JuliaHEP 2023 Workshop
08.11.2023

Cumulants & Co.

Piotr Kalaczyński on behalf of Krzysztof Domino, Piotr Gawron, Łukasz Pawela, Dariusz Kurzyk, Tony Kelman, Alex Arslan and Kristoffer Carlsson

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Polish Academy of Sciences

IITiS

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Introduction

Code presented here was developed at IITiS in Gliwice, Poland

Based on: arXiv:1301.7744v3
Exploiting Symmetry in Tensors for High Performance: Multiplication with Symmetric Tensors
(M. D. Schatz, T. M. Low, R. A. van de Geijn, T. G. Kolda)

By:
- Krzysztof Domino
- Piotr Gawron
- Łukasz Pawela
- Tony Kelman
- Alex Arslan
- Kristoffer Carlsson

NOT by me!

Repos:
- github.com/iitis/Cumulants.jl → arXiv:1701.05420v4
- github.com/iitis/CumulantsFeatures.jl → doi/10.1016/j.physa.2020.124995, arXiv:1808.03513v1
- github.com/iitis/CumulantsUpdates.jl → doi/10.2478/amcs-2019-0015

Me:

Just a humble technician in the Scientific Computing & IT Group at ASTROCENT in Warsaw, Poland

Particle Astrophysics Science and Technology Centre
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current focus: maintenance of python & C++ simulation codes,
excited to dive deeper into Julia ☺

Cumulants

What are cumulants anyway?

quantitative measures of the shape of the distribution

(an alternative to the moments)

Can be generated from a Taylor expansion:

$$H(t) = \sum_{d=1}^{\infty} \kappa_d \frac{(it)^d}{d!} = \underset{\kappa_1}{\underset{\|}{\mu}} it - \underset{\kappa_2}{\underset{\|}{\sigma^2}} \frac{t^2}{2} + \cdots$$

d – order of the cumulant

which must be differentiated and evaluated at $t = 0$ to extract the cumulants κ_d

(hello Julia ☺)

The symbols may seem familiar for a good reason:

$\kappa_1 = \mu$: mean

$\kappa_2 = \sigma^2$: variance

$\kappa_3 \sim$ skewness (after rescaling)

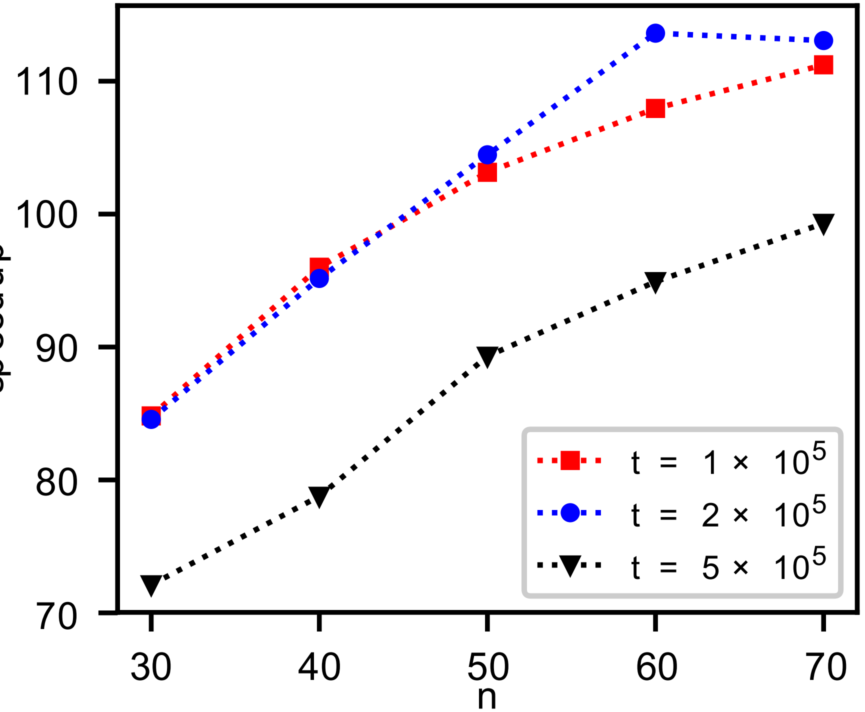
$\kappa_4 \sim$ kurtosis (after rescaling)

no special names for higher orders (that I know of …)

from arXiv:1701.05420v4

Storage of symmetric tensors is optimized wrt. the naïve storage scheme (storing all elements)

