# High-granularity hadronic calorimeter for tens-of-TeV jets at a 100 TeV pp collider

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*With contributions from:*
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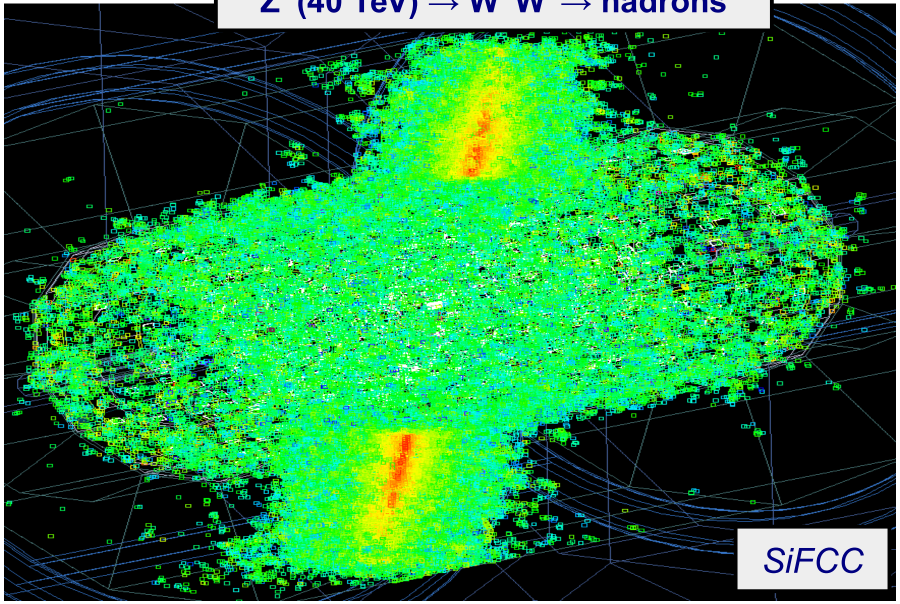
**Z' (40 TeV) → $W^+ W^-$ → hadrons**




Two 20 TeV jets in ~12 $\lambda_I$ calorimeter

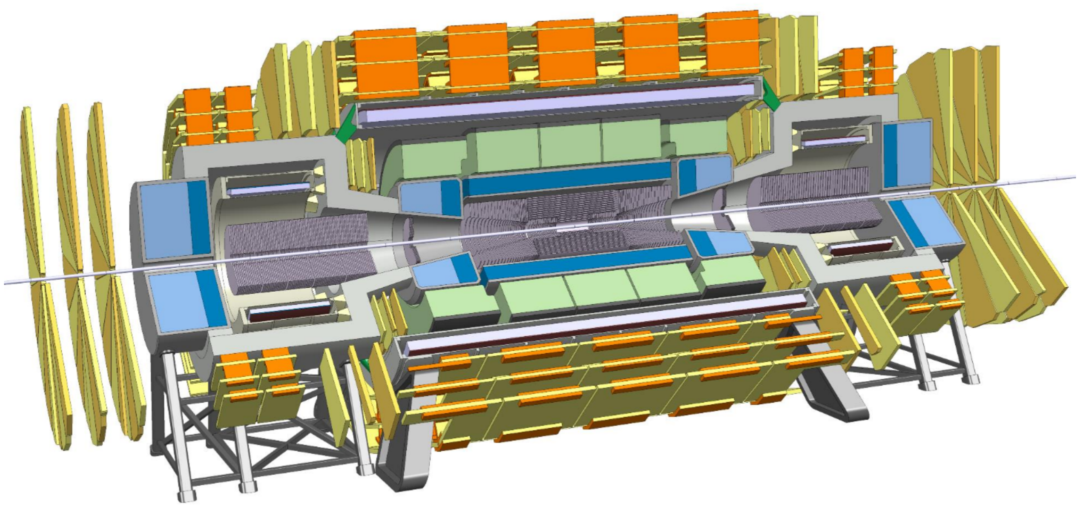
# Detector requirements driven by physics at 100 TeV

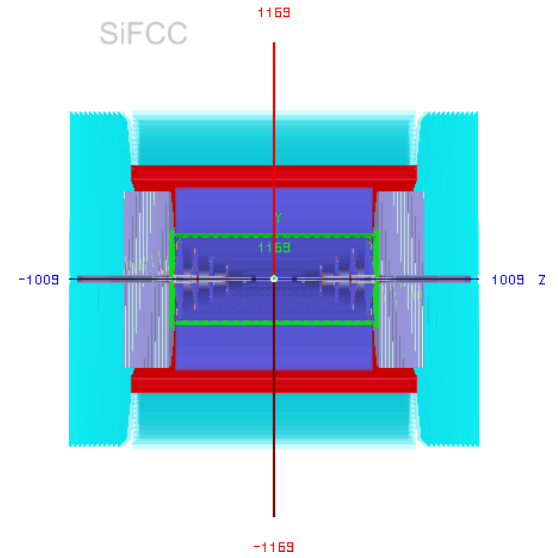
- **Good containment up to pT(jet)~30 TeV: 12 $\lambda_I$ for ECAL+HCAL**
  - affects jet energy resolution
  - leakage biases, etc.
- **Small constant term for HCAL energy resolution**
  - dominates jet resolution for pT>5 TeV, important for searches of heavy particles
  - single-particle studies using ATLAS-like design indicate that < 3% is achievable
- **Longitudinal segmentation:**
  - Not studied
- **Good transverse segmentation for resolving boosted particles:**
  - baseline is $\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$ from Delphes fast simulations
  - current baseline 5x5 cm assuming ~ATLAS-like inner radius (~2.3 m from IP)

Study these questions using realistic Geant4 simulations and reconstruction

# Detector simulations for 100 TeV physics

| FCC-hh **reference** detector | SiFCC: **performance** detector |
| --- | --- |






- Larger than ATLAS
- Optimized forward region
- Twin solenoid + forward dipoles
- Fast detector simulations

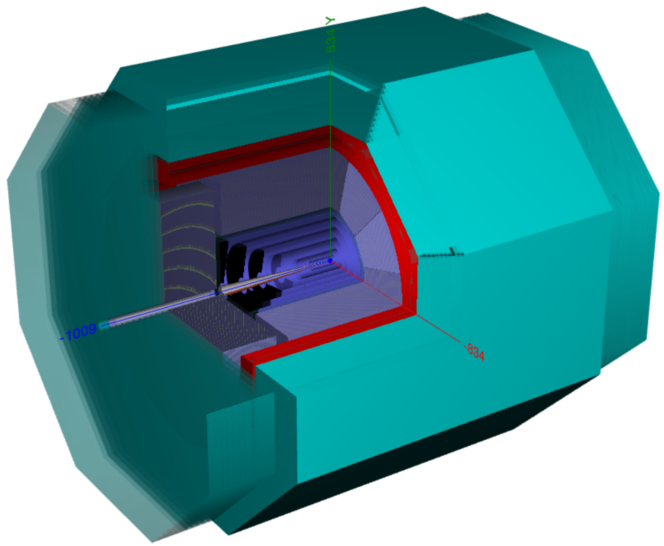
- Derived from the SiD/CLIC "all silicon" concept
- Compact (~20% smaller than ATLAS + muon det.)
- $|\eta|<2.5$ optimized for 100 TeV collisions
- Playground for various detector designs and technologies
- Fast turnover to modify the detector & create Monte Carlo events using HepSim
- Geant4 simulation & reconstruction since 2016

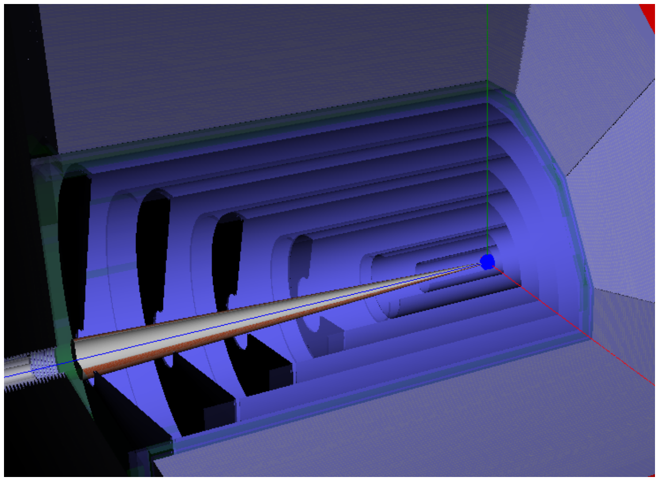
# Characteristics of SiFCC (version 7)

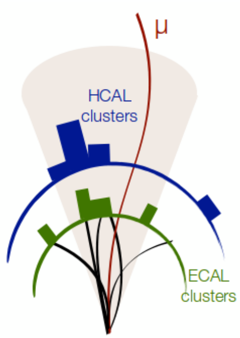
http://atlaswww.hep.anl.gov/hepsim/detectorinfo.php?id=sifcch7

Click here to explore this detector in 3D

- **5 T solenoid outside HCAL**
- **Si pixel and outer trackers (5 + 5 layers):**
  - 20 um pixel (inner), 50 um (outer)
- **ECAL (Si/W):** 2x2 cm. 32 layers, ~35 X0
- **HCAL (Scint. / Fe)** **~ FCC-hh reference**
  - 5x5 cm cells: $\Delta\eta \times \Delta\varphi = 0.022 \times 0.022$
    x4 smaller than for CMS & ATLAS
  - 64 longitudinal layers → 11.3 $\lambda_I$
  - 3.1% sampling fraction
- > 150 M non-projective cells (ECAL+HCAL)








*S.V. Chekanov, M. Beydler, A.V. Kotwal, L. Gray, S. Sen, N.V. Tran, S.-S. Yu, J. Zuzelski.* https://arxiv.org/abs/1612.07291.

