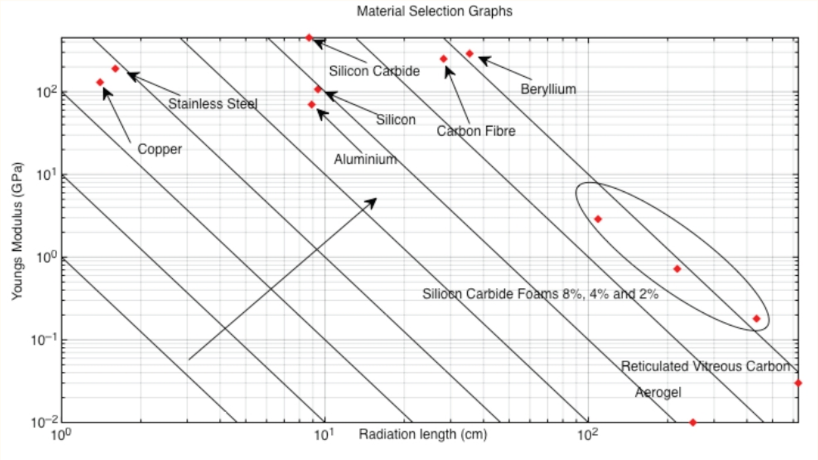




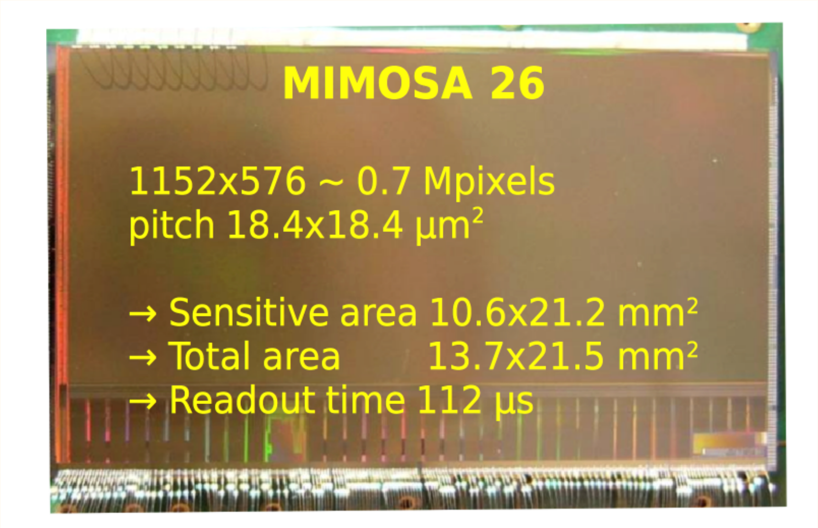
Properties

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

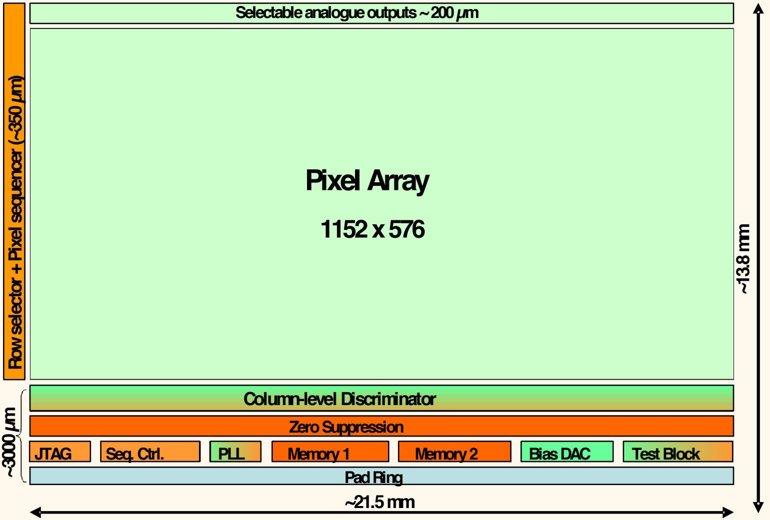
Young Modulus



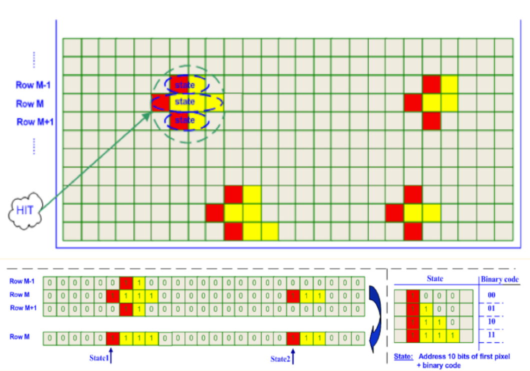
MIMOSA-26 description



MIMOSA-26 architecture



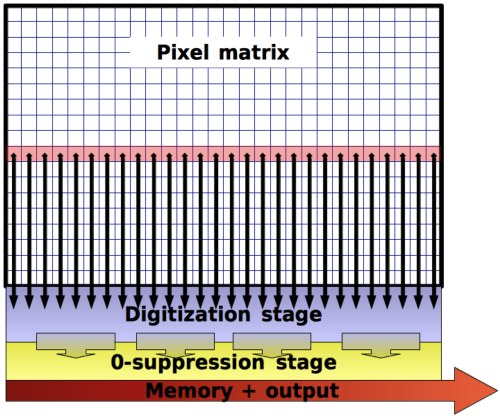
Zero Suppression logic (SUZE)



