Exploring the structure of hadronic showers and the hadronic energy reconstruction with highly granular calorimeters

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CNRS IN2P3 Les deux infinis

université PARIS-SACLAY GRADUATE SCHOOL Physique — P2I Physique des deux Infinis

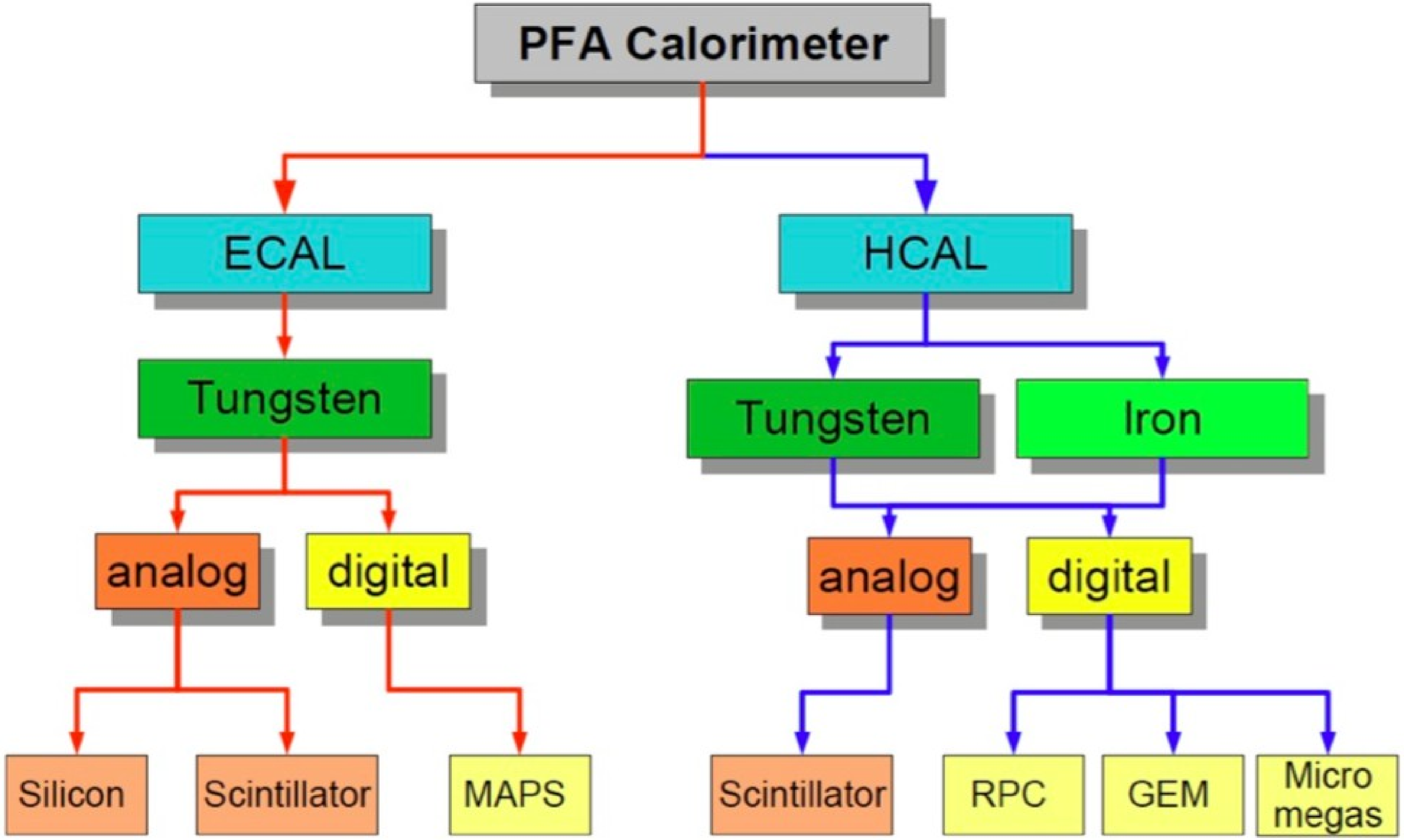
On behalf of

CALICE

TIPP 2023 – September 2023 Cape Town, South-Africa

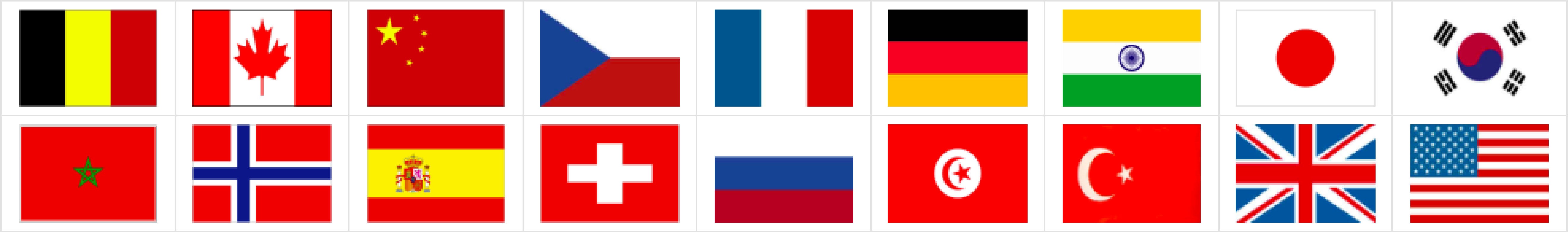
Calorimeters for PFA

Mainly organised within the: CALICE Collaboration



The CALICE Collaboration

Calorimeter R&D for large imaging calorimeters



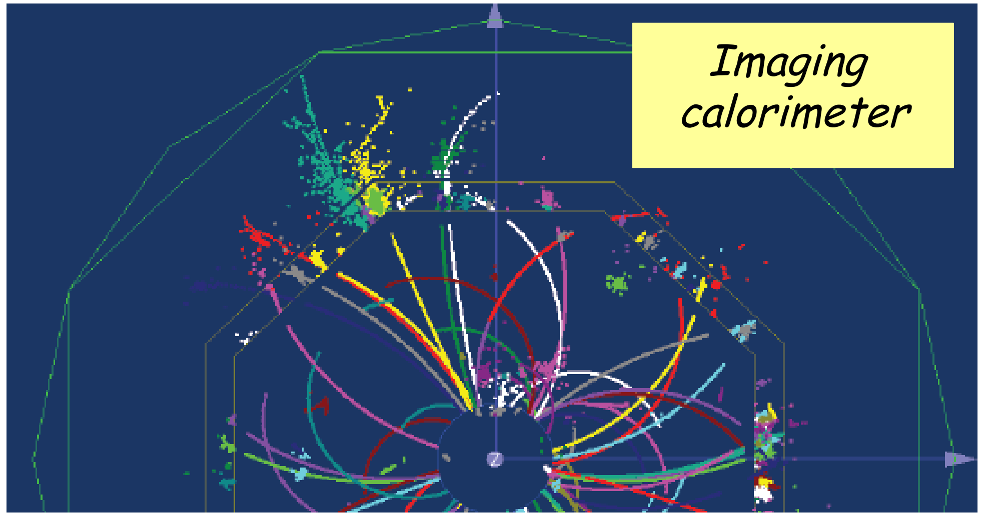
~270 physicists/engineers from 62 institutes and 18 countries from 4 continents

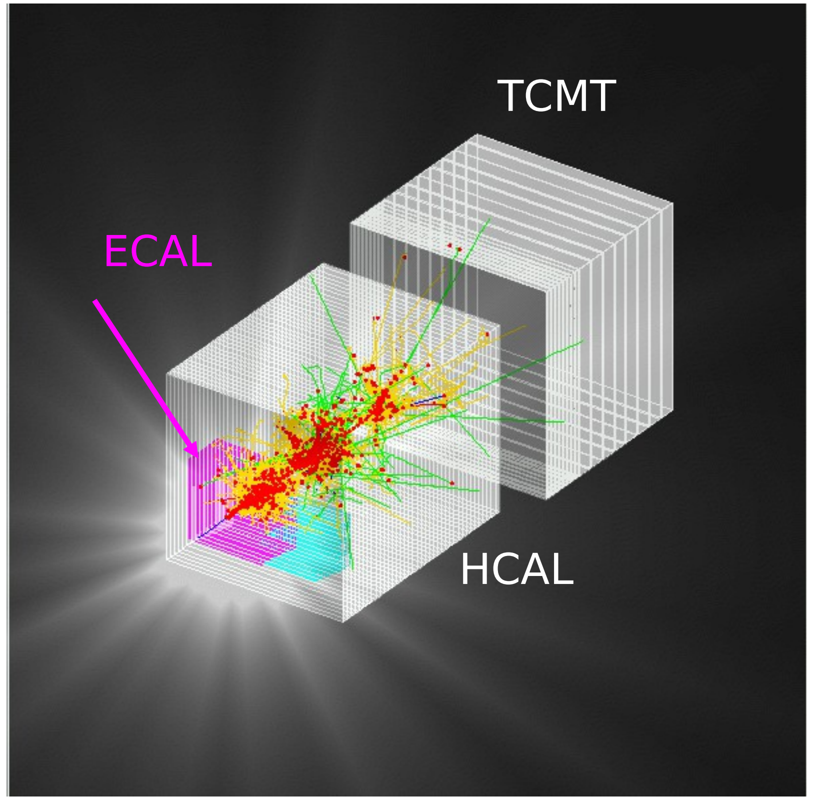
- Integrated R&D effort
- Acceleration of detector development due to *coordinated* approach
- MOU 2005

The CALICE Mission

Final goal:

A highly granular calorimeter optimised for the Particle Flow measurement of multi-jets final state at the International Linear Collider

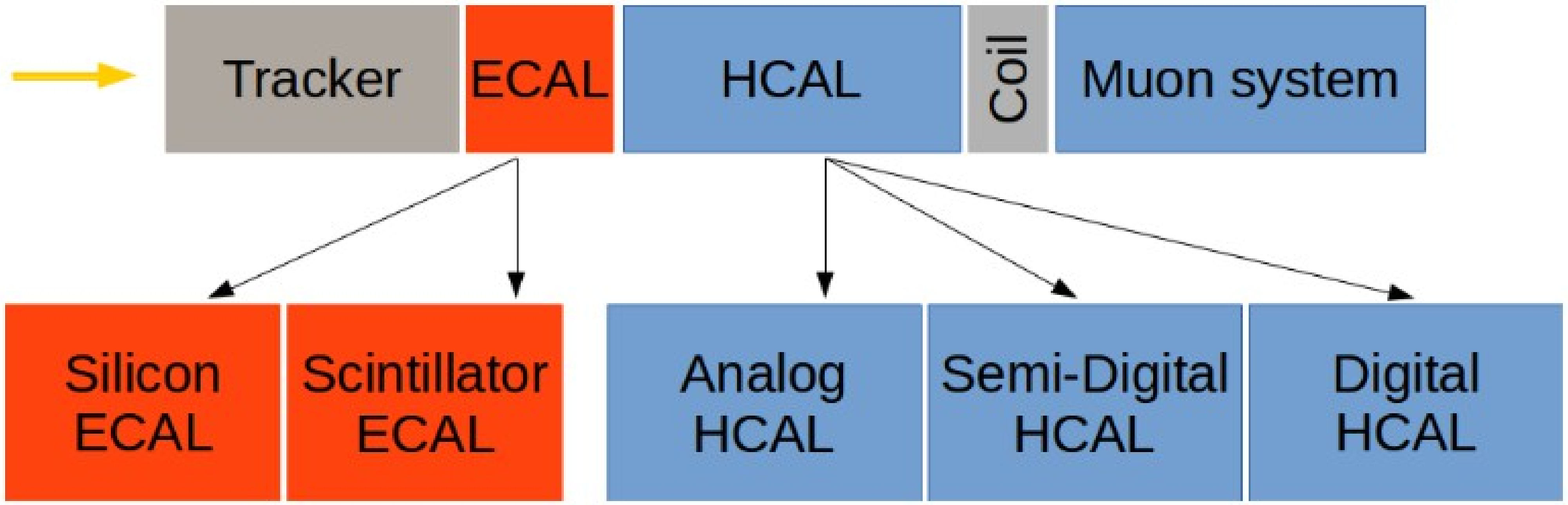




Intermediate task:

Build prototype calorimeters to
- Establish the technology
- Collect hadronic showers data with unprecedented granularity to
- tune clustering algorithms
- validate existing MC models

CALICE Collaboration - Prototypes



Active material:	Si Diodes	Scintillator	Scintillator	Gas	Gas
Granularity [mm^3]	10x10x0.5	45x5x3	30x30x5	10x10x2	10x10x1.15
Absorber:	W	W	W and Fe	Fe	W and Fe
Layer x Thickness [mm]:	10x1.4 10x2.8 10x4.2	30x3.5	Fe: 38x21.4 W: 38x10	48x20	Fe: 38x20 W: 39x10
	Si-ECAL	**Sc-ECAL**	**AHCAL**	**SDHCAL**	**DHCAL**

E. Sicking, VCI16

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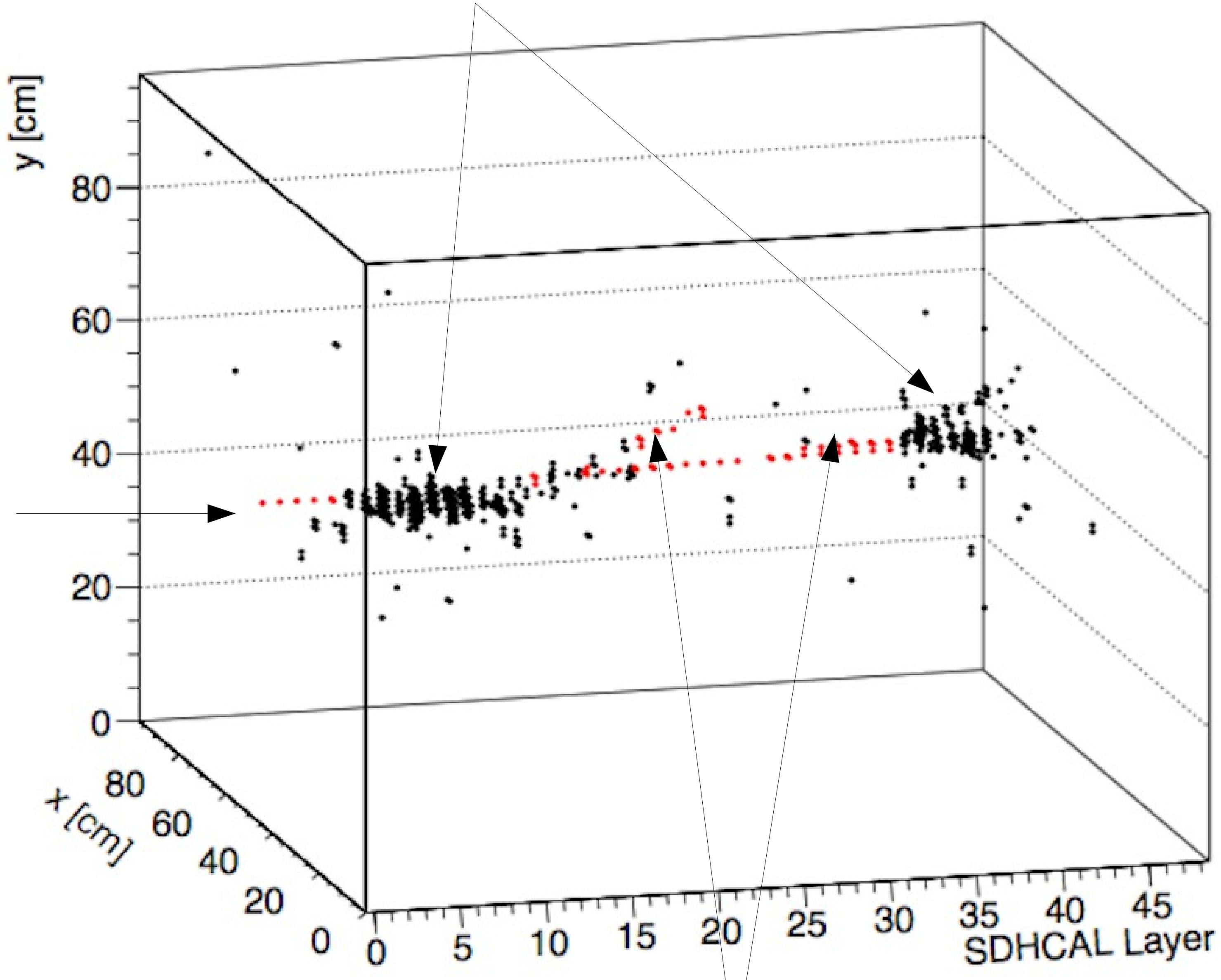
Granular Calorimeters – What do we see?

