International Workshop on Future Linear Colliders

LCWS2016

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Detector R&D for Linear Colliders

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DESY

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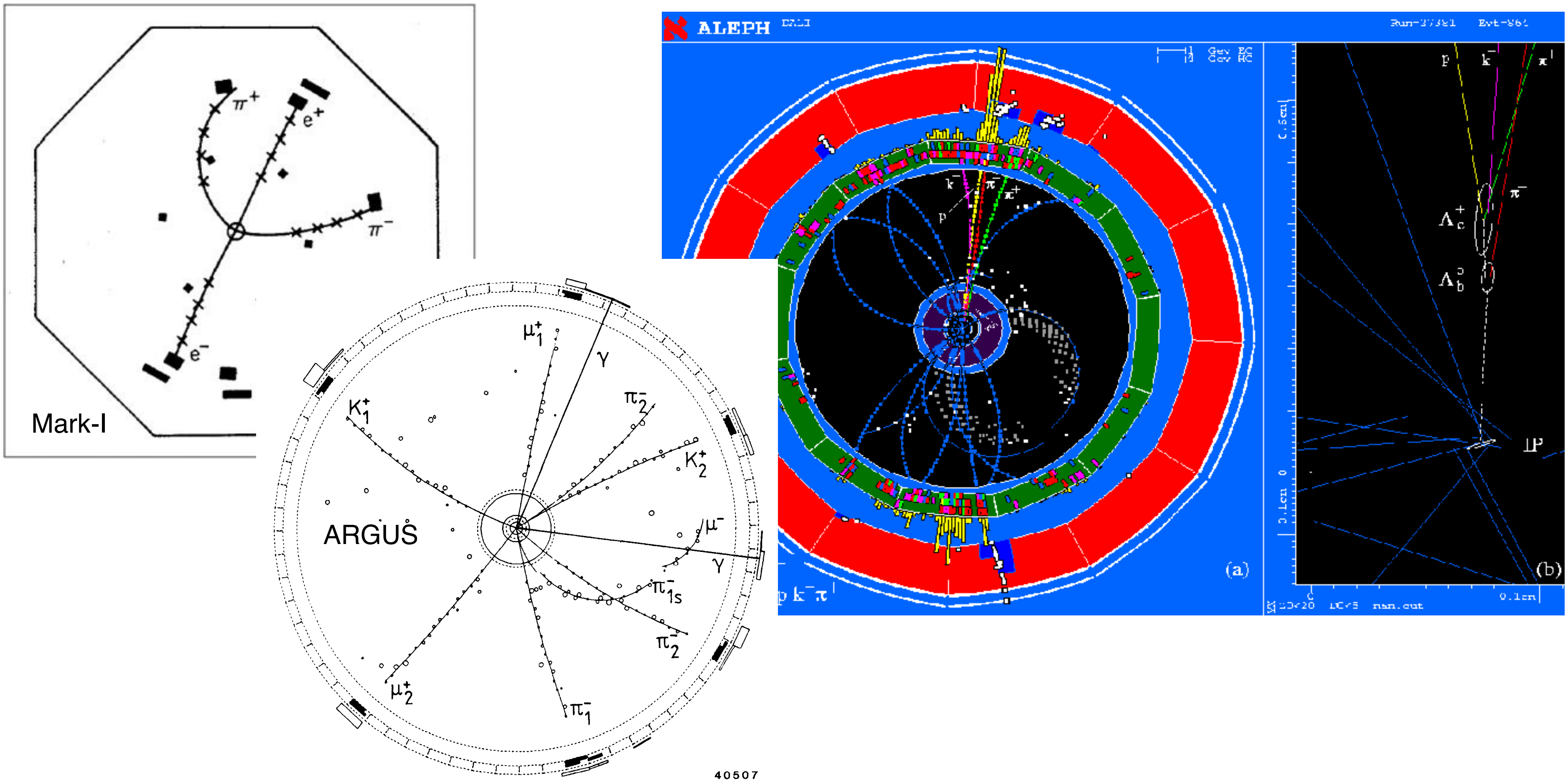
Outline

- Introduction: goals and efforts
- Status and recent highlights
  - calorimetry
  - gaseous tracking
  - Silicon tracking and vertexing
- Common issues
- Conclusions

- Personal selection; see Maxim Titov's talk at the ECFA LCWS 2016 in Santander for a comprehensive overview
- Focus on HEP, see M.Demarteau's talk for spin-offs

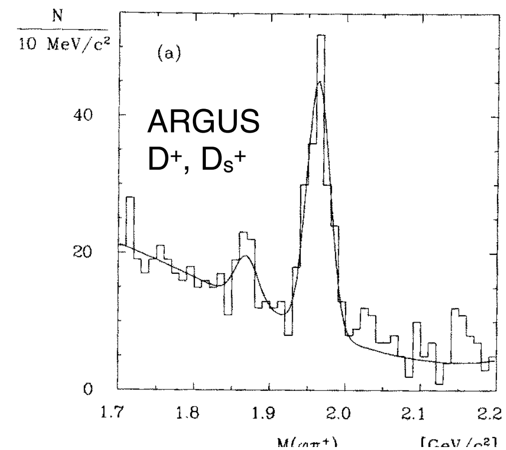
e+ e- events

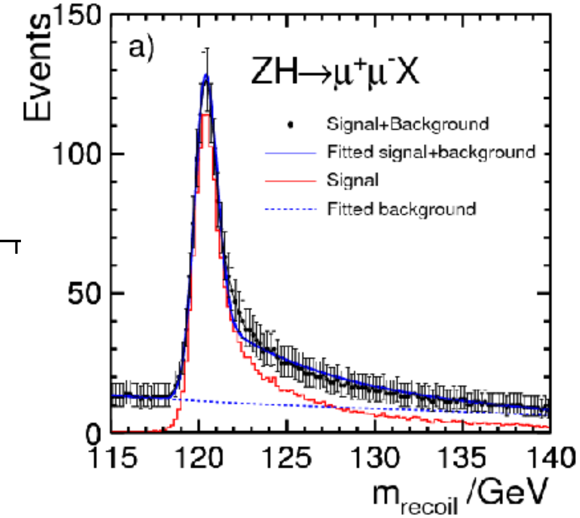


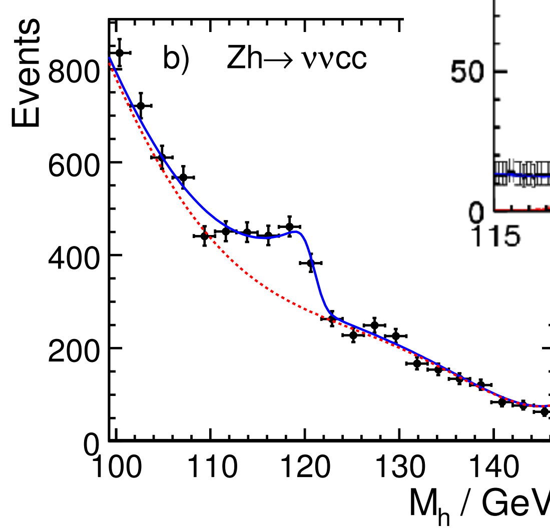
- Clean final states, full reconstruction, kinematic constraints
- Small cross sections: get the best precision for every event

Detector requirements for LC physics

- Physics with Higgs and top: need to identify H, t and their heavy daughters, W and Z, by invariant di-jet mass
  - need 3-5% jet energy resolution
  - particle flow **calorimeters**: granularity *and* resolution
- Higgs recoil mass for model-independent ZH cross section, g_Z, decay spectra endpoints
  - need $1/p_T$ resolution $2\cdot10^{-5}$
  - **tracker** material 0.1-0.2 X_0
- Charm **vertex** tagging in the presence of overwhelming b background
  - impact parameter resolution $5\oplus15/p(\mathrm{GeV})$ μm resolution
- Hermetic angular coverage
  - tag very **forward** electrons







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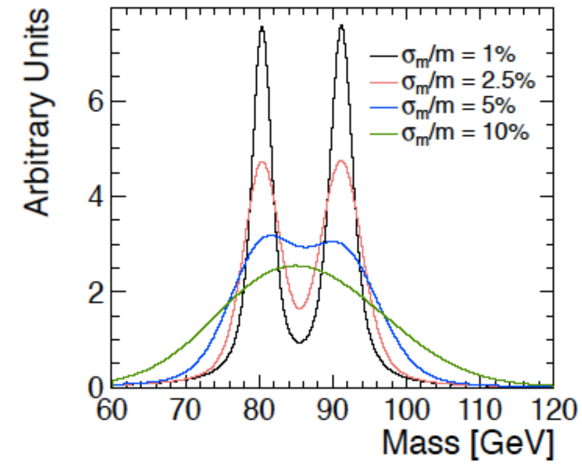
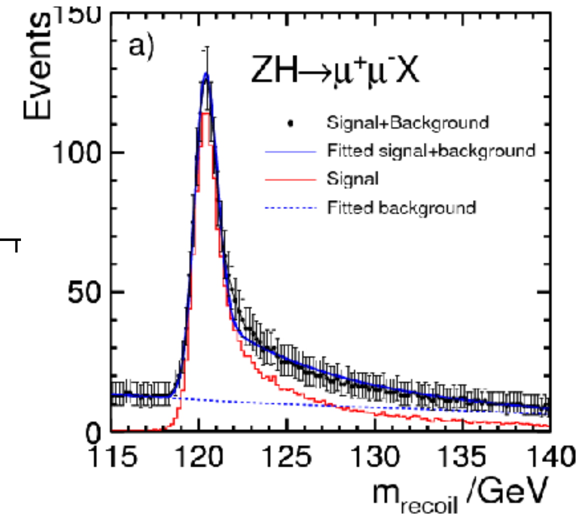
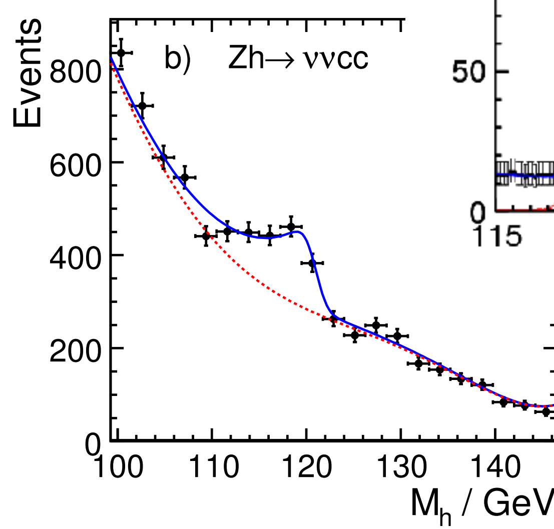






