Analysis preservation & recasting with the Rivet toolkit

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Rivet for *ep* workshop
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Introduction

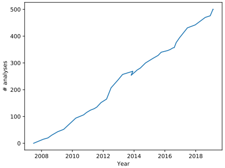
- **Experiment/theory interaction growing**
  - $\Rightarrow$ more direct collaboration on methods and modelling, from SM QCD & Top to Higgs and BSM
- **Rivet** analysis toolkit is a common dialect for exchanging analysis details and ideas
- Implementing a Rivet code to complement the data analysis is increasingly expected of experiment analyses. **Everyone benefits.**
- **This talk: description/discussion + demo/exercises**
  Philosophy and recent/relevant developments, plus a few technicalities
  Time limited so I'll skip a lot, but the full set of slides is a useful reference

Rivet

Rivet is an analysis system for MC events + *lots* of analyses

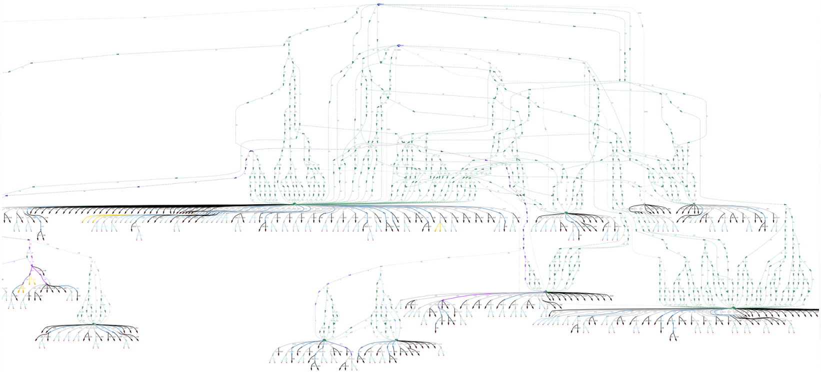
∼ 500 built-in! ∼ 50 are pure MC, and some double-counting

- Easy and powerful way to get physics numbers & plots from *any* MC gen
- LHC standard for preserving data analyses: standard in ATLAS & CMS SM
- Origins in SM, and particularly QCD for MCs – extended for search preservation since v2.5 by adding detector transfer-function features
- C++ library with Python interface, analyses are plugins, code is "clean"
- **"If you can't write a Rivet analysis for it, it's probably unphysical"!**



Generator independence

A Pythia8 $t\bar{t}$ event visualised from HepMC output:



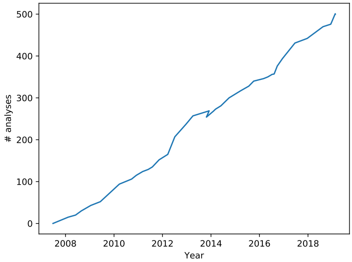
PDF link

Most of this is not standardised: Herwig and Sherpa look *very* different. But final states and decay chains have to have equivalent meaning.

Analysis coverage / wishlist

Lots of analyses, but we're still missing a lot! You can help…

Semi-automatic Rivet LHC analysis wishlist



Rivet LHC analysis coverage

Rivet analyses exist for 218/827 papers = 26%. 116 priority analyses required.

Total number of CDS papers scanned = 2185, at 2018-06-14

Breakdown by identified experiment (in development):

Key	ALICE	ATLAS	CMS	LHCb	Unknown
Rivet wanted:	226	332	302	82	0
Rivet REALLY wanted:	28	25	53	10	0
Rivet provided:	11 (6%)	136 (44%)	60 (24%)	11 (15%)	0

Show greylist Show blacklist

2622139: Search for a dimuon resonance in the Υ mass region [LHCB]
CDS Inspire

2622094: Search for chargino-neutralino production using recursive jigsaw reconstruction in final states with two or three charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector [ATLAS]
CDS Inspire

2621963: Search for pair production of heavy vector-like quarks decaying into high-p_T W bosons and top quarks in the lepton-plus-jets final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector [ATLAS]
CDS Inspire HepData

