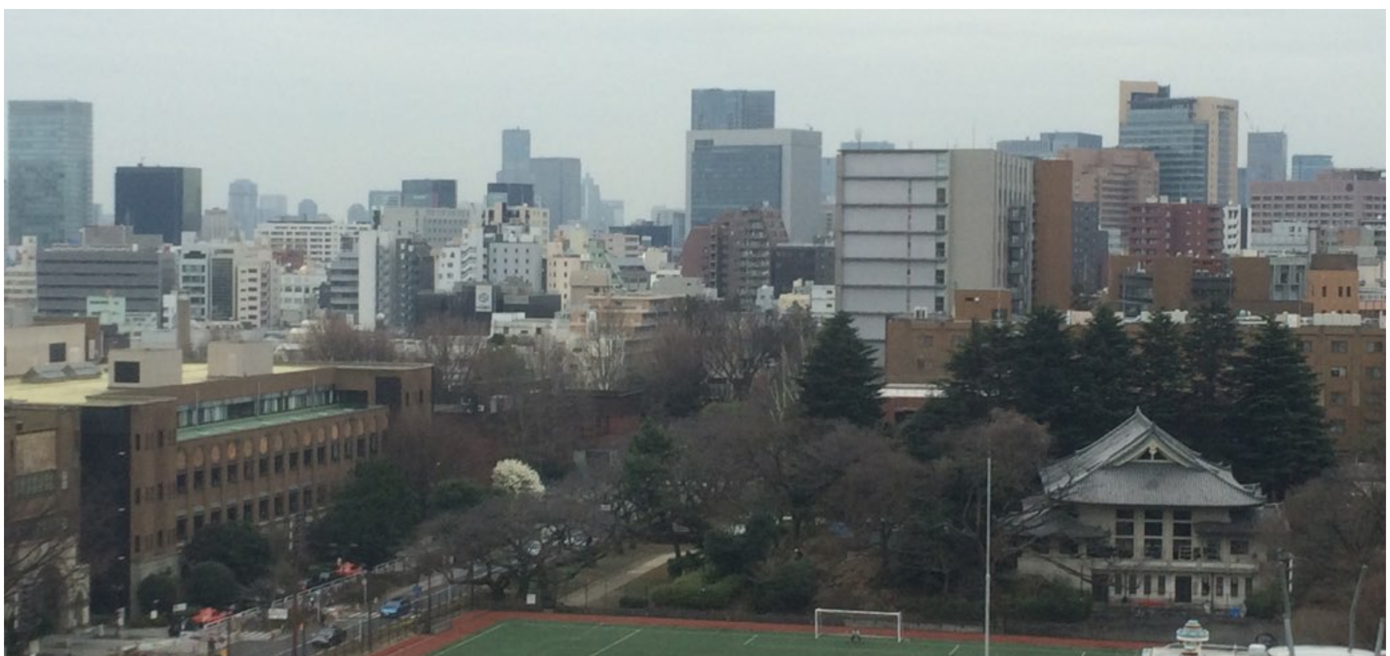
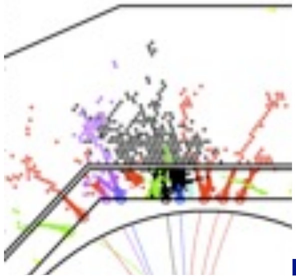
Imaging calorimeters for precision physics at the ILC

Felix Sefkow

LINEAR COLLIDER COLLABORATION
Designing the world's next great particle accelerator

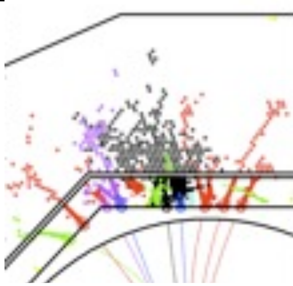
Seminar at ICEPP, University of Tokyo, March 11, 2016





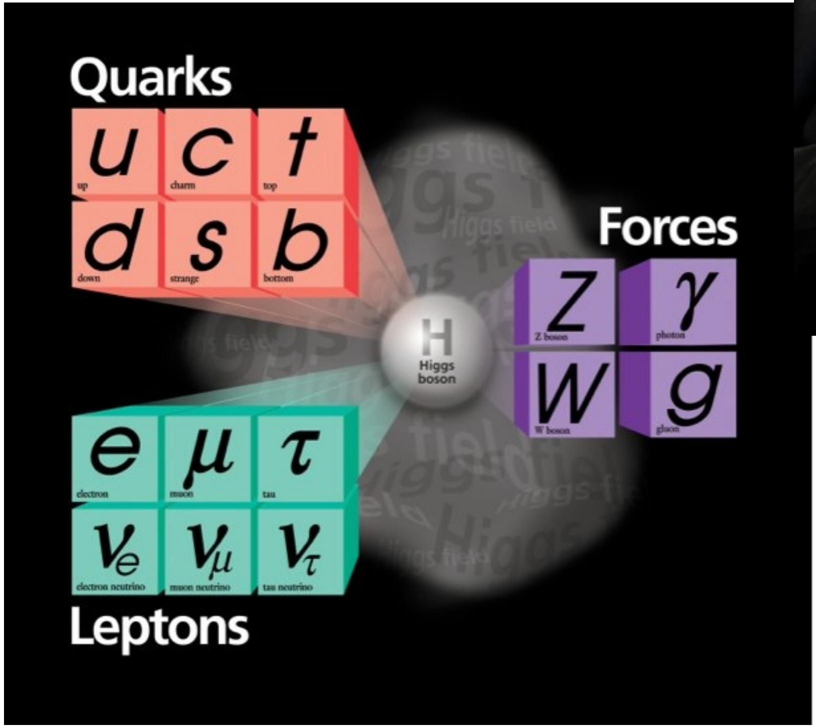
Program

- Linear Collider physics with jets
- Particle flow calorimetry
- Test beam experiments
- Energy resolution and imaging

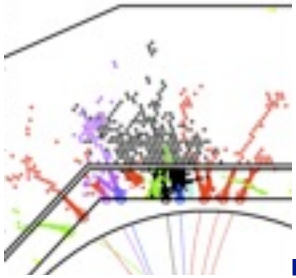


Higgs discovery

2013 Nobel prize in physics

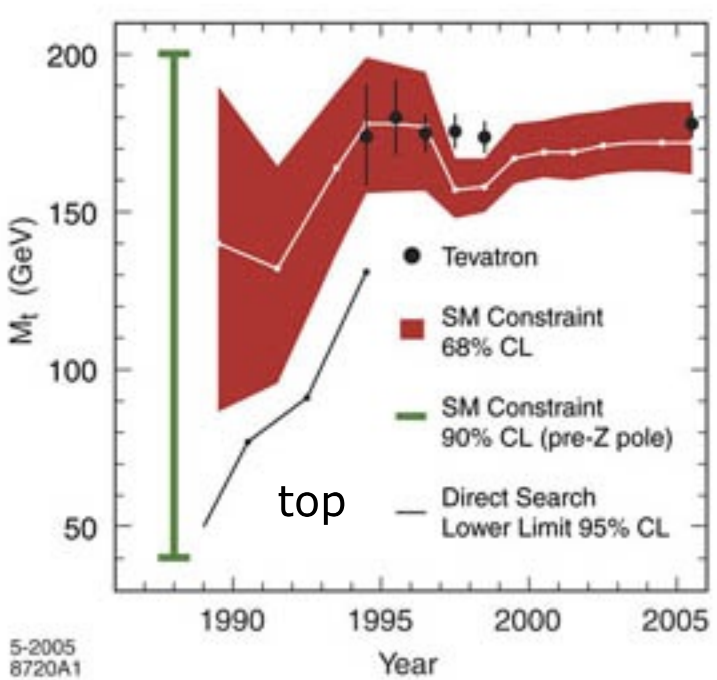


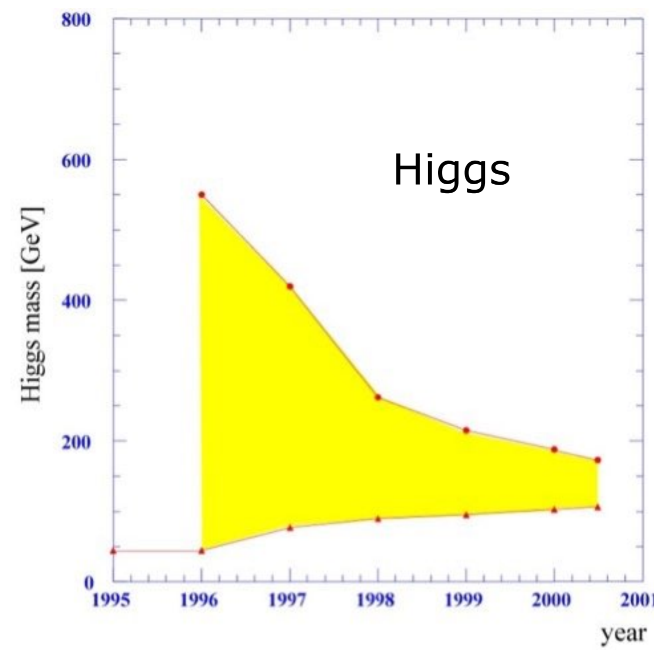
- A turning point:
- after 50 years the last building block falls into place
- and opens the door to something completely new



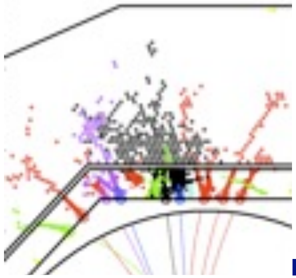
Anticipated discoveries

- The history of particle physics is full of predicted discoveries:
  - Positron, neutrino, pion, quarks, gluons, W, Z bosons, charm, bottom, top - and now Higgs
- Precision directs the way forward





From precision tests of electroweak quantum corrections



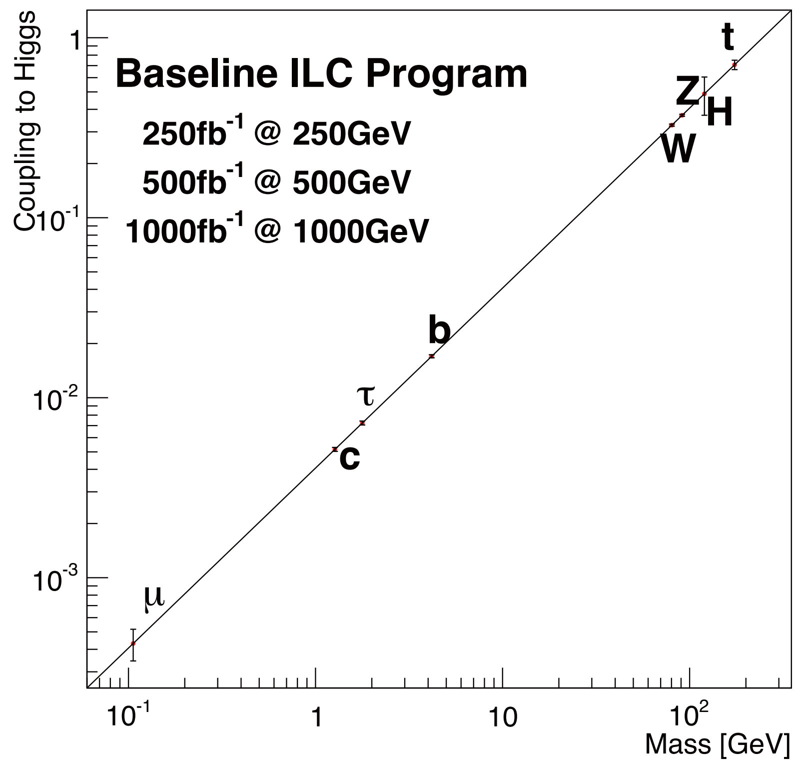
Higgs physics drives the field

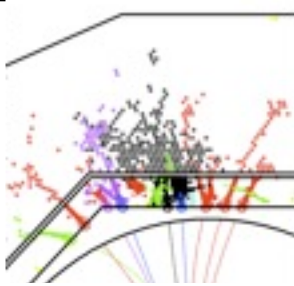
"Driver" = a compelling line of inquiry that shows great promise for major progress over the next 10-20 years. Each has the potential to be transformative. Expect surprises.

- Use the Higgs as a new tool for discovery.

S.Ritz, Report on P5

- The main question today:
- establish the Higgs profile
  - mass, spin, parity
  - above all: couplings
- Is the Higgs(125) *the* Higgs and does it fulfil its role in the Standard Model?
- Or does it hold the key to New Physics?



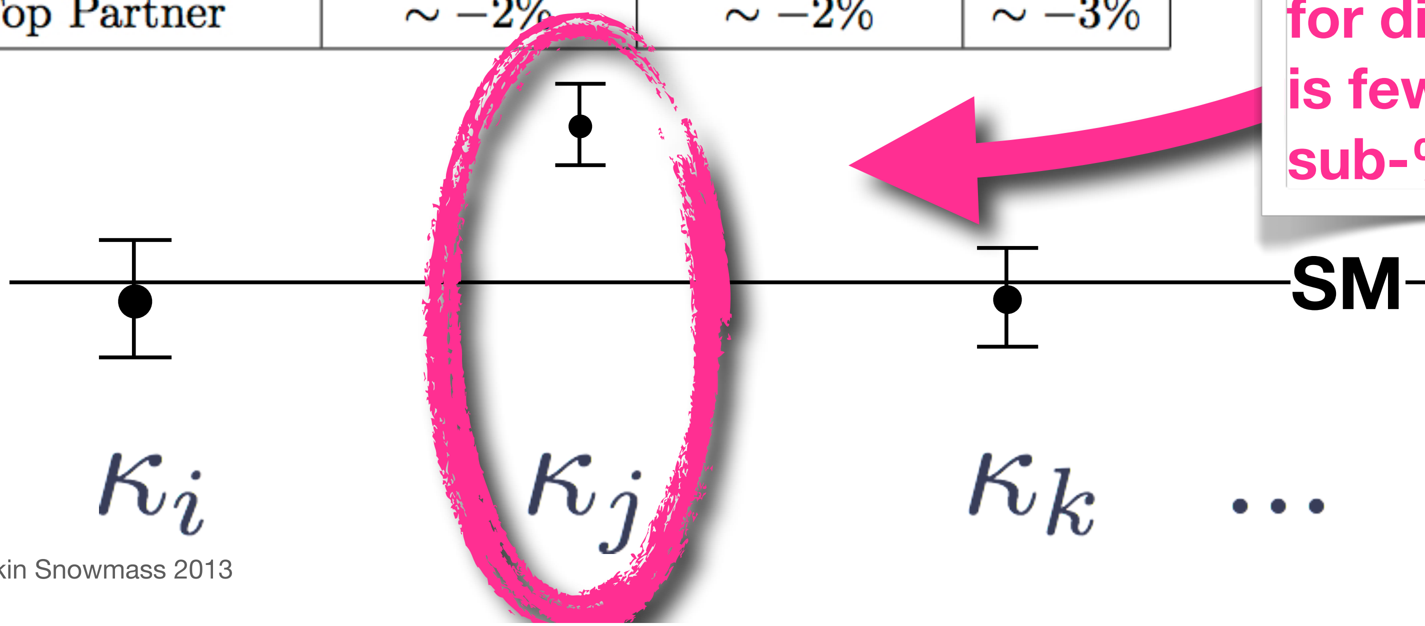


Precision for discovery

Models which are not ruled out by LHC results

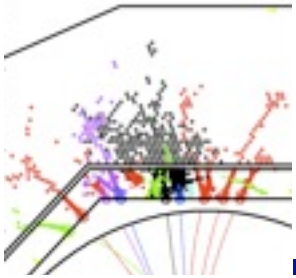
	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Benchmark for discovery is few % to sub-%



Brock/Peskin Snowmass 2013

83

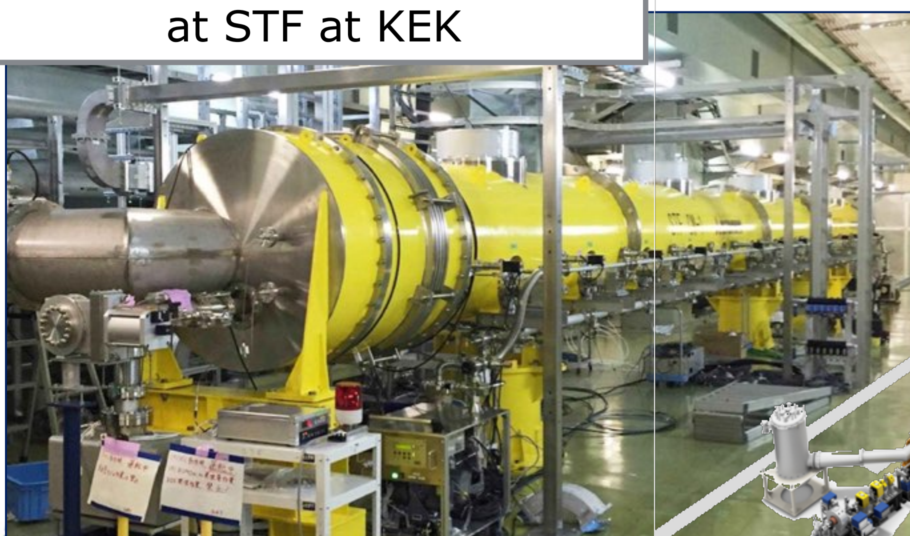


International Linear Collider

- e+e- collisions
  - E_{CM} = 250-1000 GeV
- Superconducting technology
  - Technical design 2012
  - studied at government level in Japan

European XFEL at DESY:
> 60% of modules installed

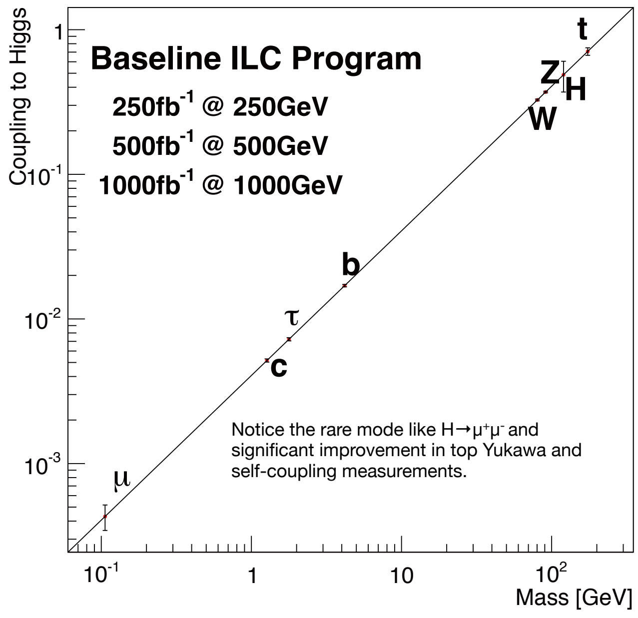
ILC cavities and cry-modules at STF at KEK

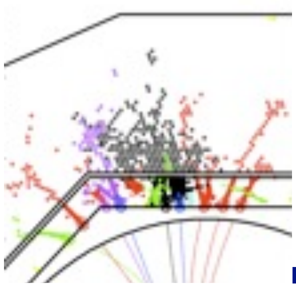


STF Beam line at KEK
to be installed in JFY2016

Waiting for Green Light in Japan

Measurements of Higgs couplings





How to measure a coupling

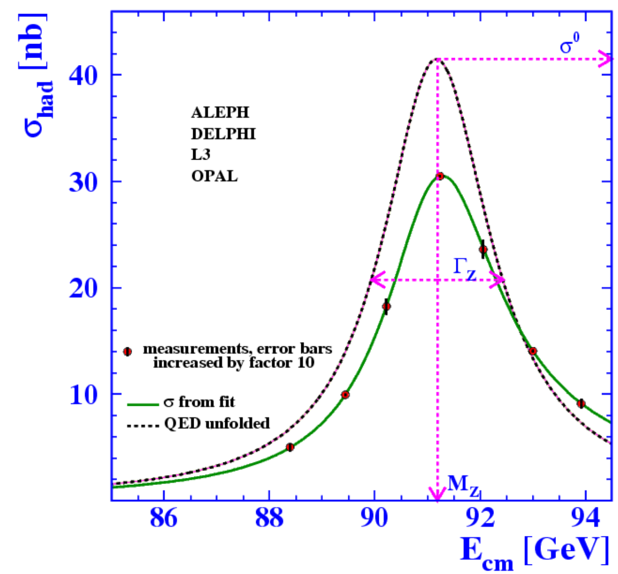
- We perform counting experiments:
- N events / integr. luminosity = cross section x branching ratio
- Branching ratio := partial width / total width

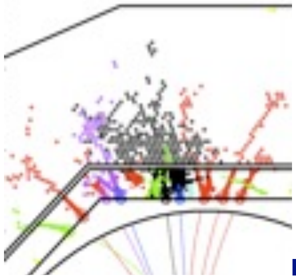
- **$\sigma \cdot BR = \sigma_i \cdot \Gamma_f / \Gamma_T \sim g_i^2\ g_f^2 / \Gamma_T$**

- Need σ and total width to convert branching ratios into couplings
  - e.g. Z line shape at LEP
- Γ_T (Higgs)$_{SM}$ = 4 MeV - unobservable

- At LHC, only poorly constraint
  - or SM value assumed

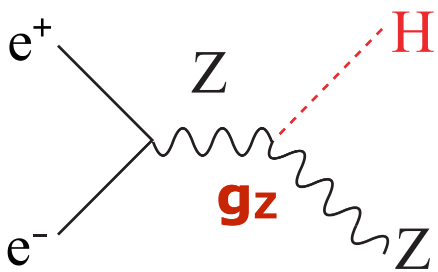
- At ILC, play the cards of e+e-…



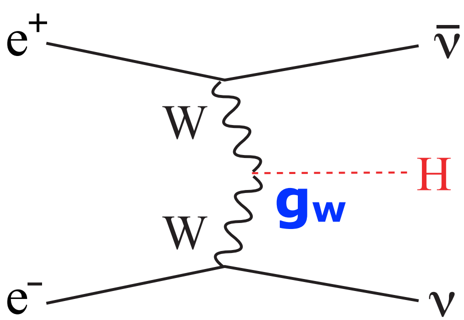


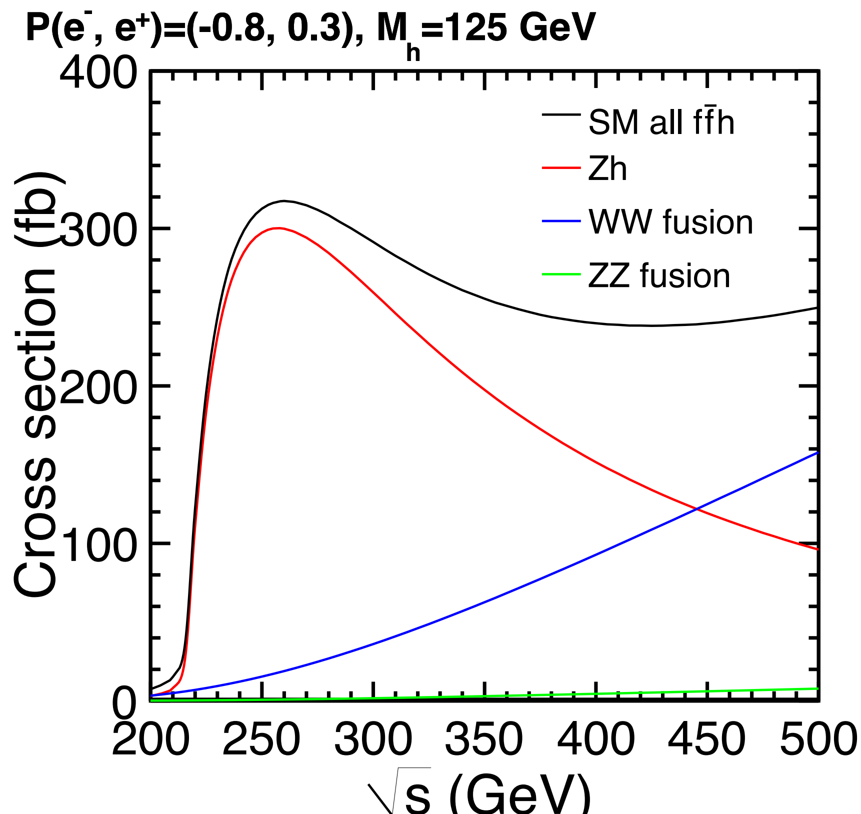
Higgs production

- Higgs strahlung

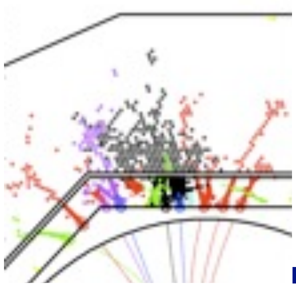


- W fusion



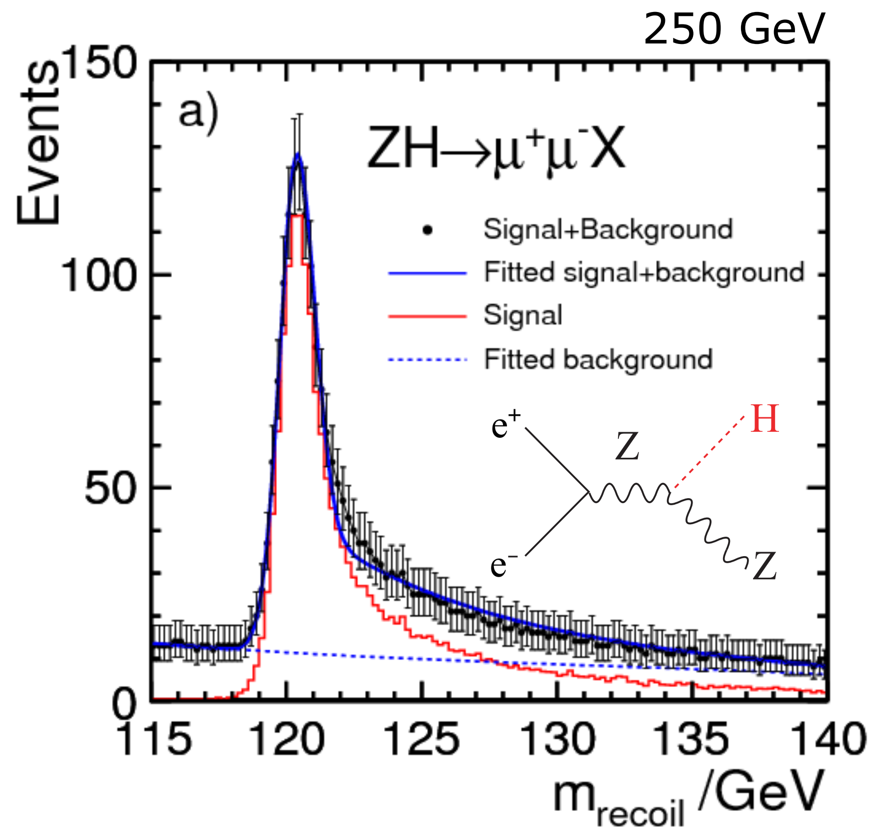


- Use polarisation to enhance cross section
- Vary beam energy to select W or Z coupling

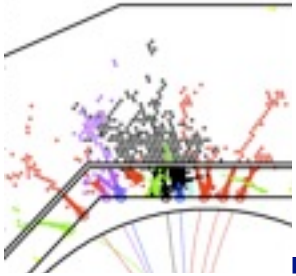


Higgs signal in Z recoil

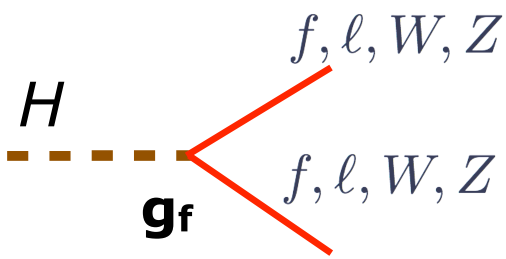
- In e+e-, use kinematic constraints
- recoil mass against Z
  - $M^2 = E^2 - p^2$
  - beam energy: $E = \sqrt{s} - E_Z$, $p = p_Z$
  - Z mass: $E_Z^2 = M_Z^2 + p_Z^2$
- No use of Higgs final state, can even be invisible
- **Model-independent** ZH cross section
- Absolute normalisation for BRs
  - sensitive to invisible decays
- **Direct extraction of g_Z**
  - *the* central measurement



works best with muons, also well with electrons
with jets: not so easy - but possible



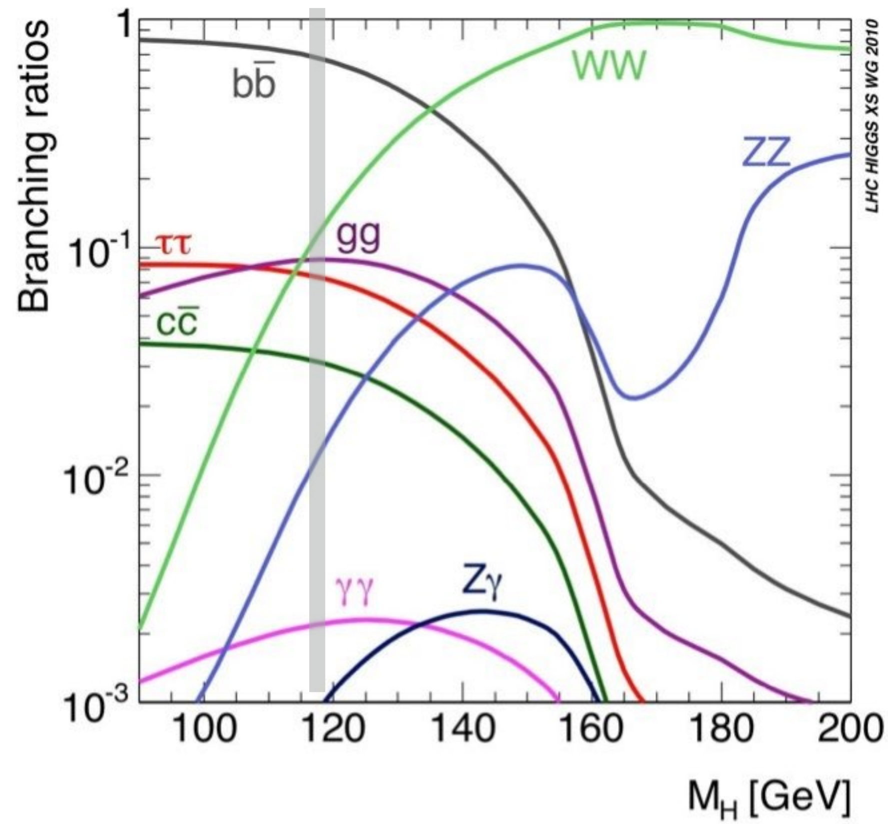
Higgs decays

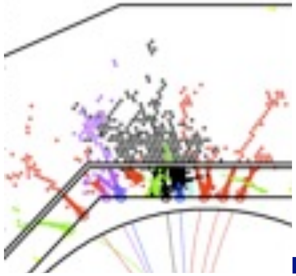


- M_H = 125 GeV
- ideal for ILC
  - but not for H → ZZ*

- BR (H→ZZ*) = $\Gamma_Z / \Gamma_T \sim g_Z^2 / \Gamma_T$
- $\Rightarrow \Gamma_T \sim g_Z^2 /$ BR (H→ZZ*)

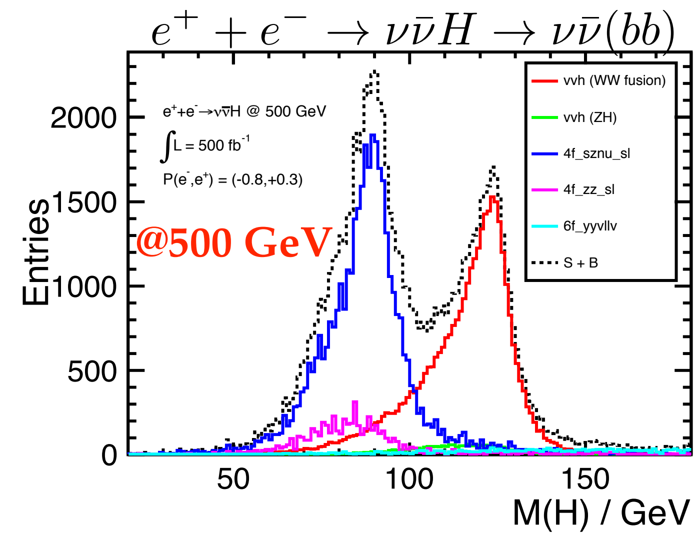
- in principle possible - but large error (20%)

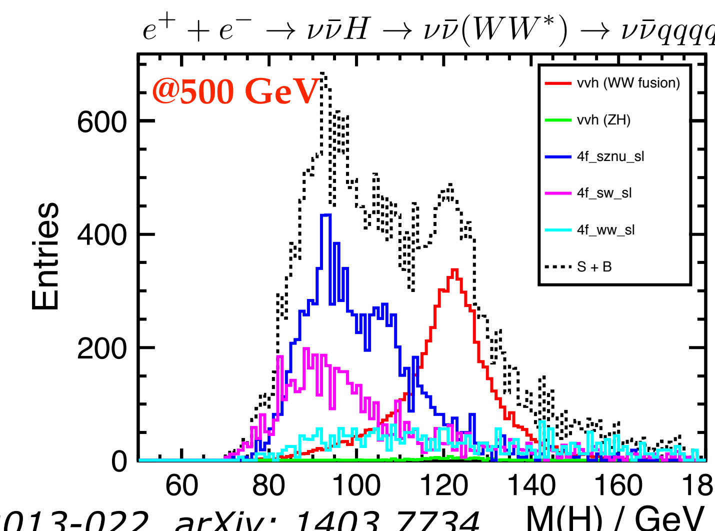




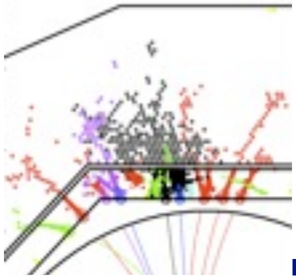
Higgs total width

- Use **W fusion cross section** and H→WW* branching ratio
- $\Gamma_T \sim g_W^2$ / BR (H→WW*)
- W fusion σ is not model independent
  - ff = bb or WW* final state
  - measure same f.s. in ZH and scale
- $g_W^2/g_Z^2 \sim \sigma_{\nu\nu H}$ B(H→ff) / σ_{ZH} B(H→ff)
- g_Z^2 from Z recoil
- BR (H→WW*) in vvH or ZH prod
- Done! 👍
  - self-contained set for absolute couplings
  - constraints on invisible decays





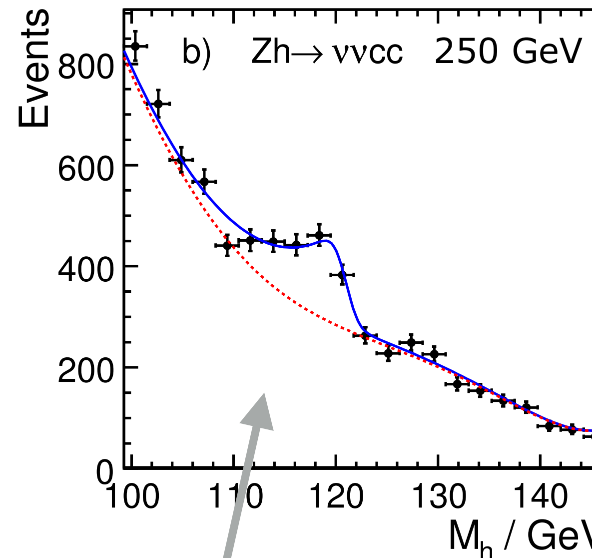
C. Duerig, J. Tian, et al. LC-REP-2013-022, arXiv: 1403.7734

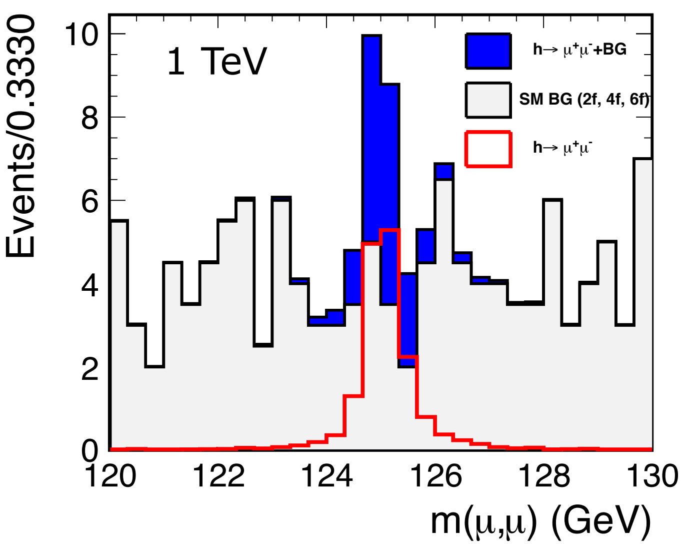


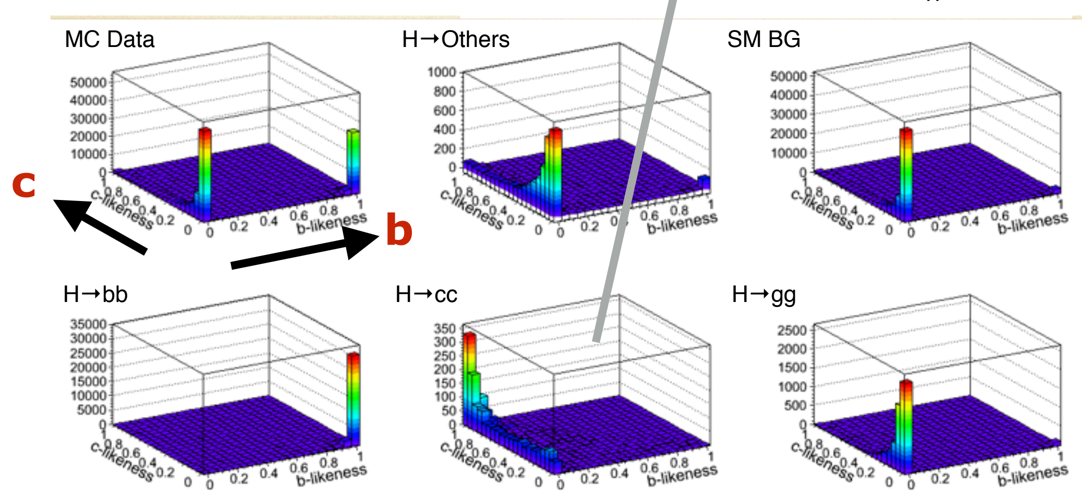
2nd generation fermion couplings

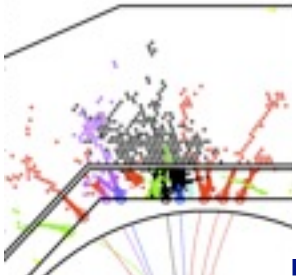
- Charm tagging at LHC: hopeless
  - constrain g_c by m_c / m_t
- At ILC: unique access to 2nd family
  - obtain bb and gg, too