Expected computational complexity reduction: by a factor $d!$



(wrt. to naïve)

number of marginal variables

Here :

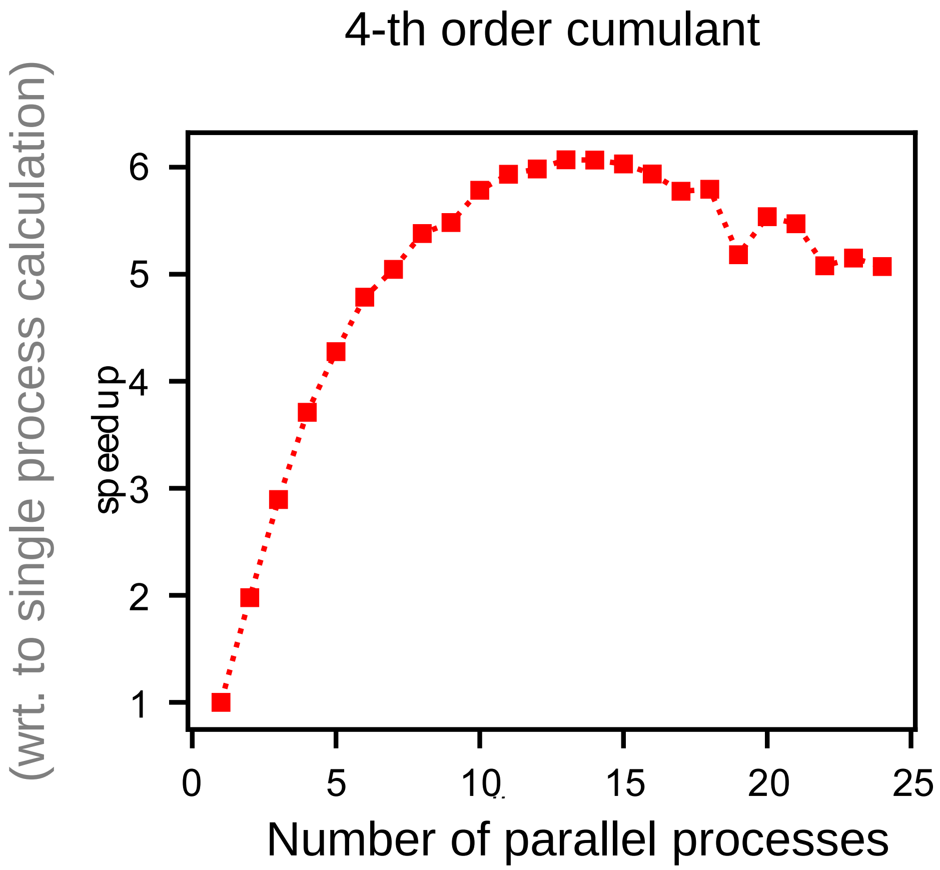
- Computation of the 4th cumulant (κ_4) tensor
- Actual speedup exceeds $d! = 4! = 24$

