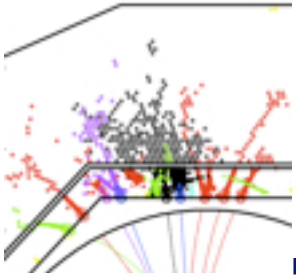
Calorimetry for Linear Collider Experiments

Felix Sefkow

INFN mini workshop on ILC and more
Como, 17. May 2013



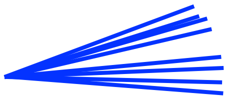
Outline

- Particle flow detectors
- Test beam validation
- ECAL and HCAL technologies
  - status and open issues

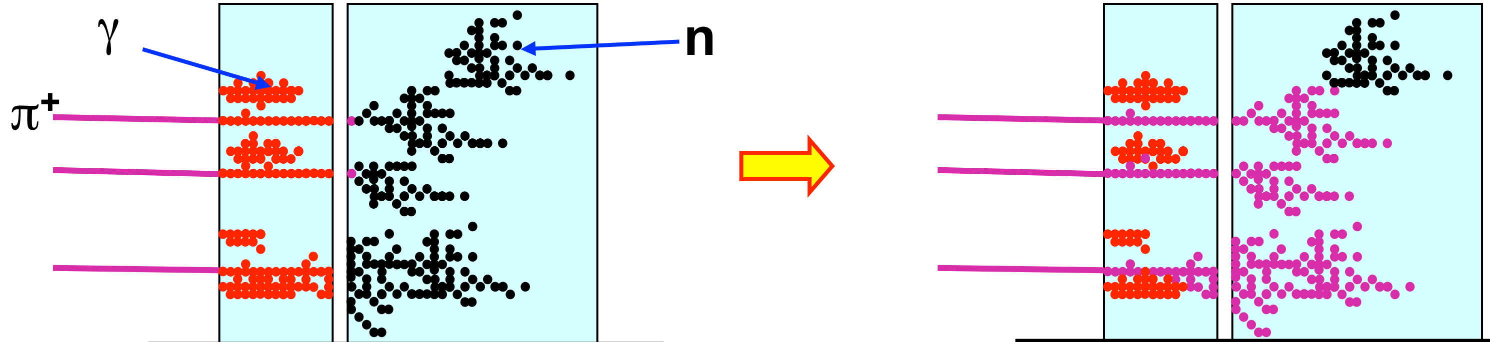
Particle flow concept and detectors

Particle Flow Calorimetry

★ **In a typical jet :**
- 60 % of jet energy in charged hadrons
- 30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
- 10 % in neutral hadrons (mainly n and K_L)



★ **Traditional calorimetric approach:**
- Measure all components of jet energy in ECAL/HCAL !
- ~70 % of energy measured in HCAL: $\sigma_\mathrm{E}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$
- Intrinsically "poor" HCAL resolution limits jet energy resolution



$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

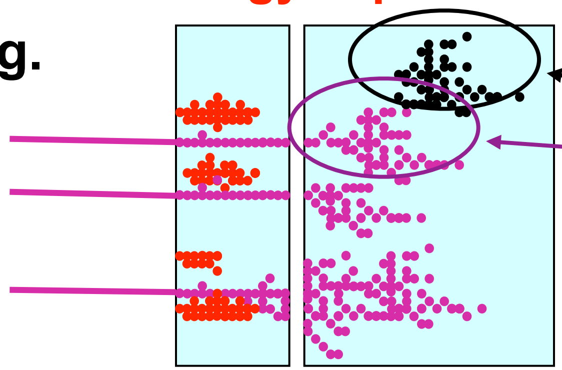
★ **Particle Flow Calorimetry paradigm:**
- charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: $\sigma_\mathrm{E}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
- Neutral hadrons (ONLY) in HCAL
- Only 10 % of jet energy from HCAL ⟹ much improved resolution

Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:

- ★ Avoid double counting of energy from same particle
- ★ Separate energy deposits from different particles

e.g.

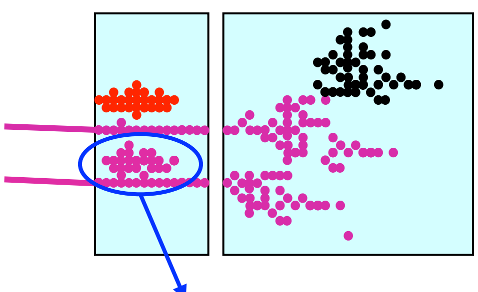


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution
not the intrinsic calorimetric performance of ECAL/HCAL

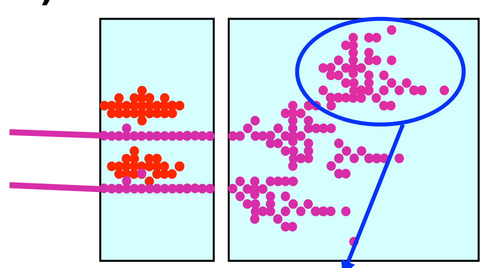
Three types of confusion:

i) Photons



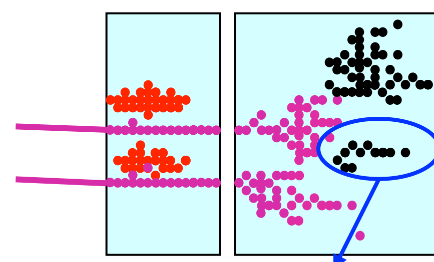
Failure to resolve photon

ii) Neutral Hadrons

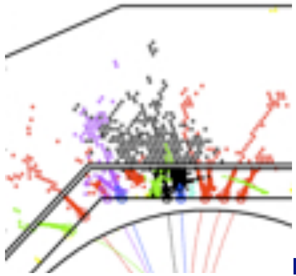


Failure to resolve neutral hadron

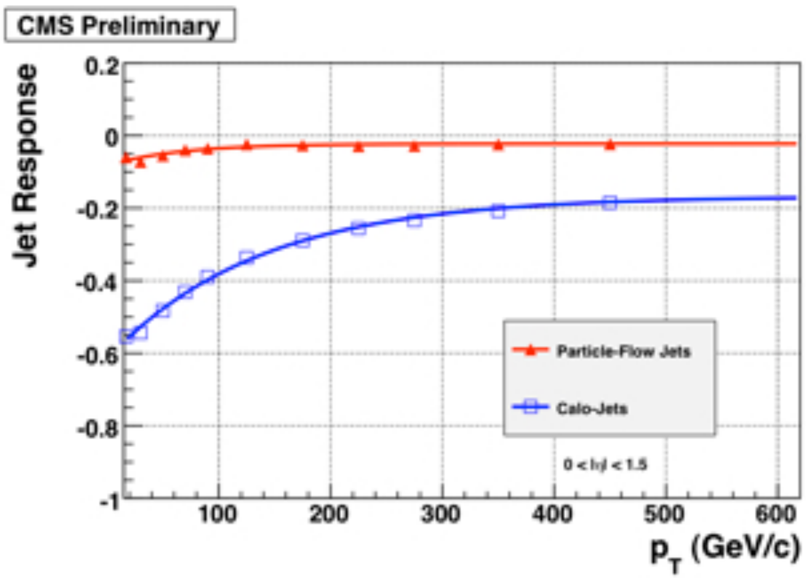
iii) Fragments

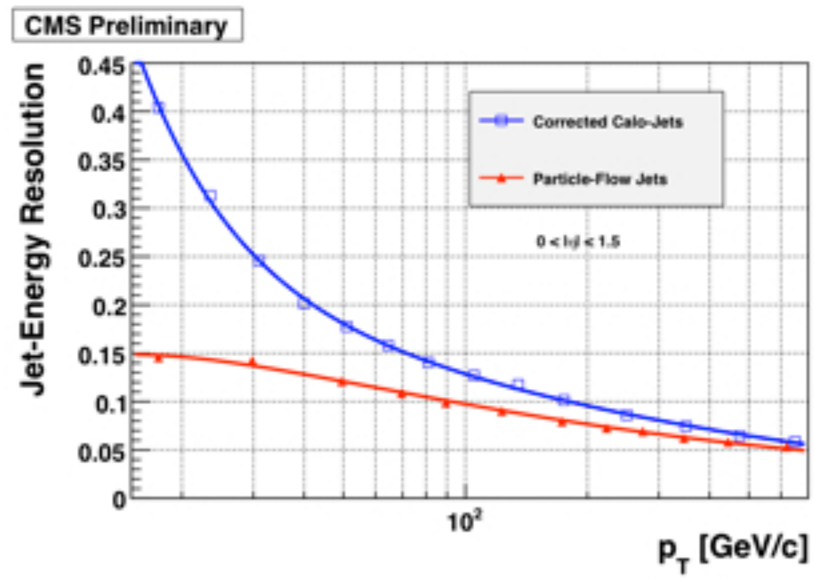


Reconstruct fragment as separate neutral hadron



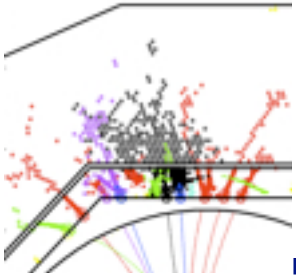
CMS jet pT response, resolution





plus: angular resolution improved by factor 3
and much reduced flavour dependence

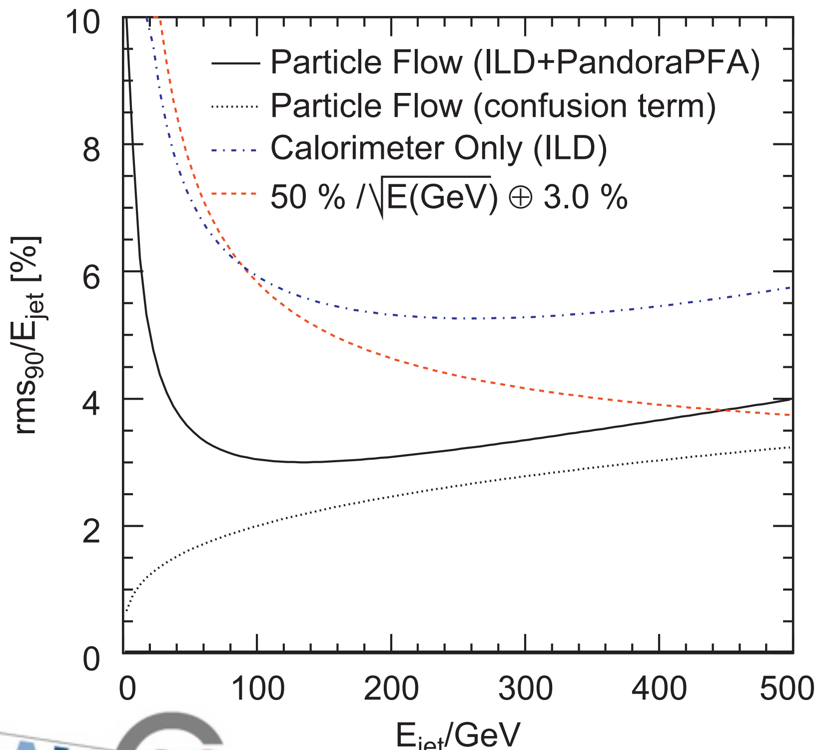
- ATLAS: better single hadron resolution
- ⇒ has to try harder to improve
- effort started

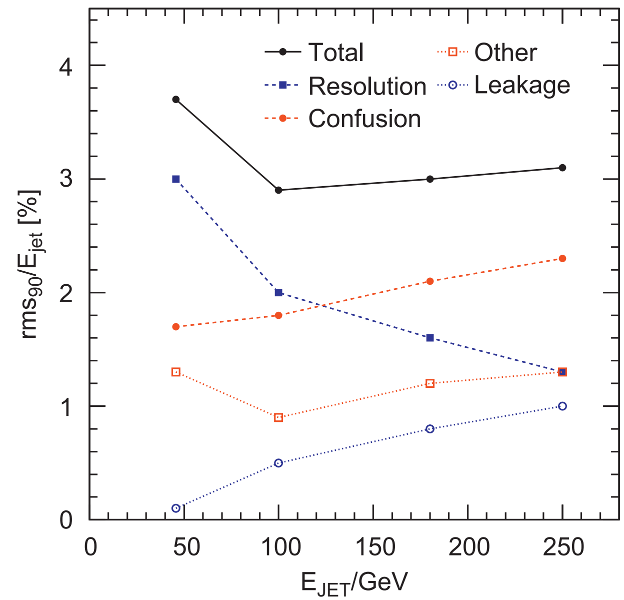


Understand particle flow performance at LC

$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{E}{100}\right)^{+0.3} \%$$

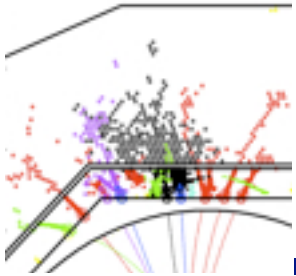
Resolution — Tracking — Leakage — Confusion





- Particle flow is always a gain
  - even at high jet energies
- HCAL resolution does matter
  - also for confusion term
- Leakage plays a role, too
  - but less than in the calo alone

M.Thomson, Nucl.Instrum.Meth. A611 (2009) 25-40



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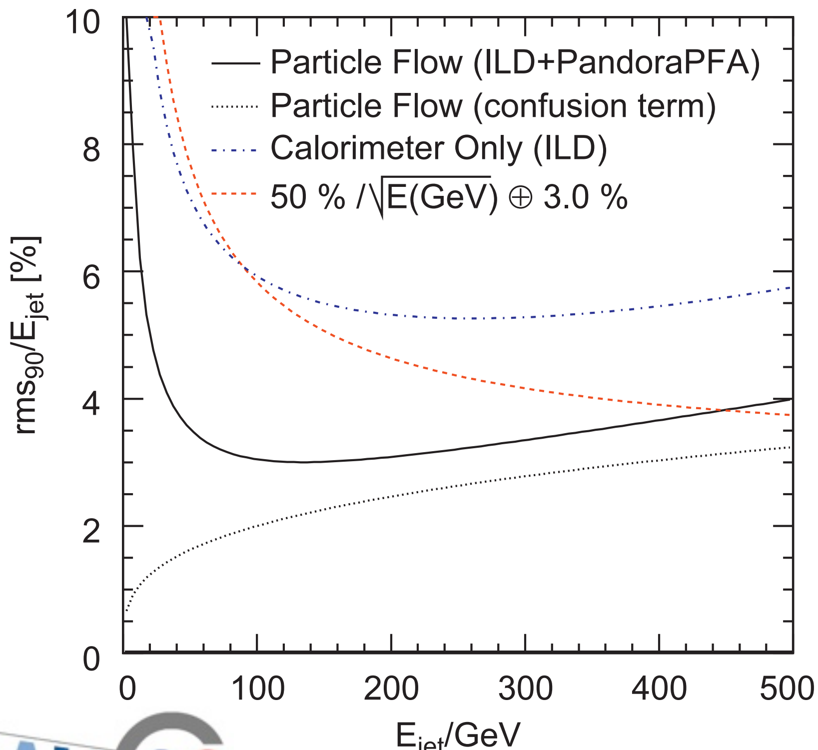

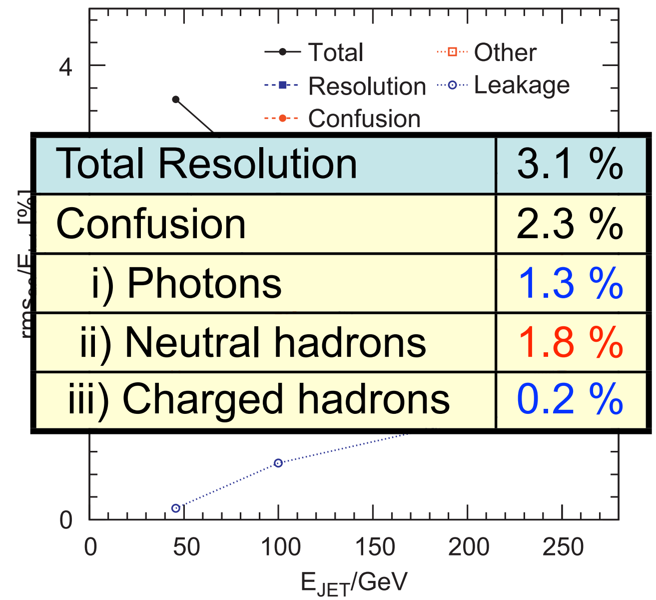

Total Resolution	3.1 %
Confusion	2.3 %
i) Photons	1.3 %
ii) Neutral hadrons	1.8 %
iii) Charged hadrons	0.2 %

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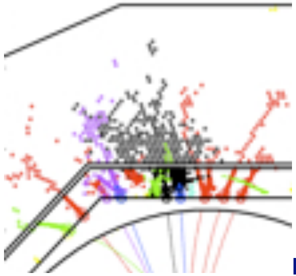

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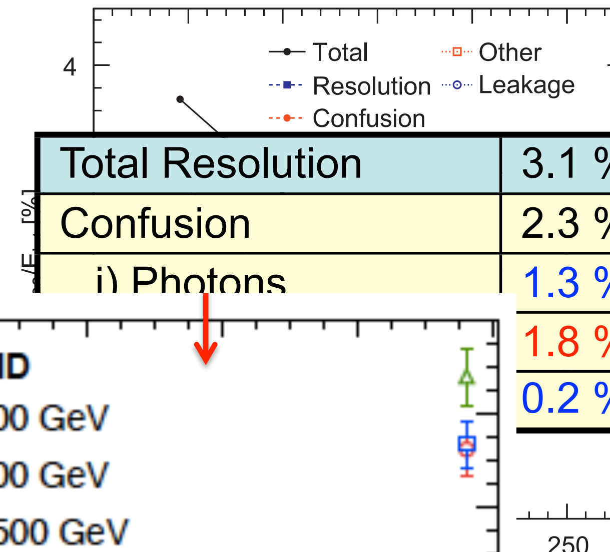

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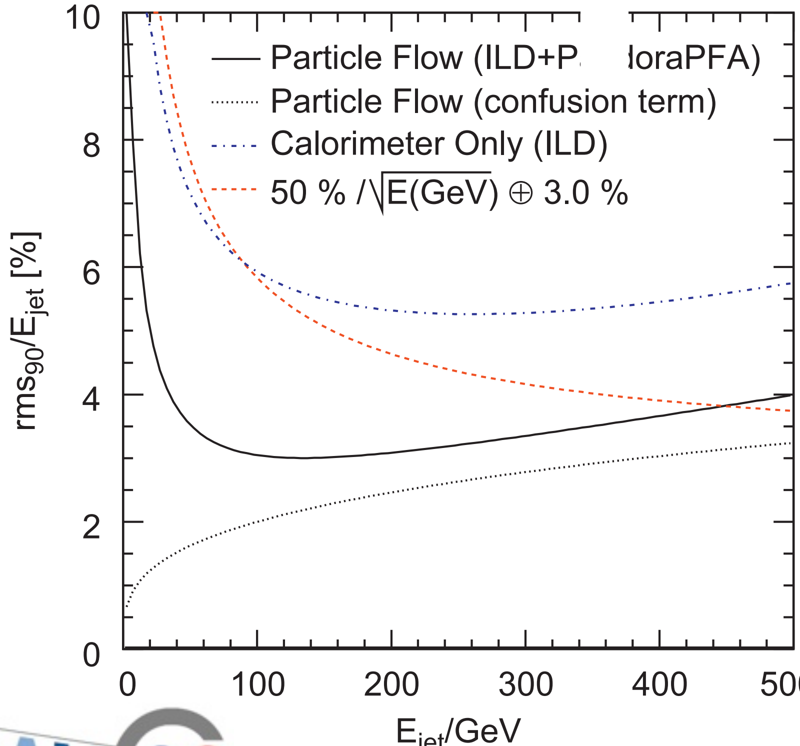

