Experimental Challenges Triggered by the ILC Physics Programme

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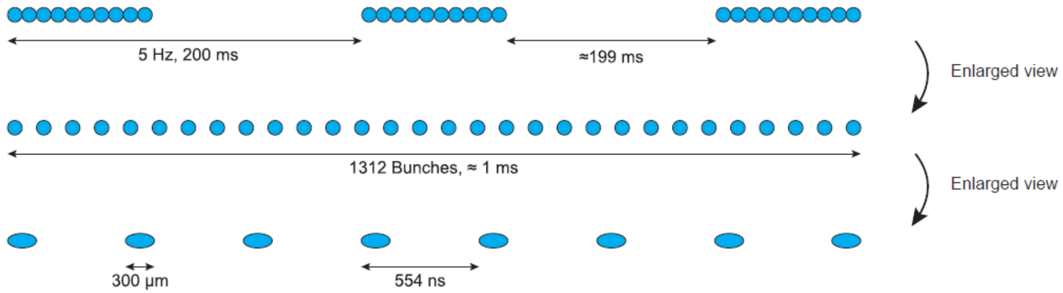
Sources: Talks at ECFALC-16, ICHEP-16, LCWS-16, INSTR-17, CALICE Web-site, ILC-TDR

International Linear Collider (ILC)

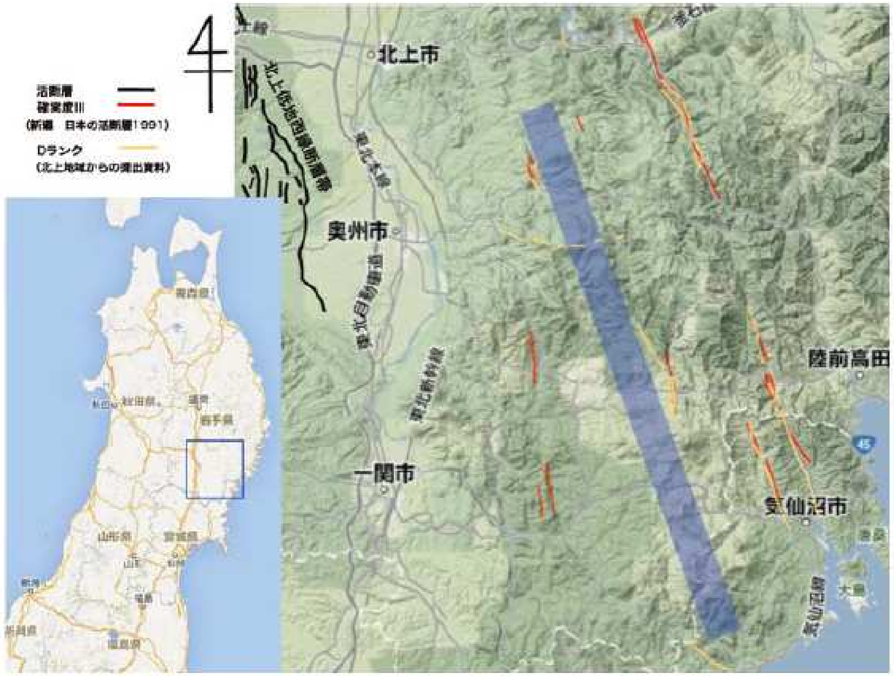
- **Project status:**
  - Electron-positron linear collider project under discussion
  - Possibly starting its physics programme in the early 2030's in Japan
  - Expected to be integrated in the update of the European Strategy

- **Collision energies:**
  - Emblematic E_{CM}: 250 GeV (Higgs), 350 GeV (top), $>$ 500 GeV (Higgs and gauge couplings)
  - Upgradable $\gtrsim$ 1 TeV
  - Tunable & known precisely: threshold scan capability (e.g. top or New Phys. production)

- **Beams:**
  - Polarisable: P(e^-/e^+) $\sim \pm$ 80/30 % (0(0.1)% precision)
  - Luminosity: few 10^{34}/cm^2/s
  - O(10^3) bunches concentrated in $\lesssim$ 1 ms long trains separated by $\sim$ 200 ms



Northern Japanese Site



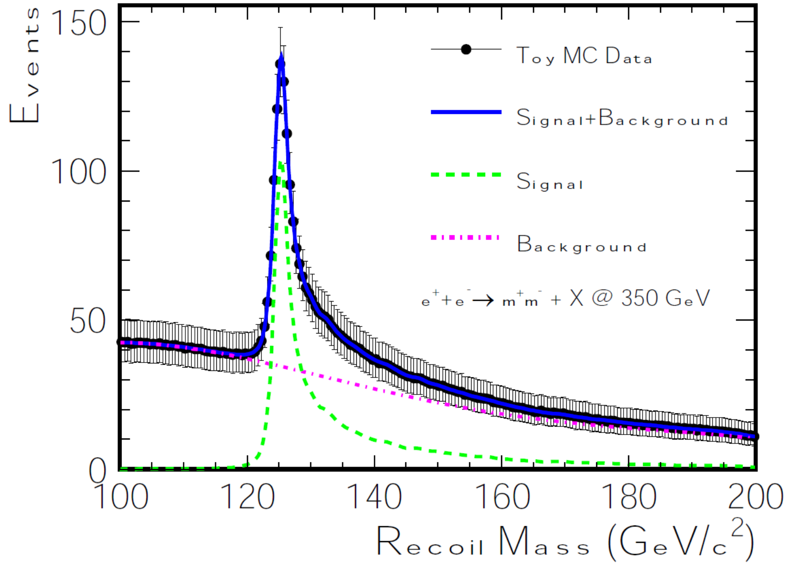
Geologically very stable area
Thinly populated, still well accessible through major roads and high speed rail roads
Closed big city: Sendai

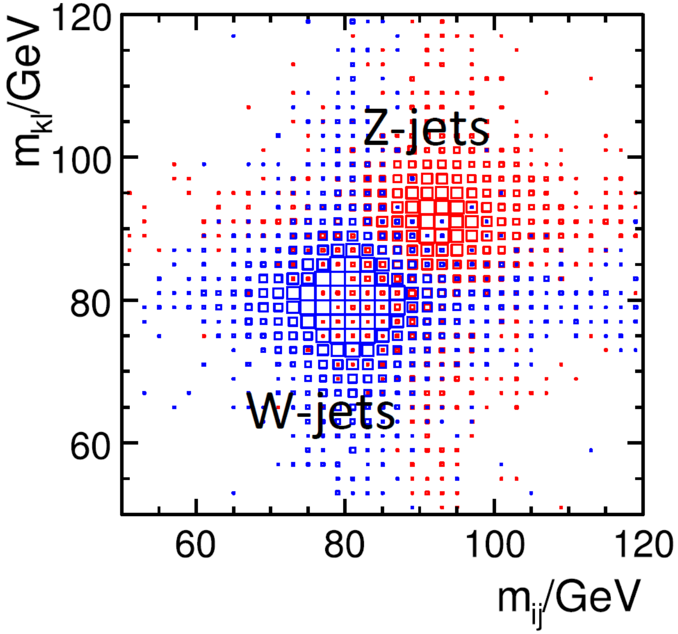
The Physics Programme: Benchmarks for Detector Requirements

- **Higgs physics:**
  - gauge and fermion couplings
  - M_H, Γ_H
  - CP, quantum numbers, etc.
  - Γ_{inv} vs DM

- **Top physics:**
  - $m_{top} \equiv$ input parametre of the SM
    (extracted from threshold scan)
  - top couplings from asymmetries

- **Direct investigation of new physics:**
  - Final states not seen at LHC (e.g. WIMP tagged by associated prompt photon radiation, light Higgsino)
  - Characterise new particles discovered at LHC or ILC
    (gauge couplings, threshold scan $\rightarrowtail$ mass)





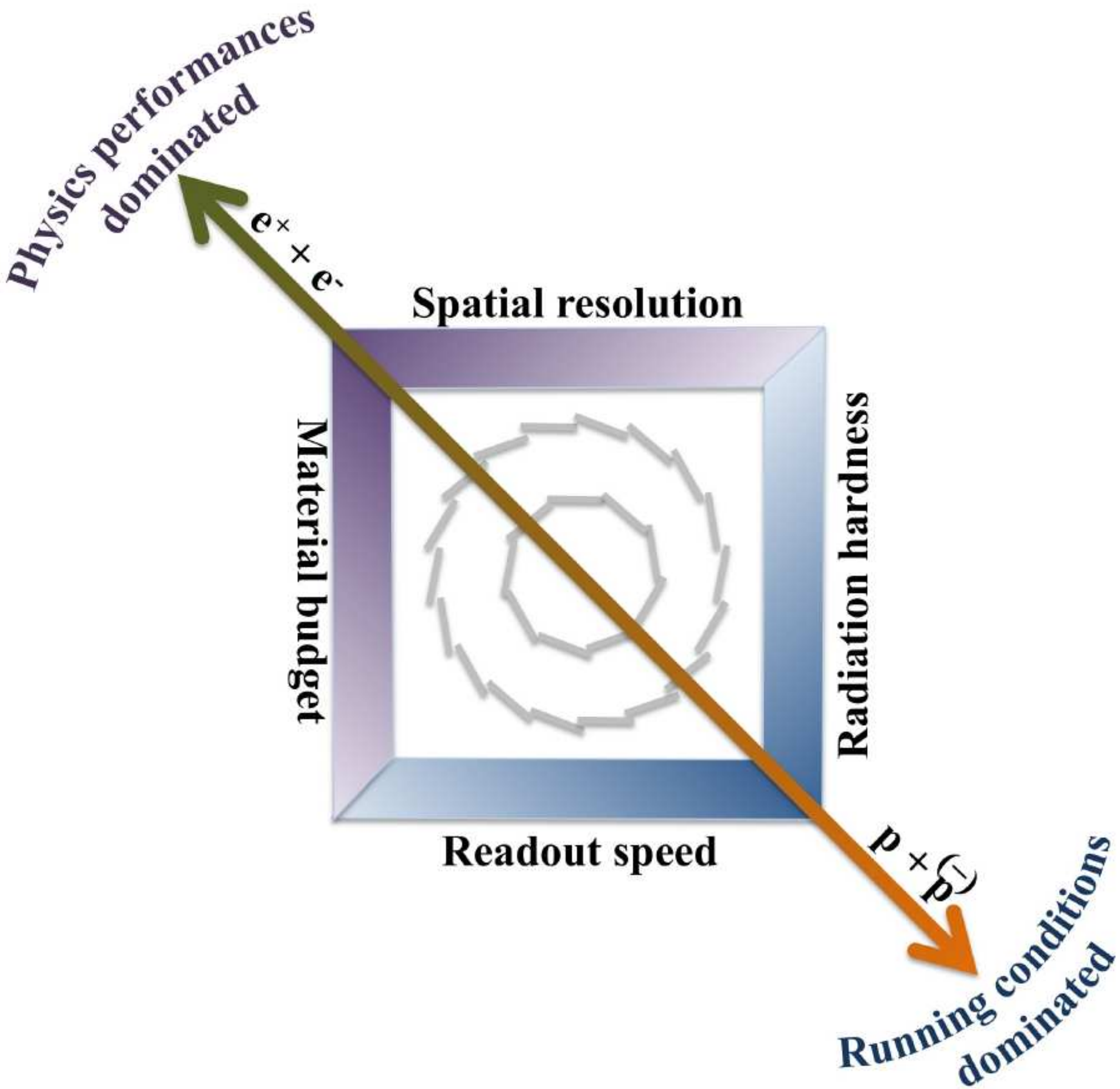
Running Conditions Driving the Detector Designs

