

# Monte Carlo simulations for future collider studies

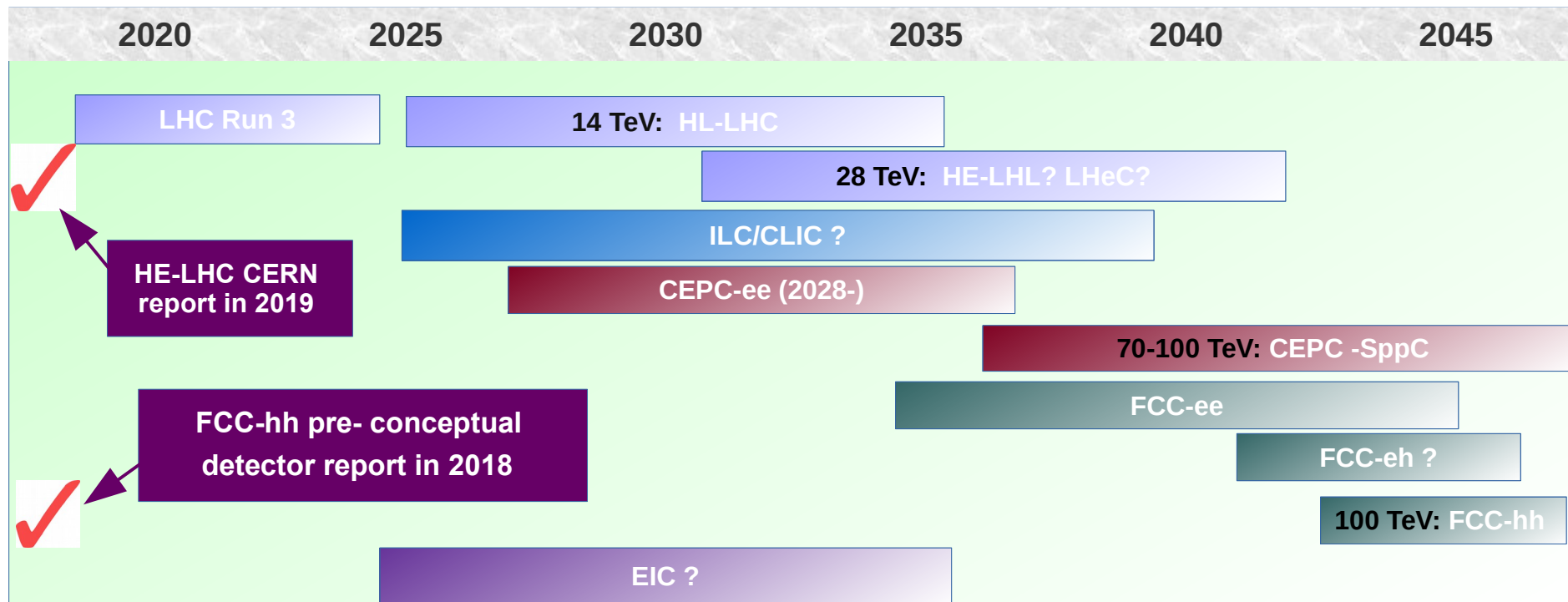
S. Chekanov  
+ contributors ([www link](#))

*HEP/ANL*

*Oct. 4, 2016*



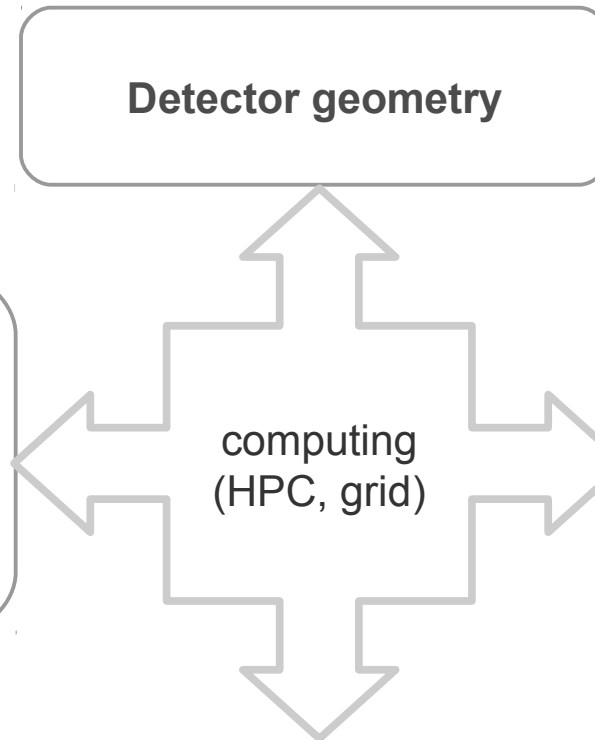
# Timeline of particle collision experiments



In the next decade we will deal with explorations of physics reach, detector parameters and new technology options for post-LHC era

**Requires detailed simulation of physics processes and detector responses**

# Simulations for particle-collision experiments



## Detector geometry

## Physics modeling

- Known particle properties & established Standard Model (SM)
- Event generators for Standard Model and beyond (LO, NLO, NNLO, NLO matched to NLO)

## Performance and physics analysis

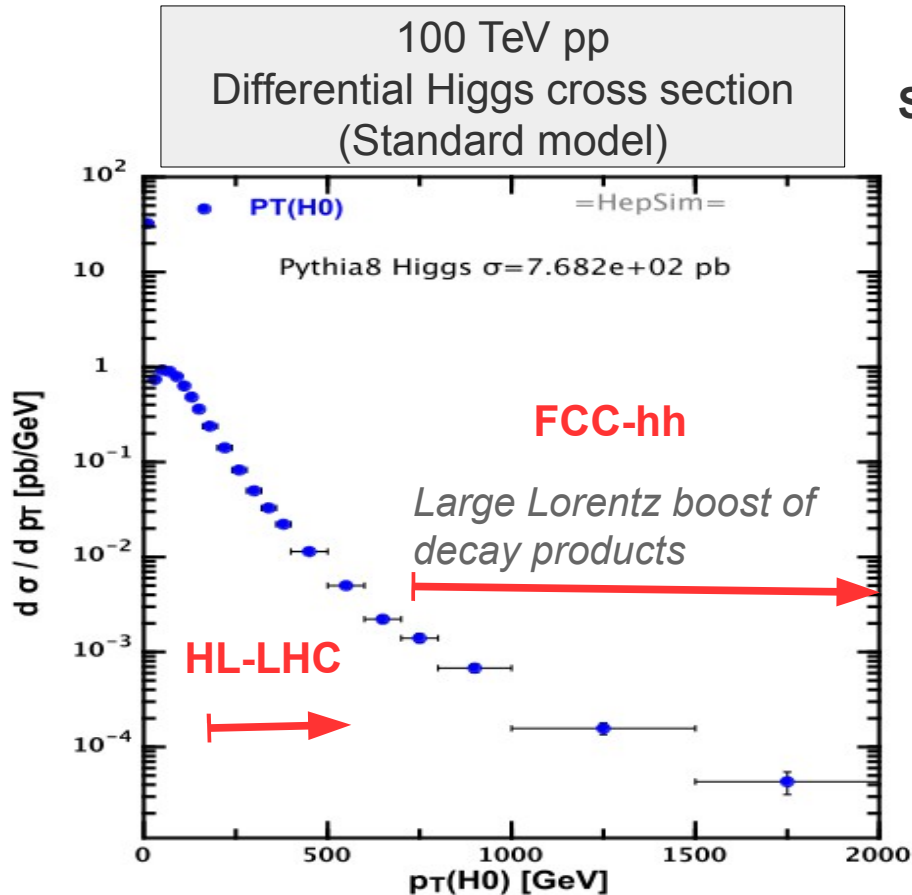
computing  
(HPC, grid)

## Simulation of detector response

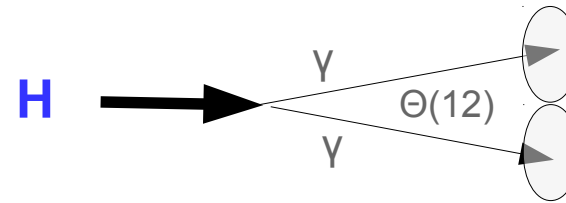
- Interactions of particles with detector material
- Many parametrized cross sections (when exact theory is unknown)
- Simulation packages (Geant4, etc.)

# Why do we need simulations? Higgs example

- 100 TeV collider will hunt for  $M \sim 30$  TeV particles decaying to Higgs/W/Z bosons
- Completely new kinematic regime  $\rightarrow$  very challenging for detector designs
- The detector must be optimized to reconstruct Higgs with  $p_T > 1$  TeV



SM predictions:  $\sim 100,000$  Higgs /  $ab^{-1}$  for  $p_T > 1$  TeV



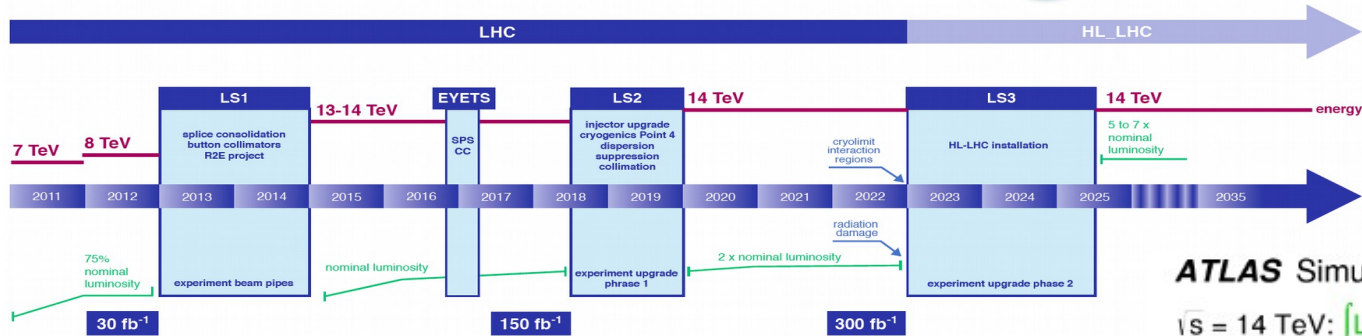
Just kinematics:

- $p_T(H) > 2$  TeV  $\rightarrow$   $\sim 5$  deg between  $\gamma$ 's
- $p_T(H) > 10$  TeV  $\rightarrow$   $\sim 1$  deg between  $\gamma$ 's

Instrumental challenges:

- identify 2 photons separated by 1 degree
- reject  $\pi^0 \rightarrow \gamma\gamma$  background at the same time!
- similar problems for electron, b-jets decays

## LHC / HL-LHC Plan

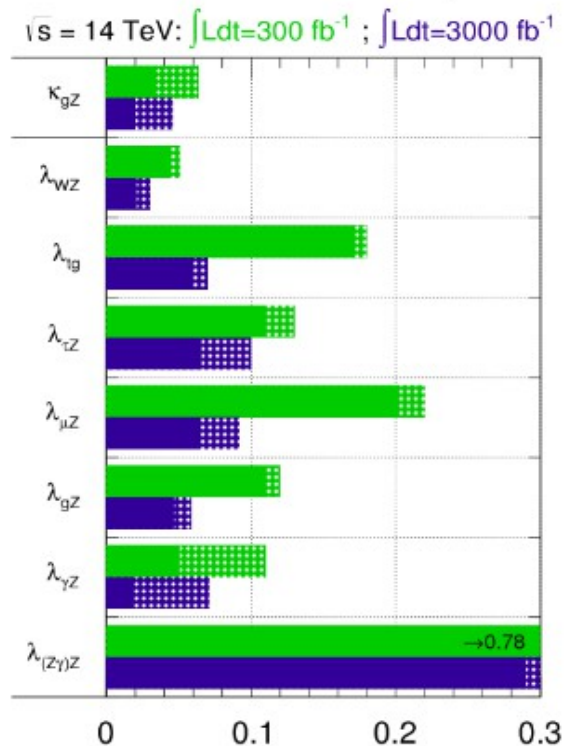


increase luminosity (rate of collisions) by a factor of 10 beyond the original design value of the LHC (from 300 to 3000 fb<sup>-1</sup>)

### Physics goals:

- Measure existing Higgs decays with better precision
- Rare Higgs decays ( $\mu+\mu^-$ ,  $Z-\gamma$ ,  $\phi$ ), double Higgs production
- Deviations from the SM & high-precision high-pT physics

### ATLAS Simulation Preliminary

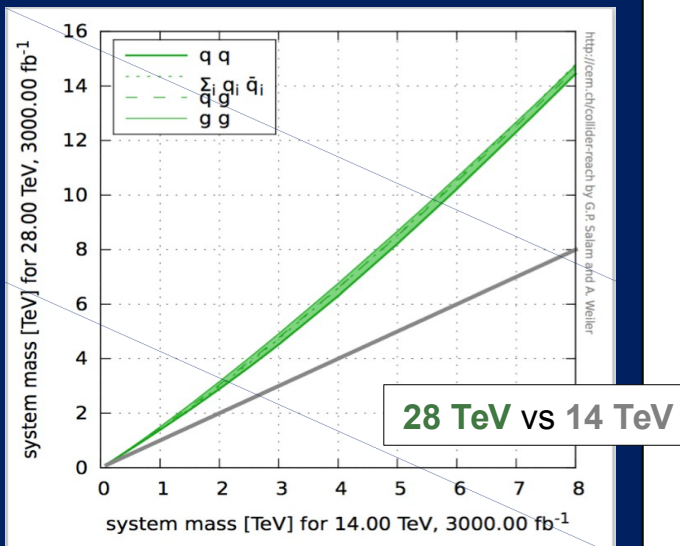
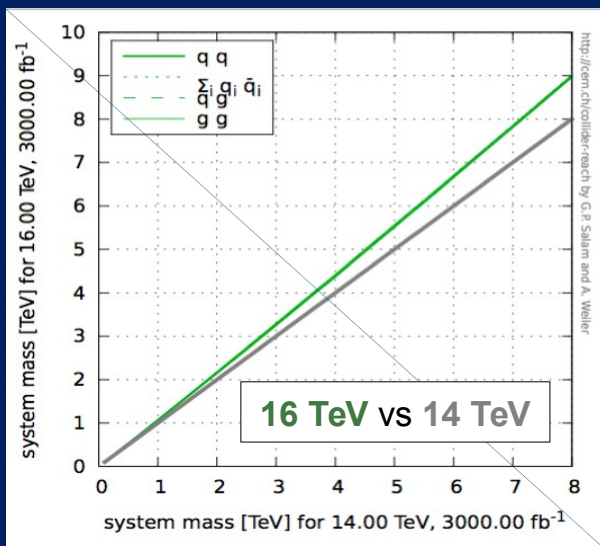


$$\Delta \lambda_{XY} = \Delta \left( \frac{\kappa_X}{\kappa_Y} \right)$$



# High-energy LHC (HE-LHC)

F. Gianotti  
+ CERN management



*Milestone:  
update of European  
Strategy for Particle  
Physics (~ 2019-2020)*

## WG set up to explore technical feasibility of pushing LHC energy to:

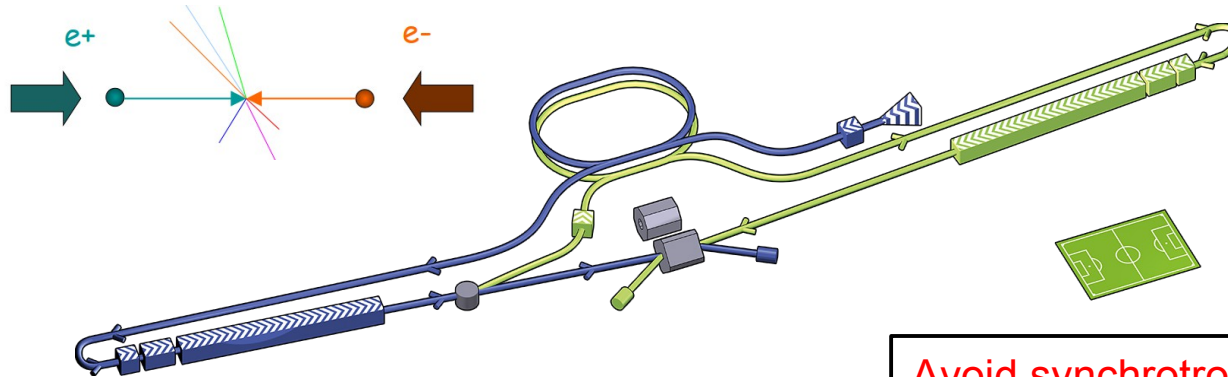
- design value: 14 TeV
- 15 TeV (dipole field of ~9.5 T) beyond (e.g. by replacing dipoles with 11 T Nb<sub>3</sub>Sn magnets)
- Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability

Report on 1) end 2016, 2) end 2017, 3) end 2018 (in time for ES)

**HE-LHC** (part of FCC study): ~16 T magnets in LHC tunnel ( $\sqrt{s}$ ~28 TeV)

- strong physics case if new physics from LHC/HL-LHC
- powerful demonstration of the FCC-hh magnet technology
- uses existing tunnel and infrastructure; can be built at constant budget

# International Linear Collider (ILC) and Compact Linear Collider (CLIC)



Avoid synchrotron radiation  $\sim E^4 / m^3$

## Advantages over proton-proton collisions:

simple initial state ( $e^+e^-$ ), variable energies, momentum conservation, democratic production of particles

- High-precision measurements at  $e^+e^-$
- Most mature post-LHC era experiment
- ILC: CM energy 500 GeV-1000 GeV
- CLIC: CM energy up to 3000 GeV
- → Interest expressed in Japan in hosting the ILC (~50% contribution)
- → CLIC is considered by CERN (but less advanced)

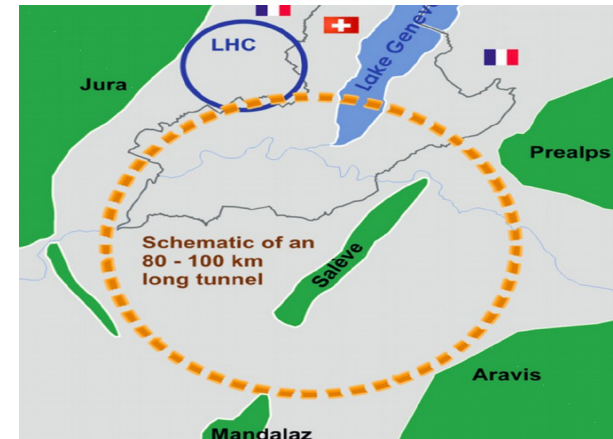




# Precision electroweak measurements

## FCC-ee (formerly known as TLEP)

- e+e- circular collider envisioned in a new 80-100 km tunnel in the Geneva area
- centre-of-mass energy from 90 to 400 GeV
- Key features:
  - $\Delta M(t) < 10 \text{ MeV}$
  - $\Delta M(W) < 0.3 \text{ MeV}$
  - $\Delta M \alpha_{\text{QED}} < 10^{-5}$
  - $\Delta M \alpha_s(Z) < 0.0001$
- Conceptual Design Report (CDR) by 2018



