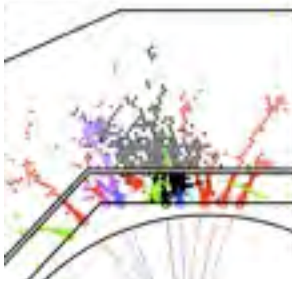
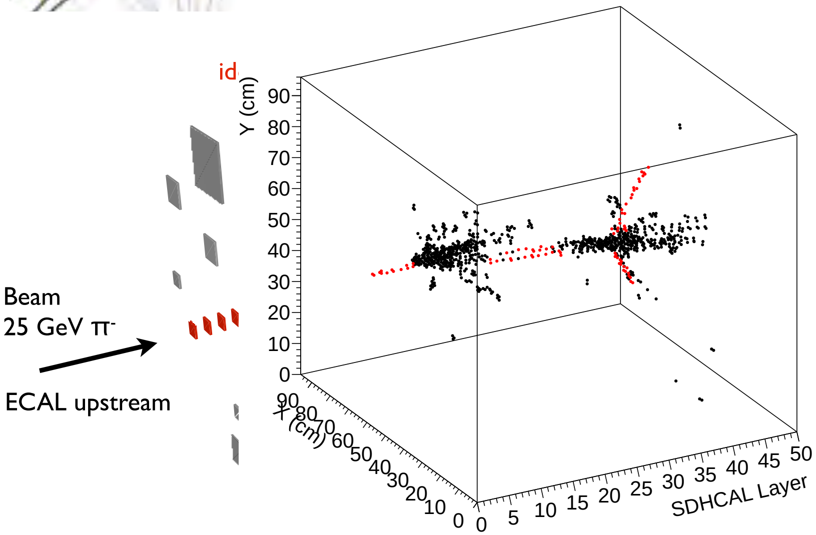
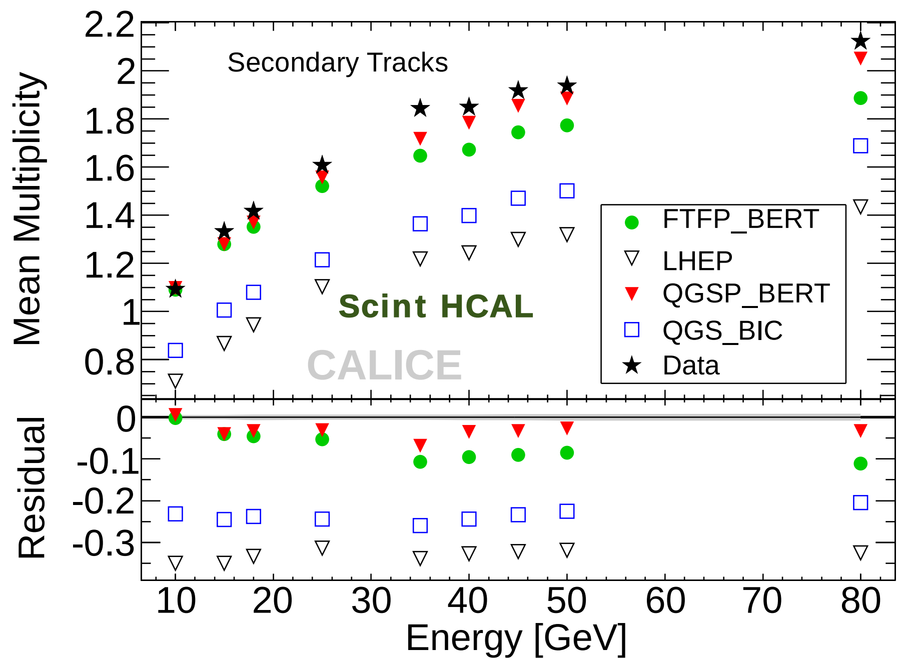
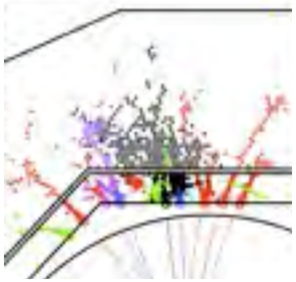


Shower fine structure





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



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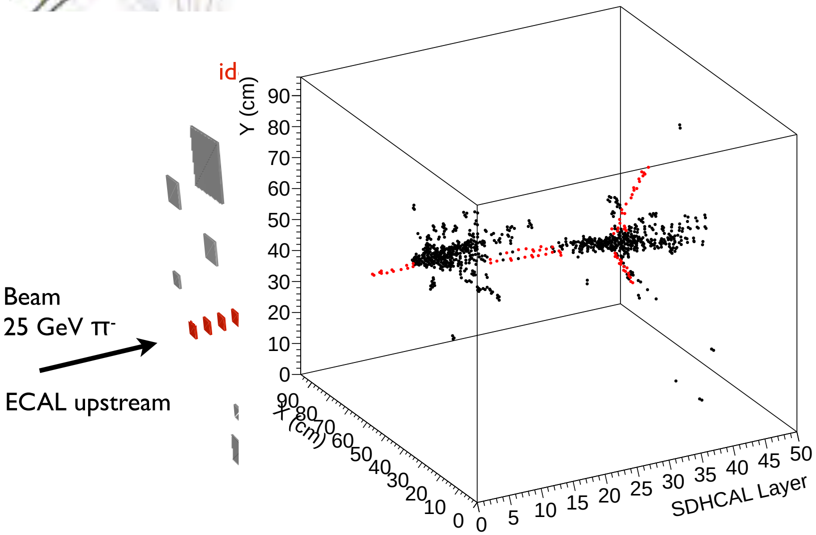

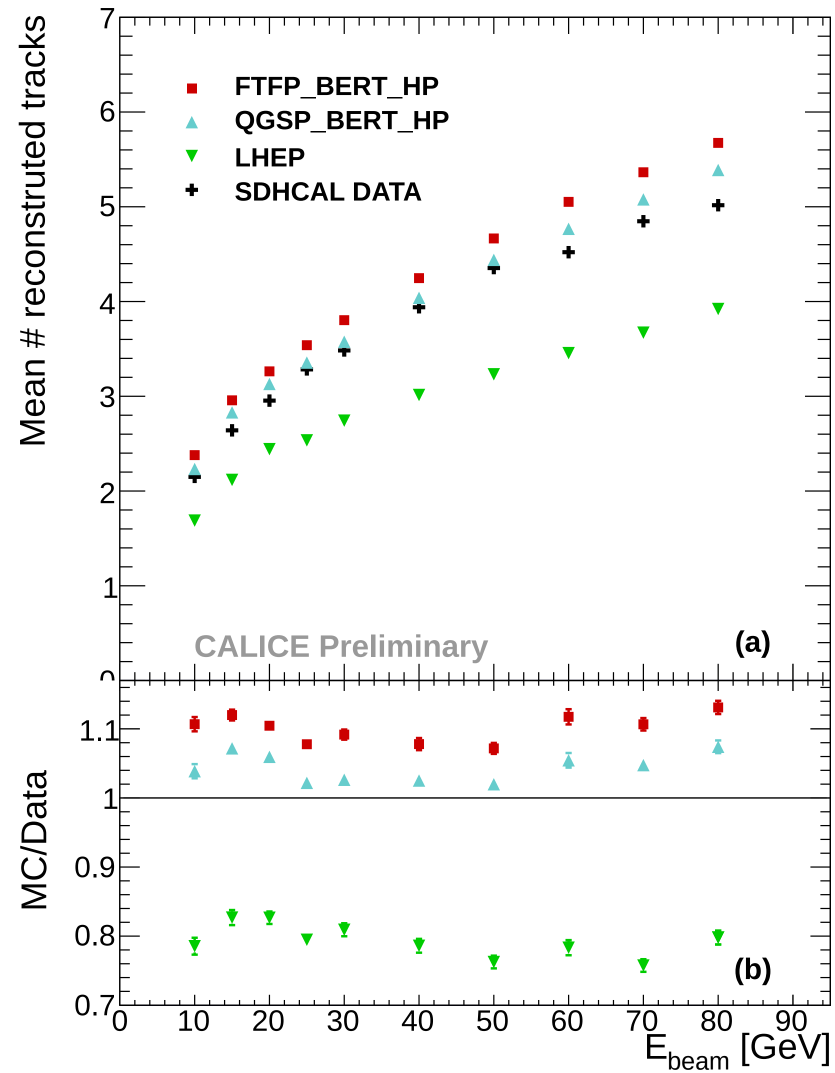

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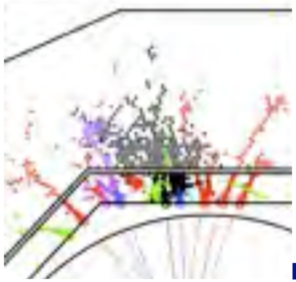
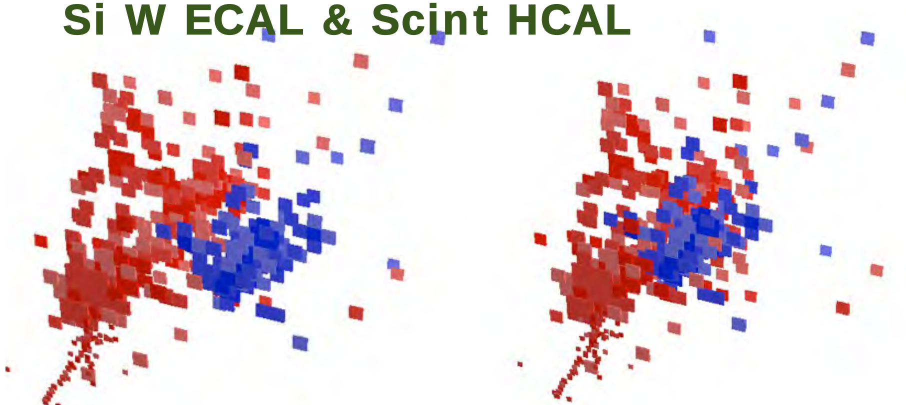


PFLOW with test beam data

Si W ECAL & Scint HCAL

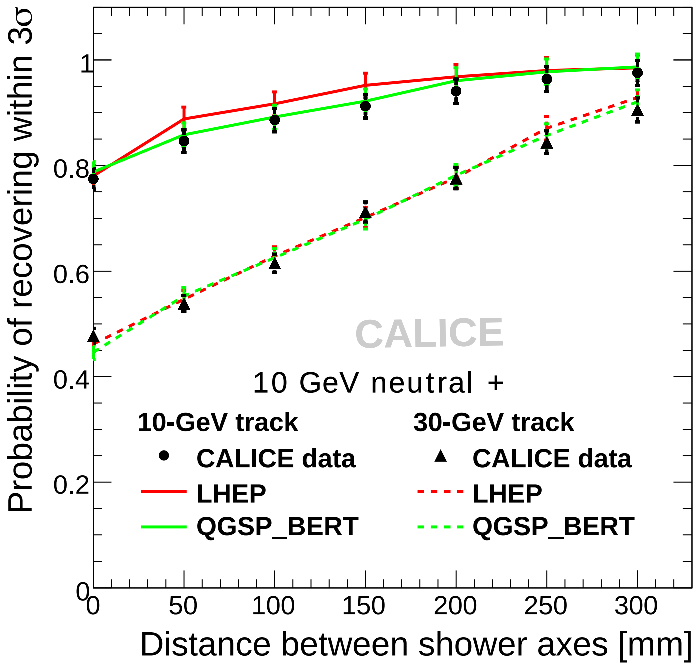


~18 cm separation of shower

~7 cm separation of shower

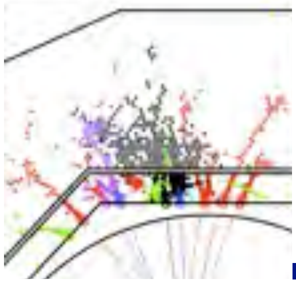
30 GeV charged hadron

10 GeV 'neutral' hadron



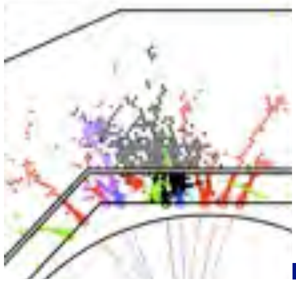
- The “double-track resolution” of an imaging calorimeter
- Small occupancy: use of event mixing technique possible
- Study degradation if second particle comes closer
- Important: agreement data - simulation

JINST 6 (2011) P07005



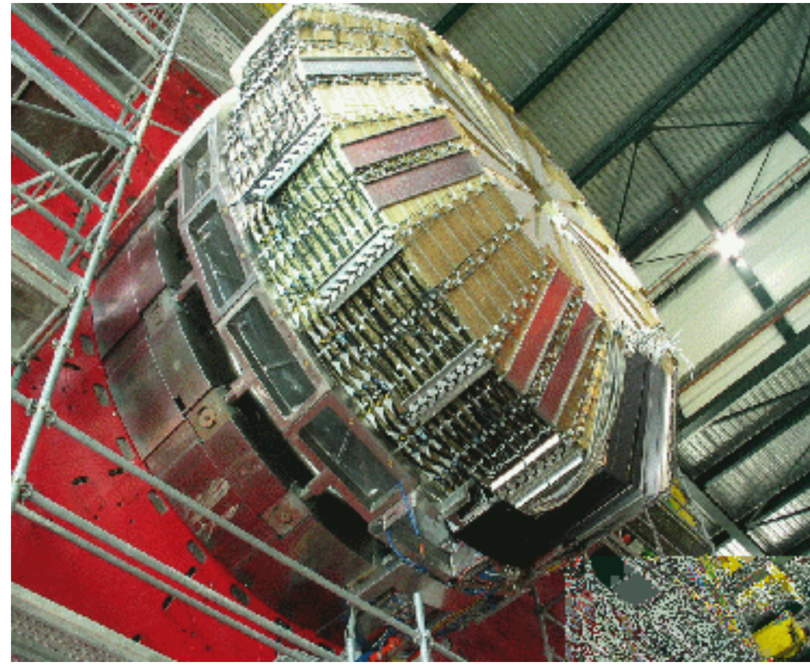
What we learnt

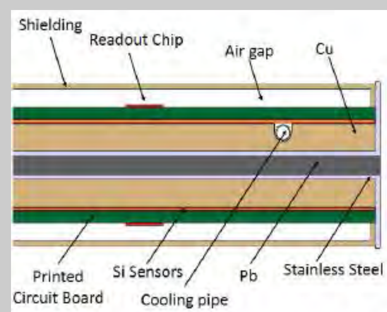
- The novel ECAL and HCAL technologies work as expected
  - Si W ECAL and Sci Fe AHCAL analysis nearly complete
  - Analysis of the more recent tests has just begun - still a huge potential
- The detector simulations are verified with electromagnetic data.
- The hadronic performance is as expected, including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

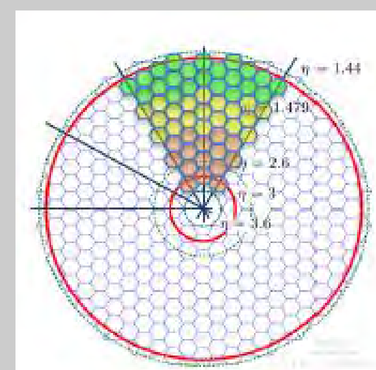


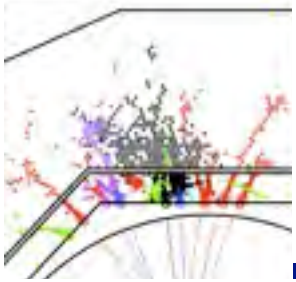
Hadron collider frontier: CMS

- CMS decided for a high granularity option of their endcap calorimeter upgrade
  - EM: Si Pb/Cu
    - 35 layers, 25 X0
  - HAD: Si brass
    - 12 layers, 5 λ
  - 600 m^2 of Si, 0.5 - 1 cm^2
  - Backing: 5 λ brass, scint or gas
- particle ID, pile-up subtraction, ..., particle flow
- Much more challenging than e+e-
  - radiation hardness
  - cooling of sensors
  - rate capability of electronics
  - no power pulsing



