**H**eavy
**I**on
**J**et
**IN**teraction
**G**enerator

**C++ version**

# XNWLX

18 08 2022


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Guoyang Ma



arXiv:1905.11272
arXiv:1901.04220
arXiv:1811.02131
arXiv:1805.02635
arXiv:1707.09973
arXiv:1701.08496

*”Modern day HEP requires high performance computing, relying on Monte Carlo simulations”*

**— Alberto Di Meglio**

The CERN Quantum Technology Initiative, 20.10.2020.





1996, Budapest, Workshop on Strangeness in Hadronic Matter:

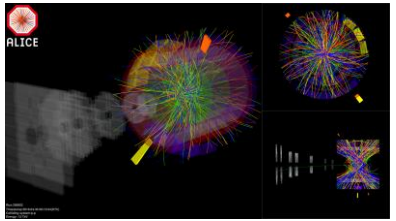
# MC event generators

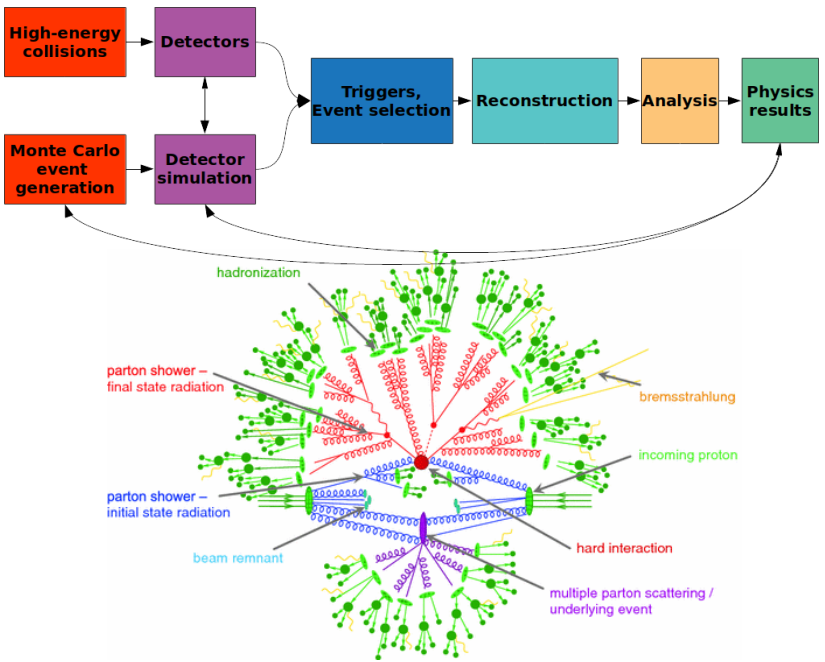
Simulation of one proton-proton collision event: complicated...

1) Perturbative QCD calculations

$$\frac{d^2\sigma^{lP\to hX}}{dxdQ^2} = \sum_{i=q,\bar{q},g} \int_x^1 \frac{dz}{z} f_i(z,\mu) d\hat{\sigma}_{il\to iX}\left(\frac{x}{z},\frac{Q}{\mu}\right) D_i^h(z)$$

1) Additional phenomenological processes: MPI, colour reconnection, hadronization scheme...
2) Compromise: computational time ←→ precision
   - Tons of random numbers
3) Empirical parameters: need to be tuned



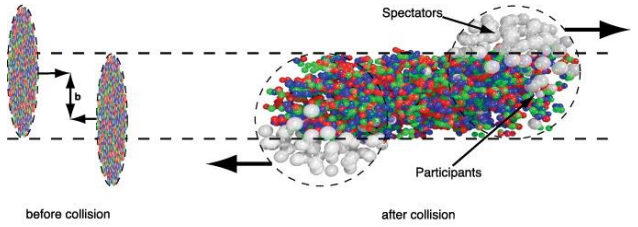
# MC event generators

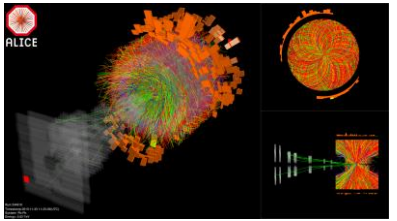
Simulation of one **heavy-ion** collision event: **even more** complicated…

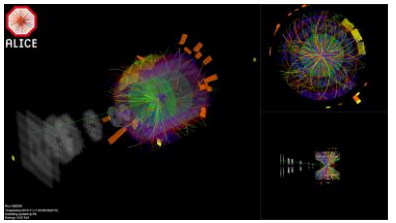
1) Perturbative QCD calculations

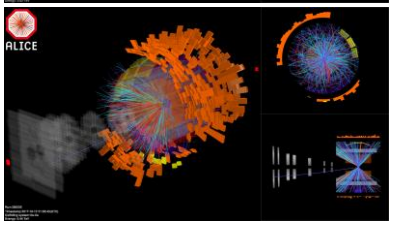
$$\frac{d^2\sigma^{lP\to hX}}{dxdQ^2} = \sum_{i=q,\bar{q},g} \int_x^1 \frac{dz}{z} f_i(z,\mu) d\hat{\sigma}_{il\to iX}\left(\frac{x}{z},\frac{Q}{\mu}\right) D_i^h(z)$$

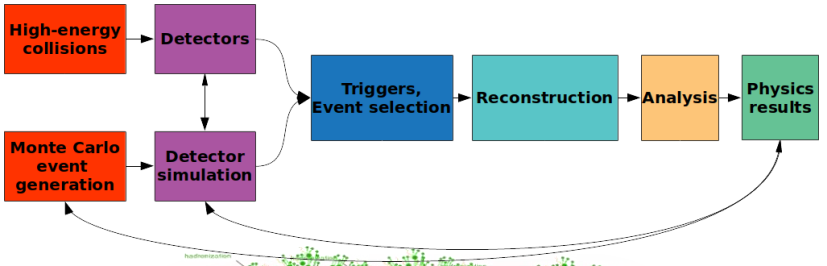
1) Additional phenomenological processes: MPI, colour reconnection, hadronization scheme…
2) Compromise: computational time ←→ precision
   - **Tons** of random numbers
3) Empirical parameters: need to be tuned
4) Multiple nucleon-nucleon interactions
5) Additional nuclear effects: jet quenching, Cronin enhancement,
6) shadowing..

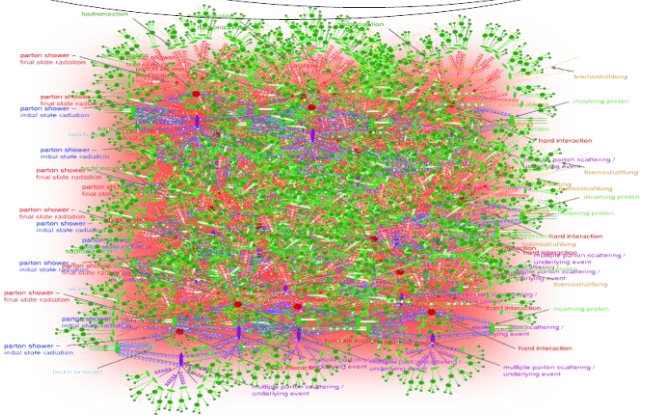


**H**eavy
**I**on
**J**et
**IN**teraction
**G**enerator

**(C++ version)**

# A NEW GENERATION OF HEAVY-ION MONTE CARLO

核易经

[ Hé –yì –jīng ]

”Nuclear change theory”; Book of Changes, ”Originally a divination manual in the Western Zhou period (1000–750 BC)”

