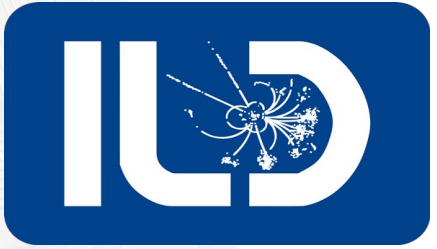
ILD: status, concrete R&D and long-term wishes

Adrián Irles
(AITANA group at IFIC – CSIC/UV)

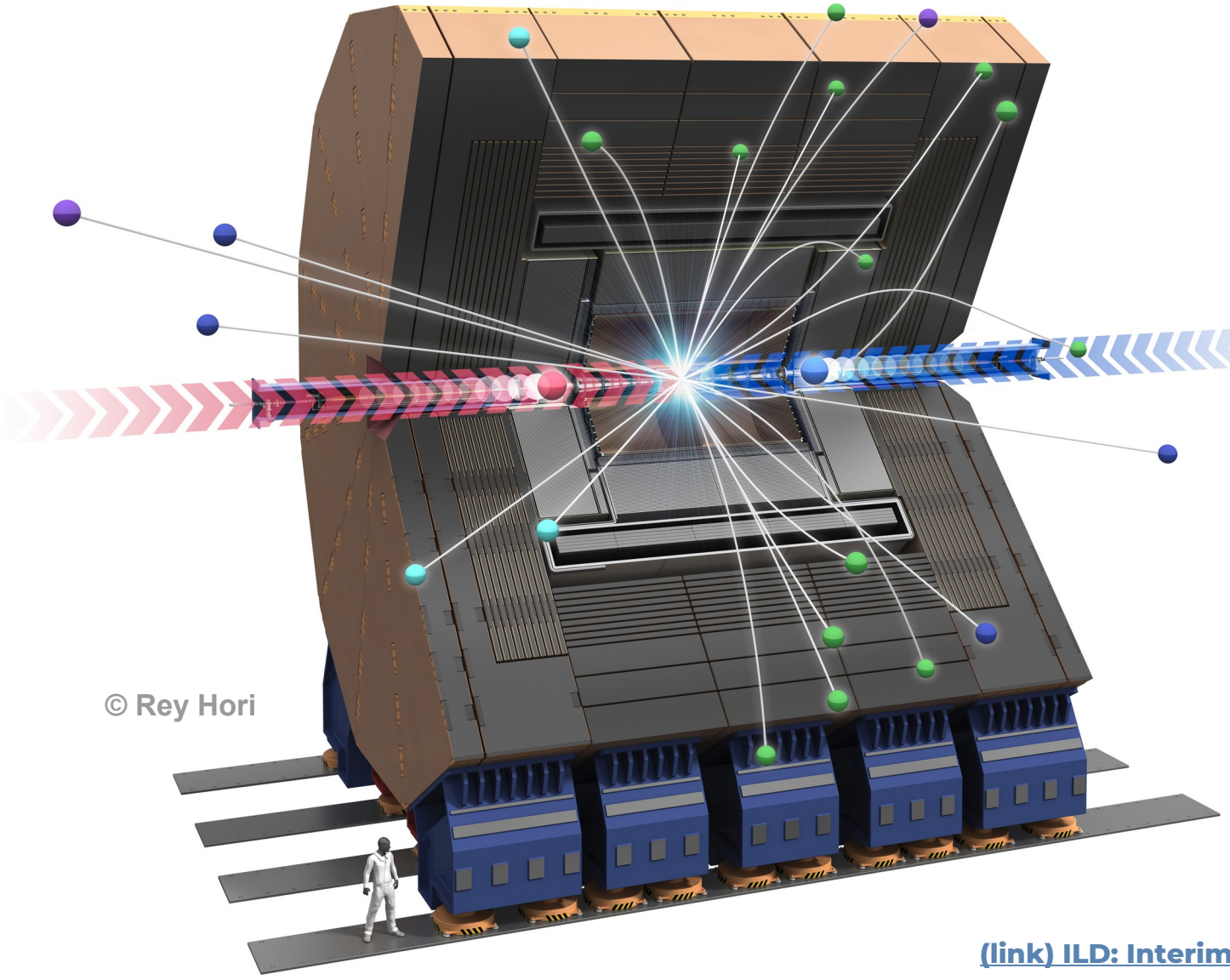
on behalf of the
ILD concept group



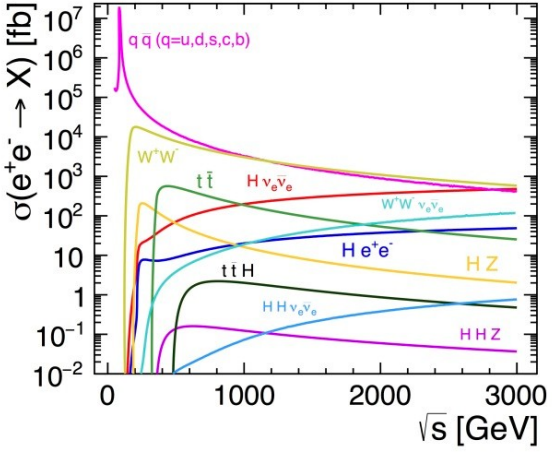
Pending actions:

wait for the ILCX-physics talks to be uploaded and fill slides 12-15

add links to a selection of hardware related talks



© Rey Hori



[(link) ILD: Interim Desing Report](#)

Optimized ILD design

From key requirements from physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}$ GeV^{-1} $\oplus$ $1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2}\theta)$ μm
- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%
- **hermeticity** ($H \rightarrow$ invis, BSM) θ_{min} = 5 mrad

To key features of the **detector**:

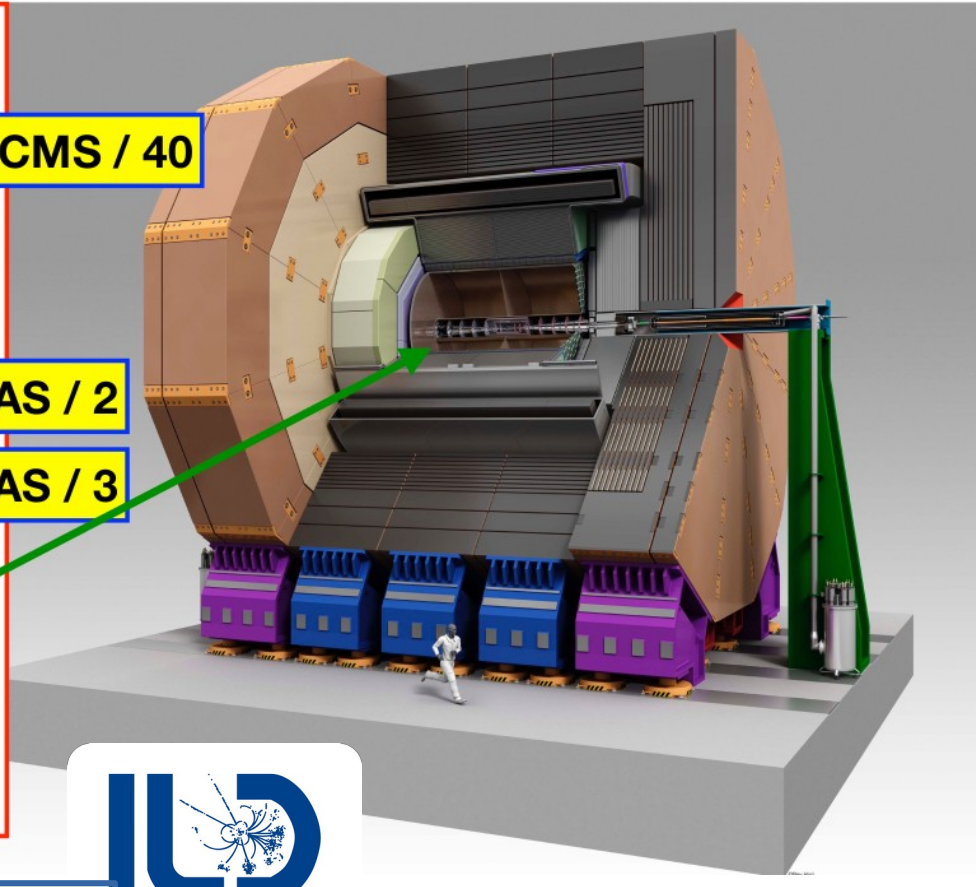
- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow

≈ CMS / 40

≈ CMS / 4

≈ ATLAS / 2

≈ ATLAS / 3



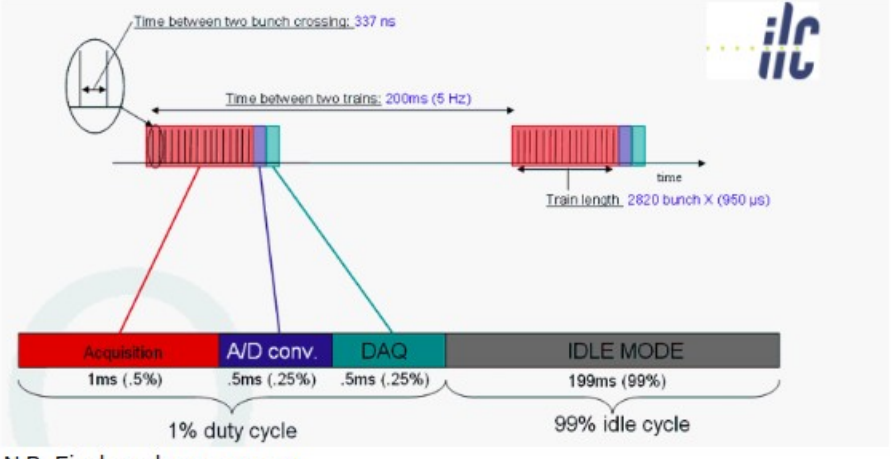
~x1000 more ro cells than LHC exps.
~x10-100 more than HL-LHC exps.

ILC offers a favorable experimental framework

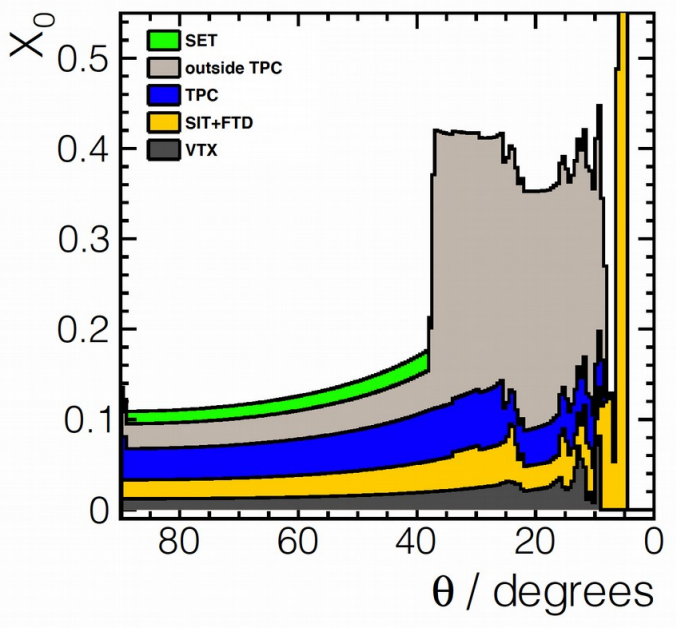
Linear Lepton Colliders favor fully optimized PFA detectors

- Possible since experimental environment at ILC very different from LHC/LEP:
  - much smaller beam spot and beam pipe (first tracking layer at ~1.6cm of the IP)
  - much lower backgrounds
  - much less radiation
  - **Pulsed beam structure**

Power pulsed electronics → low material budget !
triggerless operation ! –> ALL events are recorded

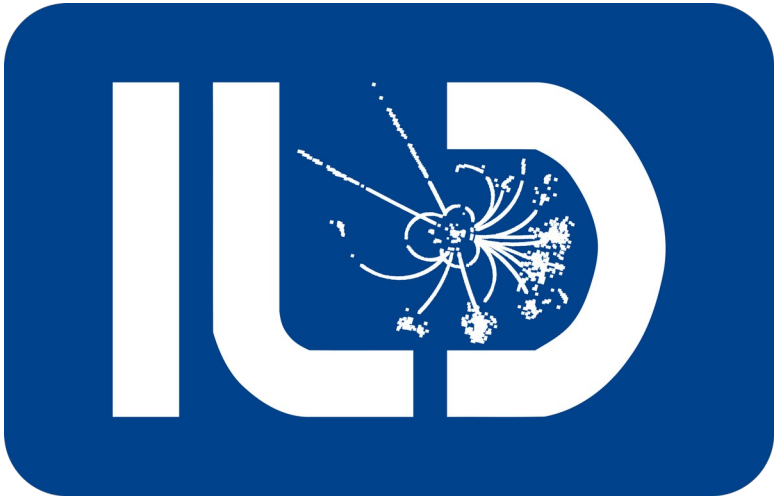


N.B. Final numbers may vary



ILD Concept Group

- **68 Institutes Worlwide are members of ILD**
- ILD Executive Team (ILD-ET)
  - Spokesperson: Ties Behnke
  - Deputy spokesperson: Kiyotomo Kawagoe
- Physics coordinator:
  - Keisuke Fujii (deputy Filip Zarnecki)
- Technical coordinator:
  - Mary-Cruz Fouz (deputy Karsten Buesser)
- Software/ reconstruction coordinator:
  - Frank Gaede (deputy Daniel Jeans)
- Elected members of the ILD executive Team:
  - Jean-Claude Brient, Jenny List, Wataru Ootani, Graham Wilson



https://confluence.desy.de/display/ILD/ILD

The ILD group participates in the ILC International Development Team (IDT), largely in Working Group 3 (physics and detectors).