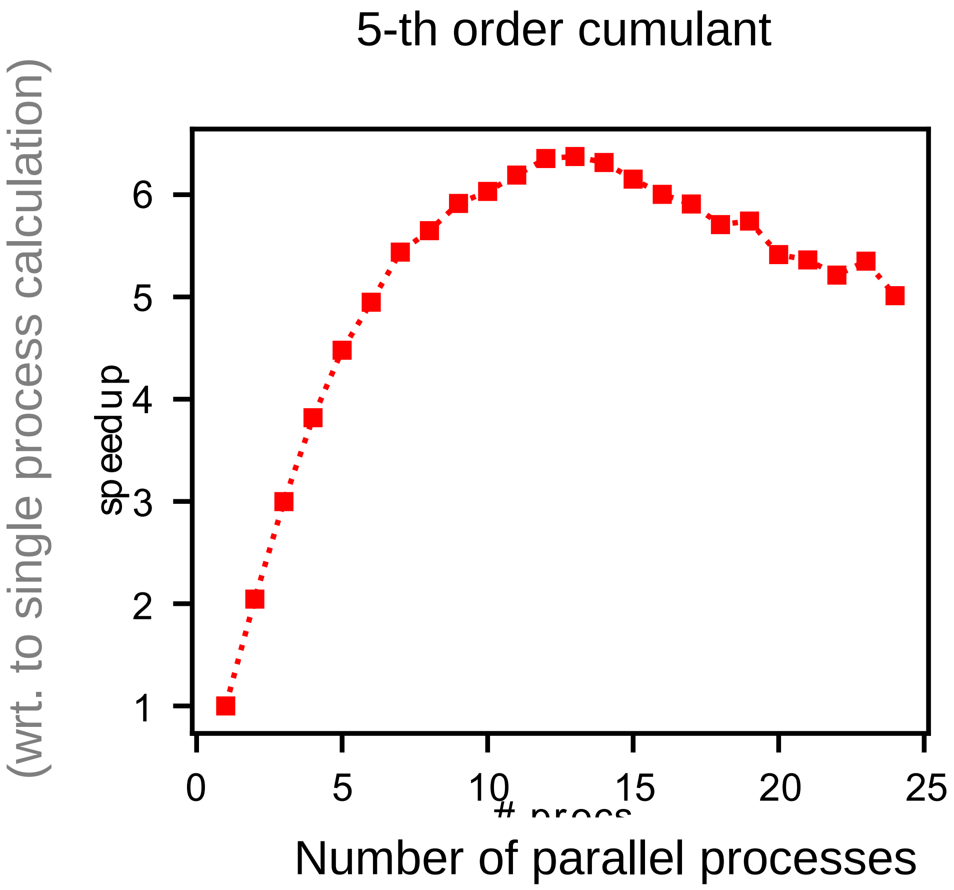
t – number of data samples

from [arXiv:1701.05420v4]

The code is not completely parallelisable, but can be accelerated by running multiple processes

speedup: with respect to single process calculation of cumulants





Performance: Julia vs R implementation

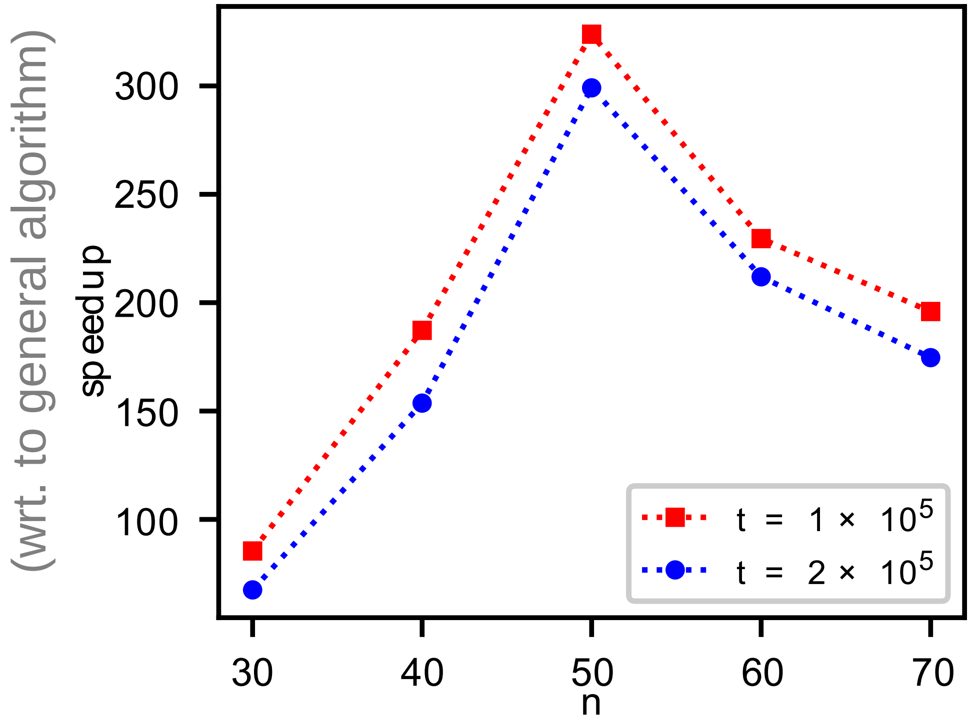
from arXiv:1701.05420v4

Speedup wrt. state of the art:

- Cumulants.jl vs the general (arbitrary cumulant order) algorithm from here
- 4th cumulant tensor

