Simulation of a high-granular hadronic calorimeter for multi-TeV physics

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HEP/ANL

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With contributions from:
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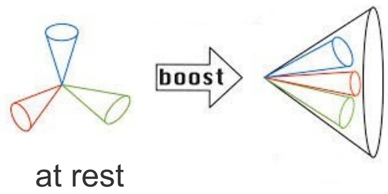
Physics requirements for FCC-hh calorimeters

(what we already know)

- **Excellent measurements of:**
  - missing transverse energy
  - jets, photons, tau, electrons etc. up to 30 TeV in pT
- **Optimized for boosted signatures of M~40 TeV particles. Resolving:**
  - Substructure in jets from decays of heavy particles (hadronic decays):
    - Examples: Z'→ $t\bar{t}$, WW, W' → HW, Higgs → $b\bar{b}$ etc.



jet with R~ 0.5 - 0.8

  - Individual particles (photons, electrons, taus) with < 1 degree separation
    - Examples: H → γγ, H → ZZ' → 4l etc, H → tau+tau-

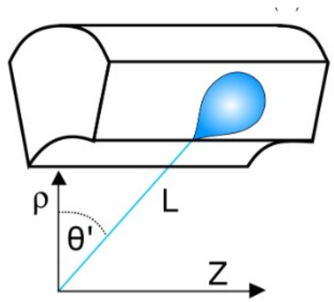
Detector requirements driven by physics at 100 TeV

(what we already know)

- **Good containment up to pT(jet)~30 TeV: 12 λ_I for ECAL+HCAL**
  - affects jet energy resolution
  - leakage biases, etc.
- **Small constant term for HCAL energy resolution: $c < 3\%$**
  - dominates jet resolution for pT>5 TeV
  - important for heavy-mass particles decaying to jets
- **Longitudinal segmentation:**
  - Not studied
- **Sufficient transverse segmentation for resolving boosted particles:**
  - baseline $\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$ from previous Delphes studies
  - 5x5 cm assuming ~ATLAS-like inner radius (~2.3 m from IP)

Resolution for single pions

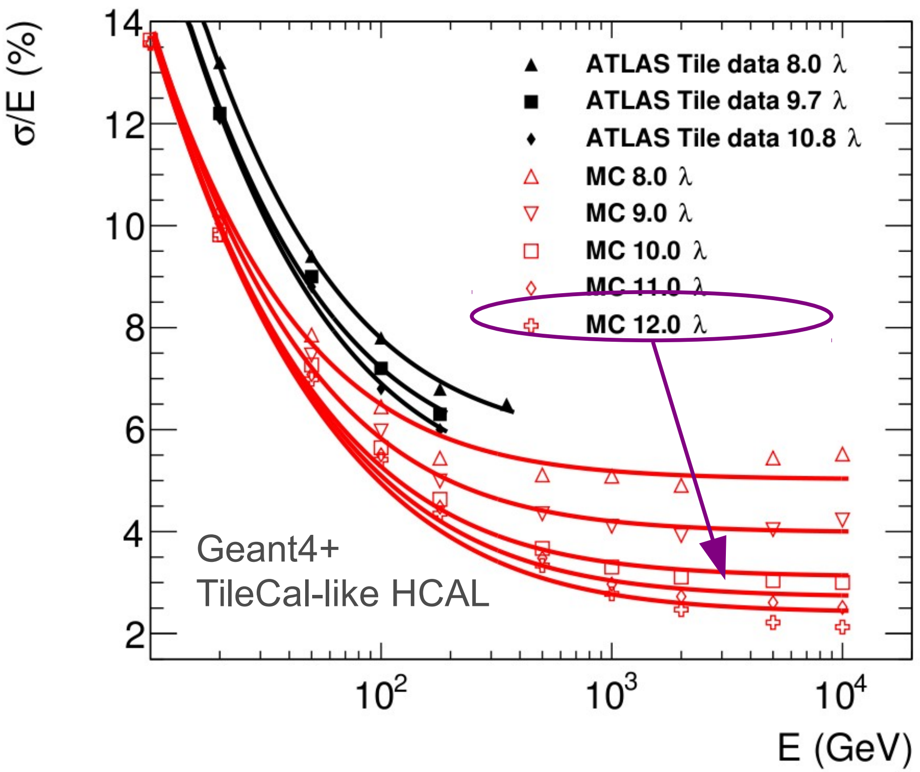
ATLAS-like setup
based on Geant4



$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a – stochastic/sampling term,
b - electronic noise term
c - constant term

"c" dominates for jet with pT>5 TeV



- Geant4 TileCal inspired simulation based on FTFP_BERT
- Calculate single-particle resolution
- Stochastic term is close to 45%/√E
- Constant term improves by ~20% with increase of **1**$\boldsymbol{\lambda}_I$

Constant term c~2.5% is achievable for 12 $\boldsymbol{\lambda}_I$

T.Carli, C.Helsens, A.Henriques Correia, C.Solans: arXiv:1604.01415

Goals of the current studies

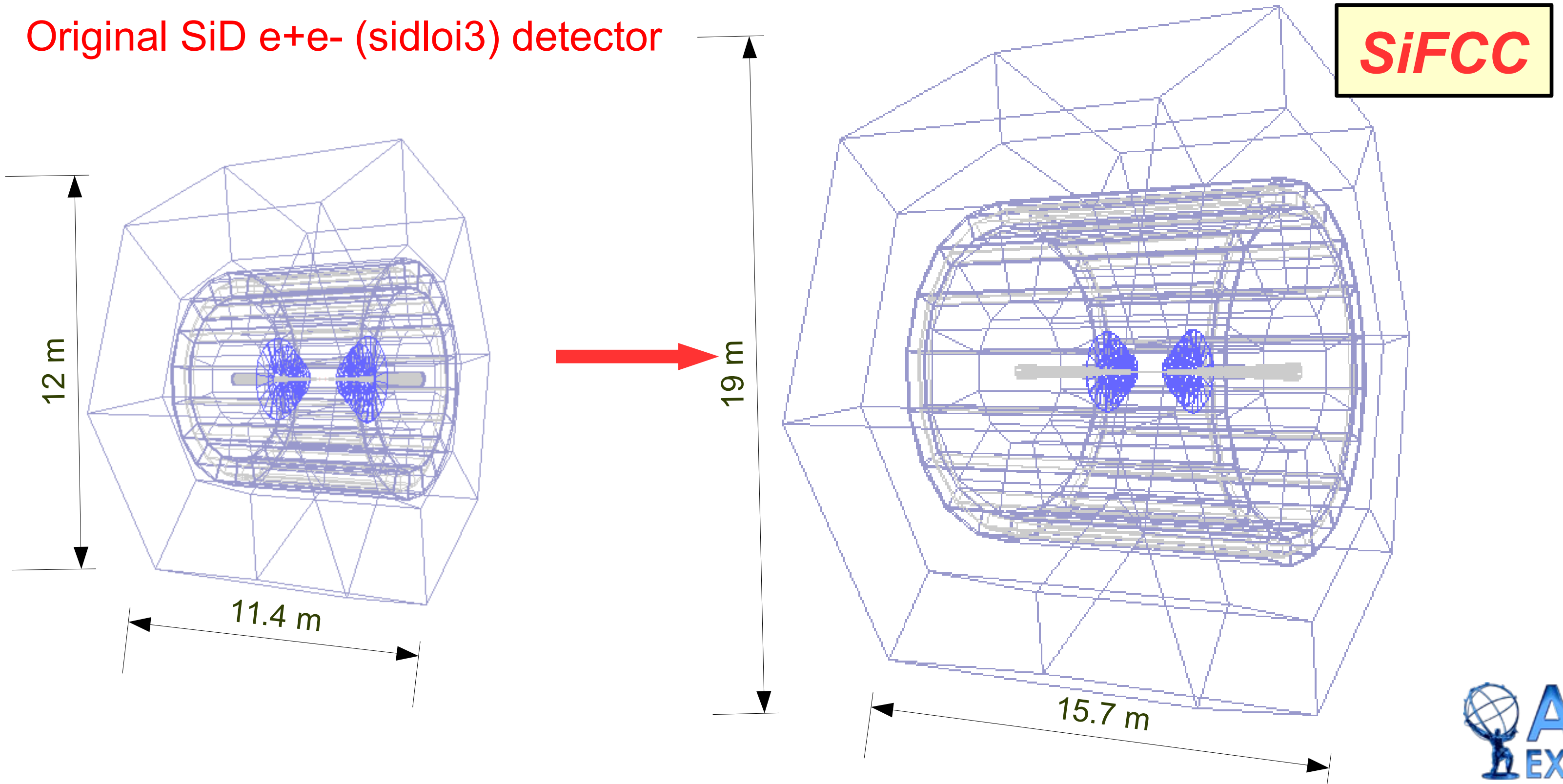
- **Optimize detector sensitivity and performance to new physics using appropriate technologies**
- **Single particle resolution studies**
- **Find optimal longitudinal and transverse cell sizes for HCAL**
  - High-granularity hadronic calorimeter for multi-TeV boosted objects?
  - Non-traditional requirement: cell sizes << interaction length?

