COFFEA (ˈkôfē):

Columnar Object Framework For Effective Analysis

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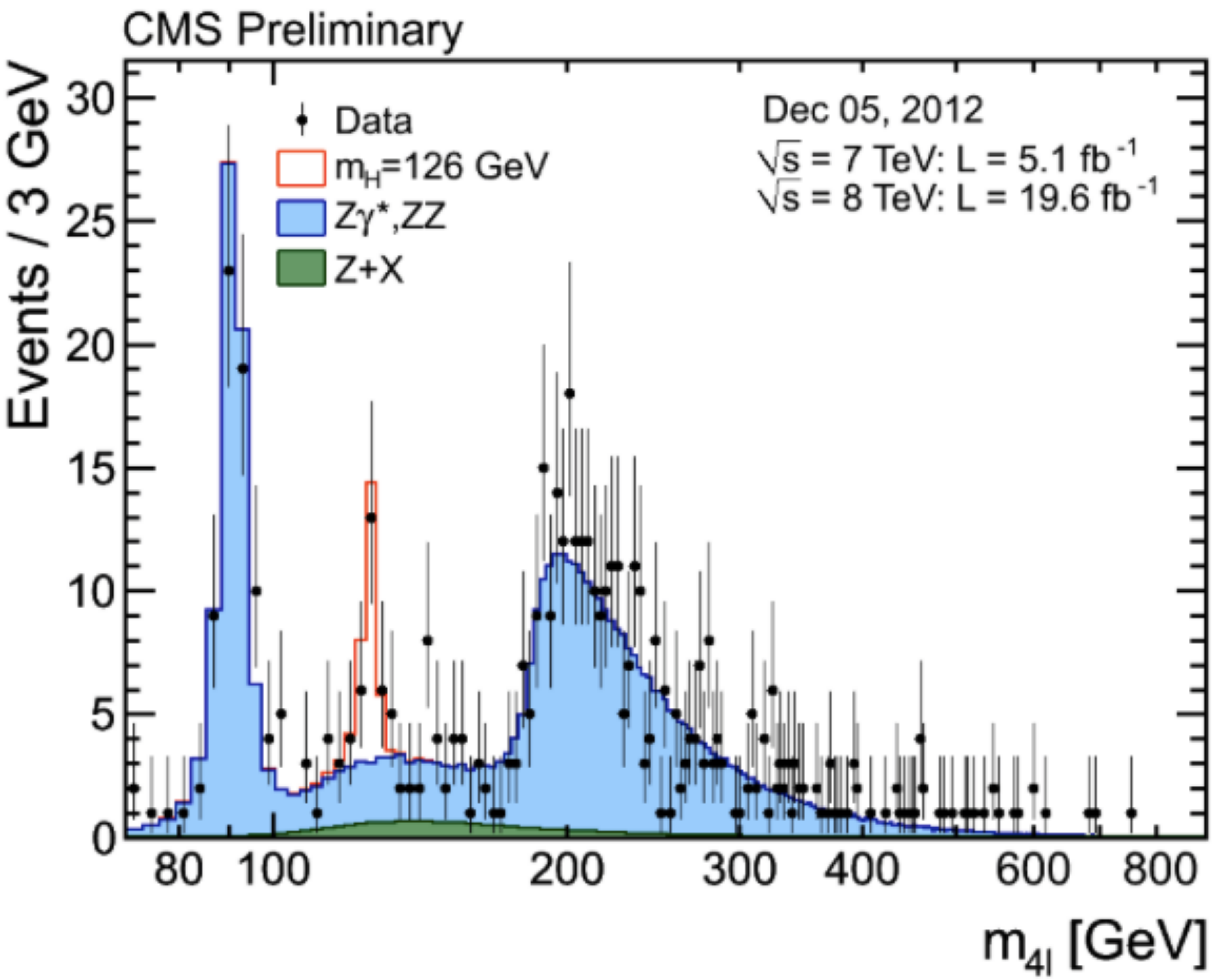
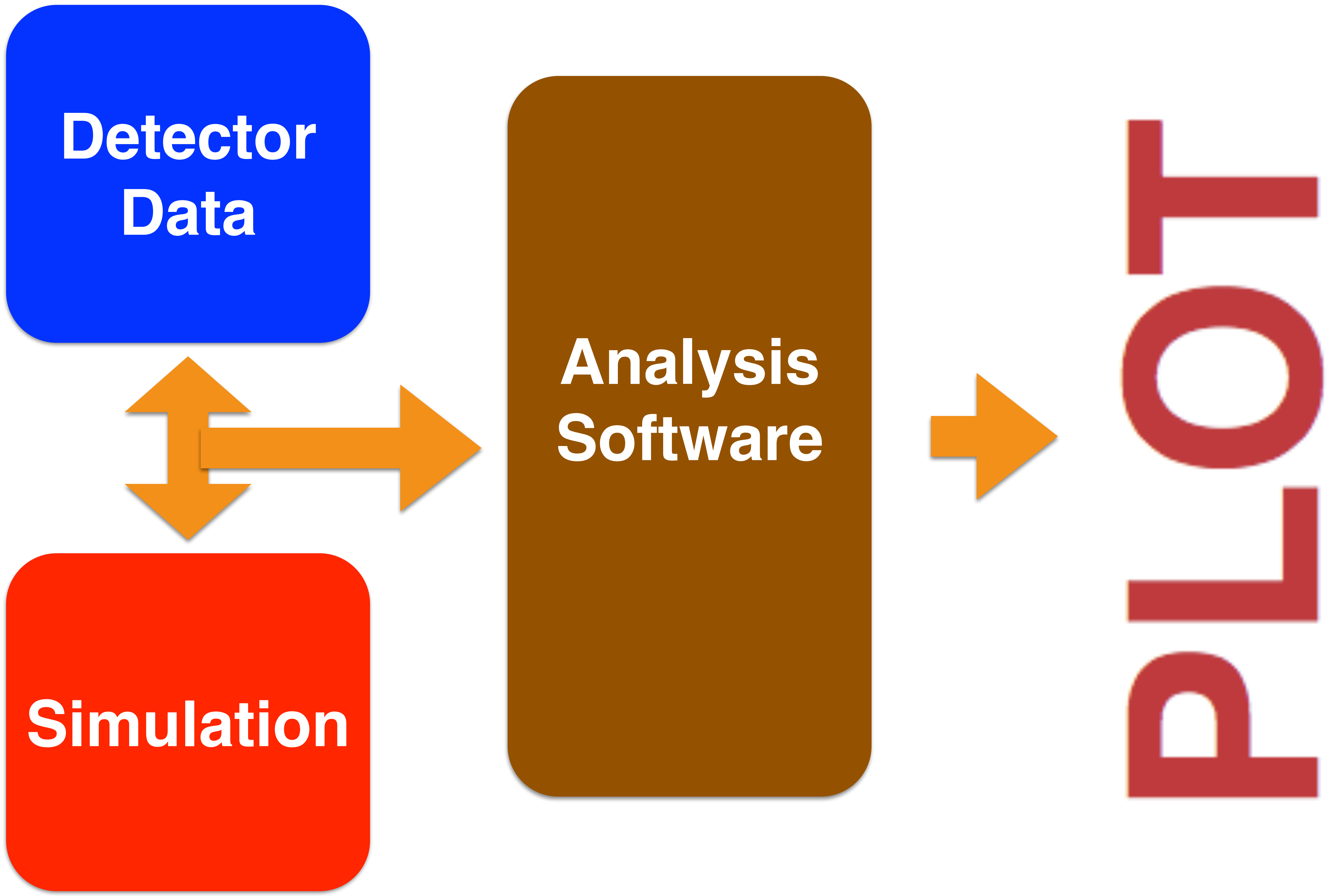
Scientific Method in HEP