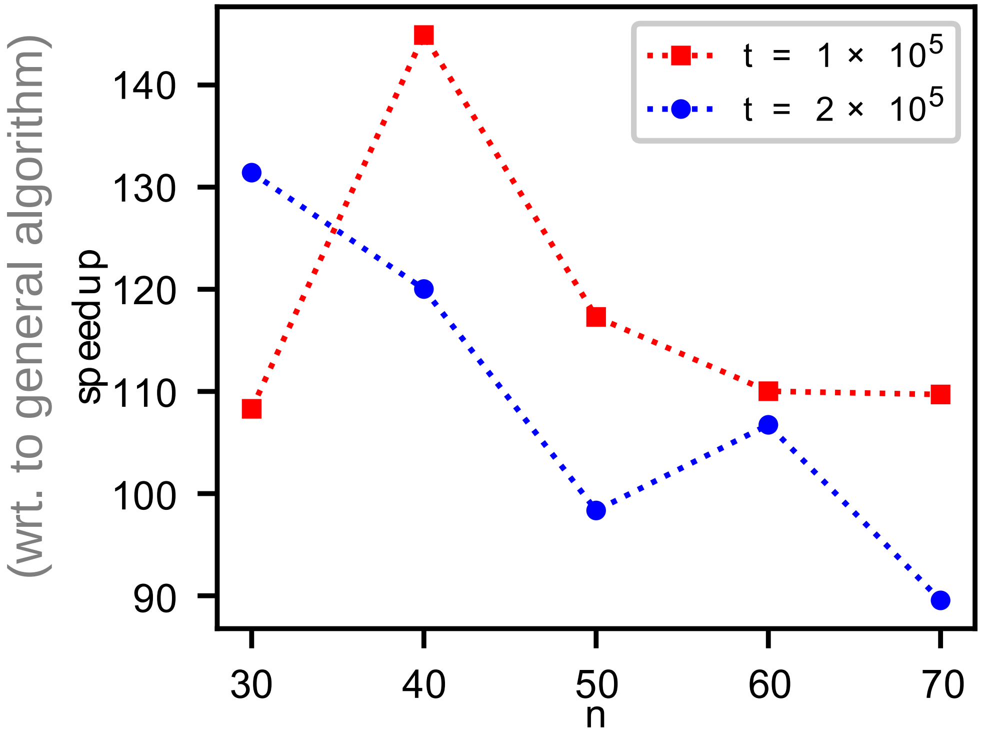
t – number of data samples

Comparing with julia reimplementation



number of marginal variables

Comparing with R reimplementation

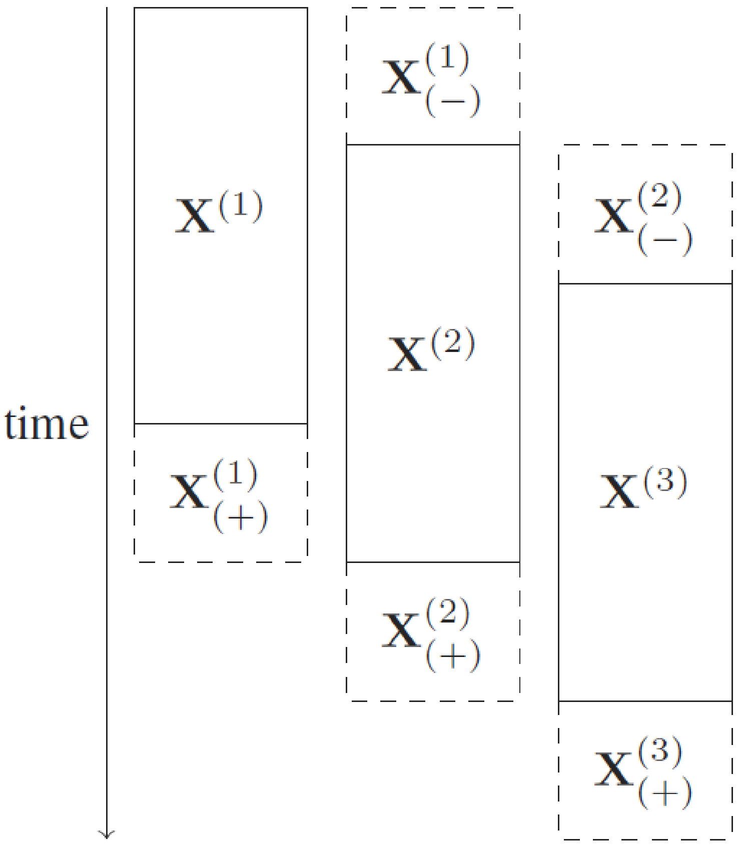


number of marginal variables

from doi/10.2478/amcs-2019-0015

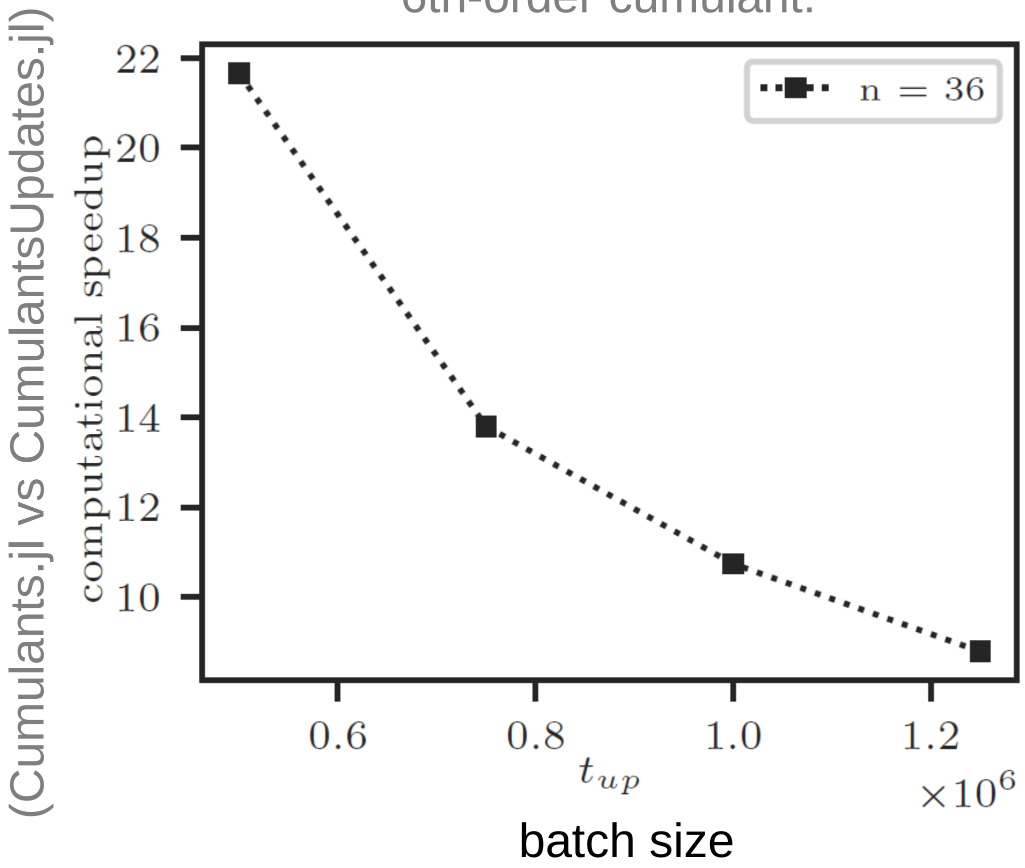
Cumulants can be computed online, in a sliding window of datastreams:

(CumulantsUpdates.jl)



… and this turns out to be even faster than Cumulants.jl:

6th-order cumulant:



$t = 2.5 \cdot 10^7$ – number of data samples

n – numer of marginal variables

Applications

Okay, where in HEP can this be used? (just some examples)

some analyses use cumulants up to 8th order

↓

specialised algorithm (orders 1-4) NOT enough!

- At colliders:
  - arXiv:1109.0593v2
    Error Estimation for Moments Analysis in Heavy-Ion Collision Experiments
    (Xiaofeng Luo)
  - arXiv:2305.13874v2
    Holographic study of higher-order baryon number susceptibilities at finite temperature and density
    (Z. Li, J. Liang, S. He, L. Li)
  - arXiv:2303.13414v1
    Higher-order correlations between different moments of two flow amplitudes in Pb−Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ *TeV*
    (ALICE Collaboration)
  - arXiv:2209.11940v2
    Higher-Order Cumulants and Correlation Functions of Proton Multiplicity Distributions in $\sqrt{s_{\mathrm{NN}}} = 3$ *GeV Au+Au Collisions at the RHIC STAR Experiment*
    (STAR Collaboration)
- In astrophysics:
  - arXiv:2204.05305v3
    Galaxy and halo angular clustering in LCDM and Modified Gravity cosmologies
    (P. Drozda, W. A. Hellwing, M. Bilicki)
  - arXiv:2209.14810v2
    Magnetic helicity fluxes from triple correlators
    (K. Gopalakrishnan, K. Subramanian)
- Lattice QCD:
  - arXiv:2305.10916v2
    Microscopic Encoding of Macroscopic Universality: Scaling Properties of Dirac Eigenspectra near QCD Chiral Phase Transition
    (H. Ding, W. Huang, S. Mukherjee, P. Petreczky)