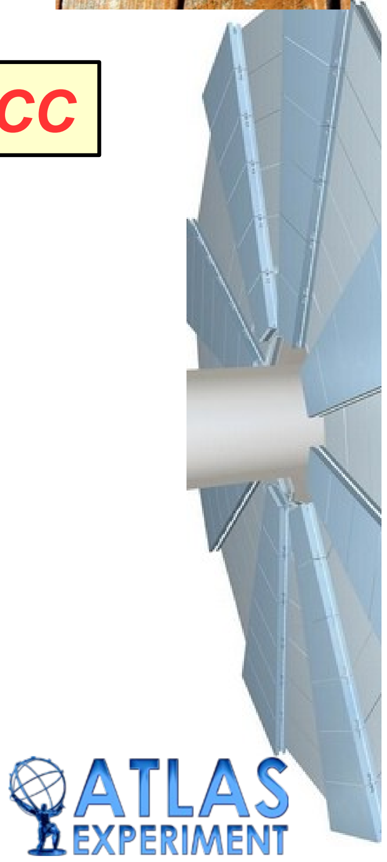
Require:

- detailed Geant4 simulations ..
- realistic reconstruction (including particle flow, i.e. tracks!)

SiFCC detector for performance studies

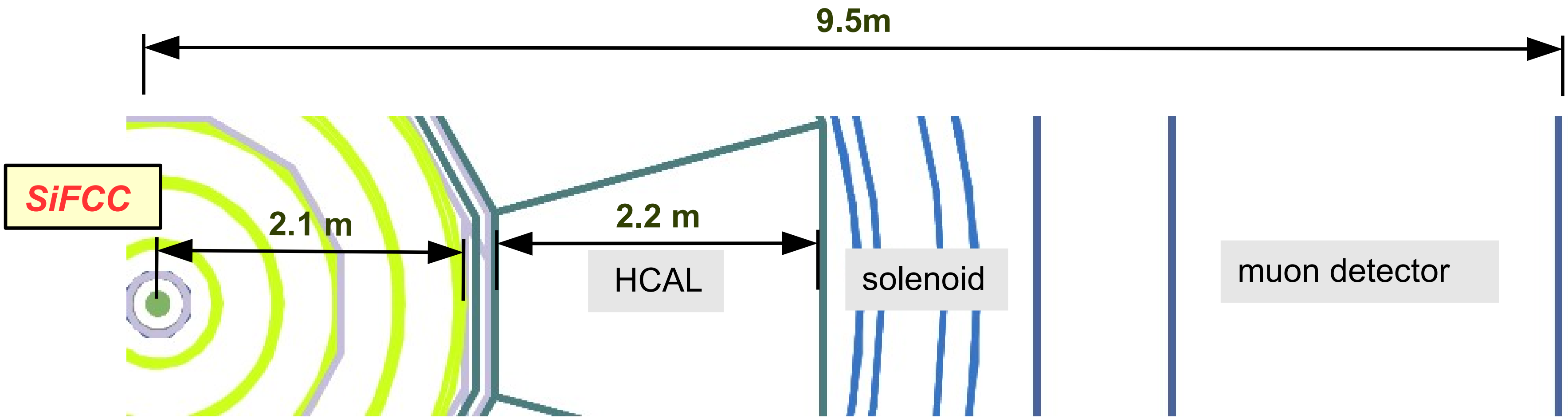
- Re-purpose SiD (ILC) detector and SLIC software
- Leverage large investments to R&D and software designs

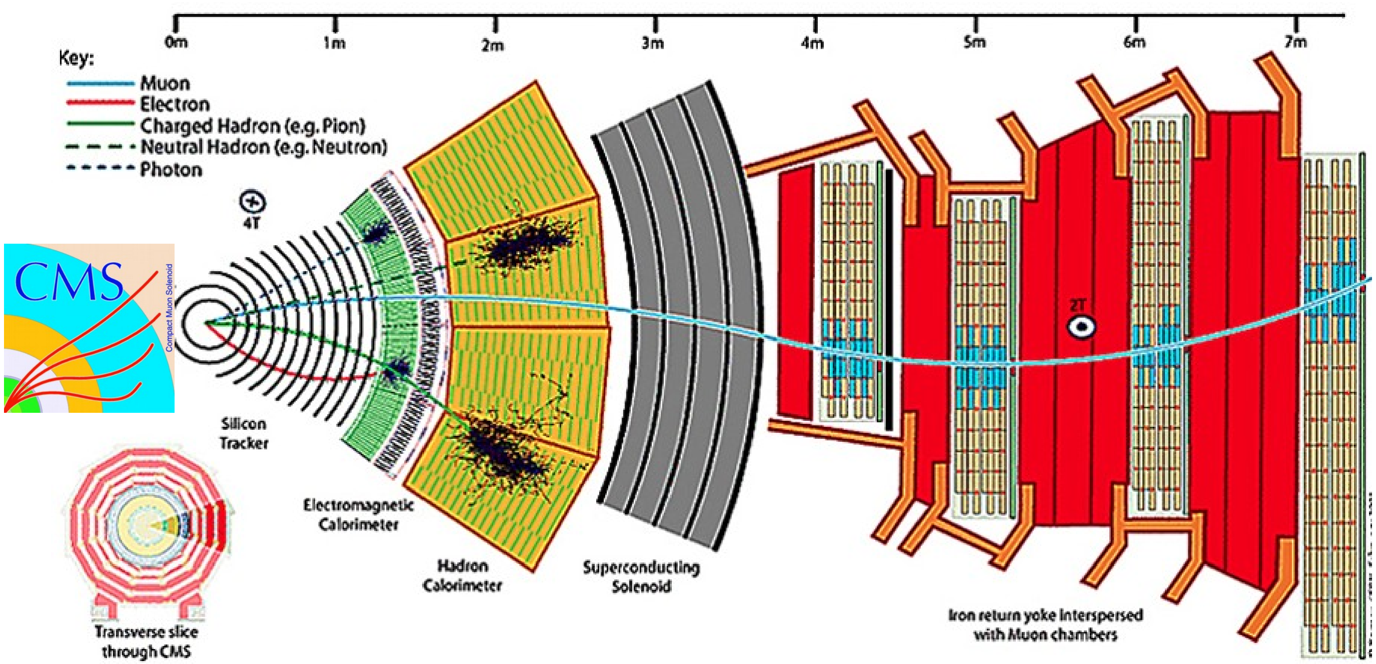




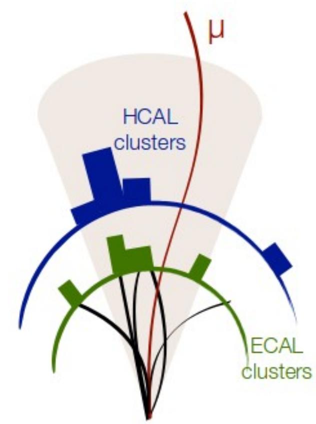
- **SiFCC (v4) detector: Multipurpose, high granularity, compact detector**
  - 30% smaller than ATLAS (R=25 m vs R=19)
  - 30% larger than CMS (R=14.6 m vs R=19 m)

SiFCC detector vs CMS





Both are optimized for Particle Flow Algorithms



Characteristics of SiFCC (version 4)

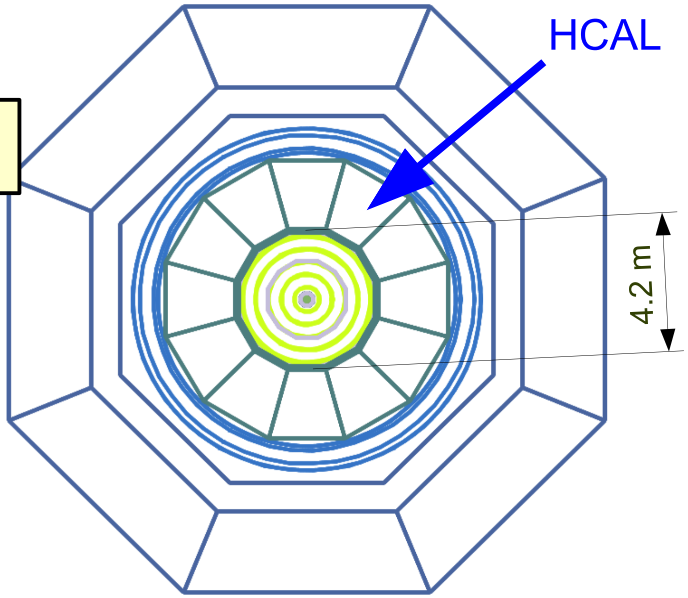
http://atlaswww.hep.anl.gov/hepsim/soft/detectors/sifcch4/sifcch4.html