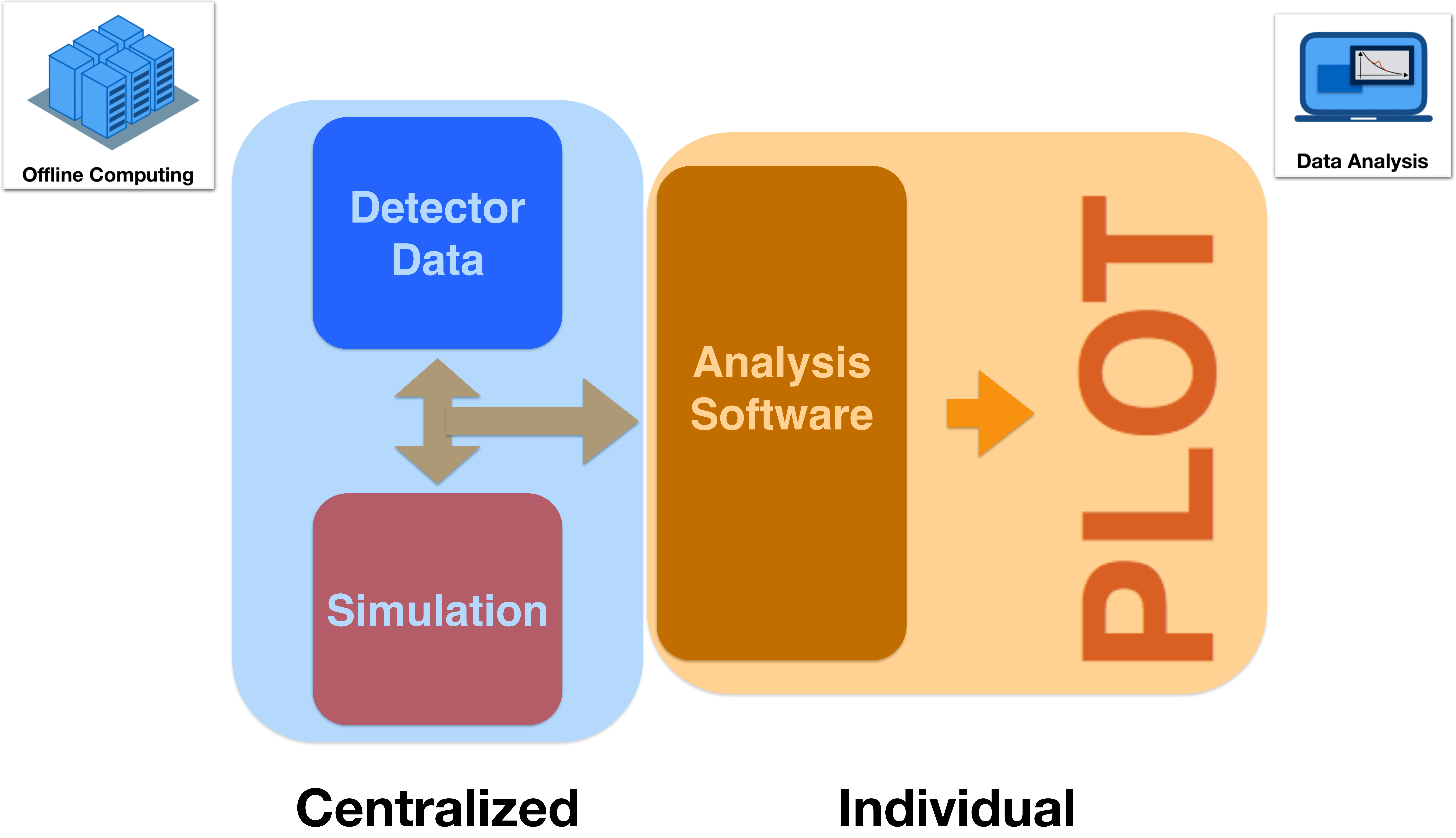
- From an hypothesis derive predictions, test the predictions in the real world
- In HEP: generate simulations based on theory, compare simulations with data

