

MC analysis with Rivet

*Andy Buckley, University of Glasgow
ATLAS UK annual meeting, 10 Jan 2020*



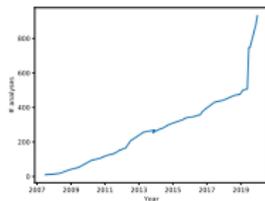
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- ▶ Easy and powerful way to get physics numbers & plots from any MC gen
 - Only requirement: use **HepMC** event record
 - Intentionally unaware of who made the event \Rightarrow don't "look inside" the event graph
 - "If you can't write a Rivet analysis for it, it's probably unphysical"!



#analyses over time:



NB. glitch from Rivet
1.x \rightarrow 2.x migration.
Note recent steps!

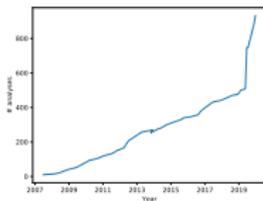
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- ▶ LHC standard to preserve & re-run measurement analysis logic
 - Key input to MC validation, MC tuning, and BSM interpretation (Contur, TopFitter)
 - **Add your analyses, too!**



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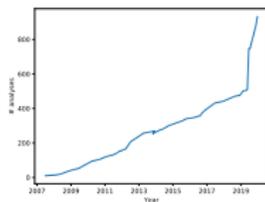
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- ▶ LHC standard to preserve & re-run measurement analysis logic
 - Key input to MC validation, MC tuning, and BSM interpretation (Contur, TopFitter)
 - **Add your analyses, too!**
- ▶ Technical details:
 - C++ library with Python interface & scripts
 - Analyses are "plugins": no need to rebuild
 - Clean interface for ease & expressiveness; efficiency tricks under the hood



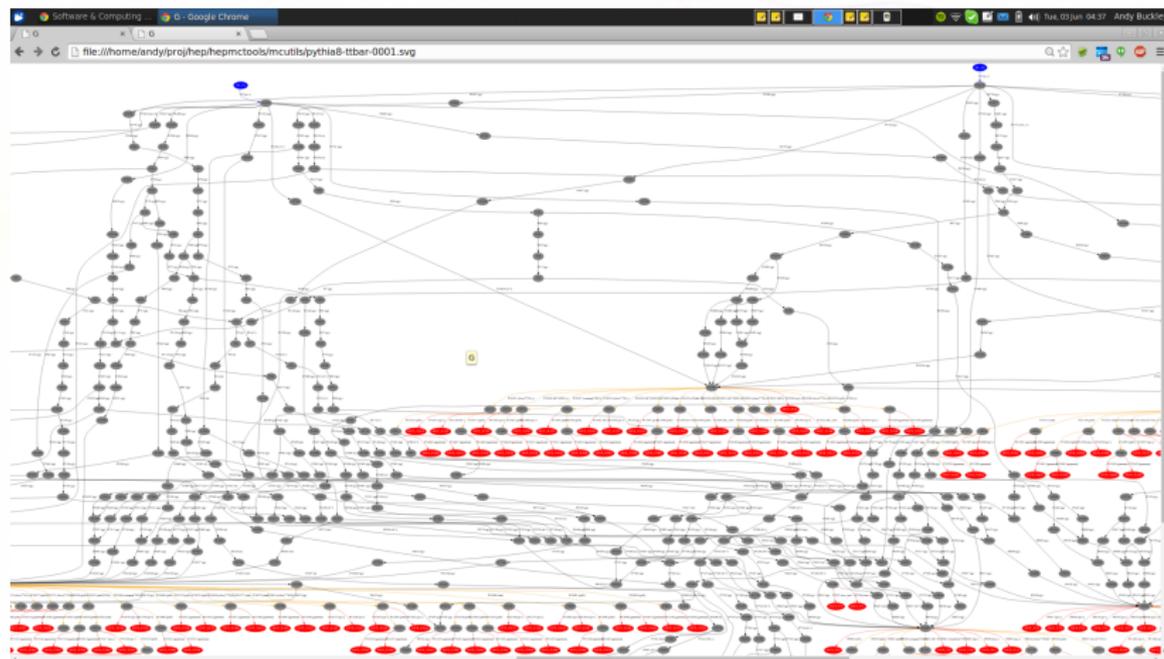
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Why wouldn't we want to look at the event graph?!

A Pythia8 $t\bar{t}$ event!