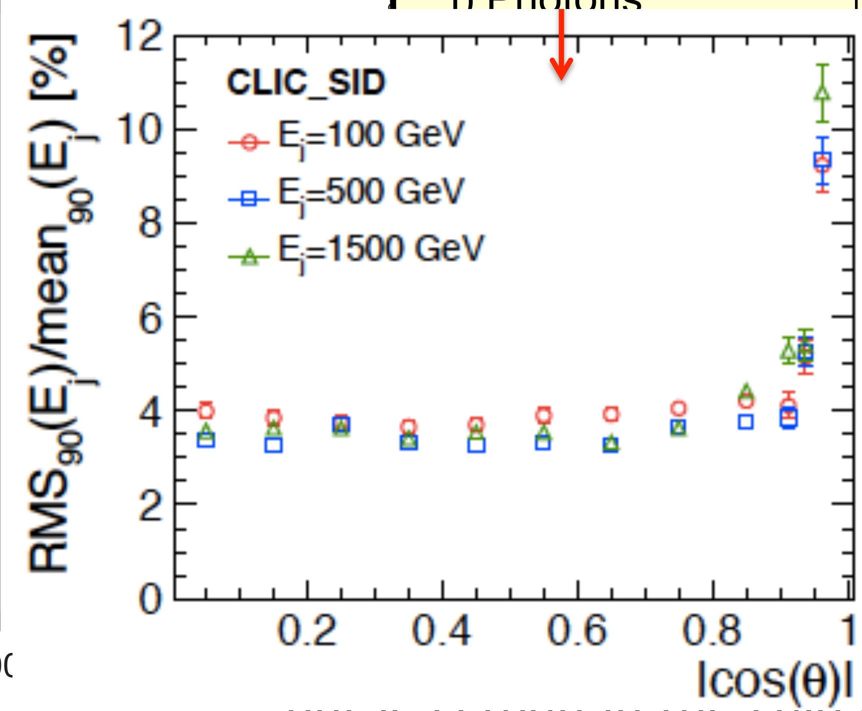

ain

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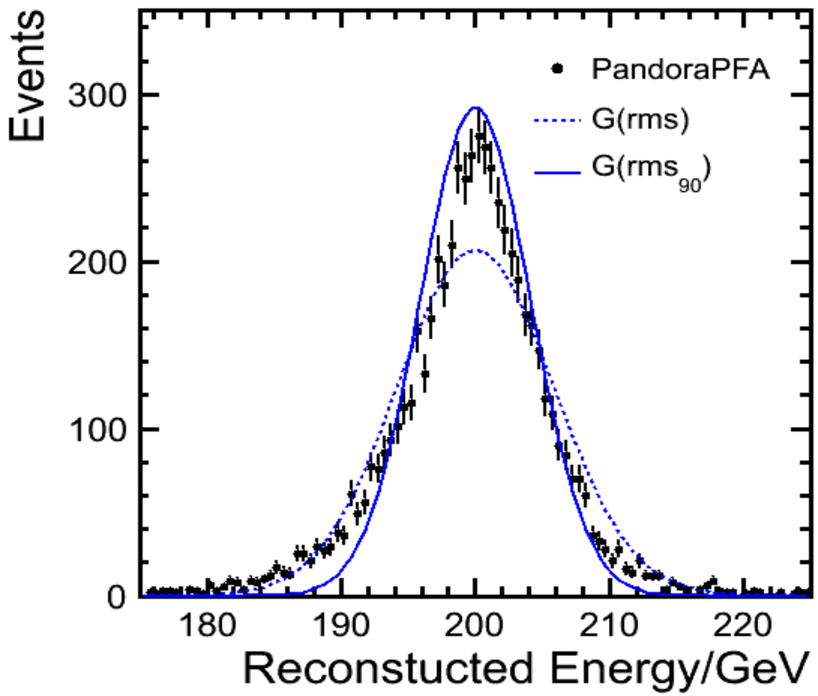
alone

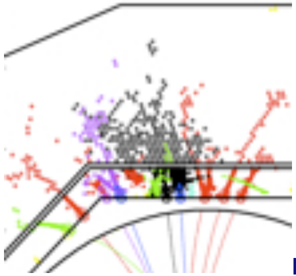
M.Thomson, Nucl.Instrum.Meth. A611 (2009) 25-40

- Particle Flow reconstruction inherently non-Gaussian, so resolution presented in terms of rms_{90}
  - Defined as "rms in smallest region containing 90% of events"
  - Introduced to reduce sensitivity to tails in a well defined manner
- For a true Gaussian distribution, $rms_{90} = 0.79\sigma$
- However, this can be highly misleading:
  - Distributions almost always have tails
  - Gaussian usually means fit to some region
  - $G(rms_{90})$ larger than central peak from PFA
- MC studies to determine equivalent statistical power indicate that:

$$rms_{90} \approx 0.9\sigma_{Gaus}$$

- Now use rms_{90} as a sensible convention, but does not mean PFA produces particularly large tails.

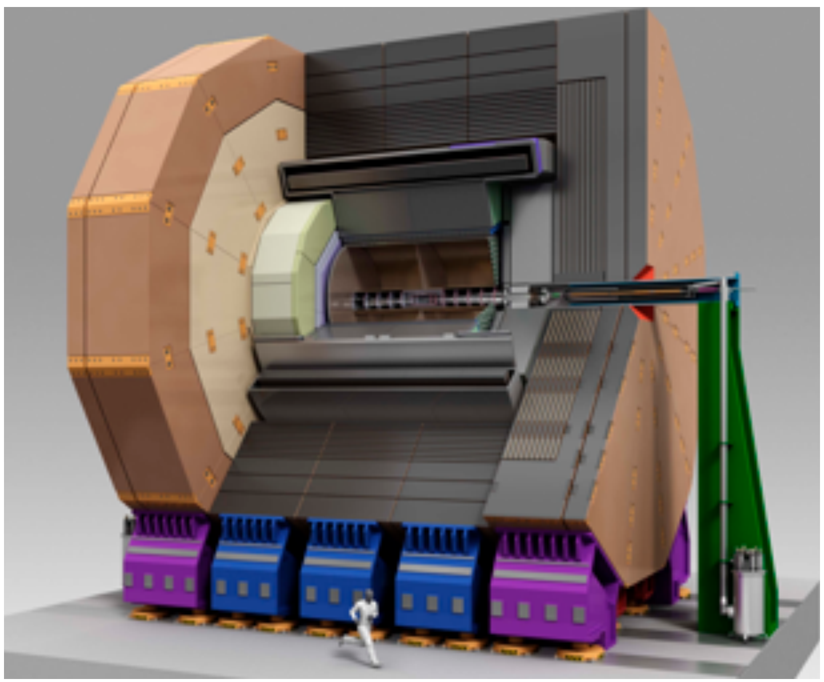




Particle flow detectors

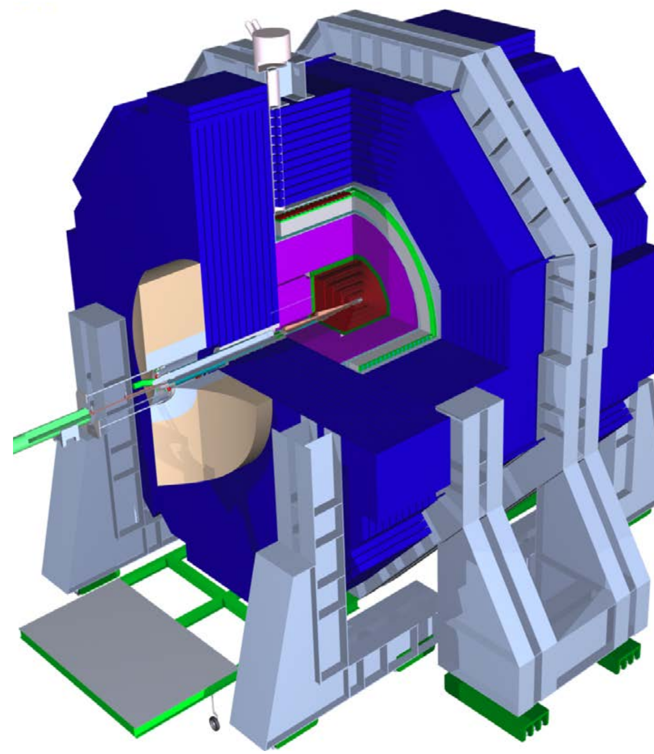
- large radius, large field, fine 3D calorimeter granularity, compact
  - Typ 1X0 long, transv: 0.5cm ECAL, 1cm gas HCAL, 3cm scint.
- optimized in full simulations and particle flow reconstruction

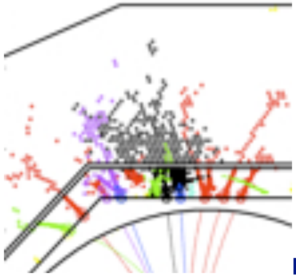
ILD: large TPC, B=3.5T, PFLOW calo



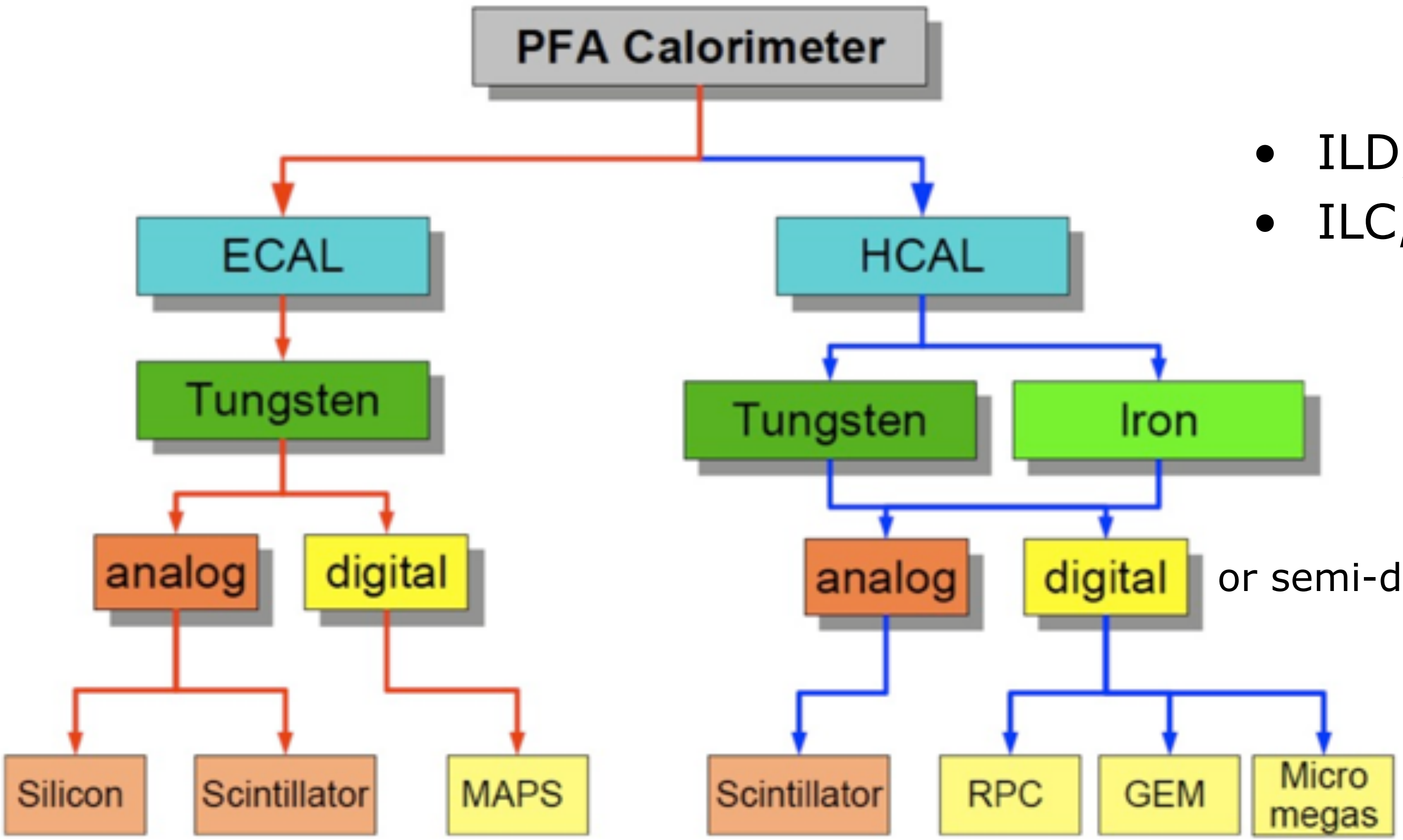
SiD:all-Si tracker, B=5T, PFLOW calo

CLIC: tungsten barrel HCAL



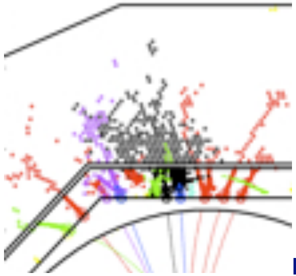


Calorimeter technology tree

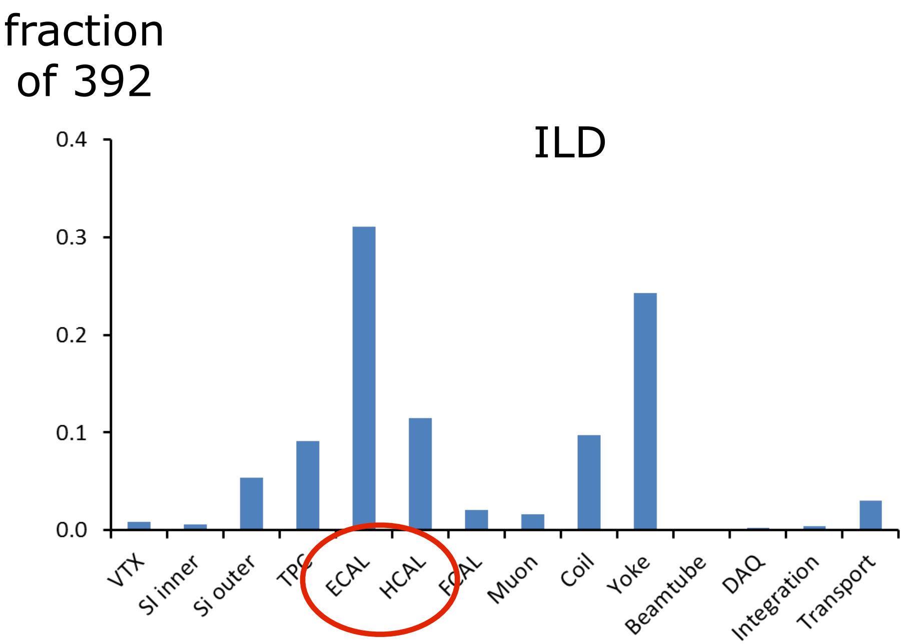


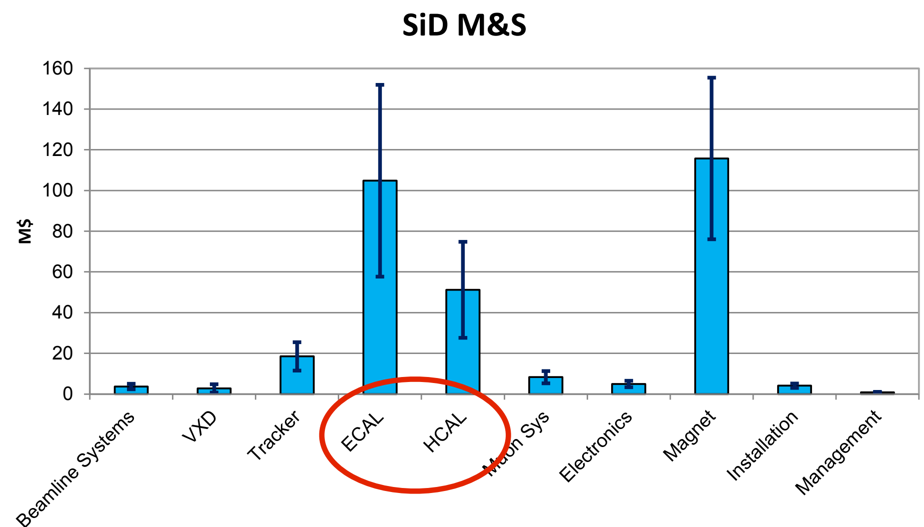
or semi-digital

- ILD, SiD
- ILC, CLIC



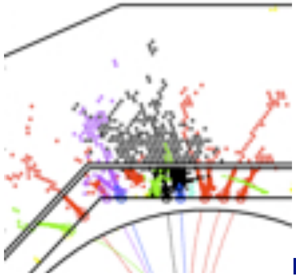
Detector cost





sum = 315

- Time (and room) for re-optimisation
- using knowledge from prototyping
- calorimeter costs mostly driven by active area
  - rather than granularity



Particle flow calorimeters:

- Particle Flow concept proven in detailed simulations: provides required resolution up to CLIC jet energies
- Extremely fine calorimeter segmentation *and* good calorimetric performance
- Demand novel read-out technologies and pose new system integration challenges
- CALICE: collaborative R&D and test beam effort to
  - develop the technologies
  - establish the performance
  - validate the physics models
  - test the algorithms
  - demonstrate the scalability

