

Julia in HEP

Graeme A Stewart, Benedikt Hegner, Pere Mató - CERN EP-SFT

Thanks also to Tamas Gal





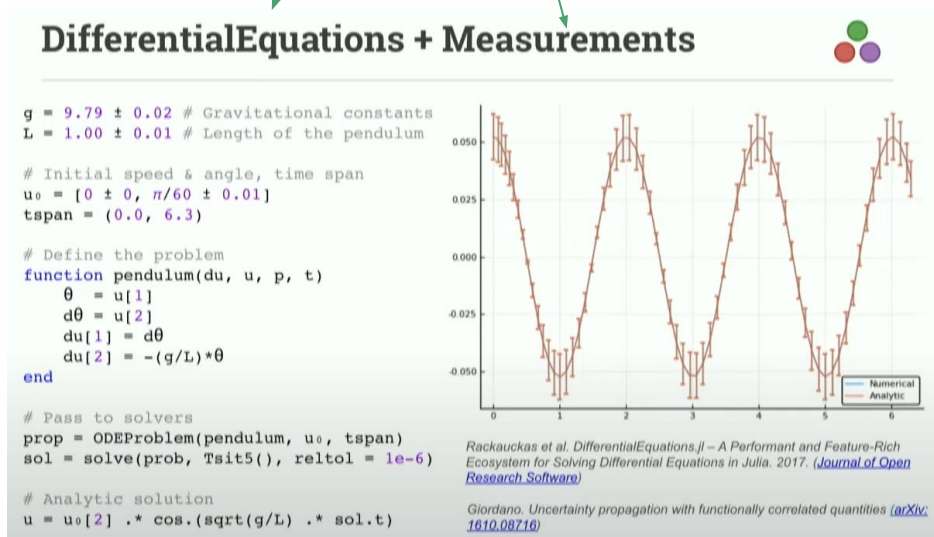
Julia - what's that then?

- The Julia language was launched in 2012 (v1.0 in 2018)
 - New, but not immature!
- Modern imperative language, multi-paradigm with reflection and object orientation
- Robust built-in tooling (learning from earlier languages)
 - Outstanding integrated package manager and build system
 - Module system with excellent code reuse
 - Modern tooling, with built in debuggers and profilers
 - Interactive - REPL and full notebook support (it's the "Ju" in Jupyter)
- Julia has been built from the ground up to be **very fast**
 - JIT compilation via LLVM to native machine code
 - Performance is comparable to C and C++ (as a baseline, see [microbenchmarks](#))

Solving the *Expression Problem*

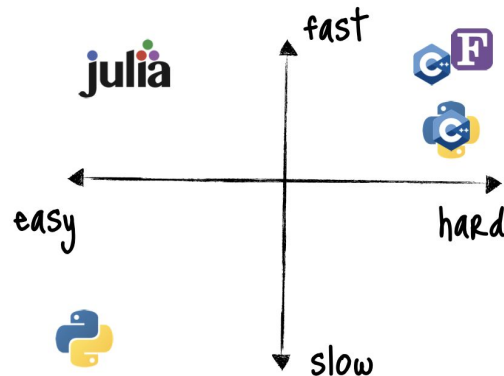
- For code reuse we want to...
 - Define new types to which existing operations apply
 - Easy in OO, hard in functional
 - Define new operations that apply to existing types
 - Hard in OO, easy in functional
- Julia uses the paradigm of multiple-dispatch
 - Generic programming allows different parts of code to mix, JIT keeps everything fast
 - Add new methods to existing generic functions for new types ✓
 - Add new methods to generic functions for existing types ✓

These packages know nothing about each other!



But is Julia interesting for HEP?