- **Electrons are elementary:**
  - no underlying event $\Rrightarrow$ clean final state
  - precisely known E_{CM}, Pol(beams) using redundant beam instrumentation
- **Interaction cross-sections:**
  - EW cross-sections are low $\Rrightarrow$ no pile-up BUT scarce signal (few Hz !)

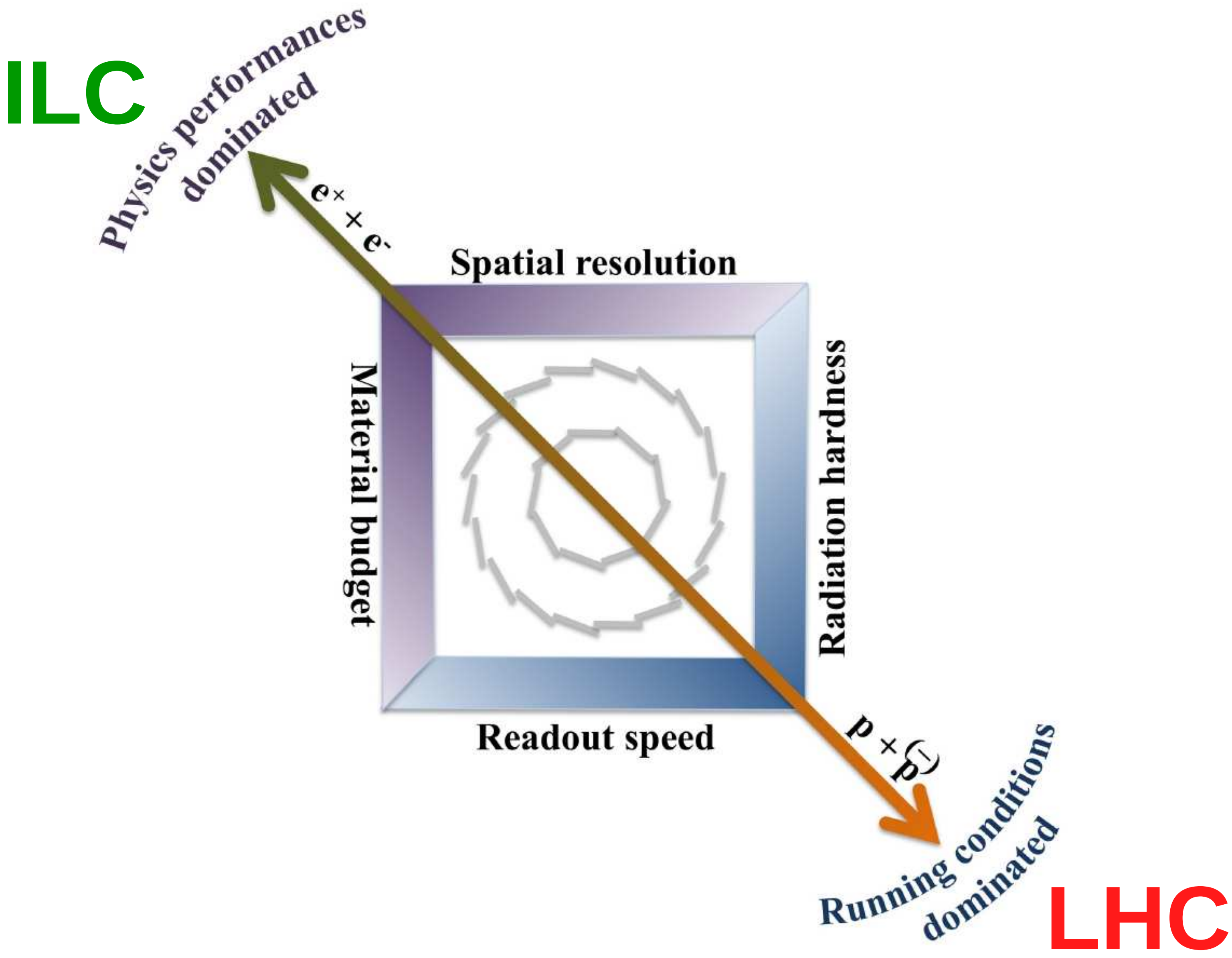
    e.g. $\sigma\,(e^+e^- \rightarrowtail HX) \sim 10^{-3}\,\sigma\,(pp \rightarrowtail HX)$ at 14 TeV
  - Higgs production: S/B $\sim$ O(10^{-2}) while at LHC: S/B $\sim 10^{-9/-10}$
  - Radiation loads are modest ($\sim 10^4$ smaller than at LHC)
- **Beam time structure:**
  - 0.5 % duty cycle of the machine allows switching off the detector inbetween trains

    $\Rrightarrow$ factor 10 to 100 power saving !!!
  - strong final focus (high lumi) generates challenging EM background (beamstrahlung) at small radii
- **Running conditions are not an obstacle to the need for high precision**

Hierarchy of Requirements at the ILC

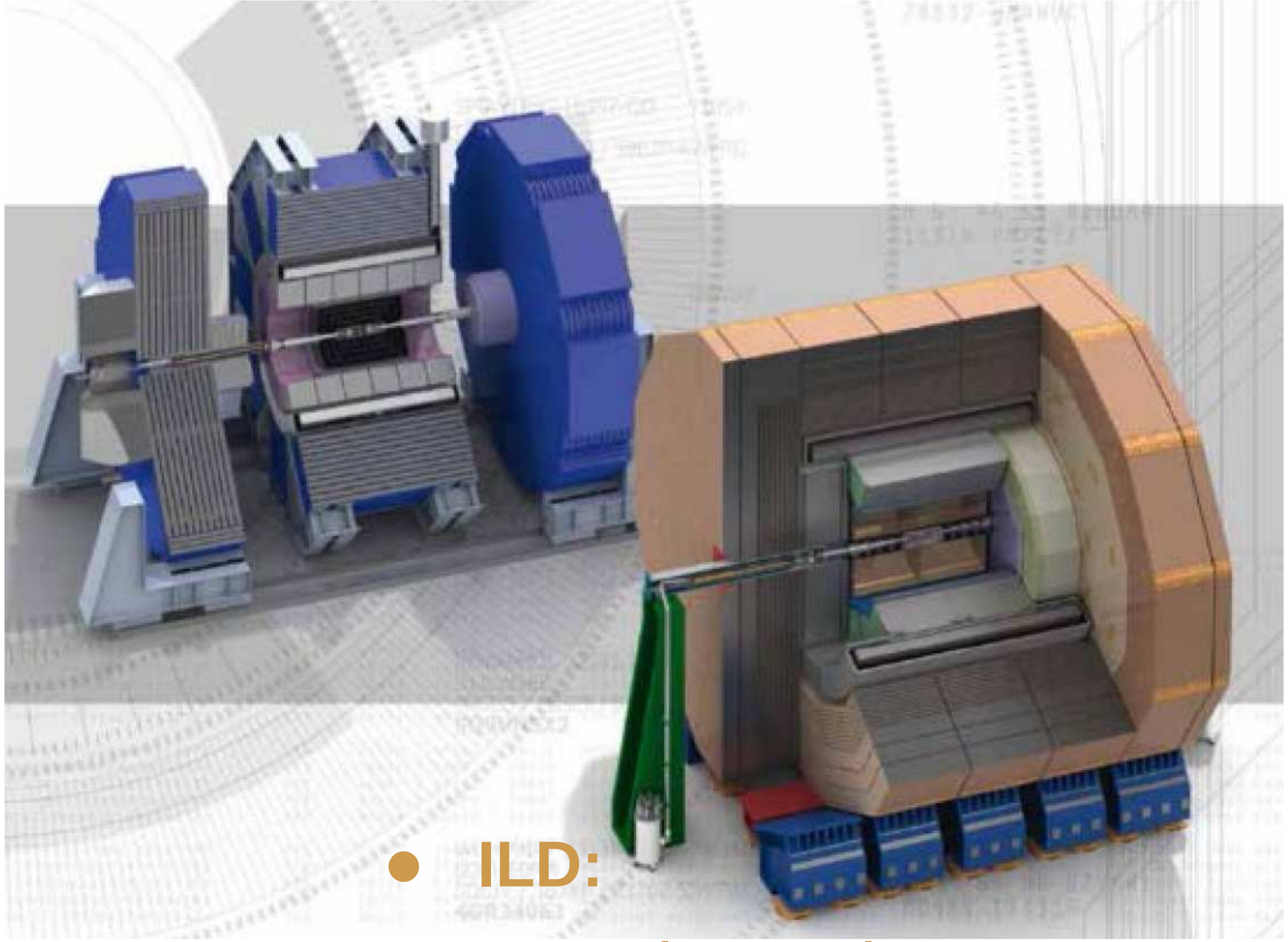


Towards High Precision Detector Concepts



Two Complementary Detector Concepts

- **SiD:**
  - Compact (cost driven)
    - $\hookrightarrow$ highest magnetic field
  - Specific aspect: main tracker
    - $\hookrightarrow$ 5 layers of 2-sided Si μstrips