~350 people, 60 institutes

recently joined: Tokyo U
discussing with:
Weizmann, Aveiro, Coimbra

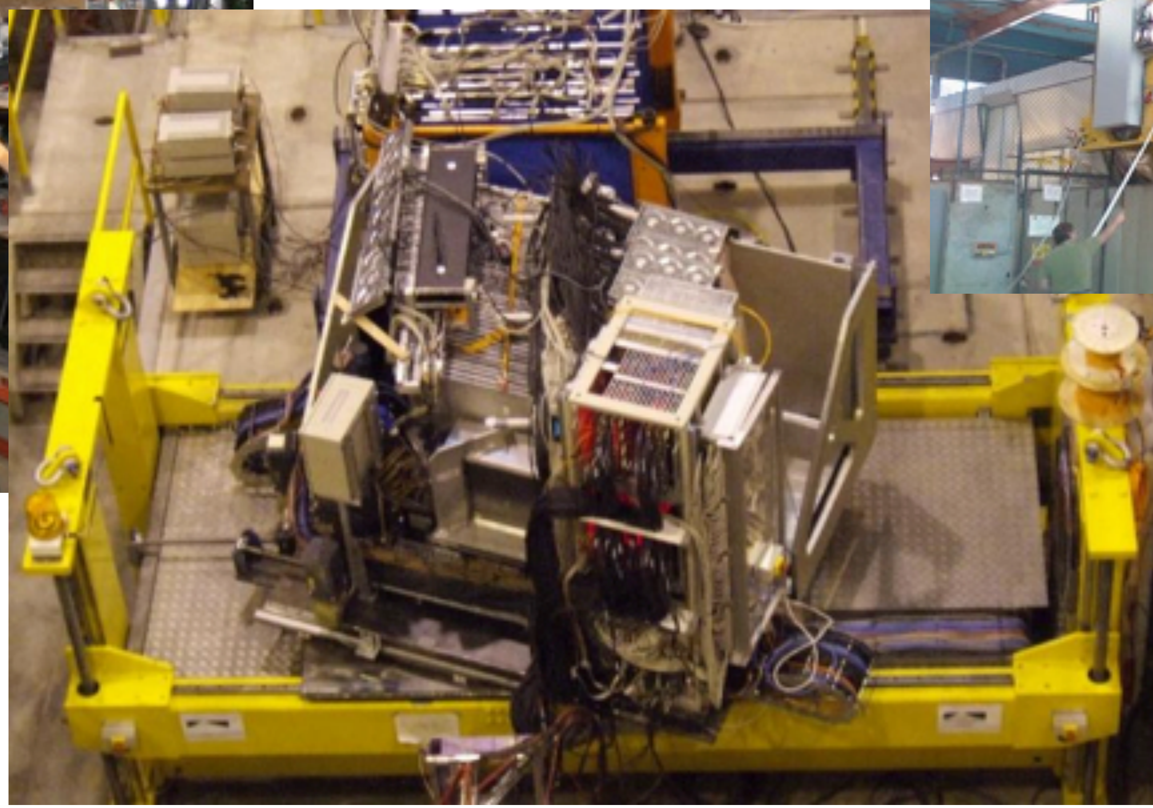
CALICE Calorimeter for ILC

Test beam experiments 2005-2012:

all ECAL and HCAL technologies

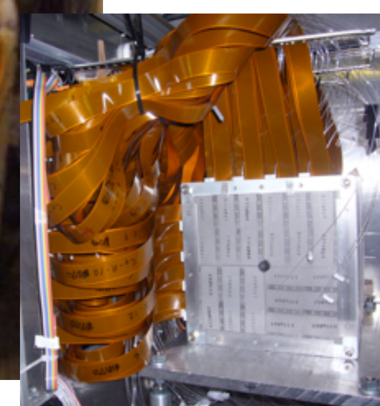
Test beam experiments

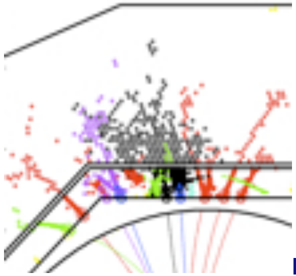
CERN 2006-2007
add Scint HCAL



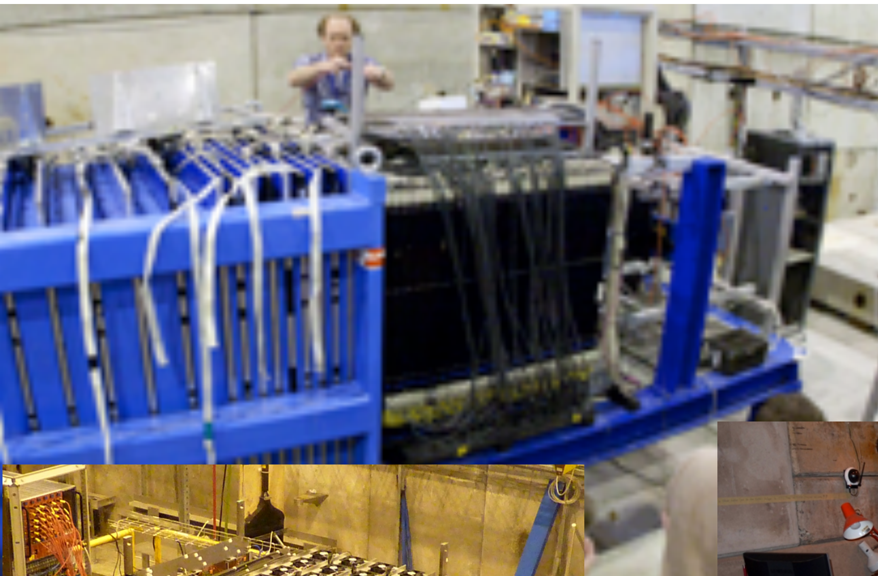
DESY 2005
SiECAL

FNAL 2008-09
Si -> Sci ECAL



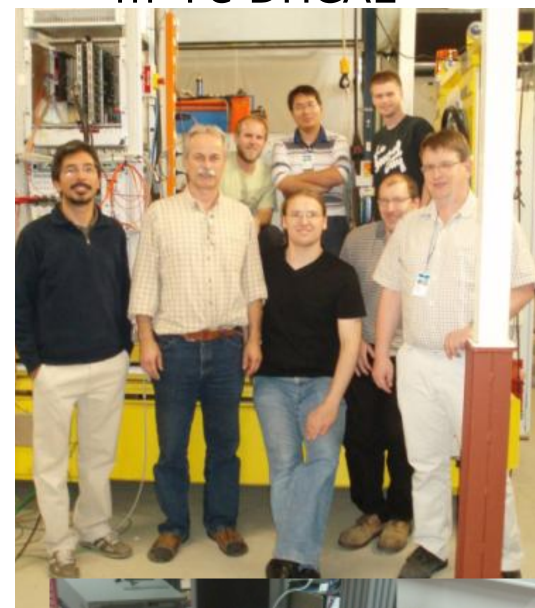


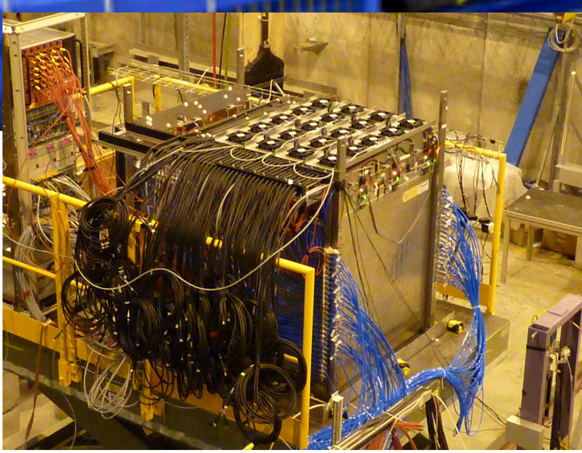
+ Test beam experiments



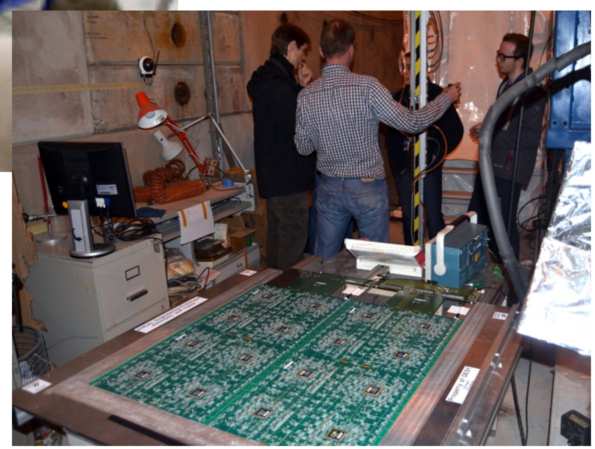
CERN 2010-11 Tungsten AHCAL
2012: DHCAL

FNAL2010-11: m^3 Fe DHCAL





CERN 2012: m^3 SDHCAL



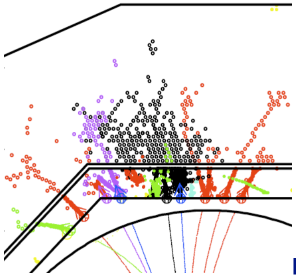
CERN 2012
2nd generation
scint HCAL

DESY 2012
2nd generation
SiW ECAL

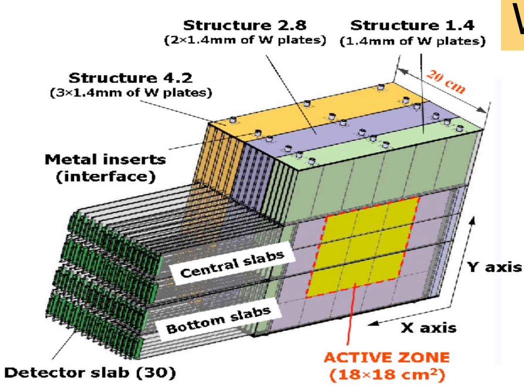
Test beam results

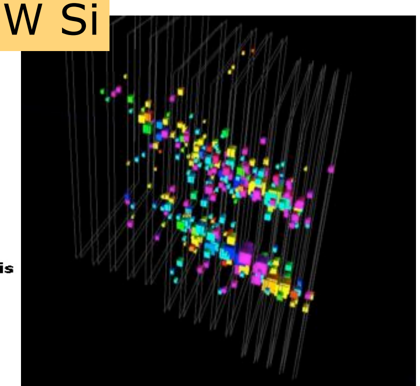
Establish
calorimeter performance,
Validate
Geant 4 simulations,
Test
particle flow algorithm

ECAL performance

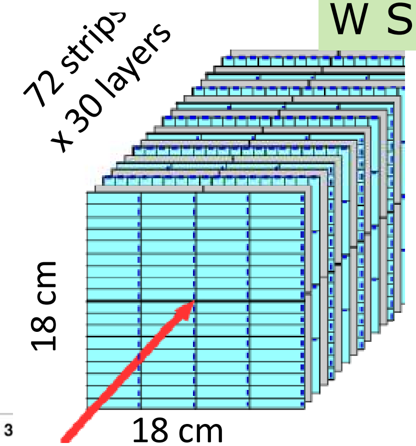


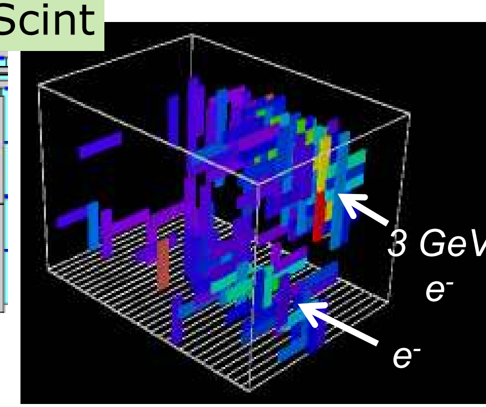
W Si

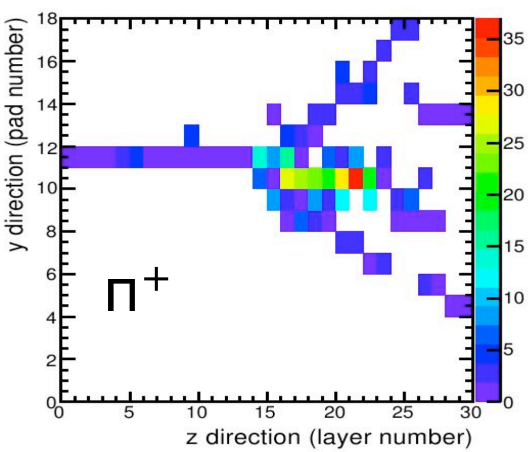


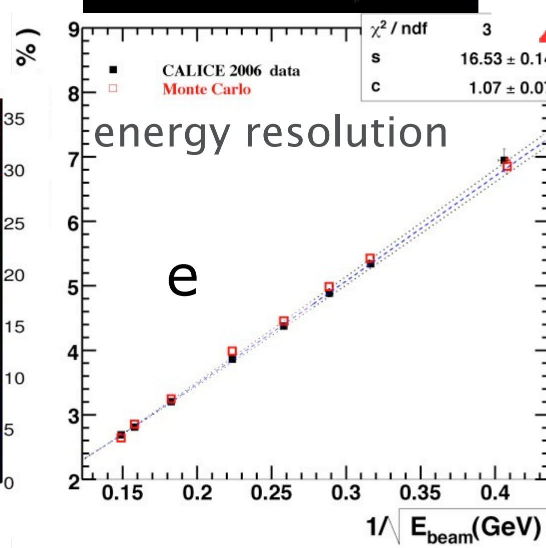


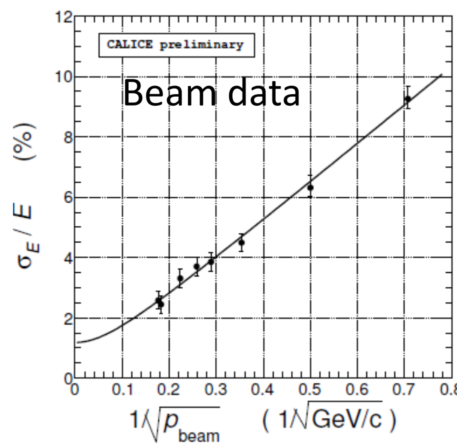
W Scint

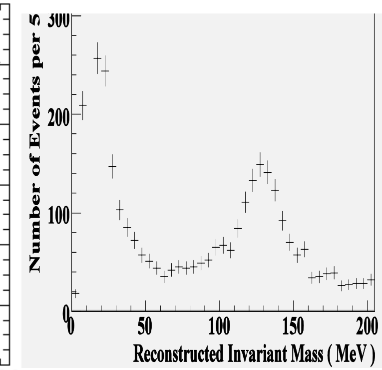








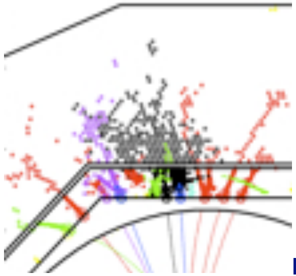




- data and sim agree for both

$12.9 \pm 0.1(\text{stat.}) \pm 0.4\ (\text{syst.})\%$

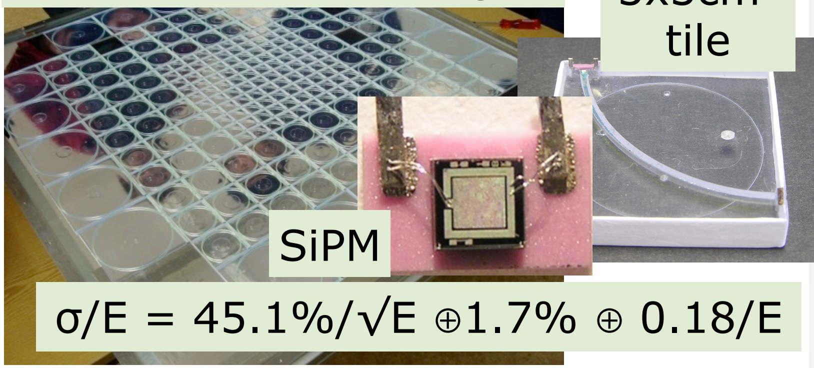
$1.2 \pm 0.1(\text{stat.})\ ^{+0.4}_{-1.2}\ (\text{syst.})\%$



HCAL performance

Fe scintillator - analogue

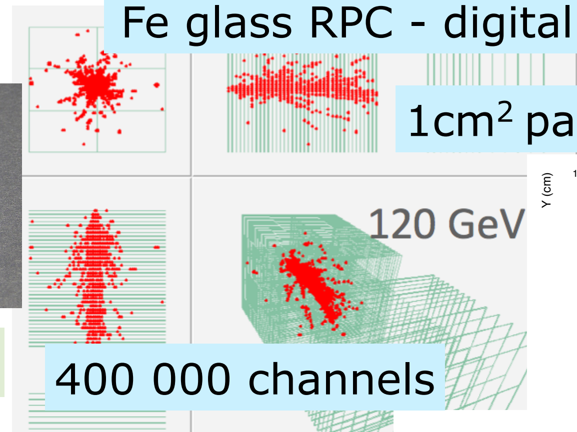
3x3cm^2 tile



$\sigma/E = 45.1\%/\sqrt{E} \oplus 1.7\% \oplus 0.18/E$

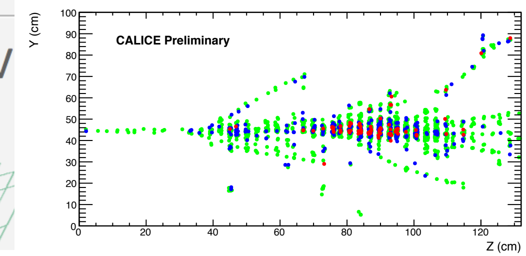
Fe glass RPC - digital

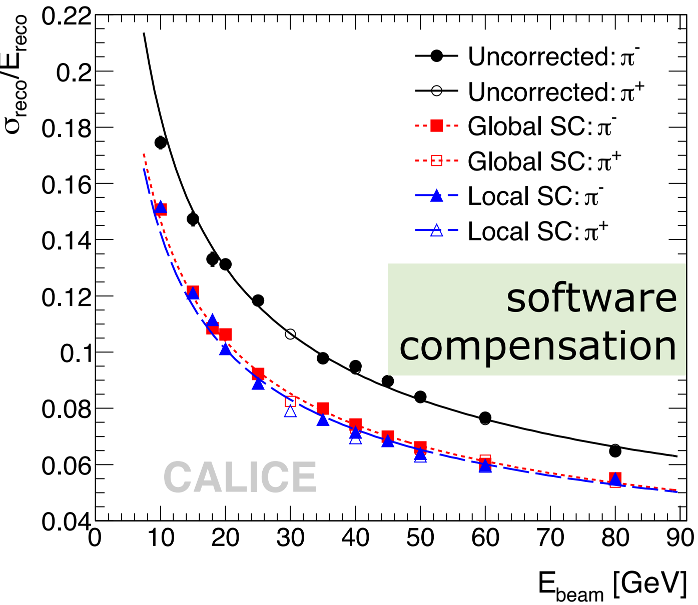
1cm^2 pads



400 000 channels

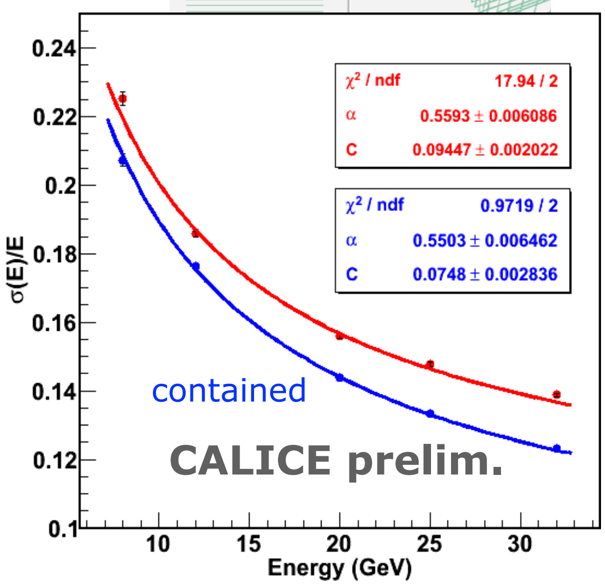
Fe glass RPC semi-digital 2-bit

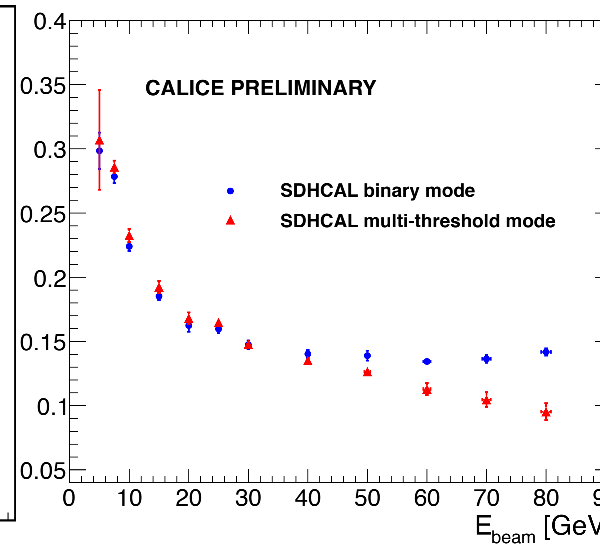


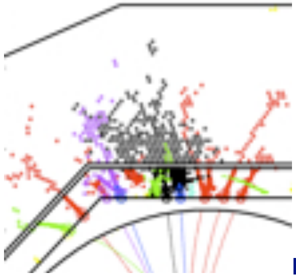


software compensation

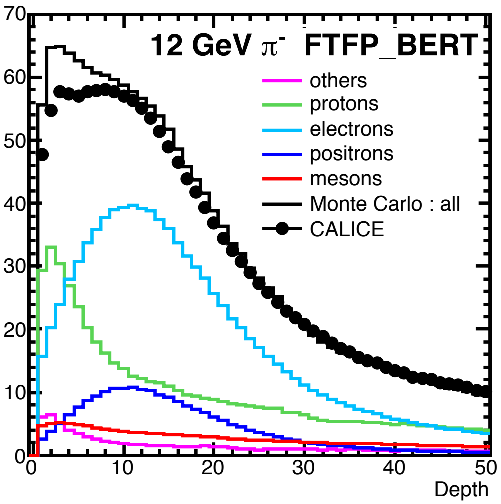
JINST 7, P00917 (2012)





