(Opportunities in) software for future experiments

Dr Sarah Williams (University of Cambridge)

Introduction

- I have been given a fairly daunting task of discussing SW for future experiments.

- Disclaimer: this is the first SWIFT-HEP event I have been to- I hope this material is useful/ will generate discussion, but I am happy to follow-up/dig further into topics after the meeting.

- My experience is mainly with the FCC software (currently BSM MC contact) which is built on the key4hep stack, but thanks go to…

  - John Marshall (Warwick) for input on PANDORA

  - Aidan Robson (Glasgow) for e+e- input (ECFA and linear collider)- further details in slides from 2022 UK e+e- meeting.

  ... For providing useful input/discussion!

Future colliders beyond the LHC?

In the aftermath of the Higgs discovery, lots of discussion on what machine should follow the LHC…

What should come after the LHC?

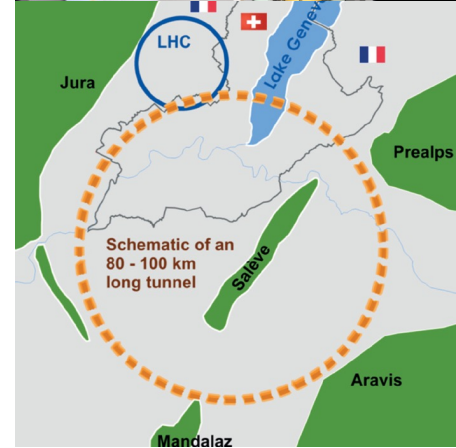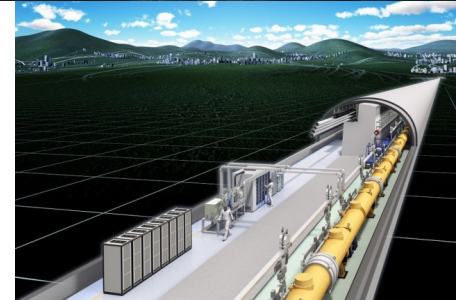e^+e^- machine?

Linear collider? → **CLIC** (CERN?)