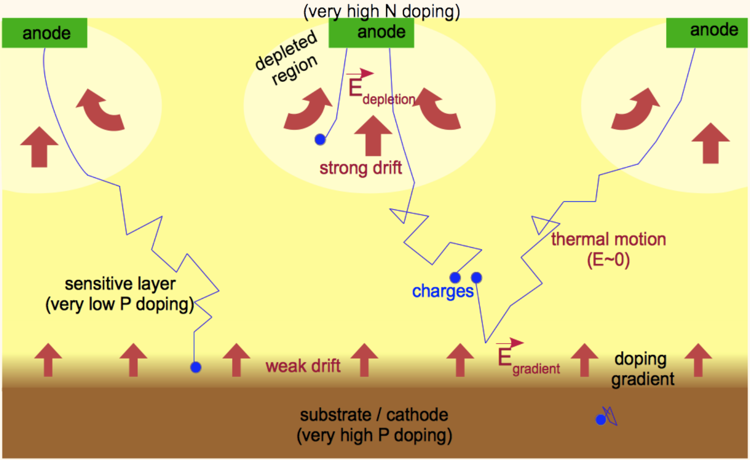
SUZE logic split in 3 blocks:

- **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).

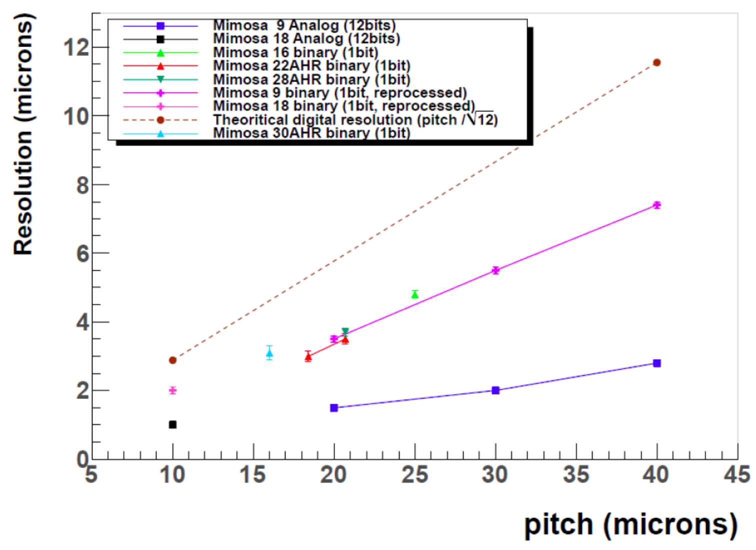
Column parallel readout



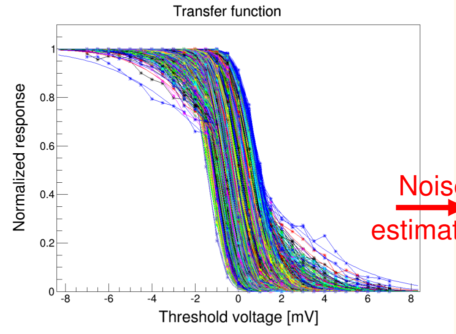
MAPS principle



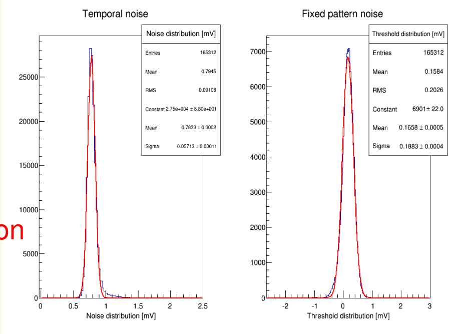
Spatial resolution for different pitch (IPHC-Strasbourg)



