Accelerating physics impact

Analysis prototyping, preservation & reinterpretation

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(borrowing heavily from Andy Buckley)

IOP workshop, Sussex
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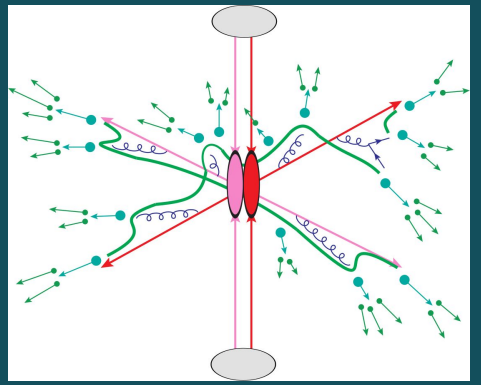
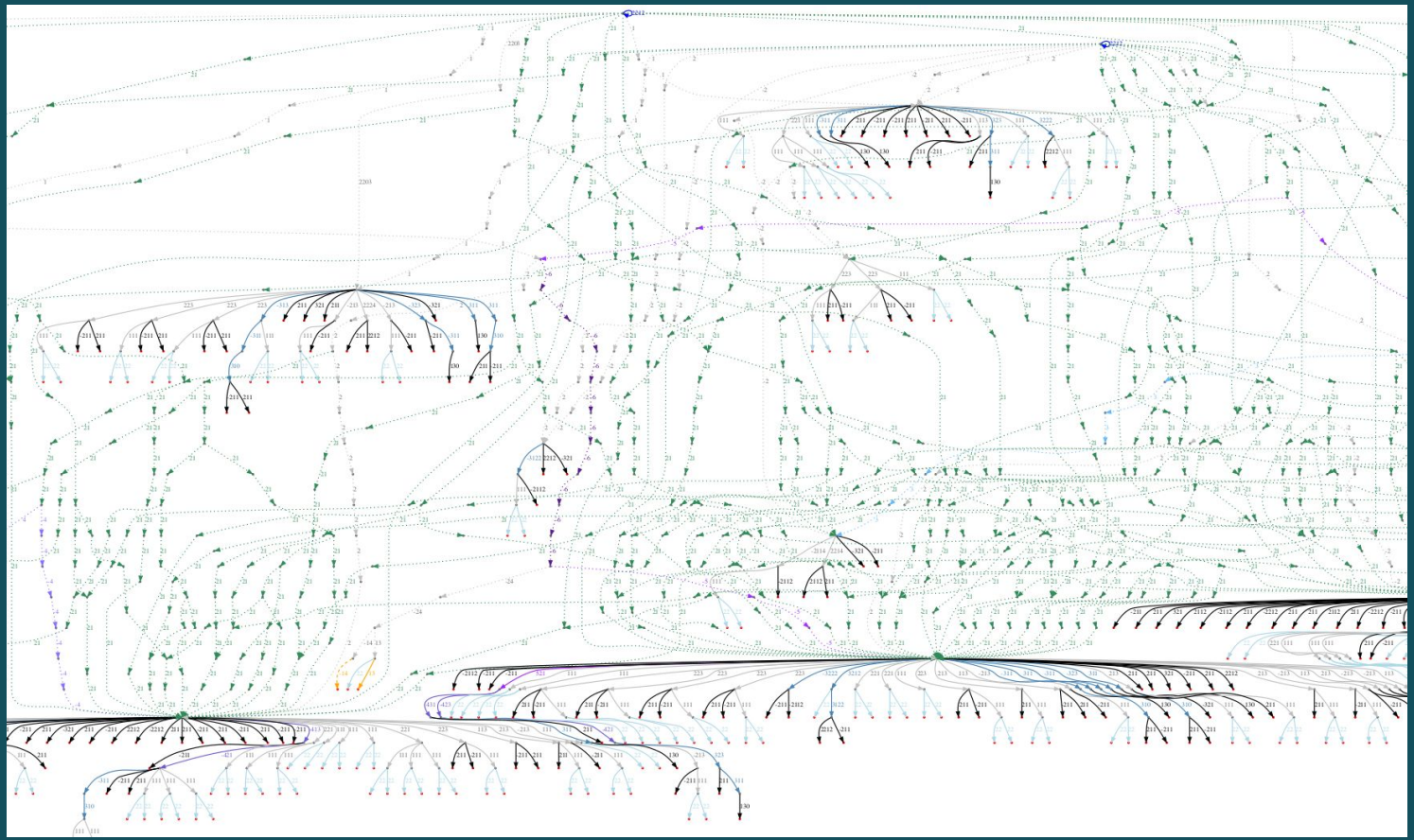
What is Rivet?