→ **ILC** (Japan?)
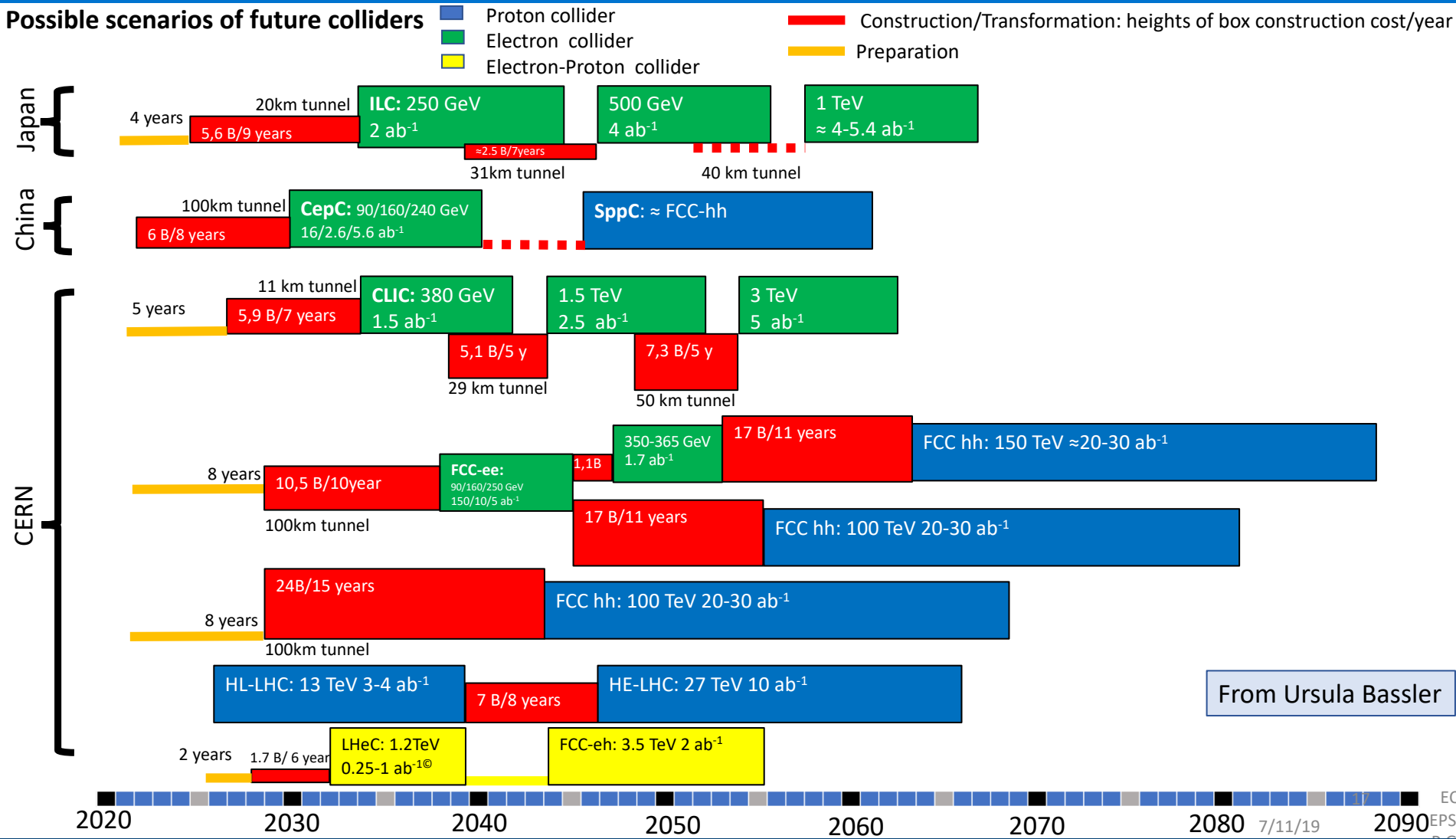
Circular collider? → **CepC** (China)

Hadron collider?

Muon collider?

→ **FCC-ee/eh/hh** (CERN)

How might Europe fit into the global context?

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"Straw-man" scenarios

Possible scenarios of future colliders

- Proton collider (blue)
- Electron collider (green)
- Electron-Proton collider (yellow)
- Construction/Transformation: heights of box construction cost/year (red)
- Preparation (orange)

Japan

- 4 years
- 5,6 B/9 years — 20km tunnel
- **ILC:** 250 GeV 2 ab^{-1}
- ≈2.5 B/7years — 31km tunnel
- 500 GeV 4 ab^{-1}
- 40 km tunnel
- 1 TeV ≈ 4-5.4 ab^{-1}

China

- 6 B/8 years — 100km tunnel
- **CepC:** 90/160/240 GeV 16/2.6/5.6 ab^{-1}
- **SppC:** ≈ FCC-hh

CERN

- 5 years
- 5,9 B/7 years — 11 km tunnel
- **CLIC:** 380 GeV 1.5 ab^{-1}
- 5,1 B/5 y — 29 km tunnel
- 1.5 TeV 2.5 ab^{-1}
- 7,3 B/5 y — 50 km tunnel
- 3 TeV 5 ab^{-1}

- 8 years
- 10,5 B/10year — 100km tunnel
- **FCC-ee:** 90/160/250 GeV 150/10/5 ab^{-1}
- 1,1B
- 350-365 GeV 1.7 ab^{-1}
- 17 B/11 years
- FCC hh: 150 TeV ≈20-30 ab^{-1}