Characterization of one sensor



Noise estimation →



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

$\Rightarrow$ **Can now define different thresholds**

Fixed Pattern Noise and Temporal Noise

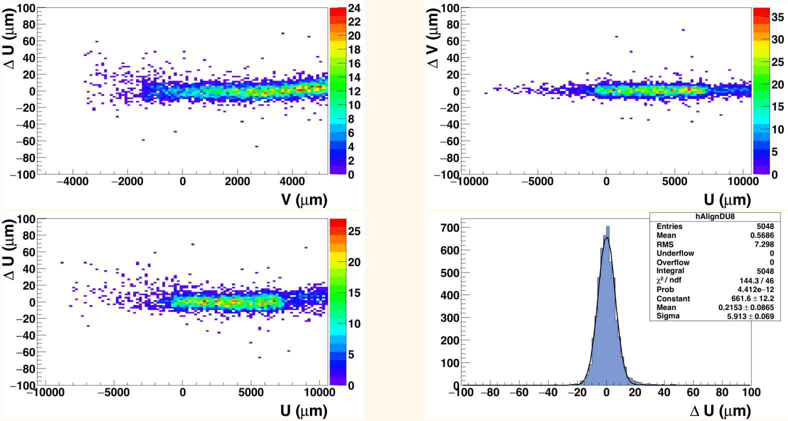
Fixed Pattern Noise

- Non-uniformities of pixel response inside the pixels submatrices
- Offset which needs to be substracted from pixel's response in order to measure the signal

Temporal Noise

- Shot noise, thermal noise or $1/f$ noise
- Depends on operation phase (reset, integration or readout)
- Reset:
  - Appears in 3T-like pixel designs when restoring charge C_d
- Integration time:
  - Leakage current diode (shot noise)
- Readout:
  - Source follower current and column switch

Correction of the deviations between real hits and extrapolated ones

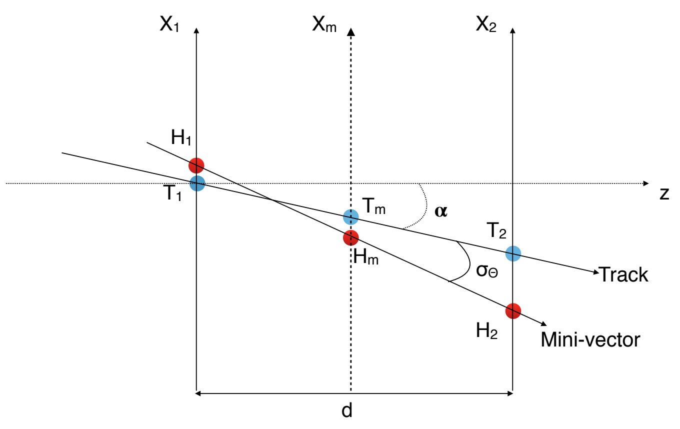


Spatial residual obtained after correction:
$\sigma_U \simeq 5.9$ μm instead of $\sigma_U \simeq 6.1$ μm

Legendre polynomials order

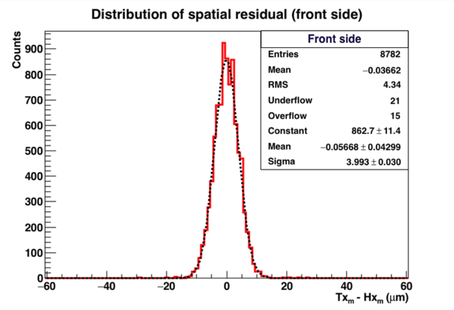
	Front plane		Back plane	
Order	χ^2/NDF	$\sigma_u^{\mathrm{front}}$	χ^2/NDF	σ_u^{back}
3	21684/84	6.5	35575/72	13.3
4	1450/83	6.2	25130/71	12.4
5	1450/82	6.0	1719/70	6.9
6	654/81	5.9	1481/69	6.8
7	304/80	5.9	635/68	6.4
8	288/79	5.9	269/67	6.2
9	225/78	5.9	251/66	6.2
10	225/77	5.9	152/65	6.2
11	158/76	5.9	132/64	6.2

