Parton Showers on GPUs with GAPS

based on [2403.08692] and `siddharthsule/gaps`

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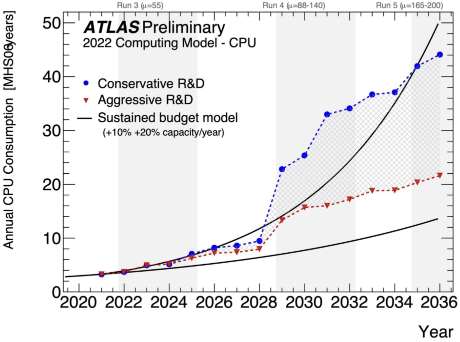
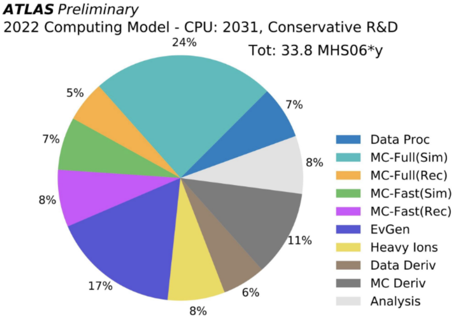
with Michael H. Seymour (Mike)

Parton Showers and Resummation, 4 July 2024

Event Generation is Expensive

CPU usage to surpass sustainable budget. Majority is MC, of which EvGen contributes 17% [CERN-LHCC-2022-005].





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Two ways to approach this problem:

1. Profiling and treating bottlenecks [2209.00843]
2. Parallelising tasks to reduce execution time and cost

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We can accelerate this parallelisation by using **GPUs:**

- Matrix Element + Phase Space: PEPPER [2311.06198], MadGraph4GPU [2303.18244]
- PDF Evaluations: LHAPDF [1412.7420, 2311.06198] PDFFlow [2009.06635]

Where do we go from here?

Even if LO/NLO events are generated on GPU, we still need to plug them into a CPU event generator for MPI, showering and hadronisation…

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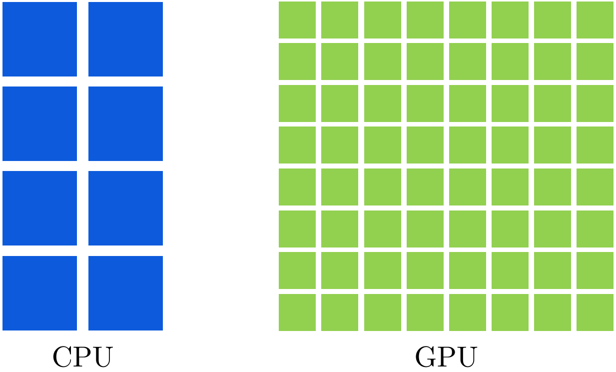
Can we do these on a GPU?