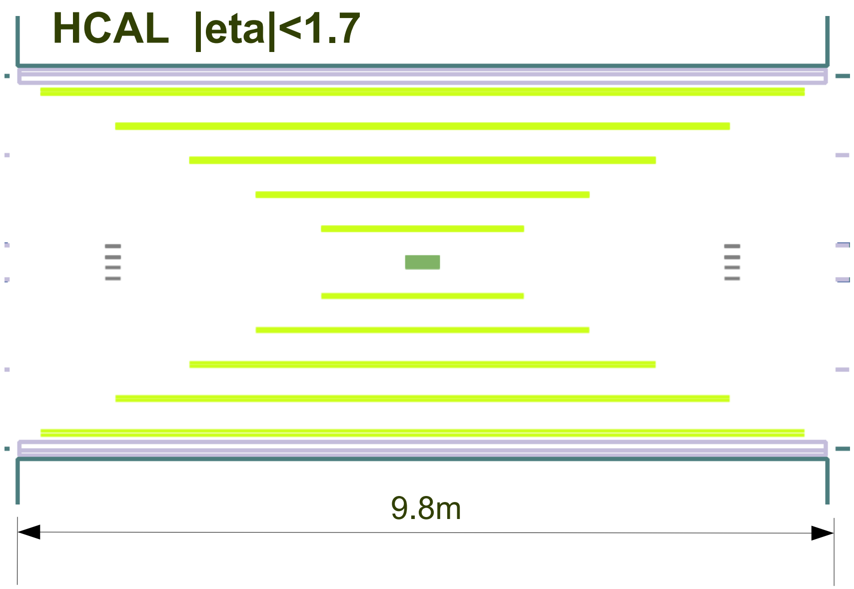
- **5 T solenoid outside HCAL**
- **Si pixel and outer trackers:**
  - 20 um pixel (inner), 50 um (outer)
- **ECAL (Si/W):** 2x2 cm. 32 layers, ~35 X0
- **HCAL (Scint. / Fe)** **~ FCC-hh baseline**
  - 5x5 cm cells: $\Delta\eta \times \Delta\varphi = 0.022 \times 0.022$
    - CMS: $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$
    - ATLAS: $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
  - Longitudinal: 64 layers, 11.3 λ_I
  - 3.1% sampling fraction
  - > 150 million cells, non-projective

trans. cell size: 5 cm ~ λ_I(Fe) / 3

Can reconstruction of TeV-scale objects benefit from small HCAL cells?

SiFCC



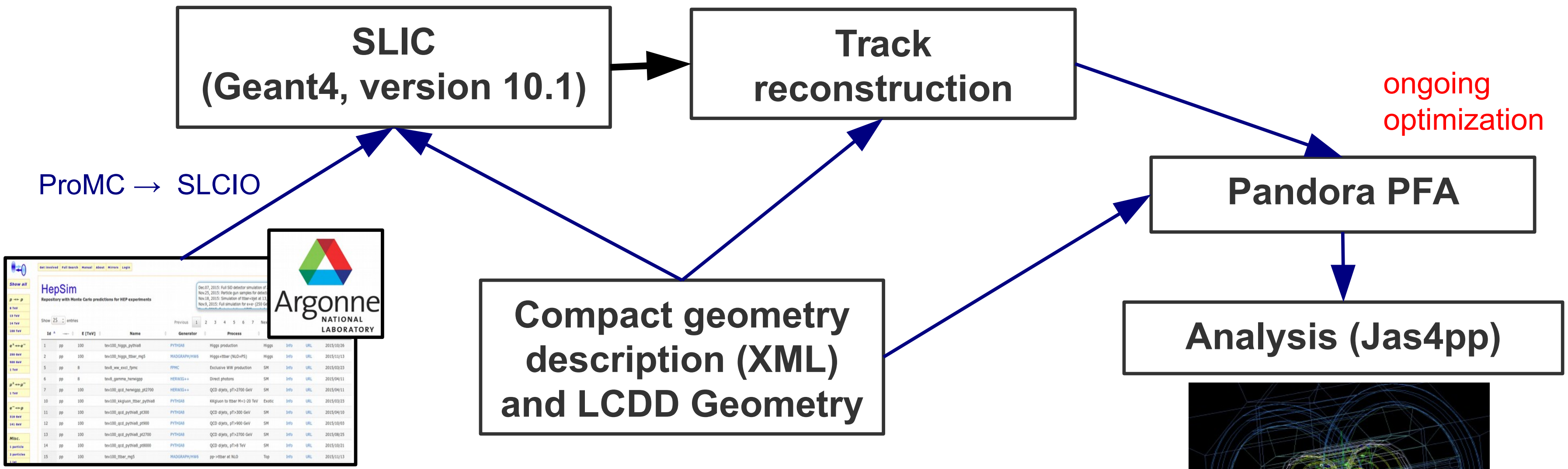


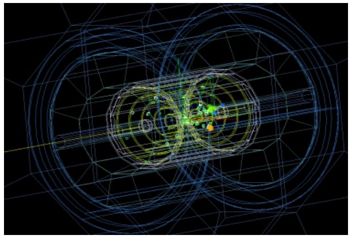
Software for full simulations

Simulator for the Linear Collider (SLIC) software

- Optimized for the SiD detector at SLAC (T.Johnson, N.Graf, J.McCormick, J.Strube)
- Re-purposed for future pp collider studies (S.C., A.Kotwal, J.Strube)
- Integrated with **HepSim.** Deployed on Open-Science Grid (OSG)
- Geant4 simulation (version 10.1). Models for inelastic processes:
  - Model: QGSP: 12 GeV → 100 TeV
  - Model: FTFP: 9.5 GeV → 25 GeV (BertiniCascade: 0 eV → 9.9 GeV)

Analysis: C++/Root or **Jas4pp** (ANL,S.Chekanov,E.May). Based on Jas3





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

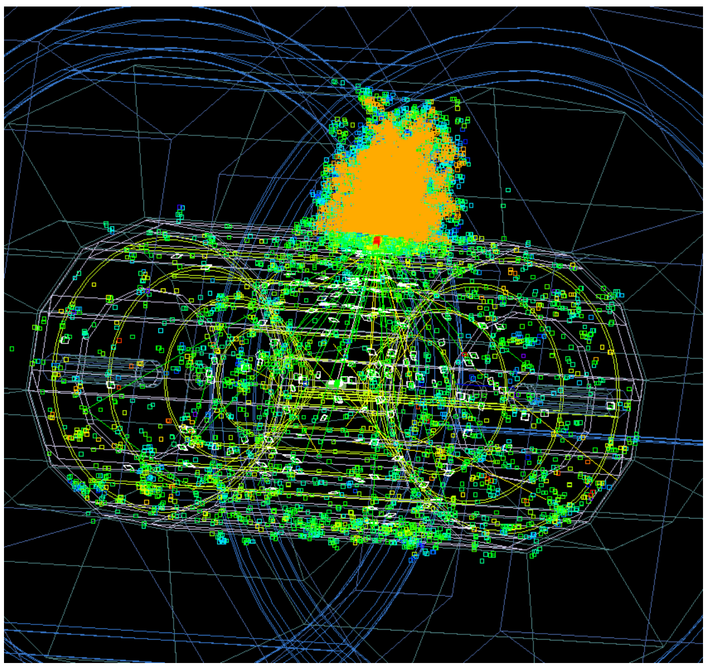
Response to single particles: 1 TeV

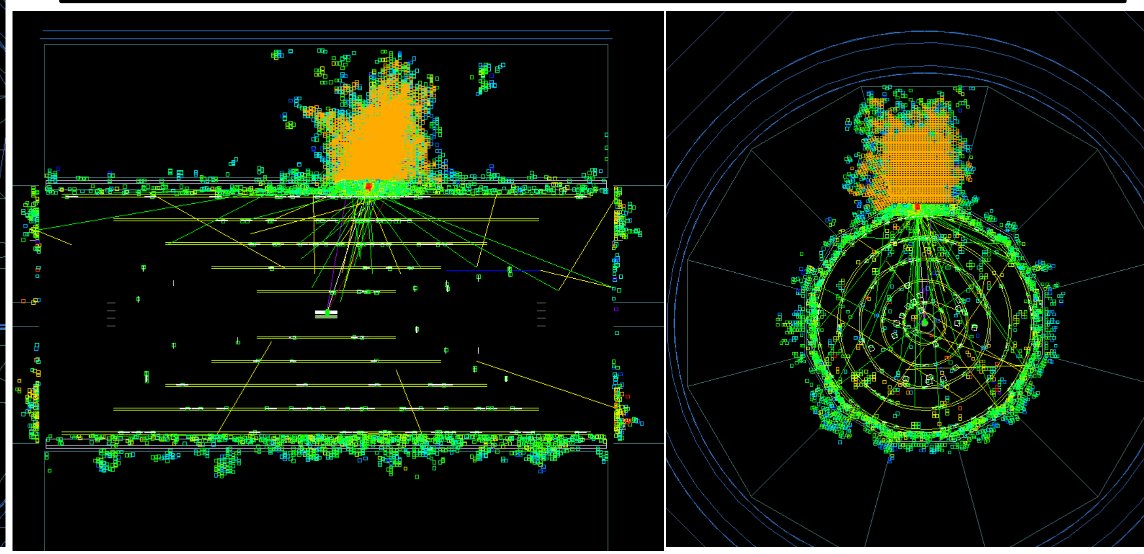
SiFCC

- Use single pions 1 GeV – 10 TeV to study detector performance
- 1 TeV pions are benchmarks used in arXiv:1604.01415 (shown in Washington DC)
  - pT(jet)>30 TeV: ~10% will be carried by 1 TeV hadrons (~9 hadrons/jet)