ILD Concept Group

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- ILD Executive Team (ILD-ET)
  - Spokes
  - Deputy
- Physics
  - Keisuke
- Technic
  - Mary-C
- Softwar
  - Frank G
- Elected
  - Jean-Claude Brient, Jenny List, Wataru Ootani, Graham Wilson

Joining ILD

- **We welcome new members**
  - No resources commitment needed
  - Key contributions are possible in many areas
- **Guest membership**
  - Simple access mechanism to ILD simulated data and tools.

ay/ILD/ILD

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ILD Concept Group

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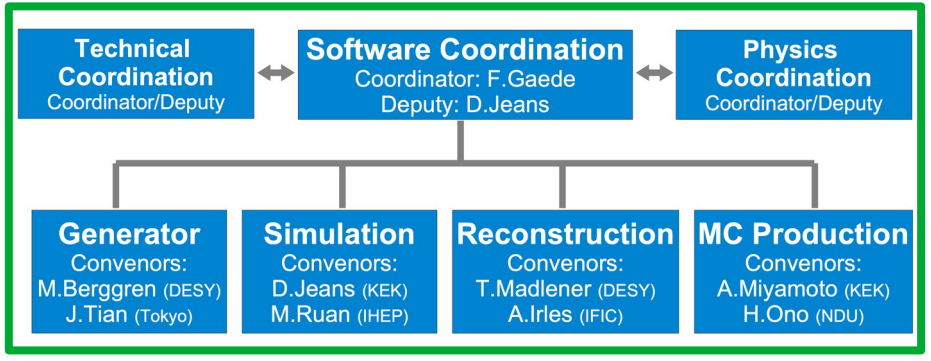
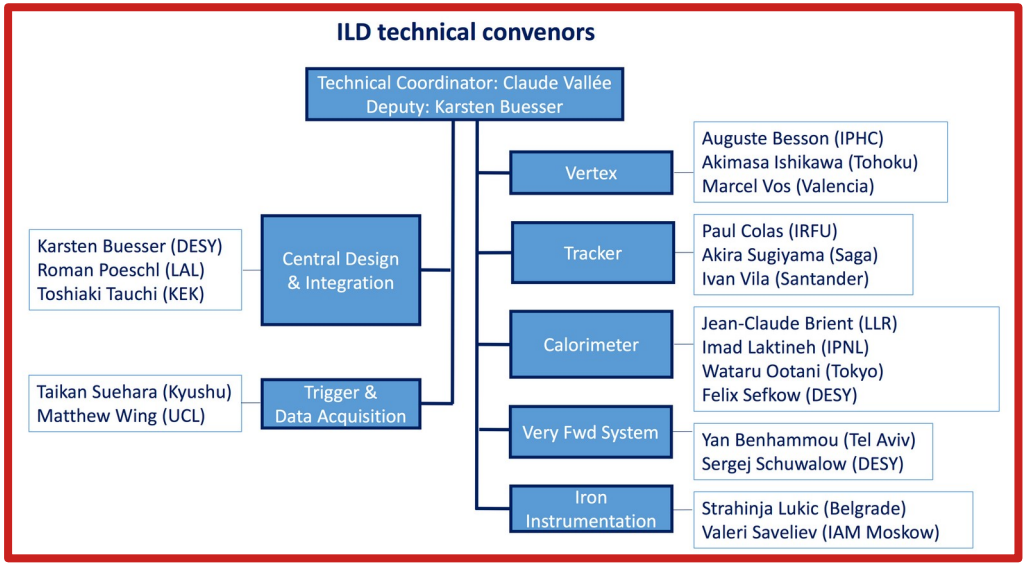
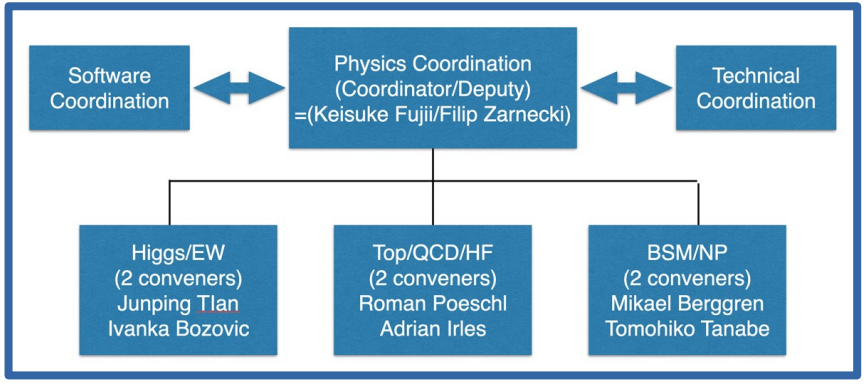


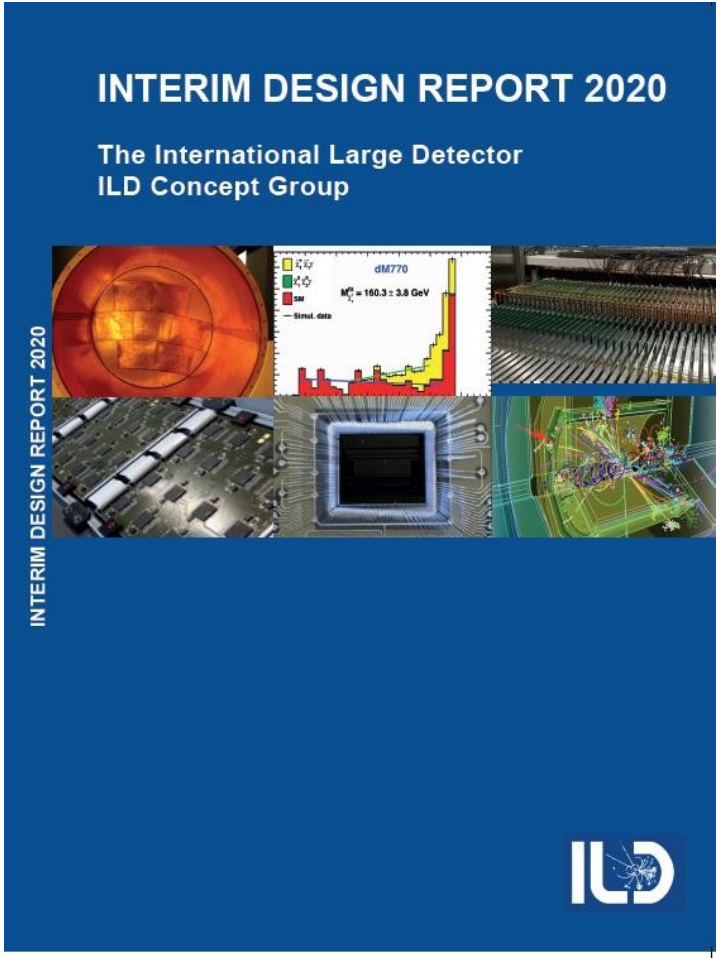




The ILD: Interim Design Report (IDR)

- Recent review of ILD potential and R&D status
  - Full - simulations
  - Dedicated revision and creation of software tools for realistic reconstruction
  - Dedicated full simulation studies on detector performance
  - Dedicated full simulation studies on physics benchmarks
  - Cost studies
  - Planned future actions

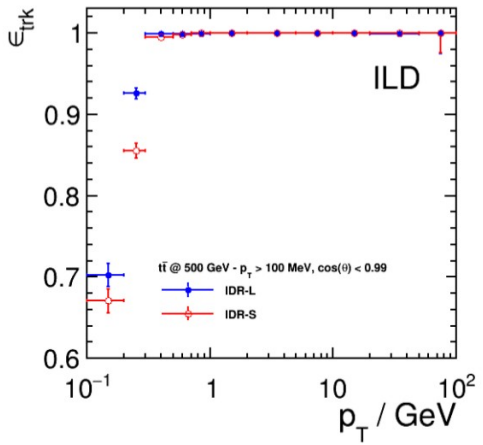
arxiv:2003.01116



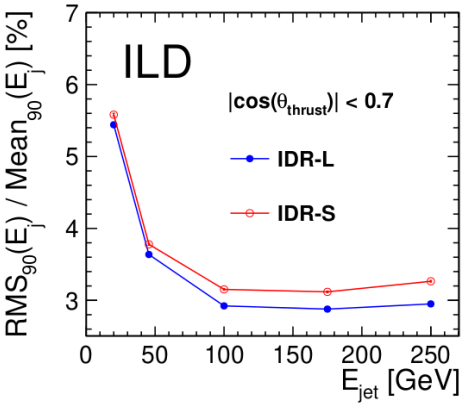
Updated ILD performance studies

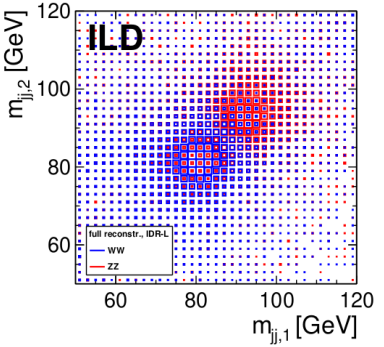
Different ILD models have been optimized to maximize the performance:
Full simulation of the baseline detector model (small & large)
+ realistic reconstruction

Tracking efficiency

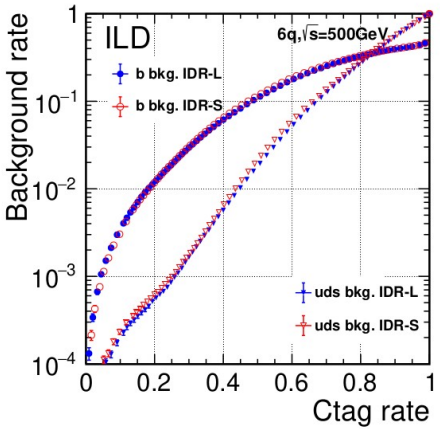


Jet Energy resolution

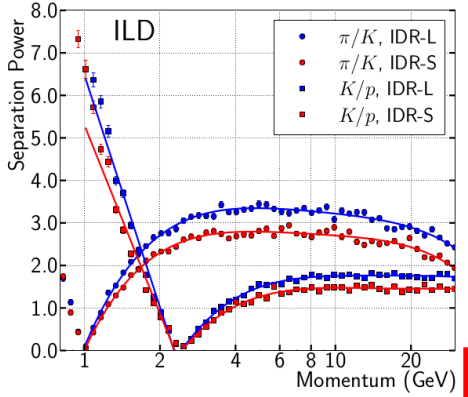




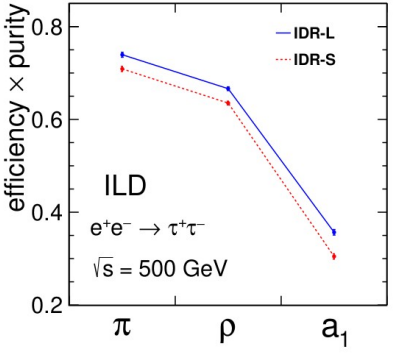
Flavour Tagging



Particle ID
jet charge measurement



Tau Decay ID

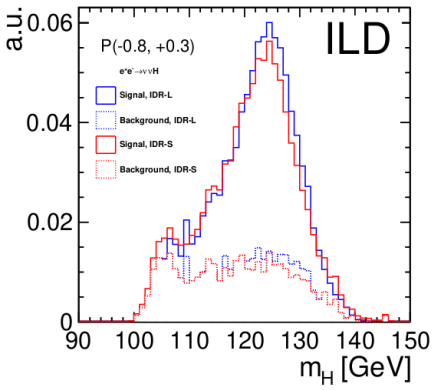


(link) ILD: Interim Desing Report

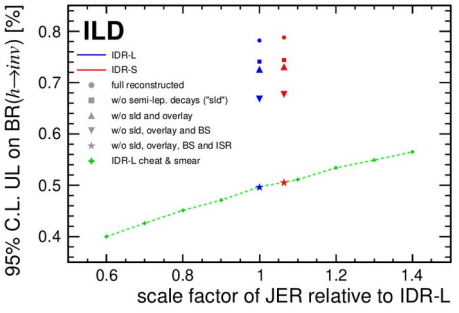
Updated ILD physics potential and benchmarking

Physics benchmarks (update for 500GeV)

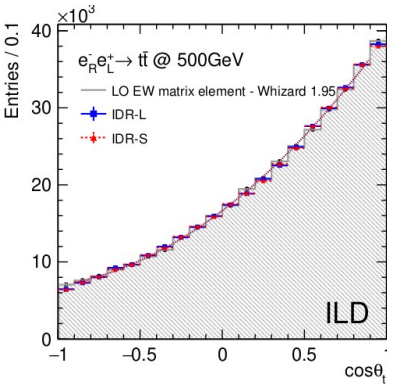
Higgs to b/c/g

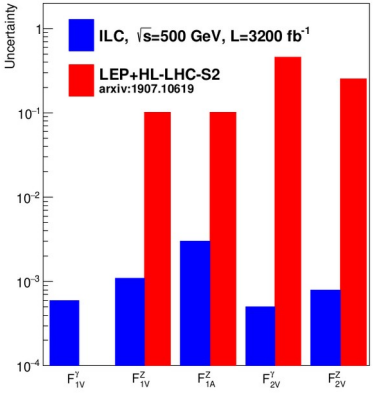


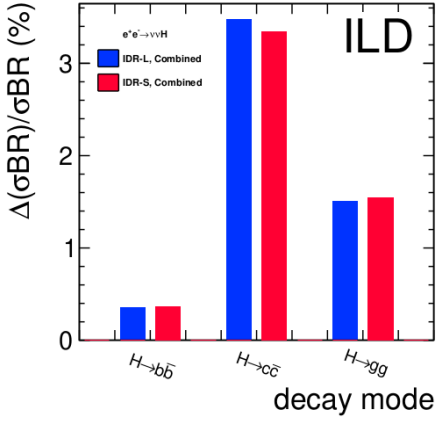
Higgs to inv.



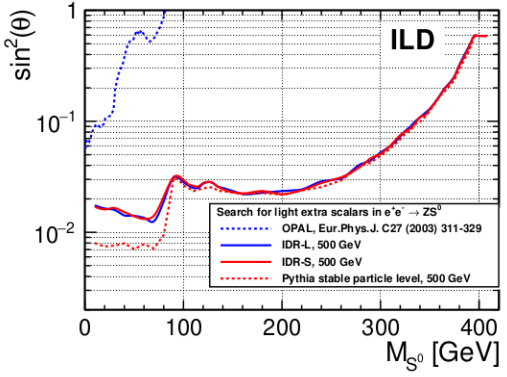
Top EW couplings

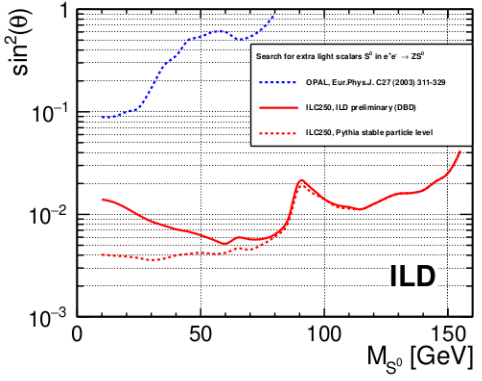






e+e-→ZS (light scalars)





(link) ILD: Interim Desing Report

ILD & ILCX2021 - I

- **Particle identification with time-of-flight**
  - Bohdan Dudar (DESY) https://agenda.linearcollider.org/event/9211/contributions/49381/
- **Jet energy calibration using e+e- → γZ process at the ILC**
  - Takahiro Mizuno (Sokendai) https://agenda.linearcollider.org/event/9211/contributions/49458/
- **Summary of the new 250 GeV MC samples production for ILD physics**
  - Hiroaki Ono (Nippon Dental University) https://agenda.linearcollider.org/event/9211/contributions/49386/
- **Timing reconstruction with deep learning**
  - Mami Kuhara (Kyushu University) https://agenda.linearcollider.org/event/9211/contributions/49382/

One or two plots to be collected from the ILCX2021 talks

Strong focus on ILC250

ILD & ILCX2021 - II

▶ Measurement of σ(e+e−→HZ)×Br(H→ZZ∗) at the 250 GeV ILC

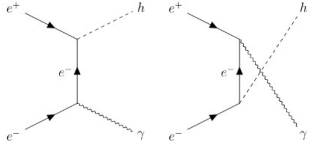
- Evgeny Antonov (Lebedev Physical Institute of the Russian Academy of Sciences) https://agenda.linearcollider.org/event/9211/contributions/49349/

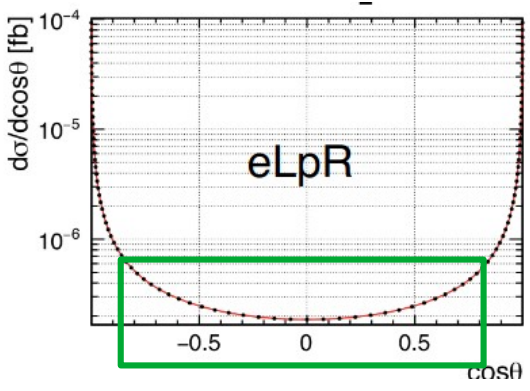
▶ Study of photon-associated Higgs production at the ILC

- Yumi Aoki (Sondekai/KE) https://agenda.linearcollider.org/event/9211/contributions/49374/

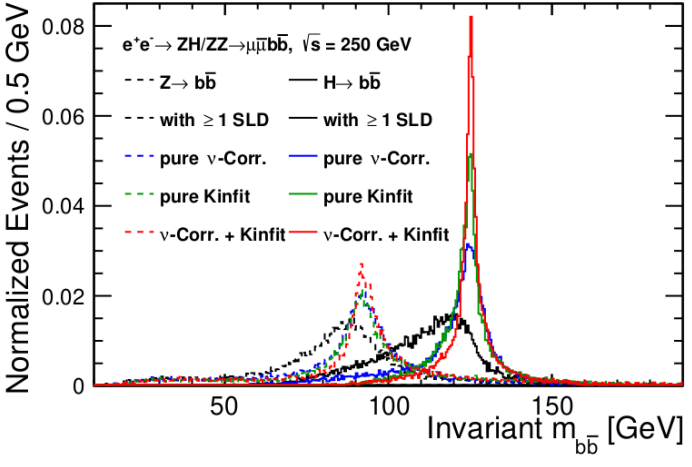
▶ Kinematic fitting for ParticleFlow Detectors at Future Higgs Factories