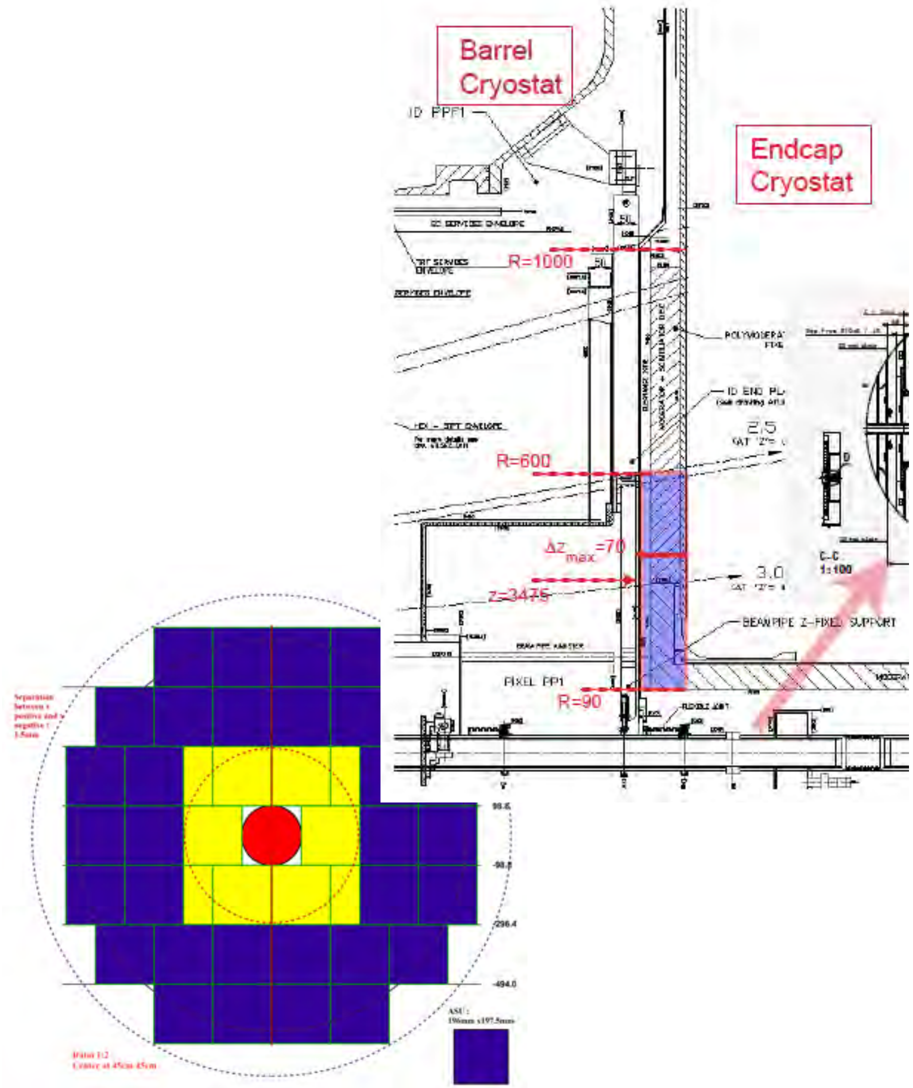




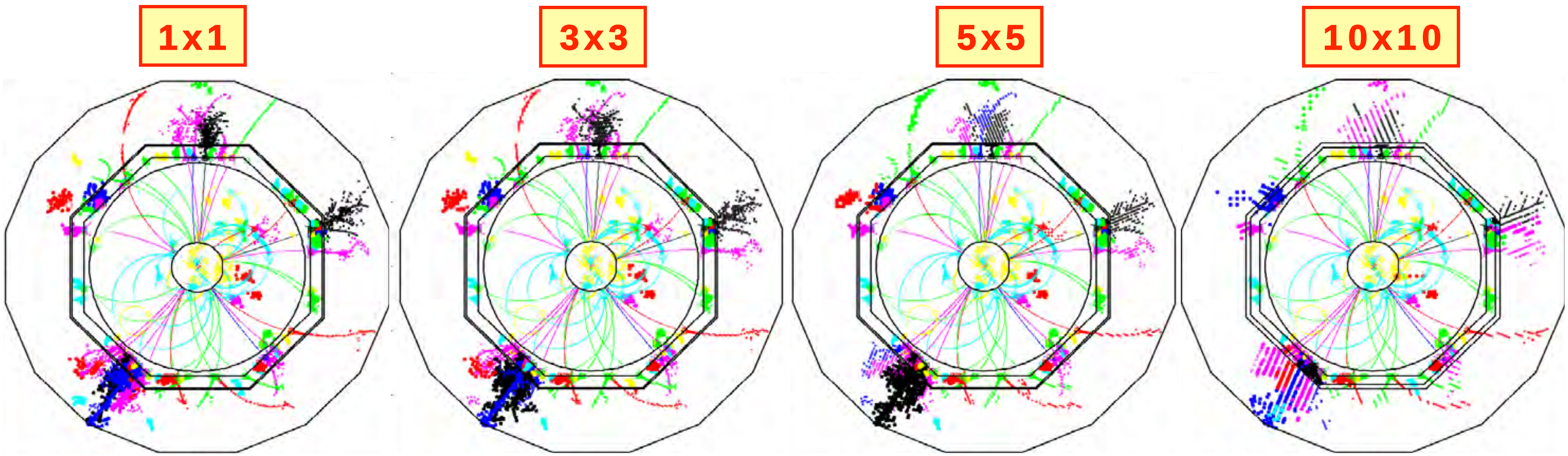


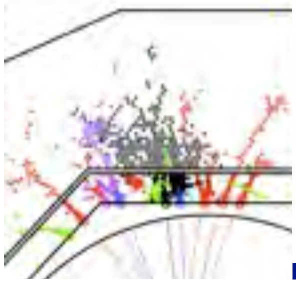
ATLAS: High granularity timing

- In ATLAS phase II upgrade reference scenario, TDR 2017
- pile-up and noise mitigation
  - vertex by E deposition timing
- More forward, more challenging environment than CMS HGCAL
- 4-5 layers
- standard or LGAD sensors
- CALICE inspired design
- Test beam and simulation studies ongoing



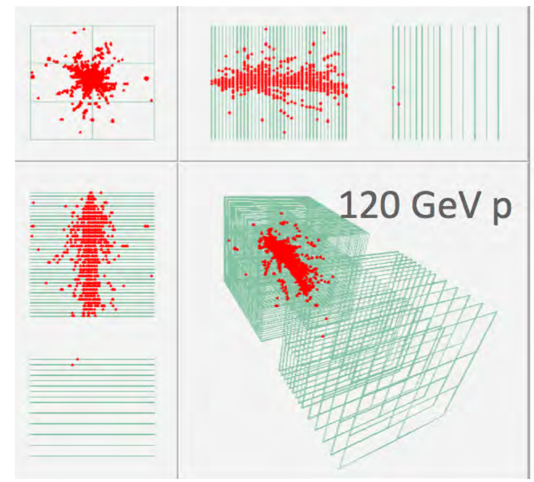
Energy resolution and Granularity





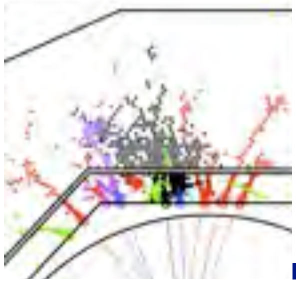
Energy and Granularity

- A central theme in jet calorimetry since the times of the conception of the HERA experiments H1 and ZEUS



“Energy resolution is everything!”

“Granularity is everything!”



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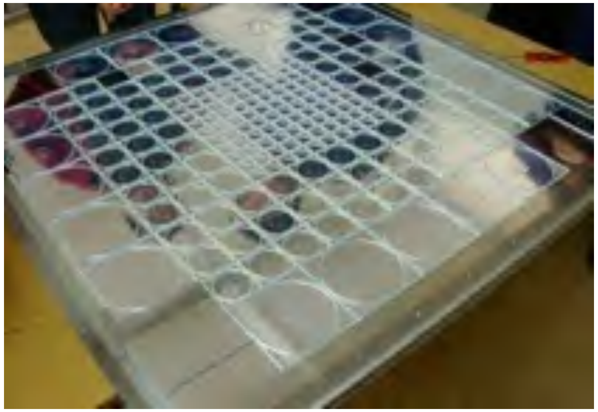
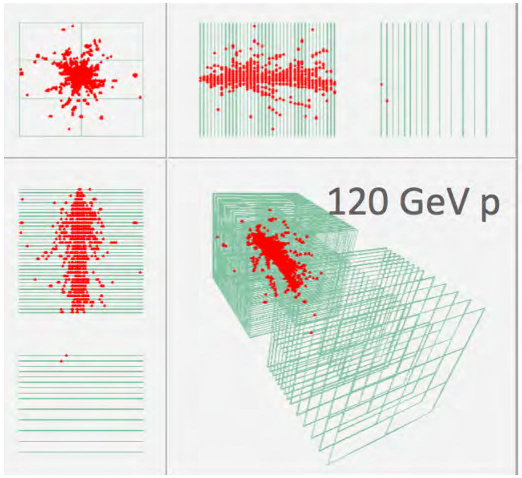
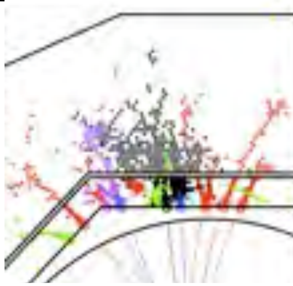




"Energy resolution is everything!"

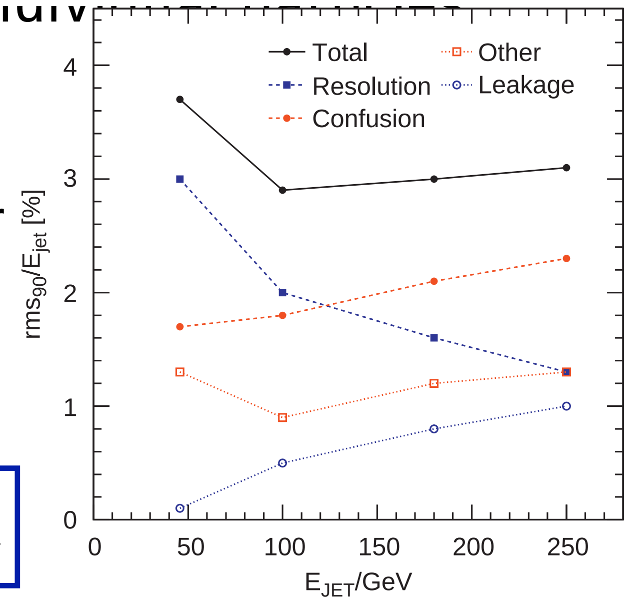
"We need enough of both!"

"Granularity is everything!"



Particle flow performance

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



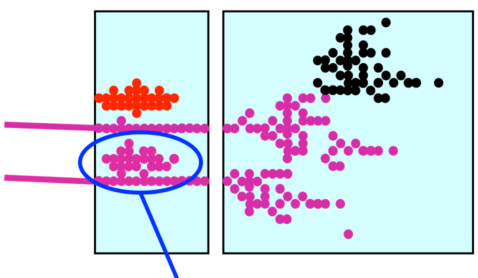
- Separating the energy depositions o
  requires high granularity

- Calorimeter resolution still does matter
  - dominates for jets up to ~ 100 GeV
  - contributes to resolve confusion

Pattern recognition
based on topology **and** energy

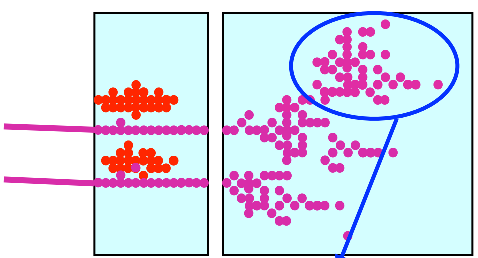
Types of confusion:

i) Photons



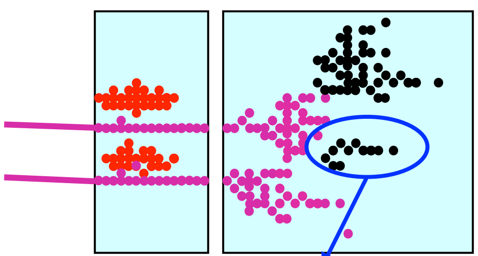
Failure to resolve photon

ii) Neutral Hadrons

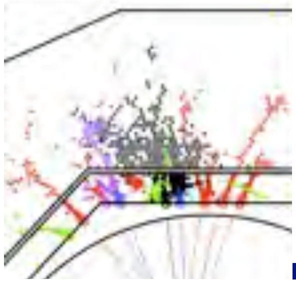


Failure to resolve neutral hadron

iii) Fragments



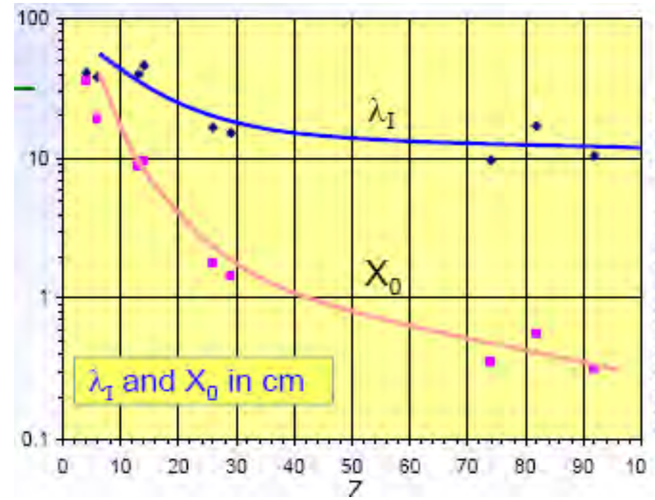
Reconstruct fragment as separate neutral hadron

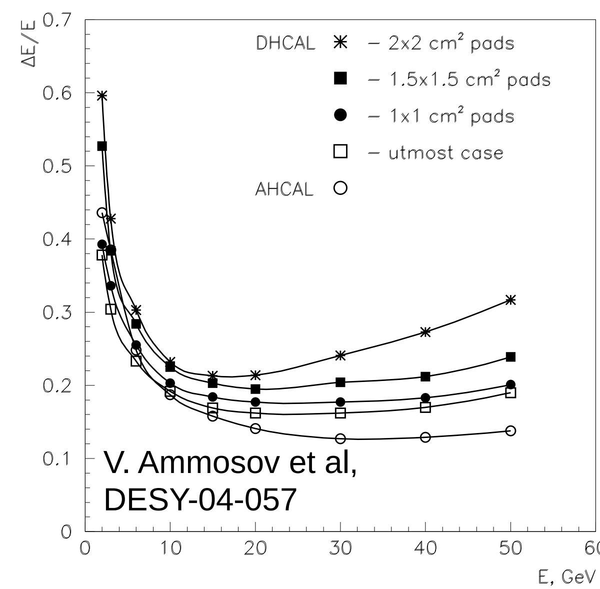


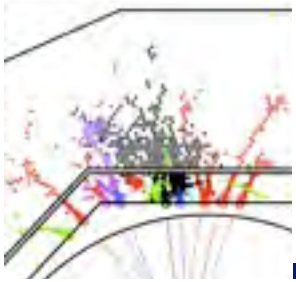
Initial choices

- Analogue:
- 3cm x 3cm at ~ 3cm sampling pitch
- corresponds to Molière radius and X_0; hadron shower sub-structure scale
- small effect on plain energy response and resolution, only via threshold
- more direct effects when software compensation methods are applied

- Digital:
- 1cm x 1cm at ~ 3cm sampling pitch
- to limit saturation effects
- affects single particle linearity and resolution directly





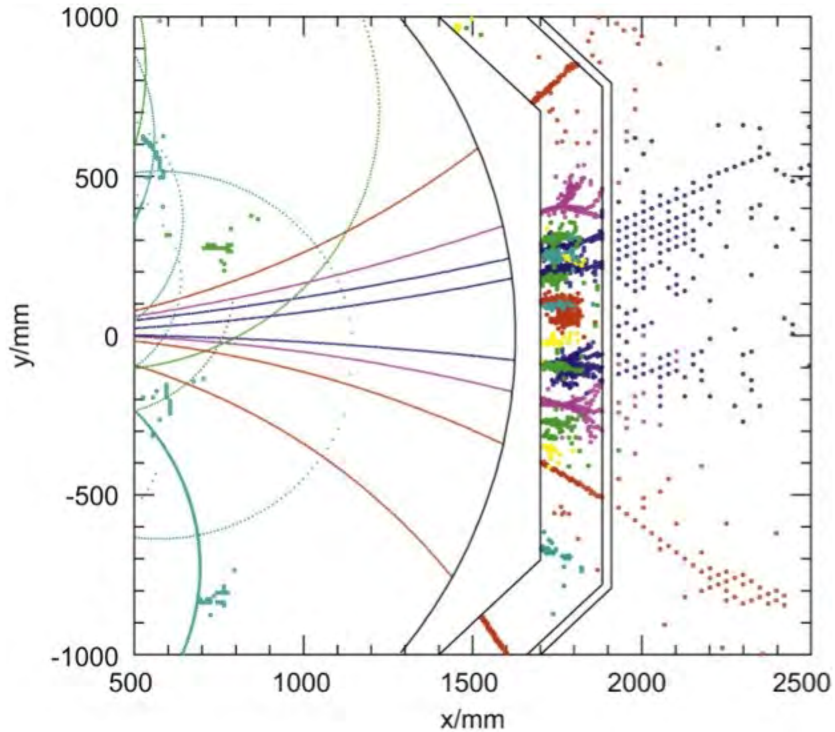


Effects of high granularity

Granularity

Confusion

Particle flow Perfomance



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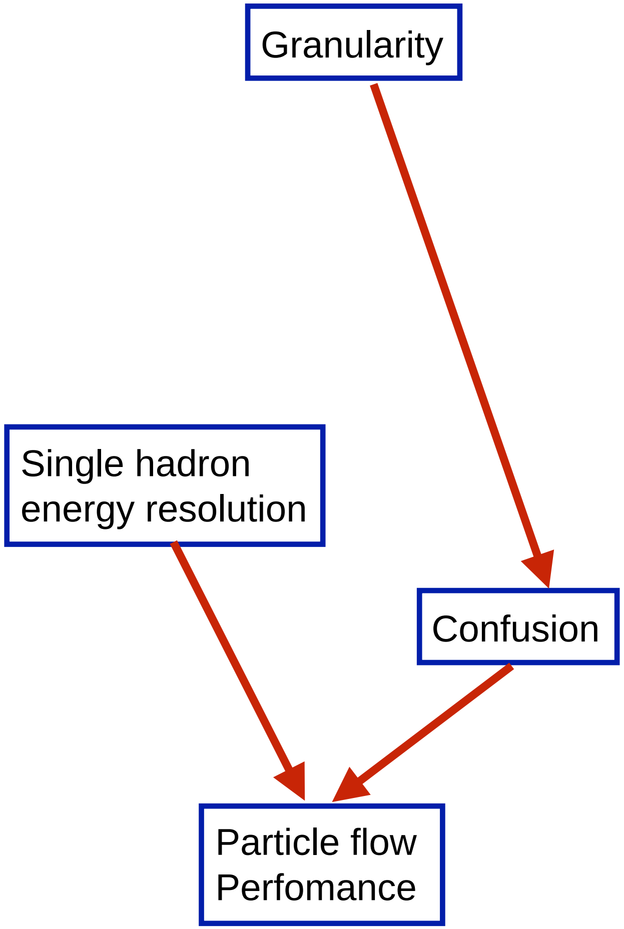