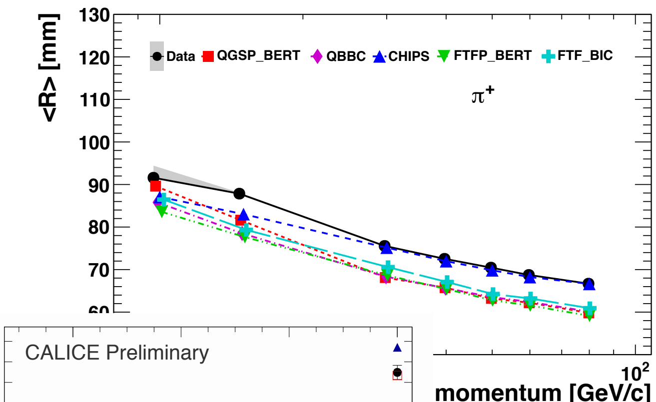


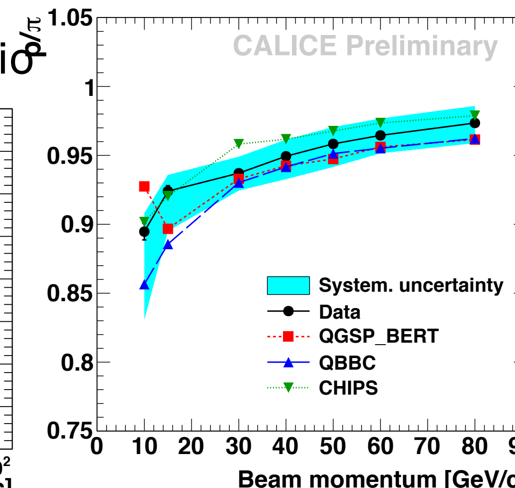
Validation of Geant 4 models

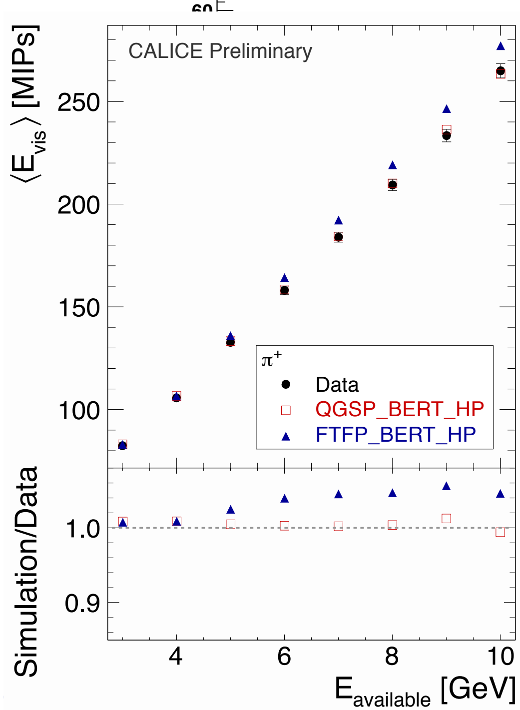


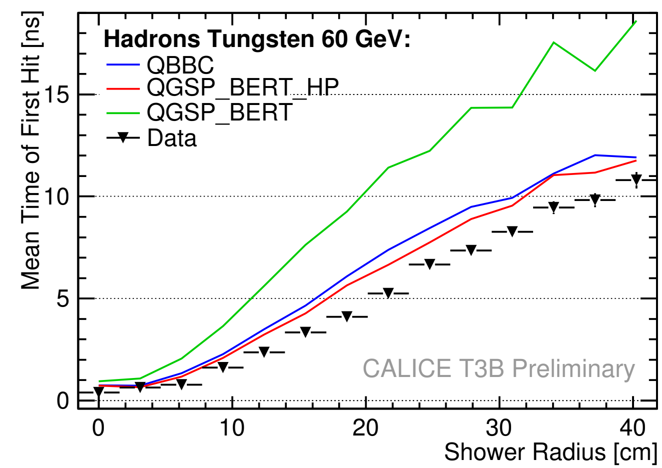
SiW ECAL
longit. profile

Fe Scint HCAL
radial profile, proton pion resp. ratio



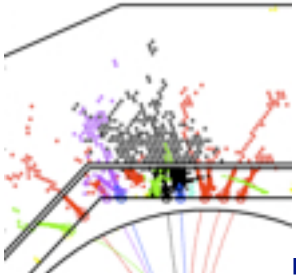






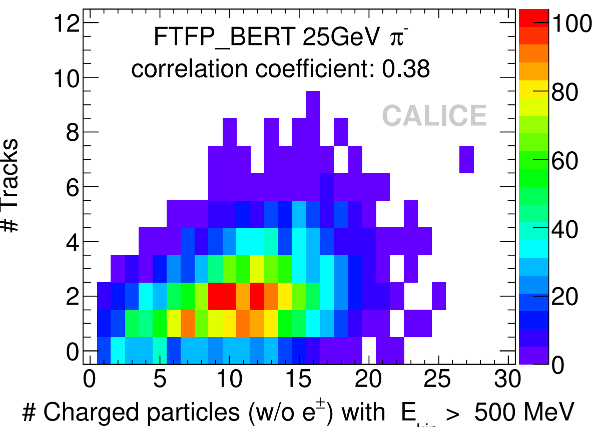
- just a few examples
- altogether at 5% or better

W Scint HCALresponse, timing

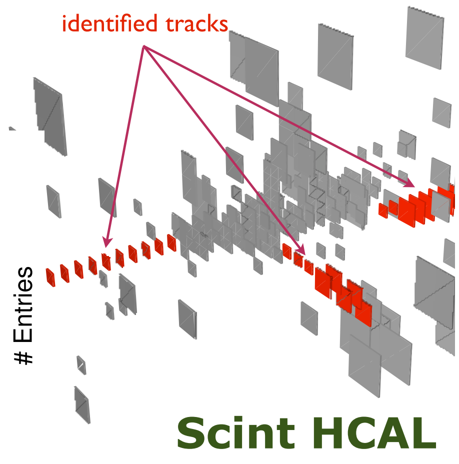


Shower fine structure

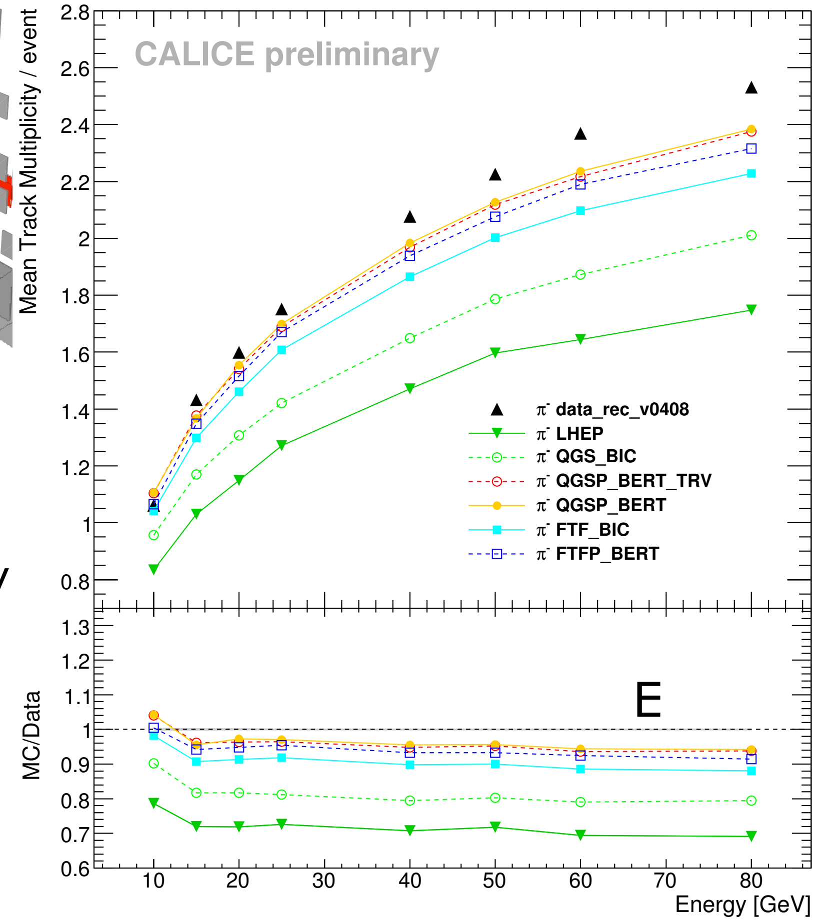
↑ MC reco



MC true ➔

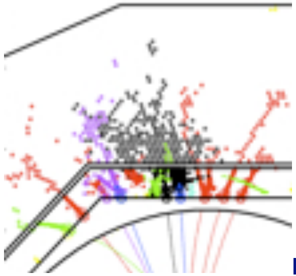


track multiplicity



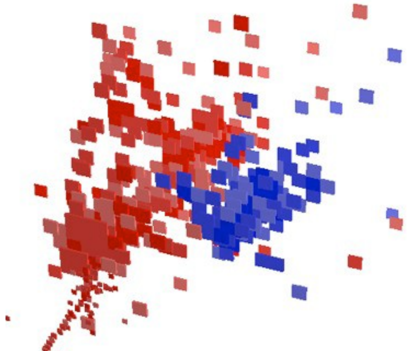
- Could have had the same global parameters with “clouds” or “trees”
- Powerful tool to check models
- Surprisingly good agreement already - for more recent models

publication draft



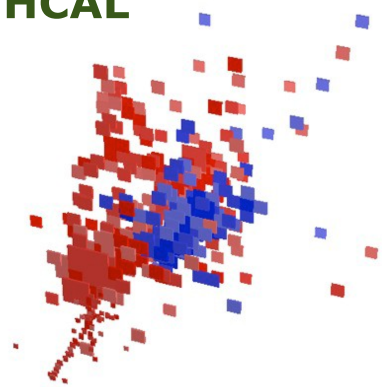
PFLOW with test beam data

Si W ECAL & Scint HCAL



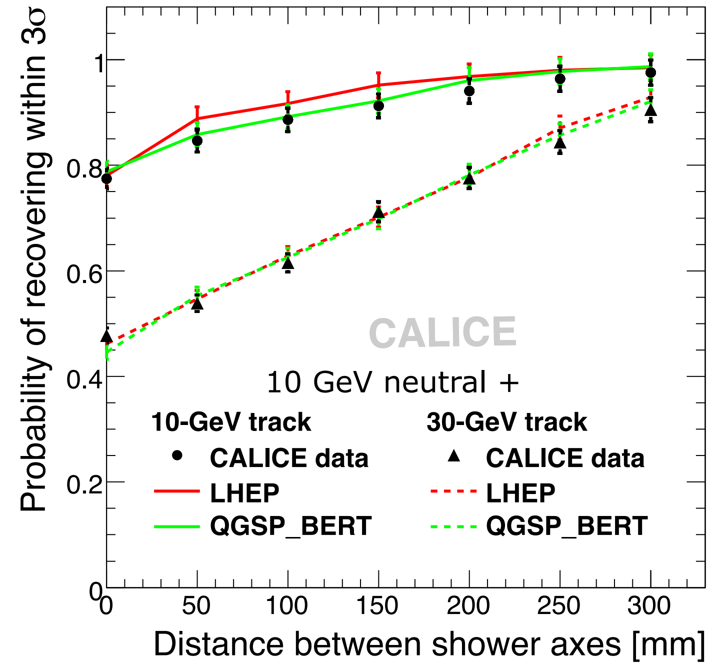
~18 cm separation of shower

30 GeV charged hadron



~7 cm separation of shower

10 GeV 'neutral' hadron



- The "double-track resolution" of an imaging calorimeter
- Small occupancy: use of event mixing technique possible
- test resolution degradation if second particle comes closer
- Important: agreement data - simulation

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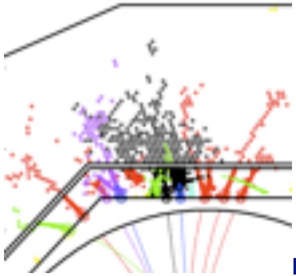
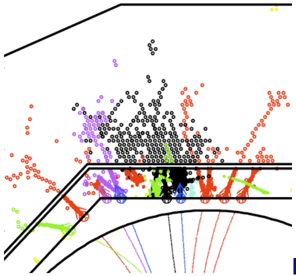


What we learnt

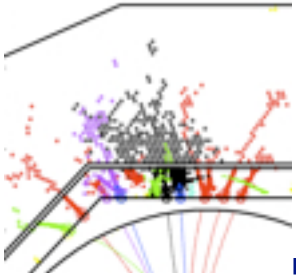
- The novel ECAL and HCAL technologies work as expected
  - Si W ECAL and Sci Fe AHCAL analysis nearly complete
  - Analysis of the more recent tests has just begun, but all results so far are encouraging - still a huge potential
- The detector simulations are verified with electromagnetic data.
- The hadronic performance is as expected, including software compensation.
- The Geant 4 shower models reproduce the data with few % accuracy.
  - Time structure is reproduced by HP simulations.
- Shower substructure can be resolved and is also reproduced by shower simulations.
- Particle flow algorithms are validated with test beam data.



Things to improve

- Test beam experience revealed many details that require further R&D to improve
- Example SiPMs for ECAL and HCAL
  - reduce temperature dependence
  - increase dynamic range
  - improve sample uniformity
- Other examples: Si sensor guard ring design, gas distribution
- Test bench characterisation
- Real-time monitoring

- **Scalablity and industrialisation**
  - **technological prototypes**



Technological prototypes

- Test and demonstrate the **scalability**
  - in construction, quality assurance, commissioning, calibration
- Complete the **integration** tasks
  - ASICs, data concentrators, power distribution and cooling
- Progress in industrialisation and **cost**
  - several 1000 m^2 of 6-8-layer PCB
- Case for complete prototypes:
- Performance validation
  - need to re-establish stable operation, perform calibration and time-dependent corrections, measure linearity and resolution and understand in terms of simulation
  - auto-trigger and zero-suppresion represent new challenges
- New **physics**:
  - hadron shower timing, finer ECAL
  -

all on this page: still to be done

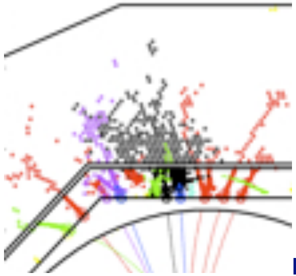
Technologies for High Granularity

Si W ECAL

Sci W ECAL

not reported this time:

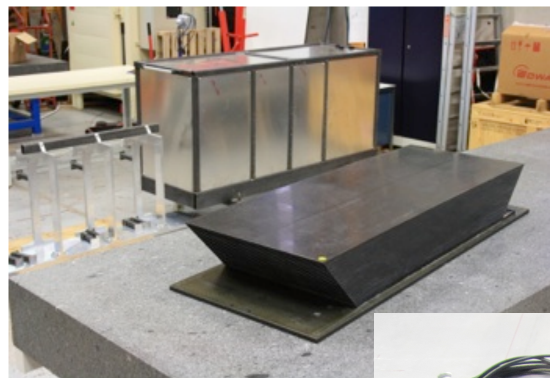
MAPS DECAL

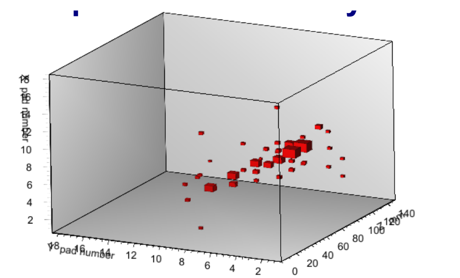


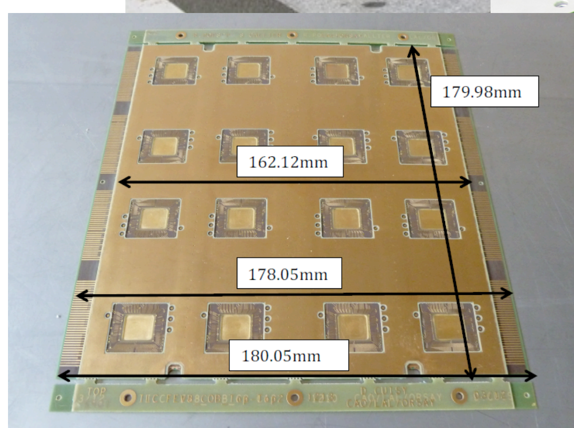
SiW ECAL

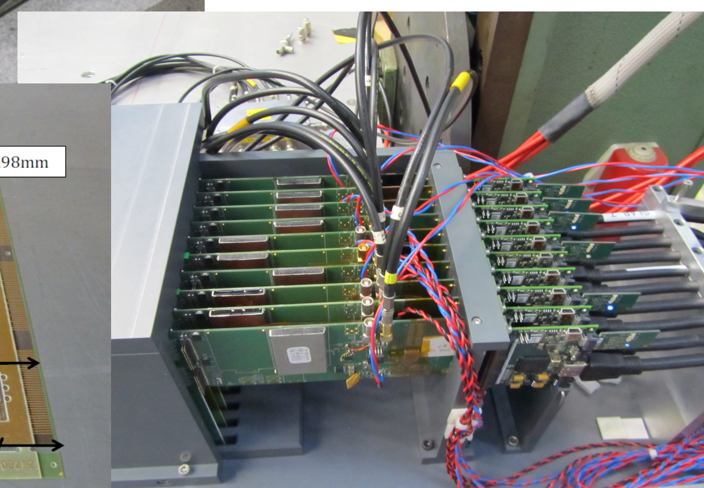
- mostly French and Japanese effort
  - LLR Palaiseau (F), LAL Orsay (F), Kyushu U (J), Tokyo U(J), ...
- Progresseing towards technological prototype

