Accelerating impact with Rivet

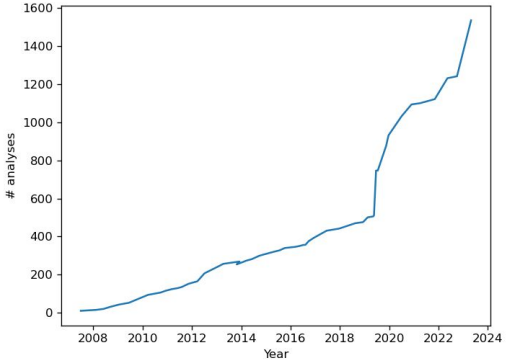
Analysis prototyping, preservation & re-interpretation

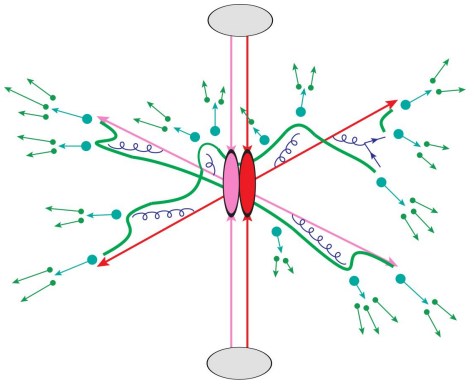
Andy Buckley,
University of Glasgow

COMAP V — Best Practices in Model Preservation
14 December 2023

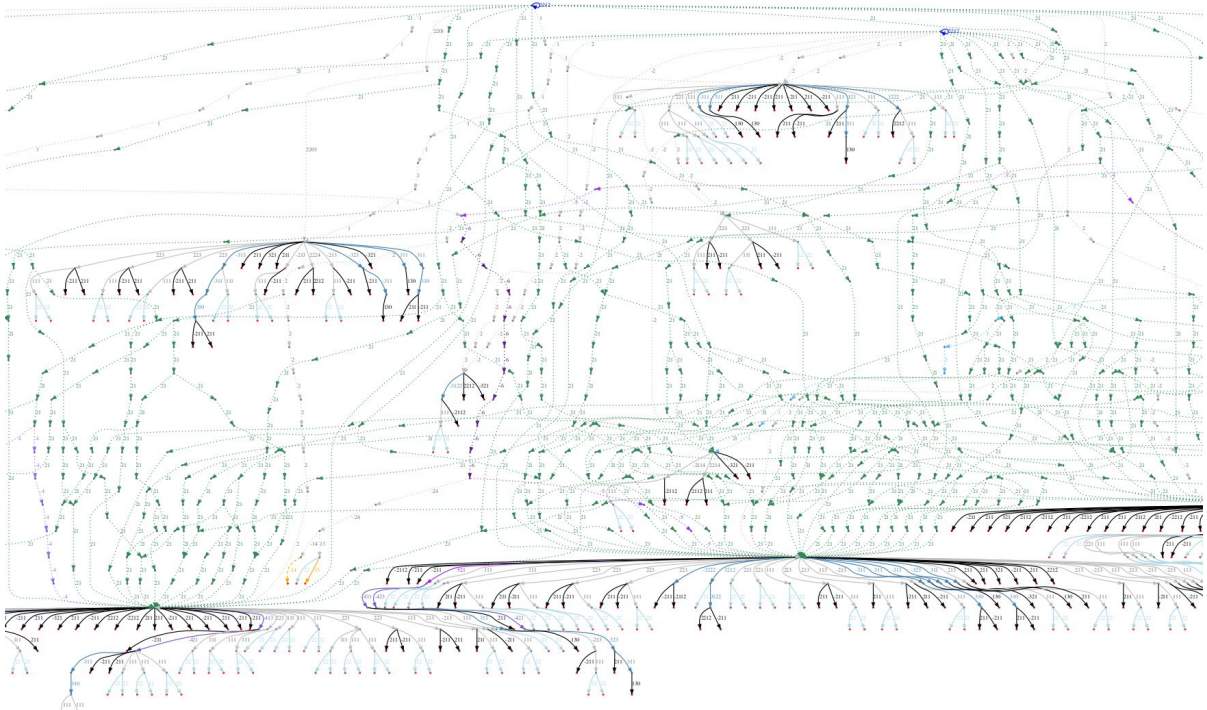
What is Rivet?