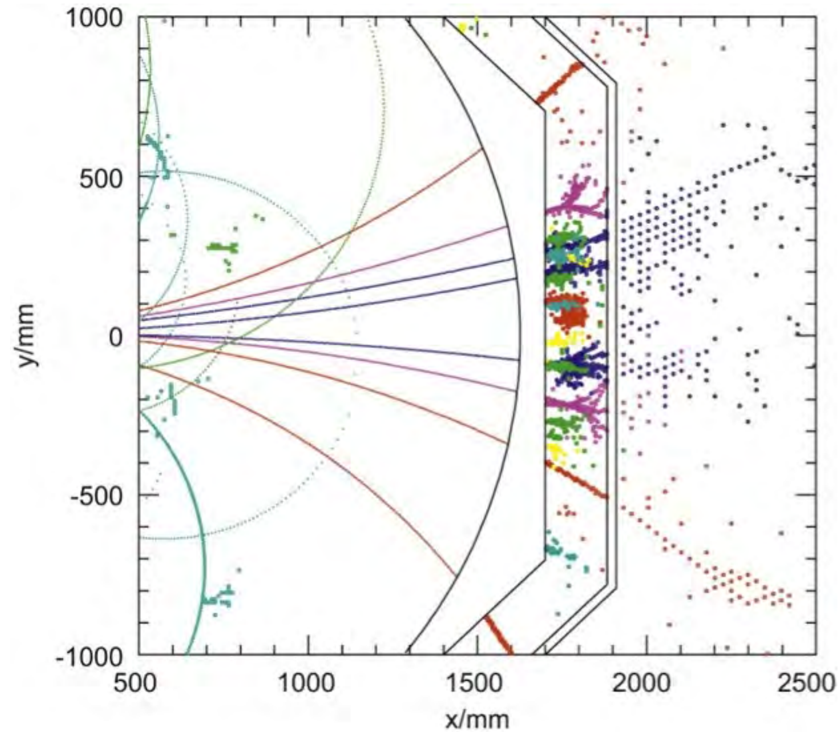

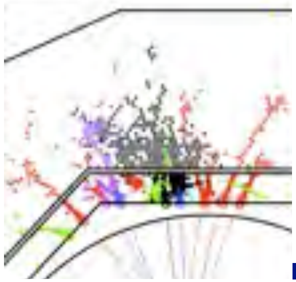

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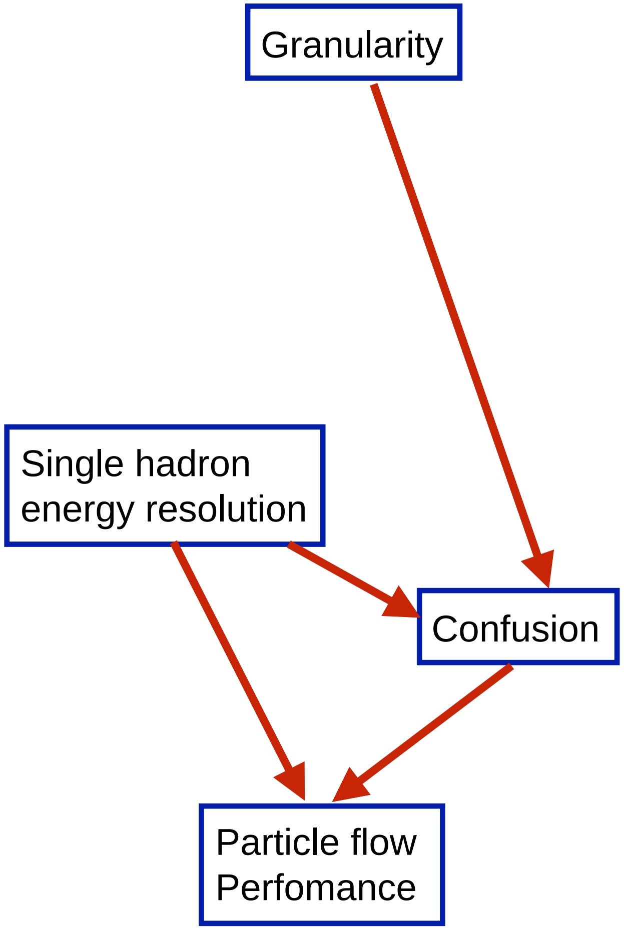

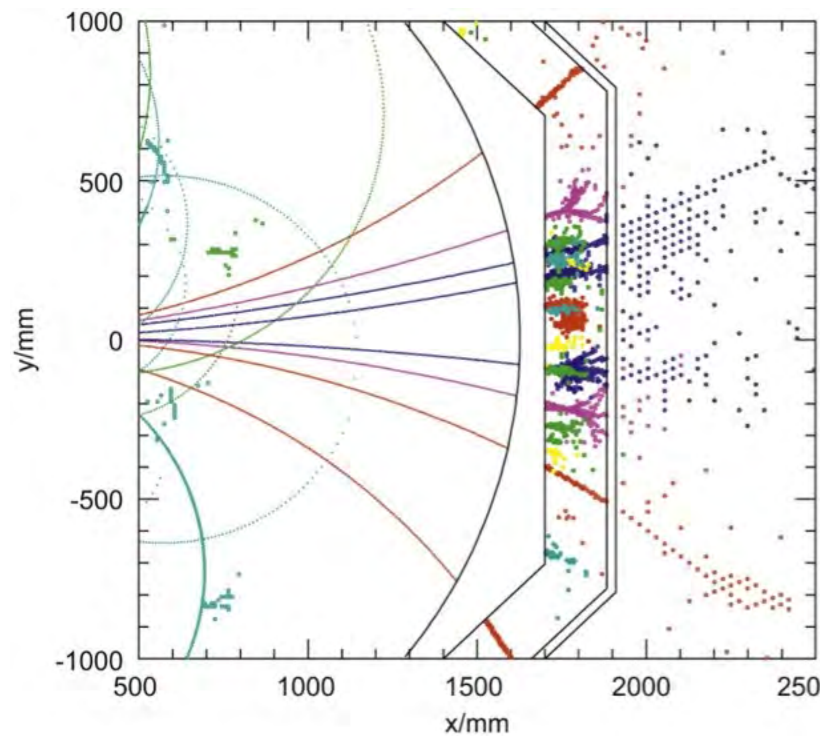

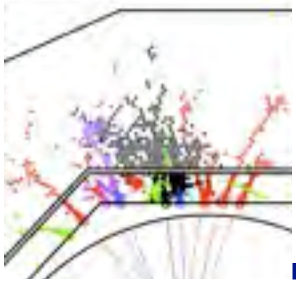

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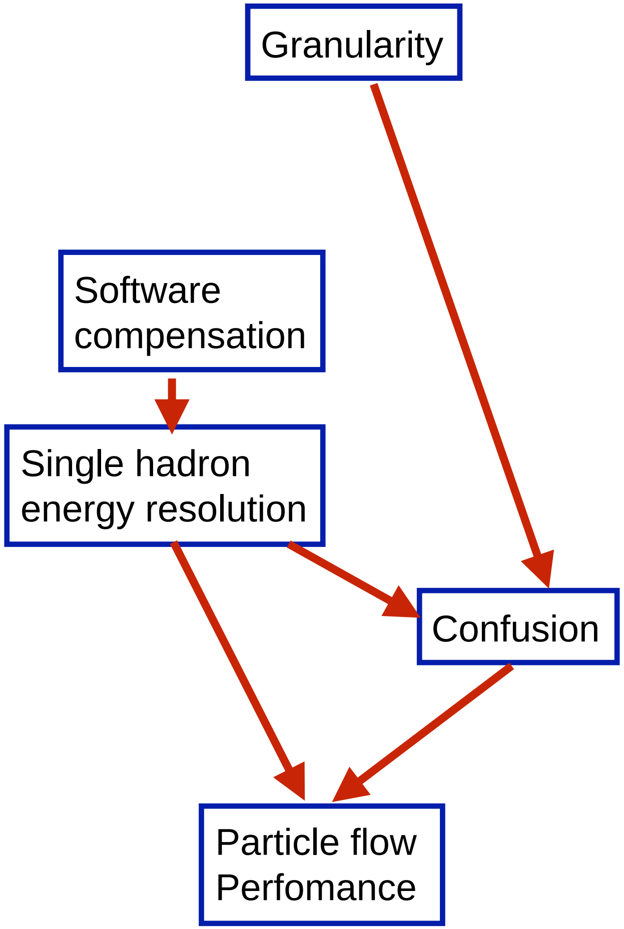

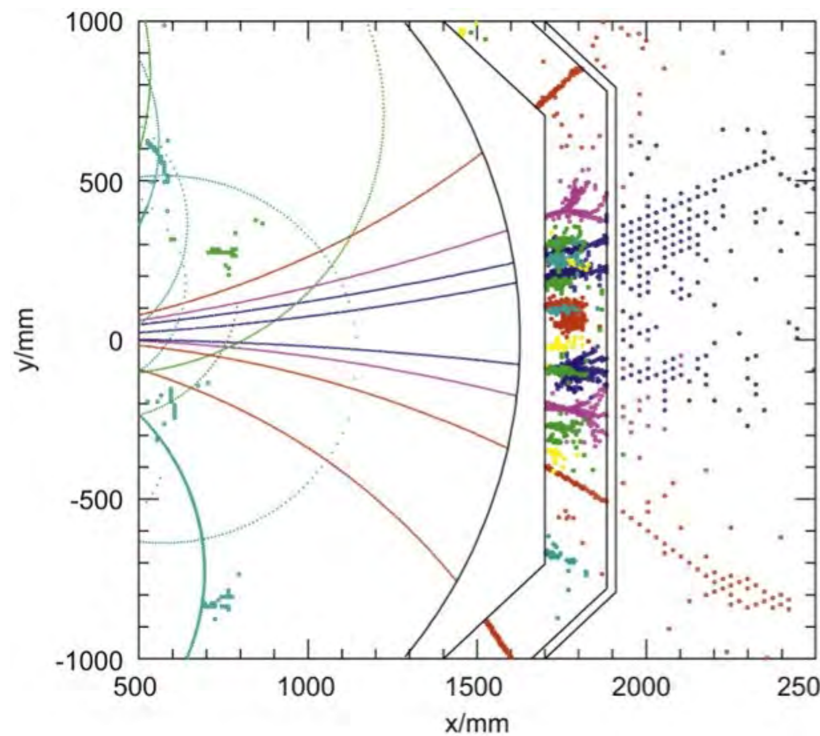

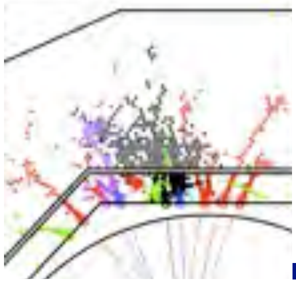

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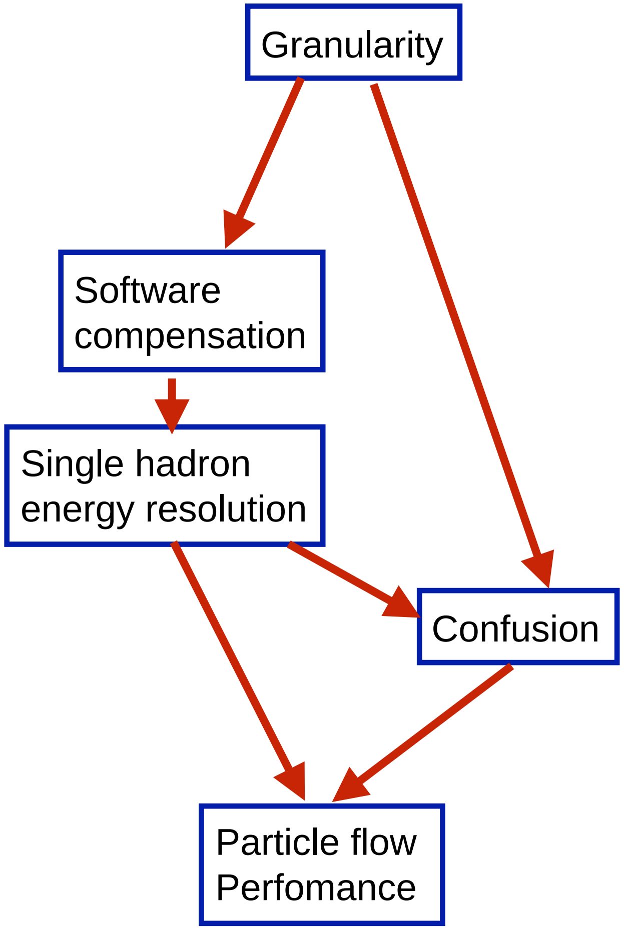

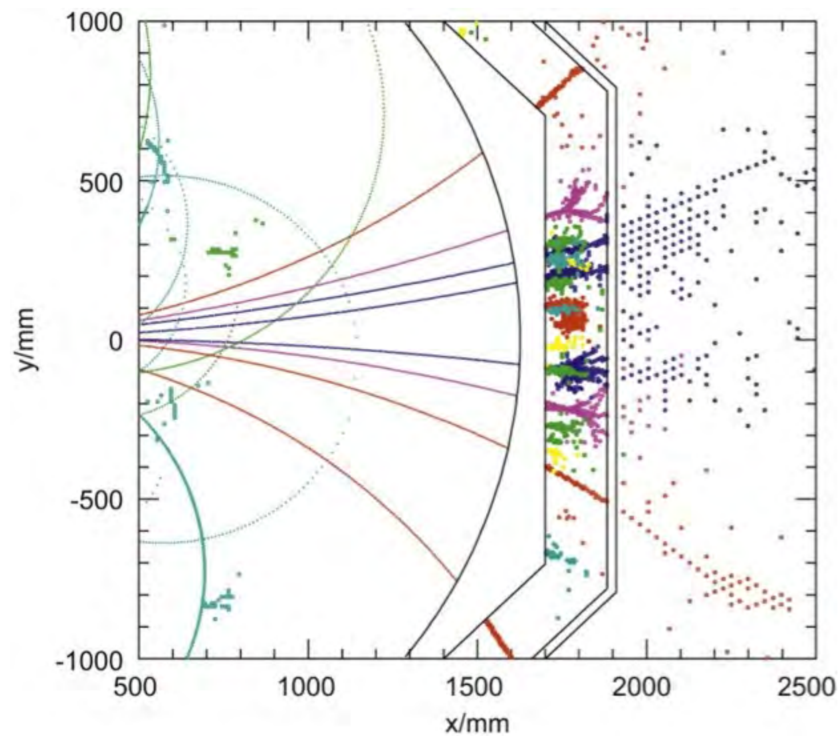

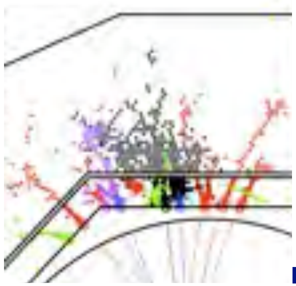

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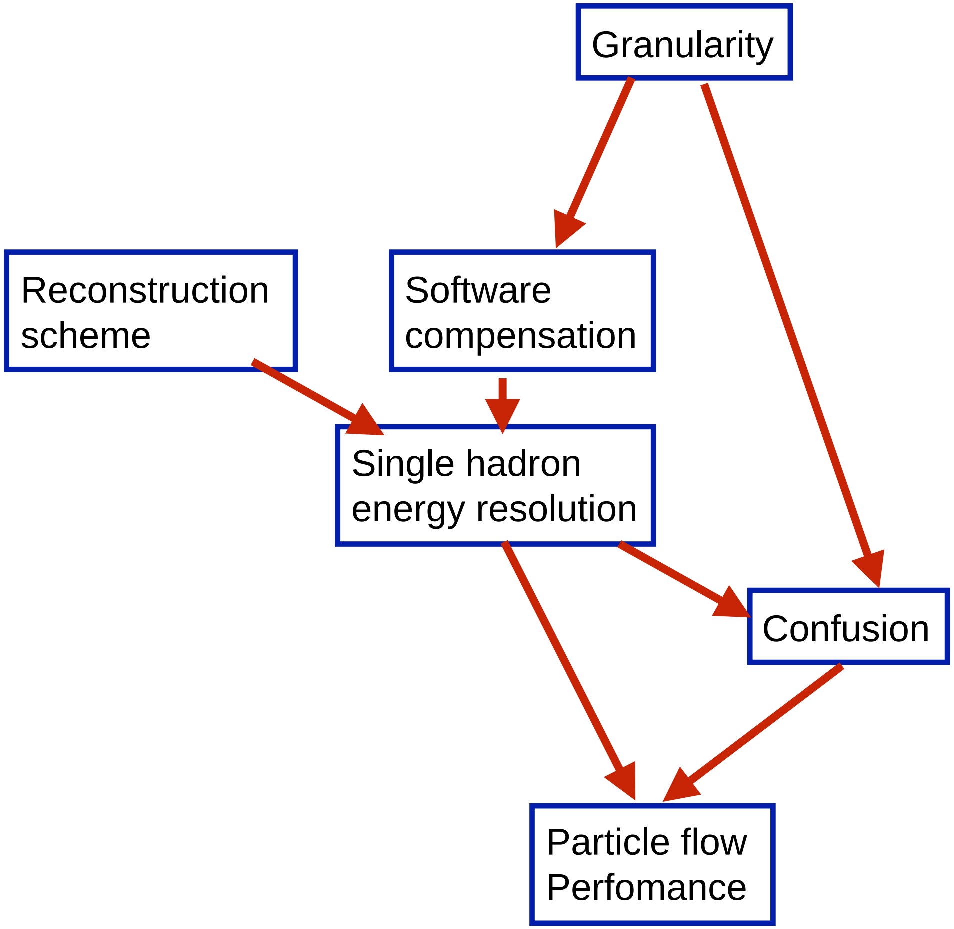