## Circular Electron Positron Collider (CEPC)

- e+e- circular “Higgs factory” planned in China
- 240-350 CM energy + higher luminosity ( $250 \text{ fb}^{-1} / \text{year}$ )
- Pre-CDR is ready
- Construction: 2021 – 2027. Data taking: 2028-2038

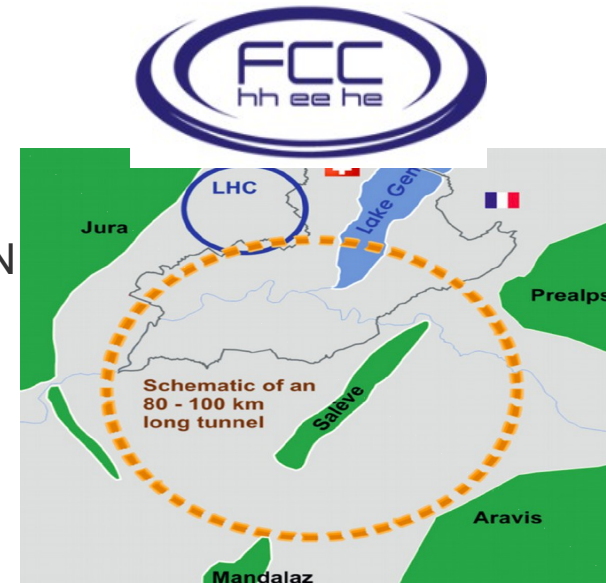




# Discovery machines & energy frontier

## FCC-hh (CERN) ~ 2040

- Proton-Proton collisions at 100 TeV in the Geneva area
- part of the Future Circular Collider design study (FCC) at CERN
- Physics reach: ~30 TeV for production of new heavy particles
- Peak luminosity  $\leq 30 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ , 25(5) ns, pileup 1020(204)
- Many challenges for the detector!
- Conceptual Design Report (CDR) by 2018



## Super Proton-Proton Collider (SppC)

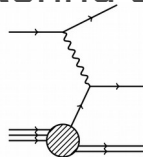
- Proton-proton collisions at 70 TeV in the same tunnel as CEPC
- Physics reach: ~ 25 TeV for masses of new particles
- Construction: **2035-2042**. Data taking: **2042-2055**



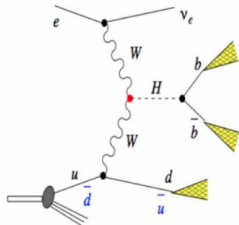
# Energy frontier + intensity frontier: LHeC, FCC-ep (CERN), Electron-ion collider (EIC)

- **LHeC:** 7 GeV proton collided with 20-60 GeV electron ( $s^{1/2} = 1.3$  TeV)
- **HE-LHC:** 15 TeV proton collided with 60 GeV electrons ( $s^{1/2} = 1.9$  TeV)
- **FCC-ep:** 50 GeV proton collided with > 20 GeV electron ( $s^{1/2} = 3.5$  TeV)
- **EIC** – electron-ion collider JLab/BNL: low energy electrons with ions ( $s^{1/2} < 0.14$  TeV)
  - tomography with resolution  $\sim 1/10$  fb, “sweet” spot for reach QCD dynamics

Deep inelastic scattering at the energy frontier

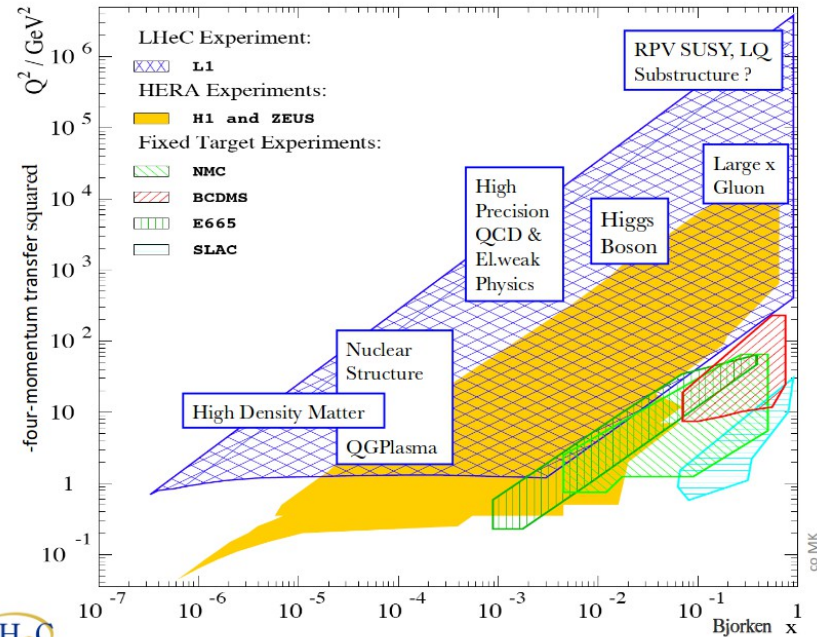


Turn LHC to precision Higgs factory  
→ H ( $\sim 200$  fb $^{-1}$  for LHeC)



→ Studies of gluon density at large x

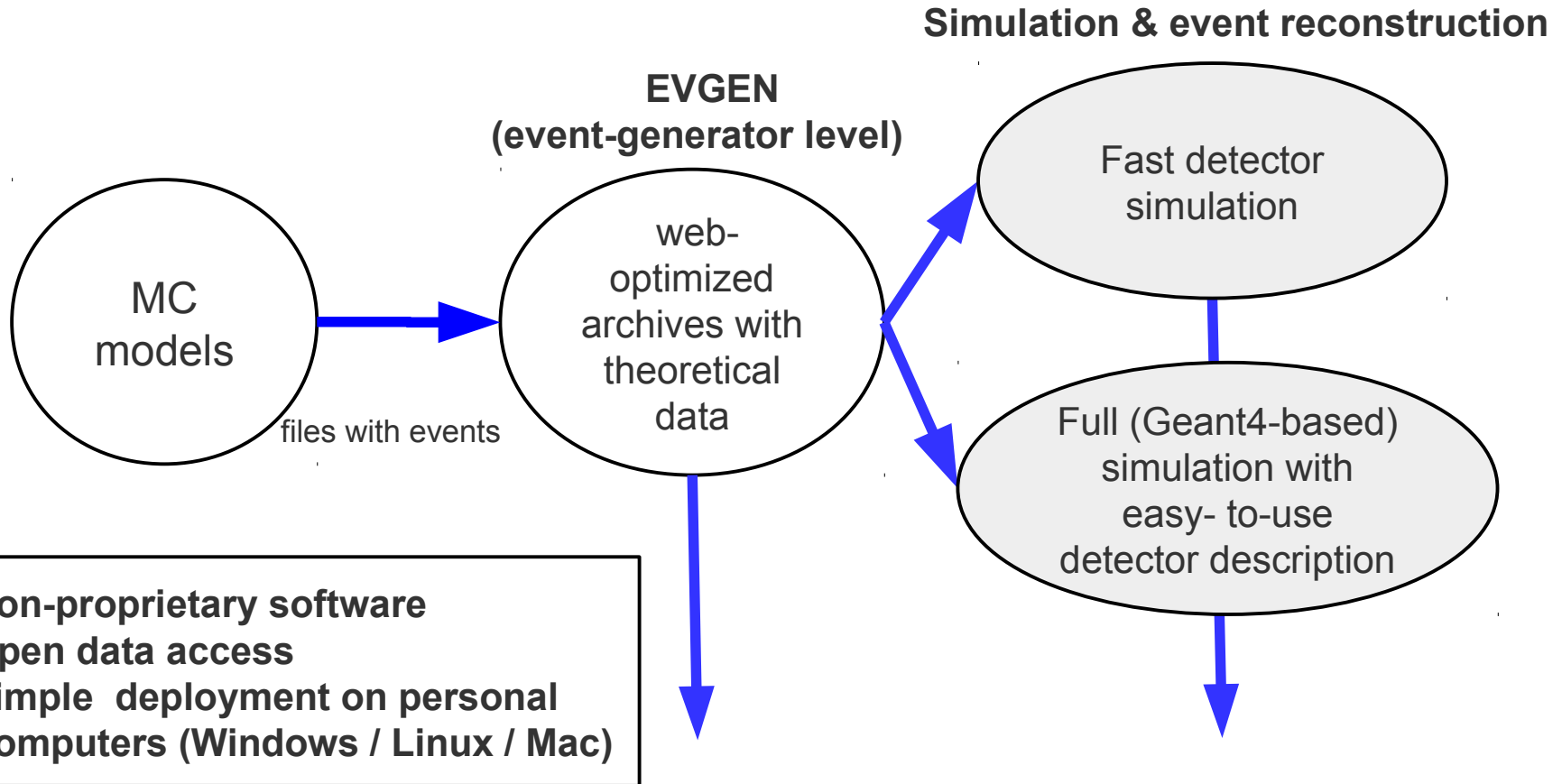
V



LHeC

# Next step after Snowmass 2013:

Public Repository with Fast and Full Monte Carlo simulations



**OPEN ACCESS** <http://>

**Long-term availability & preservation**

# Long-term preservation of theoretical calculations

- Storing Monte Carlo predictions in files makes sense if:

$$\frac{\text{time to download \& analyze on commodity computer}}{\text{CPU*h needed to create the prediction}} \equiv \varepsilon \ll 1$$

$\varepsilon \sim 0.01-1$	- for LO MC
$\varepsilon \ll 0.01$	- for NLO etc.

- $\varepsilon \ll 1$ :
  - Madgraph5 etc. (NLO+PS+hadronisation), ALPGEN
  - Some fast-converging NLO calculations (MCFM, jetPHOX etc)
  - MC with  $\varepsilon \sim 1$  but after mixing with pile-up (CPU intensive)
- $\varepsilon \sim 1$ : Less appropriate approach for:
  - LO simulations (Pythia)
  - Some NLO programs with slow convergence
    - requires too large data volumes to keep weighted events

# New data format for EVGEN: ProMC

S.C., E.May, K. Strand, P. Van Gemmeren, Comp. Physics Comm. 185 (2014), 2629

- “Archive” self-described format to keep MC events:
  - Event records, NLO, original logfiles, PDG tables etc.
- 30% smaller files than existing formats after compression

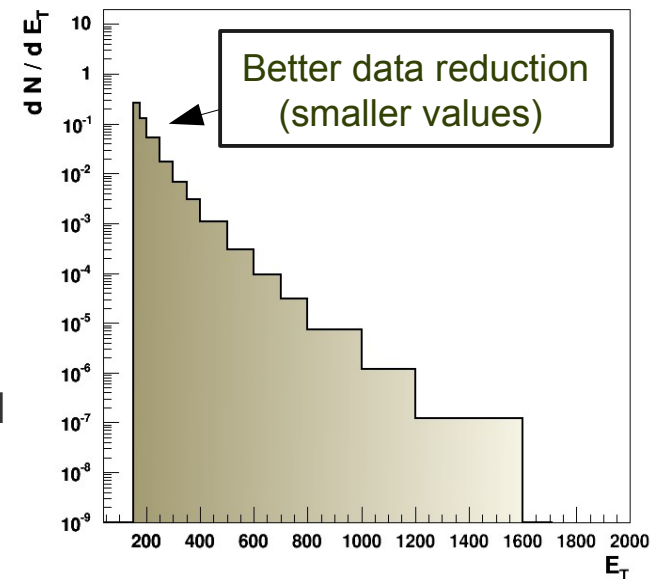
Number of used bytes depends on values.  
Small values use small number of bytes

Google's Protocol buffers  **protobuf**  
Protocol Buffers - Google's data interchange format

- Effective file-size reduction for pile-up events
  - Particles with small momenta → small nr of bytes used
- Installed on HPC (Mira / BlueGene/Q)
- Separate events can be streamed over the Internet:
  - similar to avi frames for web video players

<http://atlaswww.hep.anl.gov/asc/promc/>

8-bytes → varint



compression strength keeping  
precision of representation  
constant

# HepSim event simulations

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

NERSC, CERN mirrors

**HepSim**  
Repository with Monte Carlo predictions for HEP experiments

Get Involved Full Search Manual About Mirrors Login

HEP.ANL.GOV

Show all

$p \rightarrow p$

- 8 TeV
- 13 TeV
- 14 TeV
- 100 TeV

$e^+ \rightarrow e^-$

- 250 GeV
- 500 GeV
- 1 TeV

$\mu^+ \rightarrow \mu^-$

- 1 TeV
- 5 TeV
- 10 TeV
- 20 TeV
- 40 TeV

$e^- \rightarrow p$

- 318 GeV
- 141 GeV

Misc.

- 1 particle
- 2 particles
- 1 jet

Show 25 entries

Id	Process	E [TeV]	Name	Generator	Process	Topic	Info	Link	Created
1	pp	100		PYTHIA8	Higgs production	Higgs	Info	URL	2016/01/07
2	pp	100	ng5	MADGRAPH/HW6	Higgs+ttbar (NLO+PS)	Higgs	Info	URL	2015/11/13
5	pp	8		FPMC	Exclusive WW production	SM	Info	URL	2015/03/23
6	pp	8		HERWIG++	Direct photons	SM	Info	URL	2015/04/11
7	pp	100	tev100_qcd_herwigpp_pt2700	HERWIG++	QCD dijets, pT>2700 GeV	SM	Info	URL	2015/04/11
10	pp	100	pythia8	PYTHIA8	KKgluon to ttbar M=1-20 TeV	Exotic	Info	URL	2015/03/23
11	pp	100	tev100_qcd_pythia8_pt300	PYTHIA8	QCD dijets, pT>300 GeV	SM	Info	URL	2015/04/10
12	pp	100	tev100_qcd_pythia8_pt900	PYTHIA8	QCD dijets, pT>900 GeV	SM	Info	URL	2015/10/03
13	pp	100	tev100_qcd_pythia8_pt2700	PYTHIA8	QCD dijets, pT>2700 GeV	SM	Info	URL	2016/01/07
14	pp	100	tev100_qcd_pythia8_pt8000	PYTHIA8	QCD dijets, pT>8 TeV	SM	Info	URL	2015/10/21
15	pp	100		MADGRAPH/HW6	pp->ttbar at NLO	Top	Info	URL	2015/11/13
16	pp	100	ng5_lo	MADGRAPH/HW6	pp->ttbar, pT>2500 GeV	Top	Info	URL	2015/04/10

Feb.5, 2016: Single particles for ITK studies (ATLAS phase II upgrade) (link)  
Feb.1, 2016: Z' with M=10,20,40 TeV decaying to qqbar, ttbar, WW for full simulations (link)  
Jan.19, 2016: 10 TeV Z' using a full simulation with 40 and 64 HCAL layers (link)

Previous 1 2 3 4 5 ... 8 Next Search:

LHC run 1/2

HL-LHC

SPPC, FCC-hh

ILC, CEPC

samples for detector performance studies

Available: EVGEN files (LO,NLO, etc), fast simulations, full Geant4 simulations



# Dataset entry:

**$e^+e^-$  collisions (CM energy = 250 GeV).  $Z \rightarrow e^+e^-$**

$p \rightarrow \bar{p}$
8 TeV
13 TeV
14 TeV
100 TeV

$e^+ \rightarrow e^-$
250 GeV
500 GeV
1 TeV

$\mu^+ \rightarrow \mu^-$
1 TeV
5 TeV
10 TeV
20 TeV
40 TeV

$e^- \rightarrow \bar{p}$
318 GeV
141 GeV

Misc.
1 particle
2 particles
1 jet

Repository with Monte Carlo predictions for HEP experiments

Sep.15, 2016: Z'(5 TeV) to diffe  
Aug.28, 2016: rfull010, rfull01

## Information about "gev250ee\_pythia6\_zpole\_ee" dataset

Name: [gev250ee\\_pythia6\\_zpole\\_ee](#)  
Collisions:  $e^+e^-$   
CM Energy: 0.25 TeV  
Entry ID: 146  
Topic: SM  
Generator: [PYTHIA6](#)  
Calculation level: LO+PS+hadronisation  
Process: Z boson to  $e^+e^-$   
Total events: 2000000  
Number of files: 100  
Cross section ( $\sigma$ ):  $1.7765 \pm 0.0126$  pb  
Luminosity (L):  $1.126E+06$  pb $^{-1}$  (or)  $1125.7948$  fb $^{-1}$  (or)  $1.1258$  ab $^{-1}$   
Format: ProMC  
Download URL: [http://mc.hep.anl.gov/asc/hepsim/events/ee/250gev/pythia6\\_zpole\\_ee](http://mc.hep.anl.gov/asc/hepsim/events/ee/250gev/pythia6_zpole_ee)  
Status: Available  
Mirrors: [http://portal.nersc.gov/project/m1758/data/events/ee/250gev/pythia6\\_zpole\\_ee](http://portal.nersc.gov/project/m1758/data/events/ee/250gev/pythia6_zpole_ee)  
EVGEN size: 0.826 GB

Fast simulation: [rfast001 \(info\)](#)  
100 / 1.75 GB  
10/13/2015

Full simulation: [rfull002 \(info\)](#)  
16 / 1.27 GB  
11/20/2015

[rfull001 \(info\)](#)  
15 / 1.18 GB  
10/17/2015

Fast/Full size: 4.20 GB  
Record slimmed: No  
Events weighted: No  
Submission time: Tue Oct 13 14:28:55 CDT 2015  
Updated on:

User description: PYTHIA version 6.4. Z production (Zpole) with decays to  $e^+e^-$ . Other de

**ProMC version: 4; Nr events: 1000; Varint E: 1000000; Varint L:**  
logfile.txt; **Last modified:** 2015-10-15 20:31:08; **Settings:** PYTHIA-6  
mix events; NTOT 0 0 1000 ! Number of events; ECME 0 0 250.0 ! CM e  
0 0 839264 ! random seed; MSEL 0 0 0 ! all mixed events; PMAS 6 1 17  
91.1876 ! Z boson mass; PMAS 24 1 80.3850 ! W boson mass; PMAS 25  
mass; MSUB 1 0 1 ! ffbar to Z; MSTP 43 0 2 ! Z only, no gamma; MDME  
MDME 175 1 0 ! U U~; MDME 176 1 0 ! S S~; MDME 177 1 0 ! C C~; M  
B~; MDME 179 1 0 ! T T~; MDME 182 1 1 ! E- E+; MDME 183 1 0 ! NU\_E  
1 0 ! MU+ MU-; MDME 185 1 0 ! NU\_MU+ NU\_MU-; MDME 186 1 0 ! TAU-  
1 0 ! NU\_TAU- NU\_TAU+; PARJ 71 0 10 ! ctau=10mm; MSTJ 22 0 2 !;

File metadata:

Validation:

Nr	Analysis code	Output plot (SVG)	(XML)
1	<a href="#">pythia6_zpole_ee.py</a> <a href="#">Launch</a> <a href="#">i</a> Desktop: <a href="#">hs-ide [URL]</a>		JDAT file

URL for EVGEN files  
(download or streaming)

Reconstruction tags  
with fast (DELPHES)  
or Geant4 (SLIC) simulations

Validation distributions created  
using Python scripts on the  
Java platform

Run via JavaWeb start by  
streaming data over the Web

# HepSim repository. How it works

large-scale computing resources

## Event Generators

PYTHIA6

PYTHIA8

HERWIG++

Madgraph5

MCFM

JetPhox

FPMC

NLOjet++

LEPTO/Ariadne

.....