- H→μμ: also possible, but few events

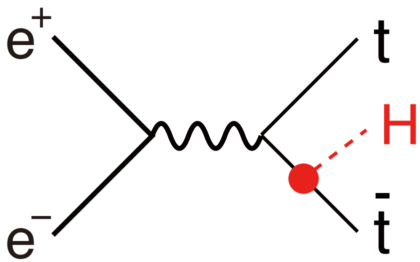


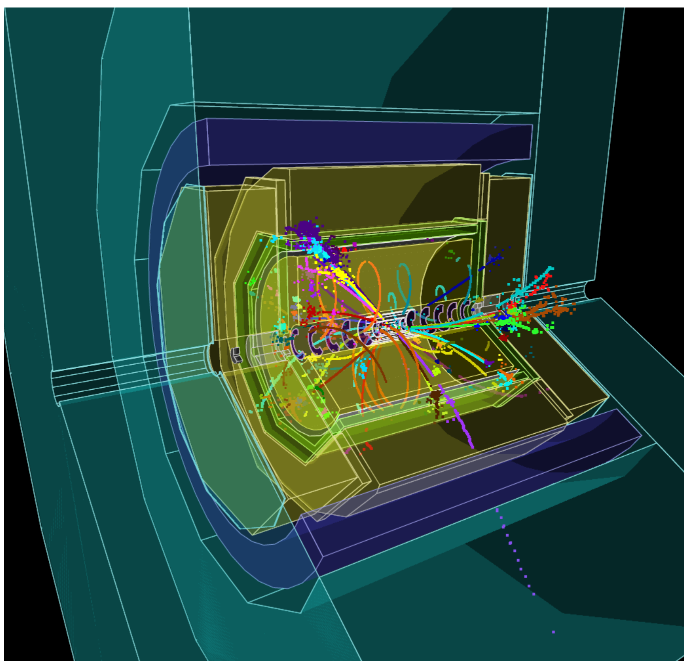


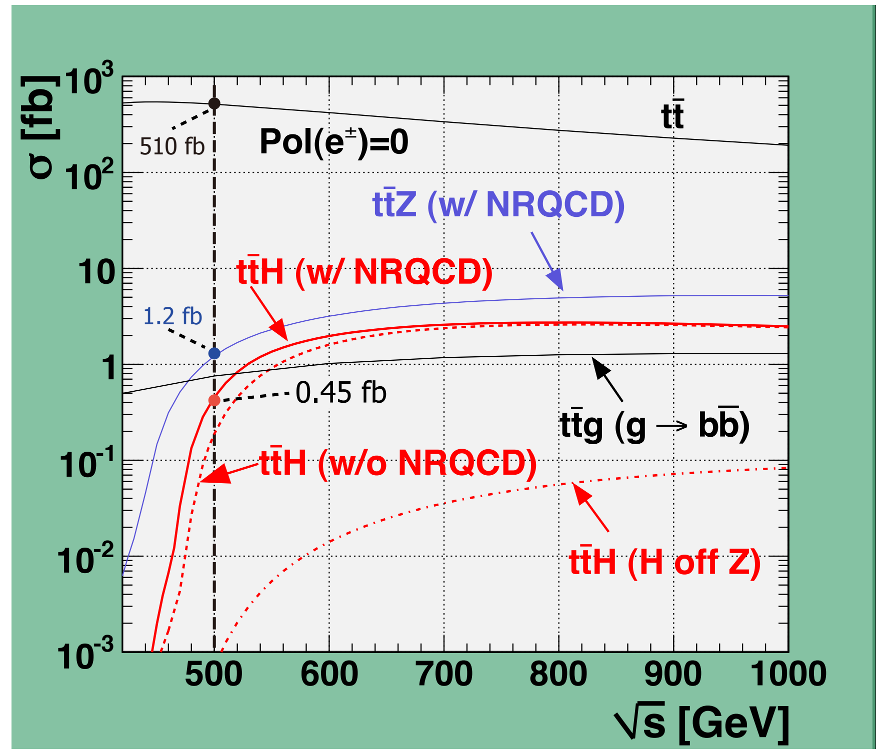




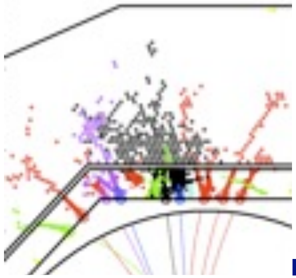
Top Yukawa coupling



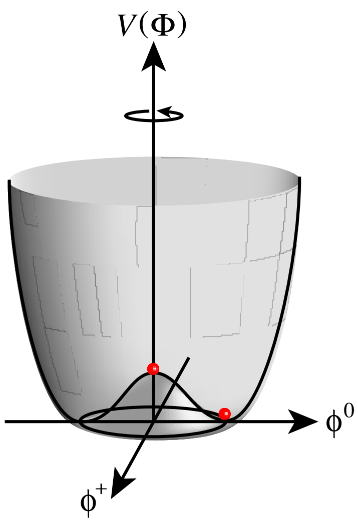


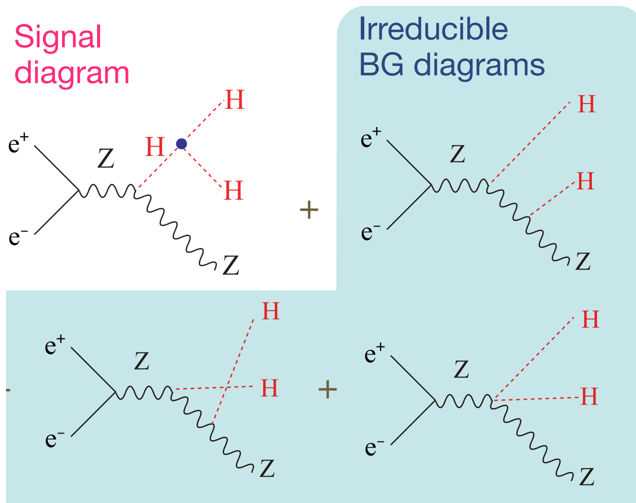


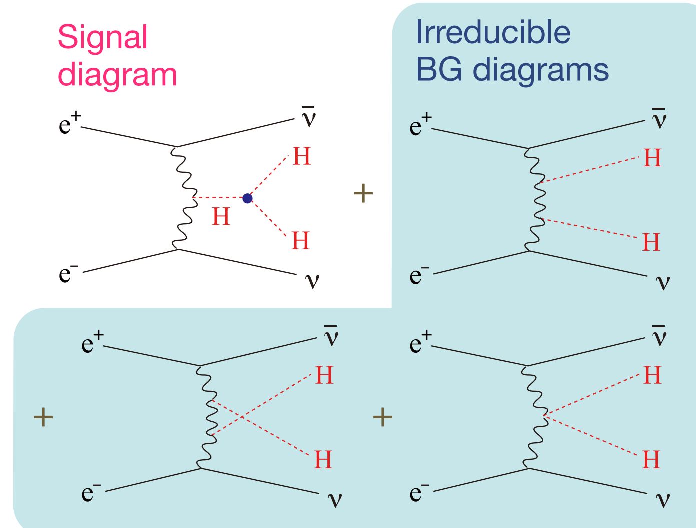
- Counting experiment, multi-jet final states
- 4% measurement of g_{ttH} possible
- sizeable QCD corrections
- a few more GeV beam energy most valuable



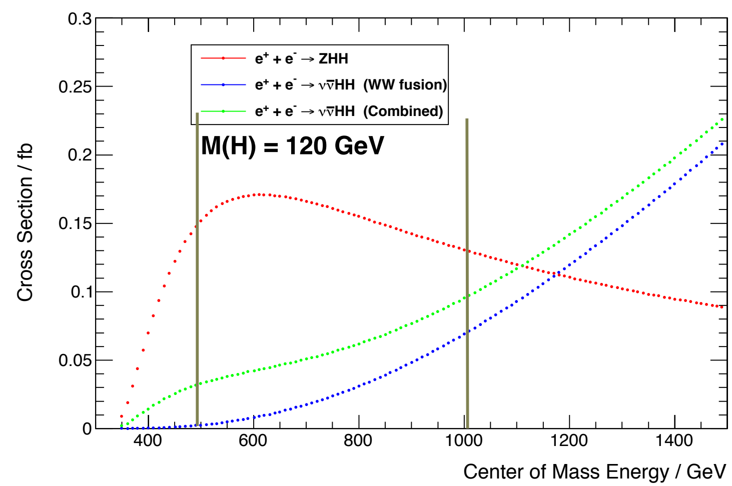
Top Yukawa and H self coupling

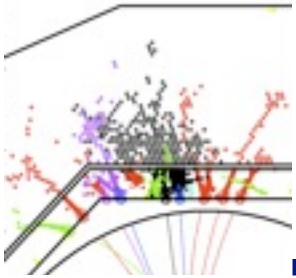






- difficult even at ILC
- $\delta\lambda/\lambda > 0.5\ \delta\sigma/\sigma$
- W fusion offers better sensitivity
- possible at 500 GeV, best at 1 TeV





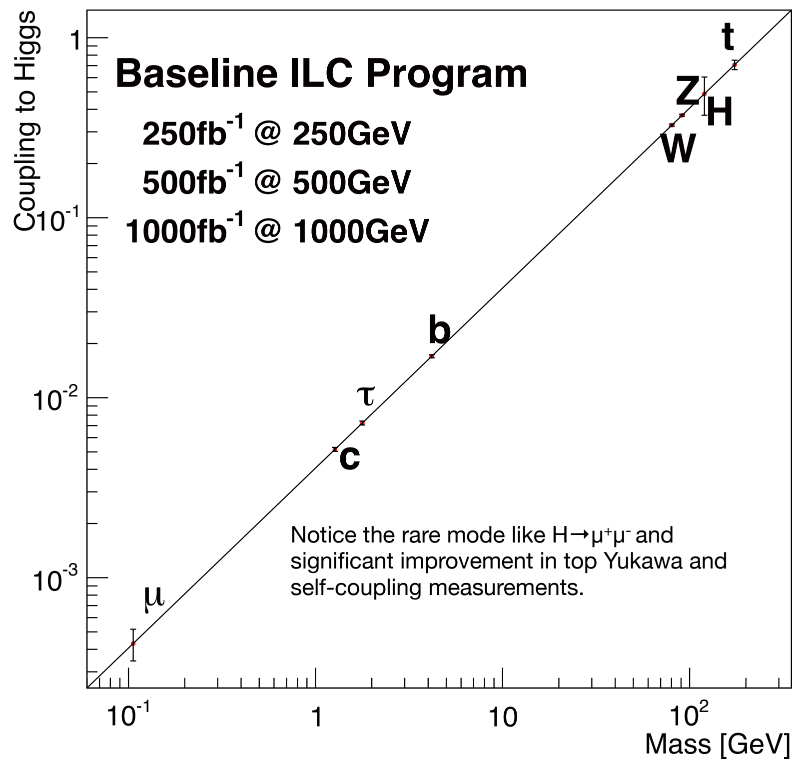
Global fits

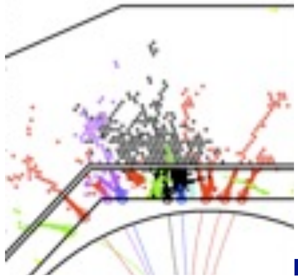
- Staged running scenario 250, 500, 1000 GeV
- 33 σ·BR measurements - 10 free parameters

$$g_{HZZ},\ g_{HWW},\ g_{Hbb},\ g_{Hcc},\ g_{Hgg},\ g_{H\tau\tau},\ g_{H\gamma\gamma},\ g_{H\mu\mu},\ g_{Htt},\ \Gamma_0$$

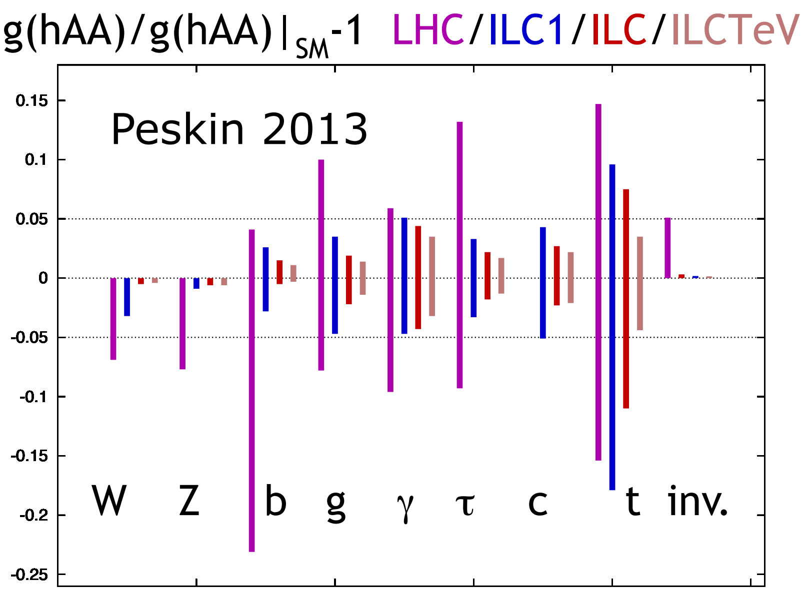
coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	1.3%	1%	1%
HWW	4.8%	1.1%	1.1%
Hbb	5.3%	1.6%	1.3%
Hcc	6.8%	2.8%	1.8%
Hgg	6.4%	2.3%	1.6%
Hττ	5.7%	2.3%	1.6%
Hγγ	18%	8.4%	4%
Hμμ	91%	91%	16%
Γ	12%	4.9%	4.5%
Htt	-	14%	3.1%
HHH	-	83%(*)	21%(*)

K.Fujii, LC School, Aug. 13, 2014

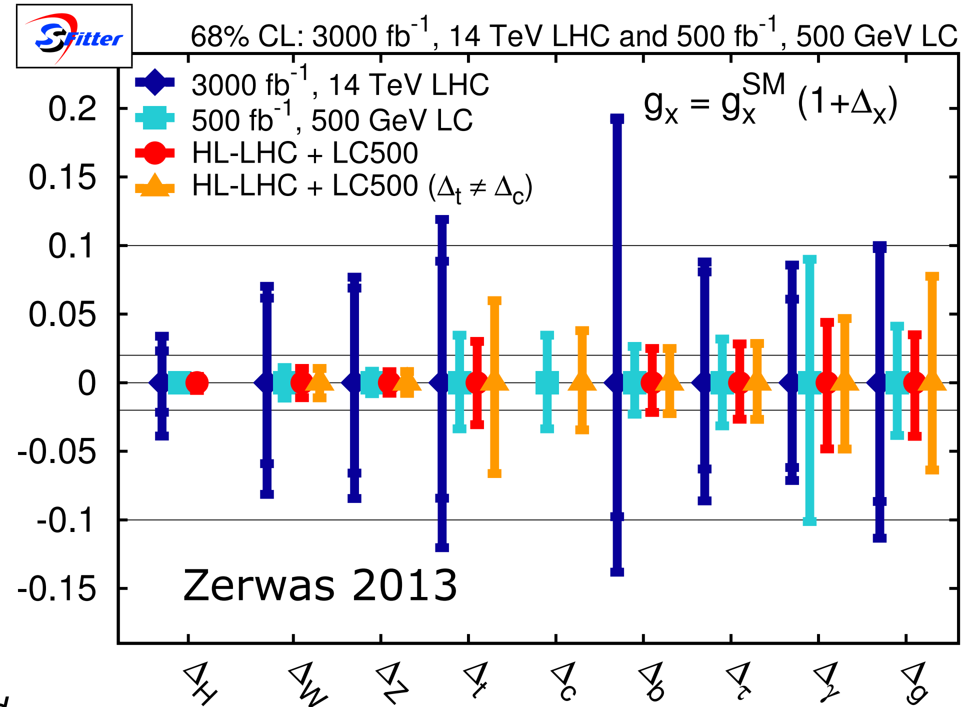




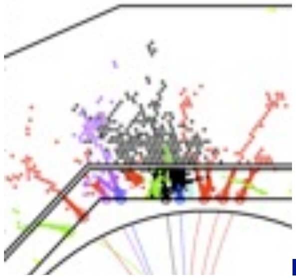
ILC and LHC



LHC 300 fb^{-1} @ 14 TeV
ILC1 250 fb^{-1} @ 250 GeV
ILC 500 fb^{-1} @ 500 GeV
ILC1T 1000 fb^{-1} @ 1 TeV *successively included*

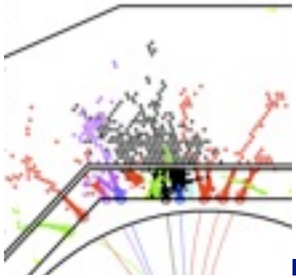


- Only with e+e- collisions one can reach the percent level precision to probe new physics
- also true w.r.t. high lumi LHC



Higgs at the ILC:

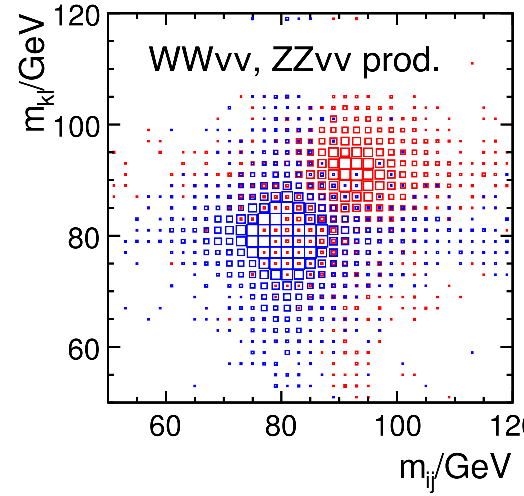
- The Higgs discovery opens the door to a completely new kind of matter and a completely new phenomenology
- An e+e- machine provides the clean conditions and a self-contained set of Higgs observables
- Only a linear collider can reach the precision at percent level to detect deviations which can direct us to new physics
- There is so much more
  - direct discoveries, top physics, ..

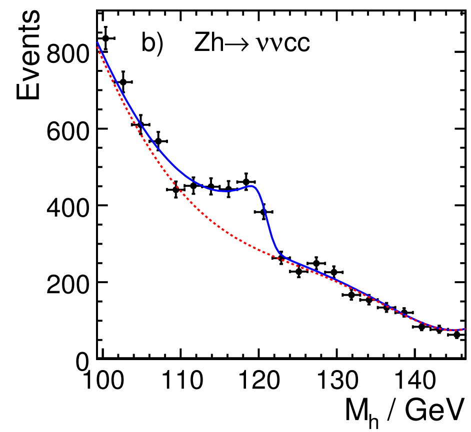


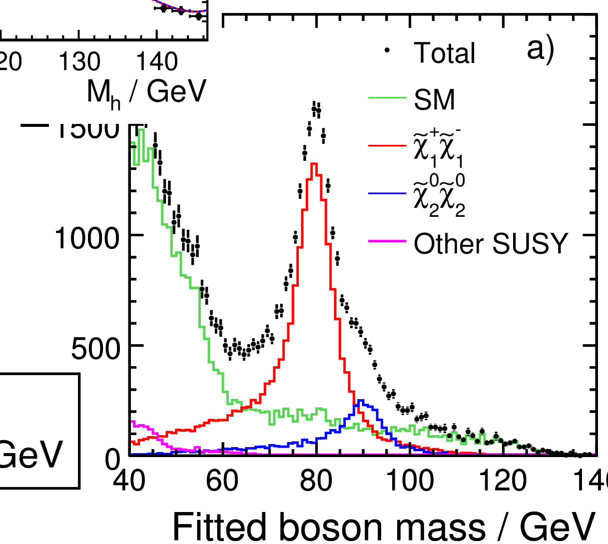
LC physics with jets: M_{inv}

- W - Z separation
  - study strong e.w. symmetry breaking at 1 TeV
- Other di-jet mass examples
  - H → cc, Z → νν
  - Higgs recoil with Z → qq
  - invisible Higgs
  - WW fusion → H → WW
    - total width and g_{HWW}
- SUSY example:
  - Chargino neutralino separation

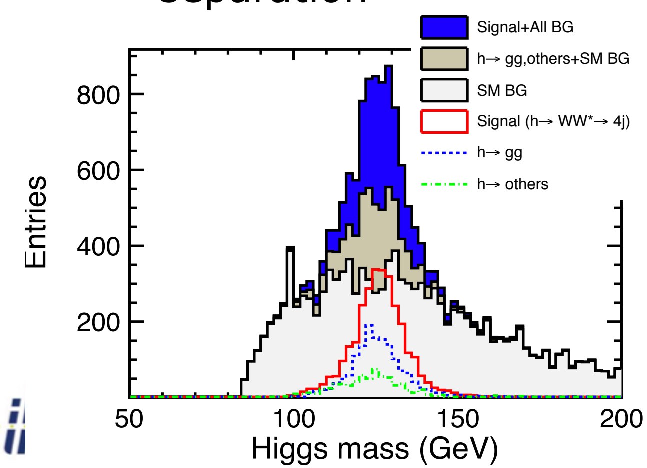
typical jet energies
at √s = 500 GeV
50-150 GeV



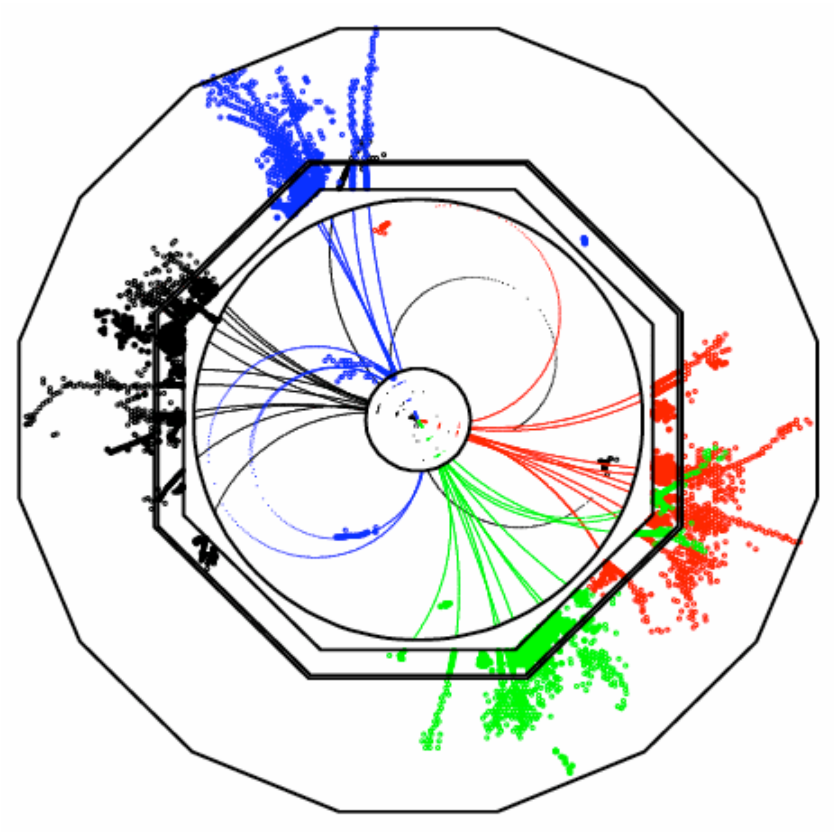


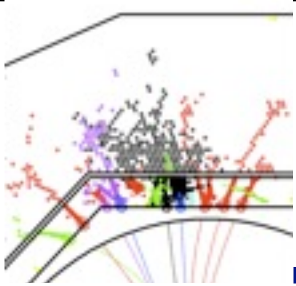


√s = 500 GeV
E_{jet} peak s @ 35 GeV



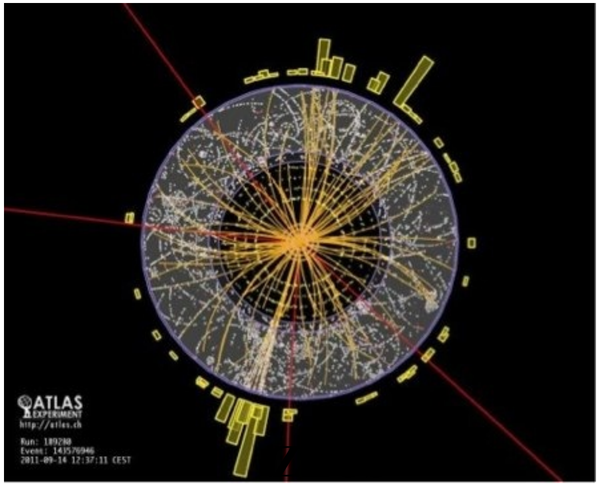
Particle flow concept

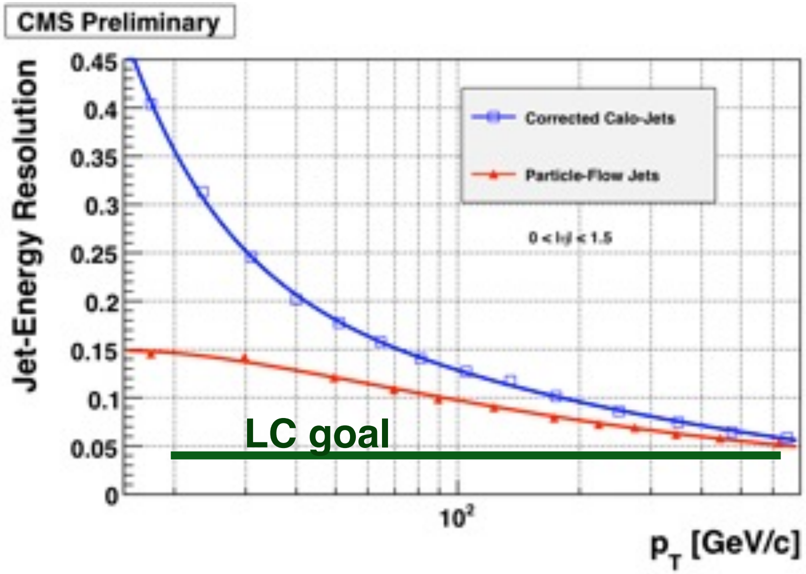




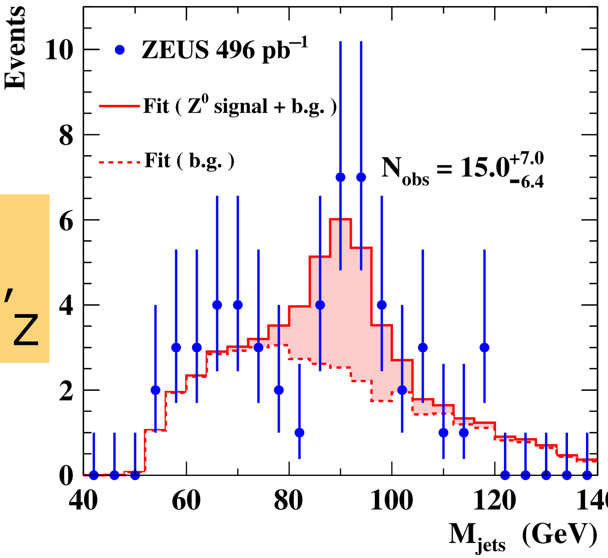
The jet energy challenge

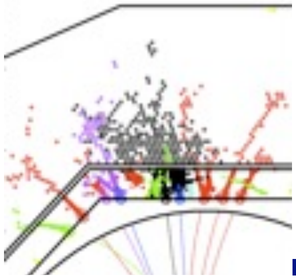
- Jet energy performance of existing detectors is not sufficient for separation of W and Z bosons
  - E.g. CMS: ~ 100%/√E, ATLAS ~ 70%/√E
- Calorimeter resolution for hadrons is intrinsically limited, e.g. nuclear binding energy losses
- Resolution for jets worse than for single hadrons
- It is not sufficient to have the world's best calorimeter





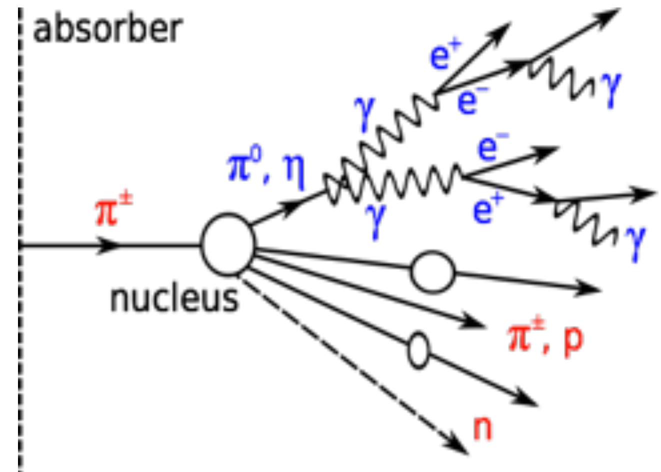
35%√E for pions, 6 GeV for Z

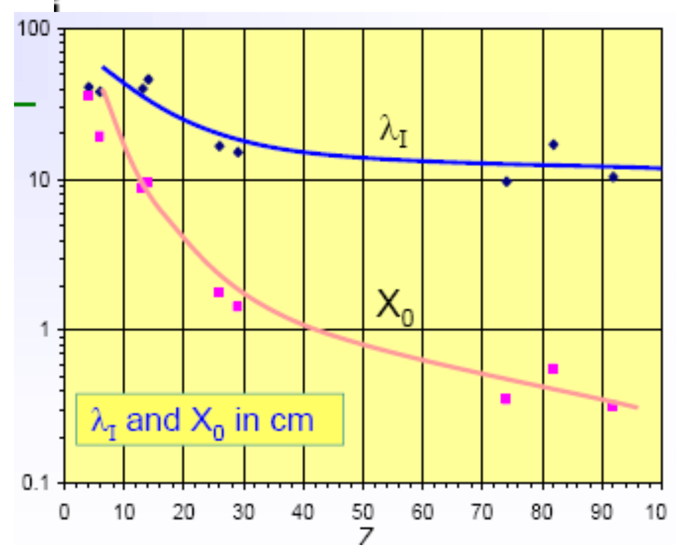




Hadron showers

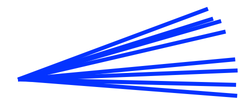
- Hadrons undergo strong interactions with detector (absorber) material
  - Charged hadrons: complementary to track measurement
  - Neutral hadrons: the only way to measure their energy
- In nuclear collisions secondary particles are produced
  - Partially undergo further nuclear interactions ➔ formation of a **hadronic cascade**
  - Electromagnetically decaying particles initiate **e.m. showers**
  - Part of the energy is absorbed as nuclear binding energy or target recoil and remains **invisible**
- Similar to em showers, but much more complex
- Small numbers , **large fluctuations**
- Different scale: hadronic interaction length
  - both **scales** present



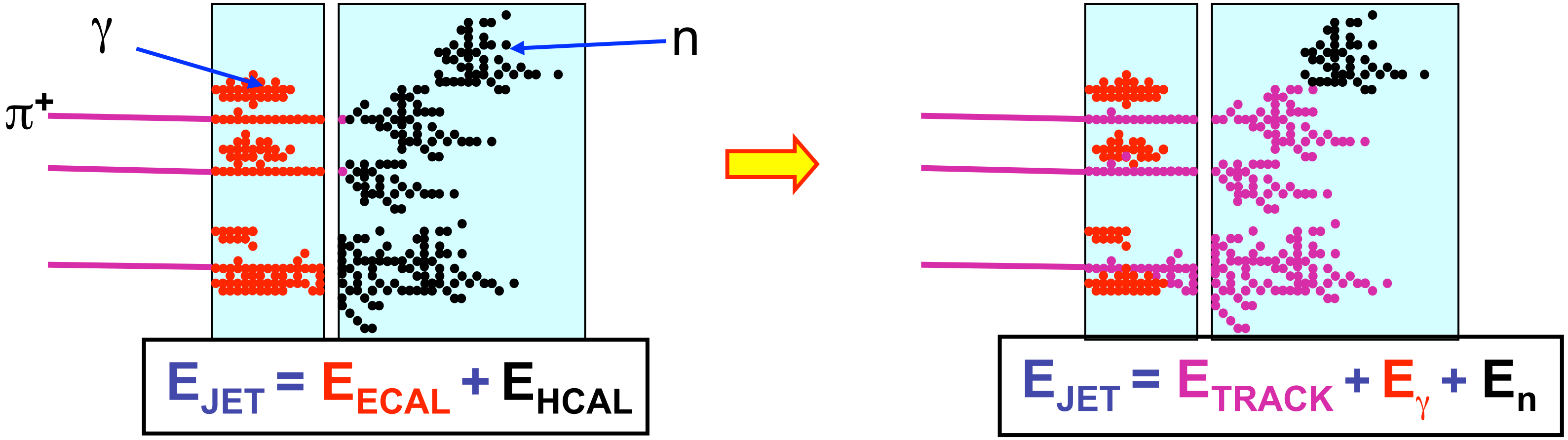


Particle Flow Calorimetry

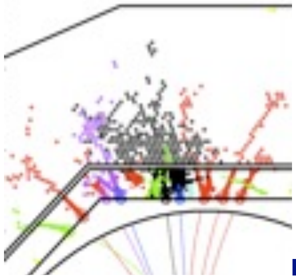
- **In a typical jet :**
  - **60 % of jet energy in charged hadrons**
  - **30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)**
  - **10 % in neutral hadrons (mainly n and K_L)**



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

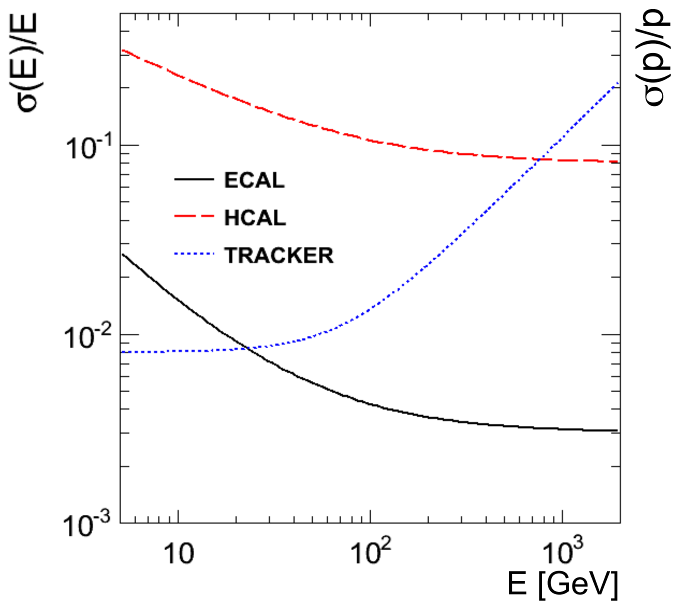


- **Particle Flow Calorimetry paradigm:**
  - **charged particles measured in tracker (essentially perfectly)**
  - **Photons in ECAL:** $\sigma_E/E < 20\,\%/\sqrt{E(\mathrm{GeV})}$
  - **Neutral hadrons (ONLY) in HCAL**
  - **Only 10 % of jet energy from HCAL** ⟹ much improved resolution



Ideal jet energy resolution

- Numerical example: E_{jet} = 100 GeV
  - photons 30 GeV
  - hadrons 70 GeV
    - charged particles 60 GeV
    - neutral hadrons 10 GeV



- Classical case
- $E_{jet} = E_{ECAL} + E_{HCAL}$
- $\sigma_{jet} = 15\% \sqrt{30} \oplus 55\% \sqrt{70} =$
  $0.8 \oplus 4.6 = 4.7 = 47\% \sqrt{100}$

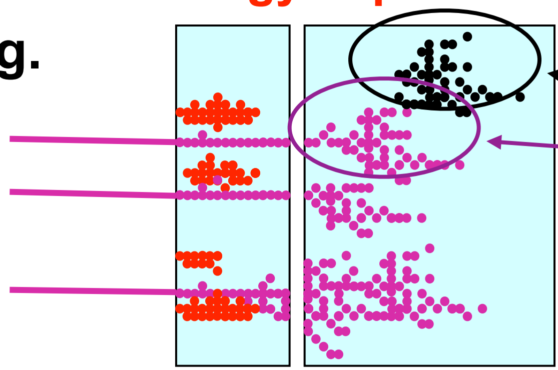
- Particle flow case:
- $E_{jet} = E_{tracks} + E_{photons} + E_{neutr.had}$
- $\sigma_{jet} = 0 \oplus 15\% \sqrt{30} \oplus 55\% \sqrt{10} =$
  $0.8 \oplus 1.7 = 1.9 = 19\% / \sqrt{100}$

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.

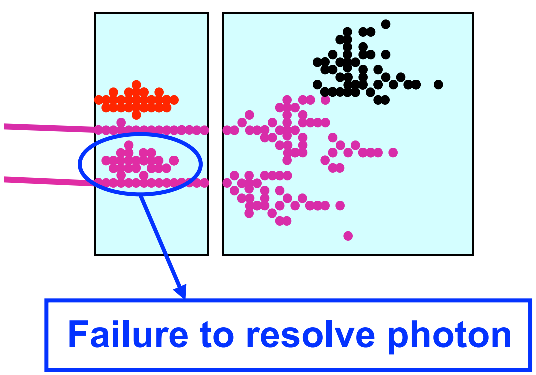


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

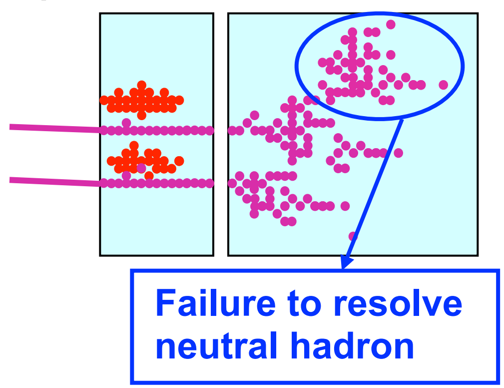
Level of mistakes, "confusion", determines jet energy resolution <u>not</u> the intrinsic calorimetric performance of ECAL/HCAL

Three types of confusion:

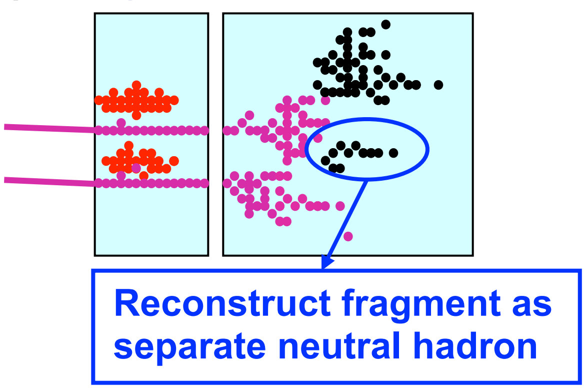
i) Photons

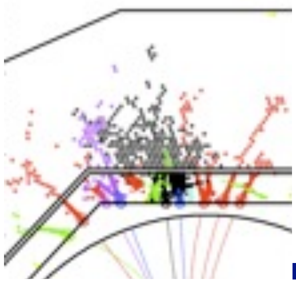


ii) Neutral Hadrons



iii) Fragments





Real jet energy resolution

- Numerical example> $E_{jet} = 100$ GeV

- Classical case
- $E_{jet} = E_{ECAL} + E_{HCAL}$
- $\sigma_{jet} = 15\% \sqrt{30} \oplus 55\% \sqrt{70} =$
  $0.8 \oplus 4.6 = 4.7 = 47\% \sqrt{100}$

- Particle flow case:
- $E_{jet} = E_{tracks} + E_{photons} + E_{neutr.had}$
- $\sigma_{jet} = 0 \oplus 15\% \sqrt{30} \oplus 55\% \sqrt{10} =$
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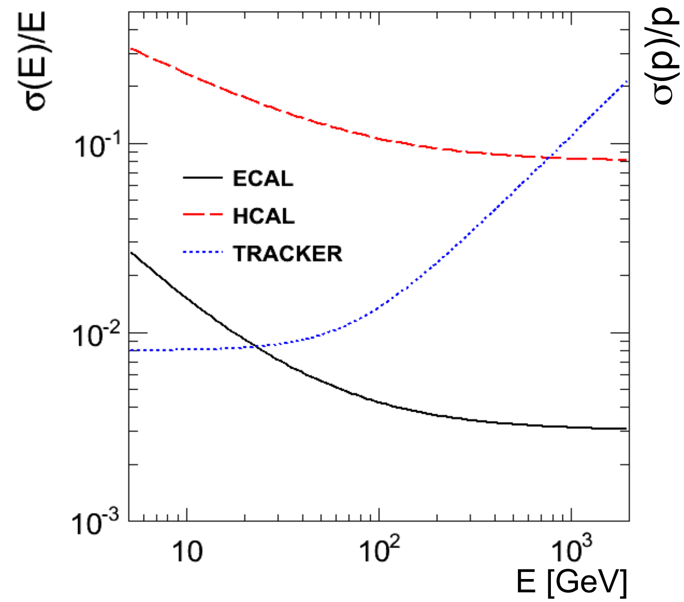
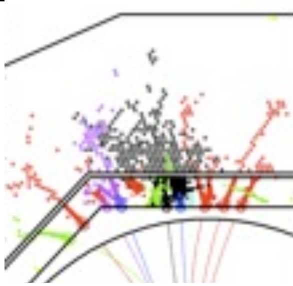


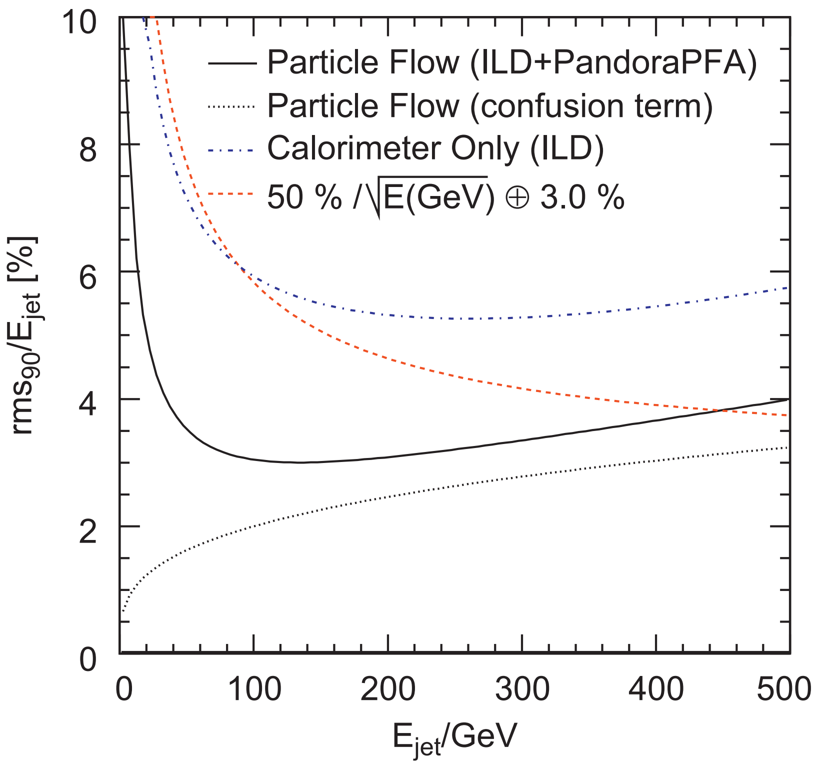
- Confusion example:
- Shower fragment of 10 GeV hadron (within 1 σ): 1.7 GeV = $17\% / \sqrt{E_{jet}}$
- Other effects (particle masses,…)
- In practice 3% at 100 GeV achievable

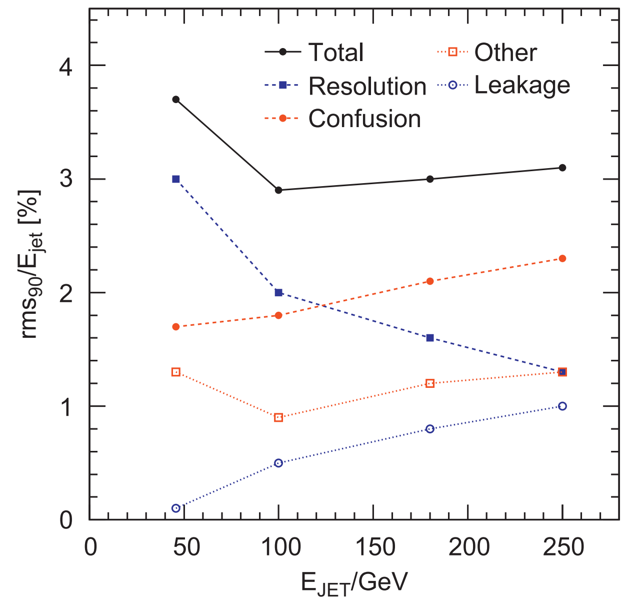


Understand particle flow performance

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

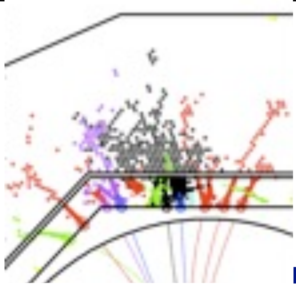
Resolution · Tracking · Leakage · Confusion