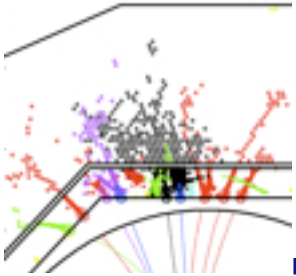
- Compact mechanical structure
- First beam tests with stacks
- Open issues
  - thin PPCBs
  - long modules
  - power pulsing
  - sensor design, cost, QC





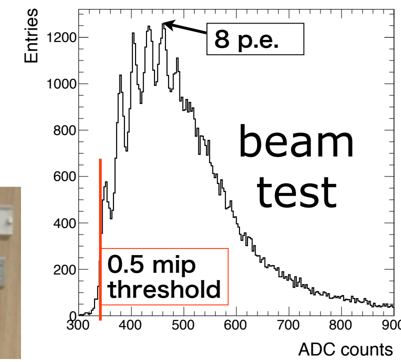


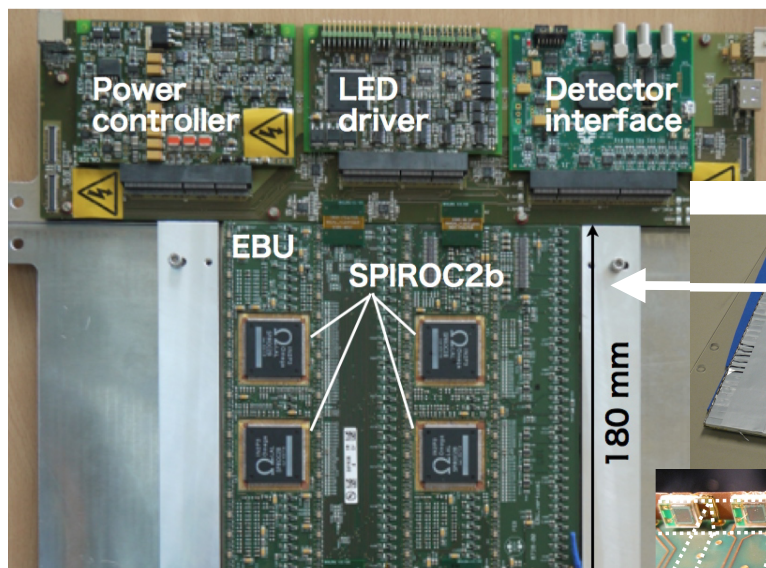


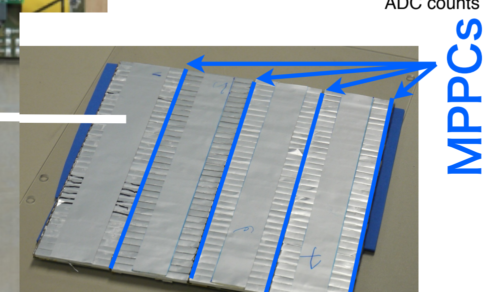


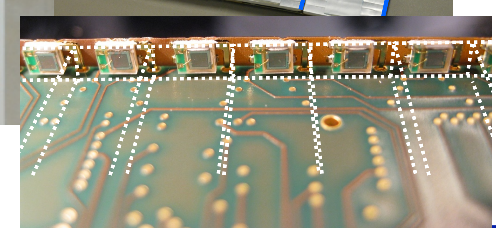
Scintillator ECAL

- originally Japanese effort (Shinshu, Kyushu, Tokyo)
  - electronics: LAL, DESY,...
- recently joined (CLIC oriented study): CERN, Cambridge, ...
- Progressing towards integrated layer design
  - based on scintillator HCAL apporach
  - mechanics relying on SiW ECAL
- Open issues:
  - SiPMs (dyn. range)
  - optical coupling
  - calibration system
  - data concentration
  - module interfaces
  - hybrid options
  - ...









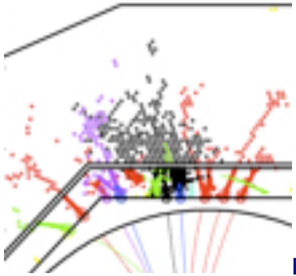
Technologies for High Granularity

Sci analogue HCAL

(Semi-) Digital HCAL

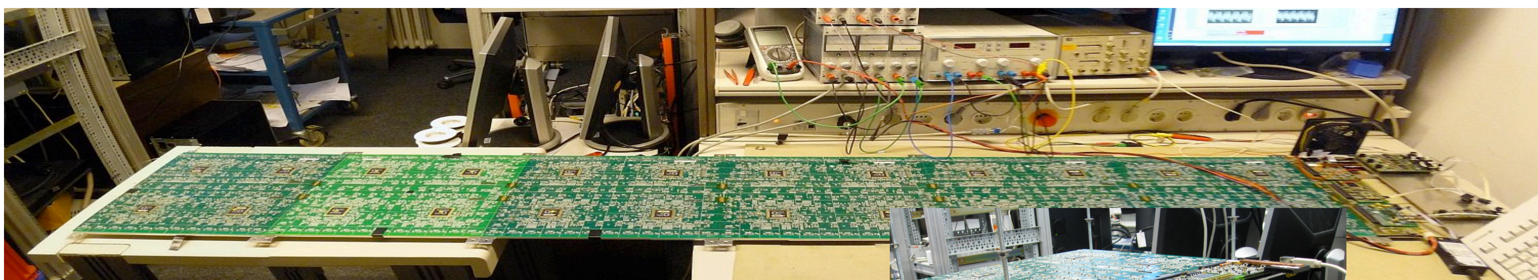
RPC, GEM, Micromegas

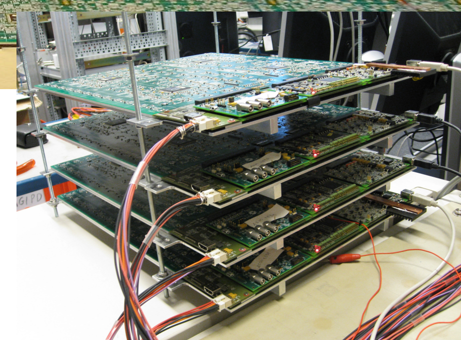
Fe, W

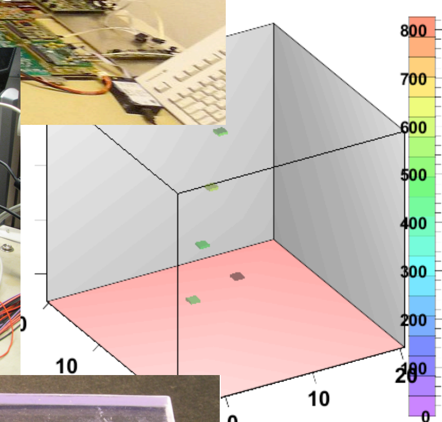


Scintillator HCAL

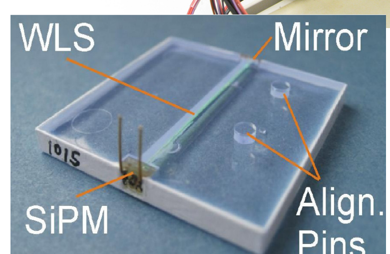
- DESY + German U, ITEP+, Prague, LAL, CERN, N.Illinois,...
- Prgressing towards a techological protoype
  - addressing integration while still open on the SiPM tile frontier
  - flexible electronics, synergies with Scint ECAL

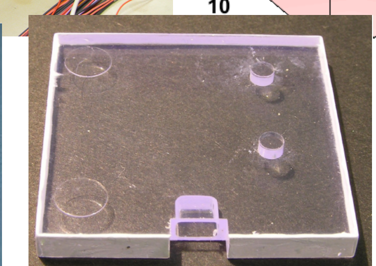


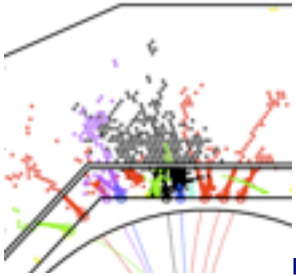




- Open issues
  - SiPMs
  - optical coupling
  - module interfaces
  - cooling (ext.)
  - mass production, QC

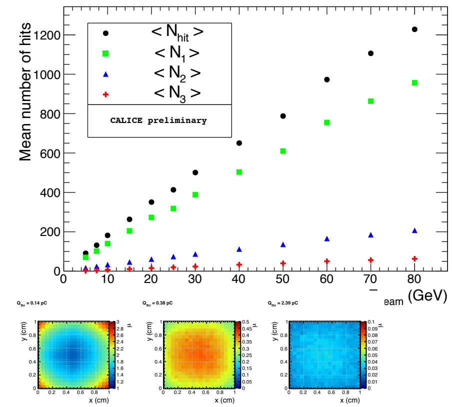


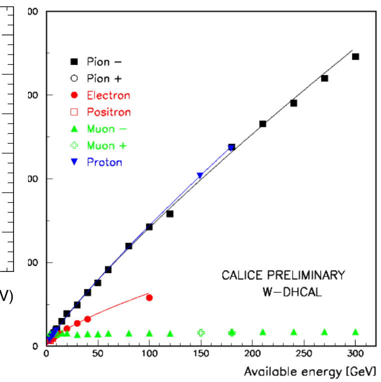




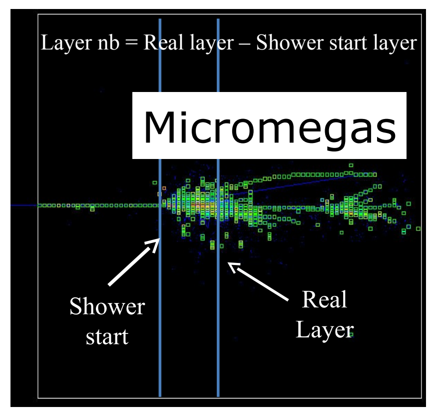
Gaseous HCAL options

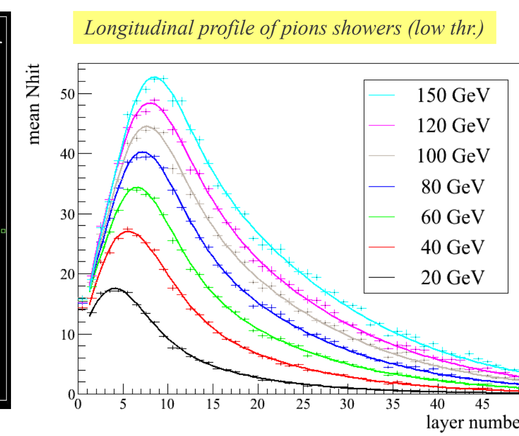
- RPCs: US led effort, Argonne, FNAL, Iowa, CERN,...
  - digital, completed m3 test
- RPCs: European effort, Lyon, Palaiseau, Madrid, Louvain, ..
  - semi-digital, ~ completed m3 test
- Micromegas: mostly Annecy,
  - 4 large layers tested
- GEMs: mostly UTx Arlington
  - modules tested
- ThGEMs: Weizmann, Portugal, starting
- + loosely associated groups

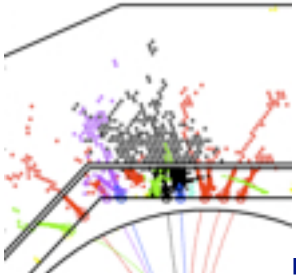




current focus on analysis, calibration, detector modeling

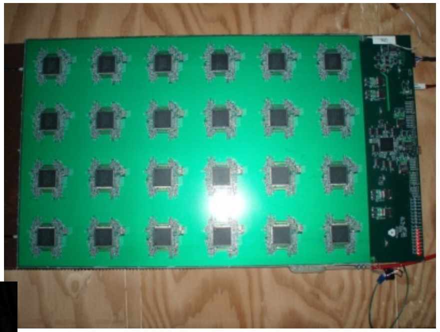


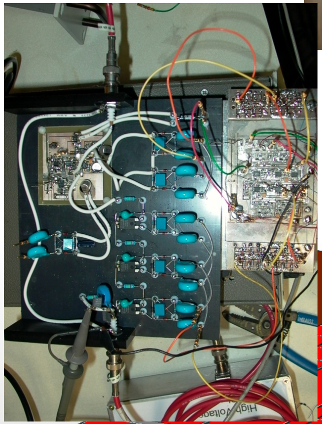


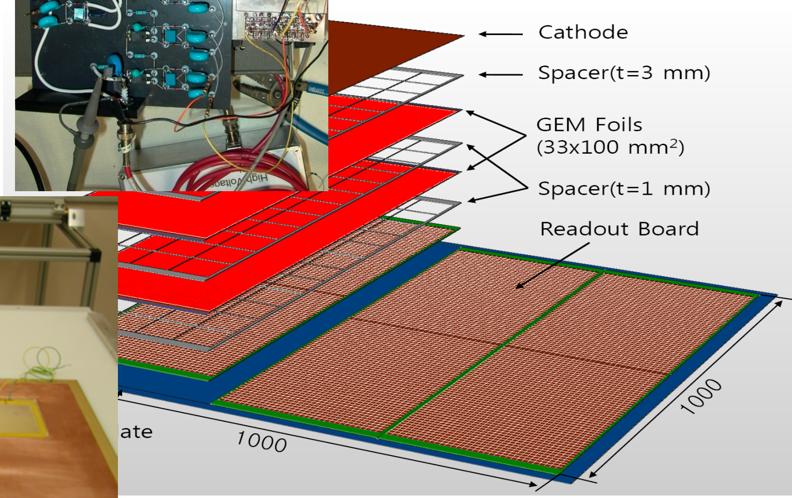


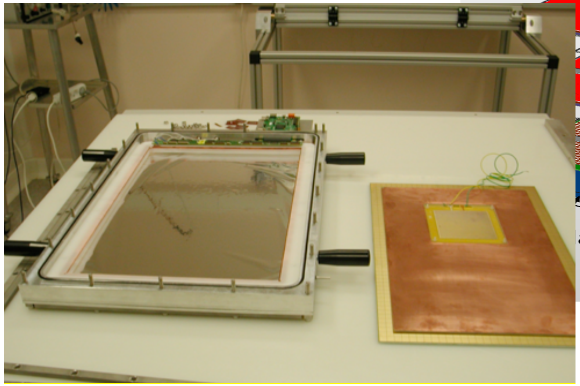
Gaseous HCAL open issues

- RPC DHCAL, sDHCAL:
  - Large area ($2m^2$) chambers
  - High rate RPCs: control plate resistivity
  - 1-glass RPC (rate, thickness, mult.)
  - HV distribution
  - Gas distribution
- Micromegas:
  - resistive detectors,reduce active components
  - single mesh large size chambers
- GEMs, TGEMs:
  - large areas
  - optimise chambers
  - integrate uM ASIC





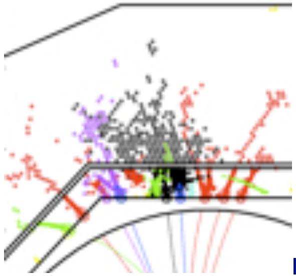




Conclusion

- Calorimetry has changed - particle flow concept established experimentally
- CALICE now fully in second phase: make it realistic
- There are many open issues = room for your ideas
- New and old collaborators are welcome
- Our collaborative framework is still fruitful
  - ILD, SiD choices open, ILC CLIC, ECAL HCAL synergies
- P.S.: It might soon be time to re-visit the muon system

Back-up slides

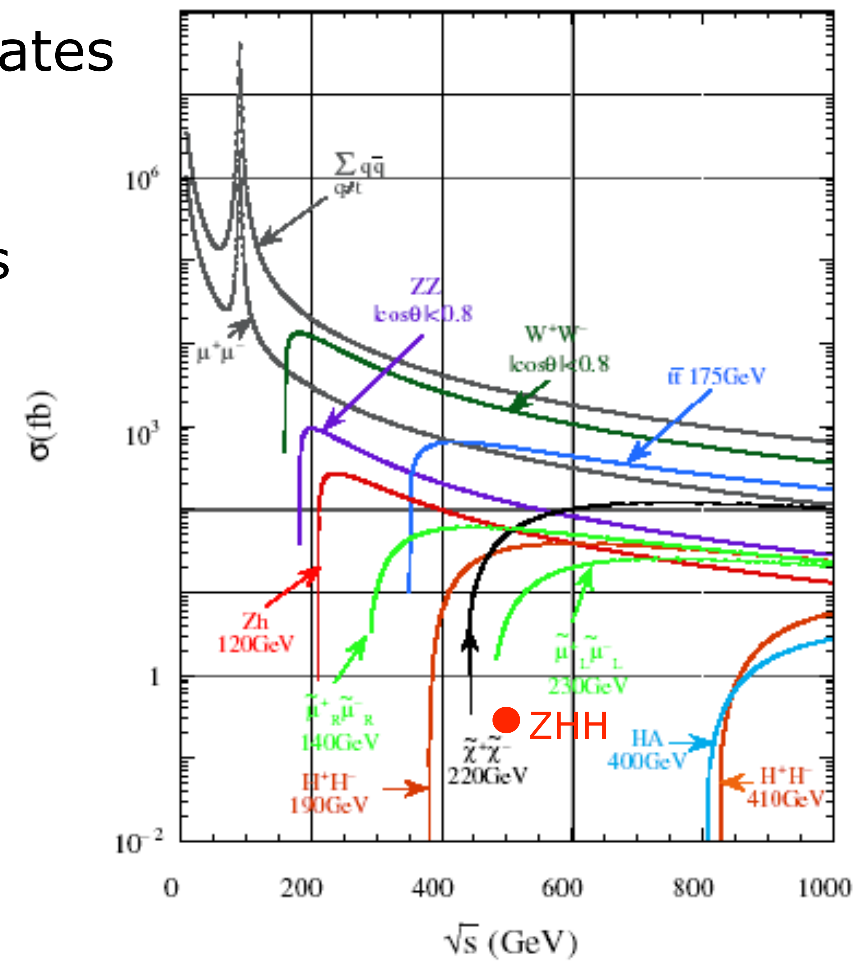


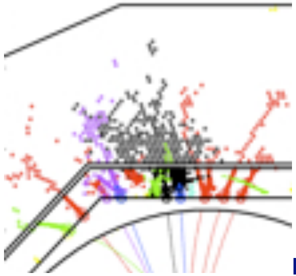
LC jet energies

- e^+e^- physics: exclusive final states
  - Q-Qbar events are boring
  - $E_{jet} = \sqrt{s}/2$ is rare
- Mostly 4-, 6-fermion final states
  - e.g. $e^+e^- \rightarrow ttH \rightarrow$ 8 -10 jets