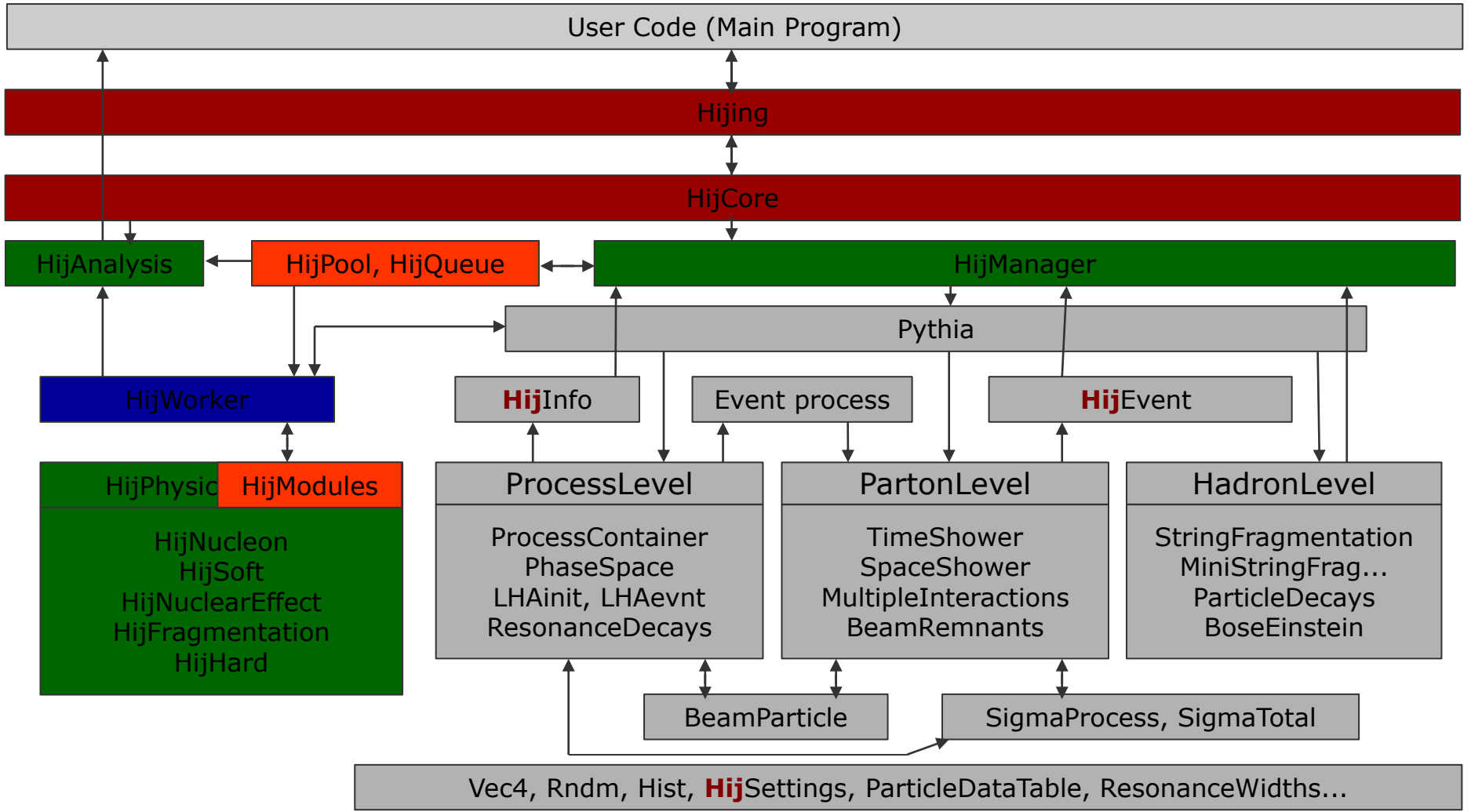
First, FORTRAN version: 1991, X.N. Wang, M. Gyulassy, **Phys. Rev. D 44, (1991) 3501.**

Computational challenge: more than 600 million collision in each second → HiLumiLHC: even more

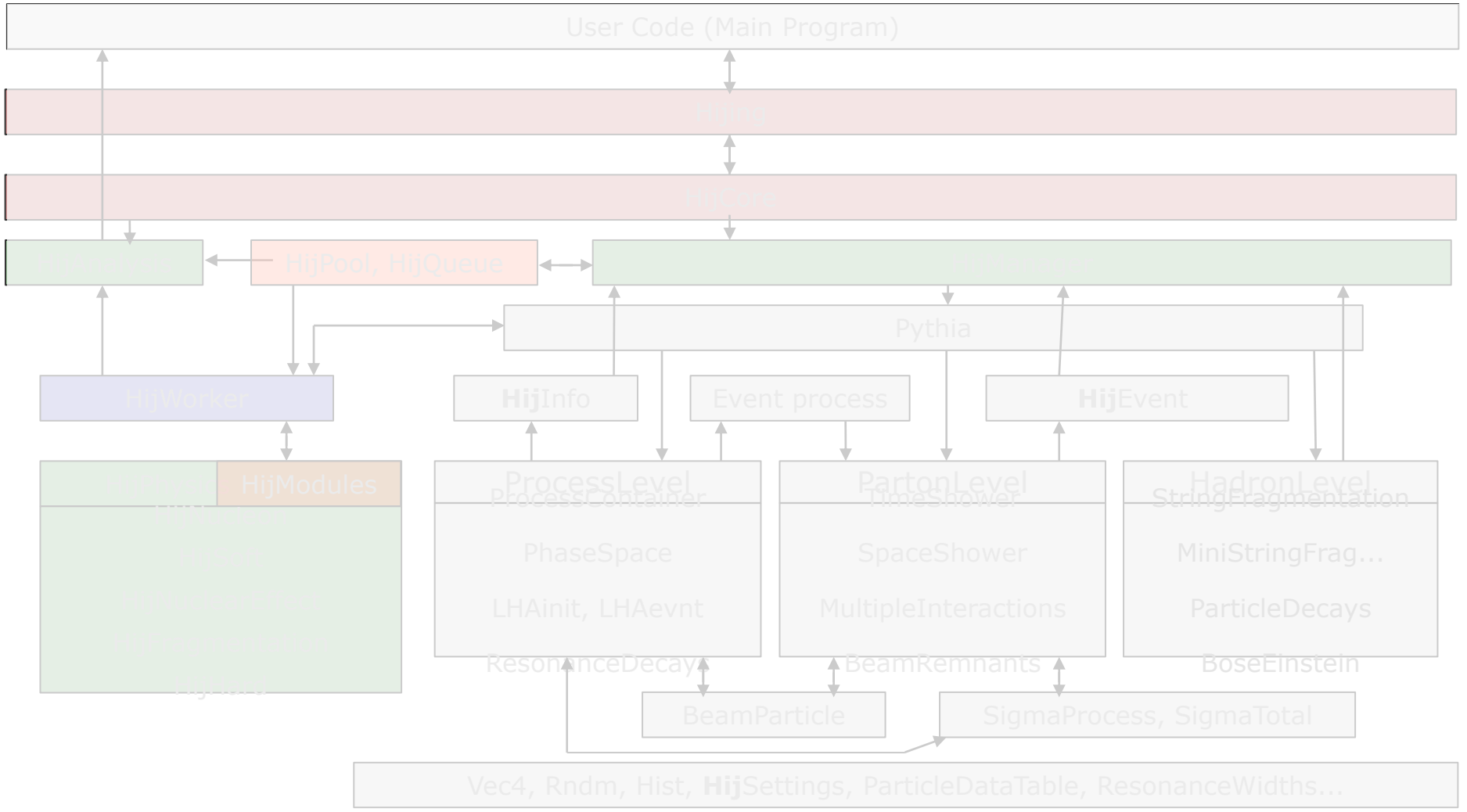
Requirements for a new version: multithreaded mode, maintainability, intuitive usage

| | FORTRAN HIJING | HIJING++ v3.0 | HIJING++ v3.1 |
|---|---|---|---|
| Precision | simple | double | double |
| Pythia version | 5.3 | 8.2 | 8.2+ |
| (n)PDF | GRV98lo | LHAPDF6.2 | LHAPDF6.2+ |
| Jet quenching | (✓) | (✓) | (✓) |
| **Multithreading** | ✗ | ✗ | ✓ |
| **Analysis interface** | ✗ | ✗ | ✓ |
| **Module management** | ✗ | ✗ | ✓ |
| **Dependencies, build system** | Makefile | Makefile | CMake |

