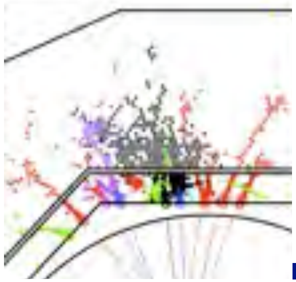
Imaging calorimeters for future collider experiments

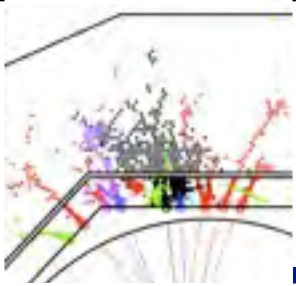
Felix Sefkow

Teilchenphysik-Kolloquium Freiburg, 6. Juli 2016



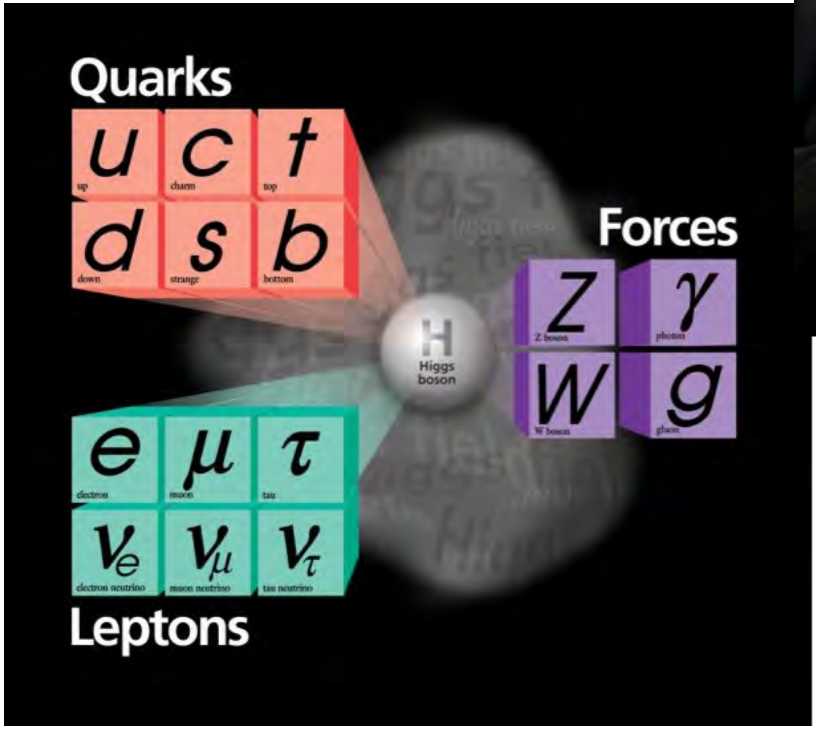
Outline

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

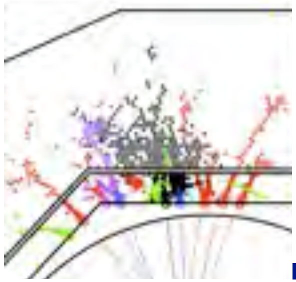


Higgs discovery

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



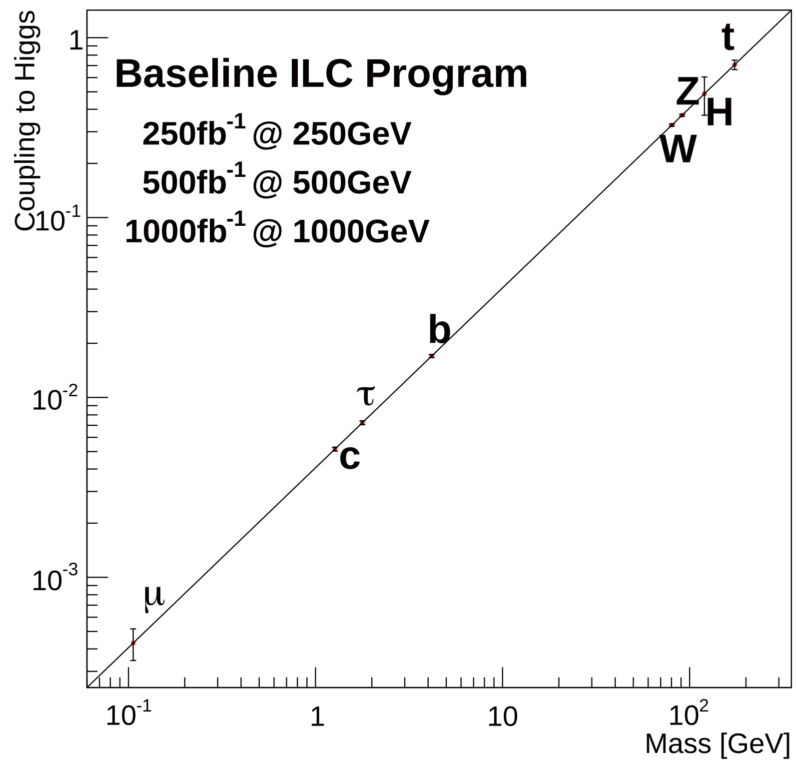
Higgs physics drives the field

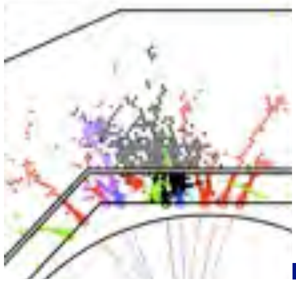
“Driver” = a compelling line of inquiry that shows great promise for major progress over the next 10-20 years. Each has the potential to be transformative. Expect surprises.

- Use the Higgs as a new tool for discovery.

S.Ritz, Report on P5

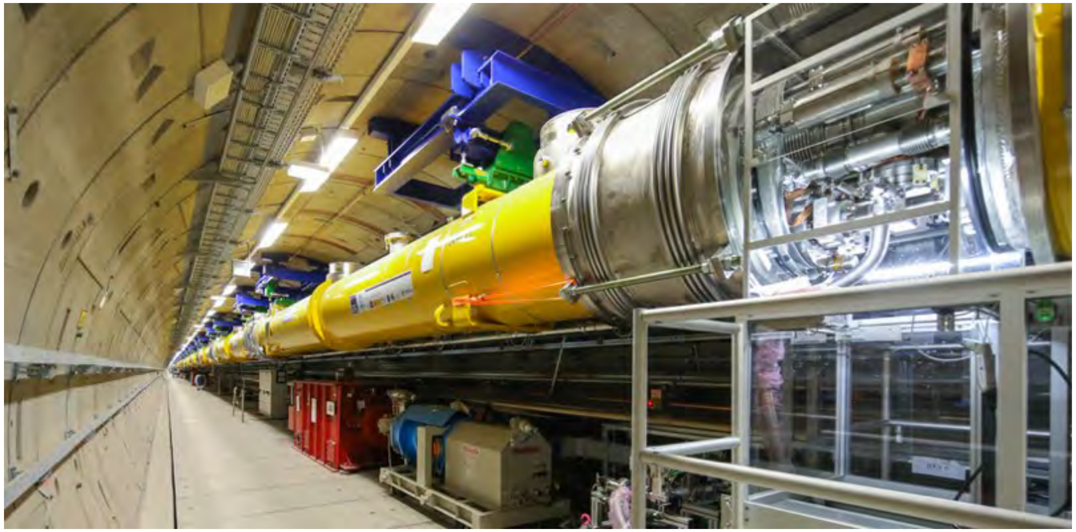
- The main question today:
- establish the Higgs profile
  - mass, spin, parity
  - above all: couplings
- Is the Higgs(125) *the* Higgs and does it fulfil its role in the Standard Model?
- Or does it hold the key to New Physics?

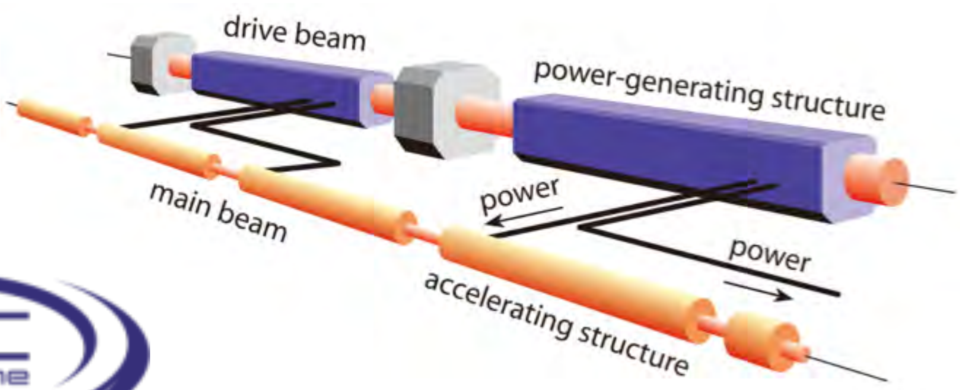




Future e^+e^- colliders

- International Linear Collider
  - 250-1000 GeV
  - TDR 2012
  - studied at government level in Japan
- Compact Linear Collider at CERN
  - 350-3000 GeV
  - CDR 2012
- Circular collider studies
  - CEPC in China
  - FCCee at CERN

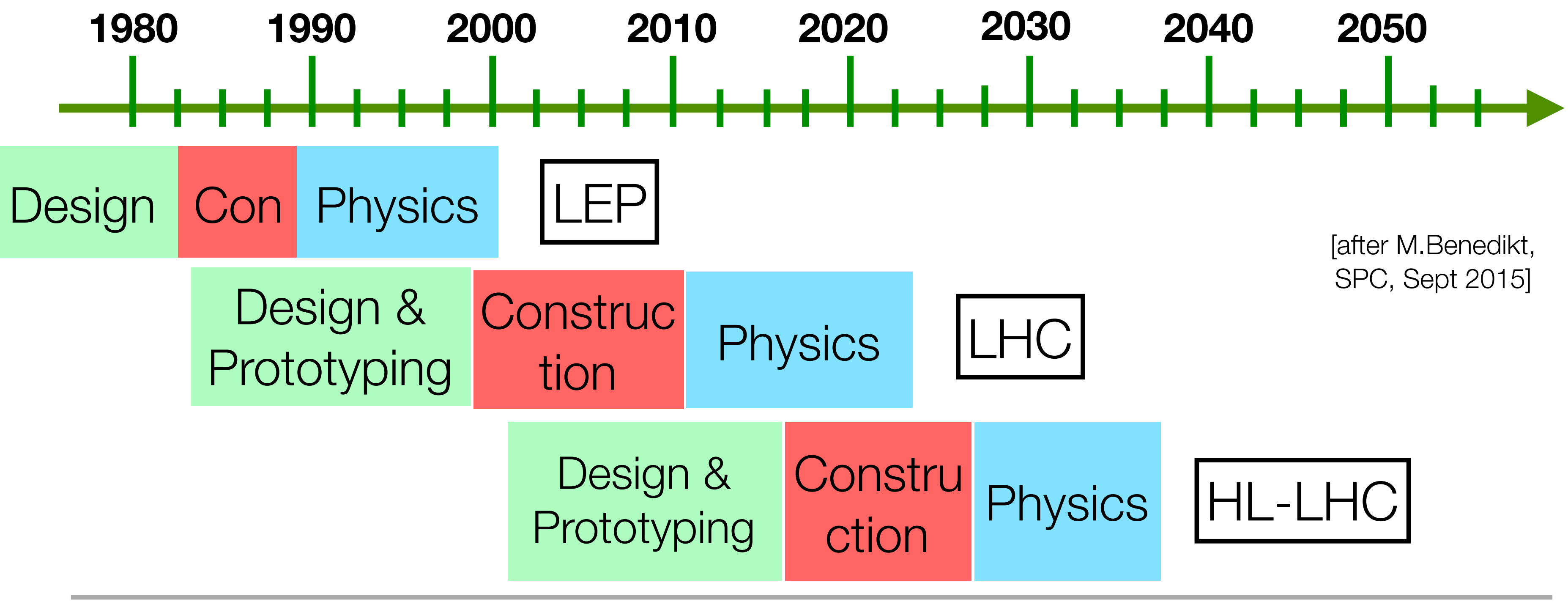




CEPC

FCC
hh ee he

Timelines: Past, Plans & Possibilities



[after M.Benedikt, SPC, Sept 2015]

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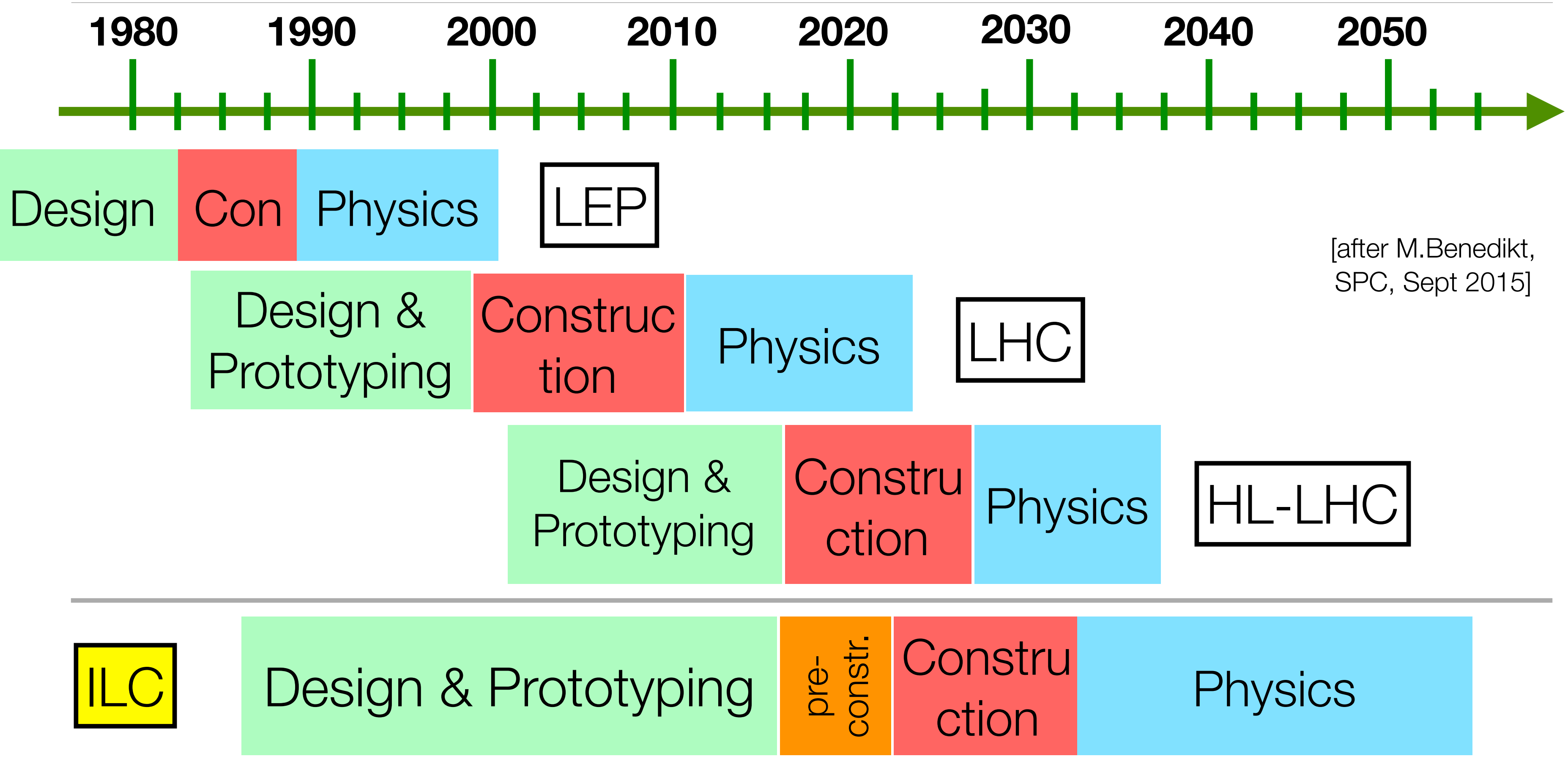

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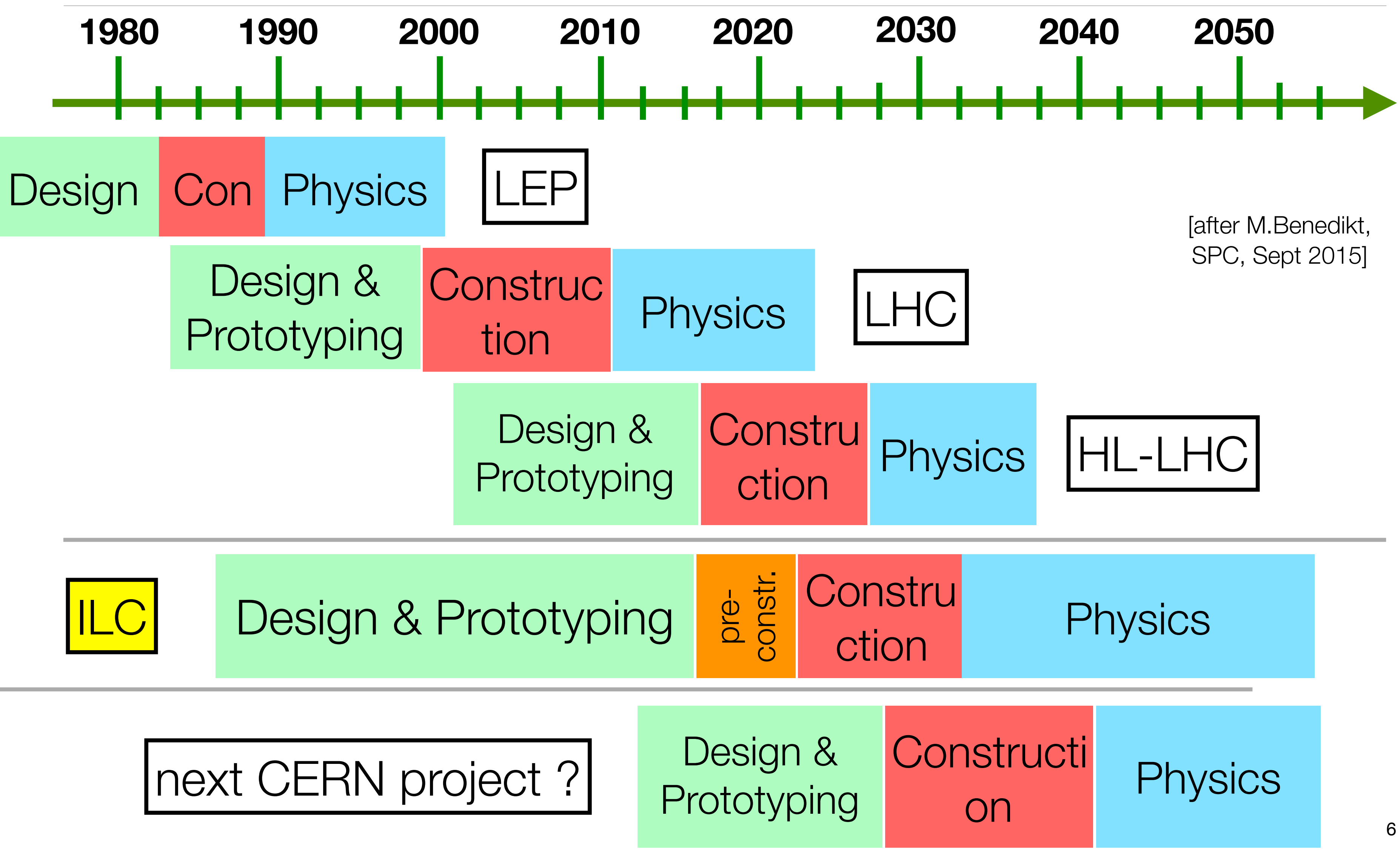