- 7300 calorimeter hits, 440 SiTracker hits
- 1 reconstructed PFA (pi+) =998 GeV
- 1 reconstructed CaloCluster at 1058 GeV
- Many back-splash interactions

Example: 1 TeV π+





Based on **HepSim**: http://atlaswww.hep.anl.gov/hepsim/info.php?item=182

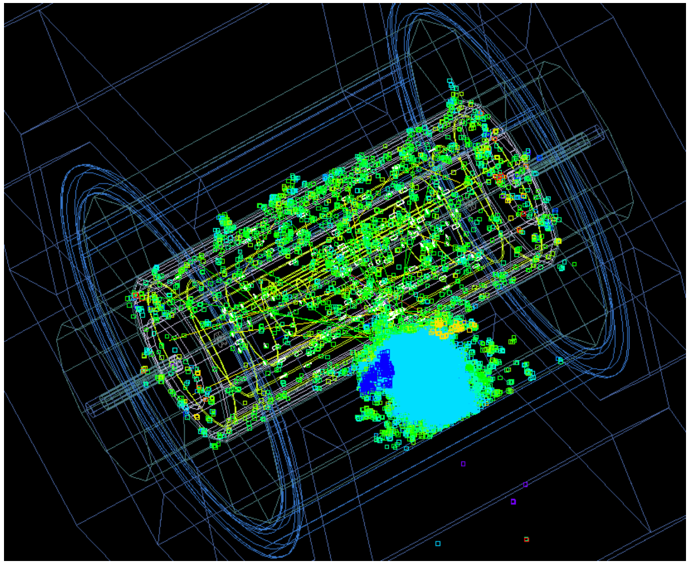
Response to single particles: 8.1TeV pions

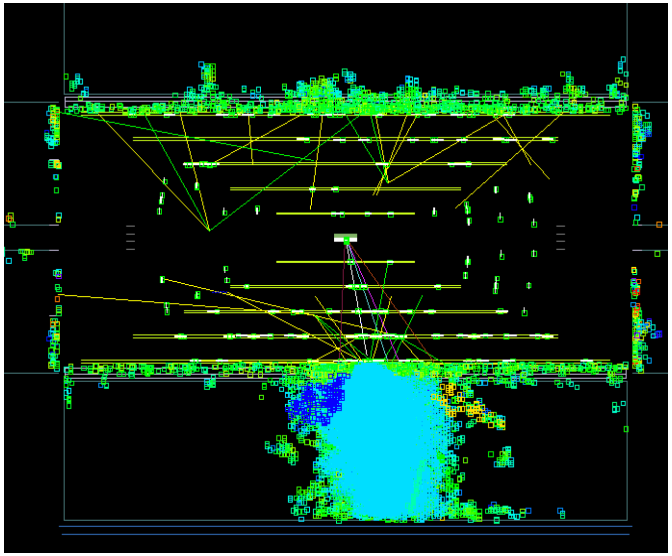
SiFCC

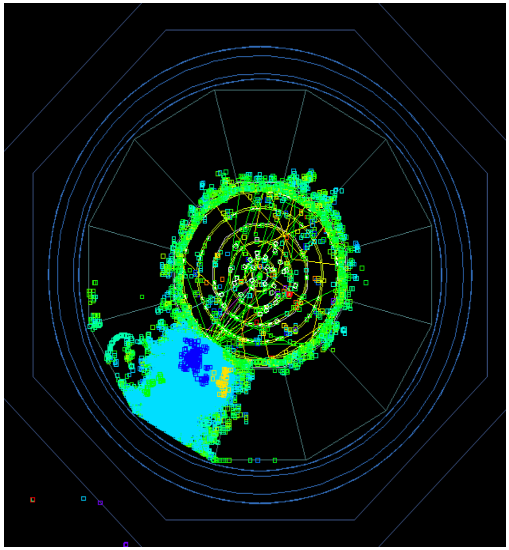
Example: 8.156 TeV π+

Energy leakage outside HCAL?

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



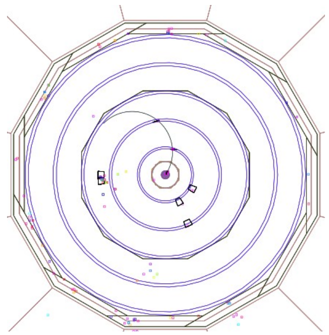


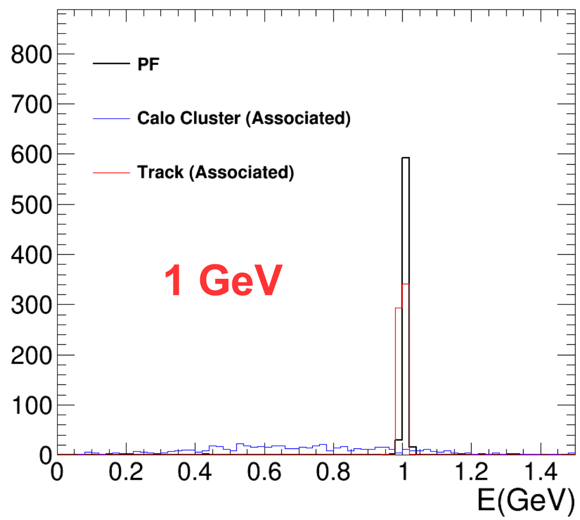


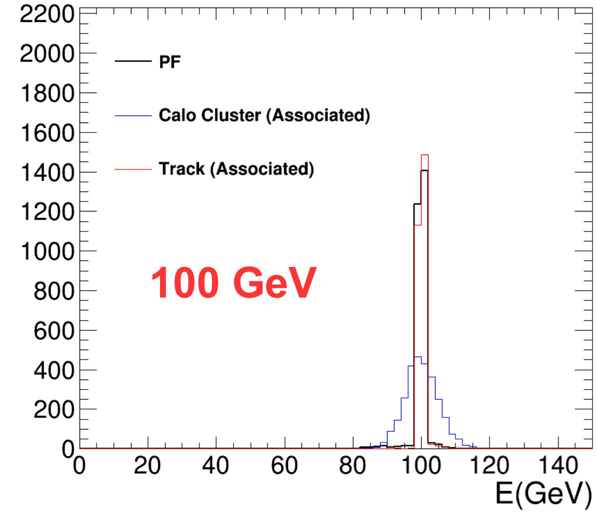
Based on **HepSim**: http://atlaswww.hep.anl.gov/hepsim/info.php?item=201

Detector response to single particles

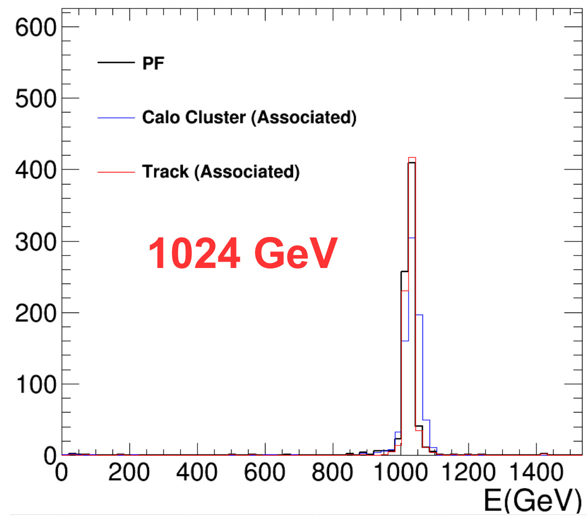
SiFCC

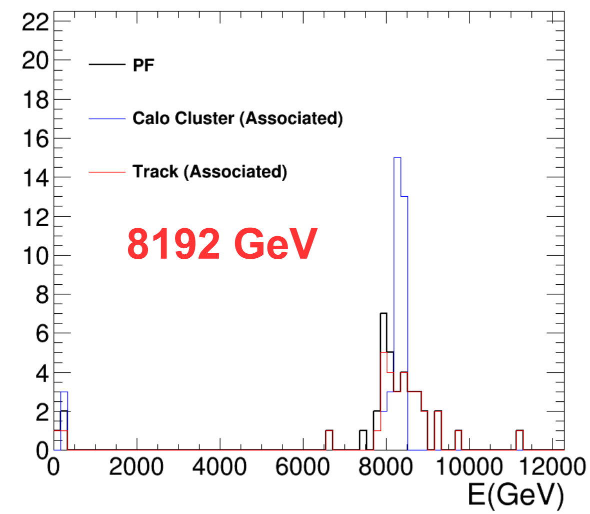






Losses of clusters for < 2 GeV charged particles due to **5 T** field and increased inner radius to 2.1 m