Discovery of the Higgs boson at the Large Hadron Collider



- Black dots: recorded data
- Blue shape: simulation
- Red shape: simulation of new theory (in this case the Higgs)


Detector Data
Simulation
Analysis Software
PLOT

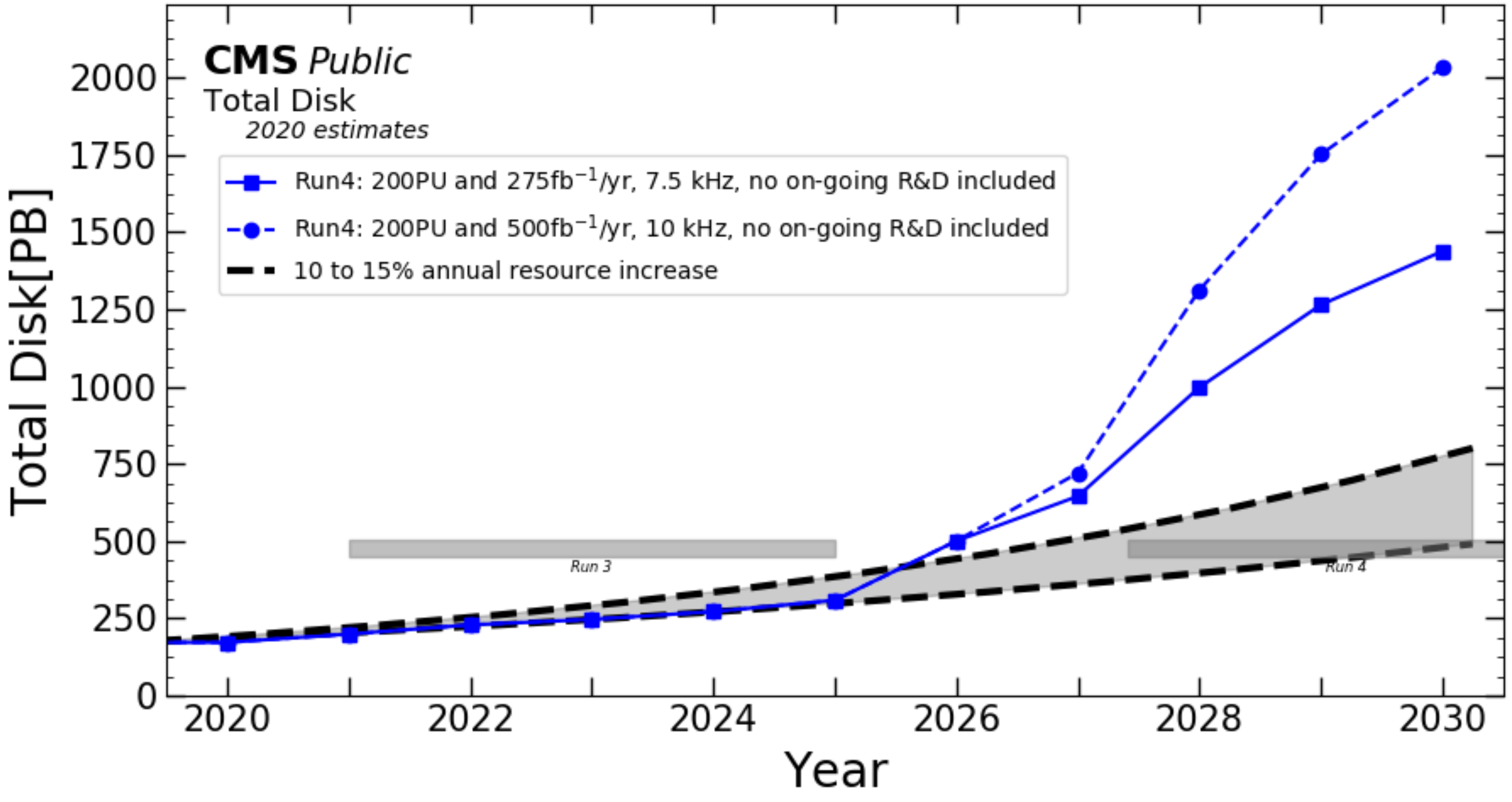

Offline Computing
Data Analysis
Detector Data
Simulation
Analysis Software
PLOT
Centralized
Individual

Organizational Aspects

- Large collaborations:
  - Thousands of particle physicists from hundreds institutes and universities from more than 40 countries
- Central production:
  - Large volume of simulation/data
    - Billions of events
  - Grid computing model
    - 300k+ CPU cores over 70+ sites spread all over the world
- Individual analysis
  - 100+ teams, all using different analysis software
  - Almost 1:1 correspondency between published papers and PhD students
    - Analysis are usually lead by the most inexperienced

