# MC event generation tutorial

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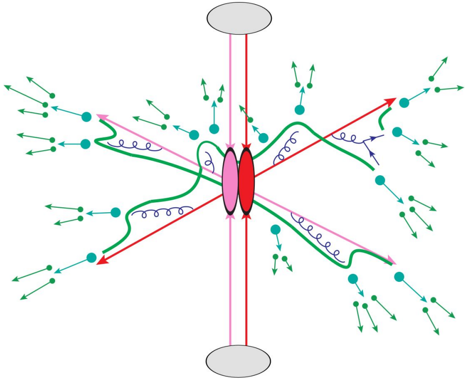
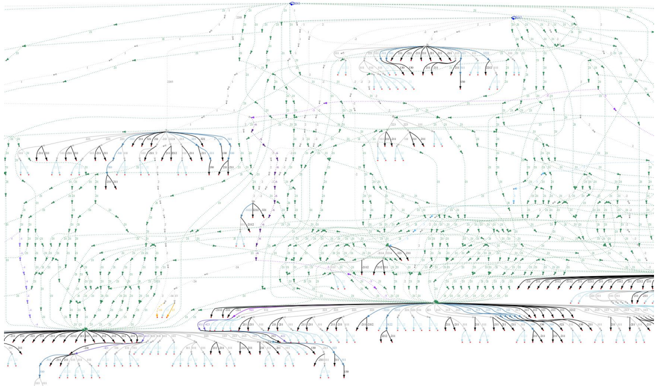
# Setup: Docker images and containers

- **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 $pp \longrightarrow jj$ 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

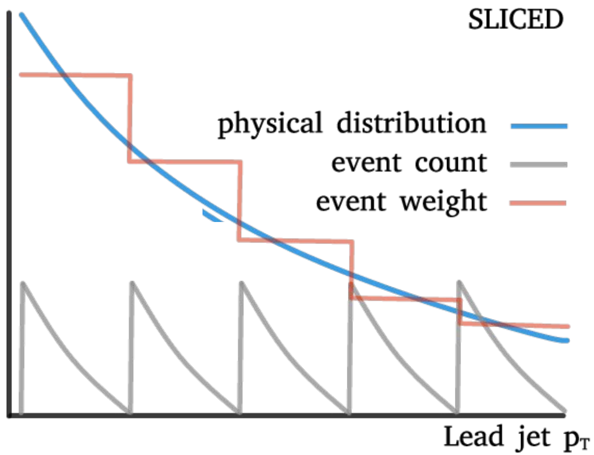
- **The statistics died off at high $p_T$**
  - The unweighted events are asymptotically distributed like the physical $d\sigma/dp_T$
  - ⇒ *far* too many low-$p_T$ events for our needs! Rapidly drop below systematics threshold
  - Simple solution: stick together several runs in orthogonal *slices* of 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 $p_T^{\text{hat},n}\, d\sigma/dp_T^{\text{hat}}$, with weights $1/p_T^{\text{hat},n}$
  - Since LO 2→2 process, $p_T^{\text{hat}}$ is unambiguous

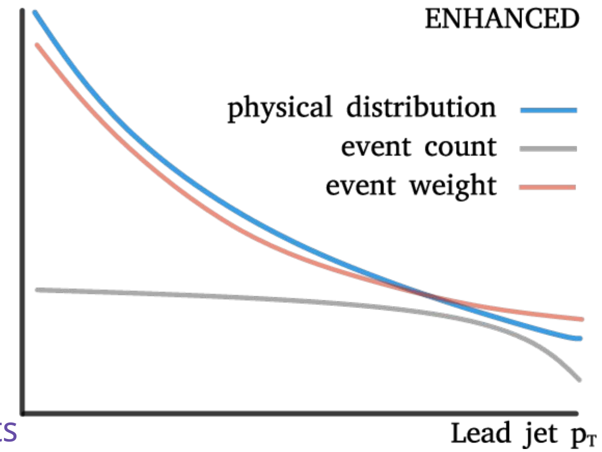
- **Enhanced dijet generation**
  - Enable biasing in py8-jets.cmnd:

```
        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
    ```
  - ```
    # 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 (first line)

    ⇒ set ickkw=0 (disables correct merging!) (run_card.dat line)
  - ```
    # cd ../PROC-ZJJMERGED
    # bin/generate_events
    ```

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

- **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 "/RAW|Weight|AUX|ALPS|\[s|/_"      # weights standard pending!
# rivet-mkhtml Py-Z.yoda MG-Z*-filt.yoda -o /host/rivet-plots-z      # add --no-weights for speed
```

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

# Writing a custom analysis

- **Just running pre-made Rivet analyses like MC_JETS would be very limiting**
  - Now we will very briefly write our own analysis code

- Inside your container, create a new C++ source file
  - Rather than start from an empty file, we use rivet-mkanalysis to make a template code:
    ```
    rivet-mkanalysis CHACAL
    nano CHACAL.cc
    ```
  - Book a new histogram:
    ```
    book(_h["jjmass"], "jjmass", logspace(20, 1.0, 1000.0));
    ```
  - Require and get the two leading jets, add 4-vectors, histogram the mass:
    ```
    if (jets.size() < 2) vetoEvent;
    FourMomentum pjj = jets[0].mom() + jets[1].mom();
    _h["jjmass"]->fill(pjj.mass()/GeV);
    ```
  - Build, run and plot:
    ```
    # rivet-build CHACAL.cc
    # rivet --pwd -a CHACAL PROC-ZJJMERGED/…/*.hepmc.gz -H chacal.yoda
    # rivet-mkhtml chacal.yoda -o /host/rivet-plots-chacal
    ```

Documentation on the code & physics objects from here:
https://rivet.hepforge.org/doc
https://gitlab.com/hepcedar/rivet/-/blob/release-3-1-x/README.md#welcome

# 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

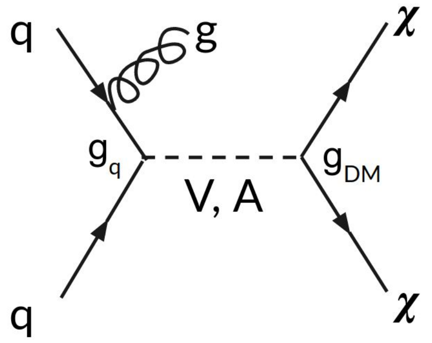
- **MG5 is really a generator generator: more flexible**
  - ⇒ can build new MEs for ~any UFO physics model (as can Sherpa, Herwig)
  - E.g. a dark matter model:

    > 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

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




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