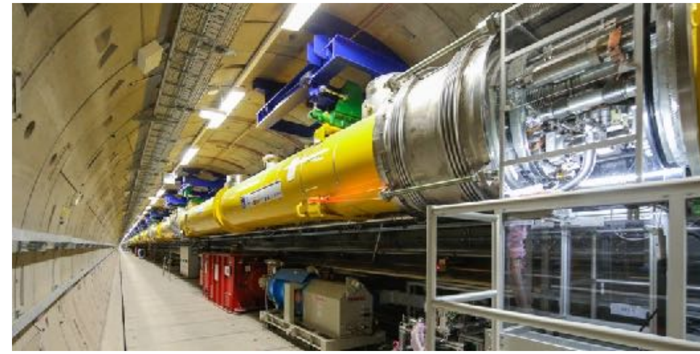
Accelerator environment

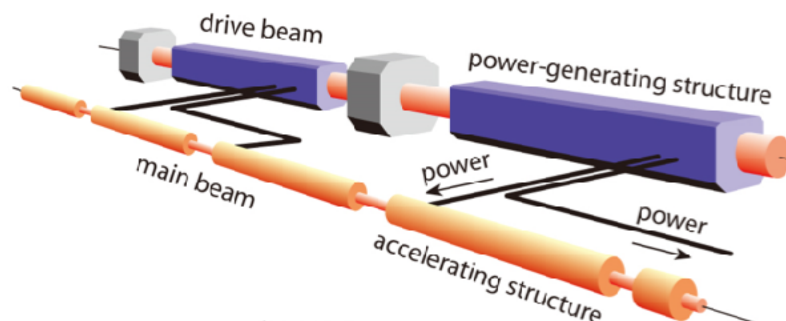
	ILC at 500 GeV	ILC at 1 TeV	CLIC at 380 GeV	CLIC at 3 TeV
L (cm^{-2}s^{-1})	1.8×10^{34}	3.5×10^{34}	1.5×10^{34}	5.9×10^{34}
$L_{0.01}$ (cm^{-2}s^{-1})	1.0×10^{34}	1.2×10^{34}	0.9×10^{34}	2.0×10^{34}
$L_{0.01}/L$	58%	59%	60%	34%
BX separation	554 ns	366 ns	0.5 ns	0.5 ns
#BX / train	1312	2450	356	312
Train duration	727 μs	897 μs	178 ns	156 ns
Repetition rate	5 Hz	4 Hz	50 Hz	50 Hz
Main linac gradient (MV/m)	31.5	38.2	72	100
Duty cycle	0.36%	0.36%	0.00089%	0.00078%
σ_x / σ_y (nm)	474/5.9	481/2.8	≈ 150 / 3	≈ 45 / 1
σ_z (μm)	300	250	70	44

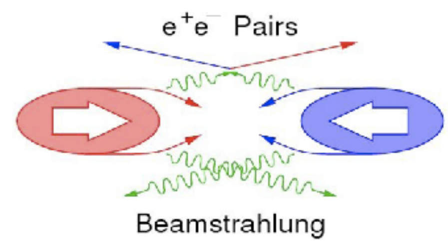
L.Linssen

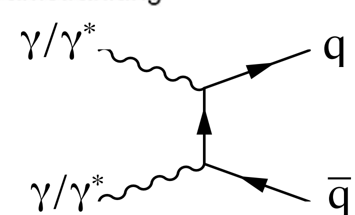
Accelerator environment

- Compared to LHC, radiation tolerance and bandwidth requirements are benign
  - except very forward regions
- Precision requirements are more demanding:
  - 2x for jet energies, 10x for track momenta, 5-10x for material budgets, 2x for strip and pixel dimensions
- At linear colliders, bunch train structure allows for power cycled operation (~1%)
  - simplifies powering and cooling
  - thinner trackers, denser calorimeters
  - trigger-less read-out
- Backgrounds from beamstrahlung and hadronic 2-photon interactions
  - more relevant for CLIC, due to higher E and smaller beam spot ($5 \times 1 nm^2$)
  - precise timing for pile-up rejection (1-10 ns)
  - somewhat higher emphasis on fine granularity and fine pixels





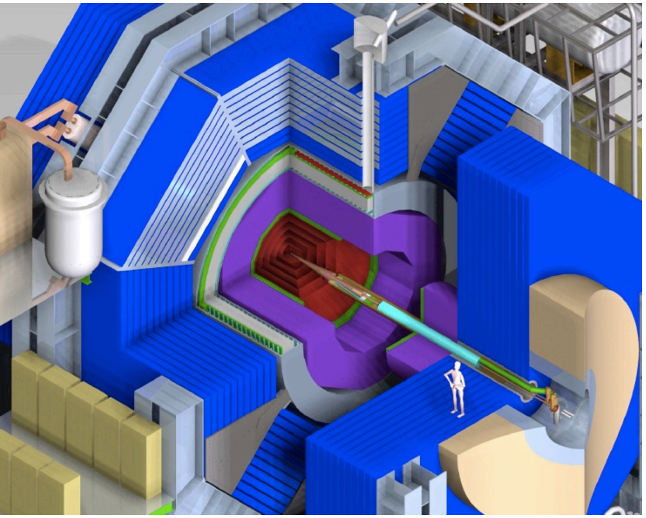




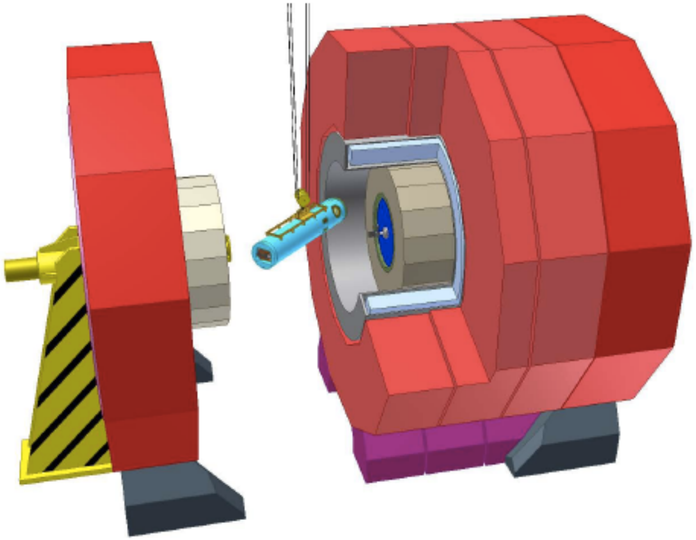
Worldwide detector R&D efforts

- Detector efforts for TESLA, NLC, JLC ramped up in 2001
- R&D "proto-collaborations" formed with the goal to globally share common tools, infra-structures and frameworks for large (expensive) prototypes
  - e.g. CALICE: common absorbers, ASICs, DAQ, software
  - less relevant for vertex detectors, but still well-working community exchange, e.g. beam telescope & test beam w/s
- CLIC detector effort started in 2008
  - conceptual studies based on ILD and SiD work
  - integrated in existing R&D collaborations where possible
- R&D groups are focussed on linear collider developments, but open for other applications
- Fruitful interaction with ILD, SiD, CLIC concept groups
  - conceptual guidance: requirements, overall performance studies and physics impact
  - experimental validation for realistic designs and simulations

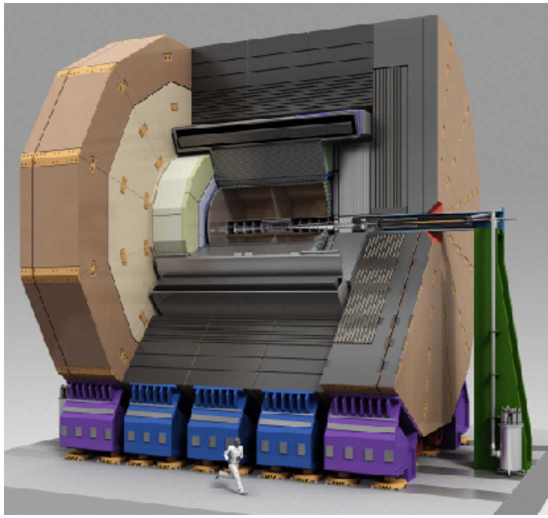
Detector concepts



SiD



CLIC

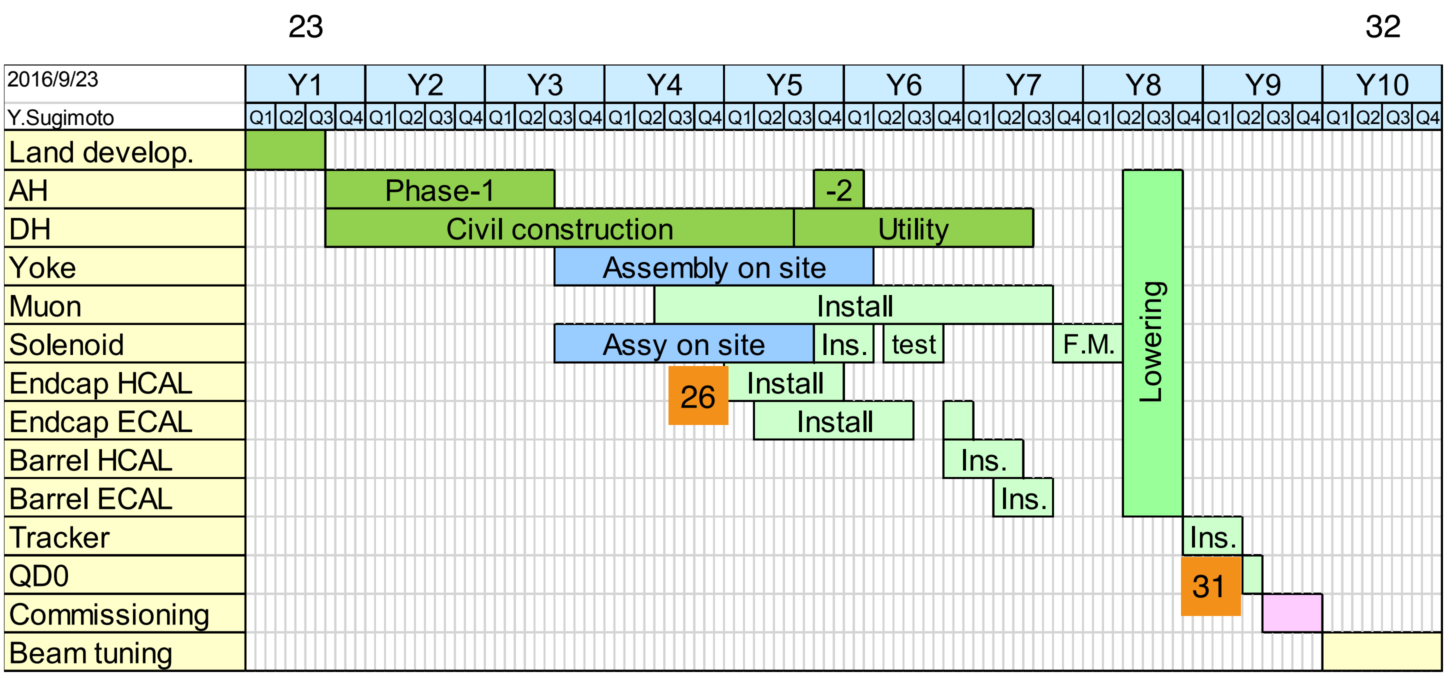


ILD

- All present detector concepts driven by particle flow idea
- Similar overall dimensions, 3-5 T solenoidal magnet
- Most sub-detector technologies are considered by all concepts
  - Choices are made for simulation and engineering studies
  - However all remain open for alternatives
  - Strong opinions but no hard constraints (except from machine) from concept on technology
  - Real choices easier when new opportunities open up