# Event simulation and reconstruction

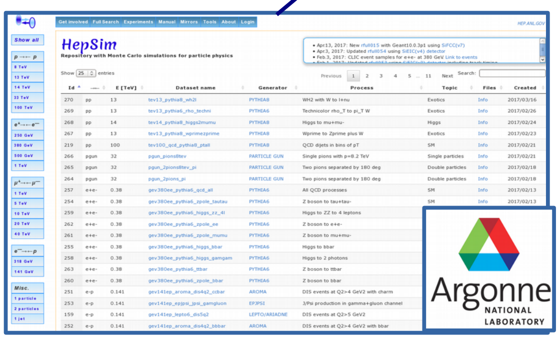
- SLIC simulation v5.1: updated for Geant 10.3p1 (J.McCormick, D.Blyth, W.Armstrong, S.C, etc)
  - *updated for Geant 10.3p1, decoupled from ILCSOFT*
- Fast LCSIM track reconstruction: (D.Blyth, J.McCormick, N.Graf, etc.)
  - *3-4 speed increase compared to the previous releases*
- Fast PandoraPFA (J.Marshall, M.Thomson)
- Integrated with HepSim ProMC EVGEN files & deployed on OSG grid
- Analysis: C++/Root or Jas4pp (ANL,S.C,E.May). Based on Jas3 (SLAC)

ongoing optimization

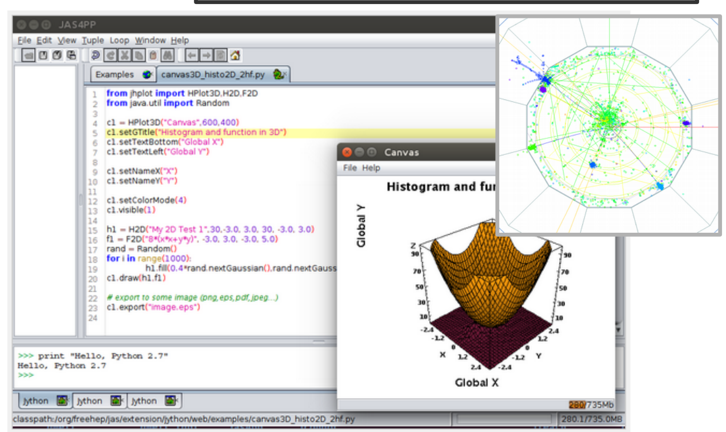
**SLIC 5.1 (Geant4, version 10.3p1)** → **LCSIM track reconstruction** → **SlicPandora and Pandora PFA** → **Event display + Analysis (C++/ROOT or Jas4pp)**

**Compact geometry description (XML) and LCDD Geometry** → SLIC 5.1, LCSIM track reconstruction, SlicPandora and Pandora PFA

ProMC → SLCIO




http://atlaswww.hep.anl.gov/hepsim/



# Energy reconstruction in HCAL (SiFCC)

**SLIC (Geant4 10.3p1) + SLIC 5.0.1**
**Inelastic models for pi+/p/n**
**(validated<400 GeV):**
**QGSP_BERT 4.0**
QGSP: 12 GeV - 100 TeV
FTFP: 9.5 GeV - 25 GeV
BertiniCascade: 0 eV - 9.9 GeV
**Elastic:** ElasticLHEP/ Gheisha: 0 eV-100 TeV

**raw hits**

**slicPandora: Sampling fractions etc.**

**cells**

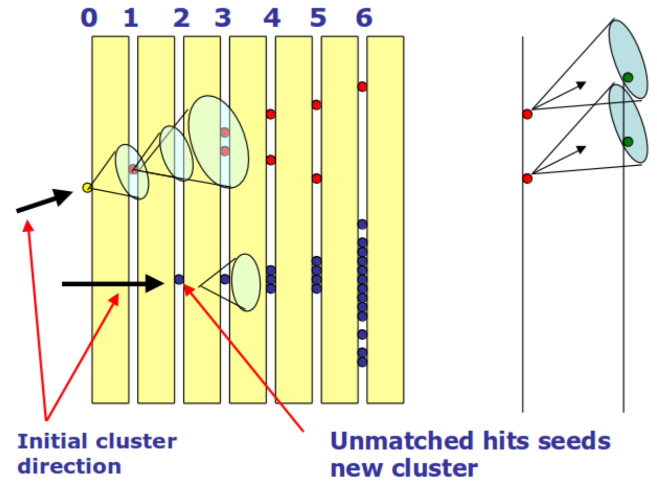
**PandoraPFA: Topological 3D RecoClusters**

**clusters**

**antiKT R=0.5 jets from RecoClustes**

**Data analysis**

From M.Thomson




Cone algorithm
Start from inner layer and work outward

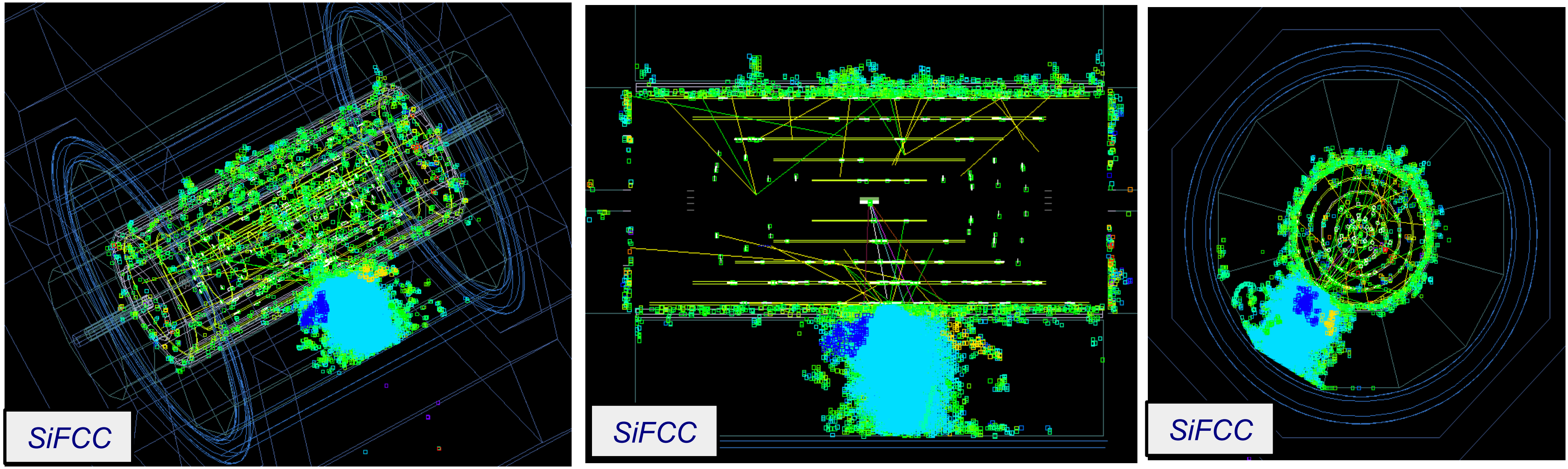
*Notes:*
*- Birks' effect was not included for simulation of hits*
*- Min mip cut was applied on hits*
*- No timing information was applied*

# Response to single particles: 8 TeV pions

Example: True momentum of π+ : 8.16 TeV

**After SiFCC reconstruction (>1.5 M HCAL cells):**

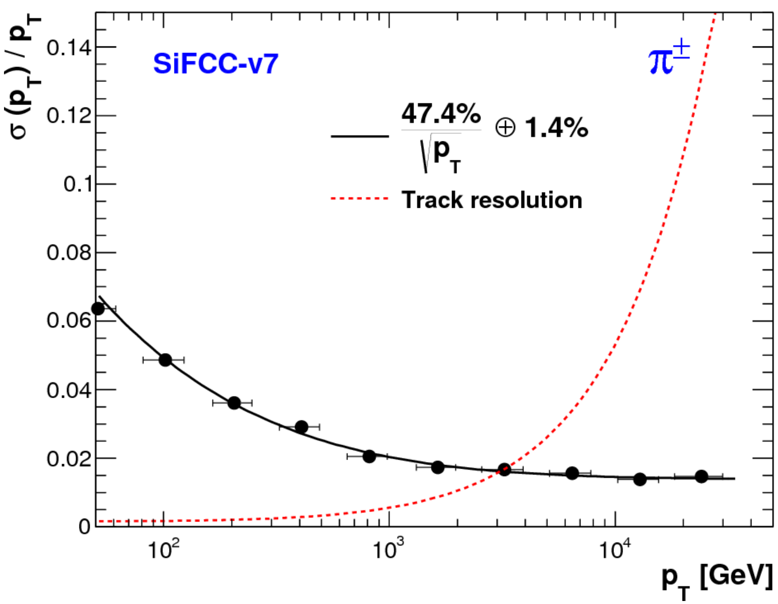
- ~30000 calorimeter hits, ~500 SiTracker hits
- 1 reconstructed PFA (pi+) P=8.97 TeV
- 1 reconstructed CaloCluster at P=8.40 TeV
- Many back-splash interactions