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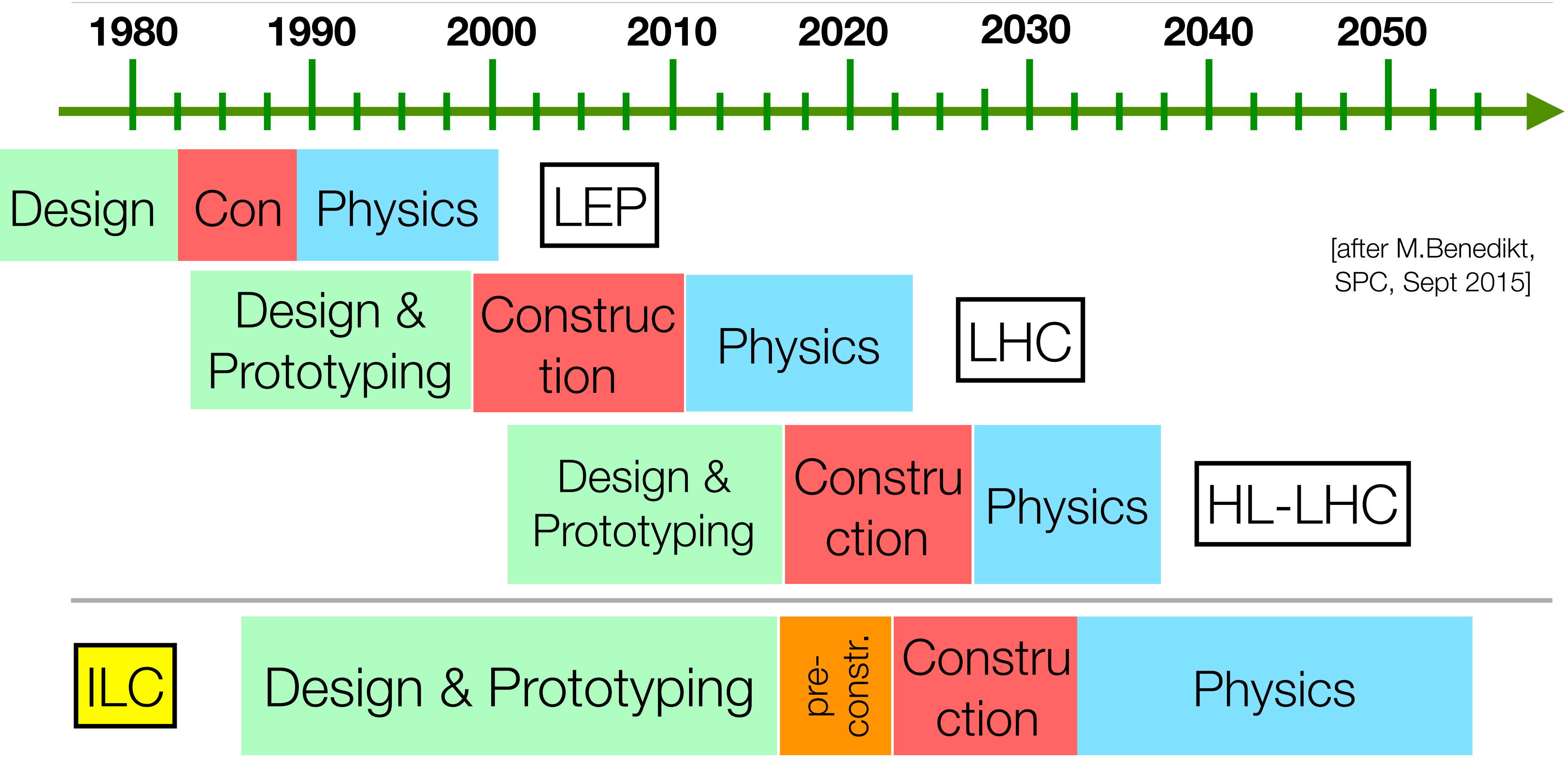

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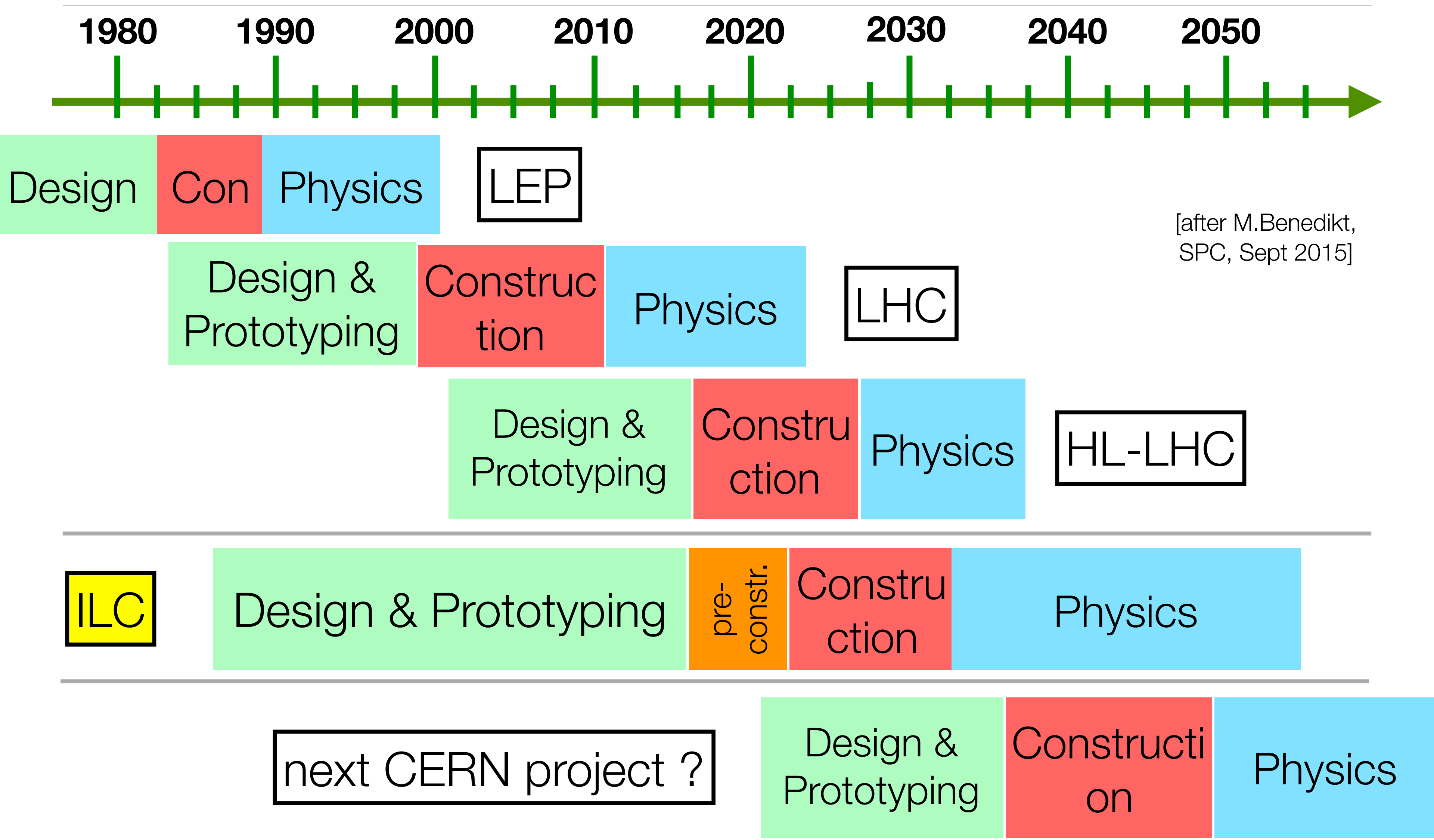
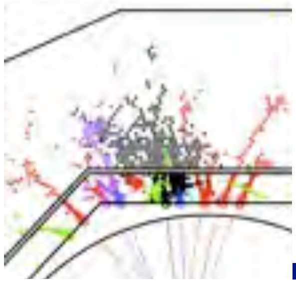
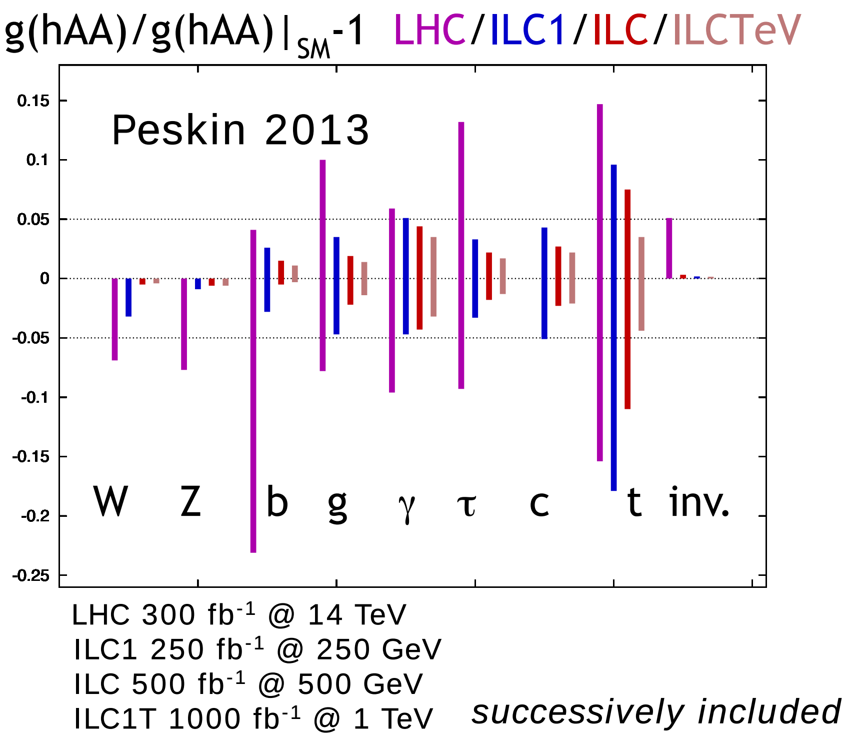
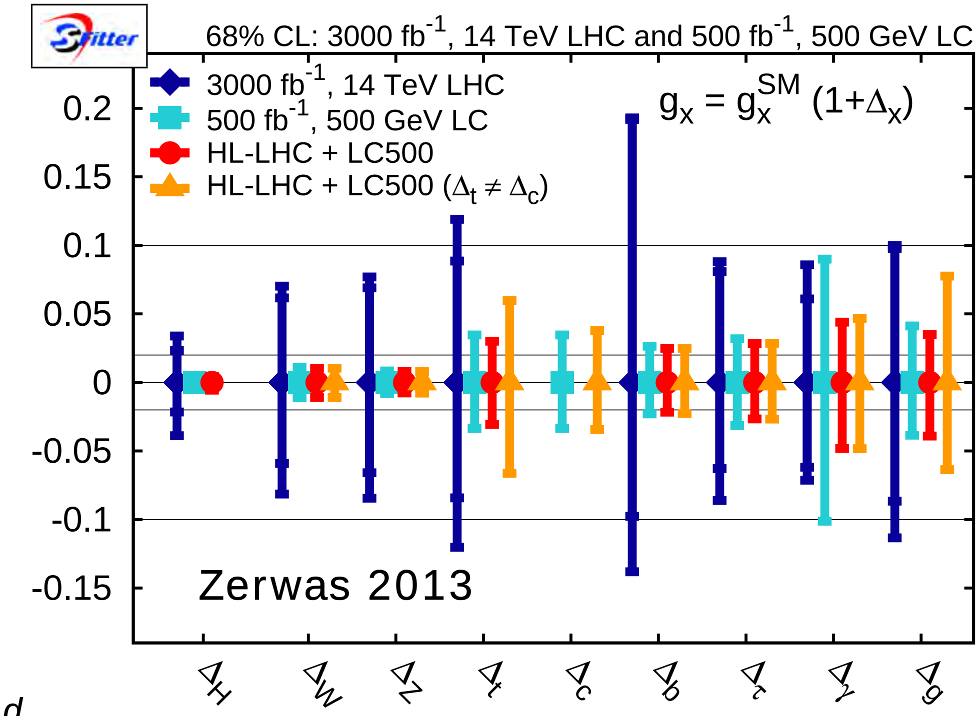


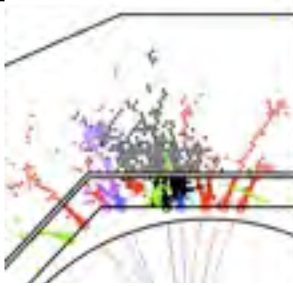


ILC and LHC



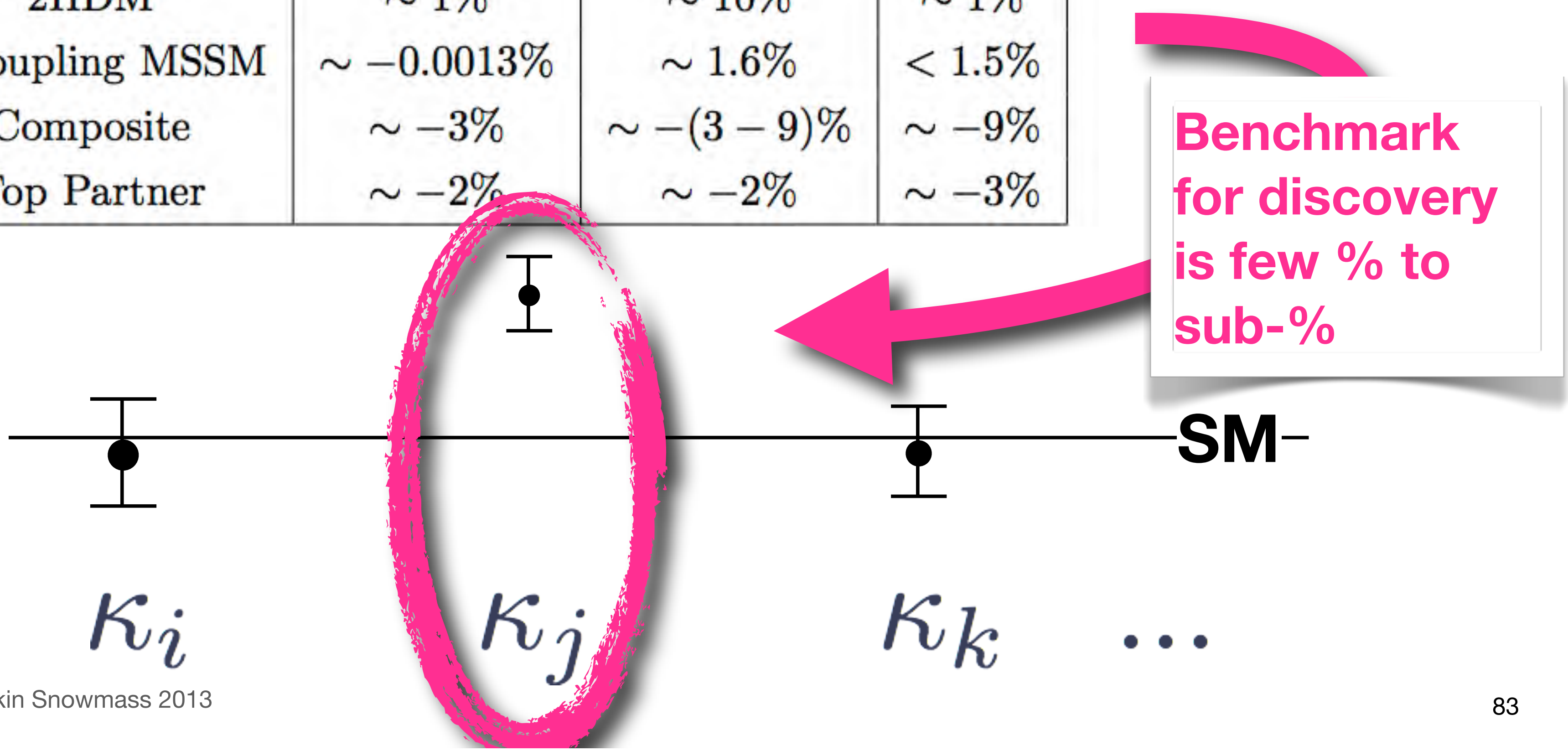


- Only with e+e- collisions one can reach the percent level precision to probe new physics
- also true w.r.t. high lumi LHC



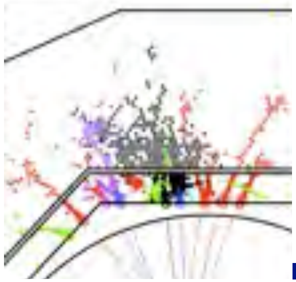
Precision for discovery

	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	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



Brock/Peskin Snowmass 2013

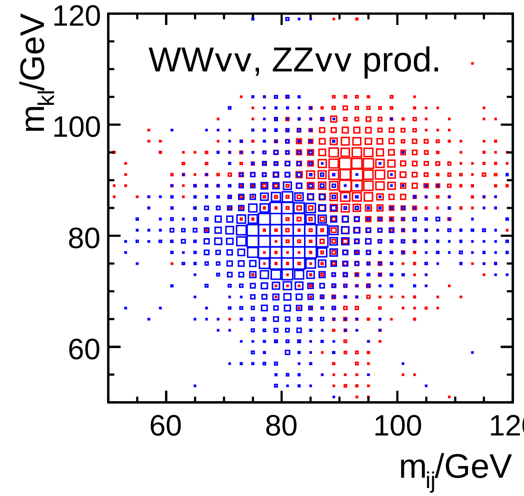
83

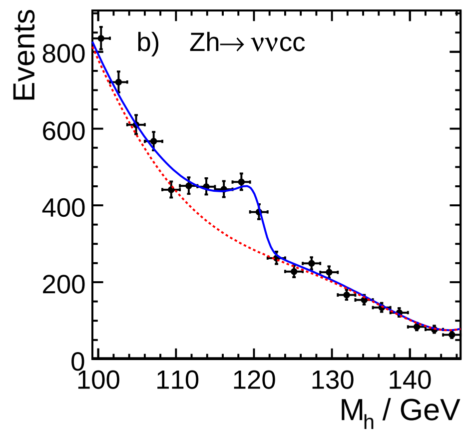


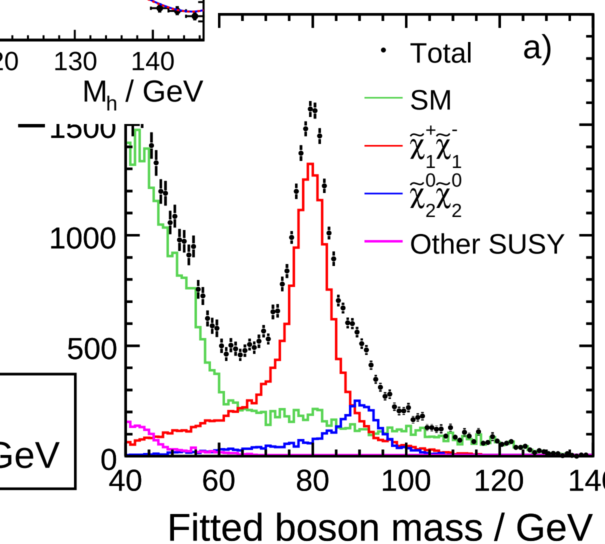
LC physics with jets: M_{inv}

- 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

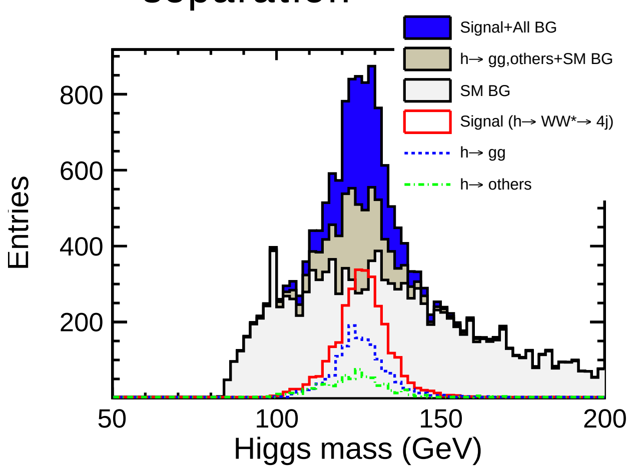
typical jet energies at √s = 500 GeV 50-150 GeV