- At ILC 500: E_{jet} = 50…150 GeV
  - Mean pion energy ~10 GeV
- At ILC 1 TeV: E_{jet} < ~ 300 GeV
- At CLIC (3 TeV) < ~ 600 GeV

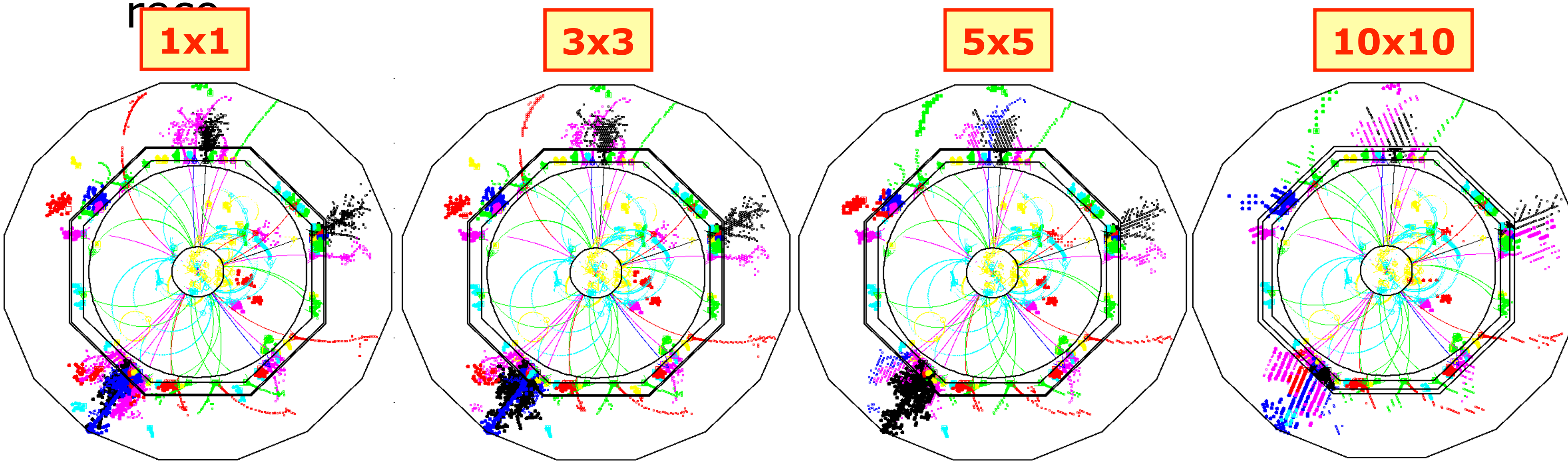
- *Mass* resolution does matter





Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reco



M.Thomson (Cambridge)

Tile granularity

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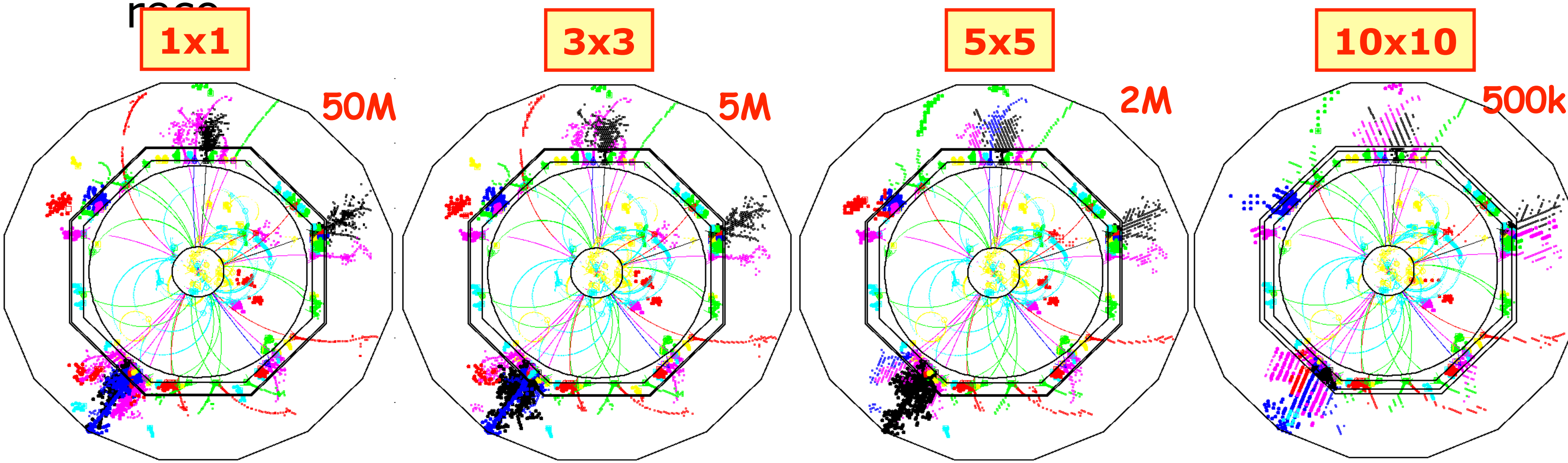

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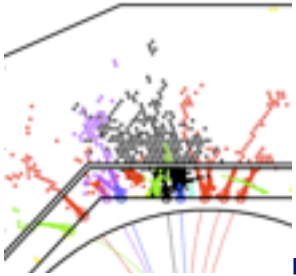

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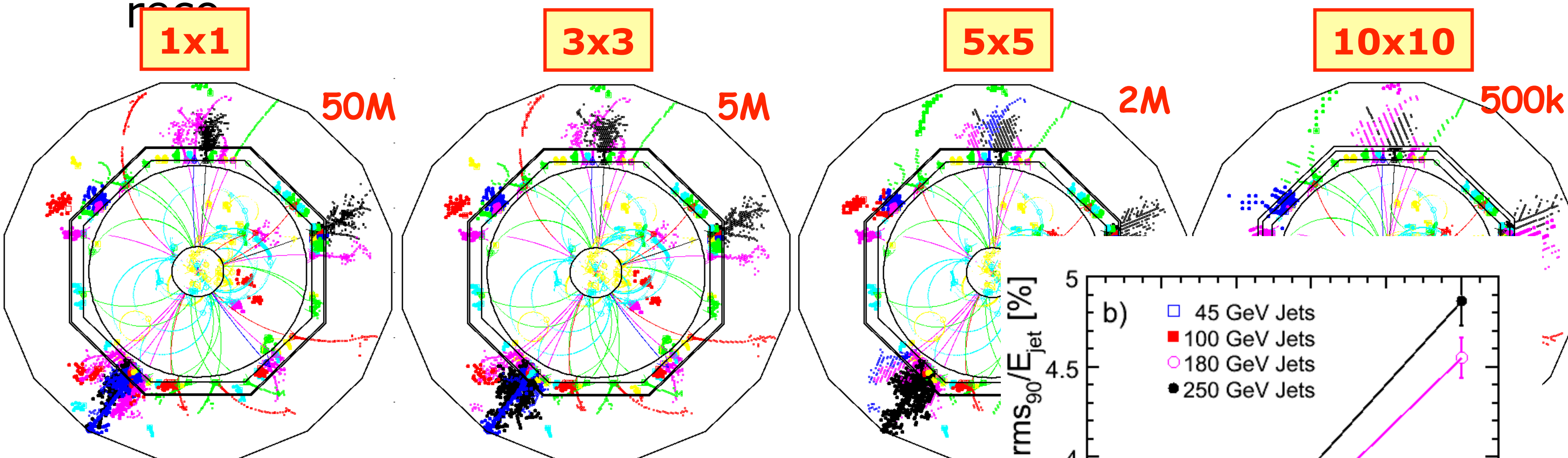
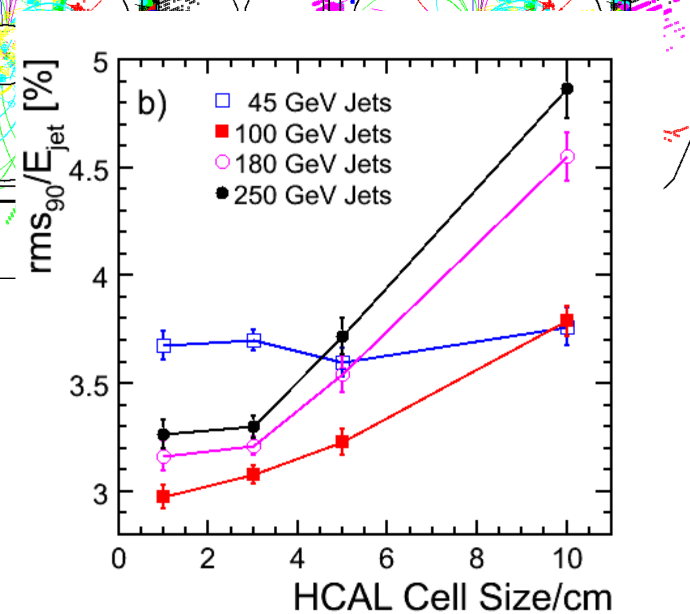
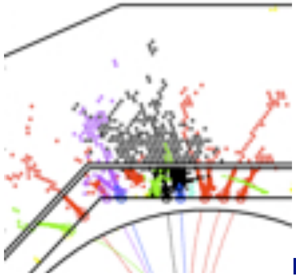




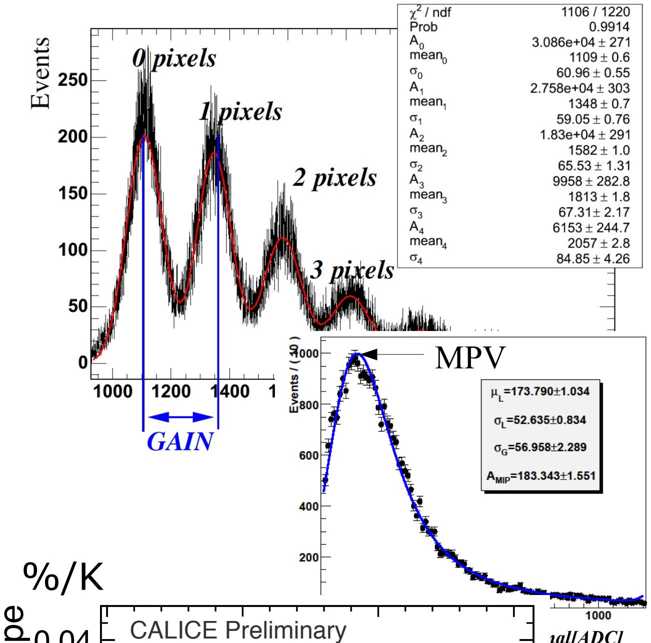
- Confirms earlier studies for test beam prototype
- 3x3 cm² nearly optimal

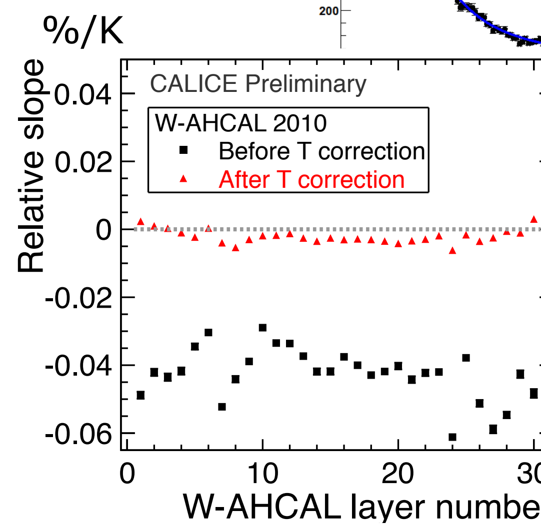
M.Thomson (Cambridge)

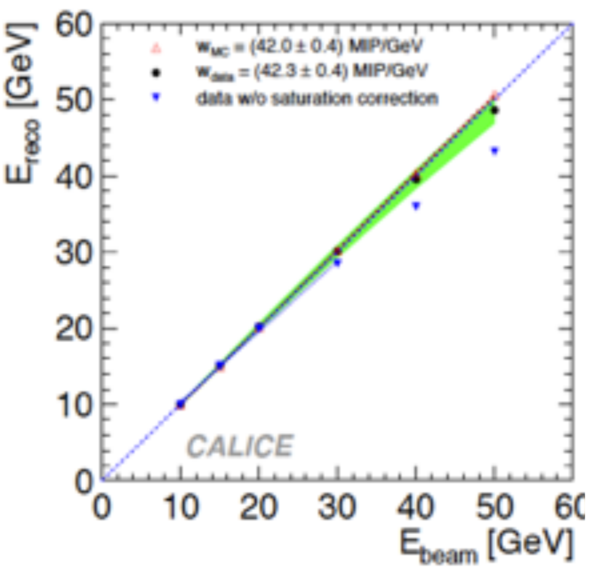


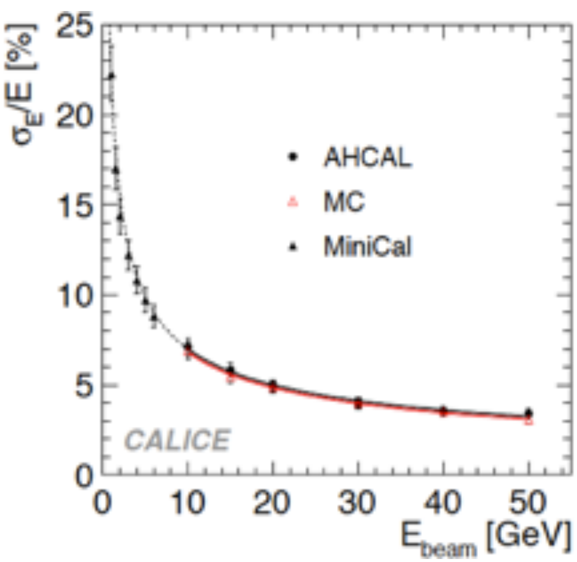
Scint AHCAL calibration and electromagnetic performance

- SiPM gain monitoring: self-calibrating
- Cell equalization: MIPs
- Temperature correction: ~4%/K
- Validation of calibration and simulation with electrons





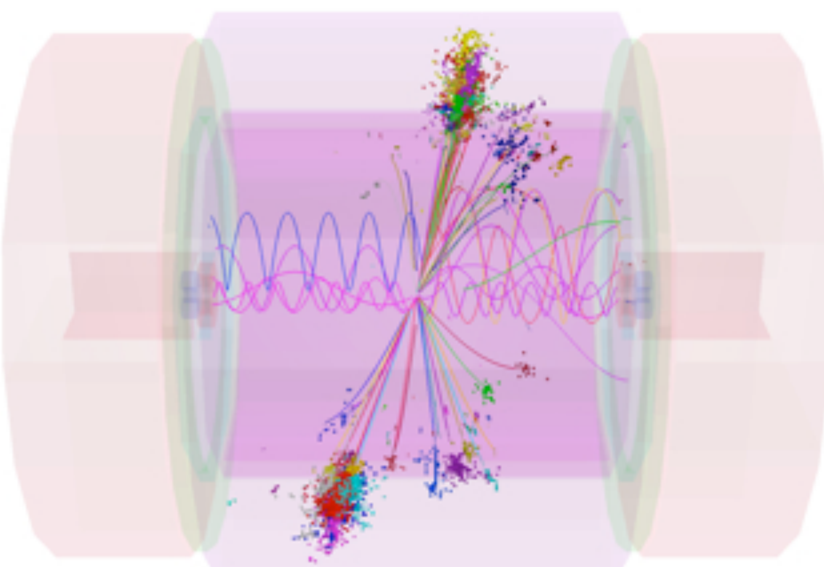




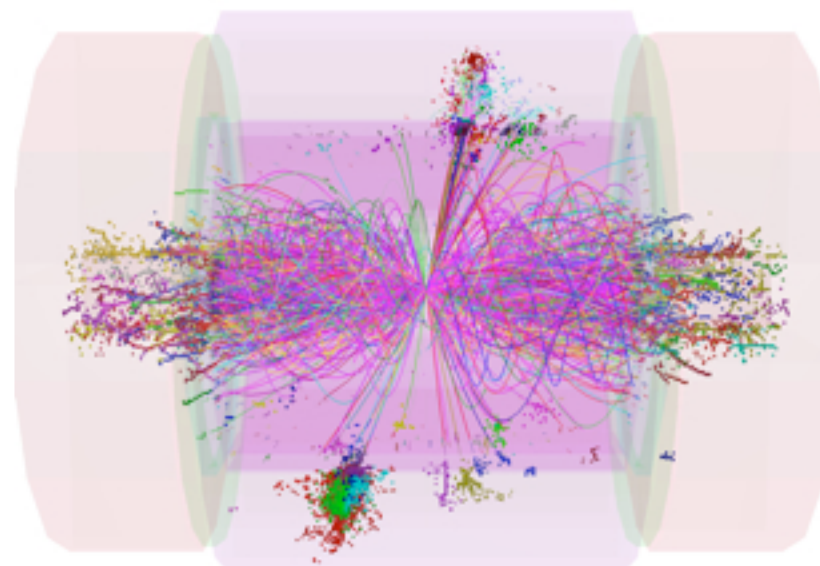
Published in JINST 6, P04003 (2011)

PFLOW under CLIC conditions

- Overlay γγ events from 60 BX (every 0.5 ns)
- take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- apply pt and timing cuts on cluster level (sub-ns accuracy)



Z @ 1 TeV



+ 1.4 TeV BG (reconstructed particles)

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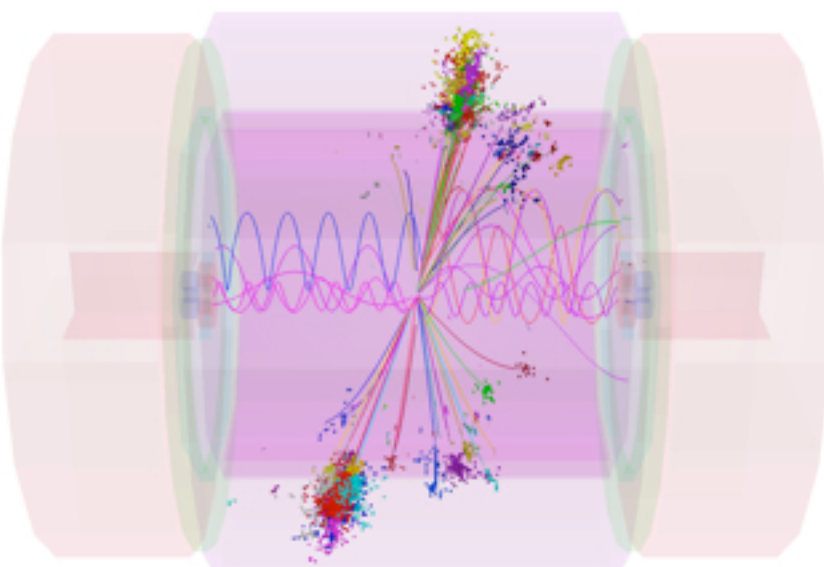