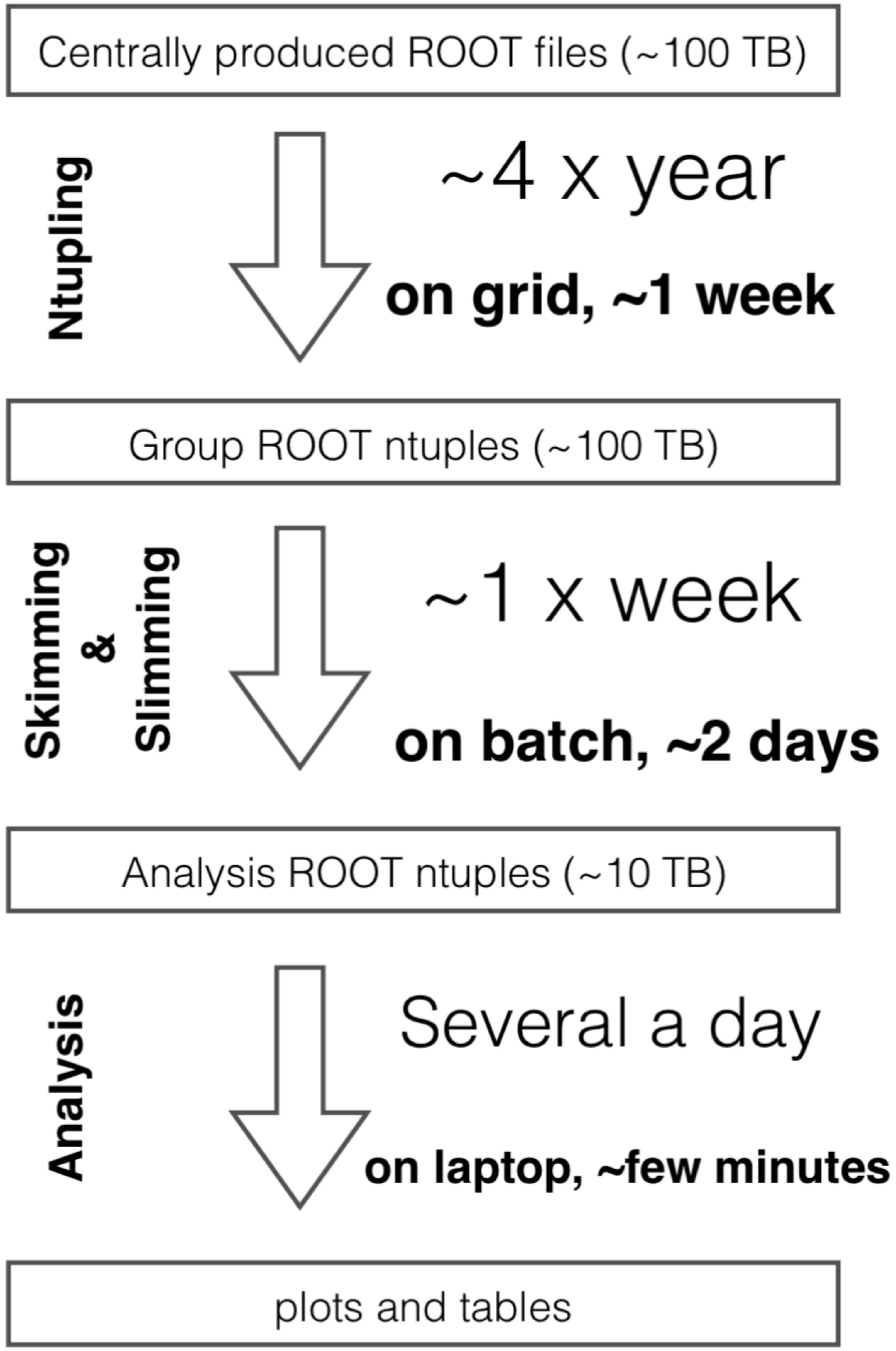
Data Volume

- Extract physics results require to handle/analyze a large datasets
  - Hundreds of PBs
  - Will increase to EBs in the next decade