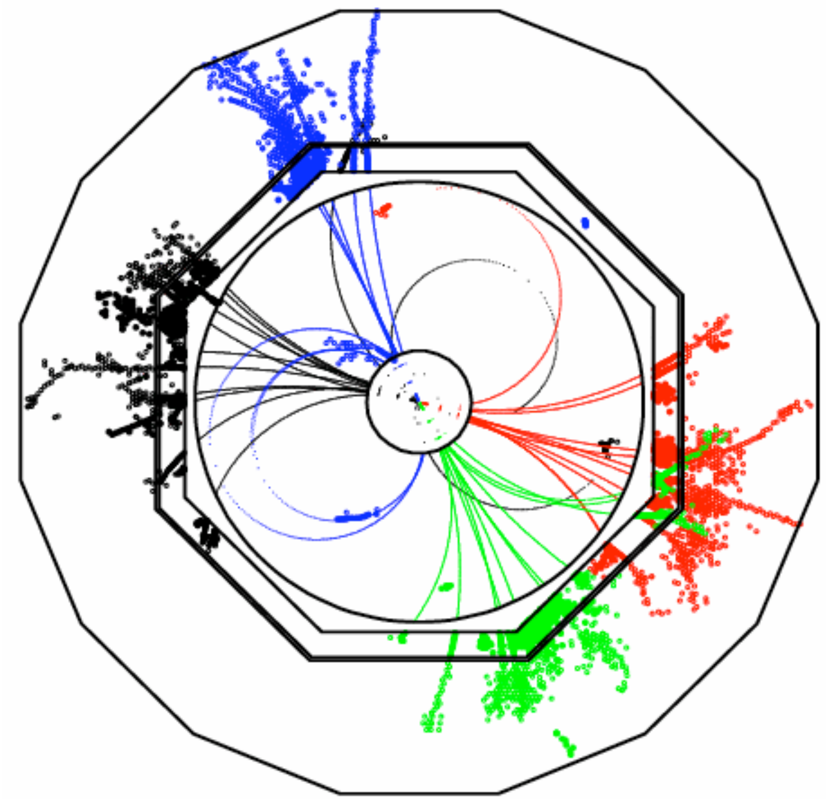


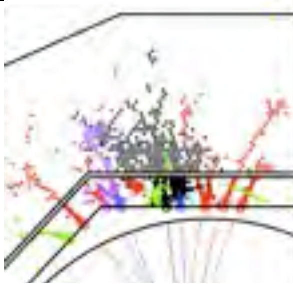


√s = 500 GeV
E_{jet} peak s @ 35 GeV



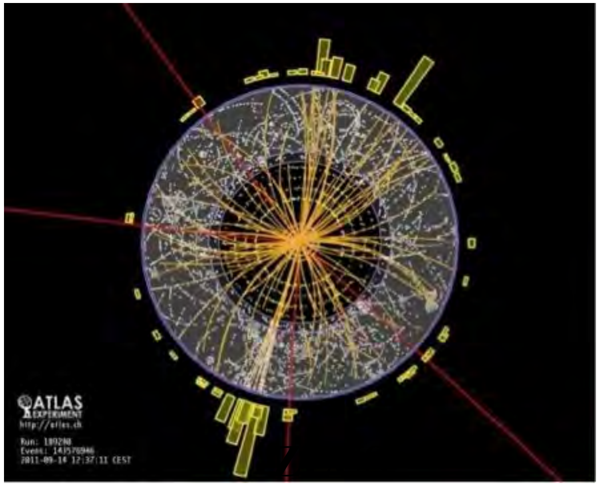
Particle flow concept

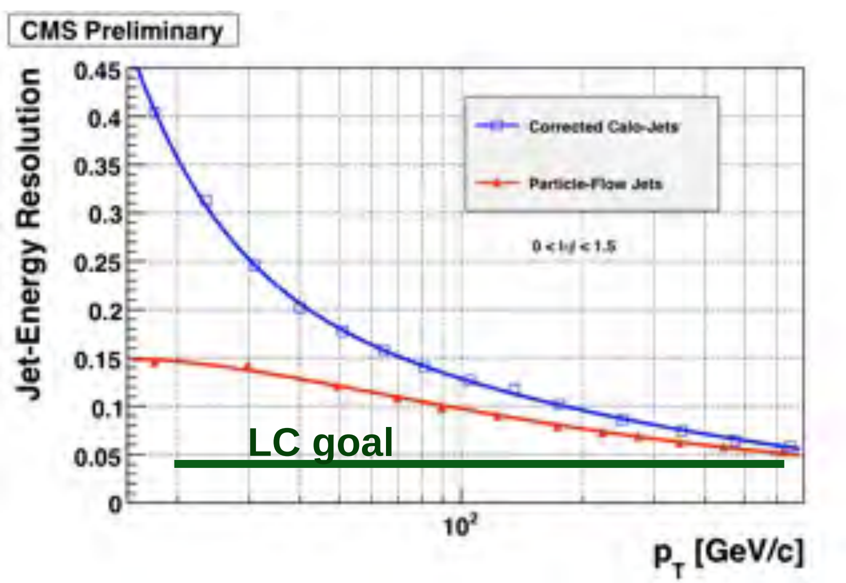




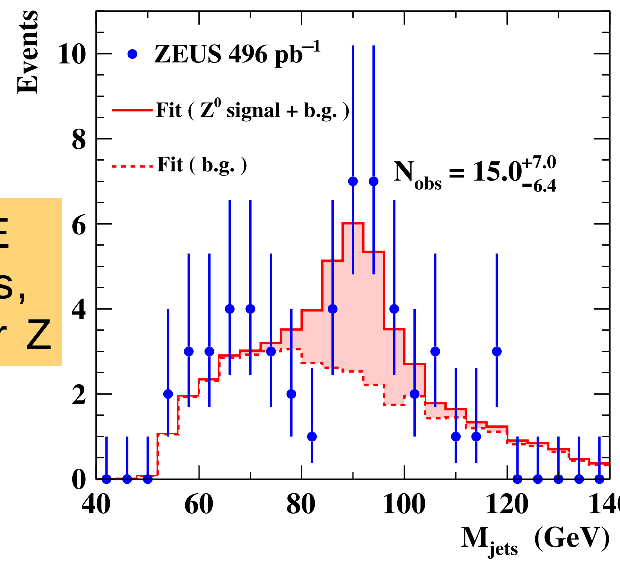
The jet energy challenge

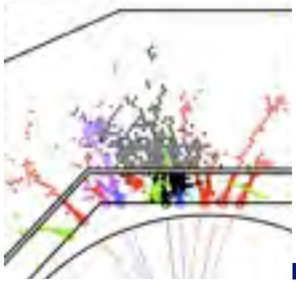
- Jet energy performance of existing detectors is not sufficient for separation of W and Z bosons
  - E.g. CMS: ~ 100%/√E, ATLAS ~ 70%/√E
- Calorimeter resolution for hadrons is intrinsically limited, e.g. nuclear binding energy losses
- Resolution for jets worse than for single hadrons
- It is not sufficient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





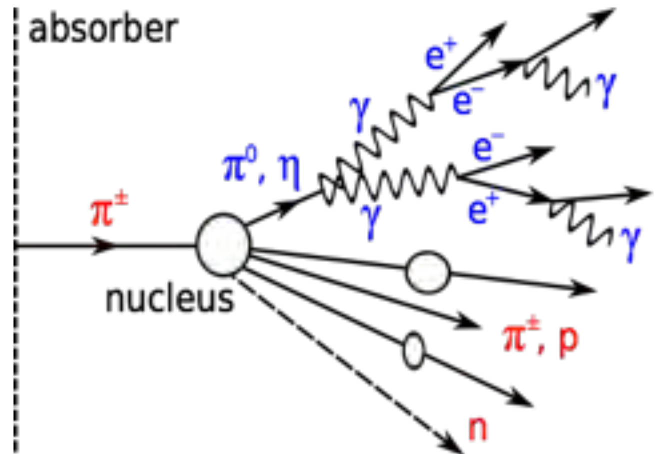
35%√E
for pions,
6 GeV for Z

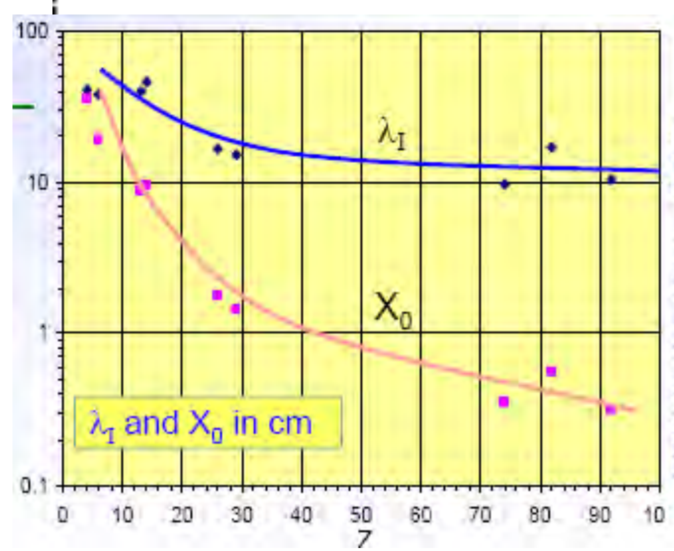




Hadron showers

- 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

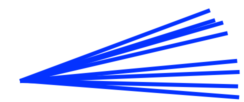




Particle Flow Calorimetry

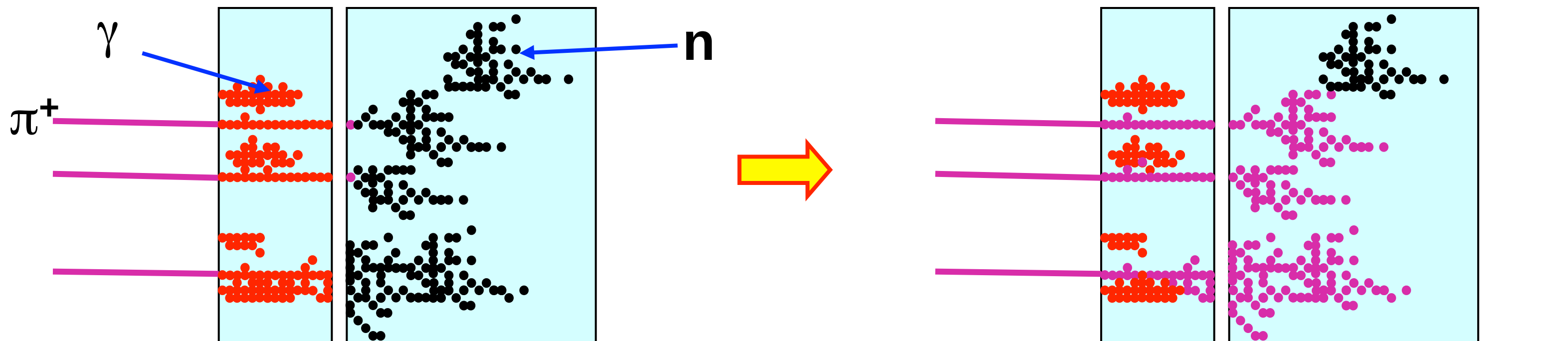
★ **In a typical jet :**

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



★ **Traditional calorimetric approach:**

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



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

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

★ **Particle Flow Calorimetry paradigm:**

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

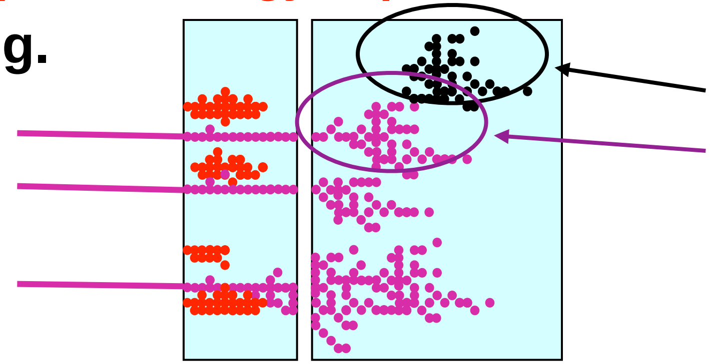
Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:

★ Avoid double counting of energy from same particle

★ Separate energy deposits from different particles

e.g.

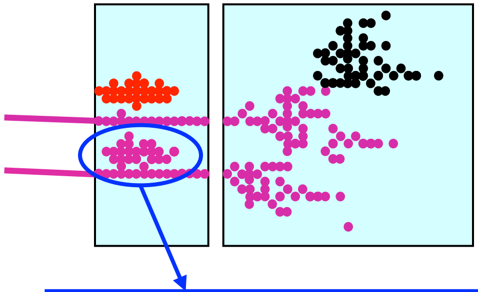


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

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

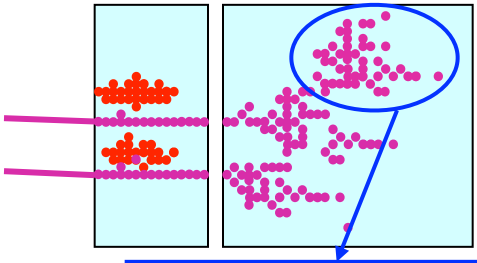
Three types of confusion:

i) Photons



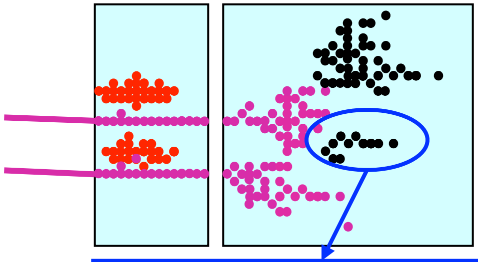
Failure to resolve photon

ii) Neutral Hadrons

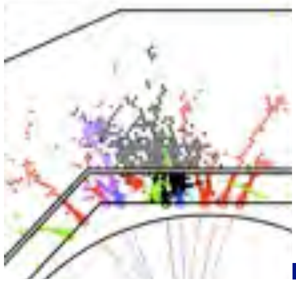


Failure to resolve neutral hadron

iii) Fragments



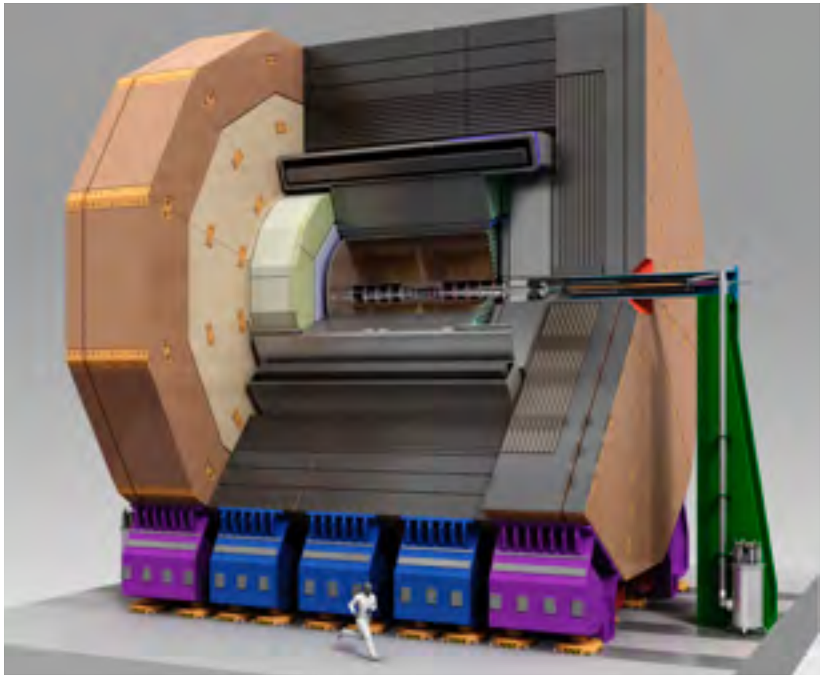
Reconstruct fragment as separate neutral hadron

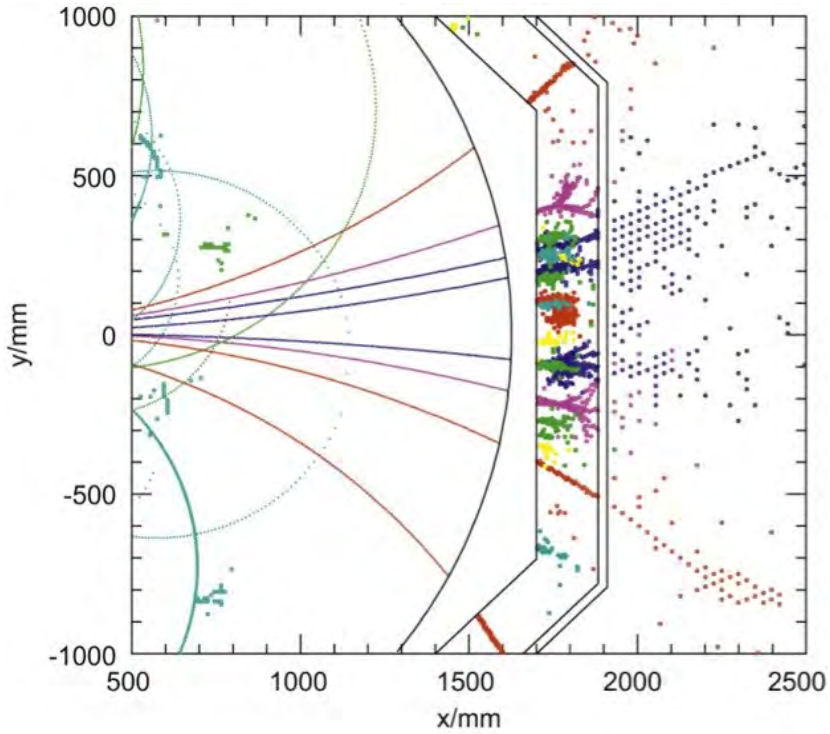


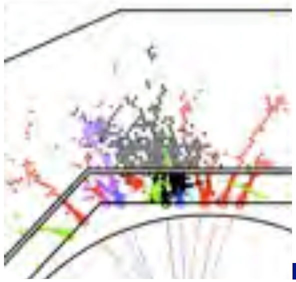
Particle flow detectors

- Large radius, high magnetic field, calorimeters inside coil
- Dense and compact design

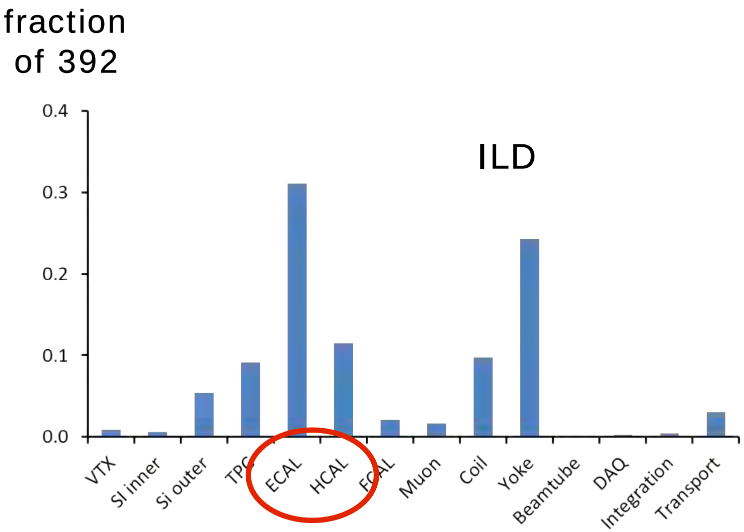
- Very high granularity
  - order of Moliere radius
  - ECAL: 0.5 - 1 cm, 10^8 cells
  - HCAL: 1 - 3 cm, 10^7 - 10^8 cells