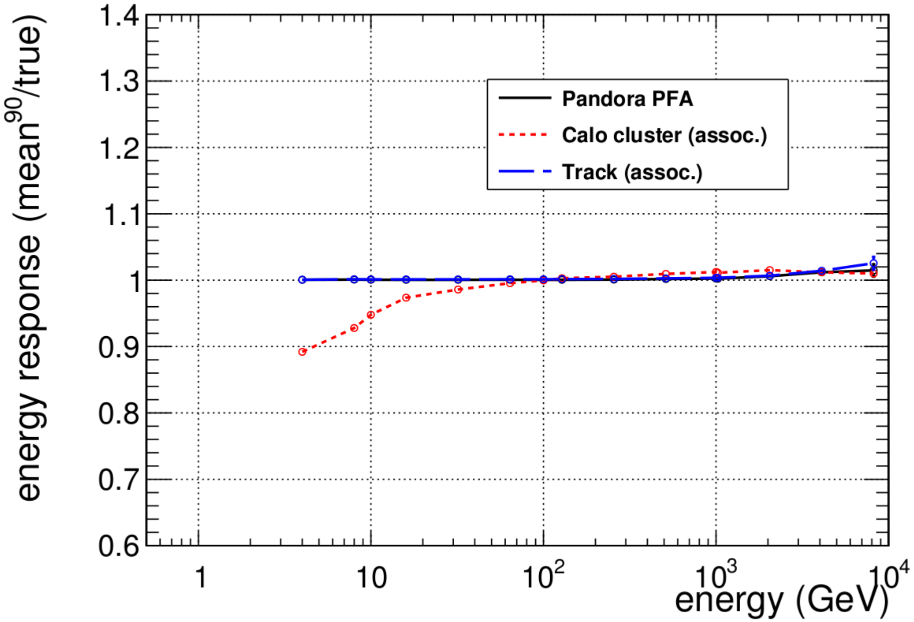


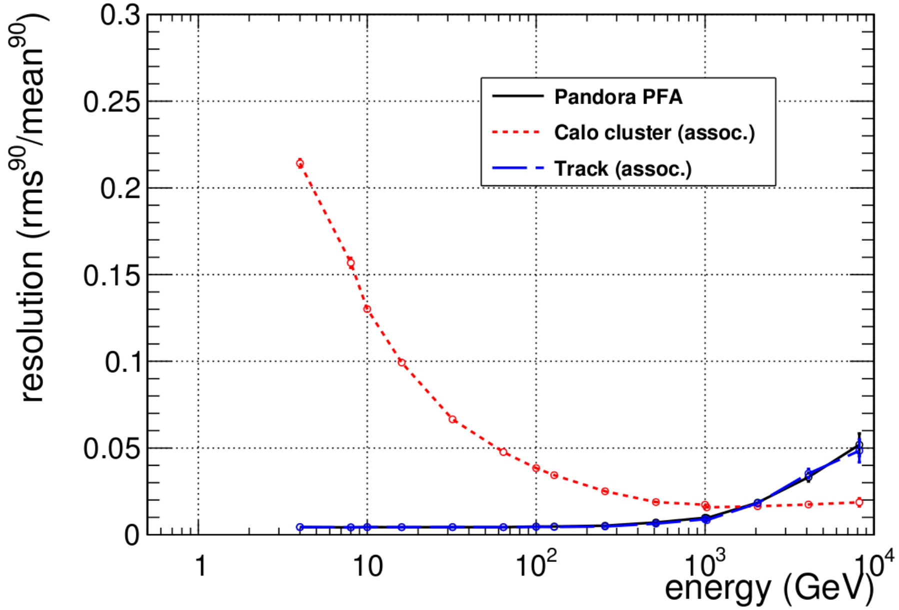


p = 0.3 * B * r

- p – momentum (GeV)
- B - solenoid field (in T)
- r - is the radius (in m)

Single particle response





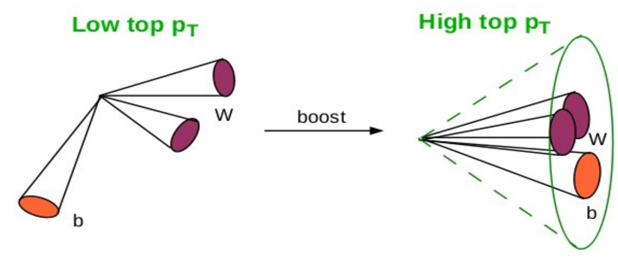
- Losses of clusters with low momentum due to 5 T
- Resolution of tracks & PFA getting worse with energy
- Resolution for CaloClusters is better than PFA/tracks for E> 2 TeV

  ~ 2% for clusters, 5% for tracker near 8 TeV

Estimates based on: dpT/pT= 8 sig*pT/(0.3*B*L2) are more conservative*

Physics processes for boosted jet studies

- Muon collisions to speed up calculations: no complications due proton beams
- Benchmark process: Z' with masses 10, 20, 30, 40 TeV and ΔΓ(Z')~ 1 MeV:
  - $\mu+\mu- \rightarrow Z' \rightarrow W+W-$
  - $\mu+\mu- \rightarrow Z' \rightarrow q\bar{q}$
  - $\mu+\mu- \rightarrow Z' \rightarrow t\bar{t}$
  - $\mu+\mu- \rightarrow Z' \rightarrow$ tau+tau-
  - $\mu+\mu- \rightarrow Z' \rightarrow b\bar{b}$



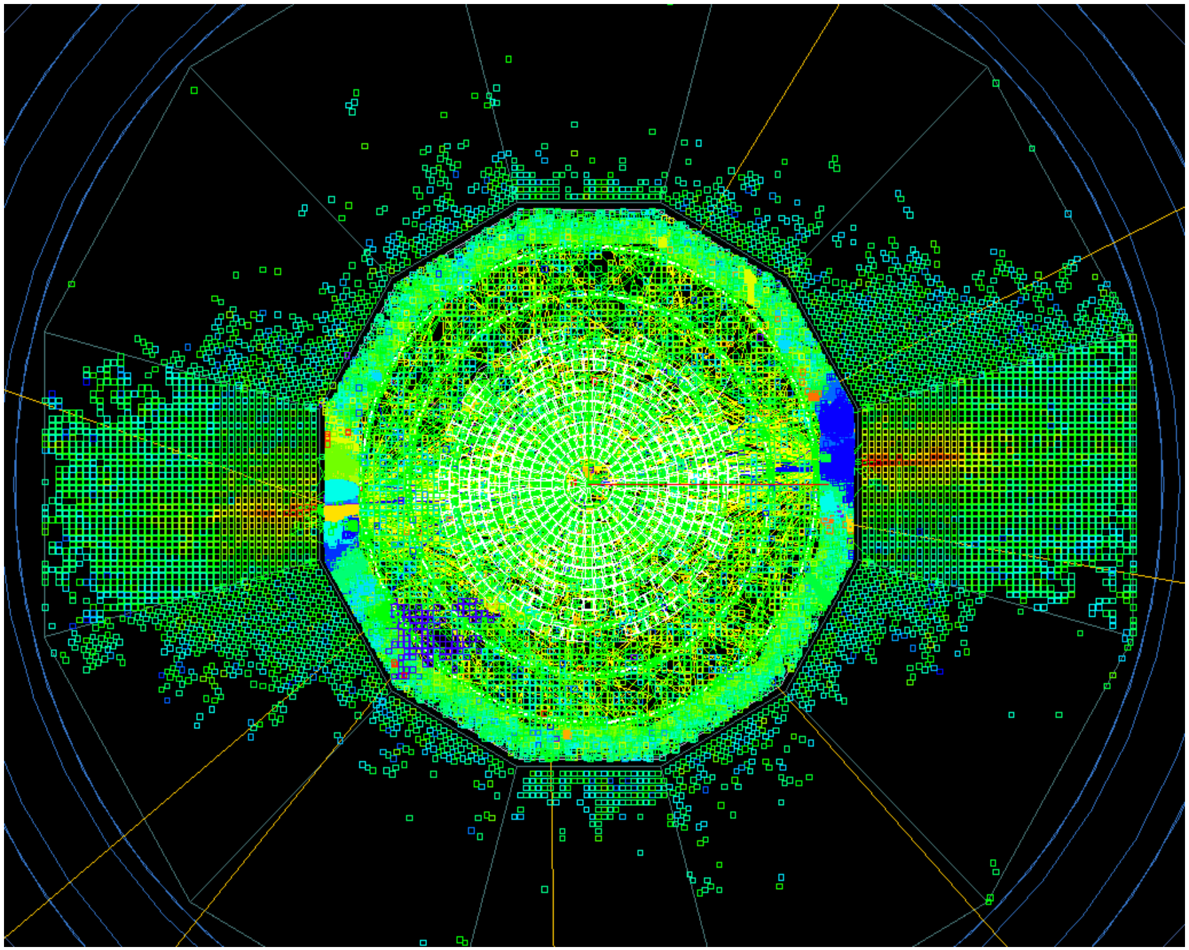
- Use substructure techniques to identify WW, $t\bar{t}$ and compare with $Z' \rightarrow q\bar{q}$