Timelines

- It is challenging to create a coherent R&D effort when time scales are uncertain
- Technologies with different readiness levels are being pursued in parallel
- Diversity will be reduced once timelines etc are known
- Still some general relationships result from detector assembly, see e.g. ILD



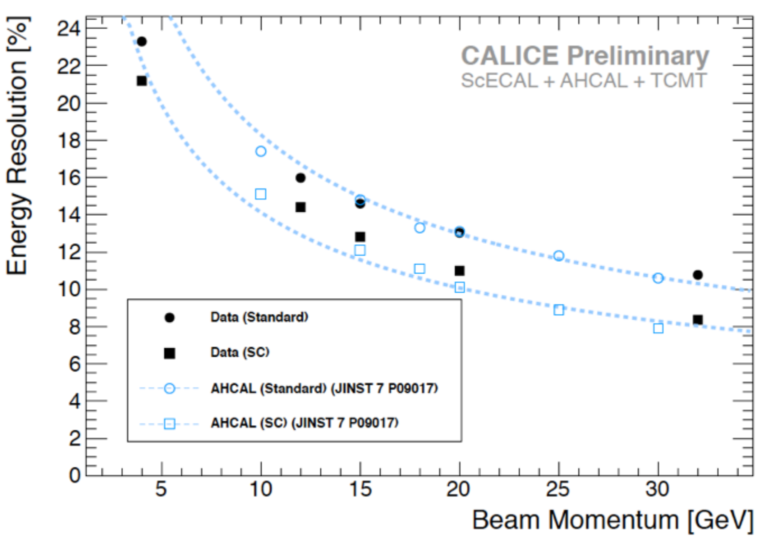
Calorimeters need to be ready 5 years before tracker - and probably 7 years before vertex. Construction time beforehand is also longer.

Calorimetry

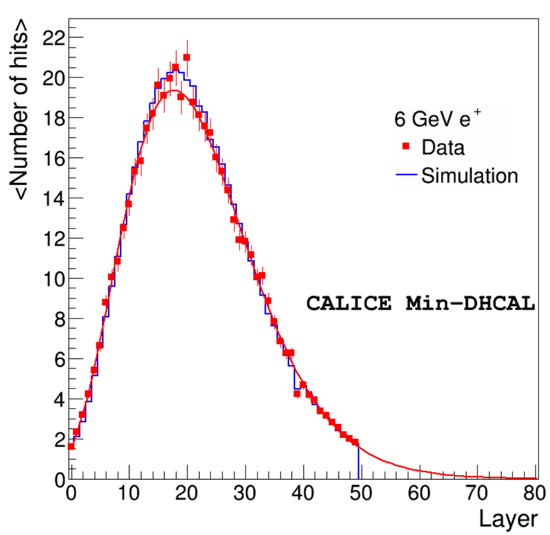
CALICE test beam results

- CALICE took data with first generation “physics" prototypes in 2006-2012
  - ECALs and scintillator analogue AHCAL had external electronics
  - Gaseous DHCAL and SDHCAL came last and had already embedded electronics and features of “technological" prototypes
- Data from all beam periods analysed, results still coming in
  - 3 of 4 papers in 2016 on gaseous HCAL, e.g. validation of shower and detector simulation - to be ported to concepts
  - experiment-based comparison of technologies comes in reach

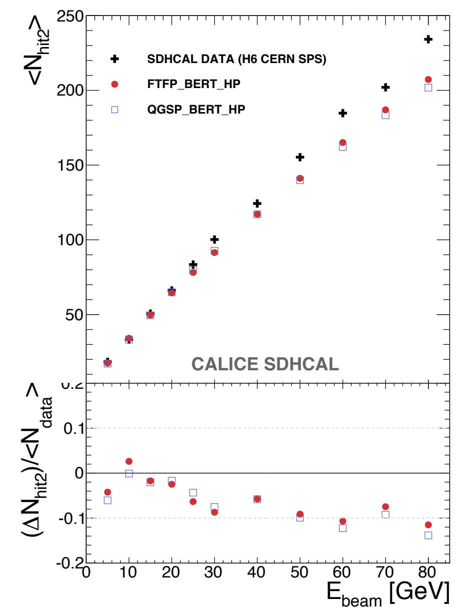
All-scintillator Japanese ECAL in front of AHCAL



RPC DHCAL w/o absorber



RPC SDHCAL Fe absorber

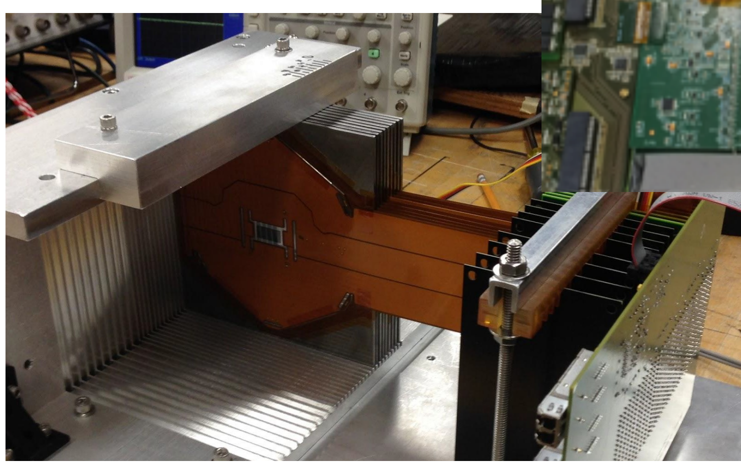


Towards 2nd generation prototypes

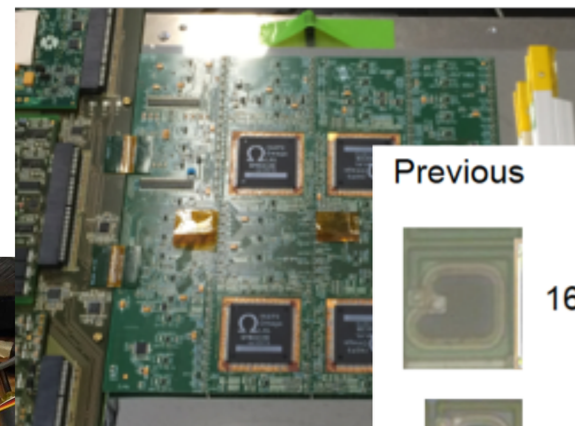
- Goal is to establish scalability
  - embedded electronics for compact detector: ROC family of ASICs from OMEGA, or kPix (SiD ECAL)
  - demonstrate feasibility of construction and QA for large channel count
- Basic layer functionality in tests with small sets of layers demonstrated
- Scintillator ECAL: focus on MPPCs with large dynamic range and on optical coupling optimisation

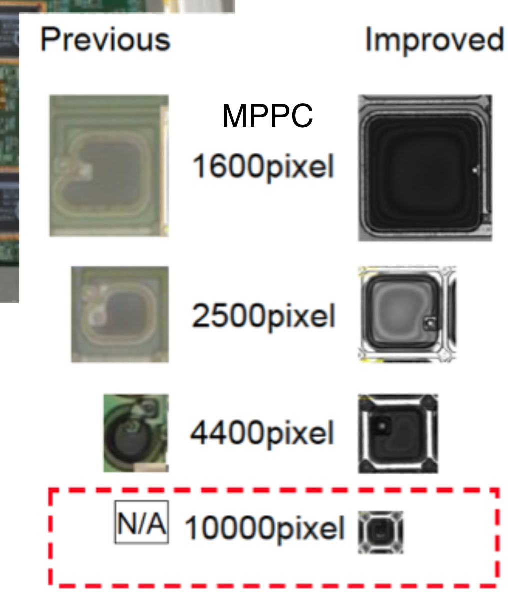
CALICE Si ECAL prototype

SiD ECAL with kPix chips



CALICE ScintECAL unit with SPIROC chips

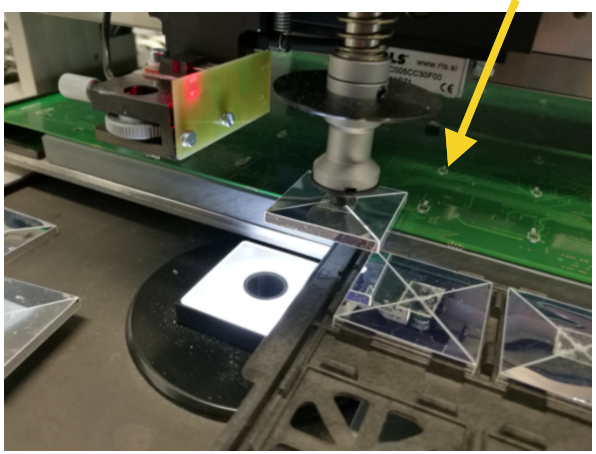




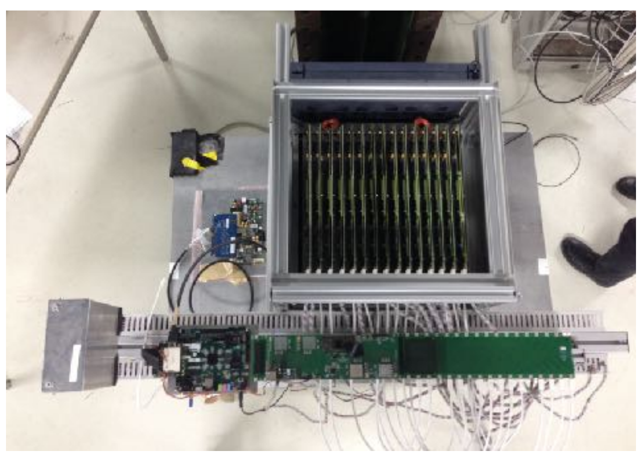
Coming 2nd AHCAL prototype

- Optimised all components, significant cost reduction
- Recent progress in photo-sensor performance and homogeneity
  - long-term cooperation with semi-conductor industry
  - main development driven by medical imaging
- Scintillator design for automatised read-out layer production
  - with MPPC integrated in PCB
- Small 15 layer prototype for e.m. showers tested
- MPPCs (HPK), tiles and ASICs for 23’000 channel AHCAL in production