- Particle flow is always a gain
  - even at high jet energies
- Calorimeter resolution does matter
  - dominates up to ~ 100 GeV
  - contributes to resolve confusion
- Leakage plays a role, too
  - but less than in classic case

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



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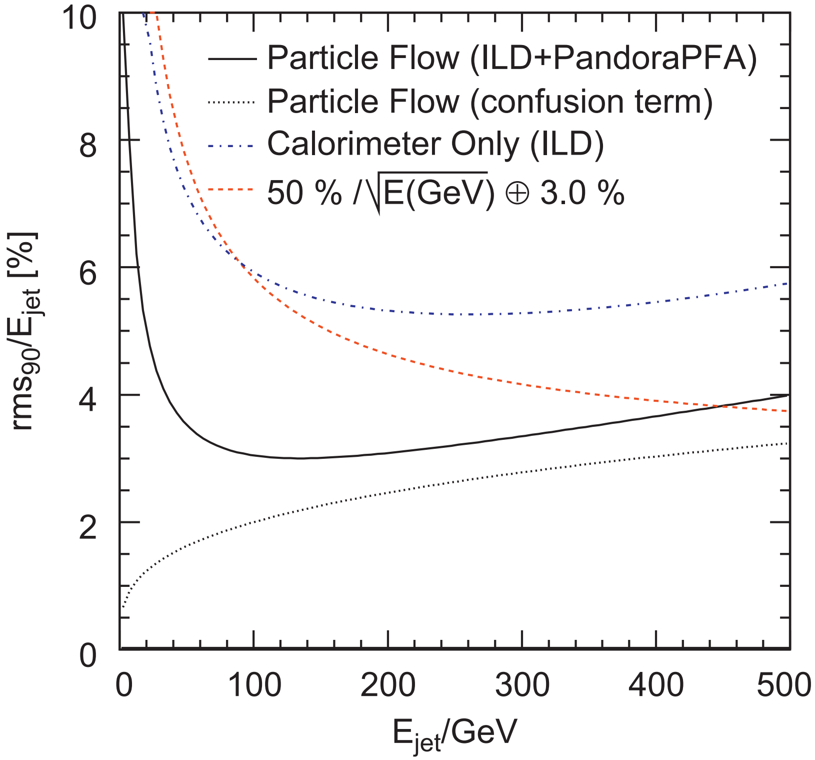
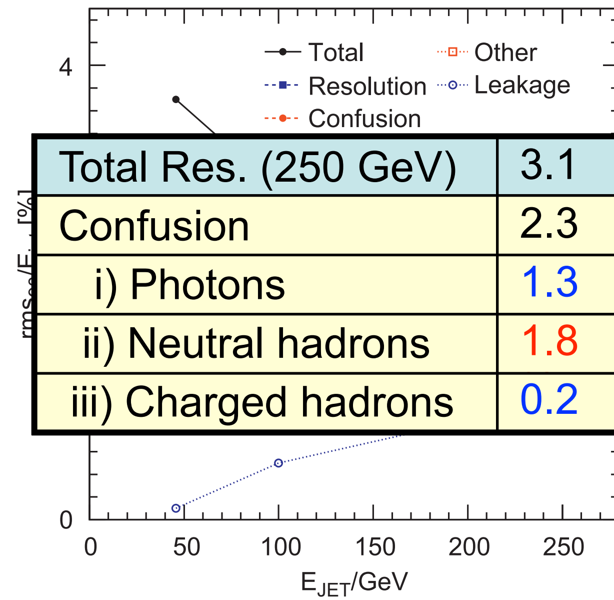
Resolution | Tracking | Leakage | Confusion





Total Res. (250 GeV)	3.1
Confusion	2.3
i) Photons	1.3
ii) Neutral hadrons	1.8
iii) Charged hadrons	0.2

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  - even at high jet energies
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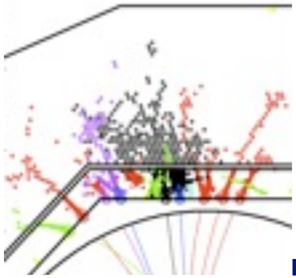
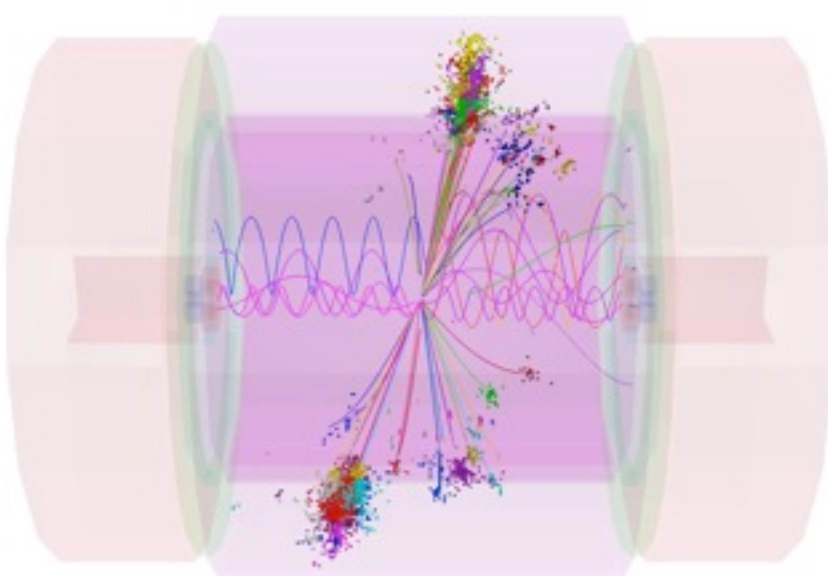
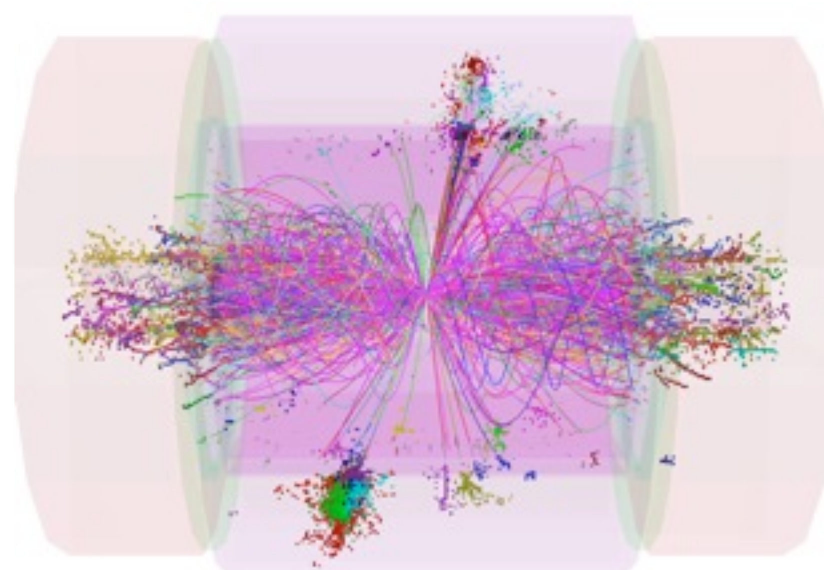


Particle flow and pile-up

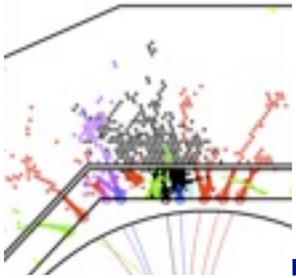
- Studied intensively for CLIC: harsh backgrounds and short BX 0.5 ns
- Overlay γγ events from 60 BX, take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- Apply combination of topological, pt and timing cuts on cluster level (sub-ns accuracy)



Z @ 1 TeV



+ 1.4 TeV BG (reconstructed particles)



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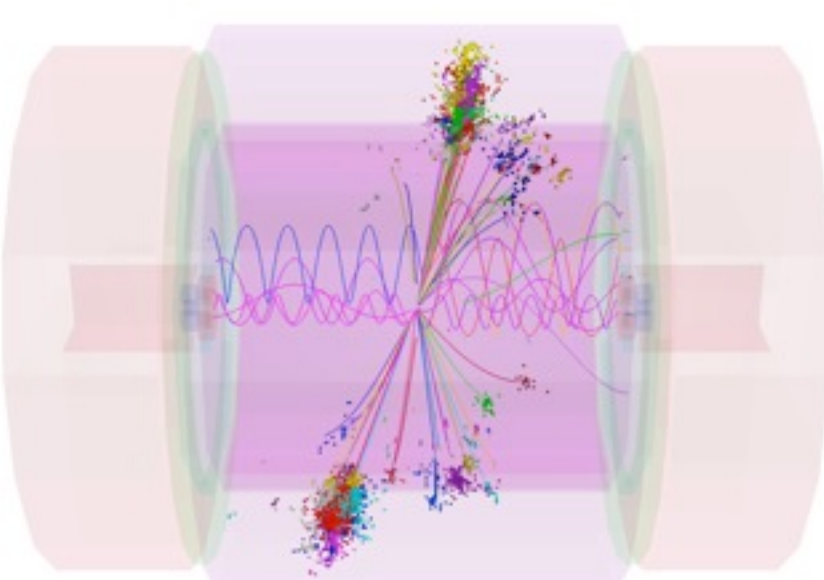

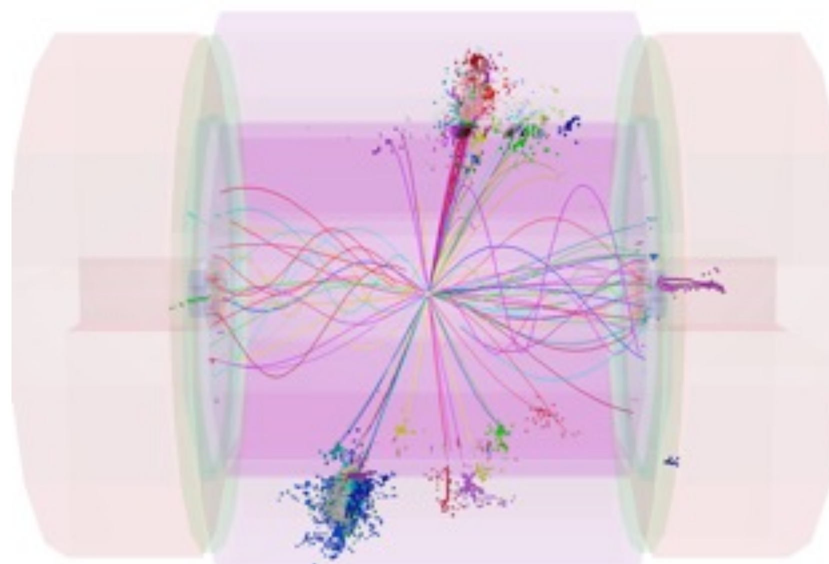

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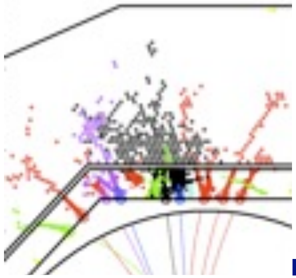
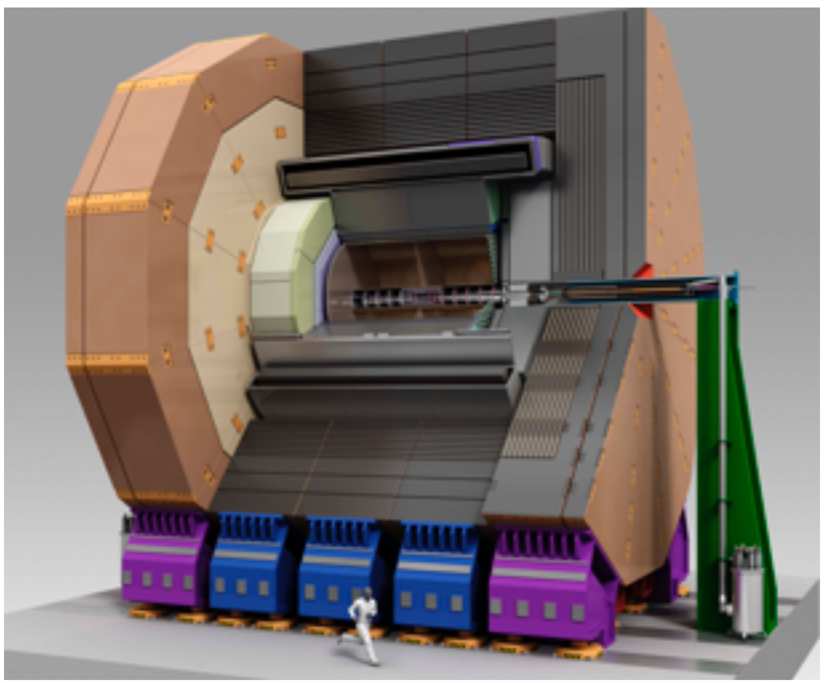
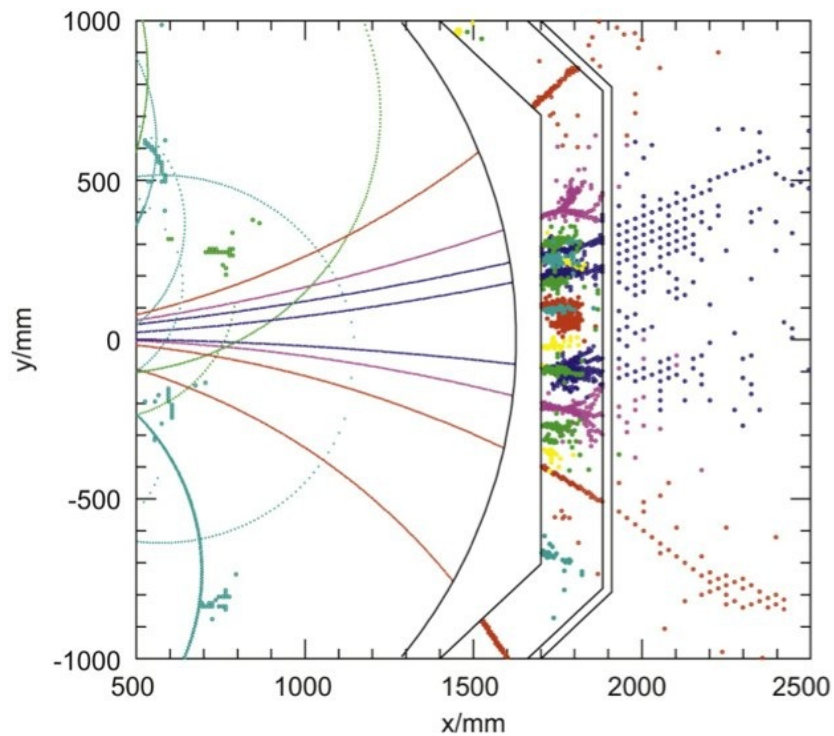
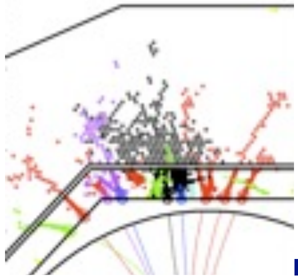


Particle flow detectors

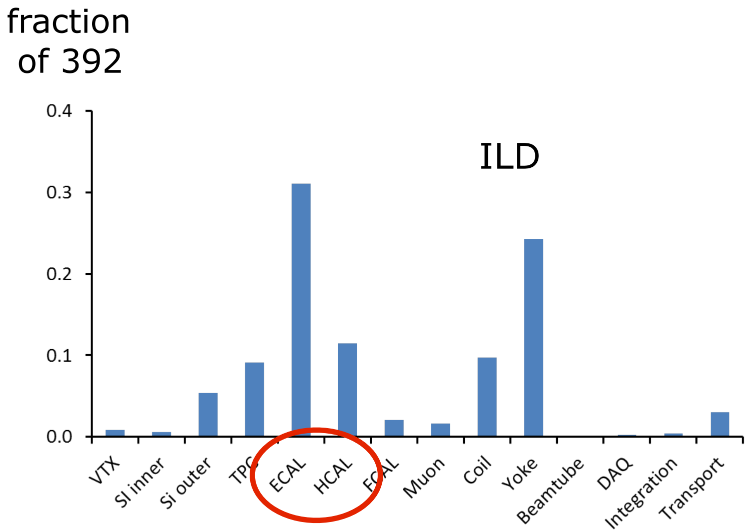
- Large radius, high magnetic field, calorimeters inside coil
- Dense and compact design
- Very high granularity
  - order of Moliere radius
  - ECAL: 0.5 - 1 cm, 10^8 cells
  - HCAL: 1 - 3 cm, 10^7 -10^8 cells

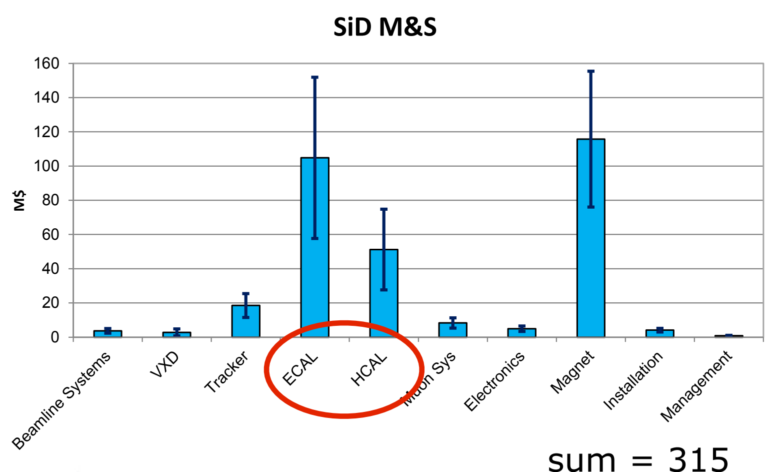




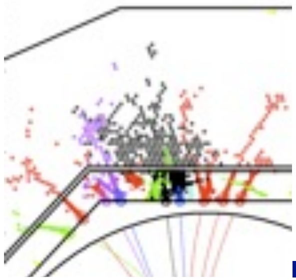


Calorimeter cost





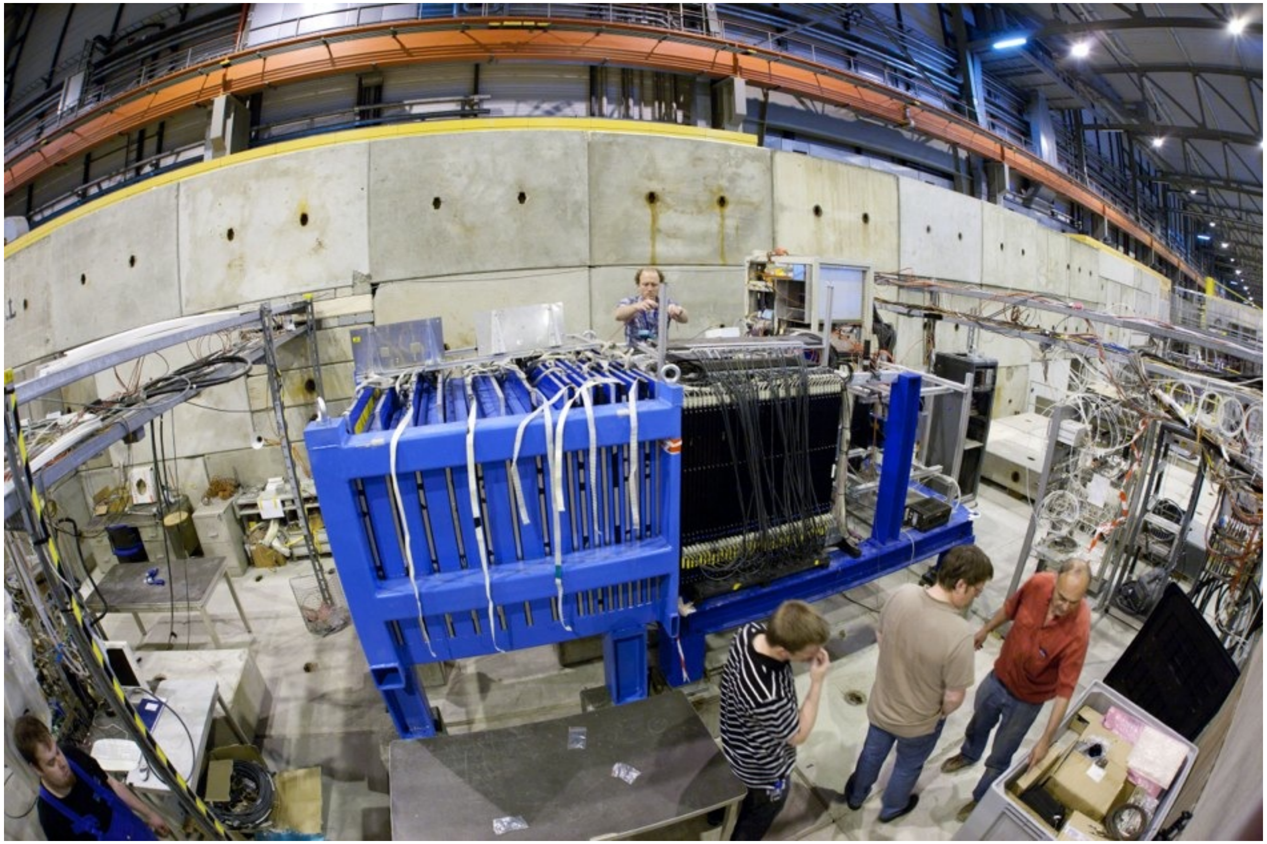
- Costing is at a very early stage
- Yet, many lessons learnt from 2nd generation prototypes
- Example ILD scint HCAL: 45M
  - 10M fix, rest ~ volume
  - 10M absorber, rest ~ area (n_{Layer})
  - 16M PCB, scint, rest ~ channels
  - 10 M SiPMs and ASICs
- HCAL cost is rather driven by instrumented area then by cell size
- ECAL cost driver: silicon area
  - ILD 2500 m2, SiD 1200 m2
  - cf. CMS tracker 200 m^2
  - cf. CMS ECAL+HCAL endcap 600 m^2

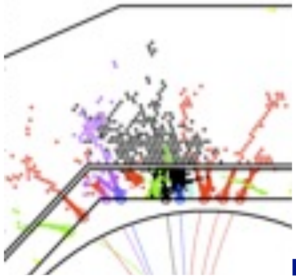


Main ideas:

- Linear collider physics demands 3-4% jet energy resolution, which cannot be achieved with classical calorimetry
- Particle flow detectors achieve this precision over a wide energy range for ILC and CLIC
  - even in harsh back/ground condition and with pile-up
- Particle flow calorimeters feature good energy resolution **and** high granularity, 10 to 100 million channels
- Detector cost driven by instrumented area rather than cell size

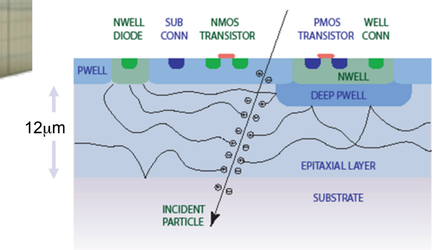
Technologies and test beam performance

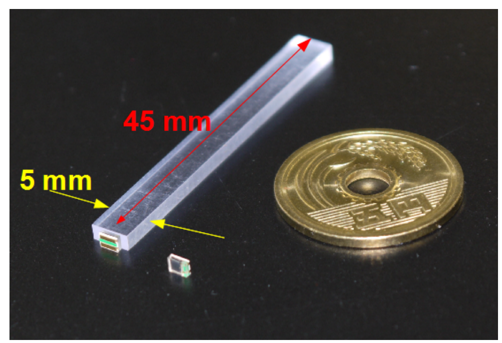


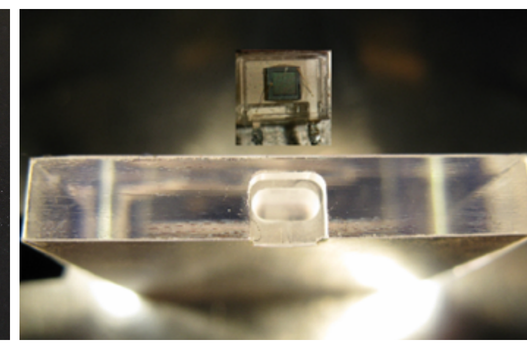


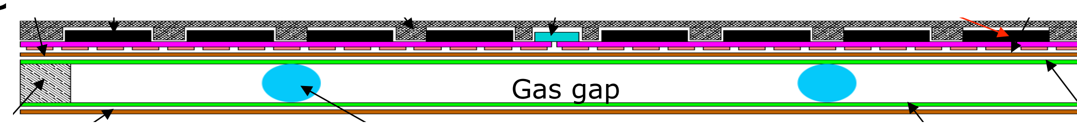
Particle flow technologies

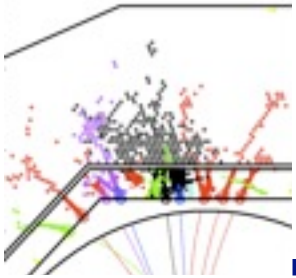
- Silicon (ECAL)
  - most compact solution, stable calibration
  - 0.5 - 1 cm^2 cell size
  - MAPS pixels also studied
- Scintillator SiPM (ECAL, HCAL)
  - robust and reliable, SiPMs..
  - ECAL strips: 0.5 - 1 cm eff.
  - HCAL tiles: 3x3 cm^2
- Gaseous technologies
  - fine segmentation: 1 cm^2
  - Glass RPCs: well known, safe
  - MPGDs: proportional, rate-capable
    - GEMs, Micromegas



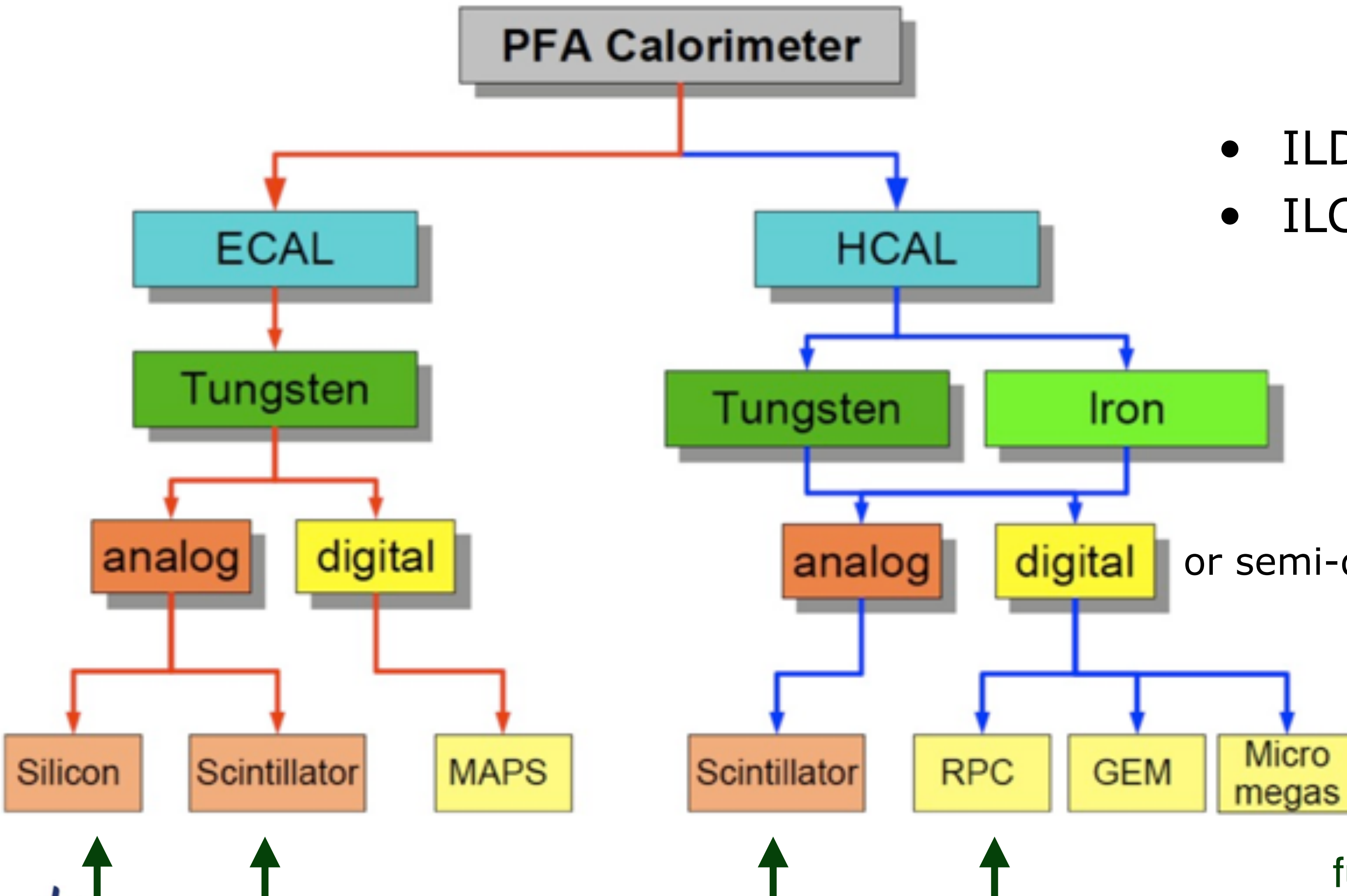




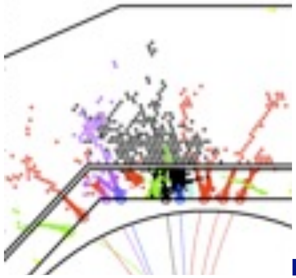




Calorimeter technologies

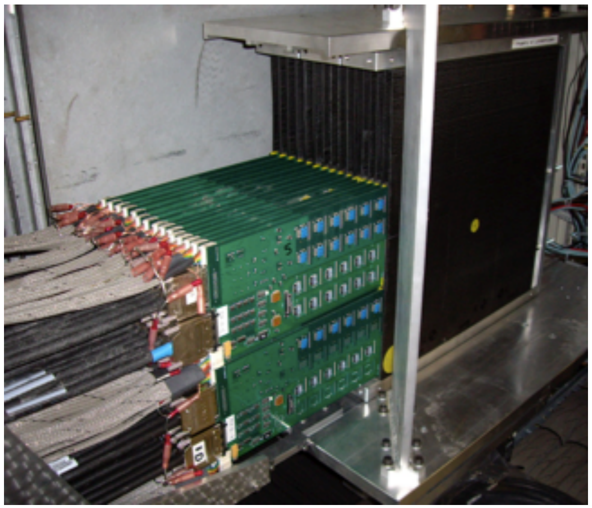


- ILD, SiD
- ILC, CLIC

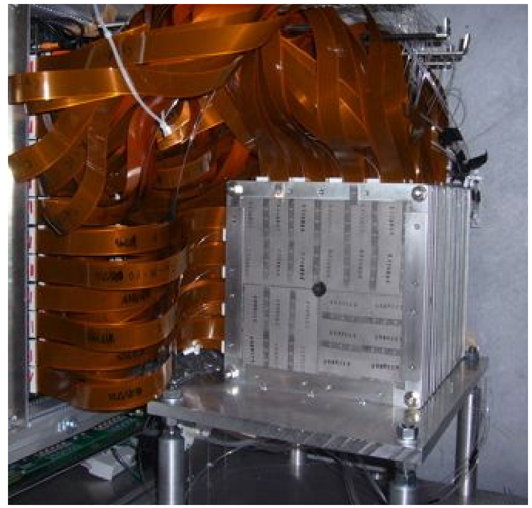


Test beam prototypes

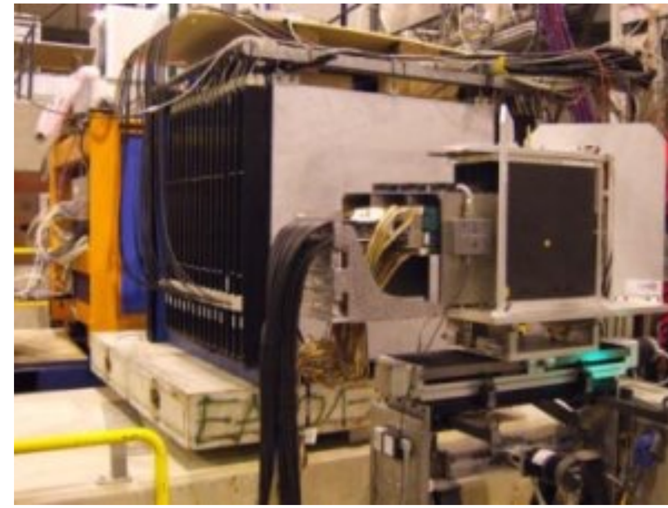
SiW ECAL



ScintW ECAL

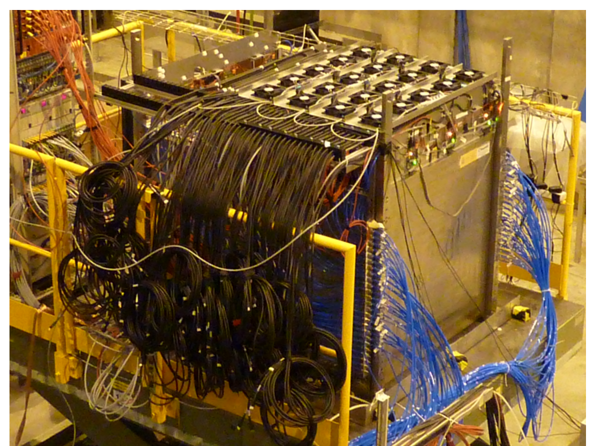


Scint AHCAL, Fe & W



RPC DHCAL, Fe & W

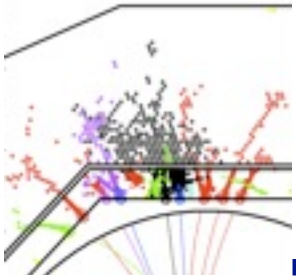
RPC SDHCAL, Fe



plus tests with small numbers of layers:

- ECAL, AHCAL with integrated electronics

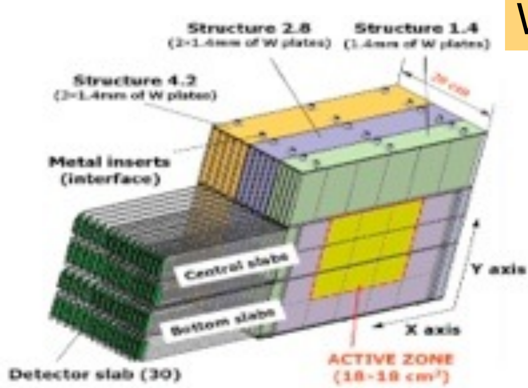
- Micromegas and GEMs

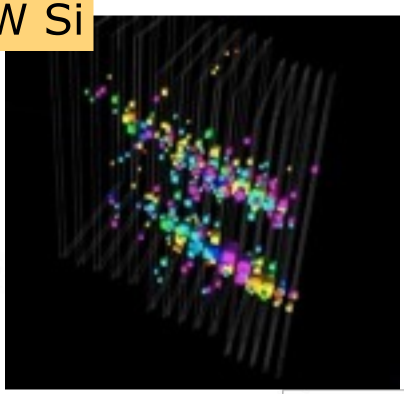


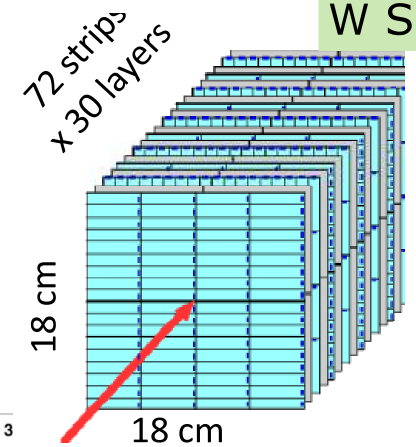
CALICE ECALs performance

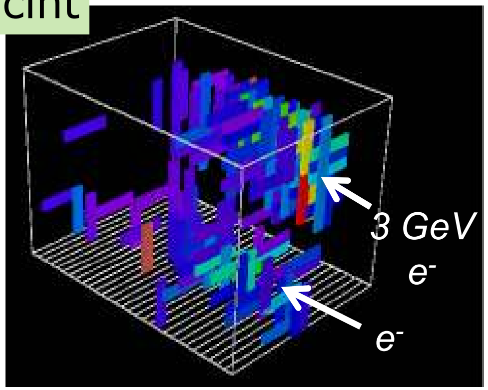
W Si

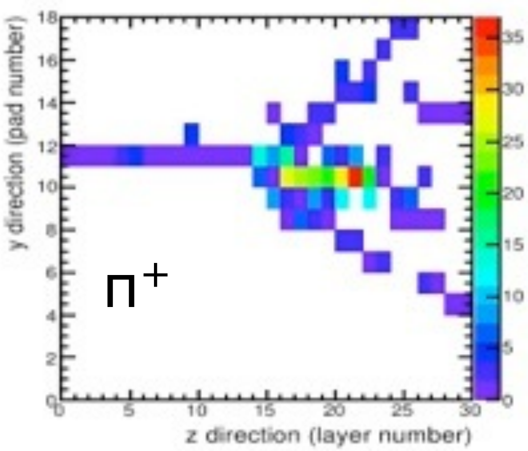
W Scint

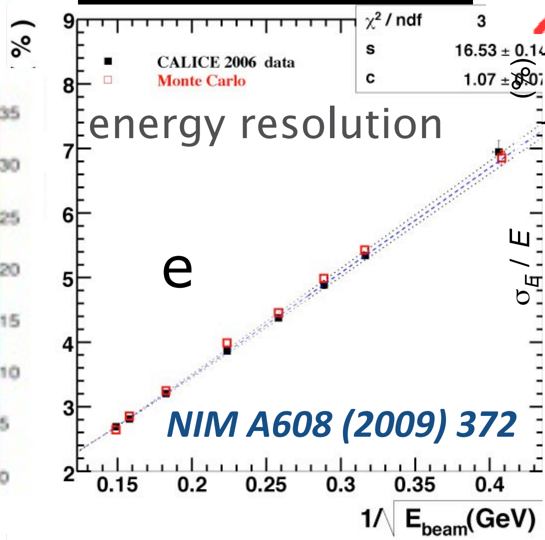


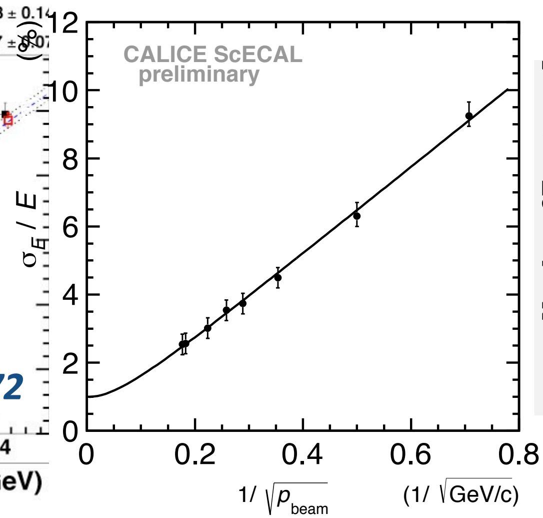


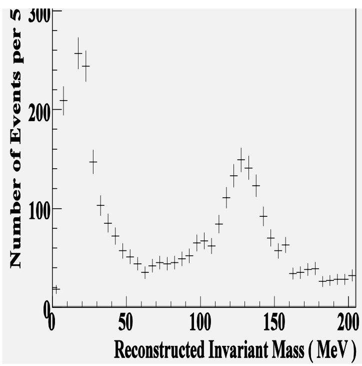




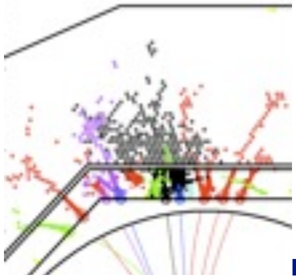




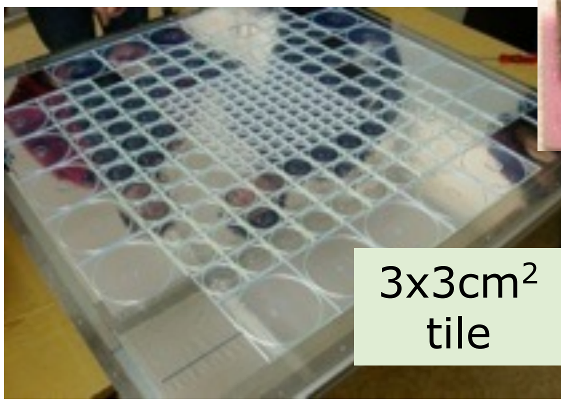




- data and sim agree

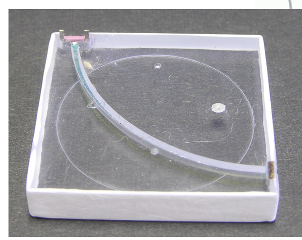


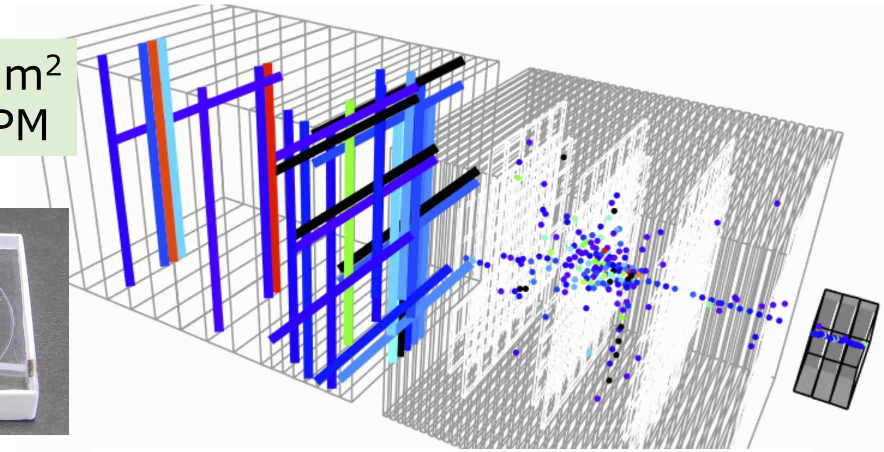
Scintillator HCAL performance



3x3cm^2 tile

1mm^2 SiPM

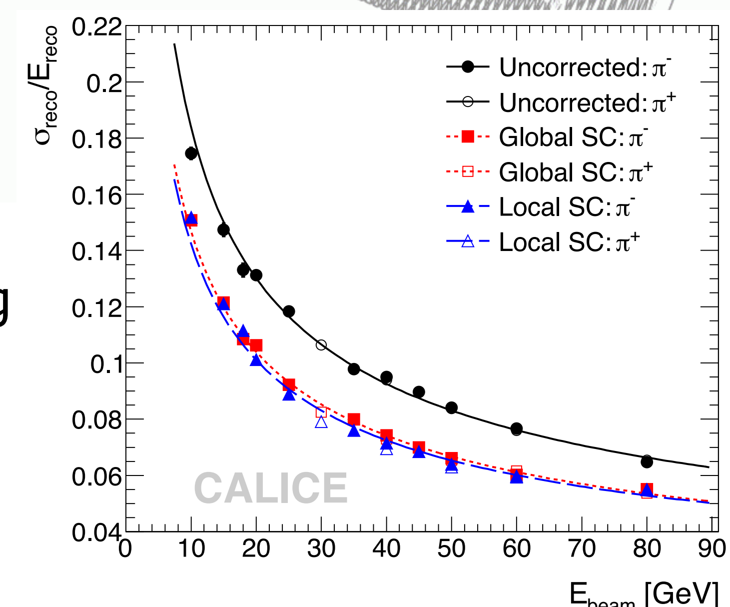




- 38 layer steel and tungsten
- 7608 channels: first large scale SiPM application
- very robust: 6 years of data taking at DESY, CERN, Fermilab
- a very good calorimeter, too