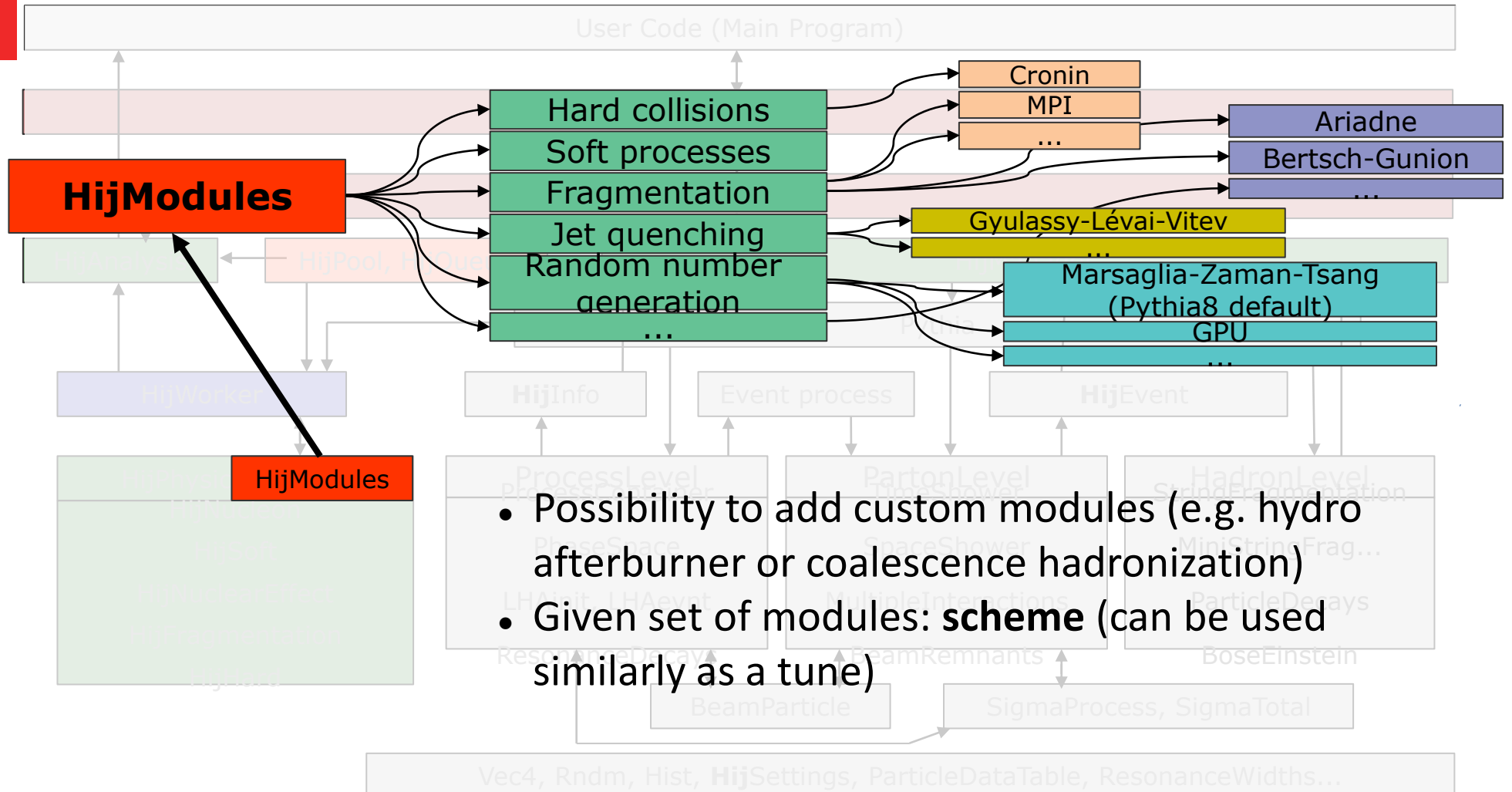
# HIJING++ structure



# HIJING++ structure

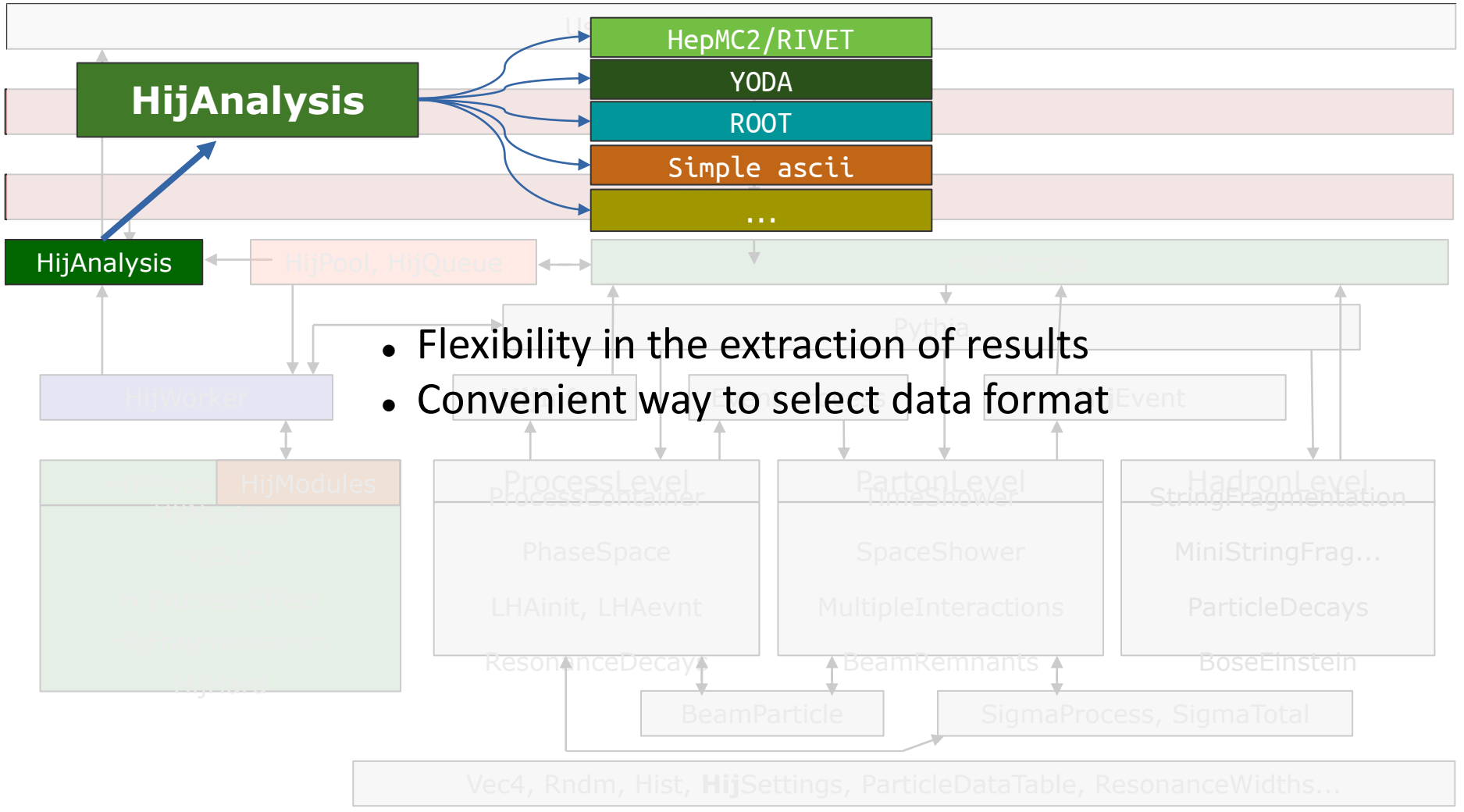


# HIJING++ structure



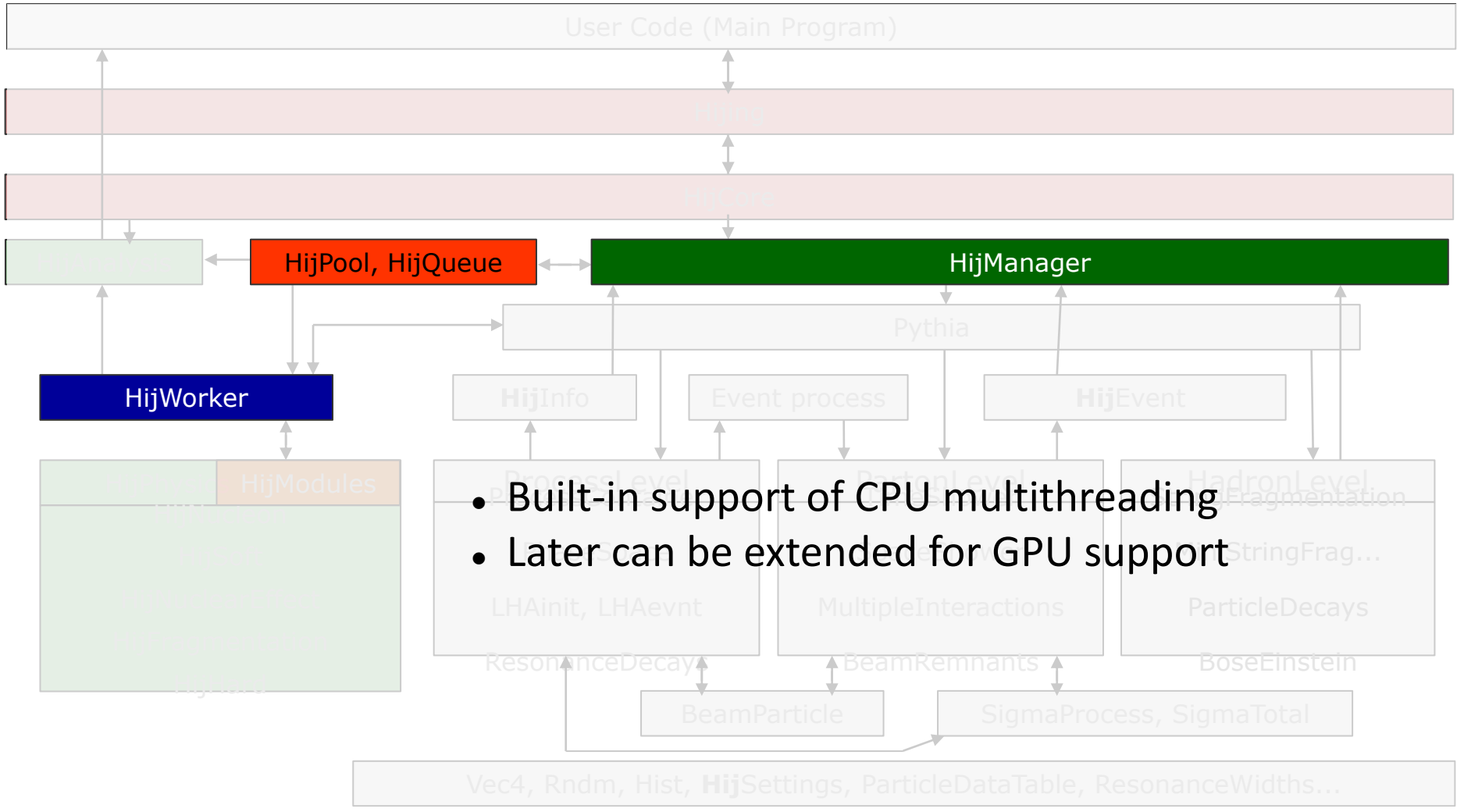

- Possibility to add custom modules (e.g. hydro afterburner or coalescence hadronization)
- Given set of modules: **scheme** (can be used similarly as a tune)