- 17 B/11 years
- FCC hh: 100 TeV 20-30 ab^{-1}

- 8 years
- 24B/15 years — 100km tunnel
- FCC hh: 100 TeV 20-30 ab^{-1}

- HL-LHC: 13 TeV 3-4 ab^{-1}
- 7 B/8 years
- HE-LHC: 27 TeV 10 ab^{-1}

- From Ursula Bassler

- 2 years
- 1.7 B/ 6 year
- LHeC: 1.2TeV 0.25-1 ab^{-1}©
- FCC-eh: 3.5 TeV 2 ab^{-1}

2020   2030   2040   2050   2060   2070   2080   2090

7/11/19

ECFA
EPS/H

Key messages

- Important decisions on future colliders beyond the LHC will be made in the coming years…

  - It is essential that these are made based on realistic physics sensitivity studies.

  AND

  - We must ensure we develop robust software and computing frameworks that can meet the simulation, reconstruction and analysis requirements of WHATEVER future collider route we take.

  - Developing and maintaining software expertise in our community will strongly benefit UK interests in these projects.

The 2020 European Strategy Update

Following ~ 2 years of concensus gathering within the community, the ESU made several key recommendations to the community:

1. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy

2. Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage

Following these recommendations, several initiatives were started within the international HEP community….

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

2020 ESU- next steps

1. ECFA detector R+D roadmap => see Conor's talk next, but this also emphasized the importance of "Making software re-usable beyond a specific experiment or project […]"

2. FCC feasibility study

3. ECFA Higgs/top/EW factory study

Both (2) and (3):
- Have significant UK participation/interest.

- Rely on (common) software developments

SECOND • ECFA • WORKSHOP
on e⁺e⁻ Higgs / Electroweak / Top Factories

11-13 October 2023
Paestum / Salerno / Italy

Agenda

Topics:
- Physics potential of future Higgs and electroweak/top factories
- Required precision (experimental and theoretical)
- EFT (global) interpretation of Higgs factory measurements
- Reconstruction and simulation
- Software
- Detector R&D

LONDON
United Kingdom

05 – 09 June
FCC WEEK 2023

https://cern.ch/fccweek2023

Agenda

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Key4Hep= "turnkey software stack for future colliders"

- Complete data processing framework from generation => data analysis.

- Contributors (and usage) across range of experiments: C^3, CEPC, CLIC, EIC, FCC, ILC, Muon collider, etc…

- For historical context- see slides and report from 2019 Future collider software workshop

**Event Data Model: EDM4hep**

Generator	Simulation	Recon-struction	Analysis
Whizard, Pythia, …	C++, Python	Overlay Digitization Tracking PFA	Vertexing Jet Clustering Flavor Tagging

Framework (Gaudi)

Detector Geometry: k4geo (DD4hep)

https://github.com/key4hep
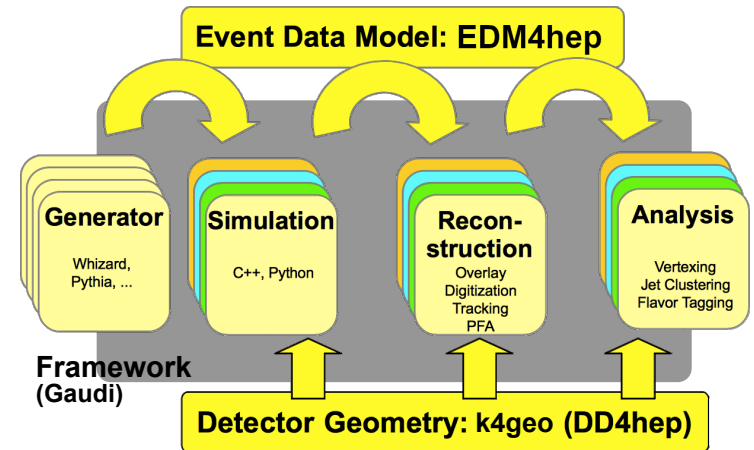
For more information see slides by J.M. Carceller at the ECFA workshop…

EDM4HEP: common data format

- Uses PODIO (event data model toolkit- https://cds.cern.ch/record/2296801?ln=en) to generate a generic EDM for future colliders.