- **The "LHC standard" MC analysis toolkit**
- **More broadly a project to preserve the logic of data analyses and encourage expt-pheno collaboration**
- **Code-wise, a C++ core and Python tools**
  - Fiducial / generator-independence emphasis
  - Integration with HepData
  - Transparent HepMC weight-stream handling
  - 1500+ analyses!
- **Central to a community of analysis reinterpretation tools, linking experiment to theory. Collider, some cosmic-ray**
- **But why? Event loops are trivial…**





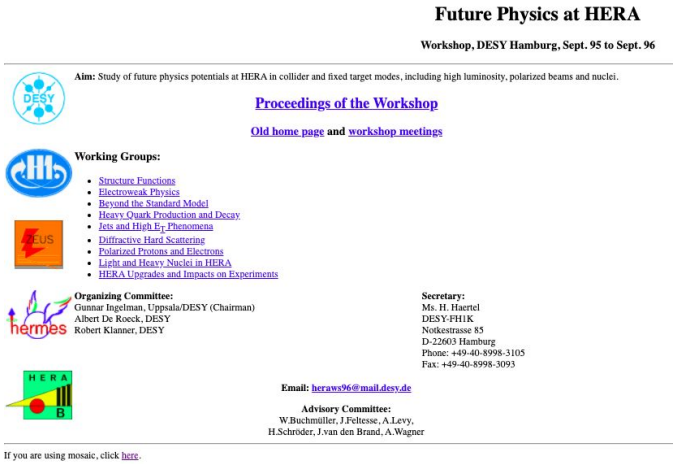
Because of this:



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

From HZTool to Rivet

- **The idea of preserving experimental analyses for MC validation was born out of HZTOOL**
  - HERA (H1 and ZEUS) DIS and photoproduction
  - Probing low-*x*, semi-perturbative physics:
    DIS with Q^2 ~ 4 GeV^2; jet p_T ~ 5 GeV; diffraction
  - Many "state of the art" models only in MCs
  - Much confusion about comparing like-with-like between generators, experiments, and analyses
  - HZTool (Fortran) for cross-experiment comparisons of similar measurements modulo cut differences
- **Direct line to Rivet, 10 years later: "HZ mark two"**
  - UK e-science funding; adopted by EU MCnet network



Future Physics at HERA

Workshop, DESY Hamburg, Sept. 95 to Sept. 96

Aim: Study of future physics potentials at HERA in collider and fixed target modes, including high luminosity, polarized beams and nuclei.

Proceedings of the Workshop

Old home page and workshop meetings

Working Groups:

- Structure Functions
- Electroweak Physics
- Beyond the Standard Model
- Heavy Quark Production and Decay
- Jets and High E_T Phenomena
- Diffractive Hard Scattering
- Polarized Protons and Electrons
- Light and Heavy Nuclei in HERA
- HERA Upgrades and Impacts on Experiments

Organizing Committee:
Gunnar Ingelman, Uppsala/DESY (Chairman)
Albert De Roeck, DESY
Robert Klanner, DESY

Secretary:
Ms. H. Haertel
DESY-FH1K
Notkestrasse 85
D-22603 Hamburg
Phone: +49-40-8998-3105
Fax: +49-40-8998-3093

Email: heraws96@mail.desy.de

Advisory Committee:
W.Buchmüller, J.Feltesse, A.Levy,
H.Schröder, J.van den Brand, A.Wagner

If you are using mosaic, click here.

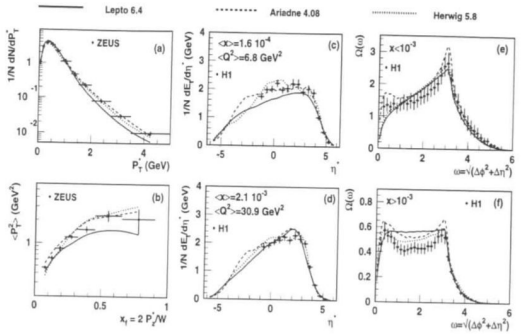
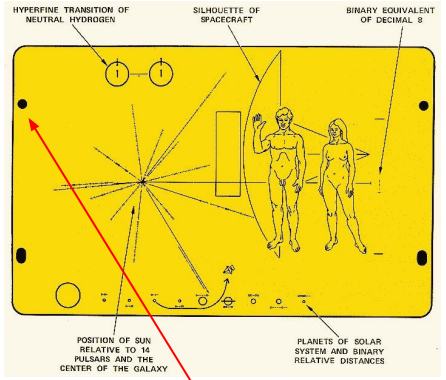