Other projects

There is more if you're into …

Quantum computing: QuantumInformation.jl

from arXiv:1806.11464v3

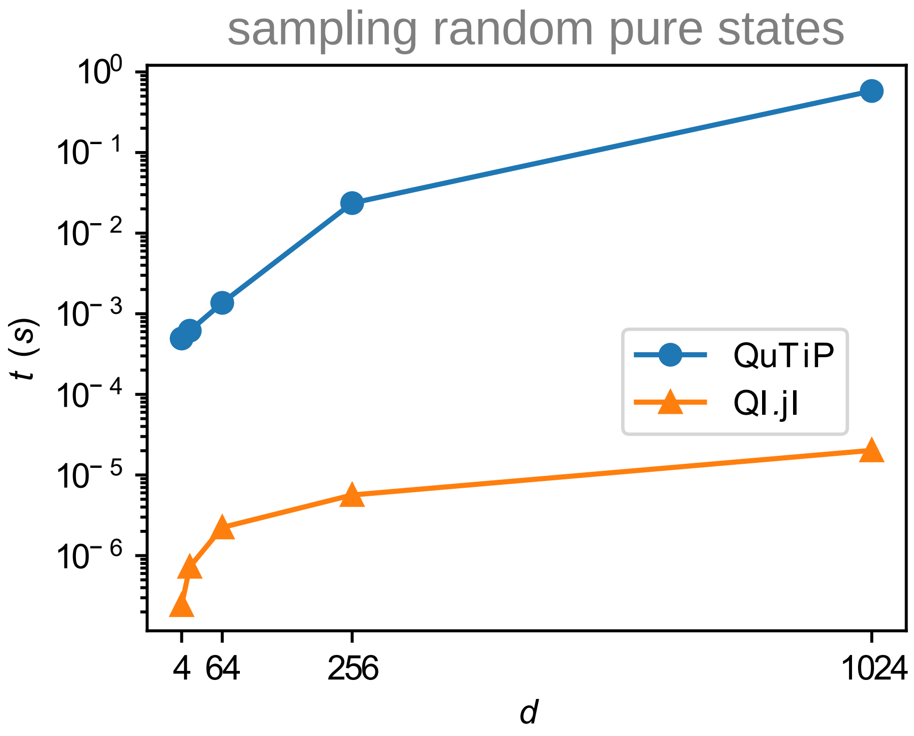
❖ natively works with bra-ket notation!

```
julia> ket(1,2)
2-element Array{Complex{Float64},1}:
 1.0 + 0.0im
 0.0 + 0.0im

julia> (1/sqrt(2)) * (ket(1,2) + ket(2,2))
2-element Array{Complex{Float64},1}:
 0.7071067811865475 + 0.0im
 0.7071067811865475 + 0.0im
```

❖ comes with many convenient implementations of states, transformations, etc.

❖ faster than QuTiP (python code)

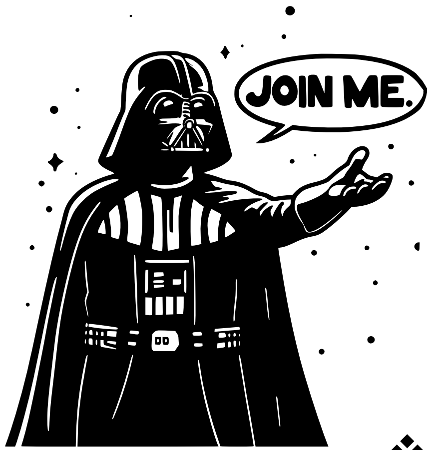


Random matrix sampling on GPU: MatrixEnsembles.jl

Summary

To sum up:

- Need to compute high-order cumulants or just do it fast? Use Cumulants.jl etc. ☺
- Want to learn more? See:
  arxiv/1701.05420
  doi/10.2478/amcs-2019-0015



My ideas for new projects:

- CORSIKA alternative in Julia:
  - I'm aware of C++ rework (C8)
  - but … maybe it can be more efficient? (looped differentiation and matrix operations under the hood …)
  - and just easier (MUCH friendlier syntax)
  - healthy competition never hurts ;-)
- Simulation of acoustic signal from HE particles:
  - thermo-acoustic mechanism: known & measured
  - simulated, but nothing really open-source and general purpose, like CORSIKA (at least that I am aware of …)
  - combined simulation of light & sound? (could allow for better event reco)

Thank you for your attention!