Hard interactions

Primary particle

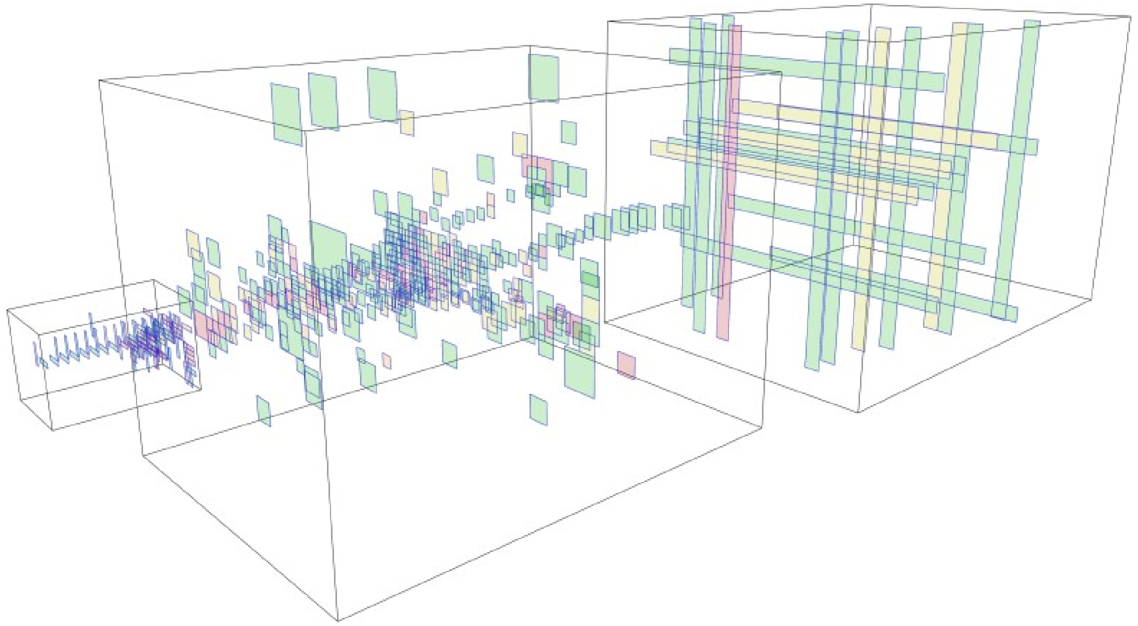


Secondary particles/tracks

- Modern bubble chambers
- Revealing details of hadronic cascades
- Allows for tracking of particles in calorimetric volume
  - => particle separation for PFA
- Rich potential for application/development of modern pattern recognition algorithms

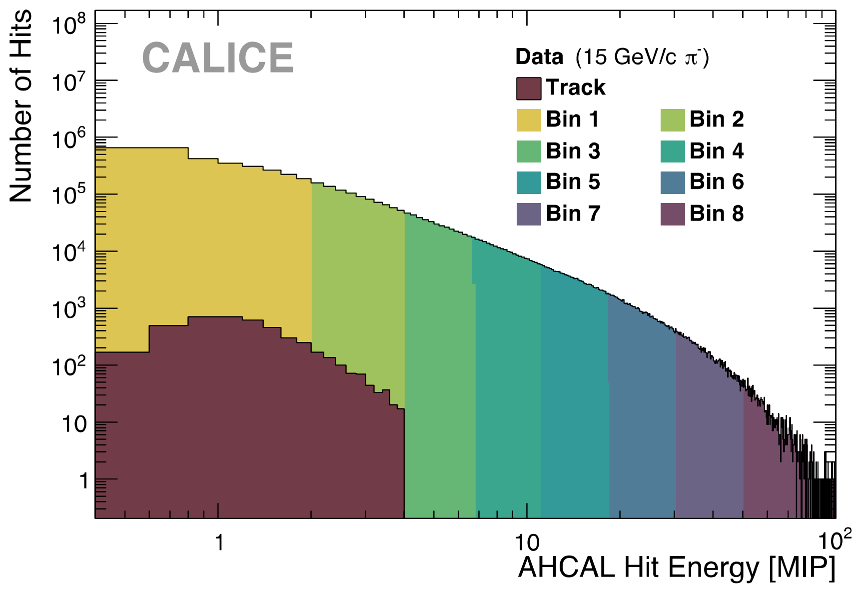
Software Compensation

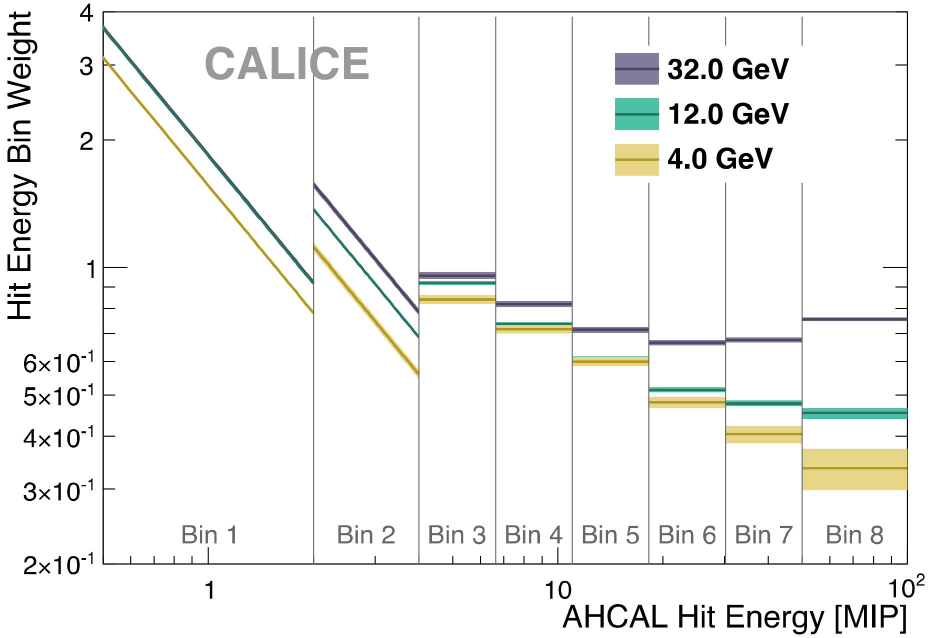
ScintECAL+AHCAL+TCMT [JINST 13, P12022 (2018)]



The basis of the technique:

- Local shower density depends on origin of energy deposits
- Higher density for electromagnetic subshowers
- Lower density for the remaining (hadronic) part





→ e/h compensation can be achieved by assigning energy-dependent weights to hits in global energy sum

significant improvement of energy resolution

- Weights are energy dependent

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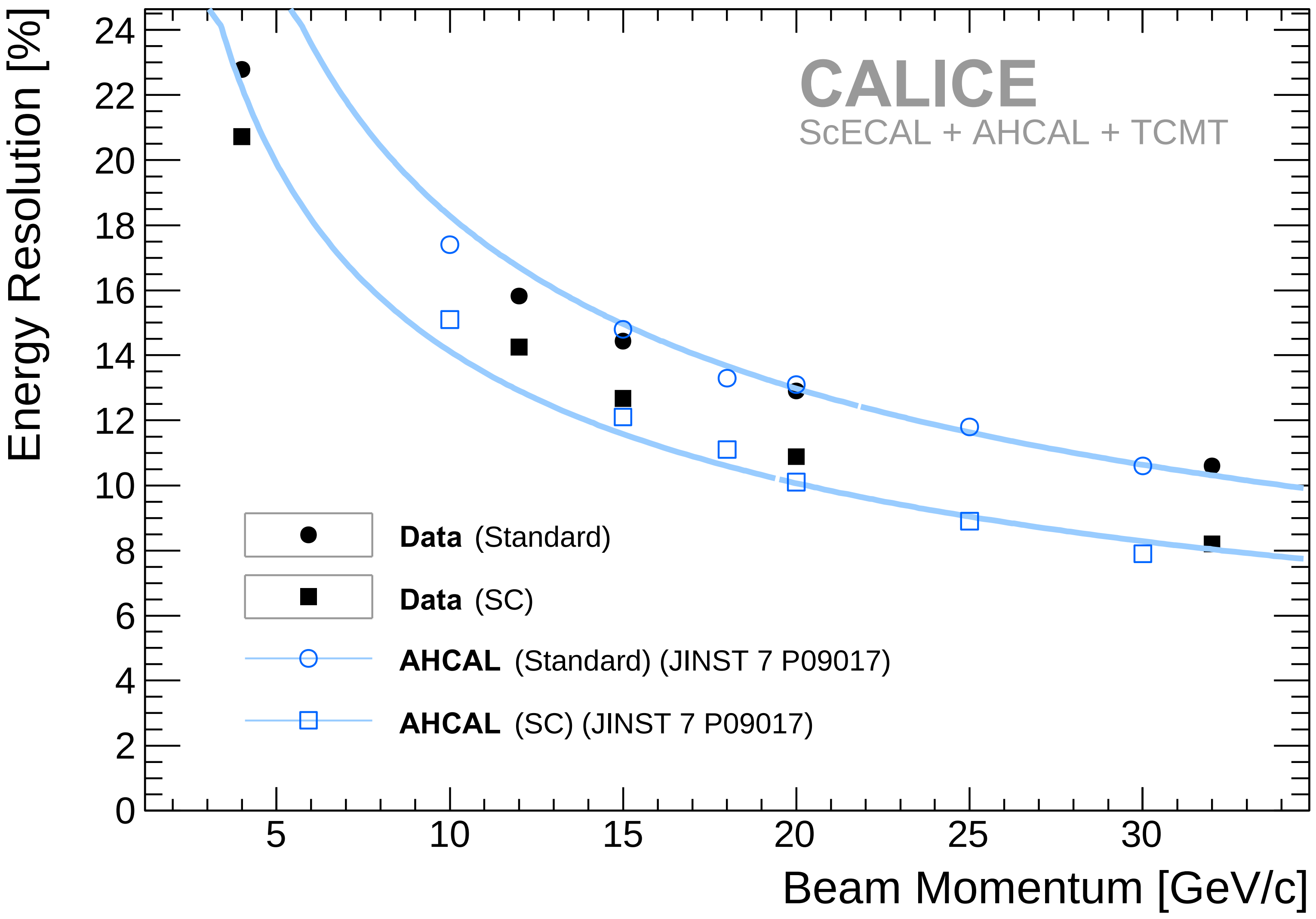
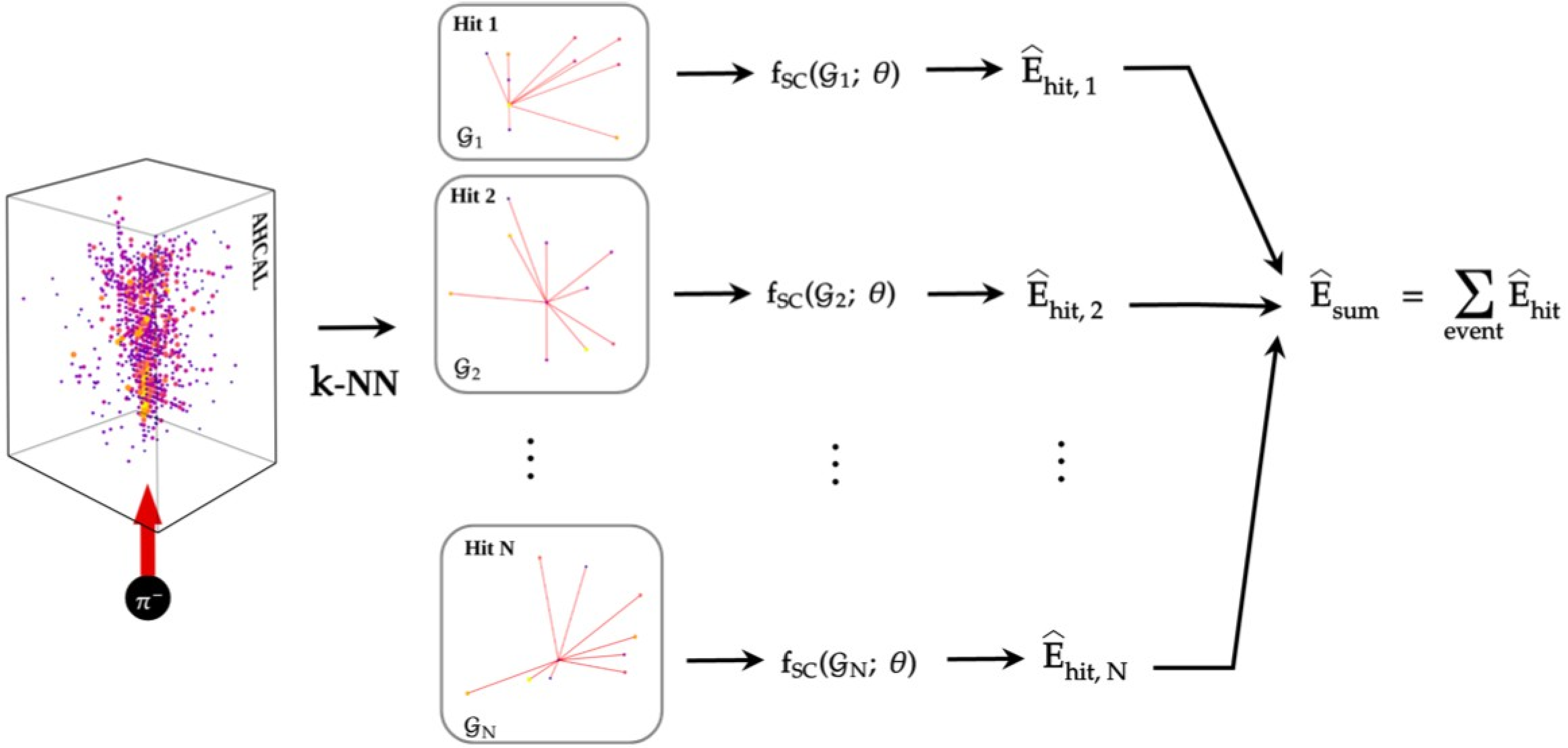
Software Compensation