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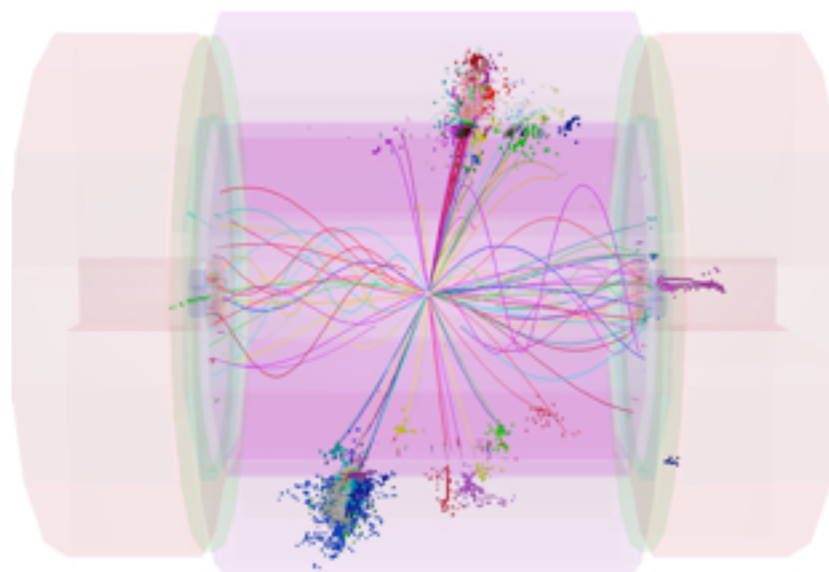

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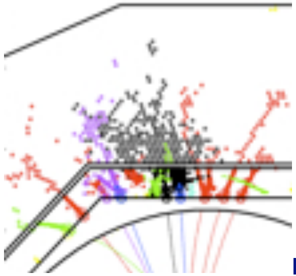

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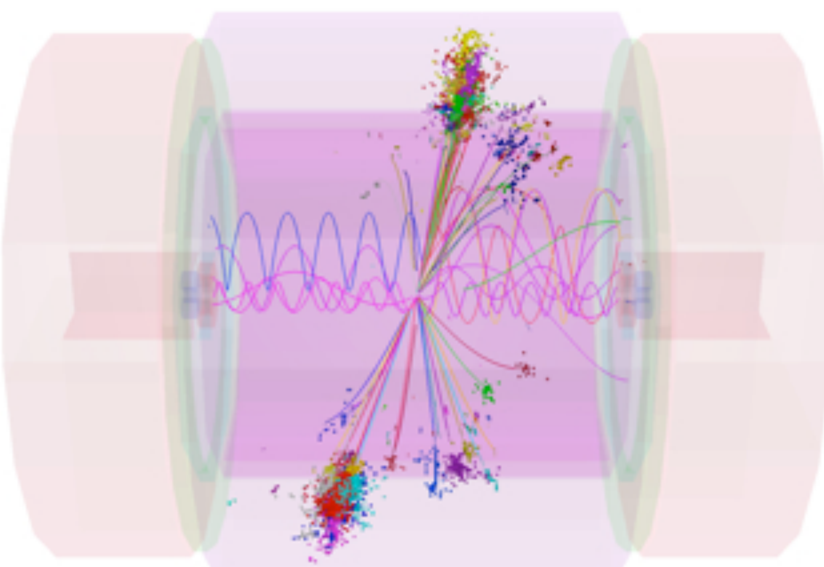
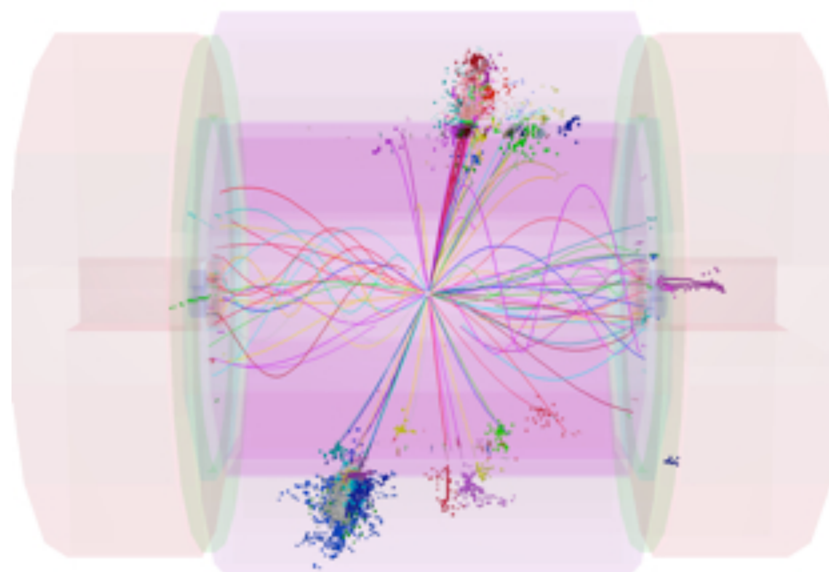
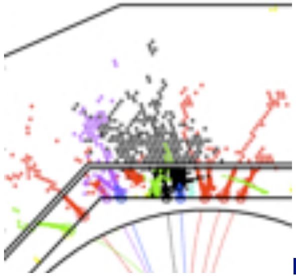
- take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- apply pt and timing cuts on cluster level (sub-ns accuracy)

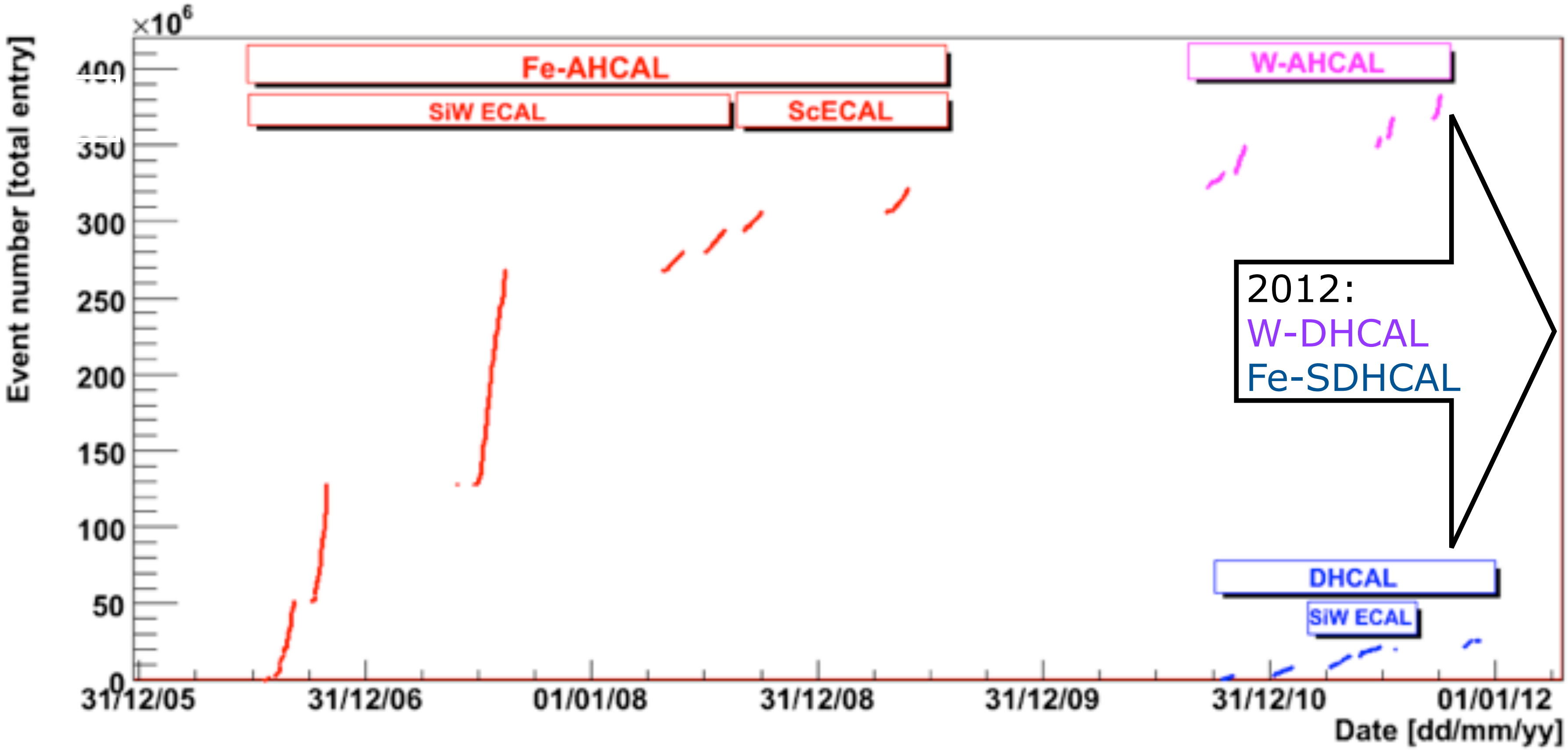




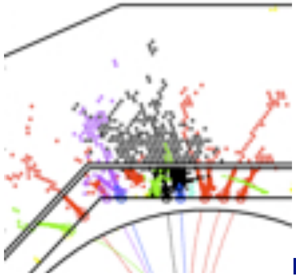
Z @ 1 TeV



Summary of data taken

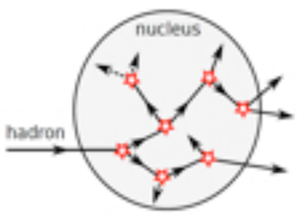


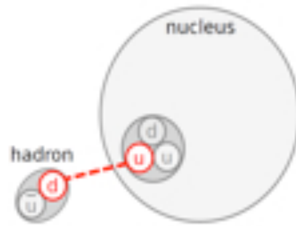
- Muon, LED and noise runs not included
- event size ~ 50kB -> 20 TB of physics data on the GRID

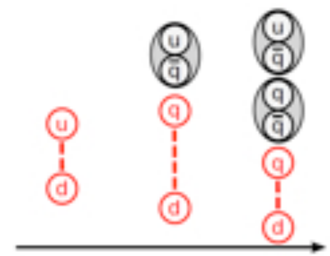


Shower simulation in Geant 4

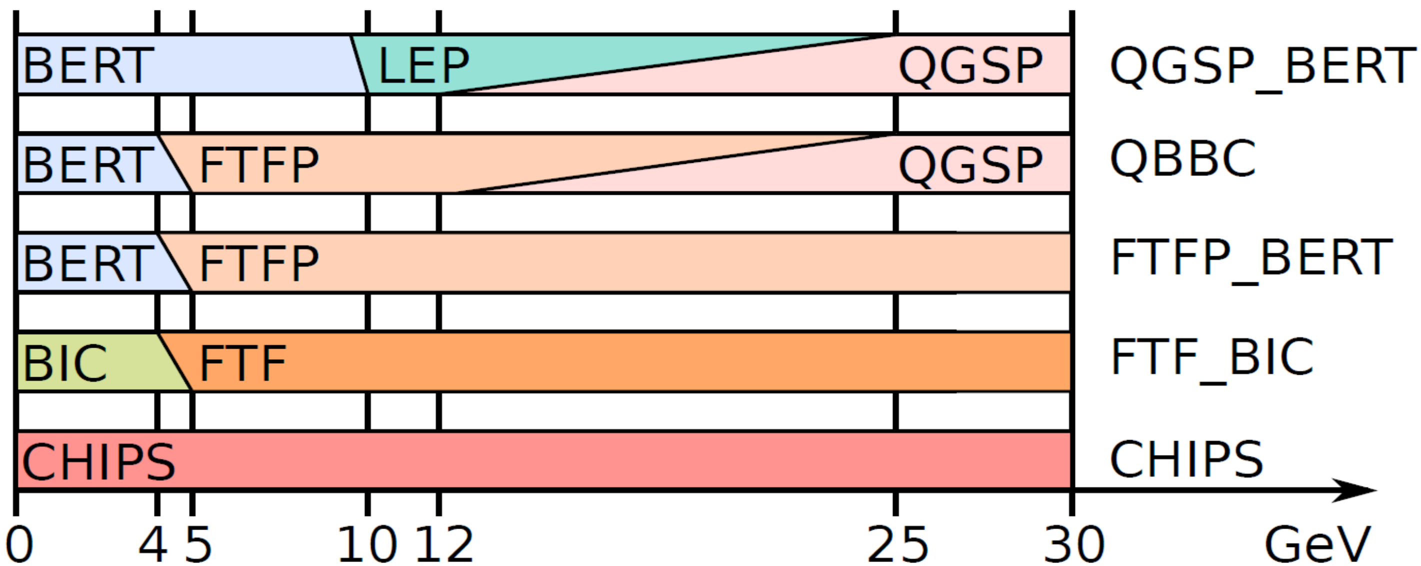
- Low energy: cascade models
- High energy: partonic models







minimize use of phenomenological parameterization



"legacy"

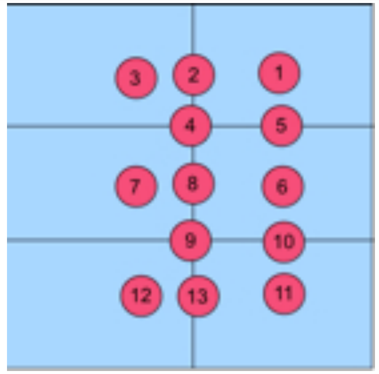
"linear combin."

"production"

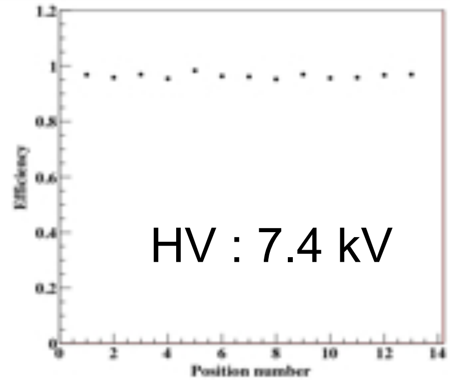
"systematics"

"experimental"

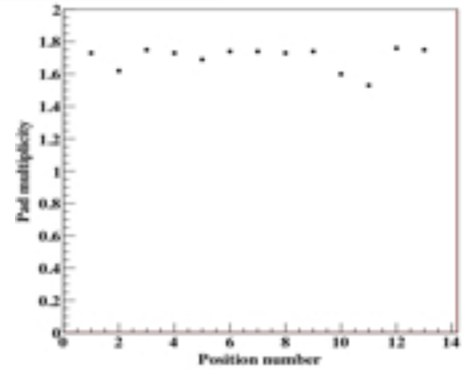
The homogeneity of the detector and its readout electronics were studied



Beam spot position



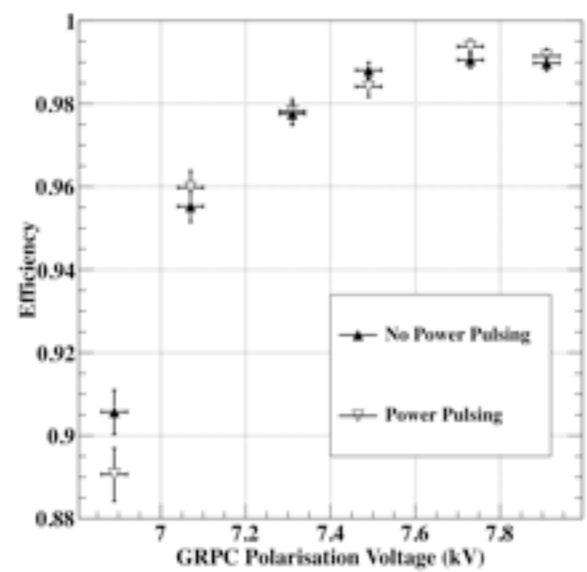
Efficiency



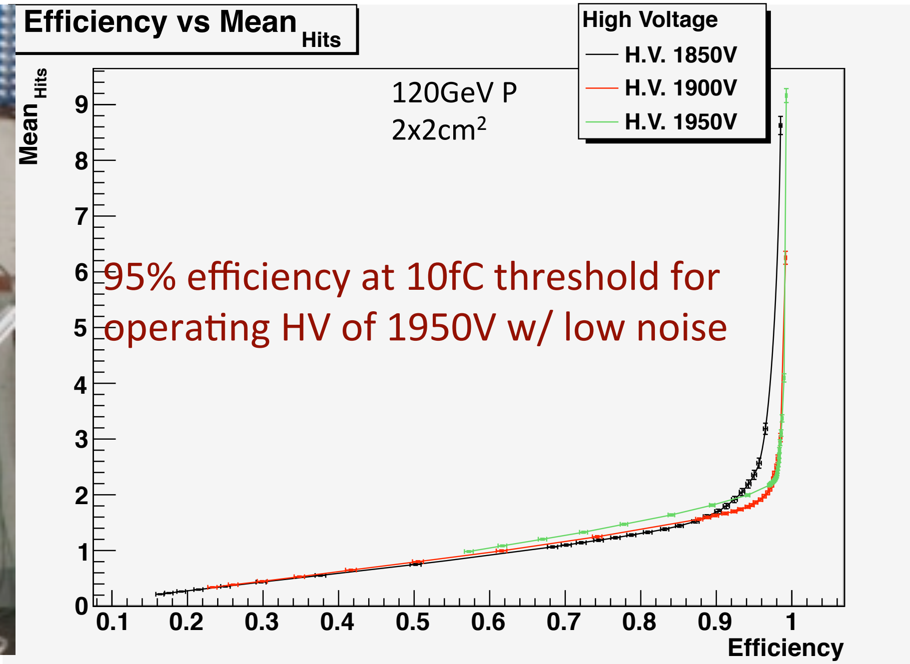
Multiplicity

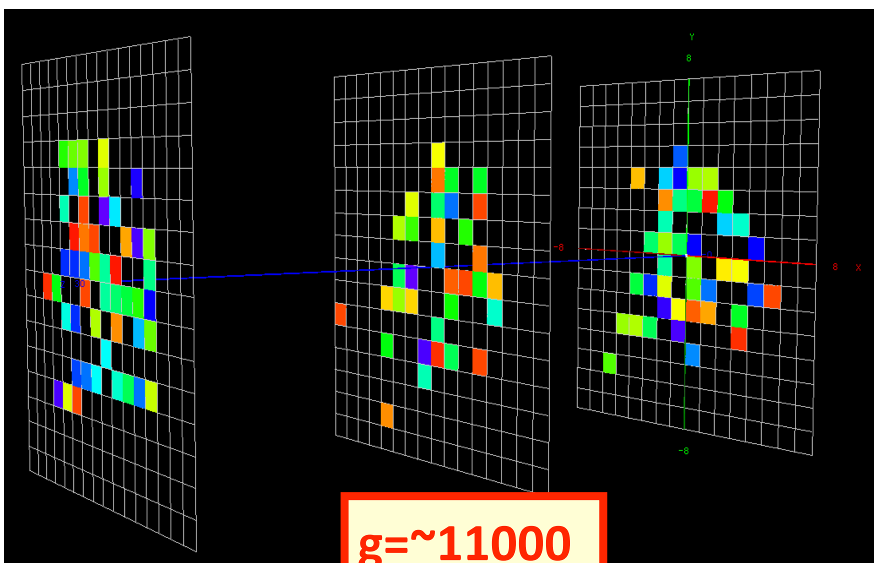
Power-Pulsing mode was tested in a magnetic field of 3 Tesla