- **ILD:**
  - Larger volume $\rightarrowtail$ lever arm
    & topological separation power
  - Specific aspect: main tracker
    - $\equiv$ TPC providing $\lesssim$ 200 points along particle trajectories

- **2 multipurpose triggerless, "hermetic" detector concepts operated in push-pull mode (baseline)**

Driving Detector Design Concepts

- **A specific approach has been adopted:**
  - Final state characterisation proceeds through jet characterisation
  - Precision decides $\Rrightarrow$ **Priority to high granularity & low material budget**

- **Particle flow drives the event reconstruction**
  - 3D ”Imaging” calorimeter concept
  - Extreme granularity more important than energy resolution
  - Excellent shower separation/identification guides the whole design

- **Very powerful tracking over wide momentum range**
  - High efficiency tracking and momentum resolution in dense environnement
  - High precision vertexing for flavour physics and low momentum tracking

    in a dense environnement

Prominent Requirements

- **Vertex Detector:**
  - $< 4\ \mu m$ precision in RΦ & Z ($\sim$ 20 x 20 μm^2 pixels) $\rightarrowtail$ $\gtrsim$ 3 times less than LHC
  - $\lesssim$ 0.15 % X_0 / layer (pixel sensors thinned to 50 μm)
  - Adapted to challenging beam related background

- **Tracker:**
  - $\sigma(1/P_t) \lesssim 2{\cdot}10^{-5}$ ($\sim$ 10 times better than at LHC)
  - overall $\lesssim$ 10–20 % material budget in central region
  - very good forward tracking

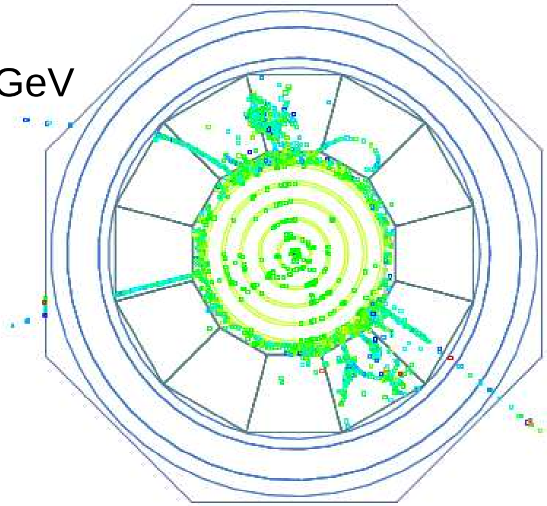
- **Calorimeters:**
  - $\sigma(E_{jet})/E_{jet} \sim$ 3–4 % over wide energy range ($>$ 100 GeV)

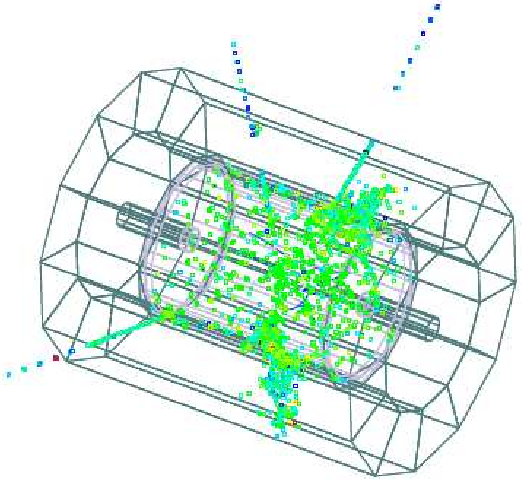
- **Globally:** Aim at single bunch tagging capability (against beam related background)

Fine Grained Event Reconstruction

- **SiD** : ZH final state at 250 GeV

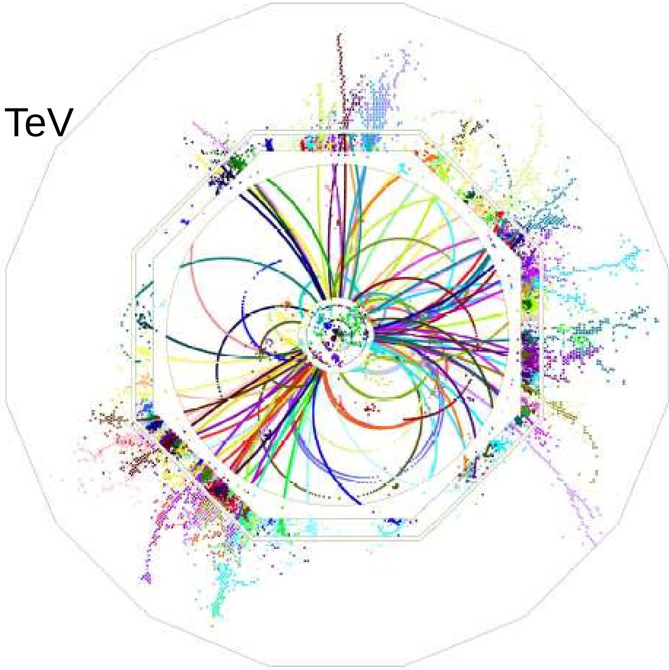
  Z $\rightarrowtail$ $\mu^+\mu^-$ and H $\rightarrowtail$ $b\bar{b}$

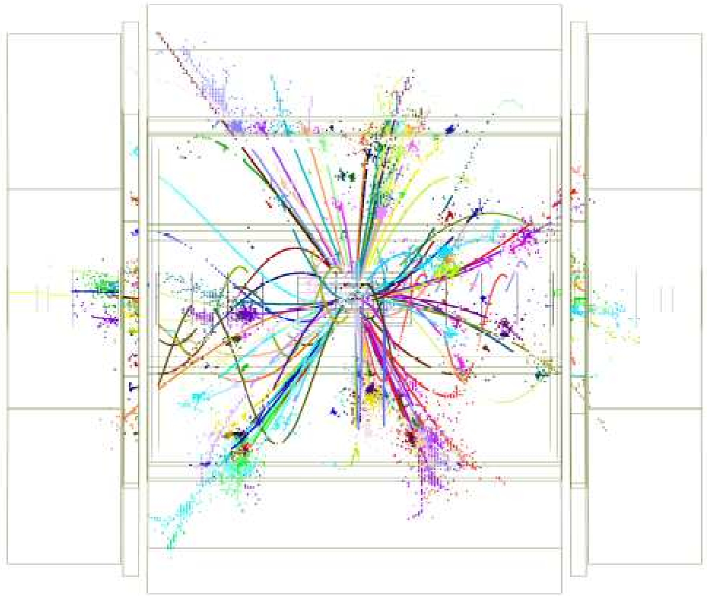




- **ILD** : $t\bar{t}H$ final state at 1 TeV

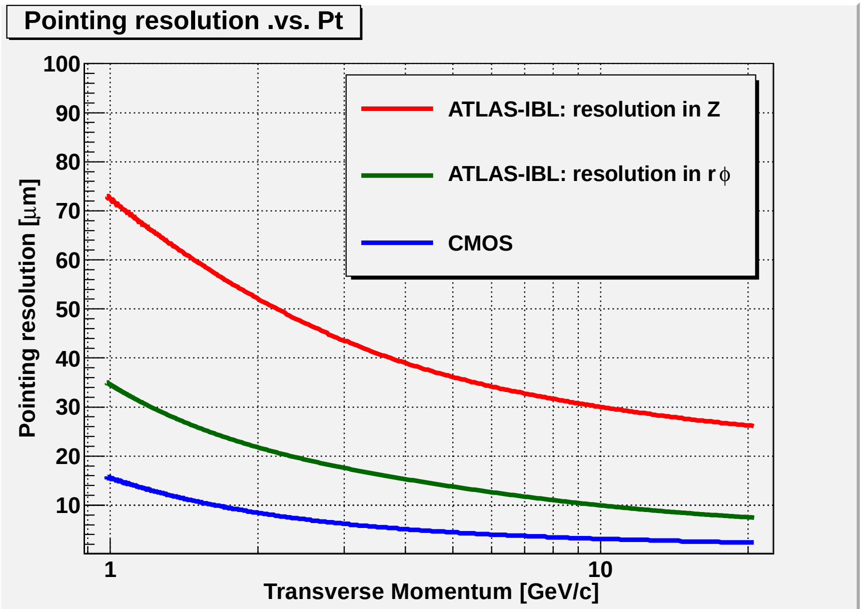
  $t\bar{t}\rightarrowtail$ 6 jets and H $\rightarrowtail$ $b\bar{b}$

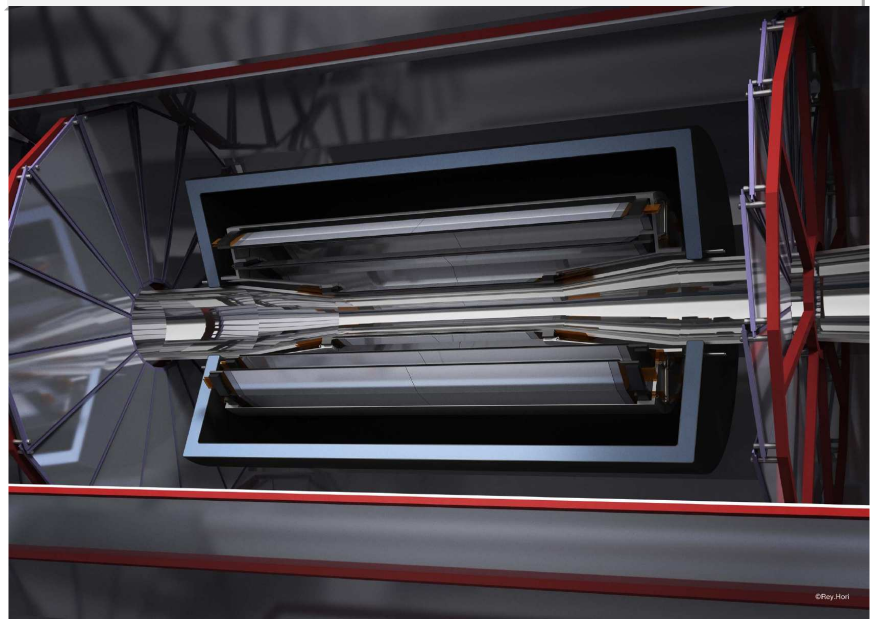




Vertex Detector: Main Requirements

- **Vertexing goal:**
  - ⋇ achieve high efficiency & purity flavour tagging
    - $\rightarrowtail$ charm & tau, b in jets, jet-flavour !!!
  - $\hookrightarrow \sigma_{R\phi,Z} \leq 5 \oplus 10/p \cdot sin^{3/2}\theta \;\; \mu m$
    - ▷ LHC: $\sigma_{R\phi} \simeq 12 \oplus 70/p \cdot sin^{3/2}\theta \;\; \mu m$
  - ▷ Comparison: $\sigma_{R\phi,Z}$(ILD) with VXD
    made of ATLAS-IBL or ILD-VXD pixels $\rightarrowtail$