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

Rivet setup

Local install

Easy to install using our *bootstrap script*:

```
wget https://gitlab.com/hepcedar/rivetbootstrap/raw/3.1.0/rivet-bootstrap
bash rivet-bootstrap
```

Latest version is 3.1.0. **Requires C++14**. On lxplus, first run e.g.:

```
source /cvmfs/sft.cern.ch/lcg/releases/LCG.96/Python/2.7.16/x86_64-centos7-gcc62-opt/Python-env.sh
export PATH=/cvmfs/sft.cern.ch/lcg/external/texlive/2016/bin/x86_64-linux:$PATH
```

Docker install

Super-easy to install:

```
docker pull hepstore/rivet
docker run -it -v "$PWD:/out" hepstore/rivet
or, for this tutorial
docker run -it -v "$PWD:/out" hepstore/rivet-tutorial
```

The `-v` flag allows you to map your current host dir to `/out` in the container, for ease of communication between host and VM. See also `docker copy`

See <https://gitlab.com/hepcedar/rivet/blob/master/doc/tutorials/installation.md>

Running Rivet in/via the ATLAS software

Rivet is interfaced to the ATLAS Athena framework: see <https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/RivetForAtlas> for all sorts of guidance

Basic setup:

```
setupATLAS
```

```
lsetup asetup
```

```
asetup 21.6.10,AthGeneration
```

```
source setupRivet.sh
```

```
rivet --version
```

 \leftarrow another way to get command-line Rivet

For running in vanilla athena:

Get the example Athena job option [from here](#), then:

```
athena jobOptions.rivet.py
```

Or built-in to running ATLAS generators:

```
Generate_tf.py ... --rivetAnas=MC.GENERIC,MC.JETS ...
```

First Rivet runs

Running Rivet

- ▶ `rivet` command line tool to query available analyses
- ▶ Can be used as a library (e.g. in big experiment software frameworks)
- ▶ Can also be used from the command line to read HepMC ASCII files/pipes: very convenient
- ▶ Helper scripts like `rivet-mkhtml`, `rivet-mkanalysis`, `rivet-build`
- ▶ Histogram comparisons, HTML plot-albums, etc. very easy

Docs online at <http://rivet.hepforge.org> — HTML analysis details and Doxygen.



Viewing available analyses

Rivet knows all sorts of details about its analyses:

- ▶ List available analyses:
`rivet --list-analyses`
- ▶ List ATLAS analyses:
`rivet --list-analyses ATLAS_`
- ▶ Show some pure-MC analyses' full details:
`rivet --show-analysis MC_`

The **HTML documentation** is also built from this info, so is always synchronised.

The analysis metadata is provided via the analysis API and usually read from a `.info` file which accompanies the analysis.

Running a simple analysis

To avoid huge files, we get the events from generator to Rivet by writing to a filesystem pipe: `mkfifo fifo.hepmc`

You can also just use a file but it'll be *big*.

NB. A FIFO has to live in a non-AFS dir, e.g. `mkfifo /tmp/$USER/fifo.hepmc`

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I'm going to use the **Sacrifice** frontend to run Pythia 8 for demonstration — use the same or run any other generator that you like with HepMC output going to the FIFO:

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run-pythia -n 2000 -c Top:all=on -o fifo.hepmc &
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```

Now attach Rivet to the other end of the pipe:

```
rivet -a MC_GENERIC -a MC_JETS fifo.hepmc
```

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```
rivet -a MC_GENERIC -a MC_JETS fifo.hepmc
```

Hopefully that worked!

By default histos are written every 1000 events: can monitor progress through the run. Killing with `ctrl-c` is safe: finalizing is run

Example output

```
$ run-pythia -e 7000 -c HardQCD:all=on -c PhaseSpace:pThatMin=80
  -c ParticleDecays:limitTau0=on -n 10000 -o fifo.hepmc &
$ rivet -a CMS_2013_I1265659 fifo.hepmc
$ rivet-mkhtml Rivet.yoda:'Py8$\star$'
```