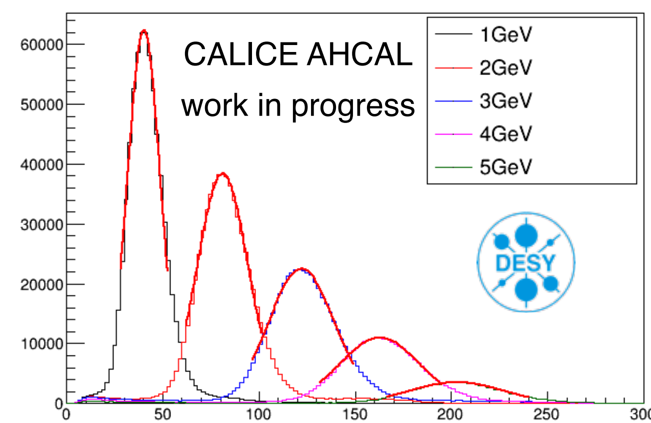
automatic tile placement MPPC



AHCAL stack for electron beam tests

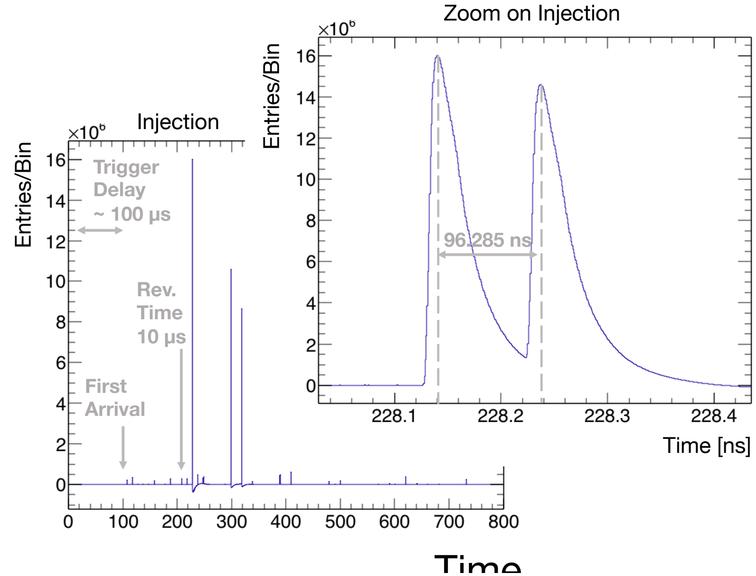


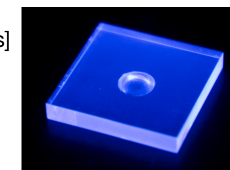
energy spectrum for 1-5 GeV



Belle 2 commissioning

- CALICE tiles were first detector to see particles at the Belle II interaction point
- Ladder system in preparation, will be part of Belle II commissioning inner detector

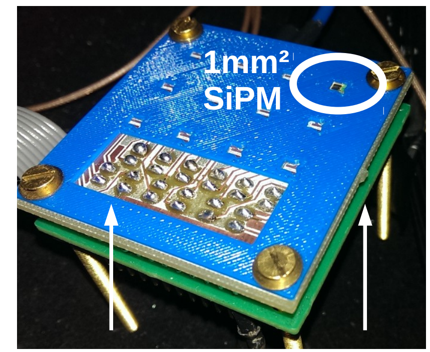




Mass characterisation

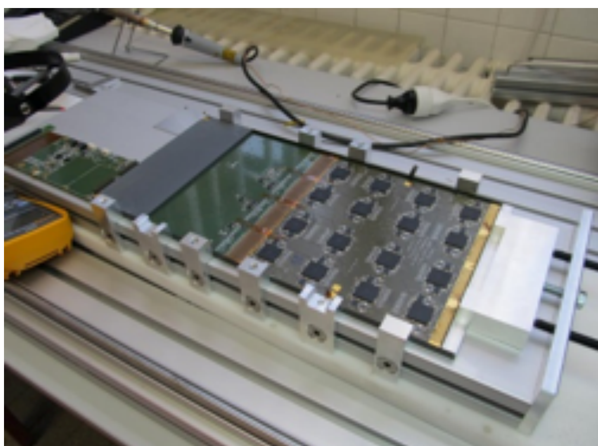
- Setting up infrastructure for mass* production and QA
  - * prototype i/s for prototype construction
- AIDA-2020 work package with linear collider and LHC participants
  - silicon and optical read-out

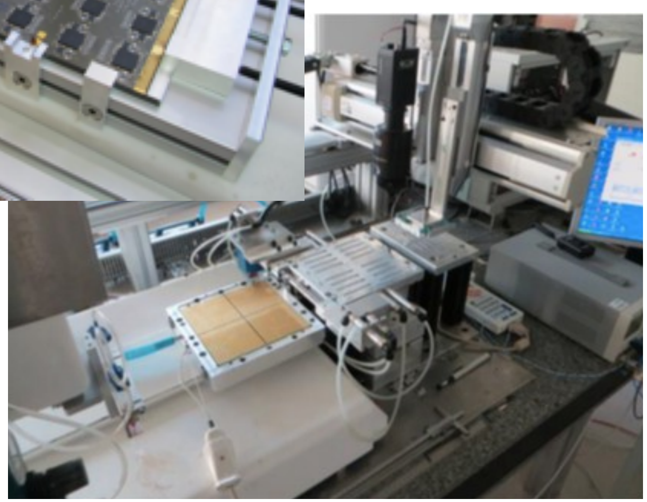
Gaseous detector infrastructure WP common with LHC muon upgrades



SiPM interconnect & mask

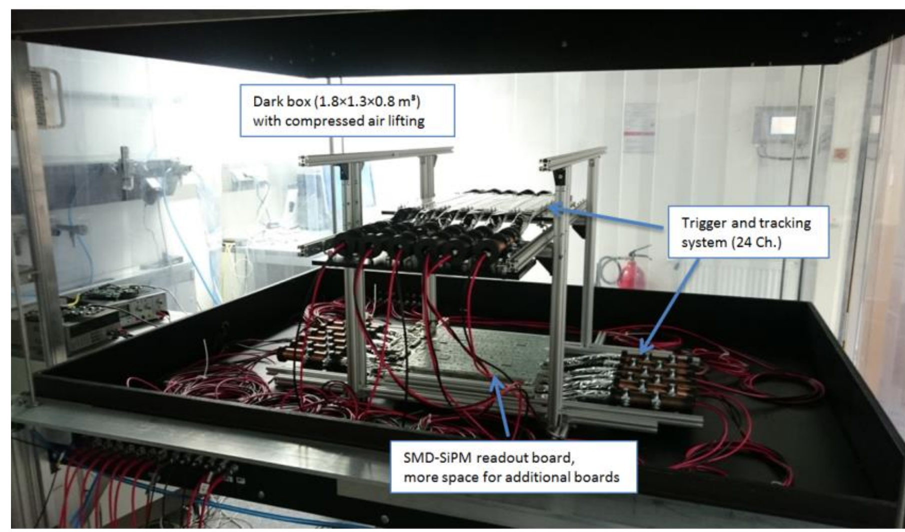
readout ASIC PCB





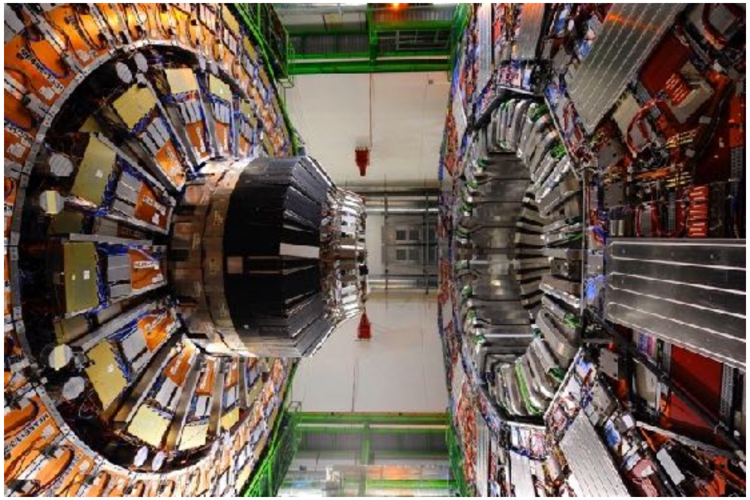
Si ECAL assembly, gluing robot

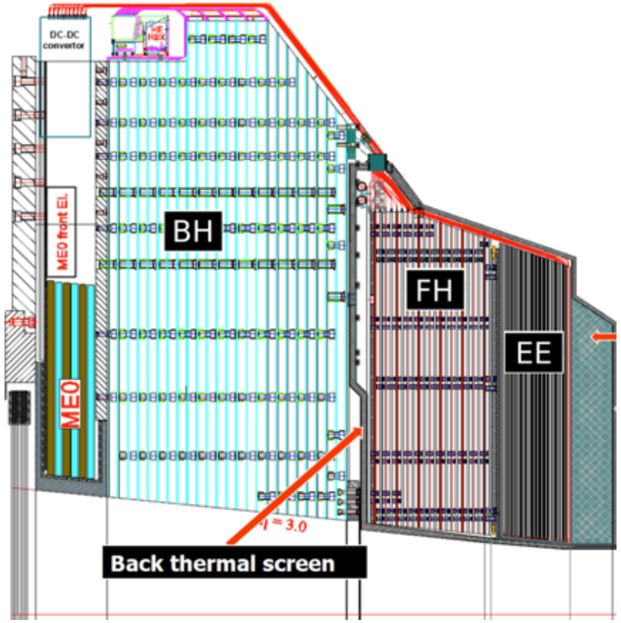
Scintillator and SiPM test stands



High granularity for LHC

- CMS endcap calorimeter upgrade for HL-LHC builds heavily on CALICE developments
  - high granularity and fast timing for PFLOW, particle ID and pile-up rejection
  - additional challenges: radiation hardness, read-out speed, cooling
- HGCAL 600 m^2 of silicon sensors and embedded electronics for electromagnetic and first hadronic section, scintillator in backing part
- Aggressive time scale, reality check for LC driven ideas
- Fruitful cooperation for both sides, common beam tests
- ATLAS high granularity timing detector HGTD
  - smaller device in very forward region, also building on CALICE ideas

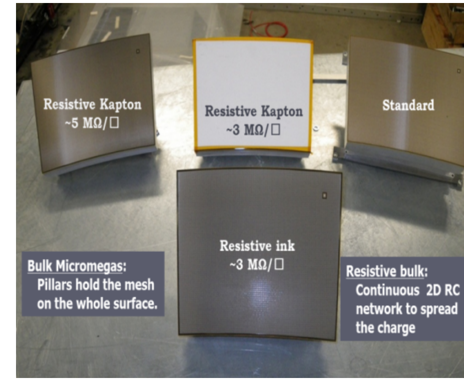


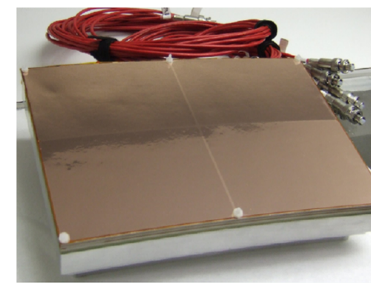


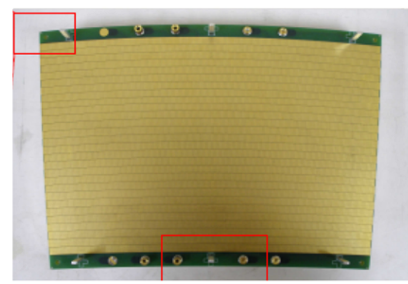
Gaseous tracking
(TPC)