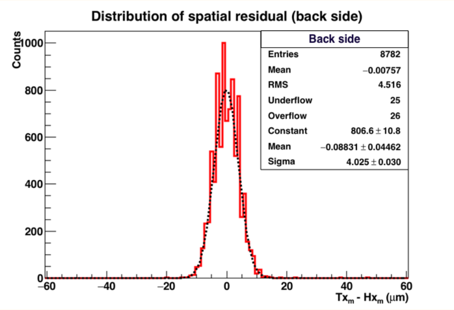
Two points measurement combination



Spatial residual

Study of two planes in normal incidence (w.r.t the beam axis)





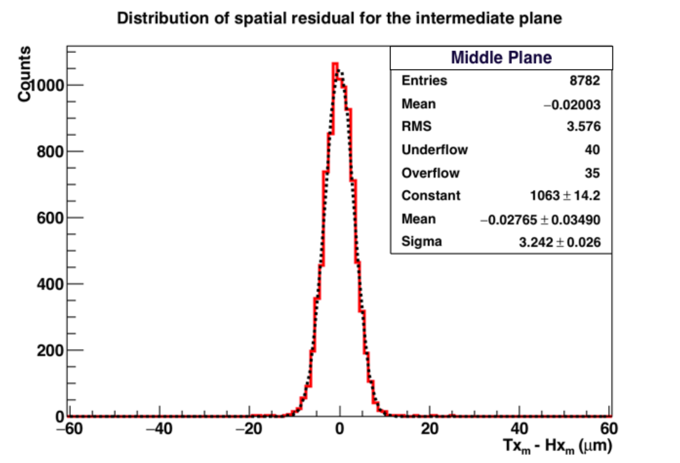
Combination of the residuals information

$$\sigma_m^2 = \frac{\sigma_{front}^2 + \sigma_{back}^2}{4} + \sigma_{tel}^2$$

$$\sigma_m \simeq 3.4\mu m$$

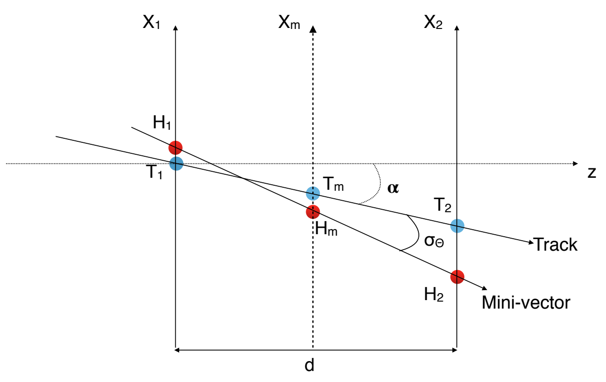
$$\Rightarrow \sigma_{resolution} = \sqrt{\sigma_m^2 - \sigma_{tel}^2} \simeq 2.9\mu m \text{ with } \sigma_{tel} \simeq 1.8\mu m$$

Mini-vector spatial residual



$$\sigma_{measured} \simeq 3.2\mu m (\sigma_{expected} \simeq 3.4\mu m)$$
$$\sigma_{resolution} \simeq 2.7\mu m (\sigma_{resolution\ expected} \simeq 2.9\mu m)$$

Estimation of the angular resolution



Estimation of the angular resolution

$$\sigma_\theta = \frac{\sqrt{\sigma_{s1}^2+\sigma_{s2}^2}}{d}$$
$$\sigma_\theta \simeq 0.146^\circ$$

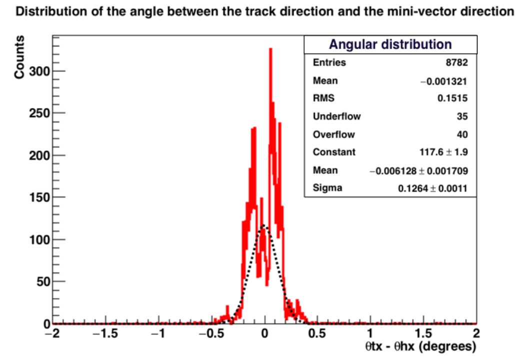
$$\text{with } \sigma_{s1} = \sigma_{s2} \simeq 3.6\ \mu m$$