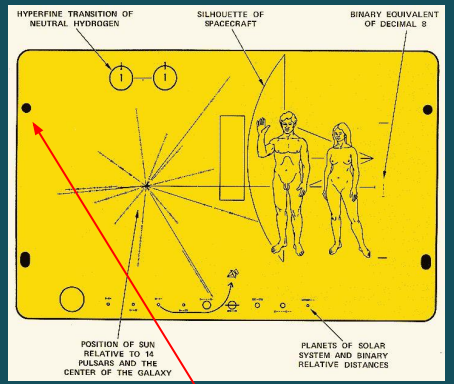
- The “LHC standard” MC analysis toolkit
- **More broadly a project to preserve the logic of HEP data analyses and further expt-pheno collaboration**
- Code wise, a C++ core and Python tools
  - Fiducial / **generator-independence** emphasis
  - Integration with **HepData**
  - Transparent **weight-stream handling**
  - **1000+ analyses!**
- **Central to a community of analysis reinterpretation tools, linking experiment to theory**
- **But why?**





We want to avoid physicists needing to repeatedly rediscover graph algorithms, conventions, pitfalls, physical/debug distinctions, …

Lessons learned …



- **A simple/obvious idea, with surprising impact:**
  - Reproducing a key plot (or not) is *powerful*
    ⇒ understand physics, communicate issues, improve MCs
  - A common language for pheno and experiment

- **But**…
  - "Obvious" to use partons, bosons, etc. direct from the event graph
  - Frequently unphysical & depend on approximations. May not even exist!
    ⇒ **predict "real" observables, from well-defined final states**

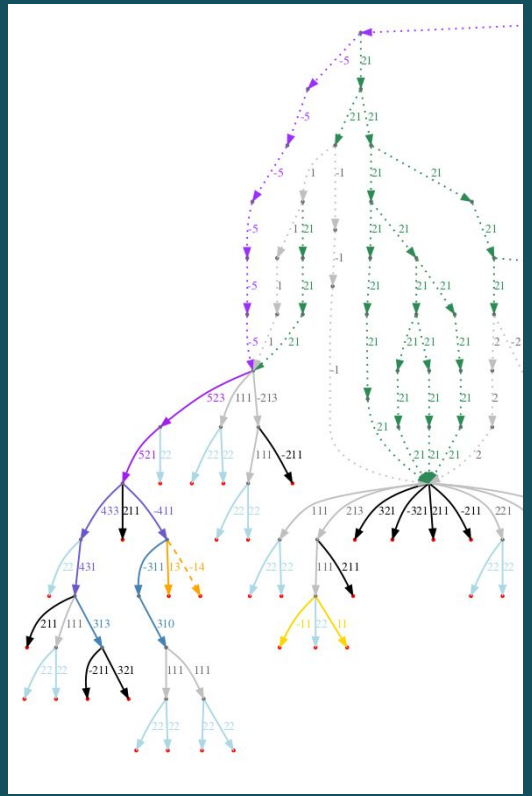
- **Standardisation**: boring but important
  - (physical) event format conventions, status codes, PDG particle numbering, weights …

- **Scalability**
  - Lots of expensive operations are repeated: sharing calculations is essential

Physically safe analysis methods

Avoiding unstandardised event-graph features was pragmatic, but led to some genuine physical insights:

- **refining the "fiducial" idea, defining *unfolding* targets**
- **Hadronisation as a "decoherence barrier"**
  use the natural dividing line between the quantum-interfering hard process & semi-classical decays: ~no tempting partons!
- **Bringing truth tagging closer to reco**
  first releases used *b*-ancestry of jet constituents to set HF labels: too inclusive! ⇒ associate the hard-fragmenting, weakly-decaying *B*
- **Promptness/directness tests**
  don't identify a particle "from the hard process"; do it backward: Label as *indirect* via recursive checks for hadron parentage
- **Dressed leptons**
  we now primarily *dress* truth leptons with their photon halo

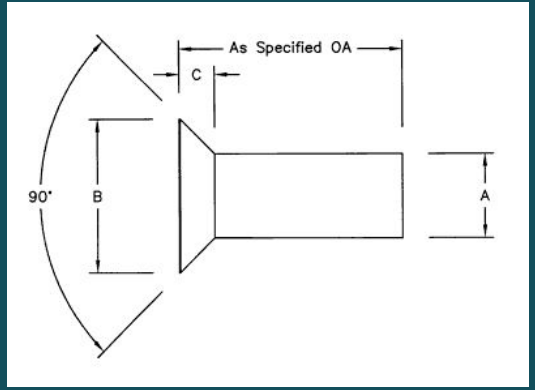


Common pitfalls

- **Colour triplets are not final-state particles**
  - MC event generators do not guarantee the physicality of a "final state top"
- **Electroweak scale particles (W, Z, H) are not final state particles**
  - Focus on the leptons and hadrons for the decay channel you care about
- **Hidden vetoes**
  - all important cuts should be reflected in the fiducial cross section definition
  - e.g. a veto on isolated photons in a dilepton analysis may make no difference to the result when running on a SM sample which is LO in the electroweak coupling, but what happens if more precise calculation is used which may include EW radiation?
- **Missing energy and neutrinos**
  - explicit use of neutrino flavour and momentum is very problematic, especially when there's more than one neutrino in the event
  - better to use the particle-level missing transverse momentum instead, which correctly accounts for possible additional (BSM or other) sources of missing momentum