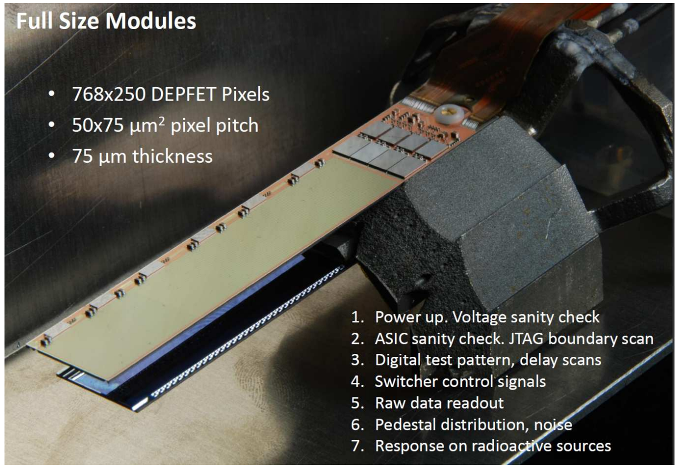


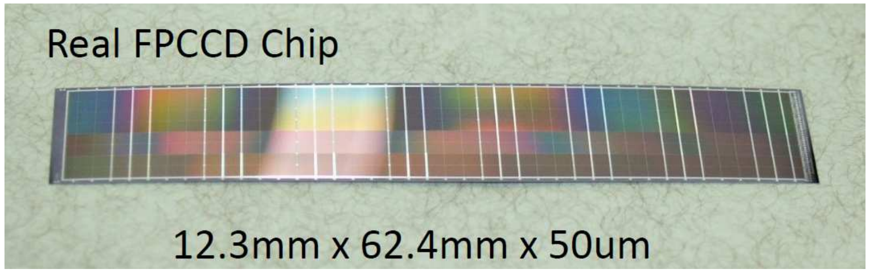


- MAJOR R&D DIRECTIONS:
  - **highly granular, thin, low power, swift pixel sensors**
  - highly integrated, low power, SEE safe, r.o. μcircuits
  - high data transfer bandwith (no trigger)
  - rigid, ultra-light, heat but not electrically conductive,
    mechanical supports, possibly with $C_{\Delta t} \simeq C^{Si}_{\Delta t}$
  - **very low mass, preferably air, cooling system**
  - **micrometer level alignment capability**

Vertex Detector: Sensor Development

- **Various technologies developed, some since 15–20 years**
  - Fine Pixel (5 μm x 5 μm) CCDs derived from the SLD vertex detector (SLC)
    with inter-train read-out $\Rrightarrow$ no power pulsing
  - CMOS Pixel Sensors derived from the EUDET BT $\rightarrowtail$ STAR-PXL $\rightarrowtail$ ALICE-ITS
    $\rightarrowtail$ CBM-MVD sensors $\rightarrowtail$ 4 μm, 2 - 4 μs with continuous read-out
  - DEPFETs derived from BELLE2-PXD with continuous read-out
  - Other approaches with specific advantages: e.g. SoI-CMOS, ChronoPix (inter-train read-out)

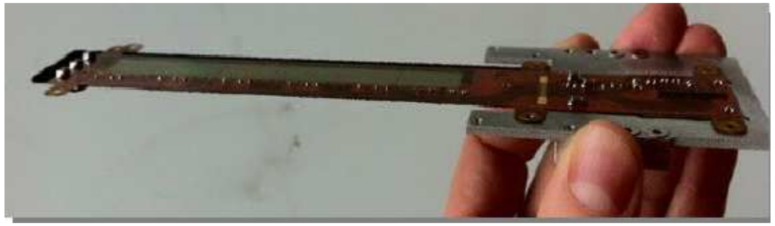


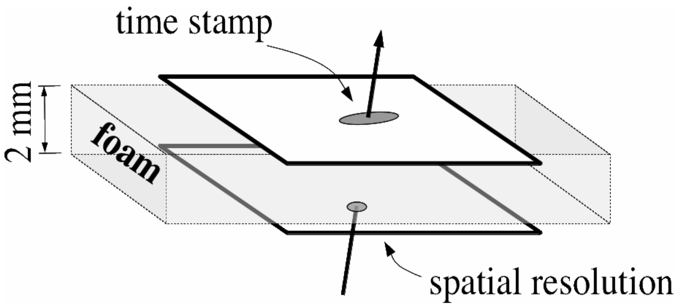


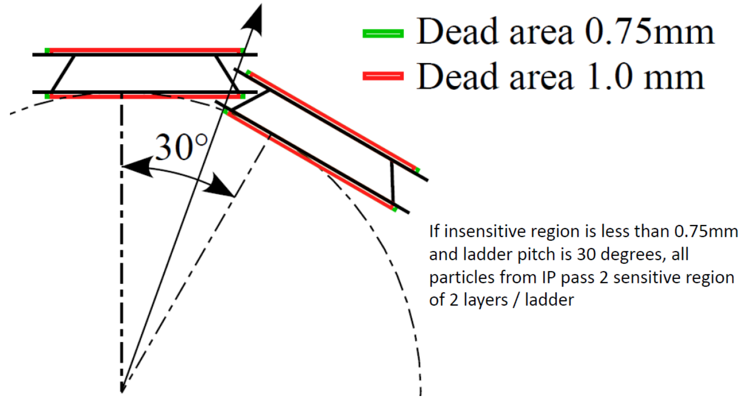
- **Pending concerns:**
  - Mitigation of beam-related background
  - Power pulsing in high magnetic field

Vertex Detector: Ultra-Light Ladder Development

- **Double-sided ladders providing mini-vectors**
  - more robust & efficient tracking (minimises confusion between physics & background impacts), in particular at low momentum ($\lesssim$ 150 MeV/c)
  - improves pointing resolution on track origin
  - objective: 0.3 % X_0 total material budget / 2-sided layer







- **Stable behaviour in a power pulsed mode inside high magnetic field needs to be established $\Rrightarrow$ concern: high precision alignment with limited amount of tracks (rate of physics final states: few Hz) try to use beam related background (and cosmic) tracks at best**

Vertex Detector: Spin-Offs

- **Beam telescopes**
  - EUDET (and AIDA) BT used at numerous beam lines
  - low energy electron (450 MeV) high precision BT part of LNF equipemnt

- **Subatomic physics experiments**
  - STAR vertex detector based on CPS (evidence of Λ_c production in HI collisions)
  - ALICE Inner Tracker Upgrade: $>$ 10 m^2 covered with CPS
  - BELLE-2 vertex detecor: 2 layers of DEPFETs
  - CBM Micro-Vertex Detector at FAIR based on CPS

- **Applications in other domains**
  - Hadrontherapy, X-Ray and Beta imaging, ...
  - satellite instrumentiaton, ...

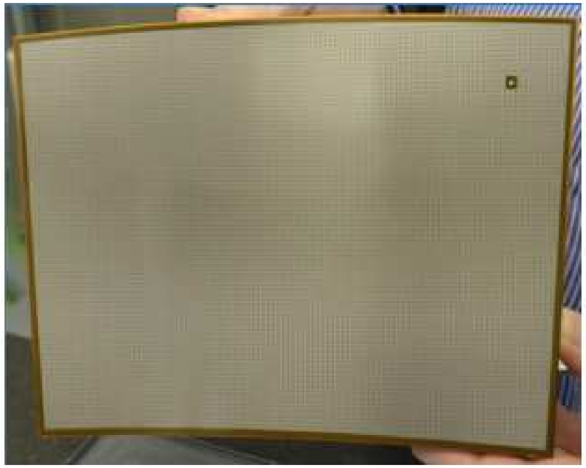
TPC as a Main Tracker

- **Prominent advantages:**
  - Continuous tracking $\Rrightarrow$ links to other detectors, find kinks & tracks starting far from IP
  - Very low material budget (/ measurement)
  - dE/dX for PID
- **Major challenges**
  - Slow read-out (150 BX): time resolution improved by surrounding detectors
  - Modest spatial resolution (benefits from surrounding high precision Si detectors)
  - Ion backflow deteriorates spatial resolution
  - Distortions induced by voltage differences between cage and read-out system
- **Main R&D topics**
  - Pixellated micro-pattern read-out chambers: Micromegas, GEMs, Ingrid, etc.