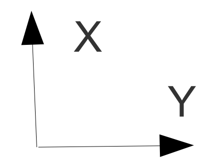
  - about 2000 fully reconstructed events per sample (Tracks, PFA, CaloClusters, HITS)
  - created on Open-Science Grid (UChicago/ANL. ~100,000 CPU*h)
  - Find: http://atlaswww.hep.anl.gov/hepsim/list.php?find=rfull006

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

SiFCC

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

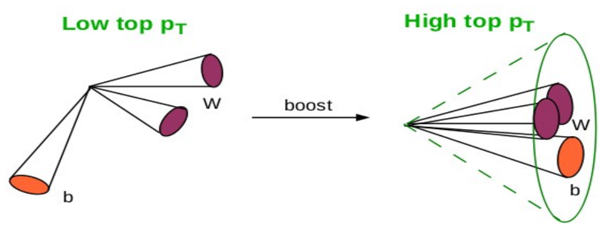


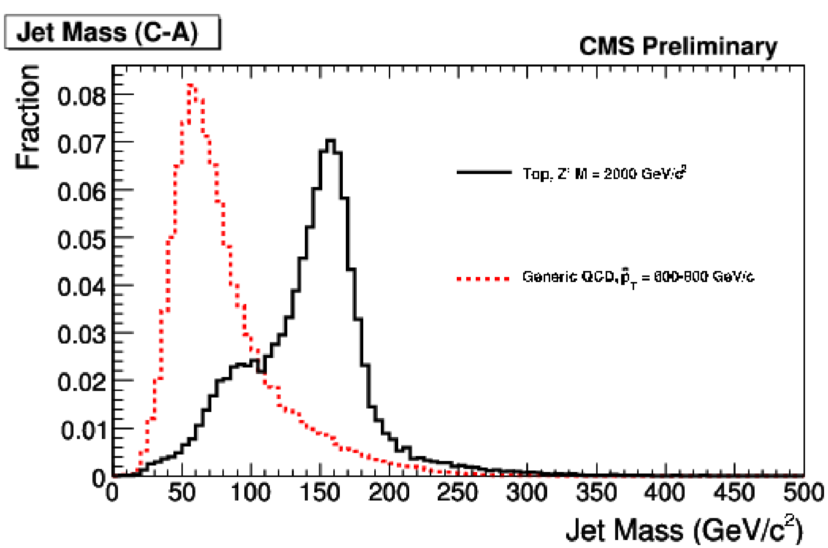


Jet masses for highly boosted jets

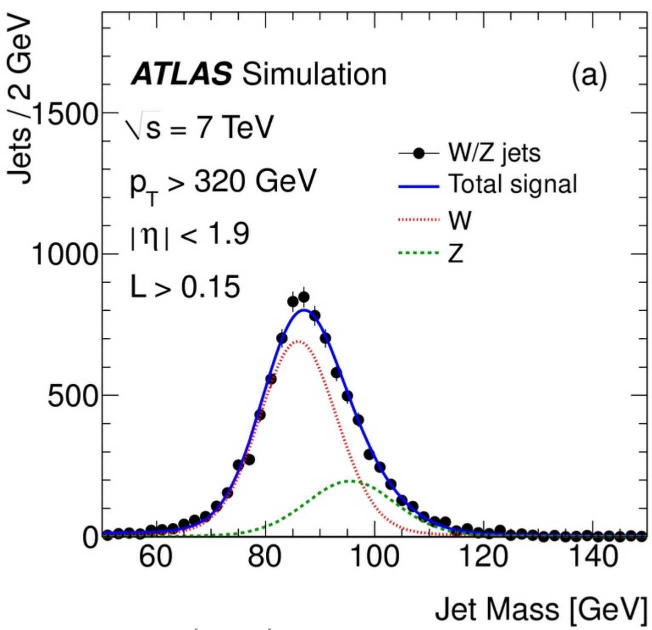
- Simple observable constructed from energies and positions of jet constituents
  - requires high spatial resolution of jet constituents
  - sensitive to calorimeter granularity
- Critical for many searches by ATLAS & CMS
  - signal extraction, background rejection etc: boosted W, top, Higgs etc.

$$m^2(jet)=\sum E_i^2-\sum \mathbf{p}_i^2$$





$W \rightarrow q\bar{q} \rightarrow$ jet



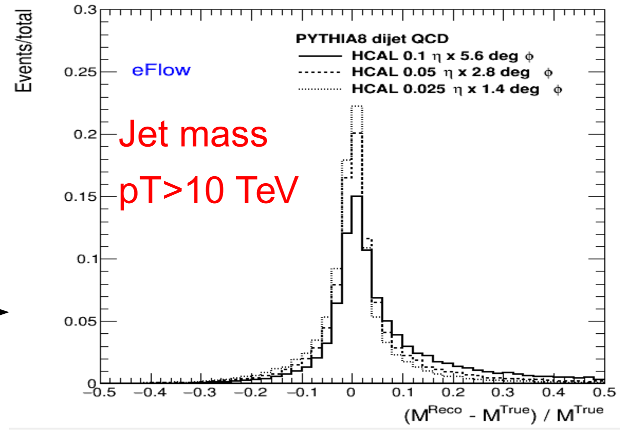
Geant4 simulations of boosted particles for a FCC-hh detector.

Jet masses in fast simulation

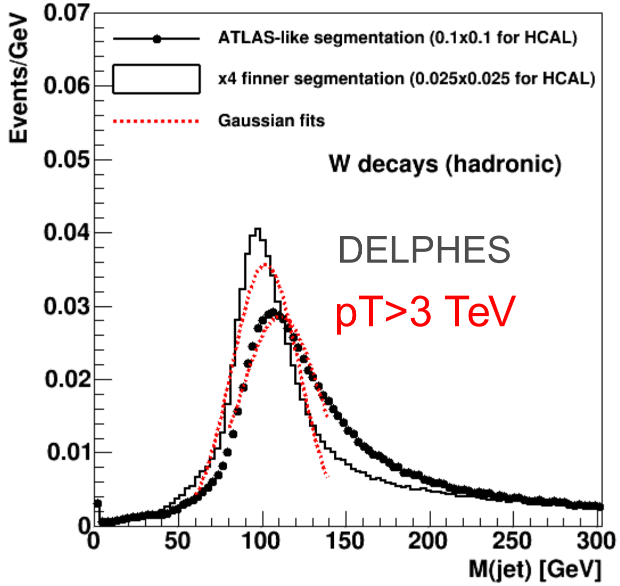
presented at Boost2015 & FCC week in DC

- DELPHES shows significant improvement in mass resolution compared to $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ cells
  - 80% for $\Delta\eta \times \Delta\varphi = 0.05 \times 0.05$
  - 120% $\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$

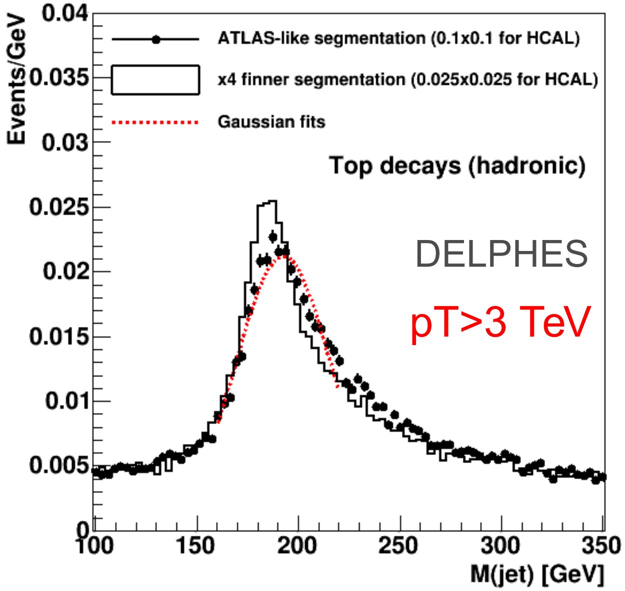
Delphes+HepSim



Boosted W



Boosted top



From the Gaussian fits:

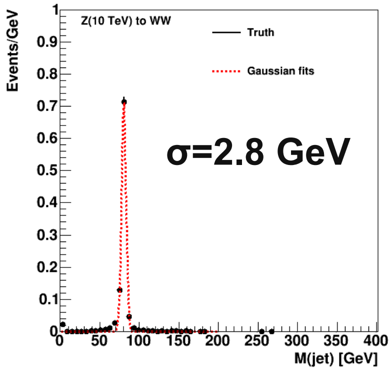
W mass:
σ = 23 GeV (0.1x0.1)
σ = 20 GeV (0.025x0.025)

Top mass:
σ = 24 GeV (0.1x0.1)
σ = 21 GeV (0.025x0.025)

Not too realistic:
no longitudinal segmentation, back-splash interactions, realistic Geant4 reconstruction, high-pT tracking loses etc. etc.