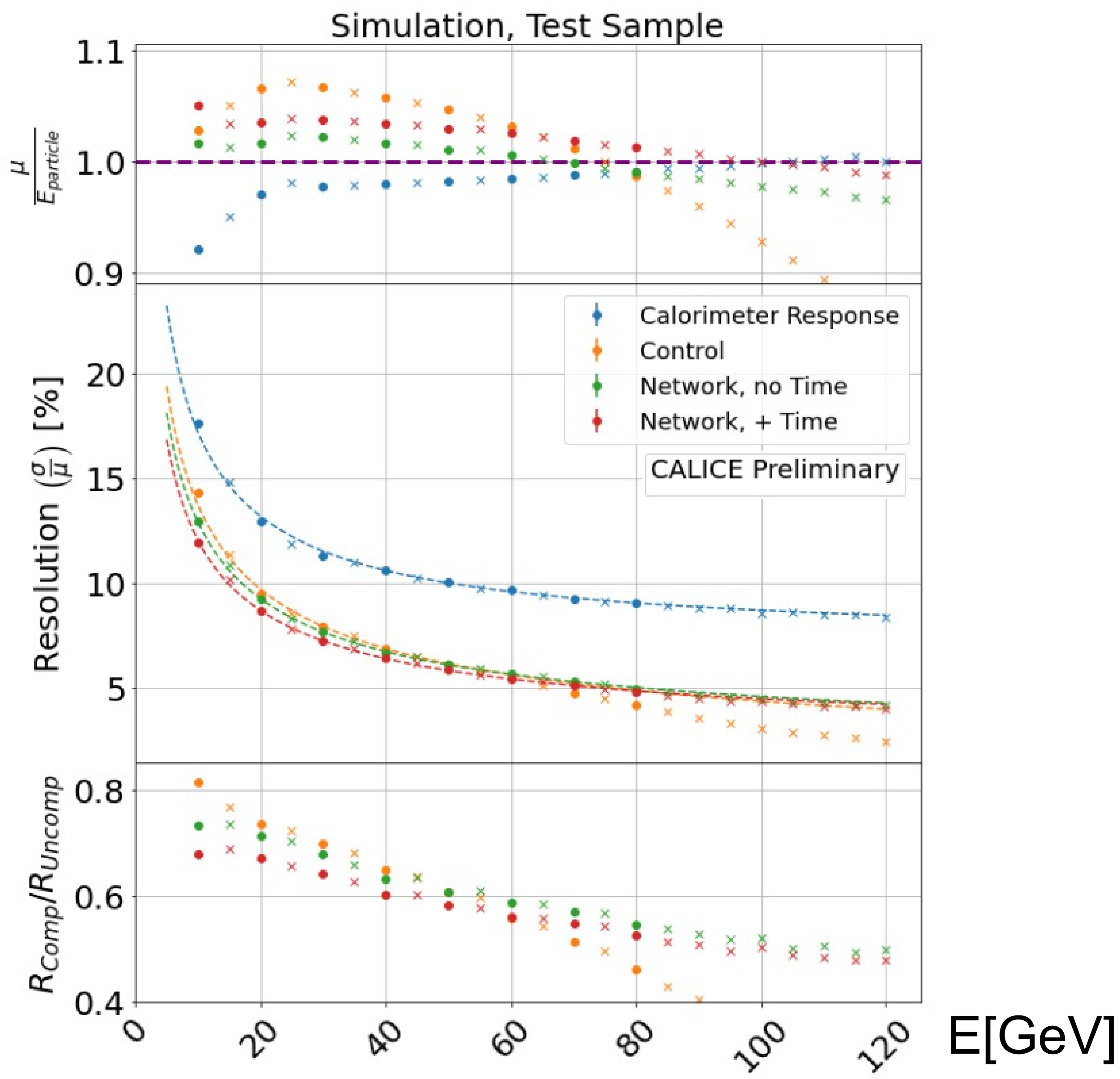


Significant improvement of energy resolution: 10 – 20% compared with « standard » reconstruction

Software Compensation using Machine Learning

Neural Network based on EdgeConv Operator





- Each calorimeter cluster is treated independently
  - => No bias from overall shower shape and energy
- Only local shower fluctuations are taken into account

- Improvement w.r.t. to calorimeter response software compensation method applied in previous slides

J.Rolph. E. Garutti
CALICE Paper with 2018 AHCAL data in preparation

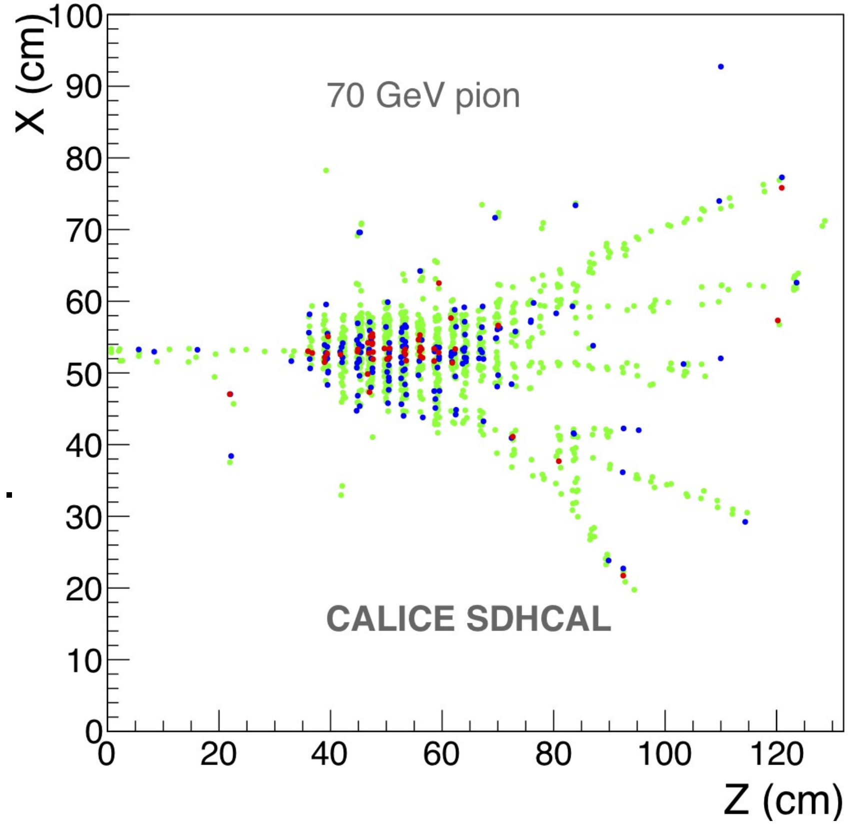
Semi-Digital HCAL – Thresholds and Weights

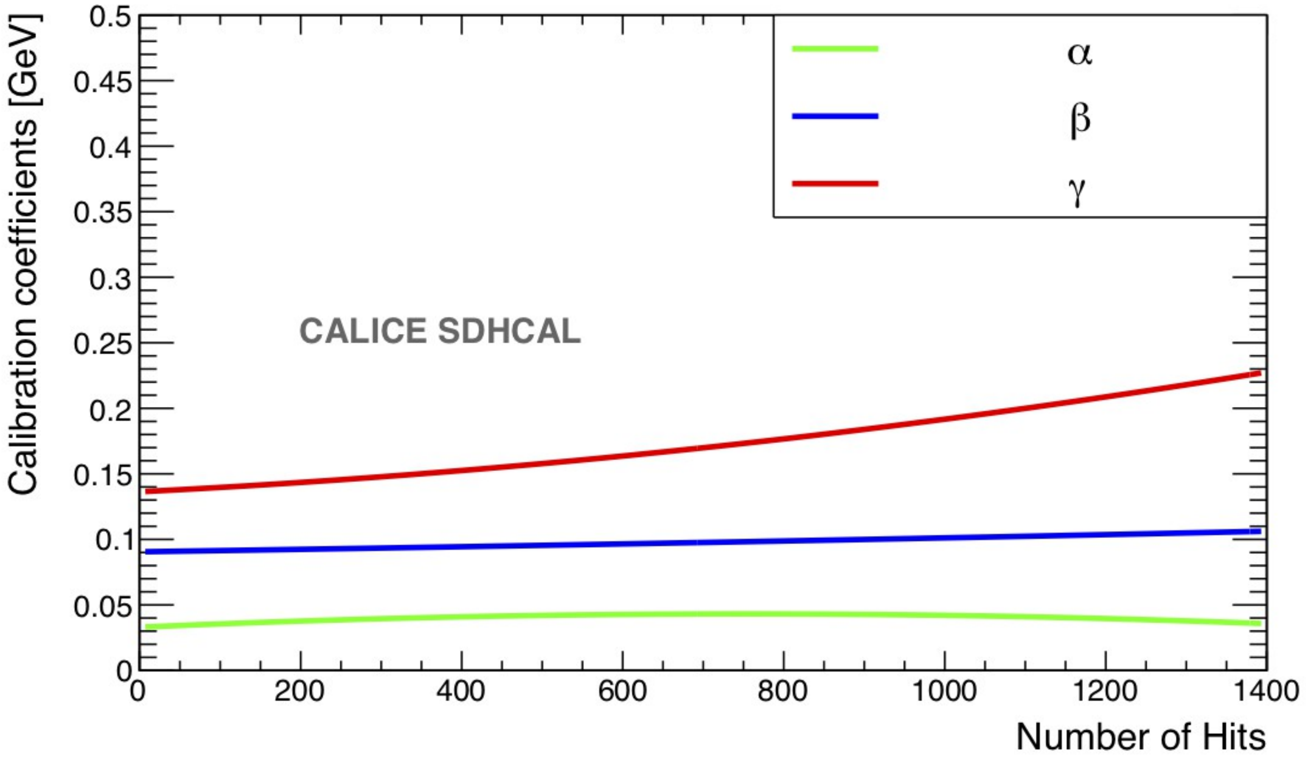
The thresholds weight evolution with the total number of hits obtained by minimizing a χ2:

$\chi 2 = (E_{beam} - E_{rec})^2 / E_{beam}$

$E_{rec} = \alpha(N_{tot})\, N_1 + \beta(N_{tot})\, N_2 + \gamma(N_{tot})\, N_3$

N_1, N_2 and N_3 : exclusive number of hits associated to first, second and third threshold.
α, β, γ are quadratic functions of the total number of hits (N_{tot})





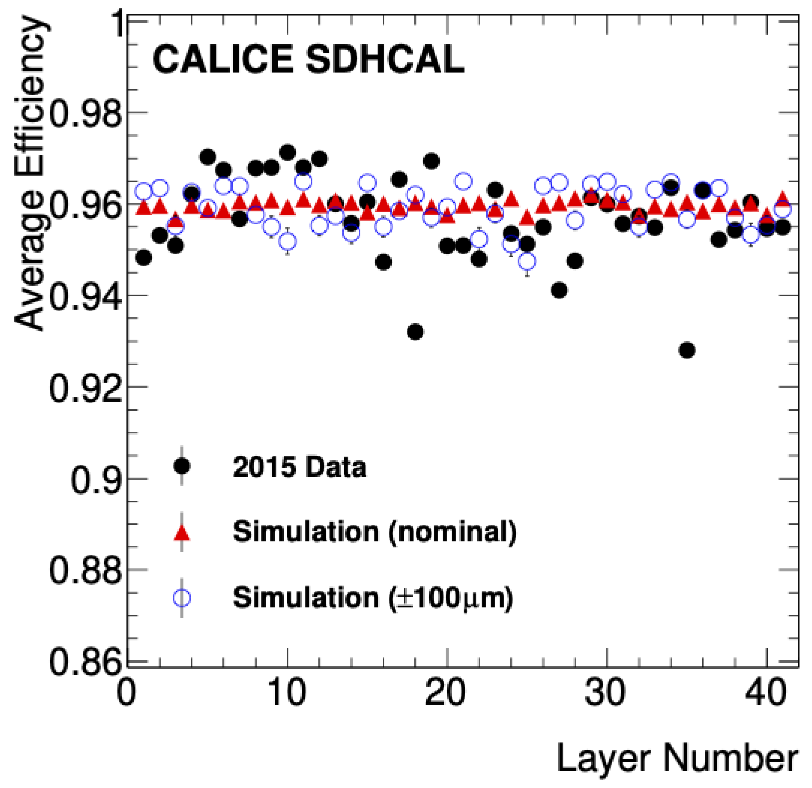
Weighting factors nearly independent of number of hits