In This Talk

The Parallelised Veto Algorithm

Preliminaries - GPUs and SIMT



Preliminaries - GPUs and SIMT

SIMT = Single Instruction Multiple Threads

CPU: For Loop

```
for i in range(len(a)):
    b[i] = 3*a[i] + 2
```

GPU: Threads in a Kernel

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if thread_i < len(a):
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if thread_i < len(a):
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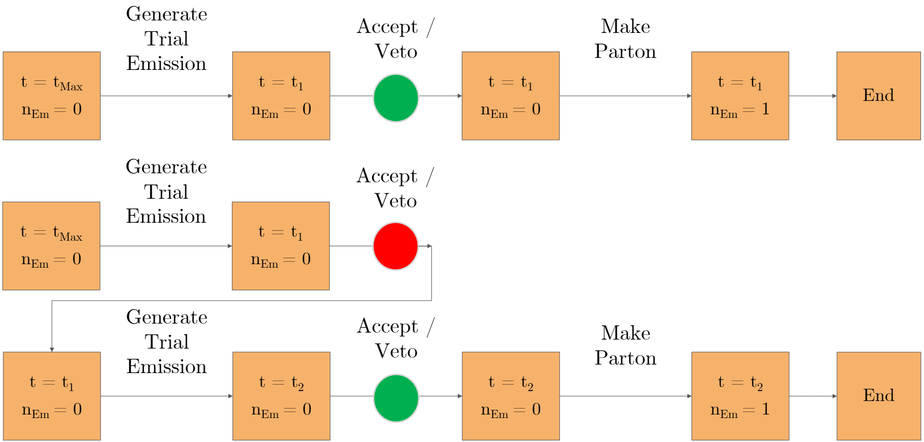
```

+ GPUs have ~ 1000 cores, so you can parallelise more tasks than a CPU cluster

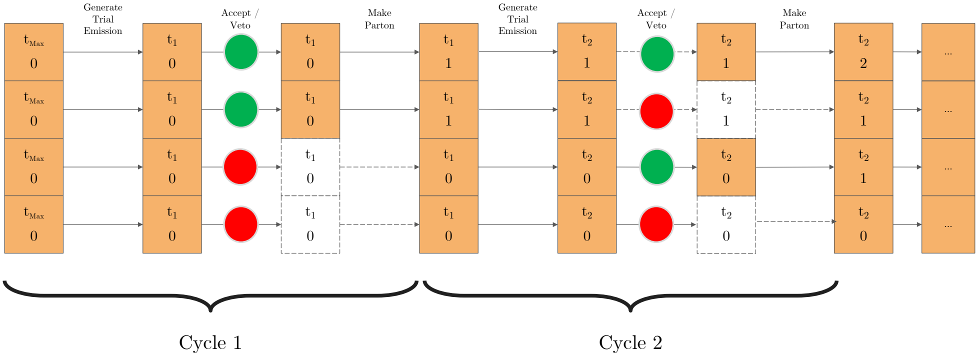
– GPU cores aren't as sophisticated as CPU cores; tasks have to be fairly simple

– SIMT doesn't allow branching tasks by construction (more on this soon…)

The Veto Algorithm



The Parallelised Veto Algorithm



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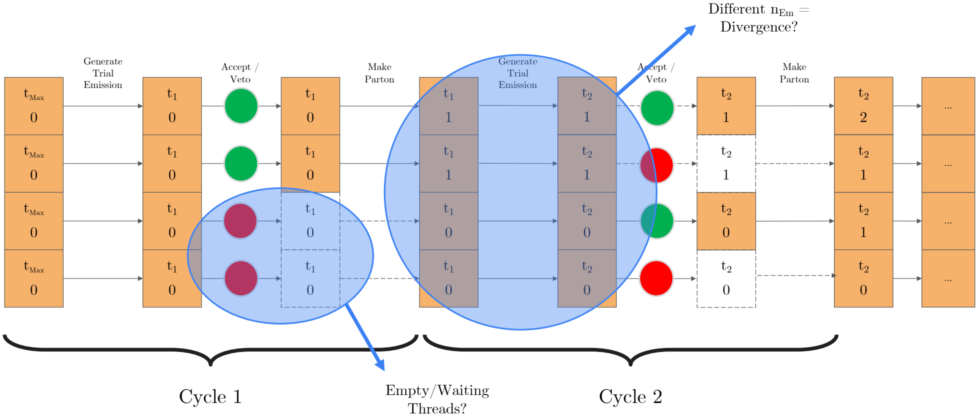


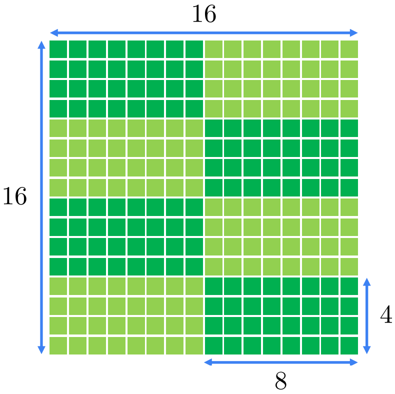
Different n_{Em} = Divergence?

Empty/Waiting Threads?

A Closer Look at GPU Architecture

Threads divided into batches of 32 called *warps*

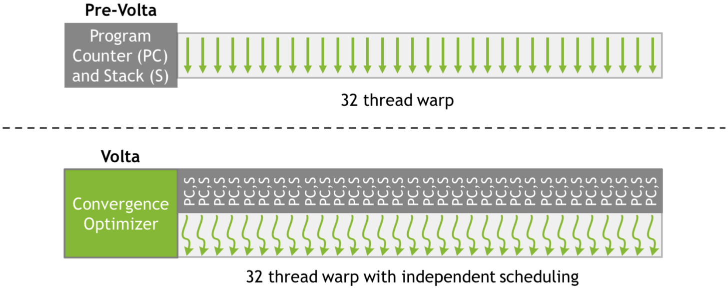
- Warps fully independent, like CPU cores
- For Example: 256 Threads = 8 Warps



