MC event generation tutorial

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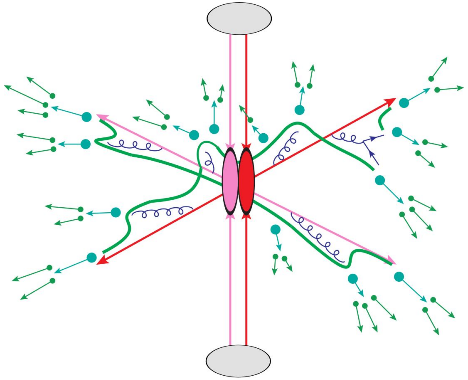
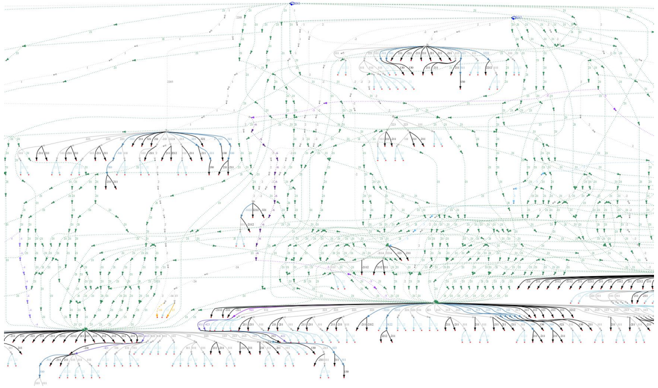
Setup: Docker images and containers

- **We will be running event generators via Docker**
  - Like a virtual Linux machine that you run inside your own PC
  - VM *image* files are O(1 GB): download these in advance!
- **Containers and volume binding**
  - You can `run` an image multiple times: each copy is a *container*
  - By default the data from each container stays on your machine… this eats a *lot* of disk space! use `--rm` to make it auto-delete, or periodically `docker system prune`
  - To make it easy to get data in and out of your container, make a “portal” directory: `-v /some/host/dir:/some/container/dir`
- **Rivet+Pythia image**
  - `docker pull hepstore/rivet-pythia:chacal24`
  - `docker run -it --rm hepstore/rivet-pythia:chacal24`
  - Test: `# rivet -h` `# pythia8-main93 -h`
- **Rivet+MG5_aMC@NLO image**
  - `docker pull hepstore/rivet-mg5amcnlo:chacal24` + `docker run …`
  - Test: `# rivet -h` `# MG5_aMC_v3_5_3/bin/mg5_aMC -h`

MC generation

- **MC generation: where theory meets experiment**
  - The fundamental pp collision, *in vacuo*
- **Components of a fully exclusive SHG chain**
  - QFT matrix element sampling at fixed order in QCD etc.
  - *Dressed* with approximate collinear splitting functions, iterated in factorised Markov-chain "parton showers"
  - FS parton evolution terminated at Q ~ 1 GeV: phenomenological hadronisation modelling. Mixed with MPI modelling.
  - Finally particle decays, and other niceties
- **Today**
  - hands-on tutorial with Pythia8 and MadGraph5
    - for background principles see the lecture slides
  - introduction to running generators and studying their output
  - generation biasing for efficient phase-space population
  - ME/PS merged generation with extra ME jets
  - ~~BSM model configuration and generation~~





Generator basics

- **First, get your Pythia Docker container started**
  - `$ docker pull hepstore/rivet-pythia:chacal24`
  - `$ docker run -it --rm -v $PWD:/host hepstore/rivet-pythia:chacal24`

purple = command shell

- **Pythia8: shower-hadronisation generator (SHG) with many LO processes built-in**
  - Pythia 8.3 docs: https://pythia.org/latest-manual/Welcome.html
  - We’ll use the “main93” example interface. Open a blank command file: `# nano py8-top.cmnd`
  - Add the lines:

```
Beams:eCM = 13000
Top:all = on
Main:writeHepMC = on
```

  - And run: `# pythia8-main93 -c py8-top.cmnd -o TOP -n 100`

blue = generator configs

- **Examine the output**
  - `less TOP.hepmc`
  - Run a basic physics analysis on it: `# rivet -a MC_FSPARTICLES TOP.hepmc -H TOP.yoda`
  - View the histogram data: `$ less TOP.yoda; # yodals -v TOP.yoda`
  - `# rivet-mkhtml TOP.yoda -o /host/rivet-plots-top`
  - And point your Web browser at it, e.g. `$ firefox rivet-plots-top/index.html`