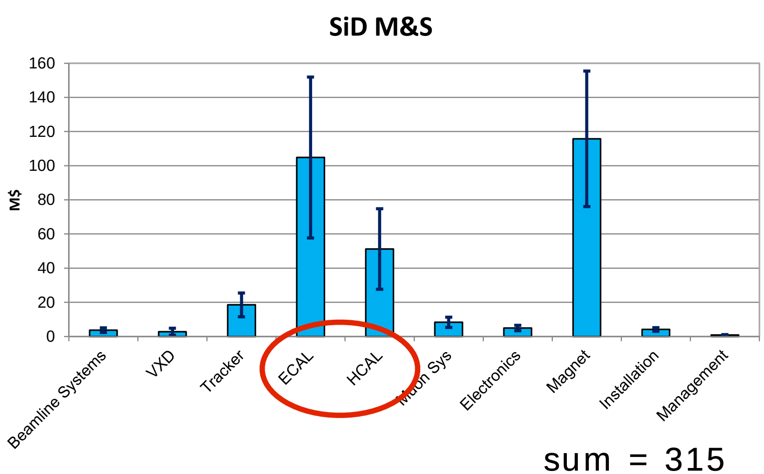




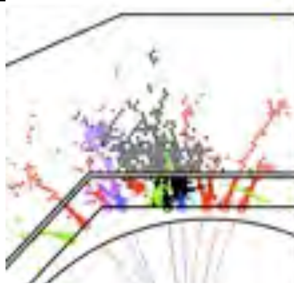


Calorimeter cost





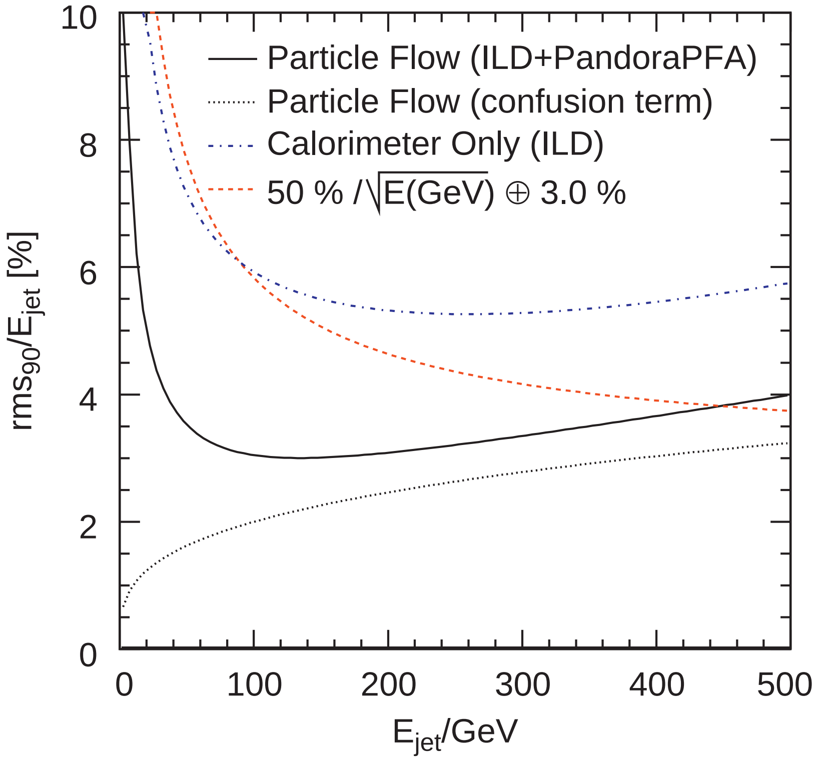
- Costing is at a very early stage
- Yet, many lessons learnt from 2nd generation prototypes
- Example ILD scint HCAL: 45M
  - 10M fix, rest ~ volume
  - 10M absorber, rest ~ area (n_{Layer})
  - 16M PCB, scint, rest ~ channels
  - 10 M SiPMs and ASICs
- HCAL cost is rather driven by instrumented area 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

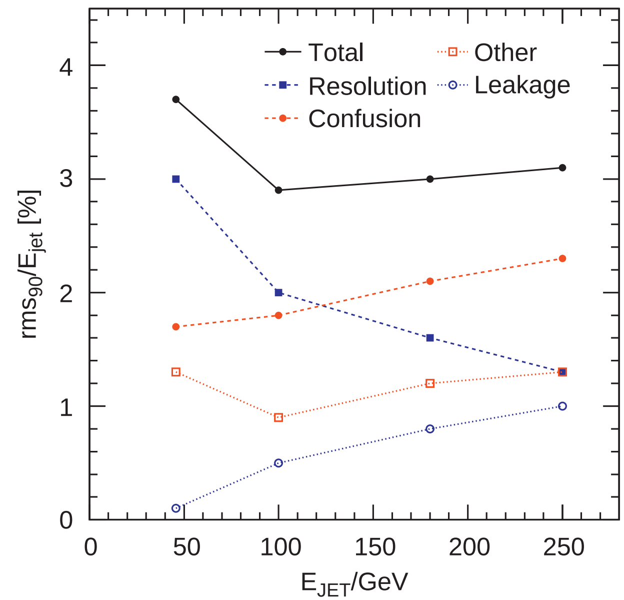


Understand particle flow performance

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

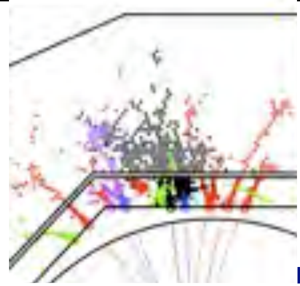
Resolution | Tracking | Leakage | Confusion





- 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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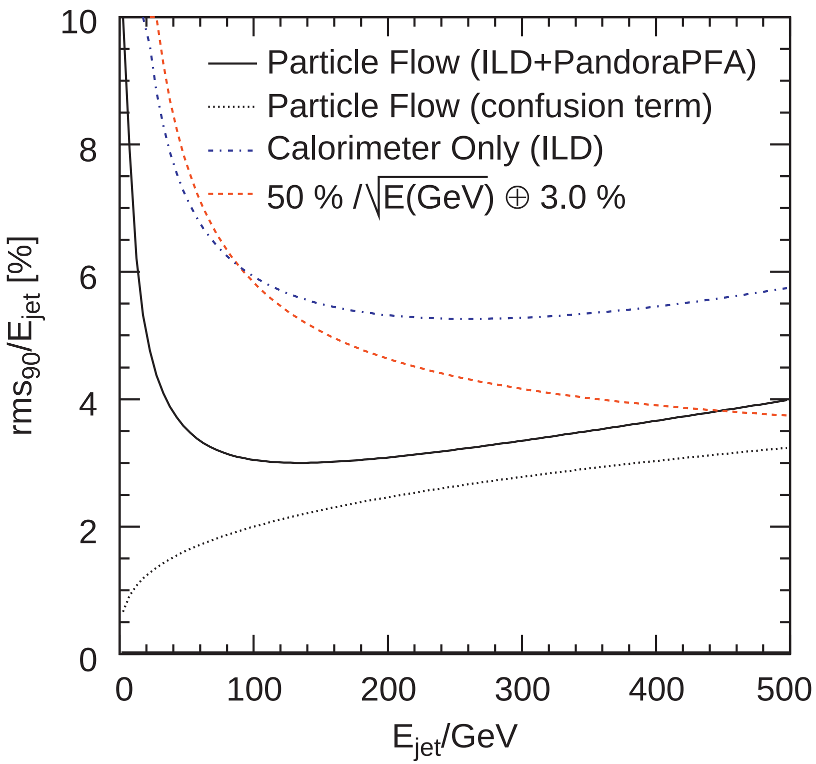

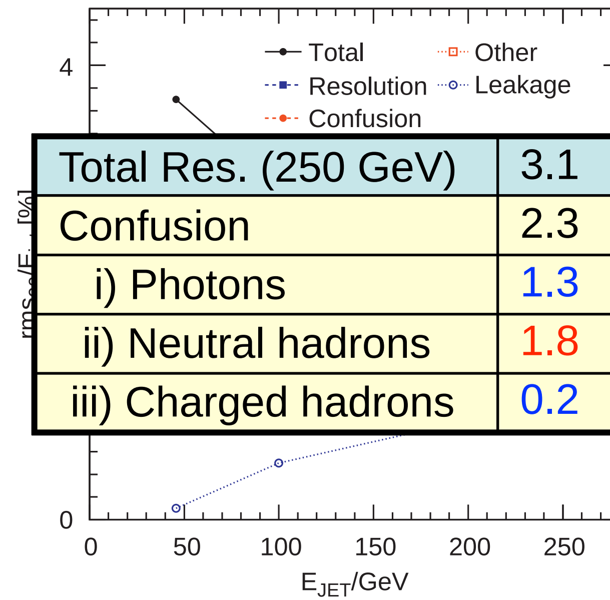

Total Res. (250 GeV)	3.1
Confusion	2.3
i) Photons	1.3
ii) Neutral hadrons	1.8
iii) Charged hadrons	0.2

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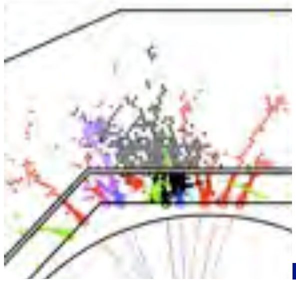
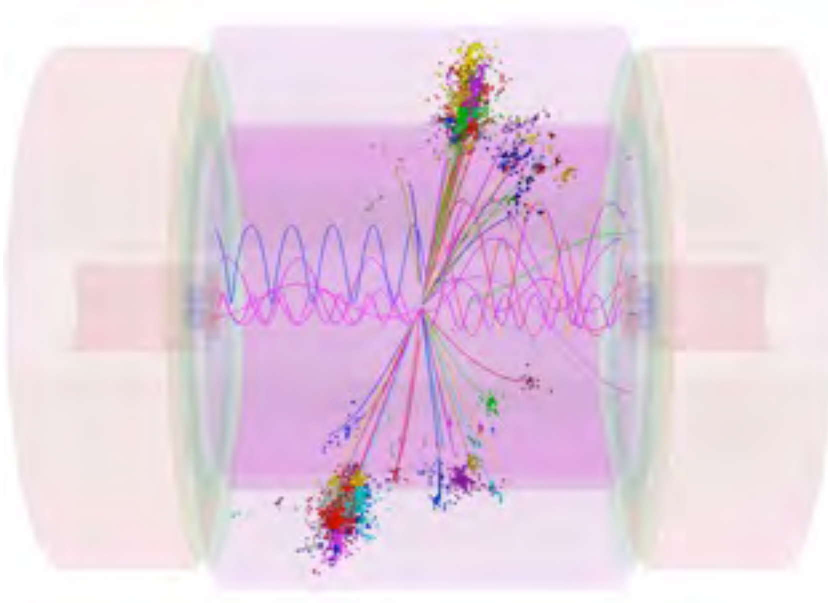
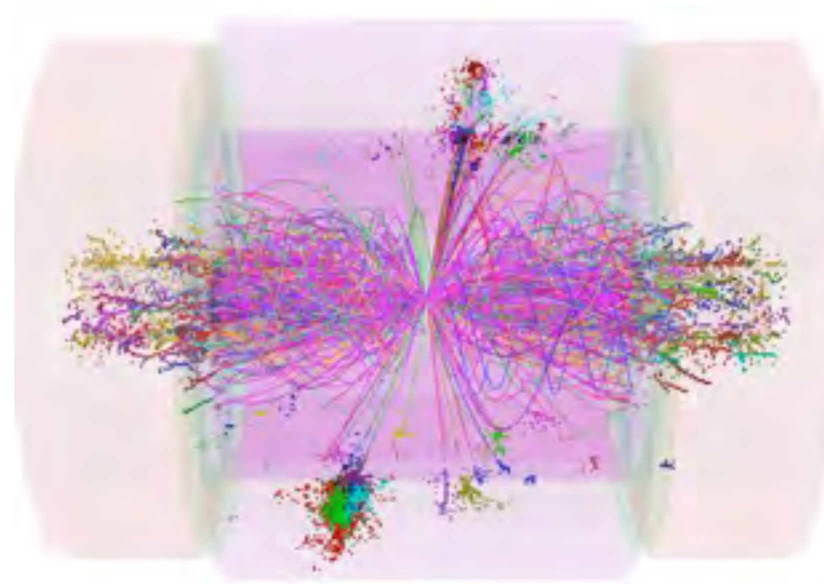
Particle flow and pile-up



- 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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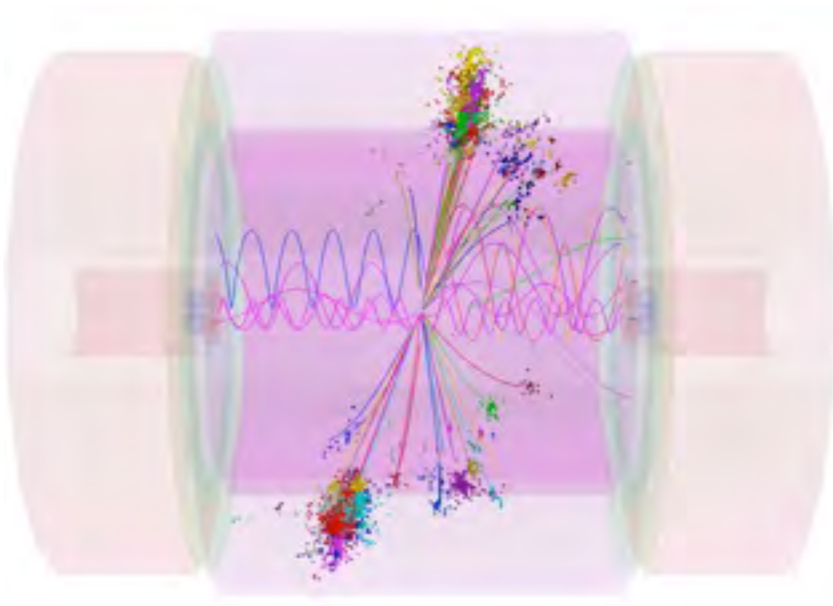

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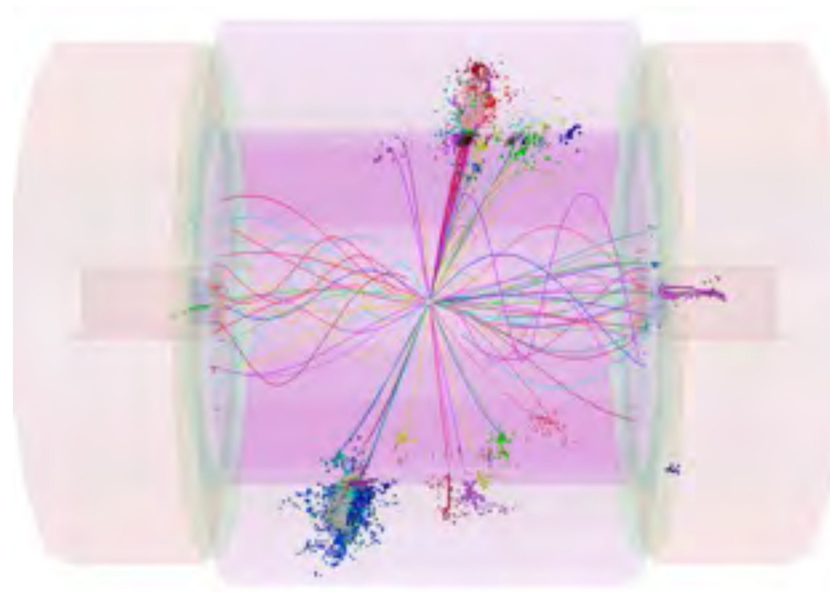

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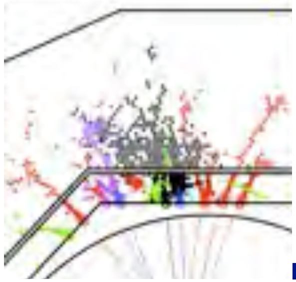

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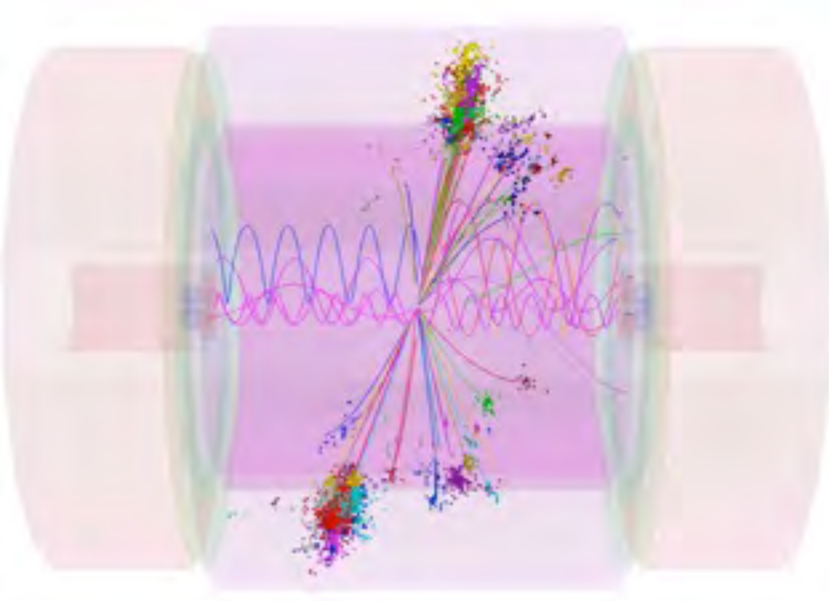
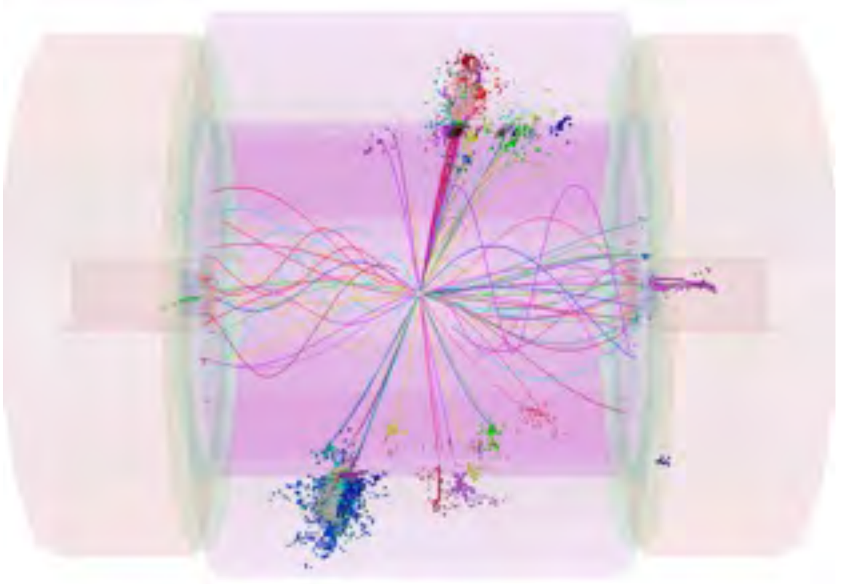
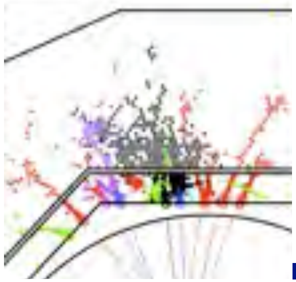
- Overlay γγ events from 60 BX, take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- Apply combination of topological, pt and timing cuts on cluster level (sub-ns accuracy)