EVGEN

fast

Delphes fast simulation  
(ROOT files)

full

SLIC (Geant4) full simulation  
and reconstruction software  
(LCIO files)

ProMC files on  
several public web  
servers

**HepSim**

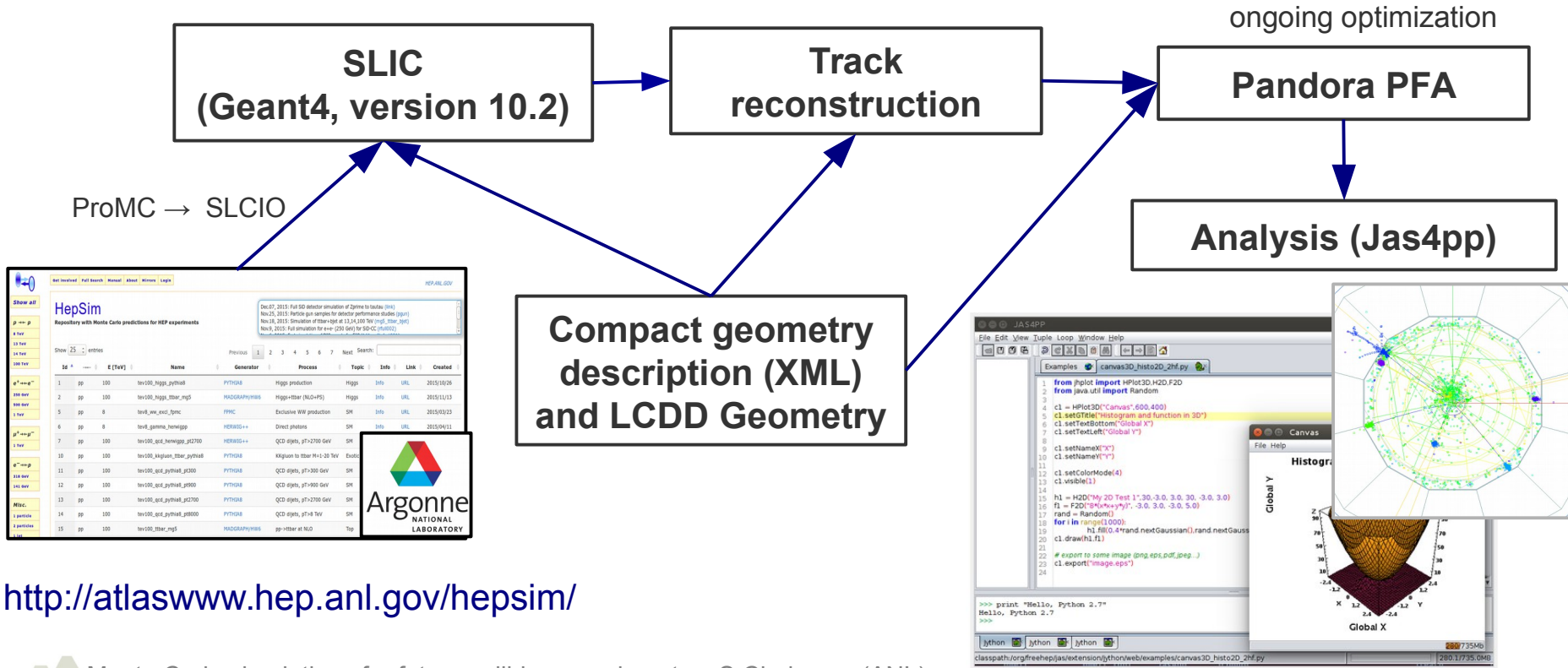
- index files
- create metadata
- prepare for batch download
- validate with Jython scripts
- create search database



# HepSim software for full simulations

## Simulator for the Linear Collider (SLIC) software:

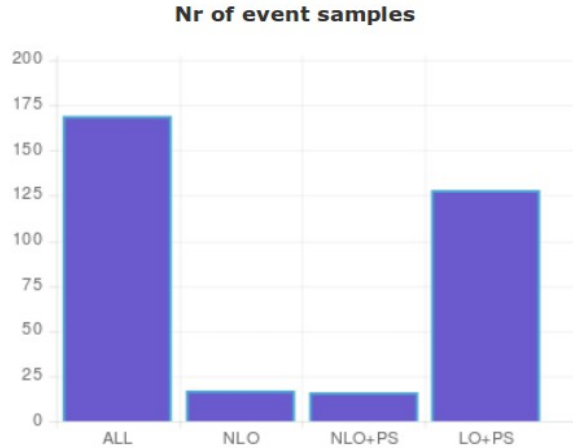
- Optimized for the SiD detector at SLAC (T.Johnson, N.Graf, J.McCormick, J.Strube)
- Re-purposed for future pp collider studies (S.C., A.Kotwal, J.Strube, J.Marshall)
  - *Geant4 10.2, implemented Fast PandoraPFA*
  - *Integrated with HepSim ProMC EVGEN files*
  - *Deployed on Open-Science Grid (OSG)*
  - *Analysis: C++/Root or Jas4pp (ANL,S.C,E.May). Based on Jas3 (SLAC)*



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

# HepSim event statistics

(excluding fast and Geant4 detector simulations)



~210 Monte Carlo samples

~1.6 billion EVGEN events

~ 10% after fast simulations(Delphes)

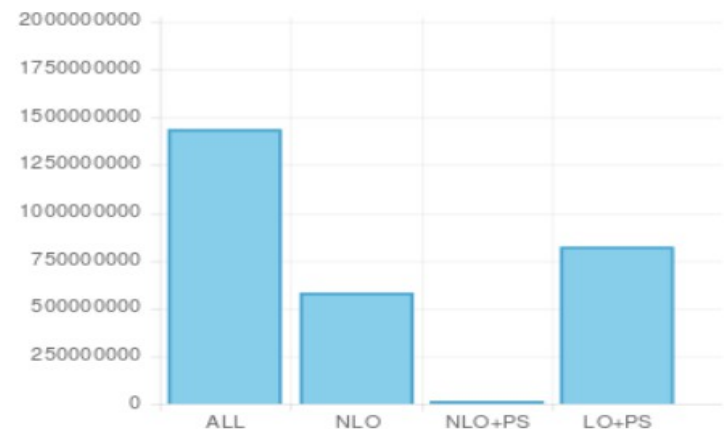
~ 0.1% after Geant4 simulations

Number of public file servers	3
Number of event samples	208
Number of NLO samples	17
Number of NLO+PS samples	17
Number of LO (+PS) samples	144
Number of events	1560741507
NLO events	583000000
NLO+PS events	32860595
LO (+PS) events	859498212
Total size (GB)	6897.468
NLO size (GB)	238.06
NLO+PS size (GB)	348.693
LO (+PS) size (GB)	6292.482
Number of files	334606

## Platforms for event generations (EVGEN)

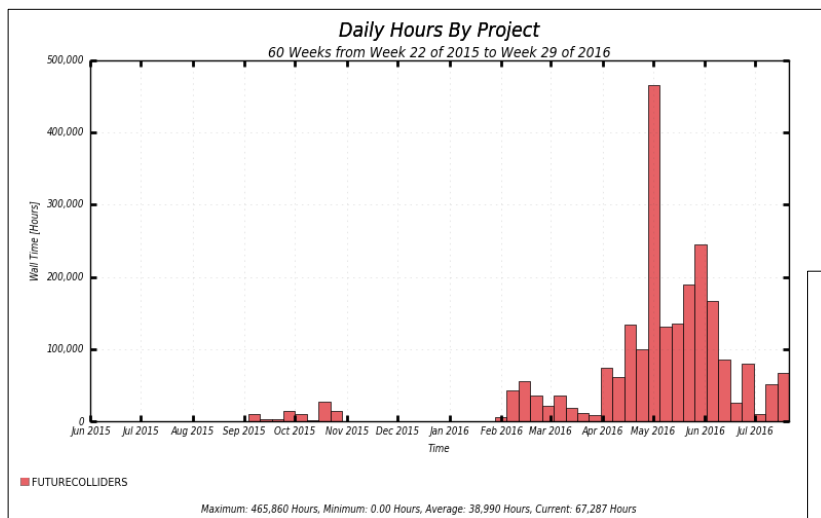
- 10% → BlueGene/Q (ANL/Mira) (Jetphox, MCFM)
- 50% → HEP-ANL (mainly Madgraph)
- 40% → OSG-CI grid and USATLAS CI (for phase II)

Nr of simulated events

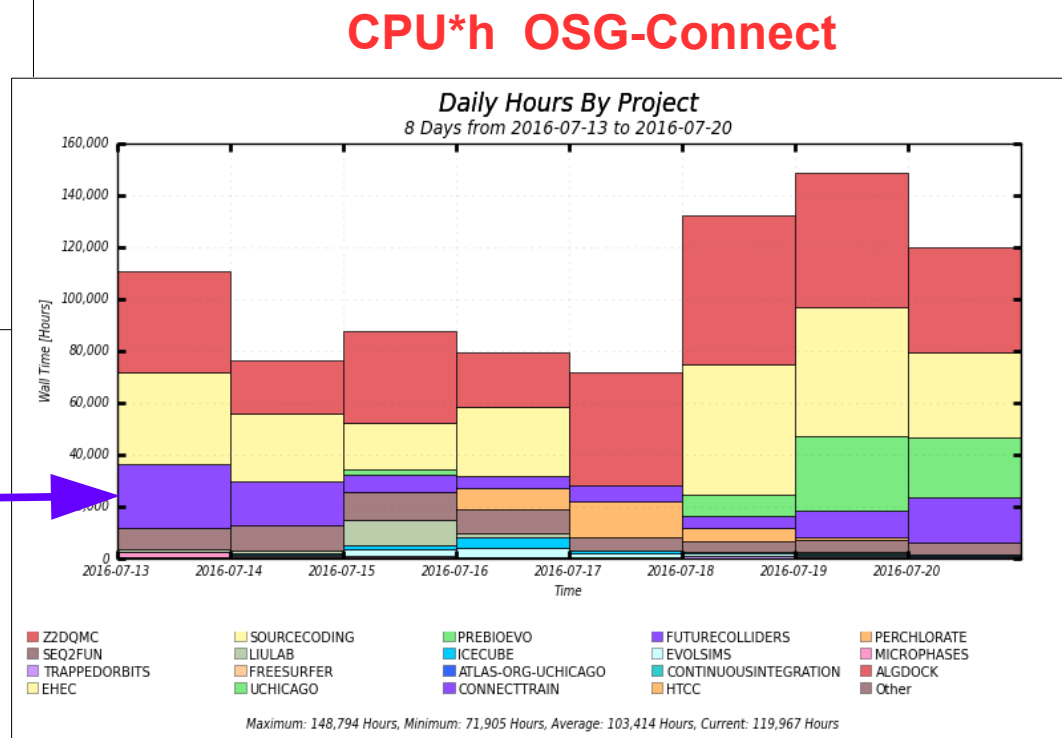


# CPU usage for SLIC (Geant4) simulations

## OSG-Connect "FutureColliders" project for HepSim jobs



HepSim simulations  
(SLIC/Geant4)  
~ 16 GB RAM per job

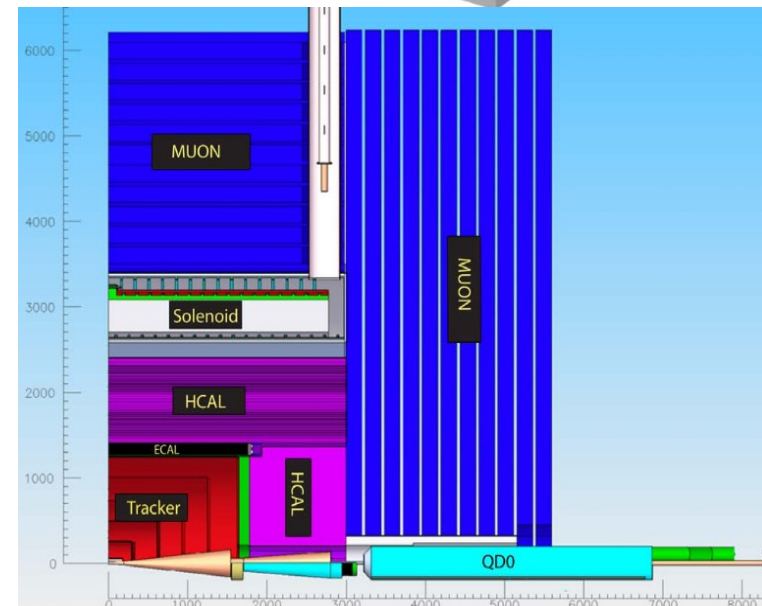
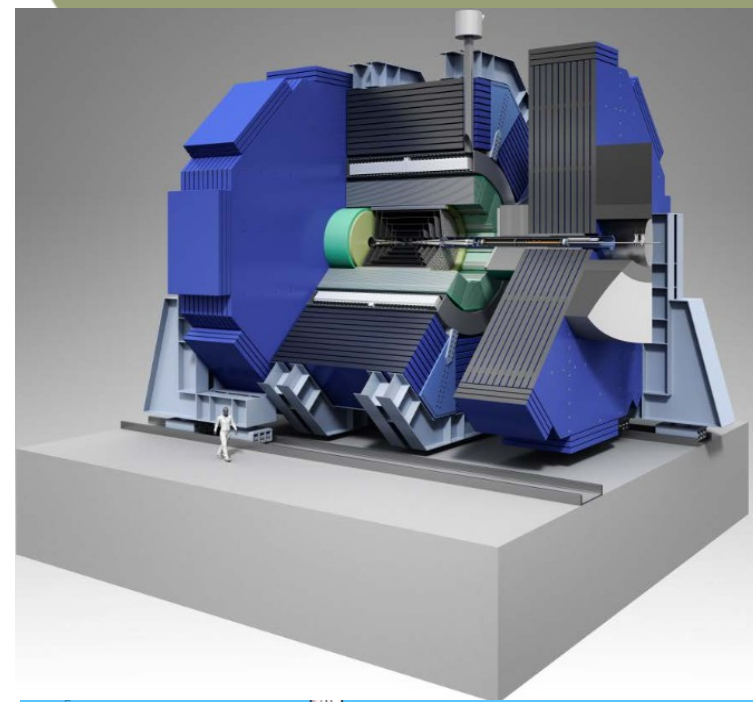


2.5 million CPU\*h in 2016 using OSG-grid for Geant4 simulations  
(equivalent to ~10 million CPU\*h on HPC BlueGene/Q Mira)

# SiD detector for ILC



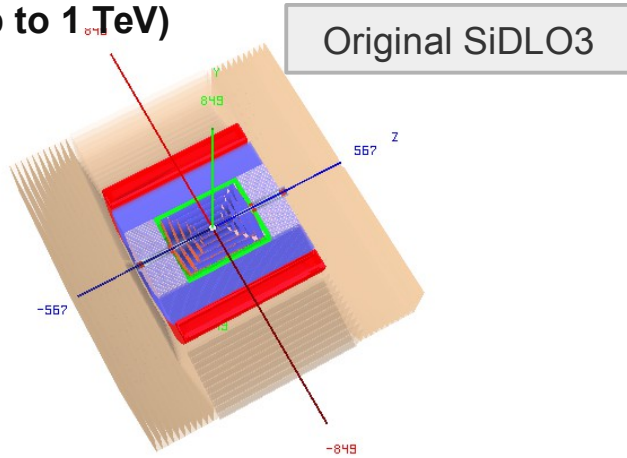
- Multi-purpose detector for the ILC
- Conceived at SLAC (USA LC Physics Group)
- The key characteristics:
  - 5 Tesla solenoid
  - Silicon tracker: 25/50 um readout pitch
  - ECAL: (0.35 cm cell size, W / silicon)
  - HCAL:
    - 1x1 cm cell size (RPC for LOI3\*)
    - 40 layers for barrel (HCAL)  $\sim 4.5 \lambda_I$
- Optimized for particle-flow algorithms (PFA)
- Fully configurable using SLIC software



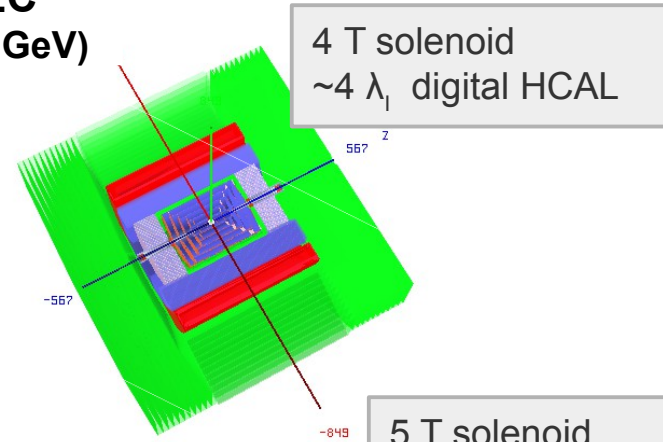


# 'All-silicon' design concepts supported in HepSim

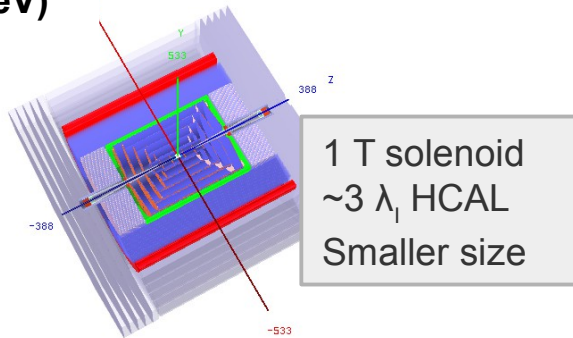
**SiD**  
( $e^+ e^-$  up to 1 TeV)