- Inefficiencies result in:
  - Waste of storage space
  - Large time-to-insight
    - ~ days to weeks
- Already unsustainable



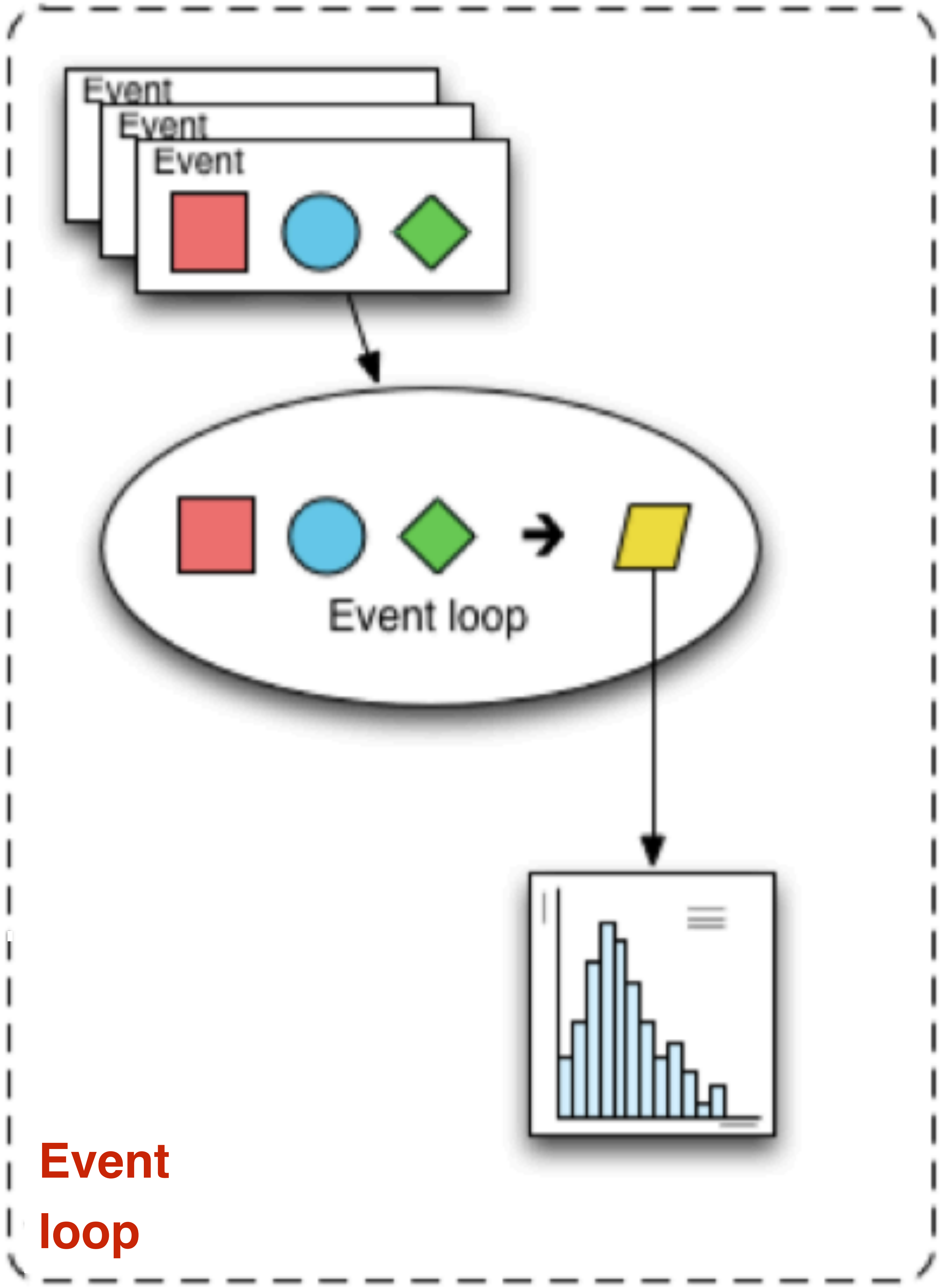
Inefficiencies of a Typical Analysis Code