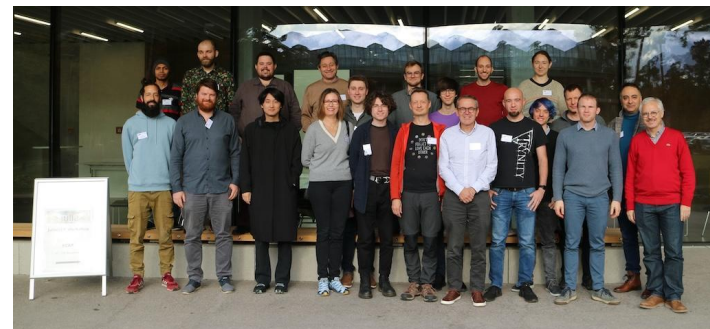
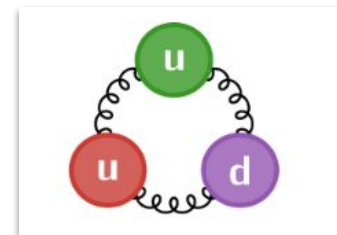
- There exist many languages in the world
 - Each has different strengths and weaknesses
- We think the answer is yes!
 - Julia is specifically designed for numerical programming for science and engineering*
 - So we are the target audience and the support for our use case is strong
 - Julia is much easier to program in than C++
 - Experience shows that students with Python experience can be productive in Julia very quickly
 - Code written in Julia is fast, often close to peak performance
 - The first prototype can evolve naturally into the production code
 - This overcomes the two language problem that we have today
 - We use Python because it's human productive, we use C++ because it's fast
 - We suffer from friction at the interface, plus a general diminishing of skills and interest in C++
 - Wrappers allow integration with existing code in C++ and Python - vital for our existing codes
 - Interfaces needed to ease the use of Julia in HEP are maturing



*Julia used a lot in ASML, Boeing, Pfizer among others

JuliaHEP

- New [HSF working group](#) created after CHEP 2023 to channel community efforts to evaluate and introduce Julia language in HEP
 - A paper on the Potential of the Julia Programming Language for High Energy Physics Computing was in the pipeline at this time and is now published [[Comput Softw Big Sci 7, 10 \(2023\)](#)]
- First [JuliaHEP workshop](#) organised at ECAP in Erlangen, Germany
 - 4 full days (6 to 9 of November)
 - 20 people in person + ~30 people remote
 - An agenda organized with tutorials, keynote presentations, long and short presentations
 - Contributions from key Julia developers (including one of the language founders, Stefan Karpinski)
 - Plenty of time for discussions