    $\hookrightarrow$ improve resolution via charge sharing among pixels
  - Ion backflow mitigation
  - Low material budget end-plates

TPC Development: Alternative Read-Out Technologies

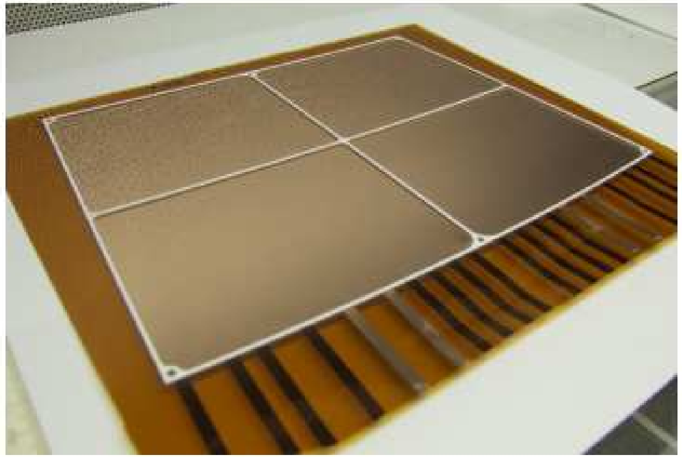
Micromegas



Mesh on top of a charge-dispersing resistive anode

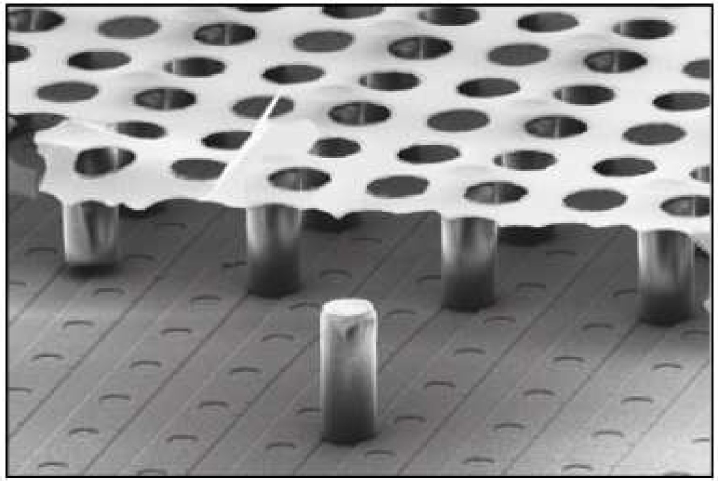
European GEMs

Standard kapton triple GEM with ceramic spacers

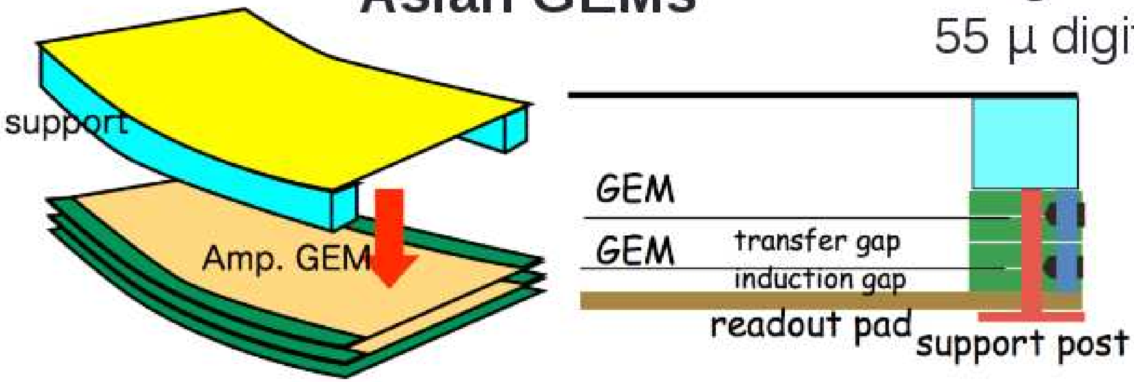


GridPix

Integrated grid on 55 µ digital pixels

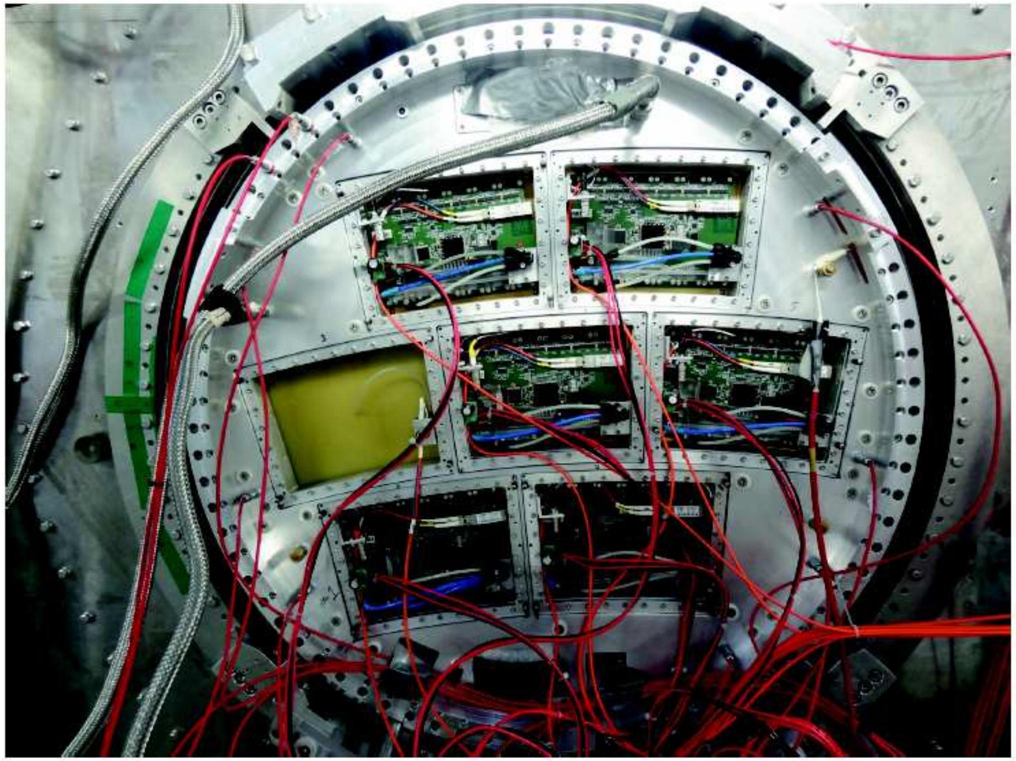


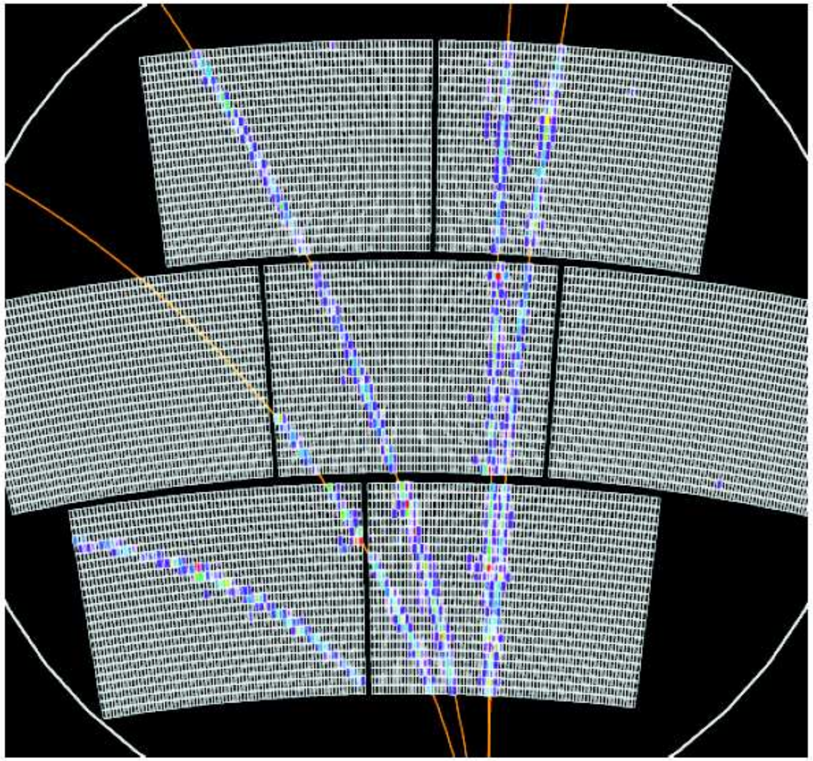
Asian GEMs



TPC Development: Tests realised on Electron Beam

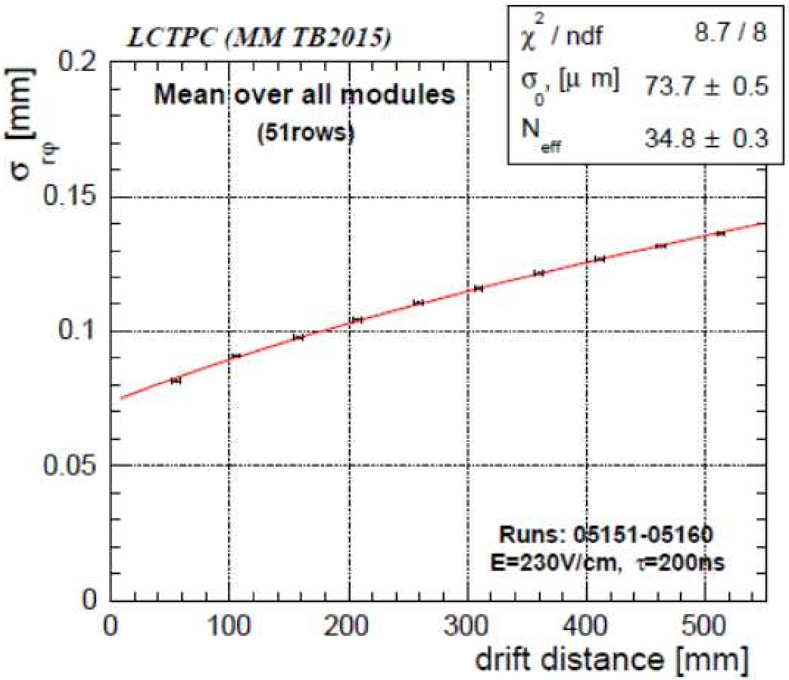
- **R&D widely based on prototype TPC with 50 cm drift distance:**
  - Eventually inserted in high magnetic field
  - May be operated on particle beams (e.g. DESY e− beam)
  - Different read-out chambers mounted and tested (predominently MicroMegas and GEMs)