- Yasser Radkhorrami (DESY) https://agenda.linearcollider.org/event/9211/contributions/49376/





Constraint on electron Yukawa coupling



ILD & ILCX2021 - III

▶ Forward Backward Asymmetry studies with heavy quarks (b/c) at ILC250

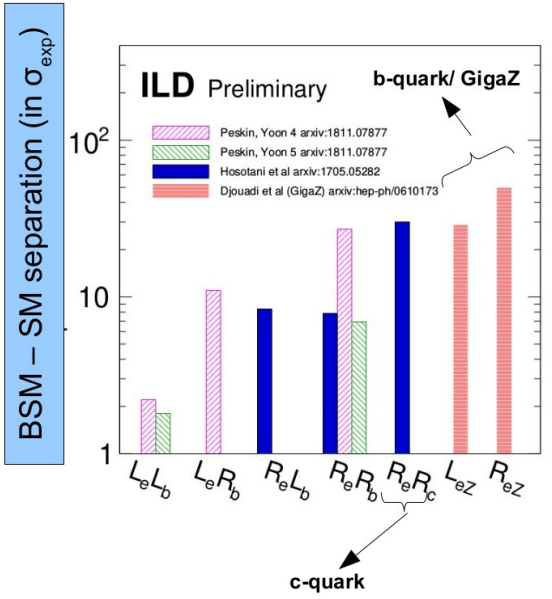
- A. Irles (IFIC)
  https://agenda.linearcollider.org/event/9211/contributions/49358/

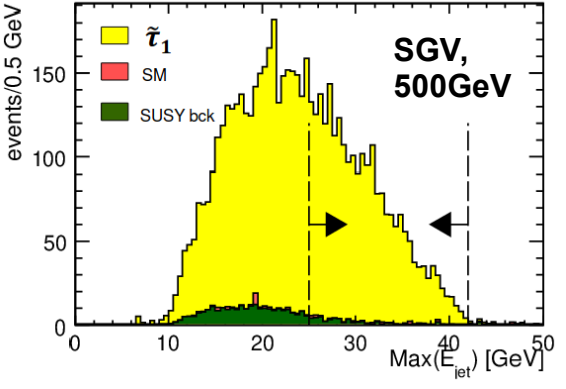
▶ Towards ee->ss at ILC250

- Yuichi Okugawa (IJCLab-Tohoku U)
  https://agenda.linearcollider.org/event/9211/contributions/49359/

▶ Stau Searches at the ILC

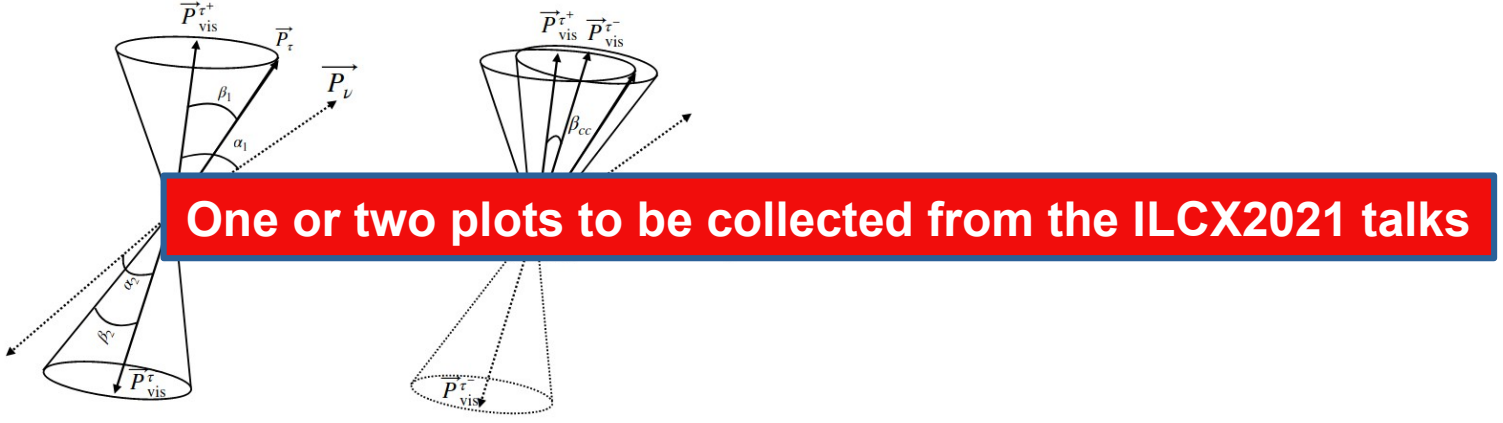
- Teresa Nuñez (DESY)
  https://agenda.linearcollider.org/event/9211/contributions/49280/





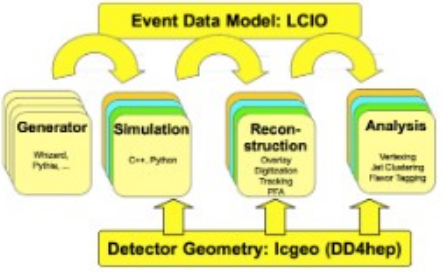
ILD & ILCX2021 - IV

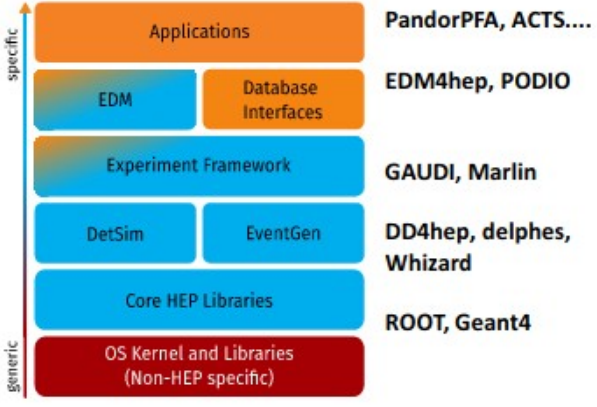
- **Exploring Right Handed Neutrinos at ILC**
  - Jurina Nkajima (Sokendai/KEK) https://agenda.linearcollider.org/event/9211/contributions/49266/
- **Tau reconstruction in e+e−→τ+τ− at the ILC250**
  - Keita Yumino (Sokendai) https://agenda.linearcollider.org/event/9211/contributions/49277/
- **Center-of-mass energy determination using dimuon events at ILC**
  - Graham Wilson https://agenda.linearcollider.org/event/9211/contributions/49276/

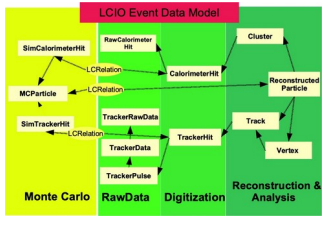


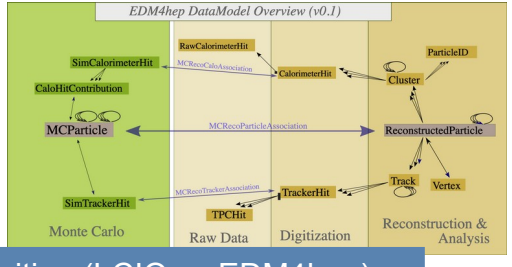
Software

- **ILD soft group is** a central player in pushing community wide software solutions in particular with **iLCSoft (LCIO, DD4hep, etc)** developed over 15 years
  - have developed **realistic and detailed ILD simulation** models and sophisticated **full (high level) reconstruction algorithms** in this framework
- We are very actively **collaborating** with **other communities (linear, circular, FCC-hh)** to modernize our software stack in the **Key4hep** project
  - strong focus on PODIO/EDM4hep based on expertise with LCIO
  - plan to eventually migrate the complete software ILD stack into Key4hep
  - ensure a smooth transition on the way (using the MarlinWrapper)







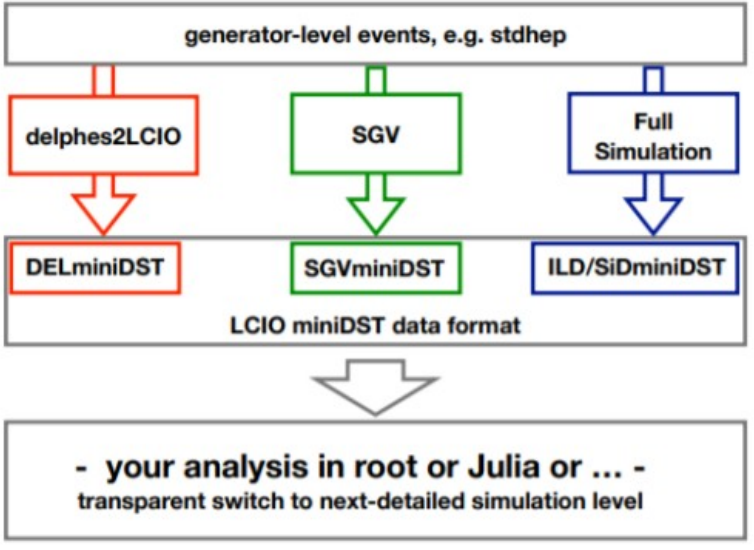


EDM evolution/transition (LCIO → EDM4hep)

Software

ILD soft and simulated data are accessible

- ILD developed a **new** high-level LCIO-based data format, **the mini-DST, which can be produced from full sim/SGV DSTs or from Delphes**
- ILD is actively contributing to the **software tutorials organized by the IDT-WG3 Software Group**
  - https://agenda.linearcollider.org/category/273/



ILD physics benchmarck studies

Large effort in updating physics studies and reconstruction software

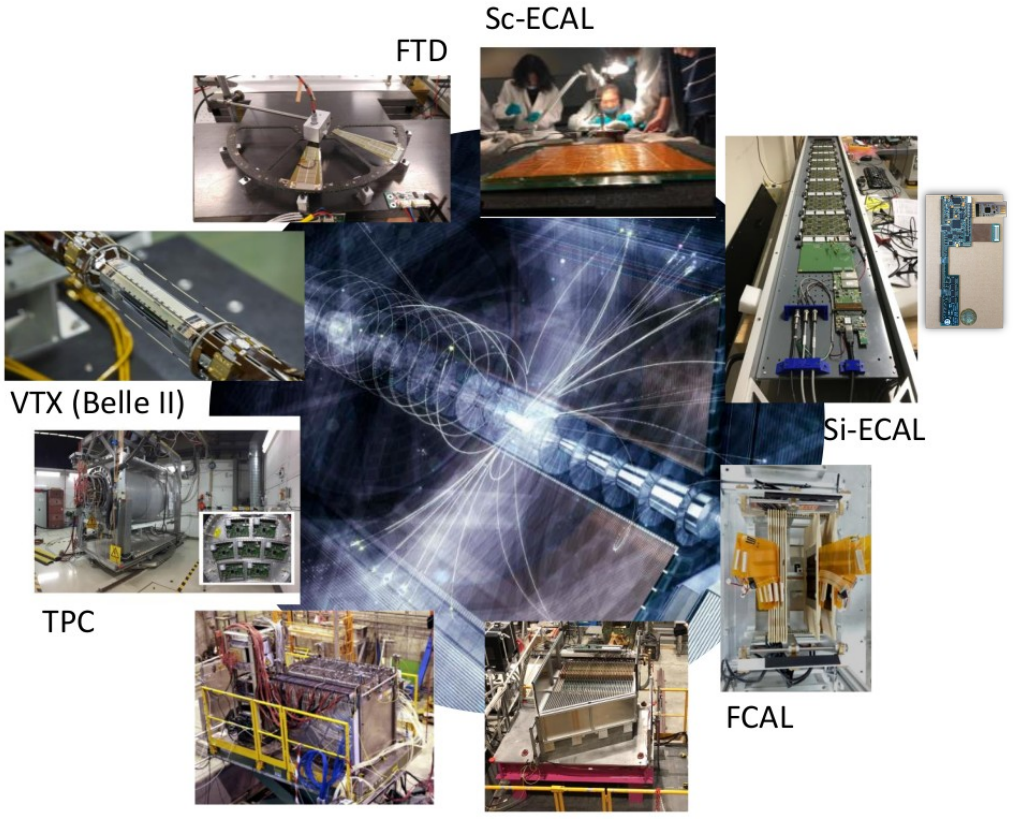
- **New ideas and newcomers are welcome**
- Some activities / open points on physics are listed in the ILD twiki
  - Lots of physics potential studies to be done: **at 250GeV but also at different energies**
  - Revisiting Higgs self-couplings in view of the recent improvements in high level reco (i.e. di-jet mass separation)
  - Exact definition of the needed energy of the second stage energy: (ZHH vs ttH needs)
  - More comprehensive coverage of exotic long-lived particles,
  - More detailed studies on systematics effects,
  - Gain by introducing new techniques as ML, AI, etc...
  - etc

Status of the R&D

R&D status

- ILD has a concept of the detector,
  - well defined
  - with technological options where sensible
- The main components of ILD
  - have been validated and beam-tested.
- A coherent System design has been developed.

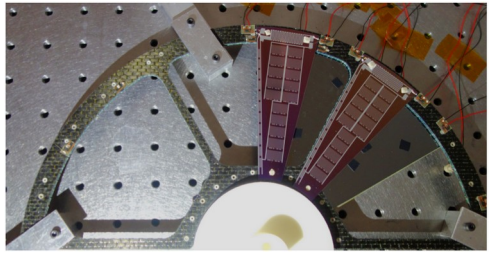
Application of our technologies: CMS Calo upgrade, Belle VTX, T2K TPC, ALICE TPC

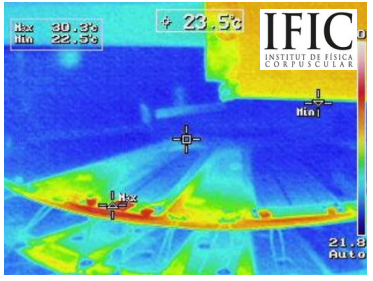


Slide borrowed from T. Benhke (ILD spokeperson)

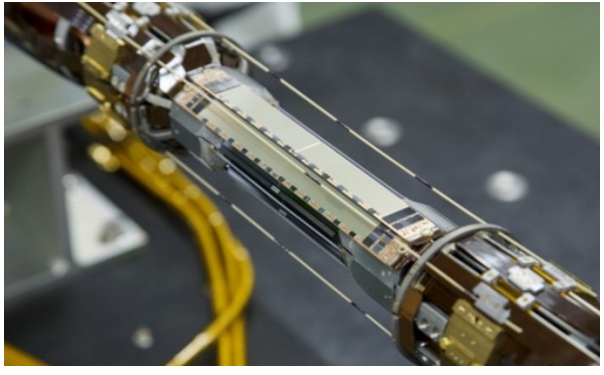
Silicon Tracking Systems R&D

Forward Tracking
Petal Thermomechanical mock-up

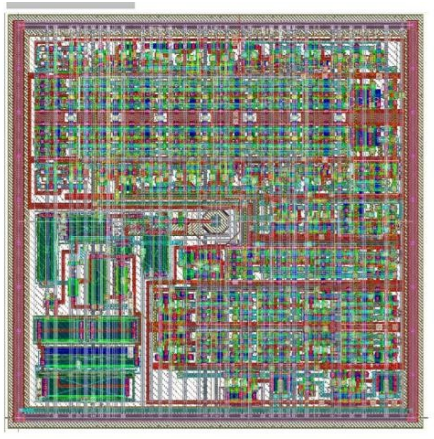




- **Silicon tracking conceptual studies**
  - VTX extensive technology studies
- **Several technology options remain open**
  - CMOS / FPCCD / DEPFET / 3D-integrated / SOI



DEPFET VXD @ Belle2



DuTiP1
Dual Timer (down time counters) in a Pixel to store signal and wait for trigger signal.