Agenda

09:00	Welcome Address ECAP (Erlangen Centre for Astroparticle Physics) 09:00 - 09:15	Unit and Integration testing in modularized Julia package eco-systems ECAP (Erlangen Centre for Astroparticle Physics) 09:00 - 09:15 BinaryBuilder.jl: distributing binary libraries for Julia packages ECAP (Erlangen Centre for Astroparticle Physics) 09:15 - 09:30 Automatic generation of Julia bindings to libraries written C++ ECAP (Erlangen Centre for Astroparticle Physics) 09:30 - 09:45 UnROOT.jl update: RNTuple, PHYSLITE, and future priorities ECAP (Erlangen Centre for Astroparticle Physics) 09:45 - 10:15 HEP.jl - An example how to wrap UnROOT to make ROOT files more accessible ECAP (Erlangen Centre for Astroparticle Physics) 10:15 - 10:25	Simeon Ehrig 09:00 - 09:15 Dr Mose Giordano 09:15 - 09:30 Philippe Gras 09:30 - 09:45 Jerry Ling 09:45 - 10:15 Tamas Gal 10:15 - 10:25	Analysis Grand Challenge with Julia ECAP (Erlangen Centre for Astroparticle Physics) 09:00 - 09:15 Using data frames in Julia to analyse HEP data ECAP (Erlangen Centre for Astroparticle Physics) 09:15 - 09:45 Efficient computation of higher-order cumulants with Julia ECAP (Erlangen Centre for Astroparticle Physics) 09:45 - 10:00 Using Symbolic Regression in Julia to find analytic functions to model low statistics ECAP (Erlangen Centre for Astroparticle Physics) 10:00 - 10:15 StochasticAD.jl: Derivatives of discrete randomness ECAP (Erlangen Centre for Astroparticle Physics) 10:15 - 10:30	Abel-Yehor Krasnopol'ski et al. 09:00 - 09:15 Philippe Gras 09:15 - 09:45 Piotr Kalczyński 09:45 - 10:00 Guni Reddy 10:00 - 10:15 Gaurav Arya 10:15 - 10:30	QED.jl - A Strong-field particle physics ecosystem ECAP (Erlangen Centre for Astroparticle Physics) 09:00 - 09:30 DAG Optimizations for Feynman Diagrams of High-Multiplicity Scattering Processes in Julia ECAP (Erlangen Centre for Astroparticle Physics) 09:30 - 09:45 Using Julia to Accelerate Monte Carlo Event Generation with Neural Importance Sampling ECAP (Erlangen Centre for Astroparticle Physics) 09:45 - 10:00	Dr Llew Hernandez Acosta 09:00 - 09:30 Anton Reinhard 09:30 - 09:45 Tom Jungnickel 09:45 - 10:00
10:00	Coffee Break ECAP (Erlangen Centre for Astroparticle Physics) 10:00 - 10:15 Neutrino.jl: Propagating n-flavour neutrinos through Earth ECAP (Erlangen Centre for Astroparticle Physics) 10:30 - 10:45 Jet Finding in Julia ECAP (Erlangen Centre for Astroparticle Physics) 10:45 - 11:20	Corpuscles.jl - A package to access particle information from the PDG particle catalogue ECAP (Erlangen Centre for Astroparticle Physics) 10:55 - 11:05 Python.jl Particle Database wrangling ECAP (Erlangen Centre for Astroparticle Physics) 11:05 - 11:20 A Julia Event Filter for the ATLAS and CMS LHC Run-2 Data ECAP (Erlangen Centre for Astroparticle Physics) 11:20 - 11:30 BAT.jl, the Bayesian analysis library ECAP (Erlangen Centre for Astroparticle Physics) 11:30 - 11:50 EFTfilter.jl - A tool for combining measurements from different EFTs ECAP (Erlangen Centre for Astroparticle Physics) 11:50 - 12:20	Johannes Schumann 10:25 - 10:55 Johannes Schumann 10:55 - 11:05 Mikhail Mikhasenko 11:05 - 11:20 Tamas Gal 11:20 - 11:30 Oleg Schuch 11:30 - 11:50 Cornelius Grunwald 11:50 - 12:20	Coffee Break ECAP (Erlangen Centre for Astroparticle Physics) 10:25 - 10:55 An Awkward module for round-tripping data structures between Python and Julia ECAP (Erlangen Centre for Astroparticle Physics) 11:00 - 11:15 HS3 - The HEP Statistics Serialization Standard ECAP (Erlangen Centre for Astroparticle Physics) 11:15 - 11:45 Advances in Amplitude Analysis with Julia ECAP (Erlangen Centre for Astroparticle Physics) 11:45 - 12:00 Serializing direct observation experiments to neutrino magnetic dipole moments ECAP (Erlangen Centre for Astroparticle Physics) 12:00 - 12:30	Tamas Gal 10:25 - 10:55 Johannes Schumann 10:55 - 11:05 Mikhail Mikhasenko 11:05 - 11:20 Tamas Gal 11:20 - 11:30 Oleg Schuch 11:30 - 11:50 Cornelius Grunwald 11:50 - 12:20 Jarina Osborne 11:00 - 11:15 Cornelius Grunwald et al. 11:15 - 11:45 Mikhail Mikhasenko 11:45 - 12:00 Rocio Branasda Babonin 12:00 - 12:30	Coffee Break ECAP (Erlangen Centre for Astroparticle Physics) 10:30 - 10:50 Geant4.jl Particle Transportation in Julia ECAP (Erlangen Centre for Astroparticle Physics) 11:20 - 11:55 A common interface for quadrivectors and particles ECAP (Erlangen Centre for Astroparticle Physics) 11:55 - 12:10	Peter Mato 10:30 - 10:50 Johannes Schumann 10:30 - 10:45 Dr Graeme A Stewart 10:45 - 11:20
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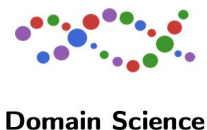
Busy workshop covering many topics - I now give some highlights of what were key things covered