- Largely based on LCIO-EDM.

EDM4hep DataModel Overview (v0.9)

- Provides classes for physical objects (MCParticle) and associations between e.g. MCParticle and ReconstructedParticle.

- Evolving based on needs of community. Adapting existing frameworks (i.e. ILCSoft) to key4hep involves adopting new EDM.
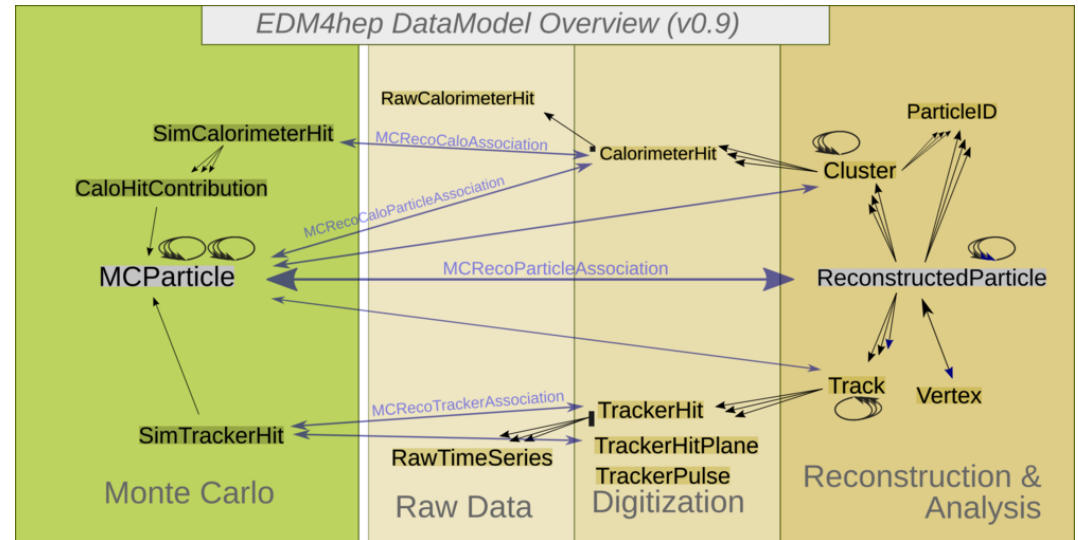
The Key4hep Framework

- Gaudi based core framework:

  - k4Gen for integration with generators

  - k4SimGeant4 for integration with Geant4

  - k4SimDelphes for integration with Delphes

  - k4geo for detector models, previously lcgeo

  - k4FWCore provides the interface between EDM4hep and Gaudi

  - k4MarlinWrapper to call Marlin processors

  - ...