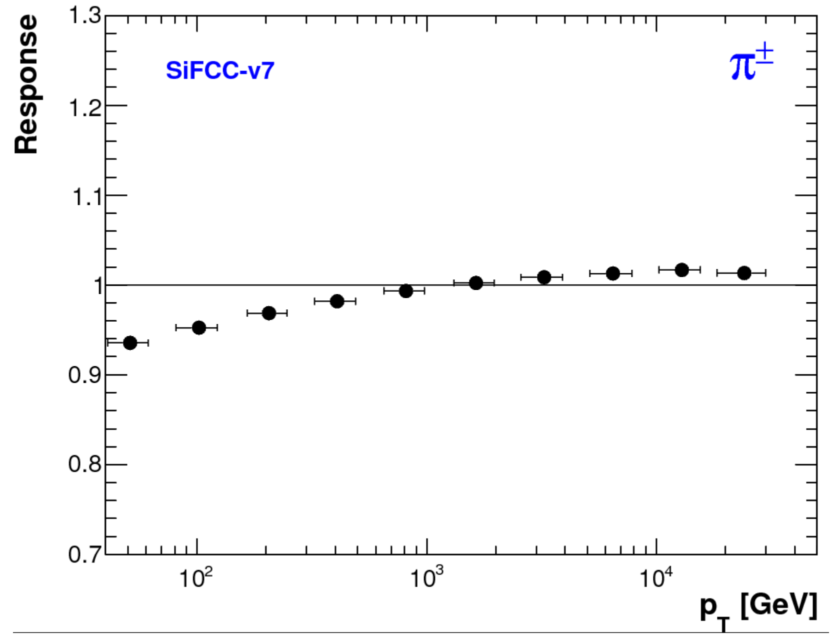



Based on **HepSim**: http://atlaswww.hep.anl.gov/hepsim/info.php?item=201

# Response to hadrons: $\pi^{\pm}$

- Single pi+ randomly distributed in eta & phi
- pT is reconstructed by collecting energies from all RecoClusters



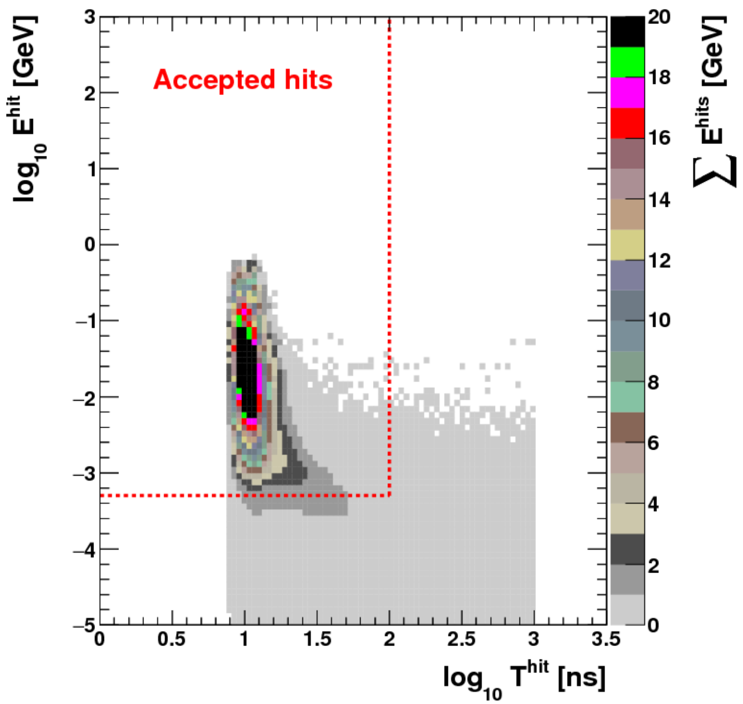




- ~47% sampling term, 1.4% constant term
  - sampling term is consistent with ATLAS-like setup (arXiv:1604.01415)
- Calorimeter resolution is better than for SiTracker for pT>3 TeV
  - Tracker: outer radius R=2.1 m, 5 T solenoid, 25 um pixel size
- Calorimeter response is non-linear → should be corrected by MC (e/h, material correction etc.)

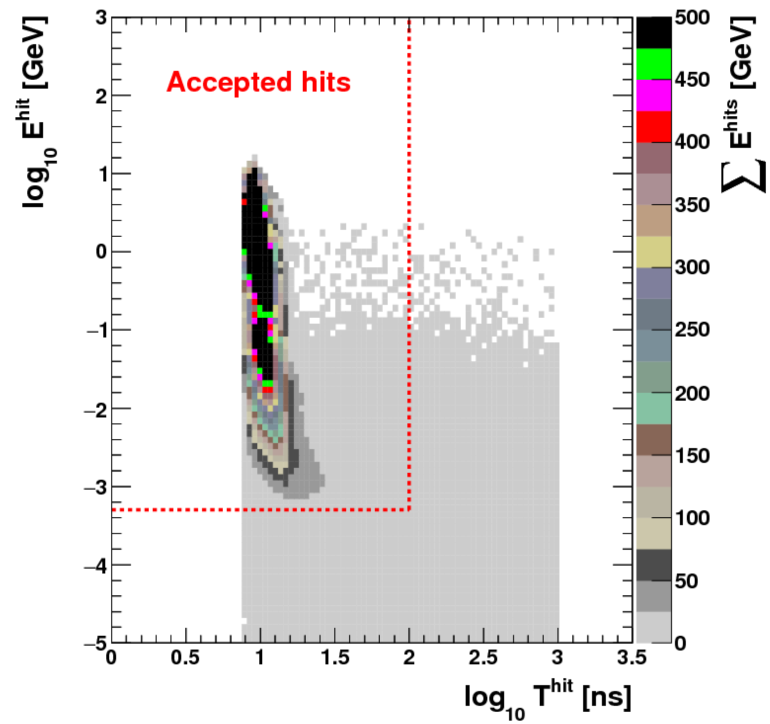
# Hit energy vs hit time for single pions

Associate hits from SLIC (before applying sampling fraction) using anti-kT algorithm running over RecoClusters created by single pions