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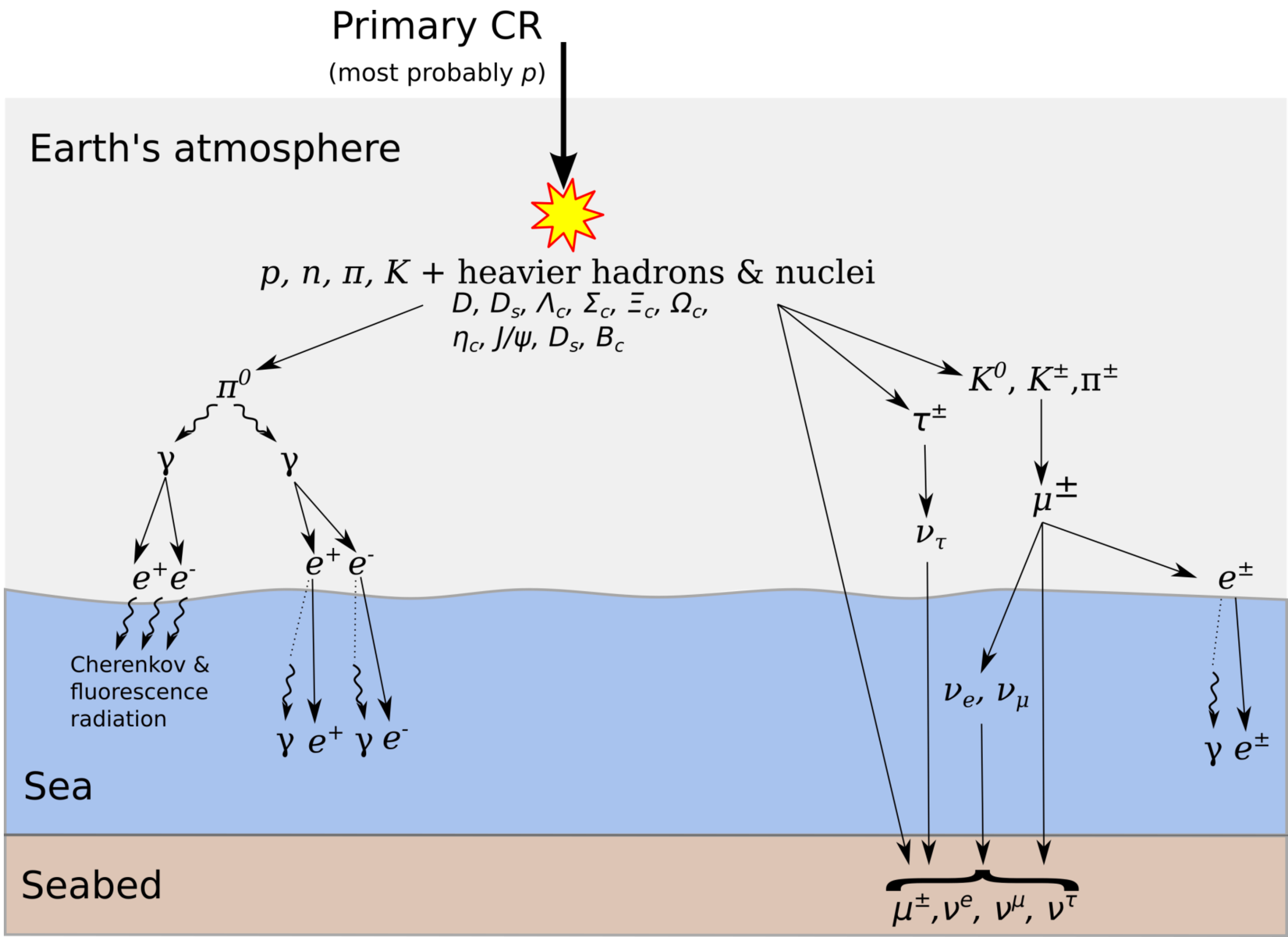
Backup