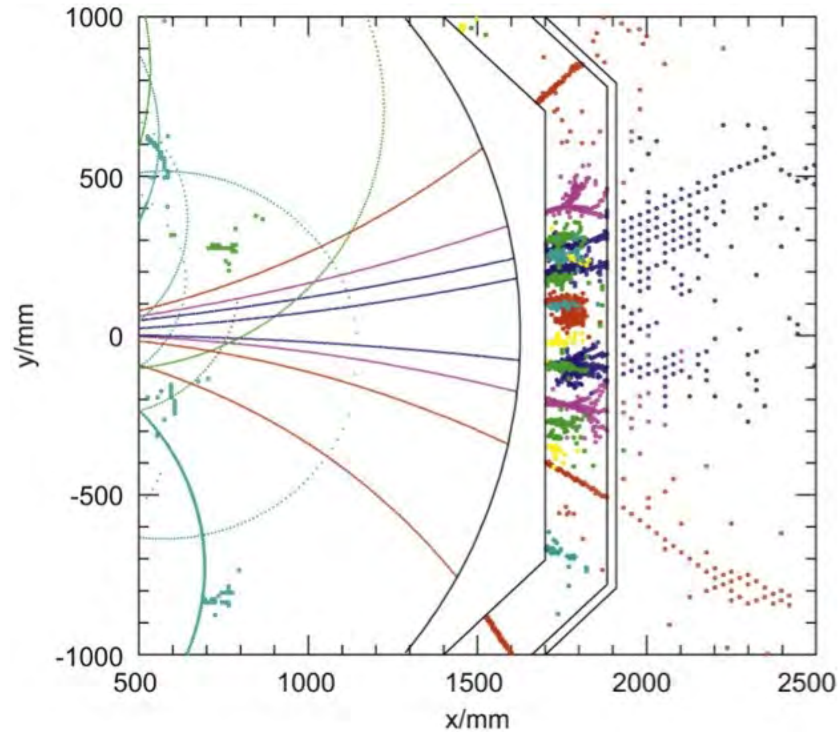

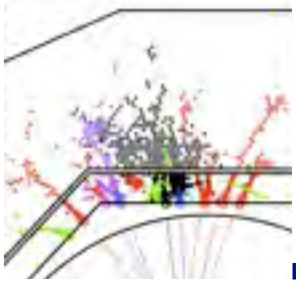

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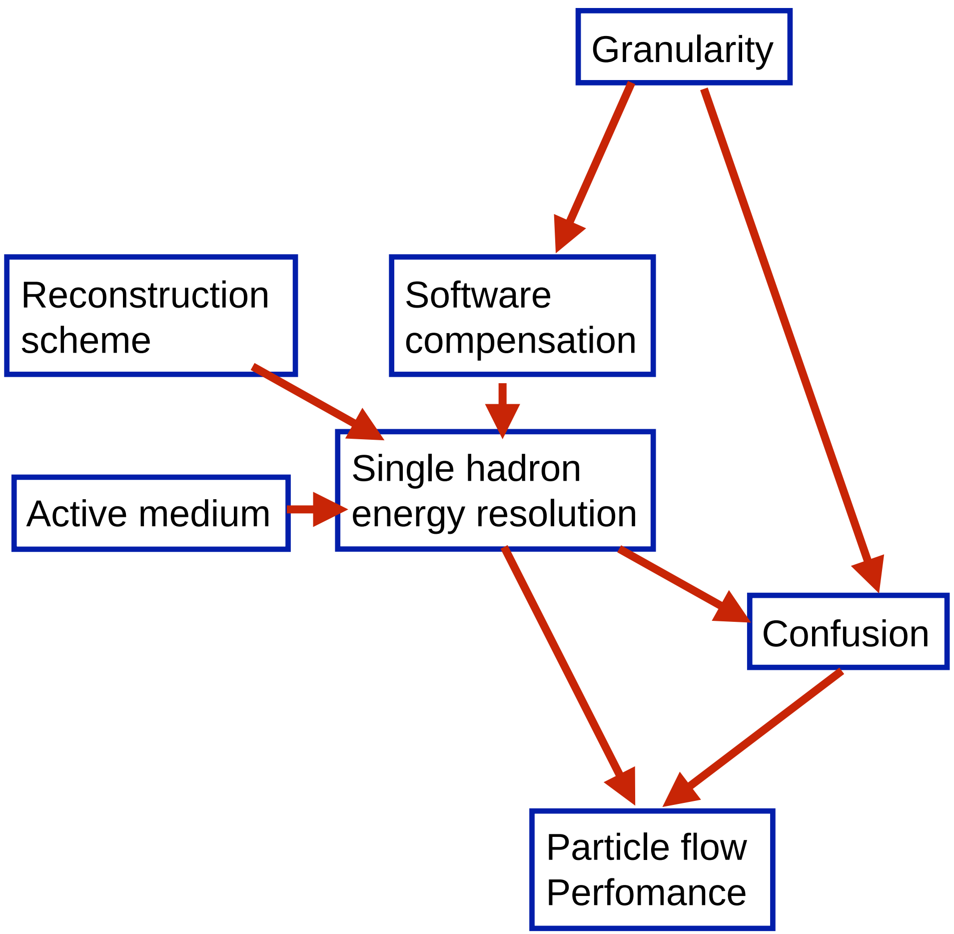
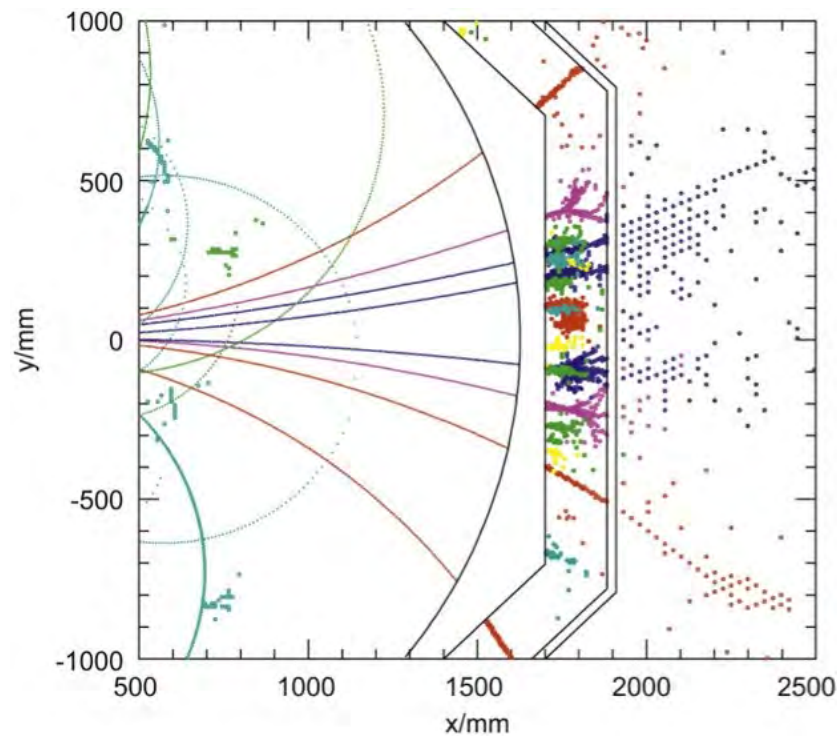
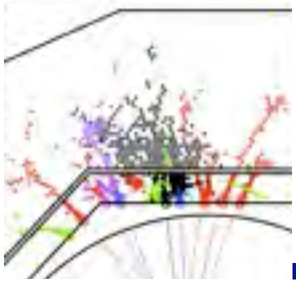
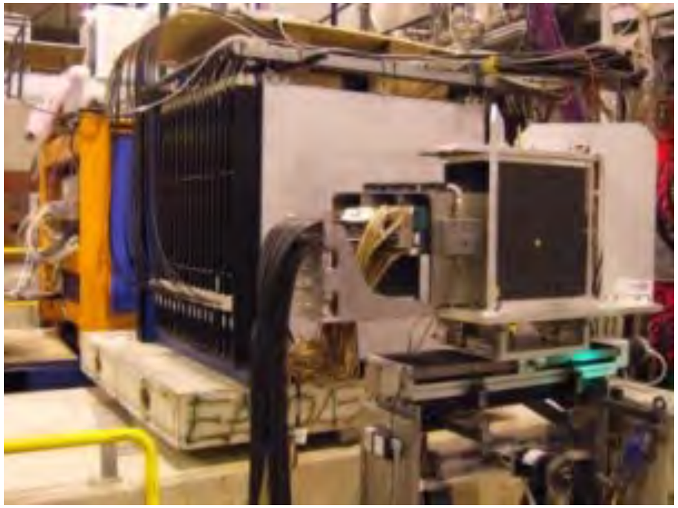


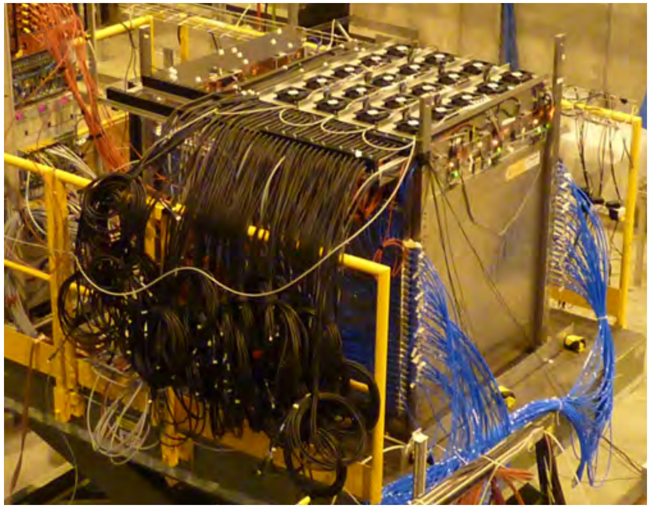


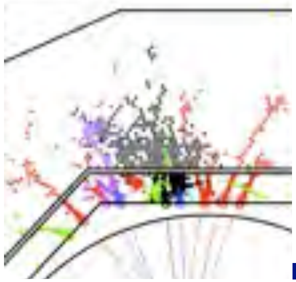


AHCAL and SDHCAL

- Scint and gas prototypes differ in medium, cell size and read-out scheme
- All of them affect single hadron and jet energy resolution
- Disentangle with validated simulations, and optimise, incl. s/w comp







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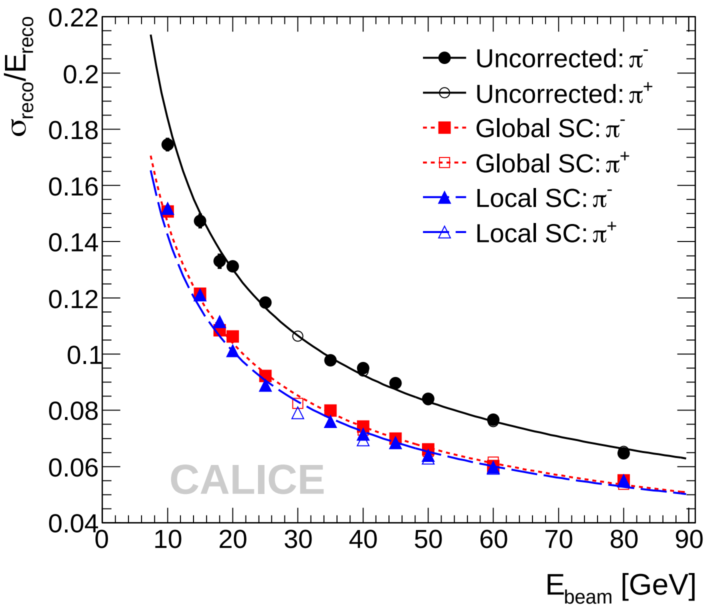
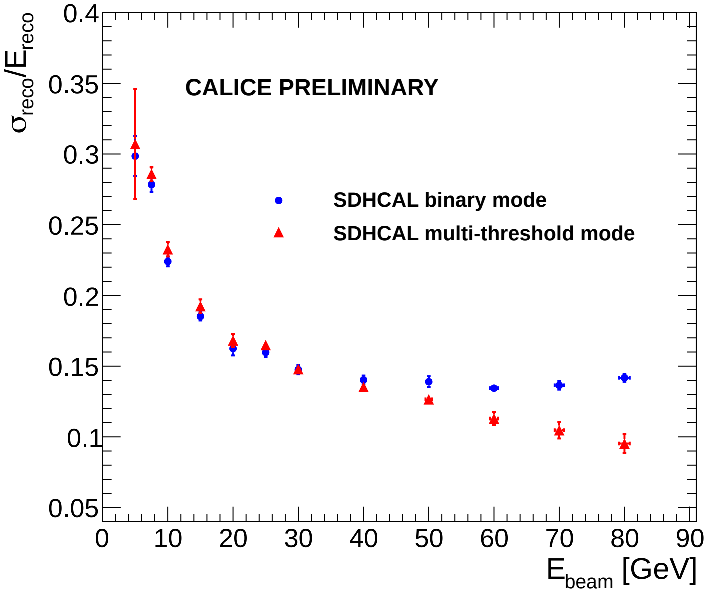
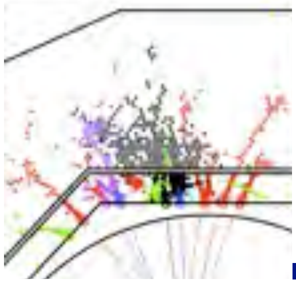
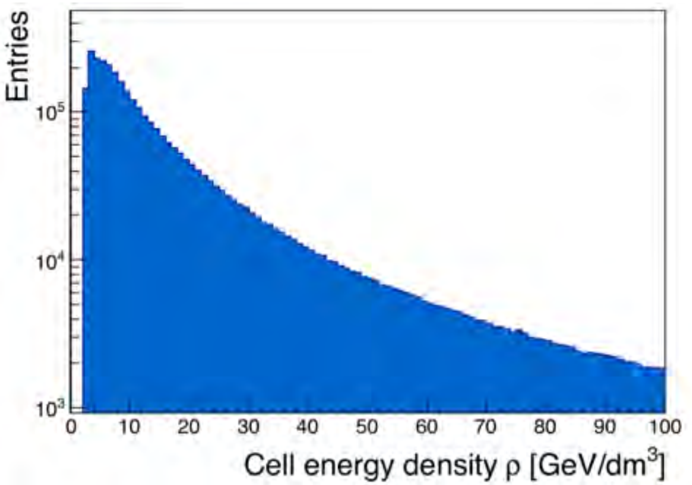


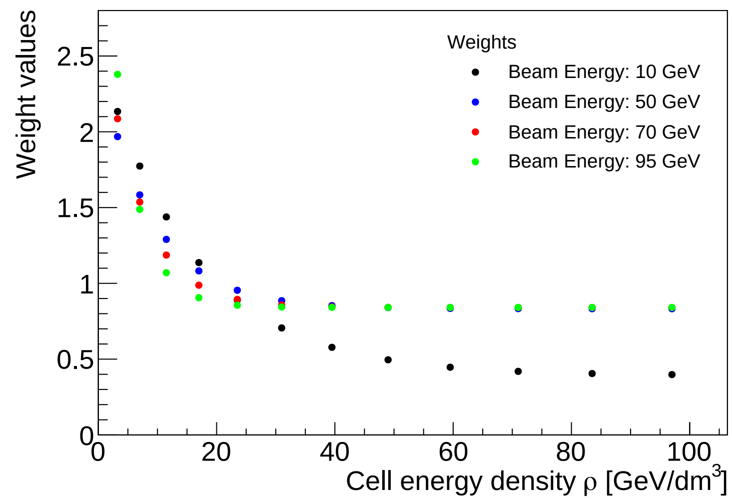




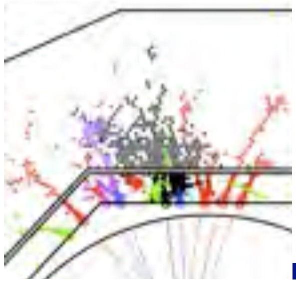
Software compensation

- Electromagnetic showers: higher density, larger response
- Software compensation: weight has according to cell energy





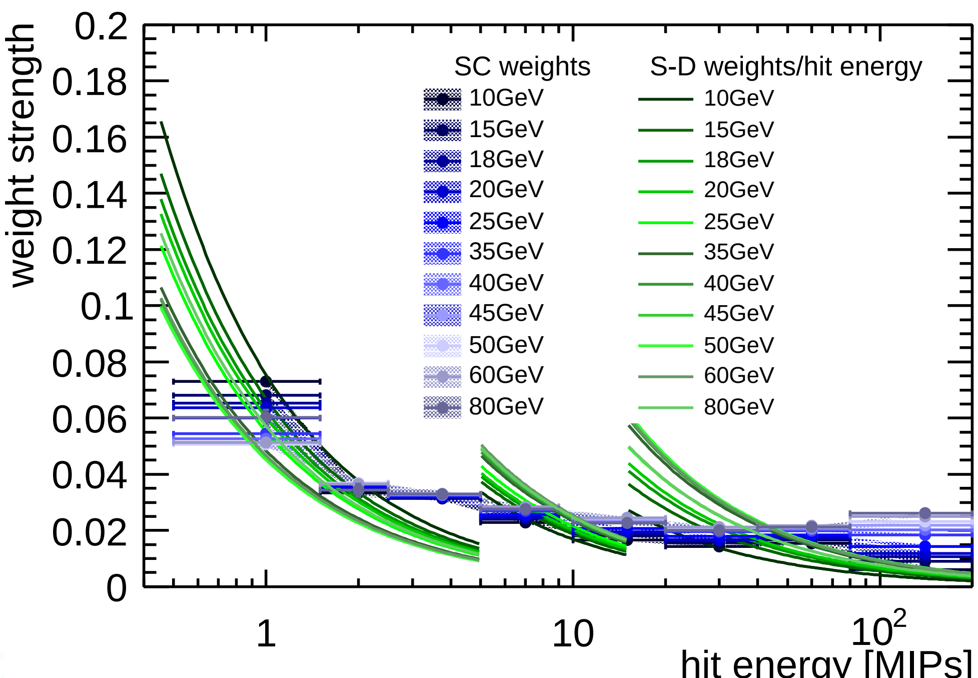
- Optimal weights depend on hit energy (density) and total energy
  - use un-weighted energy as first estimator



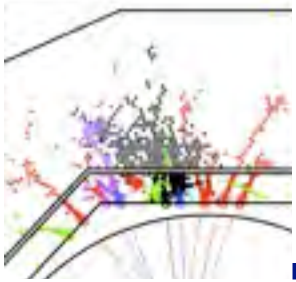
Analogue and digital weighting

- Analogue: $E_{rec,SC} = \sum_i \omega_{SC,i} \cdot E_i$ $\omega = \omega(E_i, E_{tot})$
- Semi-digital: $E_{rec,semi-digital} = \alpha \cdot N_1 + \beta \cdot N_2 + \gamma \cdot N_3$ $\alpha = \alpha(N_{tot})$, $N_{tot} \sim E_{tot}^{\alpha}$

- Counting is equivalent to weighting with $1/E_{hit}$: $\omega = \alpha/E_{hit}$
- Use common formalism and learn from each other



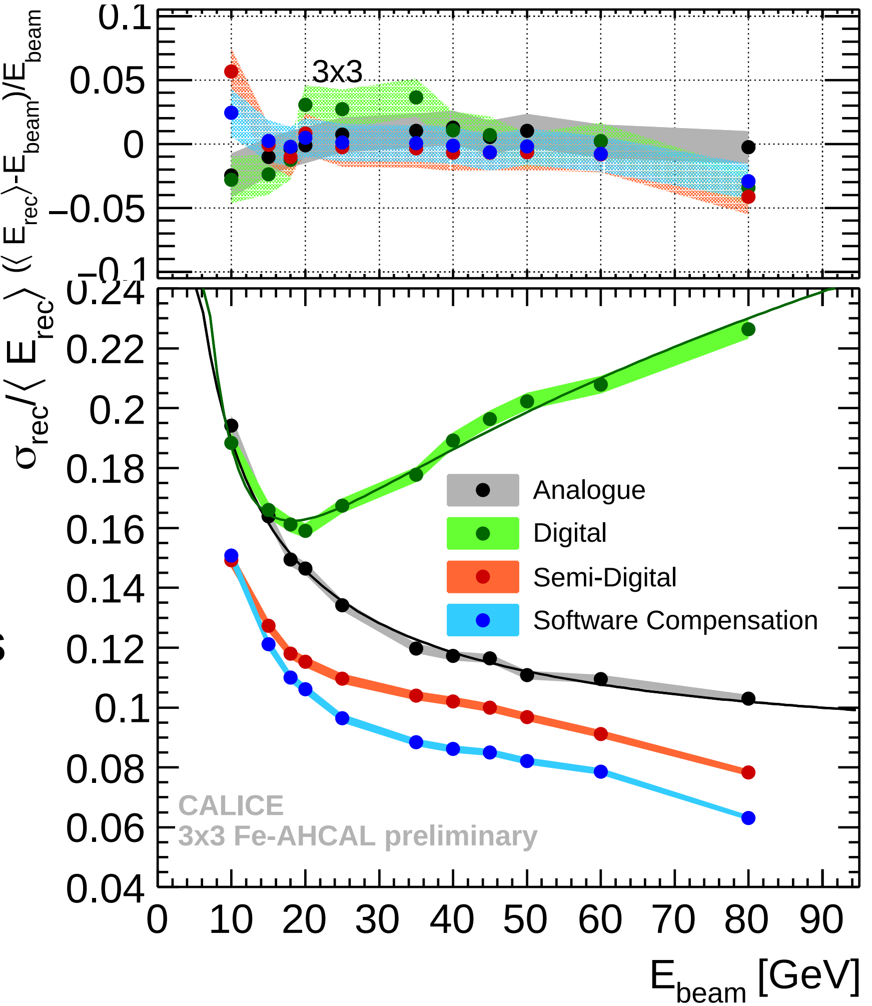
in principle the same
differences in detail

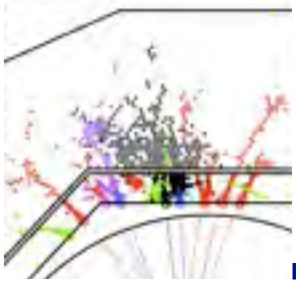


(Semi-) digital reconstruction of AHCAL

- Digital reconstruction:
  - 3x3 is too coarse
- Semi-digital
  - better than analoge
  - with less information?