More statistics = no more event files

- **The HepMC ASCII files are very large!**
  - They waste space, and CPU due to the writing/re-reading time
  - Useful for debugging, though
- **Better that we pass the events to Rivet in memory instead**

  -
    ```
    # nano py8-top.cmnd
    ```
  - And change to:
    ```
    Beams:eCM = 13000
    Top:all = on
    Main:runRivet = on
    Main:analyses = MC_TTBAR,MC_JETS,MC_FSPARTICLES,MC_ELECTRONS,MC_MUONS
    ```

  -
    ```
    # pythia8-main93 -c py8-top.cmnd -o TOP -n 5000
    ```

  -
    ```
    # rivet-mkhtml TOP.yoda -o /host/rivet-plots-top
    ```
- **Inspect the output**
  - Do the lepton distributions make sense?
  - The jets?
  - What happens to the statistics at high p_T?

Jet-event generation

- **Let’s make some inclusive-jet events**
  - In Pythia, this just means a *pp* ⟶ *jj* ME. Everything else comes from the PS, especially ISR
  - It does remarkably well for that (thanks to a few tricks)
  - But mostly we use higher-order generators for the ME nowadays. Py8 is quick, though!

- **We start with the obvious configuration**
  - `# nano py8-jets.cmnd`

```
Beams:eCM = 13000
HardQCD:all = on
PhaseSpace:pThatMin = 10
Main:runRivet = on
Main:analyses = MC_JETS
```

  - `# pythia8-main93 -c py8-jets.cmnd -o JETS -n 6000` (there’s a reason for this number of events!)

- **View the output**
  - `# rivet-mkhtml JETS.yoda -o /host/rivet-plots-jets`
  - And view: what’s happened to the p_T tails and 3rd, 4th jet distributions?
  - We can improve this with ME phase-space slicing and/or enhancement

Jet-event slicing

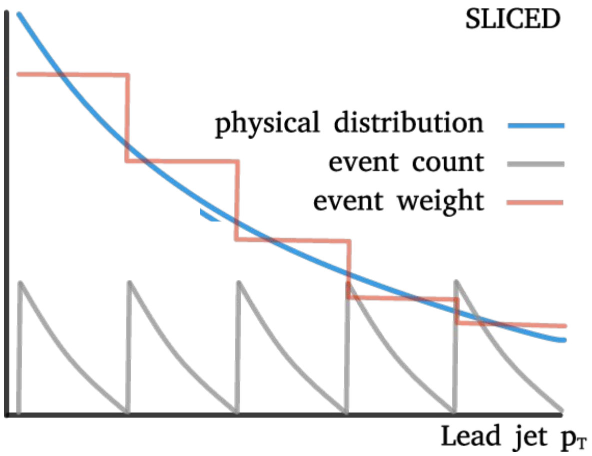
- **The statistics died off at high p_T**
  - The unweighted events are asymptotically distributed like the physical $d\sigma/dp_T$
  - ⇒ *far* too many low-p_T events for our needs! Rapidly drop below systematics threshold
  - Simple solution: stick together several runs in orthogonal *slices* of ME phase-space

- **Three slices, the top-one open-ended**
  - Add a max p_T^{hat} to py8-jets.cmnd:

    ```
            PhaseSpace:pThatMin = 10
            PhaseSpace:pThatMax = 50
    # pythia8-main93 -c py8-jets.cmnd -o JETS0 -n 2000
    ```
  - Then a min/max pair above that:

    ```
            PhaseSpace:pThatMin = 50
            PhaseSpace:pThatMax = 100
    # pythia8-main93 -c py8-jets.cmnd -o JETS1 -n 2000
    ```
  - And a final min-only:

    ```
            PhaseSpace:pThatMin = 100
    # pythia8-main93 -c py8-jets.cmnd -o JETS2 -n 2000
    ```



  - Plot and study:

    ```
    # rivet-merge JETS?.yoda -o JETS_SLICE.yoda
    # rivet-mkhtml JETS{0,1,2}.yoda:LineStyle=dotted JETS_SLICE.yoda:Sliced -o /host/rivet-plots-jets
    ```

Jet-event enhancement

- **The statistics work better now, and the correctly xs-normalised sum is smooth**
  - We still have falling stats in each slice, though: “sawtooth” statistical error
  - Can we “continuously slice”? Yes! Sample from $p_T^{\mathrm{hat},n}$ dσ/dp$_T^{\mathrm{hat}}$, with weights $1/p_T^{\mathrm{hat},n}$
  - Since LO 2→2 process, p_T^{hat} is unambiguous

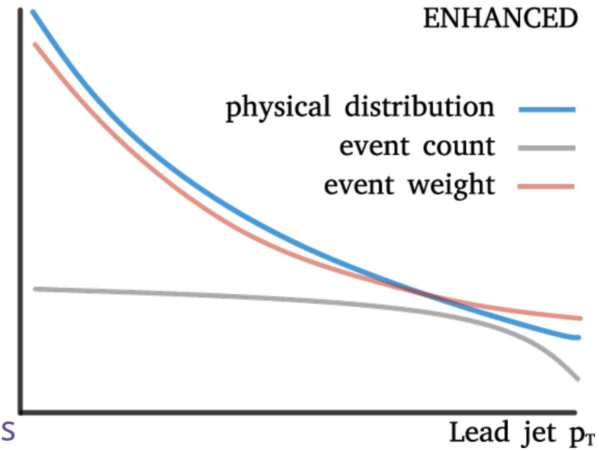
- **Enhanced dijet generation**
  - Enable biasing in py8-jets.cmnd:

```
PhaseSpace:pThatMin = 10
PhaseSpace:bias2Selection = on
# pythia8-main93 -c py8-jets.cmnd -o JETS_ENH -n 3000
```

  - Pretty-printing of all methods:

```
# rivet-mkhtml JETS.yoda:Raw:LineColor=red \
    JETS{0,1,2}.yoda:LineColor=purple:LineStyle=dotted \
    JETS_SLICE.yoda:Slice:LineColor=green \
    JETS_ENH.yoda:Enh:LineColor=orange -o /host/rivet-plots-jets
```

  - Study the output. Which is better at phase-space coverage?
    Compare the numbers of events generated



V+jets production

- **W/Z+jets are the biggest and most CPU-consuming MC samples at the LHC**
  - Followed by ttbar, single-top, diboson, …
  - The “classic” development lab for beyond-LO methods, because
    - Born process at 2→1 tree level; jets (and hence all Z p_T) is beyond LO
    - colour-singlet boson is unproblematic for QCD
    - vector boson: symmetry protection ⇒ small NLO corrections wrt Higgs
    - massive boson = naturally “anchored” scale choices: more stable than massless jets or photons

- **First, let’s make a Pythia8 version, then go to MG5**

  -
    ```
    # nano py8-zmm.cmnd
            Beams:eCM = 13000
            WeakBosonAndParton:qqbar2gmZg = on
            WeakBosonAndParton:qg2gmZq = on
            PhaseSpace:pThatMin = 20
            23:onMode = off
            23:onIfAny = 13
            Main:runRivet = on
            Main:analyses = MC_JETS
    ```

  -
    ```
    # pythia8-main93 -c py8-zmm.cmnd -o ZMM -n 5000
    ```

  -
    ```
    # mv ZMM.yoda /host/Py-ZJ.yoda
    ```

V+jets production: MG5

- **Get the MG5 image and open it in a separate terminal**

  -
    ```
    $ docker pull hepstore/rivet-mg5amcnlo:chacal24
    ```

  -
    ```
    $ docker run -it --rm -v $PWD:/host hepstore/rivet-mg5amcnlo:chacal24
    # cd MG5_aMC_v3_5_3/
    # bin/mg5_aMC
    ```
  - MG5 is a fixed-order ME generator that interfaces with Pythia’s showers, decays, etc.

- **Generate the lowest-order jet-multiplicity sample**

  -
    ```
    > generate p p > mu+ mu- j
    > output PROC-ZJ
    > launch
    > … (enable Pythia, run)
    > quit
    ```

  -
    ```
    # cp -r PROC-ZJ /host/
    ```
    ⇒ look at diagrams in the host file browser, xsec in web browser

  -
    ```
    # cd PROC-ZJ/Events/run_01/
    ```
    ⇒ look at the LHE (and HepMC) event files:
    ```
    # zless unweighted_events.lhe.gz
    ```

JPG Feyn diagrams will be generated automatically in the SubProcesses (sub)folders. You can also use the `> display diagrams` command… but not very effectively in Docker since there’s no graphics

V+jets production: MG5 jet-merging

- ❖ **We can also make higher-order MEs (here just tree-level)**
  - ➢

```
# …
# bin/mg5_aMC
> generate  p p > mu+ mu- j
> add process  p p > mu+ mu- j j
> output PROC-ZJJMERGED
> quit
```

Add a [QCD] suffix to generate a process at QCD NLO. Slow!!

One-loop matching with MC@NLO; loop and legs merging/matching with FxFx

  - ➢