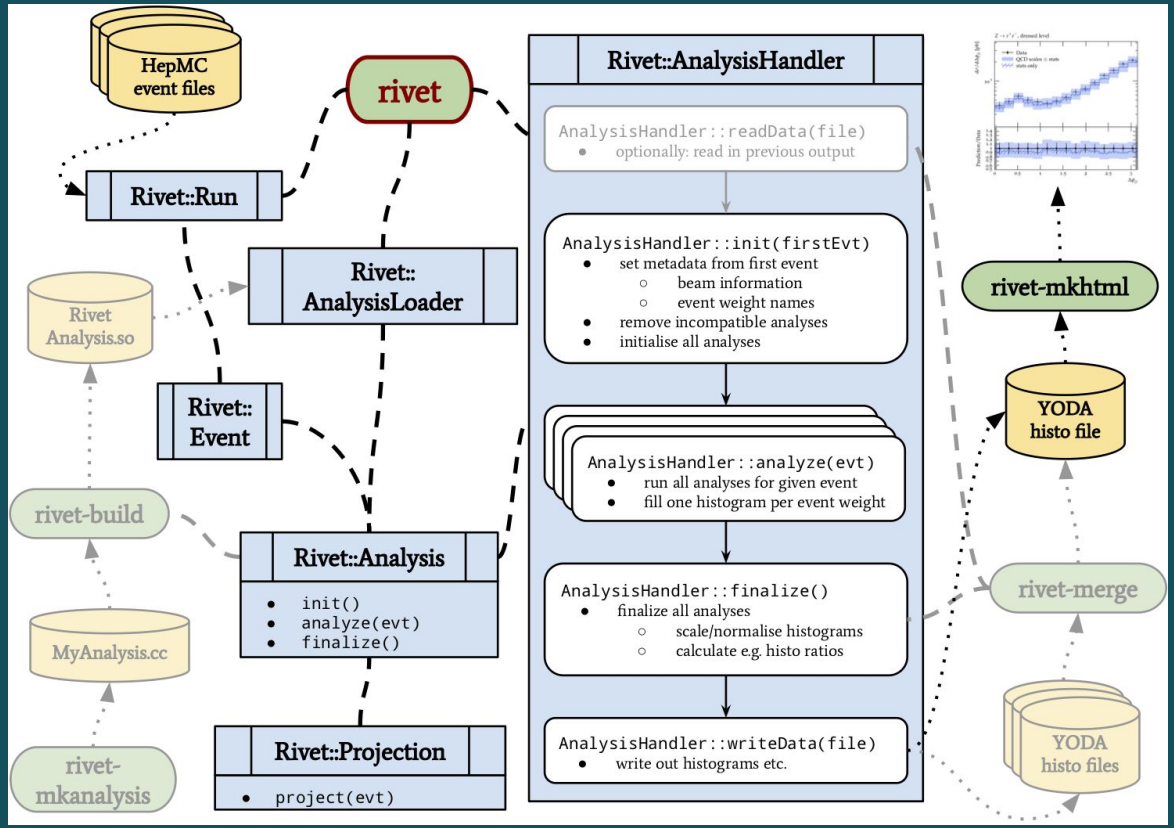
Designing the Rivet

- **Ease of use**
  - **Big emphasis on “more physics, less noise”!**
  - Minimal boilerplate analysis code, HepData sync
  - Event loop and histogramming basically familiar
  - Tools to avoid having to touch the raw event graph
- **Embeddable**
  - OO C++ library, Python wrapper, sane user scripts
  - Generator independence: communication via HepMC
  - Analysis routines factorised, and loaded as “plugins”
- **Efficient**
  - Avoid recomputations via “projection” caching system
- **Physical**
  - **Measurements primarily from final-state particles only**



The result

- **As of Rivet v3.1.0**
  arXiv:1912.05451
- Streamlined set of tools from analysis coding to event processing to plotting (and other applications)
- And a key gateway to connect your analysis to theory (and back again)
  - integral part of MC validation on the experiments
- Let's review some of the early impacts…

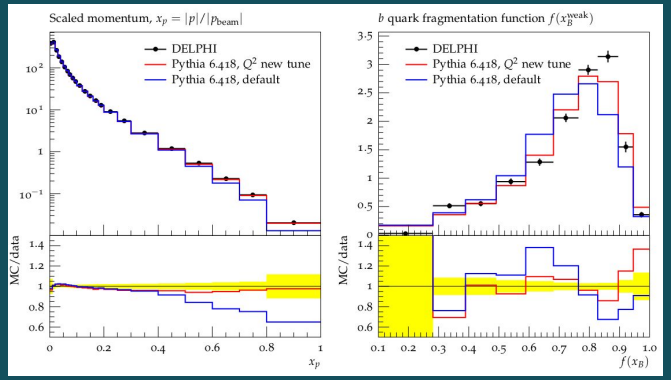


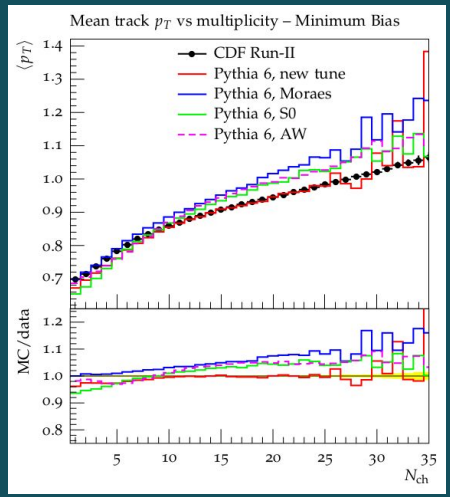
Event generator tuning

Event generators all have dirty secrets.