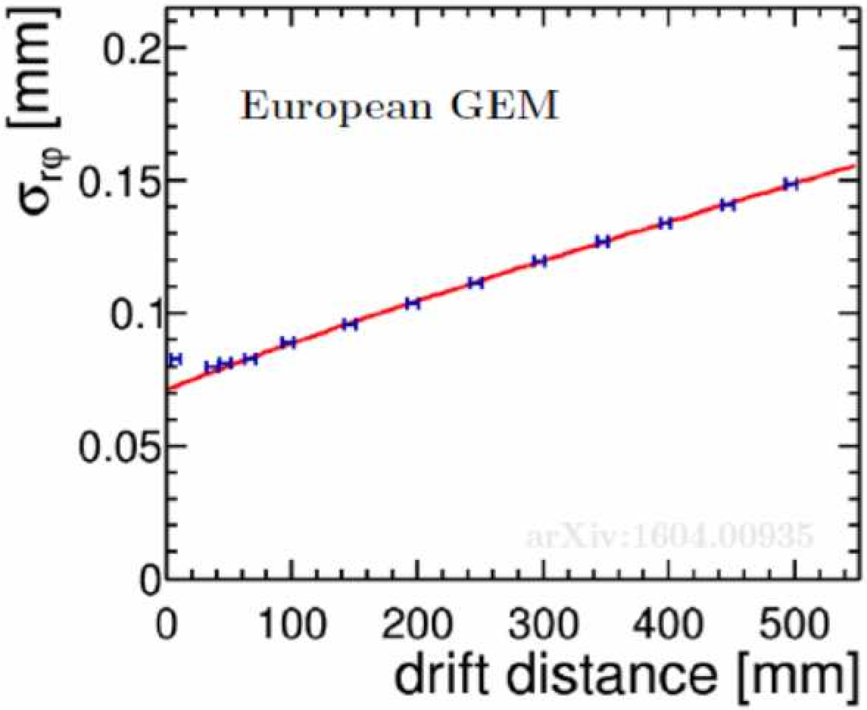




TPC Development: Observed Spatial Resolution

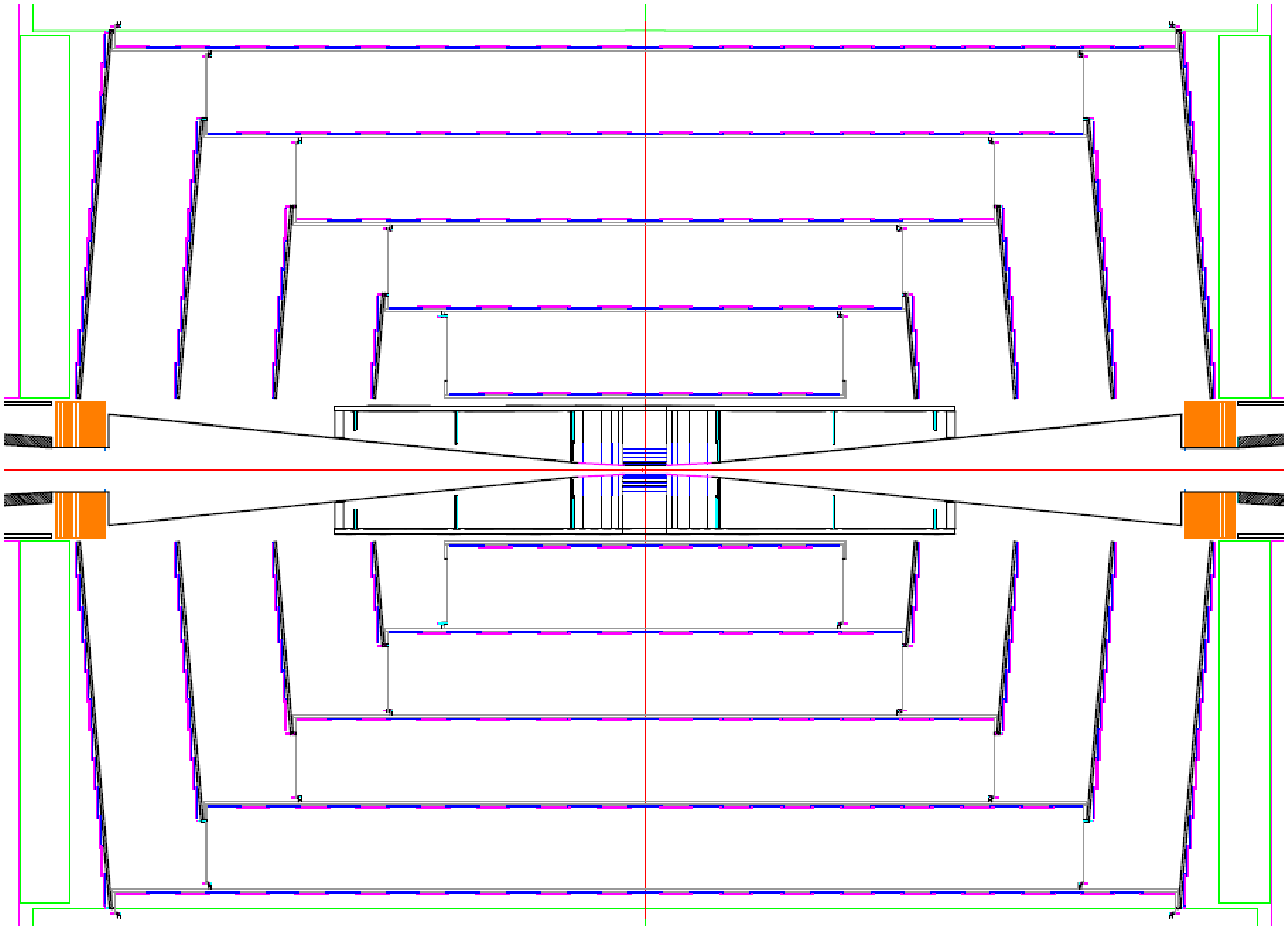
- Single point resolution (in absence of magnetic field) as a function of drift distance for MicroMegas (left) and Triple-GEM read-outs





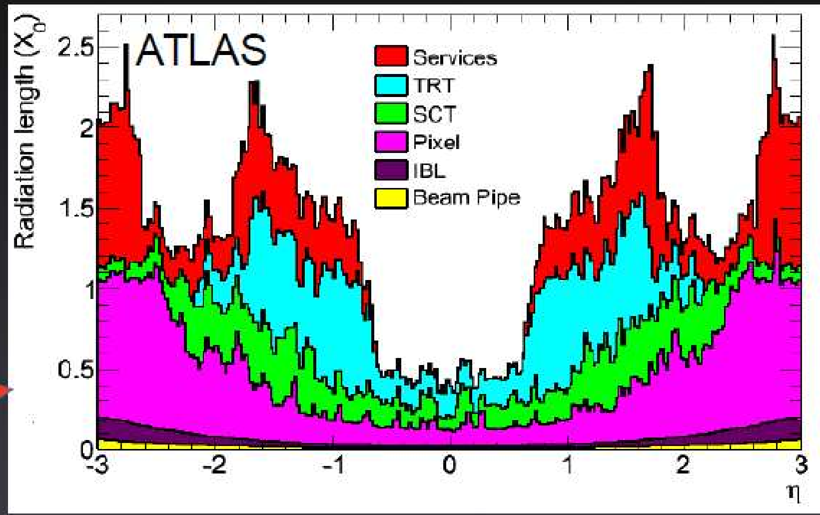
- **No significant difference between both read-out chambre types**
- **Observed resolution in 1 T mag. field indicates that $\lesssim$ 100 μm may be reached with foreseen high magnetic field ($\geq$ 3.5 T)**

SiD Main Tracker

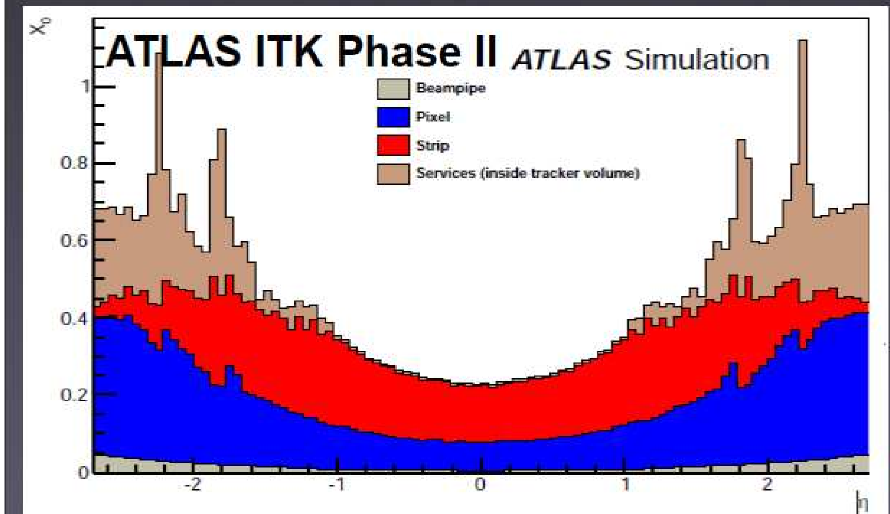


- Si μtrips $\rightarrowtail$ 0.9 % X_0 / layer material budget constrains nb of layers ($\equiv$ measured points: 5)
- Imposes track seeding with vertex detector against fake hit association $\Rrightarrow$ fast vertex detector

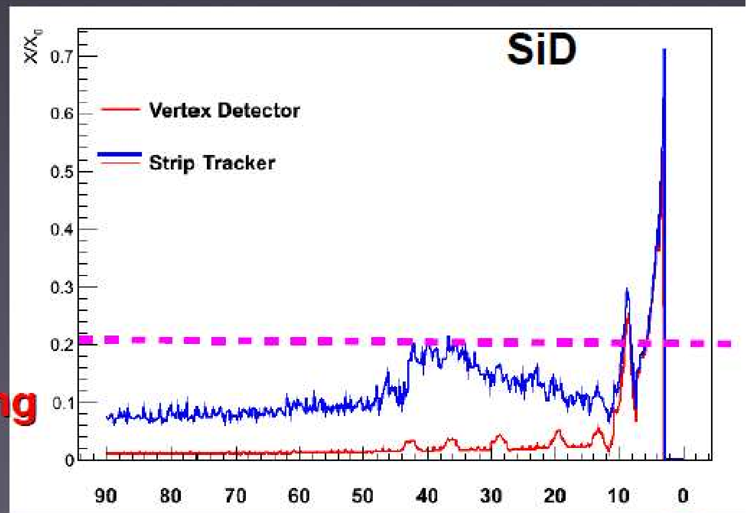
Comparing with LHC/HL-LHC



R&D on Services, Mechanics, Cooling



Power pulsing
Air cooling



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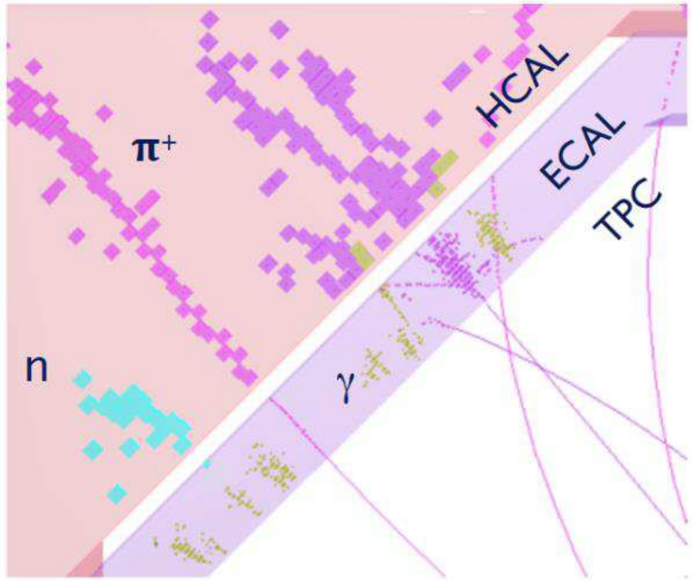
ILC Calorimeters: Motivation for High Granularity