2621727: Search for resonant WZ production in the fully leptonic final state in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector [ATLAS]
CDS Inspire HepData

2621538: Search for pair-produced resonances each decaying into at least four quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV [CMS]
CDS Inspire

2621428: Measurement of the weak mixing angle using the forward-backward asymmetry of Drell-Yan events in pp collisions at 8 TeV [CMS]
CDS Inspire

2621423: Search for narrow and broad dijet resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark matter mediators and other new particles [CMS]
CDS Inspire

2320693: Search for new phenomena using the invariant mass distribution of same-flavour opposite-sign dilepton pairs in events with missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector [ATLAS]
CDS Inspire HepData

2320574: p-p, p-Λ and Λ-Λ correlations studied via femtoscopy in pp reactions at $\sqrt{s}$ = 7 TeV [ALICE]
CDS Inspire

Rivet setup

Docker

VM-like pre-prepared environments: avoid platform issues, integrates well with host. Instructions at https://rivet.hepforge.org/trac/wiki/Docker

```
docker pull hepstore/rivet-tutorial
docker run -it -v $PWD:/out hepstore/rivet-tutorial
```

Local install

Easy to install using our *bootstrap script*:

```
wget https://phab.hepforge.org/source/rivetbootstraphg/browse/2.7.0/\
  rivet-bootstrap?view=raw -O rivet-bootstrap
bash rivet-bootstrap
```

Needs valid compiler (C++11), etc. environment

You can also run the bootstrap with **INSTALL_RIVETDEV=1** enabled, to get the development version

First Rivet runs

Command-line interface

`rivet` and other command line tools to query and run routines

- List available analyses:
  `rivet --list-analyses`
- List ATLAS analyses:
  `rivet --list-analyses "ATLAS|CMS"`
- Show some pure-MC analyses' full details:
  `rivet --show-analysis MC_`

Same metadata and API docs online at http://rivet.hepforge.org

All Rivet commands start with `rivet-`, so tab-complete lists them all

Running existing analyses

To avoid huge files, we get the events from generator to Rivet by writing HepMC (from Py8) to a filesystem pipe

```
$ mkfifo fifo.hepmc

$ run-pythia -n 200000 -e 8000 -c Top:all=on -o fifo.hepmc &

$ rivet fifo.hepmc -a MC_TTBAR,MC_JETS,MC_FSPARTICLES
    -a ATLAS_2015_I1404878,CMS_2016_I1473674

$ rivet-mkhtml Rivet.yoda:'Pythia 8 $t\bar{t}$'
```

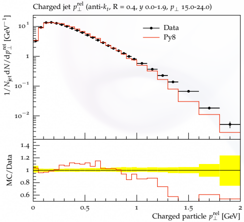
By default *unfinalised* histos are written every 1000 events: monitor progress through the run. Killing with `Ctrl-C` is safe: finalizing is run

Plotting

"YODA" stats library — http://yoda.hepforge.org
Bin-width handling, bin gaps, object ownership, thread-safety ⇒ non-ROOT histogramming

- Separation of stats from presentation: plotting via **`make-plots`** script
- Text-based data format with all second-order stat moments: full stat merging up to all means and variances
- YAML metadata and zipped read/write from v1.7.0
- Being gradually extended to handle more complex physics data types

CLI tools: **`yodals`**, **`yodadiff`**, **`yodamerge`**, **`yodascale`**, **`yoda2root`**, etc.



Writing a first analysis

Writing an analysis

Writing an analysis is of course more involved

But the C++ interface is pretty friendly: most analyses are short, simple, and readable

An example is usually the best instruction: take a look at
https://rivet.hepforge.org/analyses/MC_FSPARTICLES.html

Code is "mostly normal":

- Typical init/exec/finalize loop structure
- Histograms $\sim$normal; titles, etc. $\rightarrow$ external `.plot` file
- Particle, Jet and FourMomentum classes with some nice things like `abseta()` and `abspid()`, constituents, decay-chain searching, and compatibility with FastJet objects
- Use of *projections* for auto-cached computations

Projections

Projections are just observable calculators: given an `Event` object, they *project* out physical observables.