So we deal with at-most 32 diverging threads, not thousands [NVIDIA Guide].

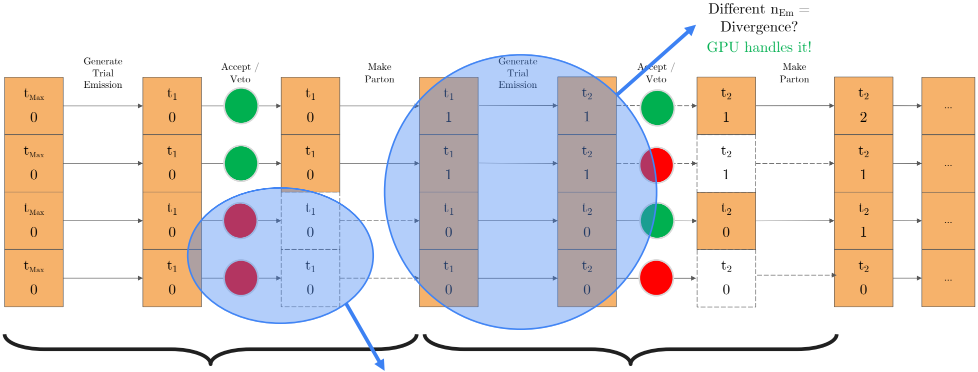
Enter Independent Thread Scheduling

GPUs now have the ability to have threads that diverge [NVIDIA Report].



Threads can execute their own commands (interleaved with other threads' commands).
If a few threads have same command, convergence optimizer runs them together.

The Parallelised Veto Algorithm

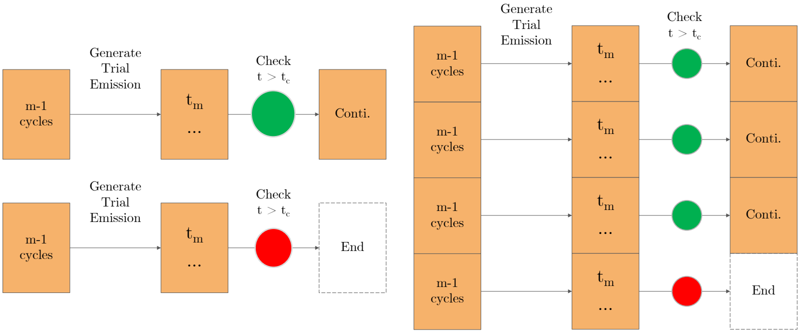


Different n_{Em} = Divergence?
GPU handles it!

Empty/Waiting Threads?
Not efficient, but OK!

The Shower Cutoff

Showering in Parallel means completed events must “wait” for incomplete events.



Implementation and Validation

Implementation Overview

Starting Point: S. Höche's Parton Shower Tutorial [1411.4085]

- Accurate Implementation of Massless Final State Catani–Seymour Shower
- Includes ME, α_s^{NLO}, Durham Alg. and Yoda File Writer

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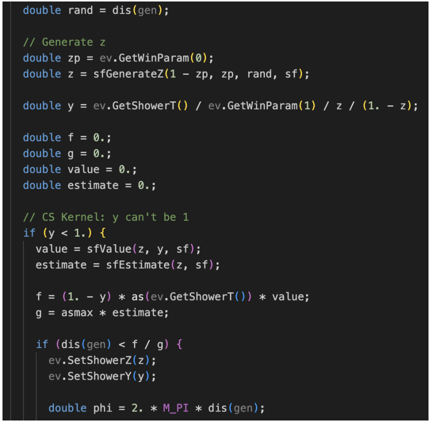
Rewritten for CPU in C++ and for GPU in CUDA C++

1. Ensure identical commands but different structure
2. Validate both codes with results from the Tutorial
3. Compare Execution Times

Implementation - Example Code Snippet