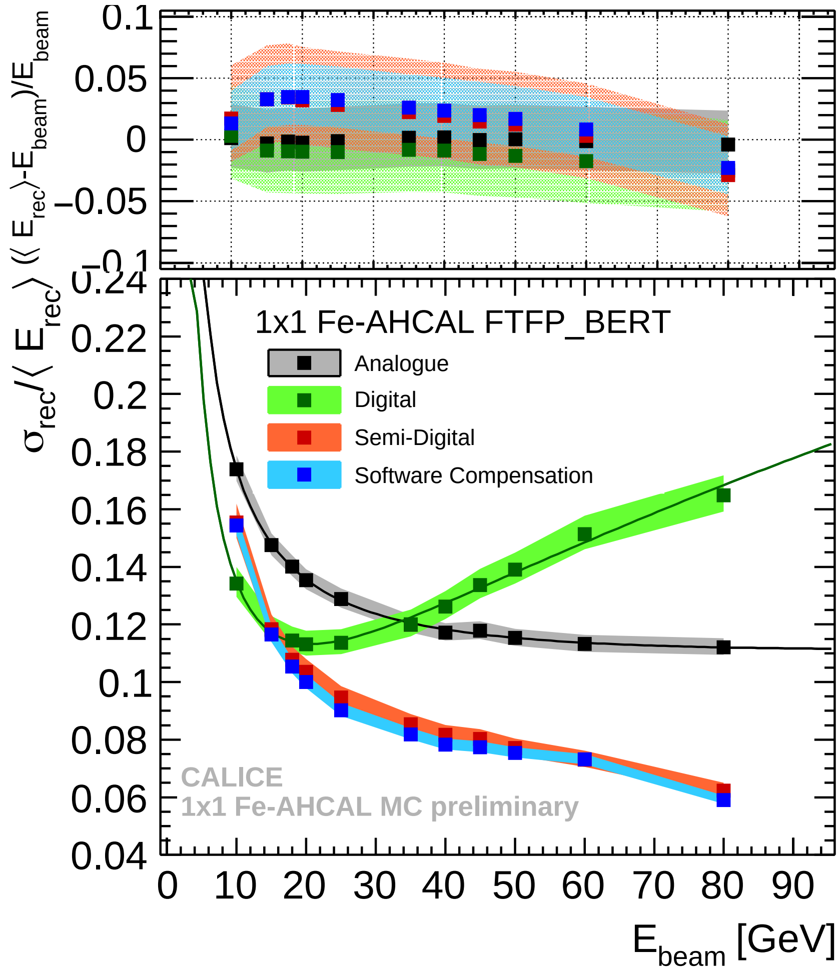
- Count hits: suppression of Landau fluctuations
- Semi-digital reconstruction uses energy-dependent weights
- Software compensation with full energy information gives best results (for 3x3cm^2)

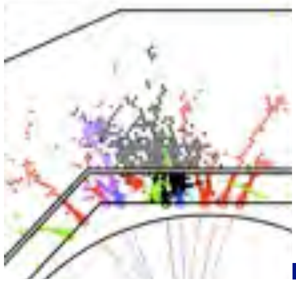




Simulate smaller granularities

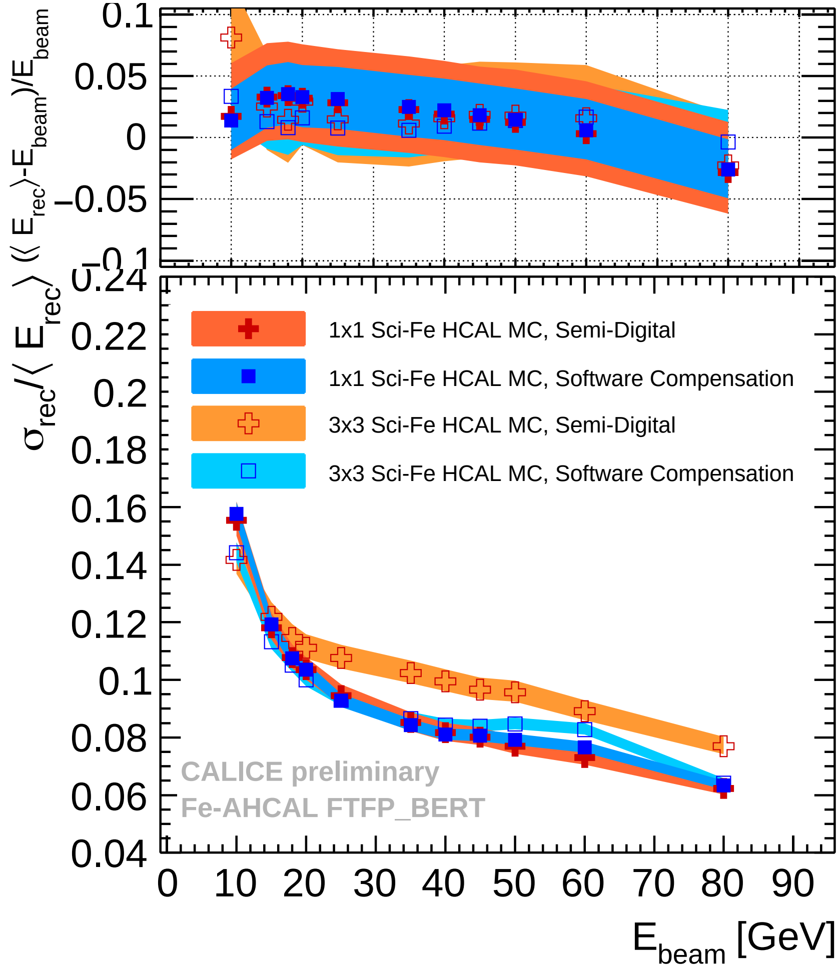
- Simulate with same degree of realism as in AHCAL test beam
  - except noise (not an issue with present SiMs)
  - and adjust threshold in order to obtain similar linearity
- Apply digital and (re-optimised) semi-digital reconstruction
- For $1\text{x}1\text{cm}^2$ case, semi-digital (2-bit) information is sufficient
- With full analogue information, 1x1 not better than 3x3

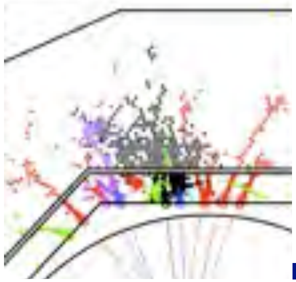




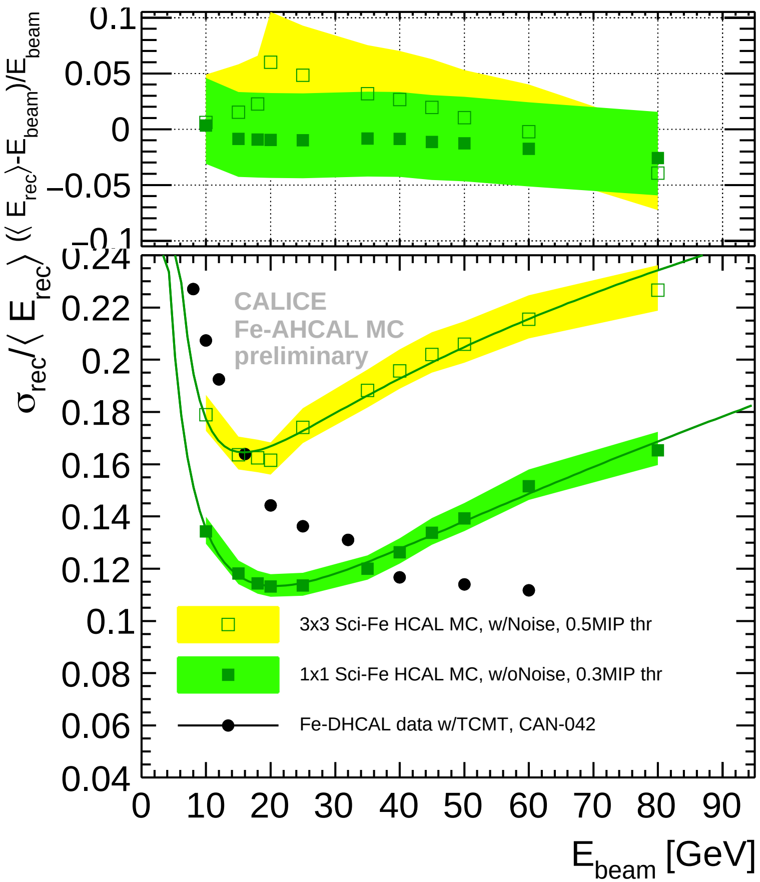
Simulate smaller granularities

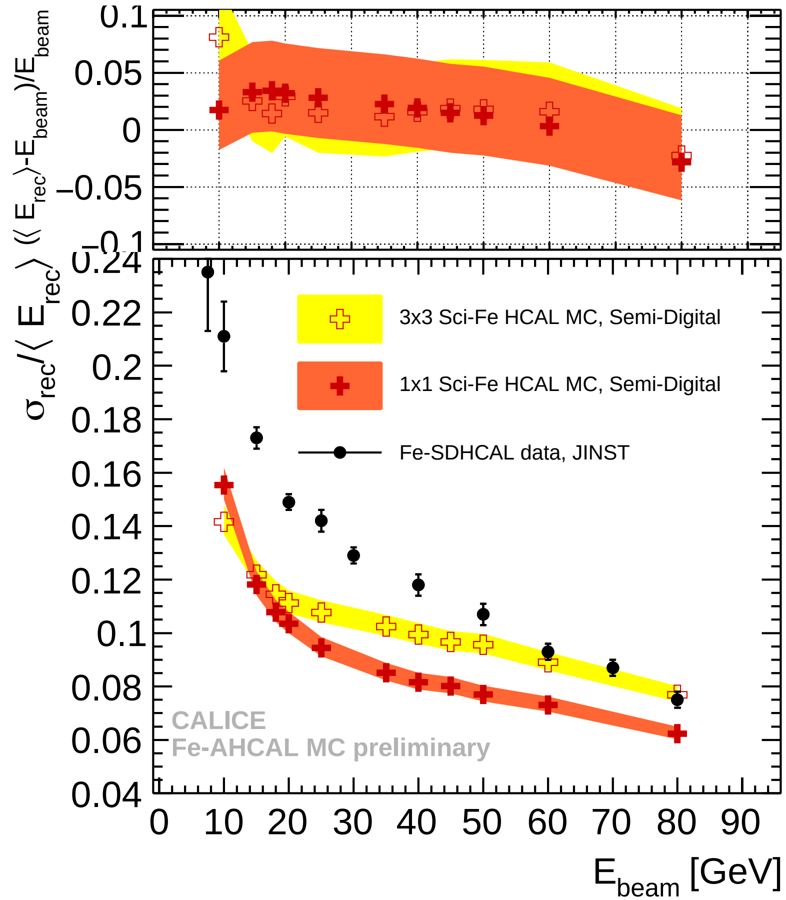
- Simulate with same degree of realism as in AHCAL test beam
  - except noise (not an issue with present SiMs)
  - and adjust threshold in order to obtain similar linearity
- Apply digital and (re-optimised) semi-digital reconstruction
- For 1x1cm^2 case, semi-digital (2-bit) information is sufficient
- With full analogue information, 1x1 not better than 3x3



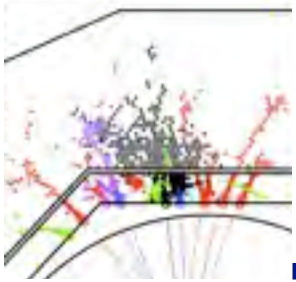


Comparison with data





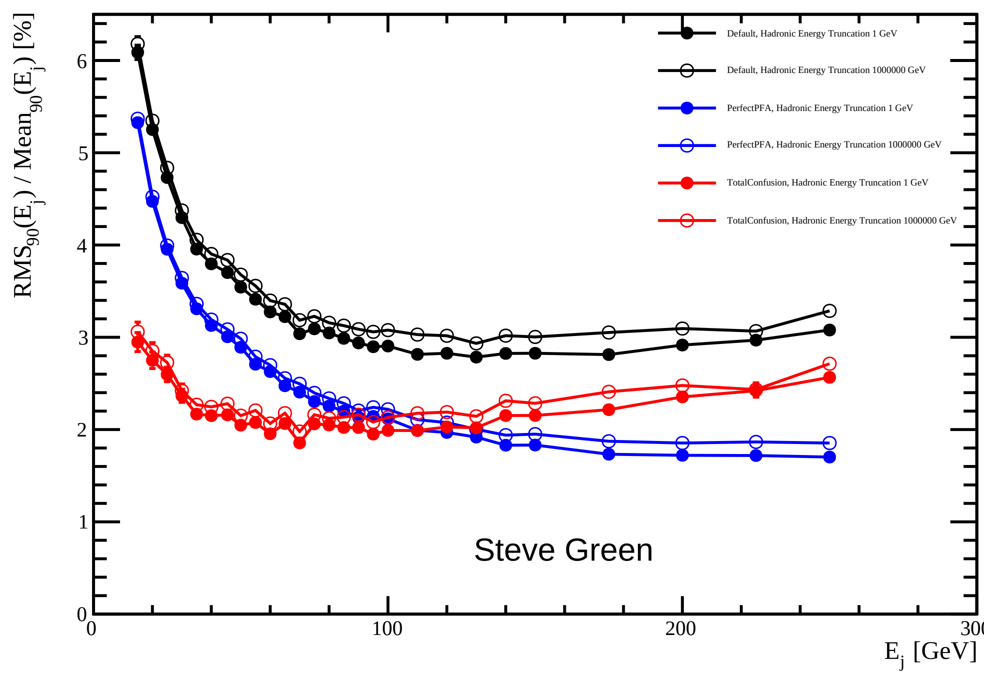
- Differences between gas and scintillator to be understood
  - validated simulations on their way



s/w compensation and PFLOW

- Jet energy resolution is the goal
- In principle can benefit in two-fold way:
  - improve resolution for neutral objects
  - improve cluster energy estimators for track-cluster association -

studies with Pandora PFA



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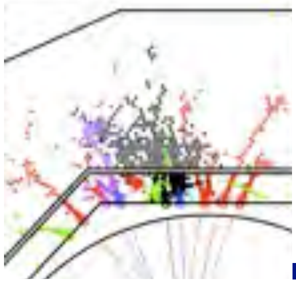

s/w compensation and PFLOW

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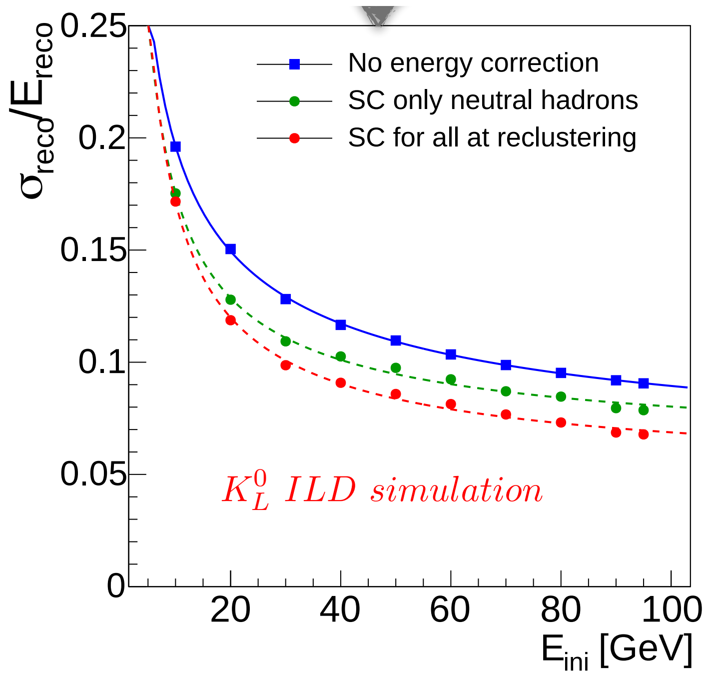