Estimation of the angular resolution

Estimation of the angular resolution

$$\sigma_\theta = \frac{\sqrt{\sigma_{s1}^2 + \sigma_{s2}^2}}{d}$$
$$\sigma_\theta \simeq 0.146^\circ$$

with $\sigma_{s1} = \sigma_{s2} \simeq 3.6\ \mu m$



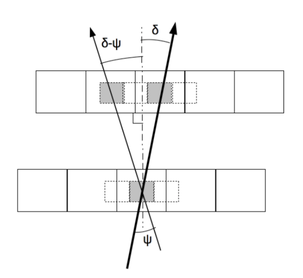
Angular resolution

Can not be simply quoted by a Gaussian standard deviation

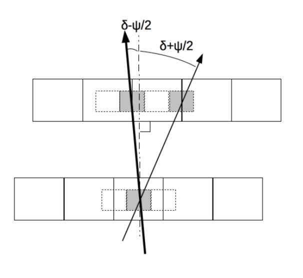
Origin of these peaks

- Cluster position determined by its centre of gravity
- Angle distribution is dependent of the cluster size taken into account

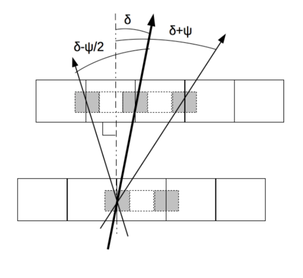
Cluster of 1 pixel on each side



Cluster of 2 pixels on one side, 1 pixel on the other



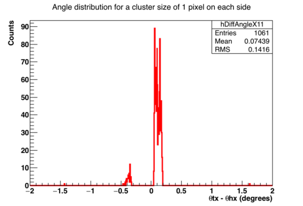
Cluster > 2px on each side



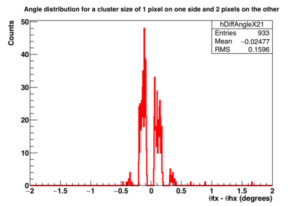
Origin of these peaks

- Cluster position determined by its centre of gravity
- Angle distribution is dependent of the cluster size taken into account

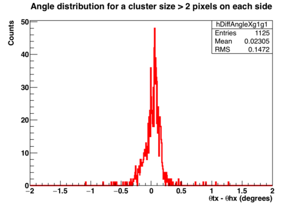
Cluster of 1 pixel on each side



Cluster of 2 pixels on one side, 1 pixel on the other

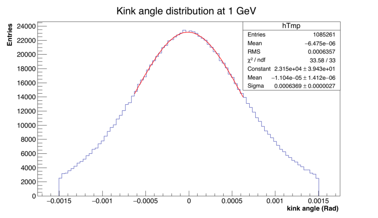


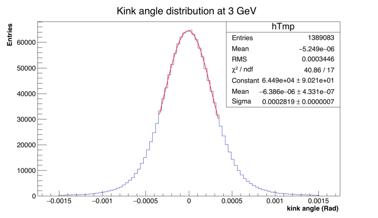
Cluster > 2px on each side

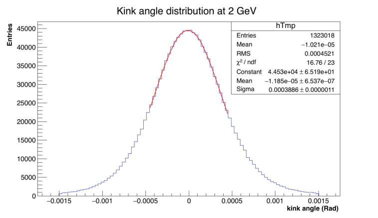


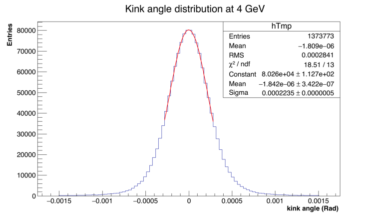
Kink angle measurement between 1 and 4 GeV