- Waste of storage space
  - Each step of the analysis workflow writes intermediate output
- Large time to insight
  - Each step of the analysis workflow takes significant time to be completed
- Why?
  - Same data representation and computing paradigm of central production are used, but for individual applications



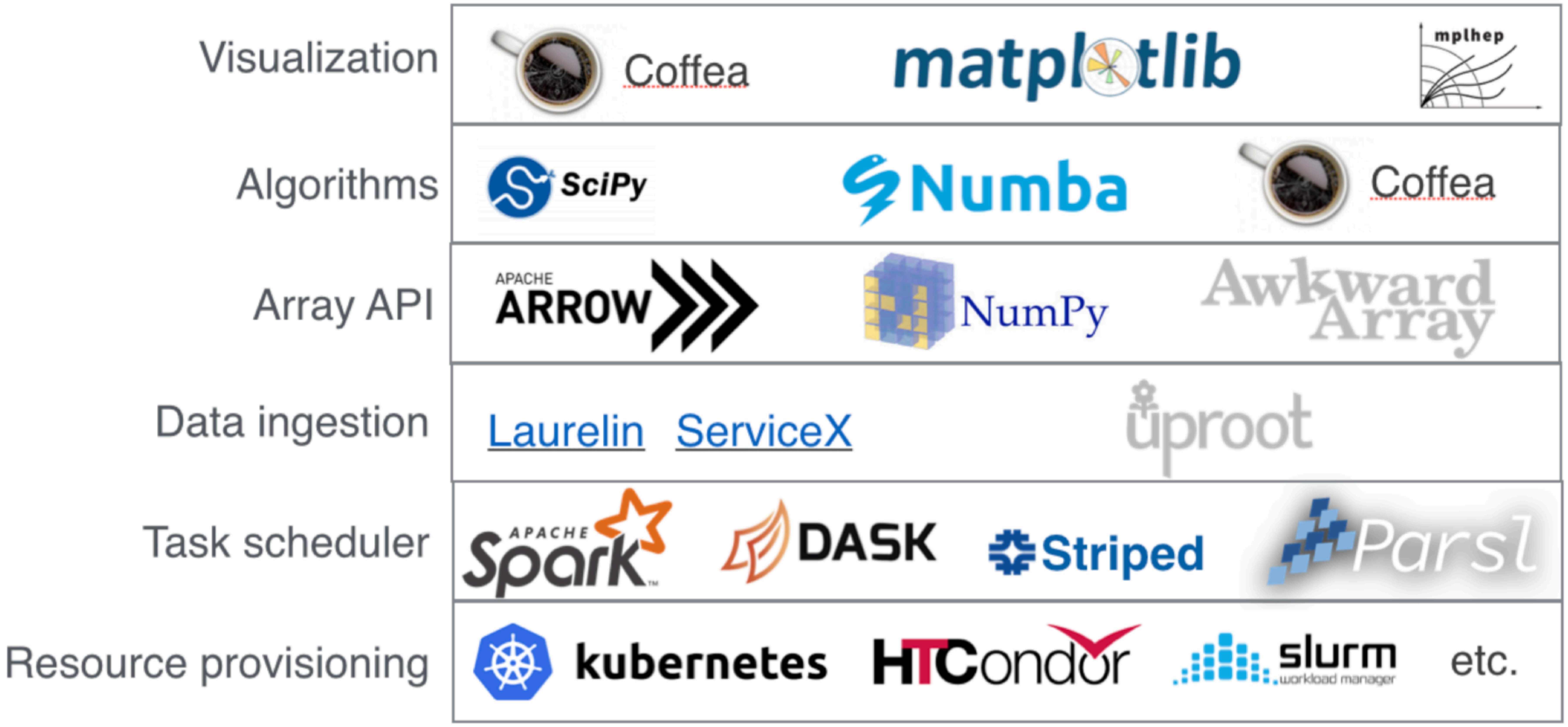
Event Loop Analysis of ROOT Files

- File-based data representation in ROOT format
  - Each file is a collection of events
- Event loop analysis of a ROOT file
  - Load relevant values for a specific event into local variables
  - Evaluate several expression
  - Store derived values in new ROOT files
    - Duplicating the variables that were not manipulated, but that will be needed later on
  - Repeat