Figure 1: *The transverse momenta dN/dp_T (a) and the 'seagull' plot $\langle P_T^2 \rangle \times x_F$ (b) of single particles in the positive hemisphere of the hadronic center of mass. The transverse energy flow $dE_T/d\eta$ in a low (c) and high (d) x and Q^2 bin. The transverse energy-energy correlations for $x > 10^{-3}$ (e) and $x < 10^{-3}$ (f).*

Lessons learned



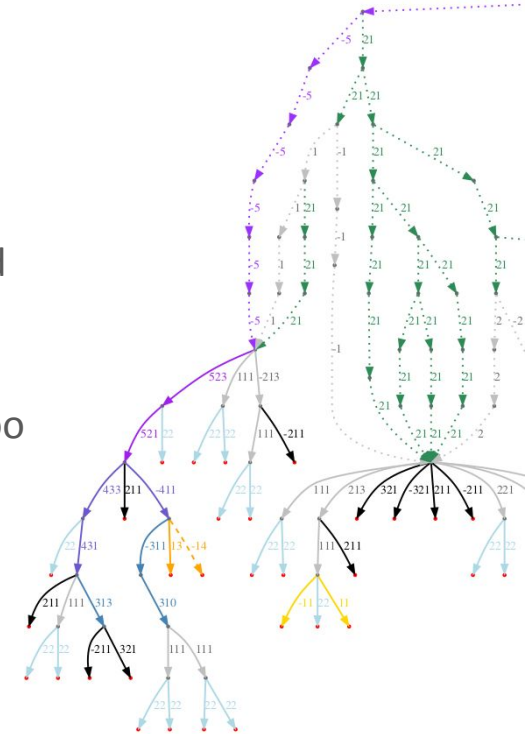
- **A simple/obvious idea, with surprising impact:**
  - **Reproducing a key plot (or not) is *powerful***
    - ⇒ *understand physics, communicate issues, improve MCs*
  - **A *common language* for phenomenology and experiment**
- **But…**
  - "Obvious" to use partons, bosons, etc. direct from the event graph
  - Frequently unphysical, depend on approximations. May not even exist!
  - Scalability of many analyses to new MCs means avoiding gen-dependence
    - **⇒ predict "real" observables, from well-defined final states**

- **Standardisation: boring but important**
  - (physical) event format conventions, statuses, PDG particle numbering, weights…
- **Scalability**
  - Lots of expensive operations are repeated: sharing calculations is essential