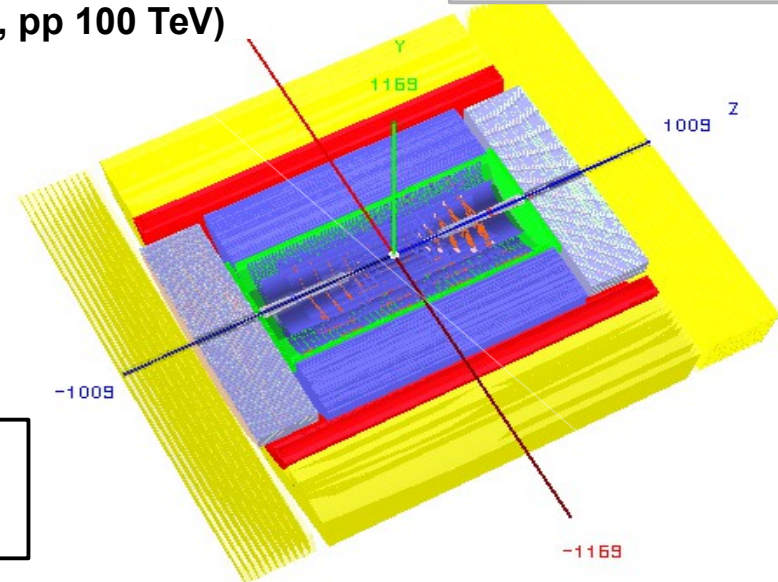
**SiCPEC**  
( $e^+ e^-$  250 GeV)



**SiEIC**  
(ep, 141 GeV)



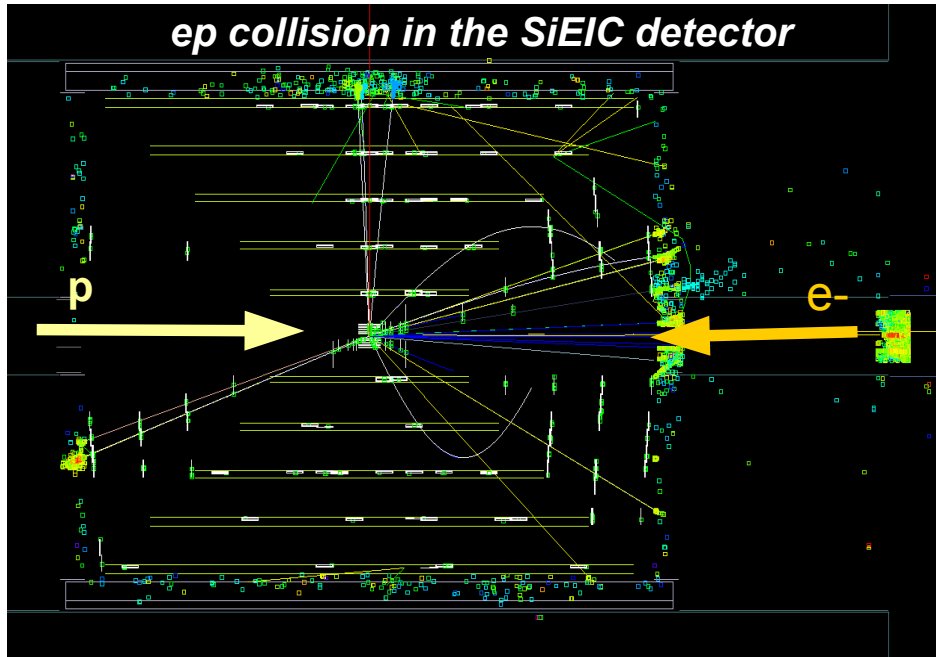
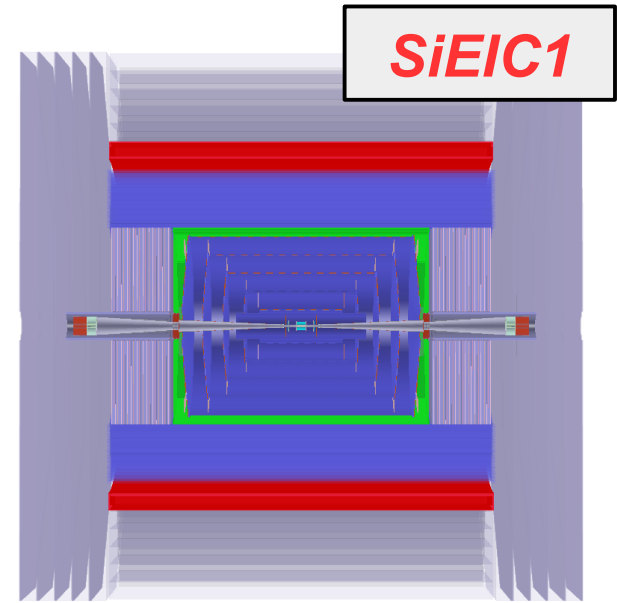
**SiFCC**  
(FCC-hh, pp 100 TeV)



**HepSim provides single-particle and physics events after simulation & reconstruction**

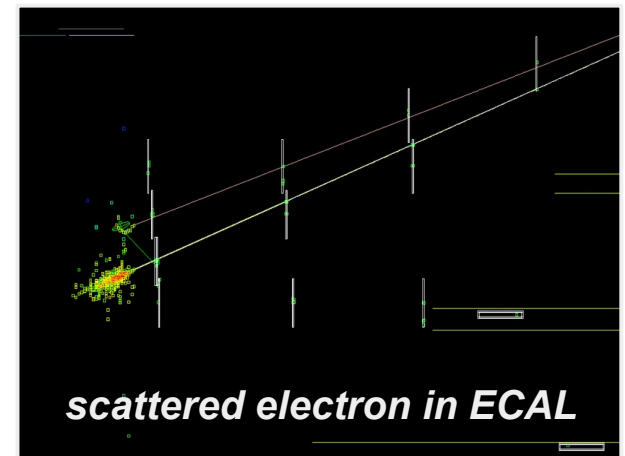
# EIC collisions in the SiEIC detector

- Re-purpose SiD for the Electron-Ion Collider (EIC)
- Optimized SiD detector concept for EIC collisions:
  - smaller size, thinner CAL, 1 Tesla solenoid etc..



PFA electron energy: **16.92 GeV**  
"EVGEN" truth energy: **16.90 GeV**

DIS sample ( $Q^2 > 5 \text{ GeV}^2$ ) → "HEP" like (HERA)  
CM energy = 141 GeV ("EIC-like")  
Monte Carlo samples available from HapSim

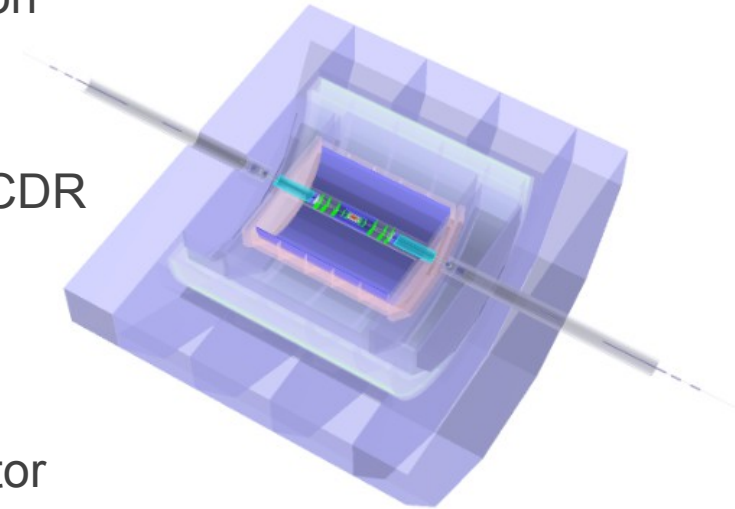


# CEPC detector studies



# A CEPC detector based on the ILD detector concept

- ILD detector is the baseline of the CEPC simulation group at IHEP (Beijing)
  - M. Ruan, Y. Fang, G. Li, Q. Li, X. Moa etc.
- Ongoing optimization of the detector concept for CDR
- Ongoing Higgs studies using Pythia6 samples
  - see a [presentation at ICHEP 2016, Chicago](#)
- A possible second option based on the SiD detector conceived by the USA LC Physics Group?
  - Many similarities in the design choices
  - Similar ILCSoft software: PFA, LCO format etc..



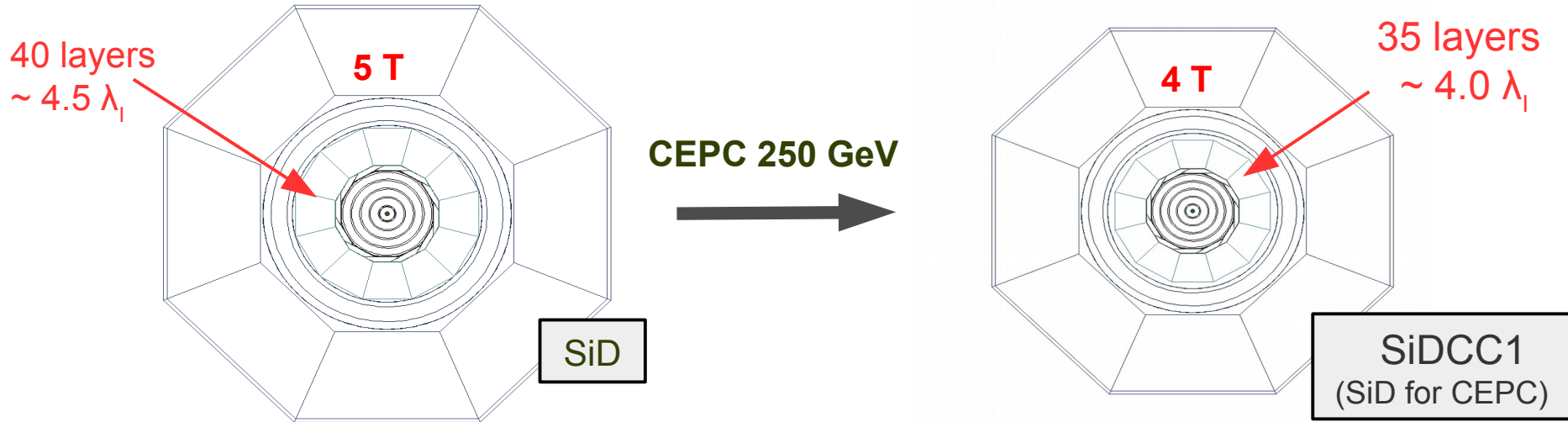
- *3.5 T solenoid*
- *Time Projection Chamber (TPC) for tracks*

# Designing a detector for CEPC ( $e^+ e^-$ CM $E=240-250$ GeV)

SiD detector is designed for  $\sim 500$  GeV particles/jets (0.5-1 TeV CM energy)  
But CEPC will measure particles/jets up to 125 GeV (250 CM energy)

## Possible optimizations:

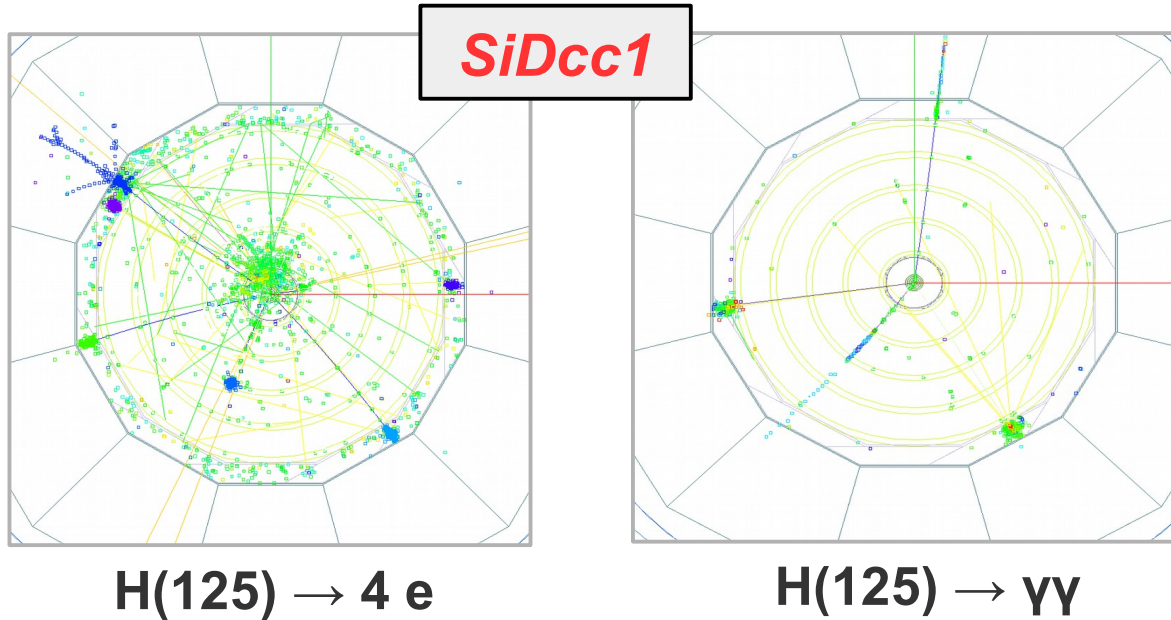
- **HCAL:** barrel:  $4.5 \lambda_1$  (40 layers)  $\rightarrow 4.0 \lambda_1$  (35 layers)  
endcap:  $5 \lambda_1$  (45 layers)  $\rightarrow 4.0 \lambda_1$  (35 layers)
- **Tracking:** 5 Tesla  $\rightarrow 4$  Tesla



**Design a light, cost-optimized version of the SiD detector for CEPC and use several physics processes to benchmark its performance**

S.C. and M.Demarteau, Conceptual Design Studies for a CEPC Detector.  
arXiv:1604.01994. HKUST IAS 2016 proceeding

## Example II: Simulations for CEPC ( $e^+e^-$ 250 GeV CM energy)



~ 10,000 reconstructed events for each physics channel after PFA (Pandora) reconstruction

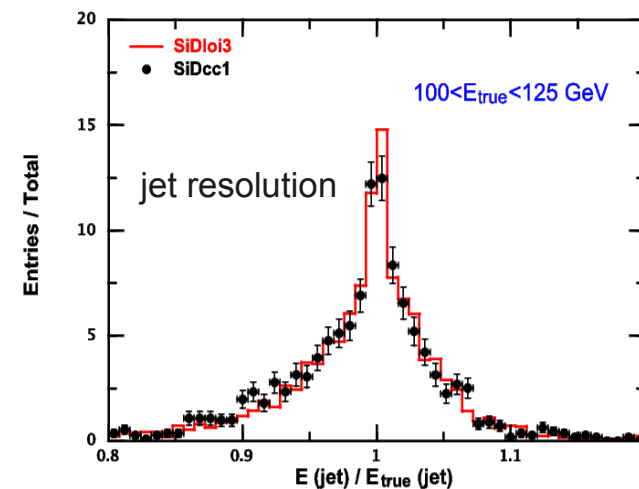
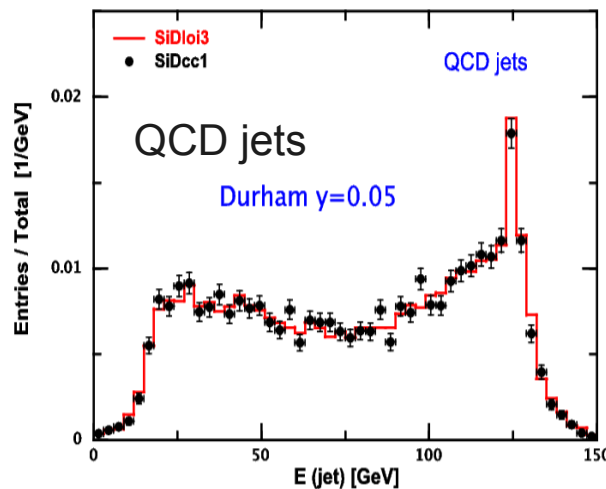
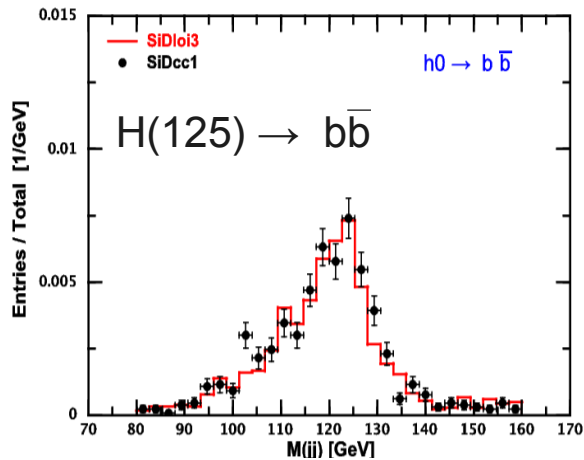
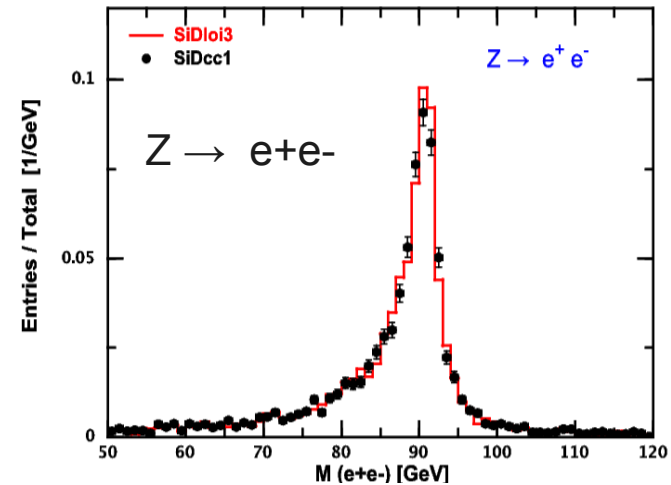
- Available full simulations for the SiD and SiDCC (for CPC) detectors:
  - $Z \rightarrow e^+e^-$ ,  $Z \rightarrow \tau\tau$ ,  $Z \rightarrow \mu^+\mu^-$ ,  $Z \rightarrow b\bar{b}$
  - $H(125) \rightarrow b\bar{b}$ ,  $H(125) \rightarrow \gamma\gamma$ ,  $H(125) \rightarrow ZZ^* \rightarrow 4l$ ,  $H(125) \rightarrow \tau^+\tau^-$