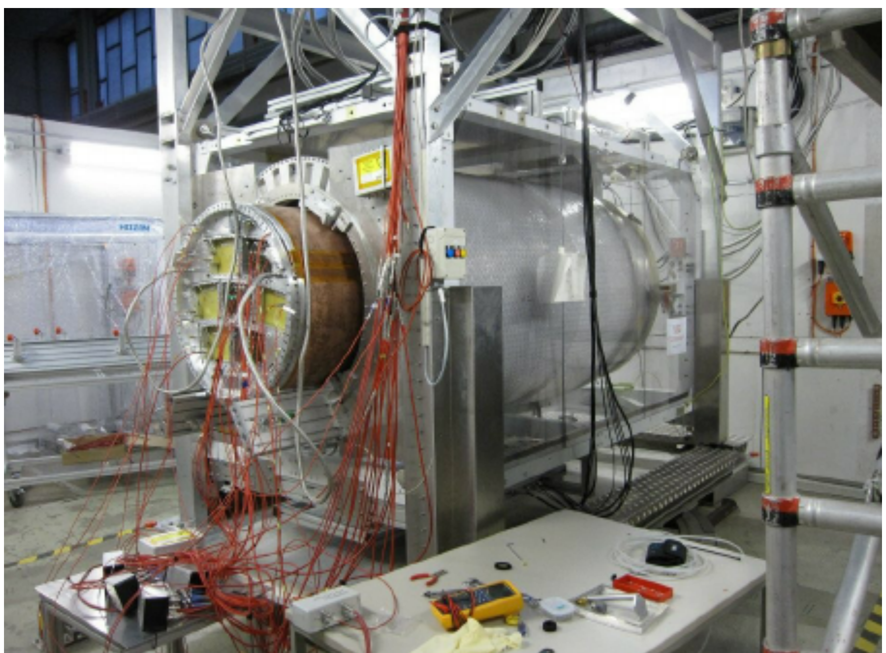
TPC technologies

- Different micro-pattern gas detector technologies under study
- Resistive micormegas
- Several GEM-based concepts
- Advanced versions with integrated pixel read-out
- Benefiting from magnet and field cage infrastructure at DESY test beam

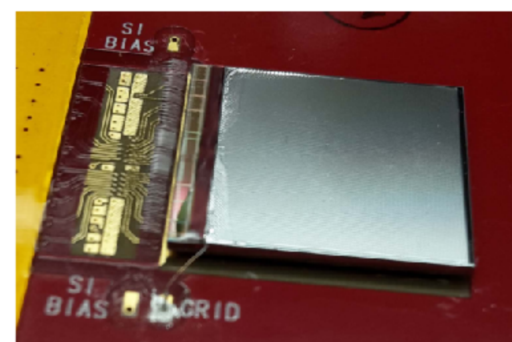






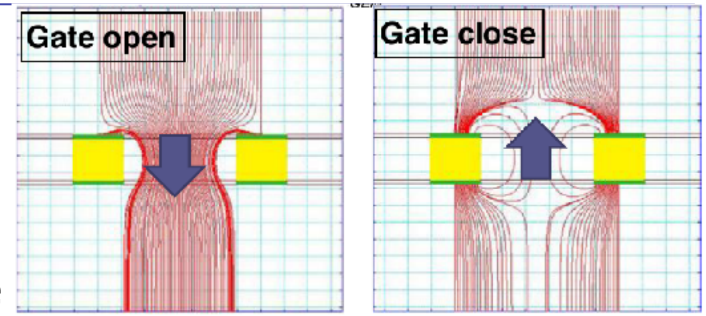


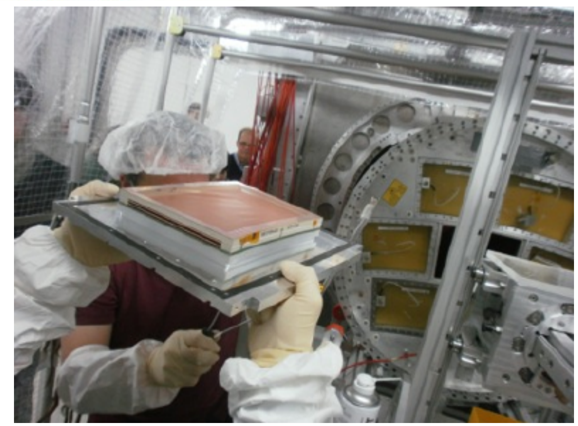
new GridPix module with TimePix-3 chips

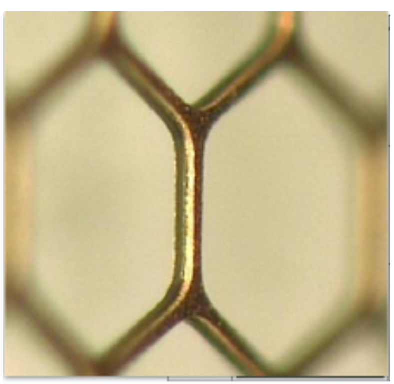


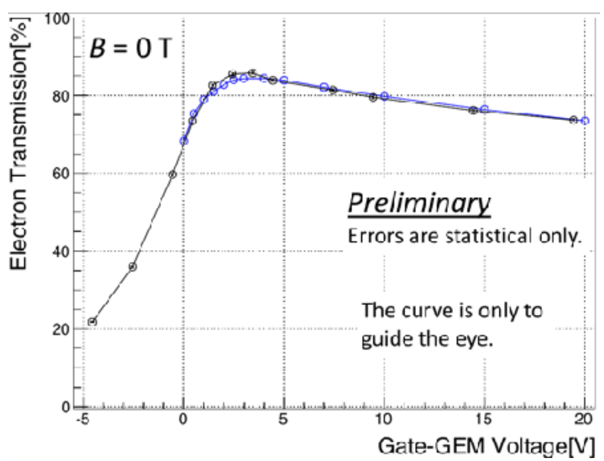
Gating studies

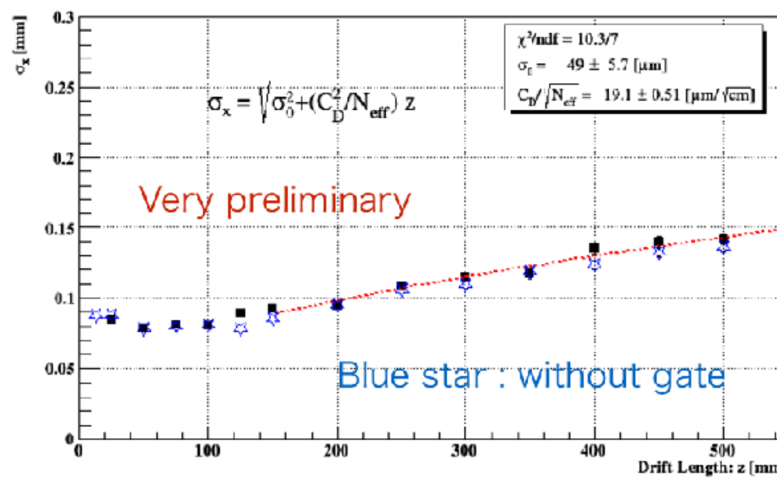
- Ion clouds slowly drifting towards cathode induce field distortions
- Gating grid to block ion back drift between trains
- Recently tested: gating GEM grid from Japanese manufacturer Fujikura
  - Hexagonal holes: 335 μm pitch, 27/31 μm rim, insulator thickness 12.5 μm
- High transparency for electrons verified
- Test beam: compare resolution with, w/o grid
- Studies on distortions to come
  - close interaction with ALICE TPC upgrade







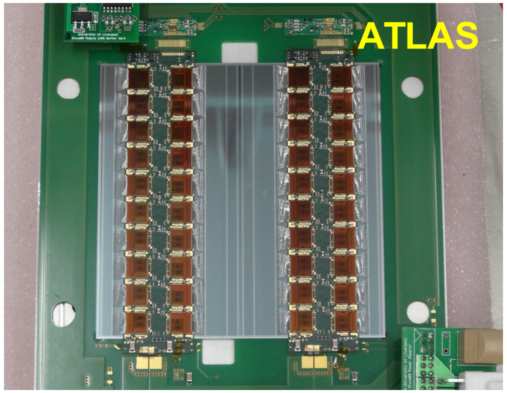




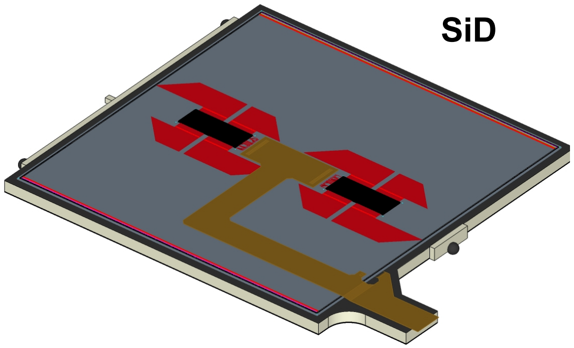
Silicon tracking and vertex detector R&D

Challenges

- Extreme material budget requirements
  - tracker: ~1% X_0 per layer
  - vertex: 0.1-0.2% X_0 per layer
    - <200 μm of Si, including cables, cooling & supports
- Demanding point resolution
  - 7 μm for tracker, 3 μm for vtx, <25 μm pixel size
- At CLIC, 10ns time stamping
- CLIC takes integrated approach to tracking and vertexing R&D
  - novel integrated sensor technologies considered for tracking
  - sensors, interconnects, ASICs, mechanics, cooling,…
- For ILC, kPix based development (SiD)