Gaudi

| Application Manager | Algorithm 1 | Algorithm 2 |

Initialization	Initialization
Evt. processing	Evt. processing
Finalize	Finalize

Event1
Event2
Event3
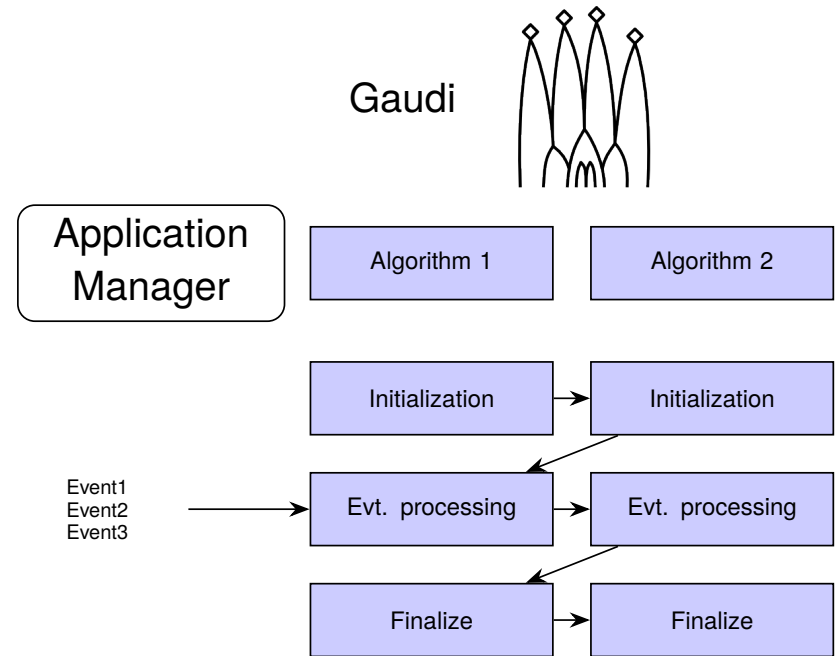
- Used by LHCb, ATLAS, Key4hep and others

Slide taken from talk by J.M Carceller at Paestum ECFA workshop

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Important (historical) notes

The linear e+e- community (of which the UK has historically had a strong involvement) laid the foundation for common software development…

- Common SW development dates back to 2003, with common event data model (LCIO) and framework (Marlin).

- Pandora for particle flow calorimetry for high-granularity e+e- detectors (now used overwhelmingly for reconstructing interactions in LArTPC detectors).
  - Recent update for SWIFT-HEP [here](#).
  - Integration into key4hep discussed [here](#) with work ongoing!
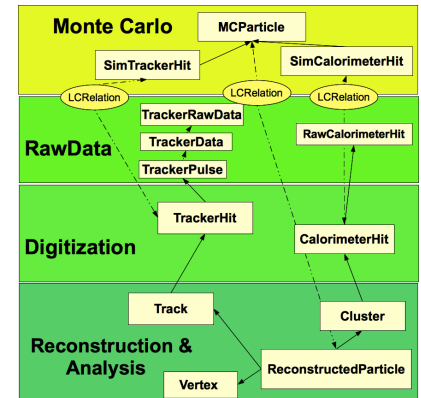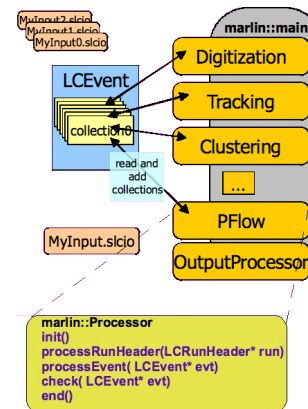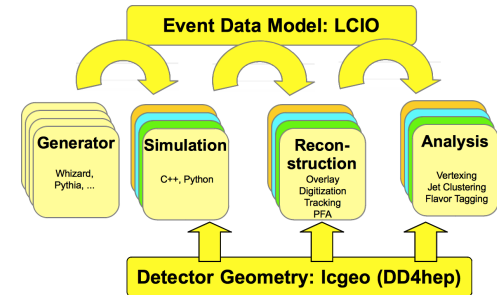
Schematics from [slides](#) by Frank Gaede at LCWS 2021

ECFA study- where to look

WG2- "Physics analysis methods" has organized dedicated topical meetings on:

- Generators
- Simulation
- Reconstruction

Plus focus meetings on Beamstrahlung and technical benchmarks

For highlights of progress so far see presentations at the Paestum workshop…

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Example- generators study - BSM needs
https://indico.cern.ch/event/1266492/

- ISR modelling
- Full treatment of beam spectra (including beam-beam correlations) + polarization.