```
double rand = dis(gen);

// Generate z
double zp = ev.GetWinParam(0);
double z = sfGenerateZ(1 - zp, zp, rand, sf);

double y = ev.GetShowerT() / ev.GetWinParam(1) / z / (1. - z);

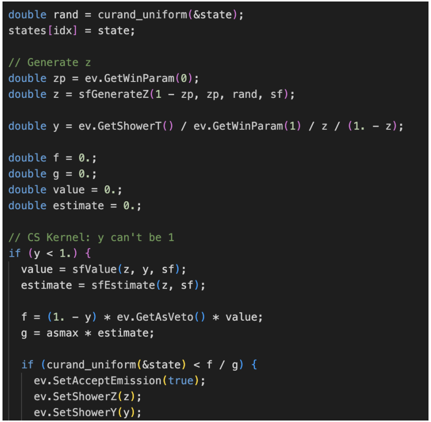
double f = 0.;
double g = 0.;
double value = 0.;
double estimate = 0.;

// CS Kernel: y can't be 1
if (y < 1.) {
  value = sfValue(z, y, sf);
  estimate = sfEstimate(z, sf);

  f = (1. - y) * as(ev.GetShowerT()) * value;
  g = asmax * estimate;

  if (dis(gen) < f / g) {
    ev.SetShowerZ(z);
    ev.SetShowerY(y);

    double phi = 2. * M_PI * dis(gen);
```



```
double rand = curand_uniform(&state);
states[idx] = state;

// Generate z
double zp = ev.GetWinParam(0);
double z = sfGenerateZ(1 - zp, zp, rand, sf);

double y = ev.GetShowerT() / ev.GetWinParam(1) / z / (1. - z);

double f = 0.;
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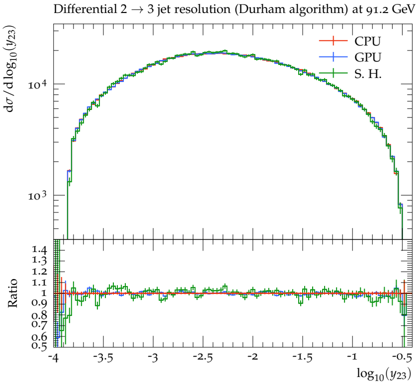
double value = 0.;
double estimate = 0.;

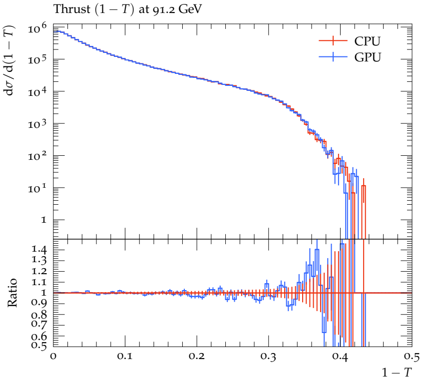
// CS Kernel: y can't be 1
if (y < 1.) {
  value = sfValue(z, y, sf);
  estimate = sfEstimate(z, sf);

  f = (1. - y) * ev.GetAsVeto() * value;
  g = asmax * estimate;