Jet mass for W → $q\bar{q}$ (boosted) in the *SiFCC* detector

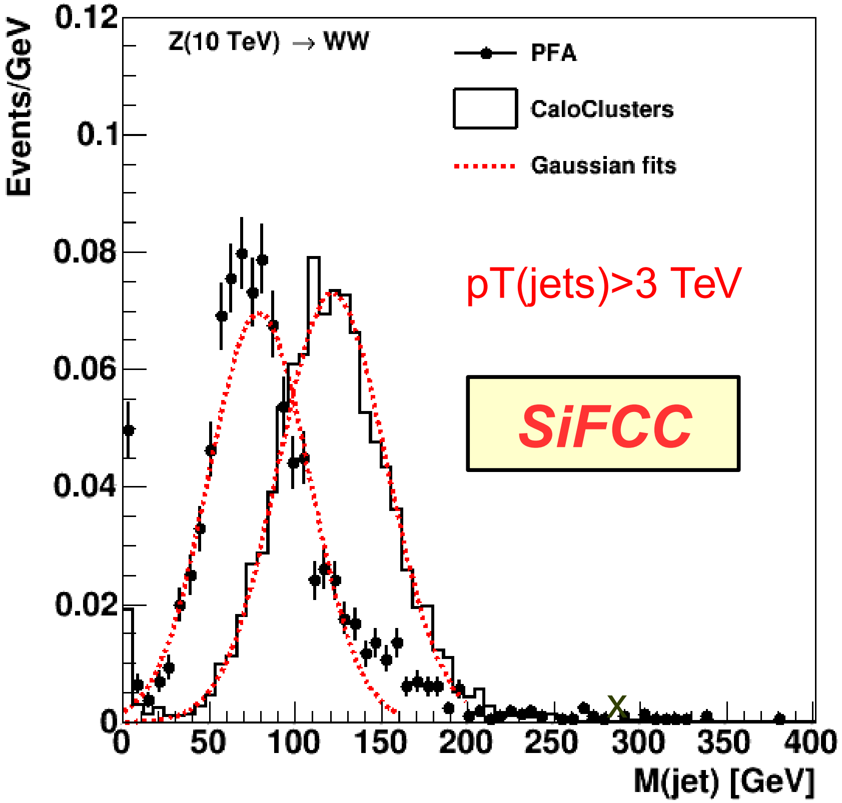
Z'(10) → W+W- → $q\bar{q}q\bar{q}$



Truth-level jets
FastJets R=0.6
pT(jet)> 3 TeV
|η(jet)|<1.2

SiFCC full simulation & reconstruction:

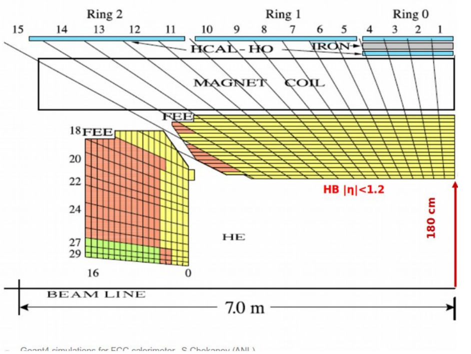
- PFA: σ=29 GeV, peak= 79 GeV
- CaloClusters: σ=31 GeV, peak=121 GeV



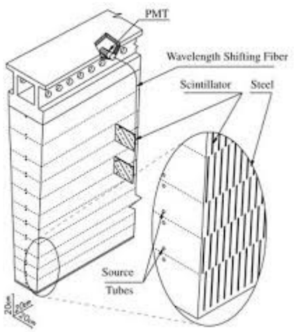
- PFA and CaloClusters have similar jet width (dominated by pT~ 5 TeV)
- Shift in jet mass for CaloClusters can be due to:
  - spread of charged particles in 5T field & back-splashes
  - removing soft constituencies (soft drop) reduces the the jet mass built from clusters
- SiFFC reconstructs larger jet width (~30 GeV) compared to DELPHES (~ 20 GeV)

Longitudinal segmentation

- **SiFCC HCAL has 64 longitudinal layers with independent readout: 2.75 cm steal (absorber), + 0.75 cm (Polystyrene,G10)**
  - optimized for large sampling fraction, 3D clusters, PFA etc
  - similar to CMS / ATLAS but SiFCC is non-projective



- **Another design option: ATLAS Tile: 3 longitudinal layers**
  - Scintillators are perpendicular to the Z
  - High granularity using SiPMT
  - Read each fiber separately (or in bundles)
  - See A.M.Henriques Correia's talk



- **ATLAS design can be verified by positioning scintillators perpendicular to the beam → Can be tested in future**

Summary

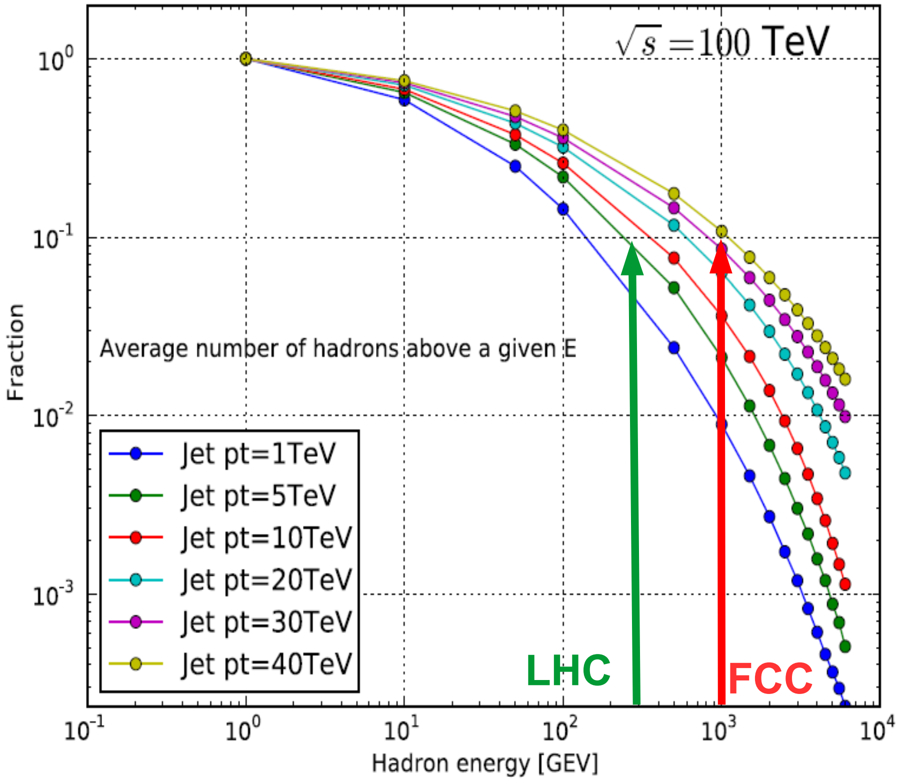
- **Compact SiFCC detector with a high-granularity calorimeter (>150 million cells) has been designed for performance studies**
  - FCC-hh baseline transverse segmentation and depths
- **Single particle studies:**
  - losses for low-energy clusters due to curved tracks (<2 GeV) in 5 T solenoid field
  - resolution of clusters ~2% for 8 TeV is better than for PFA / tracks (5%)
  - no significant leakage outside HCAL
- **First realistic physics processes for boosted topologies have been simulated and reconstructed → files publicly available from HepSim**
- **Realistic simulations of boosted Z' indicate:**
  - Larger jet width for boosted W compared to DELPHES fast simulations
  - Jet mass is shifted for CaloClusters. Larger spread of jet constituents
- **More geometries will be studied for different segmentation, numbers of layers, magnetic field etc..**
  - Additional physics studies are ongoing (exotic particles decaying to Higgs, tau etc.)