Generator/ requirement	Pythia	Sherpa	Herwig	Whizard	MadGraph
ISR modelling	Multiple PS options available- e.g. "simple" neglects interference between ISR/FSR	2 approaches for QED radiation: (1) electron structure function (2) Soft photon resummation (YSF)	Available in "angular ordered shower"	Resummation for colinear factorisation available at LL (NLL coming)	ISR @ LL (NLL coming?)
Beam spectra treatment	(?)	Allow "two-step" definition of particles entering hard interaction (different beam/bunch) CIRCE interface	Ignored	CIRCE interface	Included through suitable PDFs
Beam polarization treatment	(?)	(?)	(?)	Supports polarisation fractions being provided.	(?)

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FCC feasibility study- software links

- FCC twiki page: https://twiki.cern.ch/twiki/bin/view/FCC/WebHome

- FCC software tutorial: https://hep-fcc.github.io/fcc-tutorials/master/software-basics/README.html

- FCC software help: https://fccsw-forum.web.cern.ch first point of call for questions.

- FCC simulation database for centrally produced samples: http://fcc-physics-events.web.cern.ch/fcc-physics-events/
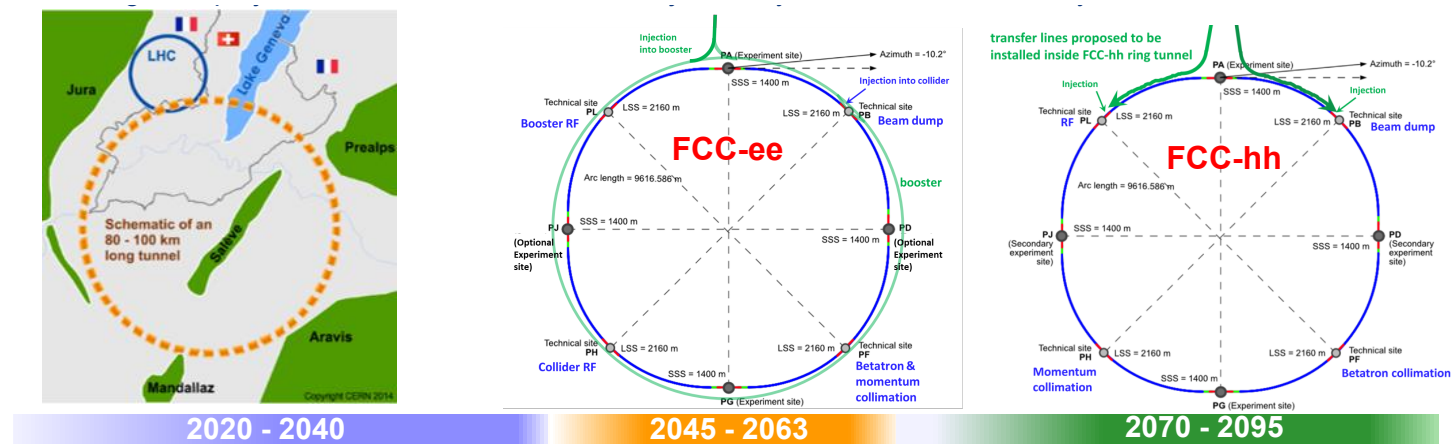
2020 - 2040   2045 - 2063   2070 - 2095