Physically safe analysis methods

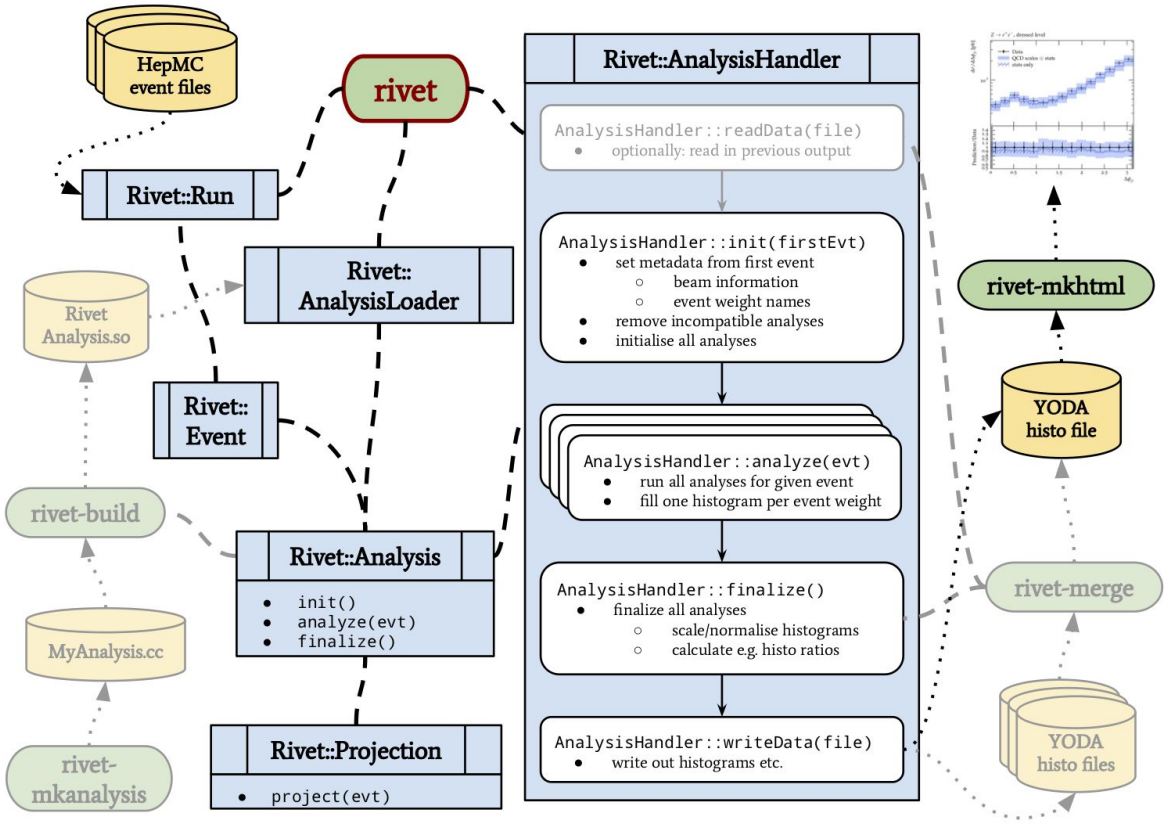
Avoiding unstandardised event-graph features was pragmatic, but led to some genuine physical insights:

- **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



The result

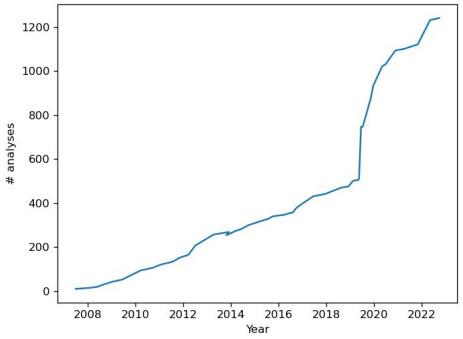
- **Rivet v3 structure**
  arXiv:1912.05451
- Streamlined set of tools from analysis coding to event processing to plotting (and other applications)
- And a key gateway to connect data analysis to theory (and back again)



The state we're in

- **Version 3.1.9 (Nov 2023) → 1500+ analyses!**

  A steady 50/yr flow of analysis submissions, plus occasional deluges from MC gen teams
  ⇒ **Major v3.2.0 imminent**

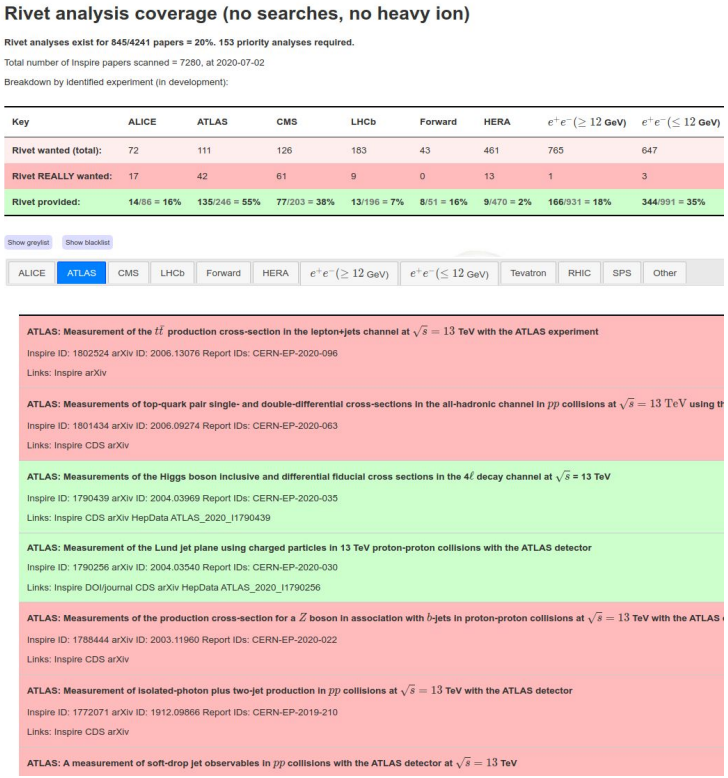


- **Official support from the (LHC) experiments is crucial**

  preservation = standard part of "how we do science", but still imperfect! We monitor paper coverage ⇒ *(including COMPASS… but not yet in detail!)*