```
# BEGIN YODA_HISTOID /CMS_2013_I1265659/d01-x01-y02
Path=/CMS_2013_I1265659/d01-x01-y02
ScaledBy=0.00018488029661016948
Title=
Type=Histoid
XLabel=
YLabel=
# Mean: 1.886500e+00
# Area: 1.745270e-01
# xlow  xhigh  sumw  sumw2  sumwx  sumwx2  numEntries
Total          Total          1.745270e-01  3.226660e-05  3.292452e-01  7.563865e-01  944
Underflow      Underflow      0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0
Overflow       Overflow       0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0
1.001800e-04   1.746272e-01  4.622007e-03  8.545181e-07  3.464255e-04  3.868572e-05  25
1.746276e-01   3.491546e-01  6.101050e-03  1.127964e-06  1.634274e-03  4.481578e-04  33
3.491549e-01   5.236819e-01  6.840571e-03  1.264687e-06  2.938932e-03  1.279250e-03  37
5.236823e-01   6.982093e-01  7.395212e-03  1.367229e-06  4.569311e-03  2.838956e-03  40
6.982097e-01   8.727367e-01  6.285930e-03  1.162145e-06  4.880735e-03  3.805391e-03  34
8.727370e-01   1.047264e+00  6.470810e-03  1.196325e-06  6.237378e-03  6.024974e-03  35
1.047265e+00   1.221791e+00  7.395212e-03  1.367229e-06  8.247895e-03  9.216318e-03  40
.
.
.
# END YODA_HISTOID
```

Plotting histograms

Rivet uses custom “YODA” stats library – <http://yoda.hepforge.org>

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- ▶ YODA stores all second-order statistical moments: can do full stat merging, compute all means and variances
- ▶ Plus general metadata annotation system — styling, notes, whatever — and evolution of data types optimised for MC

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

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

Plotting `.yoda` files is easy: `rivet-mkhtml mc1.yoda mc2.yoda ...`

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

or, if you want complete control:

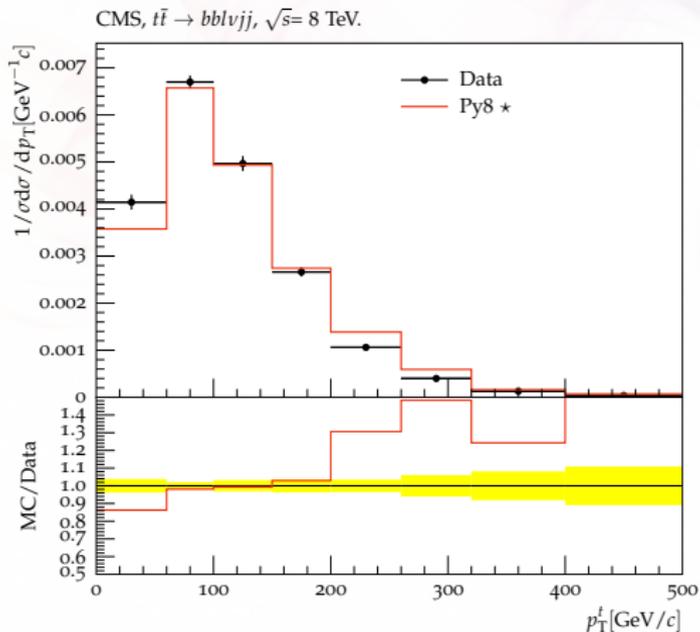
```
rivet-cmphistos Rivet.yoda:'My title':LineColor=red && make-plots *.dat
```

Then view with a web browser/file browser/...

NB. A `--help` option is available for all Rivet scripts.

Example plot output

```
zcat tt-20k.hepmc.gz | rivet -a  
ATLAS.2015_I1376945,CMS.2015_I1370682,CMS.2016_I1473674  
$ rivet-mkhtml Rivet.yoda:'Py8 $\star$'
```



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/EXAMPLE.html>

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Code is “mostly normal”:

- ▶ Typical init/exec/finalize loop structure
- ▶ Histograms ~normal; titles, etc. → 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
- ▶ *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 SomeProjection sp(foo, bar);  
    declare(sp, "MySP");  
    ...  
}
```

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

```
void analyze(const Event& evt) {  
    ...  
    const SomeProjectionBase& mysp =  
        apply<SomeProjectionBase>(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`

- ▶ `FinalState` finds all final state particles matching kinematic/ID criteria
- ▶ `PromptFinalState` is the same, but for final-state particles *not from hadron decays*
- ▶ `VisibleFinalState` excludes invisible particles like neutrinos & dark matter
- ▶ FS subclasses `ChargedFinalState`, `NeutralFinalState`, `IdentifiedFinalState`, `VetoedFinalState` unimportant now: can do their job via Cuts
- ▶ `DressedLeptons` is a special composite-particle finder that “dresses” charged leptons with prompt photons in a narrow cone
- ▶ `UnstableParticles` finds physical non-final-state particles
- ▶ See also `TauFinder`, `WFinder`, `ZFinder`, ...

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 FinalState myfs(Cuts::pT > 500*MeV && Cuts::abseta < 2.5);  
    declare(myfs, "FS");  
    ...  
}
```

```
void analyze(const Event& evt) {  
    ...  
    const FinalState& fs = apply<FinalState>(evt, "FS");  
    MSG_INFO("Total mult. = " << fs.size());  
    for (const Particle& p : fs.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

Projection specification and object retrieval functions almost all accept `cut` objects

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)`

Most functions with `cut` args also accept *functors* for filtering: includes functions, C++ lambdas, and many pre-made ones in Rivet, for example `pTGr()`, `hasBTag()`, etc., or this advanced usage:

```
select(jets, [](const Jet& j){return j.particles(Cuts::abscharge > 0 && Cuts::pT > 5*GeV).size() > 3;})
```

Selection tools

Object filtering is very important, e.g. for isolation / overlap removal checks.

- ▶ Filtering functions: `select(const Particles/Jets&, FN)`, `discard(...)` + `iselect/iscard*` in-place versions
- ▶ Lots of *functors* for common “stateful” filtering criteria:
`PtGtr(10*GeV)`, `EtaLess(5)`, `AbsEtaGtr(2.5)`, `DeltaRGtr(mom, 0.4)`
 - Lots of these in `Rivet/Tools/ParticleBaseUtils.hh`,
`Rivet/Tools/ParticleUtils.hh`, and `Rivet/Tools/JetUtils.hh`
- ▶ `any()`, `all()`, `none()`, etc. — accepting functions/functors
- ▶ `sum()`, `transform()`, `minmax()`, etc. — vector tools in `Rivet/Tools/Utils.hh`
- ▶ + a cut-flow monitor via `#include "Rivet/Tools/Cutflow.hh"`

Selection tools: examples