Automatic caching of results leads to slightly odd calling code:

Declaration with a string name in the `init` method:

```
void init() {
  ...
  const SomeProj sp(foo, bar);
  declare(sp, "MySP");
  ...
}
```

Application in the `analyze` method via the same name:

```
void analyze(const Event& evt) {
  ...
  const SomeProjBase& mysp = apply<SomeProj>(evt, "MySP");
  mysp.foo()
  ...
}
```

Then query it about the things it has computed, via the object/ref API

Particle finders & final-state projections

Rivet is mildly obsessive about calculating from final state objects

So a *very* important set of projections is those used to extract final state particles, which inherit from `FinalState`

- The `FinalState` projection finds all final state particles in a given η range, with a given p_{T} cutoff.
- Subclasses `ChargedFinalState` and `NeutralFinalState` have the predictable effect!
- `IdentifiedFinalState` can be used to find particular particle species. Nowadays arguably done more nicely via a `Cut`
- `VetoedFinalState` finds particles *other* than specified. Ditto
- `VisibleFinalState` excludes invisible particles like neutrinos, LSP

NB. Most FSPs can take another FSP as a constructor argument and augment it

Using an FSP to get final state particles

```
void init() {
  ...
  const ChargedFinalState cfs(Cuts::pT > 500*MeV && Cuts::abseta < 2.5);
  declare(cfs, "ChFS");
  ...
}
```

```
void analyze(const Event& evt) {
  ...
  const FinalState& cfs = apply<FinalState>(evt, "ChFS");
  MSG_INFO("Total charged mult. = " << cfs.size());
  for (const Particle& p : cfs.particles()) {
    MSG_DEBUG("Particle eta = " << p.eta());
  }
  ...
}
```

More complex projections like **DressedLeptons**, **FastJets**, **WFinder**, **TauFinder** ...implement expt-like strategies for dressing, tagging, mass-windowing, etc.

Selection cuts

Passing ordered lists of doubles to configure "automatic" cut rules is inflexible, illegible, and error-prone. So…

Combinable `Cut` objects:

- `FinalState(Cuts::pT > 0.5*GeV && Cuts::abseta < 2.5)`
- `fs.particles(Cuts::absrap < 3 || (Cuts::absrap > 3.2 && Cuts::absrap < 5), cmpMomByEta)`

Can also use cuts on PID and charge:

- `fs.particlesByPt(Cuts::abspid == PID::ELECTRON)`, or
- `FinalState(Cuts::charge != 0)`

Use of *functions/functors* for ParticleFinder filtering is also possible: very general, especially with C++ *lambdas*

Jets

One more important projection set is those which find *jets*

There's a `JetAlg` abstract interface, but almost always use FastJet, via `FastJets`

Define the input particles (via a `FinalState`), and the jet alg & params:

```
const FinalState fs(-3.2, 3.2);
declare(fs, "FS");
FastJets fj(fs, FastJets::ANTIKT, 0.6,
            JetAlg::ALL_MUONS, JetAlg::ALL_INVISIBLES);
declare(fj, "Jets");
```

Get the jets and loop over them in decreasing p_T order:

```
const Jets jets =
  apply<JetAlg>(evt, "Jets").jetsByPt(20*GeV);
for (const Jet& j : jets) {
  for (const Particle& p : j.particles()) {
    const double dr = deltaR(j, p); //< auto-conversion!
  }
}
```

Remember to `#include "Rivet/Projections/FastJets.hh"`

NB. Lots of handy functions in `Rivet/Math/MathUtils.hh`!

Jet flavour

`FastJets` automatically ghost-tags jets using b and c hadrons (and τ's):

- `if (myjet.bTagged()) ...`
- `if (myjet.bTags().size() > 1) ...`

And you can use `Cuts` to refine the truth tag:

- `myjet.bTagged(Cuts::abseta < 2.5 && Cuts::pT > 5*GeV)`

Jet substructure

Looking inside jets is now common practice.