- **"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 845/4241 papers = 20%. 153 priority analyses required.

Total number of Inspire papers scanned = 7280, at 2020-07-02

Breakdown by identified experiment (in development):

Key	ALICE	ATLAS	CMS	LHCb	Forward	HERA	$e^+e^-(\geq 12$ GeV)	$e^+e^-(\leq 12$ GeV)
Rivet wanted (total):	72	111	126	183	43	461	765	647
Rivet REALLY wanted:	17	42	61	9	0	13	1	3
Rivet provided:	**14**/86 = **16%**	**135**/246 = **55%**	**77**/203 = **38%**	**13**/196 = **7%**	**8**/51 = **16%**	**9**/470 = **2%**	**166**/931 = **18%**	**344**/991 = **35%**

Show greylist Show blacklist

ALICE | ATLAS | CMS | LHCb | Forward | HERA | $e^+e^-(\geq 12$ GeV) | $e^+e^-(\leq 12$ GeV) | Tevatron | RHIC | SPS | Other

ATLAS: Measurement of the $t\bar{t}$ production cross-section in the lepton+jets channel at $\sqrt{s} = 13$ TeV with the ATLAS experiment
Inspire ID: 1802524 arXiv ID: 2006.13076 Report IDs: CERN-EP-2020-096
Links: Inspire arXiv

ATLAS: Measurements of top-quark pair single- and double-differential cross-sections in the all-hadronic channel in pp collisions at $\sqrt{s} = 13$ TeV using th
Inspire ID: 1801434 arXiv ID: 2006.09274 Report IDs: CERN-EP-2020-063
Links: Inspire CDS arXiv

ATLAS: Measurements of the Higgs boson inclusive and differential fiducial cross sections in the 4ℓ decay channel at $\sqrt{s}$ = 13 TeV
Inspire ID: 1790439 arXiv ID: 2004.03969 Report IDs: CERN-EP-2020-035
Links: Inspire CDS arXiv HepData ATLAS_2020_I1790439

ATLAS: Measurement of the Lund jet plane using charged particles in 13 TeV proton-proton collisions with the ATLAS detector
Inspire ID: 1790256 arXiv ID: 2004.03540 Report IDs: CERN-EP-2020-030
Links: Inspire DOI/journal CDS arXiv HepData ATLAS_2020_I1790256

ATLAS: Measurements of the production cross-section for a Z boson in association with b-jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS
Inspire ID: 1788444 arXiv ID: 2003.11960 Report IDs: CERN-EP-2020-022
Links: Inspire CDS arXiv

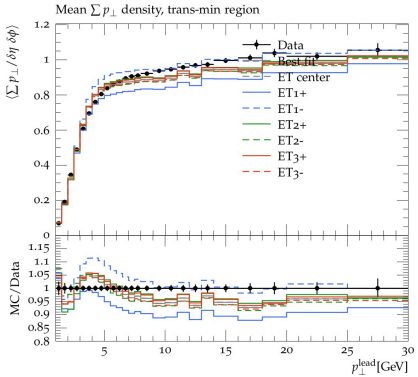
ATLAS: Measurement of isolated-photon plus two-jet production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
Inspire ID: 1772071 arXiv ID: 1912.09866 Report IDs: CERN-EP-2019-210
Links: Inspire CDS arXiv

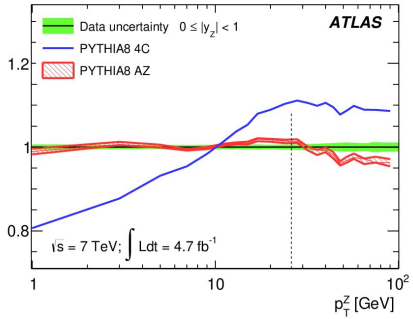
ATLAS: A measurement of soft-drop jet observables in pp collisions with the ATLAS detector at $\sqrt{s} = 13$ TeV