# Comparing SiD with SiDCC1

Done with Jas4pp

- Benchmark processes for  $e^+e^-$  (250 GeV)
  - $Z \rightarrow e^+e^-$ ,  $Z \rightarrow b\bar{b}$ ,  $Z \rightarrow \tau^+\tau^-$ ,  $H \rightarrow \gamma\gamma$
  - $H \rightarrow 4l$ ,  $H \rightarrow b\bar{b}$ , QCD jets
- Particle flow objects to reconstruct invariant masses and jet energy resolutions (Durham jets)



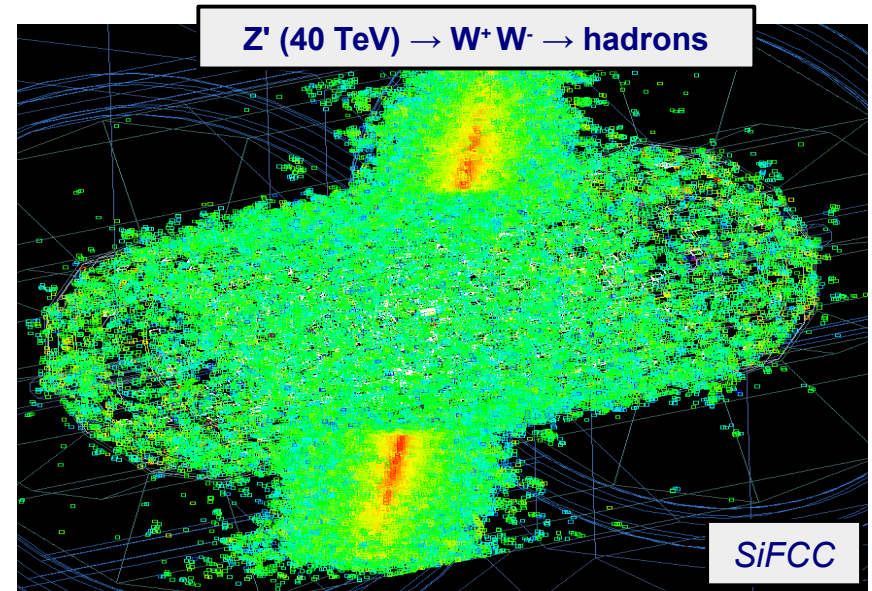
**Simplification of the SiD detector does not compromise physics performance**

S.C. and M.Demarteau. arXiv:1604.01994. HKUST IAS 2016 proceeding

# High-granularity hadronic calorimeter for tens-TeV physics at FCC-hh, SppC and HE-LHC

*With contributions from:*

M.Beydler (ANL) A.Kotwal (Fermilab/Duke), L.Gray (Fermilab), J.Strube (PNNL), N.Tran (Fermilab), S. Yu (NCU), S.Sen (Duke), J.Repond (ANL), J.McCormick (SLAC), J.Proudfoot (ANL), A.M.Henriques Correia (CERN), C.Solans (CERN), C.Helsens (CERN)

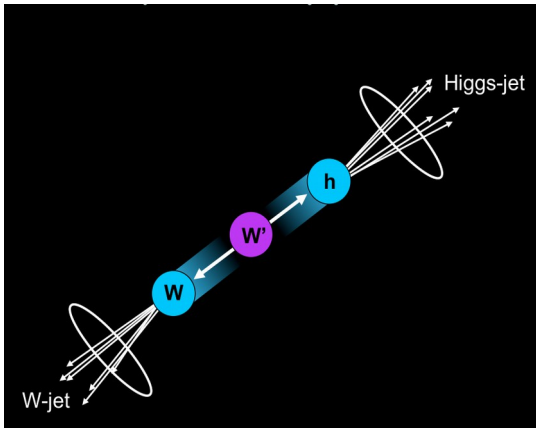


Two 20 TeV jets in  $\sim 12 \lambda_1$  calorimeter

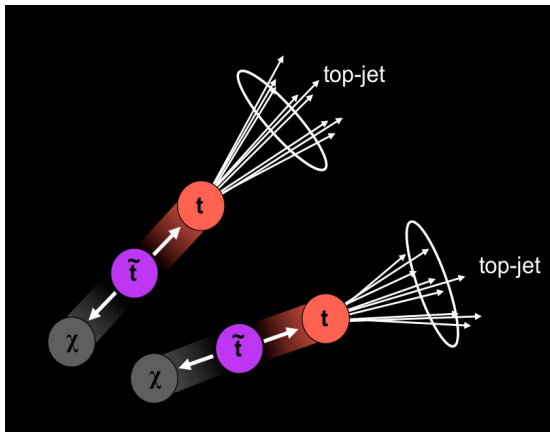
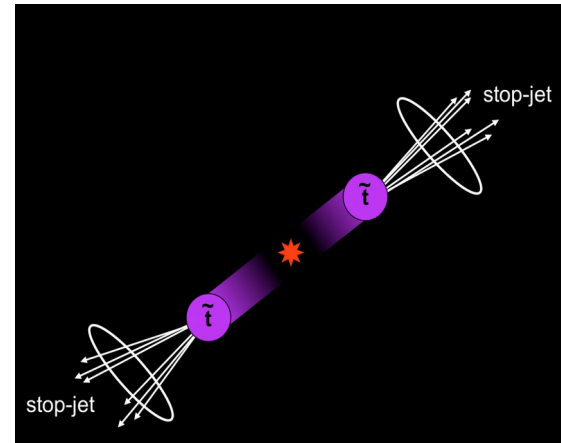
# Lateral segmentation. Where does it matter..

Brock Tweedie. Next steps in the Energy Frontier. LPC@FNAL. Aug. 24, 2014

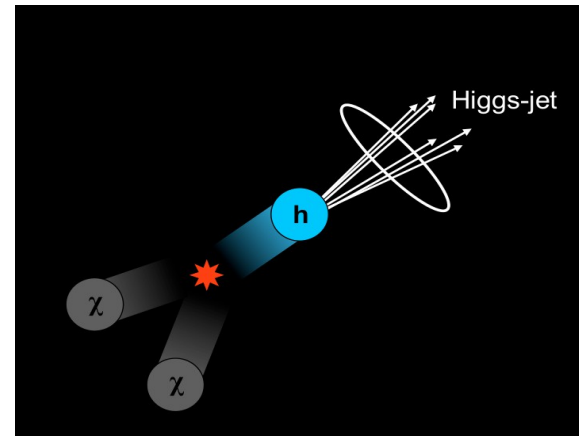
$X \rightarrow W / Z / \text{Higgs} / \text{top}$



$X \rightarrow \text{quarks/gluons}$



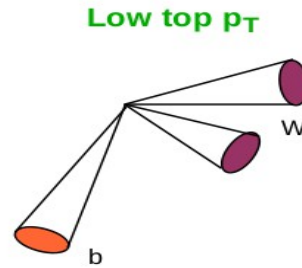
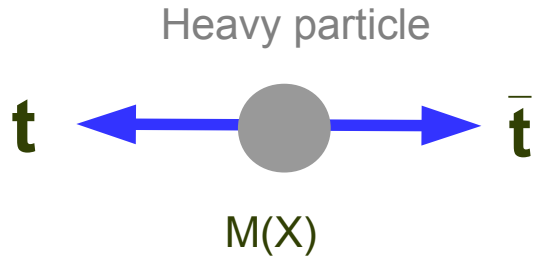
TeV-scale pair-produced



SM + dark matter

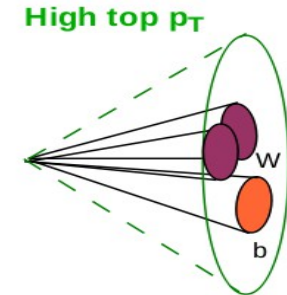
Large mass  $\rightarrow$  large Lorentz boost  $\rightarrow$  large collimation of decay products

# Boosted top from high-mass particles



boost

$$\Delta R \sim 2 p_T / m(\text{top})$$



[www.quantumdiaries.org](http://www.quantumdiaries.org)

- $M(X) \sim 10 \text{ TeV} \rightarrow$  top quarks with  $p_T(\text{top}) > 3\text{-}5 \text{ TeV}$
- $\Delta R$  distance between 2 particles ( $W, b$ ) from top decay
- SM physics &  $10 \text{ ab}^{-1}$  for FCC-hh:  $5M \bar{t}t$  events with  $p_T(\text{top}) > 3 \text{ TeV}$

## ▪ SSC TDR:

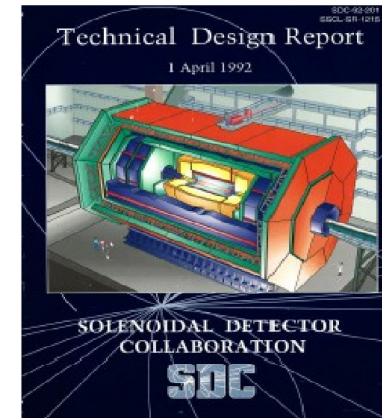
- mentions **substructure signatures** and large R-jets for boosted Z (SSC-SR-1217 TDR 1992 p 3-26)

## ▪ LHC:

- Boosted signatures is **one of the major topics**

## ▪ FCC-hh:

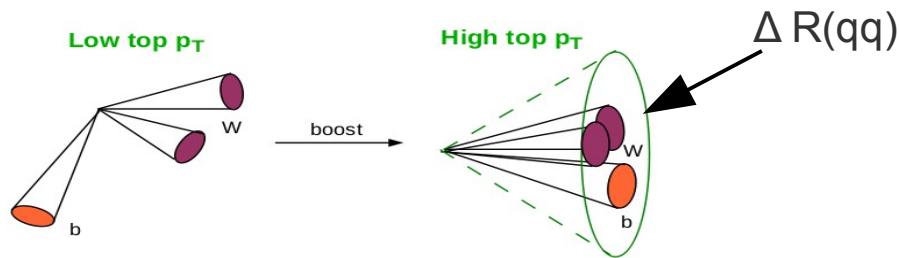
- Detector design will be **based on boosted signatures** for top, Z/W, Higgs + modern techniques



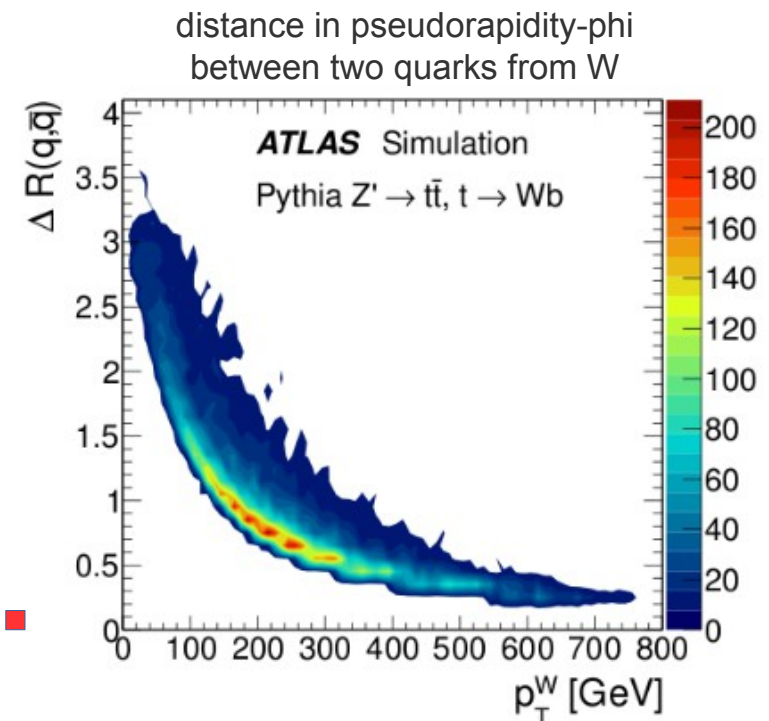
# Hadronic calorimeter (HCAL) for next collider experiments

- 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  $p_T > 5-25$  TeV from Higgs, W, Z, top decays

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



Typical cell size for  
ATLAS & CMS HCAL



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

# Detector requirements driven by physics at 100 TeV

(what we already know)

- **Good containment up to  $p_T(\text{jet}) \sim 30$  TeV:  $12 \lambda_1$  for ECAL+HCAL**
  - affects jet energy resolution
  - leakage biases, etc.
- **Small constant term for HCAL energy resolution:  $c < 3\%$** 
  - dominates jet resolution for  $p_T > 5$  TeV
  - important for heavy-mass particles decaying to jets
- **Longitudinal segmentation:**
  - Not studied  $\rightarrow$  *require realistic Geant4 simulations*
- **Good transverse segmentation for resolving boosted particles:**
  - baseline is  $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$  from Delphes fast simulations
    - 5x5 cm assuming  $\sim$ ATLAS-like inner radius ( $\sim 2.3$  m from IP)
  - *Require realistic Geant4 simulations*

done



done



to be done



this study



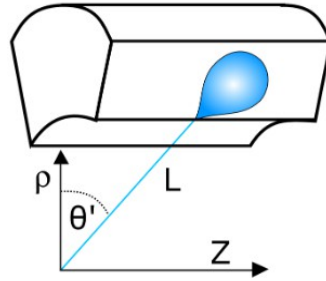
See presentations given at the FCC week 2016 (Rome) and CALOR 2016





# Resolution for single pions

ATLAS-like setup  
based on Geant4



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

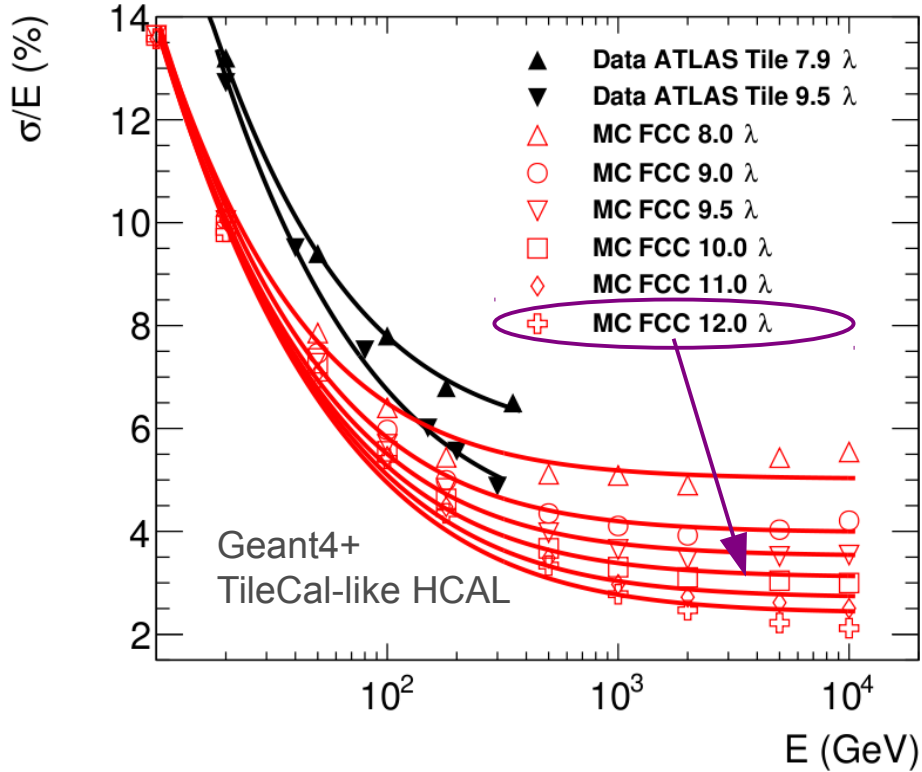
*a* – stochastic/sampling term,  
*b* – electronic noise term  
*c* – constant term

“c” dominates for jet with  $p_T > 5$  TeV

- Geant4 TileCal inspired simulation based on FTFP\_BERT
- Stochastic term is close to  $45\%/\sqrt{E}$
- Constant term improves by  $\sim 20\%$  with increase of  $1\lambda_1$