# HIJING++ structure



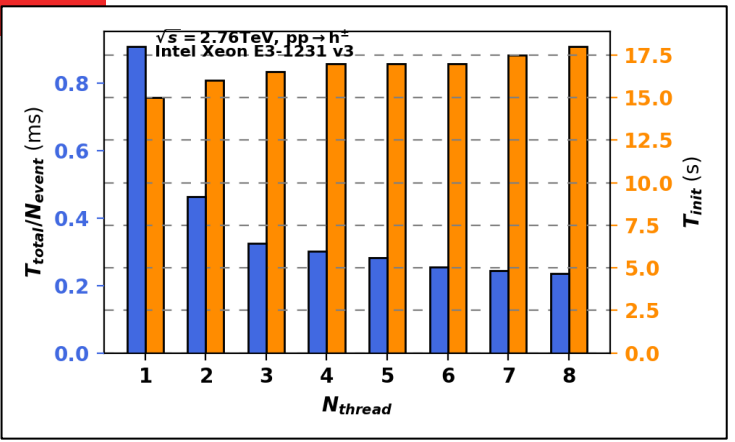

- Flexibility in the extraction of results
- Convenient way to select data format

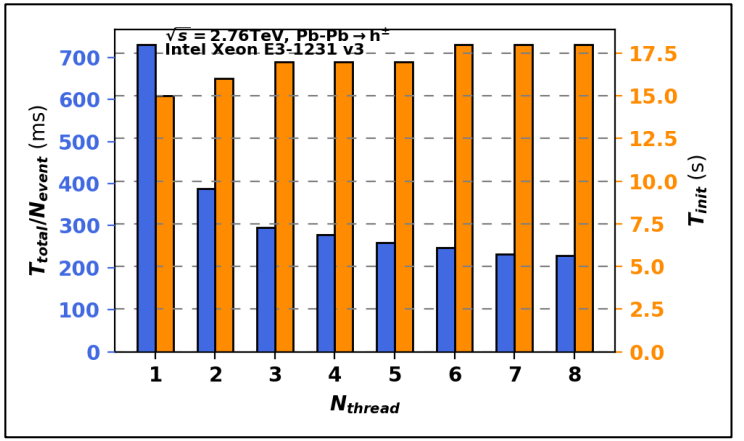
# HIJING++ structure

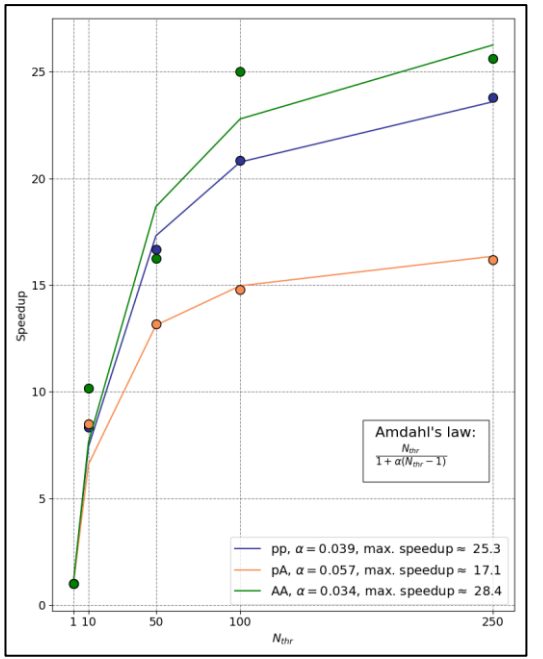



- Built-in support of CPU multithreading
- Later can be extended for GPU support

# HIJING++ multithreading



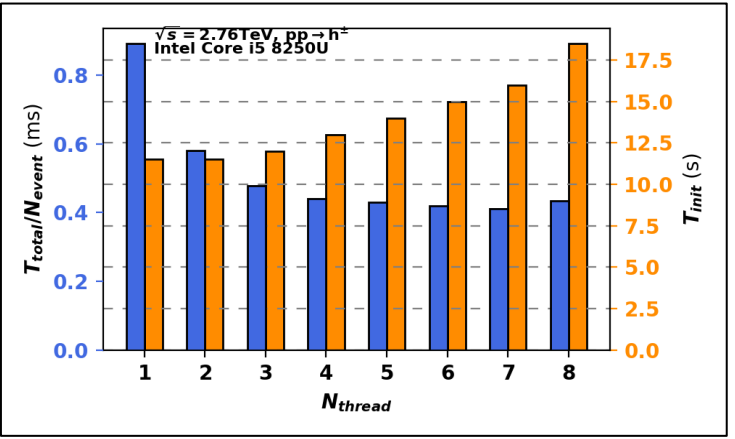



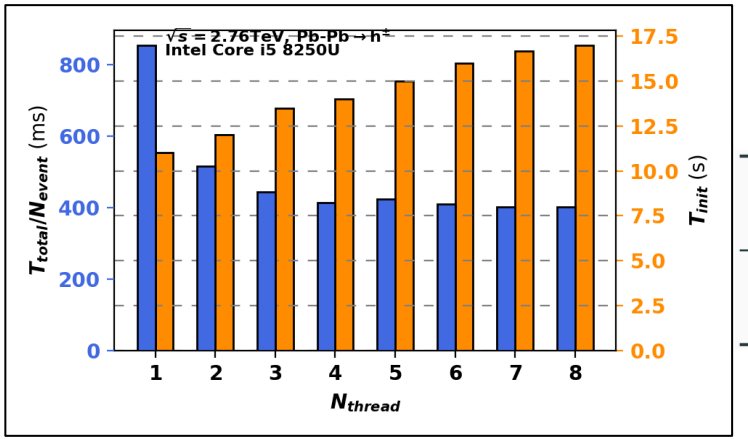

Data center: Intel Xeon E3 312 (4 core, 8 thread)

Laptop: Intel Core i5 8250U (4 core, 8 thread)

Proton-proton

Pb-Pb




| CPU | Speedup | | |
|---|---|---|---|
| | pp | p-Pb | Pb-Pb |
| Intel Core i5-8250U | 2.6x | 2.7x | 2.6x |
| Intel Xeon E3-1231 v3 | 6.4x | 6.6x | 4.5x |

## Installation

# Introduction

These are the setup instructions.

# Prerequisites

- git
- cmake (min. v3.2)
- LHAPDF6 (v6.2.0 or newer)
- Pythia8 (v8219 or newer)
- c++ compiler with c++14 support (gcc 5 or later)

---

## LHAPDF6

```
wget http://www.hepforge.org/archive/lhapdf/LHAPDF-6.X.Y.tar.gz
tar -xvf LHAPDF-6.X.Y.tar.gz
cd LHAPDF-6.X.Y
./configure --prefix=/where/to/install
make -jN
sudo make install
```

### Install (nuclear) pdf sets

The pdf set *GRV98lo* is included in the downloaded package. It is mainly used during the development, since it is an unvalidated, "unofficial" set. However, if you wish

1. copy the *GRV98lo* folder (you can found it in `misc`) into `/path/to/install/LHAPDF6/share/LHAPDF`
2. insert into the file `pdfsets.index` at the correct line number (i.e. between 80000 and 80111) the following: *80060 GRV98lo 1*:

```
sed -i '/80000\ METAv10LHC\ 2/a 80060 GRV98lo 1' /path/to/install/LHAPDF6/share/LHAPDF/pdfsets.index
```

If you wish to use other npdf sets, visit http://lhapdf.hepforge.org/pdfsets.html and repeat the first step.