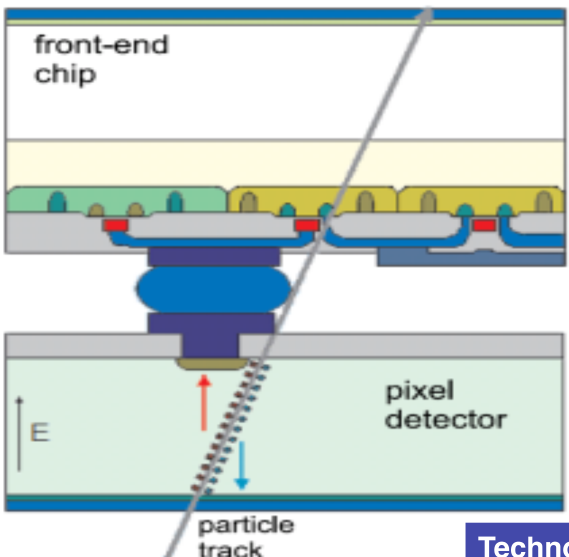
wire-bonded
hybrid
CO_2 cooled



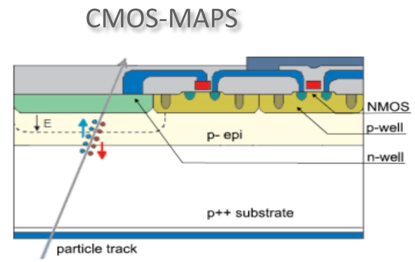
bump-bonded
hybrid-less
air cooled

Technologies

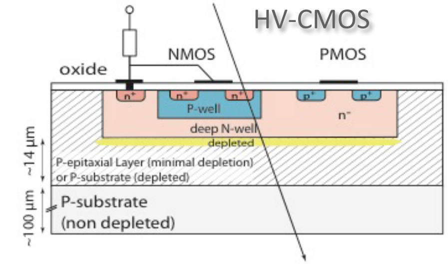
- Hybrids
- Monolithic active sensors



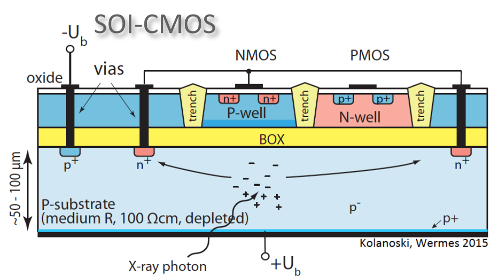
Depleted Hybrid Pixels



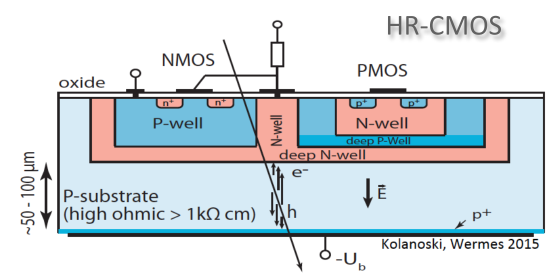
- Charge collection by diffusion



- HV process, 10 – 15 µm depletion region under deep N-well



- Fully depleted or HV process



- Can be fully depleted

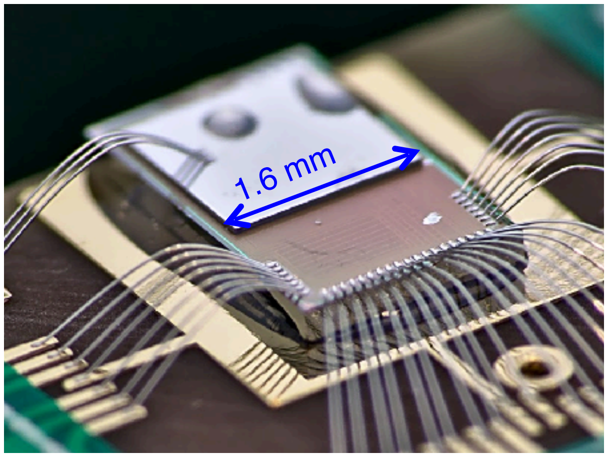
Technology	Examples	Small pixels	Low mass	Low power	Fast timing
Monolithic CMOS MAPS	Mimosa CPS	++	++	**++**	-
Integrated sensor/amplif. + separate r/o	DEPFET, FPCCD	+/++	o	+	-
Monolithic CMOS with depletion	HV-CMOS, HR-CMOS	+	++	**o**	**+**
3D integrated	Tezzaron, SOI	++	+	o	++
Hybrid	CLICpix+planar sensor, HV-CMOS hybrid	+	o	+	++

images: Demarteau
Table: Dannheim

CLIC vertex-detector R&D – recent planar sensor developments

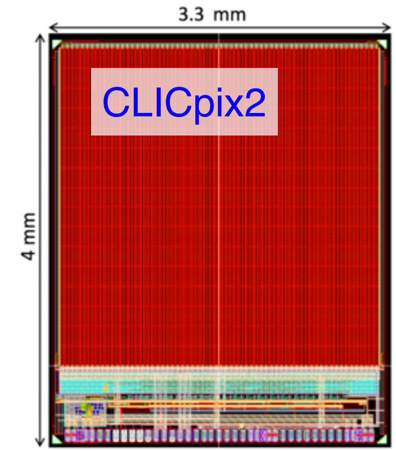
- Beam tests of 65 nm CLICpix (25 µm pitch) bump bonded to 50 µm thick active-edge sensor:
  - Bond yield ~30% → will increase (ongoing process optimization)
  - Hit efficiency ~99% → will increase (new CLICpix2 ASIC with lower threshold)
  - Hit resolution ~7 µm → limited by lack of charge sharing, new sensor concept needed

CLICpix with 50 µm sensor

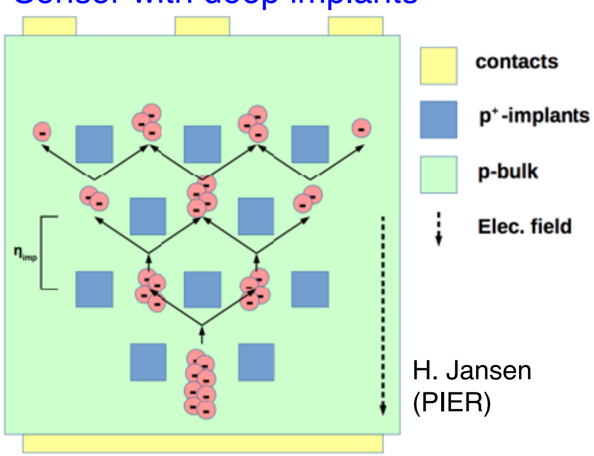


New CLICpix2 65 nm ASIC:

- 128x128 pixels
- ↓threshold, ↑dynamic range
- Submitted 23. November
- Delivery January 2017
- Additional submission with RD53 in April 2017
  → access to full wafers for bump bonding



Sensor with deep implants



H. Jansen (PIER)

Proposal for sensors with deep implants

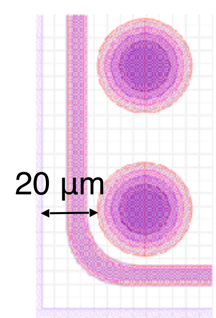
→ Modify E-field to enhance charge sharing

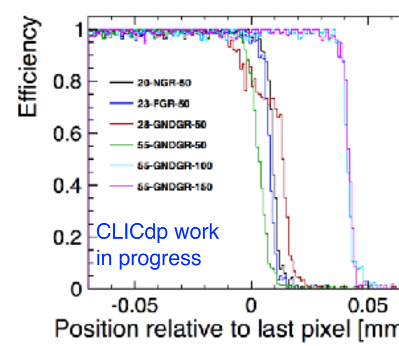
→ Improved resolution

- PIER project: Sensor wafer submission planned for 2017
- Use Timepix3 for proof-of-principle studies

Ultra-thin active-edge sensors

- Advacam wafer (with ATLAS et al.), Timepix3 sensors 50-150 um thickness
- Comparison of edge designs / TCAD sim.
- FBK submissions with AIDA-2020 WP7

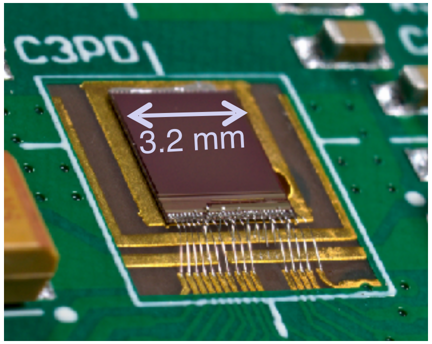




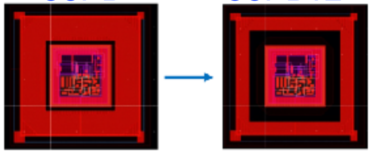
CLIC vertex-detector R&D – recent HV-CMOS developments

- New version of capacitively coupled active sensor produced in 180 nm HV-CMOS: C3PD
  - 128x128 pixels (matching CLICpix2)
  - Faster amplifier (~20 ns rise time)
  - Standalone test results for single test pixels confirm simulations
  - No degradation in performance for devices thinned to 50 µm
- New version (C3PDv2) submitted for production in engineering run with Mu3e and ATLAS → high-resistivity wafers (20/80/200 Ωcm) and higher break-down voltage

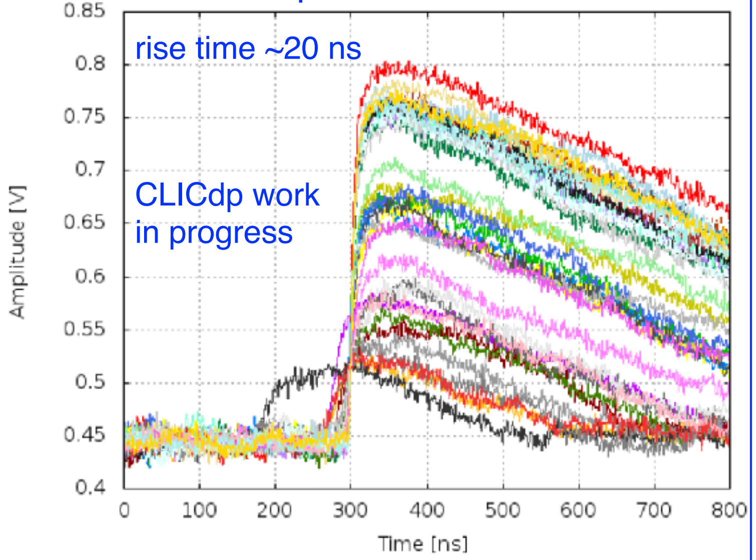
C3PD thinned to 50 µm



C3PD → C3PDv2

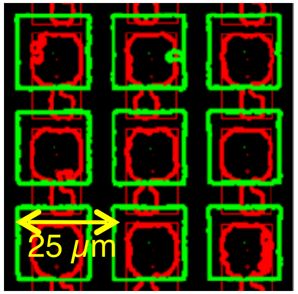


C3PD response to ^{55}Fe

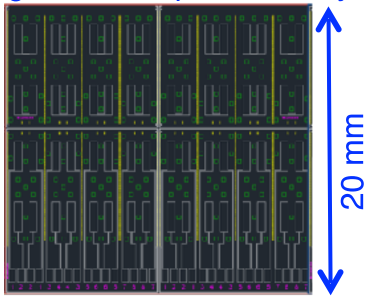


- Studies of capacitive coupling:
  - Alignment with pattern recognition
  - Finite-element capacitance simulations
  - Uniformity tests with segmented capacitors (with ATLAS and AIDA-2020 WP6)