FCC analysis software

Sophisticated software ecosystem in place to perform simulations and physics/detector studies…
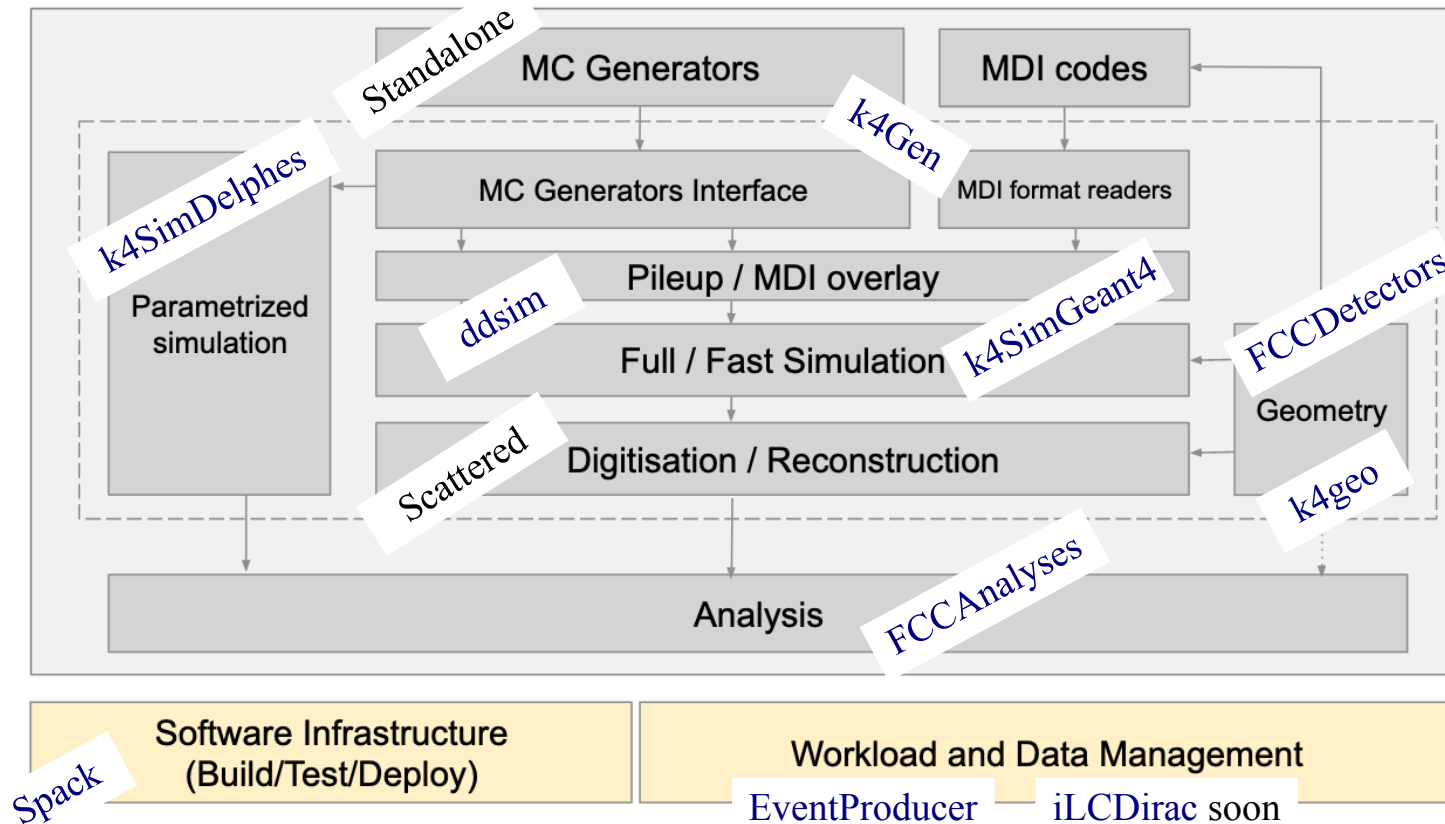
FCC analysis software

- Integrated in the Key4Hep ecosystem which also provides a common EDM for future collider studies.

- Central MC samples produced (in EDM4HEP format) to facilitate physics/detector studies.

- FCC Analysis software developed to analyse EDM4HEP files and support sensitivity/detector development studies
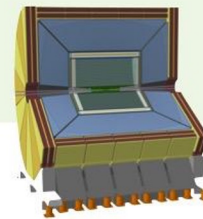