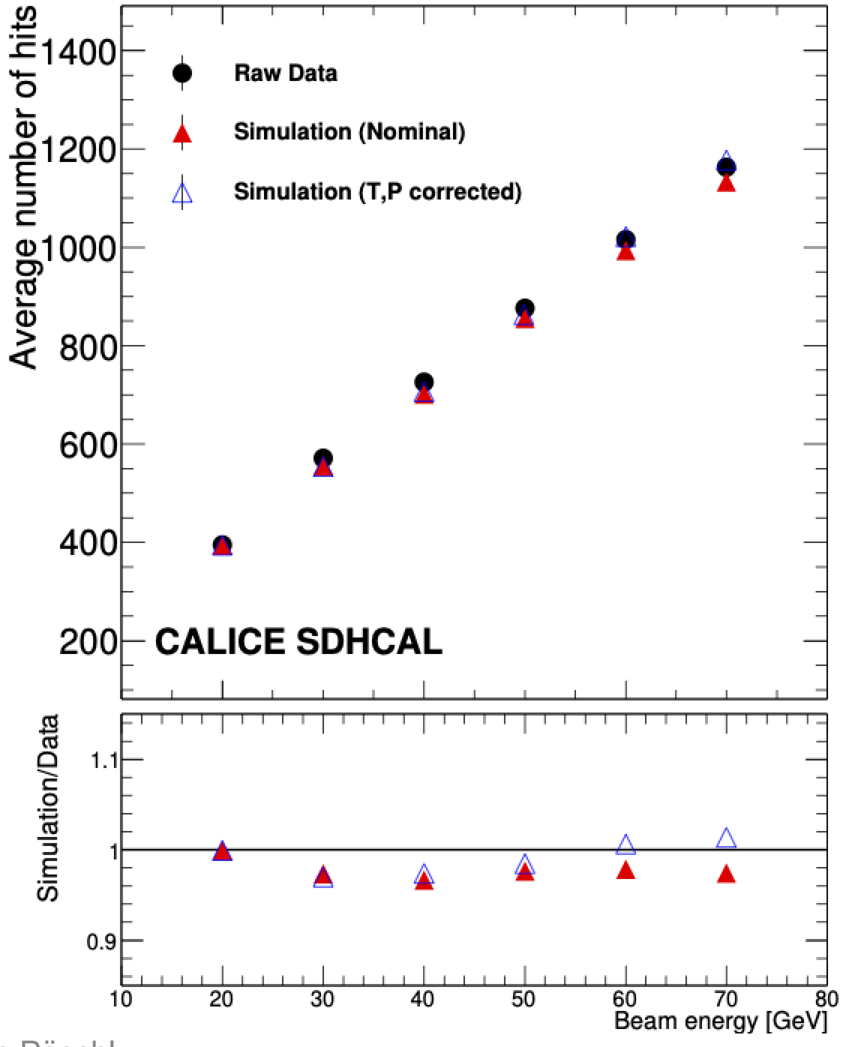
Slight dependency for highest threshold
(γ factor, sensitive to electromagnetic part of had. shower)

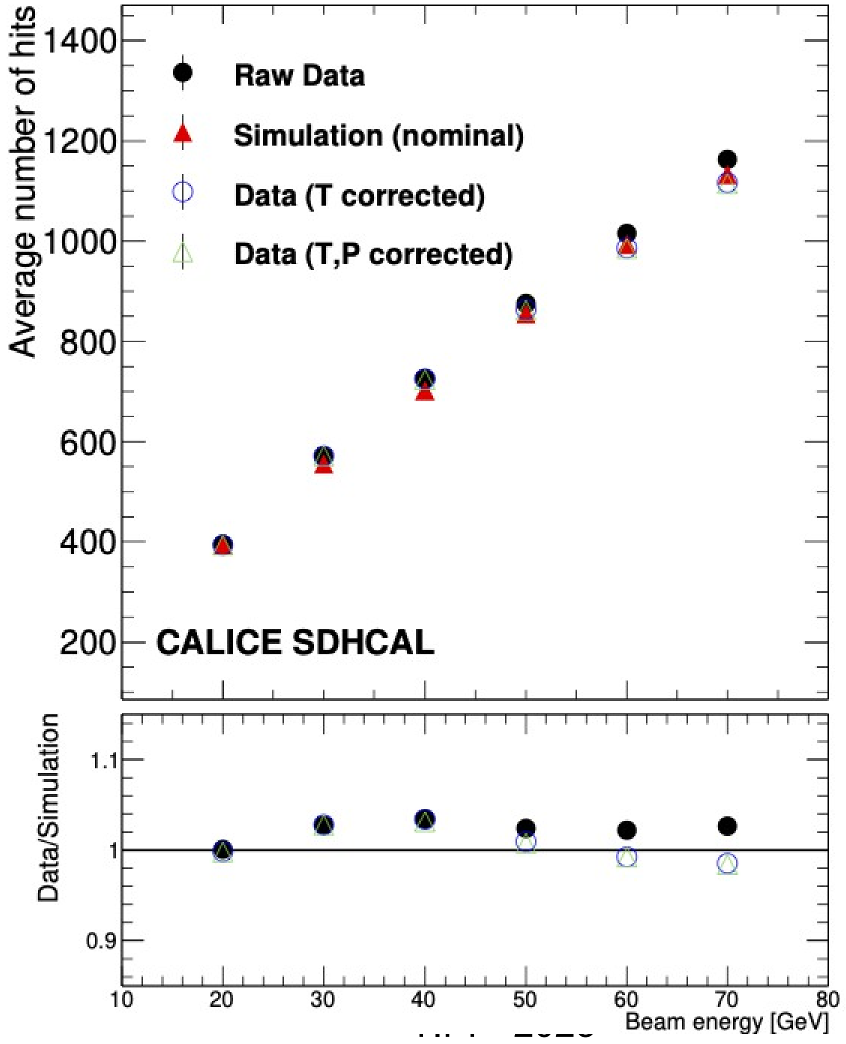
JINST 18 P03035 (2023)

Varied Parameters

		$\Delta Q/Q$ [%]	$\Delta N_{tot}/N_{tot}$ [%]	$\Delta N_2/N_2$ [%]	$\Delta N_3/N_3$ [%]	$\Delta E/E$ [%]
Gap	+10 µm	-7.2 ± 0.3	-3.5 ± 0.2	-8.0 ± 0.3	-12.3 ± 0.5	-8.6 ± 0.5
	±100 µm		-7.9 ± 0.2	-13.7 ± 1.8	-19.2 ± 0.2	-6.9 ± 0.2
T	+1°C	4.1 ± 0.4	1.9 ± 0.2	4.3 ± 0.4	7.5 ± 0.7	4.2 ± 1.1
P	+10 mbar	-11.1 ± 0.9	-4.5 ± 0.3	-11.3 ± 0.4	-18.7 ± 0.9	-11.9 ± 0.8
SF_6	+5%	-6.4 ± 0.4	-2.8 ± 0.2	-6.5 ± 0.2	-11.6 ± 0.2	-7.2 ± 0.7





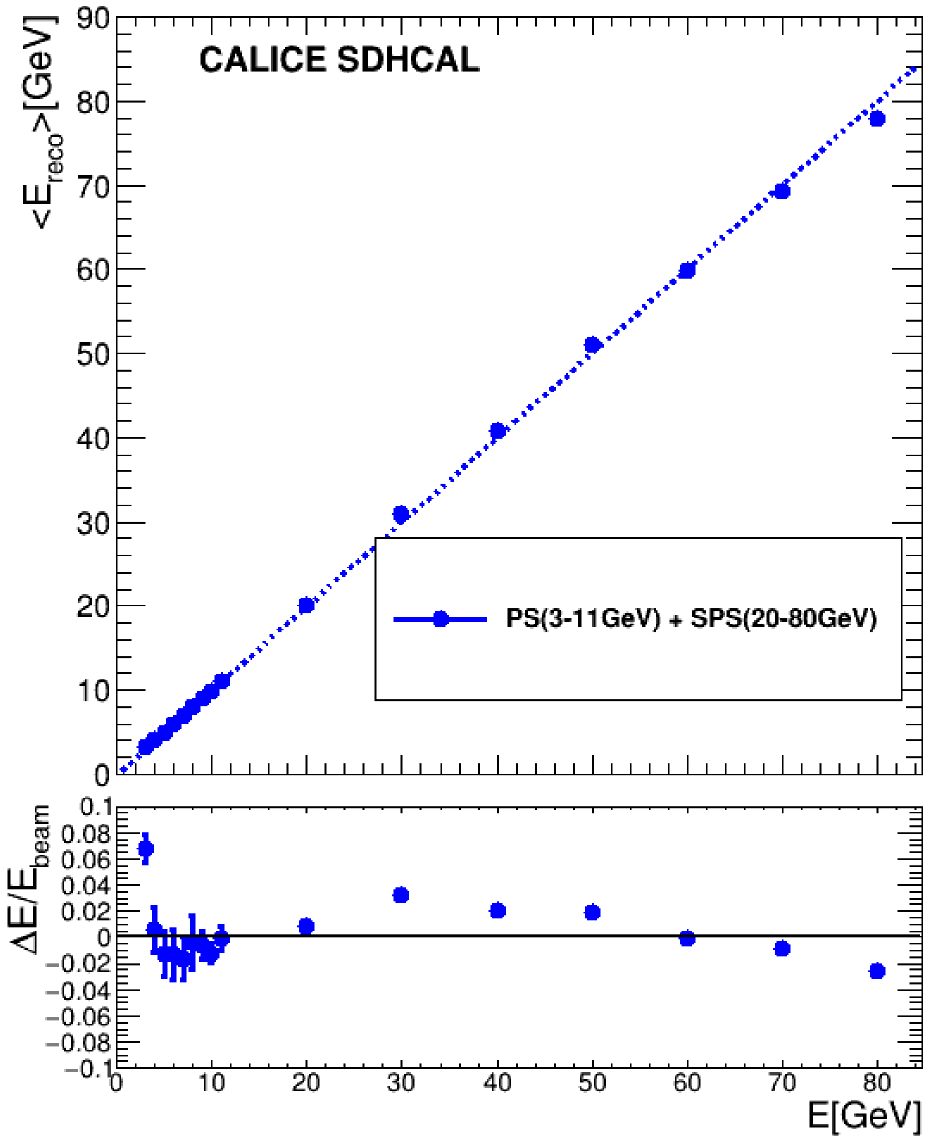


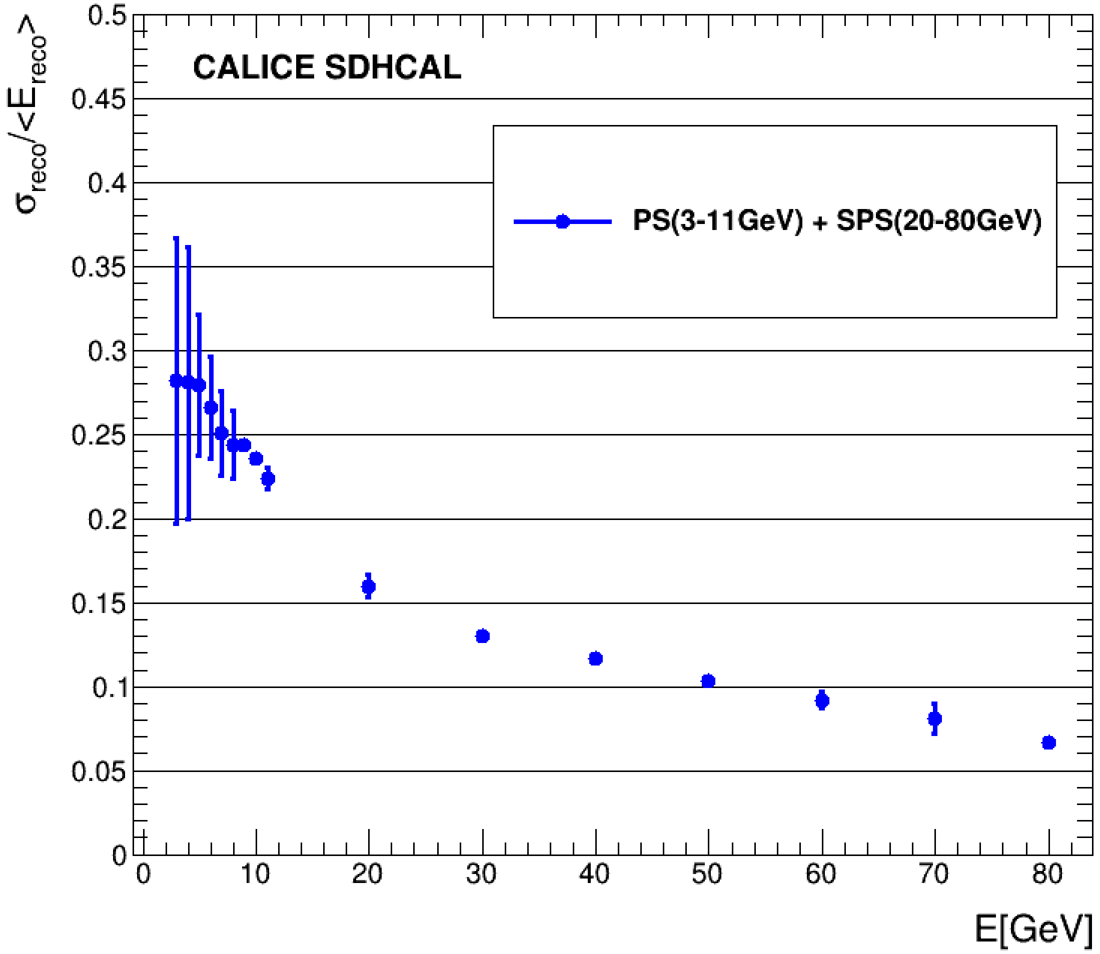
- Visible effect of varied parameters
  - Typically 2-3%
- The more precise the data are the more these effects have to be taken into account

Semi-Digital HCAL – Detector Response

π momentum range 3-80 GeV, combining PS and SPS Data

JINST 17 P07017 (2022)





- Linear response within 5-10%
- Consistent results for data taken at PS and SPS

=> stable performance

- Energy resolution reaches ~7.7% at 80 GeV (even without electronics gain correction)

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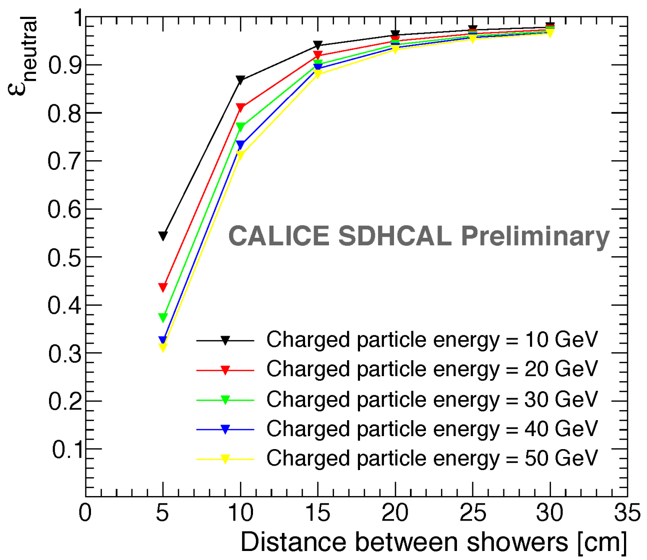
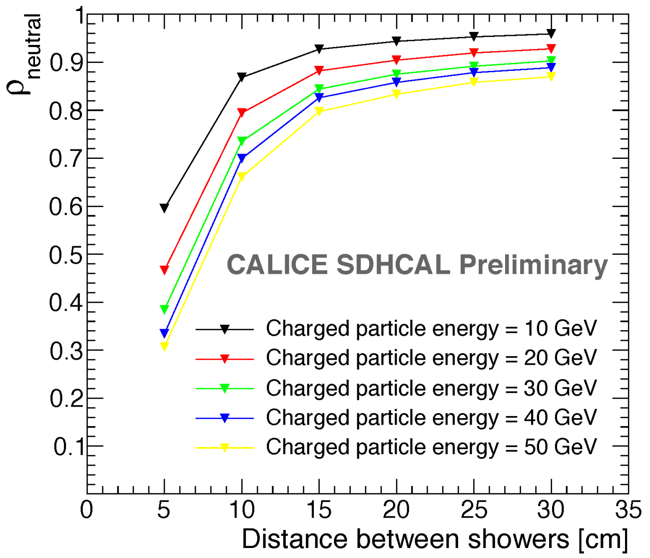
Exploiting the high granularity – Particle Separation