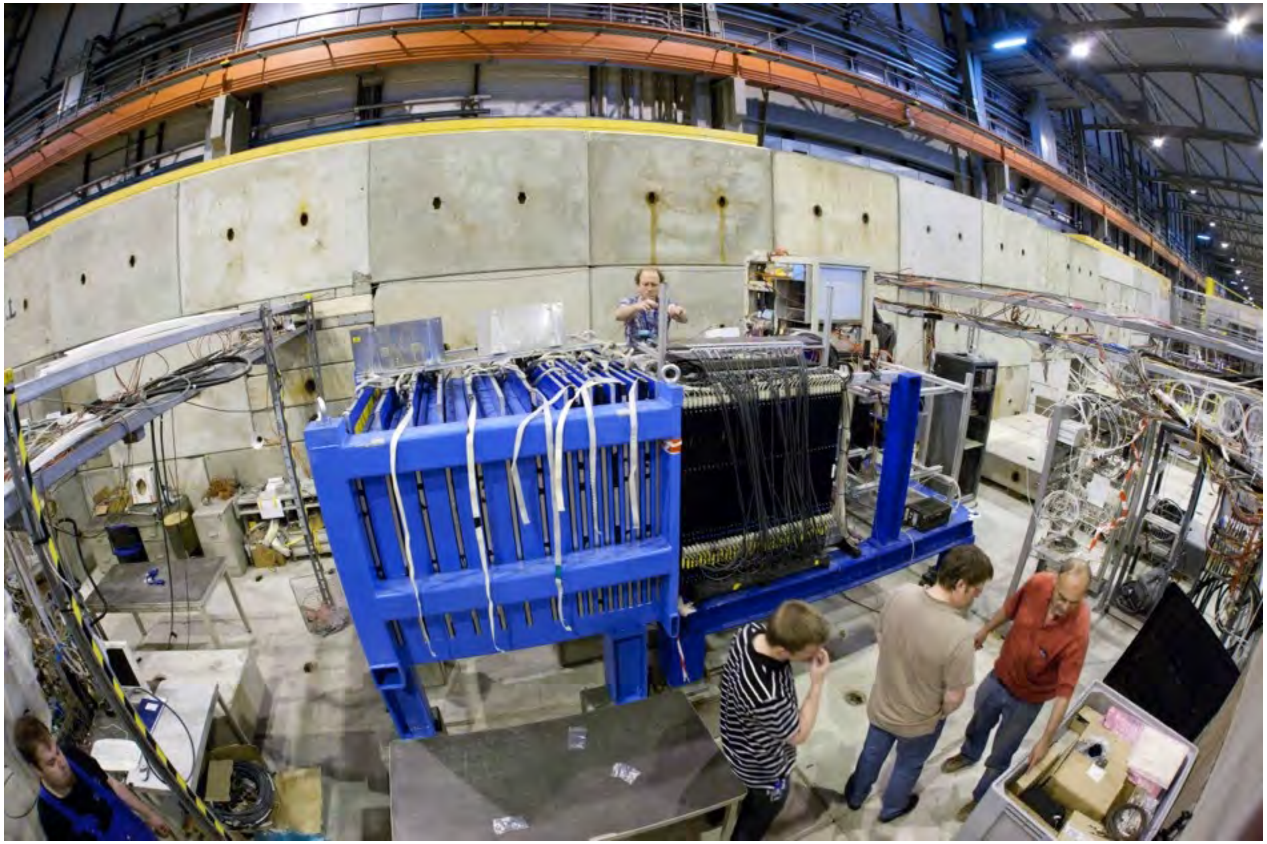
Z @ 1 TeV

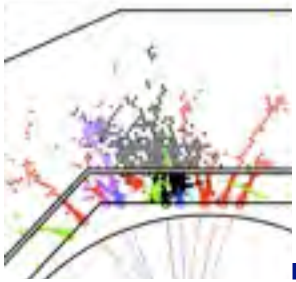


Main ideas:

- 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

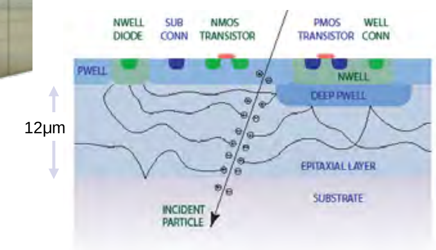
Technologies and test beam performance



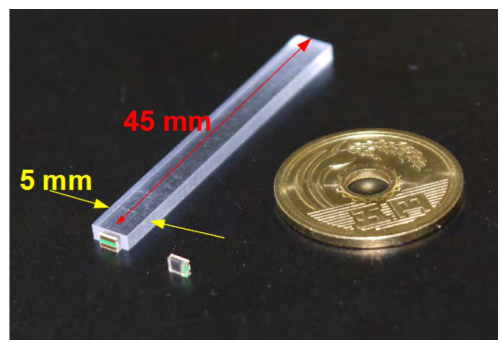


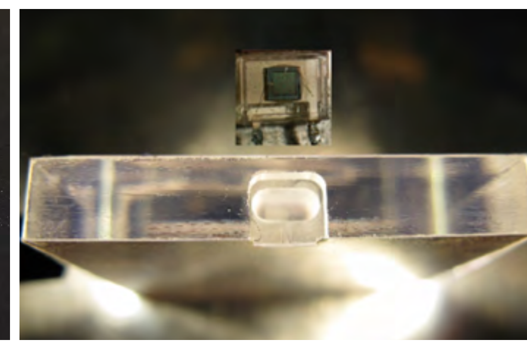
Particle flow technologies

- Silicon (ECAL)
  - most compact solution, stable calibration
  - 0.5 - 1 cm^2 cell size
  - MAPS pixels also studied

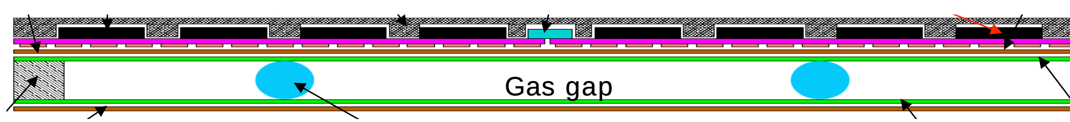


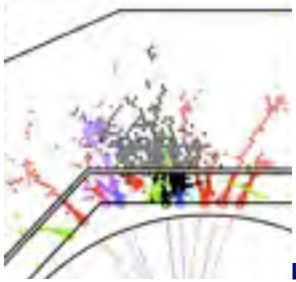
- Scintillator SiPM (ECAL, HCAL)
  - robust and reliable, SiPMs..
  - ECAL strips: 0.5 - 1 cm eff.
  - HCAL tiles: 3x3 cm^2



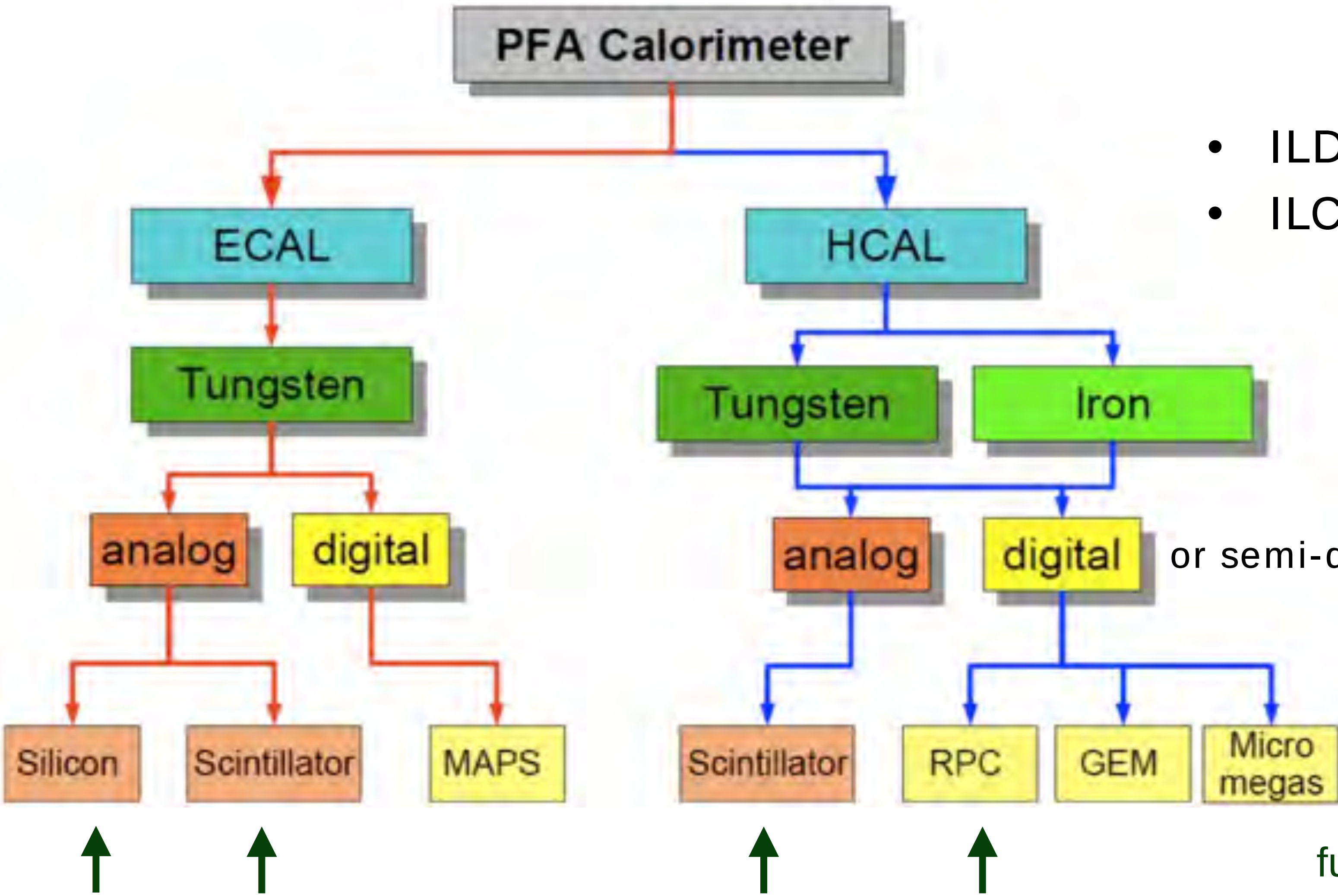


- Gaseous technologies
  - fine segmentation: 1 cm^2
  - Glass RPCs: well known, safe
  - MPGDs: proportional, rate-capable
    - GEMs, Micromegas





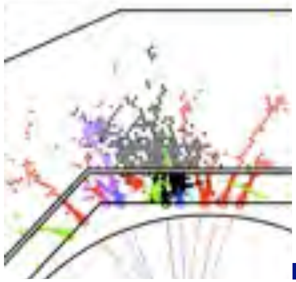
Calorimeter technologies



- ILD, SiD
- ILC, CLIC

or semi-digital

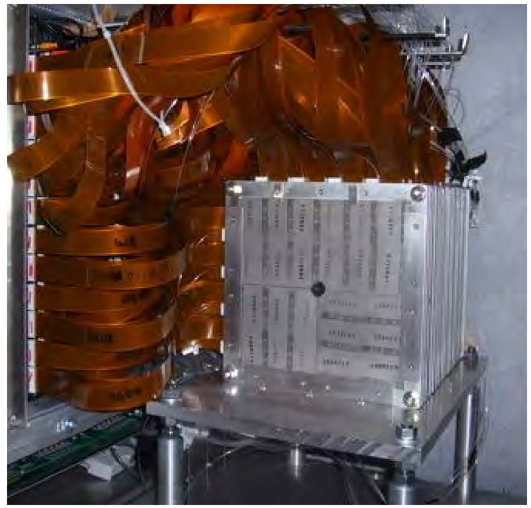
full prototypes



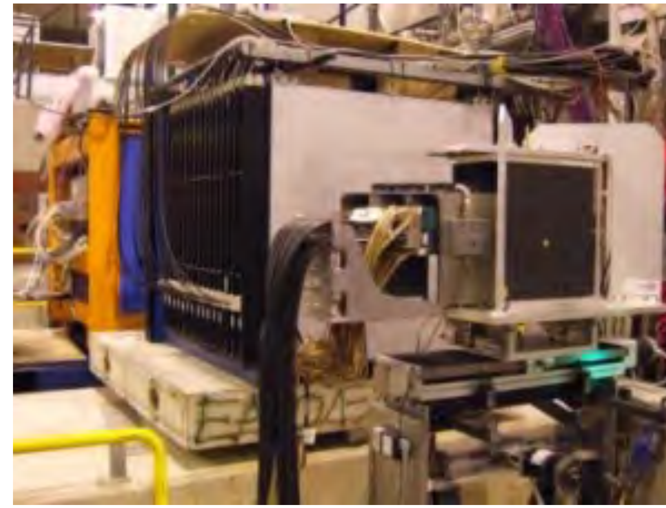
Test beam prototypes

SiW ECAL

ScintW ECAL

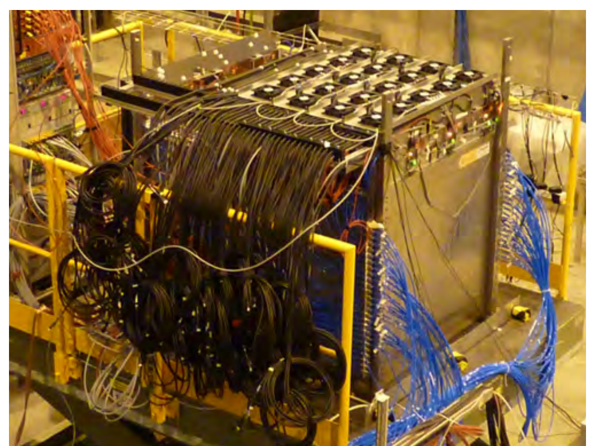


Scint AHCAL, Fe & W



RPC DHCAL, Fe & W

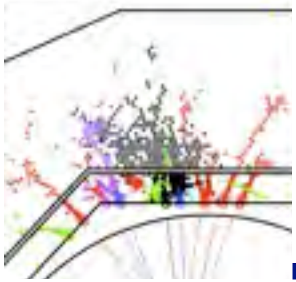
RPC SDHCAL, Fe



plus tests with small numbers of layers:

- ECAL, AHCAL with integrated electronics

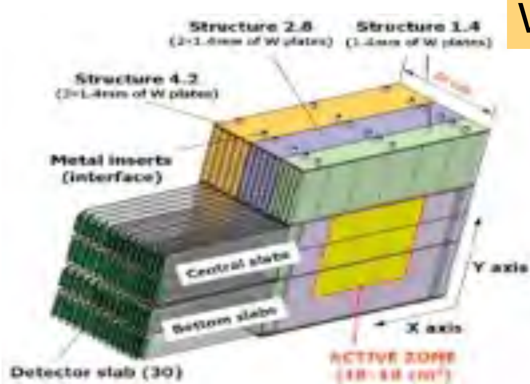
- Micromegas and GEMs

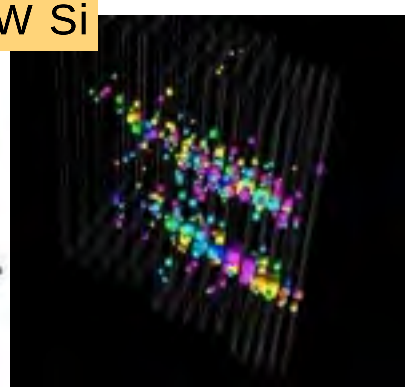


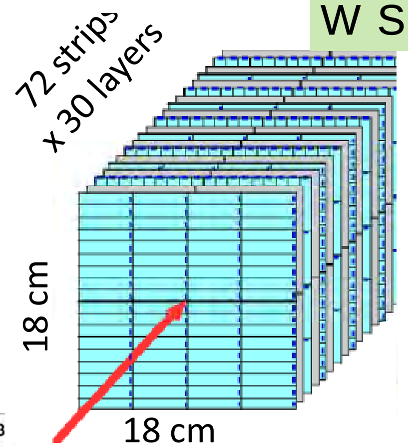
CALICE ECALs performance

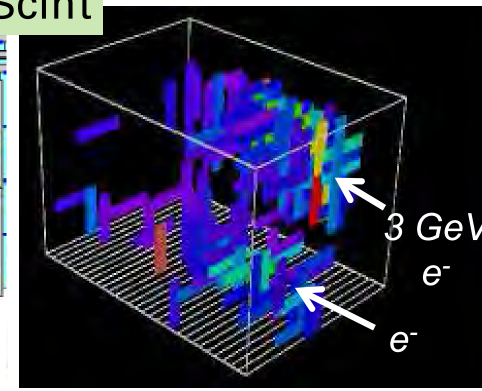
W Si

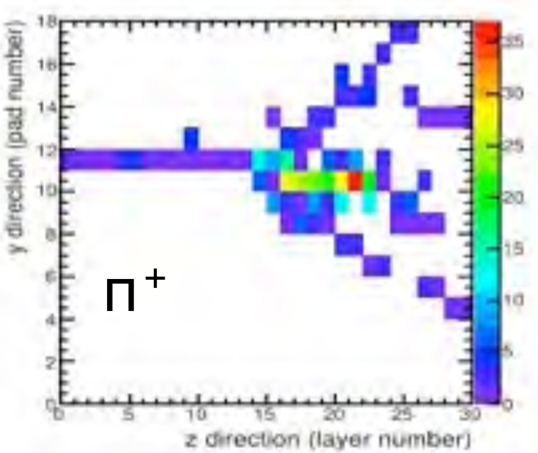
W Scint

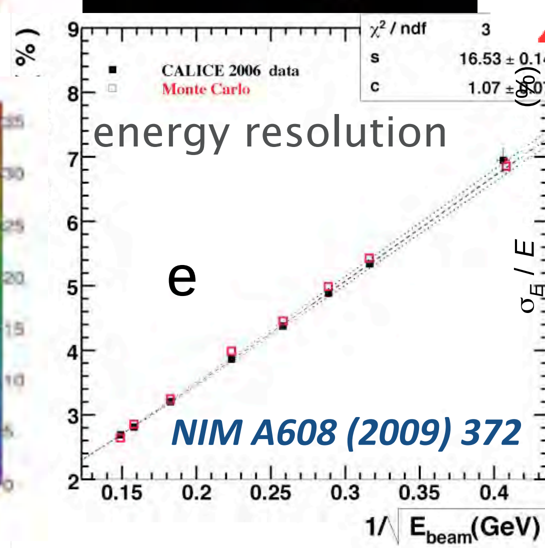


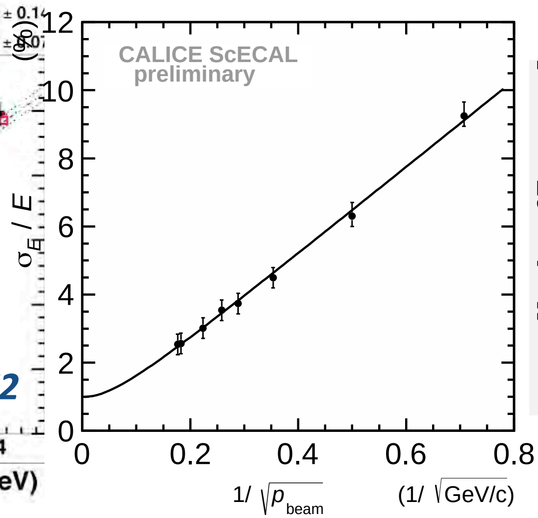


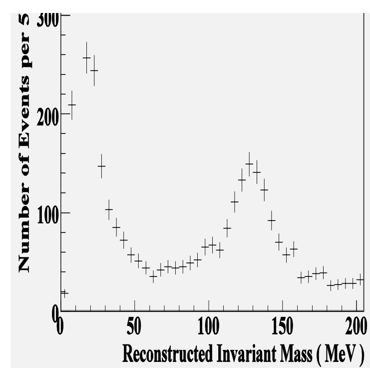




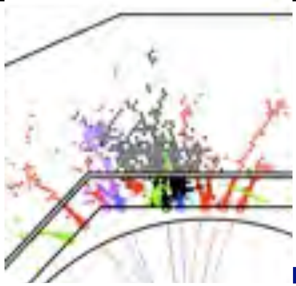






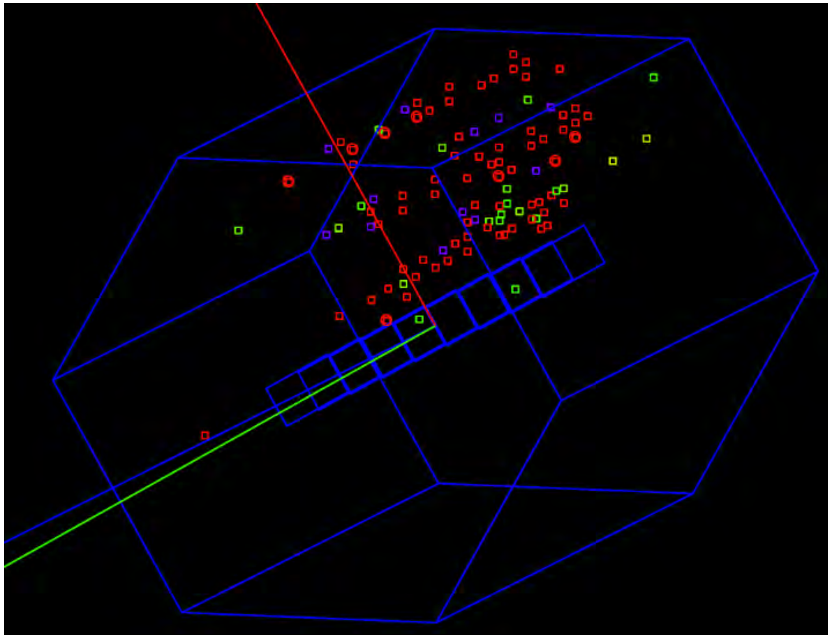


- data and sim agree

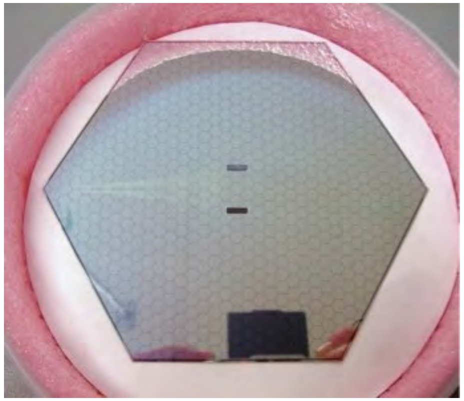


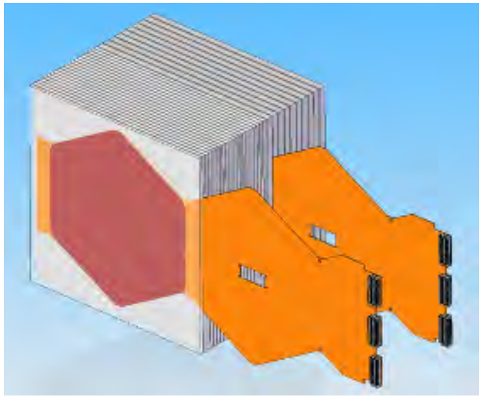
SiD ECAL

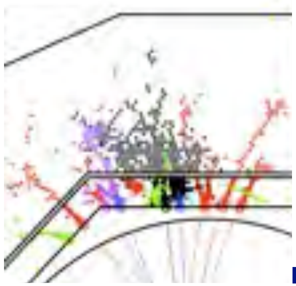
- SiD made some ambitious design choices
  - most compact ECAL
    - smallest $R_{Moliere}$
  - most light-weight Silicon tracker
  - both based on KPiX chip (1024 ch)
  - directly bonded to wafer
- ECAL: no PCB
  - 1.1 mm thin active gap



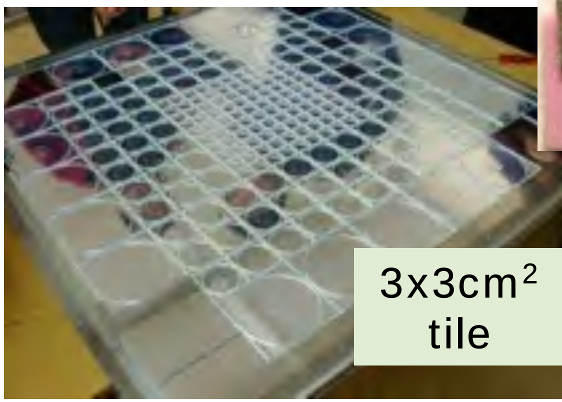
July 2013
9 layers in the beam
at SLAC End Station A



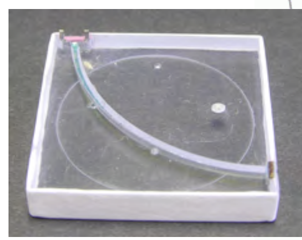


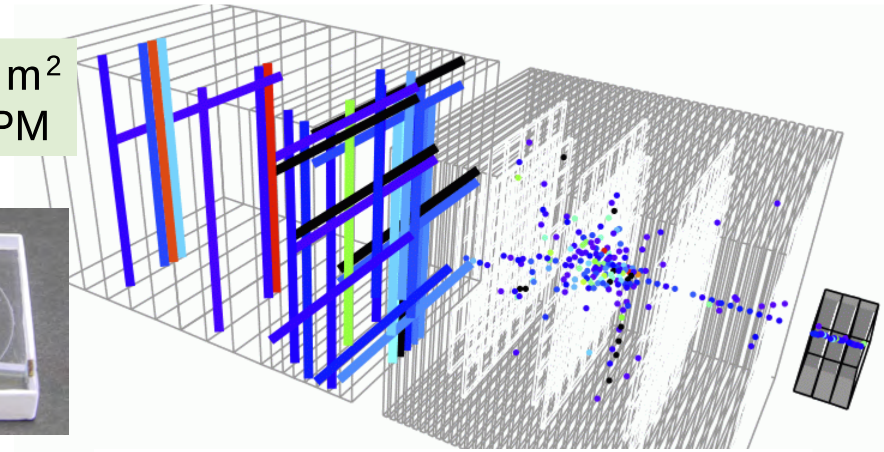


Scintillator HCAL performance



1mm^2
SiPM

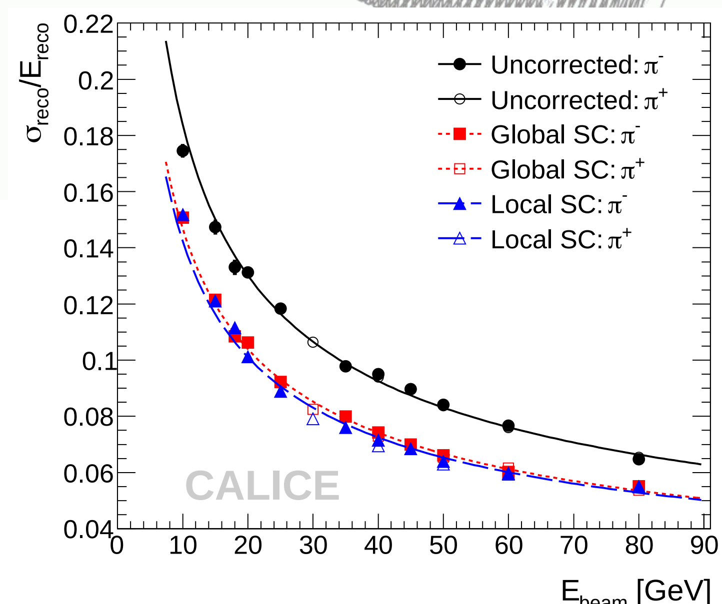




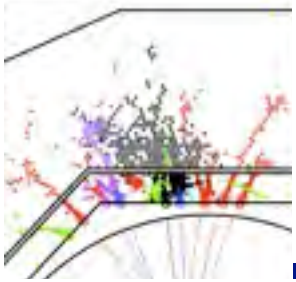
- 38 layer steel and tungsten
- 7608 channels: first large scale SiPM application
- very robust: 6 years of data taking at DESY, CERN, Fermilab
- a very good calorimeter, too

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

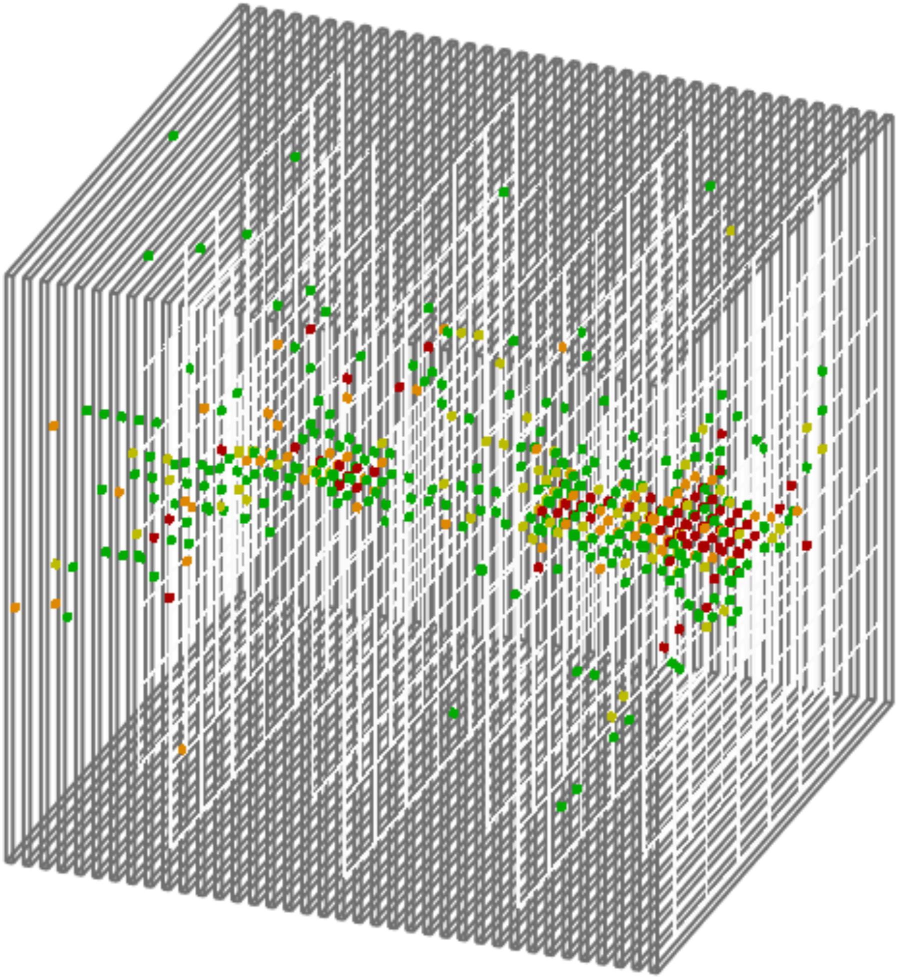
software compensation



JINST 7, P00917 (2012)

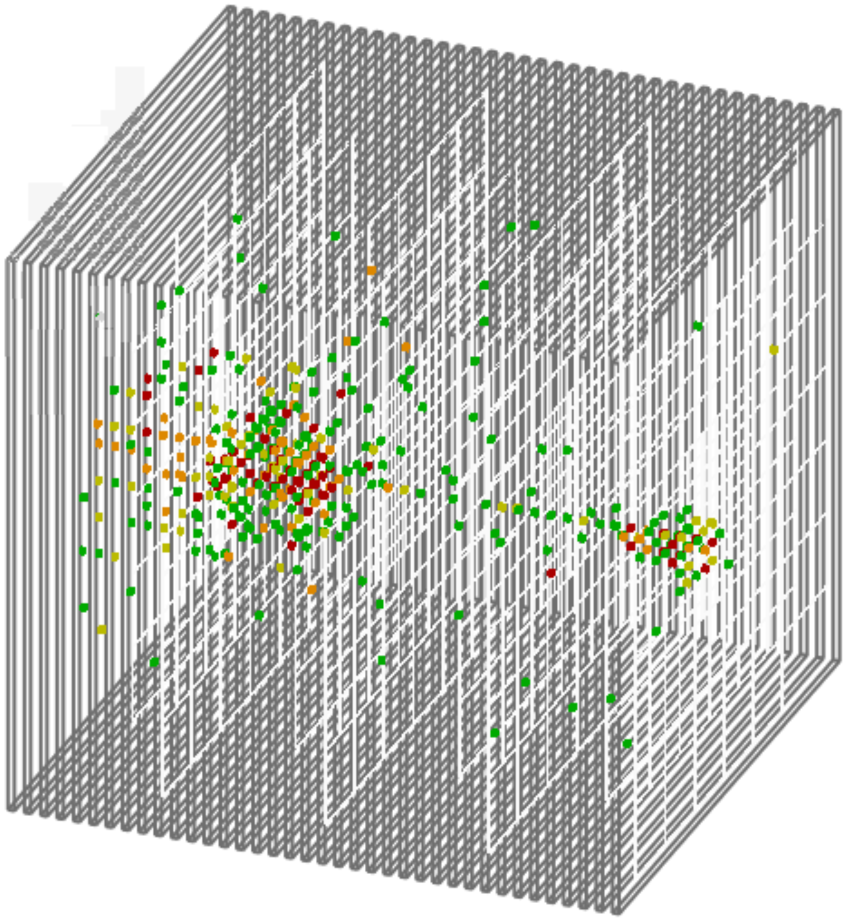


Event displays



- pions 80 GeV
- W absorber

Event displays



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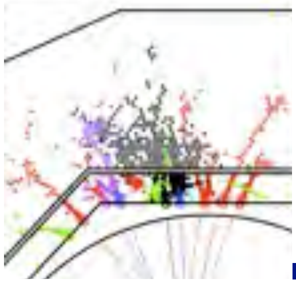

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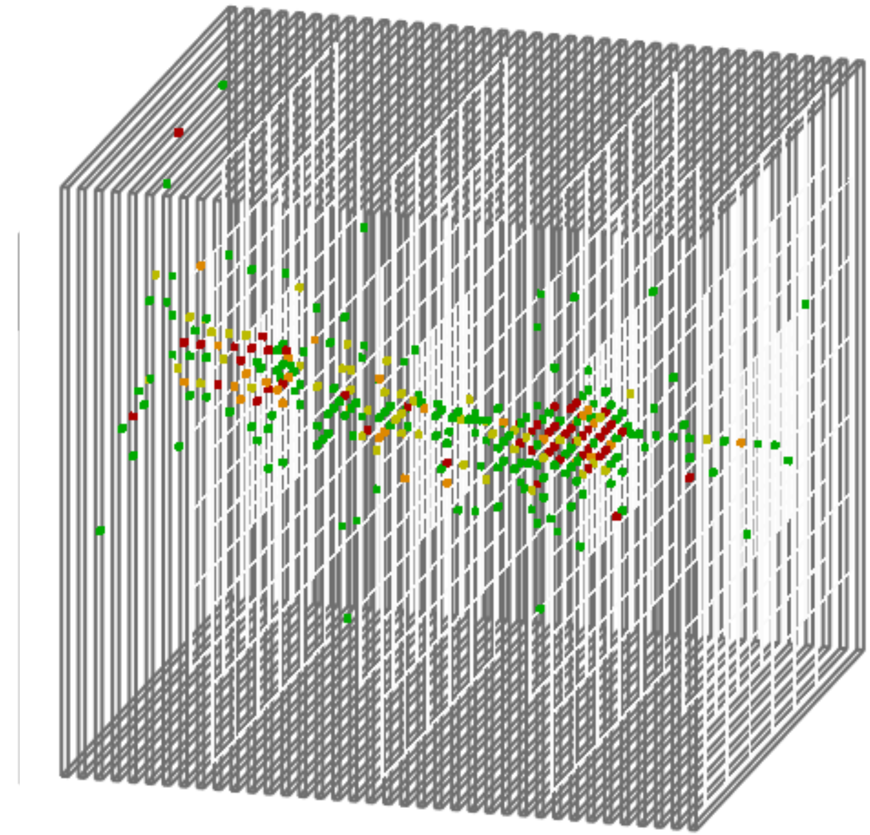

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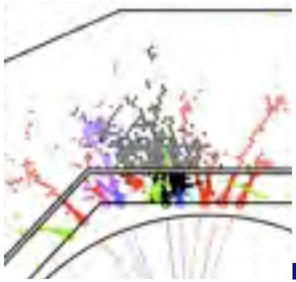
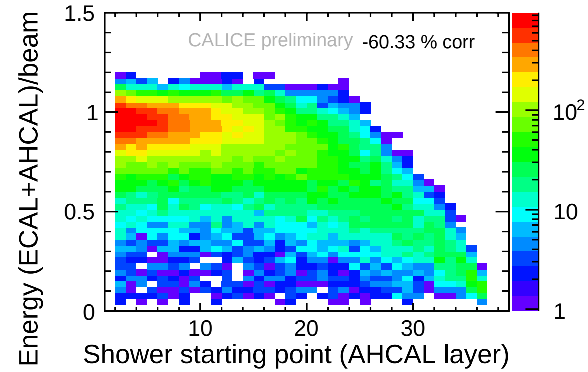
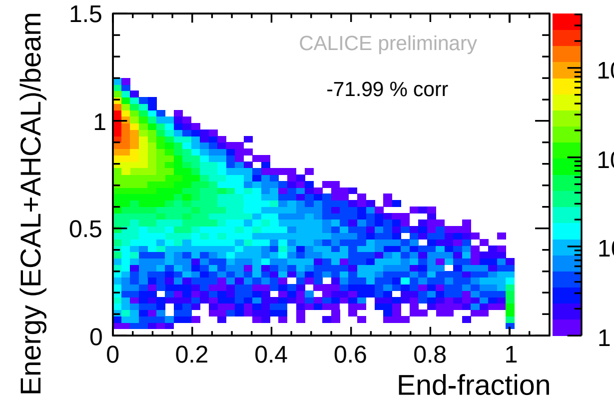
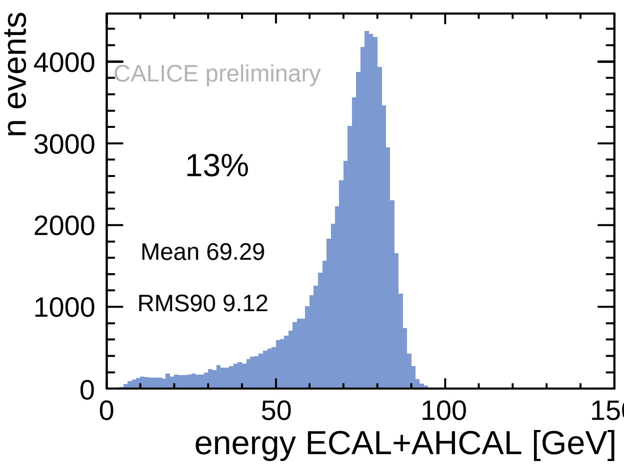