JuliaHEP WS: Tutorials

- **Introduction to Julia** - Sam Skipsey and Graeme Stewart
 - Intended for beginners to get started (language basics, multidimensional arrays, functions, multiple dispatch, plotting, dataframes, etc.)
 - New [training material](#) developed for the occasion
 - Presented as Jupyter Book (collection of notebooks)
 - Available also in the [HSF Software Training Center](#)
- **Julia for High-Performance Computing (HPC)** - Carsten Bauer
 - After a 3 short introductory talks on Julia on HPC (Carsten Bauer, Mose Giordano, Ludovic Räss) we had a hands-on tutorial using the [Noctua 2 cluster](#) (143.872 cores)
 - <https://github.com/carstenbauer/juliahep-hpctutorial>
 - Provided login credentials to all interested participants
- **BAT.j: Bayesian Analysis Toolkit** - Oliver Schulz
 - Hands on tutorial



HPC



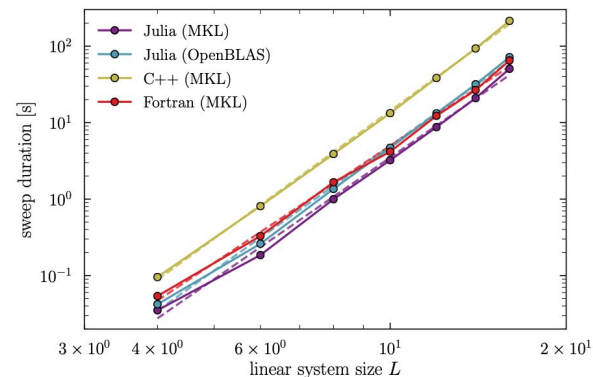
- Julia can be a great option for HPC!
 - **Serial and parallel performance on-par with Fortran/C/C++**
 - **portability and high-productivity** (same julia packages on Laptop and HPC clusters)
 - **New opportunities** (e.g. interactive HPC)

- **Challenges**

- Julia depot (downloaded packages and artifacts) can get under (a lot) of pressure!
- Memory footprint, O(1 GB) per process

- **Examples HPC projects**

- CiMA @ Caltech - Climate Modeling Alliance
- CESMIX @ MIT - Exascale simulation of materials in extreme environments
- Trixi @ RWTH Aachen / HLRS - Computational fluid dynamics
- GPU4GEO @ ETH / CSCS - Computational earth science



QMC
(MonteCarlo.jl)

Tooling

- [BinaryBuilder.jl](#)
 - To produce and pack binaries as Julia packages (**Julia** packages) for large combinations of architecture/operating system/compiler and resolving all dependencies
- [UnROOT.jl](#)
 - Julia package to read ROOT **TTrees** and **RNTuples**
 - Implements **Tables.jl** interface with the **LazyTree** to read the requested column when needed. It is fast and multi-threading friendly
- [WrapIt](#)
 - Automatically generate code to wrap C++ packages (**CxxWrap.jl**)
- [Unit and Integration testing](#)
 - Native support for unit tests and easy deployment of integration tests
- [Scientific project reproducibility](#)
 - Practical guidelines to achieve reproducibility
 - Each project comes with two essential files for **Project.toml** (direct dependencies and version requirements) and **Manifest.toml** (the exact version of all dependencies)

Data Analysis

- Analysis Grand Challenge

- Columnar data extraction, filtering, new columns, systematic variations into histograms. Statistical model construction and visualisation.
- Equivalent results as Coffea and PyHEP tools. Loop with < 100 lines. Good scaling on 25 nodes.