---

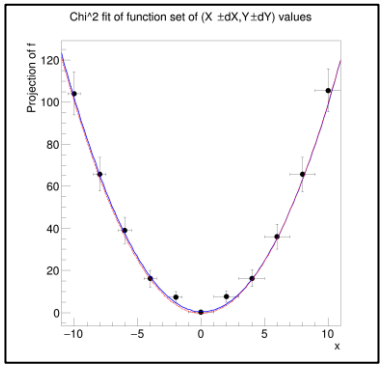
## Pythia8

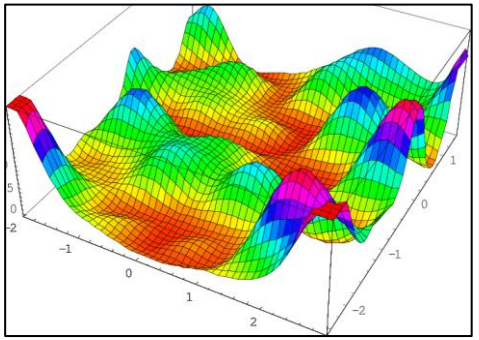
Download and install the latest version from the official webpage:

# HIJING++ analysis interface

```cpp
#include "Hijing.hpp"

using namespace Hijing3;

int main(int argc, char* argv[])
{
        Hijing hijing;

        // collision energy, beams, #threads, event number...
        hijing.readFile("testSettings.cmnd");

        hijing.init();
        hijing.newAnalysis("root", "EventEnd", "histo_id1", 50, 0.0, 20.0);
        hijing.newAnalysis("ascii","EventEnd", "eta_charged_ascii", 20, -5.0, 5.0);
        // ...
        hijing.newAnalysis("yoda", "EventEnd", "ALICE_2010_I880049/d01-x01-y01", binnum_cent, edges_cent);
        hijing.newAnalysis("hepmc2", "ascii", "EventEnd", "output_file");

        hijing.analysisCustomCode(90001, [&](HijEvent &hijevent, pair<double, double> &val) {
                int cent = getMultClass(hijevent.b(), hijevent.Nbin(), hijevent.Npart());
                val.first = edges_cent[cent] + 0.1;
                double mult = 0;
                Event &event = hijevent(EventType::mainEvent);
                for (int iE = 0; iE < event.size(); iE++) {
                        if (event[iE].isFinal() && abs(event[iE].y()) < 0.5 && event[iE].isCharged())
                                mult++;
                        else
                        continue;
                }
                val.second = mult;});

        hijing.analysisProperties("histo_id1", "final", "pT", "yw-0.5to0.5", "ID211", "ID-211");
        hijing.analysisProperties("ALICE_2010_I880049/d01-x01-y01", "CC#90001", "nonorm");
        // ...
        hijing.start();
```

# HIJING++ tuning (WIP)



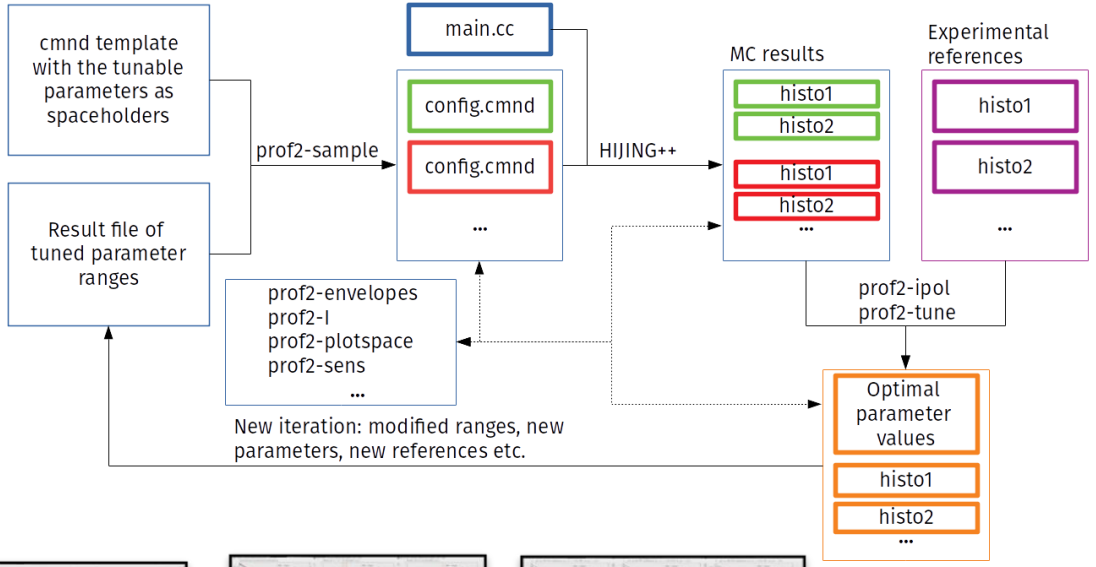



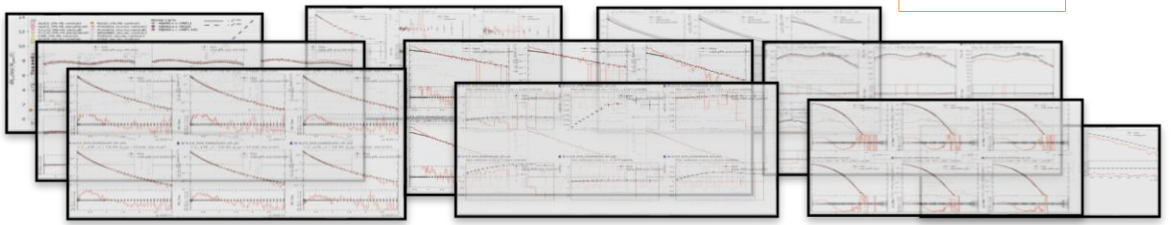
Tuning: set the empirical parameters to fit the experimental data → basically ~~„just"~~ an iterative $\chi^2$ minimization → **very serious business**

$$\chi^2 = \sum_i \left[ \frac{y_i - f(x_i)}{\sigma_i} \right]^2$$

**sample→*calculate*→minimize→repeat**


YODA (Yet more Objects for Data Analysis)
Rivet (Robust Independent Validation of Experiment and Theory)
Professor (Tuning tool for Monte Carlo event generators)
MCNNUTNES (A machine learning based optimization tool)



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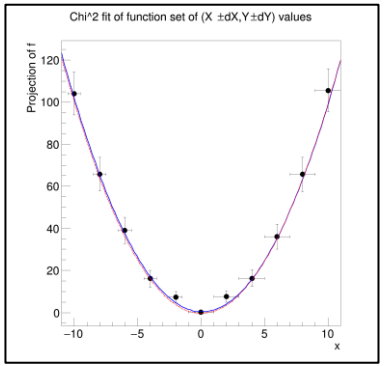


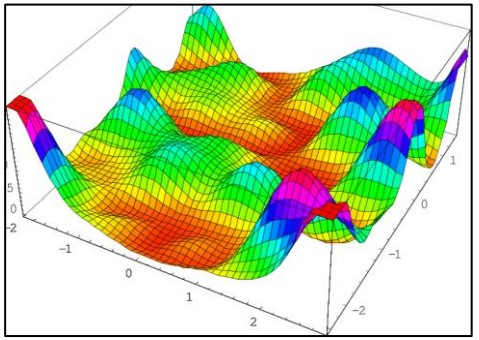

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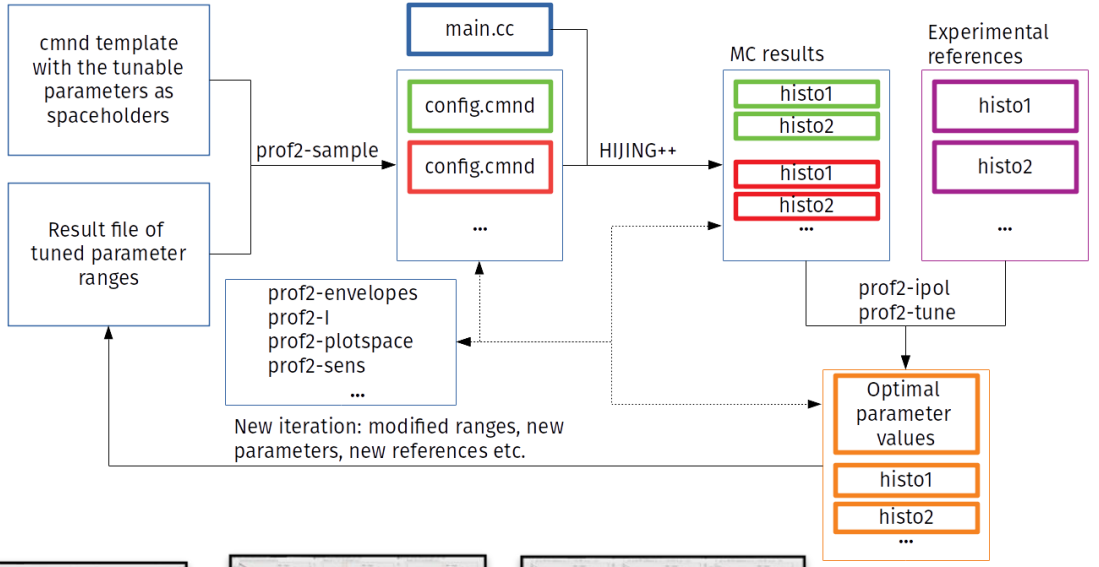