Rivet doesn't duplicate existing tools: best just to use FastJet directly

```
const PseudoJets psjets = fj.pseudoJets();
const ClusterSequence* cseq = fj.clusterSeq();

Selector sel_3hardest = SelectorNHardest(3);
Filter filter(0.3, sel_3hardest);
for (const PseudoJet& pjet : psjets) {
  PseudoJet fjet = filter(pjet);
  ...
}
```

Note: if using FastJet3 tools, you'll need to add `lifastjettools` to the `rivet-buildplugin` command line. And a `-L/path/to/` arg as well, until the next release. Just compilation, no magic

Rivet's `Jet` and `Particle` classes auto-convert to `PseudoJet`:
⇒ `d23 = cs.exclusive_subdmerge(jetproj.jetsByPt[0], 2)`

DIS projections

`DISLepton` to find in/out leptons (best guess), `DISKinematics` for variables, `DISFinalState` for a boosted-frame view of the event.

`DISKinematics` calls `DISLepton` internally, so can often just use DISK:

```
// Determine kinematics, including event orientation
// since ZEUS coord system is for +z = proton direction
const DISKinematics& kin = apply<DISKinematics>(event, "DISKin");
const int orientation = kin.orientation();

// Q2 and inelasticity cuts
if (kin.Q2() > 1*GeV2) vetoEvent;
if (!inRange(kin.y(), 0.2, 0.85)) vetoEvent;

...
```

https://rivet.hepforge.org/code/2.7.0/classRivet_1_1DISLepton.html
https://rivet.hepforge.org/code/2.7.0/classRivet_1_1DISKinematics.html
https://rivet.hepforge.org/code/2.7.0/classRivet_1_1DISFinalState.html

Writing, building & running your own analysis

Let's start with a simple "particle analysis", just plotting some simple particle properties like η, p_T, ϕ, etc. Then we'll try jets or W/Z.

To get an analysis template, which you can fill in with an FS projection and a particle loop, run e.g. `rivet-mkanalysis MY_TEST_ANALYSIS` – this will make the required files.

Once you've filled it in, you can either compile directly with `g++`, using the `rivet-config` script as a compile flag helper, or run `rivet-buildplugin MY_TEST_ANALYSIS.cc`

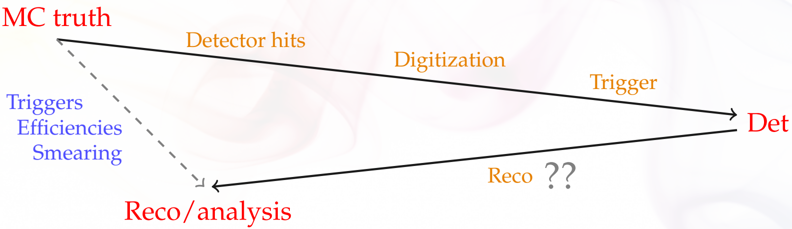
To run, first `export RIVET_ANALYSIS_PATH=$PWD`, then run `rivet` as before. . . or add the `--pwd` option to the `rivet` command line.

BSM searches and detector effects

Detector effects

Normal in SM, top, etc. measurements to *unfold* detector effects.
Usually "uneconomic" to do that for BSM searches

Explicit fast detector simulation vs. smearing/efficiencies:



- **(Private) reco algorithms already reverse most detector effects**
- Reco calibration to MC truth, so kinematics *usually* subleading
- Efficiency & mis-ID effs dominate – tabulated in all fast-sims
- $\Rightarrow$ flexible parametrisation: effs change with analysis phase-space, experiment reco-code version, collider run, ...

and *need to guarantee stability for preservation*

Using Rivet's fast-sim tools

Smearing is provided as "wrapper projections" on normal particle, jet, and MET finders.

Smearing configuration via efficiency/modifier functions.