**$12 \lambda_1$  calorimeter:**

- no leakage up to 10 TeV
- constant term  $c \sim 2.5\%$

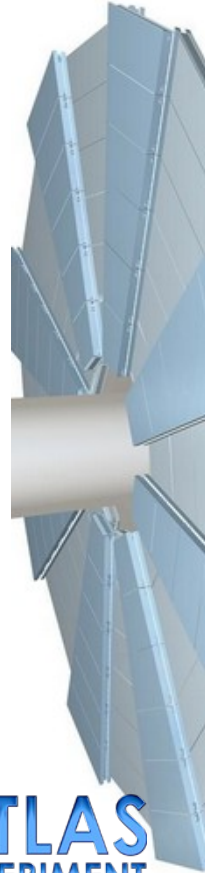
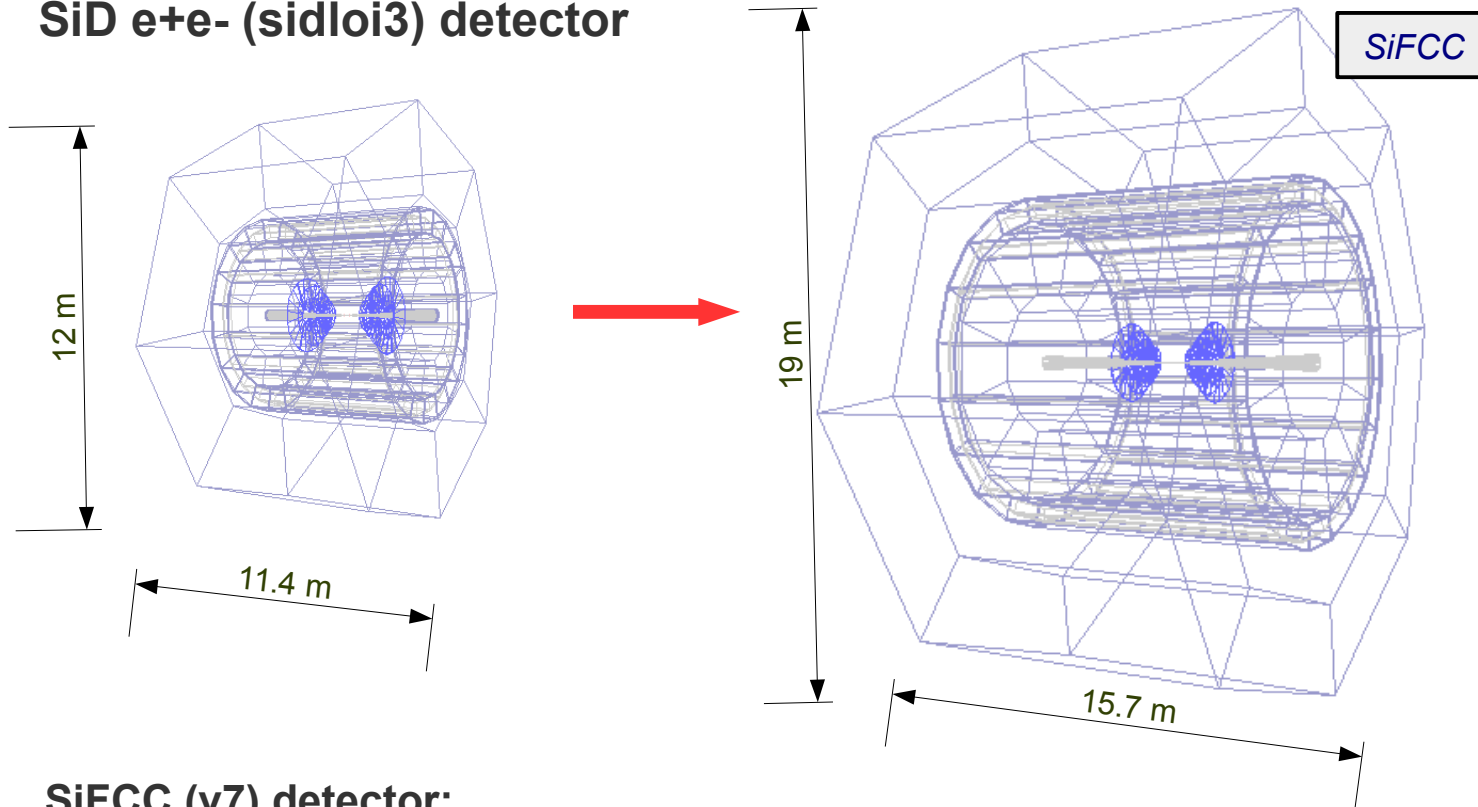


T.Carli, C.Helsens, A.Henriques Correia, C.Solans: 016\_JINST\_11\_P09012. arXiv:1604.01415

# SiFCC detector for performance studies

- Design a FCC-like detector using SiD (ILC) detector software
- Study energy resolution, response and granularity for ~tens TeV physics

## SiD e+e- (sidloi3) detector



## SiFCC (v7) detector:

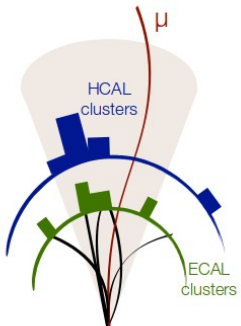
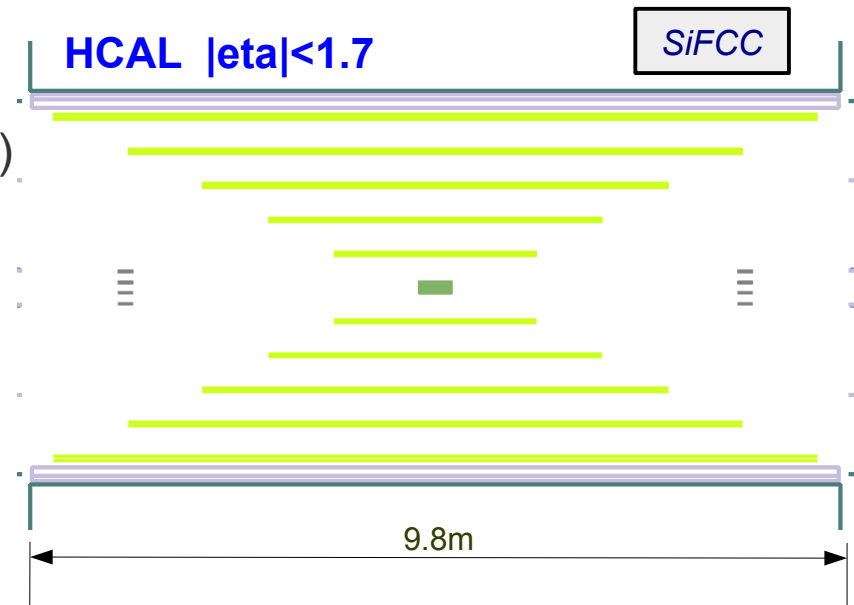
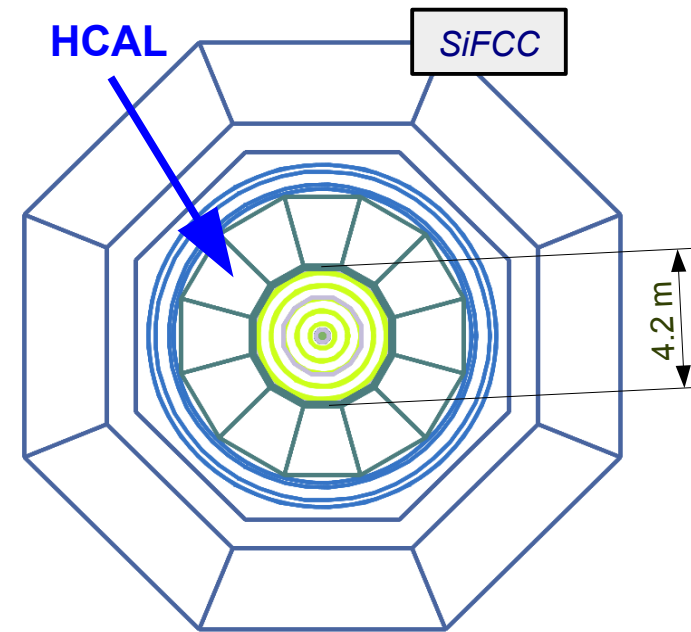
- Multipurpose, high granularity, compact detector
- 30% smaller than ATLAS ( $R=25$  m vs  $R=19$ ), 30% larger than CMS ( $R=14.6$  m vs  $R=19$  m)



# Characteristics of SiFCC (version 7)

<http://atlaswww.hep.anl.gov/hepsim/soft/detectors/sifcch7/sifcch7.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 X<sub>0</sub>**
- **HCAL (Scint. / Fe) ~ FCC-hh baseline**
  - 5x5 cm cells:  $\Delta\eta \times \Delta\phi = 0.022 \times 0.022$
  - x4 smaller than for CMS & ATLAS
  - 64 longitudinal layers  $\rightarrow 11.3 \lambda_I$
  - 3.1% sampling fraction
- > 150 M non-projective cells (ECAL+HCAL)



Optimized for Particle Flow Algorithms

# High granularity HCAL for 100 TeV physics?

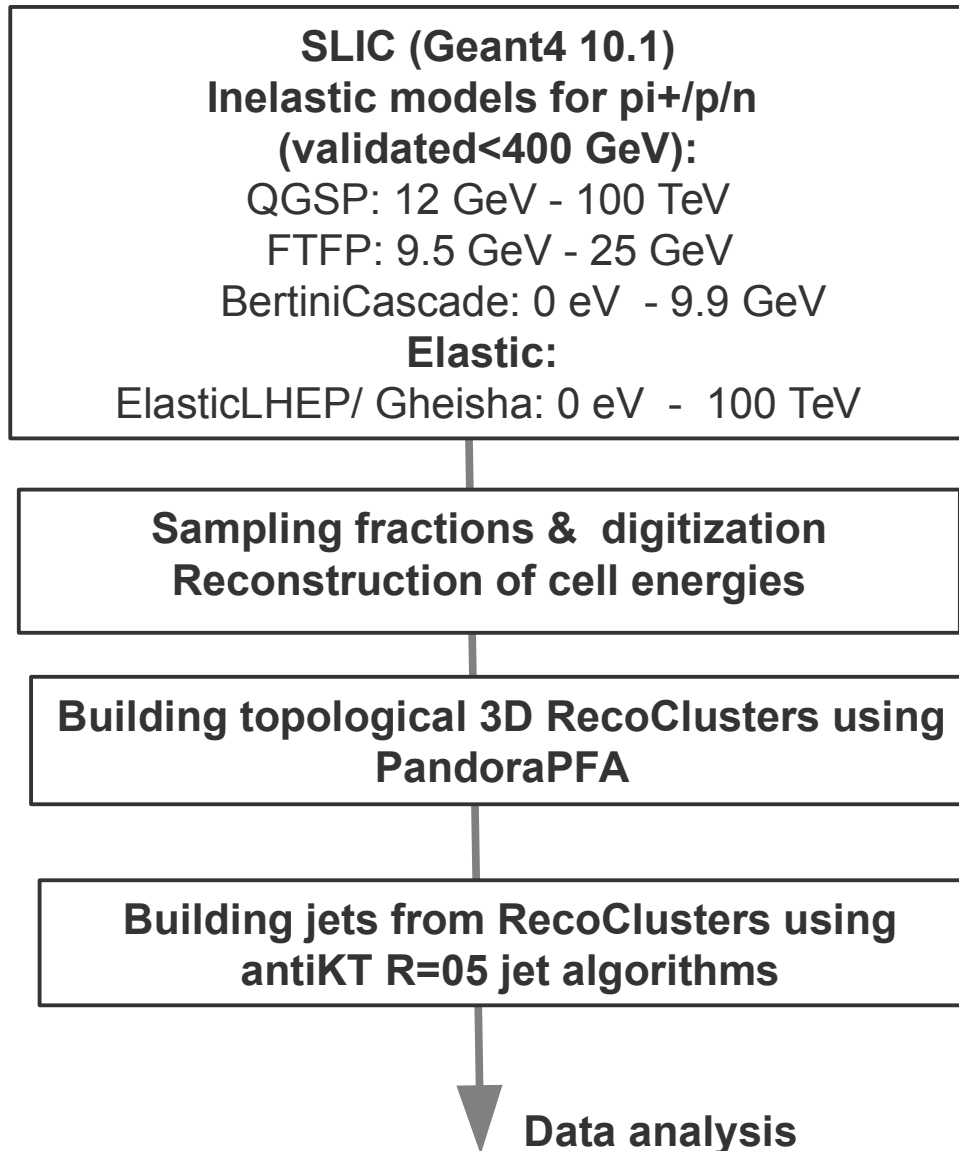
- Baseline for past & operational detectors:
  - **transverse cell size is similar or larger than nuclear interaction length:  $\lambda_I$**
- **Recent high-granularity HCAL: CMS (upgrade), CALICE R&D:**
  - 2x2 or 1x1 cm cell sizes required to reconstruct PFA & separate particles
- **Main question for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

**Can reconstruction of jets and particles at tens-TeV scale benefit from small HCAL cells ( $\ll \lambda_I$ ) ?**

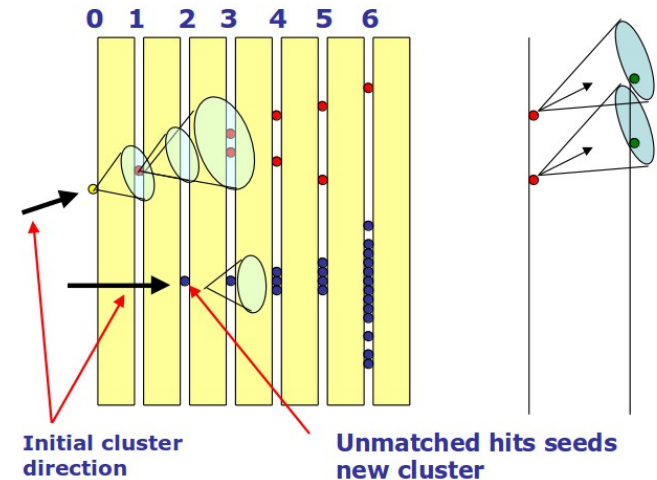
Data with simulations available from HepSim repository: <http://atlaswww.hep.anl.gov/hepsim/>

SiFCC detector version (Fe/Scin. HCAL)	Transverse size of HCAL cells (cm)	Transverse size of HCAL cells in $\lambda_I$	Simulation tag in HepSim
<b>SiFCC-v7 (baseline)</b>	5X5 cm	$\sim \lambda_I/4$	rfull009
<b>SiFCC-v8 (traditional)</b>	20x20 cm	$\sim \lambda_I$	rfull010
<b>SiFCC-v9 (as ECAL)</b>	2x2 cm	$\lambda_I/8$	rfull011
<b>SiFCC-v10 (fine)</b>	1x1 cm	$\lambda_I/17$	rfull012

# Energy reconstruction in HCAL (SiFCC)



From M.Thomson



Cone algorithm

Start from inner layer and work outward

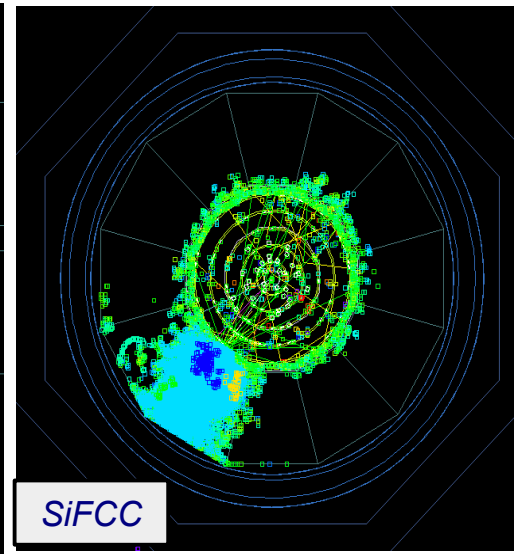
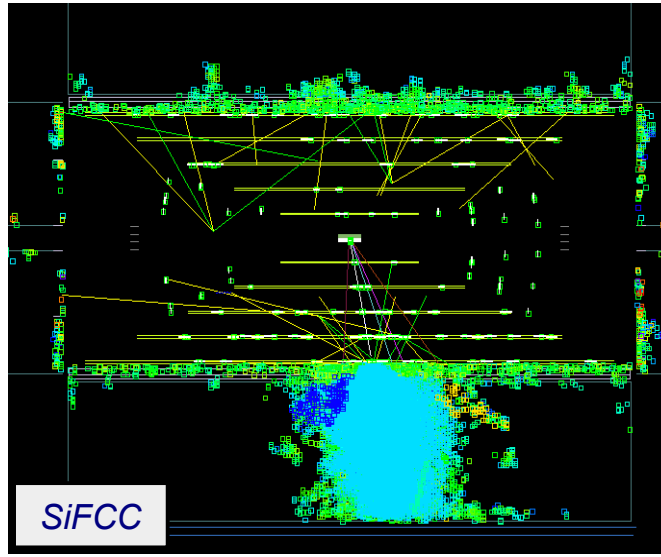
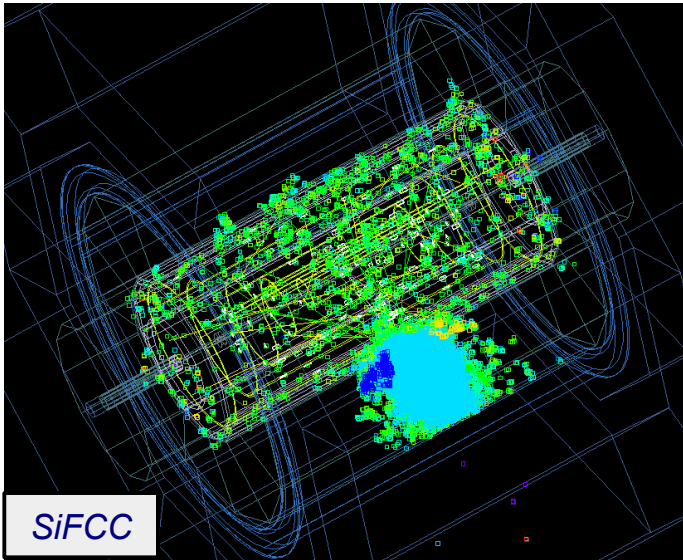
\* Pandora PFA objects with track information are used  
→ requires optimization

# Response to single particles: 8 TeV pions

Example: True momentum of  $\pi^+$  : 8.156 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

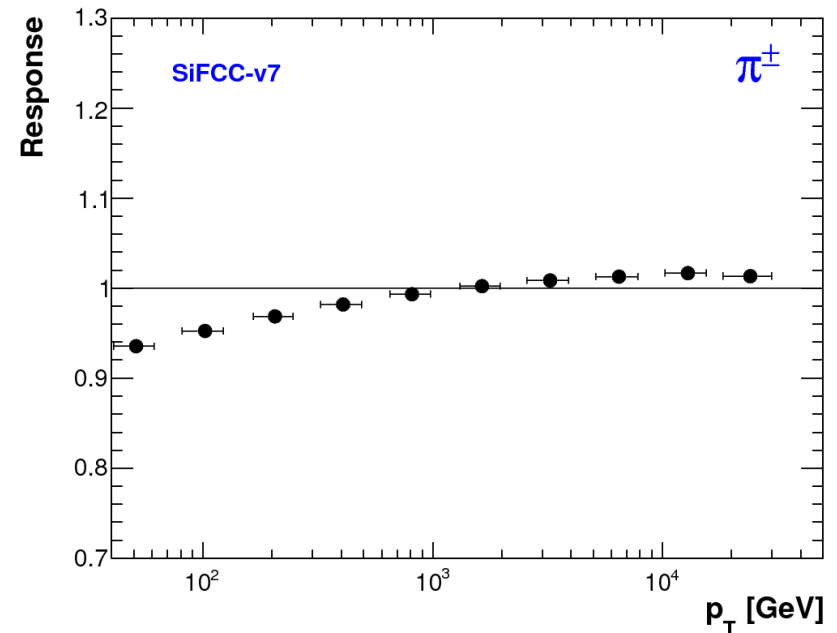
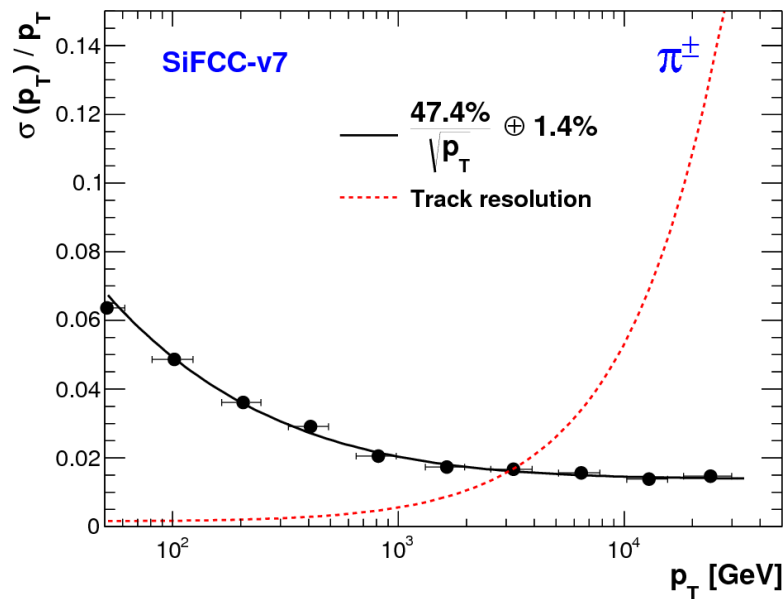