DuTiP SOI pixel detector for the Belle II under development

CMOS R&D news

▶ CMOS (MAPS) are specially suited for applications requiring low mass and excellent position resolution

- Continuous readout: speed ? (trade off consumption vs speed)
- Industrial technology

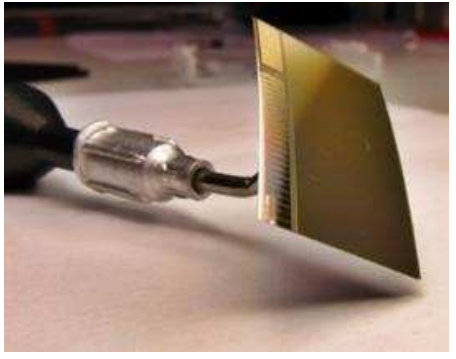
▶ 180 nm technology: VALIDATED

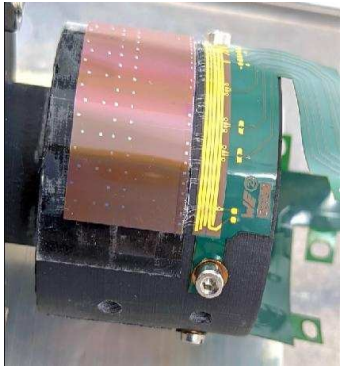
- ALPIDE@ ALICE ITS-3, MIMOSIS @ CBM-MVD)
- ILD doable in 180nm tech: 4um / 4us resolution, <100mW/cm^2
- MIMOSIS-1 → unique in terms of hit density treatment and readout speed (design adaptable to <1us). Testbeams and data analysis in progress.

▶ 65 nm technology:

- being explored in order to validate it for charged particle detection → test beams in progress
- smaller pixels, more in-pixel functionalities, less power consumption, faster readout
- driven by CERN EP R&D WP 1.2 and ALICE ITS-3 upgrade with other labs.

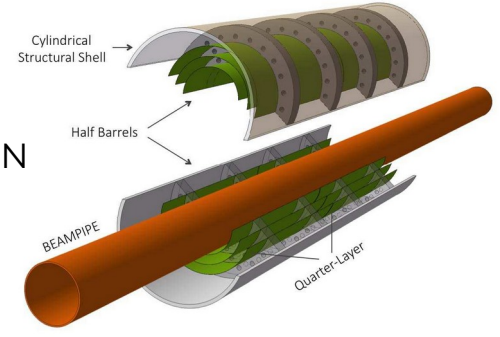
MIMOSIS-1 and bent ALPIDE (at IPHC-Strasbourg)





▶ Bending thin Si-Layers

- ALPIDE sensors bent by CERN and IPHC-Strasbourg for ALICE-ITS3
- *suportless*
- New geometries allowed



▶ Stitching

- Using several reticles from the same wafer
- Possible with both 180nm and 65nm

CMOS R&D news

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- smaller pixels, more in-pixel functionalities, less power consumption, faster readout
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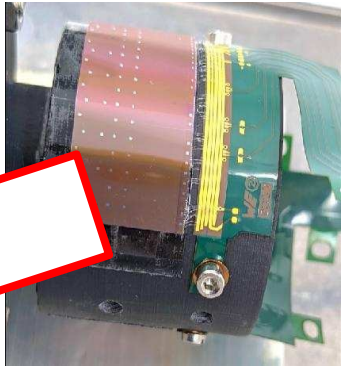
Rapidly evolving R&D: stay open for new ideas / layouts proposals

MIMOSIS-1 and bent ALPIDE (at IPHC-Strasbourg)



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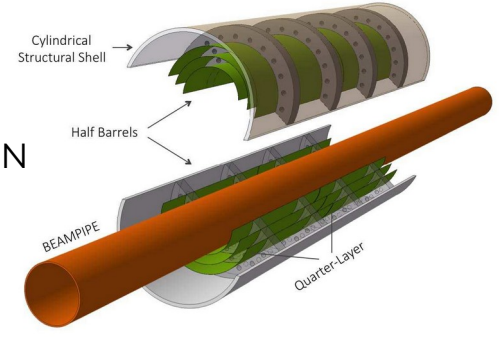
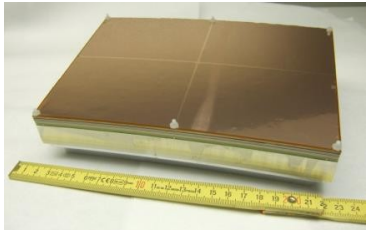


▶ **Stitching**

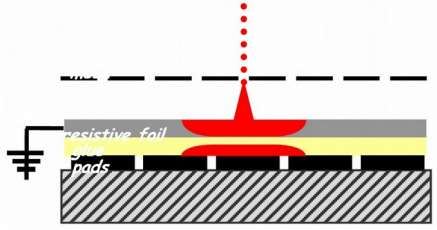
- Using several reticles from the same wafer
- Possible with both 180nm and 65nm

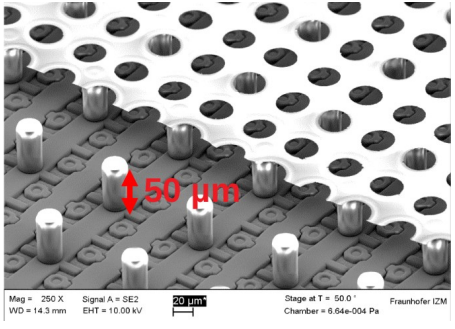
TPC Tracking System R&D

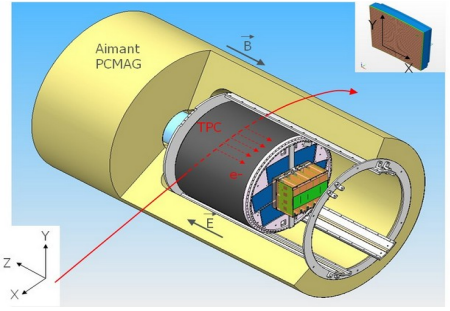
- **GEMs**: double thick – Asia – or triple standard GEMS – DESY
  - Minimize dead area -> no frame at modules sides but a 1 mm grid to hold GEM

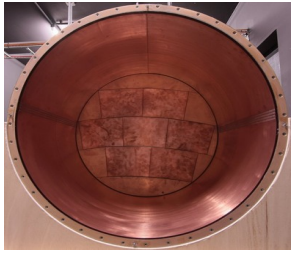


- **Resistive Micromegas** (Saclay)









PCMAG: B < 1.2 T,
bore diameter: 85 cm
Electron test beam: E = 1- 6 GeV

- **GridPix (Nikhef Bonn)**
  - Timepix3 readout + micromegas as gas amplification → smaller pads/pixels

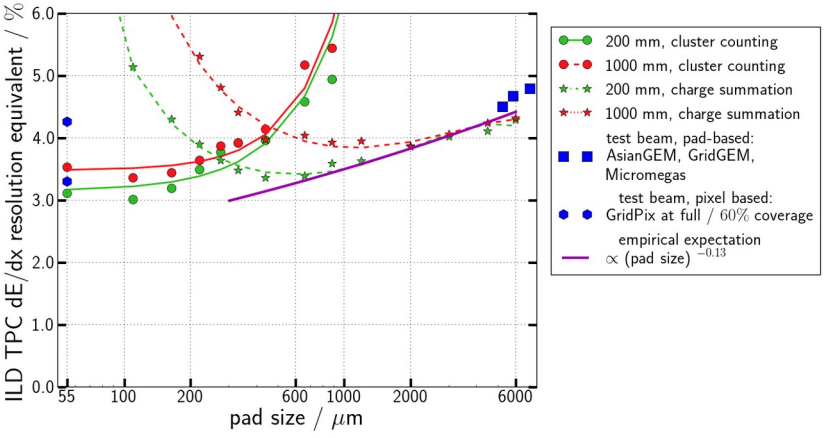
Large Prototype has been built to compare different detector readouts under identical conditions and to address integration issues

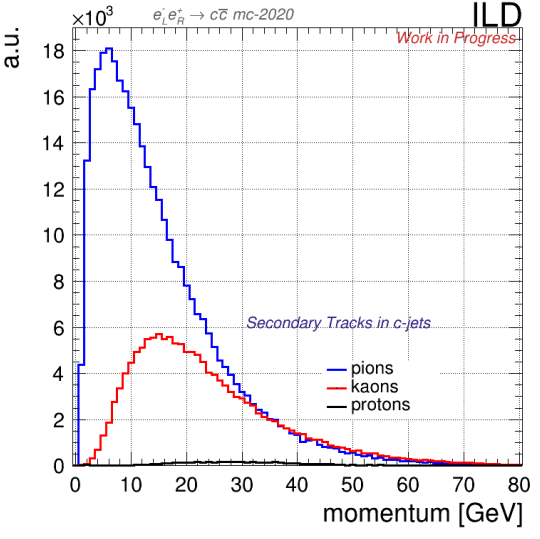
LCTPC planning a new generation of modules with comparable design (for better comparisons)

dE/dx particle Identification

- **Conventional dE/dx method: sum of all charge of a track**
  - Landau shaped, large RMS… compensated with truncated mean algorithms
- **Alternative approach: cluster counting**
  - Count number of ionising interactions (Poisson shaped)
  - Allows for better particle separation but depends on counting efficiency.
  - Can improve the separation power by a factor … 30-40%

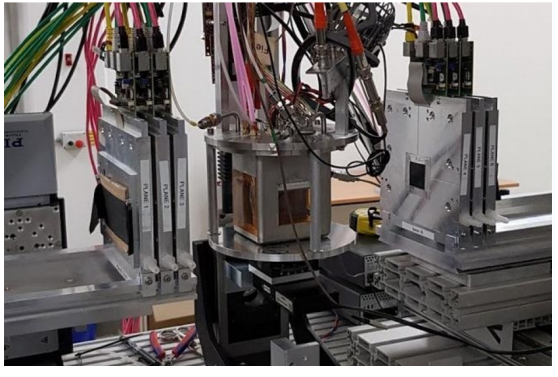
Under study (dedicated simulations and TBs)





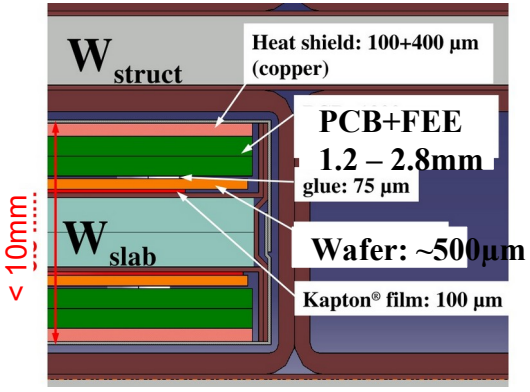
Decisive for topologies with b/c/s quarks in final states

GridPix, beam test at ELSA test beam @Uni Bonn



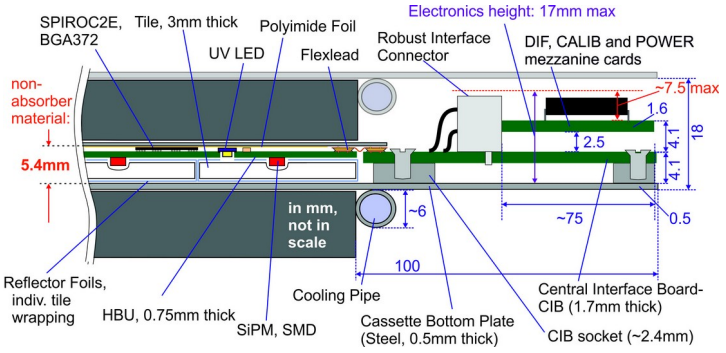
HG Calorimetry: Technological solutions I

SiW Ecal



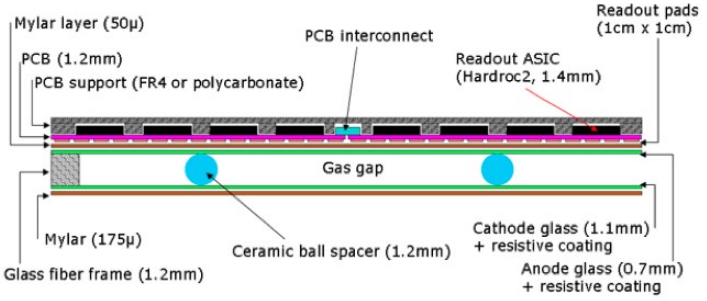
Semi-conductor readout
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



Optical readout
Typical segmentation: 3x3cm^2

Semi Digital HCAL



Gaseous readout
Typical segmentation: 1x1cm^2

Integrated front end electronics

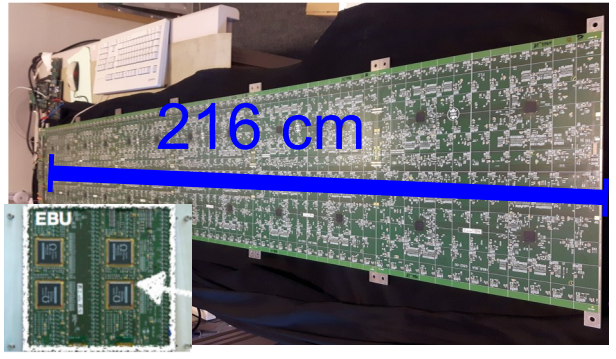
No drawback for precision measurements *NIM A 654 (2011) 97*

HG Calorimetry: Technological solutions II

SiW Ecal

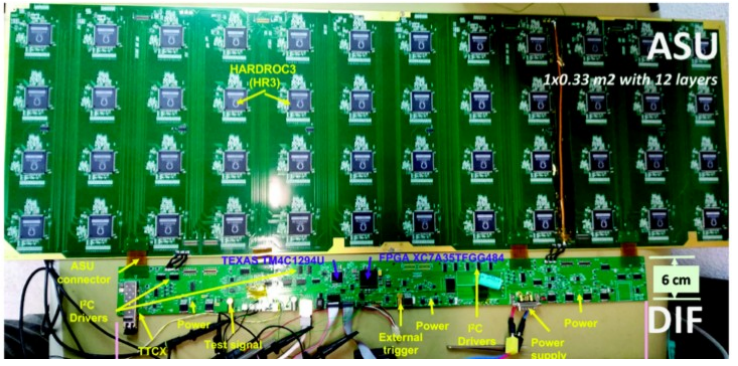
Semi-conductor readout

Analogue Hcal and Scintillator Ecal



Optical readout

Semi-digital Hcal



- **Realistic detector dimensions**
  - **Structures of up to 3m in length (more than 10000 cells)**
  - With compact external components
- Challenge for the power pulsing techniques (for the power consumption management)

CALICE Calorimeter for ILC

HG Calorimetry: Technological solutions II

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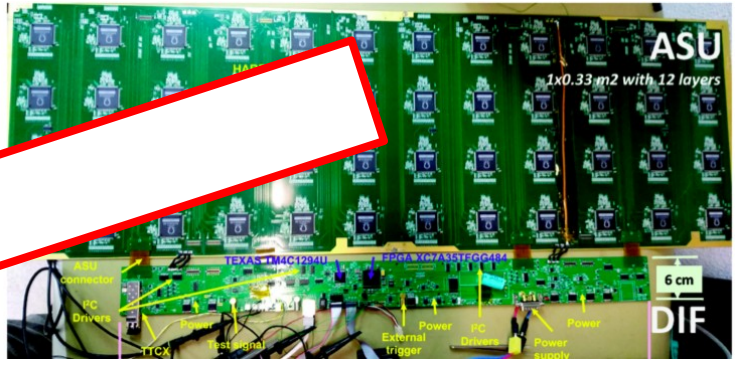
SiW Ecal