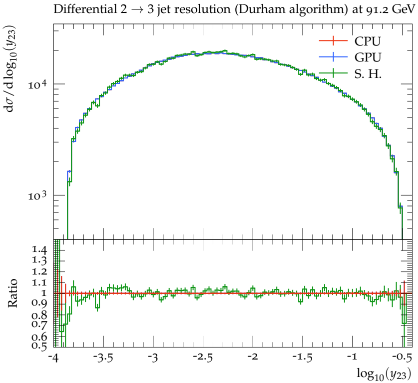
  if (curand_uniform(&state) < f / g) {
    ev.SetAcceptEmission(true);
    ev.SetShowerZ(z);
    ev.SetShowerY(y);
```

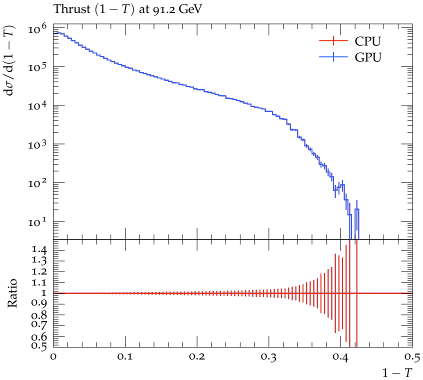
Validation - Jet Rates and Event Shapes





(New!) Using Identical RNG and Seed


Differential 2 → 3 jet resolution (Durham algorithm) at 91.2 GeV


Thrust $(1-T)$ at 91.2 GeV

Comparison of Execution Times

Definitions and Criteria

Execution Time: Time taken for a component in its *entirety*:

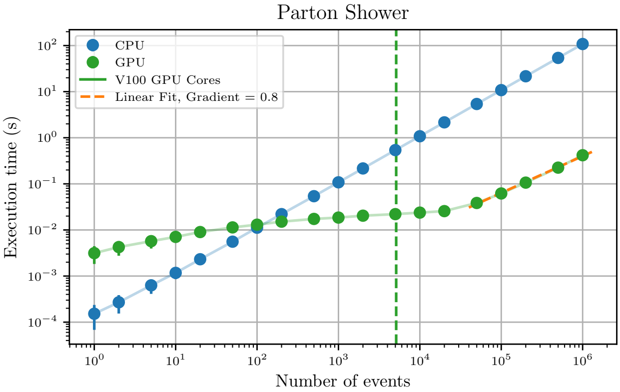
- Include any initialisation and setup tasks in execution time
- Mainly because GPU tasks are surrounded by smaller CPU Tasks

We compare **1 CPU Core** against **1 CPU Core + 1 GPU**

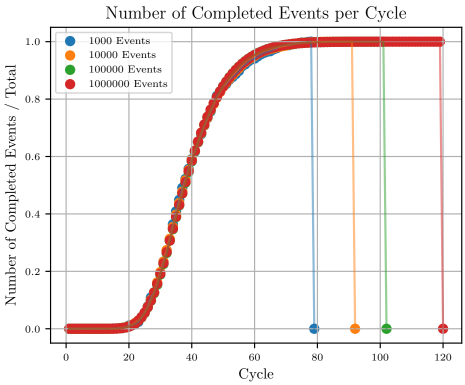
- CPU: Intel Xeon CPU E5-2620 v4 @ 2.10GHz [Specifications]
- GPU: NVIDIA Tesla V100 for PCIe, 16 GB, 5,000 Cores [Specifications]

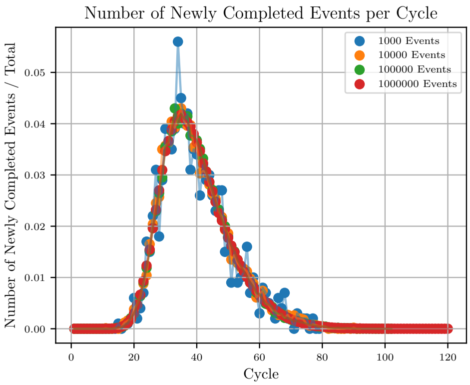
Execution Time - Parton Shower

Maximum speed up: 258x at 1,000,000 events (0.4s vs 103s)



Studying the Shower Cycles

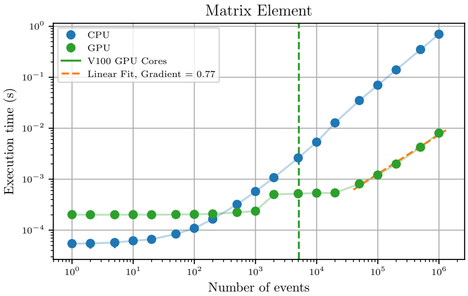


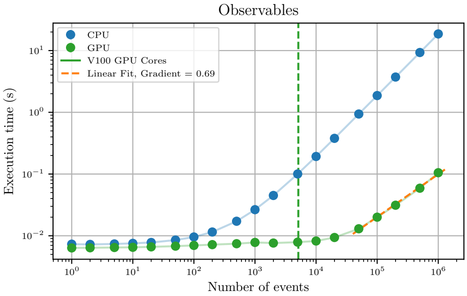


IMPORTANT: Cycle $\neq$ Time! A smaller number of events leads to quicker cycles.

Matrix Element and Observables

Maximum speed up: 87x for ME and 177x for Observables at 1,000,000 events


Matrix Element


Observables

Maximum Speedup of ME + PS + Ob: 239x for 1,000,000 events (0.5s vs 120s)

Context - Costs of CPUs vs CPU+GPU

Type	ID	Cost	Power
CPU	Intel Xeon (16 Cores)	≈ $ 500	85 W (5 W per core)
GPU	NVIDIA V100	≈ $ 5000	250 W

Around 15–16 CPUs (240–256 Cores) needed to match 1 CPU Core + 1 GPU:

- 16 × $ 500 = $ 8000, more expensive than CPU+GPU
- 16 CPUs = 1360 W, 1 CPU Core + 1 GPU = 255 W

Using GPUs leads to cheaper setup and 5x less power consumption

Next Steps and Conclusion

Next Steps

Aim: To produce a Complete ISR+FSR shower and measure speedups

- To combine with LHAPDF on GPU (work done by M. Knobbe)
- Followed by simulating LHC and DIS processes

Also: To develop this code as a *parton shower sandbox*

- For use in testing new shower kernels and kinematics
- As a starting point for anyone interested in GPU Hadronisation :)