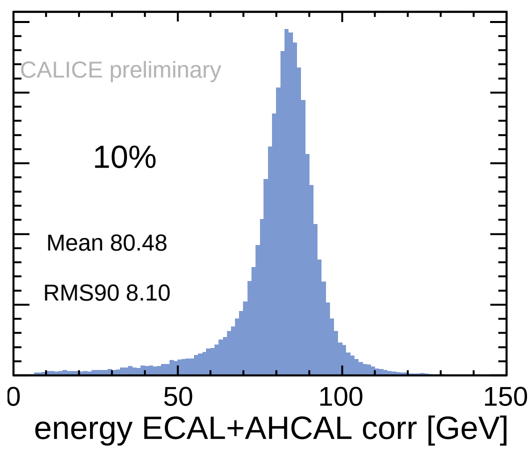
Leakage estimation

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





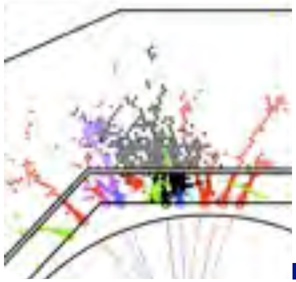




cf : with tail catcher, no coil: 5.4%

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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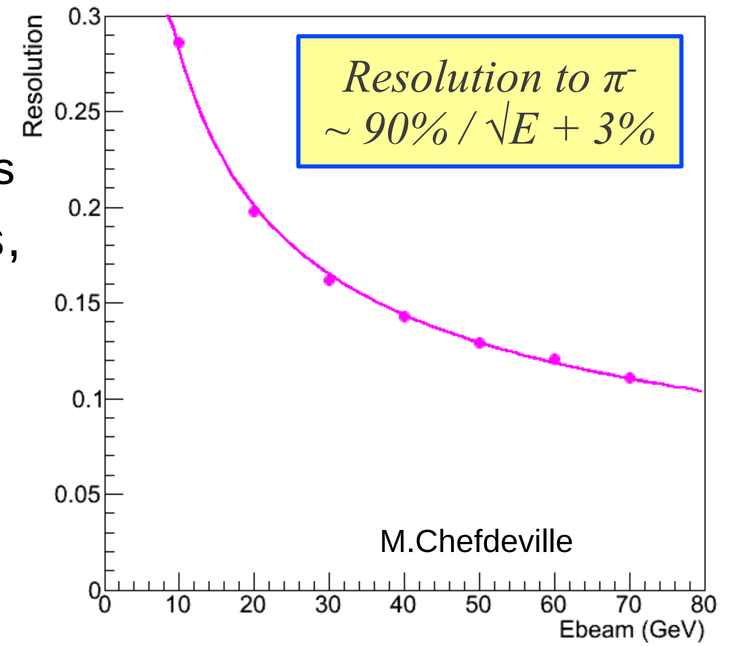

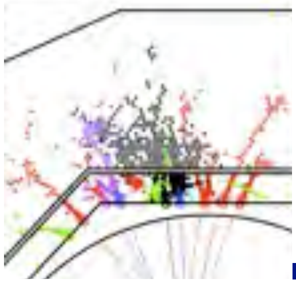

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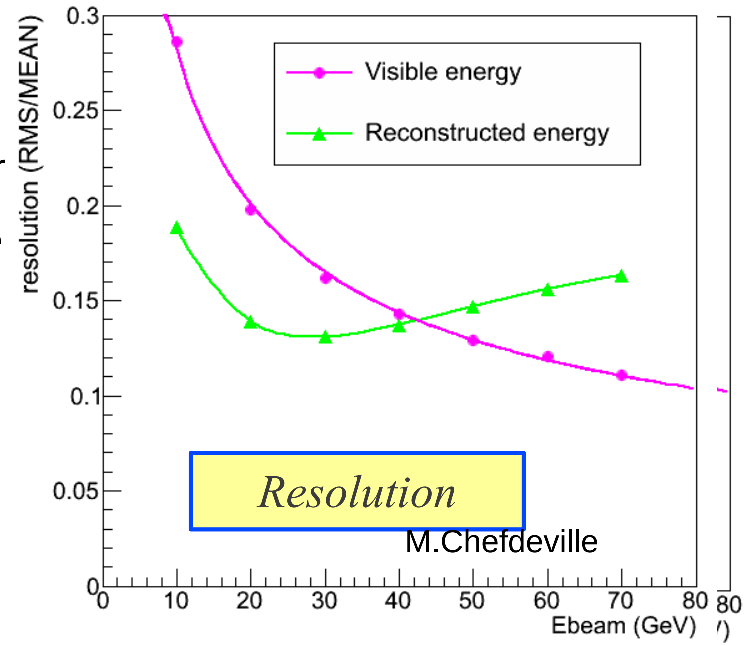

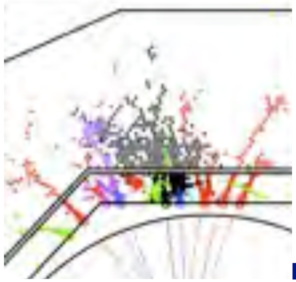

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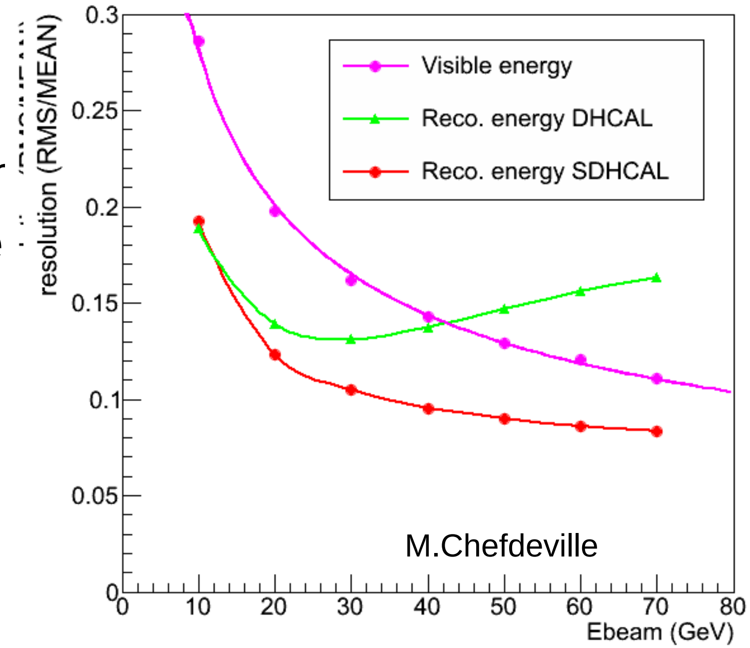

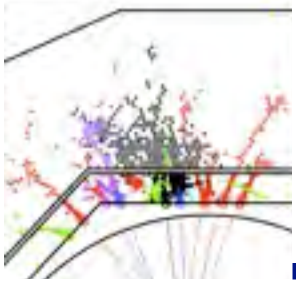

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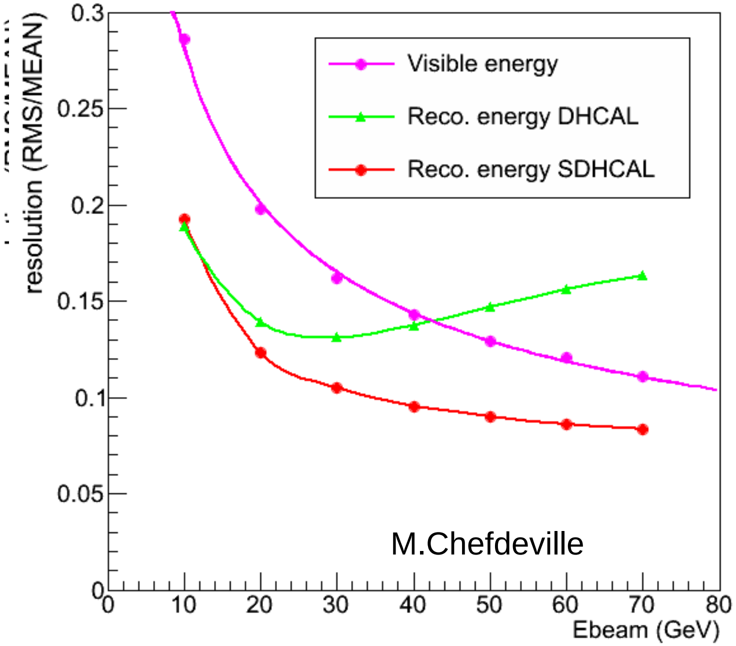
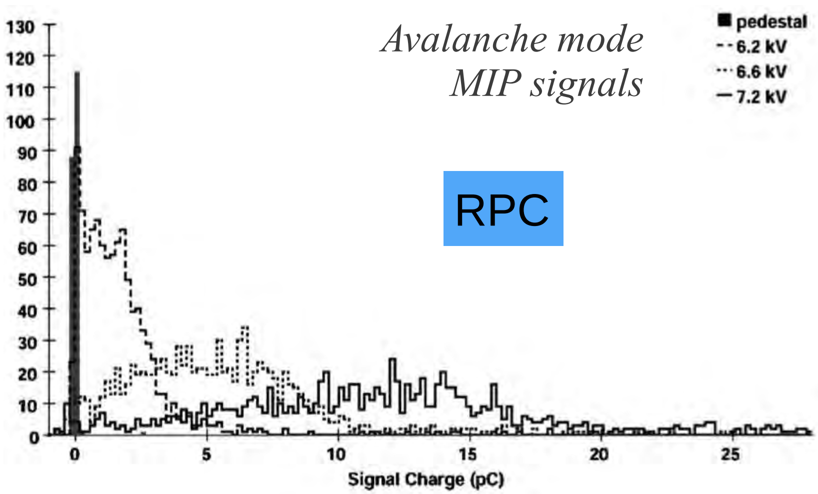
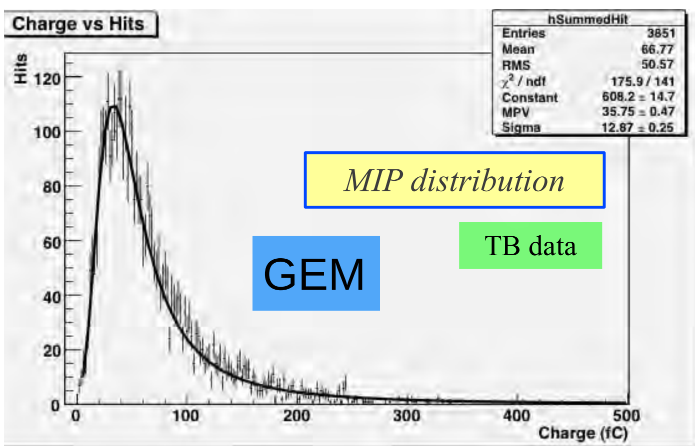
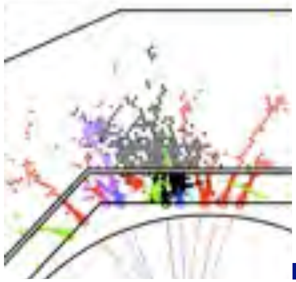