Semi-conductor readout

Analogue Hcal and Scintillator Ecal

Optical readout

Semi-digital Hcal



VERY LONG DETECTORS

Realistic detector dimensions

- **Structures of up to 3m in length (more than 10000 cells)**
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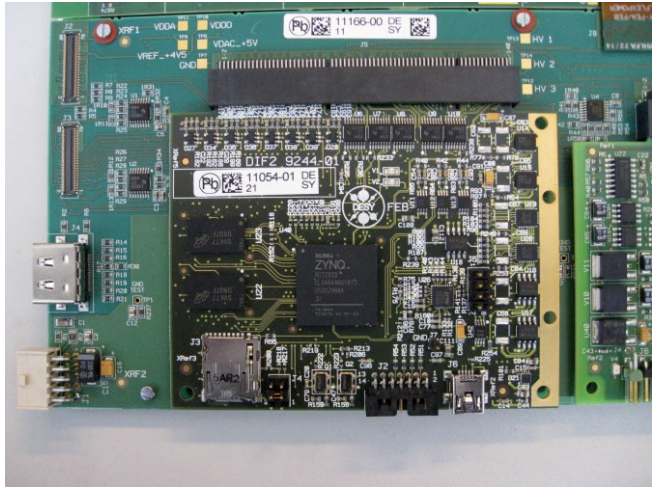
- Challenge for the power pulsing techniques (for the power consumption management)

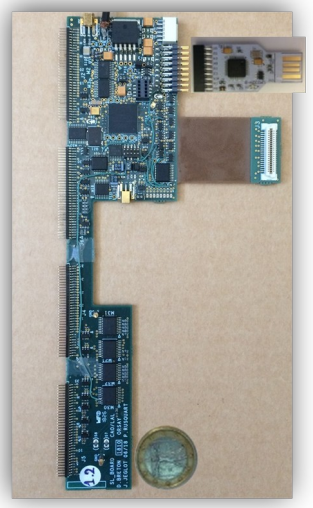
CALICE Calorimeter for ILC

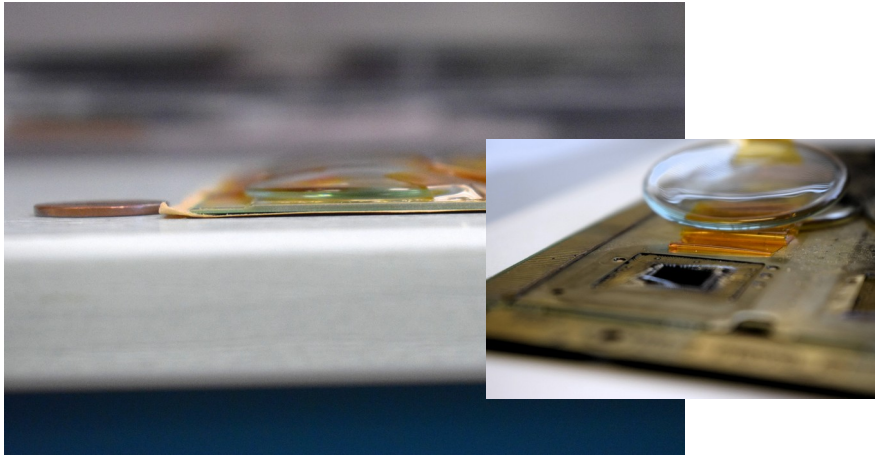
HG Calorimetry: Technological solutions III

Current detector interface card - AHCAL



Current detector interface card and thin detection unit – SiW Ecal





Current detector interface card - SDHCAL

- "dead space free" granular calorimeters put **tight demands on compactness**
- Current developments within **CALICE meet these requirements**

Unique successes in worldwide detector R&D

- Can be applied/adapted wherever compactness is mandatory
- Components will/**did already go through scrutiny** phase in beam test

HG Calorimetry: Technological solutions III

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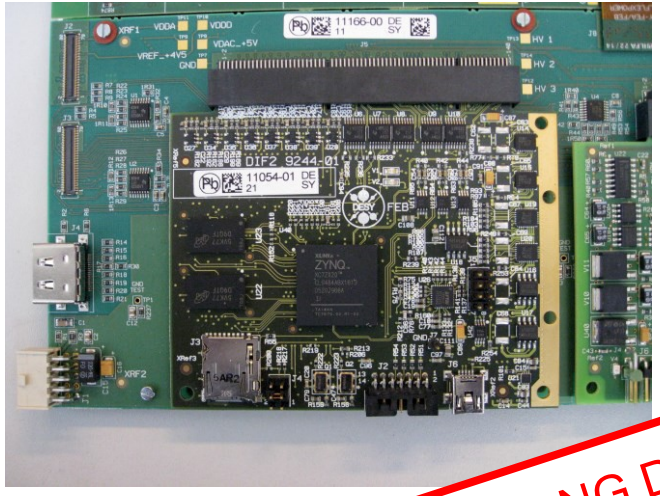

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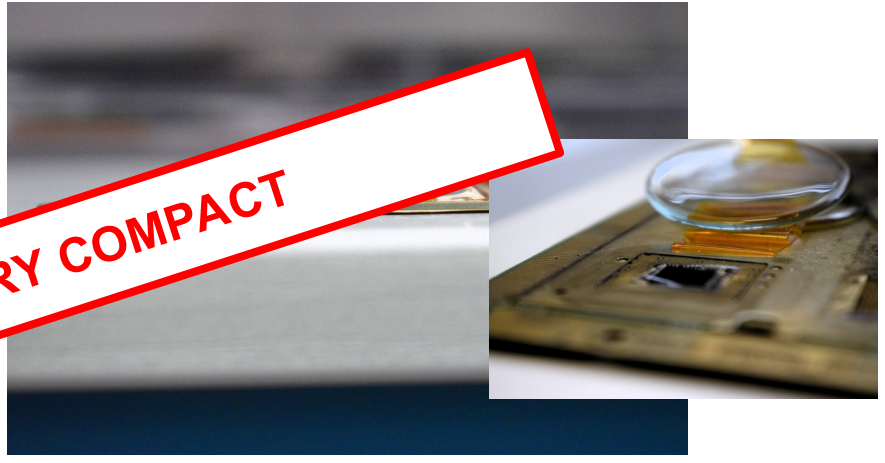
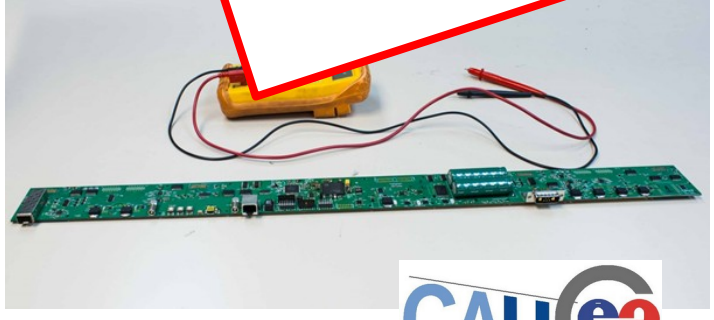


LONG DETECTORS but VERY COMPACT

Current detector int… …HCAL



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Prototyping + intensive TB phase

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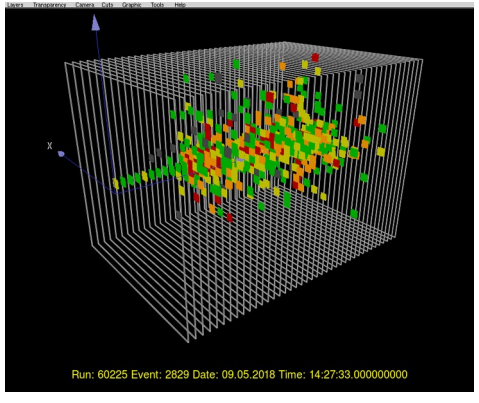
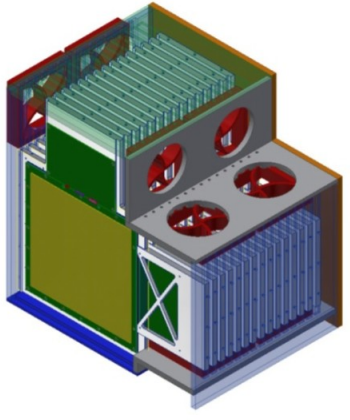
AHCAL

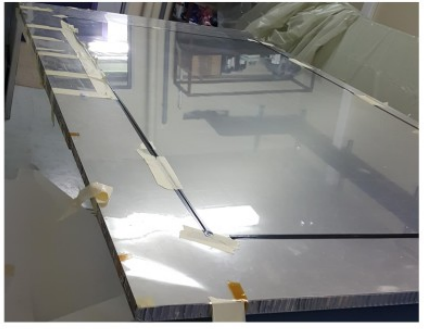


Sc-ECAL



SDHCAL

2 m^2 RPC assembled



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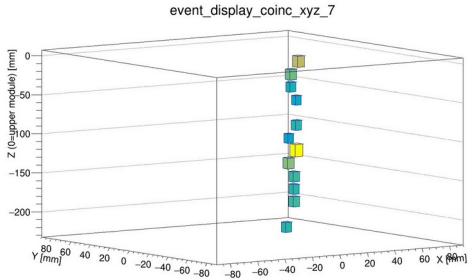

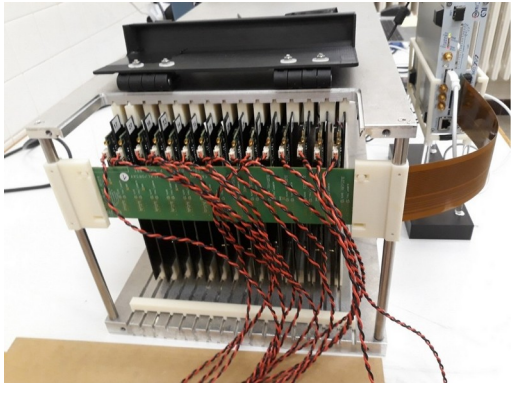

Prototyping + intensive TB phase

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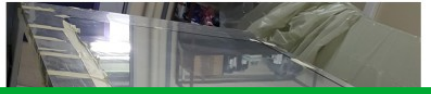
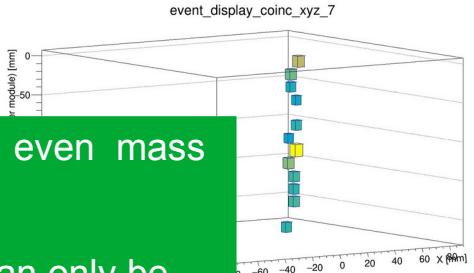


SiW-ECAL

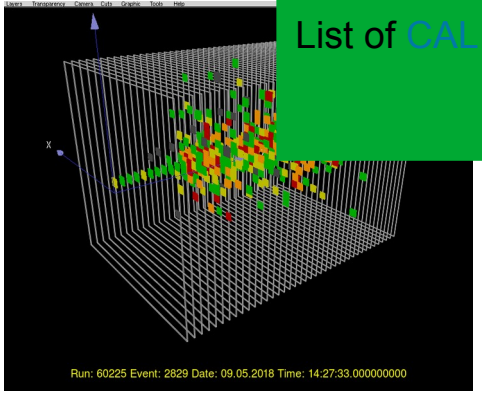


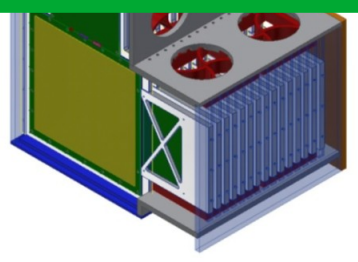
The different proposals are addressing technological feasibility aspects: even mass production feasibility.

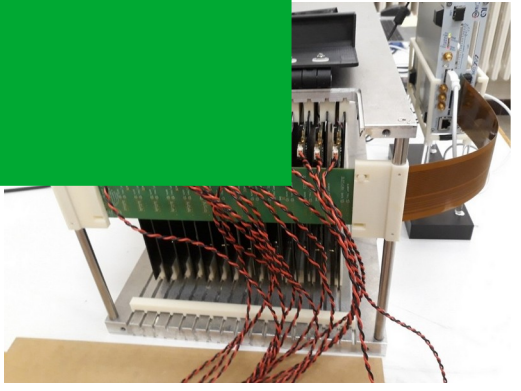
PF calorimetry is much more than energy resolution: fair comparisons can only be done with global studies (physics benchmarking comparisons) and **common testbeams !**

Common test beam campaign starting in 2022

List of CALICE results



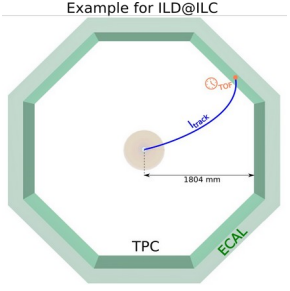




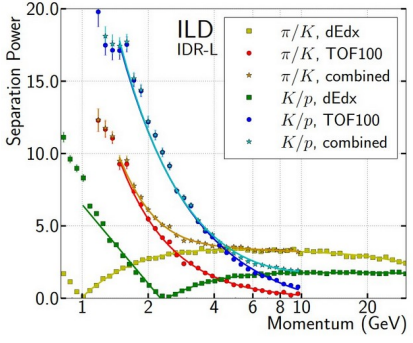
The 5th dimension?

TOF in the ECAL or outer trackers – Particle ID

- "Standard" silicon sensors could reach O(20-50ps)
- LGAD sensors could get us to O(10ps)
- Timing in MIPs or tracks or energetic showers ? Algorithms can improve "poor" single cell timing capabilities



B. Dudar

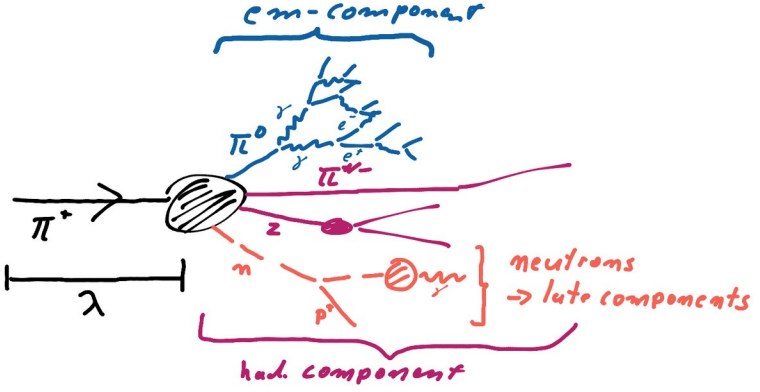


Impact in the physics reach?

- kaon ID impact on physics (relatively soft kaons)
- Full 5-D PF ? new ML techniques ? M. Kuhara

Timing measurements for shower developments

- Neutral and slow components
  - Require ~ns precision
  - Reachable today with today's CALICE prototypes
- ~0.1 ns scale: near the corner
- An even lower with GRPC (20ps)



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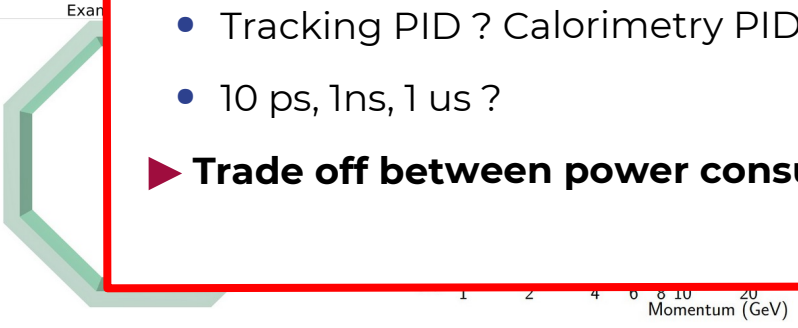
- Timing in
  Algorithm
  capabilitie

Timing measurements for shower developments

CALICE

Still lots of opportunities in ILD optimization:
physics goals, software developments and technology options

- **What are the real goals (physics wise)**
  - Tracking PID ? Calorimetry PID ? Shower development ?
  - 10 ps, 1ns, 1 us ?
- **Trade off between power consumption and timing capabilities**



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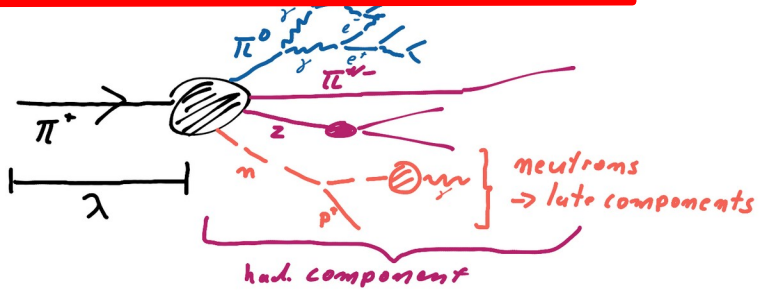


ILD detector optimisation

Large effort in software, detector and reconstruction optimization.