Fitted kink angle distributions

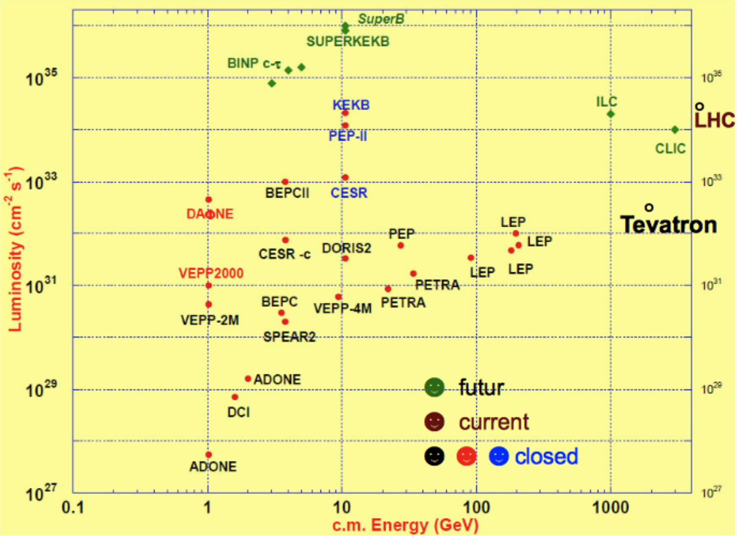








Luminosity and centre-of-mass energy for different colliders



Other technologies for the ILD-VXD

SOI

FPCCD

DEPFETH

Detector performances

Vertexing

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

Tracking

$$\sigma(1/p) = 2x10^{-5} (GeV^{-1})$$

Jet ernergy

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

Impact parameter

Resolution on the impact parameter

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

Parameter a

$$a = \sigma_{s.p} \frac{R_{int} \oplus R_{out}}{R_{ext} - R_{int}}$$

- R_{int}: radius of the inner layer
- R_{out}: radius of the outter layer
- $\sigma_{s.p}$: single pointing resolution

Parameter b

$$b = R_{int} \frac{13.6(MeV)}{\beta c} \cdot Z \cdot \sqrt{\frac{x}{X_0}} \left[1 + 0.036 \cdot \ln\left(\frac{x}{X_0 \sin\theta}\right)\right]$$

- Z: charge of incoming particle
- $\frac{x}{X_0 \sin\theta}$: material crossed by particle
- R_{int}: distance of the inner layer to the IP

Impact parameter for various colliders

Collider	a (μm)	b (μm GeV/c)
LEP	25	70
SLC	8	33
LHC	12	70
RHIC	13	19
ILC	$\leqslant$ 5	$\leqslant$ 10

Particle Flow Algorithm

- Typical jet:
  - Charged hadrons $\simeq$ 60 %
  - Photons $\simeq$ 30 %
  - Neutral $\simeq$ 10 %
- Standard approch
  - 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?

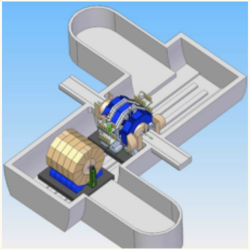
Limitations of e^+e^- colliders

- Synchroton radiation loss $\sim \mathrm{E}^4/r$
- Synchroton cost: $\sim$ quadratically with energy
- Power consumption

Avantages of linear colliders

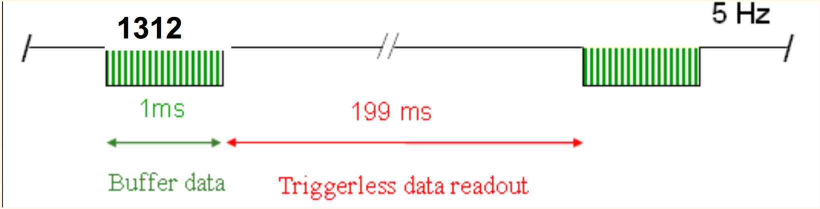
- Not limited by synchrotron radiation
- Cost: $\sim$ linear with energy
- Polarisation of both beams
- Detectors close to the IP $\Rightarrow$ optimum for c-tagging

ILC interaction region



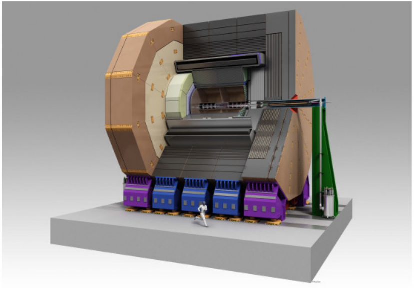
- 1 interaction region for 2 detectors
- Push-pull:
  - Detectors mounted on movable platforms
  - Sharing of beam time
  - Switching time: 24h to 48h
  - Allow cross-checking

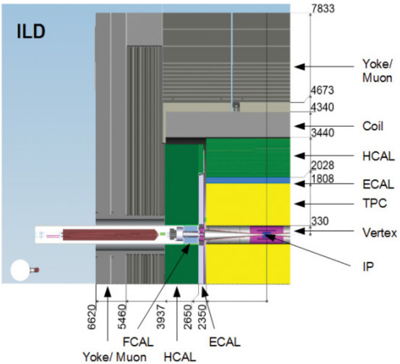
ILC environment



- 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

Overview of the ILD





SuperKEKB collier

- Asymmetric beams: e^-: 7 GeV, e^+: 4 GeV
- Collision with E_{cm} around Y(4S) and Y(5S)
- BEAST-II = collider commisioning
- Validation of the simulation of the background induced by SuperKEKB