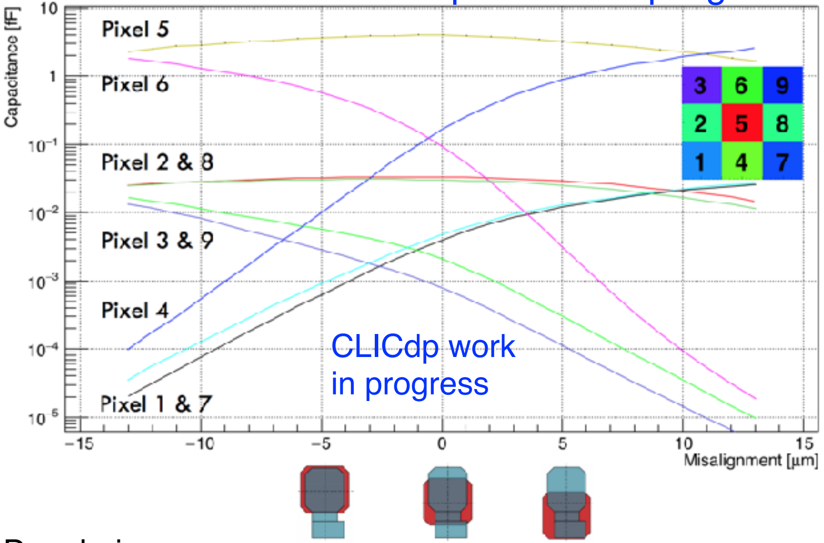
PixelShop alignment



Segmented capacitor array



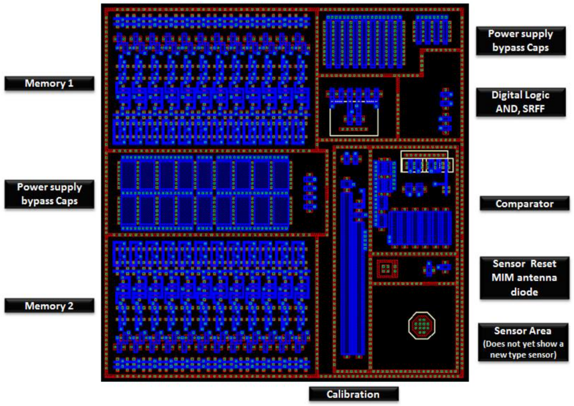
FE simulation of capacitive coupling

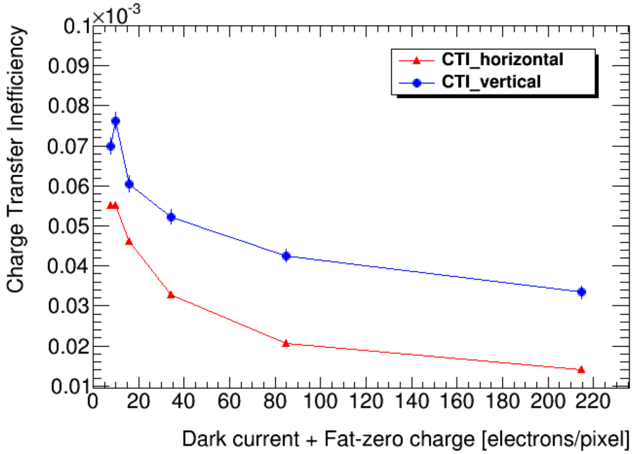


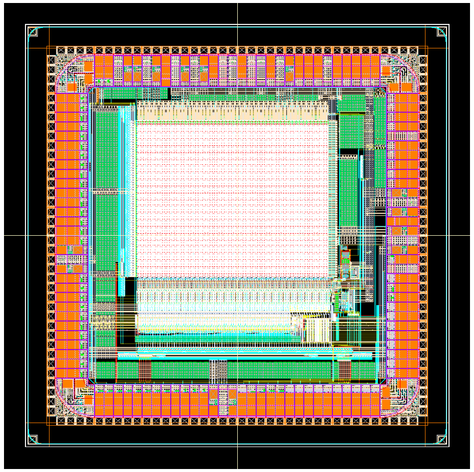
D.Dannheim

Recent progress in vertex R&D

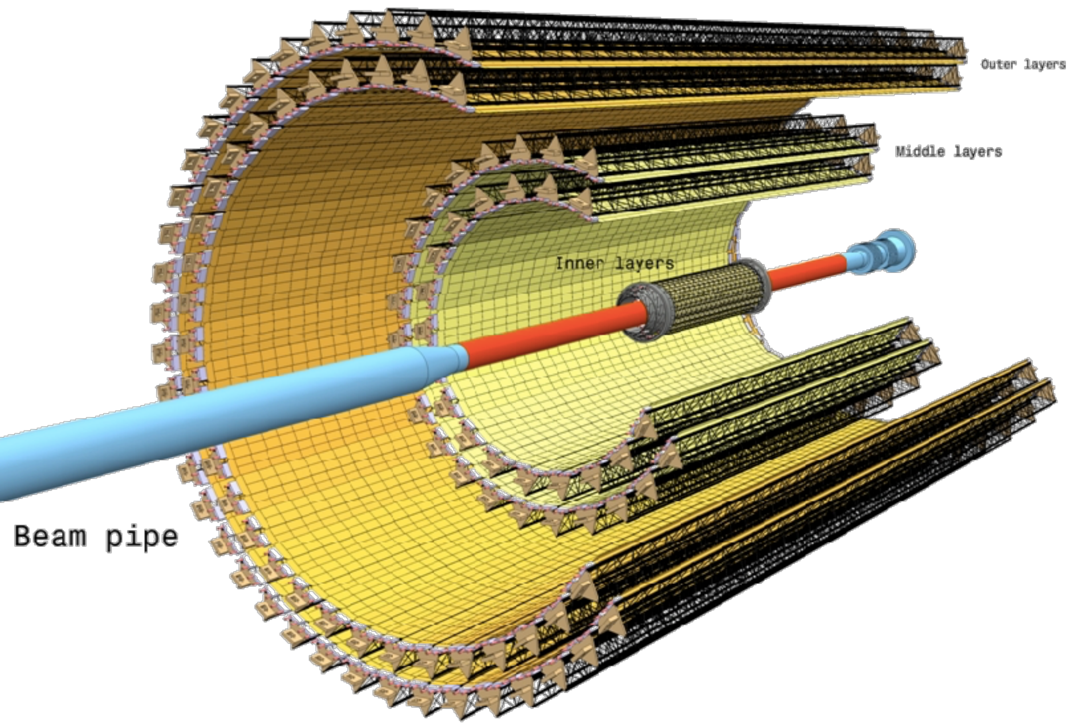
- Chrono-pixel prototypes:
  - 300 ns time stamping and sparse readout demonstrated
  - power-pulsing
  - small capacitances
- FPCCD: charge transfer inefficiency improved
  - charge injection to fill traps
- SOI: test chip submitted





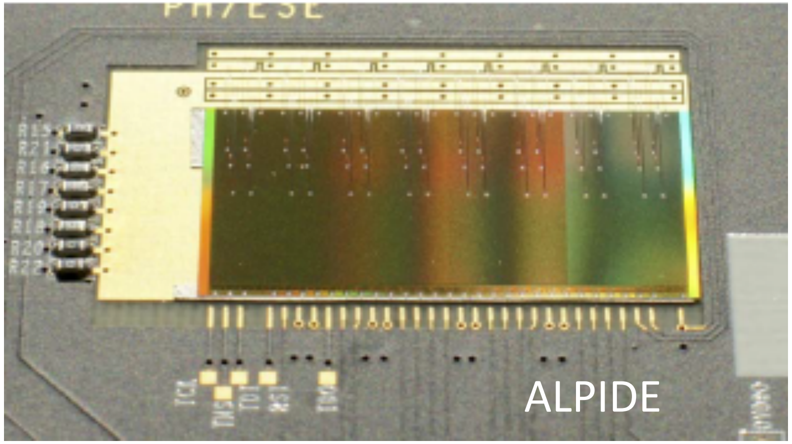


ALICE CMOS Inner Tracker System (ITS)

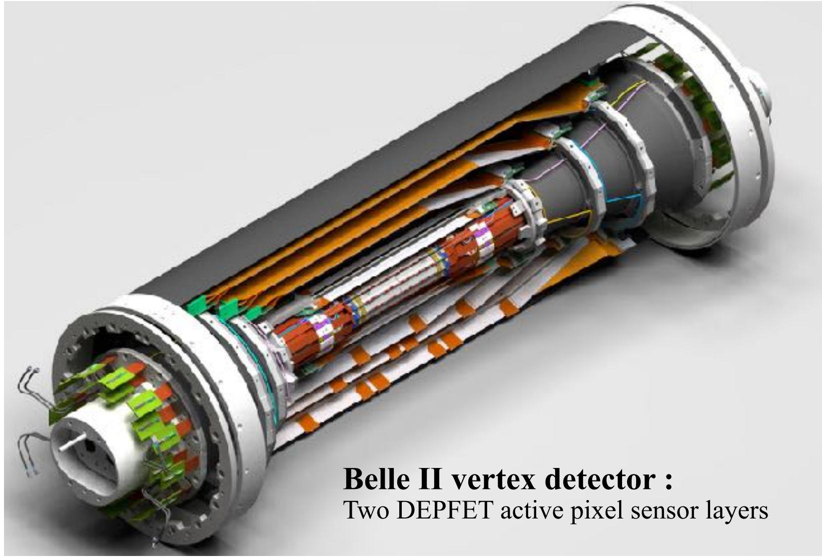


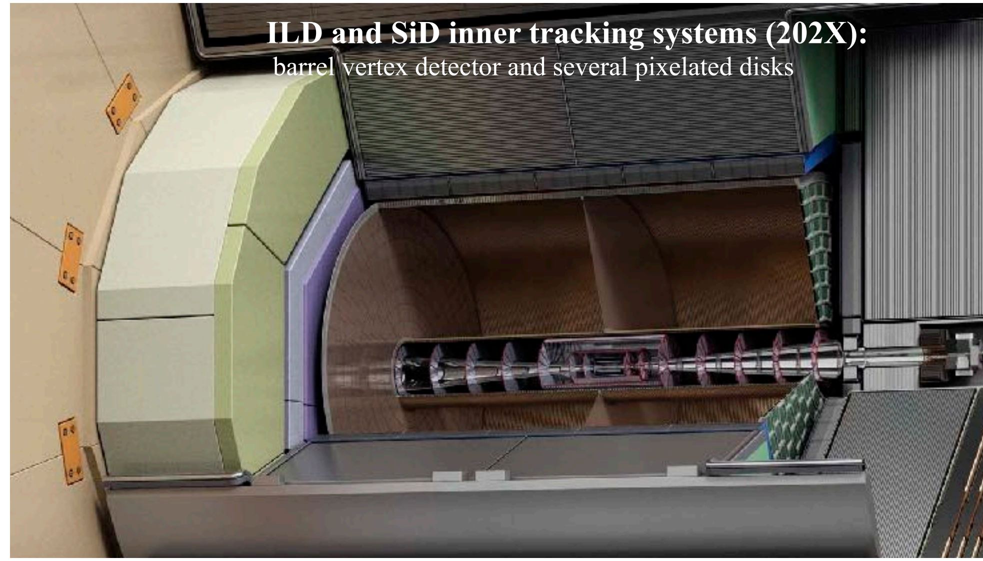
- 10 m^2 CMOS MAPS Pixel detectors
- 12.5 Giga pixels
  - 180 nm Tower Jazz process
  - 3 inner barrel layer (IB)
  - 4 outer barrel layers (OB)
  - Radial coverage 21-400 mm

- ALPIDE Chips
  - Dimensions: 30mm x 15 mm
  - Pixel Matrix: 1024 columns x 512 rows
  - Pixel pitch: 28µm x 28µm
  - Power consumption: < 40mW/cm^2



Belle II vs future LC - synergy





Most requirements are similar. The Belle II VXD is an excellent two-layer prototype for the ILC.
To be shown: small pixel size (demonstrated in 2010), material in services, solution for forward disks.