- Julia DataFrames Analysis

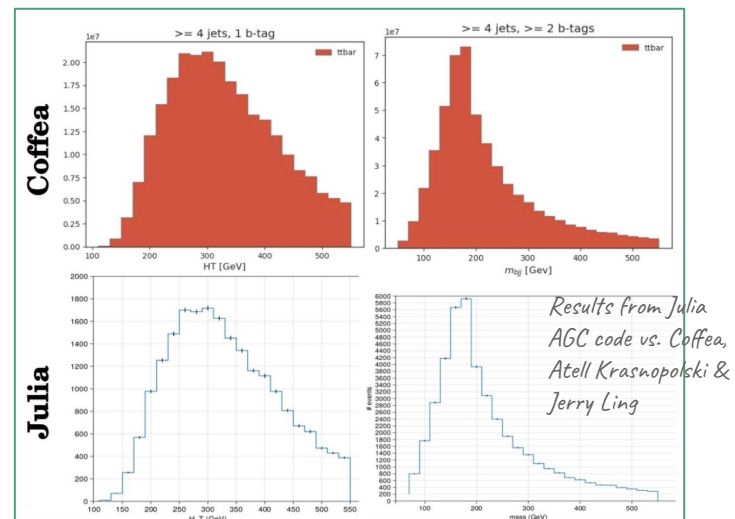
- Demonstrated that analysis can also be done with DataFrames.jl (equivalent to Pandas in Python)

- Corpuscles.jl & PDGdb.jl

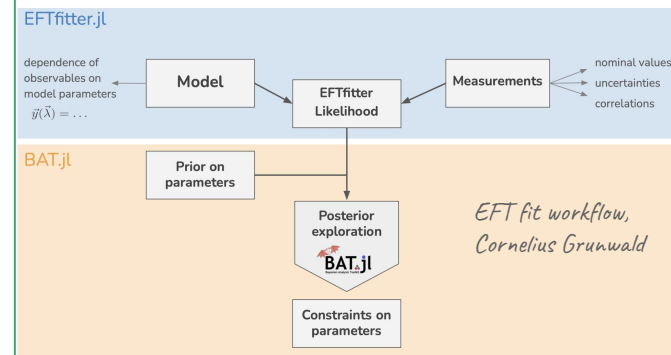
- Modules to provide easy access to Particle Data (PDG)

- BAT.jl and EFTFitter.jl

- Powerful tools for Bayesian analysis and to constrain free model parameters by combining multiple measurements

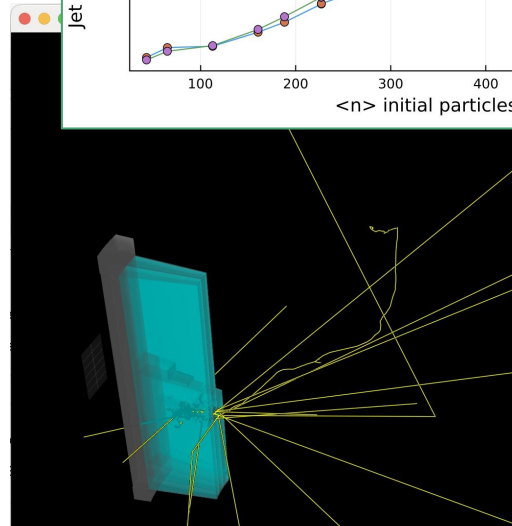
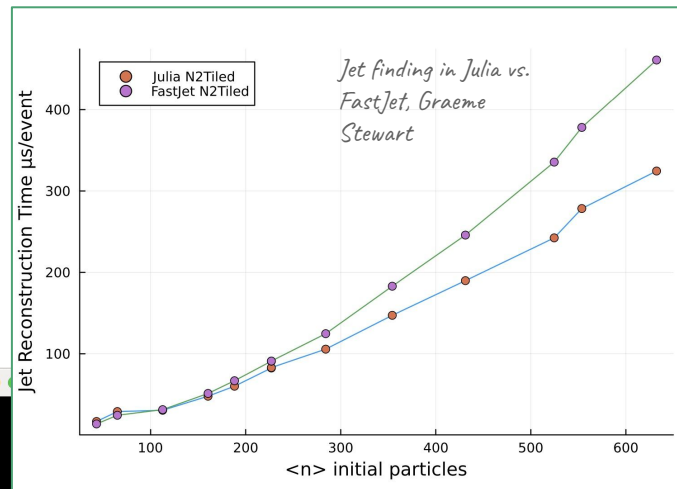


