Readable and efficient HEP data analysis with bamboo using python, PyROOT, cling, and RDataFrame

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• change a selection, and compare N plots between the two cases

• add a correction that a) is a per-event weight, or b) changes object kinematics, and/or c) tracks changing detector conditions — only for simulation, not for data
• add a higher-statistics sample that covers part of the phasespace of an already included one
• include systematic variations
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Personal experience: need for speed makes analysis code messy (hard to find bugs), inflexible, or both
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There are many ideas to address this problem — this is only one attempt, based on what seemed promising for my use-case

Image credit: Claudio Caputo

(Definition of not see the wood for the trees from the Cambridge Advanced Learner’s Dictionary & Thesaurus © Cambridge University Press)
RDataFrame: ROOT’s declarative data analysis approach

Analyses as computation graphs

ROOT::RDataFrame df(dataset);
auto df2 = df.Filter("x > 0")
  .Define("r2", "x*x + y*y");
auto rHist = df2.Histo1D("r2");
auto g = df2.Graph("x","y")

e. guiraud, “rdataframe”, root users’ workshop 2018

From this talk, see also today’s CERN EP Software Seminar
Cling (C++ interpreter / JIT compiler) and PyROOT

• The ROOT interpreter is based on Clang/LLVM: correctly handles almost any valid modern C++ code (templates, lambda functions...)

• PyROOT exposes almost all of ROOT’s functionality in python (and that of any C++ you add)

• Experimental PyROOT is bringing python callables to RDataFrame (and much more)

• Current bamboo compromise: pass expressions to RDataFrame as strings (generated with python)
bamboo ingredients — outline for the rest of the talk

• High-level python analysis code to define plots and selections (using loops, functions that take function arguments etc.)
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• When the analysis is complete: convert expressions to strings for RDataFrame, run over all samples, and make plots

• Every analysis derives from a base class, such that e.g. splitting in batch jobs, and plotting code can be reused
Why decorate TTrees?

Example: plot a dimuon invariant mass distribution. The momenta are in the branches Muon_pt[nMuon], Muon_eta[nMuon], Muon_phi[nMuon], and Muon_mass[nMuon] (and there may be more than two muons in the event)
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```cpp
using ROOT::Math::VectorUtil::InvariantMass;
using LorentzVector = 
    ROOT::Math::LorentzVector<ROOT::Math::PtEtaPhiM4D<float>>;
df.Define("Dimuon_mass",
    [] (const auto& pt, const auto& eta, const auto& phi, const auto& m) {
        return InvariantMass(LorentzVector(pt[0], eta[0], phi[0], m[0]),
            LorentzVector(pt[1], eta[1], phi[1], m[1]));
    },{"Muon_pt","Muon_eta","Muon_phi","Muon_mass"}).Histo1D(..., "Dimuon_mass", ...);
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            LorentzVector(pt[1], eta[1], phi[1], m[1]));
    }, {"Muon_pt", "Muon_eta", "Muon_phi", "Muon_mass"});
).Histo1D(..., "Dimuon_mass", ...);

Alternative, using the JIT compiler instead of a lambda function

df.Define("Dimuon_mass_v2",
    "InvariantMass("
        "LorentzVector(Muon_pt[0], Muon_eta[0], Muon_phi[0], Muon_mass[0]),"
        "LorentzVector(Muon_pt[1], Muon_eta[1], Muon_phi[1], Muon_mass[1]))")
).Histo1D(..., "Dimuon_mass_v2", ...);
```
Why decorate TTrees?

bamboo equivalent:

```python
from bamboo import treefunctions as op
Plot.make1D(...,
    op.invariant_mass(t.Muon[0].p4, t.Muon[1].p4), ...)
```

• The example on the previous slide assumes no selection or sorting is needed (could e.g. keep a list of indices with sorted good muons)

• For jets: need to take different branches for systematic variations

• In practice: need to compose, e.g. invariant mass of the two highest-pT b-tagged jets that are not within ΔR < 0.3 from any selected muon

Solution to #3:

```python
 cleanedBJets = op.select(t.Jet, lambda j : op.AND( op.NOT(op.all(muons, lambda mu : op.deltaR(mu.p4, j.p4) < 0.3)), j.bTag > 0.6))
Plot.make1D(..., op.invariant_mass(cleanedBJets[0].p4, cleanedBJets[1].p4), ...)
```

Not the fairest comparison — just to show how this can make code simpler
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Solution to #3:

```python
cleanedBJets = op.select(t.Jet, lambda j : op.AND(
    op.NOT(op.rng_any(muons, lambda mu : op.deltaR(mu.p4, j.p4) < 0.3)),
    j.bTag > 0.6))
Plot.make1D(...,
    op.invariant_mass(cleanedBJets[0].p4, cleanedBJets[1].p4), ...)
```

Not the fairest comparison — just to show how this can make code simpler
Expressions

• are composed of simple python objects, e.g. t.Muon[0].pt (Muon_pt[0]) becomes GetItem(GetArrayLeaf("Muon_pt"), 0)

• can be converted to a string for RDataFrame/JIT

• are considered immutable as soon as they are fully constructed and passed around (but a fresh clone can be modified by the owner)

Proxies

• Wrap an expression

• Emulate the value type of expression’s result (through python operator overloading and other magic methods)

• float-like, integer-like, object-like, and a few list-like classes — but no complete type system (yet), so limited checks at construction

Currently each of these interfaces has about 25 implementations — the user should only need the decorated tree and the bamboo.treefunctions module
Implementation: tree decorations

- Tree proxy class generated on the fly, based on the branches that are found
- By default, each branch is an attribute of the tree proxy (the class is generated with `type()`)

image credit
Pieter David (UCLouvain)
Implementation: tree decorations

- Tree proxy class generated on the fly, based on the branches that are found
- By default, each branch is an attribute of the tree proxy (the class is generated with `type()`)
- Groups of non-array branches: “group proxy” in between: `t.HLT.MuXX`, `t.pdf.x1`
- Groups of array branches: container proxy, and a proxy for the elements: `t.Muon[0].IDLoose`
- Can also add references and arbitrary functions: `t.Jet[0].Mu1.pt`, `t.Muon[0].p4.E()`
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- Can also add references and arbitrary functions: `t.Jet[0].Mu1.pt, t.Muon[0].p4.E()`
- Needs to be adapted to recognize different tree formats, but for *flat trees* (most common) this is fairly straightforward (examples are from CMS NanoAOD, one other format is implemented)
Selections and plots

Zooming in on the currently main use case of different selections and histograms now (skims also work)

• This only needs two fundamental RDataFrame actions: Filter and Histo{1D,2D} (and Define, to calculate intermediate values)

• Important distinction: Filter changes control flow, whereas the others do not — so there is some freedom in ordering the Define nodes (in between the Filter that makes sure the expression is valid and the first use)

Current solution (bamboo.plots):

• Selection class, with each instance (optionally) holding a set of selection requirements (cuts) and weight factors

• Selections are defined by adding cuts or weights to a more inclusive selection (starting point: all events in the input, unit weight)

• Plot instances are defined by a Selection, variable(s), binning(s), and layout options

• RDataFrame nodes are created when Selection and Plot objects are constructed
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Selections and plots: an example

def definePlots(self, t, noSel, sample=None, sampleCfg=None):
    from bamboo.plots import Plot, EquidistantBinning
    from bamboo import treefunctions as op
    plots = []
    muons = op.select(t.Muon, lambda mu : mu.pt > 20.)
    twoMuSel = noSel.refine("dimu", cut=(op.rng_len(muons) > 1))
    plots.append(Plot.make1D("dimu_M",
                           op.invariant_mass(muons[0].p4, muons[1].p4), twoMuSel,
                           EquidistantBinning(100, 20., 120.),
                           title="Dimuon invariant mass"))
    jets = op.select(t.Jet, lambda j : j.pt > 20.)
    plots.append(Plot.make1D("dimu_nAllJets",
                            op.rng_len(jets), twoMuSel,
                            EquidistantBinning(10, 0., 10.),
                            title="Number of jets (uncleaned)")
    cleanedJets = op.select(jets, lambda j :
                             op.NOT(
                             op.rng_any(muons, lambda mu :
                             op.deltaR(mu.p4, j.p4) < 0.3))
    plots.append(Plot.make1D("dimu_nJets",
                            op.rng_len(jets), twoMuSel,
                            EquidistantBinning(10, 0., 10.),
                            title="Number of jets (cleaned)")
    twoMuTwoJetSel = twoMuSel.refine("dimudijet",
                                   cut=(op.rng_len(cleanedJets) > 1))
    plots.append(Plot.make1D("dimudijet_leadJetPT", cleanedJets[0].pt,
                               twoMuTwoJetSel,
                               EquidistantBinning(50, 0., 250.),
                               title="Leading jet PT").
    return plots
Pieter David (UCLouvain)
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Implementation: interface to RDataFrame and Cling