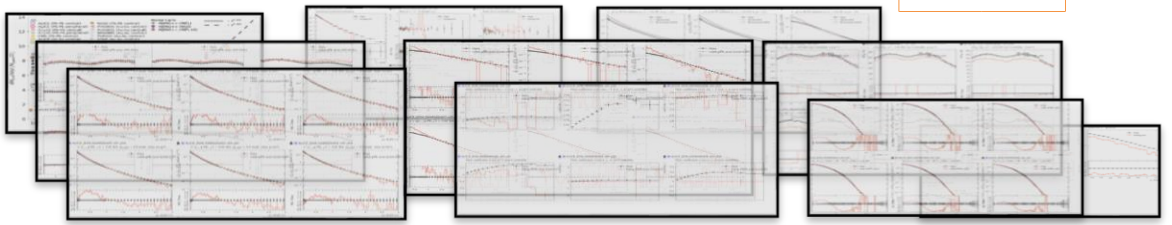

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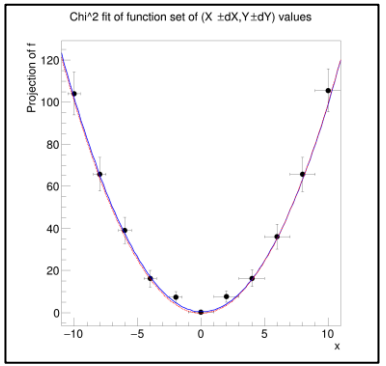


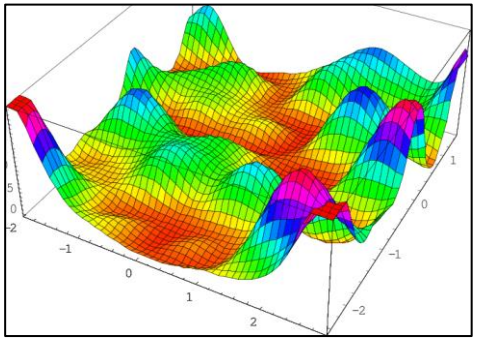

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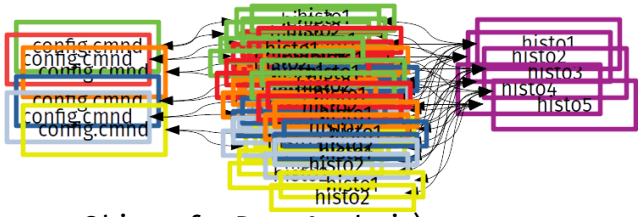


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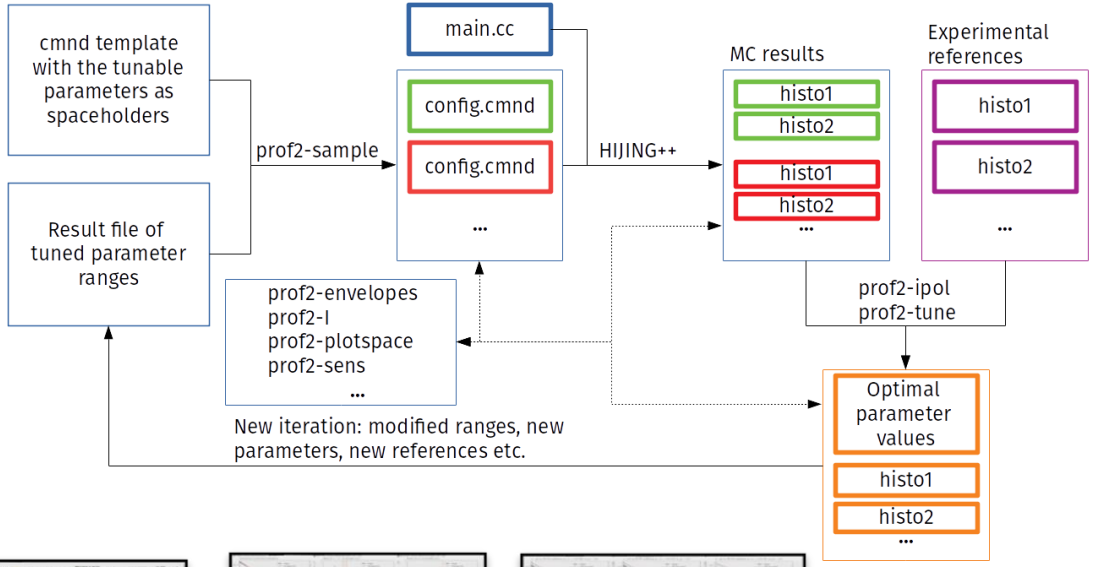
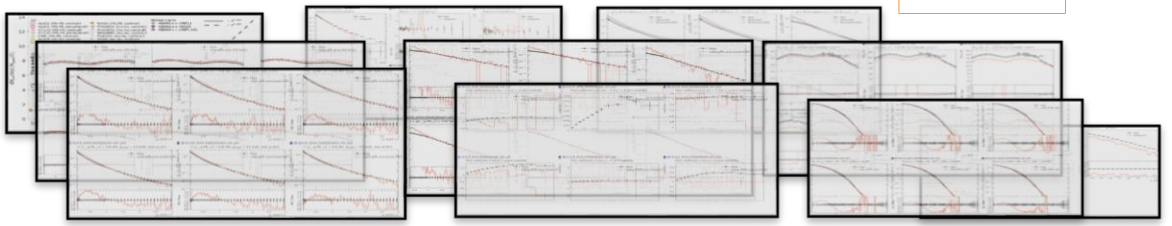
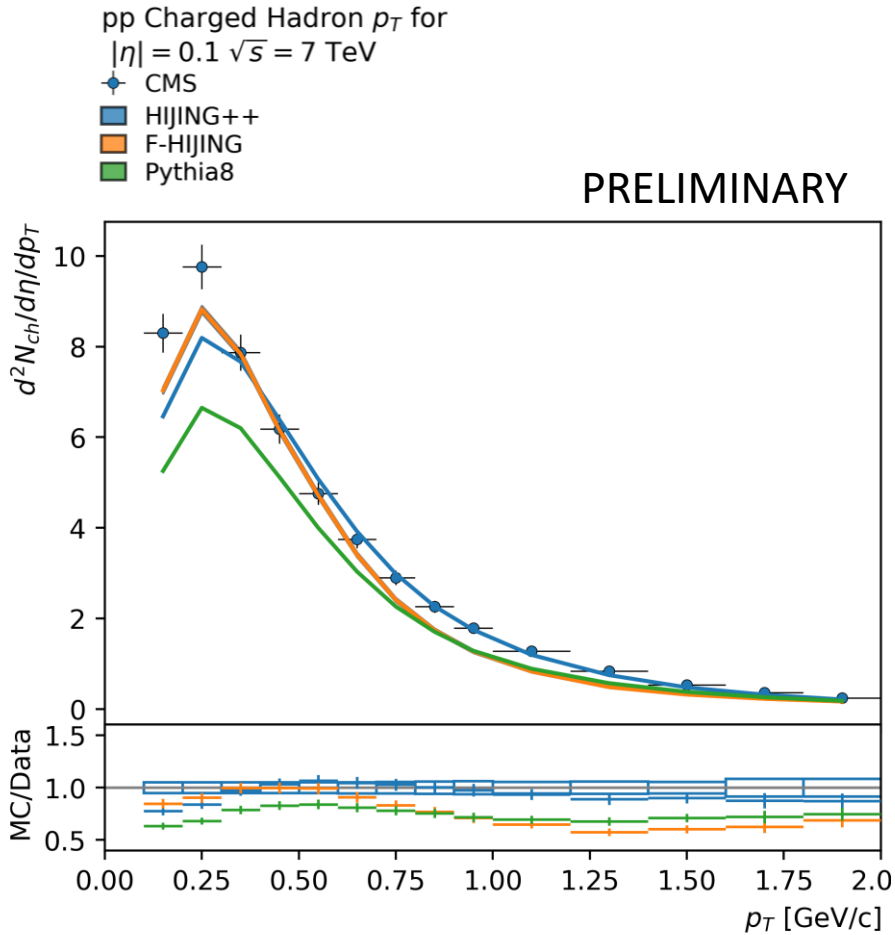
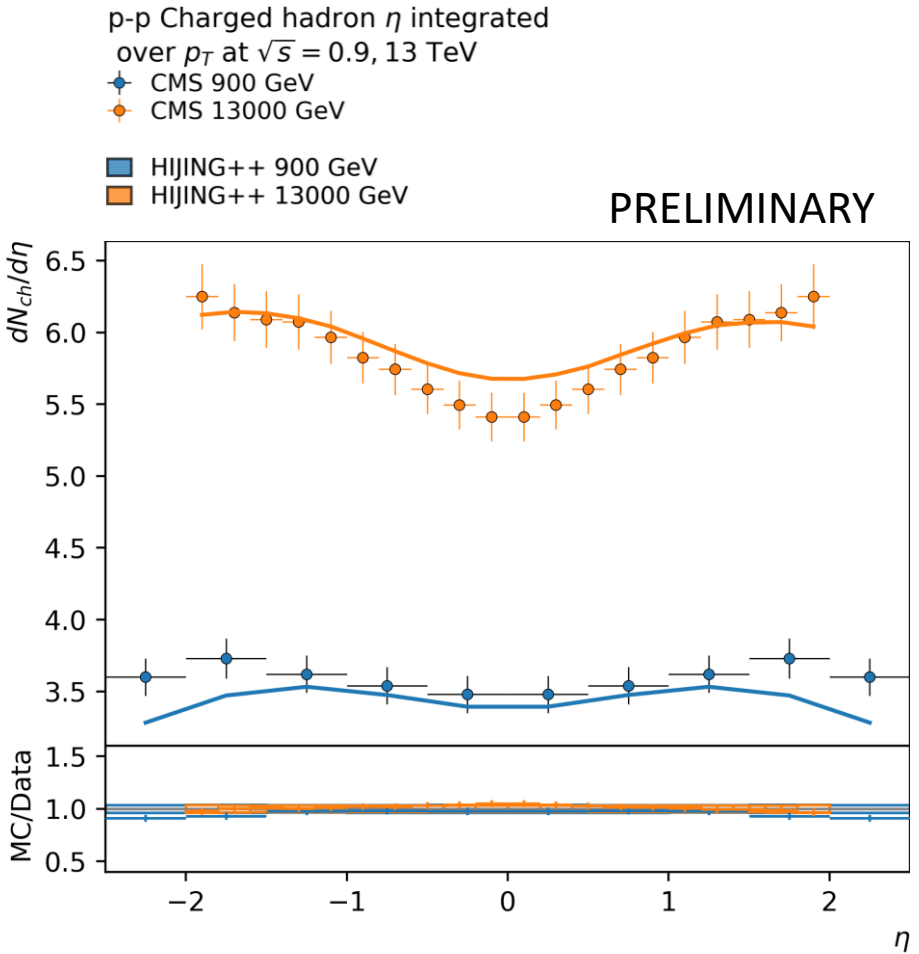