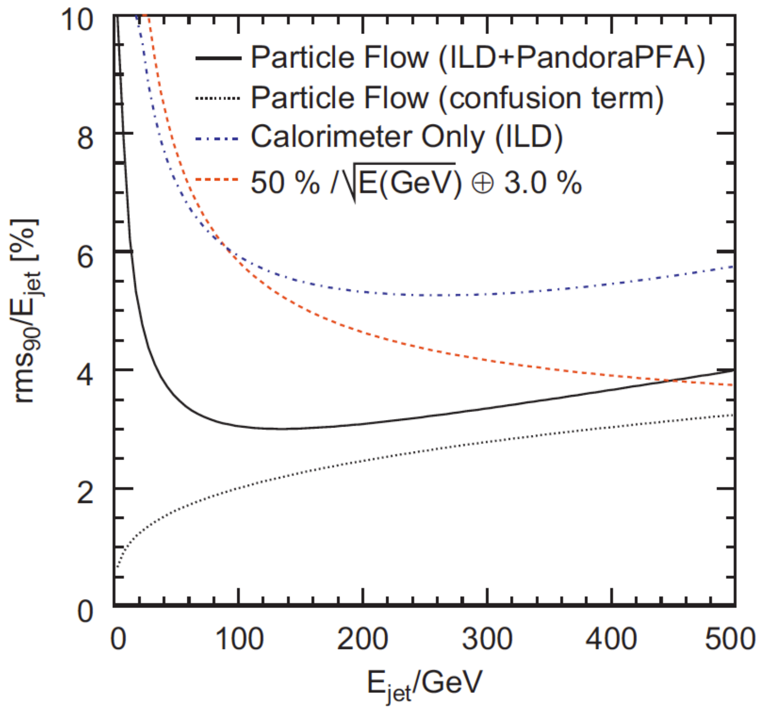
- **High granularity are mandatory for:**
  - high precision physics programme underlying the ILC
  - particle flow
  - several other experiments (e.g. at LHC or CLIC)

- **Particle flow relies on:**
  - Ability to separate energy depositions from close-by particles
  - Connecting information from all sub-systems:
    - charged particles measured in trackers
    - photons (and hadron showers) measured in ECAL
    - neutral hadrons measured in HCAL

- **Objective: excellent JET 4-momentum resolution:**
  - crucial for W/Z jet separation
  - target value: $\lesssim$ 30%/$\sqrt{E(GeV)}$

    for di-jet energies of typically 100 GeV



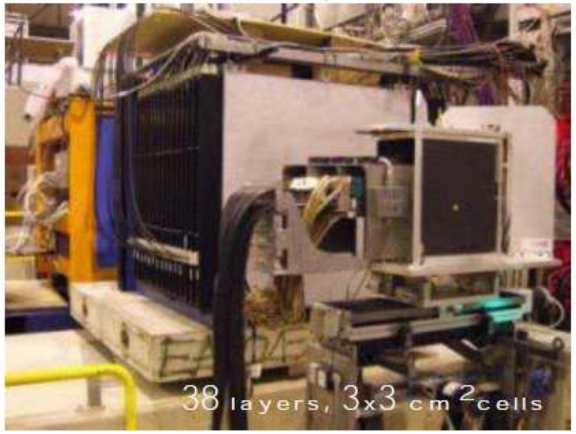


ILC Calorimeters: Beam tests of Various Real Scale Prototypes

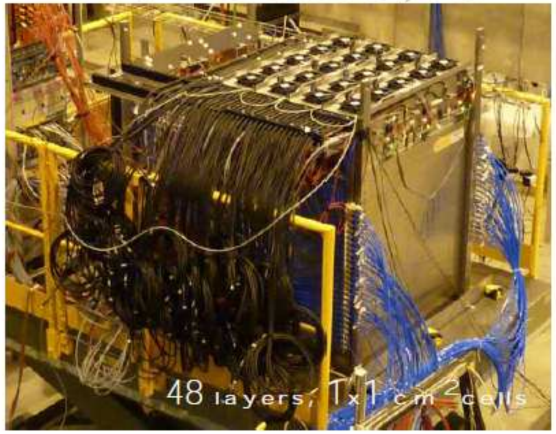
The CALICE physics prototypes

Si-W ECAL

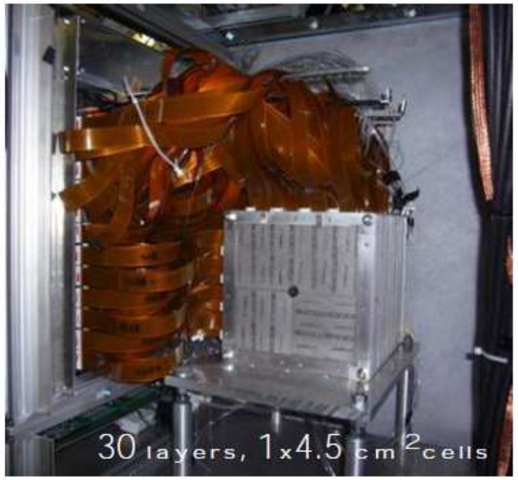
Sc-AHCAL, Fe&W



GRPC-SDHCAL, Fe



Sc-W ECAL

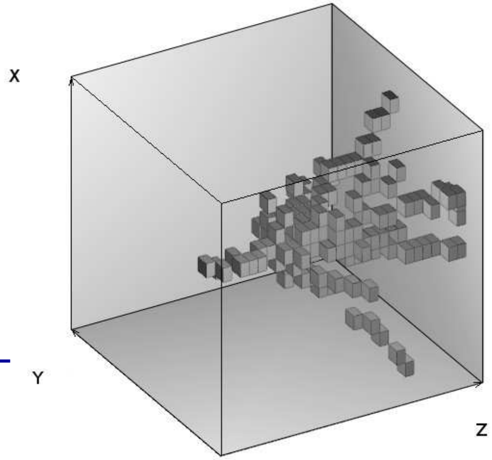


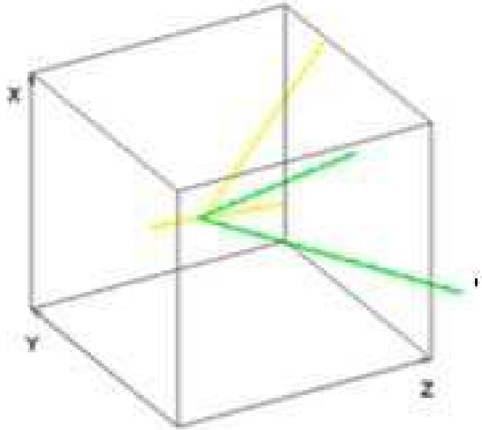
RPC-DHCAL, Fe&W

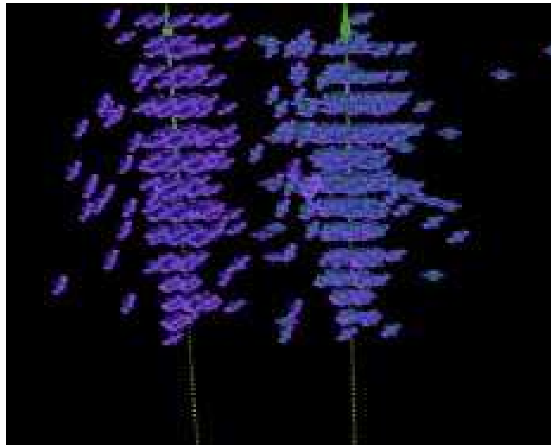
- Various beam tests
- Detector concepts validated with physics prototypes
- Large data sets for precision shower studies

ILC Calorimeters: Establishing Fine Grained Shower Reconstruction

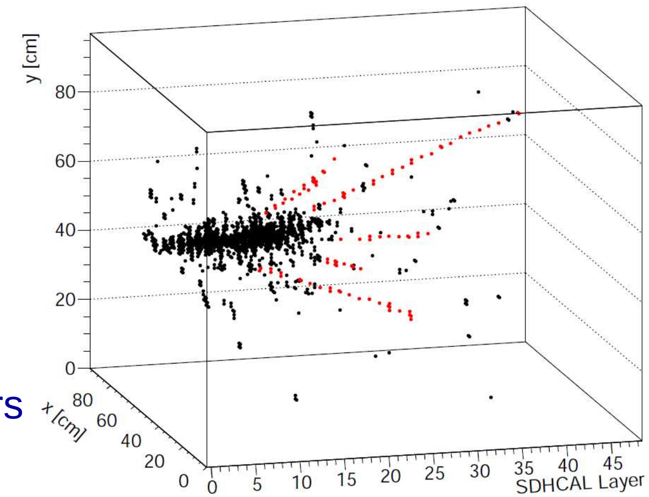
- **SiW ECAL beam tests:**
  - Granularity 1x1 cm^2 cells
  - Reconstruction of hadronic shower starting in ECAL
  - Photon – Pion separation