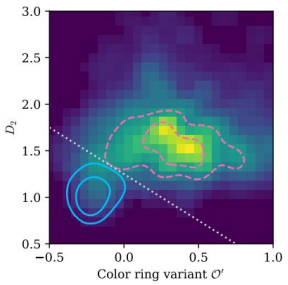
Applications: from tuning to…

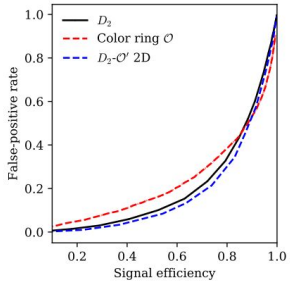
***First* "killer app": huge pre-LHC soft-QCD uncertainties:**

- **Tuning required Rivet analyses from expt**
- **Feed in to underlying event, pile-up, etc. modelling**
  - Better tunes ⇒ better analysis, better results
  - Impact: LEP and Tevatron analyses published for ~10 years suddenly got *used*! And cited…
    - ⇒ ATLAS tunes, CMS tunes, eigentunes…
    - ⇒ Rapid responses to preliminary data
  - Model development: matching & merging, addition of energy evolution & colour-reconnection to Herwig, …
- Recently, also use of Rivet's large analysis collection for *BSM (see Contur) & Higgs*
  - Uptake still growing, e.g. in CMS



