ECFA HET Factory study:
WG2 Physics Analysis Tools

ECFA Plenary, CERN, November 14-15, 2024

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Reminder: Physics Analysis Tools (WG2)

GENERATORS

SIMULATION

RECONSTRUCTION

ALGORITHMS & TOOLS

SOFTWARE ECOSYSTEM

- Monte Carlo generators for e+e- precision EW, Flavour, Higgs, and top physics,
- Luminosity measurements
- Software framework
- Fast simulation and its pro/con
- Full Simulation
- Track and vertex reconstruction
- Jet algorithms / jet reconstruction
- Particle-flow reconstruction and global event description
- Particle identification strategies
- Flavour tagging algorithms
- Importance of timing information
- Constrained fits
- etc. etc. etc.

Several specific meetings with experts…

In addition to the general annual ECFA Workshops

- 1st Topical Meeting on Generators (9-10 November 2021, CERN, hybrid format) (jointly with WG1) https://indico.cern.ch/event/1078675/
- Focus Meeting on Beamstrahlung (12 January 2022) https://indico.cern.ch/event/1100734/
- 1st Topical Meeting on Simulation (1-2 February 2022) https://indico.cern.ch/event/1097819/
- 1st Topical Meeting on Reconstruction (4-5 May 2022, Desy) https://indico.cern.ch/event/1124095/
- 2nd Topical Meeting on Generators https://indico.cern.ch/event/1266492/ 21-22 June 2023 (Brussels and ZOOM)
- 2nd Topical Meeting on Reconstruction https://indico.cern.ch/event/1283129/ 11-12 July 2023 (CERN and ZOOM)
- Focus Meeting on Technical Benchmarks :https://indico.cern.ch/event/1324117/ 18 September 2023

Software Ecosystem - Key4hep

- HEP community decided 5 years ago to develop a **common turnkey software stack** – for future collider studies
- create a software ecosystem integrating in an o**ptimal way the best software components** to provide a **ready-to-use full-fledged solution** for data processing of (future collider) **HEP** experiments
- involved communities/contributors: CEPC, CLIC, EIC, FCCee, FCChh, ILC, LUXE, Muon Collider …
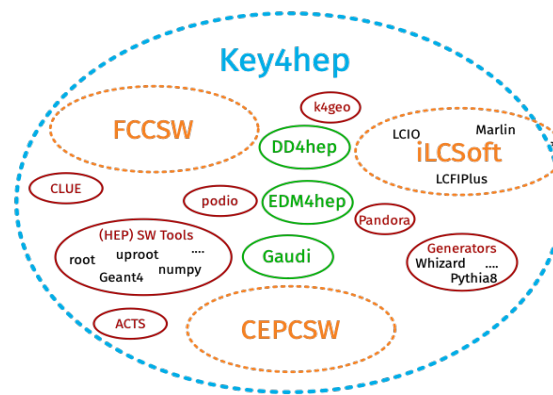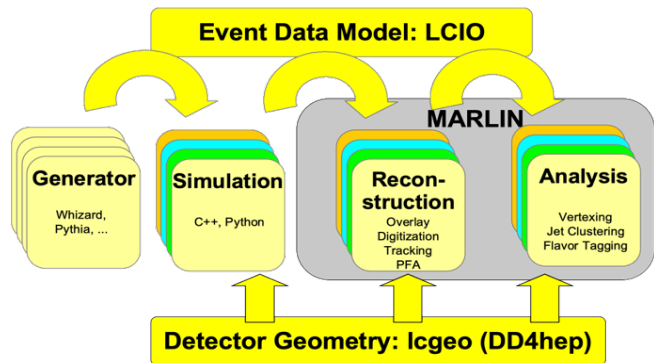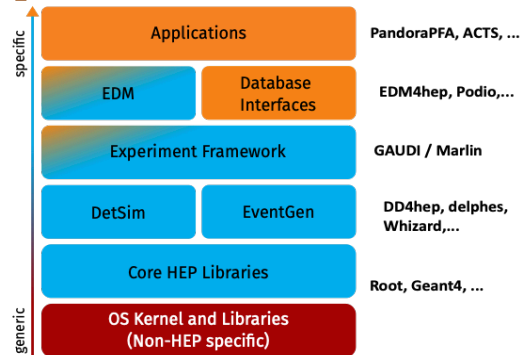
Software experts heavily involved in WG2 organization:
- Frank Gaede
- Gerardo Ganis
- Andrè Sailer