```
const Jets jets = apply<JetAlg>(event, "Jets")
    .jetsByPt(Cuts::pT > 20*GeV && Cuts::abseta < 2.8);
const Particles elecs = apply<ParticleFinder>(event, "Elecs").particlesByPt();
const Particles mus = apply<ParticleFinder>(event, "Muons").particlesByPt();
MSG_DEBUG("Number of raw jets, electrons, muons = "
    << jets.size() << ", " << elecs.size() << ", " << mus.size());
```

Selection tools: examples

```
const Jets jets = apply<JetAlg>(event, "Jets")
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    << jets.size() << ", " << elecs.size() << ", " << mus.size());
```

```
// Discard jets very close to electrons, or low-ntrk jets close to muons
const Jets isojets = discard(jets, [&](const Jet& j) {
    if (any(elecs, deltaRLess(j, 0.2))) return true;
    if (j.particles(Cuts::abscharge > 0 && Cuts::pT > 0.4*GeV).size() < 3 &&
        any(mus, deltaRLess(j, 0.4))) return true;
    return false;
});
```

Selection tools: examples

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const Jets jets = apply<JetAlg>(event, "Jets")
    .jetsByPt(Cuts::pT > 20*GeV && Cuts::abseta < 2.8);
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const Jets isojets = discard(jets, [&](const Jet& j) {
    if (any(elecs, deltaRLess(j, 0.2))) return true;
    if (j.particles(Cuts::abscharge > 0 && Cuts::pT > 0.4*GeV).size() < 3 &&
        any(mus, deltaRLess(j, 0.4))) return true;
    return false;
});
```

```
// Discard electrons close to remaining jets
const Particles isoelecs = discard(elecs, [&](const Particle& e) {
    return any(isojets, deltaRLess(e, 0.4));
});
```

...

One more important projection set is those which find *jets*
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!  
    }  
}
```

Jets are automatically ghost-tagged using b and c hadrons:

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

Jet substructure

Looking inside jets is 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);
    ...
}
```

Rivet's `Jet` and `Particle` classes auto-convert to `PseudoJet`:

⇒ `d23 = cs.exclusive_subdmerge(jetproj.jetsByPt[0], 2)`

Writing, building & running your own analysis

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 in the `.cc` file, you can compile into a plugin library with

```
rivet-build MY_TEST_ANALYSIS.cc
```

This is just a front-end to calling the C++ compiler: you can add custom compiler flags if you want

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

EXERCISE: a dilepton + jets analysis

We are going to compare Drell-Yan events with $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$

See the `TUTORIAL.*` analysis files in the Docker working dir, and on lxplus in `~abuckley/public/rivet-tutorial/`. This is the starting point for our exercise: the tasks are documented in a comment in the `analyze()` function.

- ▶ The first step is to find high- p_T leptons: try a `FinalState` looking for > 20 GeV e/μ in a sensible acceptance.

This analysis uses an *option flag*, to specify if it's being run in e or μ mode, so choose your `Cuts::abspid` cut based on the value of `_eemode` (`true == electron`).

If there are two suitable leptons in the event, get the mass of the pair like `FourMomentum l1 = leps[0].mom() + leps[1].mom(); l1.mass()`

EXERCISE: a dilepton + jets analysis (2)

- ▶ To run your analysis, use `rivet-build` and run (with Pythia) like `run-pythia -n 10000 -e 13000 -s -c WeakSingleBoson:ffbar2gmZ=on -c 23:onMode=off -c "23:onIfAny=11" -o Zee.hepmc & rivet --pwd -a TUTORIAL:LMODE=EL Zee.hepmc -H Zee.yoda` and similar for the $\mu\mu$ case. Make the plots and inspect: `rivet-mkhtml --remove-options Z*.yoda`
- ▶ After 5-10k events, you should see a distinction between ee and $\mu\mu$ in the $m_{\ell\ell}$ distribution: the electrons are losing more energy via QED. Use the `DressedLeptons` projection to fix this, and fill the `m11.dressed` histo.
- ▶ Now jets: use the `FastJets` projection to construct $R = 0.4$ anti- k_t jets from final-state particles in a reasonable calorimeter acceptance: no p_T cut, but e.g. $|\eta| < 4.5$.