SDHCAL: Separation of 10 GeV neutral hadron from charged hadron [CALICE-CAN-2015-001]

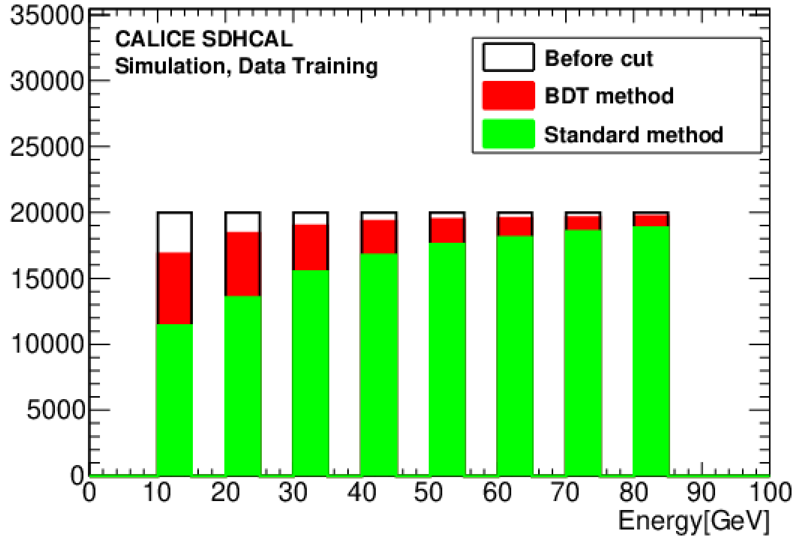


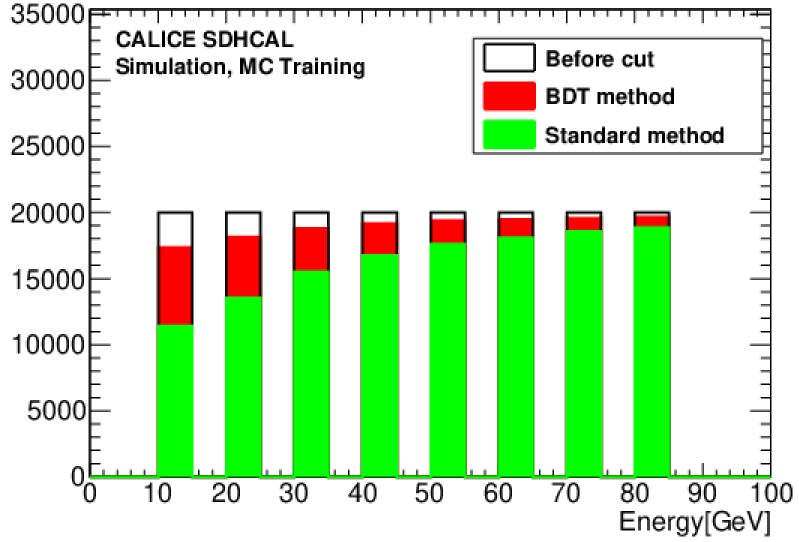


More than 90% efficiency (ε) and purity (ρ) for distances ≥ 15 cm

SDHCAL: Multi-variate analysis for Particle ID

[arxiv:2004.02972, accepted by JINST]

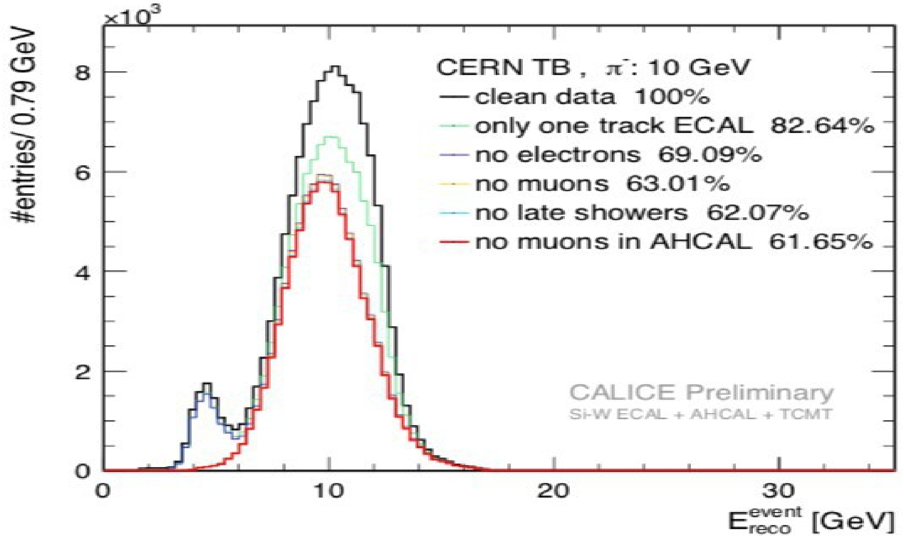




BDT enhance pion selection efficiency at small energies

SiW ECAL: Tracking capabilities to select single π-events

[CALICE-CAN-2017-002]



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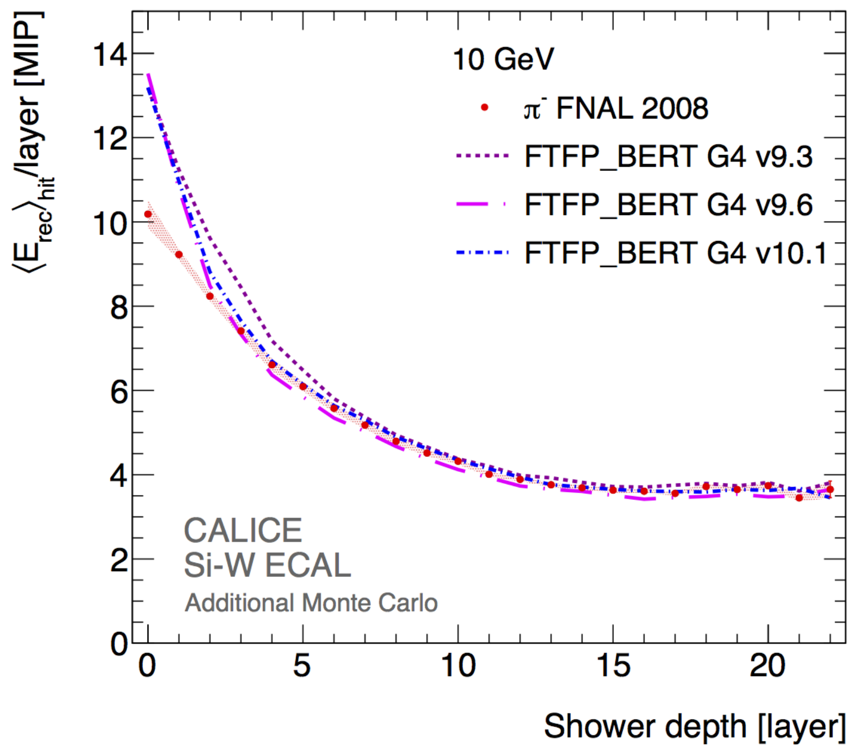
Exploiting the high granularity – Particle Separation

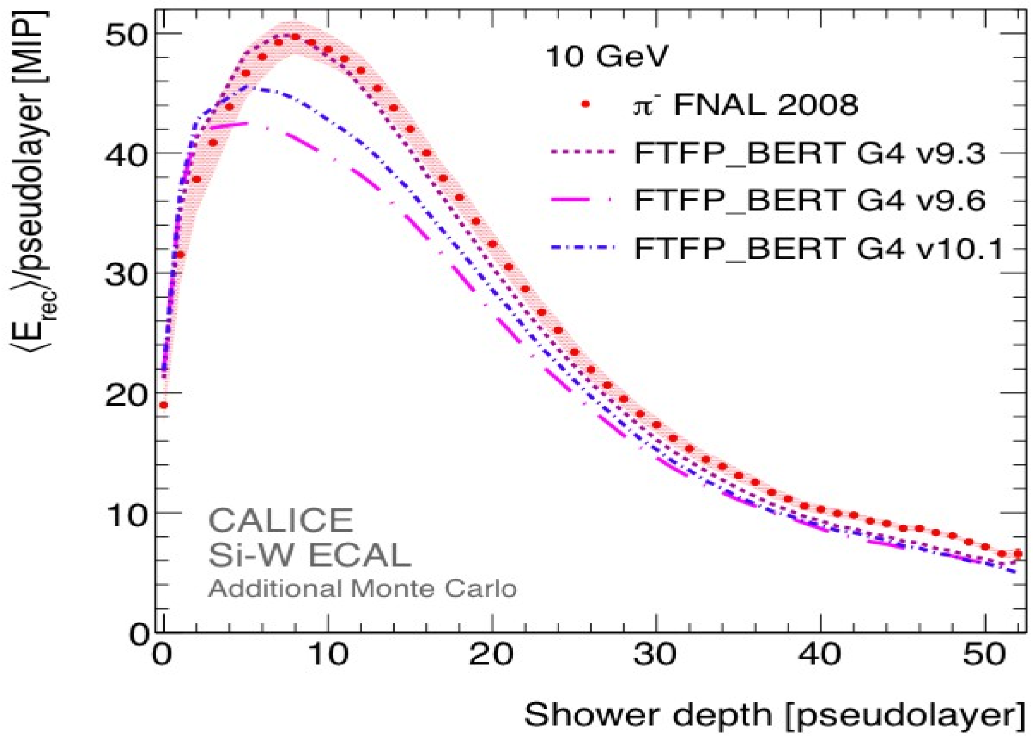
[NIM A794 (2015) 240-254]

Fine sampling of shower start 2-10 GeV pions in SiW ECAL

Mean hit energy/pseudolayer



Visible energy / pseudolayer



Big change observed in FTFP_BERT observed between GEANT4 Versions 9.3 and 9.6

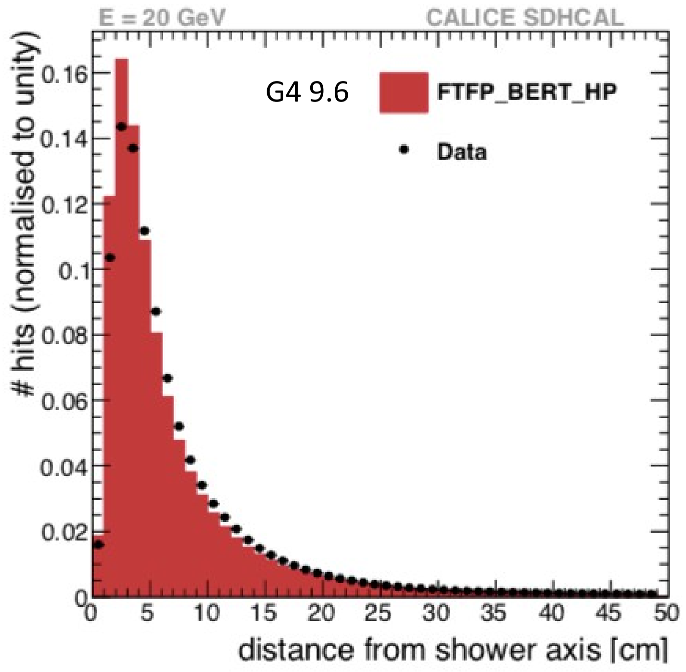
- Only observed in silicon, not for scintillator prototypes;
- Bug in G4 v9.6, fixed in v10.0, however still insufficient energy in v10.1
- Disagreement in individual hit energies between data and G4 affects longitudinal profile

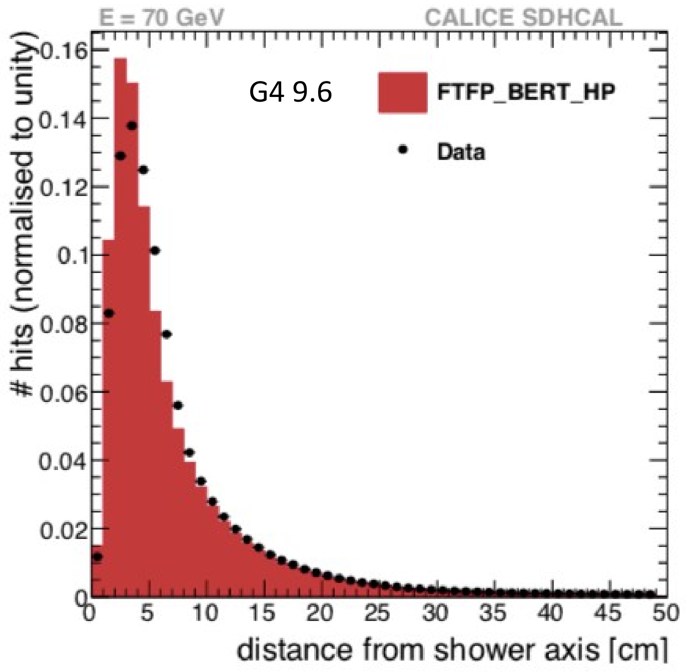
- More on this later ... .