The Power-Pulsing mode was applied on a GRPC in a 3 Tesla field at H2-CERN
(2ms every 10ms)
No effect on the detector performance

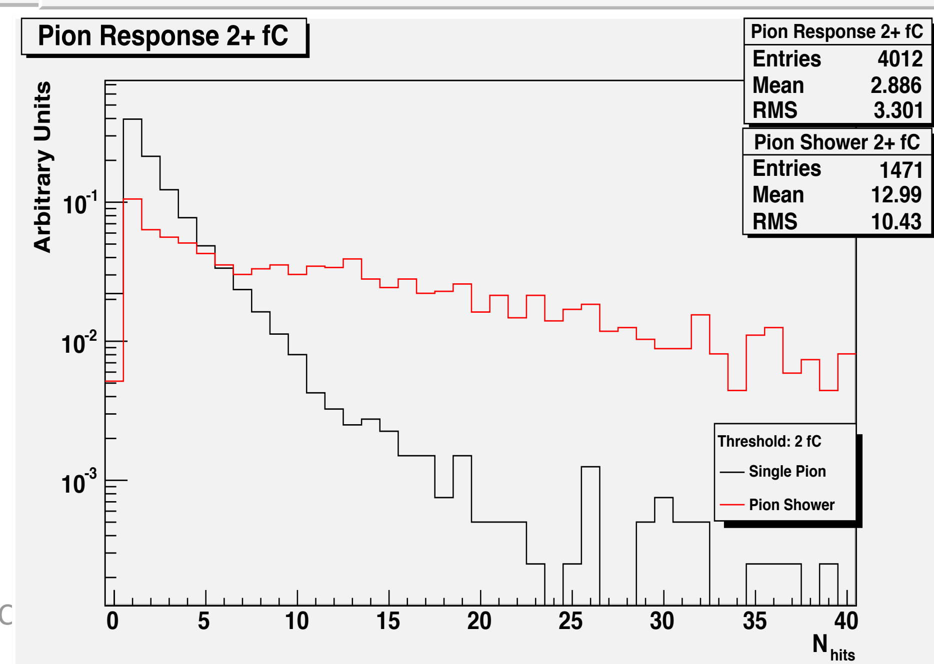


GEM Test Beam with KPiX: Efficiencies, Hit multiplicities

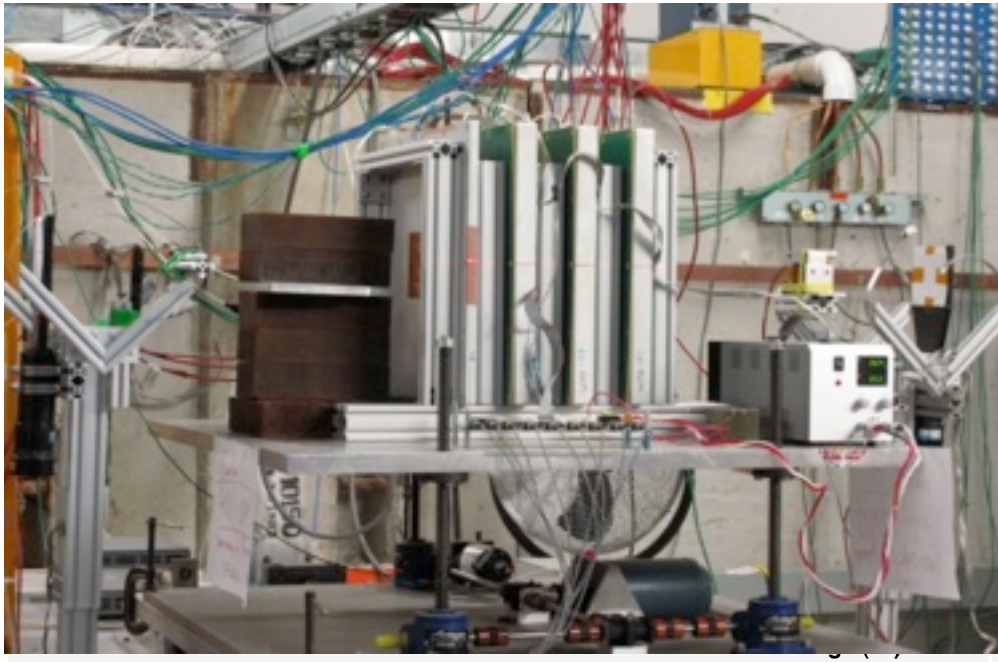


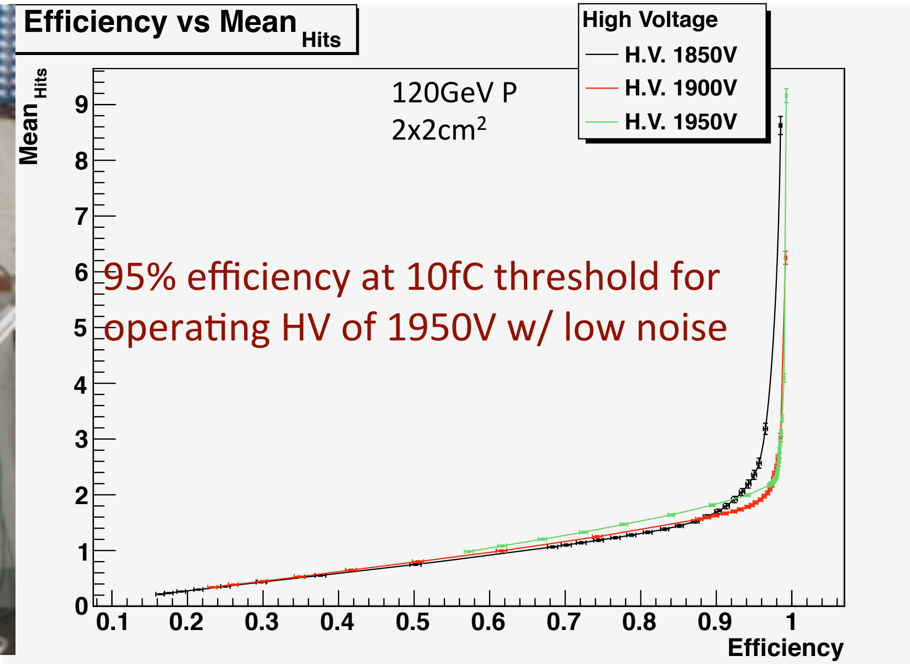


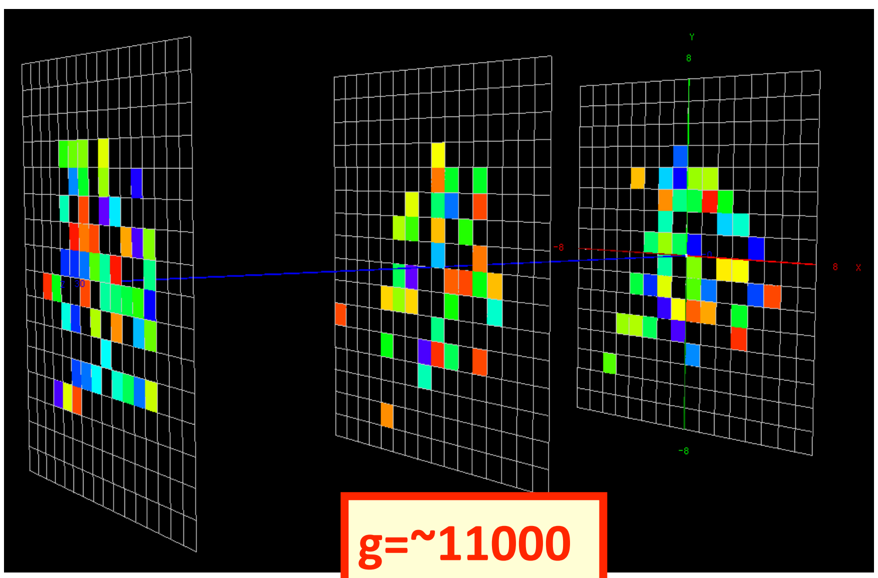
g=~11000

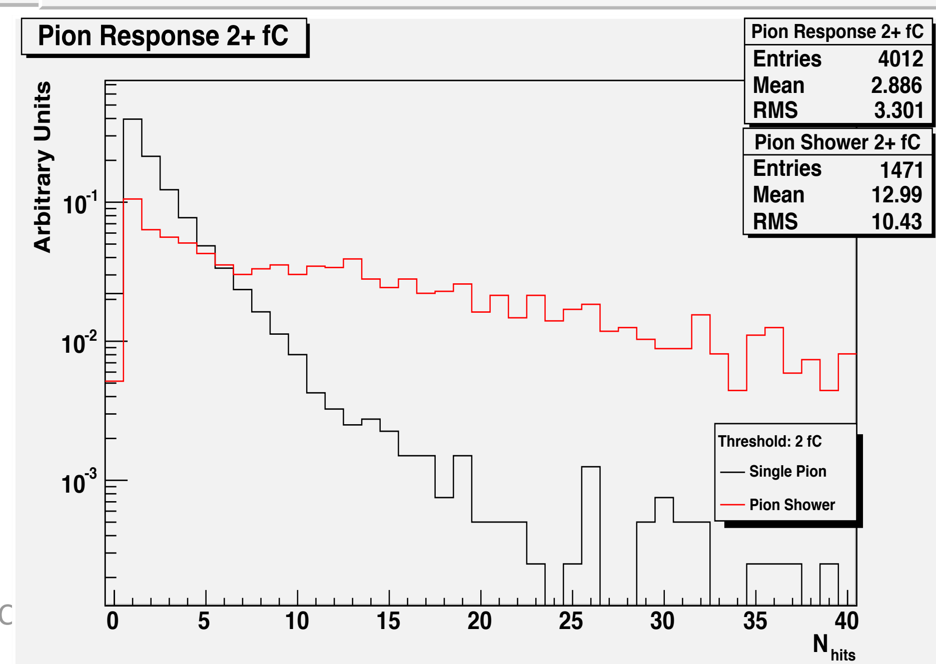


GEM Test Beam with KPiX: Efficiencies, Hit multiplicities



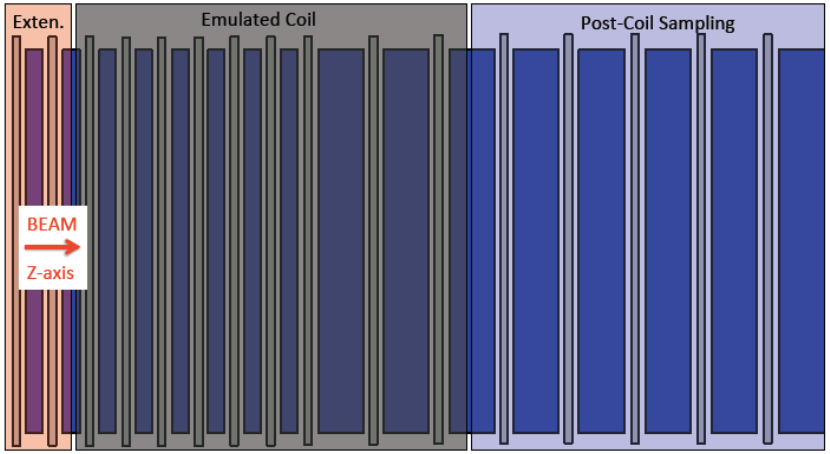






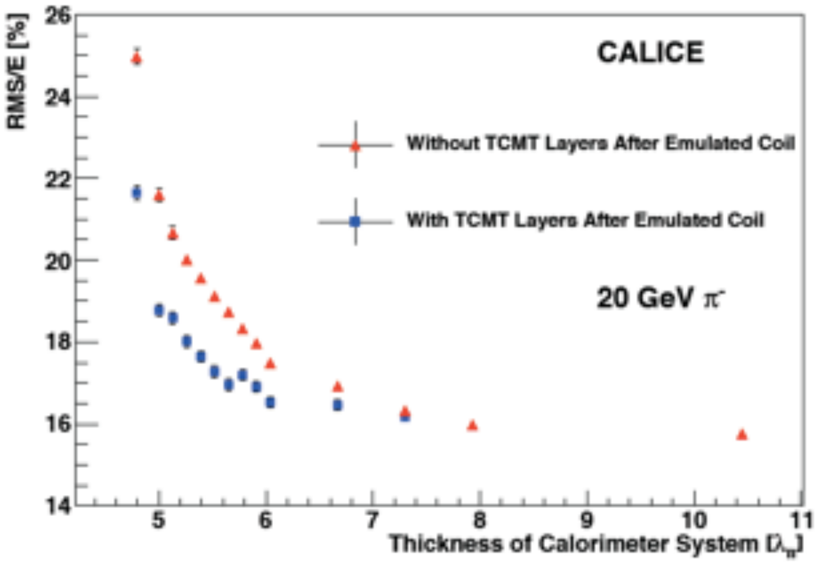
Containment – use of Tail Catcher

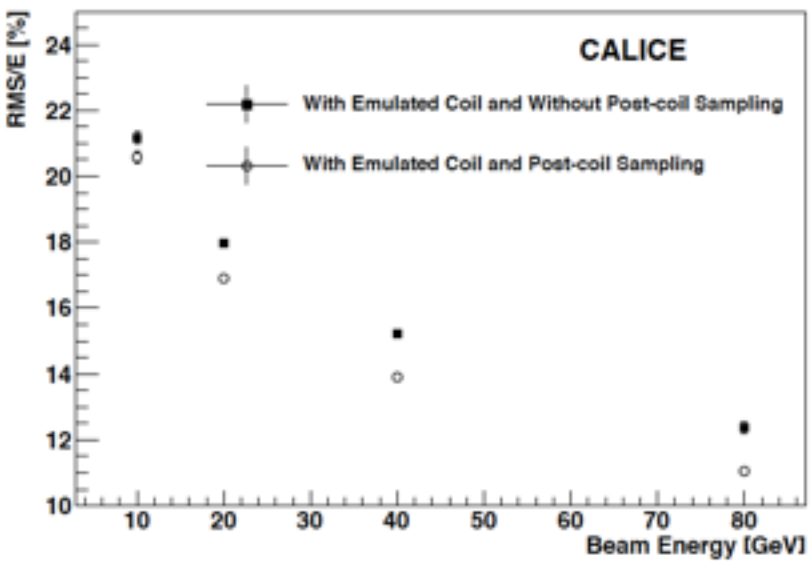
- Tail catcher gives us information about tails of hadronic showers.
- Use ECAL+HCAL+TCMT to emulate the effect of coil by omitting layers in software, assuming shower after coil can be sampled.
- Significant improvement in resolution, especially at higher energies.



2012_JINST_7_P04015

arxiv:1201.1653 (accepted by JINST)





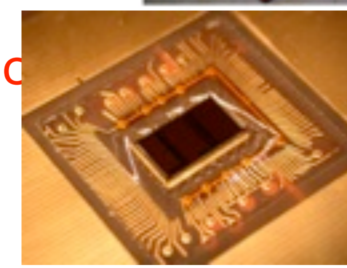
Common developments

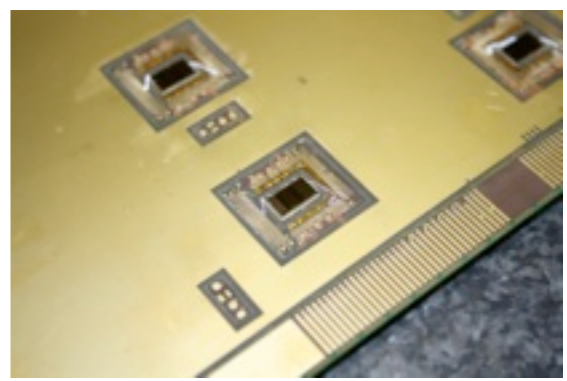
Front end electronics

not reported here: test beam infrastructure, DAQ, software and computing

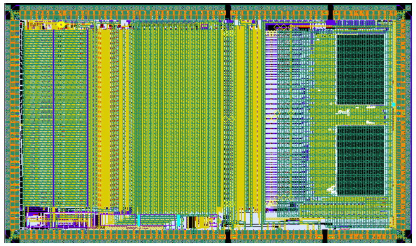
ILC Challenges for electronics

- Requirements for electronics
  - Large dynamic range (15 bits)
  - Auto-trigger on ½ MIP
  - On chip zero suppress
  - Front-end embedded in detector
  - 10^8 channels
  - **Ultra-low power : (25μW/ch)**
  - Compactness
- « Tracker electronics with calorimetric performance »

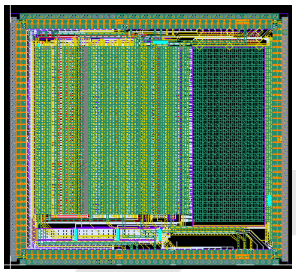




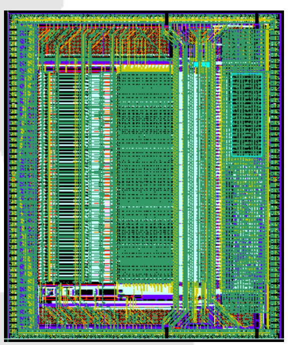
ASICs for ILC prototypes



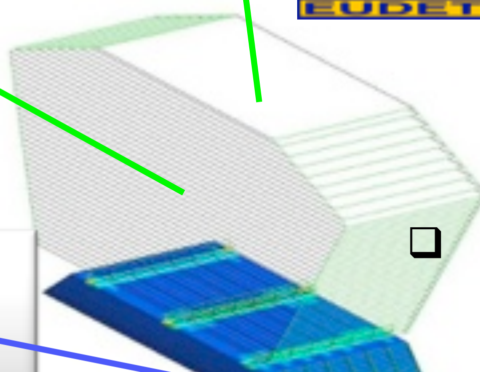
SPIROC2
Analog HCAL (AHCAL)
(SiPM)
36 ch. 32mm²
June 07, June 08, March 10



HARDROC2 and MICROROC
Digital HCAL (DHCAL)
(RPC, μmegas or GEMs)
64 ch. 16mm²
Sept 06, June 08, March 10



SKIROC2
ECAL
(Si PIN diode)
64 ch. 70mm²
March 10



- 1st generation ASICs: FLC-PHY3 and FLC_SiPM (2003) for **physics prototypes**
- 2nd generation ASICs: ROC chips for **technological prototypes**
  - ✓ Address integration issues
  - ✓ Auto-trigger, analog storage, internal digitization and token-ring readout
  - ✓ Include power pulsing : <1 % duty cycle
  - ✓ Optimize commonalities within CALICE (readout, DAQ…)
- 3rd generation ASICs (AIDA funded):
  - ✓ **Independent channels to perform Zero suppress**