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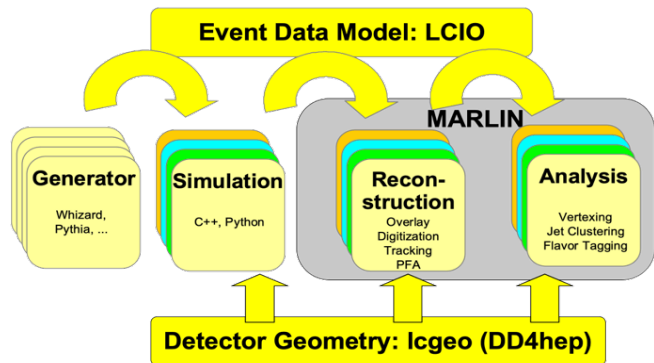- involved communities/contributors: CEPC, CLIC, EIC, FCCee, FCChh, ILC, LUXE, Muon Collider …
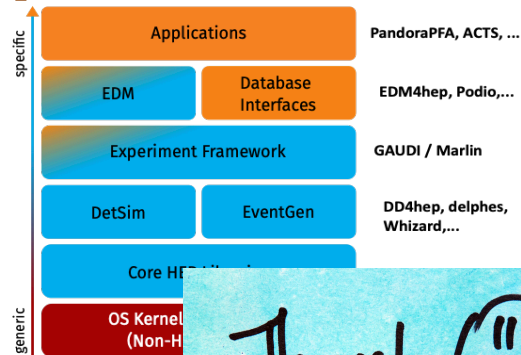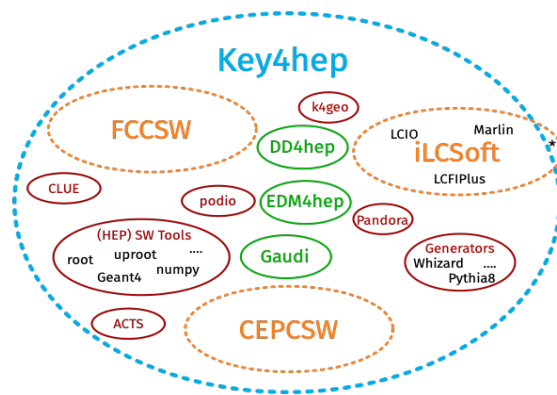
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Generators

- Automated calculations are the standard for LHC
- **Interface through standard event formats is mandatory** to interact with detector simulation and analysis software
- **The theoretical accuracy of LEP results needs to be pushed down for future e+e- machines.** This demands systematic improvements in the control of radiative corrections in the SM.
- **Benchmarking and tuned comparisons essential to establish technical precision and estimate theoretical accuracy**

Generators: update and extend

LEP era generators:
- Pythia
- Herwig
- KKMC
- Babayaga, BHLUMI (specialized)

LHC era generators:
- Madgraph
- Sherpa

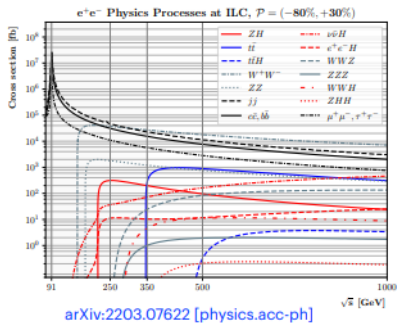**Modern e+e- era generators**:
- Whizard
- CIRCE (specialized)