Usually non-perturbative ones… O(30+) parameters

- **First systematic hadron collider "tunes" of PYTHIA6 by Rick Field for CDF ~ 2001**
  - Tune A, Tune D, Tune DW, etc. etc.
- **Limited datasets, variation by hand**
  - Rivet and its analyses were a game-changer
  - You only know a model is incapable when you've scanned its whole parameter space… and then the argument is over
- **The "Professor" tunes, 2008; and …**

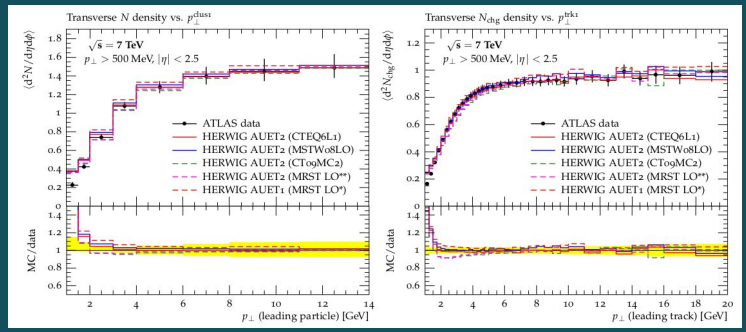


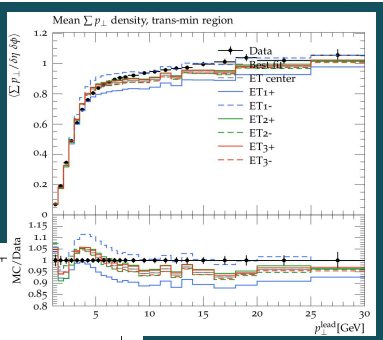


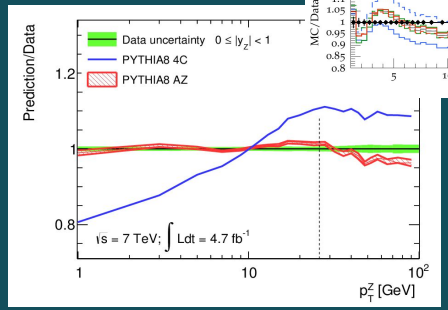
More tuning…

It's getting hard to remember now, but pre-LHC the soft QCD uncertainties were *huge*

- **Factor x2 uncertainty on 7 TeV σ_{tot}!**
- **Feed in to underlying event, pile-up, etc.**
  - Tuning an essential task: better tunes
    ⇒ better analysis designs, better limits, …
  - Impact: LEP and Tevatron analyses published for ~10 years suddenly got used! And cited…
  - ATLAS AMBT, AUET, AZ, A14 etc. tunes + CMS
  - Rapid responses to preliminary data, changes of model (e.g. Py8 for ATLAS pile-up)
  - Model development: matching & merging, addition of energy evolution & colour-reconnection to Herwig, …



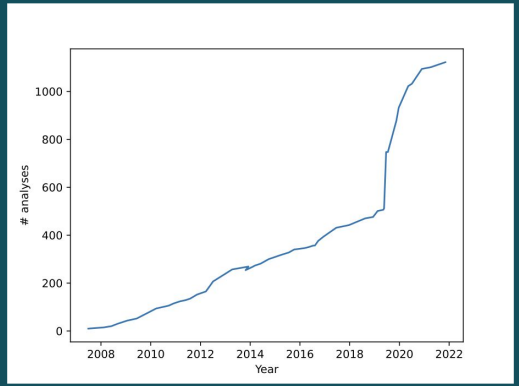




The state we're in

- **Version 3.1.0 crossed the 1000 analysis mark**

  A steady flow of analysis submissions, plus the occasional deluge of (mainly hadronisation) routines from Herwig!

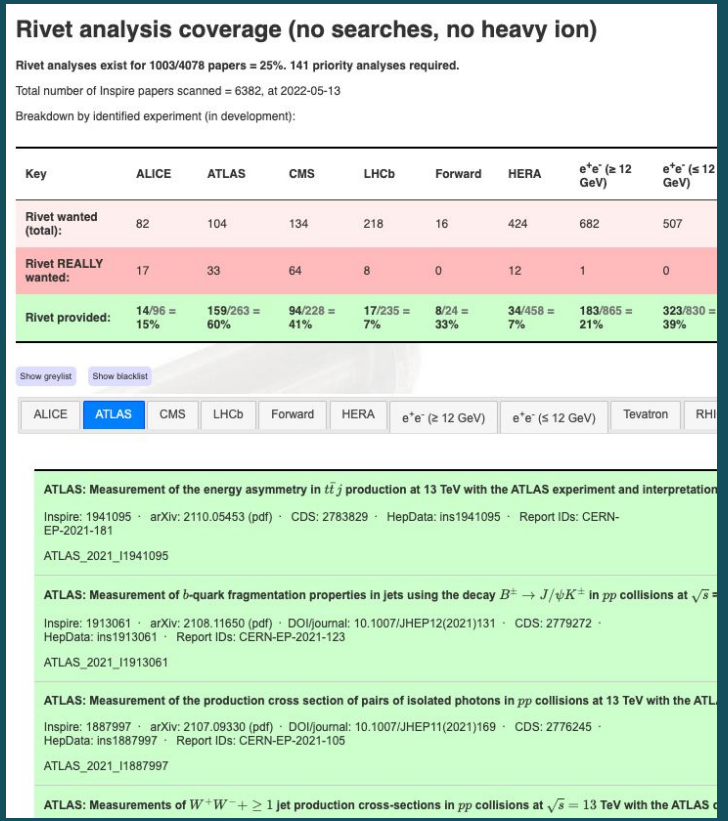


- **Official support from the LHC experiments is crucial**

  preservation = just part of how we do science; but still some way to go! Coverage monitoring:

- **"New" features since the v1 vision:**

  systematics multiweights, "perfect merging", heavy ions, detector smearing functions, analysis options



Rivet analysis coverage (no searches, no heavy ion)

Rivet analyses exist for 1003/4078 papers = 25%. 141 priority analyses required.