Typical workflow

Sample generation of models
- MadGraph5_aMC@NLO for parton-level e^+e^-
- PYTHIA for parton shower and hadronisation
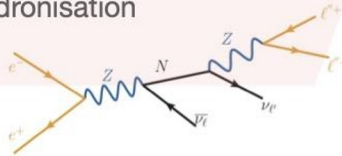
Parametrised detector simulation
- IDEA DELPHES card
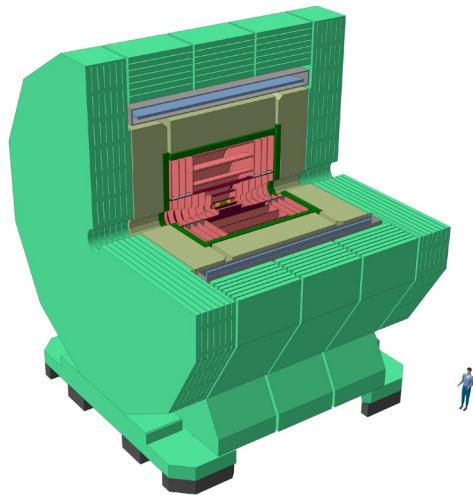
Analysis tools
- FCC analysis
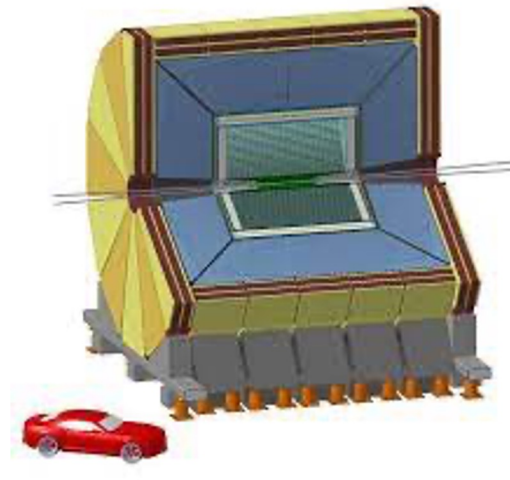
Sensitivity to studied model

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Detector concepts for FCC-ee

CLD ("CLIC-like Detector")

IDEA ("Innovative Detector for Electron-positron Accelerator")

…Plus new proposals …
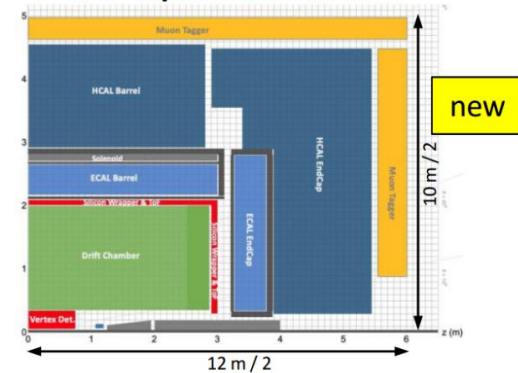
Full silicon vertex-detector+ tracker
3D high-granularity calorimeter
Solenoid outside calorimeter

Silicon vertex detector
Short-drift chamber tracker.
Dual-readout calorimeter

New proposal using liquid LAr calorimeter!

Work to support FullSim samples underway…

FCC software- plans + UK activities

(These are just a few I am aware of- there may be more…)

- Move to full-sim samples (many still use Pythia+Delphes)

- Skimmed MC samples- important for LLP studies at the Z-pole (and presumably other areas).

Anecdotally- FCC software supported by a small number of core developers so many improvements are person-power-limited.

- FCC UK meeting at QMUL 29th November: https://indico.ph.qmul.ac.uk/indico/conferenceDisplay.py?confId=1763

- FCC-hh analysis software "hackathon" earlier this year: https://indico.cern.ch/event/1254077/

Conclusion/outlook

- I have tried to summarise some ongoing activities related to future collider which require software and computing developments.

- Most common efforts sit under the key4hep umbrella- natural point to consider contributing going forwards.

- Personal opinion: investing in (developing expertise in) future collider software now could significantly increase the UK's capacity to contribute to these efforts more broadly going forwards!

Huge challenges and opportunities ahead- happy to take questions/comments, and discuss how we in the UK might get (more) involved…