**120 GeV single pions**

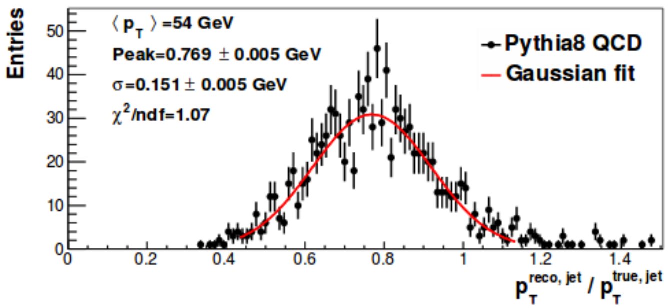


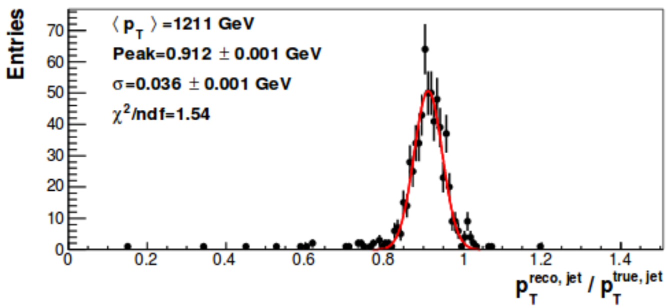

**8.2 TeV single pions**

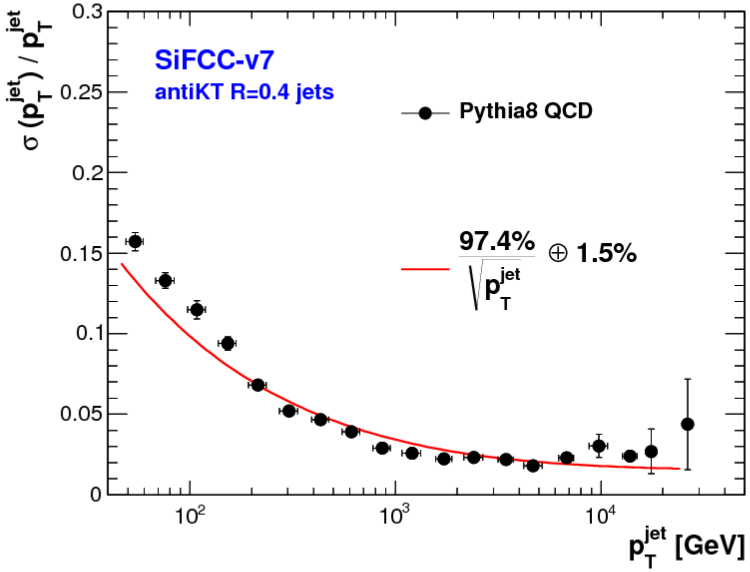


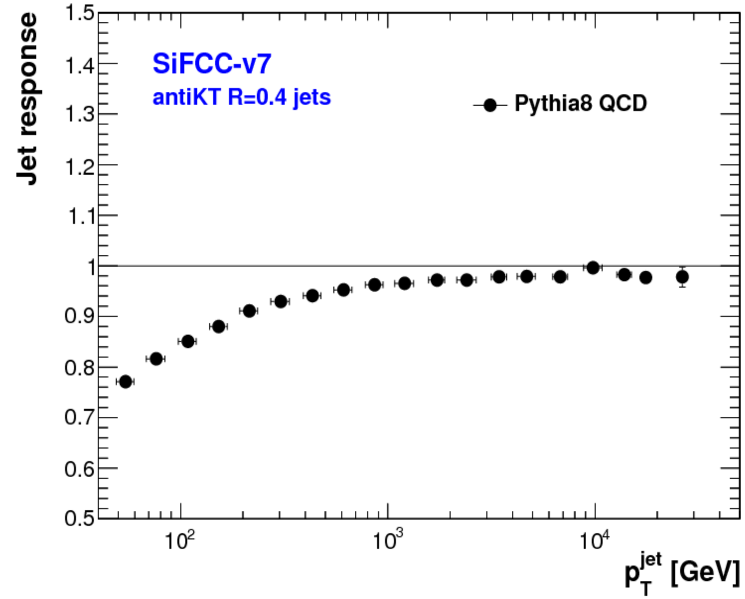

No significant contribution from hits > 100 ns

# Jet resolution and response



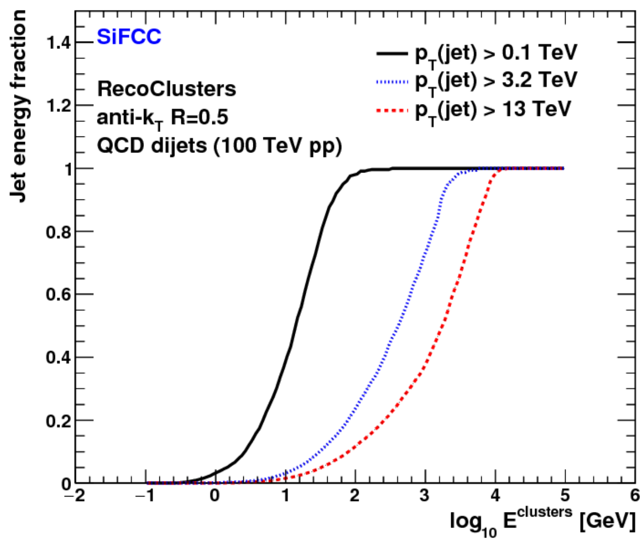



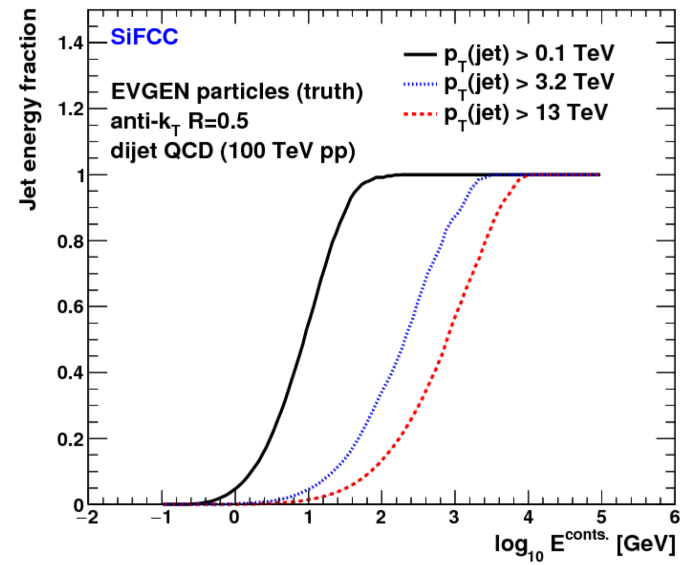

- Jet resolution and response were determined using Gaussian fits
- Jet energy resolution is similar to ATLAS jets before correction (“EM” scale) for pT<1 TeV
- Constant term ~2% can be achieved, but the fit with sampling term is not ideal
- Jet response ~1 at large pT

# Differences between jets & single particles

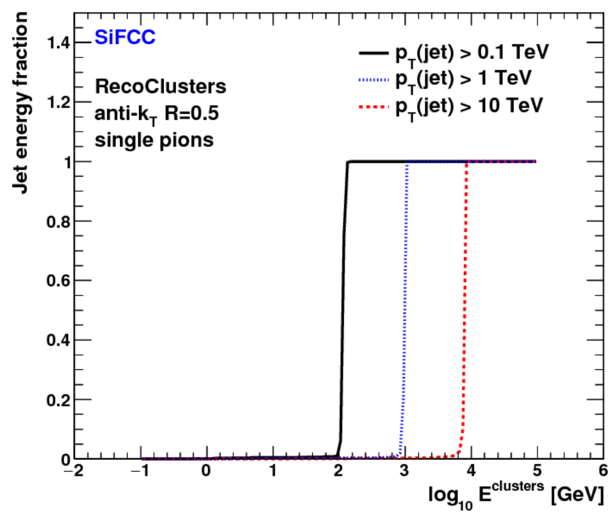
Jets from RecoClusters




Jets from Truth-level




Jets from RecoClusters (single particles)




**Features of constituents of tens-of-TeV jets:**

- span 4 orders of magnitude in energy
  - vs 2 orders for 100 GeV jets
- dependence on fragmentation function?

# High granularity HCAL for 100 TeV physics

- Baseline for past & operational detectors:
  - **transverse cell size is similar or larger than nuclear interaction length: $\lambda_I$**
- **Recent high-granularity HCAL: CALICE R&D:**
  - 2x2 or 1x1 cm cell sizes required to reconstruct PFA & separate particles
- **Main question for a 100 TeV collider:**

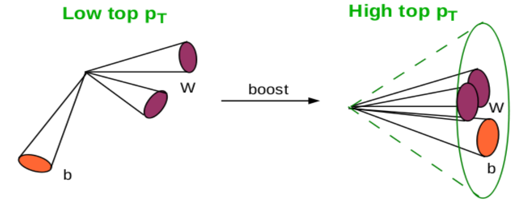
**Can reconstruction of jets and particles at tens-TeV scale benefit from small HCAL cells?**

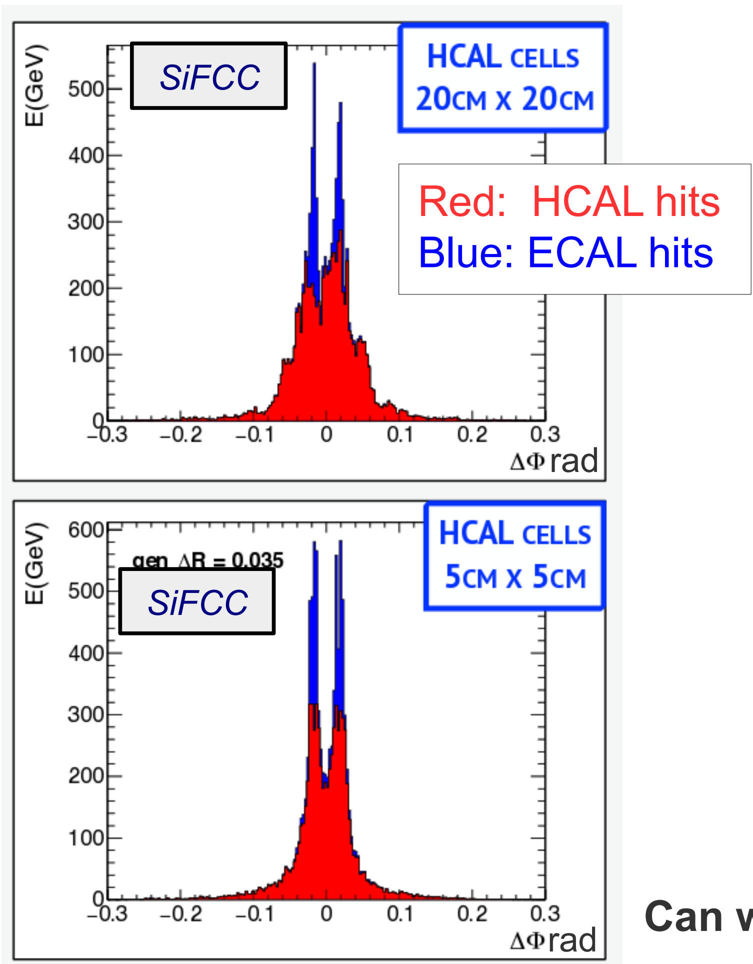
Several simulations with ECAL cells 2x2 cm while HCAL cell sizes were varied:

| SiFCC detector version (Fe/Scin. HCAL) | Transverse size of HCAL cells (cm or $\Delta\eta x \Delta\varphi$) | Transverse size of HCAL cells in $\lambda_I$ | Simulation tag in HepSim |
|---|---|---|---|
| **SiFCC-v7 (baseline)** | 5X5 cm ($\Delta\eta x \Delta\varphi$ = 0.022 x 0.022) | ~ $\lambda_I$/4 | rfull009 |
| **SiFCC-v8 (traditional)** | 20x20 cm ($\Delta\eta x \Delta\varphi$ = 0.1 x 0.1) | ~ $\lambda_I$ | rfull010 |
| **SiFCC-v9 (as ECAL)** | 2x2 cm ($\Delta\eta x \Delta\varphi$ = 0.01 x 0.01) | $\lambda_I$/8 | rfull011 |
| **SiFCC-v10 (fine)** | 1x1 cm ($\Delta\eta x \Delta\varphi$ = 0.005x 0.005) | $\lambda_I$/17 | rfull012 |

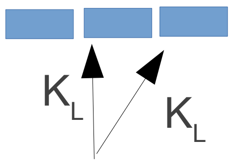
# HCAL segmentation: double particles

- Almost every physics channel will show boosted signatures at 100 TeV → important requirement for HCAL
- Look at hits associated with two close-by particles




truth-level separation between 2 $K_L$ is 0.035 rad (2 deg)



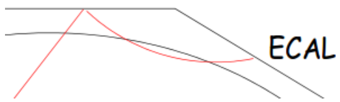

- Generate two $K_L$ (E=100 GeV) particles at η=0.
  - First $K_L$ is always at $\Phi^{true}=0$
  - Second is shifted by $\Delta\Phi^{true}=2$ deg
- Simulate and reconstruct with SiFCC
- Calculate energy of hits in Φ with respect to Φ=0
- Repeat for different HCAL cell sizes

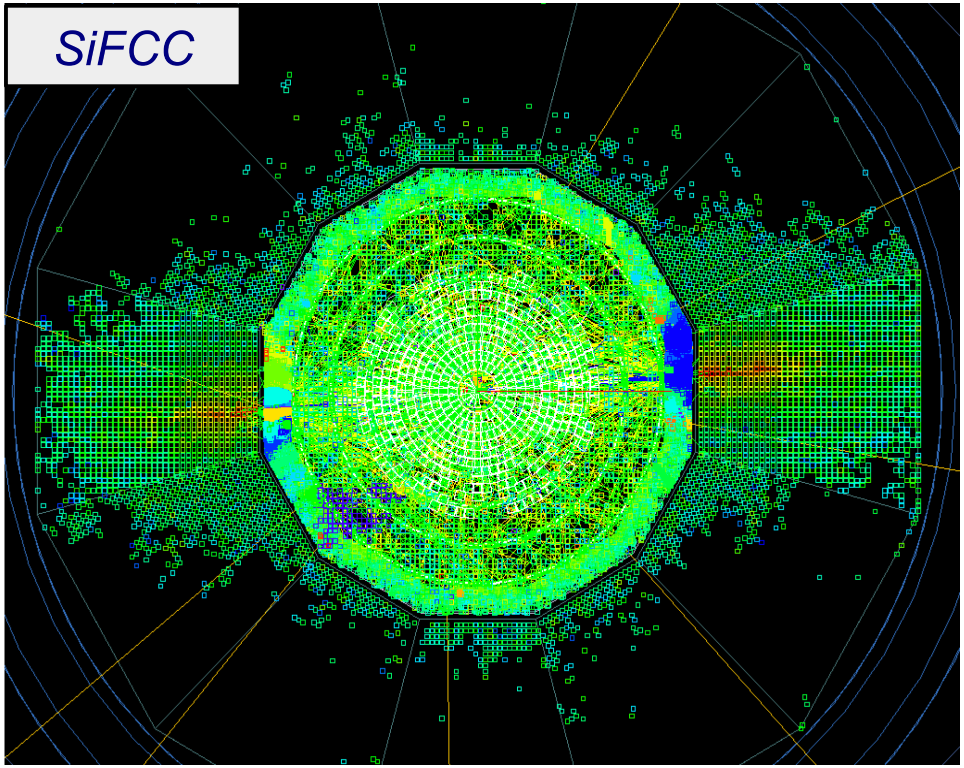
Small HCAL cells (~ $\lambda_I$ /4 size) helps separate hits in hadronic showers produced by two $K_L$ separated by 2 deg. See https://arxiv.org/abs/1612.07291.

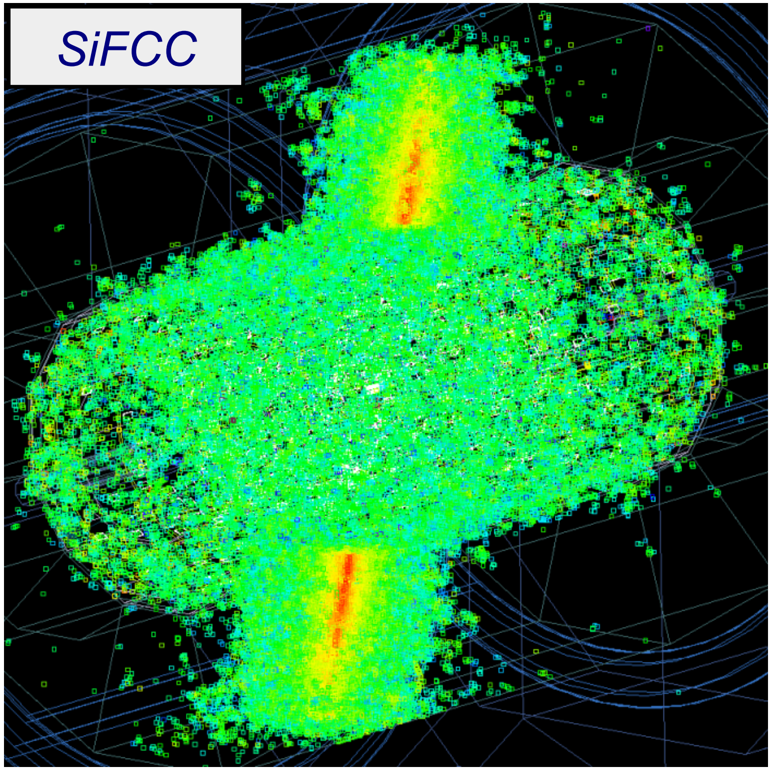
**Can we prove the same using jet substructure variables?**

# Event display of Z' (40 TeV) → $q\bar{q}$

Busy event, large number of back-splash interactions in ECAL/HCAL/Tracker
~4 CPU*h to simulate/reconstruct one event → CPU intensive!