Total number of Inspire papers scanned = 6382, at 2022-05-13

Breakdown by identified experiment (in development):

Key	ALICE	ATLAS	CMS	LHCb	Forward	HERA	e^+e^- (≥ 12 GeV)	e^+e^- (≤ 12 GeV)
Rivet wanted (total):	82	104	134	218	16	424	682	507
Rivet REALLY wanted:	17	33	64	8	0	12	1	0
Rivet provided:	14/96 = 15%	159/263 = 60%	94/228 = 41%	17/235 = 7%	8/24 = 33%	34/458 = 7%	183/865 = 21%	323/830 = 39%

Show greylist Show blacklist

ALICE | ATLAS | CMS | LHCb | Forward | HERA | e^+e^- (≥ 12 GeV) | e^+e^- (≤ 12 GeV) | Tevatron | RHI

ATLAS: Measurement of the energy asymmetry in $t\bar{t}j$ production at 13 TeV with the ATLAS experiment and interpretation

Inspire: 1941095 · arXiv: 2110.05453 (pdf) · CDS: 2783829 · HepData: ins1941095 · Report IDs: CERN-EP-2021-181

ATLAS_2021_I1941095

ATLAS: Measurement of b-quark fragmentation properties in jets using the decay $B^{\pm} \to J/\psi K^{\pm}$ in pp collisions at $\sqrt{s}$ =

Inspire: 1913061 · arXiv: 2108.11650 (pdf) · DOI/journal: 10.1007/JHEP12(2021)131 · CDS: 2779272 · HepData: ins1913061 · Report IDs: CERN-EP-2021-123

ATLAS_2021_I1913061

ATLAS: Measurement of the production cross section of pairs of isolated photons in pp collisions at 13 TeV with the ATL

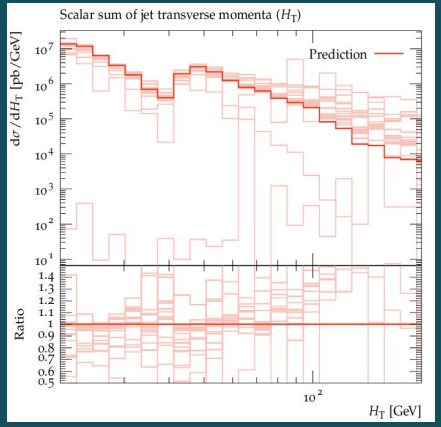
Inspire: 1887997 · arXiv: 2107.09330 (pdf) · DOI/journal: 10.1007/JHEP11(2021)169 · CDS: 2776245 · HepData: ins1887997 · Report IDs: CERN-EP-2021-105

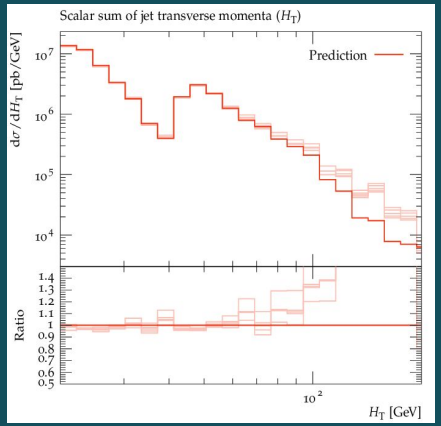
ATLAS_2021_I1887997

ATLAS: Measurements of $W^+W^- + \geq 1$ jet production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS c

Multiweights and re-entry

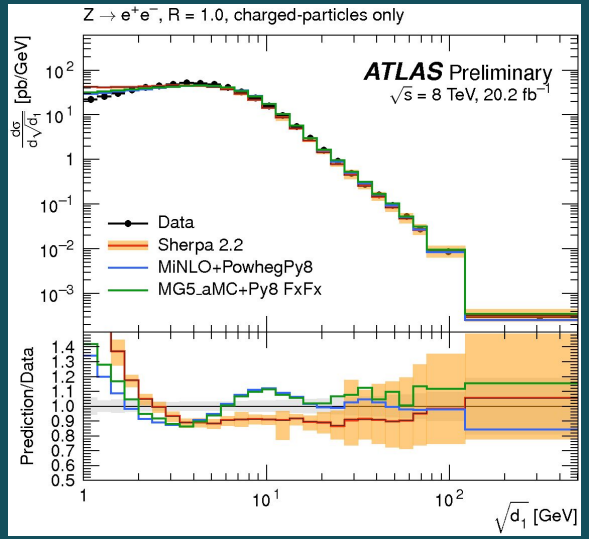
- **MC weight vectors allow expression of increasingly complex theory uncertainties.** But a burden for analysis chains: have to propagate and correctly combine O(200) weight streams!
- **Rivet 3: complex automatic handling of weights** ~invisible to users: data objects *look* like histograms etc. but are secretly multiplexed
- **Can now re-call finalisation to combine runs:** RAW histogram stage preserves pre-finalize objects
  ⇒ "re-entrant" perfect data-object merging
  Key for e.g. *pA/pp* or *W/Z* ratios, + BSM recasting
- **Data types are important:** glimpses of a fully coherent separation of semantics from presentation