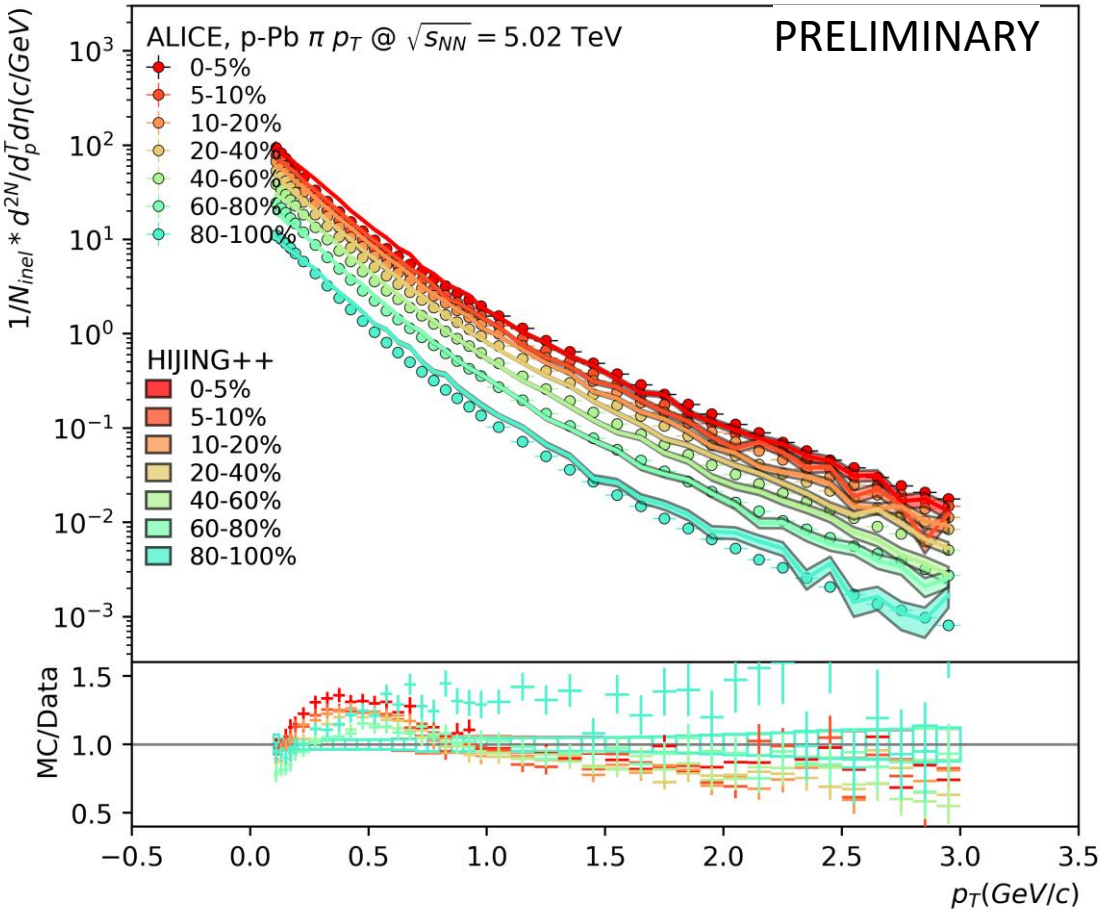



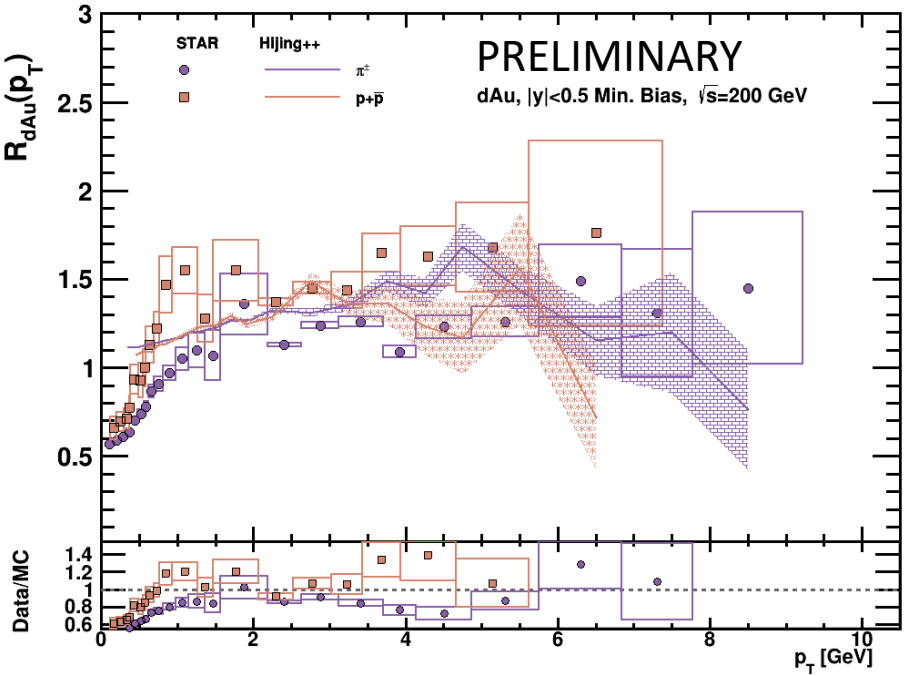
# Results


pp Charged Hadron $p_T$ for
$|\eta| = 0.1$ $\sqrt{s} = 7$ TeV
CMS
HIJING++
F-HIJING
Pythia8
PRELIMINARY
$d^2N_{ch}/d\eta/dp_T$
MC/Data
$p_T$ [GeV/c]