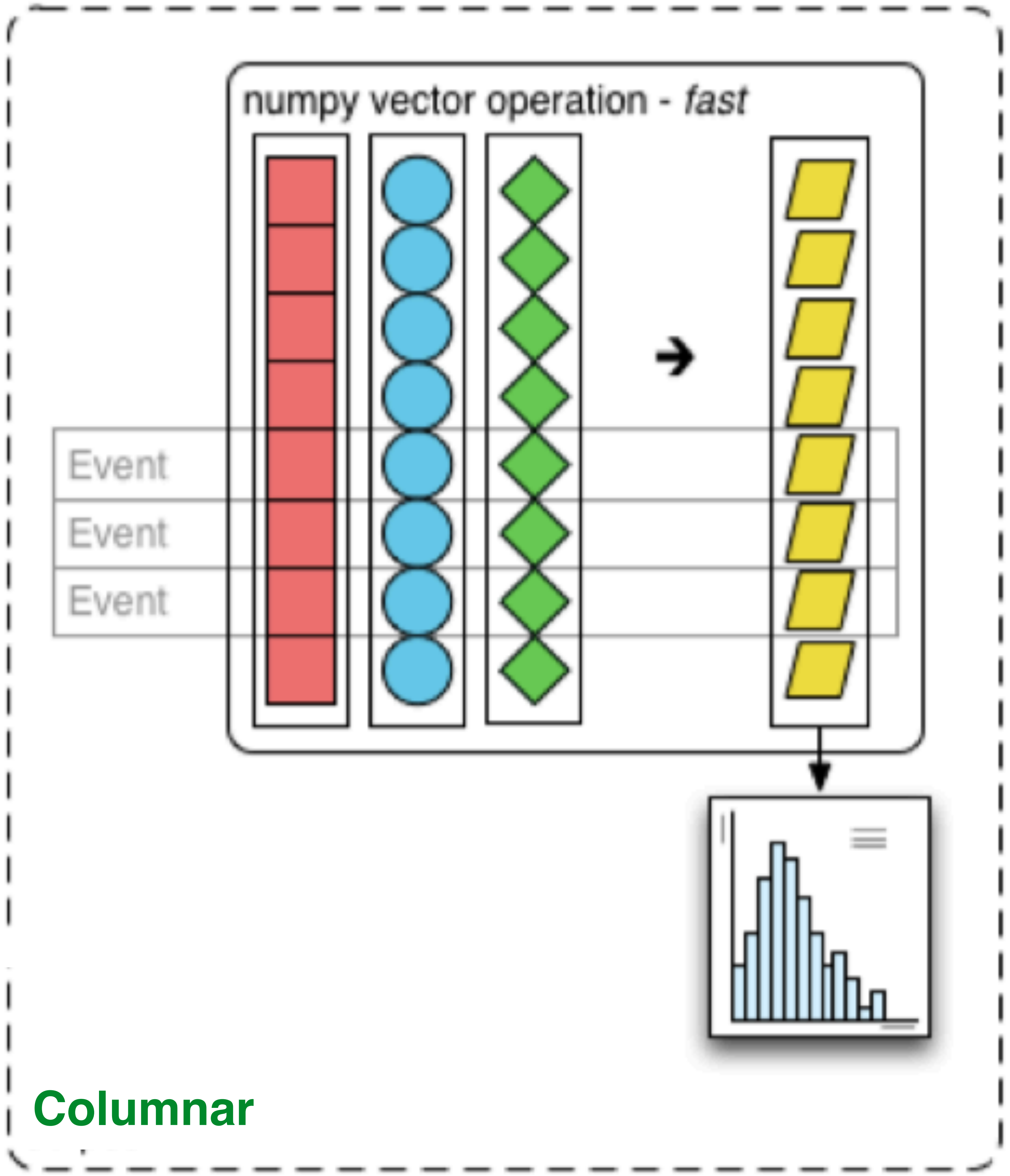
What is COFFEA?

A package in the scientific python ecosystem that provides a user interface for columnar analysis in HEP



Columnar Analysis: A Paradigm Shift

- Columnar data representation
  - Load relevant values for many events into contiguous columns
  - Events are rows
- Columnar analysis
  - Evaluate array programming expressions
    - Simple vector operations to act on an entire columns at once
    - **No explicit loops**
  - Store derived values in new contiguous columns
    - **No new files written on disk**



Main Benefits of COFFEA

- Ease of use and readability
  - Column analysis is a higher-level description of manipulations than an event loops
  - **Code is human-readable**
- Efficient code
  - Columnar analysis aligns with strengths of modern CPUs
  - **Make it easy to write computationally efficient code**
- Community support
  - **Take advantage of off-the-shelf tools from data science**

What COFFEA Provides

- Physicist friendly tools for column based analysis
  - Implements typical recipes needed to operate on NanoAOD-like ntuples
    - histogramming, plotting, and look-up table functionalities for weights and MC corrections
  - Supplies facilities for horizontally scaling
- Currently in https://github.com/CoffeaTeam/coffea
  - `pip install coffea`
- Realized using:
  - Scientific python ecosystem:
    - numpy, numba, scipy, matplotlib
  - Awkward-array:
    - array programming primitives to handle “Jagged Arrays”

HEP Data in Columnar Form: Jagged Arrays

HEP data is not “rectangular”:

- Cannot be represented as a flat table
  - different numbers of muons/electrons/jets etc in each event
- Can be represented as arrays of variable-length (jagged arrays)
  - https://github.com/scikit-hep/awkward-array

Muon pt: table

Event 1	***40.2***	***25.6***	***10.2***
Event 2	***71.1***	***35.7***	
Event 3	***52.3***		
Event 4	***34.5***	***15.7***	

Muon pt: jagged array

[[***40.2*** ***25.6*** ***10.2***] [***71.1*** ***35.7***] [***52.3***] [***34.5*** ***15.7***]]

Event 1 Event 2 Event 3 Event 4

Apply Selections: Masking Jagged Arrays

To apply selections, one uses a *mask*:

mu_pt = [[40.2 25.6 10.2] [71.1 35.7] [52.3] [34.5 15.7]]

mask = (mu_pt > 30) = [[T F F] [T T] [T] [T F]]

mu_pt[mask] = [[40.2] [71.1 35.7] [52.3] [34.5]]

Note that there was no explicit for loop over the events, and the mask was applied to each muon in each event

Coffea `processor`

- Abstraction to encapsulate analysis code
- Keep it separate from input column delivery and output reduction (i.e. histogramming)
- Defines the analysis selections, weights, and output histograms
  - Input: dataframe of awkward arrays
  - Output: histograms, counters, small arrays

```python
from coffea import hist, processor

class MyProcessor(processor.ProcessorABC):
    def __init__(self, flag=False):
        self._flag = flag
        self._accumulator = processor.dict_accumulator({
            # Define histograms
        })

    @property
    def accumulator(self):
        return self._accumulators

    def process(self, df):
        output = self.accumulator.identity()

        # PHYSICS GOES HERE

        return output

    def postprocess(self, accumulator):
        return accumulator

p = MyProcessor()
```

Coffea `executor`

- Handles the interaction with the column delivery mechanism
  - communicating with back-end scale-out systems
    - Dask, Spark, Parsl, HTCondor
- Once defined, your `processor` can be passed to different executors with a single line change

NanoEvents

- Coffea utility to wrap the CMS NanoAOD format into a single awkward array, with:
  - appropriate object methods, such as Lorentz vector methods
  - cross references
  - nested objects
- Instantiate an event object reading a NanoAOD file:

```
import awkward as ak
from coffea.nanoevents import NanoEventsFactory, NanoAODSchema

fname = "https://raw.githubusercontent.com/CoffeaTeam/coffea/master/tests/samples/nano_dy.root"
events = NanoEventsFactory.from_root(fname, schemaclass=NanoAODSchema).events()
```

- Access the energy of the GenJets:

```
events.GenJet.energy

<Array [[217, 670, 258], ... 16], [76.9]] type='40 * var * float32'>
```

Processor Code Examples

- Python allows very flexible interface, under-the-hood data structure is columnar
- One line of code to define analysis objects with NanoEvents:

```
electrons = events.Electron
```

- One line of code to define the mask to select tight electrons:

```
electronSelectTight = ((electrons.pt>35) &
                       (abs(electrons.eta)<2.1) &
                       (abs(electrons.eta) < 1.4442) | (abs(electrons.eta) > 1.566) &
                       (electrons.cutBased>=4)
                      )
```

- One line of code to select tight electrons from all events - **no** explicit for loop over electrons!

```
tightElectron = electrons[electronSelectTight]
```

- One line of code to define events passing tight electron requirements - **no** explicit for loop over events!

```
eventSelection = (ak.num(tightElectron) ==1)
```

Using COFFEA for CMS Analysis

- Tens of analysis in CMS have already adopted COFFEA
  - User community is growing, ~40/50 people contributing at some extent
  - Some analyses go from centrally produced NanoAOD directly to plots, with no usage of standard tools
- Results
  - No intermediate output written on disk
    - **Directly from inputs to plots**
  - Analysis turn-around time reduced by more than two order of magnitudes
    - **From days to hours**

Conclusions

- An innovative tool has been developed for data analysis in particle physics
  - It pioneers the utilization of columnar analysis
- It addresses the main issues that affect the current way of doing analysis
  - Shortage of disk space
  - Long time-to-insight, limited interactivity
- It is a real-world solution
  - It takes into account the constraints, does not require organizational changes or additional resources
  - Already used for publishable (or already published) results

Documentation

- Coffea documentation
  - https://coffeateam.github.io/coffea/
- Simple examples (with comments) for IRIS-HEP benchmarks*
  - https://github.com/mat-adamec/coffea-benchmarks/tree/master/benchmarks
  - *Set of tasks designed to demonstrate and compare usability against other analysis systems
- Coffea users egroup: cms-coffea-users.cern.ch
  - Biweekly coffea users meeting on Mondays

Backup

Baby Ecosystem

- Coffea serves as incubator for rapid prototyping of missing pieces in our ecosystem. Good abstractions are factored out.