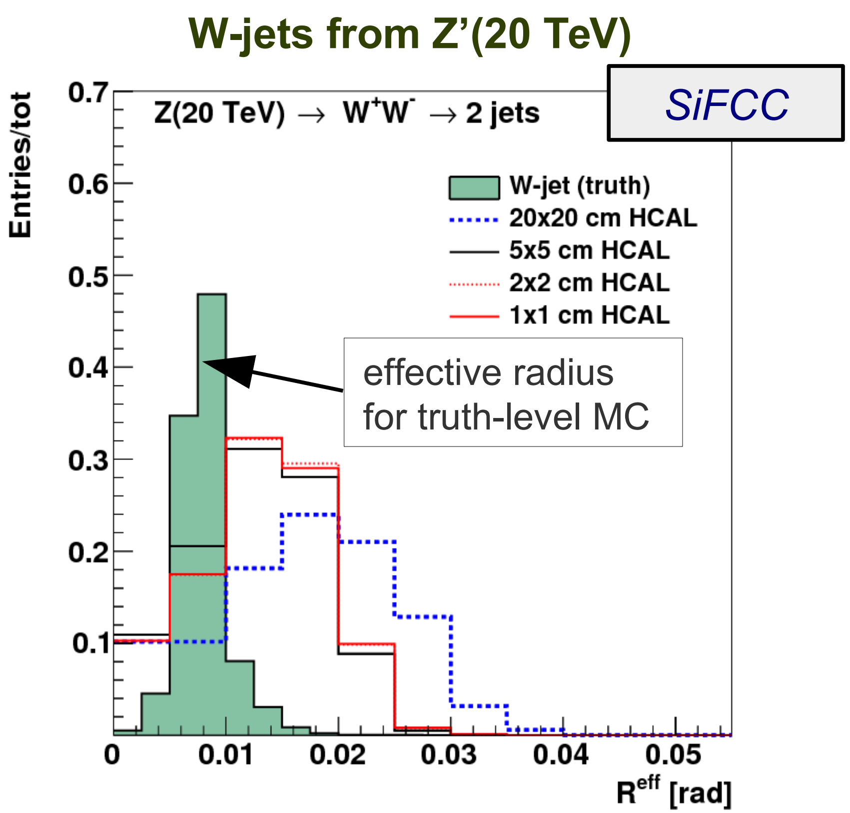



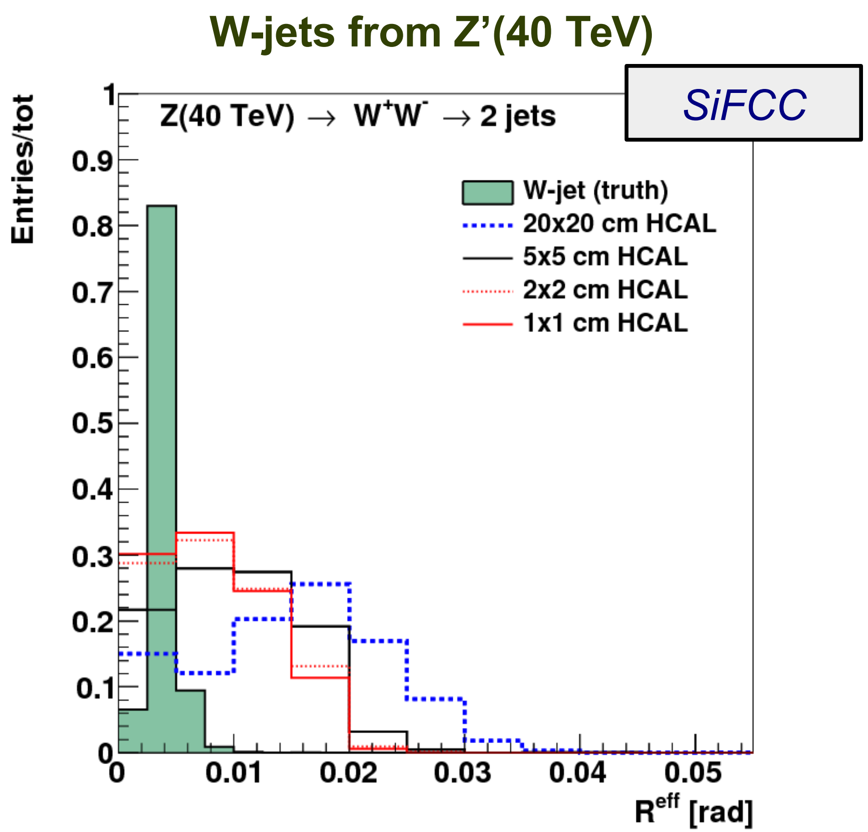



# Effective jet radius for antiKT5 jets

Phys. Rev. D 91 (2015) 034014

Sum over all distances between energy deposits and jet center, weighted with E(const) / E(jet)



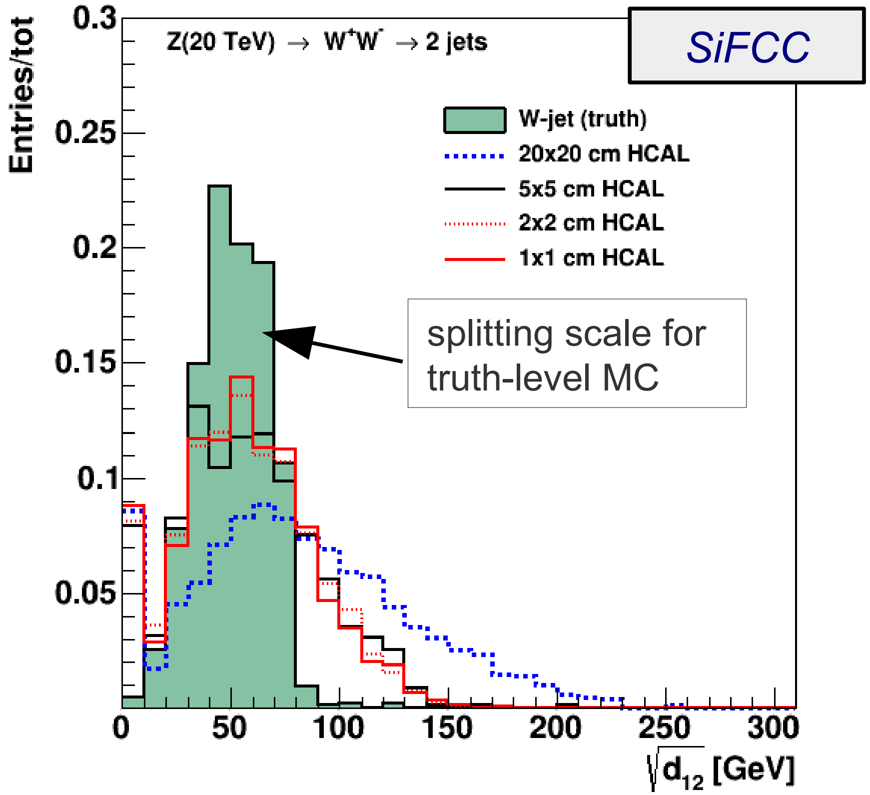



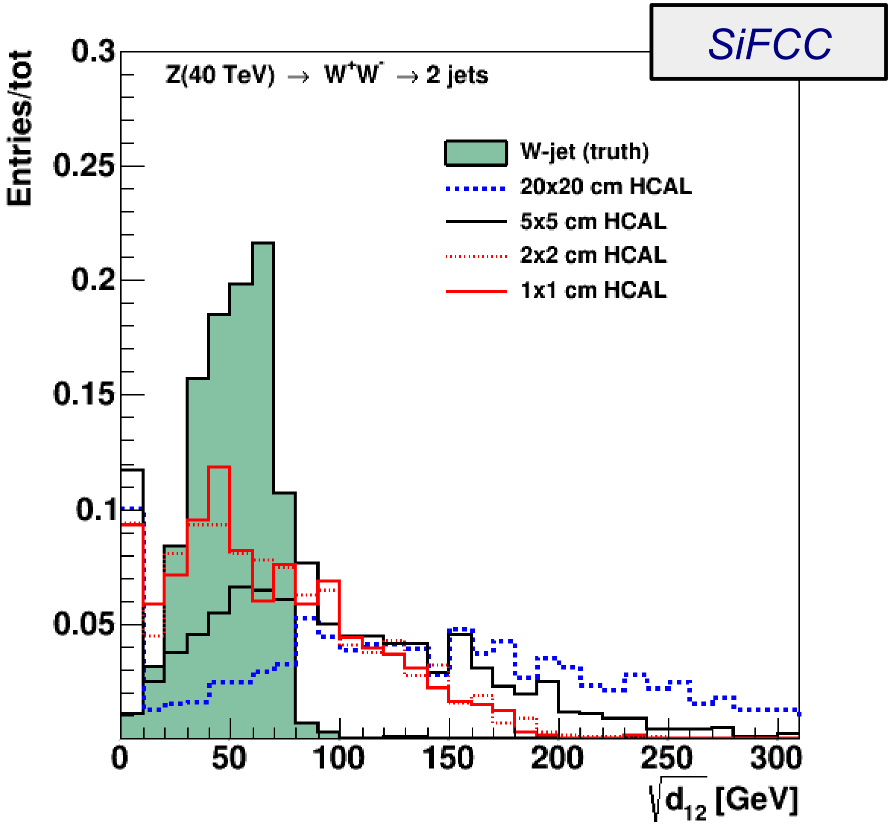

- Jets with pT>10,20 TeV, each from W decays ($q\bar{q}$)
- Narrow (ΔR ~ 2* pT / M(W)) compared to QCD jets (not shown)
- 5x5 cm cells (ΔηxΔφ = 0.022x 0.022) show improvement compared to ΔηxΔφ = 0.1x 0.1 (ATLAS)
- Small difference between 2cm and 1cm cell sizes

# Jet splitting scale: $d_{12}$

$K_T$ scale at which a jet splits into 2. Used to differentiate QCD jets from 2-body decays (W,H,etc)

**W-jets from Z'(20 TeV)** **W-jets from Z'(40 TeV)**




- Jets with pT>10,20 TeV, each from W decays (qqbar)
- 5x5 cm cells ($\Delta\eta x \Delta\varphi$ = 0.022x 0.022) show improvement compared to $\Delta\eta x \Delta\varphi$ = 0.1x 0.1 (ATLAS)
- Small difference between 2cm and 1cm cell sizes

# Summary

- **Some aspects of single particles and jets have been studied in transverse momentum up to 30 TeV using SiFCC detector** → files publicly available from HepSim

- **Studies of single particles (p,n,π, γ,e..) in the range 2 GeV – 33 TeV:**
  - Resolution and energy response were studied
  - Good performance in the range 2 GeV – 33 TeV: No leakage, constant term below ~2 %

- **Studies of AntiKT5 jets in the range 50 GeV – 26 TeV:**
  - Constant term of 2% can be achieved (without including readout infrastructure)
  - Working with Geant4 and SLIC developers to understand timing of hits and its impact on realistic readout