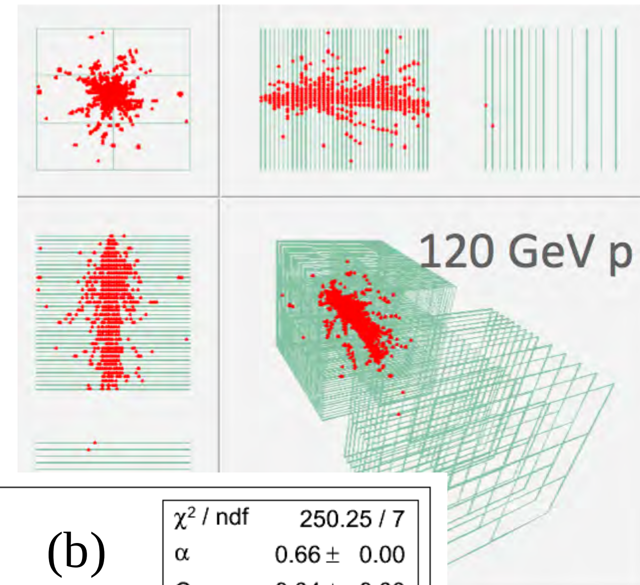


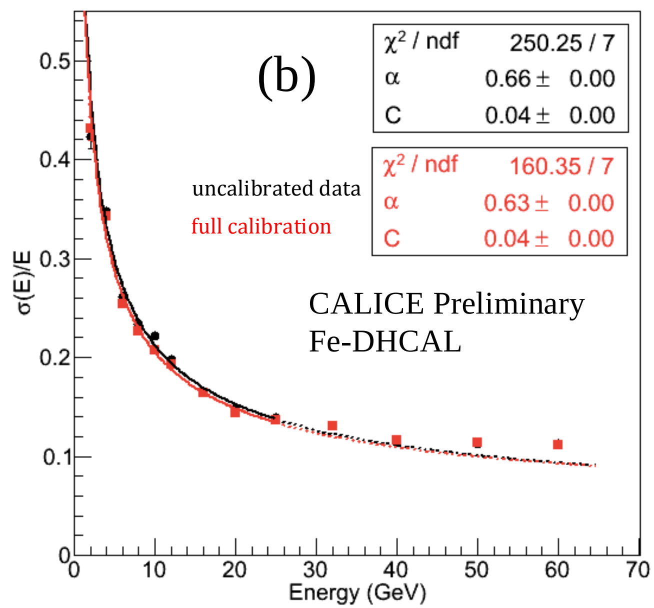


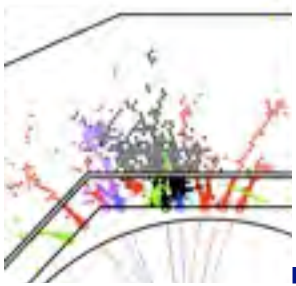


Digital RPC HCAL

- 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

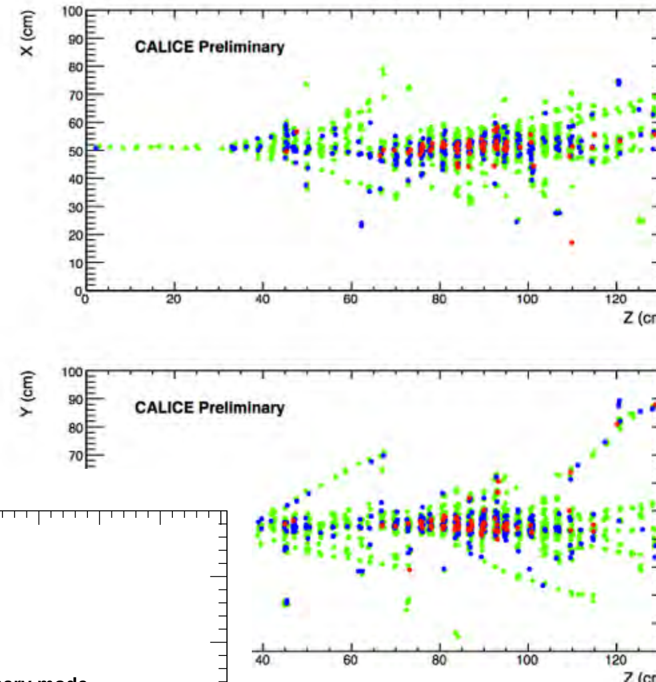


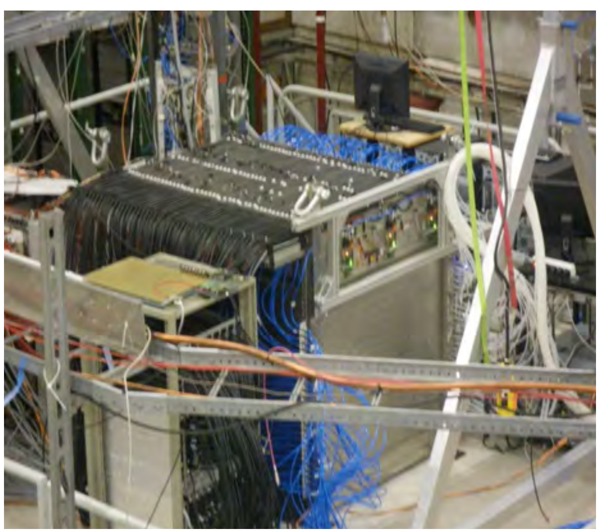


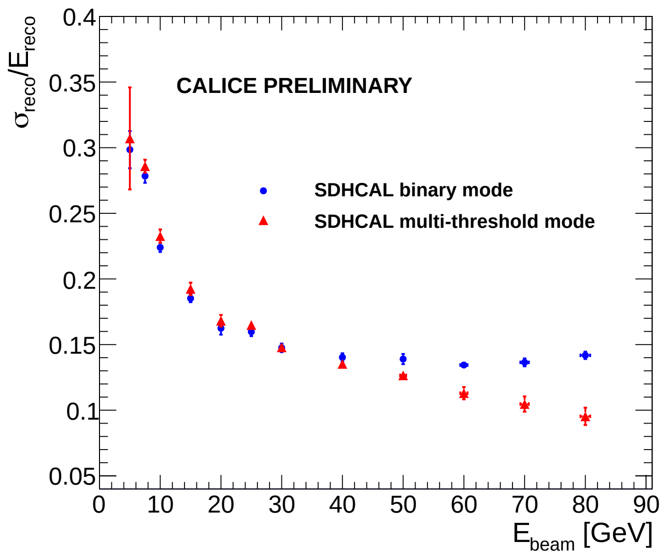


Semi-digital RPC HCAL

- 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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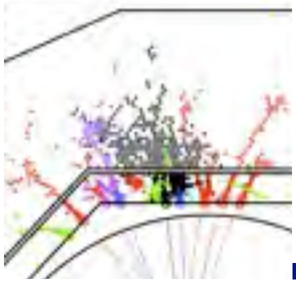
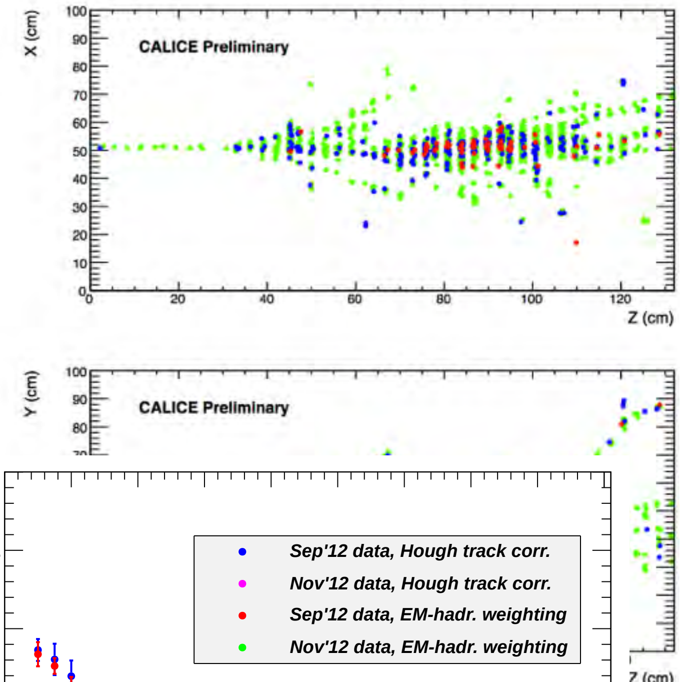
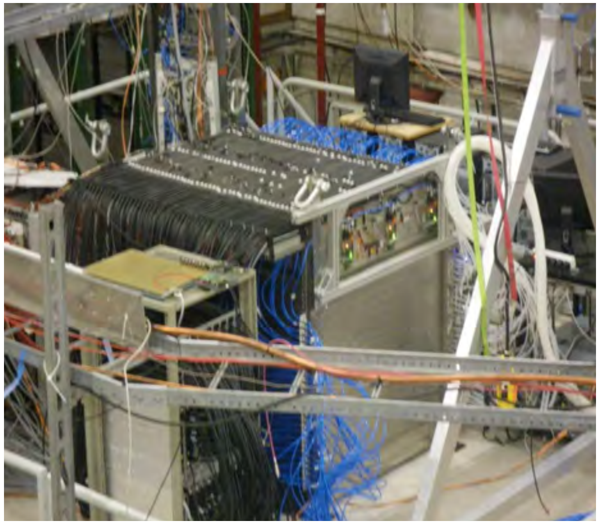
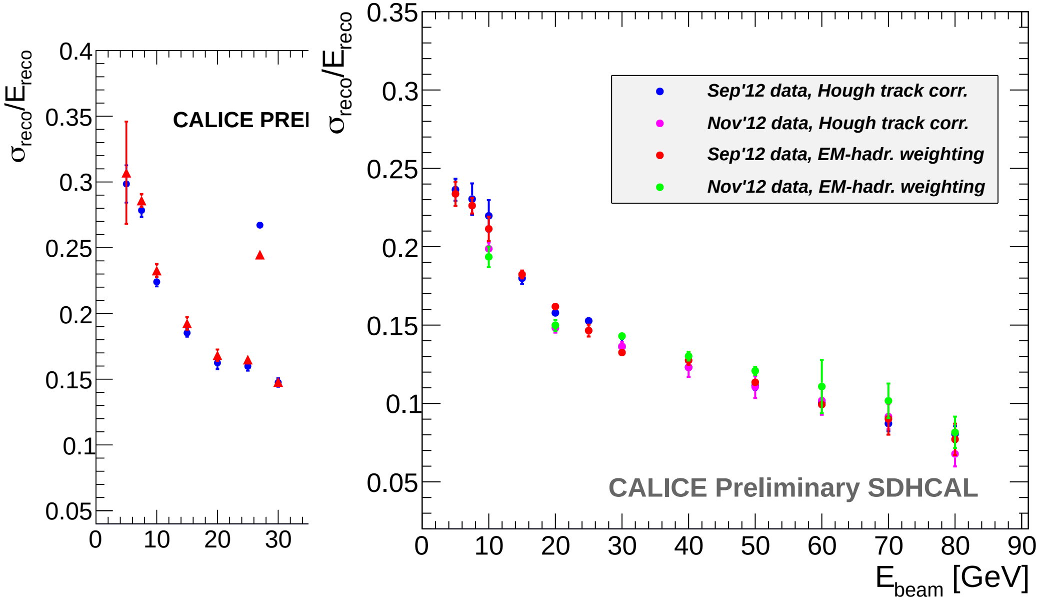
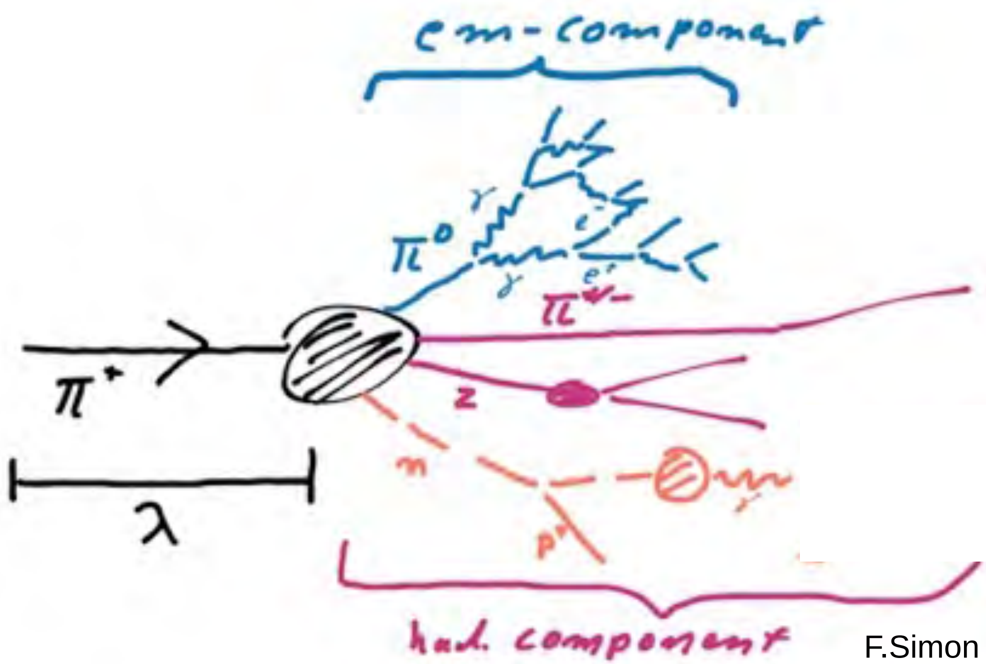




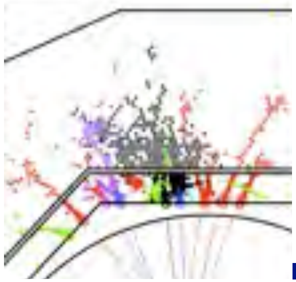




Validation of
Geant 4 shower models

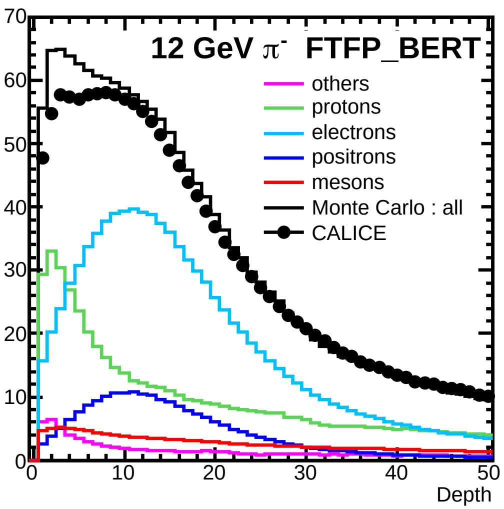


F.Simon



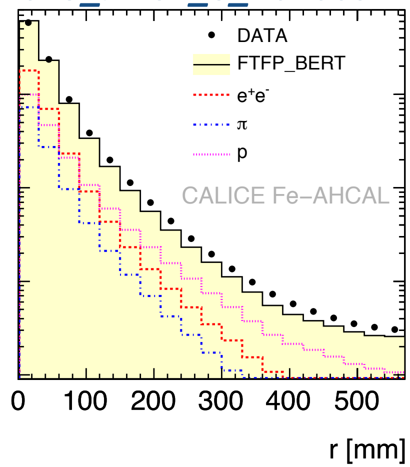
Validation of Geant 4 models

2010_JINST_5_P05007



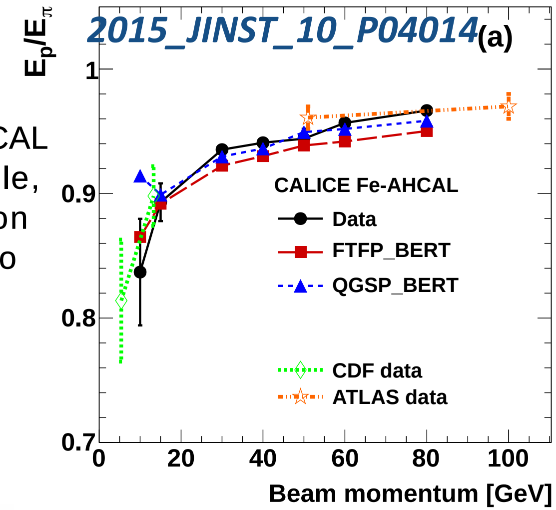
SiW ECAL longit. profile

2013_JINST_8_P07005

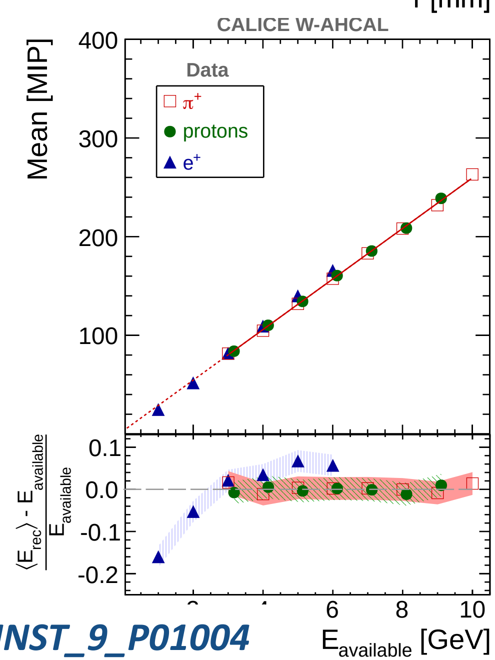


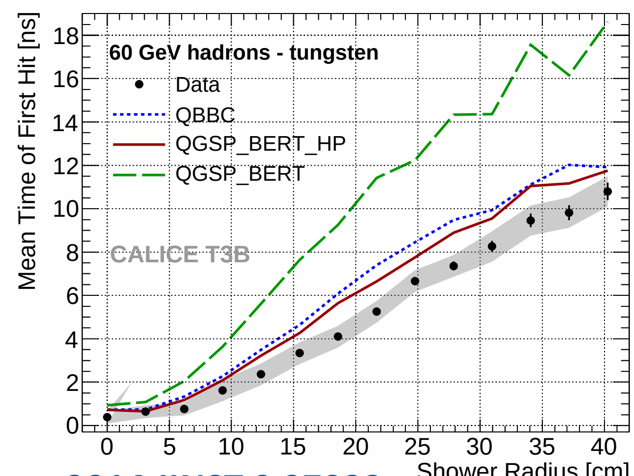
Fe Scint HCAL radial profile, proton pion resp. ratio

2015_JINST_10_P04014



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

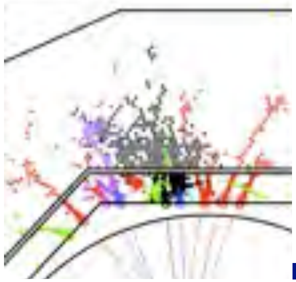




2014 JINST 9 07022

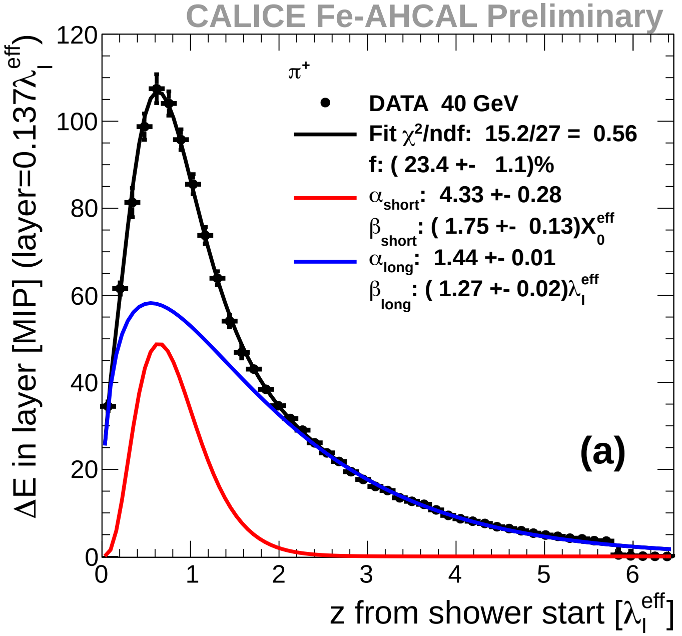
W Scint HCALresponse, timing

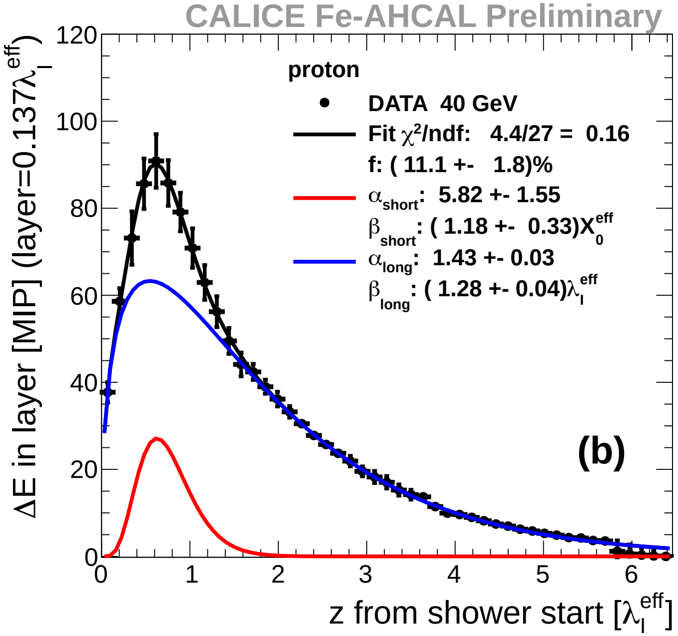
2014_JINST_9_P01004

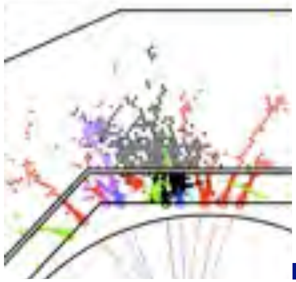


Longitudinal shower profiles

- 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







Longitudinal shower profiles

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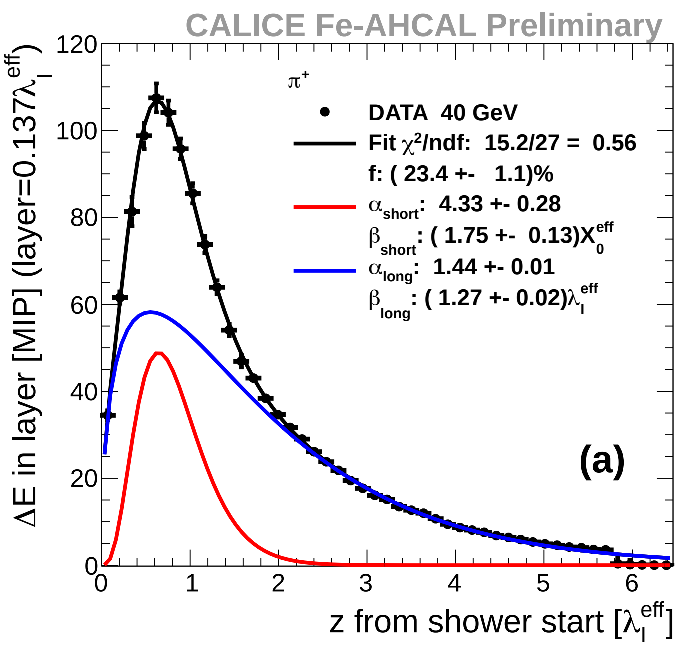
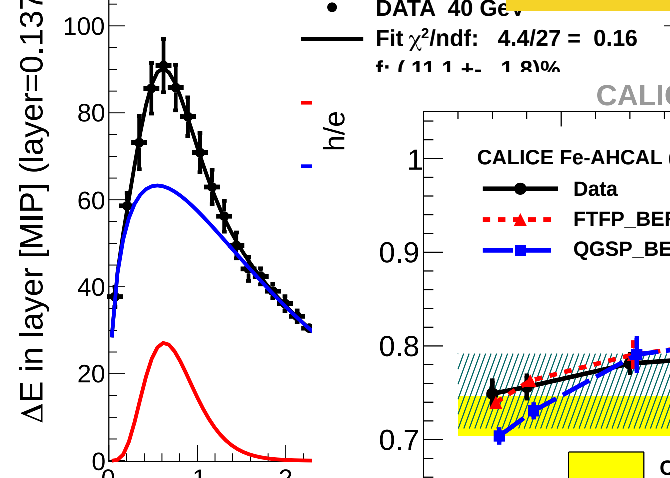
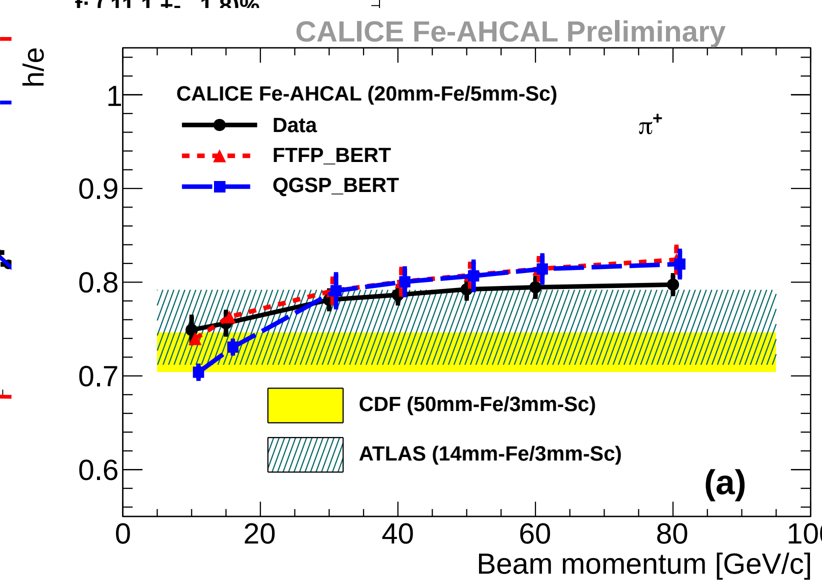
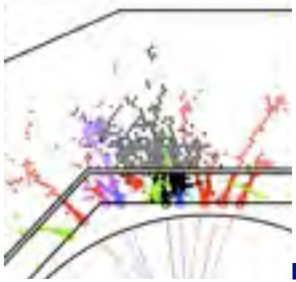
- Determine h / e ratio without assumption on energy dependence

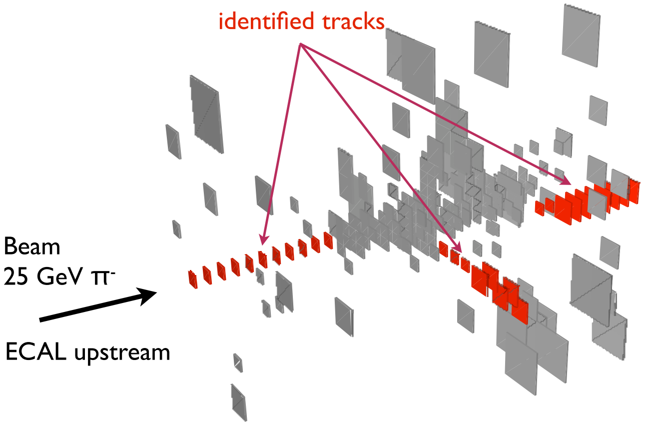


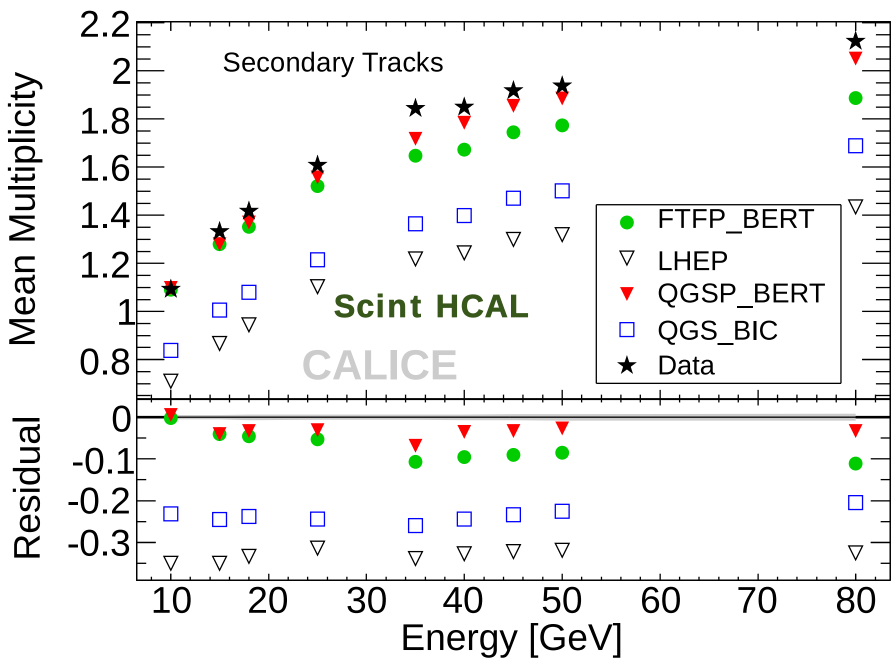






Shower fine structure





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