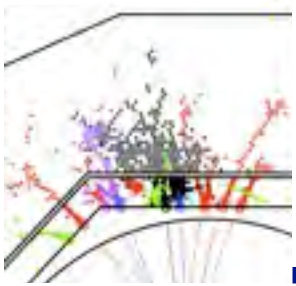

s/w compensation and PFLOW

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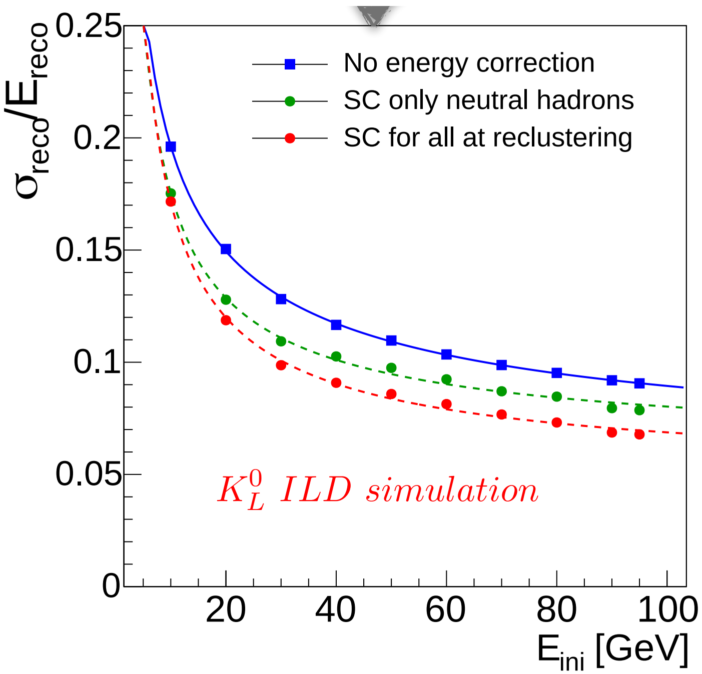
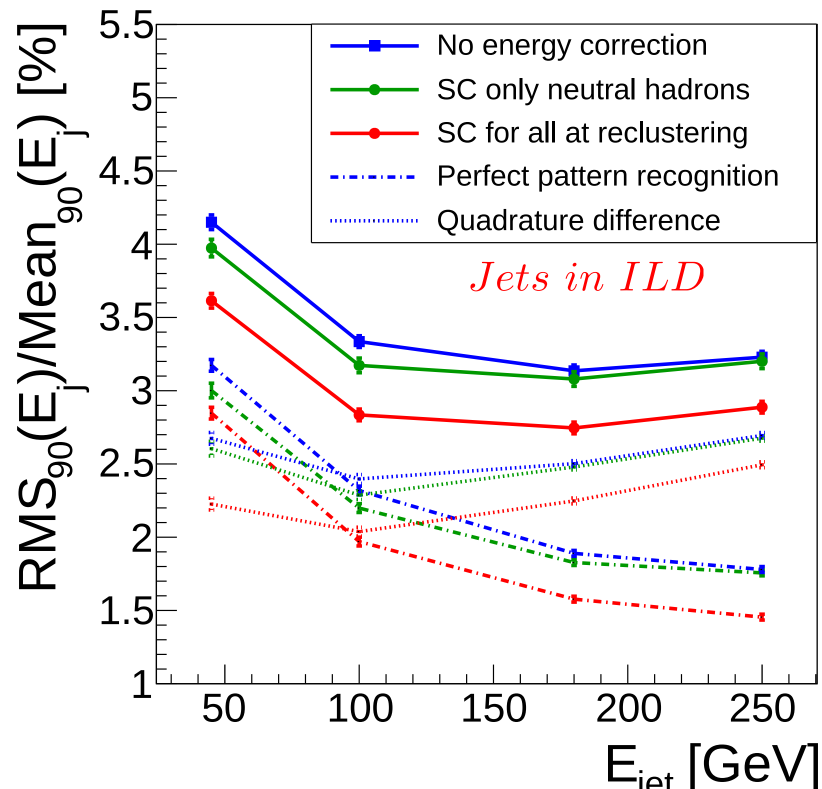
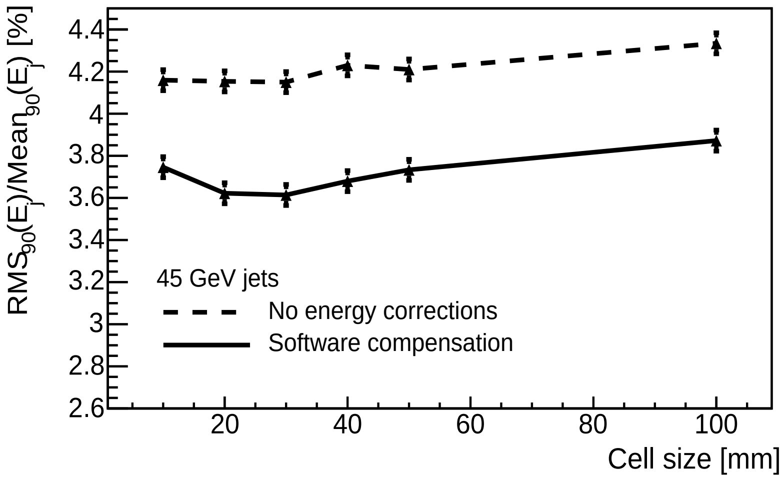
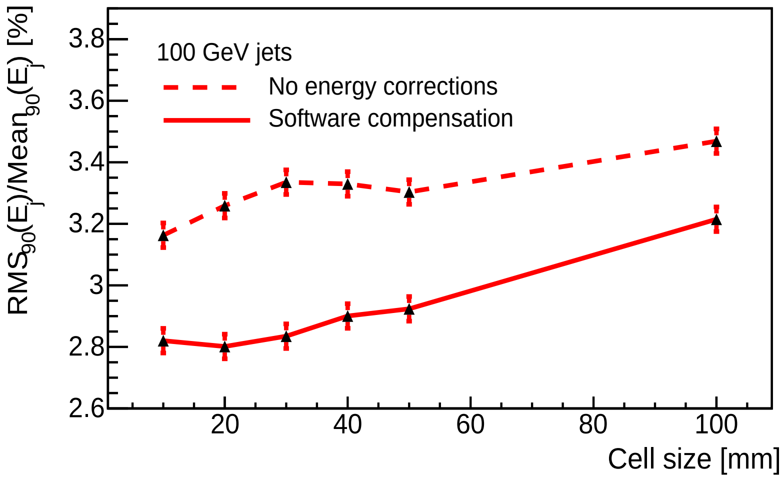
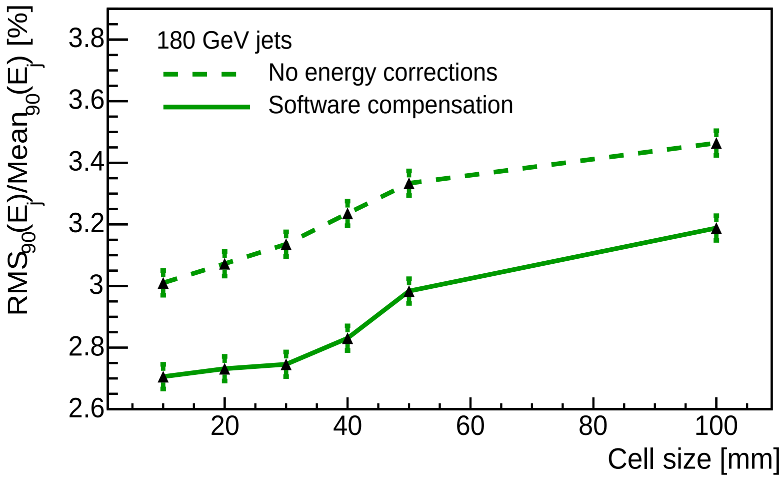


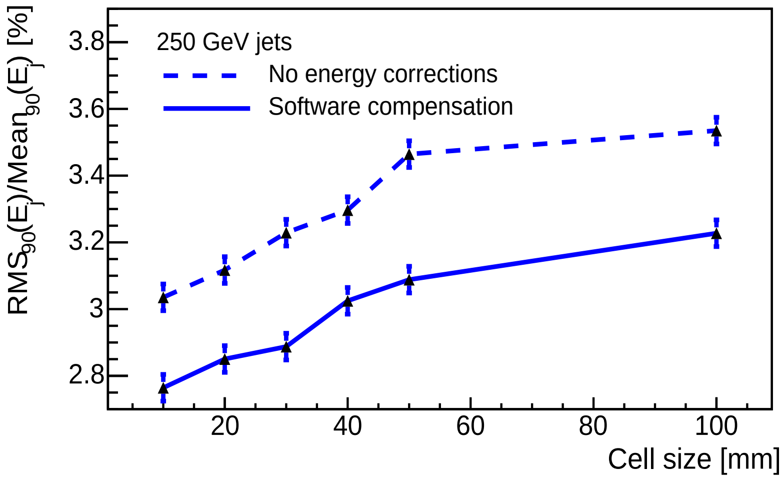


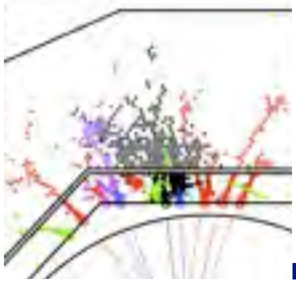
Granularity and resolution 2











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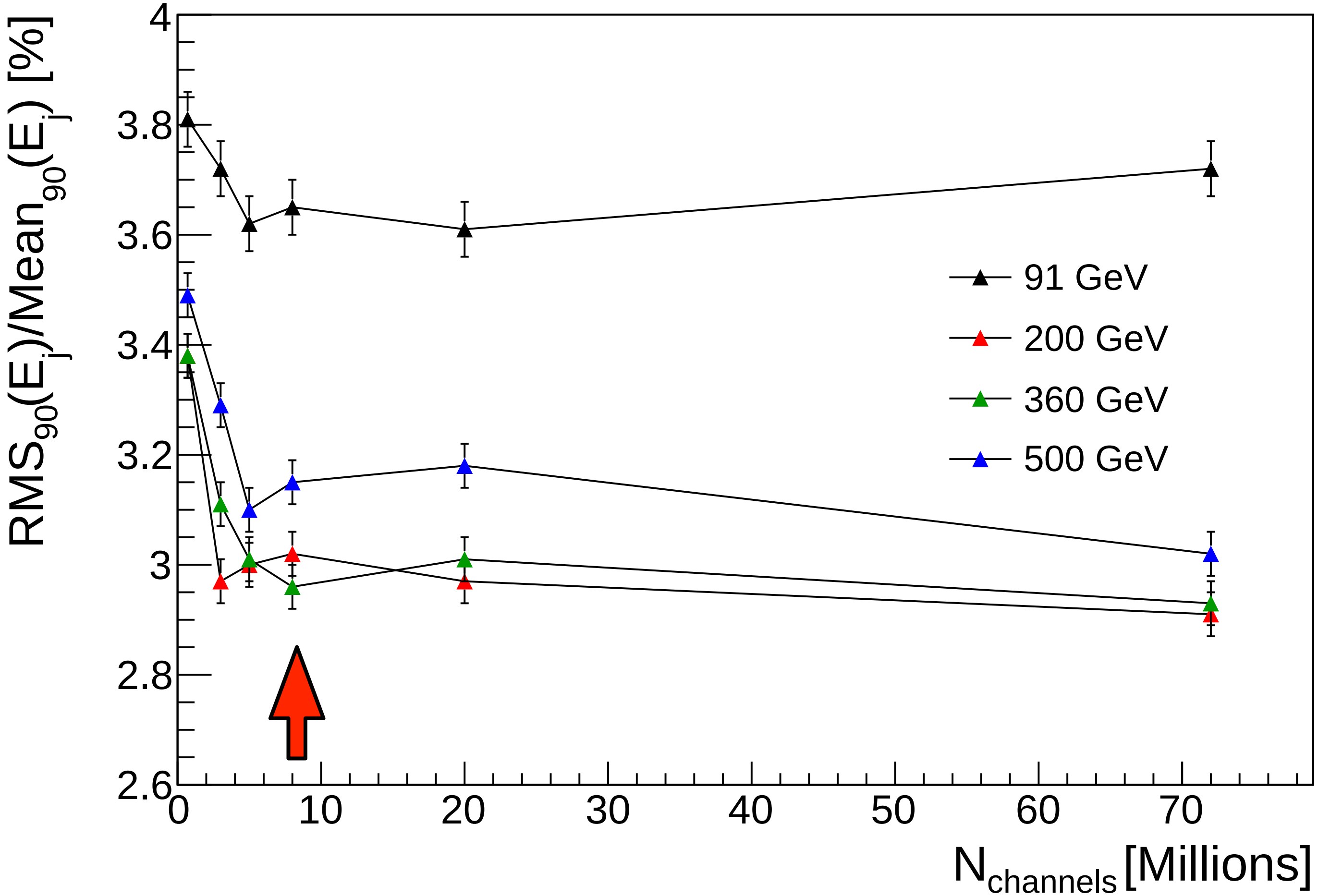
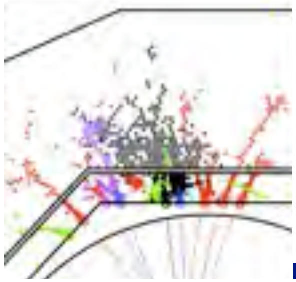


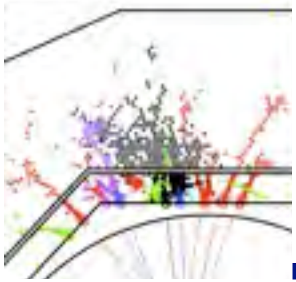
- 3 cm still a very reasonable choice



Conclusion

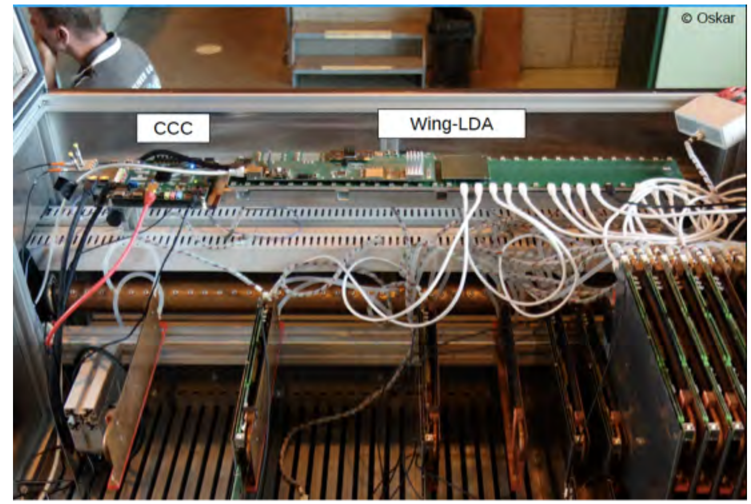
- Calorimetry has changed - particle flow concept established experimentally
- Bearing fruit beyond LC community
- Still test beam results coming in and deepening our understanding
- Now fully in second phase: make it realistic
  - German groups (DESY, Hamburg, Heidelberg, Mainz, Munich MPI, Wuppertal) build a scalable prototype with fully integrated electronics
- There are many open issues = room for new ideas

Back-up slides

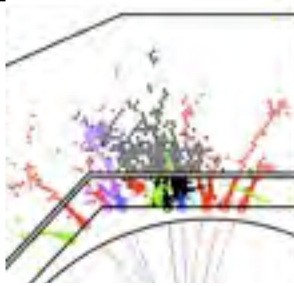


Frontiers

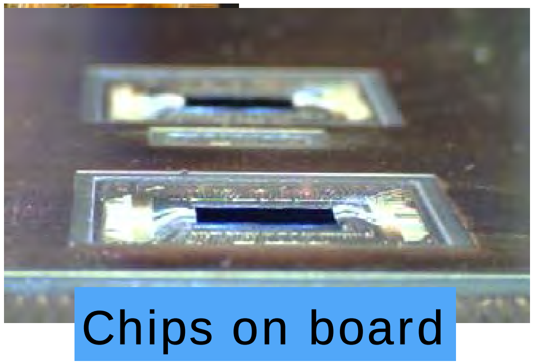
- Technology frontier
  - 10 years progress in SiMs
  - 1 glass RPCs, THGEMs, resistive μMs
- Integration frontier
  - electronics integration, low power
  - scalable solutions for DAQ and services
- Industrialisation frontier
  - design simplifications
  - mass production and QA schemes
- Calibration frontier
  - monitoring and correction procedures
- Simulation frontier
  - model μ, e, π showers in gaseous HCAL: low and high density
- Reconstruction frontier
  - threshold weights, software compensation
- Algorithm frontier
  - understand relative importance of active medium, granularity and r/o scheme
  - develop second, independent algorithm
- Hadron collider frontier
  - ...