Extensive Air Showers

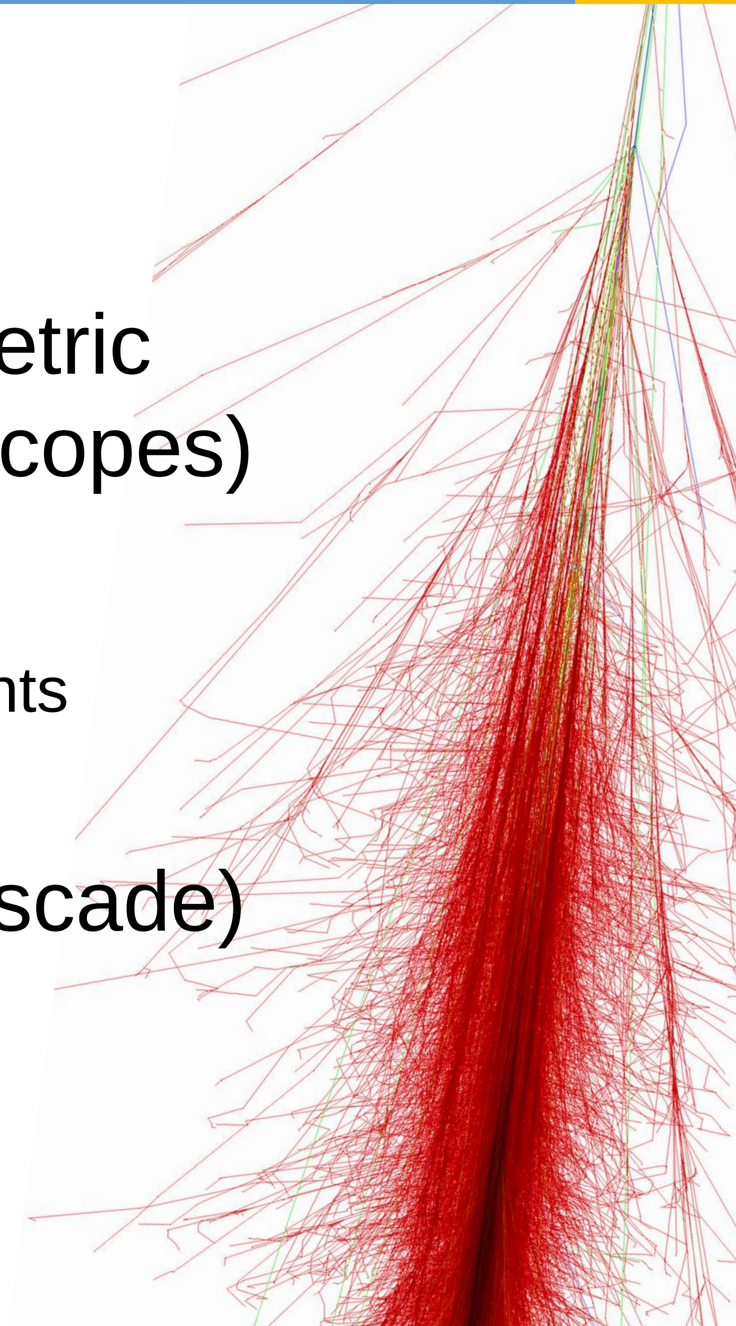
EAS:

- Caused by primary CR
- Typically start at $h{\sim}30-40\text{km}$
- 3 main components:
  - electromagnetic (EM)
  - hadronic
  - muonic
- Simulated with CORSIKA



We have 2 options:

1. MUPAGE (atmospheric **MU**ons from **PA**rametric formulas: a fast **GE**nerator for neutrino telescopes)
   - developed for ANTARES
   - fast muon MC generator
   - based on parametric formulas and MACRO measurements
   - parameters can be freely tuned
2. CORSIKA (**CO**smic **R**ay **SI**mulations for **KA**scade)
   - developed for KASCADE
   - full simulation of air showers
   - customizable (models, primaries, etc.)



git.km3net.de/opensource/gseagen

gSeaGen

Code for propagating muons and/or neutrinos to neutrino telescopes. Developed for KM3NeT, but applicable to other experiments

My work in this project:

- Implement processing of CORSIKA showers
- Speed, memory & storage optimization
- Rework of the geometry: no more flat Earth!
- Code maintenance

A paper by me under internal review …

Tech stack:

- C++
- ROOT
- PERL
- PROPOSAL
  (github.com/tudo-astroparticlephysics/PROPOSAL)

Current devs:

- Carla Distefano
- Alfonso Andres Garcia Soto
- Piotr Kalaczyński
- Johannes Schumann
- Rodrigo Garcia
- Andrey Romanov