- **Jet substructure studies for jets up to 20 TeV:**
  - Optimal HCAL cell size is $\Delta\eta \times \Delta\varphi = 0.022 \times 0.022$ (vs $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ for ATLAS)
    - confirm previous FCC-hh studies based on fast simulations
    - smaller cell sizes show less improvements

- **Work on cost-effective options for signal readout (fibers+SiPMT) is ongoing**

# Backup

# Hadronic calorimeter (HCAL)

- Strong interactions make jets
  - billions of jets with > 2 TeV at future colliders (28-100 TeV CM energy)

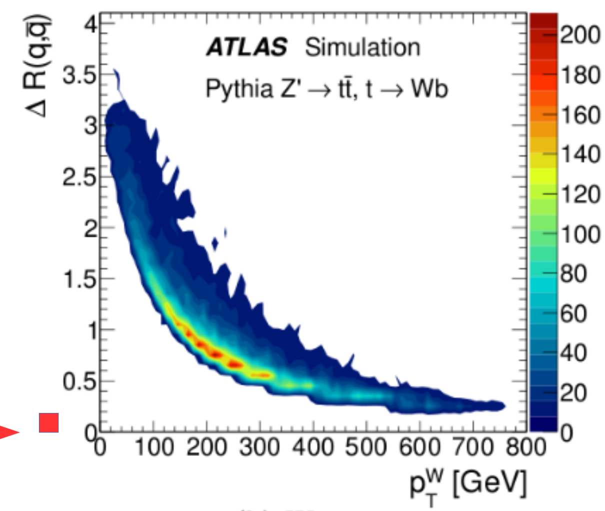
- Higgs, W, Z, top (pT>2 TeV) decay to narrow jets with jet radius smaller than 0.2 in $\varphi x \eta$. Such narrow jets have substructure (2 or 3 subjets)

- Physics goals of future colliders - search for particles with masses 10-50 TeV that can decay to Higgs, W, Z, top decays

  → narrow jets with pT>5-25 TeV from Higgs, W, Z, top

- How to build a HCAL that can:
  - measure jet energies (up to 30 TeV)?
  - resolve internal structure of narrow jets?

Typical cell size for
ATLAS & CMS HCAL




(b) $W \to q\bar{q}$

# SiFCC detector

https://arxiv.org/abs/1612.07291

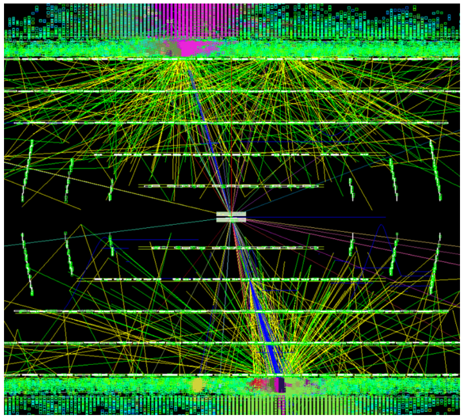
Table 1: Technology and dimensions of the SiFCC sub-detectors in the barrel region. The solenoid field is given inside and outside the solenoid, respectively.

| Barrel | Technology | pitch/cell | radii (cm) | $\|z\|$ size (cm) |
|---|---|---|---|---|
| Vertex detector | silicon pixels/5 layers | 25 $\mu$m | 1.3 - 6.3 | 38 |
| Outer tracker | silicon strips/5 layers | 50 $\mu$m | 39 - 209 | 921 |
| ECAL | silicon pixels+W | 2×2 cm | 210 - 230 | 976 |
| HCAL | scintillator+steel | 5×5 cm | 230 - 470 | 980 |
| Solenoid | 5 T (inner), -0.6 T (outer) | - | 480 - 560 | 976 |
| Muon detector | RPC+steel | 3×3 cm | 570 - 903 | 1400 |

Table 2: Technology and dimensions of the SiFCC sub-detectors for the endcap region.

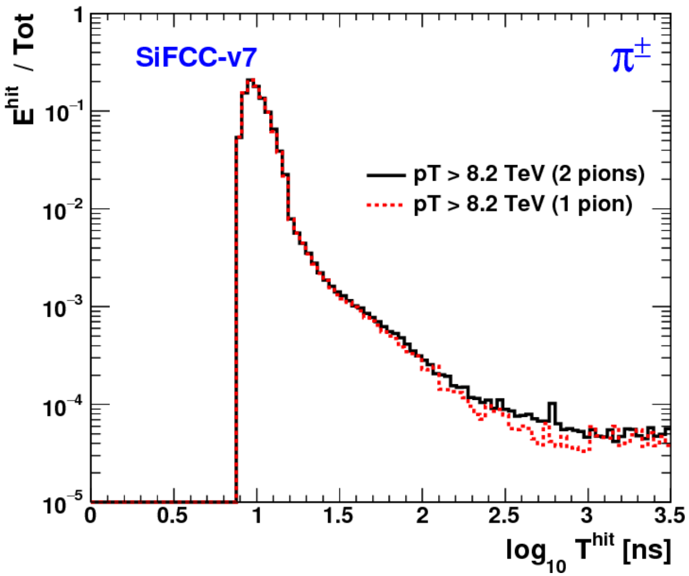
| Endcap | Technology | pitch/cell | $z$ extent | outer radius |
|---|---|---|---|---|
| | | | (cm) | (cm) |
| Vertex detector | silicon pixels | 25 $\mu$m | | |
| Outer tracker | silicon strips | 50 $\mu$m | | |
| ECAL | silicon pixels+W | 2×2 cm | 500 - 516 | 250 |
| HCAL | scintillator+Steel | 5×5 cm | 518 - 742 | 450 |
| Muon detector | RPC+Steel | 3×3 cm | 745 - 1010 | 895 |
| Lumi calorimeter | silicon+W | 3.5×3.5 mm | 495 - 513 | 20 |
| Beam calorimeter | semiconductor+W | 3.5×3.5 mm | 520 - 539 | 13 |

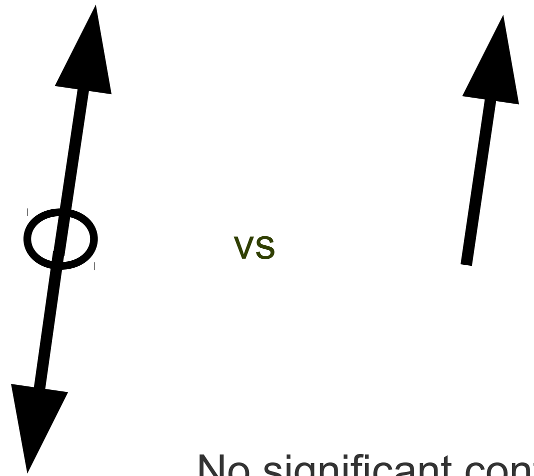
# Can back-scattering explain slow hits in  jets?



Two back-to-back jets with pT=20 TeV.
Straight lines show Geant4 (truth level) particles

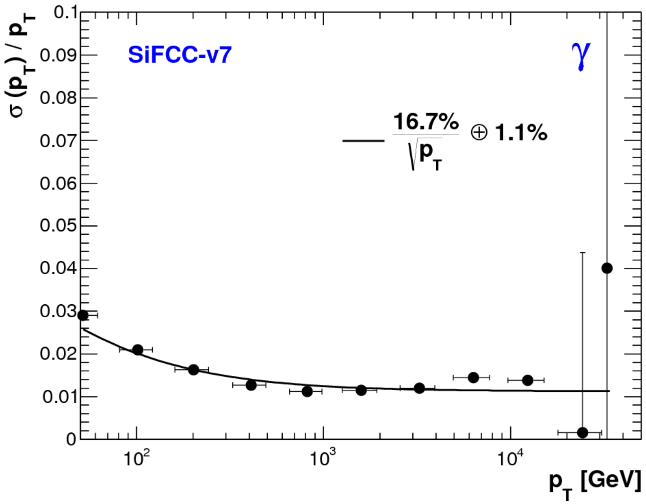
Test:
Compare hits from single-particles with hits from two particles where 2 particles are separated by 180 deg