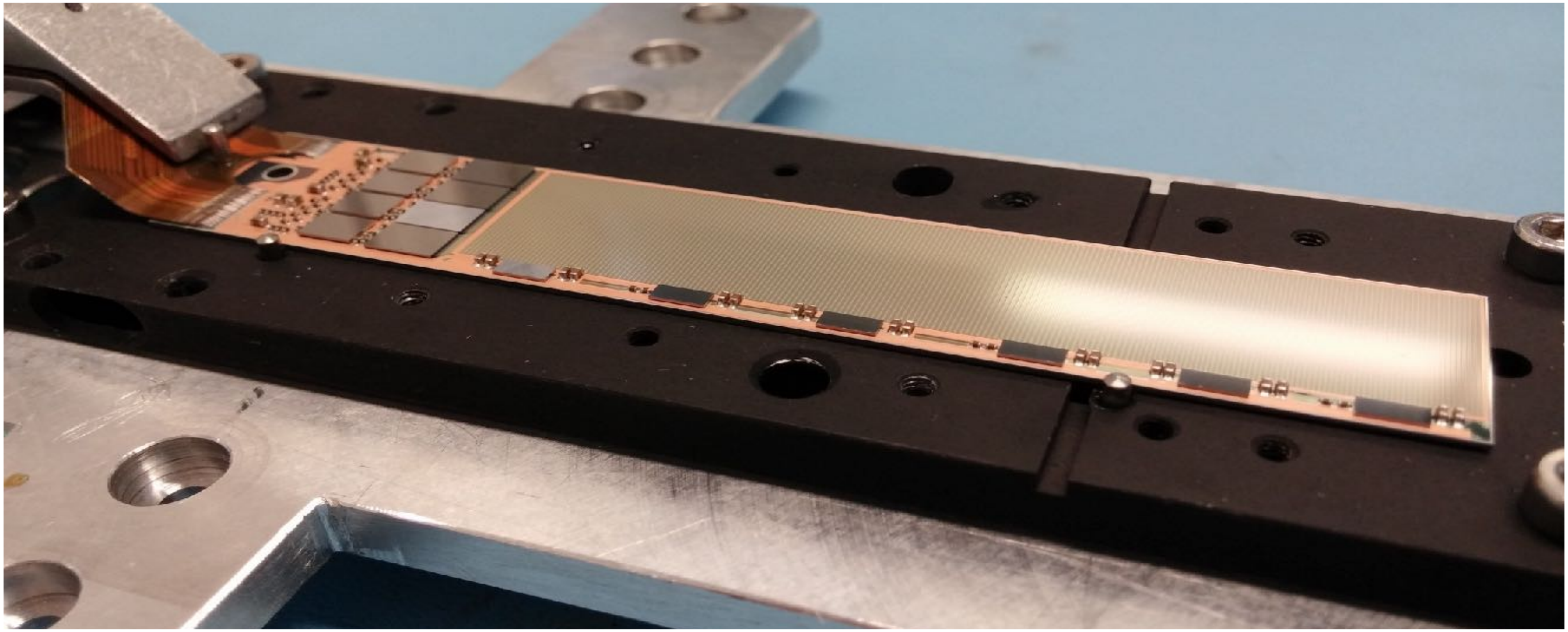
occupancy	0.13 hits/mm^2/s	0.4 hits/mm^2/s
Radiation	< 100 krad/year, 10^{11} 1 MeV n_{eq}/year	> 1Mrad/year, 2 x 10^{12} 1 MeV n_{eq}/year
Duty cycle	1/200	1
Frame time	25-100 ms (10 ns @ CLIC)	20 ms
Momentum range	All momenta	Low momentum (< 1 GeV)
Acceptance	6°-174°	17°-150°
Resolution	Excellent 3-5 mm, pixel size = 20 x 20 mm^2	Moderate, pixel size = 50 x 75 mm^2
Material budget	0.15 % X_0/layer	0.21 % X_0/layer

M.Vos

DEPFET
Active Pixel Detector

Final half-ladder

First fully functional ladder....
… major milestone for the DEPFET project!

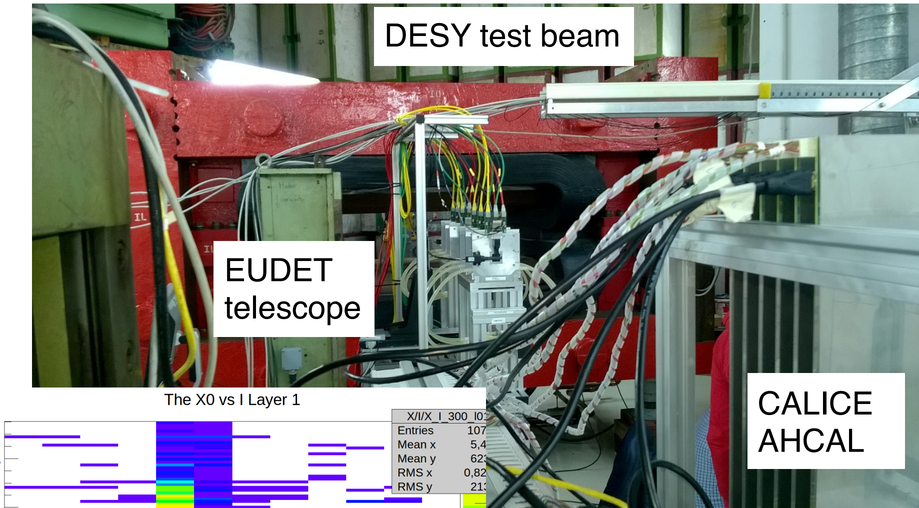


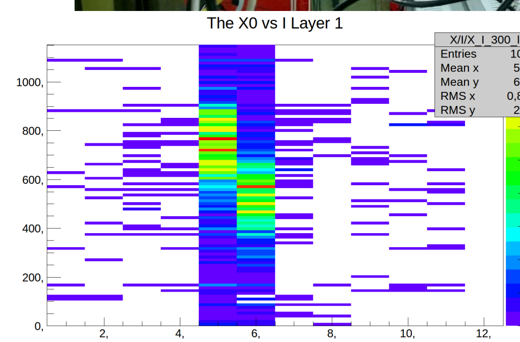
Belle II funding has been key to continue and accelerate the development of the sensors, to enable several iterations of the ASIC design, and to force the collaboration to come up with a complete solution for the off-detector system (from cables to cooling to DAQ)

Common issues

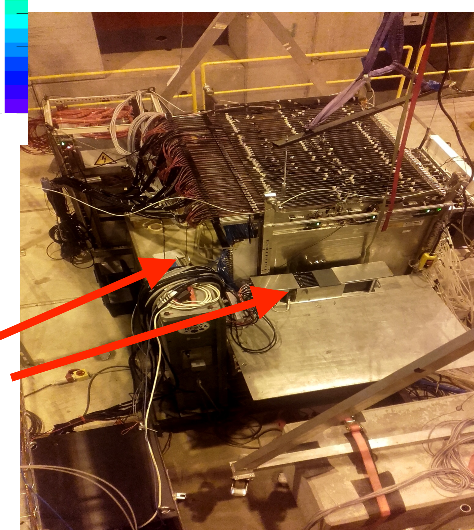
Common DAQ for combined beam tests

- LC detector community priority for AIDA-2020
- Effort on synchronisation hardware (TLU), run control and software (EUDAQ), monitoring (DQ4HEP)
- Recently achieved combination of trigger-less time-stamped (AHCAL) and trigger-marked (EUDET telescope) read-out
- Number of recent or up-coming combined runs
  - FCAL sensors and beam telescope
  - SiECAL and SDHCAL
  - in preparation: TPC with kPix reference tracker





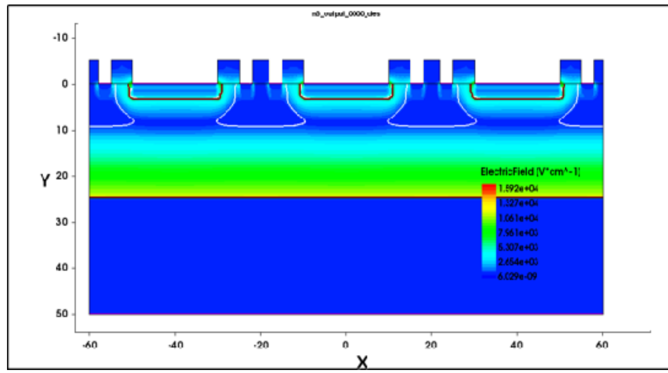
spatial correlation of synchronous pixel and HCAL hits

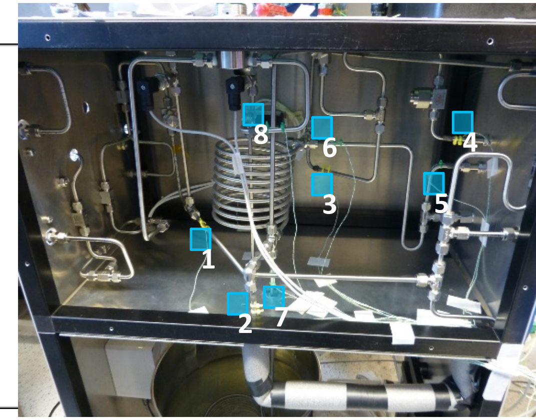


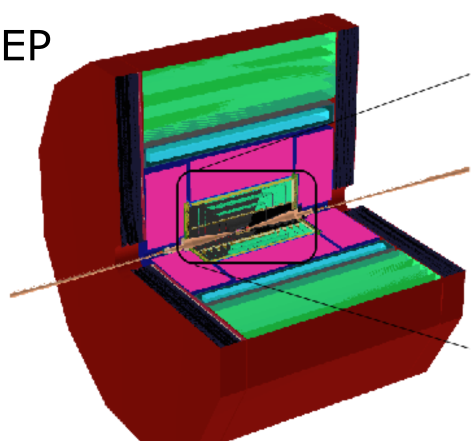
RPC HCAL
SiECAL

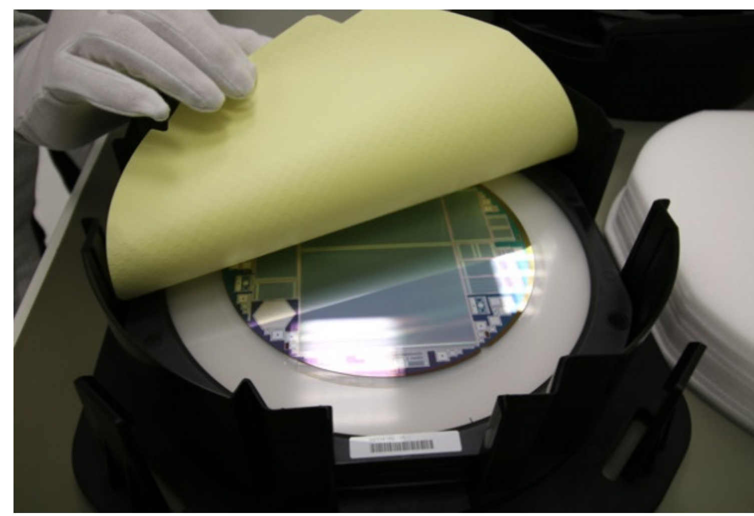
More common issues

- Test beam infrastructures, telescopes
- QA and production infrastructure
  - LHC and LC
- Advanced cooling techniques
- TCAD simulations for sensor design
- Industrial large area silicon production
- And software!
  - geometry DD4HEP
  - Pandora
  - Si tracking









Conclusion

- In a challenging funding environment, LC detector R&D is progressing and focussed on the most critical issues to be solved for the precision e+e- physics we aim at

- Close and fruitful interplay with concept groups

- Two-way synergies with other developments in HEP (and beyond)
  - LC developments bear fruit and enhance precision reach
  - collect experience in realistic environment and challenging time lines

- R&D groups bring in valuable expertise across concepts, across ILC and CLIC, across collider communities

Thanks!

- Y.Arai, J.Brau, D.Dannheim, M.Demarteau, J.Kaminski, K.Krüger, T.Peitzmann, F.Simon, Y.Sugimoto, T.Takeshita, M.Vos
- and those from whom I have shameless stolen material

- Apologies for the many things I had no time to cover, in particular FCAL

Backup