- **New ideas and newcomers are welcome**
  - **Hardware and software -wise**
- Some activities / open points are listed in the ILD twiki
  - Reoptimisation of silicon tracking systems
  - Fast timing implementation into ILD – 5D PF ?
  - Tracker alignment
  - Optimize photon reconstruction, reconstruction tools for long-lived particles, etc
  - Most of the R&D, optimization studies are done for the central regions of the detector…
  - More realism to be added in the simulations (cables, service systems…)
  - **Hardware/software needs must be driven by physics.**

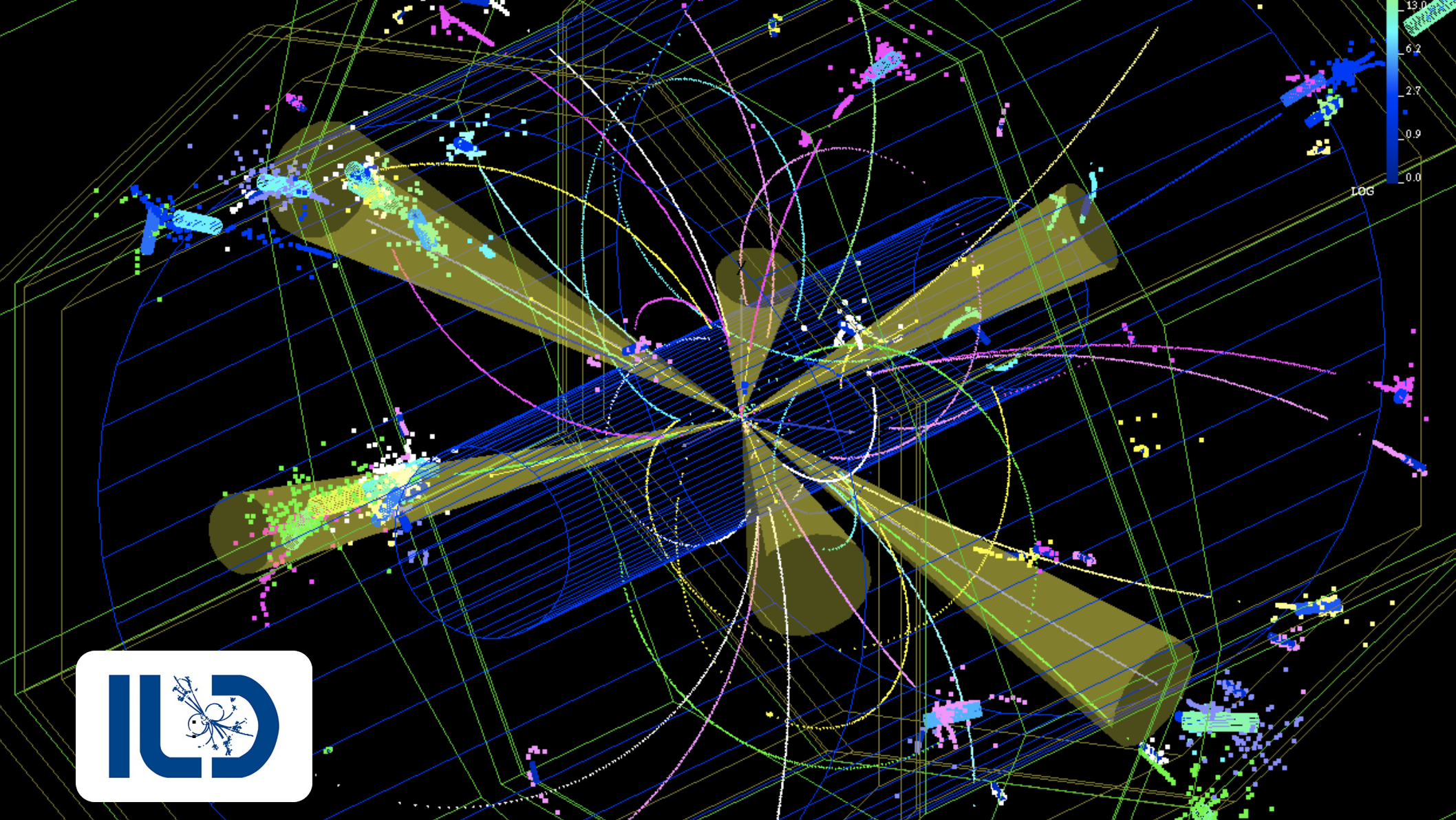
Summary

- **Most of the required technologies for an ILD are in the market**
  - Realistic prototypes already constructed or in process for several of the sub-detectors
- **Still open points**
  - Optimization of present designs ? Dedicated studies on integration:

    are the assumptions that we made in the past years still true? Can we do better?

    Could we live with more relaxed “requirements” that open the field to other technologies?
  - Improvements in Forward detector layout ? Inclusion of Timing ?
- **Detector optimization must be driven by the trade off between gain in physics and technological feasibility**
- **New ideas and participants are welcomed**

- **Unfortunately: several studies/technologies/systems could not be covered by this talk.**

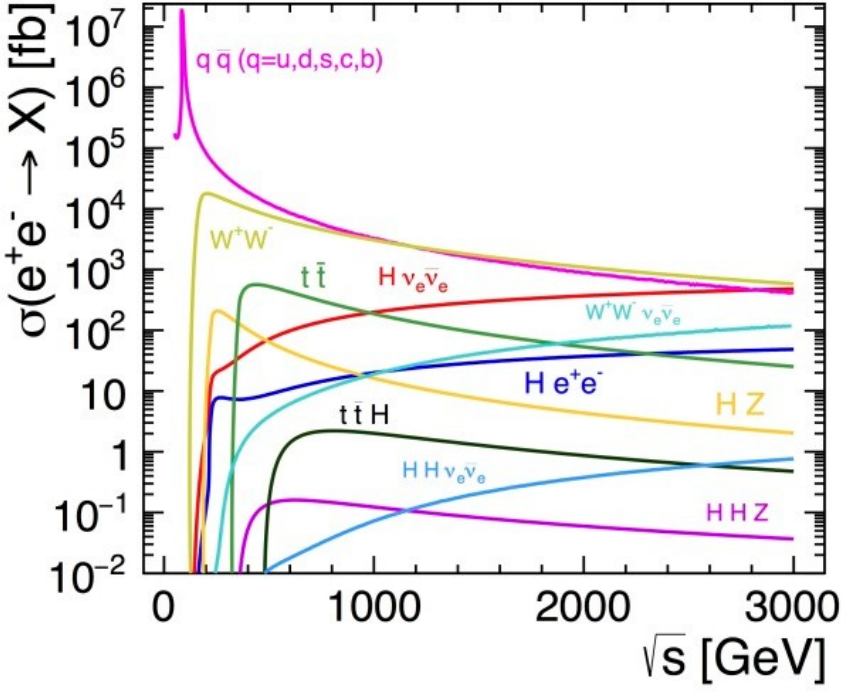

13.0
6.2
2.7
0.9
0.0
LOG

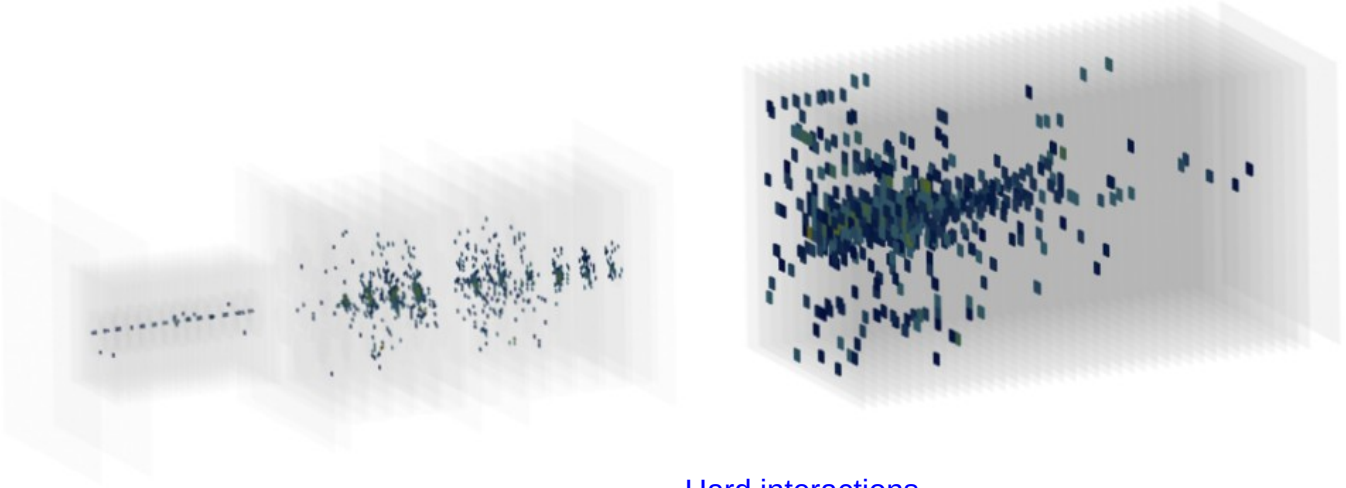
Higgs factory (and EW, and top-quark and…)

- **All Standard Model particles within reach of the ILC project**
- High precision tests of Standard Model over wide range to detect onset of New Physics
  - **Machine settings can be "tailored" for specific processes → straightforward at the ILC**
  - **Centre-of-Mass energy**
  - **Beams polarisation** (±80% e^-, ±30%e^+)

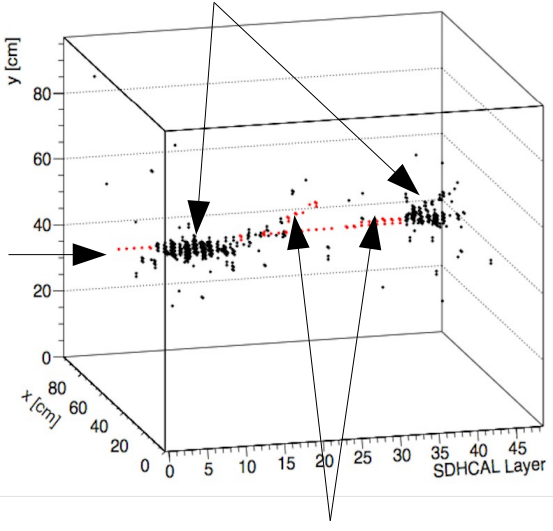
- Higgs factories but also…
  - **"light" qq factory**

    (and Z-factory at Z-pole)
  - **WW factory**
  - **Top-quark factory**
  - **ttH factory**
  - **…**





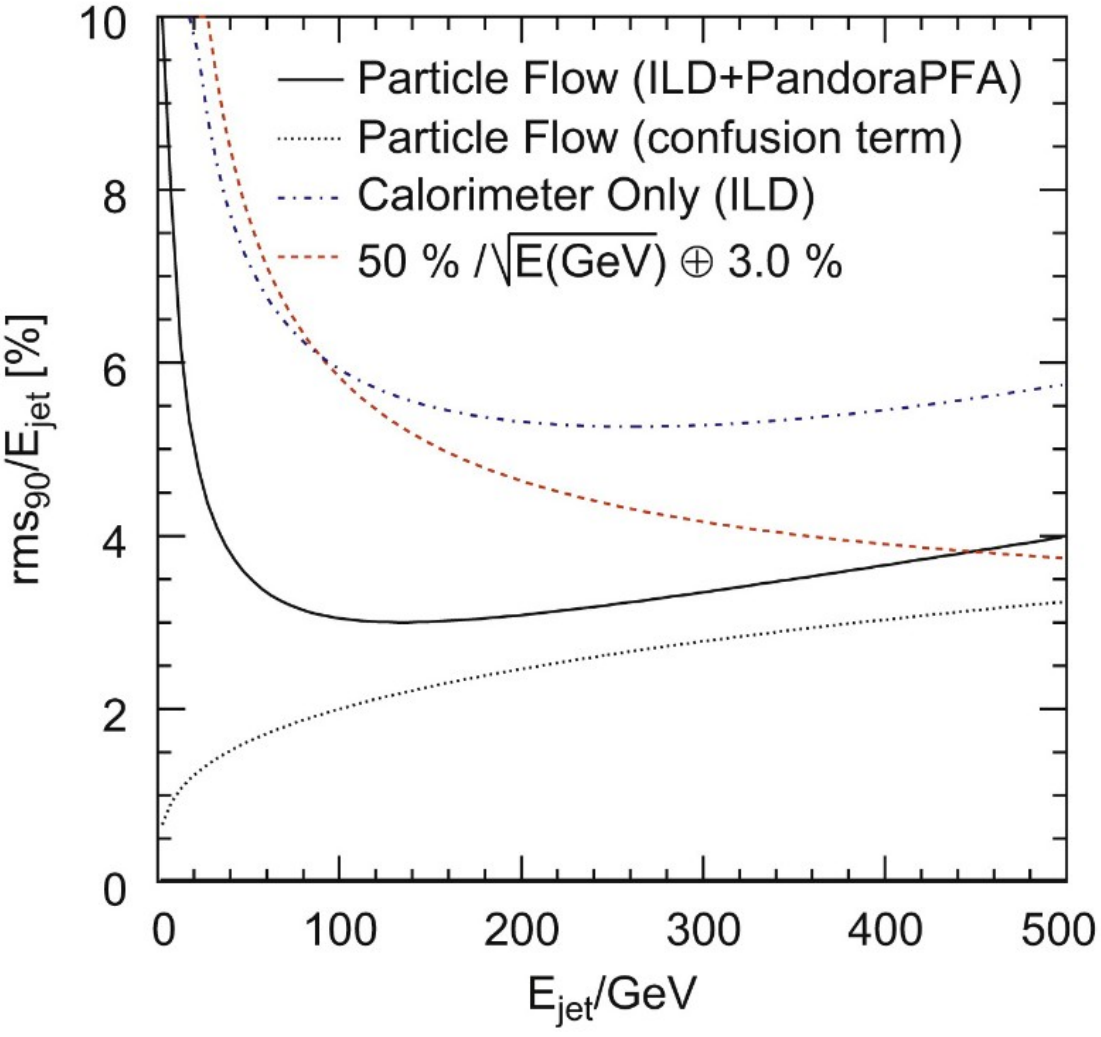
Hard interactions



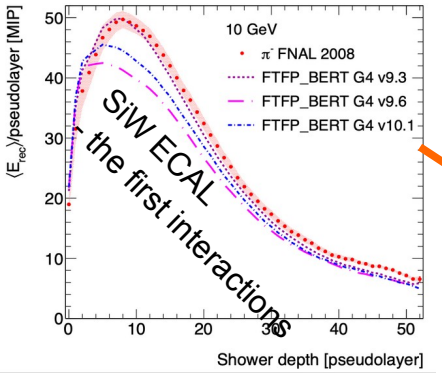
Primary particle

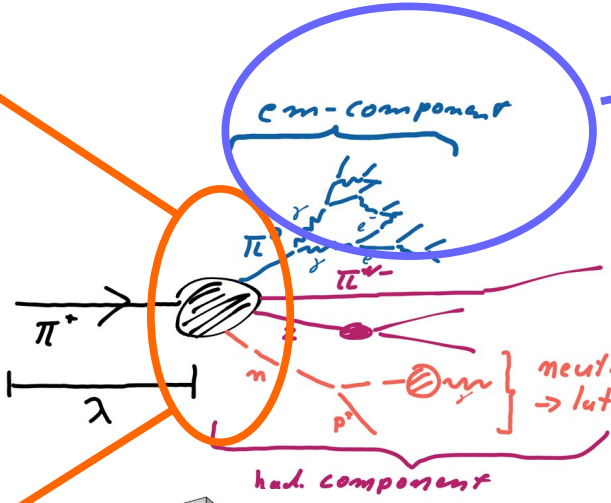
Secondary particles/tracks

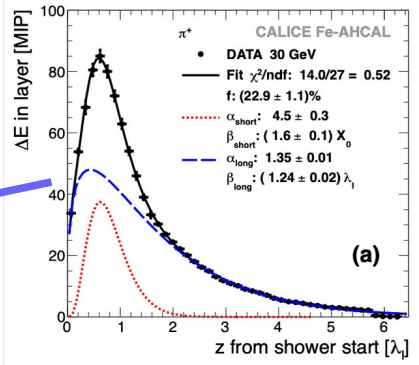
High granular calorimetry

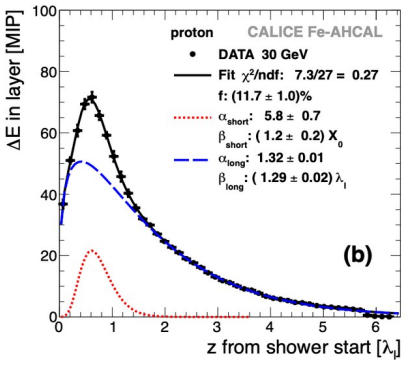


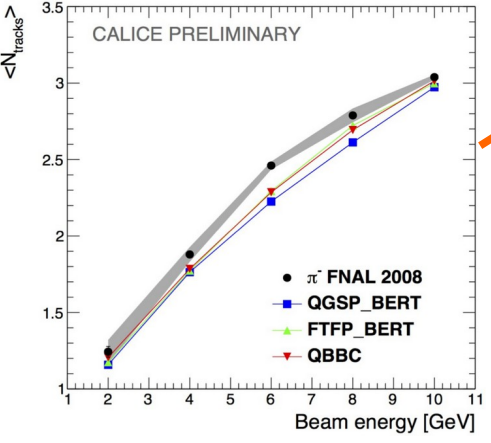
High granularity calorimeters: more than "only" PFA