	JULIA DF	JULIA Loop	Coffea
Execution (t/t_{fastest})	33 s (1.2)	27 s (1)	158 s (5.9)
JIT compilation	+4.9 s	+2.2 s	–
Mem. allocation	40 GiB	19 GiB	–



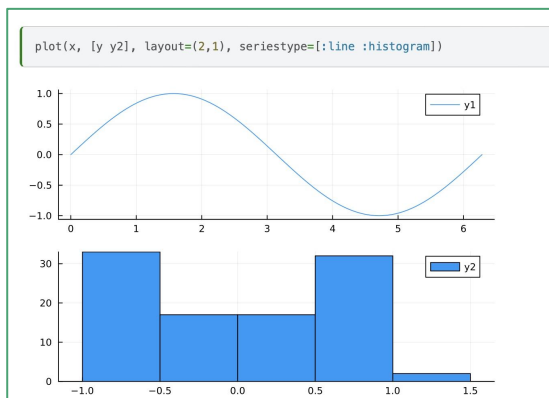
MC Generator, Simulation and Reconstruction

- [QED.jl](#) - Strong-field particle physics ecosystem
 - Fields, processes, phase space, event generation, etc.
 - Optimizations for large number of Feymann diagrams
 - Neural importance sampling (better than classical VEGAS)
- [Jet Finding](#)
 - Test-case for algorithm development and testing ergonomics
 - Julia reaches C++ speed
- [Geant4.jl](#)
 - Wrapping C++ Geant4 with a new simpler and more ergonomic API
 - MT support and very good performance
- [Neurthino.jl](#)
 - Neutrino oscillation probability calculator