Summary

Using modern GPU technology, individual steps of the veto algorithm can be run for many events together. This allows us to simulate parton showers in *parallel*.

While there are setbacks, we demonstrate a reduction in execution time whilst producing identical results.

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Using modern GPU technology, individual steps of the veto algorithm can be run for many events together. This allows us to simulate parton showers in *parallel*.

While there are setbacks, we demonstrate a reduction in execution time whilst producing identical results.

This talk is based on “An Algorithm to Parallelise Parton Showers on a GPU” [2403.08692]. The program, GAPS (a GPU Amplified Parton Shower), can be accessed here:

`https://gitlab.com/siddharthsule/gaps`

Try it, test it, break it, critique it, and send us your feedback!

...And That's All!

Thanks for Listening!

My details:

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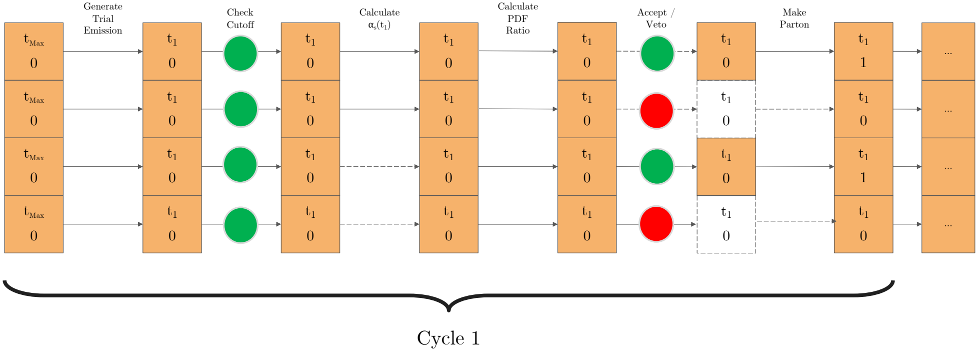
Appendix Slides

The Paralleised Veto Algorithm - In Full



NVIDIA V100 GPU Diagram

Profiling

Name	**Instances**	**Total Time (ns)**	**Time (%)**
Selecting the Winner Emission	119	291,300,033	46.3
Device Prep.	1	105,578,119	16.8
Vetoing Process	119	45,518,957	7.2
Thrust	1	42,478,087	6.8
Durham Algorithm	1	26,657,439	4.2
Checking Cutoff	119	25,702,499	4.1
Doing Parton Splitting	119	23,646,846	3.8
Calculating $\boldsymbol{\alpha}_s$	119	20,654,227	3.3
Histogramming	1	17,950,803	2.9
Matrix Element	1	7,605,270	1.2
Set Up Random States	1	7,439,289	1.2
Jet Mass/Broadening	1	5,758,537	0.9
Validate Events	1	5,580,426	0.9
Prep Shower	1	2,651,686	0.4
Set Up $\boldsymbol{\alpha}_s$ Calculator	1	8,800	0.0
Pre Writing	1	5,856	0.0
Set Up ME Calculator	1	3,968	0.0

Unanswered Questions / To Do List

Can you combine some of your Kernels in your Diagram? How does it affect the Speed Up?

What about allowing the user to vary $\alpha_s(m_Z)$ and t_C?

S. Höche's Tutorial also contains Matching. Are you planning on implementing that?

Is it possible to connect this to something like PEPPER or MadGraph4GPU?

Any attempts to optimize the code?