Radial Shower Profile

[JINST 11 (2016) P06013]

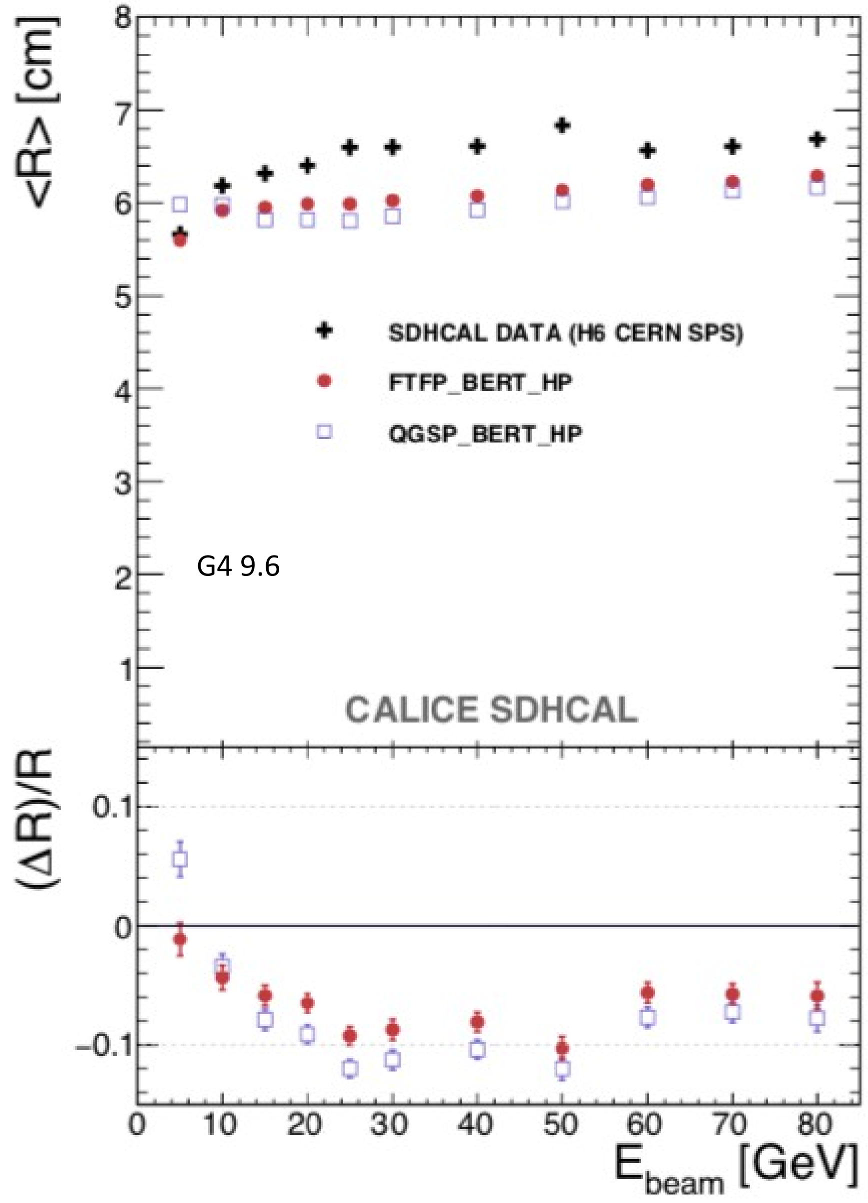
5-80 GeV π in SDHCAL





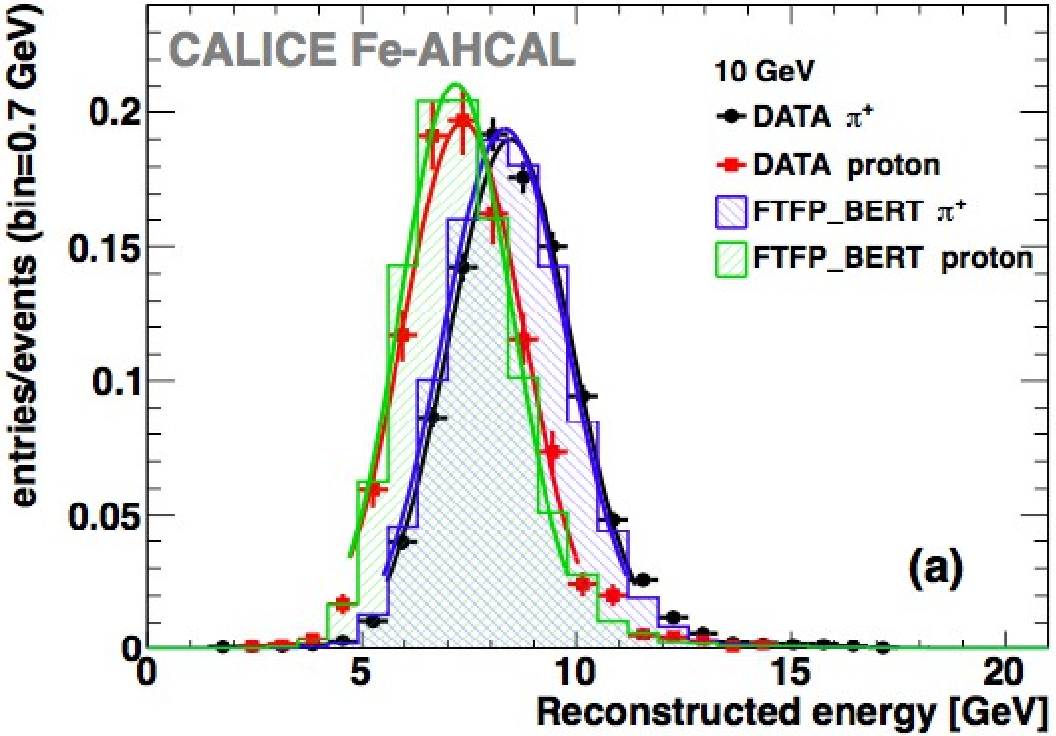
$$\langle R \rangle = \frac{1}{N_{\mathrm{event}}} \sum_{i=0}^{N_{\mathrm{event}}} \sum_{r=0}^{R_{\mathrm{max}}} r \frac{N_{r,i}}{N_{\mathrm{tot},i}}$$

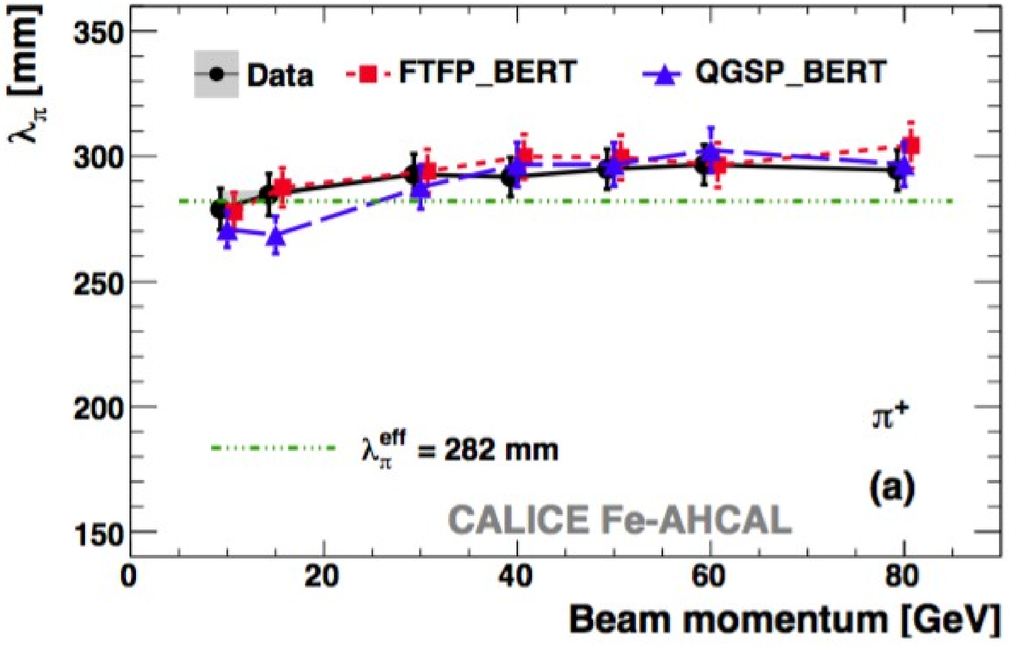
Radial profile:
Number of hits in 1-cm rings around shower barycenter

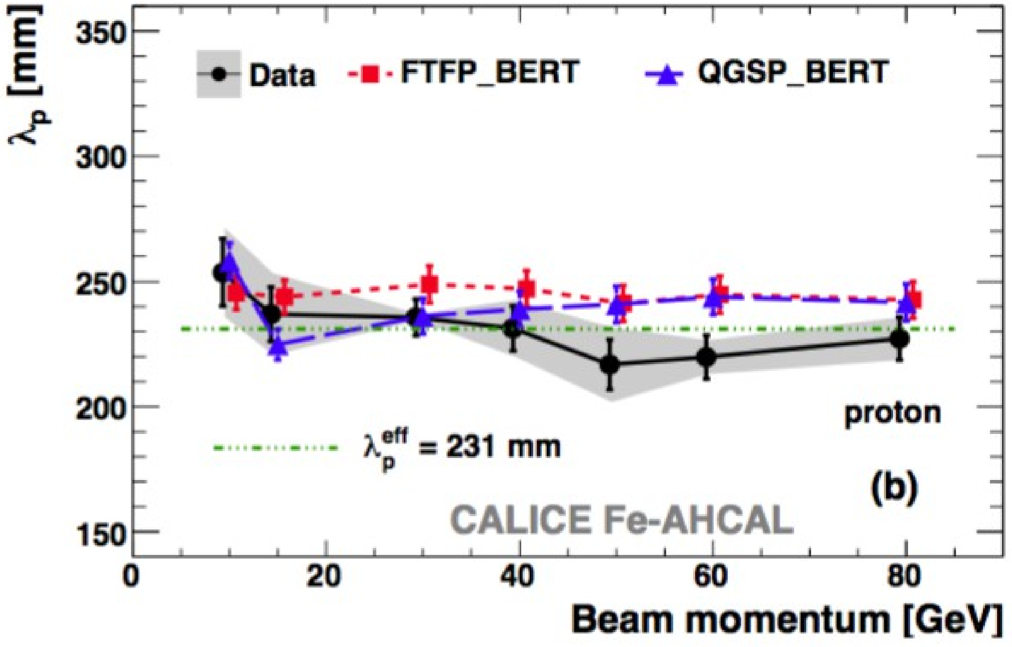


Pion and proton showers

[JINST 10 (2015) P04014]

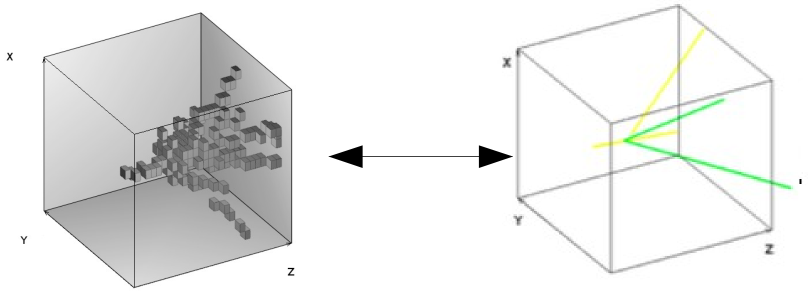


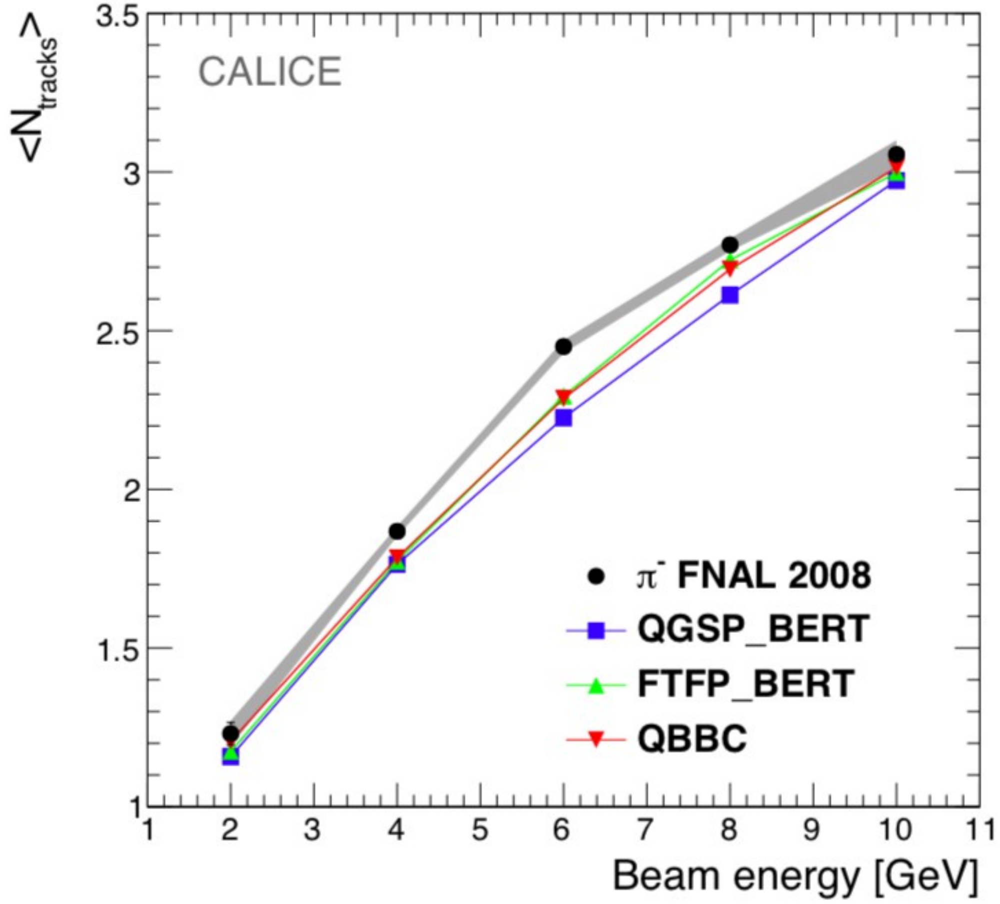




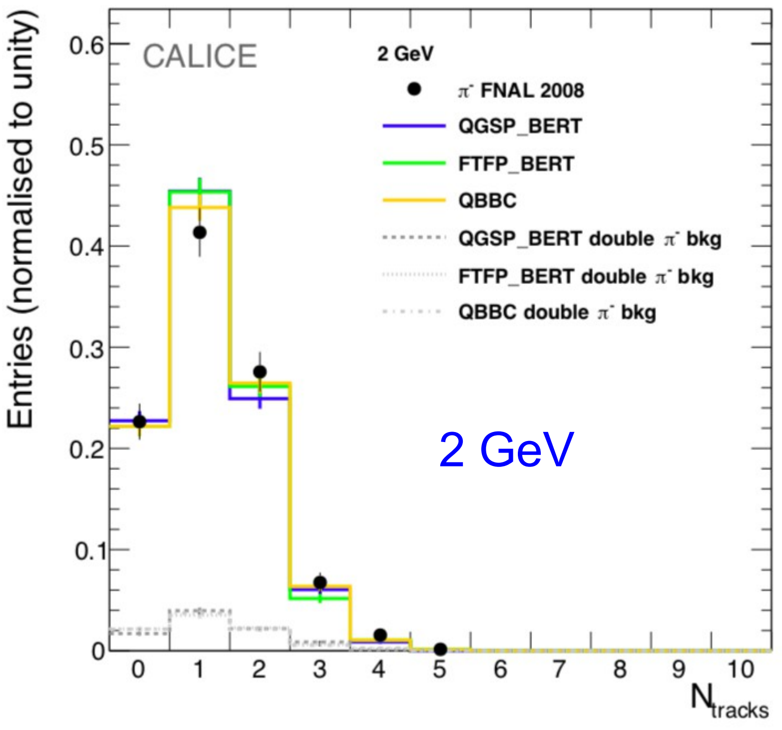
- Smaller signal if proton is primary particle
  - Proton is Baryon
  - Baryonnumber conservation favors production of baryons in cascade and suppresses meson i.e. π^0 production
- Different hadronic interaction lengths measured for π and protons
- In general GEANT4 reproduces the data with obvious differences for protons