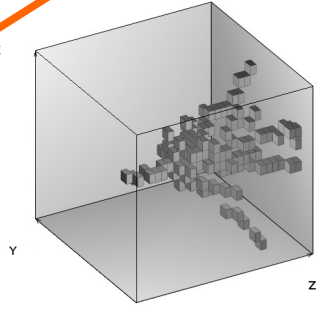


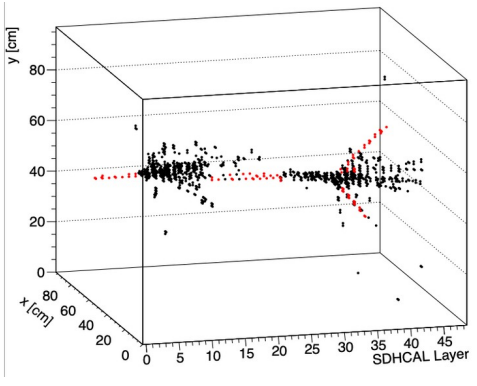


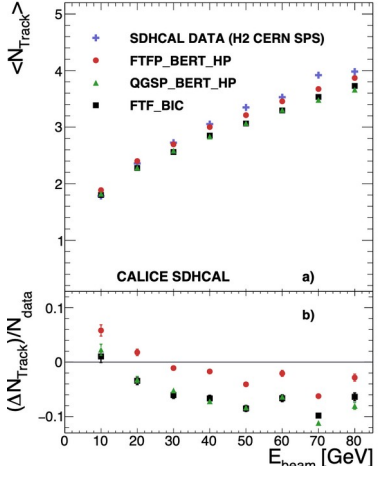






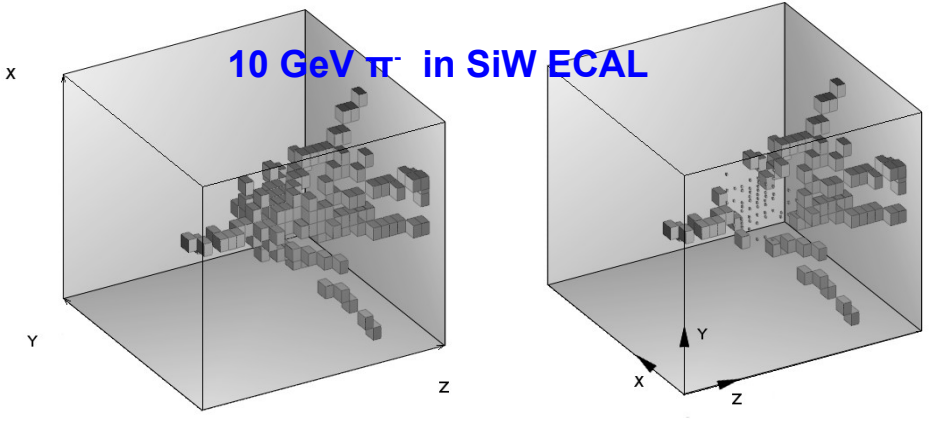


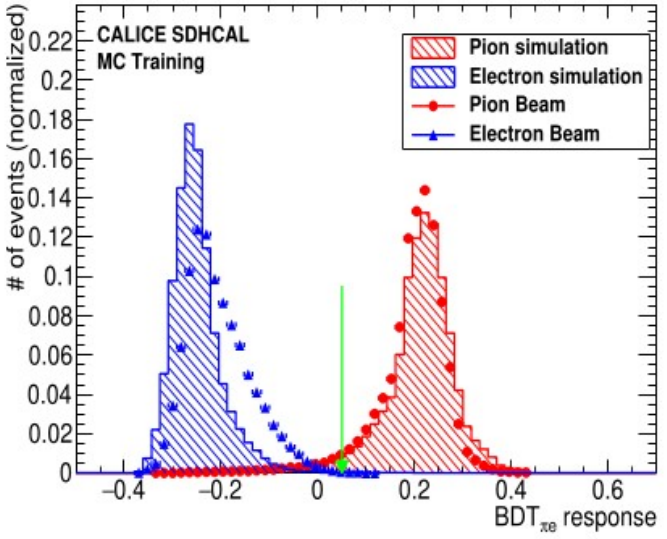




F. Simon, FCCee Meeting, Jan. 2020

High granularity calorimeters: more than “only” PFA





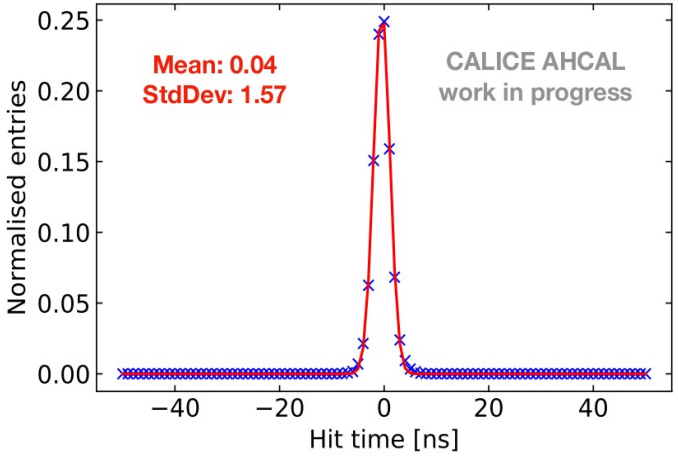
- **study of first hadronic interaction in the SiW-ECAL** (physics prototype)
  - NIM A 937 (219) 41-52

- **SDHCAL** using 6 variable discriminnating **BDT for Particle Identification** [JINST 15 (2020) P10009]

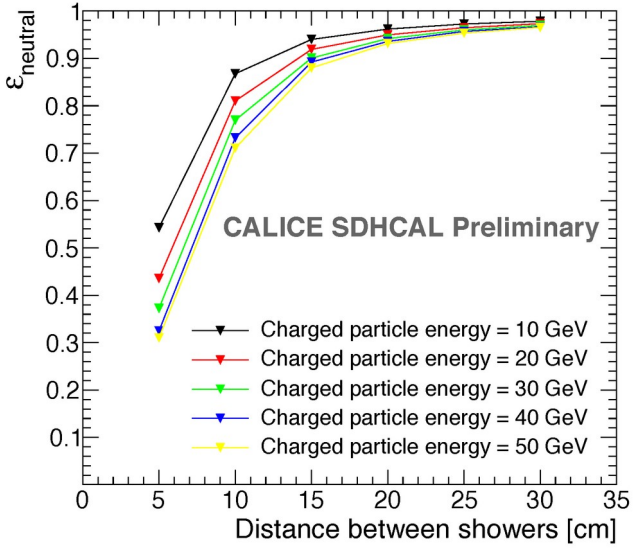
The unprecedented granularity of the proposed calorimeters offers also unprecedented capabilities to study the development of showers

High granularity calorimeters: more than “only” PFA

Clock frequency 5 MHz,
Powering pulsing



- Hit time resolution: Results from **2018 beam test** of **AHCAL** with muons
  - Encouraging results (1-2 ns resolution)
  - Distinction between slow and fast components in the showers (neutral vs charged)



- **SDHCAL**: Separation of 10 GeV between neutral hadron and charged hadron [CALICE-CAN-2015-001]
  - More than 90% efficiency and purity for distances ≥ 15 cm

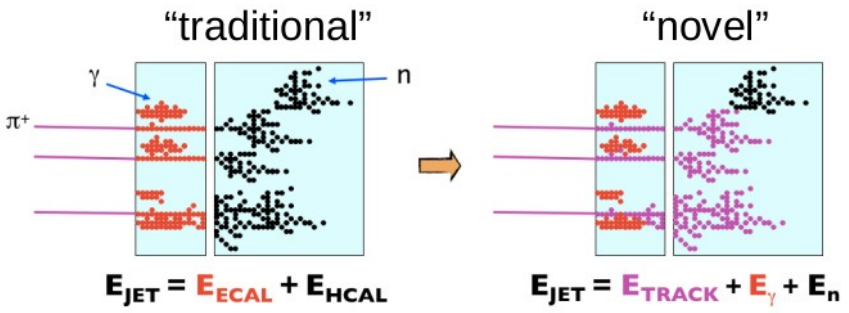
The unprecedented granularity of the proposed calorimeters offers also unprecedented capabilities to study the development of showers

Pandora PFA

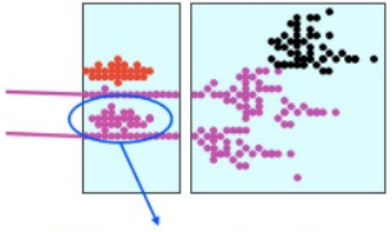
M. Thomson, J.B. Marshall
Cambridge LC Group

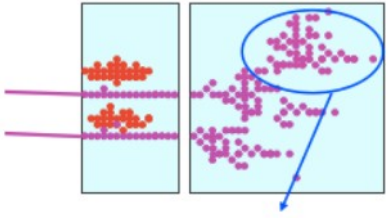
A PFA is a set of algorithms for pattern recognition and particle reconstruction.

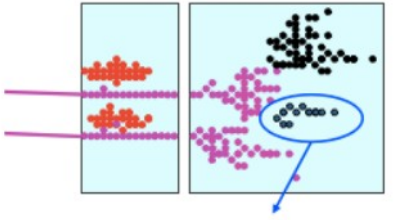
arXiv:1308.4537



However, there might be *confusion* in particle reconstruction, such as:


Failure to resolve photons

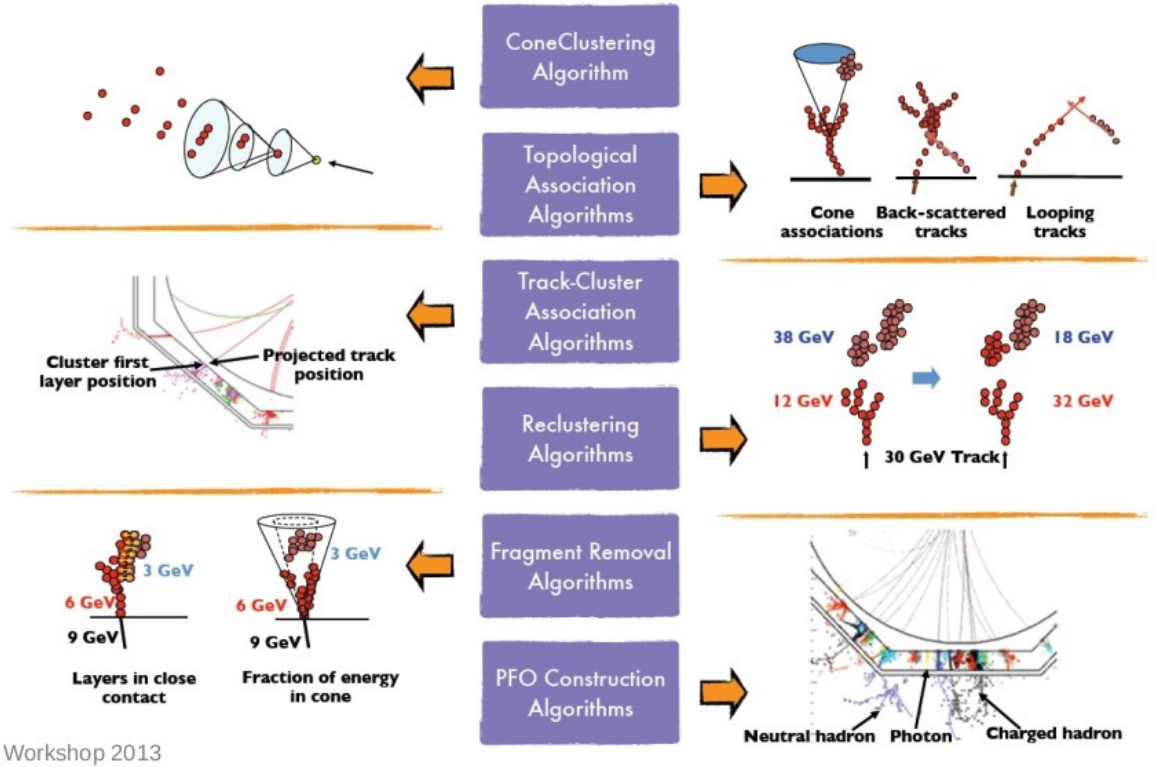

Failure to resolve neutral hadrons


Reconstruct fragments as separate neutral hadrons

Hence constraints on both calorimeters and software.