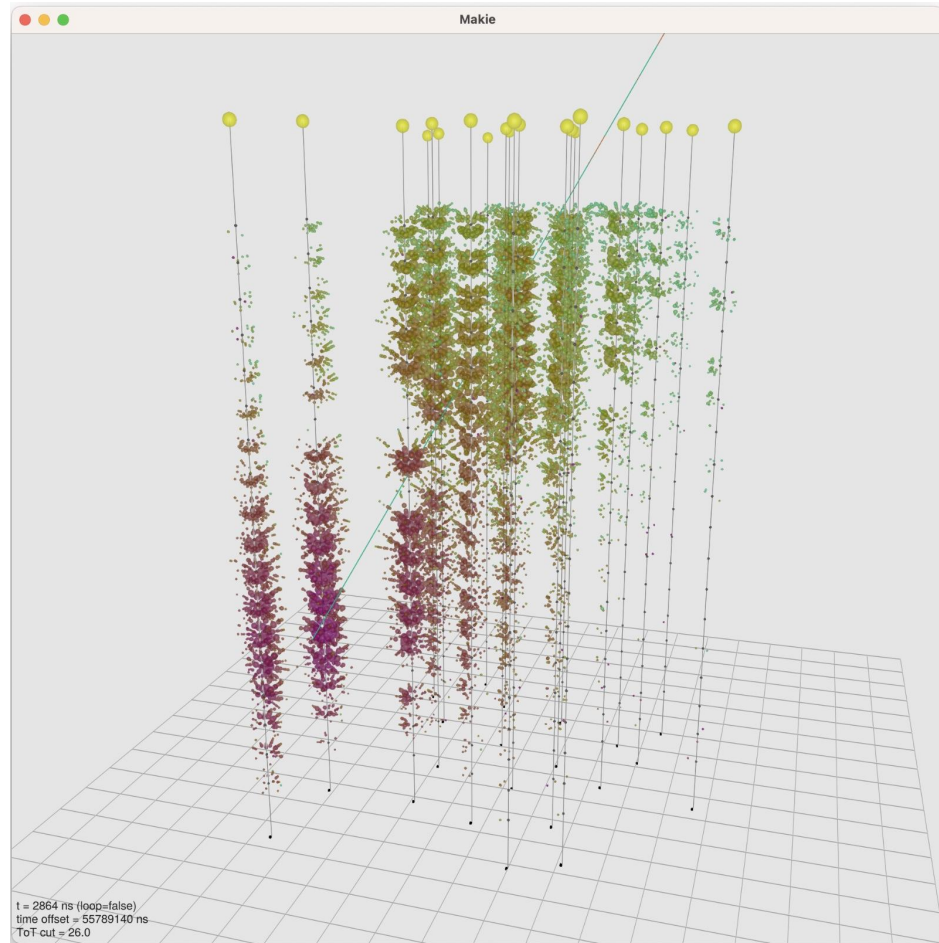


Visualization

- Two major packages for data visualization: **Plots.jl** and **Makie.jl**
 - Plots.jl is probably easy to use out of the box, while Makie.jl is more powerful but requires some learning



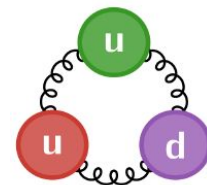
- Makie Example: Event display for Neutrino Detectors (KM3NeT)



Display from RainbowAlga.jl, Tamas Gal, ECAP

Automatic Differentiation and Scientific ML

- Chris Rackauckas (Julia Lab Co-PI) gave a masterclass on *Differentiable Simulation* (using the whiteboard and advanced calculus)
- Impossible to reproduce here :-)
- Main messages we got:
 - Add a NN only on the unknown parts of the ODE system. It gives much better predictivity
 - Julia has many packages for AD using different methods, from symbolic manipulation to operator overloading, in forward and reverse mode (<https://juliadiff.org>)



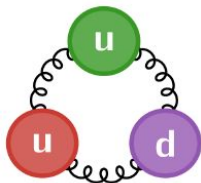
What's Next?

- We identified a number of important items to work on to improve integration into the HEP world
 - More wrappers to speak to existing code: HepMC3, Minuit, FastJet, Pythia8, etc.
 - The ability to *write* RNTuples (see an [update](#) from Jerry Ling on this important topic)
 - Develop better support for histograms in FHist.jl (or redo) and support statistical standards like HS3
 - Generic HEP support for Lorentz Vectors, etc, plus plotting recipes in Plots.jl and Makie.jl
- And we need to work on topics that make Julia deployable at the large scale
 - Precompilation of packages (we don't want to JIT on 1M nodes!)
 - Can leverage a lot of experience from the HPC community here

What's Next?

- Julia for ML
 - Native packages for deep learning, relying on Julia's great strengths in autodifferentiation and JIT speeds
- Julia on GPUs
 - CUDA, HIP, oneAPI supported
 - More interestingly the *kernel abstractions package* allows all of these specifics to be hidden
- Training
 - Keep developing material and presenting it!

HSF JuliaHEP WG now organising monthly meetings - lots to get involved in!



*Next JuliaHEP workshop will be
30 September - 4 October at CERN*