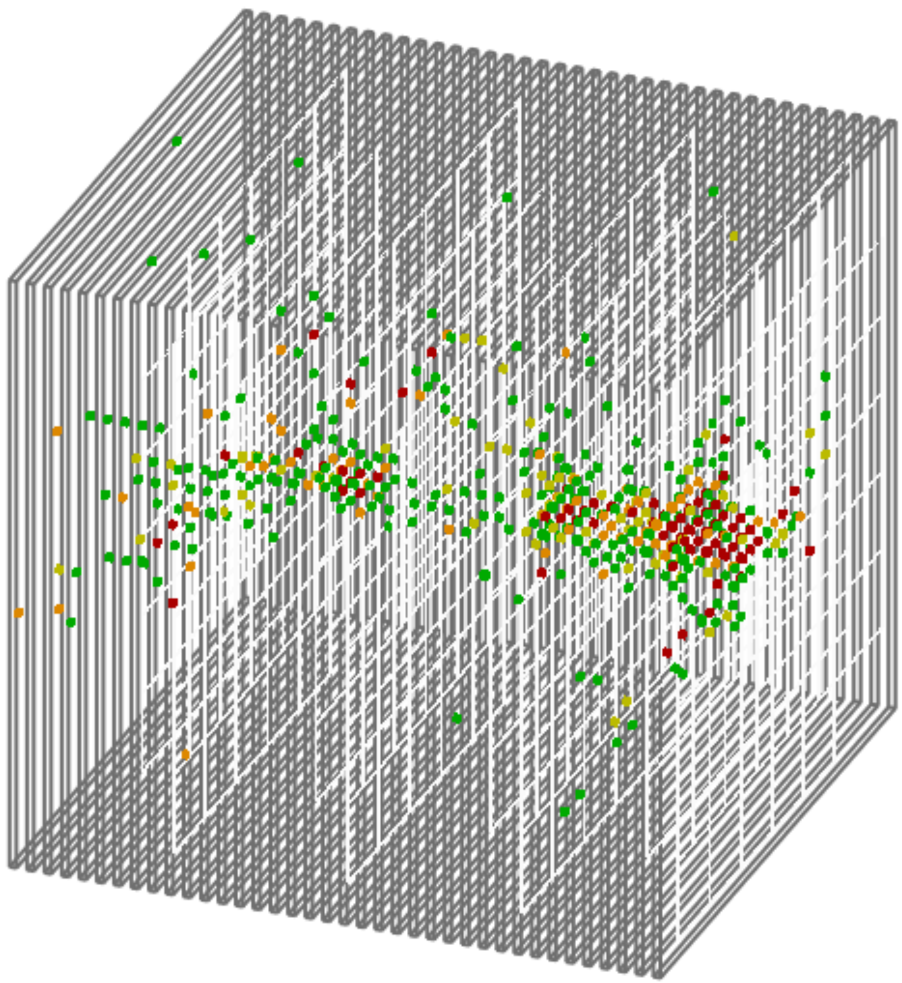
$\sigma/E = 45.1\%/\sqrt{E} \oplus 1.7\% \oplus 0.18/E$

software compensation

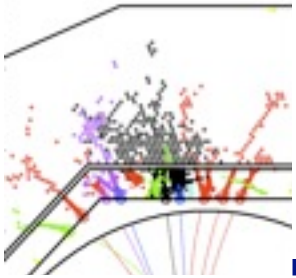


JINST 7, P00917 (2012)

Event displays



- pions 80 GeV
- W absorber



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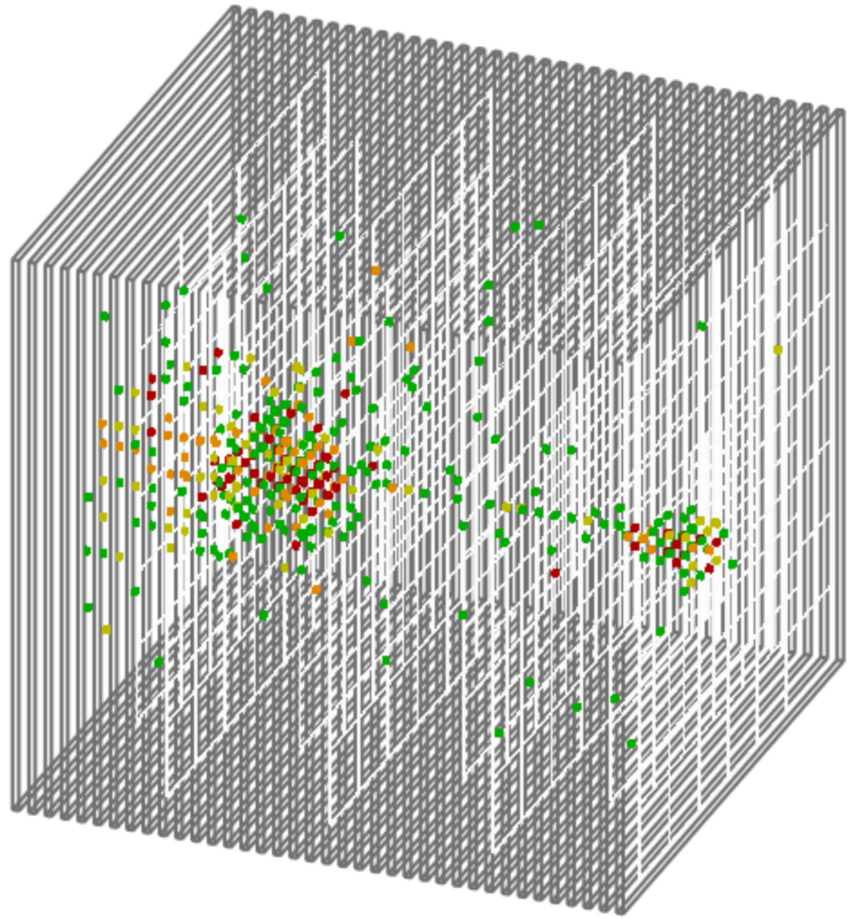

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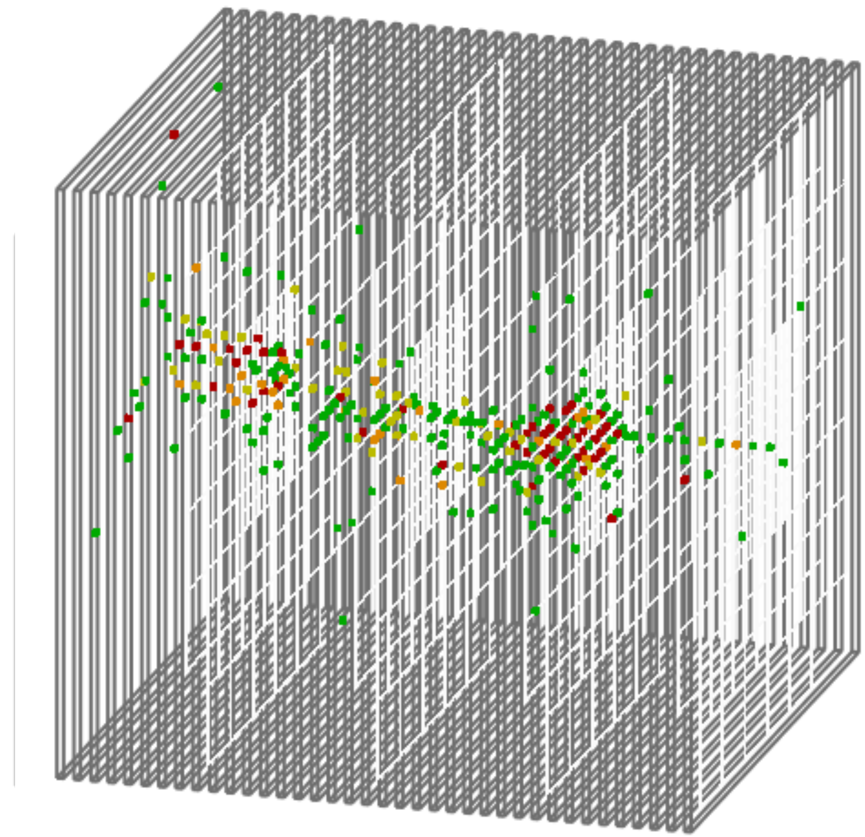

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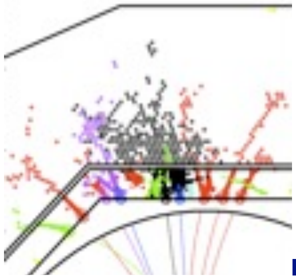
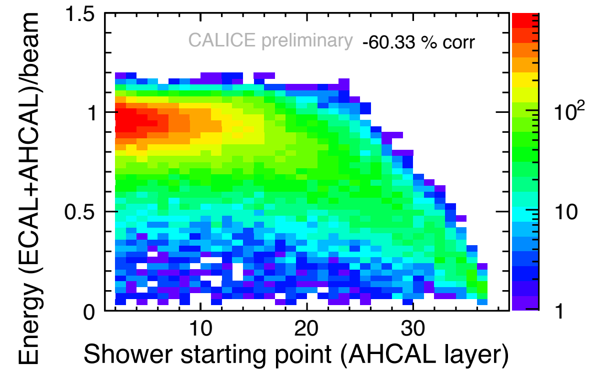
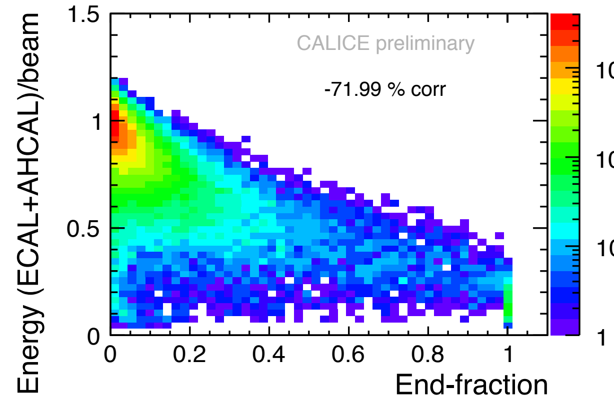
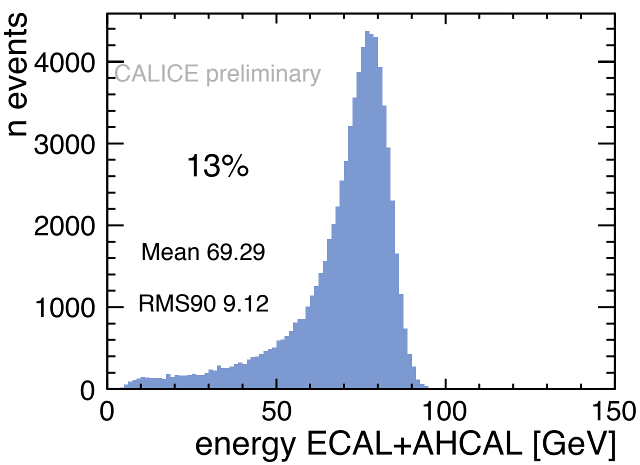


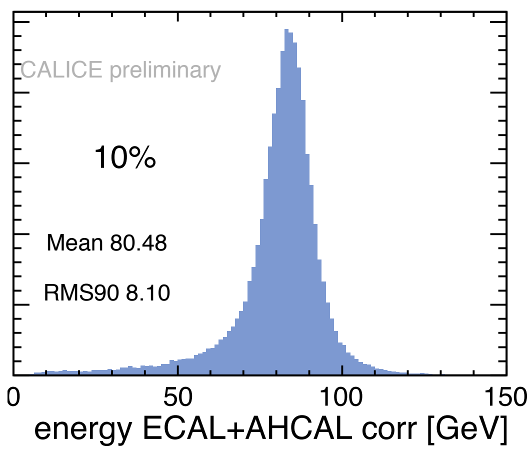
Leakage estimation

- Exploit the fine granularity
- ECAL 1λ, HCAL 4.5λ
- Observables
  - shower start
  - energy fraction in rear layers
  - measured energy

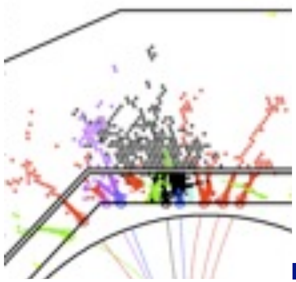






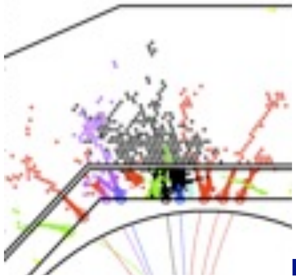


cf : with tail catcher, no coil: 5.4%



Gaseous calorimeters

- Gaseous HCAL with **analogue** readout would have poor resolution
  - small sampling, large Landau fluctuations
- **Digital** calorimeter idea: count particles, ignore fluctuations
  - $1cm^2$ cells: saturate above 30 GeV
- **Semi-digital** idea: mitigate saturation using several thresholds and weights
  - assumes signal prop. to E deposition



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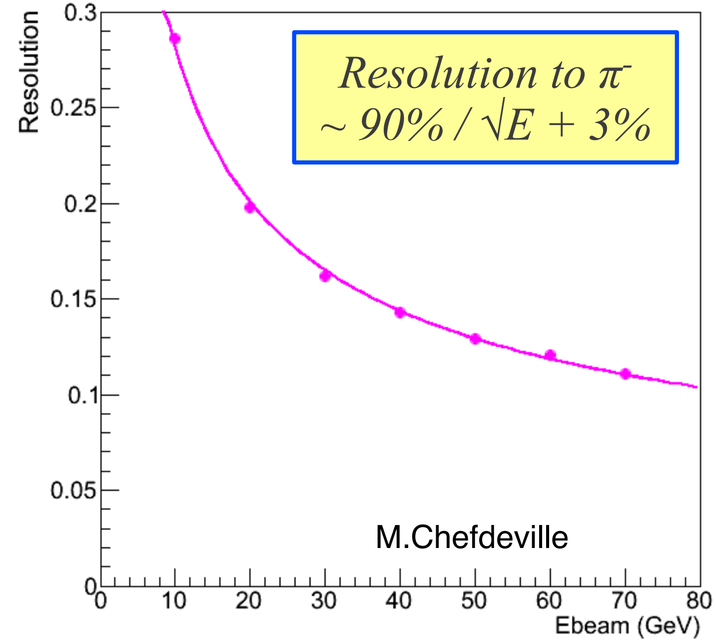

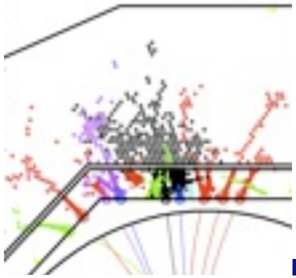

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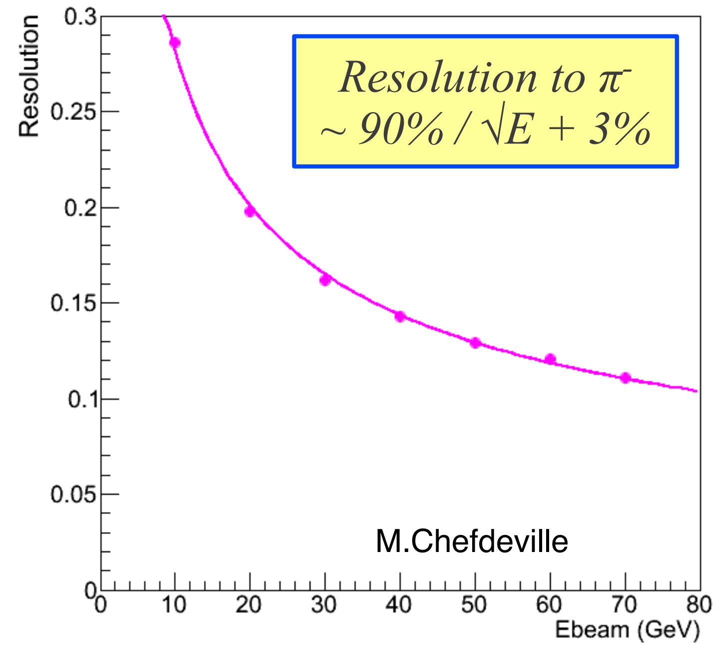

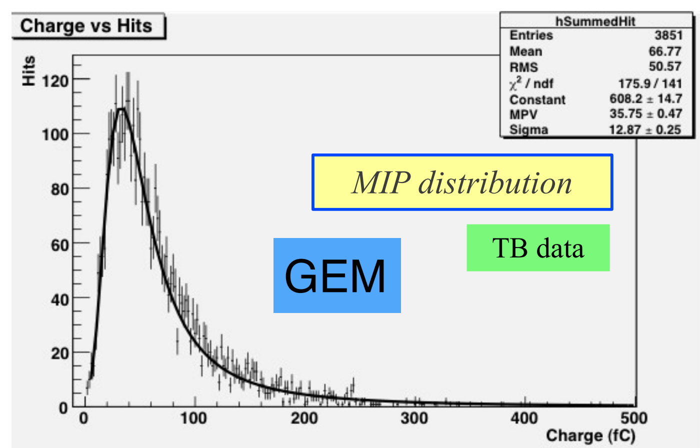

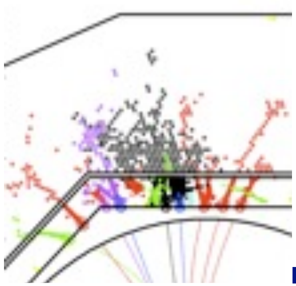

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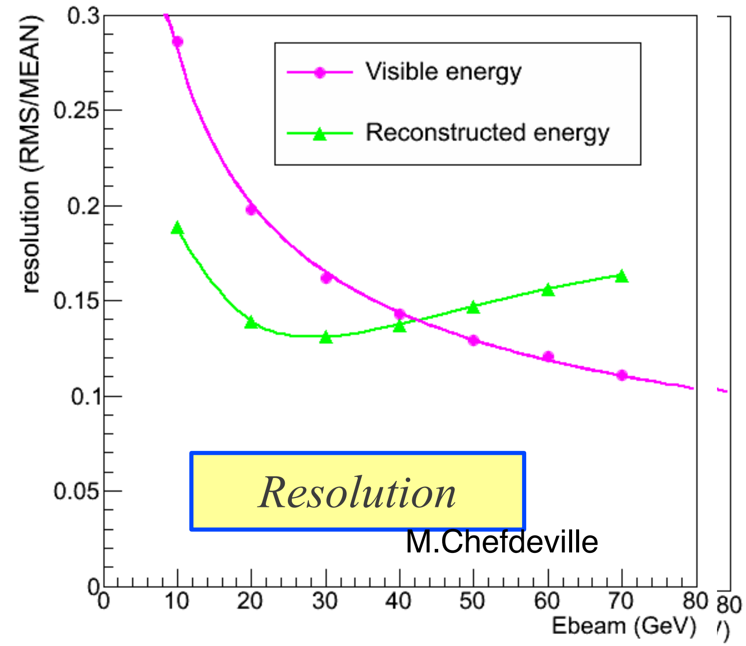

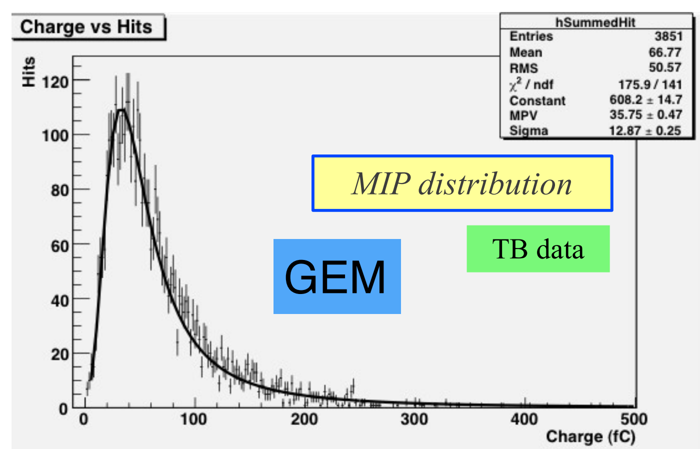

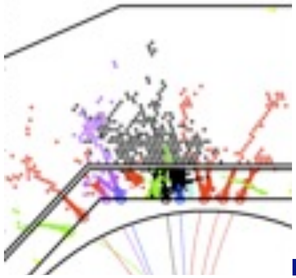

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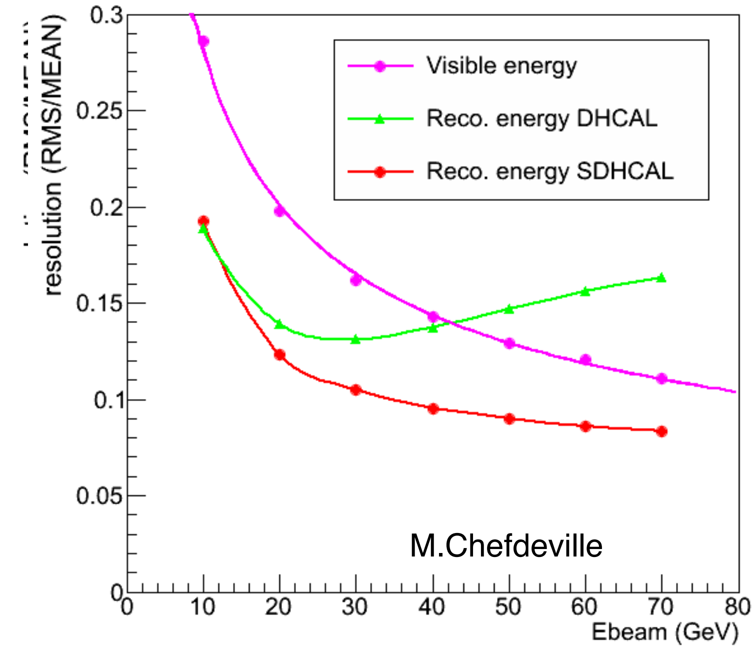

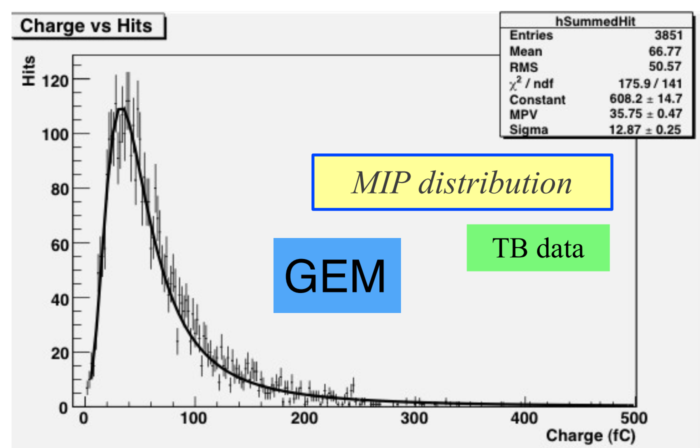

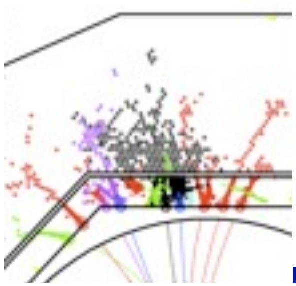

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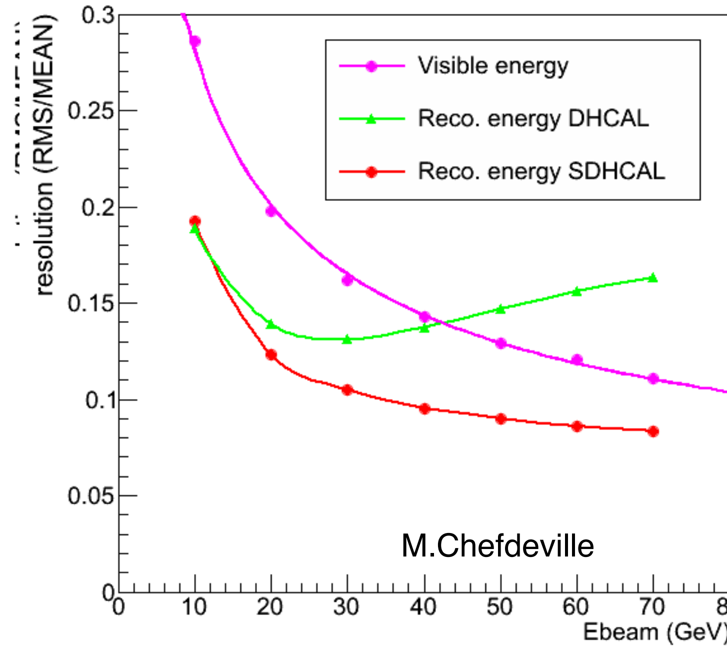
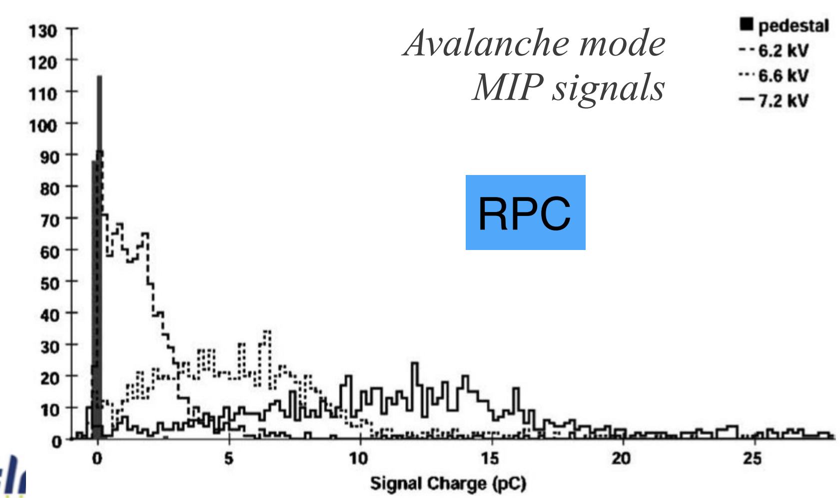
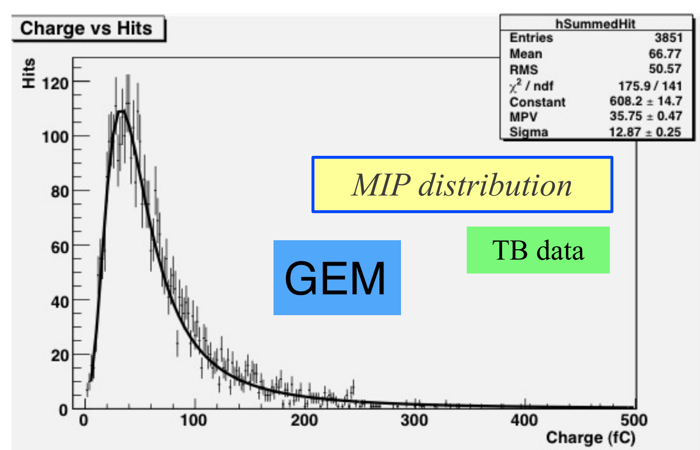
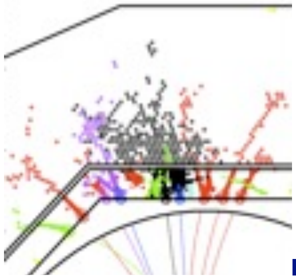


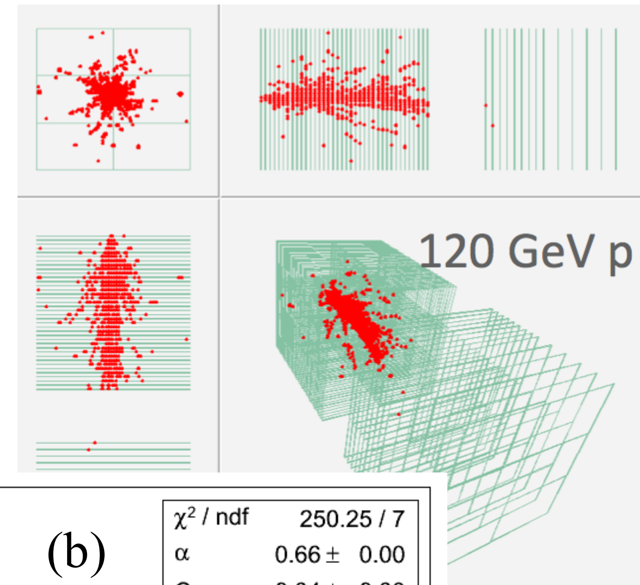


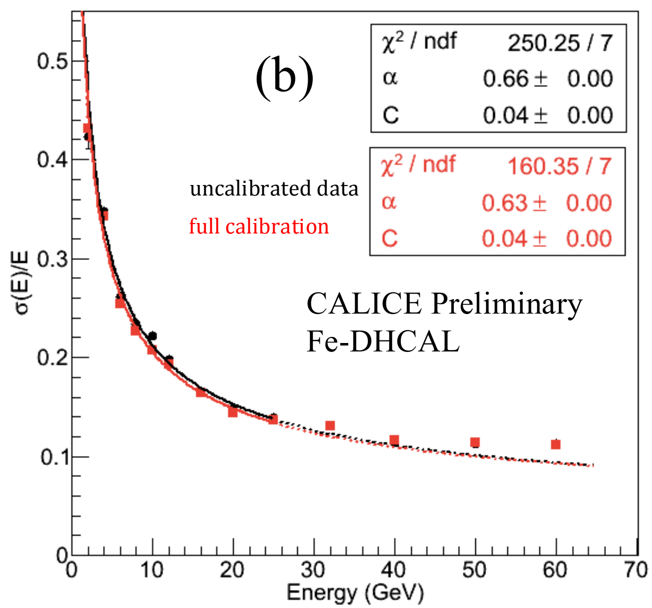


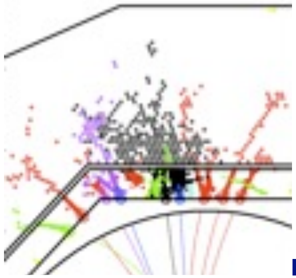


Digital RPC HCAL

- Resistive plate chambers
- 1x1cm^2 pads, 1 bit read-out
- 500’000 channels
- digitisation electronics embedded
- tested with steel and tungsten
- digital calorimetry does work

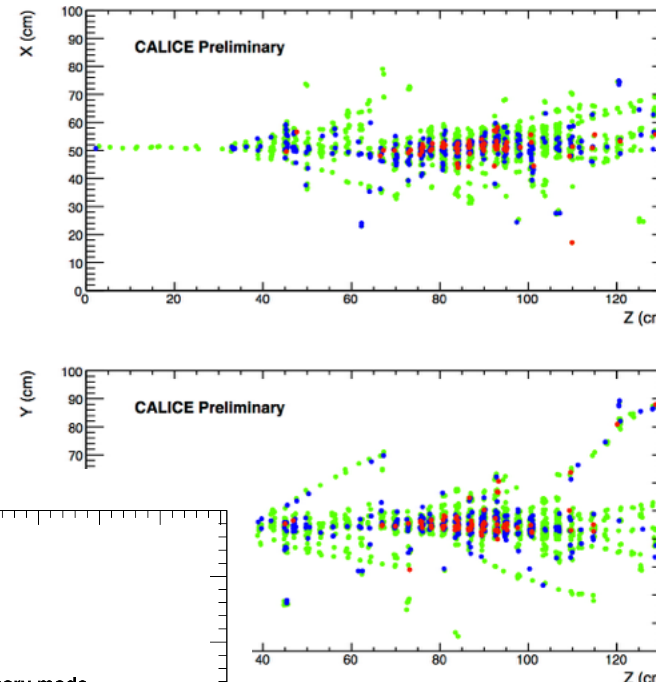


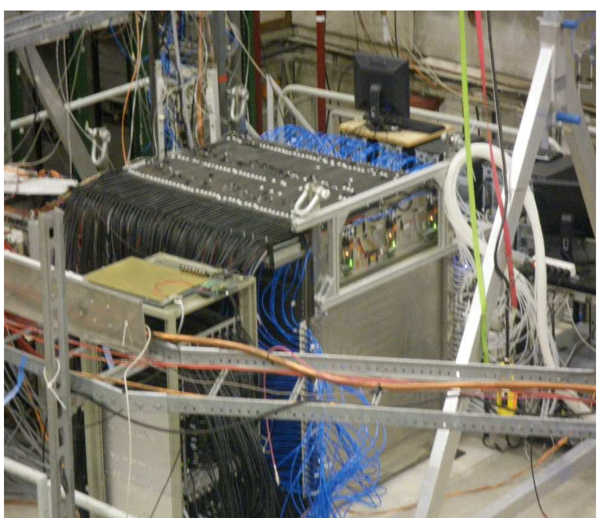


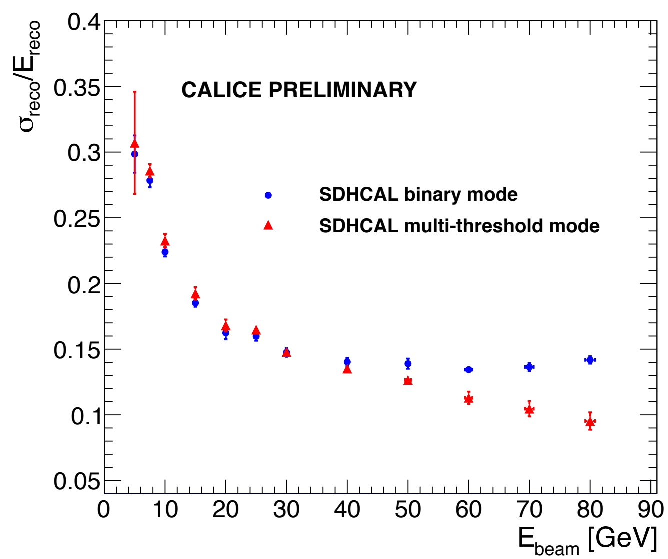


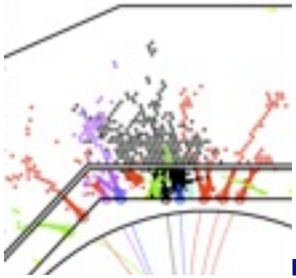
Semi-digital RPC HCAL

- 48 RPC layers, 1cm^2 pads
- embedded electronics
  - power-cycled
- 2 bit, 3 threshold read-out
  - mitigate resolution degradation at high energy









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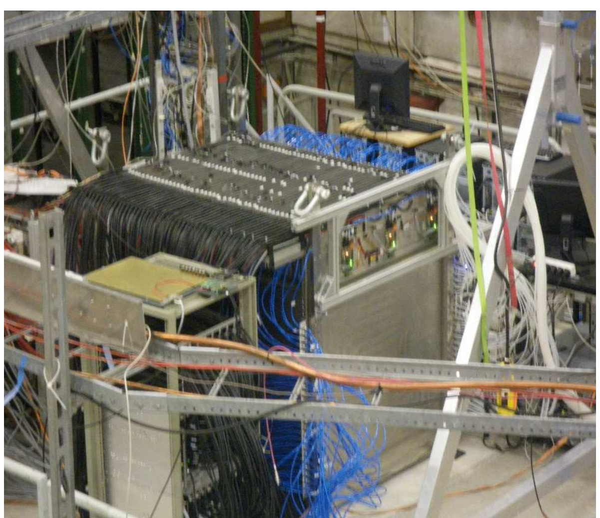
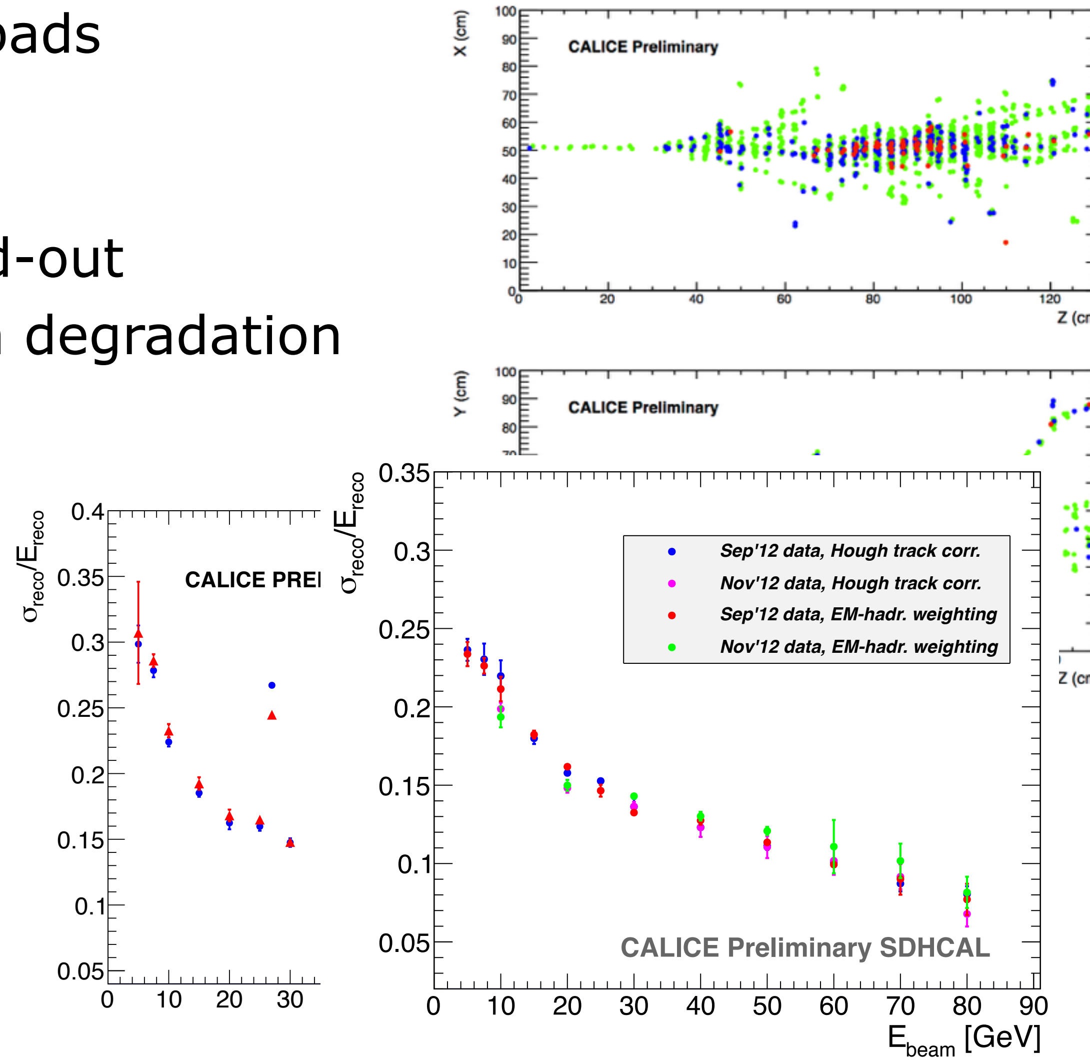
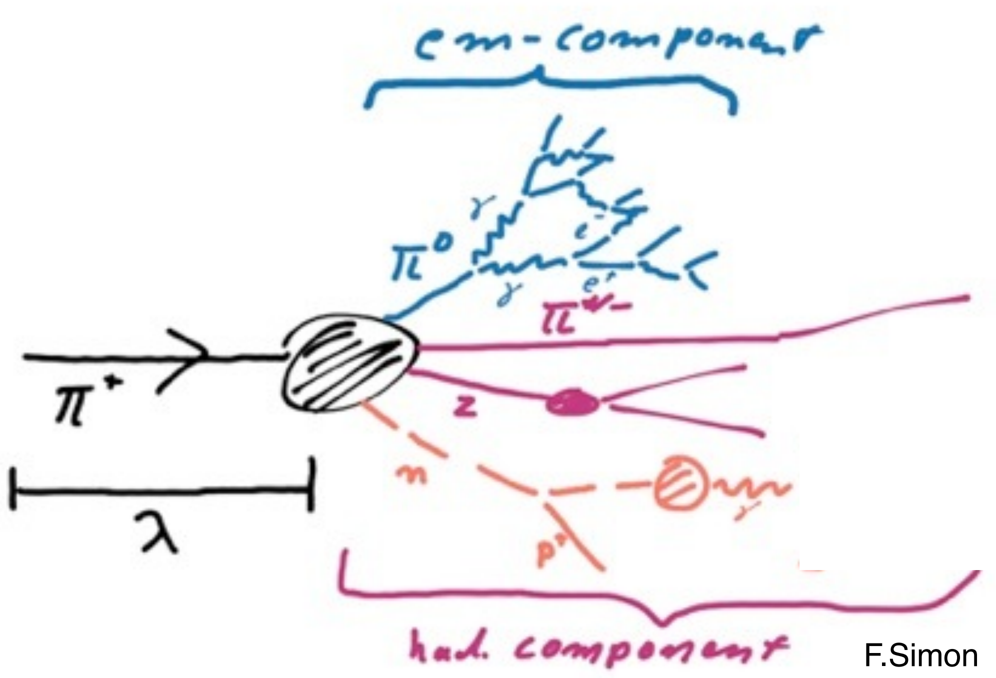
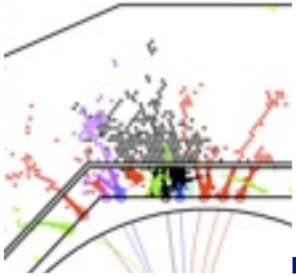