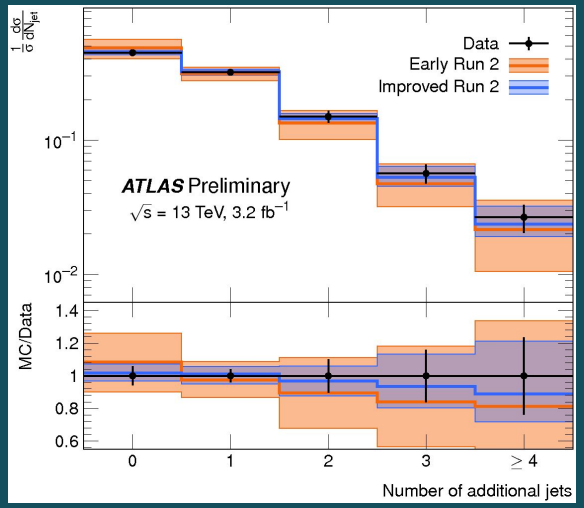


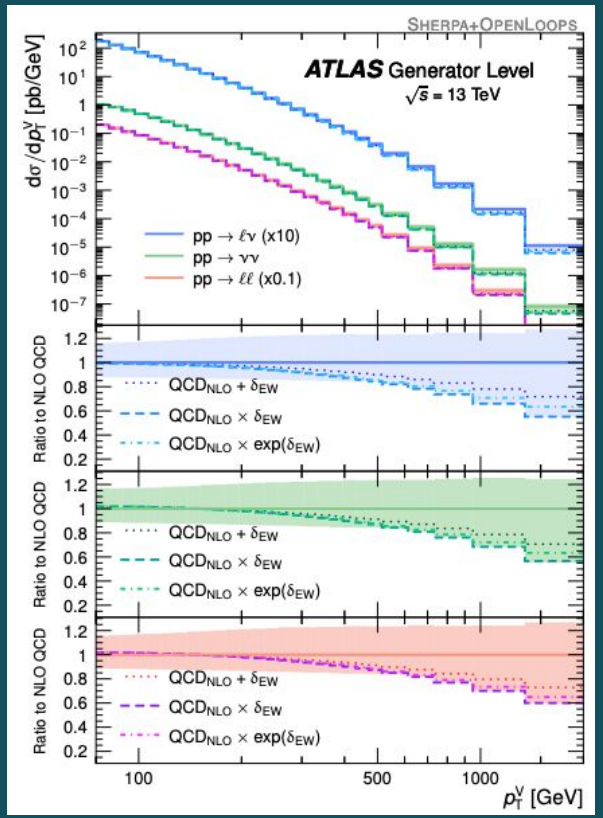


Rivet multiweights in action

ATLAS MC studies have been a significant driver of this feature



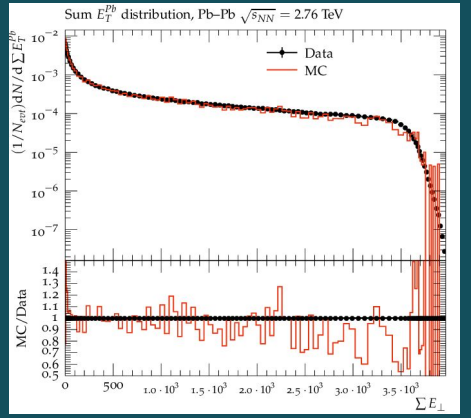


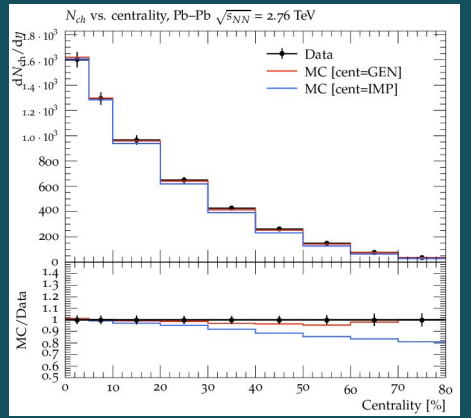


Weight-naming standardisation via MCnet (arXiv:2203.08230)