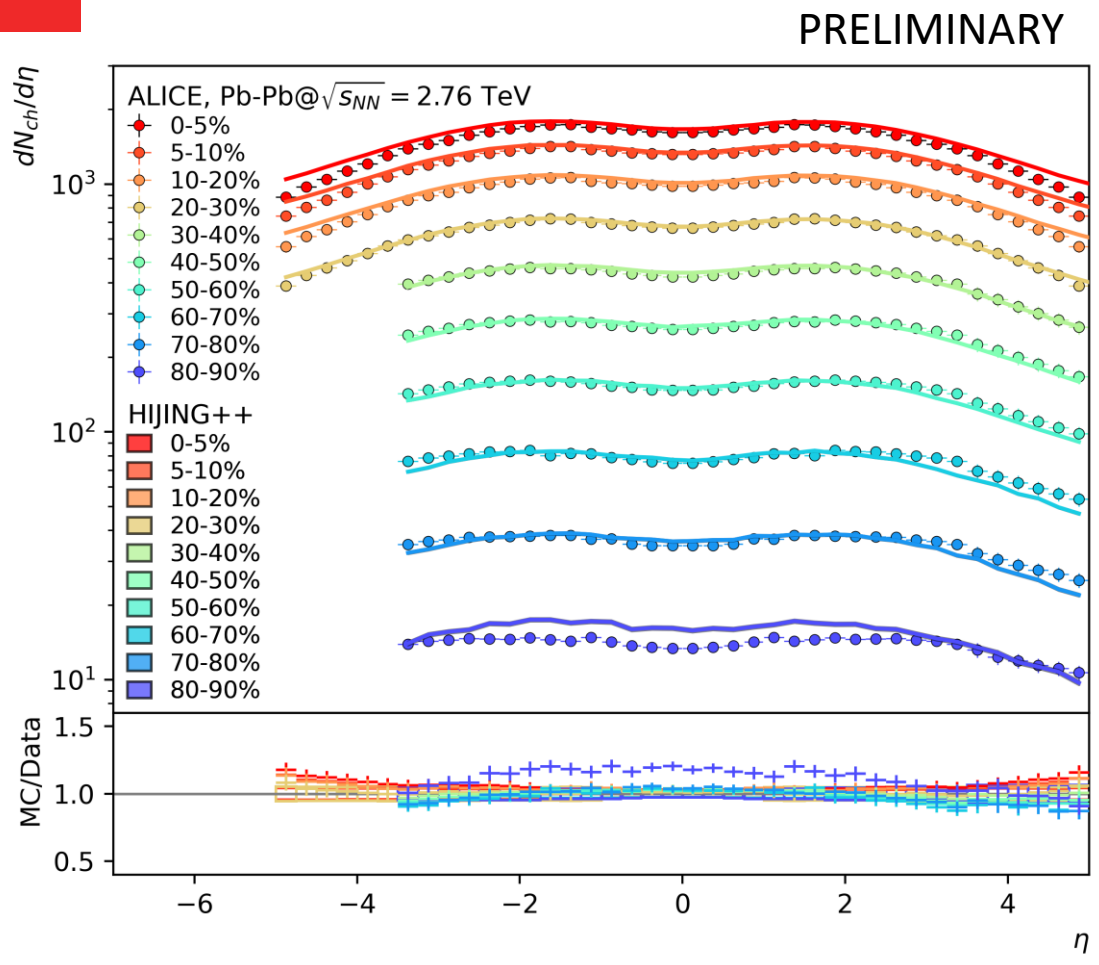

p-p Charged hadron $\eta$ integrated
over $p_T$ at $\sqrt{s} = 0.9, 13$ TeV
CMS 900 GeV
CMS 13000 GeV
HIJING++ 900 GeV
HIJING++ 13000 GeV
PRELIMINARY
$dN_{ch}/d\eta$
MC/Data
$\eta$

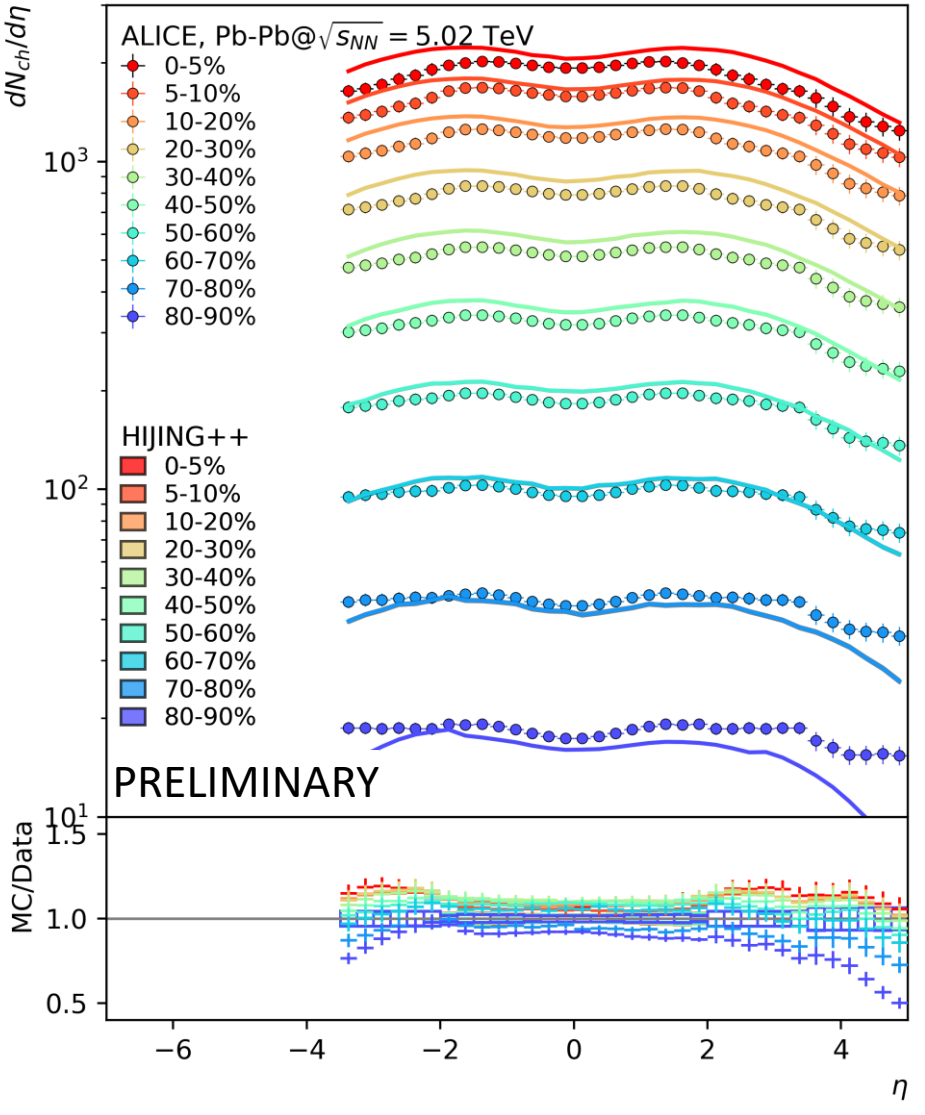
# Results


ALICE, p-Pb π $p_T$ @ $\sqrt{s_{NN}}$ = 5.02 TeV
PRELIMINARY
0-5%
5-10%
10-20%
20-40%
40-60%
60-80%
80-100%
HIJING++
0-5%
5-10%
10-20%
20-40%
40-60%
60-80%
80-100%
$1/N_{inel} * d^{2N}/d_p^T d\eta (c/GeV)$
MC/Data
$p_T (GeV/c)$


STAR
HIJING++
$\pi^{\pm}$
$p+\bar{p}$
PRELIMINARY
dAu, |y|<0.5 Min. Bias, $\sqrt{s}$=200 GeV
$R_{dAu}(p_T)$
Data/MC
$p_T$ [GeV]

# Results


PRELIMINARY
ALICE, Pb-Pb@$\sqrt{s_{NN}}$ = 2.76 TeV
0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
70-80%
80-90%
HIJING++
0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
70-80%
80-90%
$dN_{ch}/d\eta$
MC/Data
$\eta$


ALICE, Pb-Pb@$\sqrt{s_{NN}}$ = 5.02 TeV
0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
70-80%
80-90%
HIJING++
0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
70-80%
80-90%
PRELIMINARY
$dN_{ch}/d\eta$
MC/Data
$\eta$

# Summary

Monte Carlo event generators **were/are/will be** crucial in high-energy physics

- Computationally very demanding (both to operate and to develop)
- **HIJING++**: the next generation of high-energy heavy-ion simulations
- Multithreaded, modular, intuitive
- Needs to be tuned → time consuming
- Room for future improvements →  compatible with other popular frameworks, e.g. **JetScape**
- **Future:** support of Machine Learning-based modules

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**See related works: Wigner Scientific Computing Laboratory (The former Wigner GPU Laboratory): https://wigner.hu/en/wsclab**

**Cutting-edge** technologies and infrastructure

Several partners both from academy and industry

**Open opportunities for collaborations!**