Validation of Geant 4 shower models

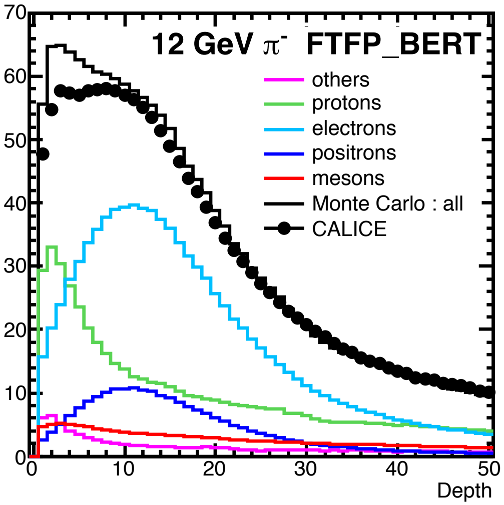


F.Simon



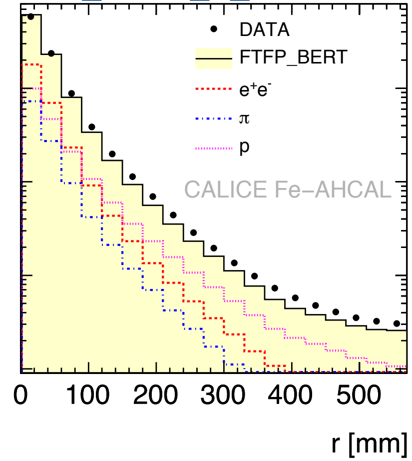
Validation of Geant 4 models

2010_JINST_5_P05007



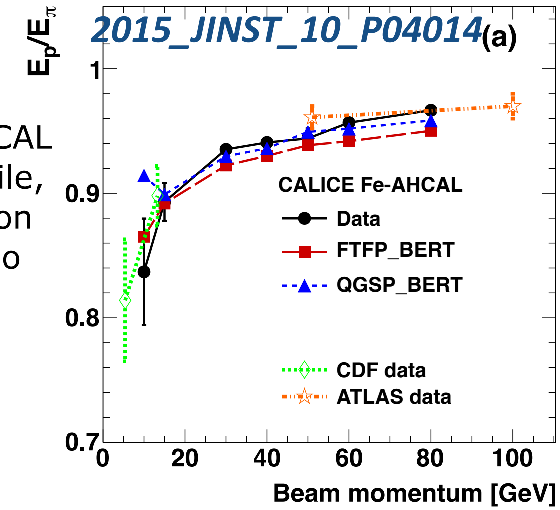
SiW ECAL
longit. profile

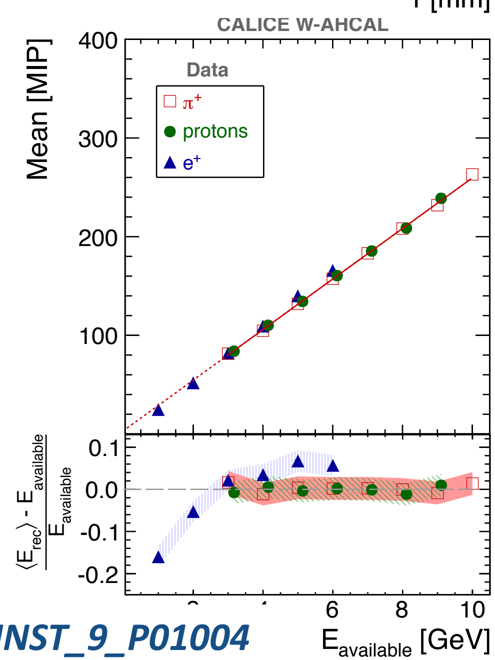
2013_JINST_8_P07005



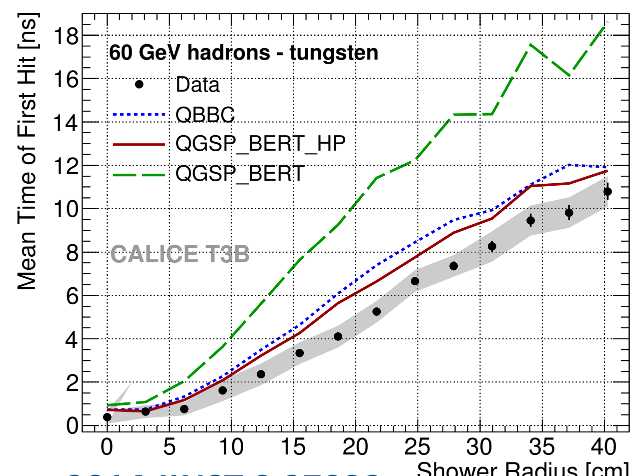
Fe Scint HCAL
radial profile,
proton pion
resp. ratio

2015_JINST_10_P04014





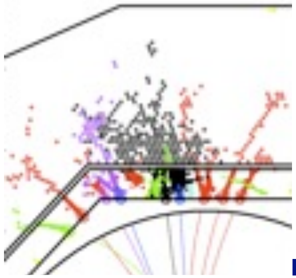
2014_JINST_9_P01004



2014 JINST 9 07022

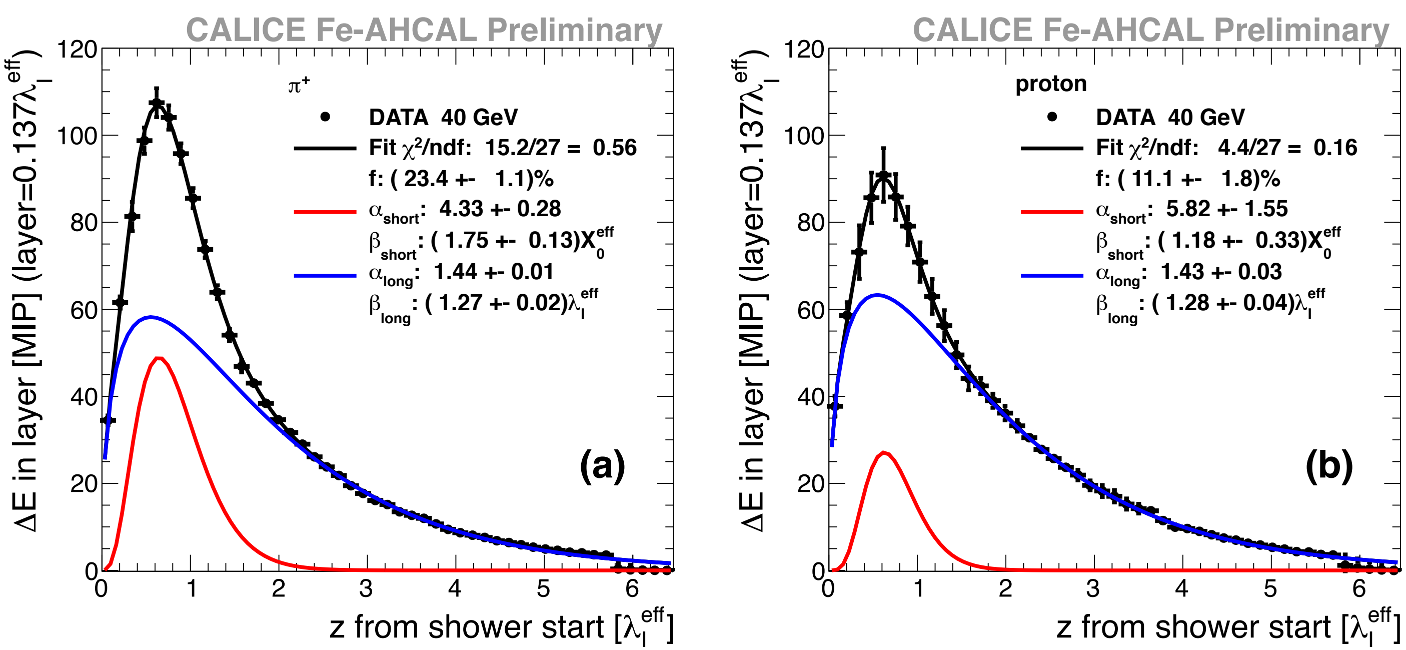
W Scint HCALresponse, timing

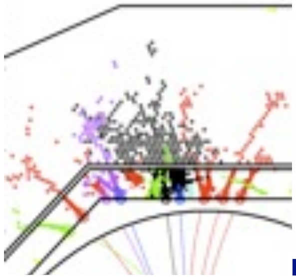
- just a few examples
- altogether at 5% or better



Longitudinal shower profiles

- Measure hadronic shower profiles from the reconstructed point of the first hard interaction
- Parameterise in terms of
  - a short component related to electromagn. component
  - a long component related to the hadronic part
  - similar decomposition works for radial profiles





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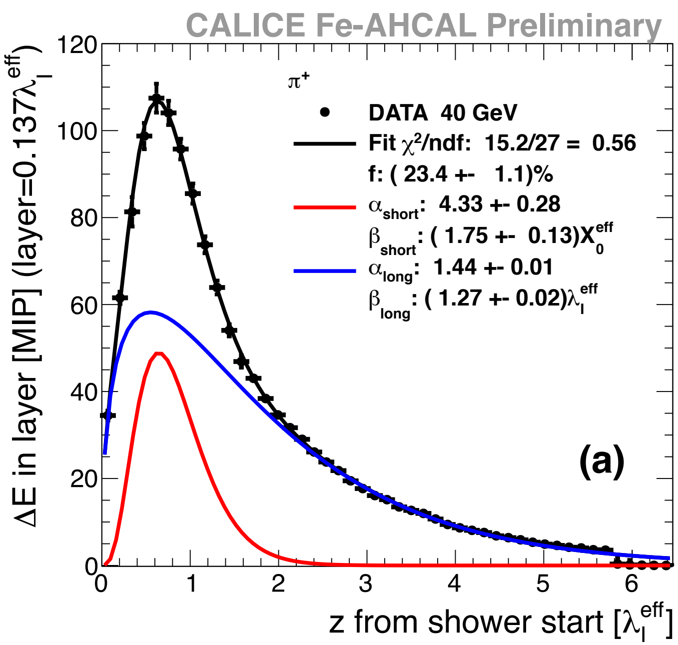
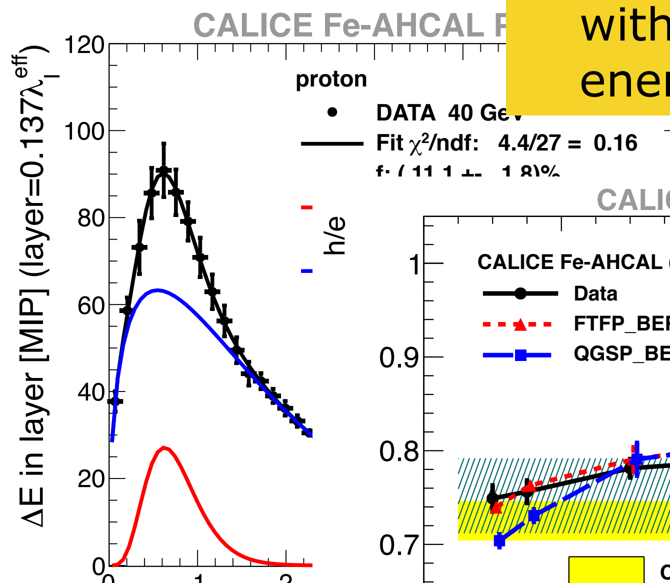
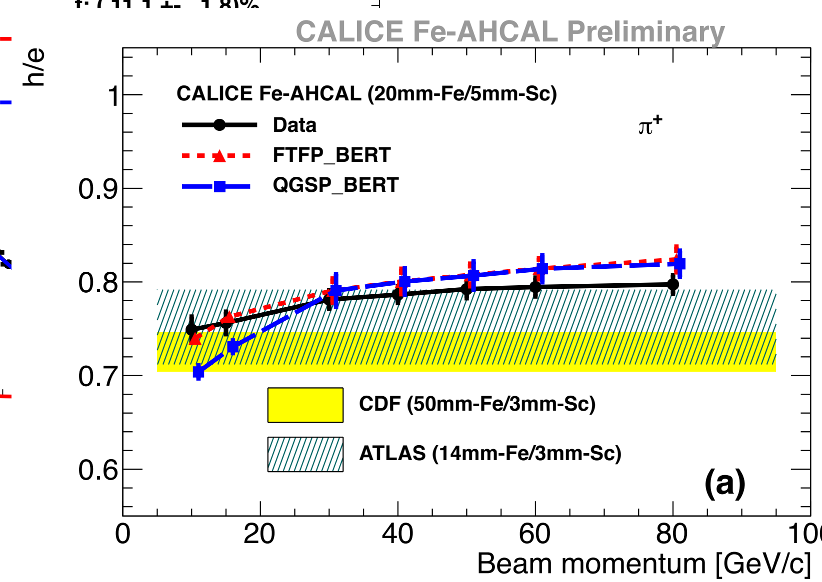
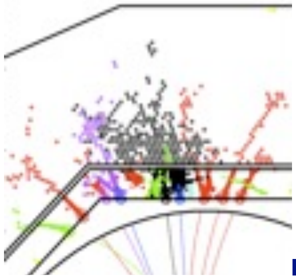


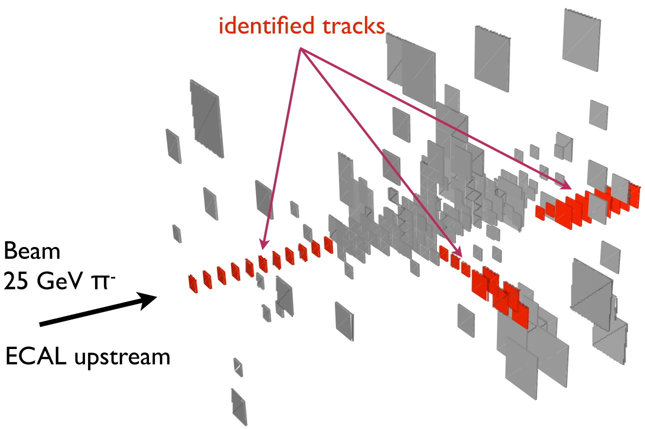


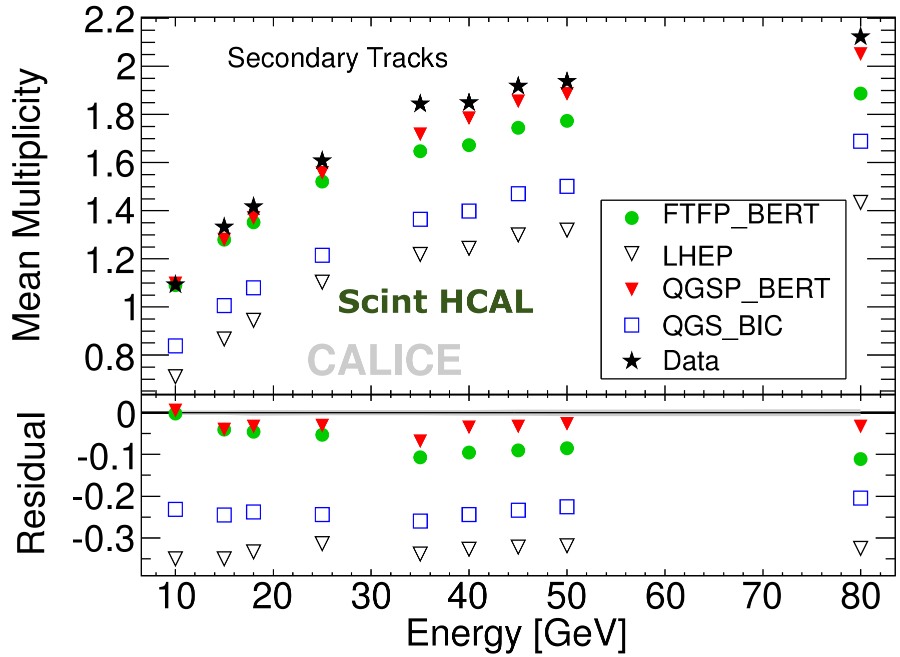
- Determine h / e ratio without assumption on energy dependence





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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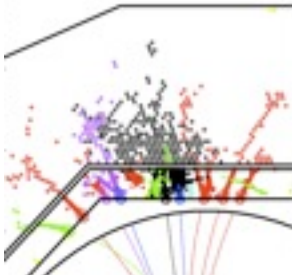

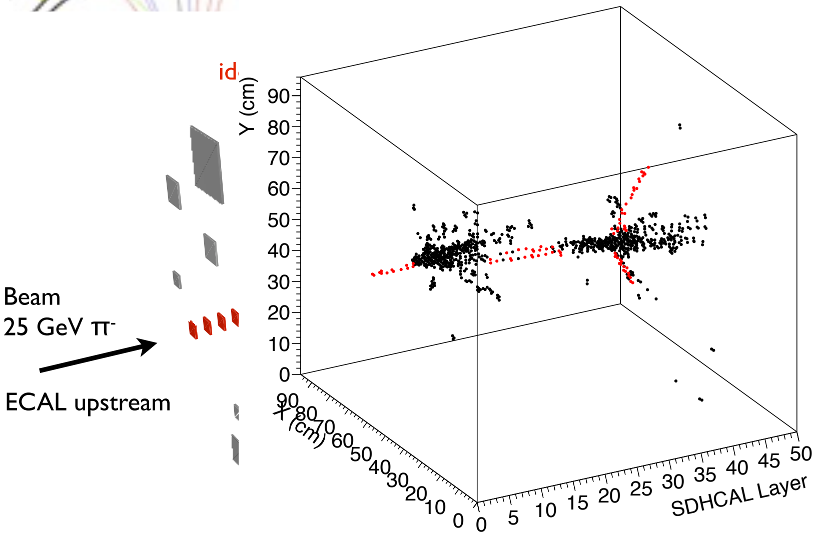

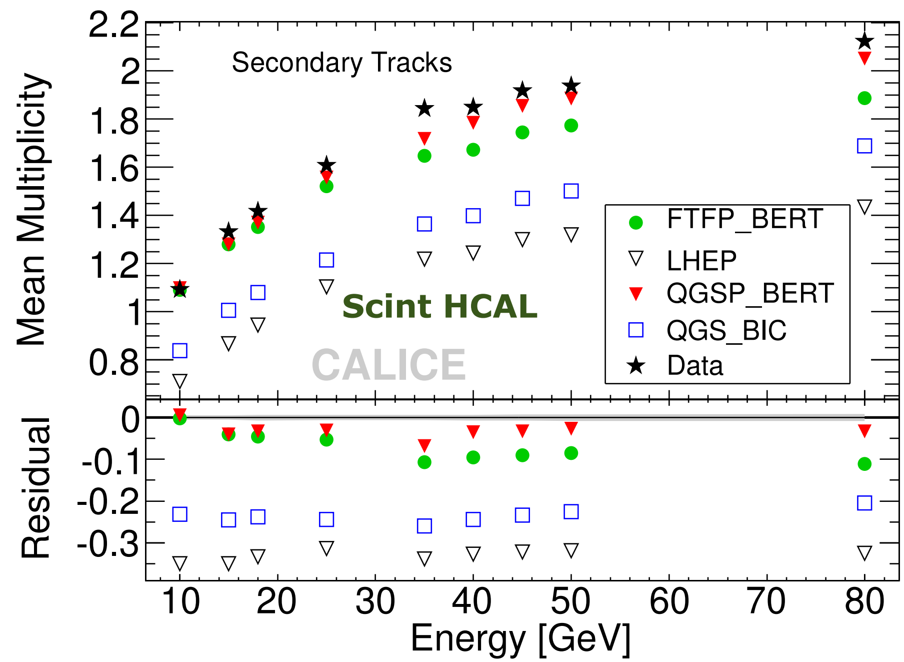

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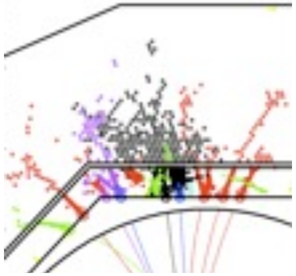

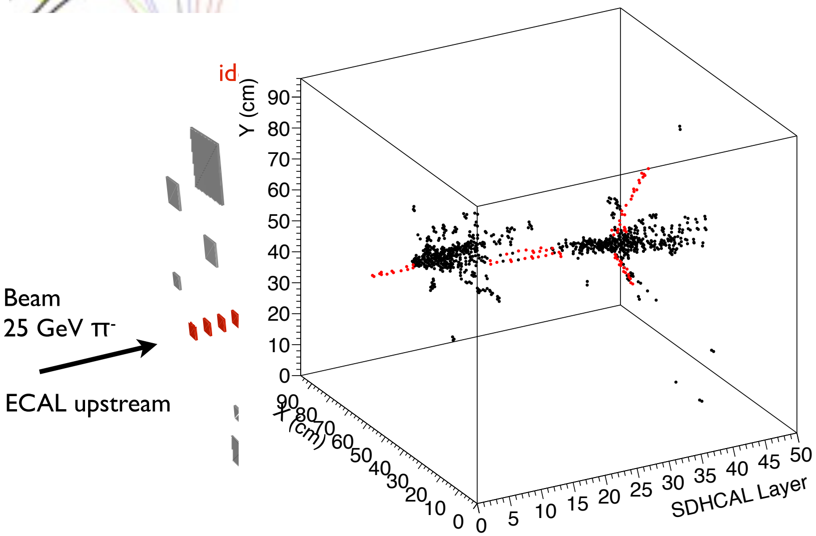

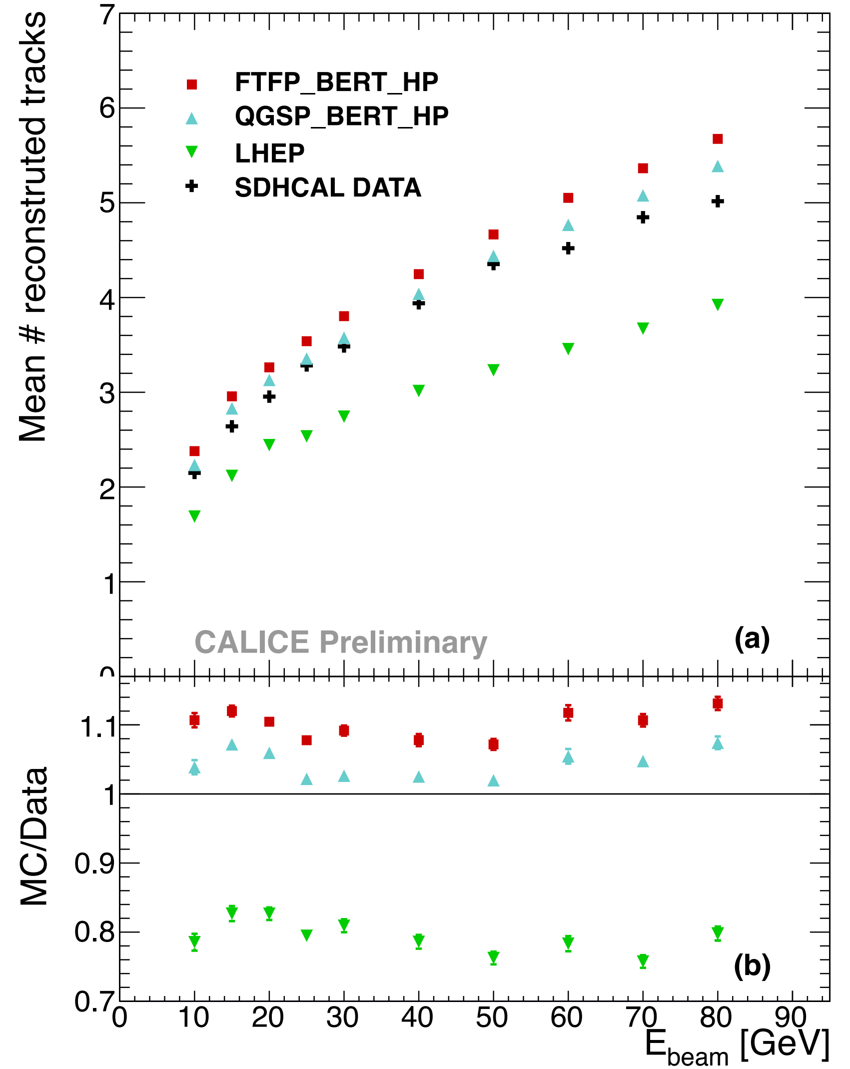

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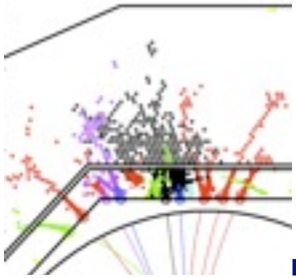
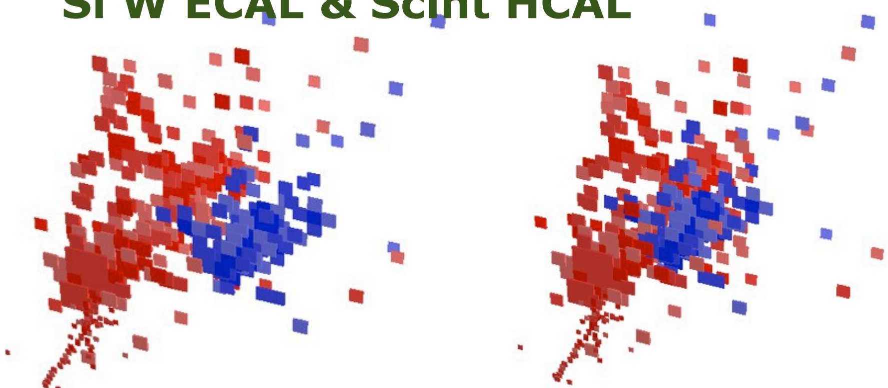


PFLOW with test beam data

Si W ECAL & Scint HCAL

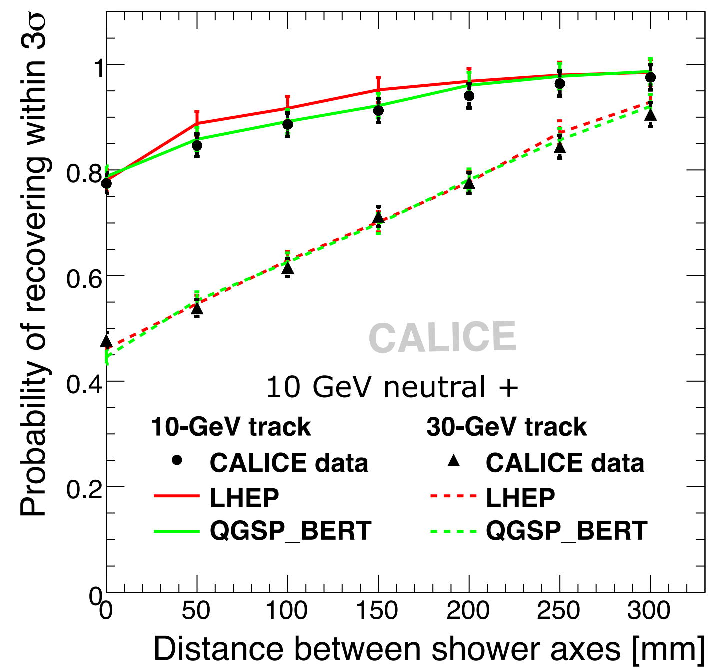


~18 cm separation of shower

~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

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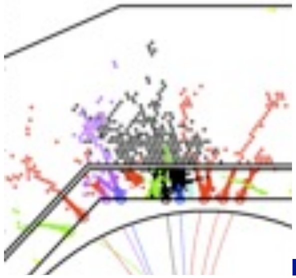
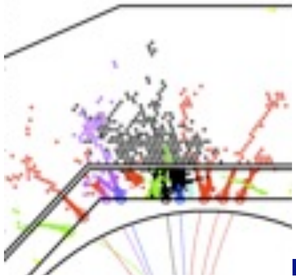


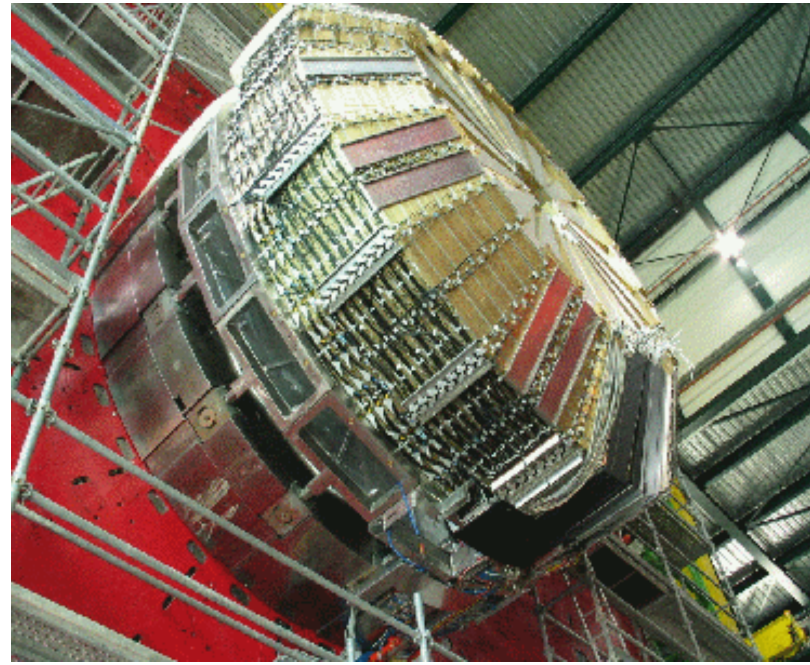
What we learnt

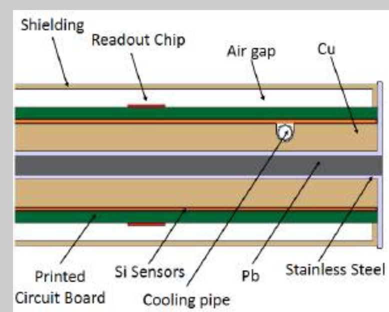
- The novel ECAL and HCAL technologies work as expected
  - Si W ECAL and Sci Fe AHCAL analysis nearly complete
  - Analysis of the more recent tests has just begun - still a huge potential
- The detector simulations are verified with electromagnetic data.
- The hadronic performance is as expected, including 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.

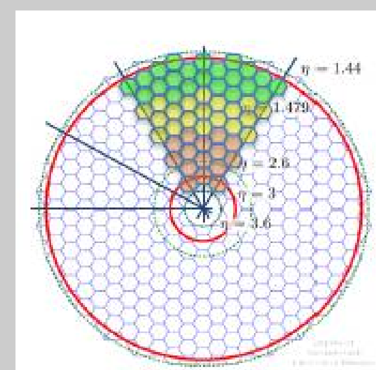


Hadron collider frontier

- CMS 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

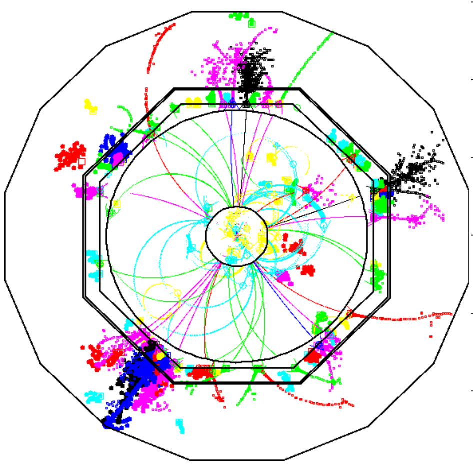




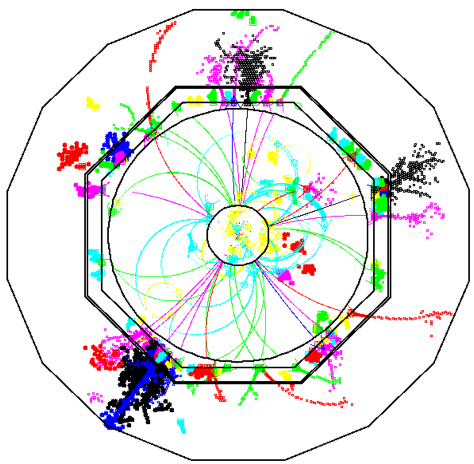


Energy resolution and Granularity

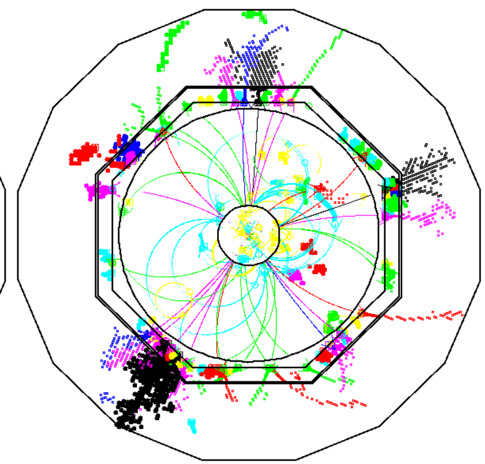
1x1



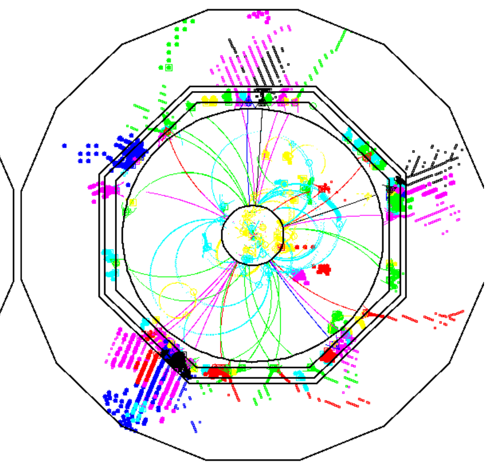
3x3

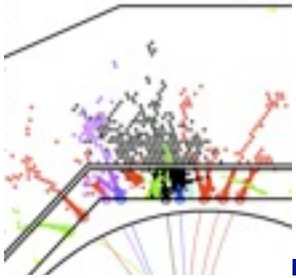


5x5



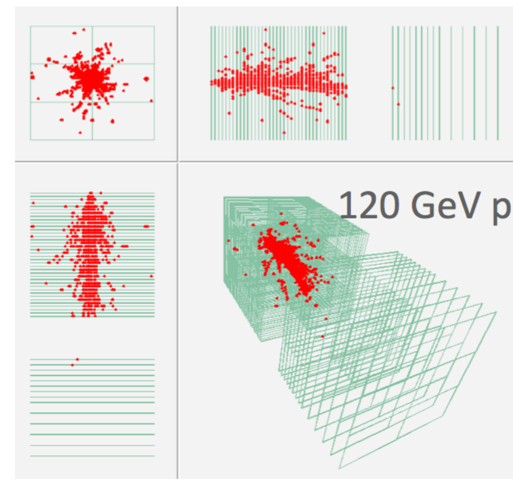
10x10





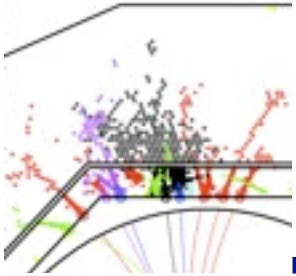
Energy and Granularity

- 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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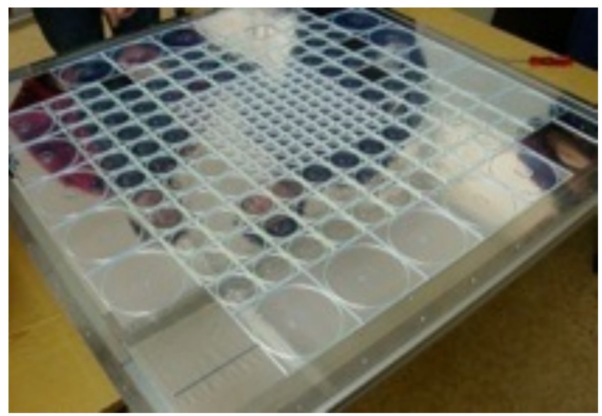
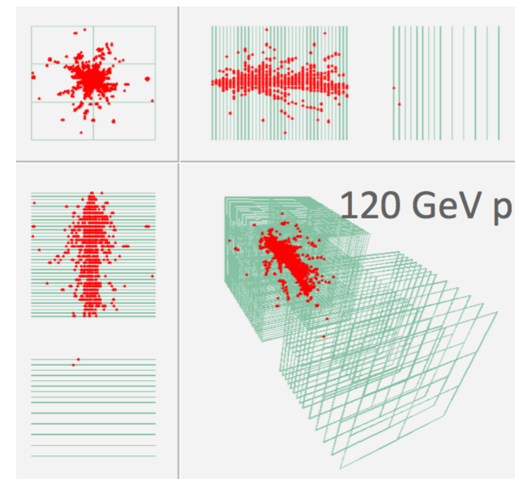
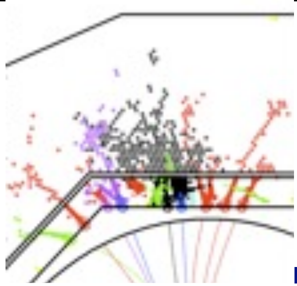




“Energy resolution is everything!”

“We need enough of both!”

“Granularity is everything!”