Pandora PFA - Approach

"Implement a large number of 'decoupled' pattern-recognition algorithms, each of which looks to reconstruct specific particle topologies, whilst carefully avoiding causing confusion"



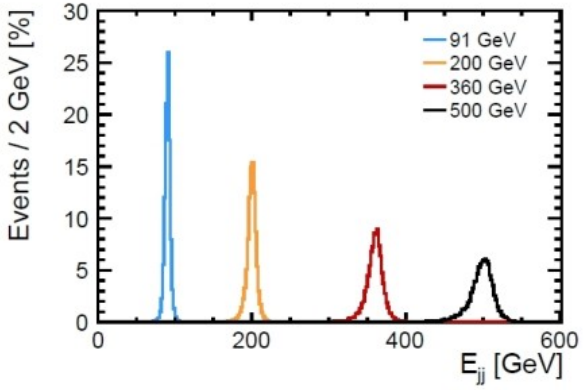
CLIC Workshop 2013

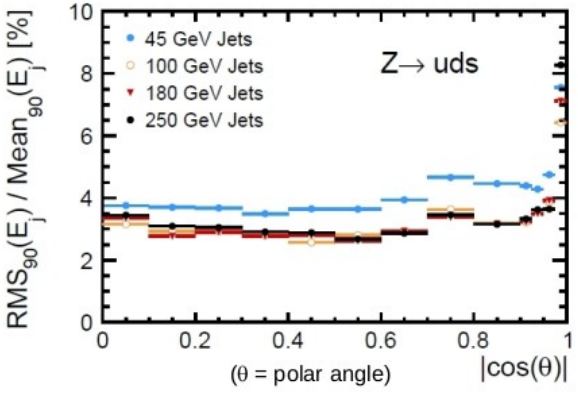
working outwards
↓
topological merging
↓
tracker-calorimeter
↓
improve match
↓
neutral vs charged
↓
particle flow objects
↓
particle identification

Pandora PFA - Performance

ILC: Tested with ILD-model Monte-Carlo Z'→jj events produced at rest at 4 energies

arXiv:1308.4537





100-250 GeV jets:
resolution ~constant (barrel)

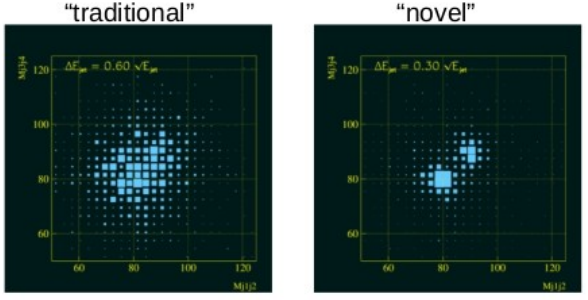
45 GeV jets:
limited by intrinsic term

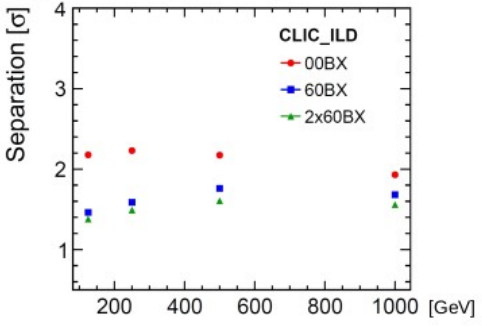
high energy jets:
limited by confusion term

PFA robust *wrt* shower parameters

CLIC (higher energies and larger backgrounds): e.g. W vs Z separation (p_T, PID)

"traditional" "novel"





$e^+e^-\to WW\to\mu\nu qq$
$e^+e^-\to ZZ\to\nu\nu qq$
W/Z energies: 125-1000 GeV
overlaid $\gamma\gamma\to$hadrons background
(BX=beam crossing)

2σ separation without background
~1.7σ with 60BX background

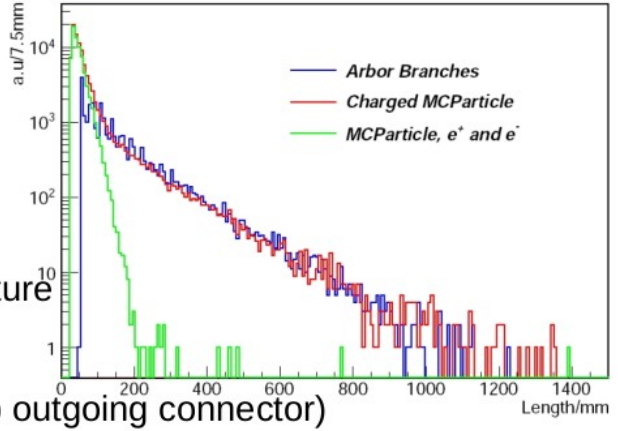
CLIC Workshop 2013

Arbor PFA

Shower development topology in an imaging calorimeter reminds of a tree structure.

Step 1: initial hit cleaning if necessary (e.g. noise)
close pairs of hits are connected
a connector is the outgoing vector between them

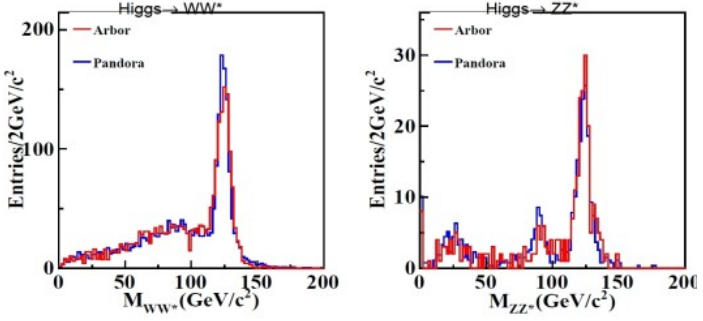
Step 2: a reference direction calculated from a hit position
and the directions of its outgoing connectors
the most likely incoming connector is kept → tree structure
this structure can be iterated. Tree means no loop.



Step 3: some hits are seeds (no ingoing connector) or leafs (no outgoing connector)
tracing from leaf to seed → branches → tree
ideal case, a tree = a particle shower
intuitive, effective is separating nearby showers

The algorithm is next applied to jets

Reconstructed energy for e.g. Higgs decay events
Jet energy resolution comparable to Pandora's



arXiv:1403.4784

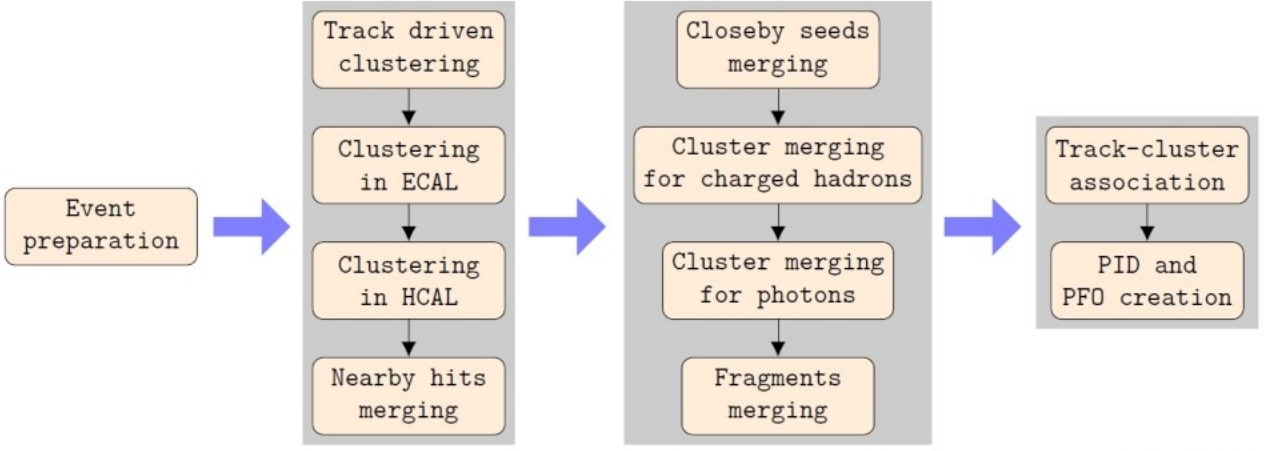
APRIL: Algorithm for Particle Reconstruction at ILC from Lyon

APRIL ≈ Arbor PFA with modified cluster merging for SDHCAL

(Pandora PFA assumes linear responses as in AHCAL case)

SDHCAL energy reconstruction: $E_{reco} = \alpha_1 N_1 + \alpha_2 N_2 + \alpha_3 N_3$

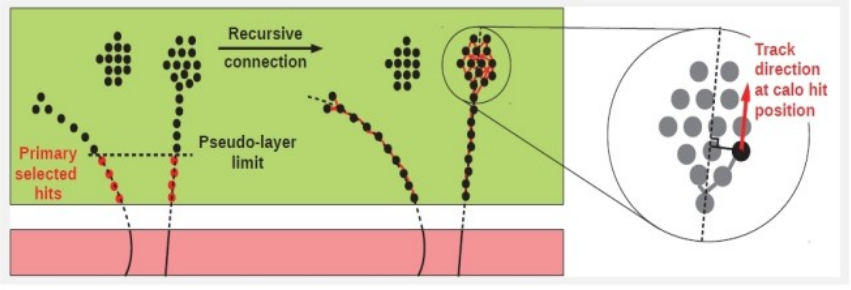
where N_i are the number of hits for each threshold

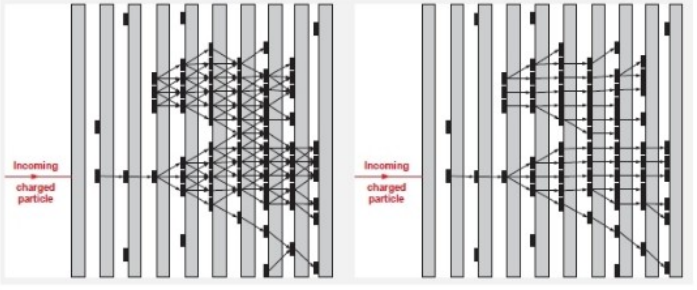


CHEF 2019

APRIL

Tracks: 1) clustering done by Arbor with parameters set to avoid big clusters
2) remaining hits merged by efficient Nearest Neighbour clustering (mlpack)
3) keep only one backward connection per hit (minimal angles × distance)





Clusters: 1) cluster merging similar to above hit clustering
2) function of cluster orientations and distances
3) (work in progress, e.g. splitting/reclustering)

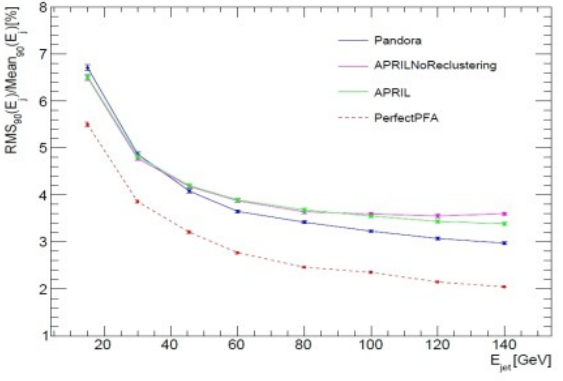
Results: jet energy resolution in barrel at M_Z

APRIL: 4.2% → competitive with Pandora (<60 GeV)

Pandora: 4.1%

"ideal PFA": 3.3%

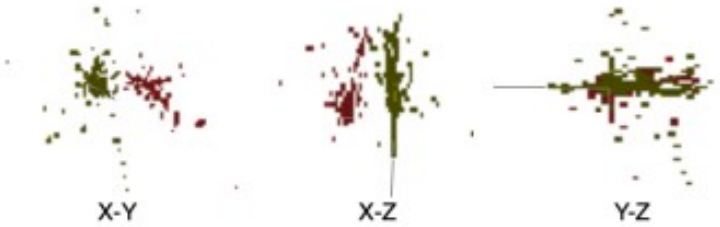
CHEF 2019

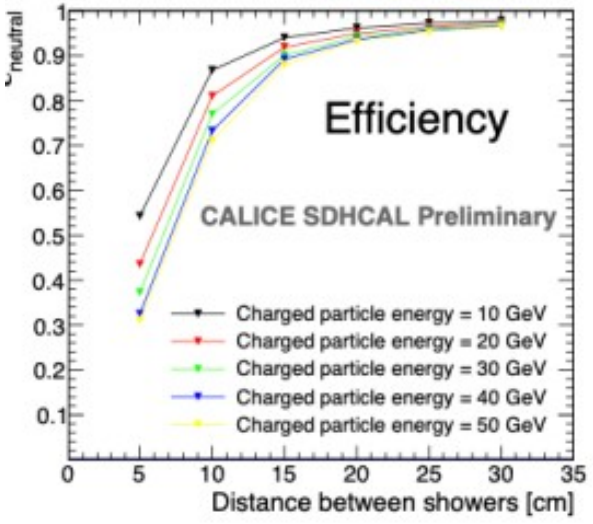


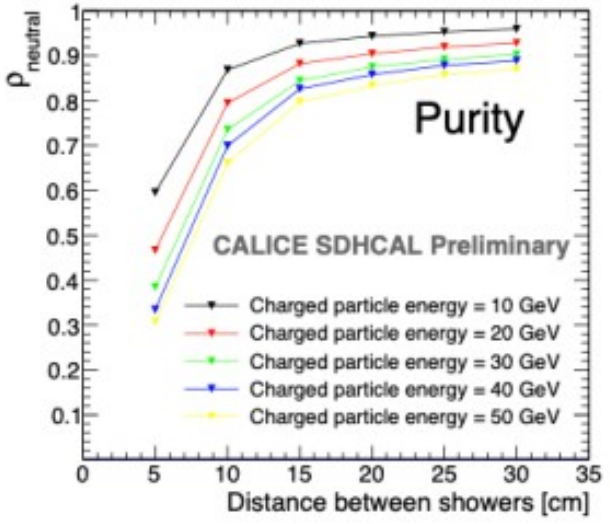
Particle Flow Algorithm Applied to CALICE Prototype Data

Two Particle Separation Performance

CALICE-CAN-2015-001





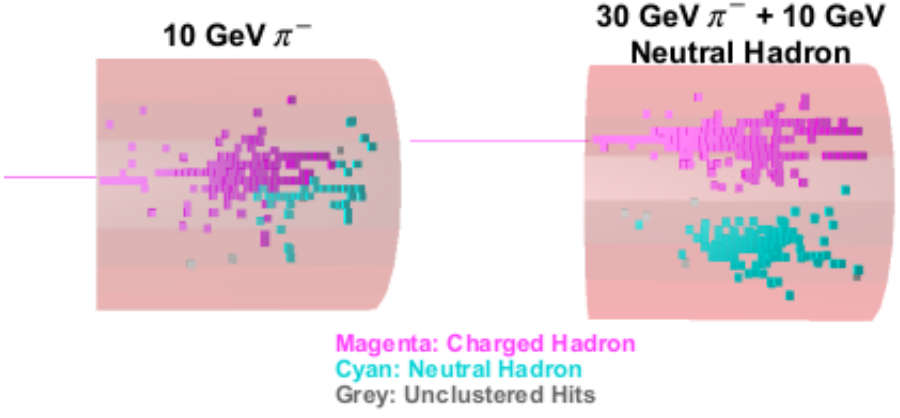


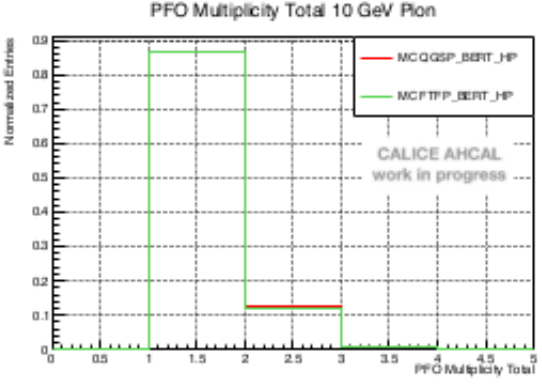
- Two particle separation studies with Arbor particle flow algorithm on SDHCAL data (10-80 GeV @ SPS CERN)
  - ➡ Overlaid 10 GeV „pseudo" neutral with a close-by charged hadron
- For nearby shower with shower axis distance > 15cm:
  - ➡ Efficiency >90% achieved

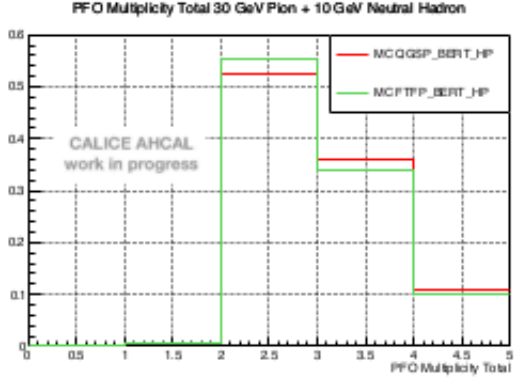
Particle Flow Algorithm Applied to CALICE Prototype Data

Single and Two Particle Reconstruction Performance 2018 - 2020

- Over the last years significant improvements & developments:
  - ➡ Particle Flow Algorithms: Optimised, more generic, directly applicable for CALICE prototype data
  - ➡ CALICE technological prototypes: Granularity, noise level,…
- Latest (ongoing) study: PandoraPFA on AHCAL technological prototype data (standalone)
  - ➡ Study of confusion in single particle reconstruction and two particle separation performance







GEANT4 v10.3