The jets by default include all muons and no invisibles. You might want to make this more ATLAS-like by including hadron-decay muons and neutrinos/invisibles (these are often included in jet calibration): see the `FastJets` constructor in [Doxygen](#)

EXERCISE: a dilepton + jets analysis (3)

- ▶ Plot the jet multiplicity, i.e. the size of the returned jets collection, with e.g. $p_T > 20$ GeV.
- ▶ Whichever way you calibrated your jet constituents, the prompt electrons are still being reconstructed as jets: you need to remove the overlap between them. Filter your jet collection to remove any jets with $\Delta R < 0.4$ of your hard leptons.

You can do this manually with two `for`-loops, but it's awkward: try a single loop in conjunction with `discard()` and `deltaRLess()`, or the very useful higher-level `discardIfAnyDeltaRLess()` function.

Fill the `njets_iso` histogram with your isolated/overlap-removed jets, and also the `pt1jet` and `HT` histograms if you like: the `sum()` function can help with the latter

- ▶ Finally, use `select()` and `hasBTag()` to fill the b -jet multiplicities

Congratulations! If you need any hints, an example solution has been hidden all along in the `work/lxplus` dir as `.TUTORIAL_SOLUTION.cc`

BSM searches and detector effects

BSM & detector effects

Explicit fast detector simulation vs. smearing/efficiencies

MC truth

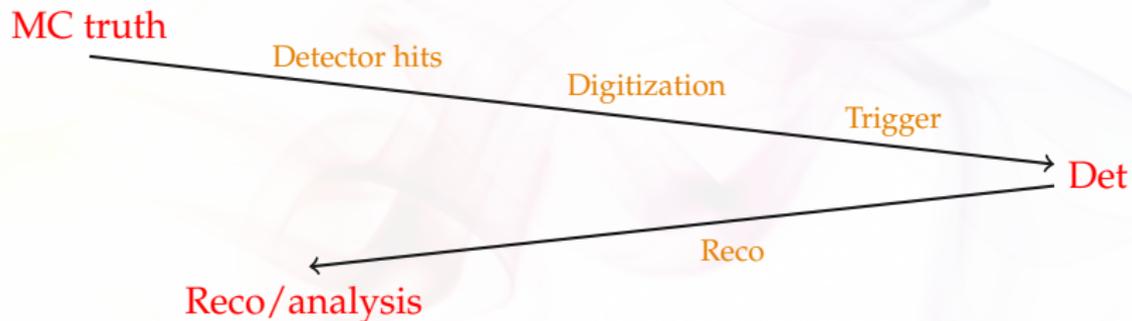
BSM & detector effects

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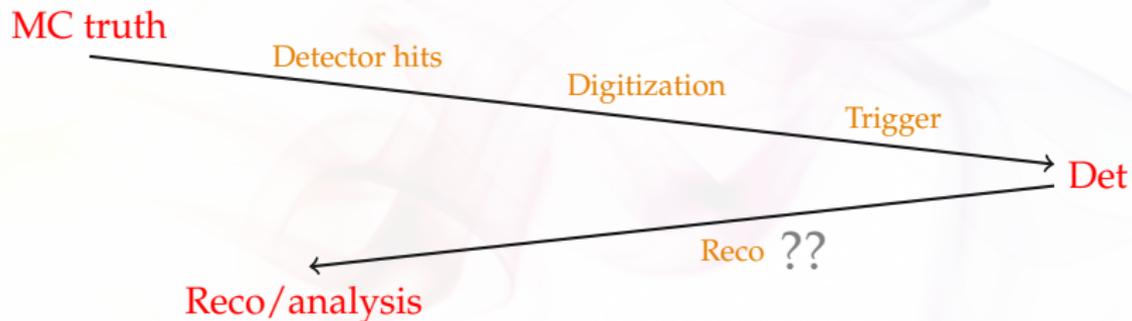
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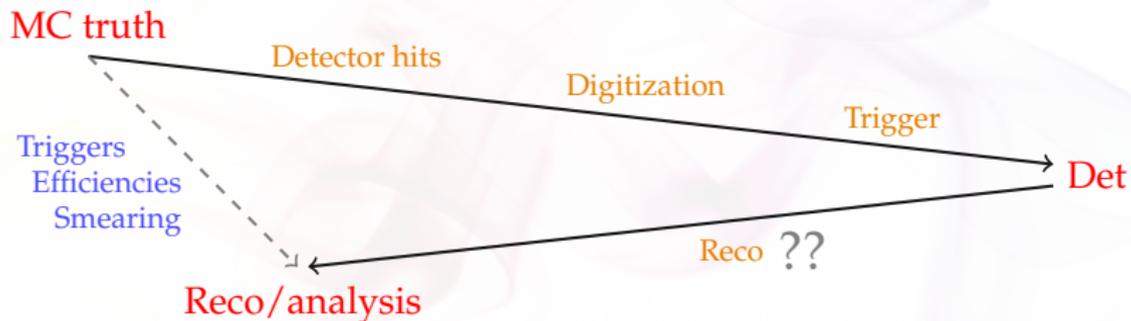
BSM & detector effects