Heavy-ion physics preservation

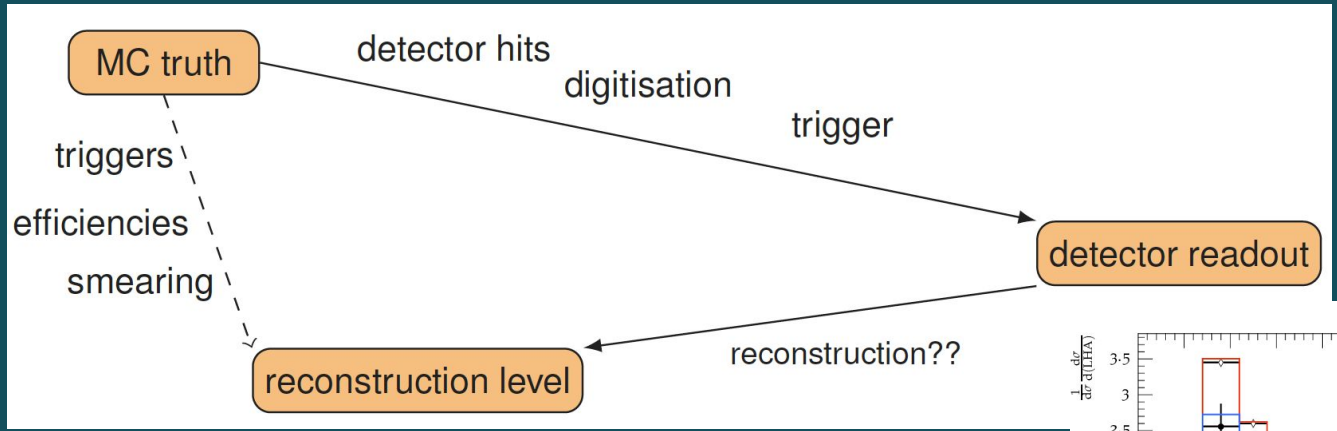
- **“Adding heavy-ion support” sounds trivial!**
- Actually a stern test, with far-reaching impacts
  - HI observables often require centrality calibration curves: we need a 2-pass run. That wasn’t planned.
  - And event/event correlations… centrality-binned!
  - Need swappable definitions: few HI generators are general-purpose enough to do
    e.g. both forward E_T *and* jet quenching
- **Paper: arXiv:2001.10737**
- HI MC standards are also in flux: having a common tool enables discussion on common standards



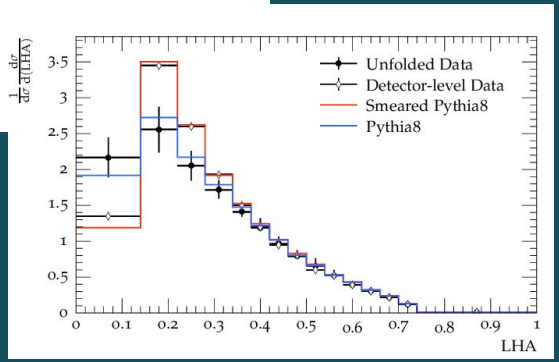


Detector emulation

- **Detector smearing built on Rivet's projection system — for reco-level analyses**
  - developed based on Gambit ColliderBit experience: no need for "full fast-sim"



  - like Delphes, but more flexible & can be analysis-specific ⇒ MA5 "SFS" mode
  - flexibility allows e.g. "tuned" jet-substructure smearing, systematics studies, …

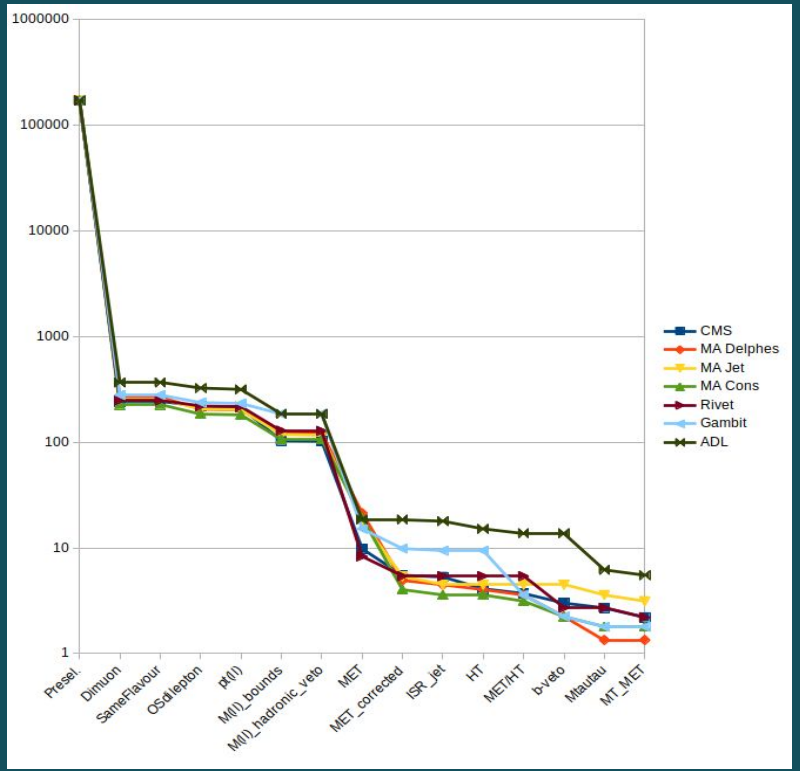


Rivet and BSM-search recasting

- **Rivet's main emphasis *isn't* BSM direct searches, but there's no reason not to**
  - lots of experiment experience and support
  - efficient scaling-up to hundreds of analyses, with distinct phase-space specific detector/efficiency functions