```
# cp -r PROC-ZJJMERGED PROC-ZJJBORKED
# cd PROC-ZJJBORKED
# nano Cards/proc_card_mg5.dat
# nano Cards/run_card.dat
# bin/generate_events
```

⇒ copy setup for broken, overlapping-process hack

⇒ set ickkw=0 (disables correct merging!)

  - ➢

```
# cd ../PROC-ZJJMERGED
# bin/generate_events
```

- ❖ **What's going on???**
  - ➢ The PS makes the different multiplicities overlap in phase-space: have to avoid double-counting
  - ➢ CKKW(L) and MLM procedures do this by phase-space weights or cuts: we're trying MLM on/off

V+jets production: analysis and comparison

- **Run Rivet on the (zipped) MG5 HepMC events**
  - MG5 events have lots of weights, cf. the LHE file. Incorporating scale and PDF variations. But MG5 doesn't specify a default weight, so we need to identify that by hand:
  -

```
# rivet -a MC_JETS \
--nominal-weight='DYN_SCALE=1_MUF=1.0_MUR=1.0_PDF=247000_MERGING=0.000' \
        PROC-ZJ/Events/run_01/tag_1_pythia8_events.hepmc.gz -H MG-ZJ.yoda

# rivet -a MC_JETS \
--nominal-weight='DYN_SCALE=1_MUF=1.0_MUR=1.0_PDF=247000_MERGING=0.000' \
        PROC-ZJJBORKED/Events/run_01/tag_1_pythia8_events.hepmc.gz -H MG-ZJJ-sum.yoda

# rivet -a MC_JETS \
--nominal-weight='DYN_SCALE=1_MUF=1.0_MUR=1.0_PDF=247000_MERGING=45.000' \
        PROC-ZJJMERGED/Events/run_01/tag_1_pythia8_events.hepmc.gz -H MG-ZJJ-merge.yoda
```

  - And plot:

```
# cp /host/Py-Z.yoda .
# yoda2yoda MG-ZJ{,-filt}.yoda -M "Weight|AUX|ALPS|\[s|/_"      # weights standard pending!
# rivet-mkhtml Py-Z.yoda MG-Z*-filt.yoda -o /host/rivet-plots-z
```

- **Inspect the output**
  - See how the samples have different kinematics & N_{jets}? ~~And the MG5 systematic uncertainty bands?~~

That’s it!

- **Thanks for your time!**
- You now know how to run two of the most popular LHC event generators at Born and merged/matched levels
- ~~And how to set up and run any UFO new-physics model~~
- This is a superpower — use it wisely!
- And the devil is in the details: black-box mode will only get you so far
- Sometimes it goes wrong, sometimes… it’s complicated
- **Good luck!**

BSM physics generation

- **Pythia8 has several built-in models, e.g. Z’, SUSY, XD resonances…**
  - Many are steered just via Py8 parameters — see the manual
  - SUSY in particular requires an SLHA file: use hepstore/rivet-tutorial
  - Set up a command file with

```
SUSY:all = on
SLHA:file = gg_g1500_chi100_g-ttchi.slha
```

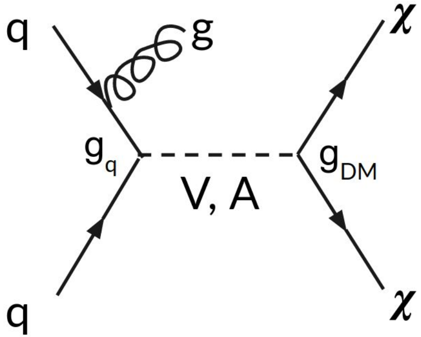
  - Run and analyse

hepstore/rivet-tutorial is just the rivet-pythia Docker image with a few extra tutorial files in the work dir

- **MG5 is really a generator generator: more flexible**
  - ⇒ can build new MEs for ~any UFO physics model (as can Sherpa, Herwig)
  - E.g. a dark matter model:

```
> import model DMsimp_s_spin1 --modelname
> generate p p > xd xd~ j
```

  - etc. DM mass, coupling can be set in the “param card” = SLHA
  - Generate and analyse
  - More control can be imposed by fixing new-physics couplings at amplitude level e.g. `NP==1` or ME-squared level e.g. `NP^2==1`



Since the MG5 conversion to use Python3, you may need to run a ‘convert’ command on your UFO, and re-import. The command-line will advise you if this is the case