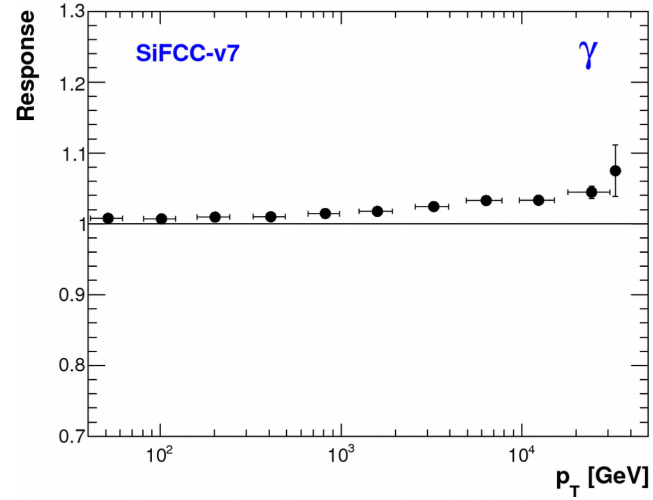


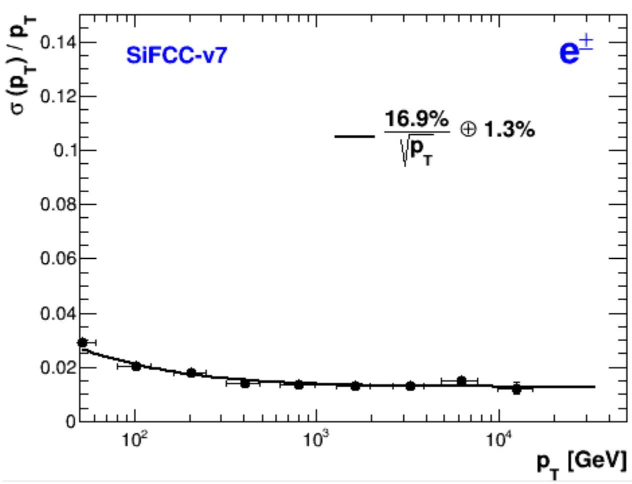



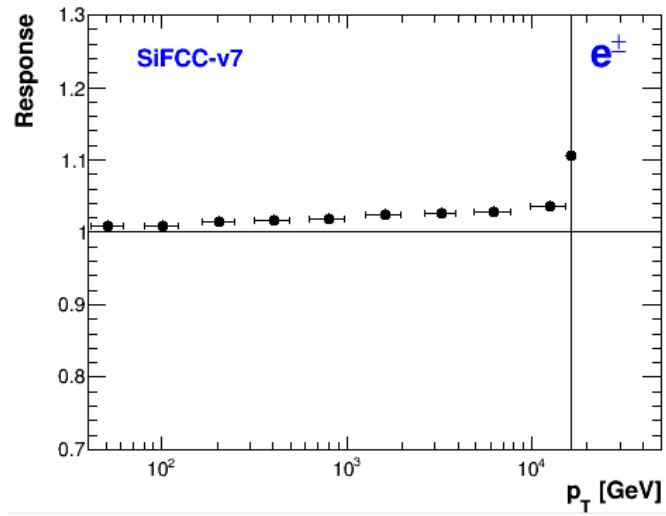

No significant contribution from back-scattering

# Single particle resolution and response ($e/\gamma/\pi^0$)



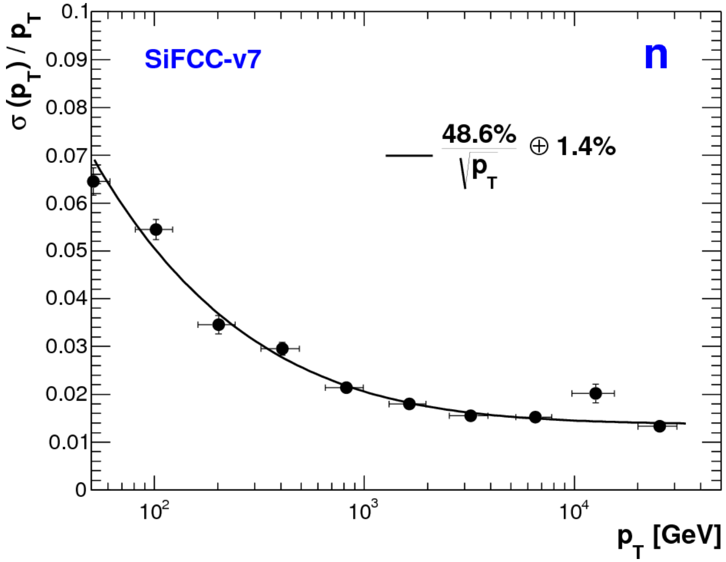



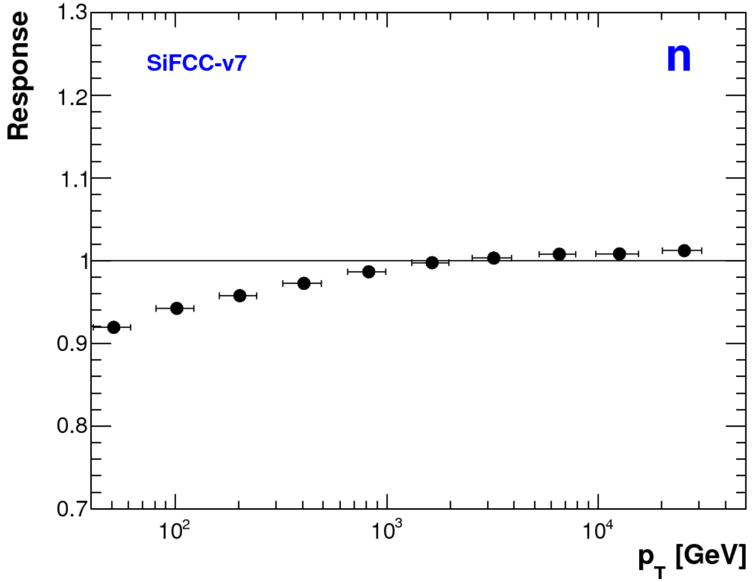



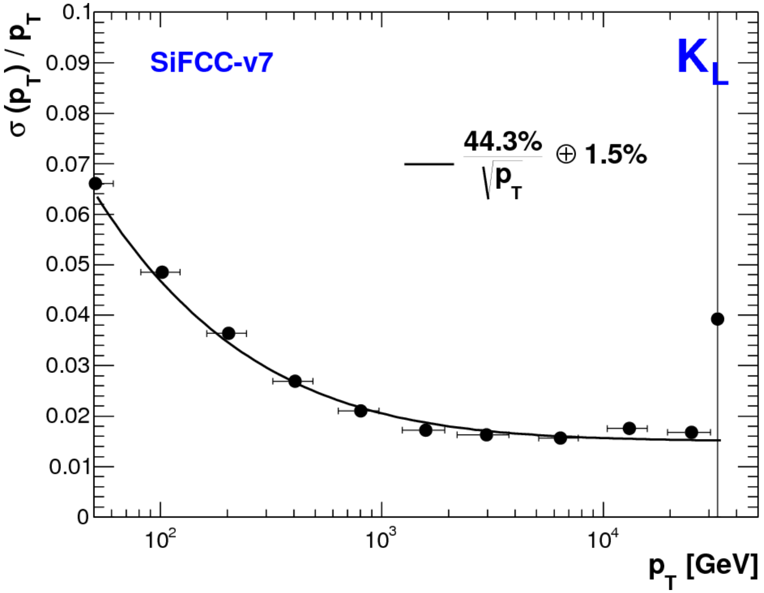



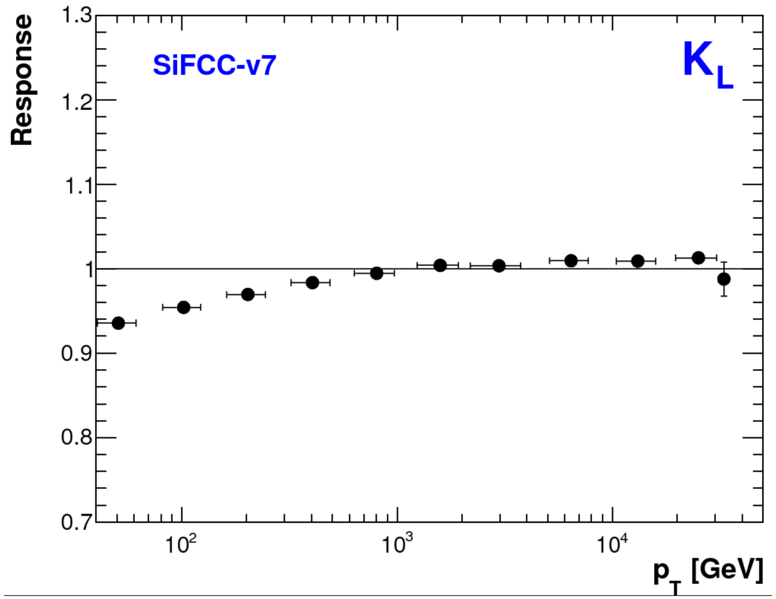

- Reasonable performance of ECAL: ~17% sampling term, 1.3% constant term
- Tracking is not used for electrons

# Response to neutrons and $K_L$



# The time structure of hadronic shower

Recently published by the CALICE collaboration

http://iopscience.iop.org/article/10.1088/1748-0221/9/07/P07022/pdf

**Summary:**

- Slow component of hadronic shower can extend to ~few hundred of ns due to:
  - evaporation neutrons, decay of meta-stable nuclear states etc.
- The late component is predominantly concentrated at lower hit energies
- Late components of hadronic showers, which are substantially more pronounced in tungsten than in steel (SiFCC has tungsten ECAL)
- QGSP-BERT physics list, which is widely used for LHC and linear collider detector simulations, substantially overestimates the amount of late energy depositions in tungsten.

→ **was fixed in Geant 10.3p1**

Working with Geant4 developers (A.Dotti, A.Ribon) to understand this issue