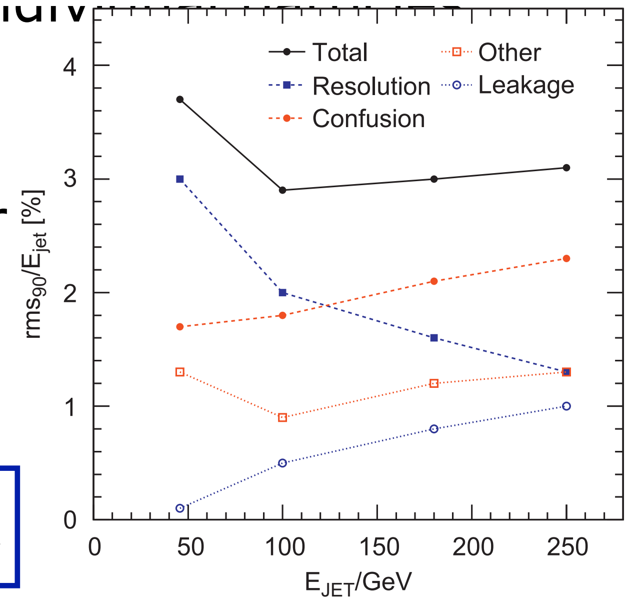


Particle flow performance

- Separating the energy depositions of individual particles requires high granularity

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

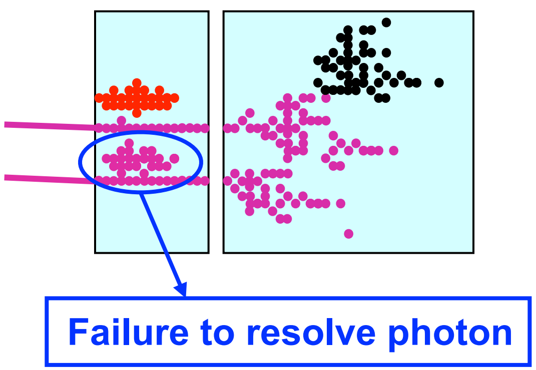
M.Thomson, Nucl.Instrum.Meth. A611 (2009) 25-40



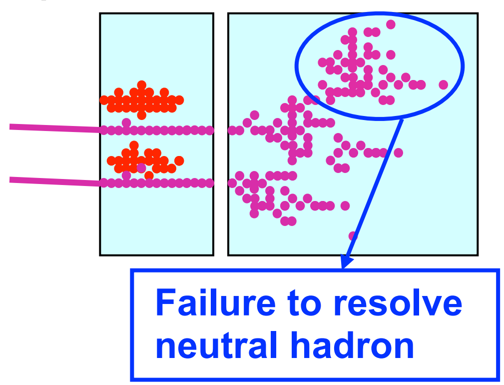
Pattern recognition based on topology **and** energy

Types of confusion:

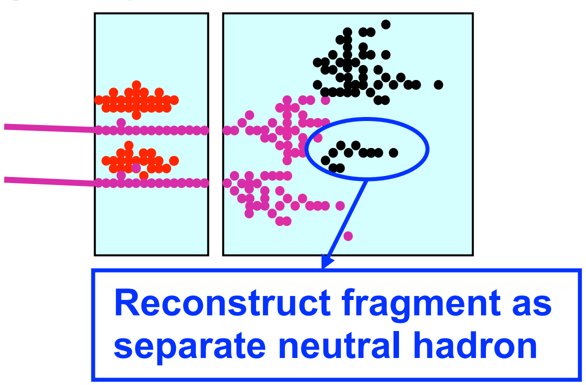
i) Photons

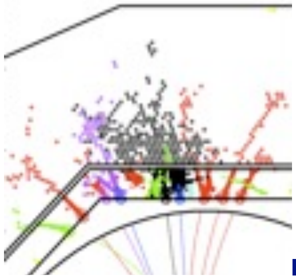


ii) Neutral Hadrons



iii) Fragments

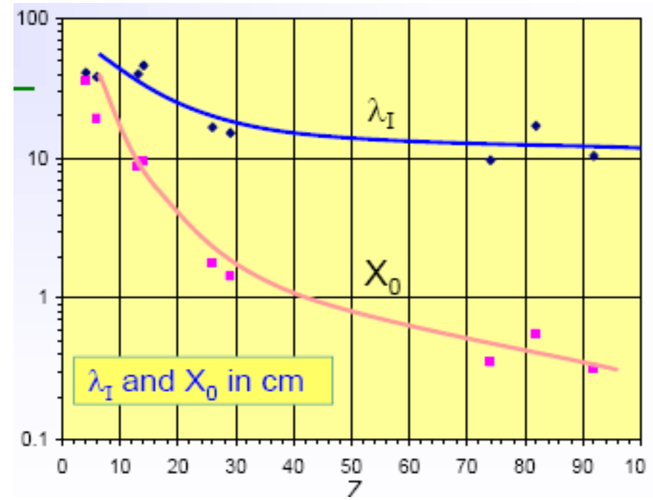


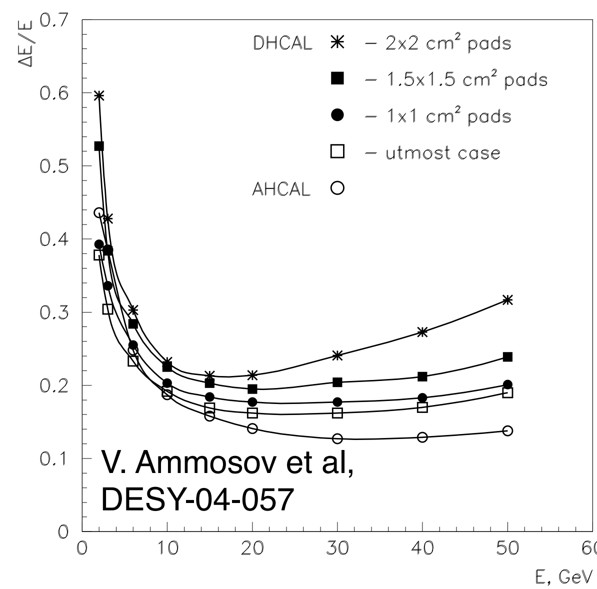


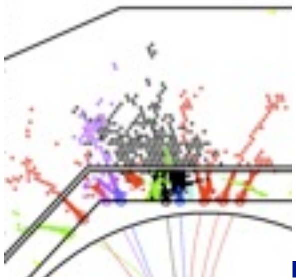
Initial choices

- 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

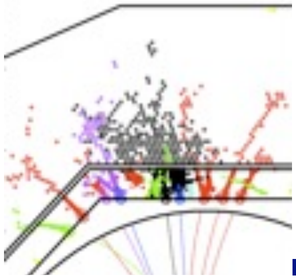






Gaseous calorimeters

- Gaseous HCAL with **analogue** readout would have poor resolution
  - small sampling, large Landau fluctuations
- **Digital** calorimeter idea: count particles, ignore fluctuations
  - 1cm^2 cells: saturate above 30 GeV
- **Semi-digital** idea: mitigate saturation using several thresholds and weights
  - assumes signal prop. to E deposition



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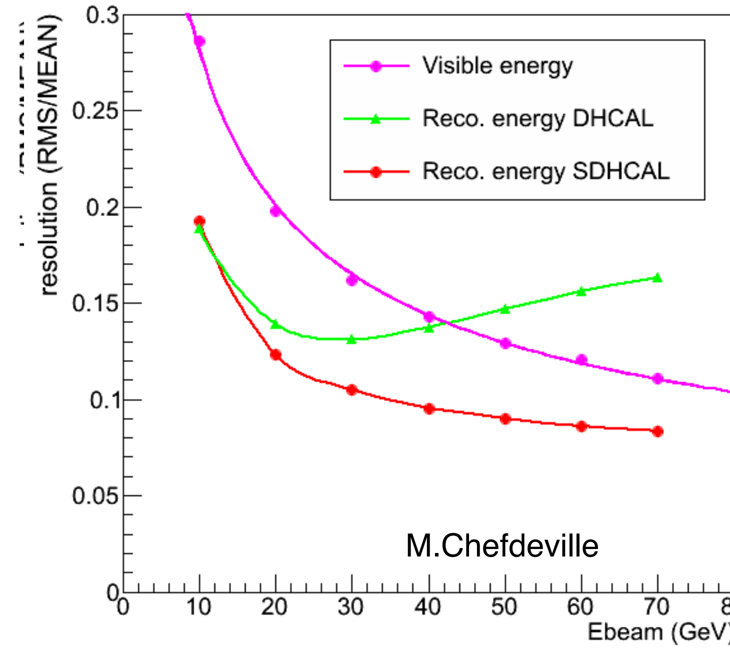
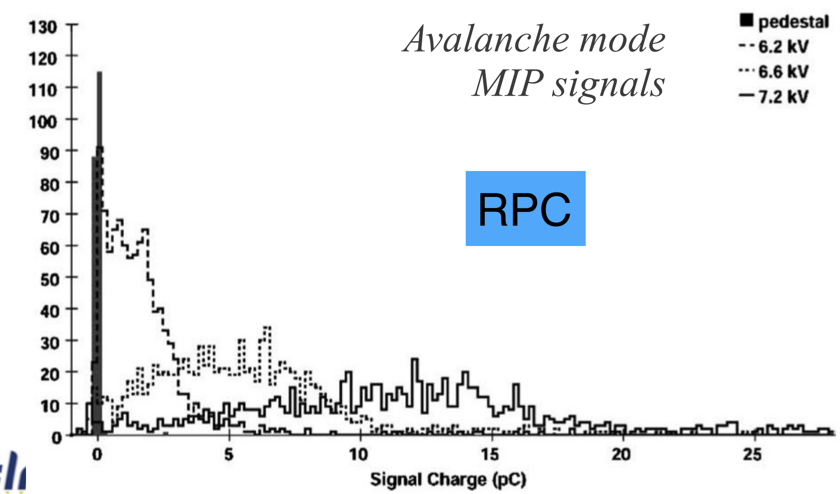
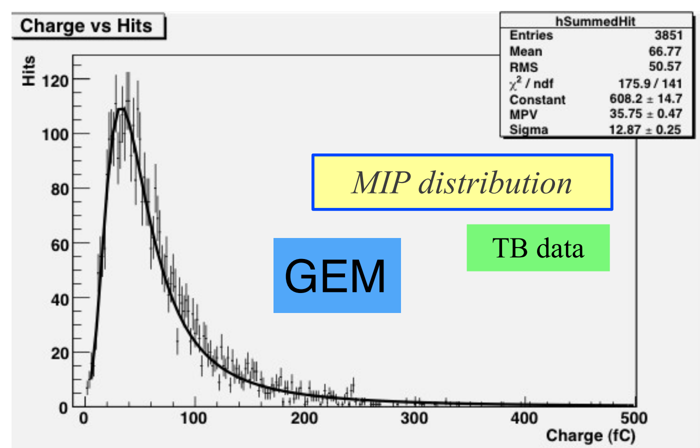
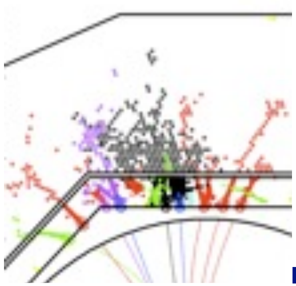






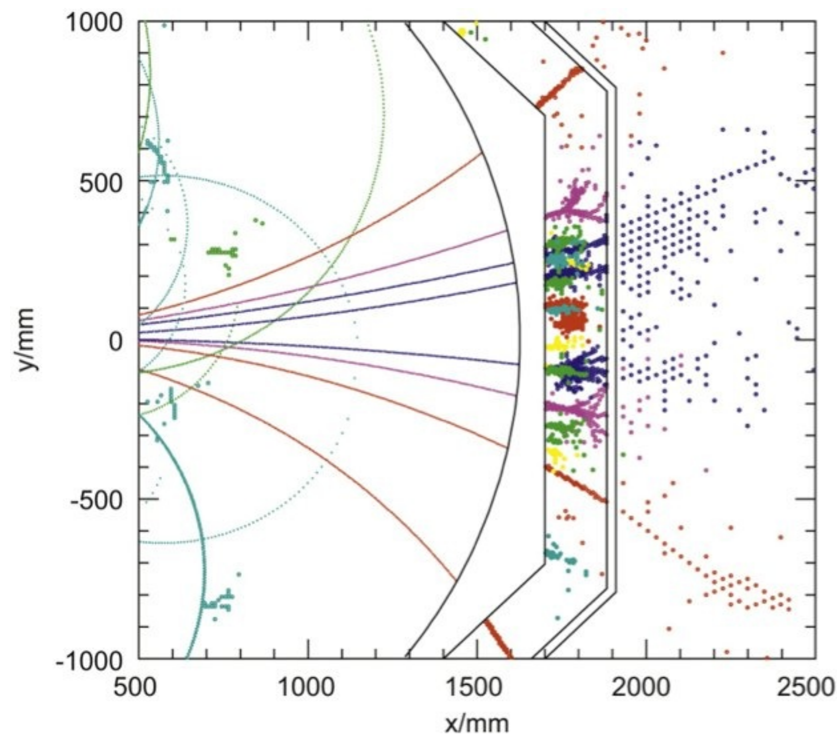


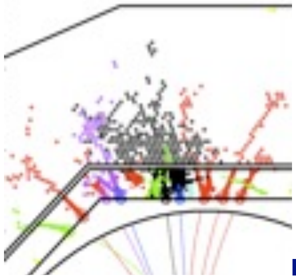
Effects of high granularity

Granularity

Confusion

Particle flow
Perfomance





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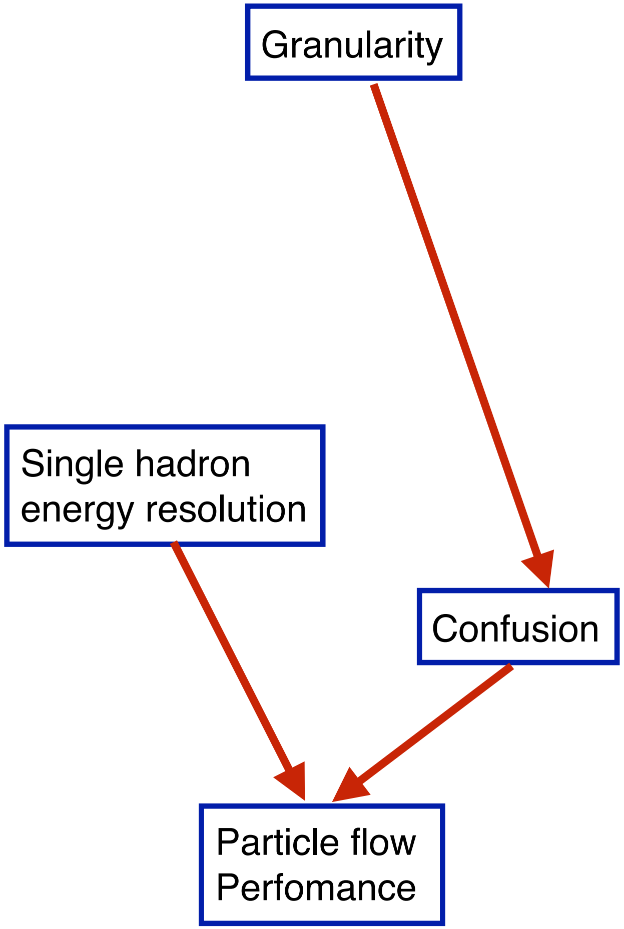

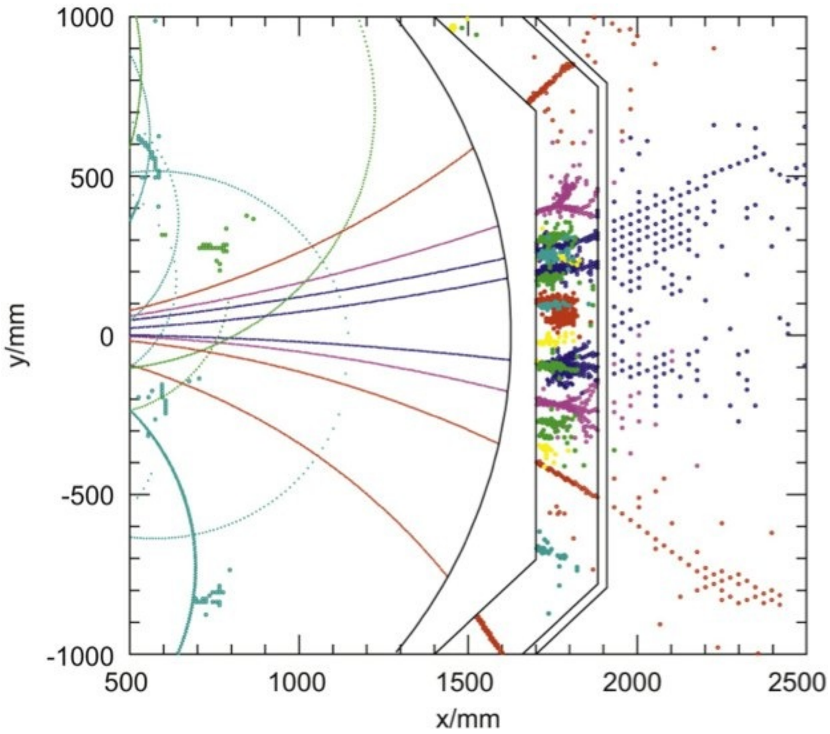

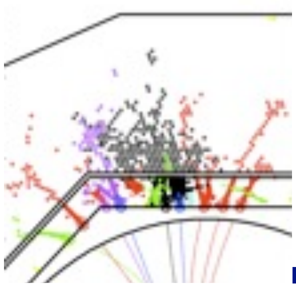

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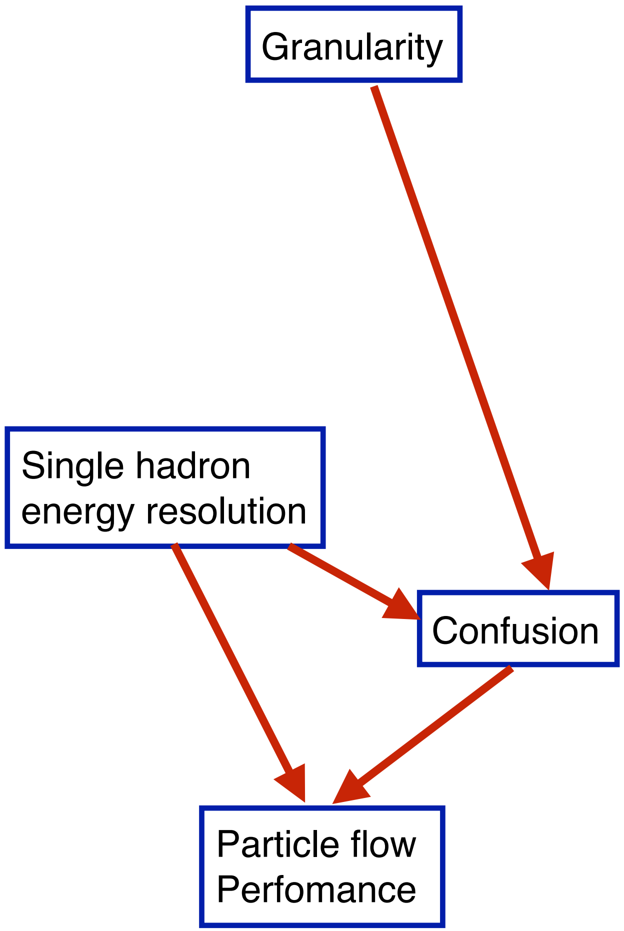

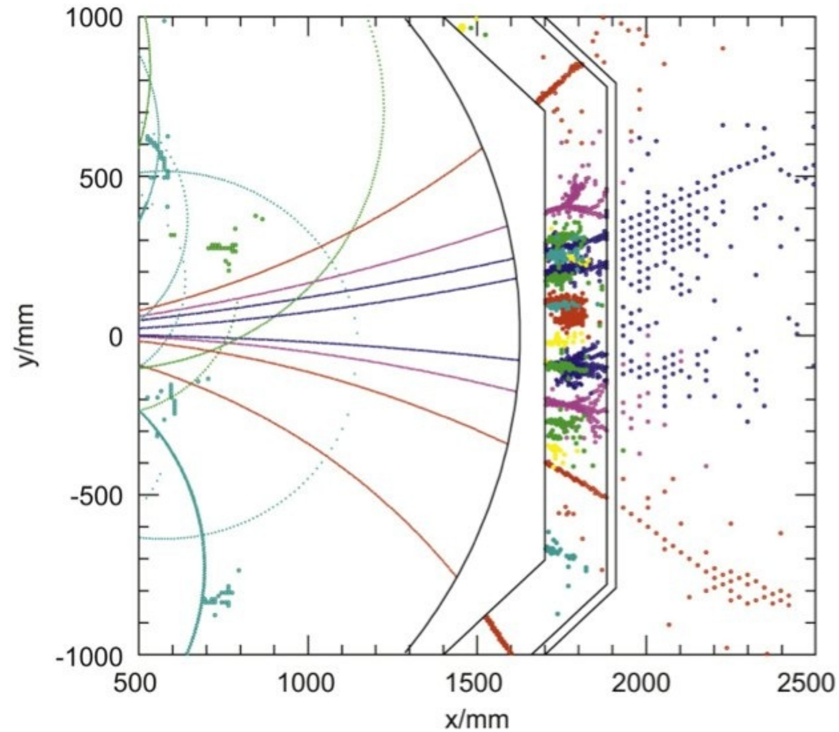

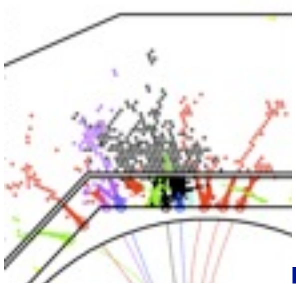

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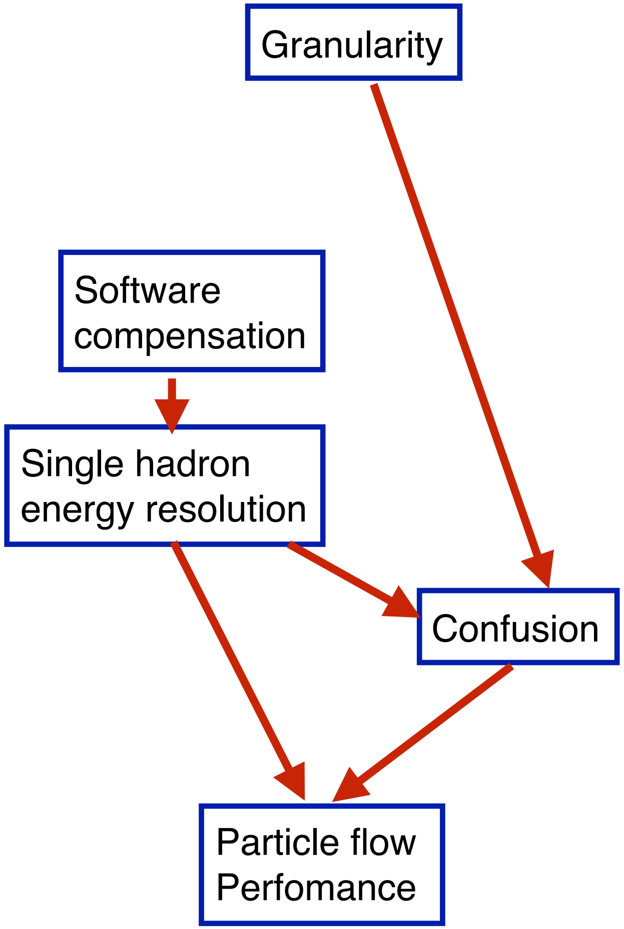

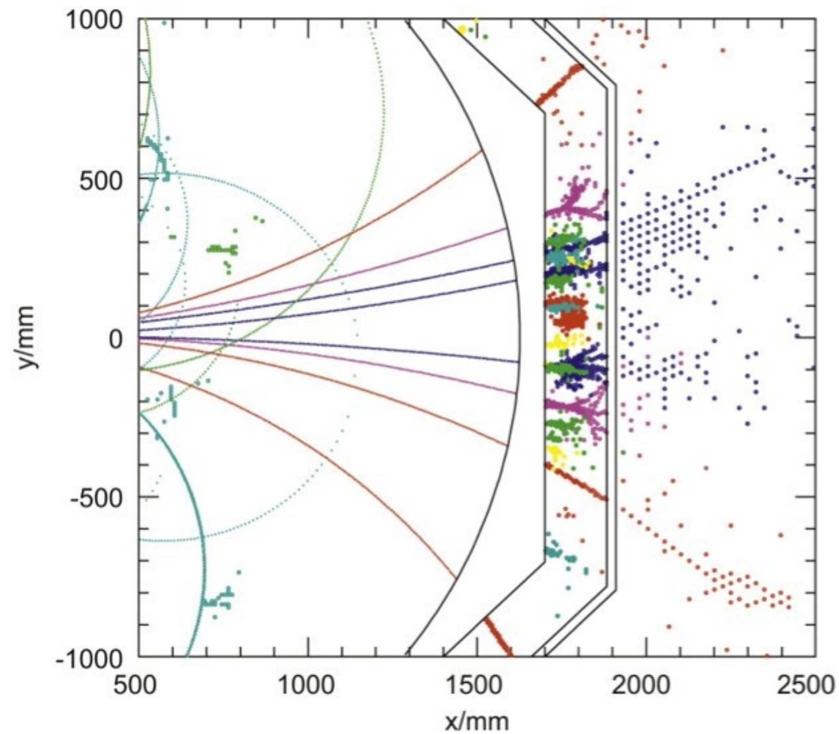

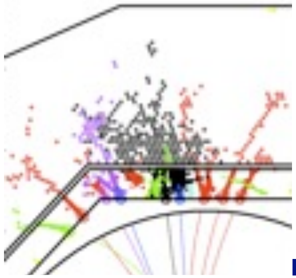

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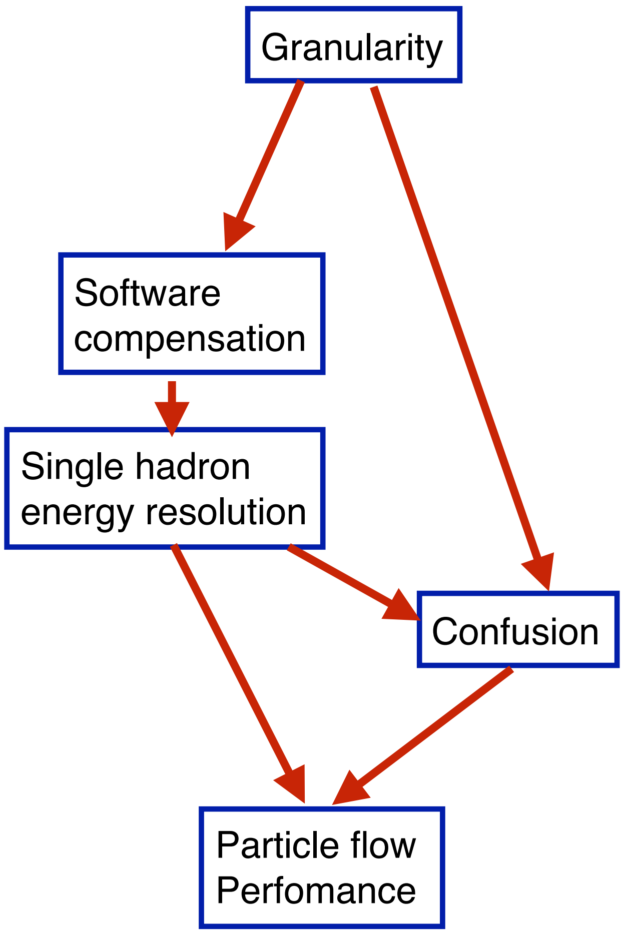

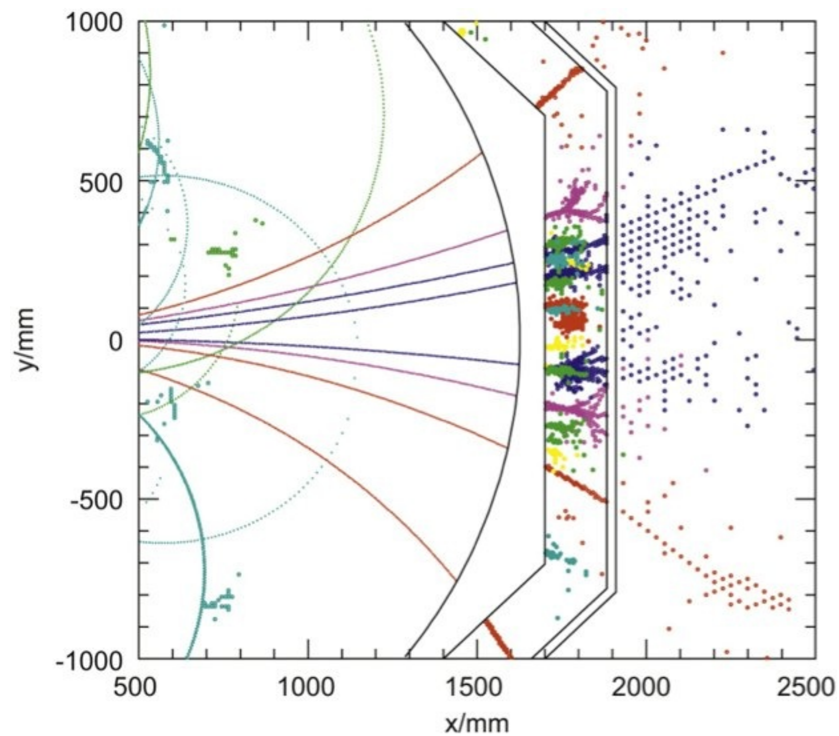

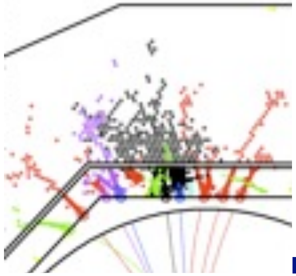

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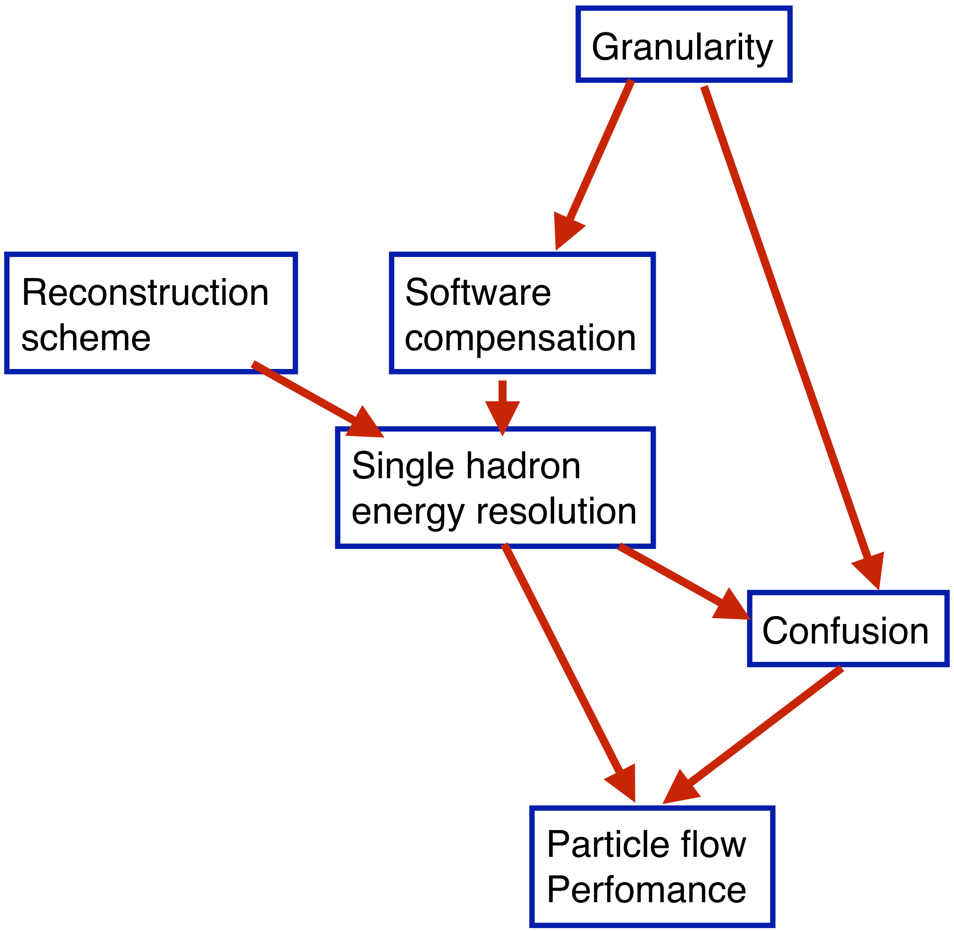

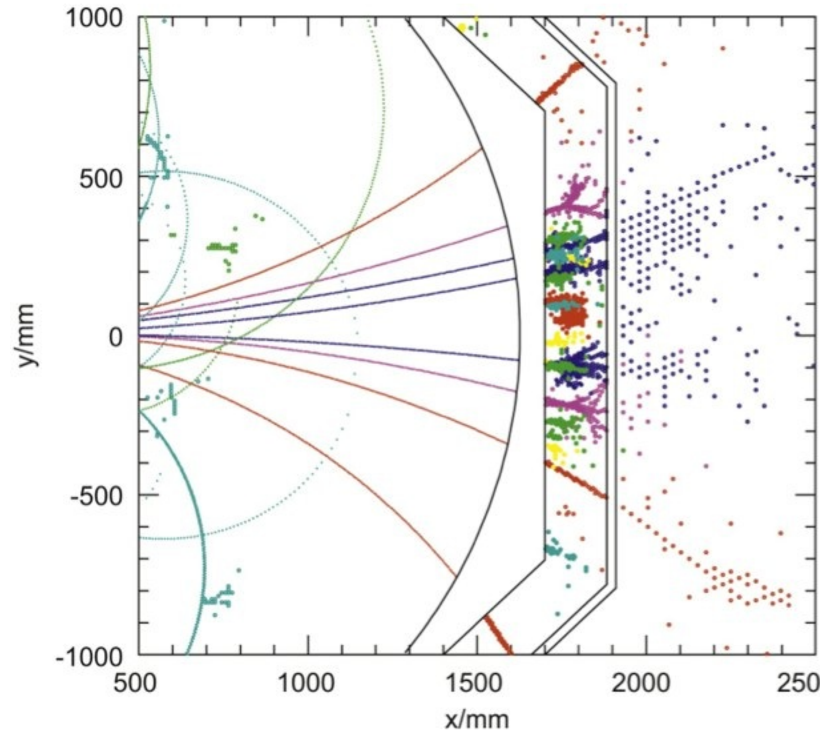

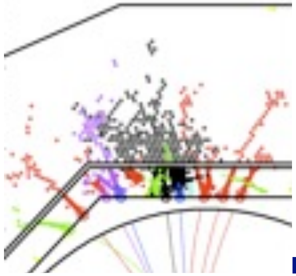

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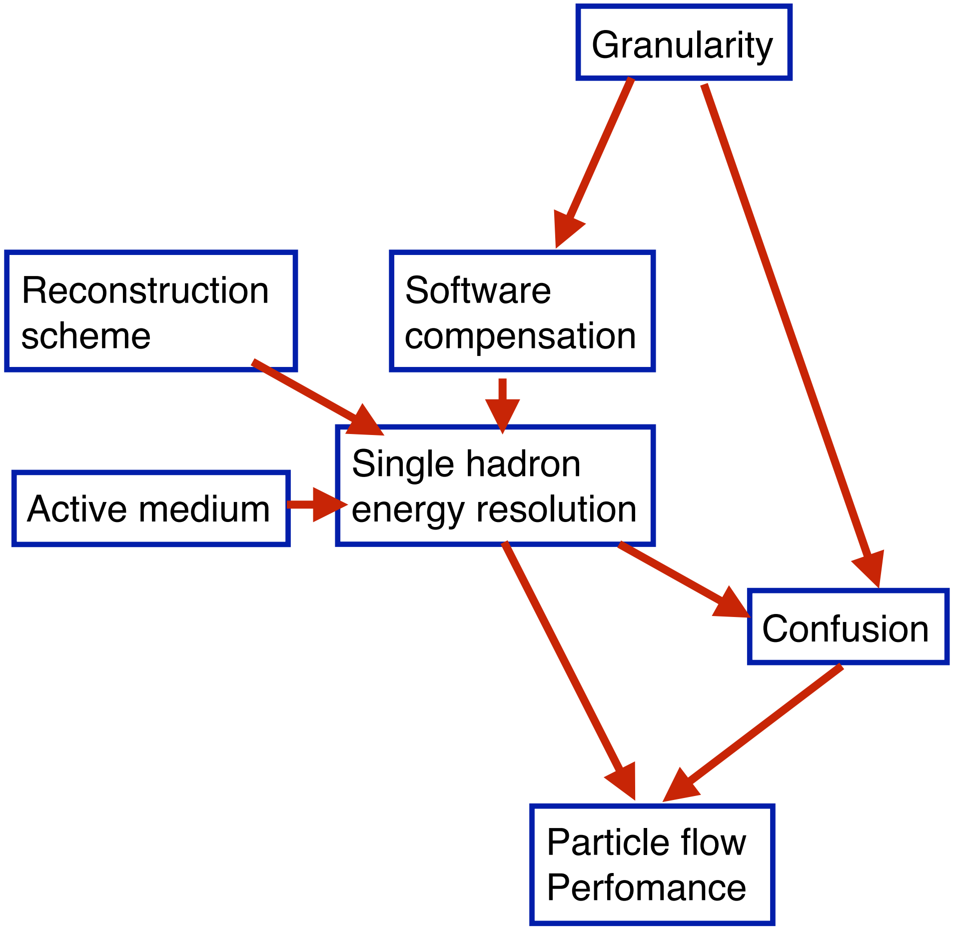
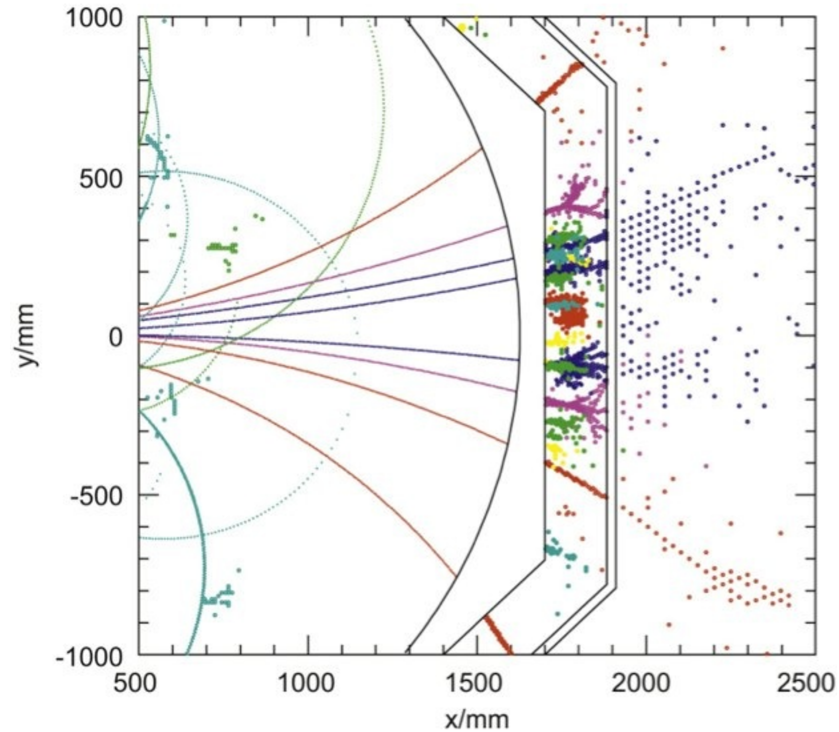
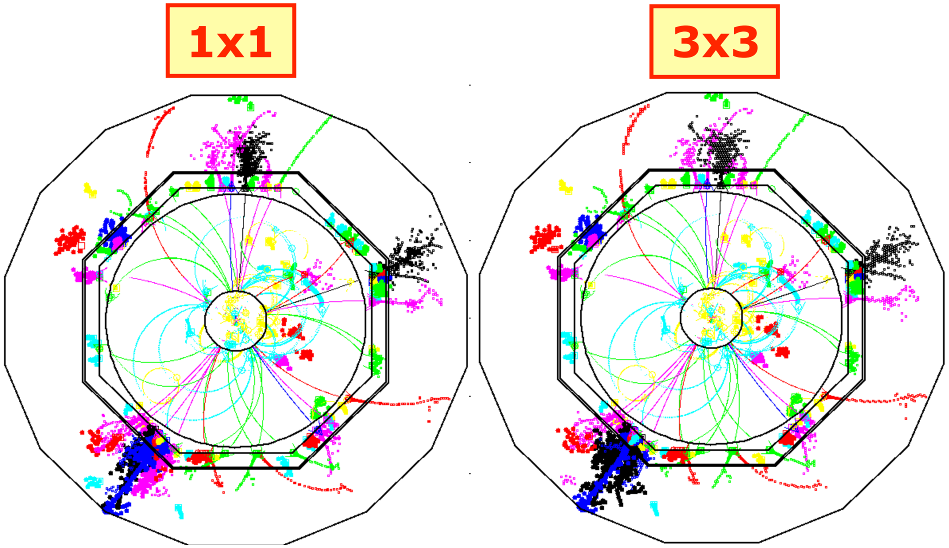
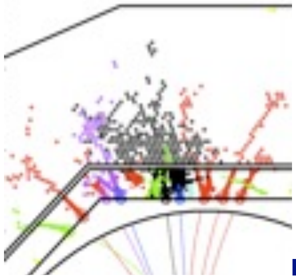




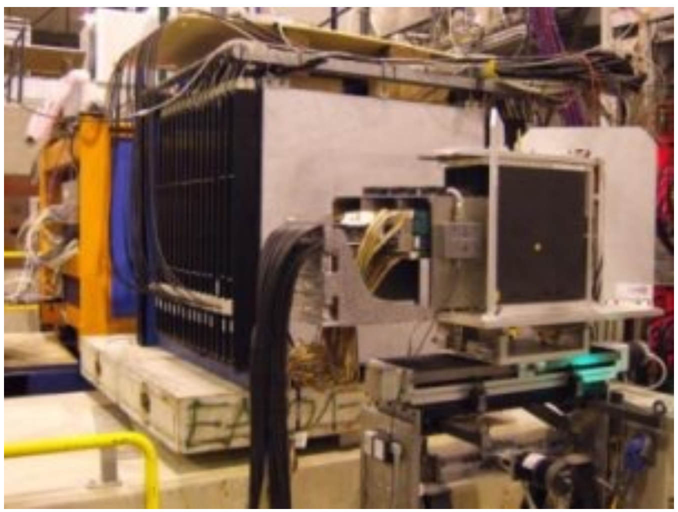
Analogue and (semi-) digital reconstruction of single hadrons