Beamstrahlung:
- machine dependent (Guinea Pig)
- Input to Generators (MADGRAPH, Whizard)
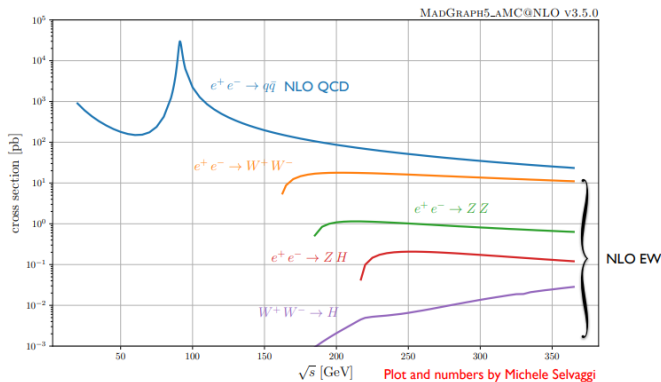- Provide a consistent set for all machines
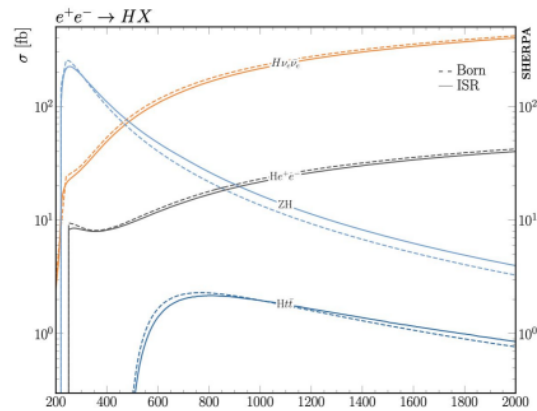
Editors: Thorsten Ohl, Daniel Schulte

QED:
- ePDF, QED Parton Shower and Yennie-Frautchi-Suura resummation

arXiv:2203.07622 [physics.acc-ph]

Whizard e+e-

MadGraph5_aMC@NLO v3.5.0

Plot and numbers by Michele Selvaggi

MADGRAPH e+e-

SHERPA e+e-

Generators: new Benchmarking tool

Editor: Alan Price

many generators claim the same precision (w/ differing approaches)

- Attobarn data with N^nLO under control needs high precision in generation
- Technical Benchmarks
  - first order: cross section
  - second order: differential distributions
- k4GeneratorsConfig in KEY4HEP for steering

```
Generators:
  - Sherpa
  - Whizard
  - Madgraph
  - KKMC
  - Pythia

OutputFormat: hepmc3
OutDir: Run-Cards
Events: 10000
EventMode: unweighted

SqrtS: 91.2
Model: SM
ISRMode: 0

Processes:
  Muon:
      Final: [13, -13]
      Order: [2,0]

  Tau:
      Final: [15, -15]
      Order: [2,0]

Sherpa:
  Run:
      EW_SCHEME: 3

ParticleData:
  23:
      mass: 91.1876
      width: 2.4952
```


$e^+e^- \to \mu^+\mu^-$

KKMC
Madgraph
Sherpa
Whizard
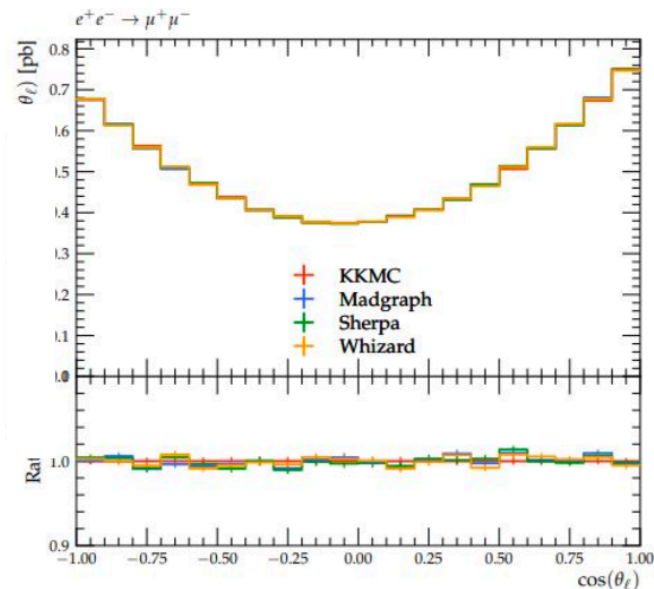
Generator Section in the Report

Editors: Carlo Carloni Calame, Jurgen Reuter, Marco Zaro

- **Preliminary** outline:

  (1) Hard processes: NLO QCD + NLO EW in the SM, NNLO

  (2) Initial state radiation: LL/NLL ePDFs / YFS (coll. vs. soft resummation)

  (3) Beam spectra: parameterized, simulated, Gaussian

  (4) Parton showers and hadronization, incl. matching

  (5) BSM simulations

  (6) Dedicated processes with dedicated tools/implementations:

    Bhabha, rad. Bhabha, $e^+e^- \to \gamma\gamma$, WW & $t\bar{t}$ thresholds

  (7) Connection to software frameworks, event formats, and all that

Physics Analysis Tools:Geometry

- DD4HEP can support the full life cycle of the experiment
- **single source** of information for full **simulation, reconstruction, conditions, alignment, visualisation and analysis**
  - used by CEPC, CLIC, CMS, EIC, FCC, ILC, LHCb, ...
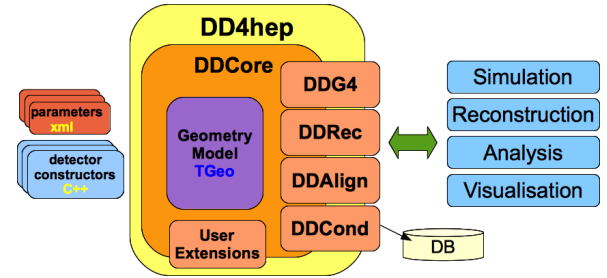
DD4hep: de facto industry standard

SiD

CLICdet

ILD

CLD

ALLEGRO

IDEA
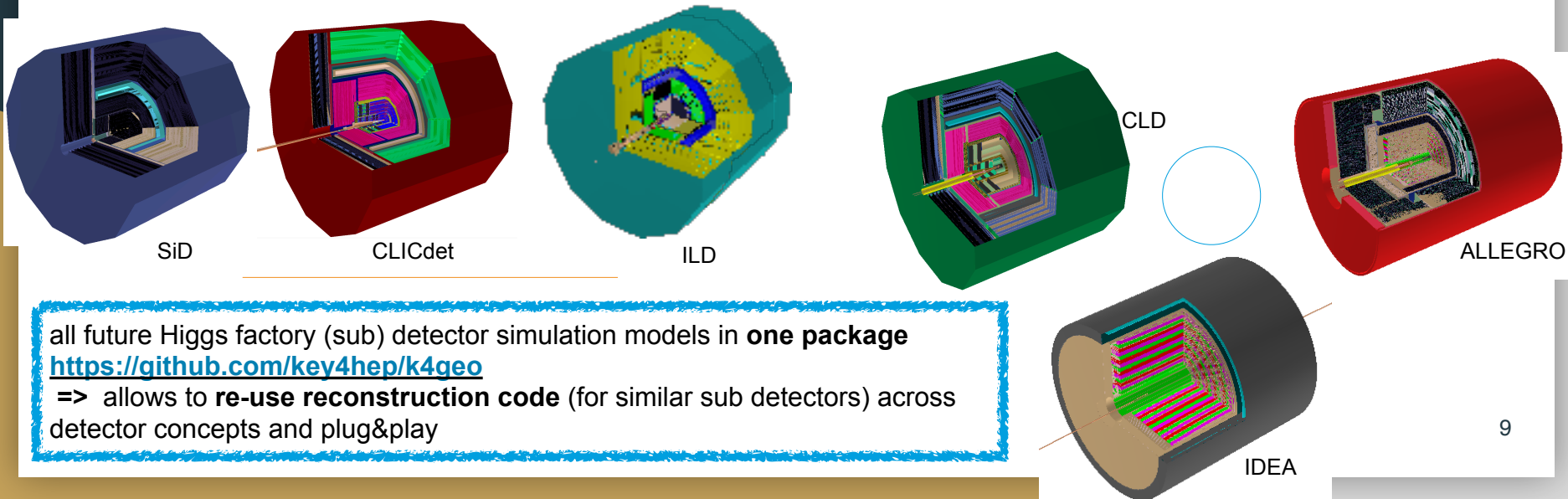
all future Higgs factory (sub) detector simulation models in **one package**
https://github.com/key4hep/k4geo
 => allows to **re-use reconstruction code** (for similar sub detectors) across detector concepts and plug&play
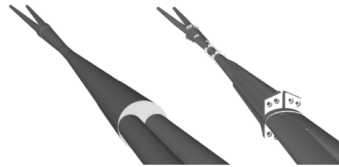
Physics Analysis Tools: Simulation

Editors: Andrè Sailer, Brieuc Francois, Daniel Jeans

Key4Hep helps new full simulation:

- tremendous effort by all groups
- necessary for detailed understanding of performance
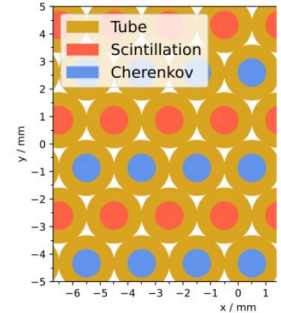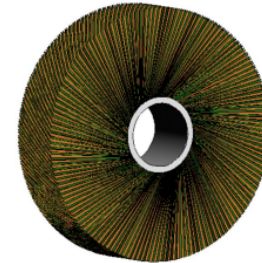- enabled by exchangeability of subdetectors (devil is in the details)
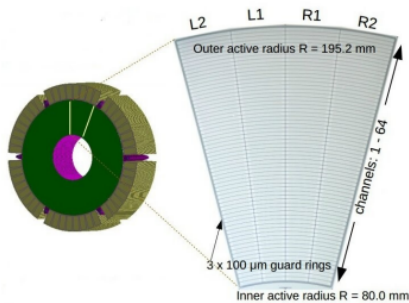
MachineDetectorInterface (MDI):
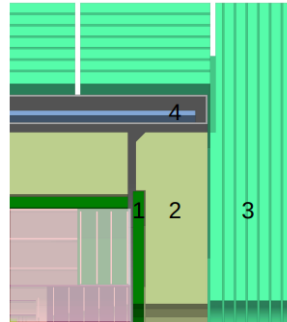
- FCC
- ILD@FCC

Tracking:

- Si+Gaseous (TPC or Drift Chamber IDEA)
- Si+Si

SiW Luminometer for ILC, FCC and CEPC:

Lumimeter geometry

Muon chambers RPC ParticleID ARCH (before Calo)

Calo:

- Calo Type 1: SiW with concurrent simulation of two HCALs
- Calo Type 2: Noble Liquid+TileCal
- Calo Type 3: Dual readout (scintillation+cerenkov)

Physics Analysis Tools: Reconstruction

SWEcosystem simplifies re-optimization for diffferent detectors. Huge spike in ML-assisted algorithm development with improved performance compared to the past

Editors: Loukas Gouskos, Taikan Suehara, Ulrich Einhaus

Track reconstruction:
- Cellular automatons+kalman extrapolation
- Conformal
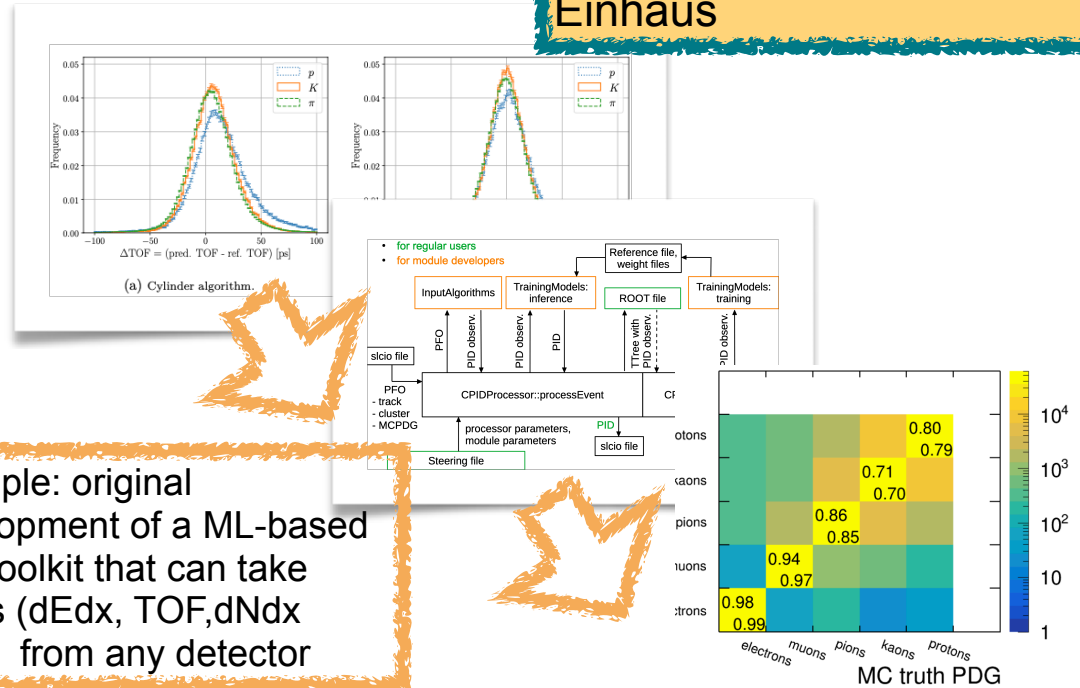- ACTS (in progress)
- GNN(in progress)