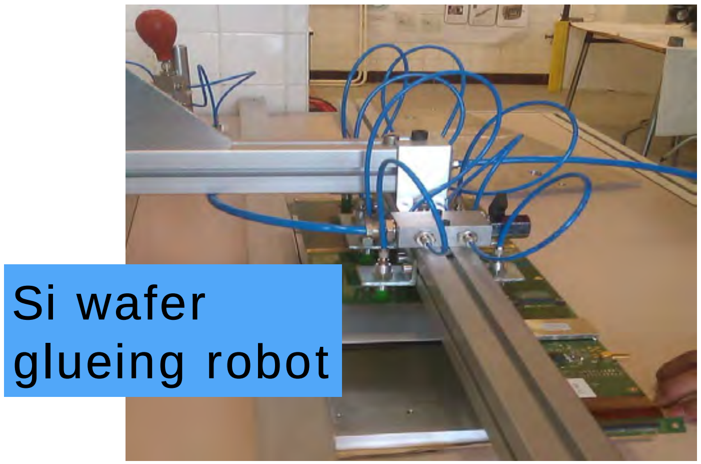


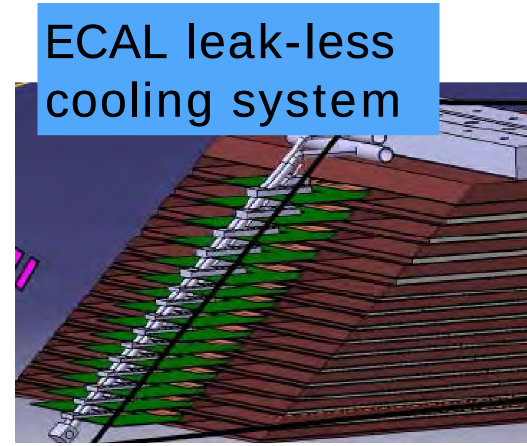
will read 2 segments. 96 layers, 250k channels

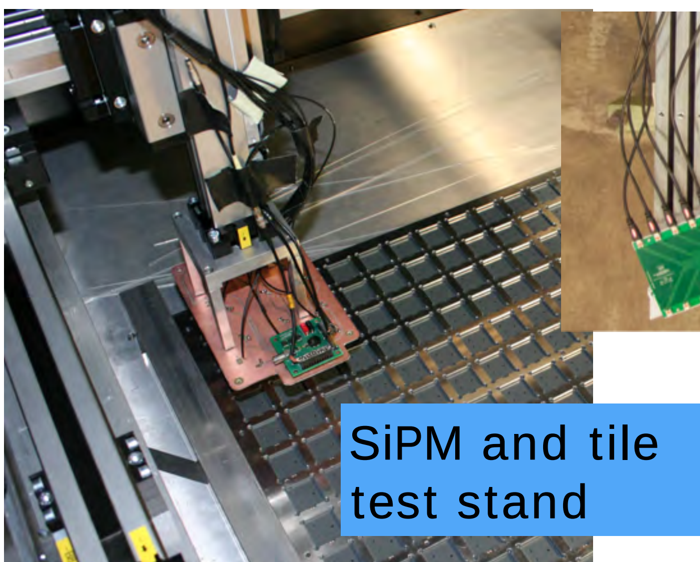


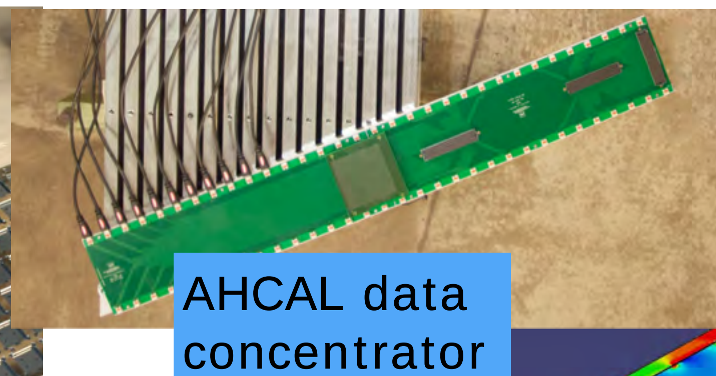
System integration & Tooling

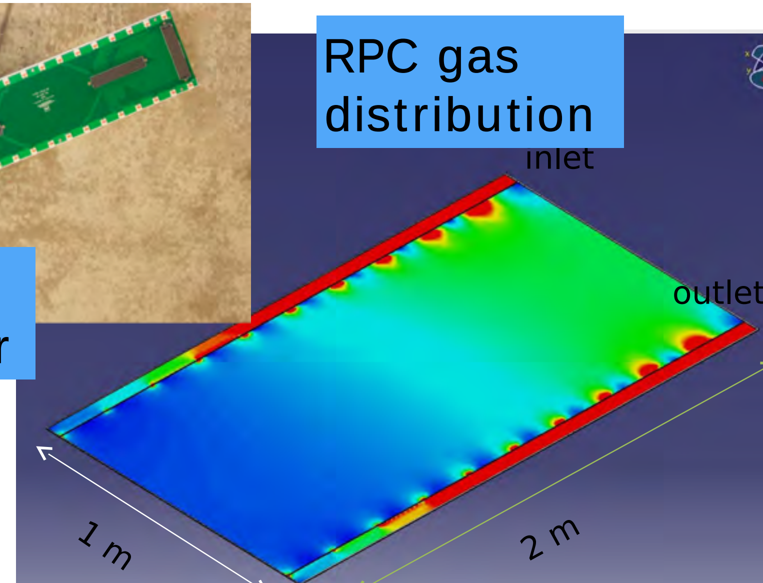


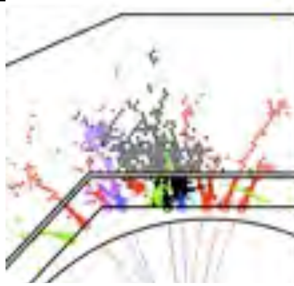






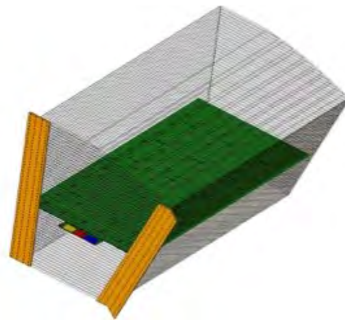


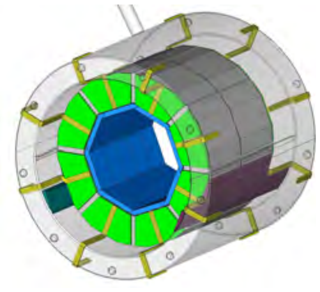


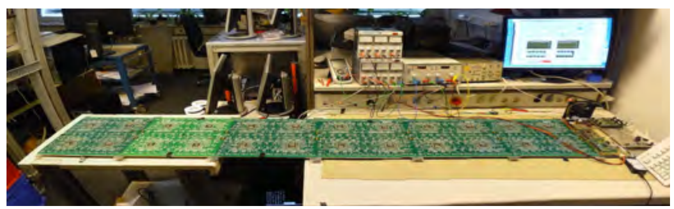


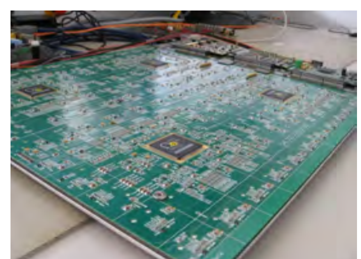
Industrialisation: Numbers!

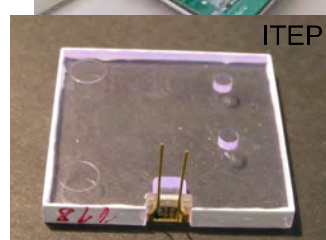
- The AHCAL
- 60 sub-modules
- 3000 layers
- 10,000 slabs
- 60,000 HBUs
- 200’000 ASICs
- 8,000,000 tiles and SiPMs



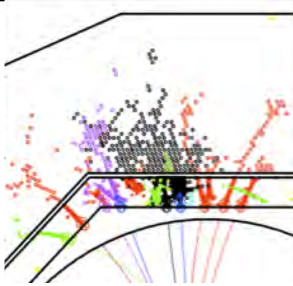






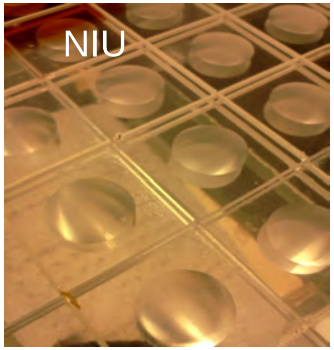


- One year
- 46 weeks
- 230 days
- 2000 hours
- 100,000 minutes
- 7,000,000 seconds

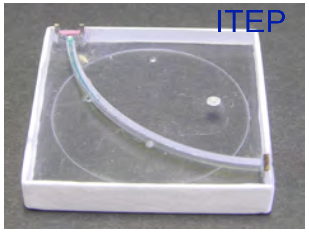


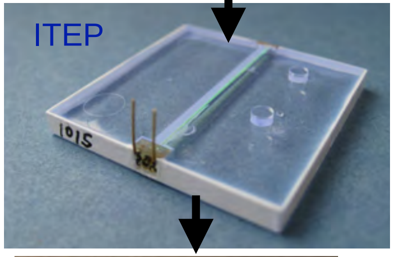
Directions in tile and SiPM R&D

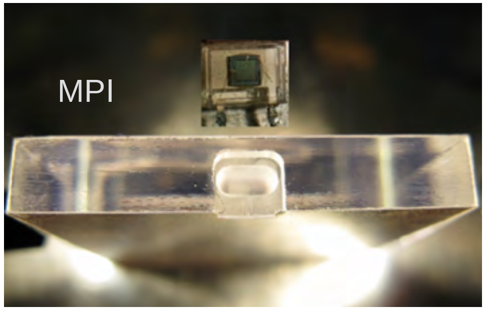
- Revise tile design in view of automatic pick & place procedures
- Consider SMD approach, originally proposed by NIU
- Light yield becomes an issue again
  - build on advances in SiPMs
- Very different assembly, QC and characterisation chain

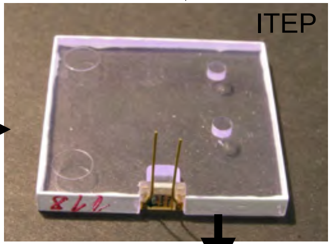


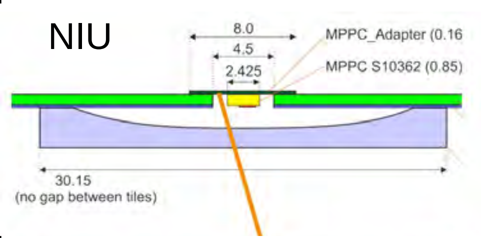
7608 ch physics prototype

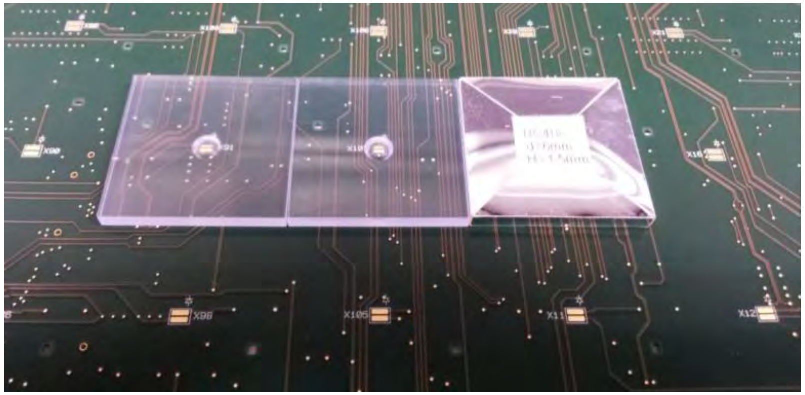


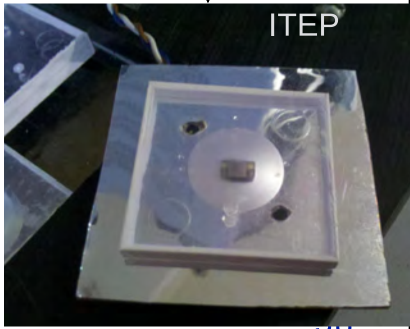


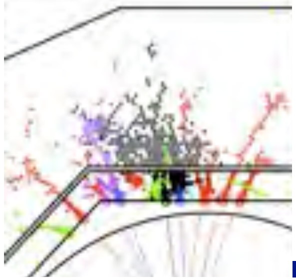






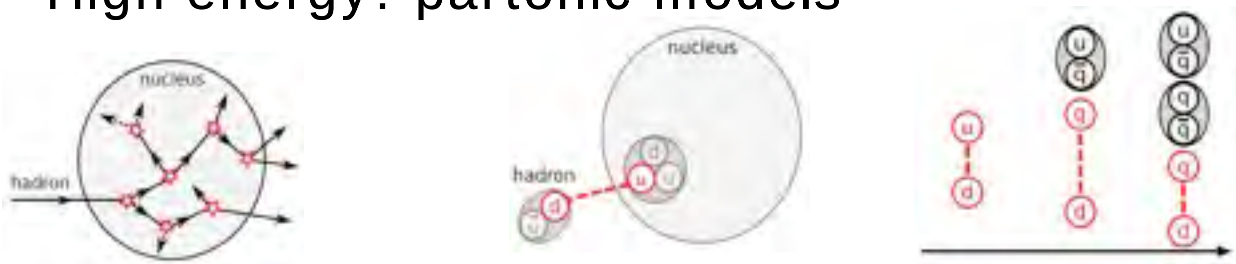




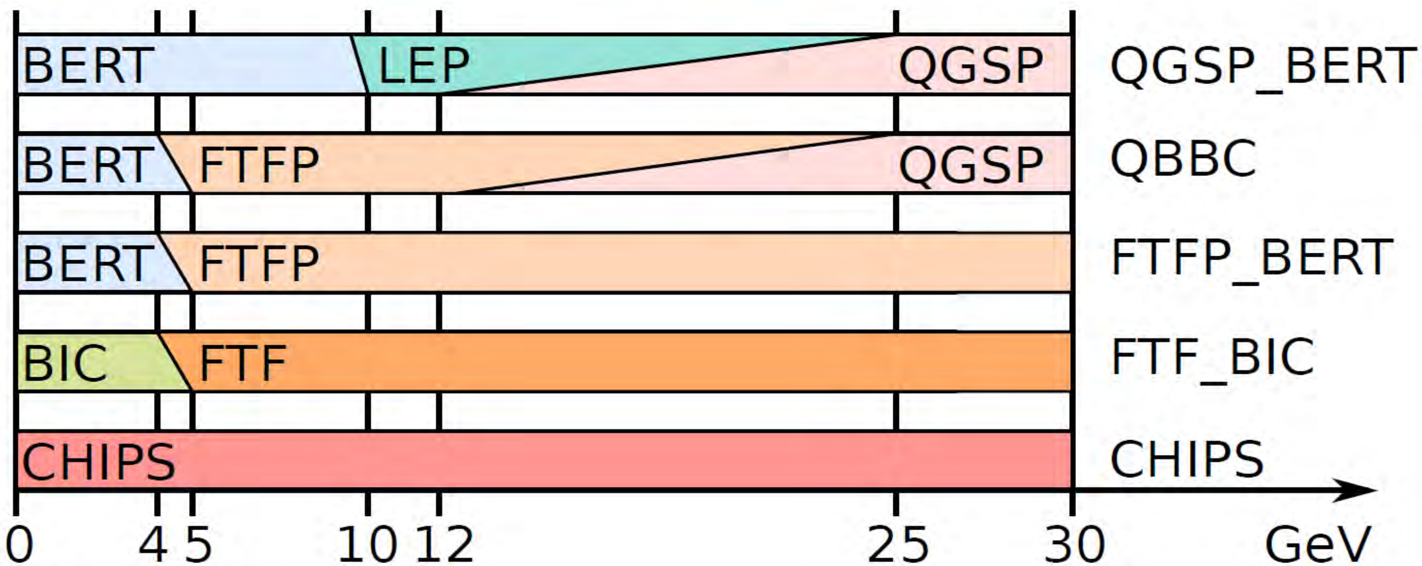


Shower simulation in Geant 4

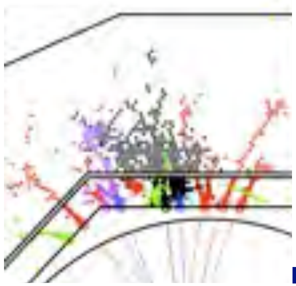
- Low energy: cascade models
- High energy: partonic models



minimize use of phenomenological parameterization

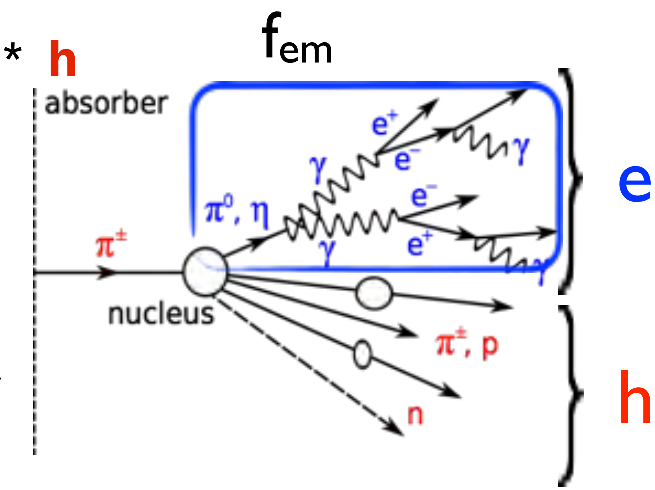


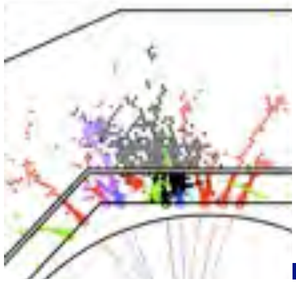
"legacy"
"linear combin."
"production"
"systematics"
"experimental"



Electromagnetic fraction

- π^0 production irreversible; “one way street”
  - $\pi^0 \rightarrow \gamma\gamma$ produce em shower, no further hadronic interaction
  - Remaining hadrons undergo further interactions, more π^0
  - Em fraction increases with energy, $f = 1 - E^{m-1}$
- Response non-linear: signal ~ f * **e** + (1-f) * **h**
- Numerical example for copper
  - 10 GeV: f = 0.38; 9 charged h, 3 π^0
  - 100 GeV: f = 0.59; 58 charged h, 19 π^0
  - Cf em shower: 100’s e^+, 1000’s e^-, millions γ
- Large fluctuations
  - E.g. charge exchange $\pi^- p \rightarrow \pi^0 n$ (prb 1%) gives f_{em} = 100%

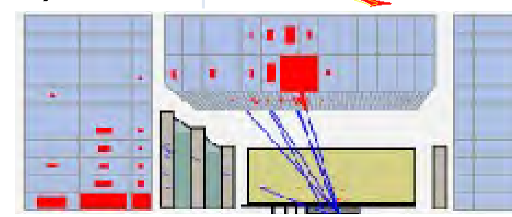




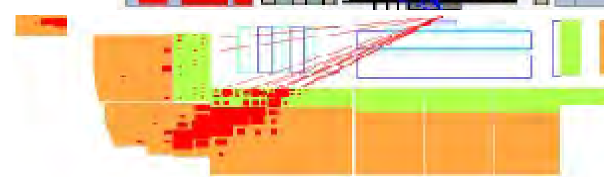
Compensation

Different strategies, which can also be combined

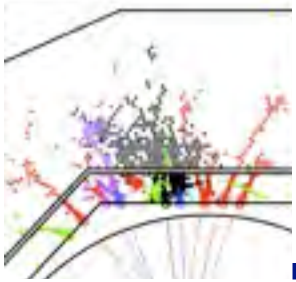
- Hardware compensation
  - Reduce em response
    - High Z, soft photons
  - Increase had response
    - Neutron part (correlated with binding energy loss)
      - Tunable via thickness of hydrogenous detector
  - Example ZEUS: uranium scintillator,
  - 35% /√E for hadrons, 45% /√E for jets