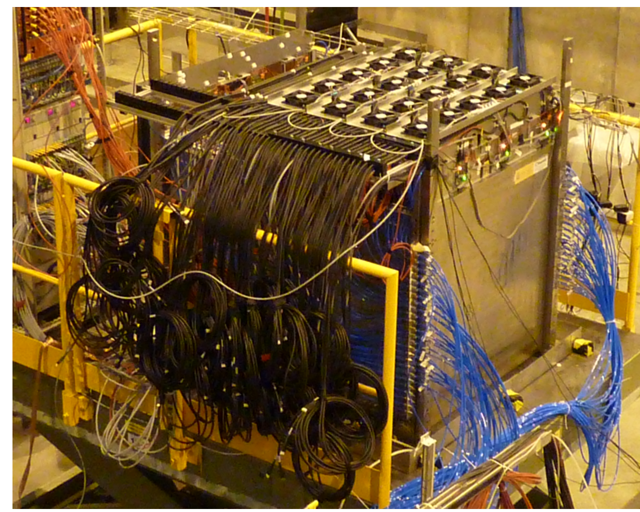


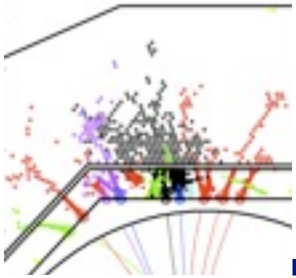


AHCAL and SDHCAL

- 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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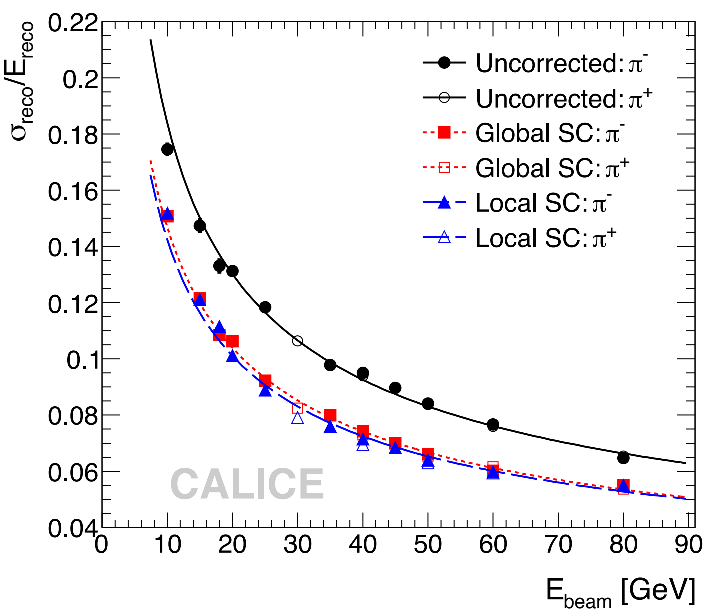
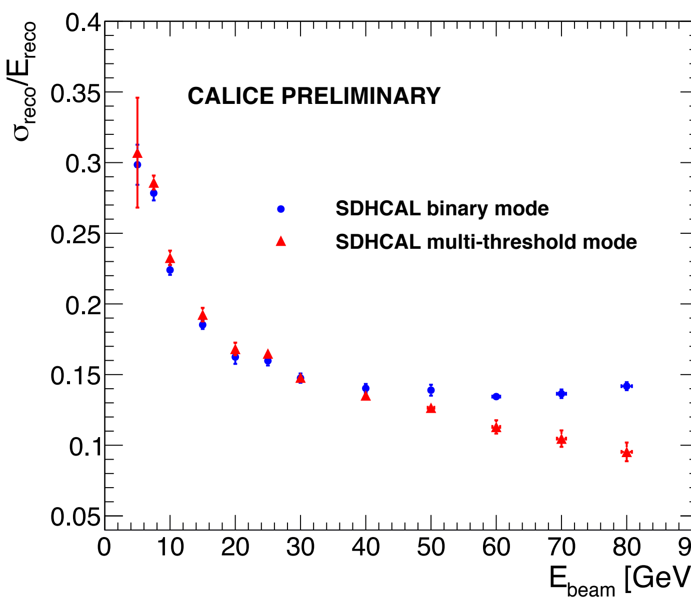
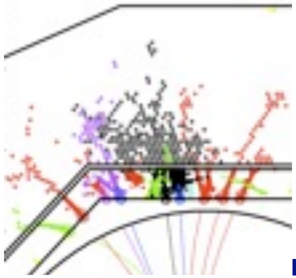
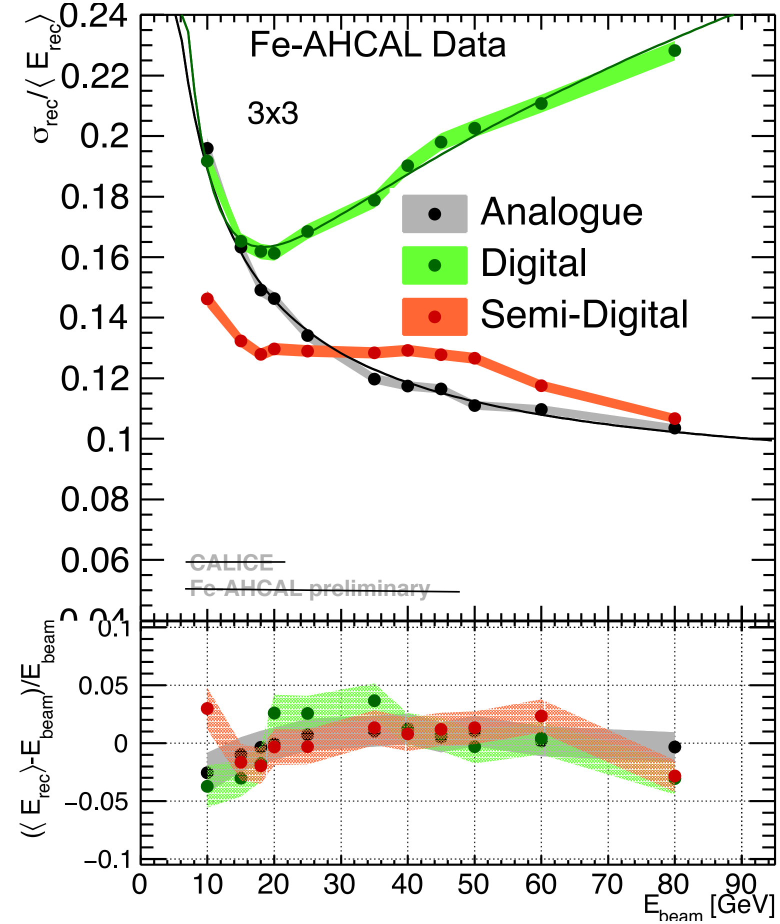


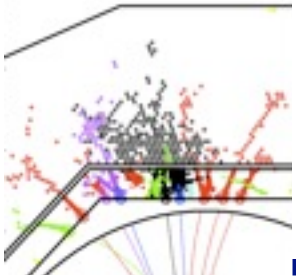




(Semi-) digital reconstruction of AHCAL

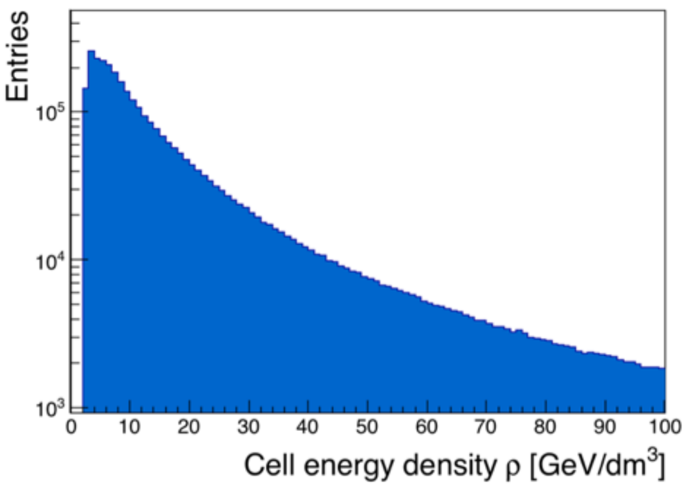
- Digital reconstruction:
  - 3x3 is too coarse
- Semi-digital
  - close to analoge
  - at low E even better
  - with less information?
- Count hits: suppression of Landau fluctuations
- Semi-digital reconstruction uses energy-dependent weights

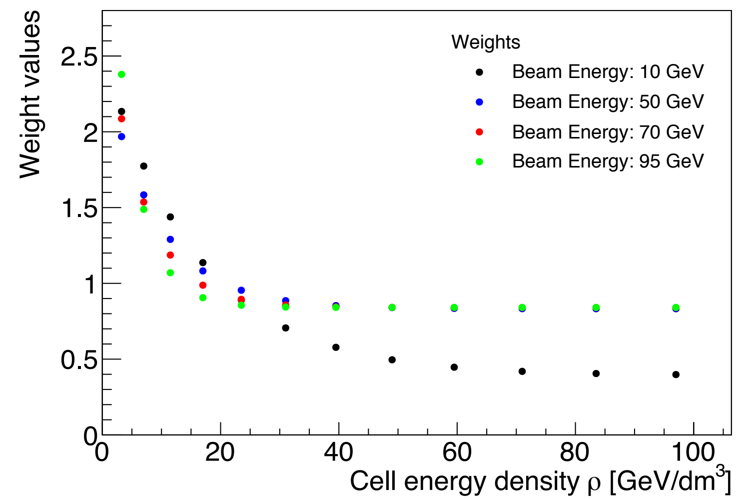




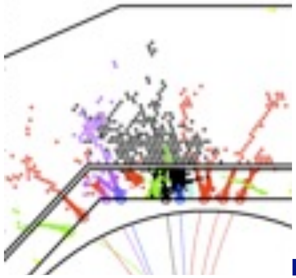
Software compensation

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





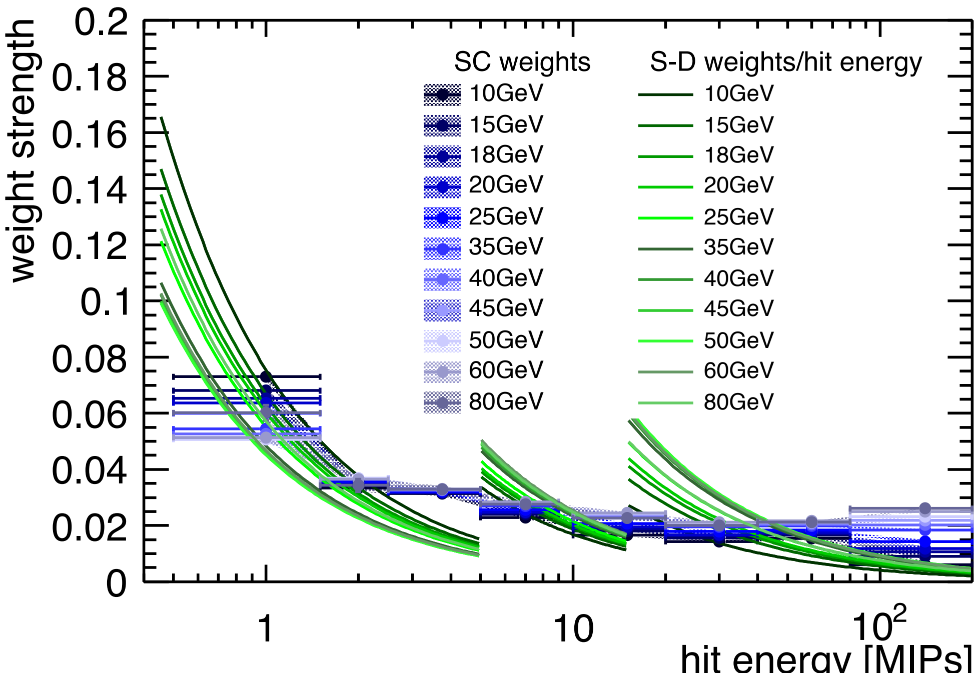
- Optimal weights depend on hit energy (density) and total energy
  - use un-weighted energy as first estimator



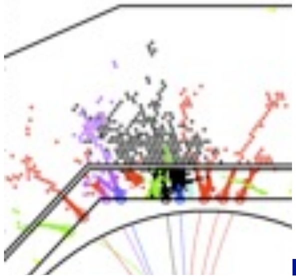
Analogue and digital weighting

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

- Counting is equivalent to weighting with 1/E_{hit}: ω = α/E_{hit}
- Use common formalism and learn from each other



in principle the same
differences in detail



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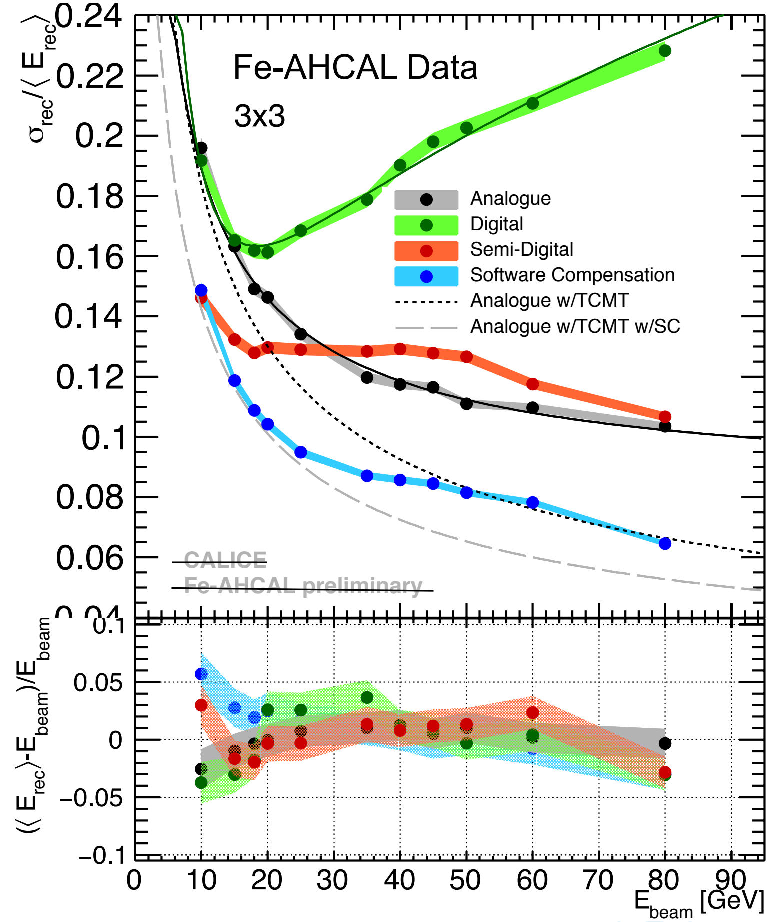
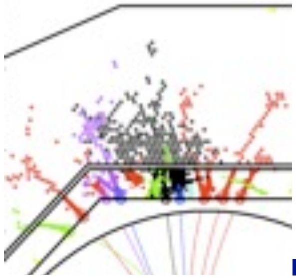
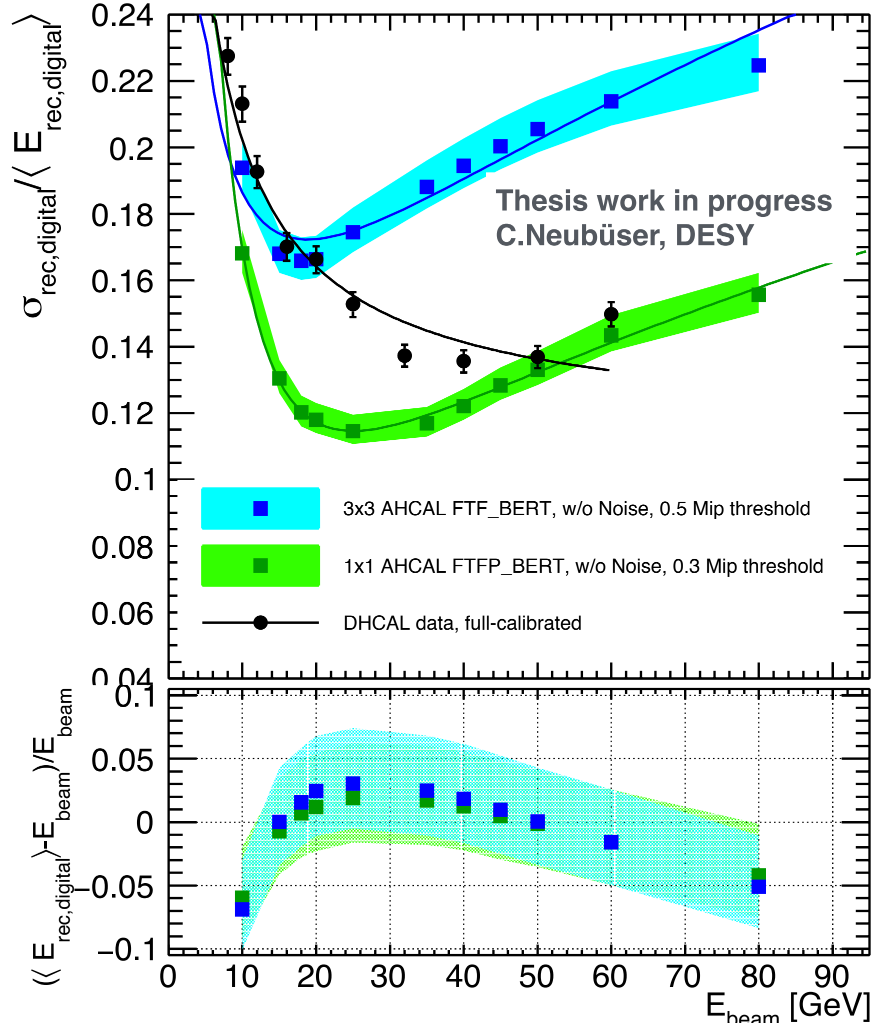


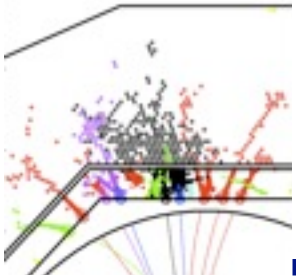
- Make full use of analogue information:
- Software compensation: best



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





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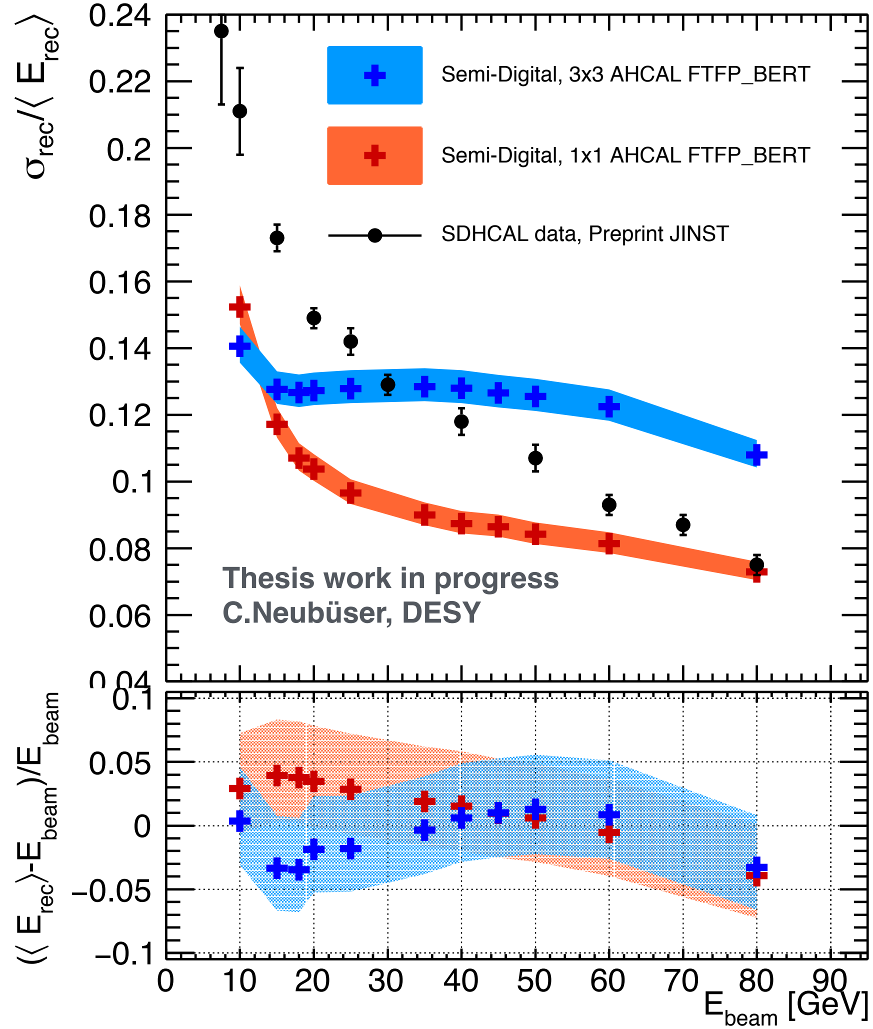
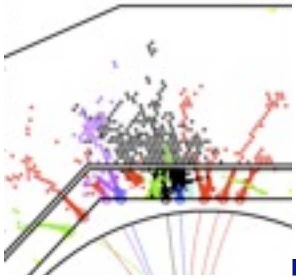
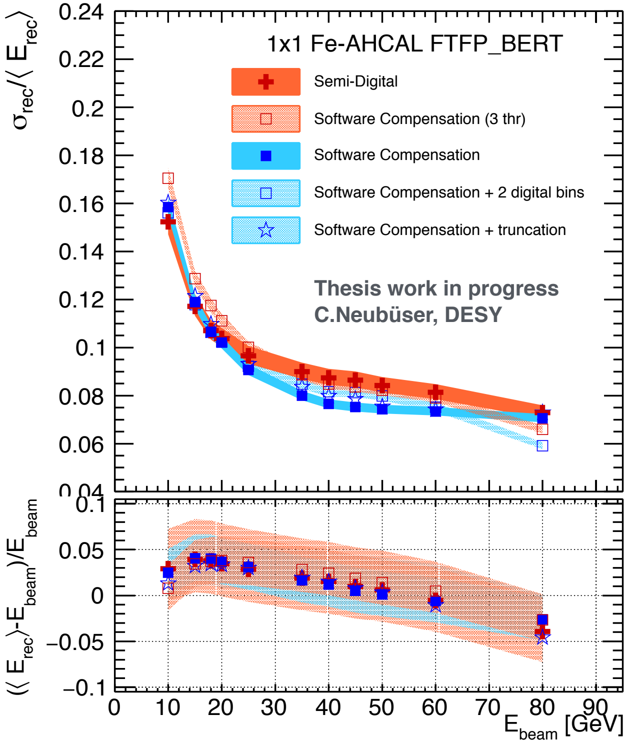
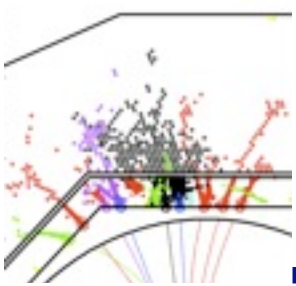




Read-out scheme and resolution



- vary number of bins and energy dependence within bins
- small differences once some weighting is applied



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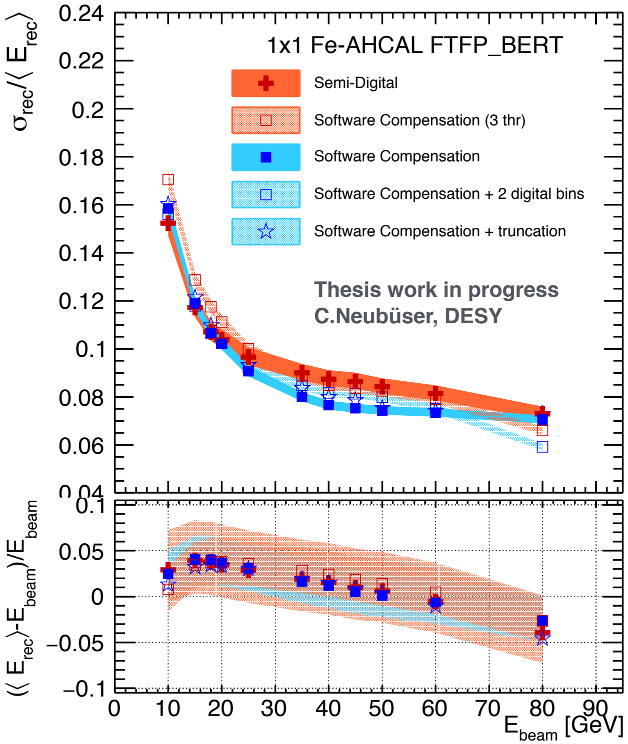

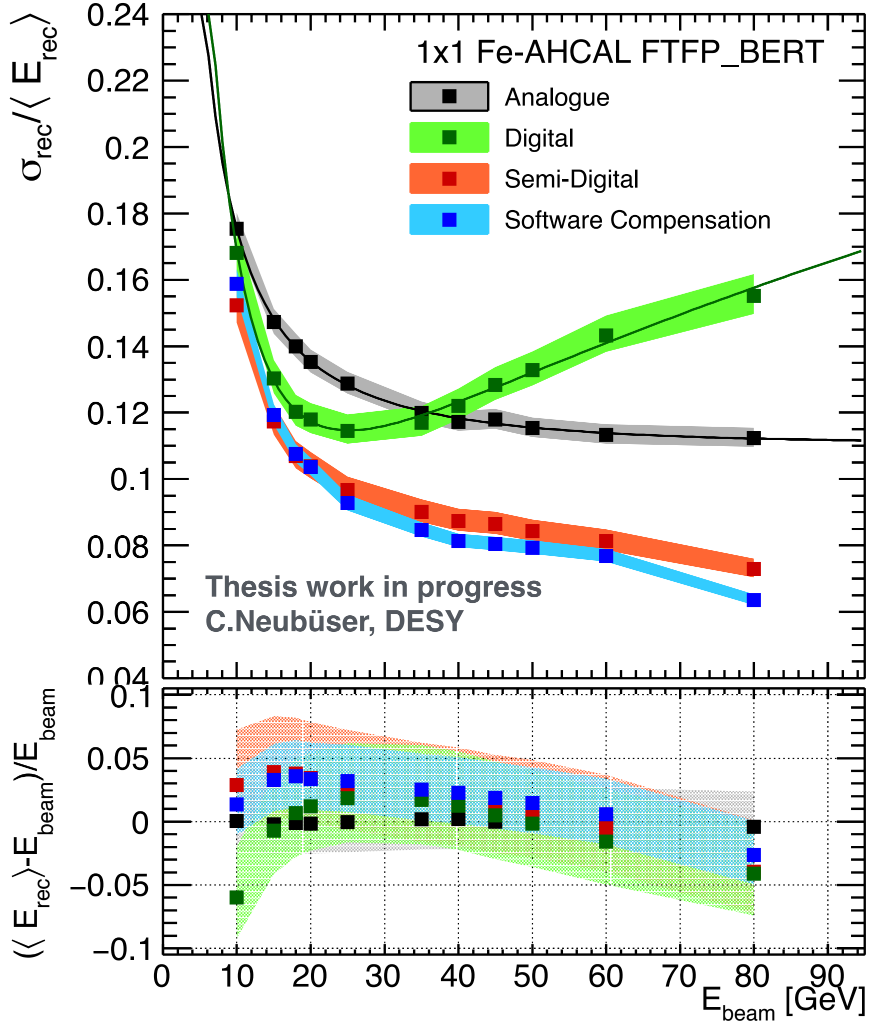

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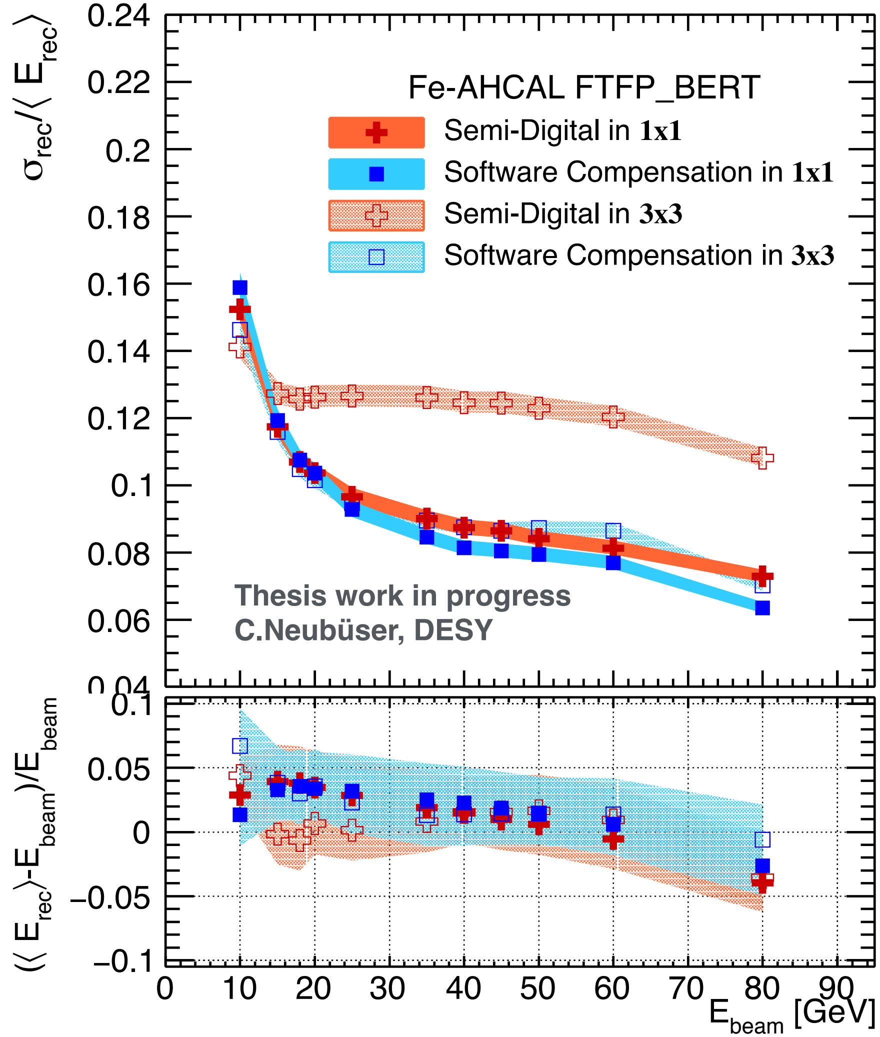
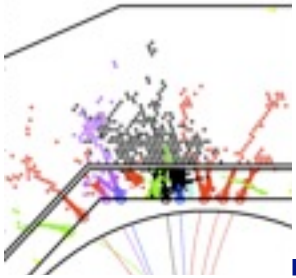
Granularity and resolution 1

- 1x1: semi-digital as good as analogue with s/w comp
  - 2 bits are enough
- 3x3: analogue with s/w comp better than SD, as good as 1x1
  - for analogue read-out 3x3 is enough

- Performance limitations of gaseous HCAL to be understood





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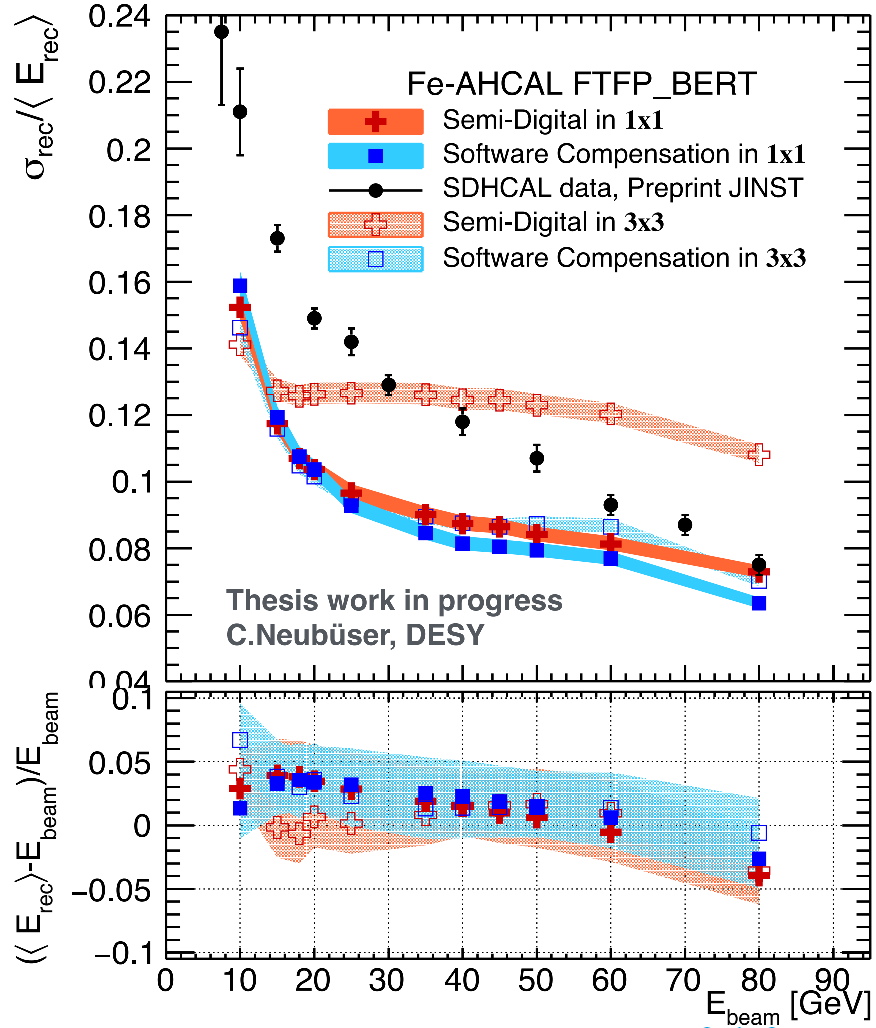
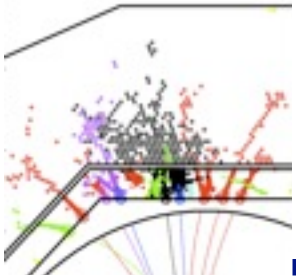
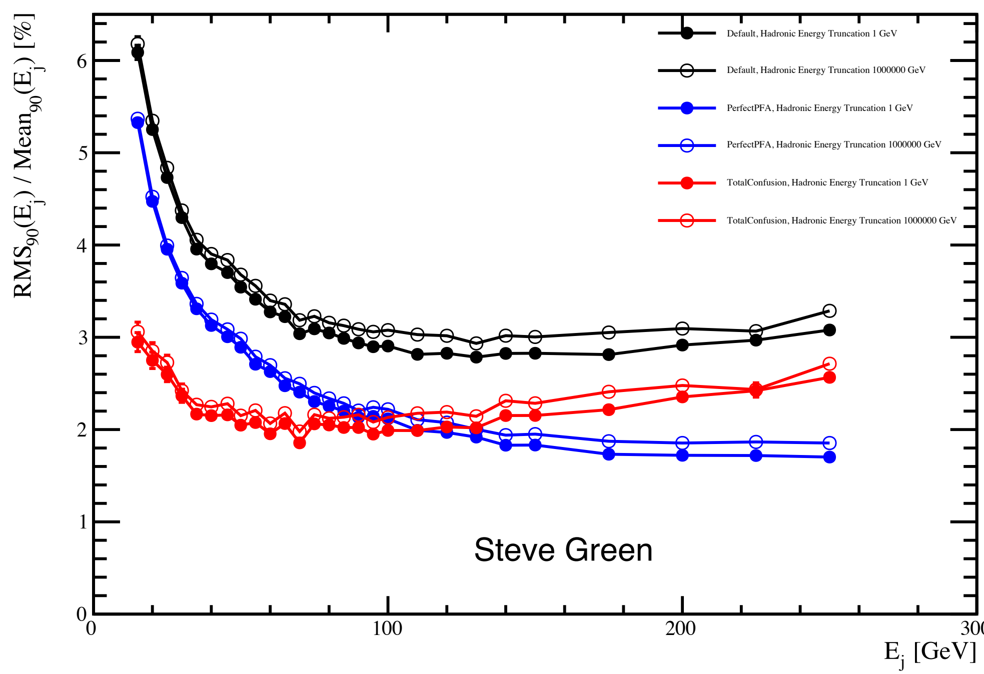


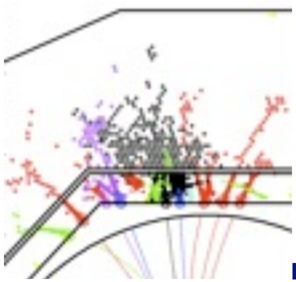


s/w compensation and PFLOW

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

studies with Pandora PFA





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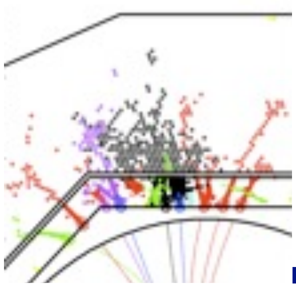

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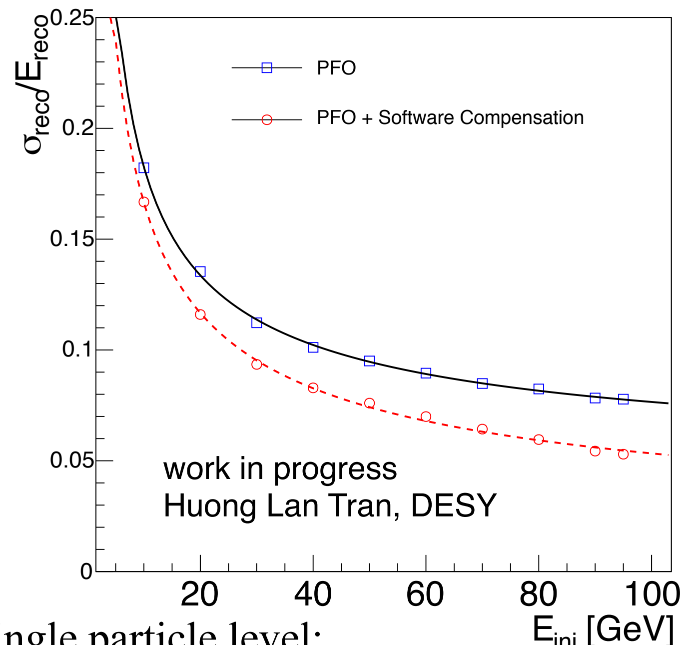
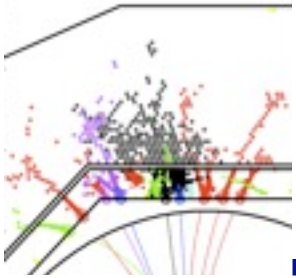


Single particle level:



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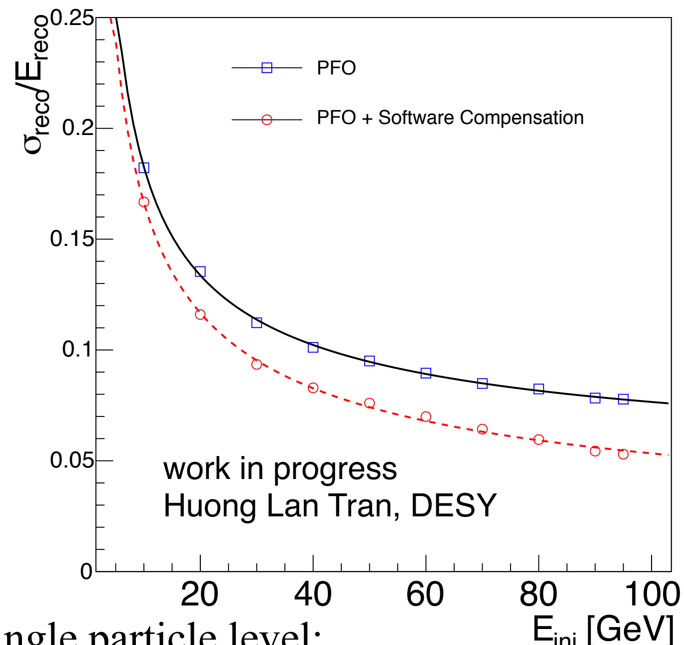
studies with F



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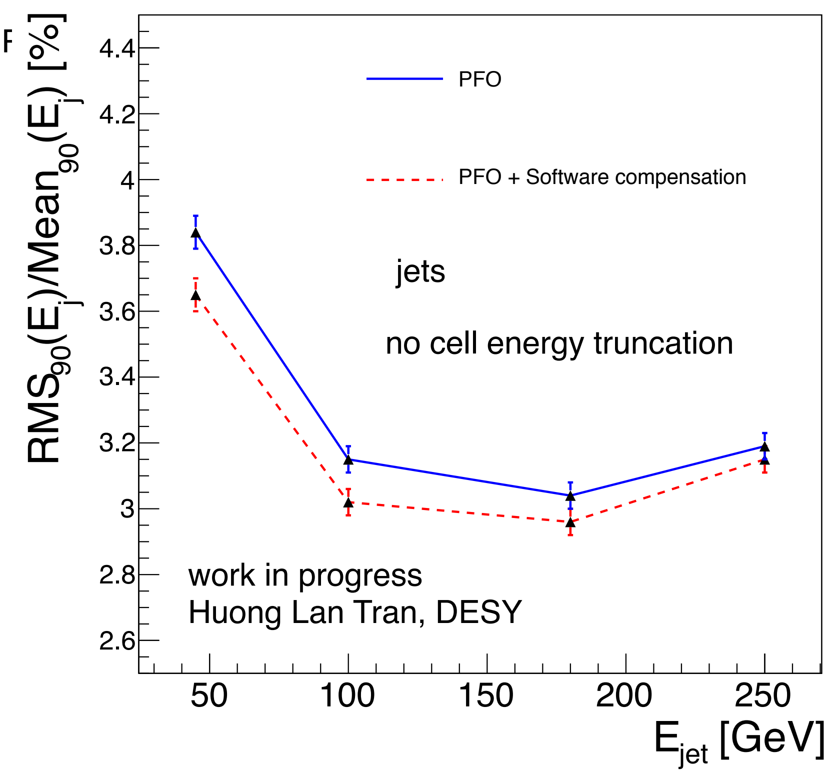
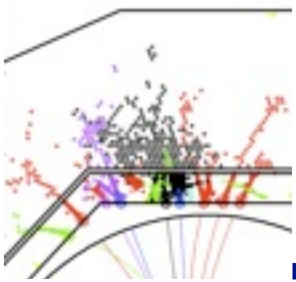
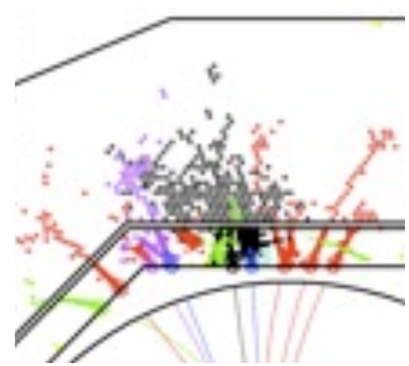
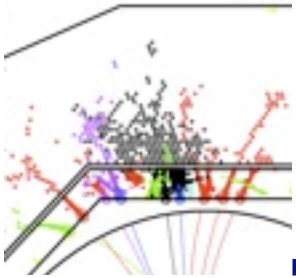