Calo Clustering:
- CLUE alg (energy density based from HGCAL)

Particle Flow:
- ARBOR (LLR and CEPC)
- Pandora
- ML/AI (on simplified events)

High Level:
- Particle ID
- Vertexing
- jet reconstruction (Fastjet)
- Flavour tagging

Example: original development of a ML-based PID Toolkit that can take inputs (dEdx, TOF,dNdx etc...) from any detector

Reconstruction: Jet Tagging

- Jet flavor tagging, a nice example of cross project collaboration:
- Originally developed for FCC (circular) as ParticleNetIDEA (from ParticleNet-CMS)
- Implemented for ILD to newer ParticleTransformer: clear improvement on the old standard (DNN etc) LCFIPlus
- Strange tagging becoming a serious opportunity for physics measurements
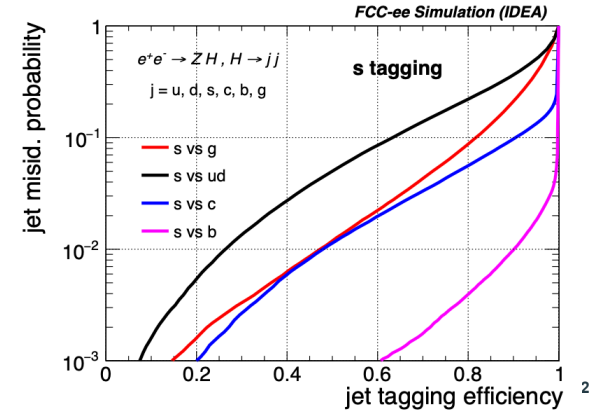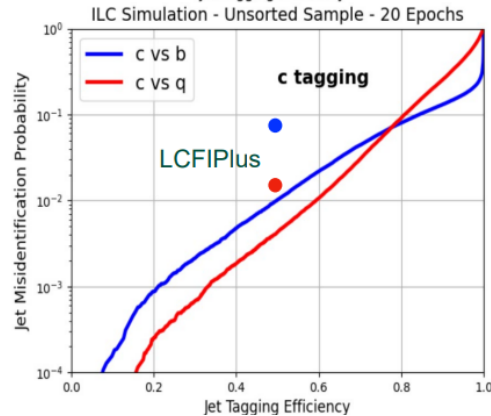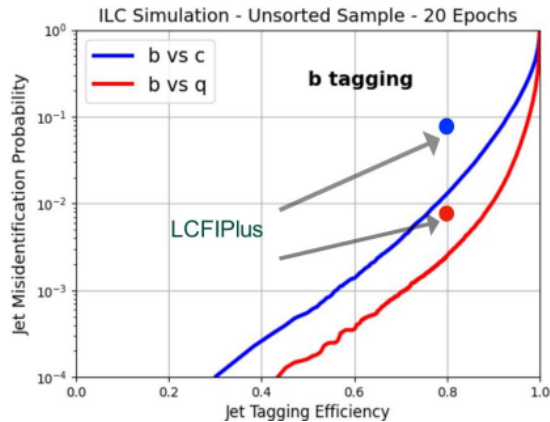
How did we make it happen?

- Obviously most of the technical work concerning analysis tools and performance studies happened inside the different projects (FCC-PED, IDT,C3 etc...)
- The WG2 served as a forum to:
  - **efficiently** share technical knowledge, not only concerning lepton colliders, but also coming from the LHC experience and B-factories
  - **optimize** the solution of common issues
  - **highlight** the new needs and **provide** solutions within a common software ecosystem
- **Through these activities, we have built new connections and expertise to be able to have a united community that would operate successfully a lepton collider and extract physics measurement with the precision the world needs.**

The last stretch

- A big big **thank you** to all our editors and authors, and all the participants to the WG2 effort during these years.
- The draft of the report is due very soon: it's the last stretch
- **From us conveners: it has been our pleasure to be able to create a forum that has brought to the development of such a large number of new ideas and common tools and connections across projects.**
- We'll see you all soon at the European Strategy Symposium in Venice Lido June 2025!

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