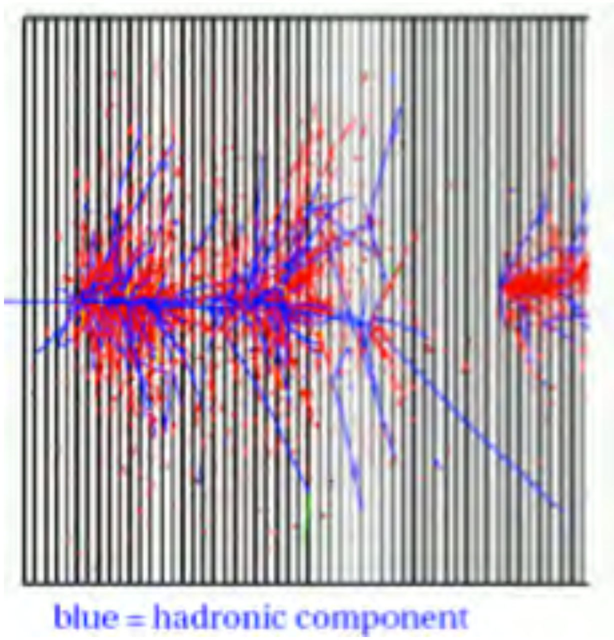
- Software compensation
  - Identify em hot spots and down-weight
    - Requires high 3D segmentation
  - Example H1, Pb/Fe LAr, ~ 50% /√E for hadrons

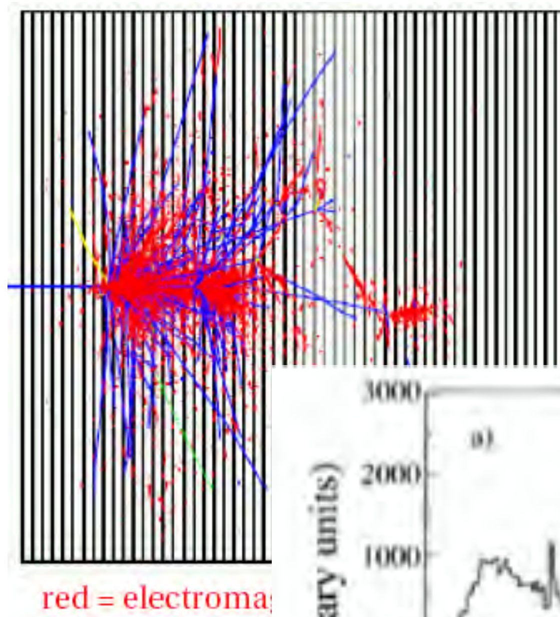


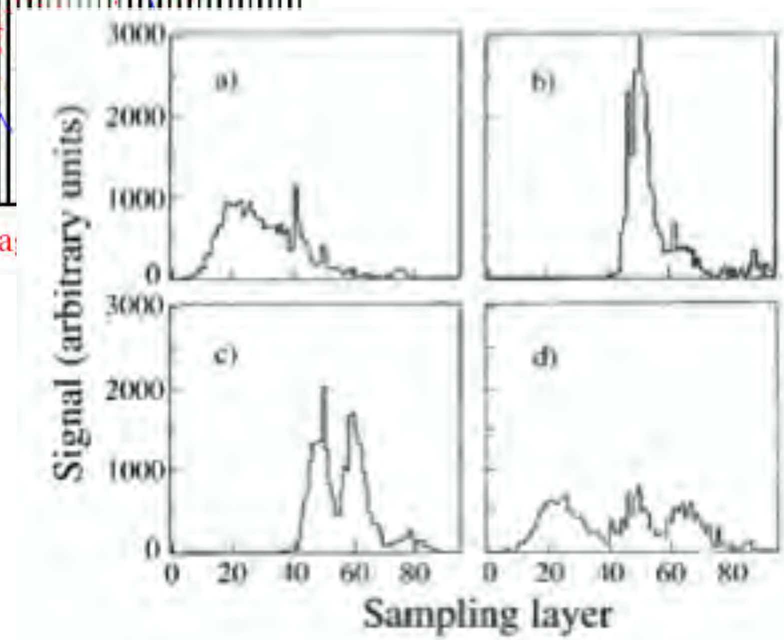
NB: Does not remove fluctuations in invisible energy



More fluctuations: leakage

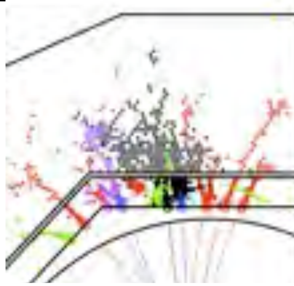






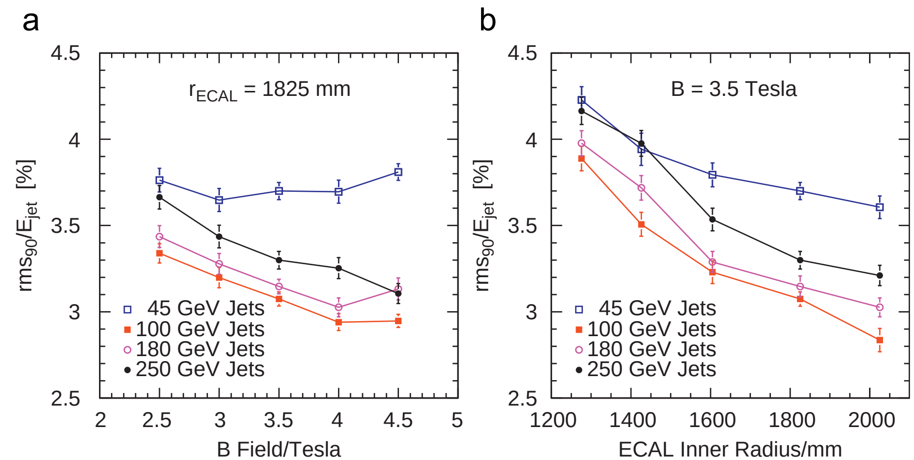
Leakage: in principle no problem
But: leakage fluctuations are!
(rule of thumb: σ_{leak} ~ 4 f_{leak})

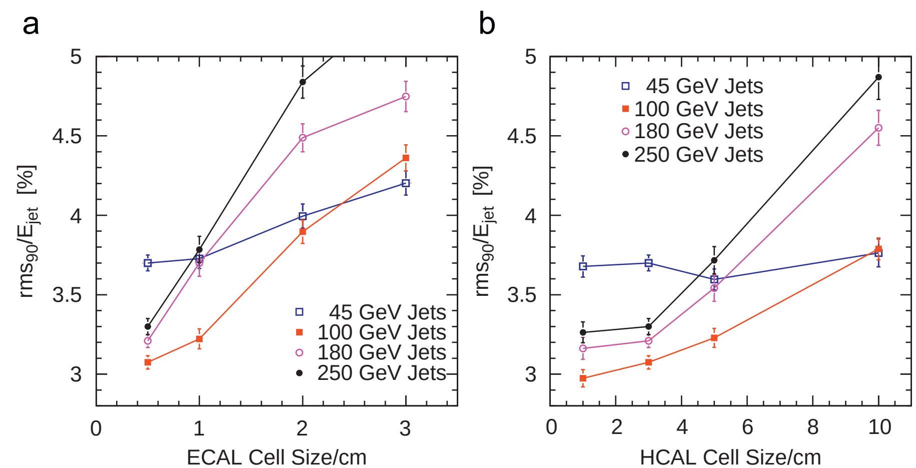
sampling fluctuations



Granularity optimisation

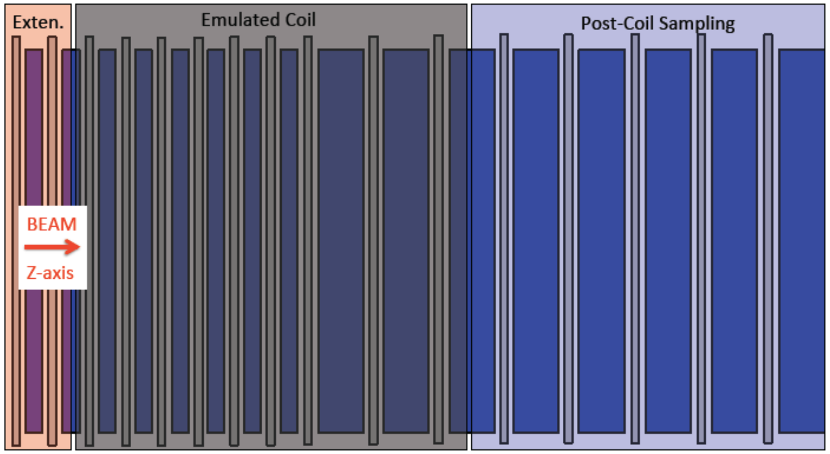
- Based of Pandora PFA
- Large radius and B field drive the cost
- Both ECAL and HCAL segmentation of the order of X_0
  - longitudinal: resolution
  - transverse: separation
- Cost optimisation to be done





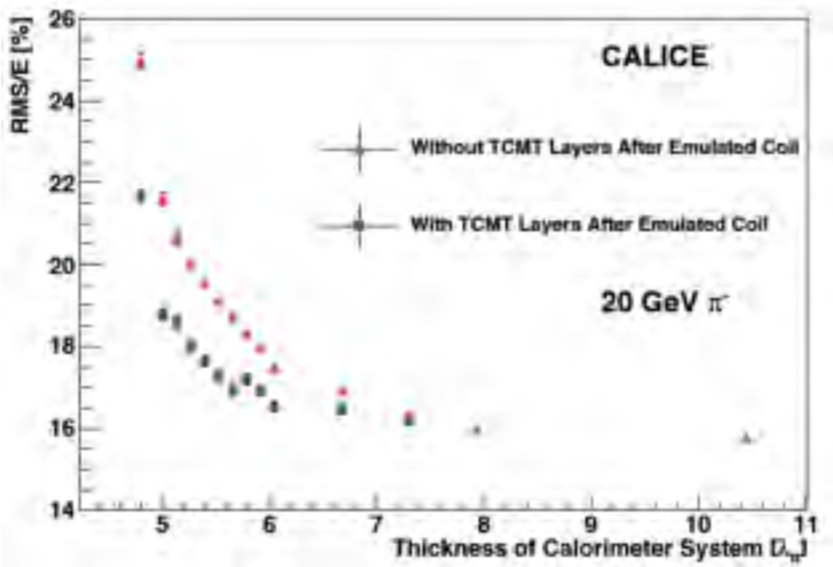
Containment – use of Tail Catcher

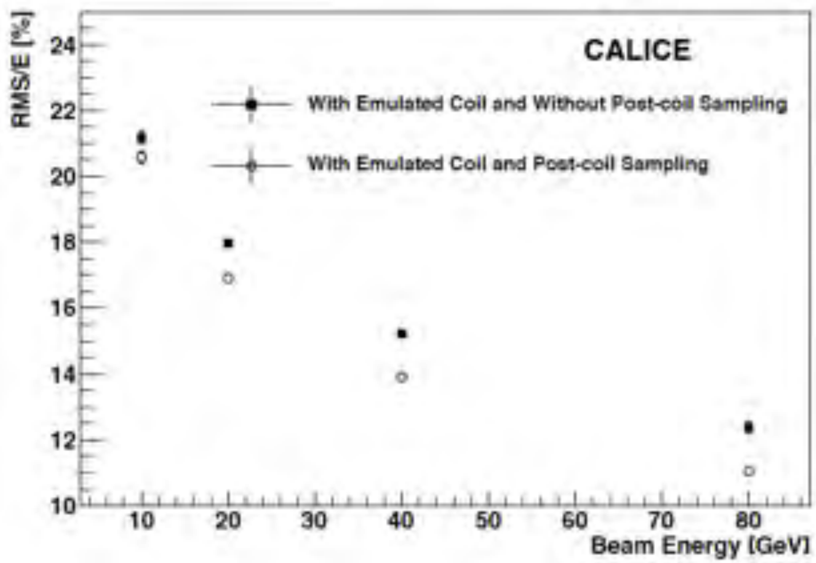
- Tail catcher gives us information about tails of hadronic showers.
- Use ECAL+HCAL+TCMT to emulate the effect of coil by omitting layers in software, assuming shower after coil can be sampled.
- Significant improvement in resolution, especially at higher energies.



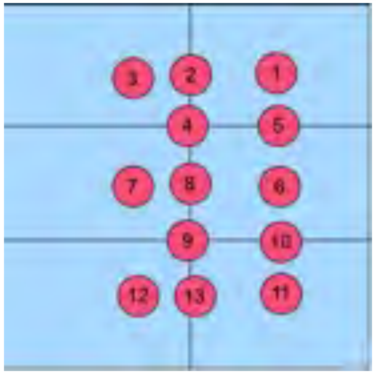
2012_JINST_7_P04015

arxiv:1201.1653 (accepted by JINST)

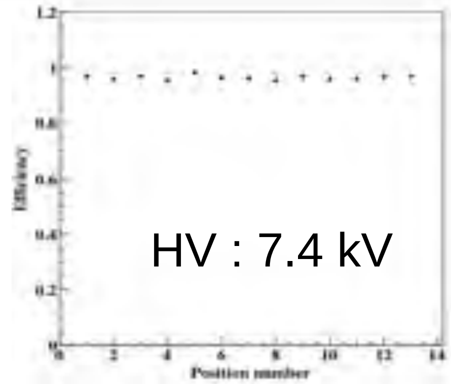




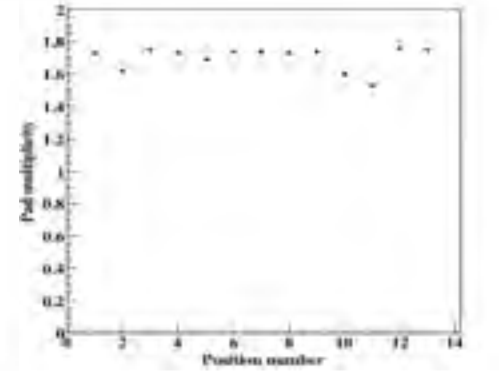
The homogeneity of the detector and its readout electronics were studied



Beam spot position



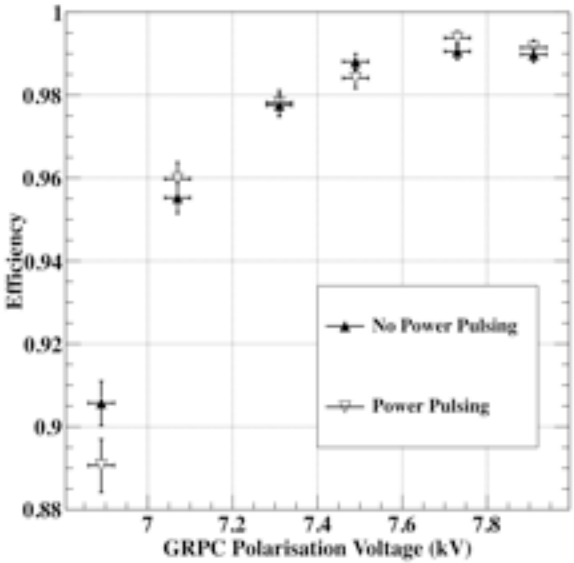
Efficiency

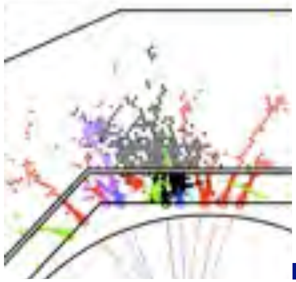


Multiplicity

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

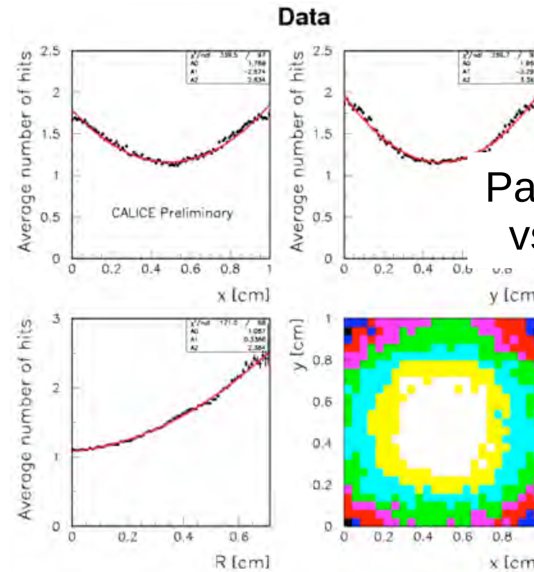
The Power-Pulsing mode was applied on a GRPC in a 3 Tesla field at H2-CERN (2ms every 10ms)
No effect on the detector performance



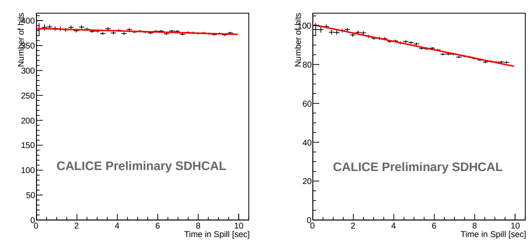


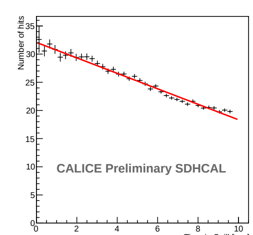
Calibration and simulation

- Main difficulty is that the DHCAL is not digital
- Response in number of hits depends on gas gain and thus on many factors
  - T, p, thickness, purity, rate, local occupancy
  - calibration & monitoring not simple
- May be mitigated for other technologies with <m> ~ 1.0
  - µM, GEM, 1-glass RPC - to be seen
- Semi-digital readout helps
  - but environmental dependence aggravated for higher thresholds
- For the use of analoge information the (semi-) digital read-out lacks redundancy for calibration & monitoring
  - concepts to be developed
- Simulation non-trivial either
  - dense environments, shielding effects,...



Pad multiplicity vs µ position





SDHCAL response for 3 thresholds vs time in spill (space charge reduces gain)