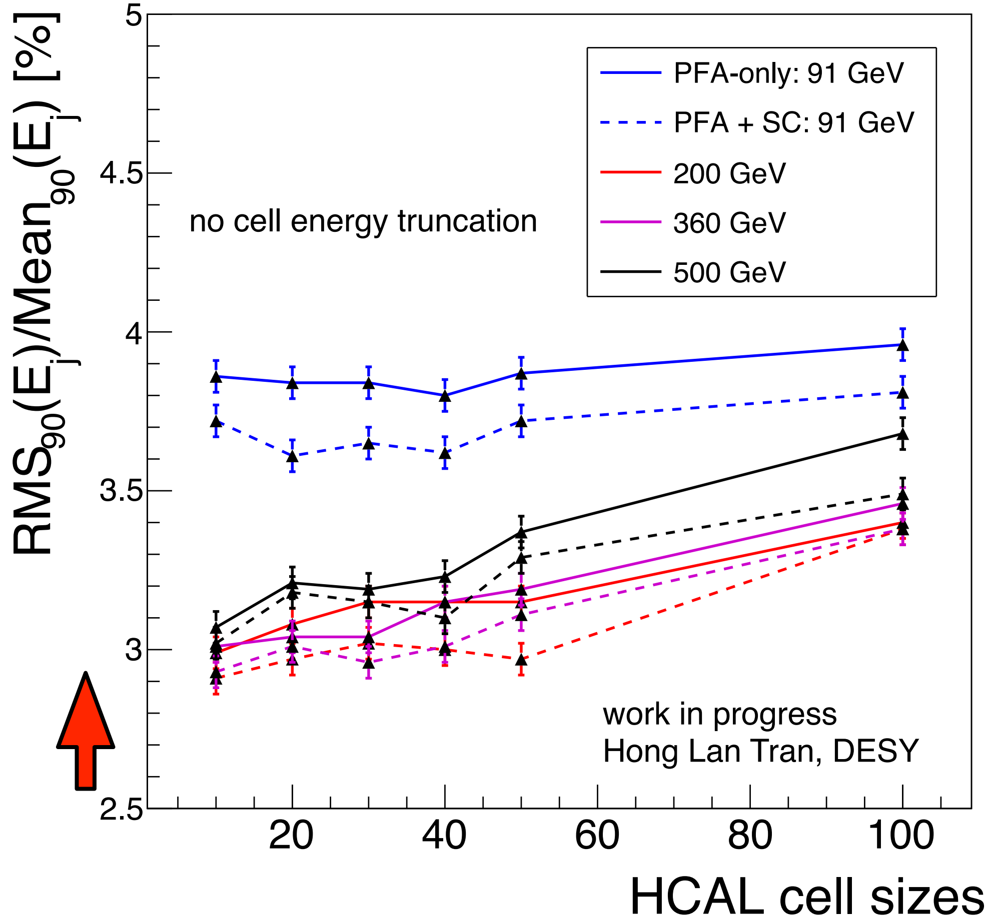
s/w compensation and clustering

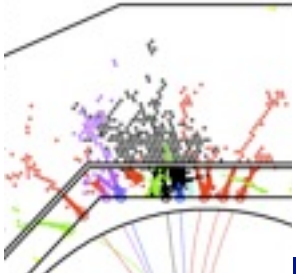
- Hypothesis testing at re-clustering stage
  - use track energy
  - benefits demonstrated earlier (fractal dim.)
- However: Weighting the energy before or during the clustering stage of particle flow reconstruction is not straightforward
  - In general $\omega = \omega(E_i, E_{tot})$
- General issue for all weighting schemes, inevitable for digital and semi-digital reconstruction
- Non-linear response: cannot revert to plain E flow in dense environments
  - $\omega E_1 + \omega E_2 \neq \omega (E_1 + E_2)$





Granularity and resolution 2





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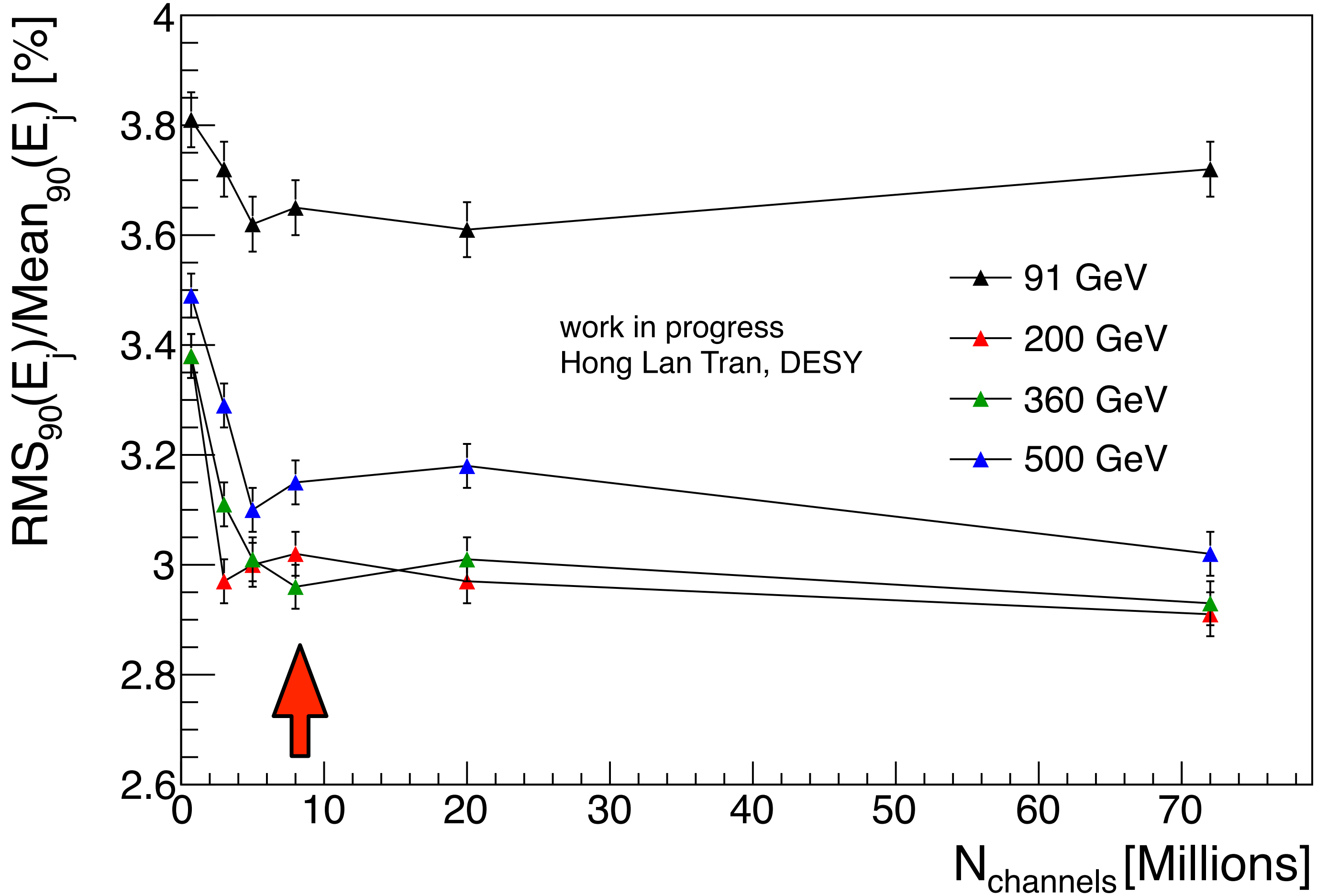
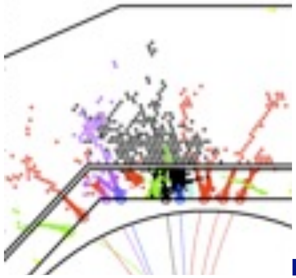


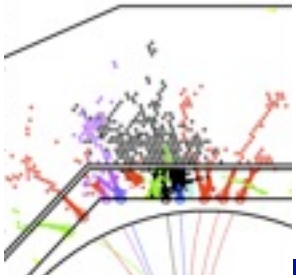
- 3 cm still a very reasonable choice



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

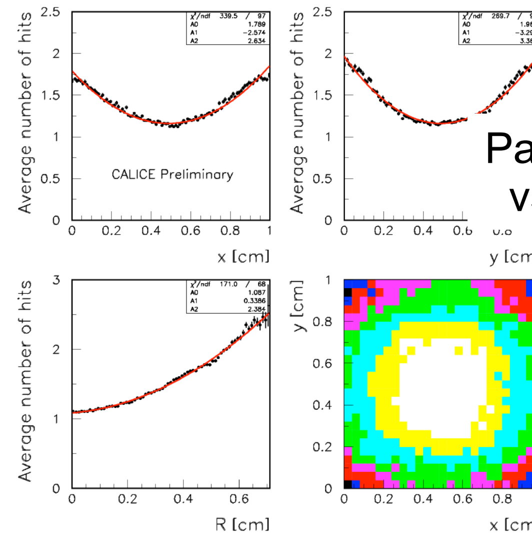
Back-up slides



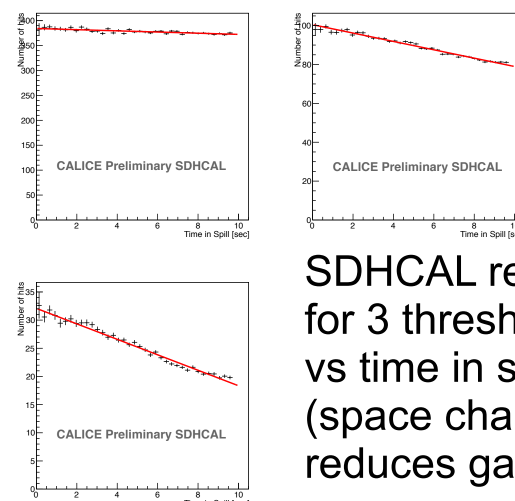
Calibration and simulation

- 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,…

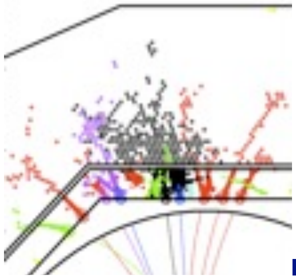
Data



Pad multiplicity vs μ position

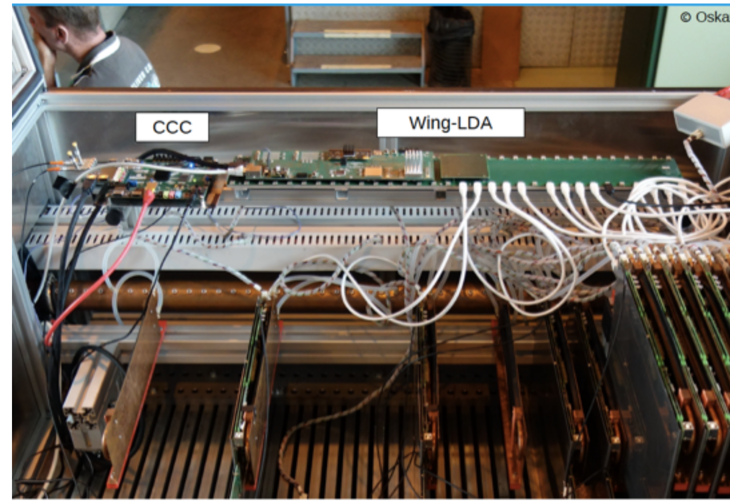


SDHCAL response for 3 thresholds vs time in spill (space charge reduces gain)

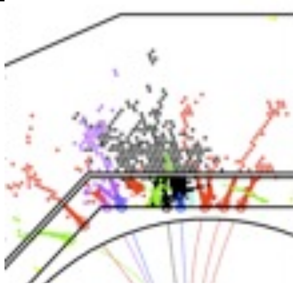


Frontiers

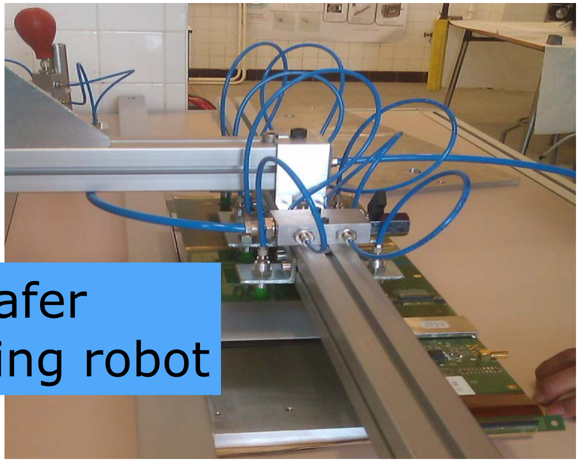
- Technology frontier
  - 10 years progress in SiMs
  - 1 glass RPCs, THGEMs, resistive μMs
- Integration frontier
  - electronics integration, low power
  - scalable solutions for DAQ and services →
- Industrialisation frontier
  - design simplifications
  - mass production and QA schemes
- Calibration 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
  - …

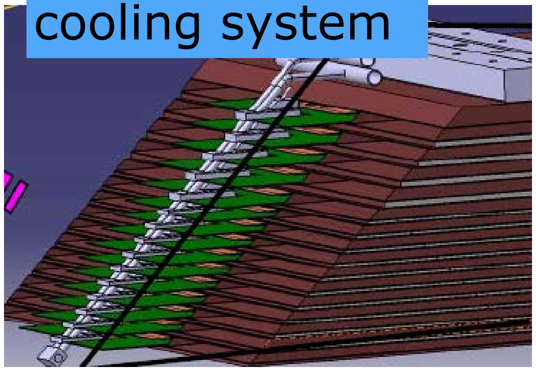


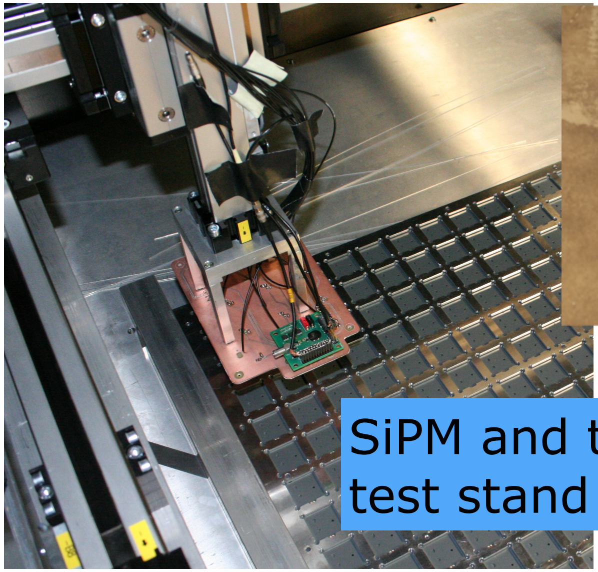
will read 2 segments. 96 layers, 250k channels

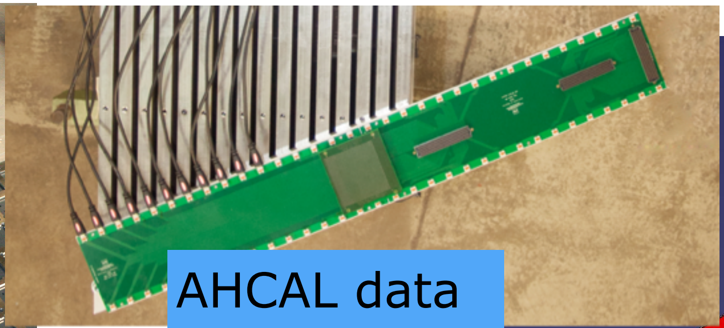


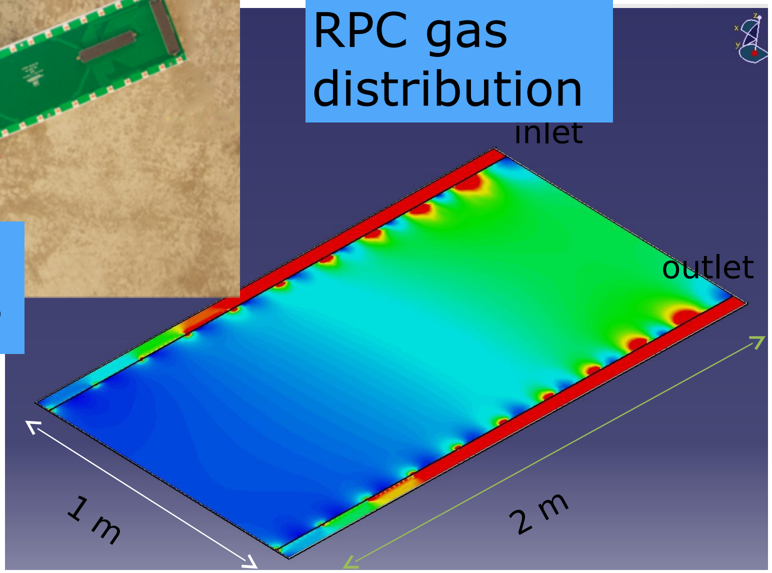
System integration & Tooling

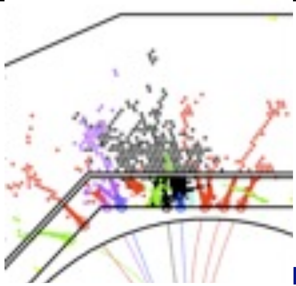






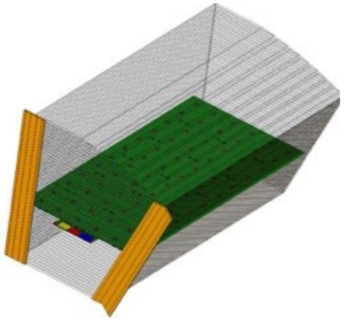


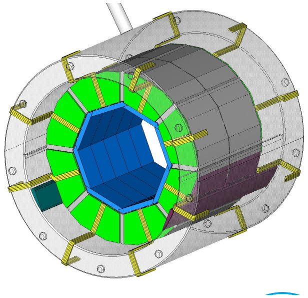


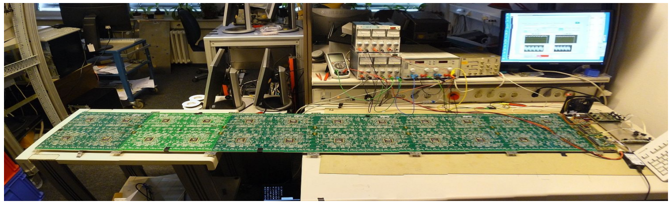


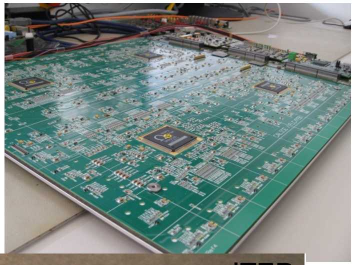
Industrialisation: Numbers!

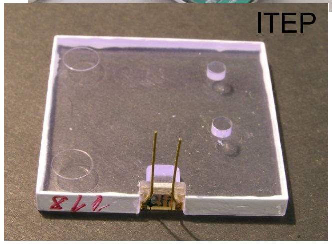
- The AHCAL
- 60 sub-modules
- 3000 layers
- 10,000 slabs
- 60,000 HBUs
- 200’000 ASICs
- 8,000,000 tiles and SiPMs



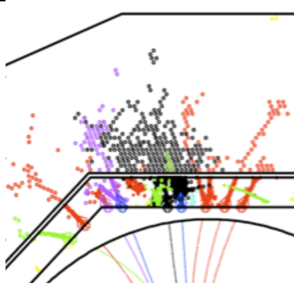






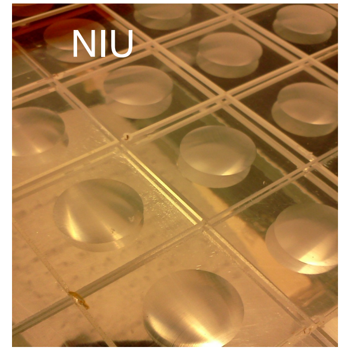


- One year
- 46 weeks
- 230 days
- 2000 hours
- 100,000 minutes
- 7,000,000 seconds

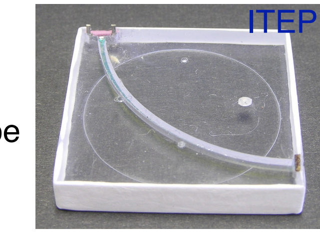


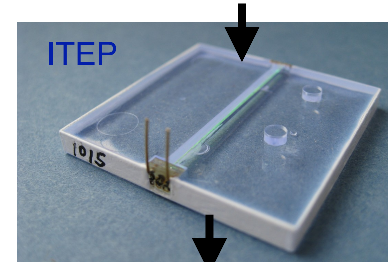
Directions in tile and SiPM R&D

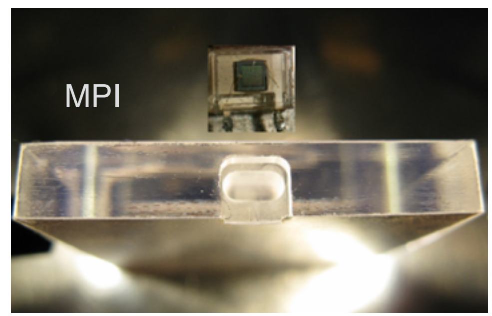
- Revise tile design in view of automatic pick & place procedures
- Consider SMD approach, originally proposed by NIU
- Light yield becomes an issue again
  - build on advances in SiPMs
- Very different assembly, QC and characterisation chain

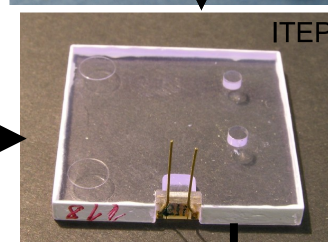


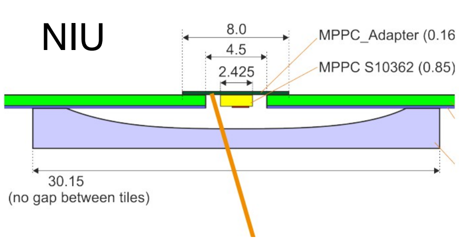
7608 ch
physics
prototype



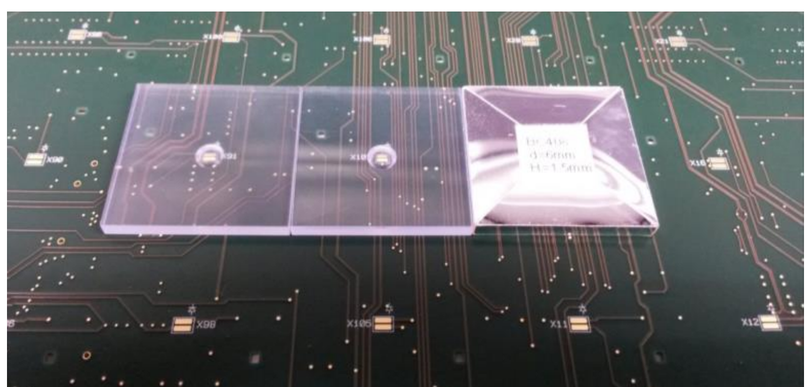


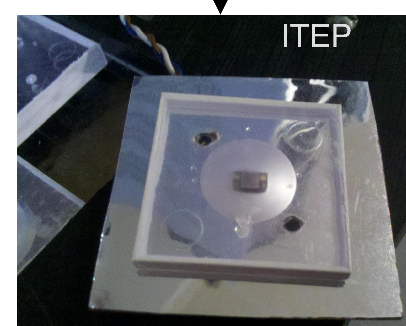


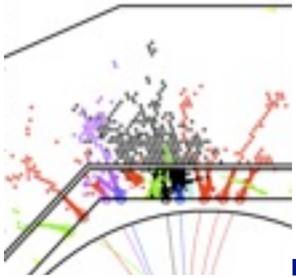




Mainz

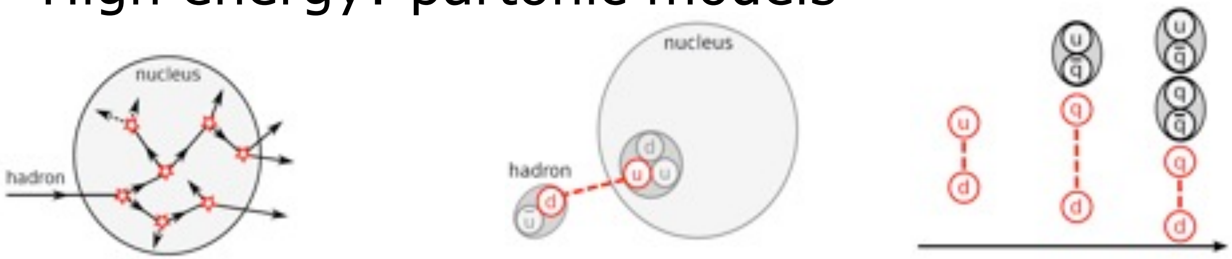




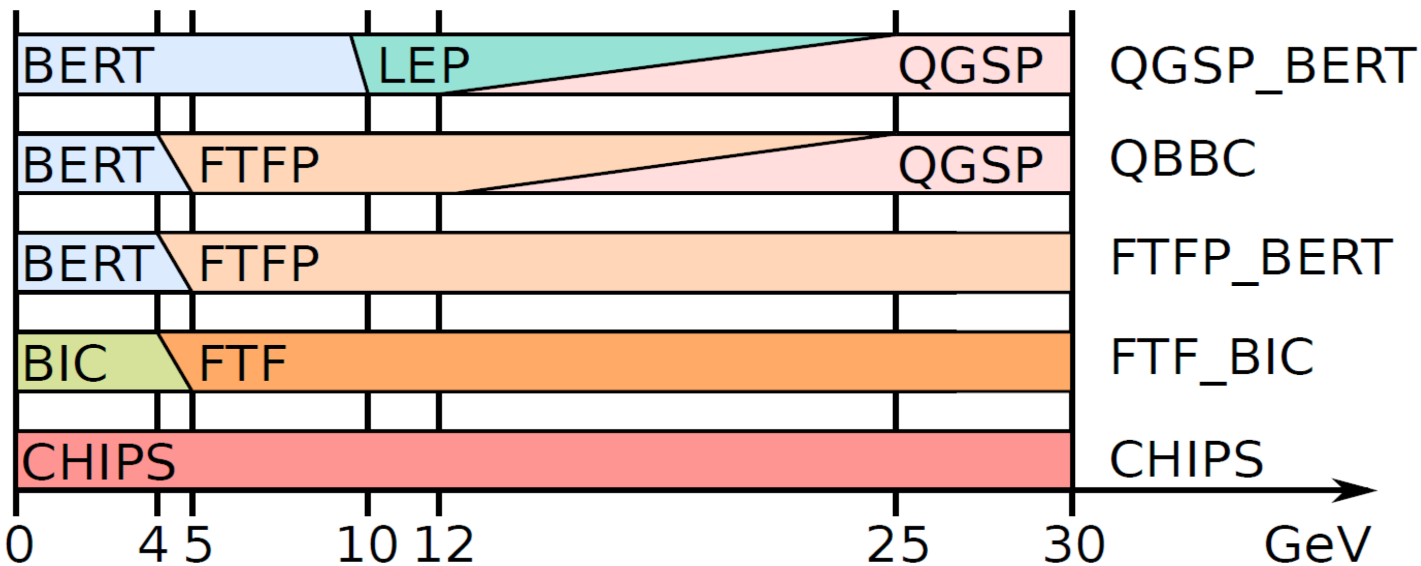


Shower simulation in Geant 4

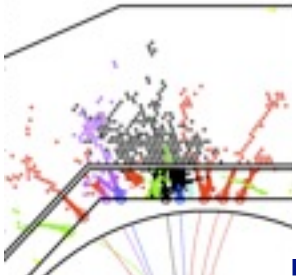
- Low energy: cascade models
- High energy: partonic models



minimize use of phenomenological parameterization

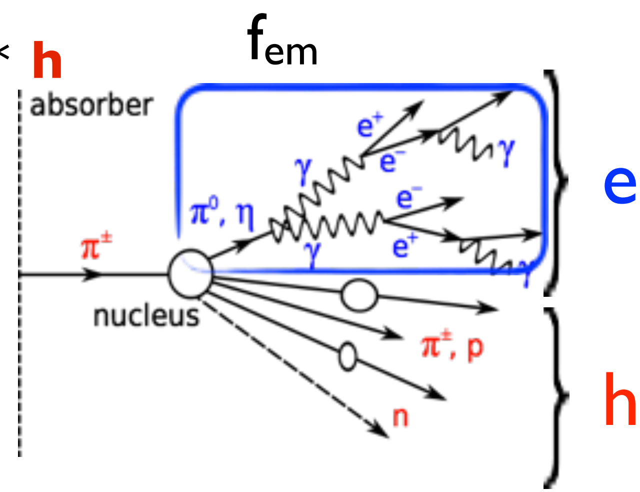


"legacy"
"linear combin."
"production"
"systematics"
"experimental"

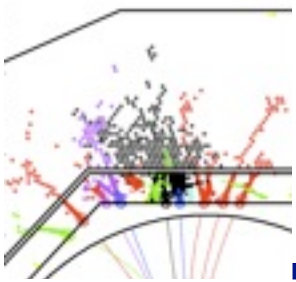


Electromagnetic fraction

- 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%

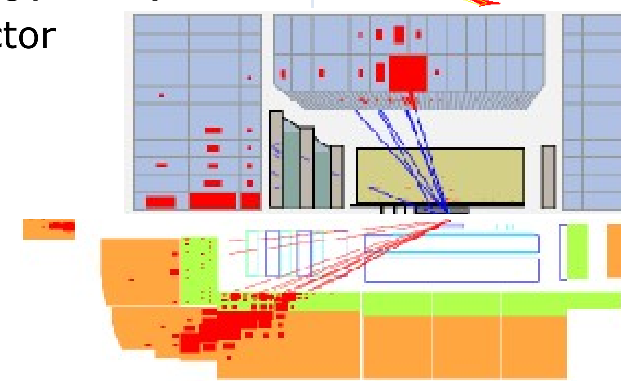


Compensation

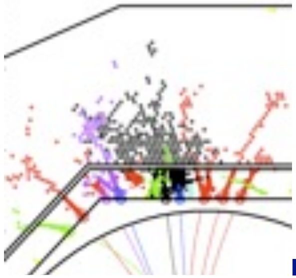
Different strategies, which can also be combined

- 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

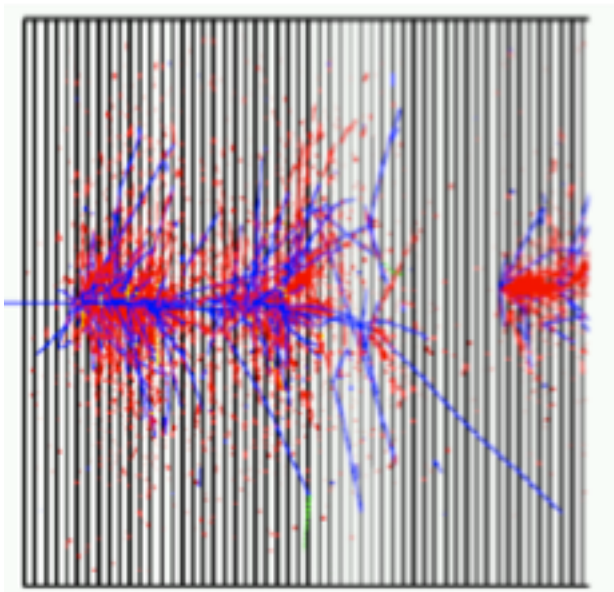
ZEUS



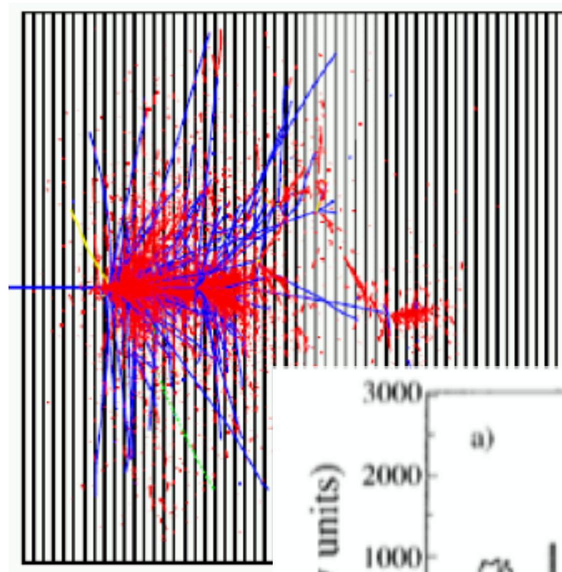
NB: Does not remove fluctuations in invisible energy



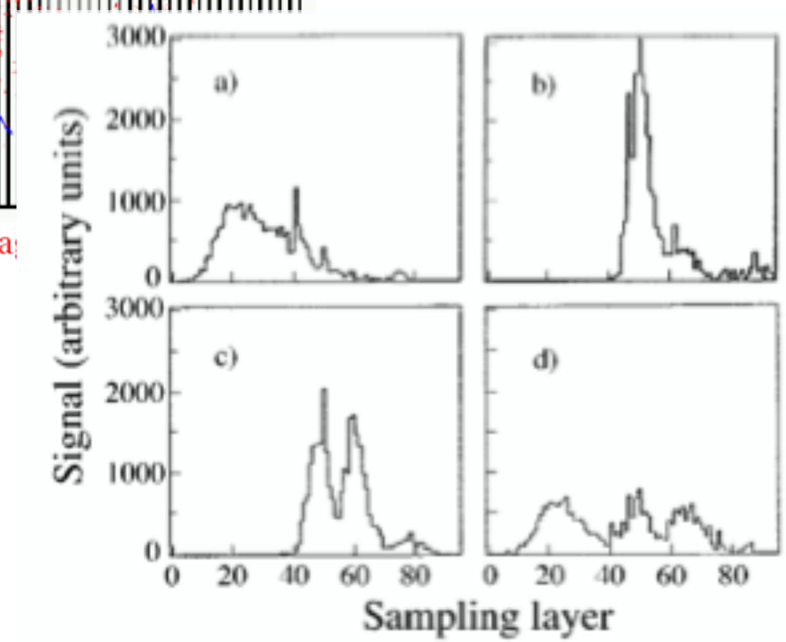
More fluctuations: leakage



blue = hadronic component

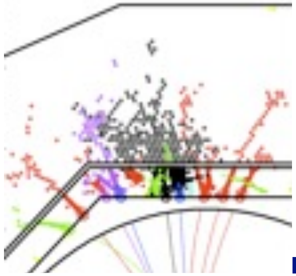


red = electroma

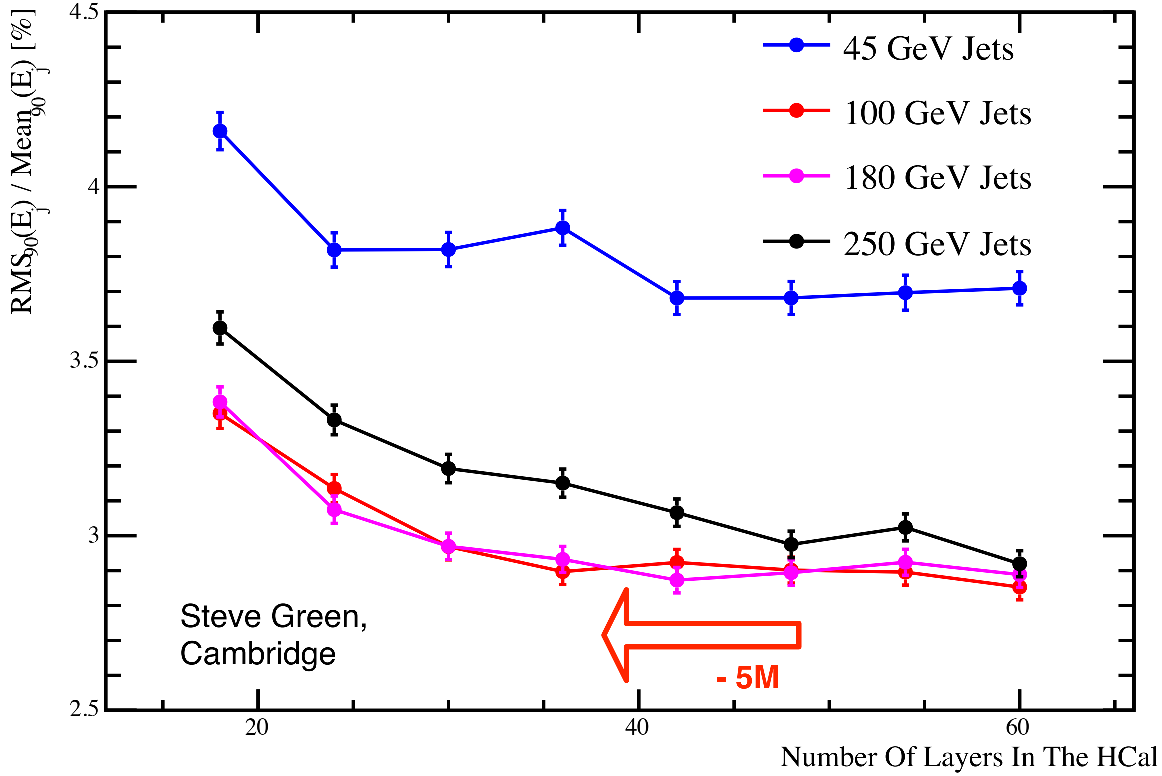


Leakage: in principle no problem
But: leakage fluctuations are!
(rule of thumb: $\sigma_{leak} \sim 4\ f_{leak}$)

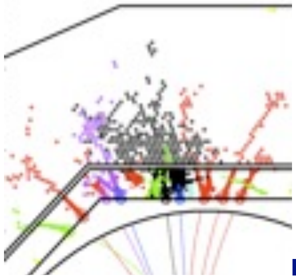
sampling fluctuations



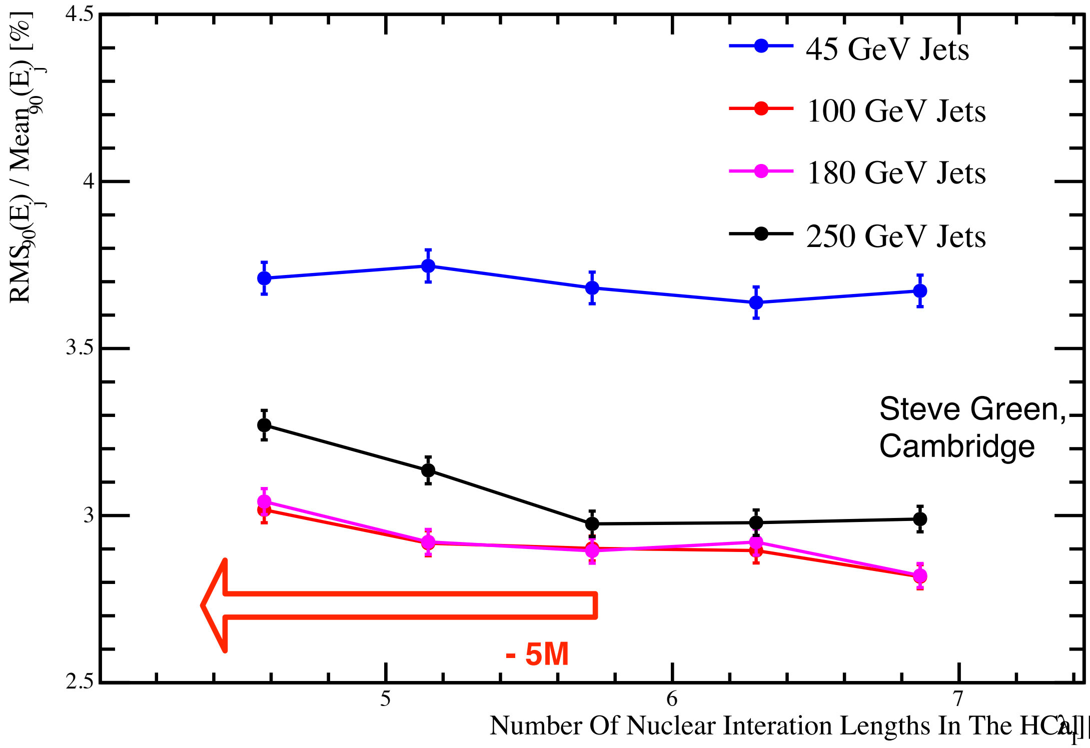
Cost optimisation: long. sampling



- fewer layers: not for free, but at least no knee
- not necessarily the same for SDHCAL

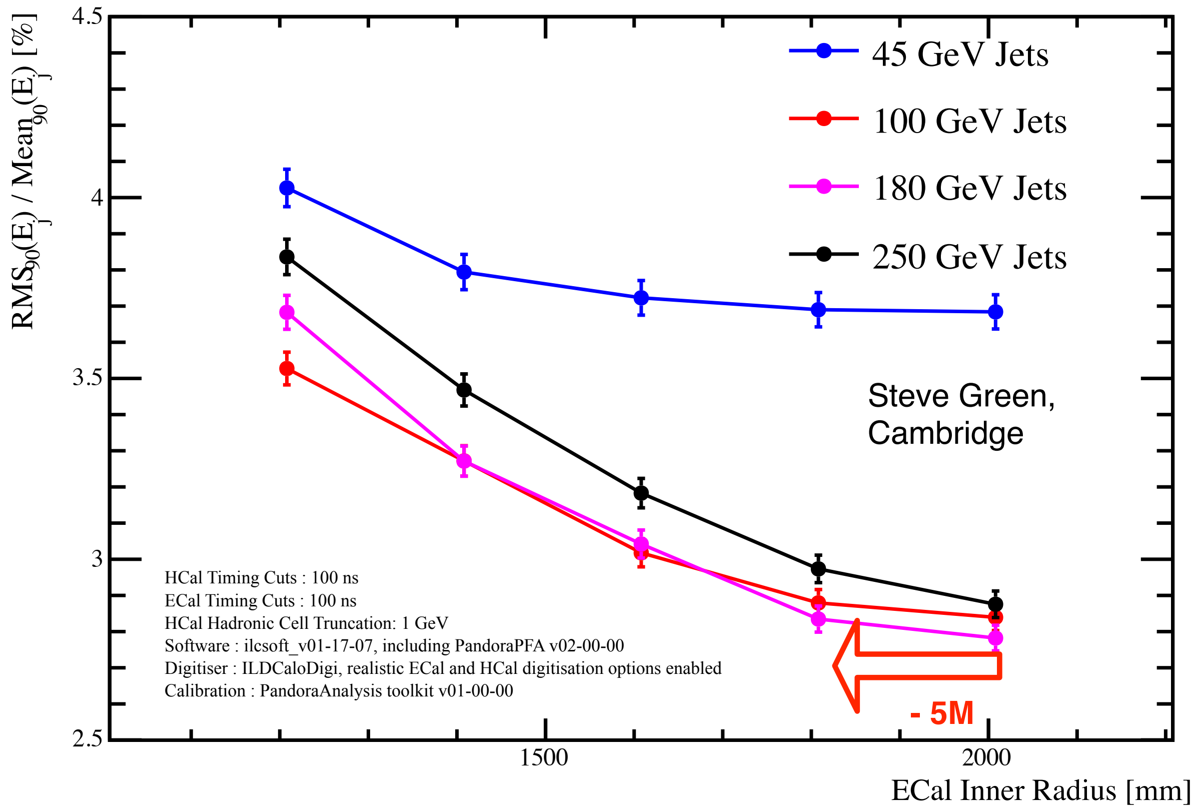


Cost optimisation: depth



- this plot n(layers) = const; should have constant pitch also
- additional savings from coil and yoke - or smaller reduction
- but should be studied with missing energy performance

Cost optimisation: inner radius



- shown: cost variation is for 18 cm smaller HCAL inner radius
- additional savings from coil and yoke - or smaller reduction