Explicit fast detector simulation vs. smearing/efficiencies



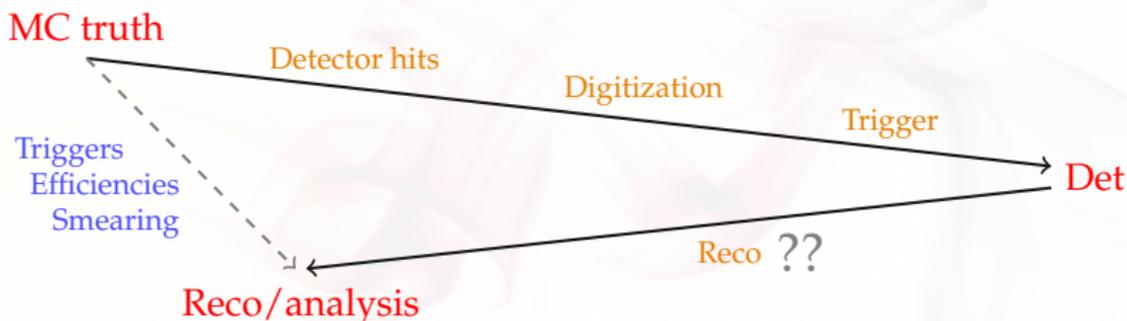
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- ▶ **Explicit fast-sim takes the “long way round”.**
- ▶ **Reco already reverses most detector effects!**
- ▶ Reco calibration to MC truth: smearing is a few-percent effect
- ▶ (Lepton) efficiency & mis-ID functions dominate — and are tabulated in both approaches
- ▶ Smearing is more flexible: effs change with phase-space, reco version, run, ... and need to guarantee *stability* for preservation

Detector effects in Rivet

In addition to last slides, *flexibility* of det-sim is important:

- ▶ “Global” fast-sims hence difficult for coverage of **multiple experiments, multiple runs, multiple reco calibrations**, etc.
- ▶ Analysis-specific efficiencies and smearings are more precise and allow use of **multiple jet sizes, tagger & ID working points, isolations**, ... ⇒ **many variations in real analyses**

⇒ **Rivet det-sim as effs+smearing, localised per-analysis**

Rivet internally caches results, so global effect sim still efficient

- ▶ Functions for generic ATLAS & CMS performance in Runs 1 & 2
- ▶ Inline or analysis-specific functions easy to write & *chain*
- ▶ Eff/smearing functions can be used directly, e.g. for object filtering
- ▶ Working on embeddability for multithreaded fitters/samplers.

Using Rivet's fast-sim tools

Smearing is provided as “wrapper projections” on normal particle, jet, and MET finders. Maximal flexibility and minimal impact on unfolded analysis tools. Smearing configuration via efficiency/modifier functions.

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

Examples:

```
IdentifiedFinalState es1(Cuts::abseta < 5, {{PID::ELECTRON, PID::POSITRON}});
SmearParticles es2(es, ELECTRON_EFF_ATLAS_RUN2, ELECTRON_SMEAR_ATLAS_RUN2);
declare(recoes, "Electrons");

FastJets js1(FastJets::ANTIKT, 0.6, JetAlg::DECAY_MUONS);
SmearJets js2(fj, JET_SMEAR_PERFECT, JET_EFF_BTAG_ATLAS_RUN2); // or lambda
declare(recoj, "Jets");

...

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

Note set of standard global functions. Private fns also ok. *Inline* via C++11 *lambda fns*

Small tweak planned, to unify eff/mod fns and give user control of *operator ordering*

That's all, folks

Summary

- ▶ **Rivet is a user-friendly MC analysis system for prototyping and preserving data analyses**
- ▶ Allows theorists to use your analyses for model development & testing, and BSM recasting: **impact beyond “get a paper out”**
- ▶ Also a very useful cross-check: quite a few analysis bugs have been found via Rivet!
- ▶ Strongly encouraged/required by ATLAS & CMS physics groups. Integrated with experiment software
- ▶ Now supports detector simulation for BSM search preservation
- ▶ Multi-weights, NLO counter-events, and heavy ion now also supported
- ▶ **Feedback, questions and getting involved in development — all welcome!**

Backup

Running a data analysis

For example, the ATLAS 7 TeV high- p_T jet shapes analysis:

```
rivet --show-analysis ATLAS_2012_I1119557
```

Note: tab completion for **rivet** options and analysis names.

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Now to run it:

```
run-pythia -n 20000 -e 7000 -c HardQCD:all=on -c  
PhaseSpace:pTHatMin=280 -o fifo.hepmc &  
rivet -a ATLAS_2012_I1119557 fifo.hepmc
```

See the Py8 manual: <http://home.thep.lu.se/~torbjorn/pythia82html/Welcome.html>

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And plot, much as before:

```
rivet-mkhtml Rivet.yoda:Pythia8
```

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

Feeding LHEF events into Rivet

If your code outputs LHEF events rather than HepMC, you can't use Rivet directly. Anyway, you're taking a risk that it won't work since Rivet is final-state focused...but you can also get hold of the raw event if you want and just use the histogramming and event loop.

At Les Houches 2011 I made a mini filter program which will convert LHEF files or streams to HepMC ones:

<http://rivet.hepforge.org/hg/contrib/file/tip/lhef2hepmc/>

Use it like this:

```
./lhef2hepmc fifo.lhef fifo.hepmc
```

or

```
./lhef2hepmc fifo.lhef - | rivet
```

Maybe some help will be needed with building this program — it's not an official part of Rivet so you have to download and build it by hand. Let us know if you need a hand.

More about Rivet/YODA histogramming & merging

- ▶ **YODA allows “simple” automatic run merging.** With some heuristics to distinguish homogeneous and heterogeneous run types.
- ▶ **Not complete:** merging (normalised) histograms and profiles is one thing, but **what about general objects, particularly ratios like H_A/H_B (or more complex)**
- ▶ **YODA paves the way to a complete treatment:**
 - User-accessible histograms will only be temporary copies for the current event group (to allow **weight vectors & counter-events**)
 - Synchronised to a less transient copy every time the event number changes in the event loop
 - Periodically, or on `finalize()`, this second copy gets used to make *final* histograms: normalised, scaled, added, etc.
 - “Final” histograms can be written and updated through the run: `finalize()` runs many times
 - And runs can be re-loaded and combined using the pre-finalize copies \Rightarrow **completely general run combination.**
- ▶ Also tie-in with heavy ion / process-ratio analysis workflow

Projections — registration

Major idea: **projections**. They are just observable calculators: given an **Event** object, they *project* out physical observables.

They also automatically cache themselves, to avoid recomputation. This leads to slightly unfamiliar calling code.

They are *declared* with a name in the `init` method:

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

Projections — applying

Projections were declared with a name... they are then *applied* to the current event, also by name:

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

We prefer to get a handle to the applied projection as a const reference to avoid unnecessary copying.

It can then be queried about the things it has computed. Projections have different abilities and interfaces: check the Doxygen on the Rivet website, e.g. <http://projects.hepforge.org/rivet/code/dev/hierarchy.html>

Physics vectors

Rivet uses its own physics vectors rather than CLHEP or ROOT. They are a little nicer to use (we think!), but basically familiar. As usual, check Doxygen: <http://projects.hepforge.org/rivet/code/dev/>

`Particle` and `Jet` both have a `momentum()` method which returns a `FourMomentum`.

Some `FourMomentum` methods: `eta()`, `pT()`, `phi()`, `rapidity()`, `E()`, `px()` etc., `mass()`. Hopefully intuitive!

Histogramming

YODA has Histo1D and Profile1D histograms (and more), which behave as you would expect. See

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```
bookHisto1D("thisname", 50, 0, 100)
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The fill weight is important! For kinematic enhancements, systematics, counter-events, etc. Use `evt.weight()` Until automatic multiweight support...

* The abstractions are key to handling systematics weight vectors, correlated counter-events, completely general run merging, etc.

Histogram autobooking

The final framework feature to introduce is histogram autobooking. This is a means for getting your Rivet histograms binned with the same bin edges as used in the experimental data that you'll be comparing to.

To use autobooking, just call the booking helper function with only the histogram name (check that this matches the name in the reference `.yoda` file), e.g.

```
hist1 = bookHistogram("d01-x01-y01")
```

The “d”, “x” and “y” terms are the indices of the HepData dataset, *x*-axis, and *y*-axis for this histogram in this paper.

A neater form of the helper function is available and should be used for histogram names in this format:

```
hist1 = bookHistogram(1, 1, 1)
```

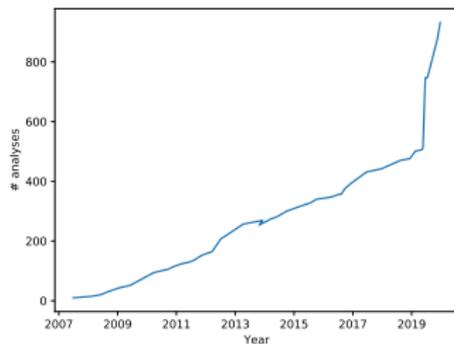
That's it! If you need to get the binnings without booking a persistent histogram use `refData(name)` OR `refData(d, x, y)`.

NB. Extra bool argument for using ref data x vals for `Scatter2Ds`

BSM analysis coverage

Currently ~ 932 analyses!

- ▶ Until recently only 27 dedicated BSM searches — and BSM-sensitive SM measurements
- ▶ SM focus on unfolded observables, not sufficient for most BSM studies
- ▶ Rivet 2.5.0 introduced detector smearing machinery. *For BSM only!*



NB. glitch from Rivet 1.x \rightarrow 2.x migration.
Note recent steps!

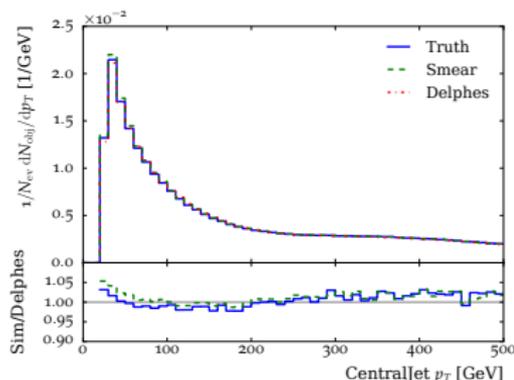
- ▶ \Rightarrow have coded up 9 more BSM routines in last few months:
 - **ATLAS:** ICHEP 2016 3-lepton & same-sign 2-lepton, 1-lepton + jets, 1-lepton + many jets, jets + MET; 2015 jets + MET and monojet
 - **CMS:** ICHEP 2016 jets + MET; 8 TeV $\alpha_T + b$ -jets
 - *Partially* validated — not many cutflows available!
 - Also added tools to help with object filtering, cutflows, etc.
 - Important as real-world examples of how to write BSM routines

Andy Buckley ▶ **Rivet is in good shape for preserving new physics searches!**

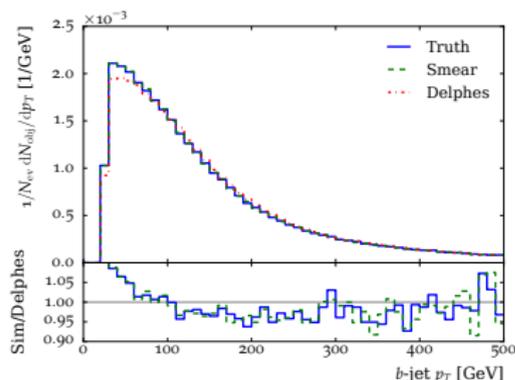
Smearing vs. fast sim vs. MC truth

CMSSM eff/smearing effects from Rivet, in turn using some DELPHES and paper/note calibration functions:

Central jet p_T



b -jet p_T

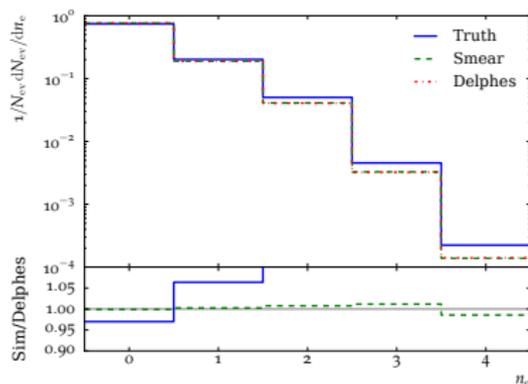


Note major lepton shifts from blue truth to green smeared: difference w.r.t red DELPHES very small

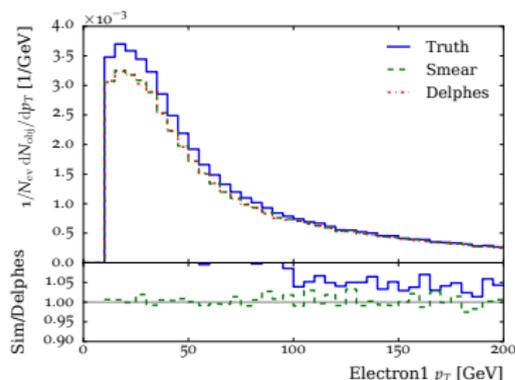
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Electron multiplicity



Leading electron p_T

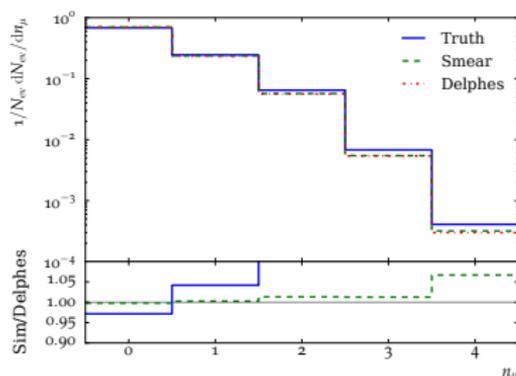


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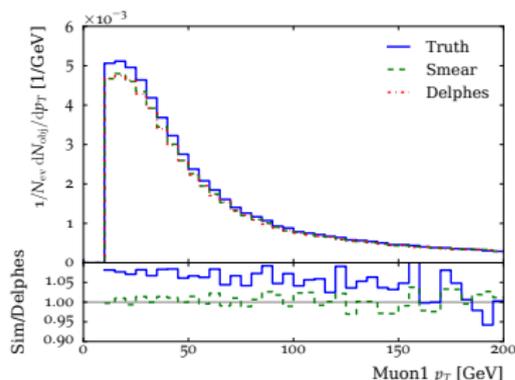
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Muon multiplicity



Leading muon p_T



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