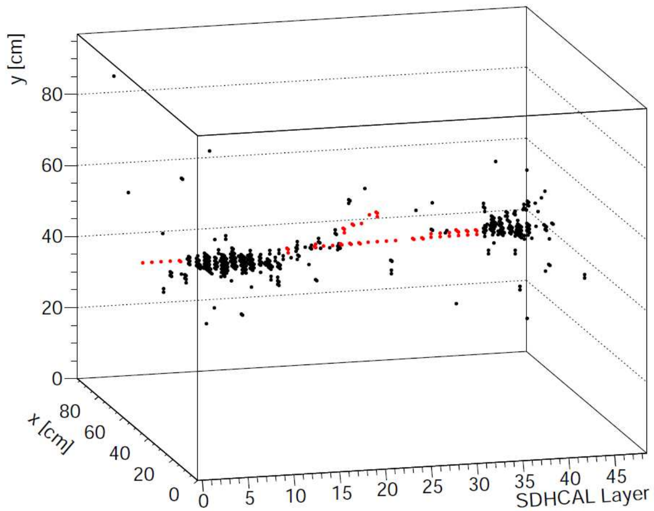




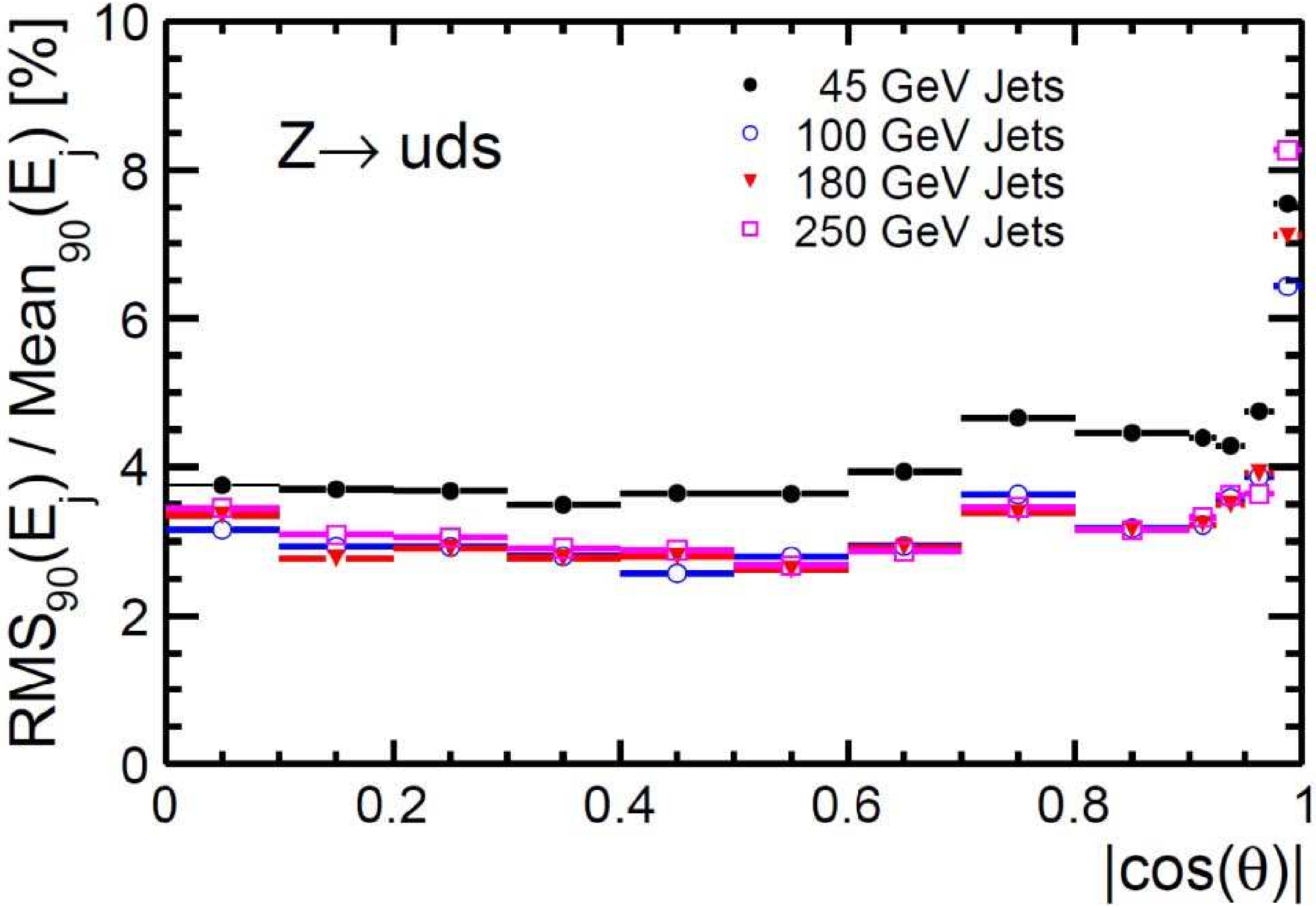


- **Fe/RPC SDHCAL beam tests:**
  - Granularity ~ 1x1x1 cm^2 cells
  - Reconstruction of track segments inside (80 & 30 GeV) hadronic showers





PFA Performance: Jet Energy Resolution derived from Beam Tests

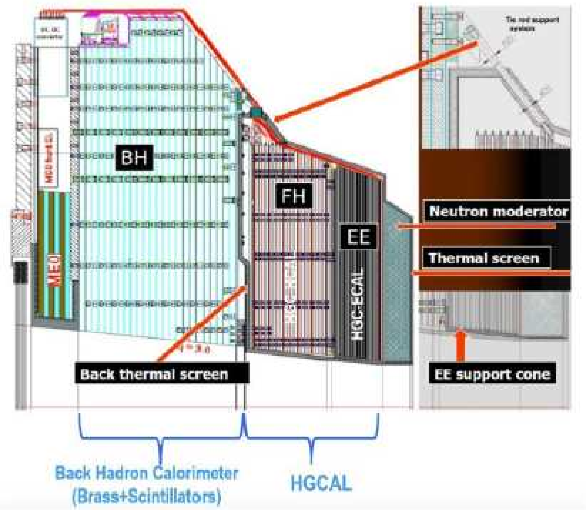


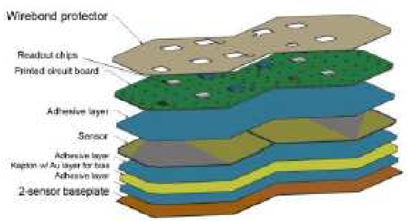
ILC Calorimeters: Spin-Offs

Applications to LHC experiments

- LHC experiments: Phase II upgrades to cope with high luminosity
  - Many challenges: high pile-up, high-level radiation, etc.
  - Good spatial resolution → high granularity
  - Timing separation between vertices → good timing resolution
- Phase II upgrades of both ATLAS and CMS detectors involve technologies developed by CALICE

CMS: High Granular Calorimeter (CMS-HGCAL)

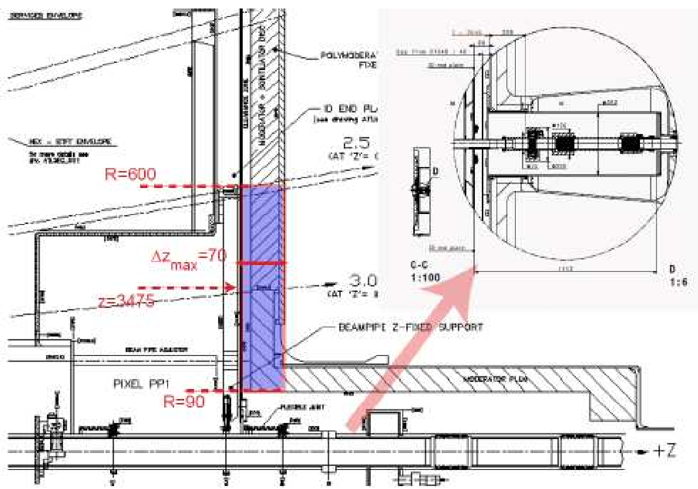




Parameters of the EE and FH.

	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

ATLAS: High Granularity Timing Detector (ATLAS-HGTD)



SUMMARY

- **The challenges of the ILC project have triggered breakthroughs in HEP instrumentation**
  - compliance with most ILC requirements is achieved $\rightarrowtail$ a few years needed to complete the R&D
  - new standards established in high precision devices relevant for future experiments
  - new technologies (& strategies) have been validated, driven by the need for granularity (e.g. PFA):
    pixel sensors, SiPM, μpattern gas detectors, high precision SC EM $\oplus$ Hadronic calorimeters, ...)
- **The progress achieved has irrigated other (subatomic physics) domains**
  - High precision pixellated vertexing & tracking devices
    (STAR at RHIC, ALICE at LHC, BELLE-2 at SuperKEKB, CBM at FAIR, etc.)
  - Highly granular calorimetres: CMS and ATLAS at LHC, ...
  - Detector concepts for future e^+e^- colliders: CLIC, CEPC, ... (watch power saving !)
  - Numerous spin-offs outside HEP: hadrontherapy, X-Ray & beta imaging, ROC for industrial needs, ...
- **Outlook:**
  - coming two years decisive for ILC (e.g. wrt European Strategy update)
  - if ILC goes ahead, fully integrated subsystems are to be built & validated
    before technological choices can take place $\gtrsim$ 2025 $\rightarrowtail$ start of physics $<$ 2035

The Central Conflict of Vertexing

- A COMPLEX SET OF STRONGLY CORRELATED ISSUES :

※ **Charged particle sensor technology :**

- highly granular, thin, low power, swift pixel sensors

※ **Micro-electronics :**

- highly integrated, low power, SEE safe, r.o. μcircuits

※ **Electronics :**

- high data transfer bandwith (no trigger), some SEE tol.
- low mass power delivery, allowing for power cycling

※ **Mechanics :**

- rigid, ultra-light, heat but not electrically conductive, mechanical supports, possibly with $C_{\Delta t} \simeq C^{Si}_{\Delta t}$
- very low mass, preferably air, cooling system
- micron level alignment capability

※ **EM compliance :**

- power cycling in high B field $\Rightarrow$ F(Lorentz)
- higher mode beam wakefield disturbance $\Rightarrow$ pick-up noise ?

※ **Radiation load and SEE compliance at T_{room}**

$\Rightarrow$ reduced material budget