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- When converting an expensive expression to a C++ string, values are defined on-demand by attaching Define nodes (and functions declared with the interpreter as needed; global scope, so can be reused everywhere)
- Much of this needs fast searches through expression trees for dependencies etc., which is achieved by caching the value-based hash of every expression (possible because they are immutable)
$ bambooRun -m myAnalysis.py:BasicPlots mySamples.yml

- Also between the command line and the analysis definition, much code can be shared or reused, e.g. for processing different samples and combining the results in one plot, using a batch system...
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• enable “implicit multi-threading”
Extending the basic functionality

Written in python, and tried to keep things loosely coupled (interfaces), so many things are straightforward to customise and extend:

• Loading additional C++ headers and libraries in the interpreter
Examples: good runs/events filter and scale factors from JSON files, jet and muon energy scale corrections calculated on the fly

• Alternative analysis (base) classes, e.g. for different tree formats, to customise plotting, or to calculate efficiencies in addition

• There is a hook to specify additional command-line arguments from the analysis module

• The sample definition (YAML) is open-ended, the base class only looks at the attributes it needs (e.g. input files, to do the job splitting), and the plotting library at a few more (normalisation for MC, grouping and ordering, colors…)
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If expressions are marked as changing under a certain systematic effect (in the decorations, or explicitly when constructing the expression), the correspondingly varied histograms can be automatically produced.
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Implementation: the backend code scans cuts, weights, and variables for marked nodes, and defines the additional RDataFrame nodes as needed (alternative weights are cheap, but anything used in cuts may change the events passing a filter, so need to branch off, and duplicate subsequent defines).

Quite some bookkeeping, but fully generic (changes to analysis code are minimal), and the code for this is localised in a handful of places.
Future developments and links

- Development status: beta; usable, but moving from a narrow proof-of-concept to actual research, so some interfaces may still change
- Performance: memory usage increases to about 5GB for 5000 histograms (more than expected, under investigation), CPU time acceptable for now ($O(1\text{min})$ for defining plots — compiled code speed for the event loop)
- Being used or evaluated for three CMS analyses — early adopter feedback has been extremely valuable; many thanks, especially to Khawla Jaffel (UCLouvain) and Sébastien Wertz (Universität Zürich)
- Technical requirements: python3.6+, a recent ROOT (6.14/06, 6.16/00 or 6.18/04), and a few python packages (typical installation: with pip in a virtualenv). plotIt (a ROOT-based C++ tool) is used for turning histograms into pdf/png stack plots
- The code is public in this repository, and there is HTML documentation
Conclusion

- RDataFrame is a very powerful tool (especially when paired with Cling for piece-by-piece compilation)
- For actual analysis use: still a lot of bookkeeping to do, especially for flat trees (e.g. indices)
- bamboo is an attempt to bridge this gap, such that the user code is little more than a compact description of the analysis
- Hopefully some (not too) creative uses of python, and interesting ideas
- Started from a simple problem and idea, ended up writing a more general tool... usable, but much room for improvement and additions

Thanks for your attention, I am looking forward to hearing your thoughts/suggestions/criticism and exchange ideas
Additional material
Suggested way to get a recent ROOT release: from the LCG software distribution on CVMFS

Installation (to be improved):

```
source /cvmfs/sft.cern.ch/lcg/views/LCG_95apython3/x86_64-centos7-gcc8-opt/setup.sh
python -m venv myvenv
source myvenv/bin/activate
git clone -o upstream git+https://gitlab.cern.ch/cp3-cms/bamboo.git
cd bamboo/ext
./getjetclasses.sh ## copy some source files from CMSSW
cd -
pip install ./bamboo
```

`plotIt` (for pdf/png output):

```
git clone -o upstream https://github.com/cp3-l1bb/plotIt.git
cd plotIt/external
./build-external.sh
cd..
BOOST_ROOT=$CMAKE_PREFIX_PATH make -j4
cd..
cp plotIt/plotIt myvenv/bin
```

Upload to pip/condaforge is planned
(the bamboo name is taken, so probably bamboo-hep)

CP3SlurmUtils on test.pypi.org, will be uploaded to production PyPI soon