- **Can we do for BSM preservation what we did for measurement analyses?**

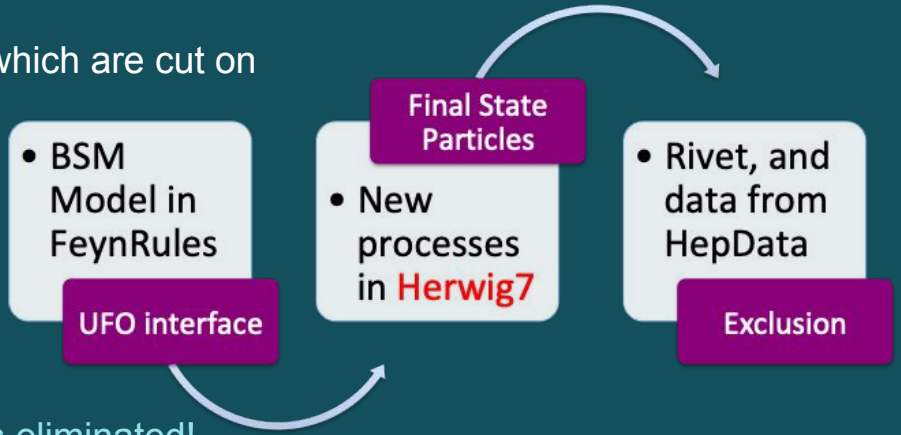
- **Friendly competition, mainly from/with MA5**
  - all good tools, all geared to getting your analysis into pheno studies asap



Les Houches 2019 CMS soft-lepton recasting-tools comparison

BSM from “Standard Model”

- **Not being focused on direct searches doesn’t mean no interest in BSM!**
- **Particle-level measurements can achieve high level of model-independence**
  - Careful definition of fiducial cross-section
  - Control distributions of “hidden variables” which are cut on
  - Reduce model sensitivity in unfolding
- **Rivet used directly in e.g.**
  - TopFitter top quark EFT fits;
  - at core of ATLAS VH EFT fits; and…
- **Contur is getting particular uptake**
  - Inject signal to “SM” measurements:
    if it’d been statistically distinct, the model is eliminated!
  - Rivet gives huge “synoptic” coverage:
    a new result with Rivet code can be in BSM fits within *hours*
  - see Jon’s talk for more details



The future of Rivet

- **Vision: Rivet as a standard for "truth-level" observables, across collider physics**
- Not just standalone, but as a library in pheno & experiment frameworks, too: standard MC definitions (cf. CMSSW), seamless systematics handling, etc.
- At its core: a physics-oriented system for physicists to **compare MC predictions to one another and to data, on many simultaneous observables, in myriad ways … we don't know all the use-cases yet!**
- **Challenges:**
  - Extension of HepData and other community infrastructure for ever more precise data. Even our compressed data format is struggling with the volume of analyses and data. Work needed on multiweight-oriented data format and tools
  - Improved, modernised visualisation and exploration
  - Connections to global (BSM) fitting tools
  - Preserving MVAs: BDT and NN in vanilla C++

Getting and using Rivet

An analysis that's immediately available to the pheno community is 10x more useful ⇒ payback!
In the past, key analyses were ignored due to the barrier to entry

As either a "user" or analysis author, the barrier is lower than ever: we recommend using our Docker images to get started

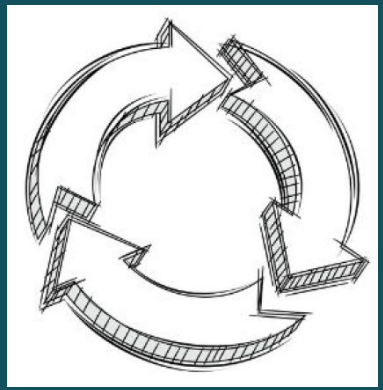
Tutorials available from the Rivet website, a walkthrough in the Rivet3 paper

Imitation is the highest form of flattery: copy an existing analysis!

```
$ docker pull hepstore/rivet-tutorial
Using default tag: latest
latest: Pulling from hepstore/rivet-tutorial
Digest: sha256:d077730d7b616722afe0ef2734a9a6799e4dabd0611798fc5ebf5ab52b8e25a8
Status: Image is up to date for hepstore/rivet-tutorial:latest
docker.io/hepstore/rivet-tutorial:latest
$
$ docker run -it hepstore/rivet-tutorial
root@31de38022200:/work#
root@31de38022200:/work# cat gg_g1500_chi100_g-ttchi.cmnd
SUSY:all = on
SLHA:file = gg_g1500_chi100_g-ttchi.slha
Main:writeHepMC = on
Main:runRivet = on
Main:analyses = MC_JETS
root@31de38022200:/work#
root@31de38022200:/work# pythia8-main93 -c gg_g1500_chi100_g-ttchi.cmnd -n 2000
```

Summary

- Rivet arose from HERA experiment/MC author collaboration, in time for the LHC
- Like HZTool, its existence has spurred many other experiment/pheno activities, e.g.
  - MC development, validation and quality control
  - Tuning
  - PDF studies, EFT, global BSM fits…
  - Heavy-ion methods
  - And teaching / UG projects
- An accelerator for analysis impact: immediate entry to many theory studies. Lots of fun collaborations!
  (cf. new LPCC RAMP initiative: exposure for good practice)
- As we head into another LHC era, there will surely be more use-cases for analysis recycling. **Join in!**



Backup

MC generation

- MC generation is where theory meets experiment
  - The fundamental pp (etc.) collision, sans detector
- Components of an “exclusive” event-generator 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 multiple partonic interaction modelling
  - Finally particle decays, and other niceties
- Modern HEP is powered by shower MCs
  - The main mechanism for translating theory to experimental signatures, from QCD to BSM
  - Generally very complex modelling and output