Based on HepSim: <http://atlaswww.hep.anl.gov/hepsim/info.php?item=201>



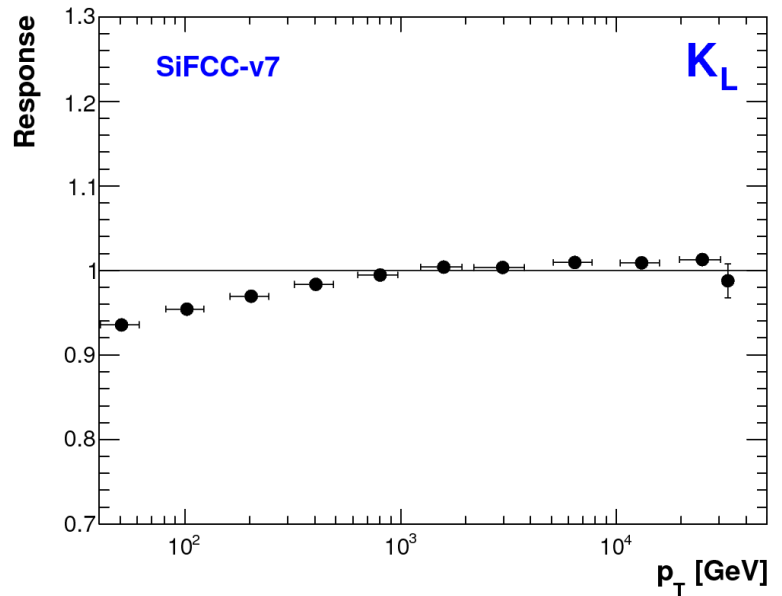
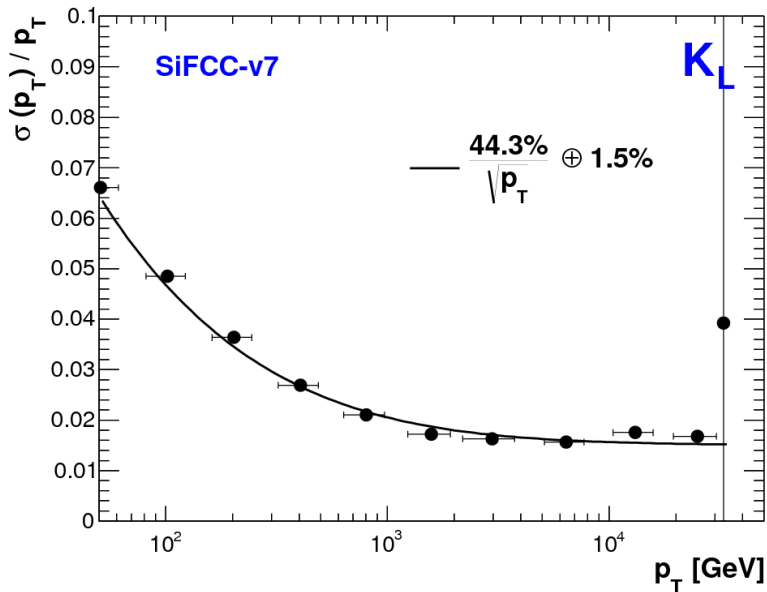
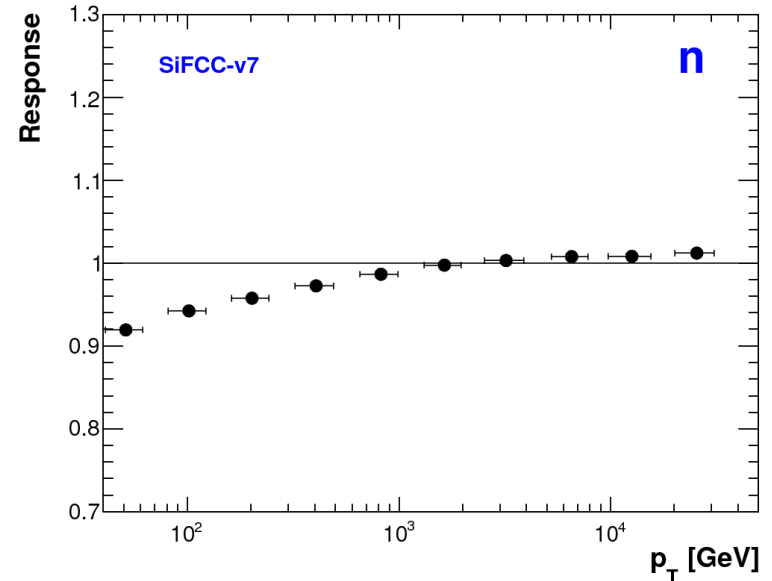
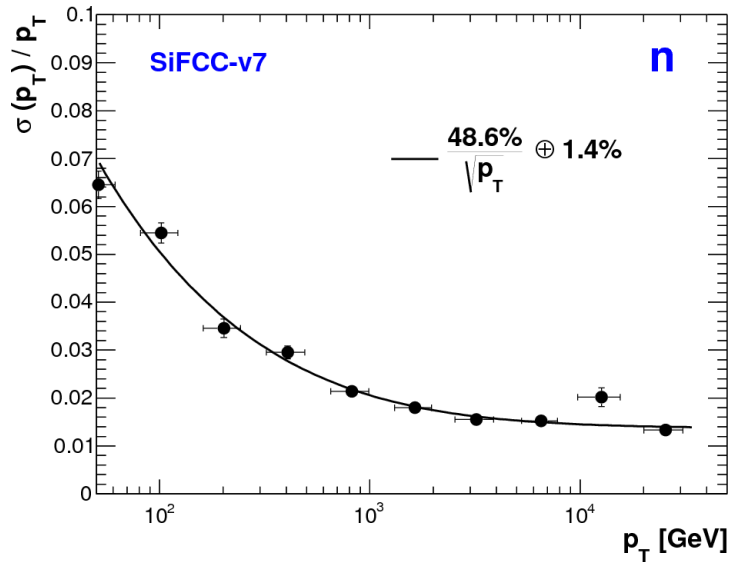
# Response to hadrons: $\pi^\pm$

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

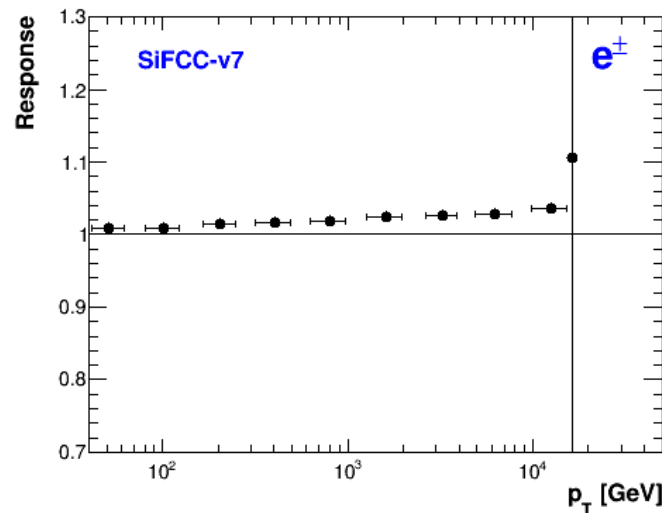
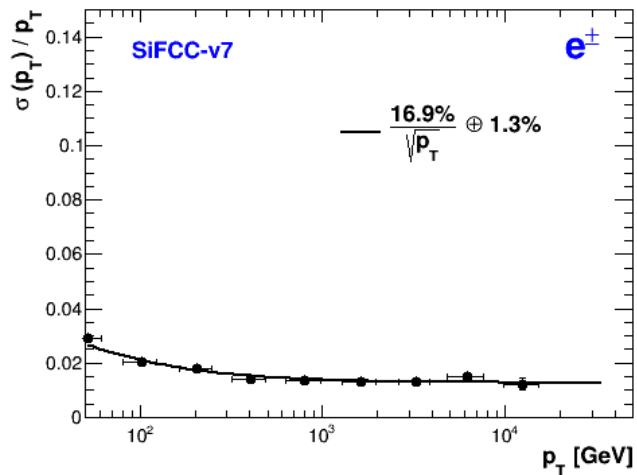
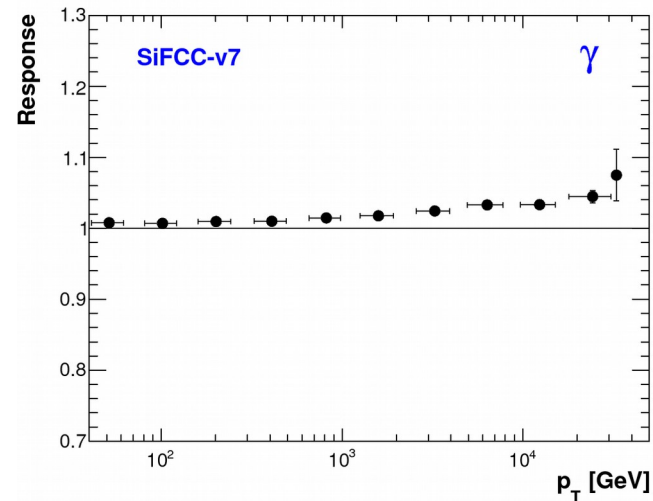
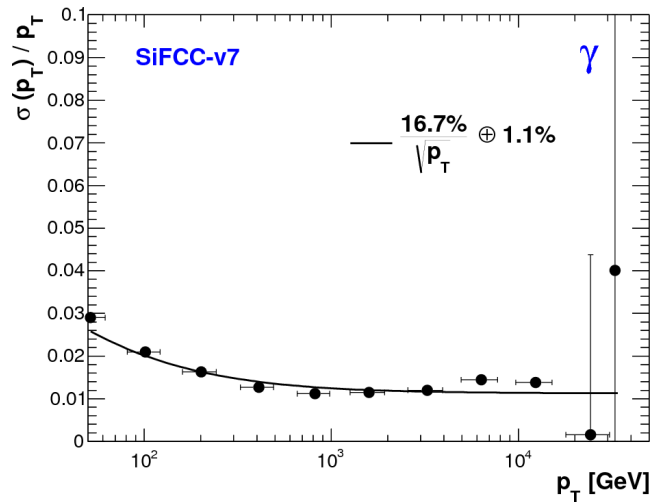


- ~47% sampling term, 1.4% constant term (the noise is small)
  - the sampling term is consistent with ATLAS-like setup (arXiv:1604.01415)
- Calorimeter resolution is better than for SiTracker for  $p_T > 3$  TeV
  - tracks were studied using single muons
- Calorimeter response is non-linear  $\rightarrow$  should be corrected by MC (e/p, material correction etc.)

# Response to neutrons and $K_L$



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

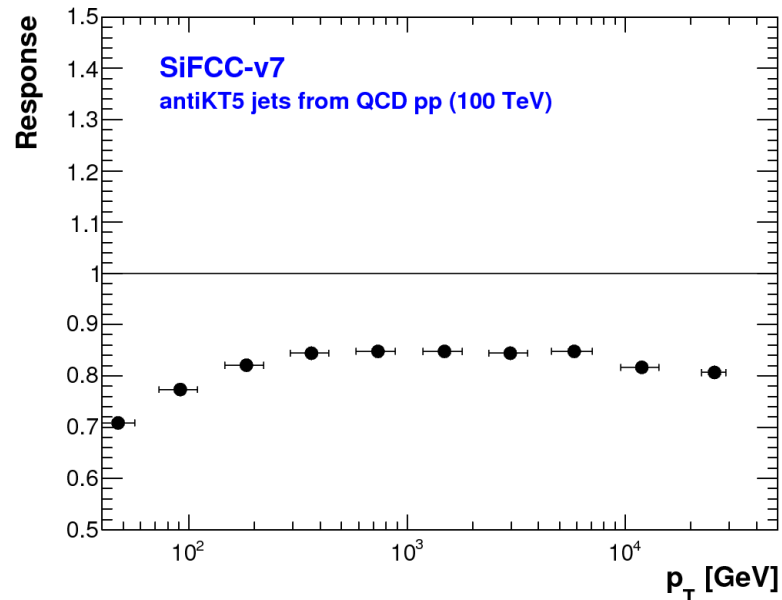
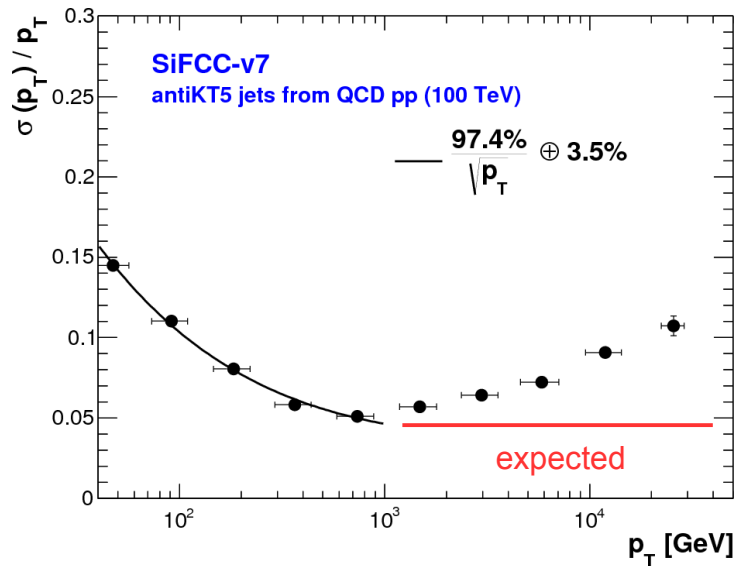


- Reasonable performance of ECAL:  $\sim 17\%$  sampling term, 1.3% constant term

# Jet energy resolution & response

tev100\_qcd\_pythia8\_ptall  
with rfull009 tag

- Jets from 100 TeV pp collisions generated with Pythia8 with different pT(min)
- Use RecoClusters for antiKT jet algorithms with size R=0.5 (not PFA, no tracks)

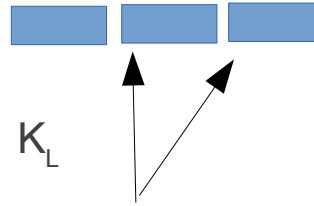
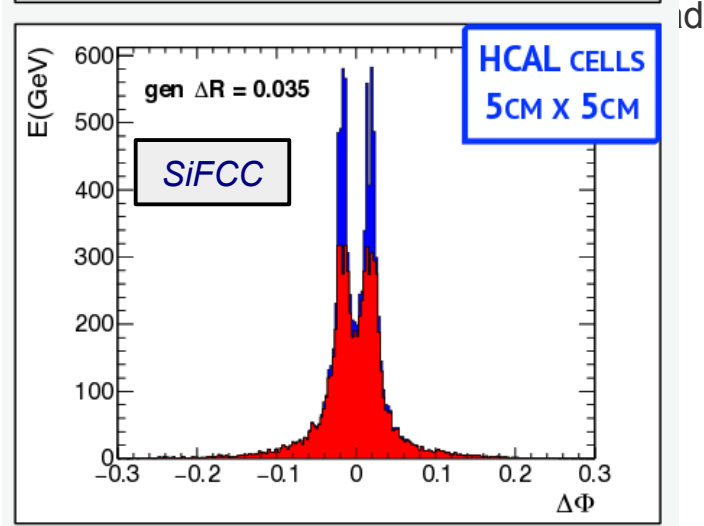
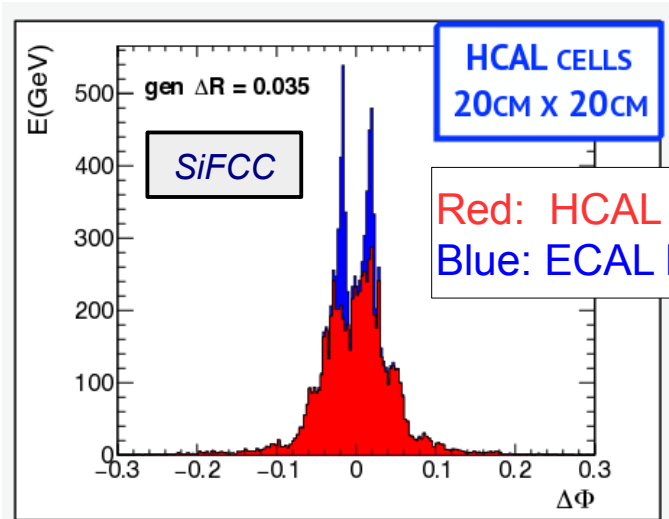


- Jet energy resolution is similar to ATLAS jets before correction (“EM” scale) for pT<2 TeV
- Jet response is lower than for single particles (curved tracks, e/p effect, inactive material, etc).
  - Requires jet energy corrections
- Surprise: resolution increases above 2 TeV and reaches 0.1 at 30 TeV
  - The result is consistent across various similar studies using SiFCC (i.e. Z' events etc.)
  - Searching for explanations (Geant4? Reconstruction problem?)