To use, first `#include "Rivet/Projections/Smearing.hh"`

Examples:

```
FinalState es1(Cuts::abseta < 5 && Cuts::abspid == PID::ELECTRON);
SmearedParticles es2(es, ELECTRON_EFF_ATLAS_RUN2, ELECTRON_SMEAR_ATLAS_RUN2);
declare(es2, "Electrons");

FastJets js1(FastJets::ANTIKT, 0.6, JetAlg::DECAY_MUONS);
SmearedJets js2(fj, JET_SMEAR_ATLAS_RUN2, JET_EFF_BTAG_ATLAS_RUN2);
declare(js2, "Jets");

...

Particles elecs = apply<ParticleFinder>(event, "Electrons").particles(10*GeV);
Jets jets = apply<JetAlg>(event, "Jets").jetsByPt(30*GeV);
```

Standard global functions here, but private fns or inline lambdas better when possible

Selection tools for search analyses

Search analyses typically do a lot more "object filtering" than measurements. Lots of tools to express complex logic neatly:

- Filtering functions: `filter_select(const Particles/Jets&, FN)`, `filter_discard(...)` + `ifilter_*` in-place variants
- *Functors* for common "stateful" filtering criteria: `PtGtr(10*GeV)`, `EtaLess(5)`, `AbsEtaGtr(2.5)`, `DeltaRGtr(mom, 0.4)`, `ParticleEffFilter(FN), ...`
  - Lots of these in `Rivet/Tools/ParticleBaseUtils.hh`, `Rivet/Tools/ParticleUtils.hh`, and `Rivet/Tools/JetUtils.hh`
- `any()`, `all()`, `none()`, etc. – accepting functions/functors
- Cut-flow monitor via `#include "Rivet/Tools/Cutflow.hh"`

BSM hands-on

Look at the source code in **TESTDET.cc**: does it make sense?

- Build & run like:

```
$ rivet-buildplugin TESTDET.cc
$ run-pythia -n 200000 -e 13000 -o fifo.hepmc -c SUSY:all=on
-c SLHA:file=gg_g1500_chi100_g-ttchi.slha &
$ rivet --pwd -a TESTDET -H bsm.yoda fifo.hepmc -lAnalysis=DEBUG
```

- Split and compare the particle- and reco-level observables:

```
$ bash truerecosplit.sh bsm.yoda
$ rivet-mkhtml bsm-*.yoda -m '/TESTDET'
```

- Try adding a constant 70% *b*-tag efficiency to the jets:

  `JET_BTAG_EFFS(0.7)` or

  `(const Jet& j) return j.bTagged() ? 0.7 : 0.0;` .

- Try the same with `CMS_2017_I1594909.cc`; browse the file with `yodals -v` to see the the CMS signal-region counts for recasting

Contur: BSM limit-setting using Rivet *SM* analyses

Contur is a layer on top of Rivet to do statistical interpretation of injected BSM signal to "Standard Model" phase spaces.

- **Idea:** make use of the full set of Rivet analyses to constrain new physics models.

  Modelling inclusivity also important: a strength of Herwig 7

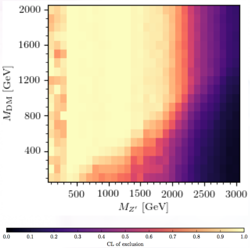
- **Benefits:** model-agnostic and very quick. Can study many possible signatures at the same time

- **Current constraints (in progress):** SM MC is complex ⇒ assume data = SM

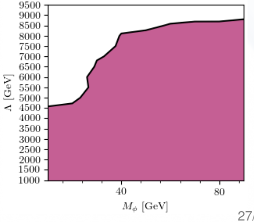
  Single-bin limits within manual analysis groupings in lieu of full correlations.

  Working to include SM predictions and uncertainties

Simplified vector+DM model



Eff-coupling light scalars



That’s all, folks

Summary

- **Rivet is a user-friendly MC analysis system for prototyping and preserving data analyses**
- Allows theorists to use analyses for model development & testing, MC tuning, and BSM recasting
- Also a very useful cross-check: quite a few analysis bugs have been found via Rivet
- Supports detector simulation for BSM search preservation
- Contributions and team membership all very welcome.
  Twice-annual Rivet hackathons in nice places!
  Funded 3+ month MCnet studentships available

- **Rivet is a great way to get a feel for MC physics, prototype analyses, and work on SM & BSM phenomenology studies with theorists**