Physics Prototype – Secondary Tracks in Si ECAL

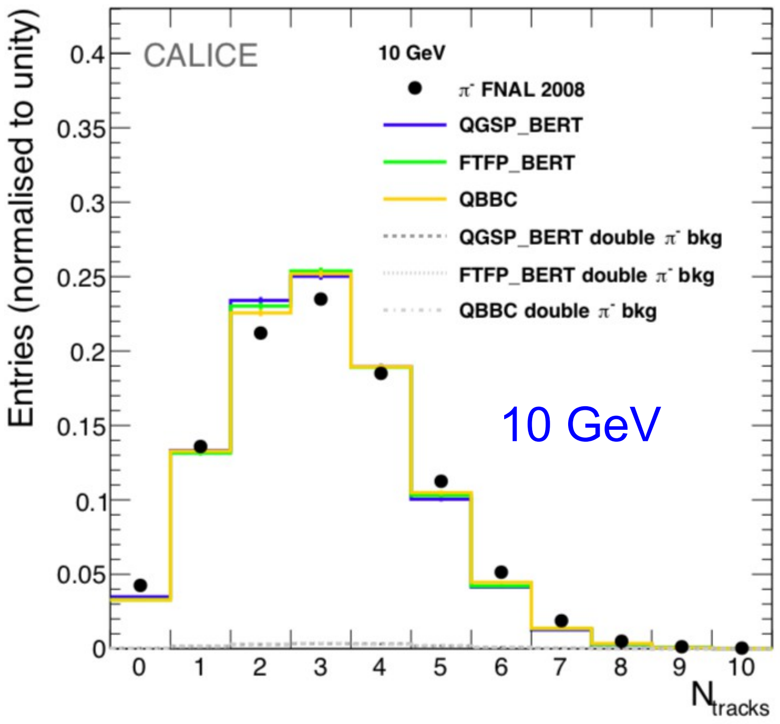




PhD Thesis, S. Bilokin (LAL)
TYL-FJPPL Young Investigator Award
NIM A937 (2019) 41-52; e-print: arXiv:1902.06161



PhD Theses P. Doublet, (LAL,) H. Li (LAL)
P2IO PD N. v.d. Kolk (LLR/LAL)
NIM A794 (2015) 240-254; e-print: arXiv:1411.7215

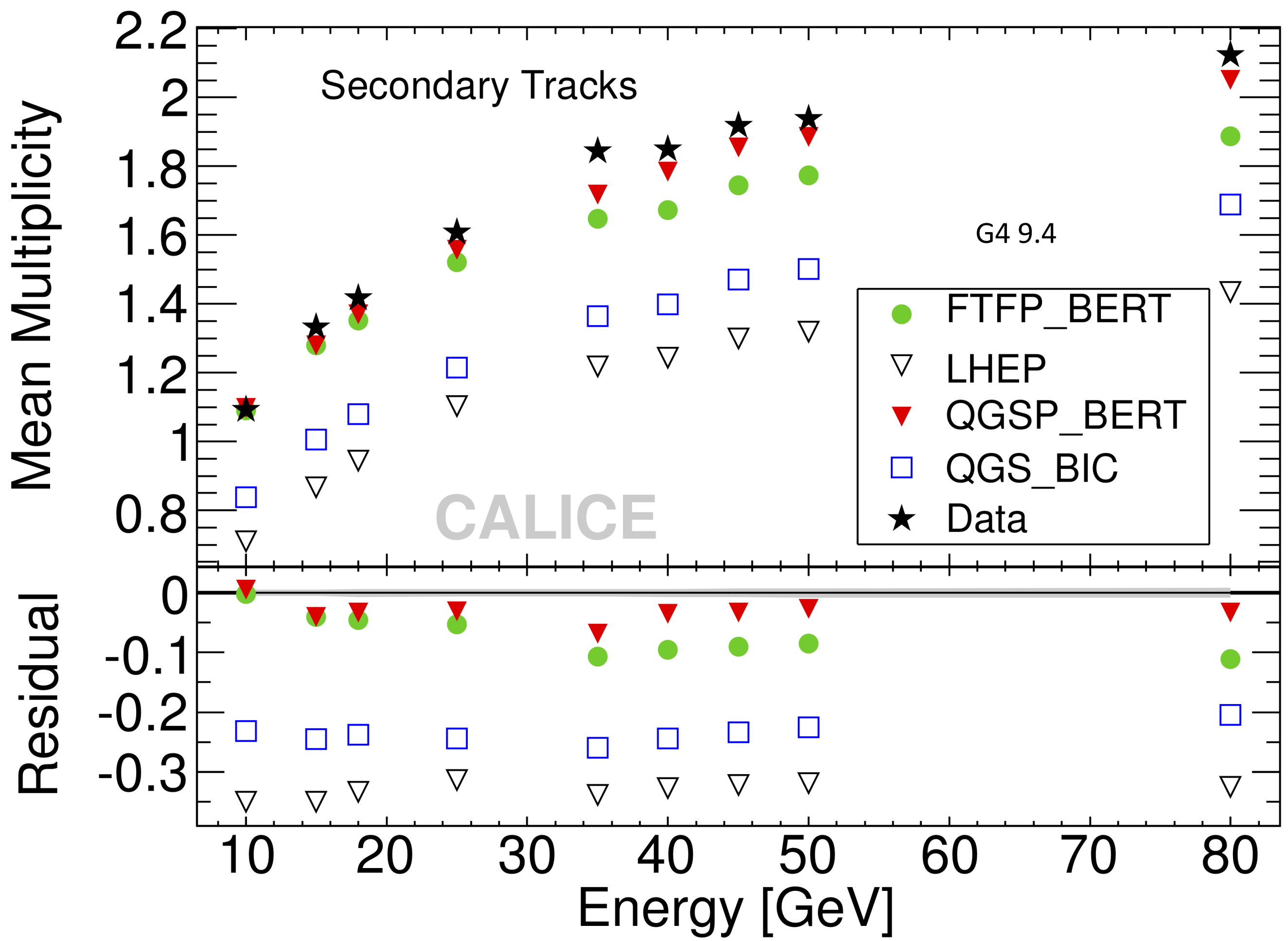


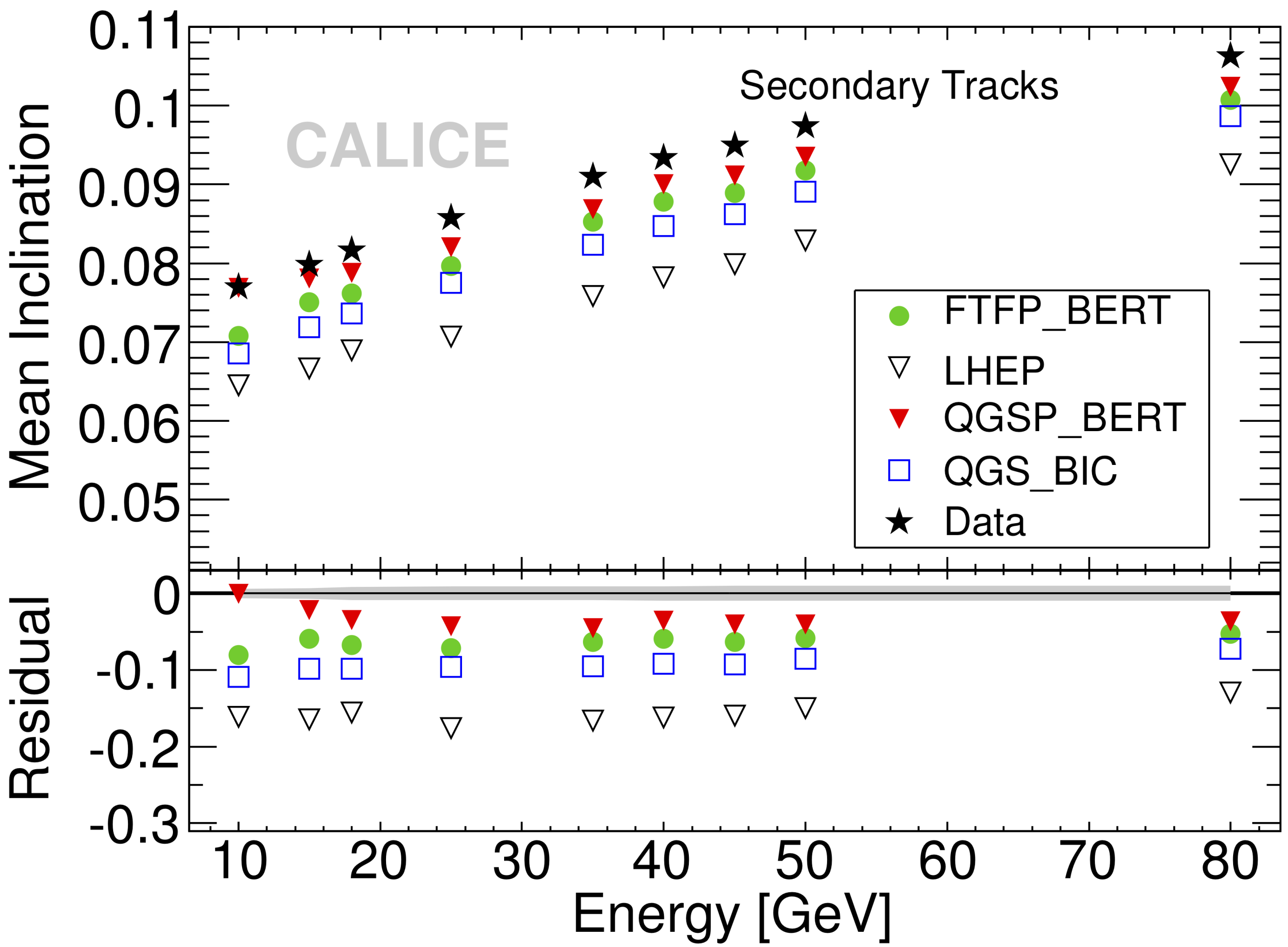
- Mean number of secondary tracks increases with beam energy as expected from fixed target kinematics for π--tungsten scattering
- Good reproduction of data by simulation with GEANT4

Physics Prototype – Secondary Tracks in AHCAL

Track multiplicity and track inclination 1-cosθ track

5-80 GeV π in AHCAL [JINST 8 (2013) P09001]