Backup

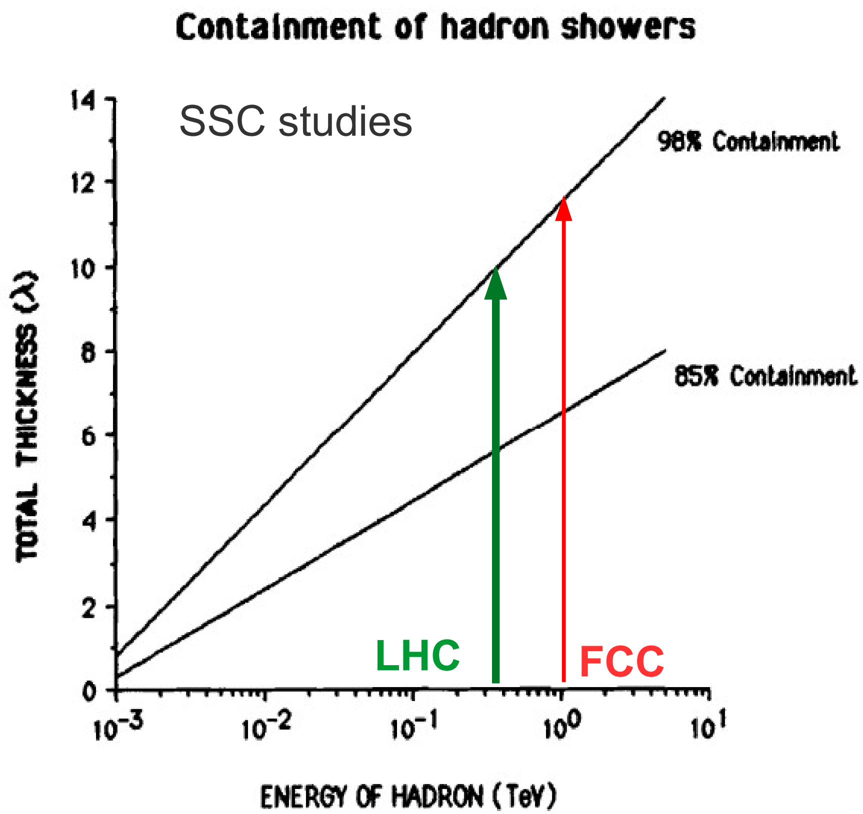
Estimating HCAL depth

Leading particles in high-pT jets

C.Helsens,C.Solans



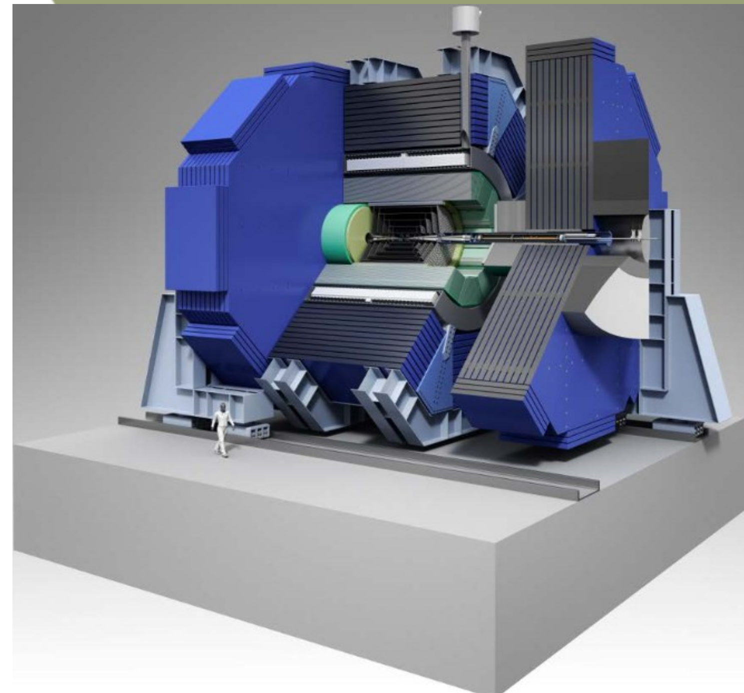
http://lss.fnal.gov/conf/C860623/p355.pdf

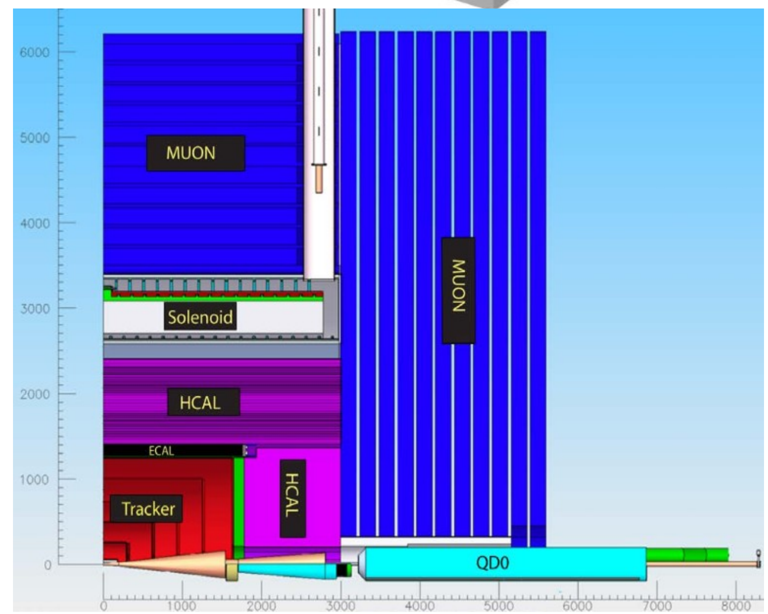


pT(jet)>30 TeV: ~10% will be carried by 1 TeV hadrons (~9 hadrons/jet)
12 λ_I is needed to contain 98% of energy of a 1 TeV hadron
Geant4 simulation agrees with calculations for SSC (.. 1984 Gordon&Grannis. Snowmass)

SiD detector for ILC

- Multi-purpose detector for the ILC
- The key characteristics of the SiD detector:
  - 5 Tesla solenoid
  - Silicon tracker: 50 um readout pitch
  - ECAL: (0.35 cm cell size, W / silicon)
  - HCAL:
    - 1x1 cm cell size (RPC)
    - 40 layers for barrel (HCAL) ~4.5 λ_I
- Optimized for particle-flow algorithms (PFA)
- Fully configurable using SLIC software



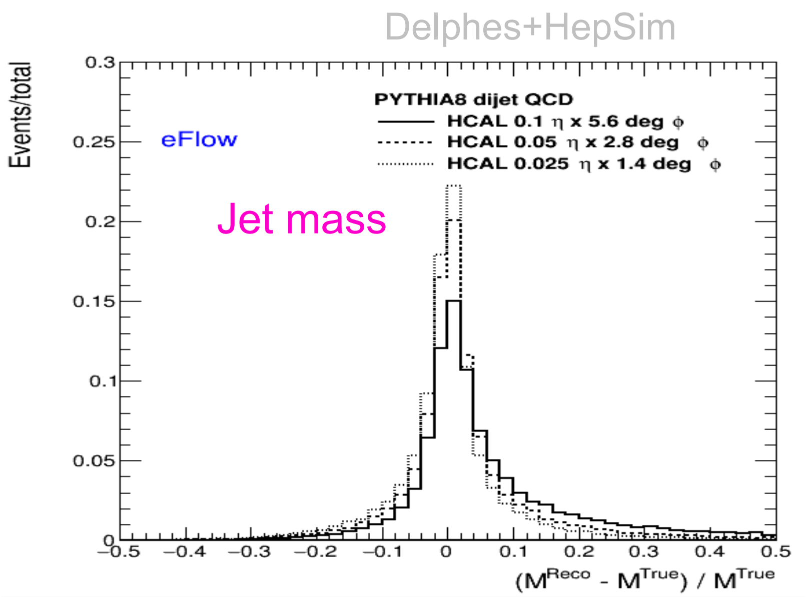


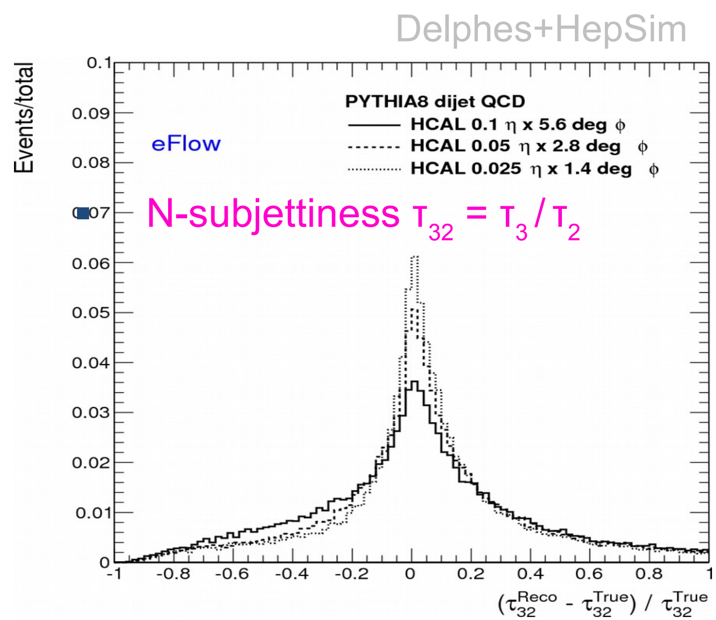
Leverage large investments to R&D and software designs

Re-purpose SLIC software for FCC-hh performance studies

Resolutions for substructure variables for pT(jet)>10 TeV (fast simulation)

Presented at
Boost2015. Chicago, Aug. 10-15, 2015





Decrease in RMS values compared to $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

	$\Delta\eta \times \Delta\varphi = 0.05 \times 0.05$	$\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$
tau21	18%	28%
tau32	9%	13%
jet mass	80%	120%

Large improvement in resolution for $\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$