# HCAL segmentation and spacial separation of hadronic showers

truth-level separation 0.035 rad (2 deg)



T.Nhan

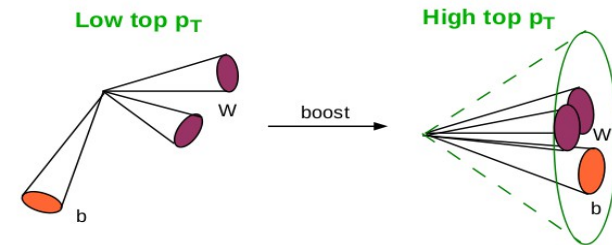
Presented at Boost2016/ICHEP16

- Generate two  $K_L$  ( $E=100$  GeV) particles at  $\eta=0$ .
  - First  $K_L$  is always at  $\phi=0$
  - Second is shifted by  $\Delta\phi=1,2,3..$  deg
- Simulate and reconstruct with SiFCC
- Calculate energy of hits in  $\Phi$  with respect to  $\Phi=0$
- Repeat for different HCAL cell sizes

Small HCAL cells ( $\sim \lambda_1/4$  size) helps separate hadronic showers produced by two  $K_L$  separated by 2 deg

# 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  $\Delta\Gamma(Z') \sim 1$  MeV:
  - $\mu+\mu^- \rightarrow Z' \rightarrow W+W^-$
  - $\mu+\mu^- \rightarrow Z' \rightarrow q\bar{q}$
  - $\mu+\mu^- \rightarrow Z' \rightarrow t\bar{t}$
  - $\mu+\mu^- \rightarrow Z' \rightarrow \text{tau}+\text{tau}^-$
  - $\mu+\mu^- \rightarrow Z' \rightarrow b\bar{b}$
- 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.  $\sim 100,000$  CPU\*h)

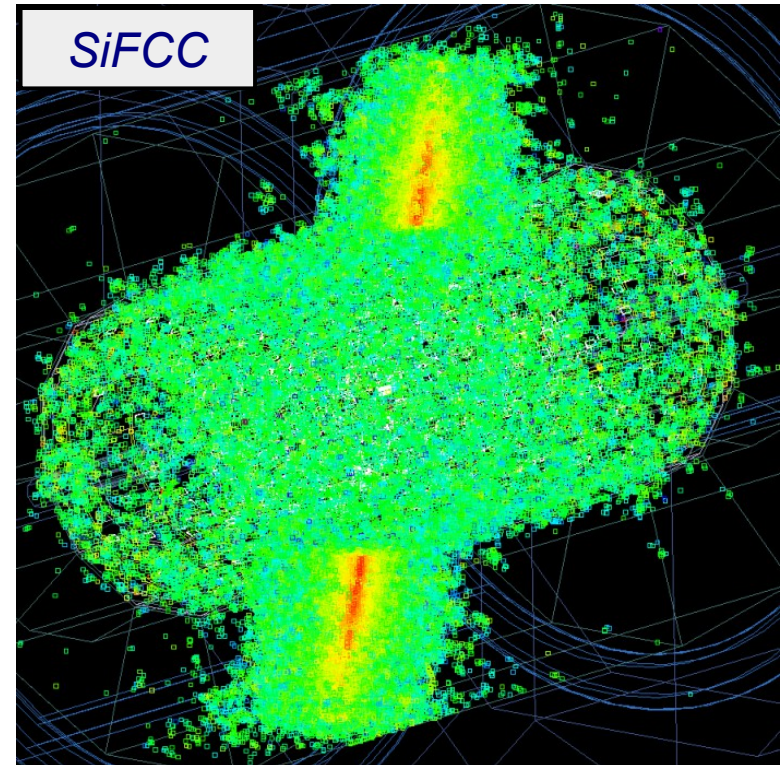
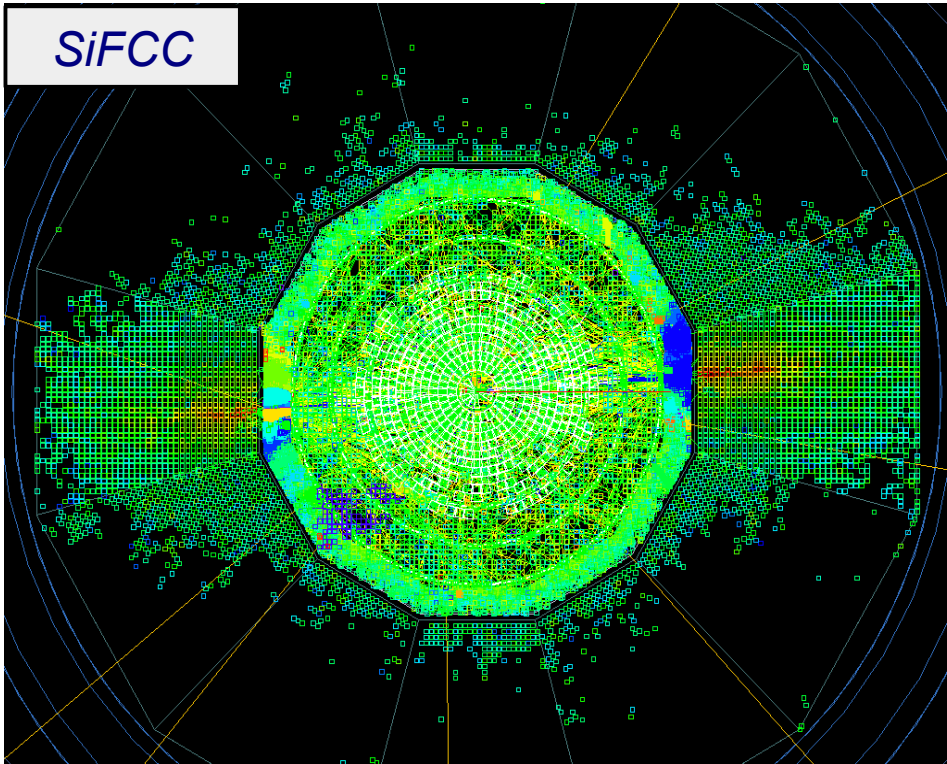
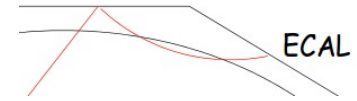


# Event display of $Z'$ (40 TeV) $\rightarrow q\bar{q}$

Busy event, large number of back-splash interactions in ECAL/HCAL/Tracker

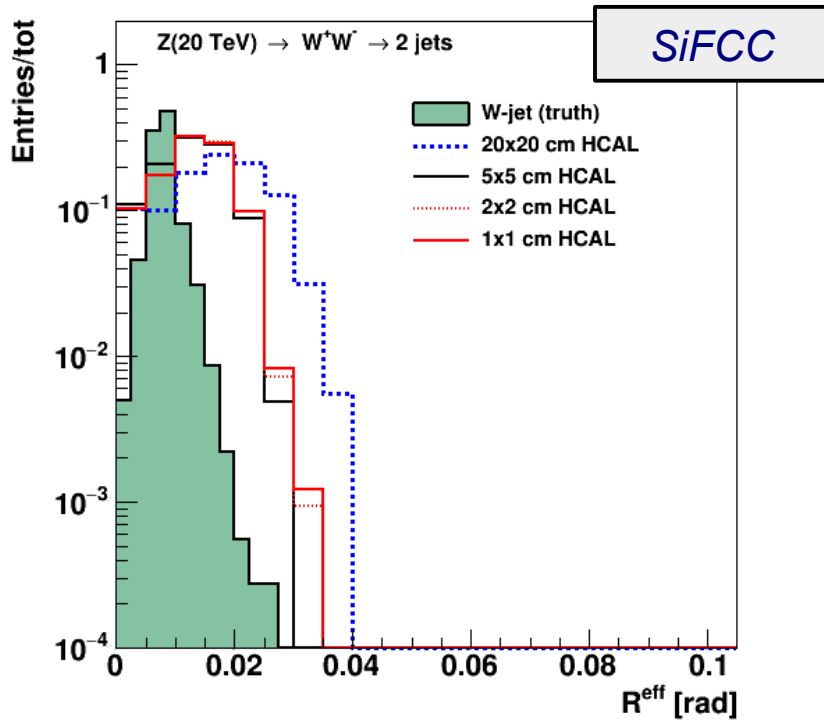
$\sim 4$  CPU\*h to simulate/reconstruct one event

$\rightarrow$  CPU intensive!

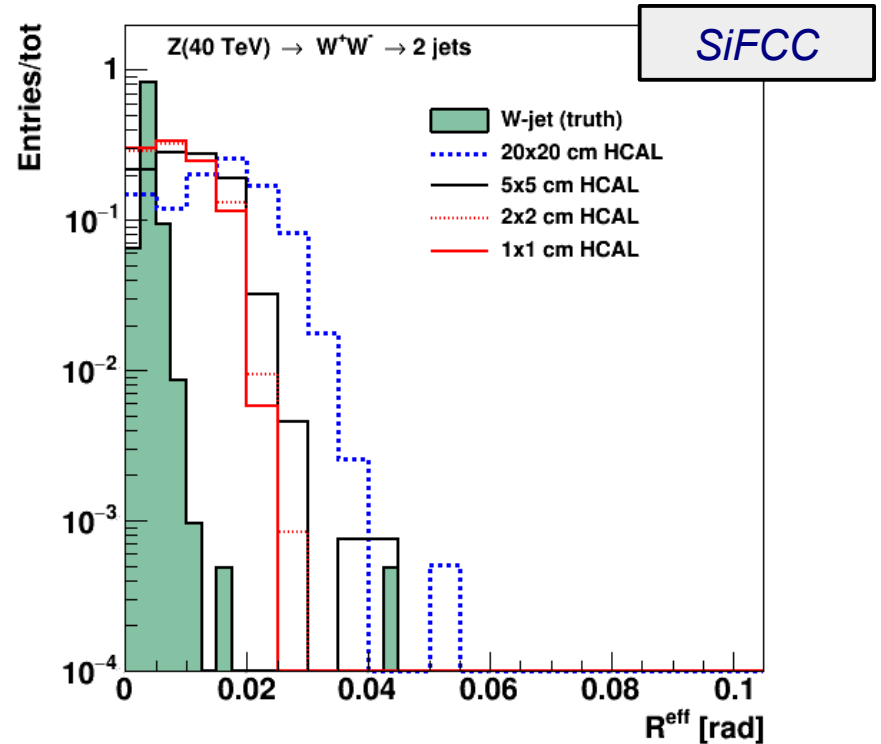


Sum over all distances between constituents and jet center, weighted with  $E(\text{const}) / E(\text{jet})$

### W-jets from Z'(20 TeV)



### W-jets from Z'(40 TeV)

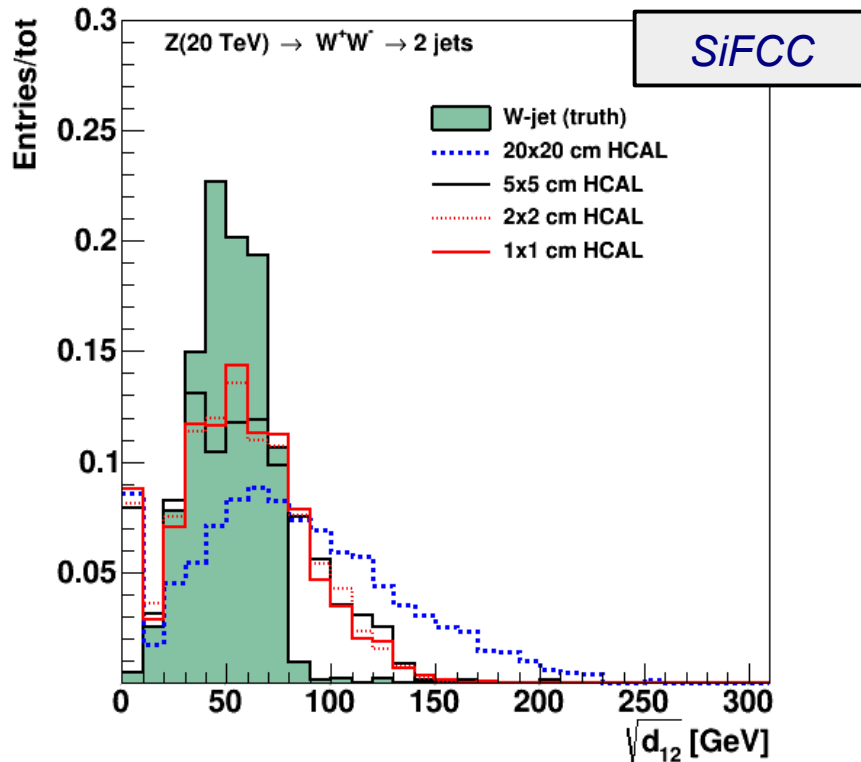


- Jets with  $p_T > 10, 20$  TeV, each from W decays ( $q\bar{q}$ )
- Narrow ( $\Delta R \sim 2 \cdot p_T / M(W)$ ) compared to QCD jets (not shown)
- 5x5 cells better reflect true effective jet size compared to  $\sim 20 \times 20$  cm (ATLAS/CMS)
- Small difference between 2 cm and 1cm cell sizes

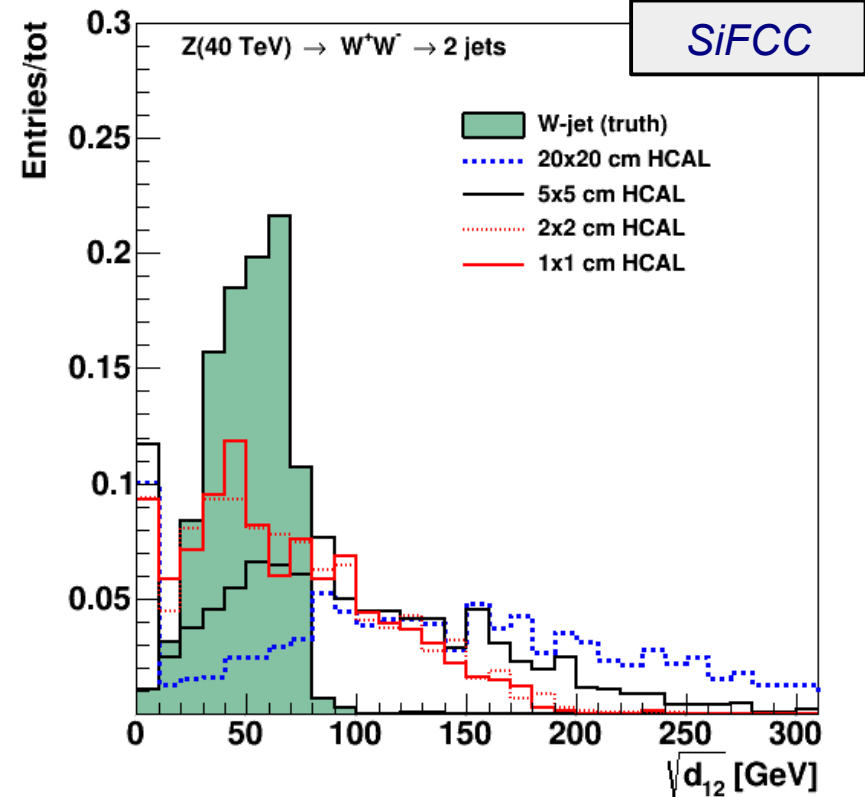
# Jet splitting scale: $d_{12}$

Kt 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  $p_T > 10, 20$  TeV, each from W decays (qqbar)
- 5x5 cells better reflect true effective jet size compared to 20x20 cm (ATLAS)
- Small difference between 2 cm and 1 cm cell sizes

# Summary of HCAL studies for energy frontier

- **First realistic physics processes for boosted topologies have been simulated and reconstructed up to 30 TeV**
- **Overwhelming evidence that we gain useful information from cell sizes smaller than nuclear interaction length for hadronic showers initiated by multi-TeV particles & jets**
  - Optimal size using RecoClusters  $\sim \lambda_1 / 4$  or (or  $\sim 5 \times 5$  cm for Fe/Sci HCAL of SiFCC)
  - Consistent with previous studies based on fast simulations (CPAD2015, FCC weeks)
- **Cost-effective technology is required to build high granularity calorimeter with large dynamic range of cells (<10\$/channel?!)**

# Summary

- **First public Monte Carlo repository with fast and full detector simulations**
- **Enable physics & detector-performance studies for current & future colliders + community outreach**
  - 1.6 billion events at the EVENT level for public downloads
  - Significant number of fast and fully reconstructed events for ep,  $\mu\mu$ , ee, pp collisions (13-100 TeV) & single-particle samples for detector studies
- **14 articles, ~25 presentations since 2014 (linked to [WWW](#)):**
  - Physics reach studies for HL-LHC, HE-LHC, FCC-hh etc.
  - Calorimeter studies (cell granularity)
  - Tracking optimization at multi-TeV scale
  - Software development
- **2.5 million CPU\*h from OSG-grid. OSG-Connect support from UChicago**
- **Contributions from 17 students/scientists**
- **Your contribution is welcome!**

# How to contribute to HepSim

In addition to physics & detector performance studies, you can contribute to the simulations too!

- Generate EVGEN archive files with physics processes
- Validate using the HEPSIM tools (if you can)
- Contribute to the software tools
- Setup a HepSim mirror:
  - data server with HTTP access
  - can maintain your own EVGEN & full simulation files

# Thanks!



## Contributions to HepSim

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Here is a list of people who contributed to the project:

- S. Chekanov (main developer and maintainer)
- E. May - ProMC format development, benchmarks on BlueGene/Q (ANL), Jas4pp debugging
- K. Strand (SULI 2014) - ProMC conversion tools
- P. Van Gemmeren - testing ProMC format
- T. Sjöstrand - ProMC integration with Pythia8
- P. Demin - ProMC integration with Delphes
- I. Pogrebnyak - (U.Michigan) software validation toolkit, fastjet in Java
- D. Wilbern (SULI 2015) - Pileup mixing tool based on ProMC
- M. Selvaggi - Delphes card for ILD geometry
- H. Gray - Delphes card for FCC geometry
- J. Strube (PNNL) - LCIO/SLIC for full simulation
- A. Kotwal (Duke Univ.) - LCIO/SLIC for full simulation
- J. Adelman (NIU) - debugging post-Snowmass Delphes 3.3 card for 13/14 TeV
- S. Padhi (prototyping Snowmass Delphes3.1 during Snowmass 2013)
- K. Pedersen (alternative b-tagging for rfast003)
- Shin-Shan Yu (heavy higgs MG5 simulations)
- Joel Zuzelski (ANL, SULI 2016) - SLCIO reader, converter promc2slcio, new tracking geometry for SiFi
- Boruo Xu (Bono) (xu@hep.phy.cam.ac.uk) - help with moving to new pandora
- John Marshall (marshall@hep.phy.cam.ac.uk) - adaptation of slicPandora for fast Pandora in HepSim

We also acknowledge the computer support by:

- Lincoln Bryant and Bala Desinghu (OSG-Connect)
- David Champion and Rob Gardner (ATLAS-connect / MWT-Tier2)

We apologies in advance if some names are missing.