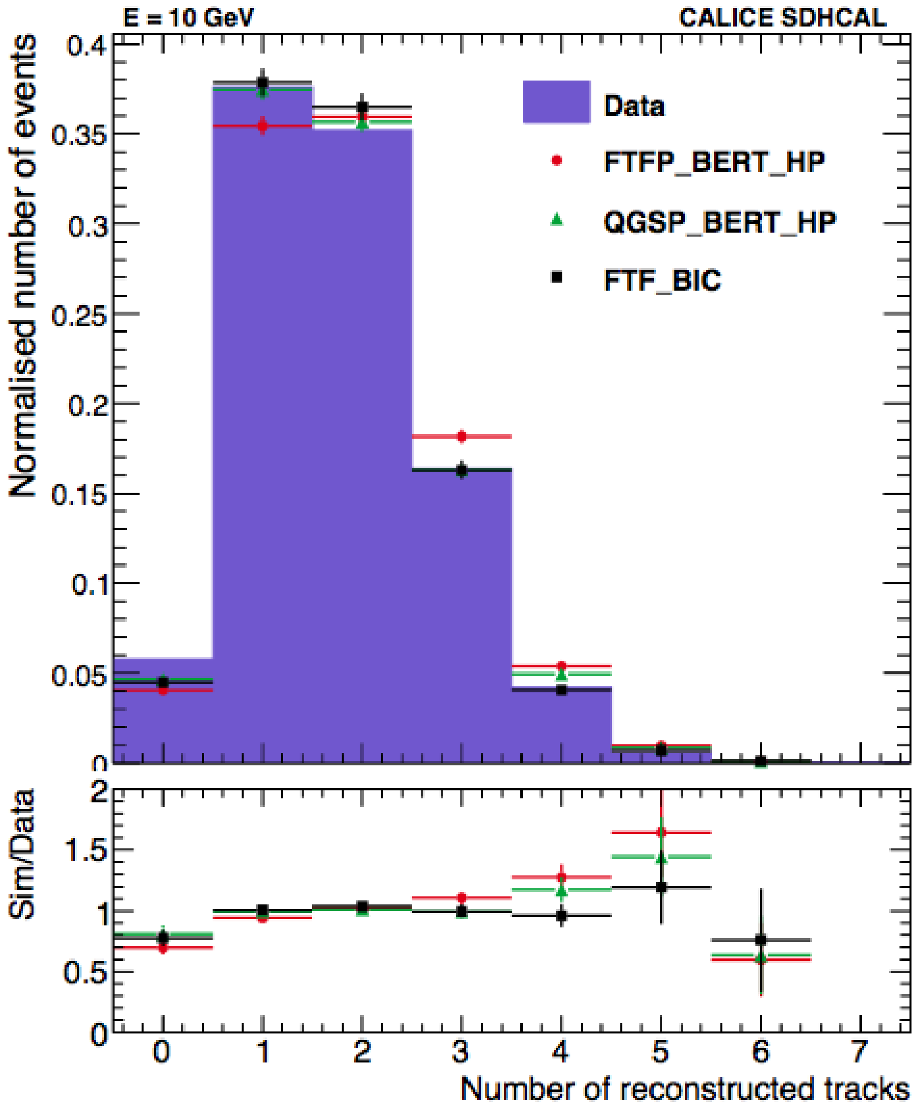


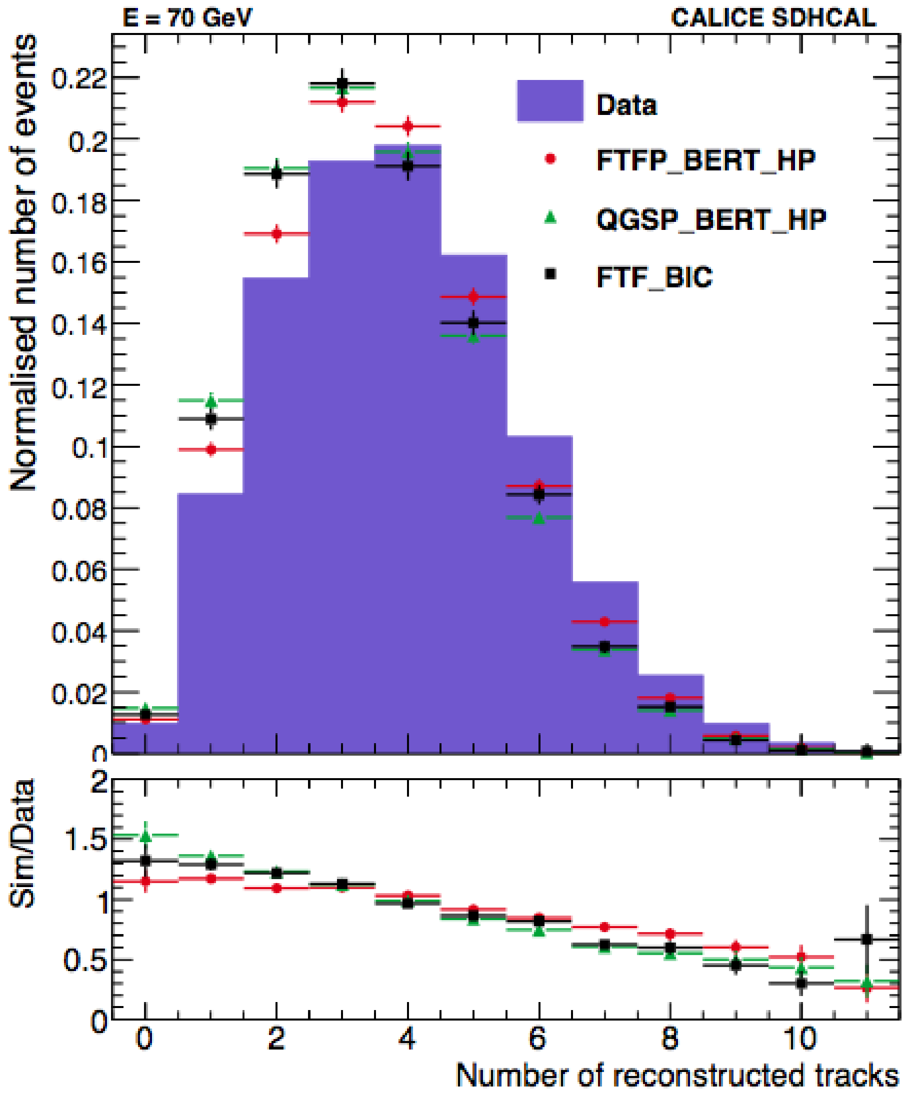
- Observables available thanks to high granularity
- Tests of shower models with discriminative power

Secondary Tracks in SDHCAL I

JINST 12 (2017) no.05, P05009,arXiv:1702.08082

Tracks reconstructed using the Hough Transformation



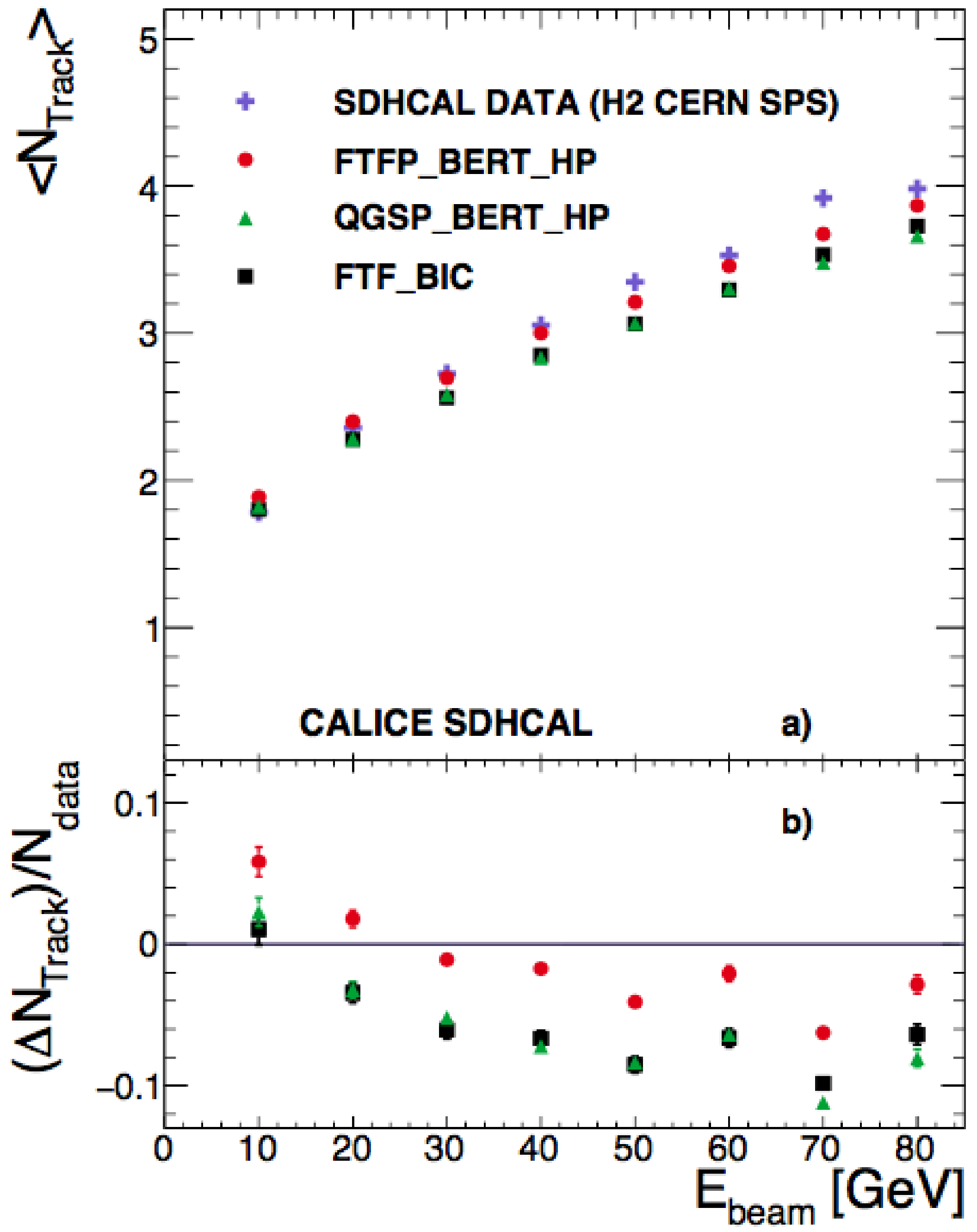


- Number of tracks adequately reproduced by G4 v9.6 at small energies

- Picture less clear at high energies, FTFBP_BERT_HP closest to data

Secondary Tracks in SDHCAL II

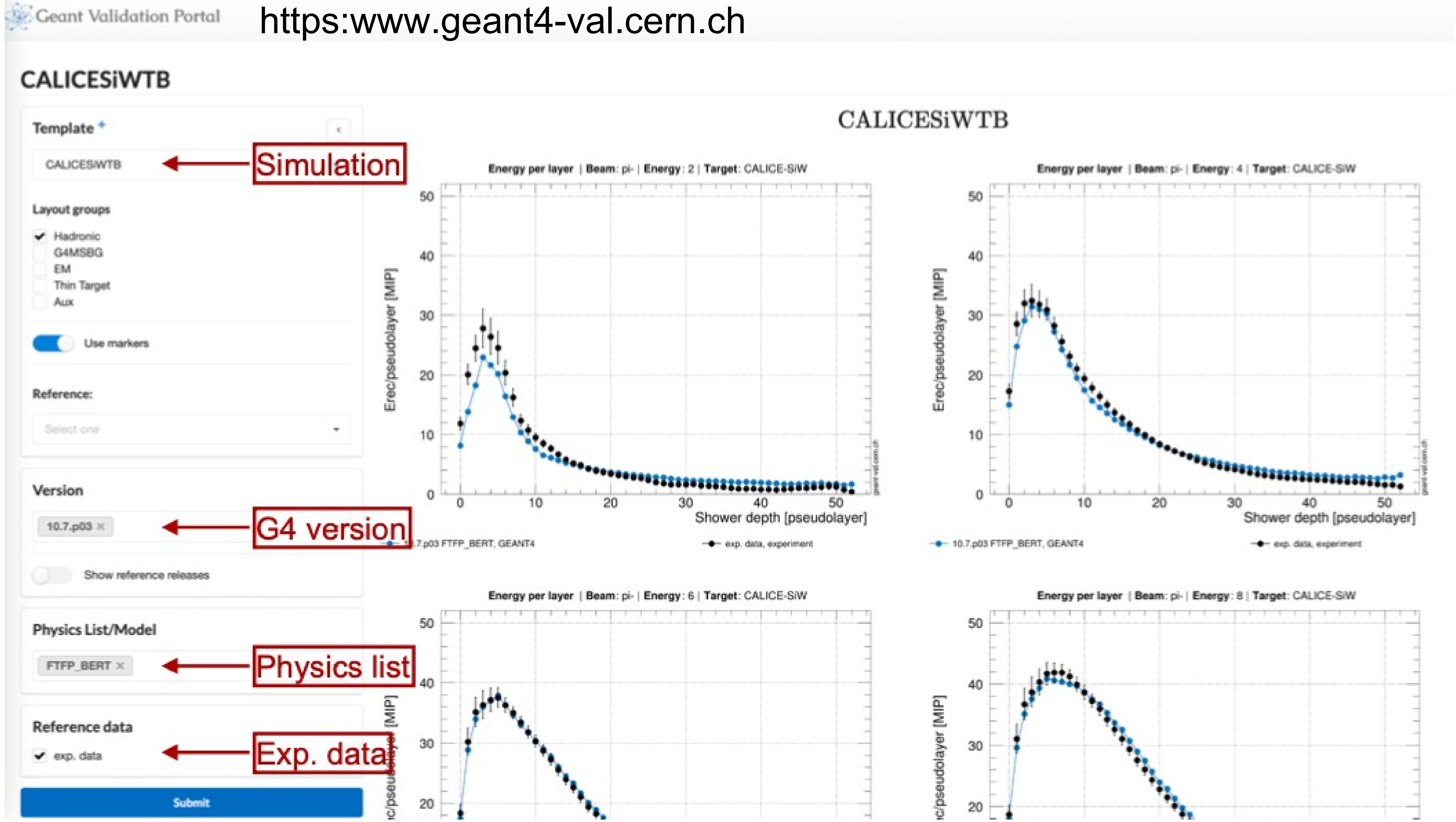
JINST 12 (2017) no.05, P05009,arXiv:1702.08082

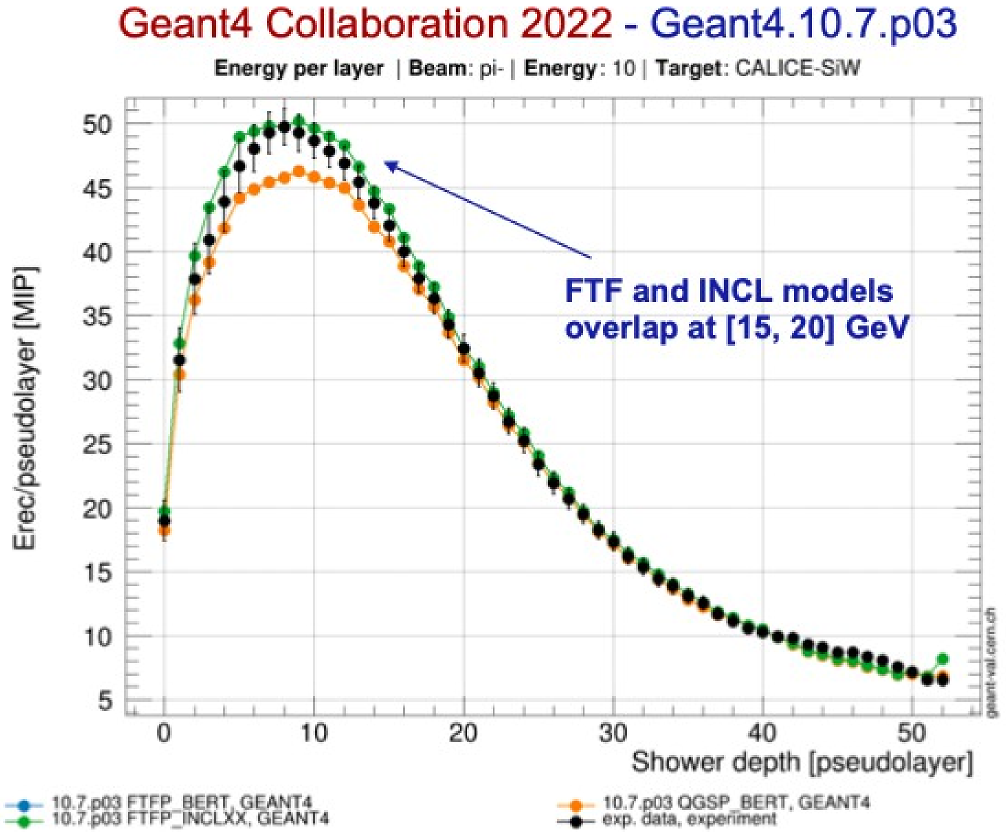


- Clearer picture in summary plot
- FTFP_BERT_HP superior to other Physics lists
- Towards higher energies MC predictions systematically below data
- However, no “catastrophy”, discrepancies max. 10%

The GEANT4 team has implemented the CALICE SiW ECAL in the GEANT4 validation chain

=> New GEANT4 versions can be validated against CALICE Data





Much improved description of Longitudinal shower profile with Recent G4 versions!

L. Pezzotti, CALICE Meeting Valencia, April 2022

Summary and Outlook

- Over the past 15 years CALICE collected a rich set of data with granular calorimeters
  - Wide energy range
  - Different type of particles
- These data are unique to test and improve models of hadronic showers
  - Implementation into GEANT4 Validation chain allow for continuous improvement
- Rich “playground” to apply modern pattern recognition algorithms
  - Boosted Decision Trees improve particle separation
  - First analysis using machine learning tools are about to be published
- More data are to come
  - Combinded beam tests AHCAL-SiW ECAL, AHCAL-ScECAL (also talk by Yong Liu)