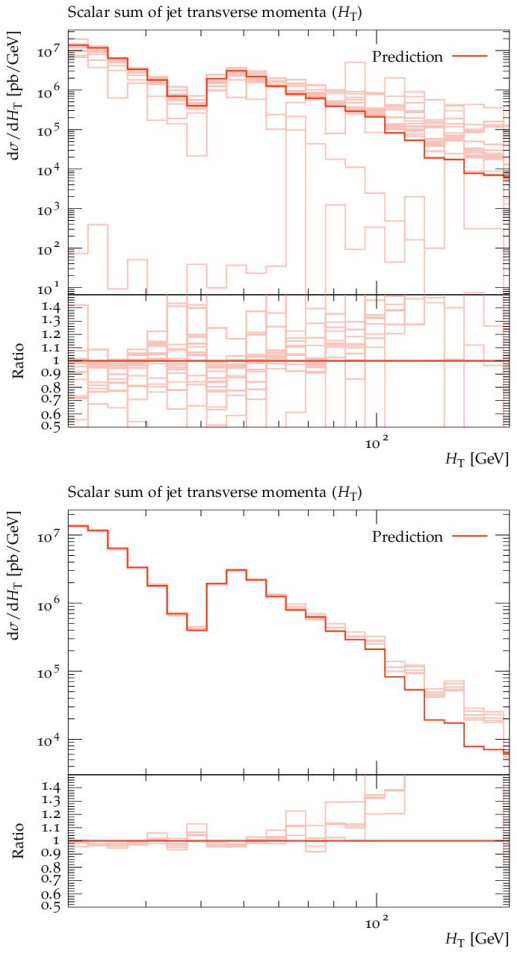






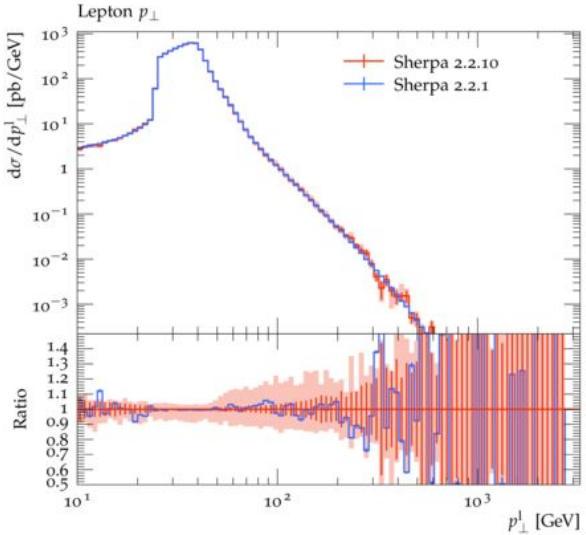
Multiweights and re-entry

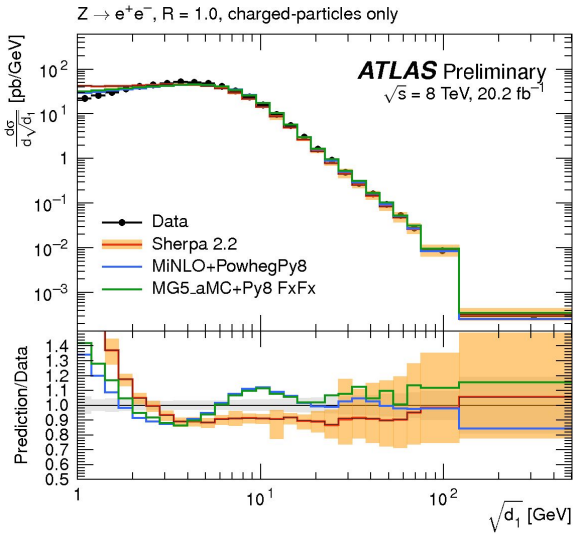
- **MC weight vectors allow expression of increasingly complex theory uncertainties.** But a burden for analysis chains: have to propagate and correctly combine O(200) weight streams!
- **Rivet 3: complex automatic handling of weights**
  ~invisible to users: data objects *look* like histograms etc. but are secretly multiplexed
- **Can now re-call finalisation to combine runs:**
  RAW histogram stage preserves pre-finalize objects
  ⇒ "re-entrant" perfect rivet-merge-ing
  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

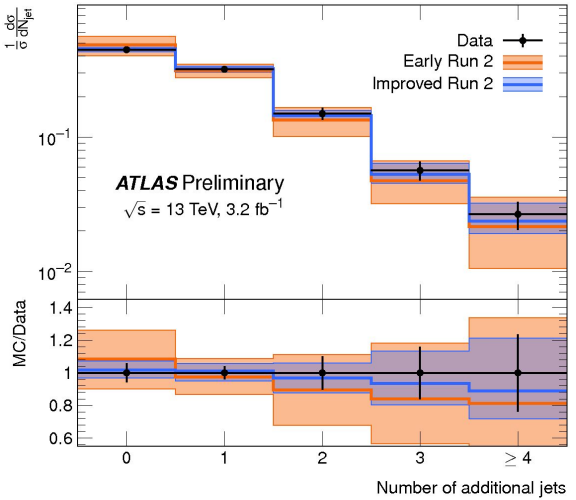


MC systematics bands via multiweights

ATLAS MC studies have been a significant driver of this feature *(thanks to Chris Gutschow)*



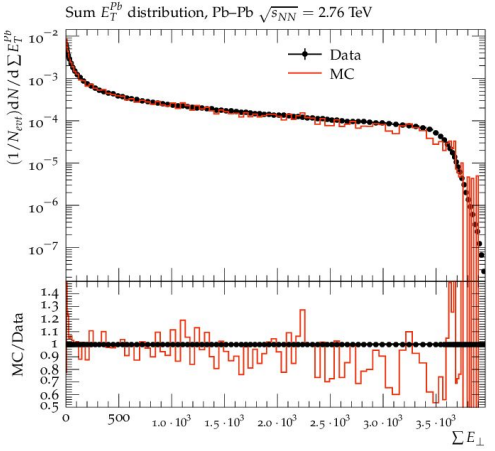


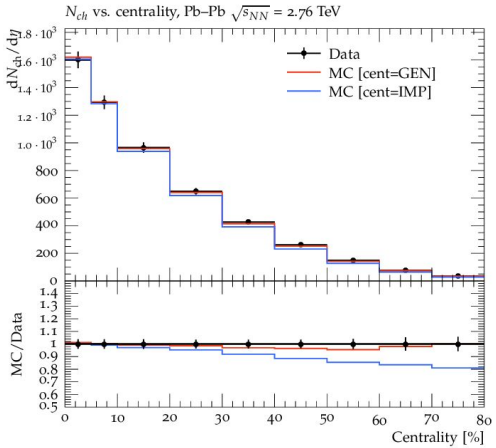


- Weight-naming standardisation: see arXiv:2203.08230

Heavy-ion physics preservation

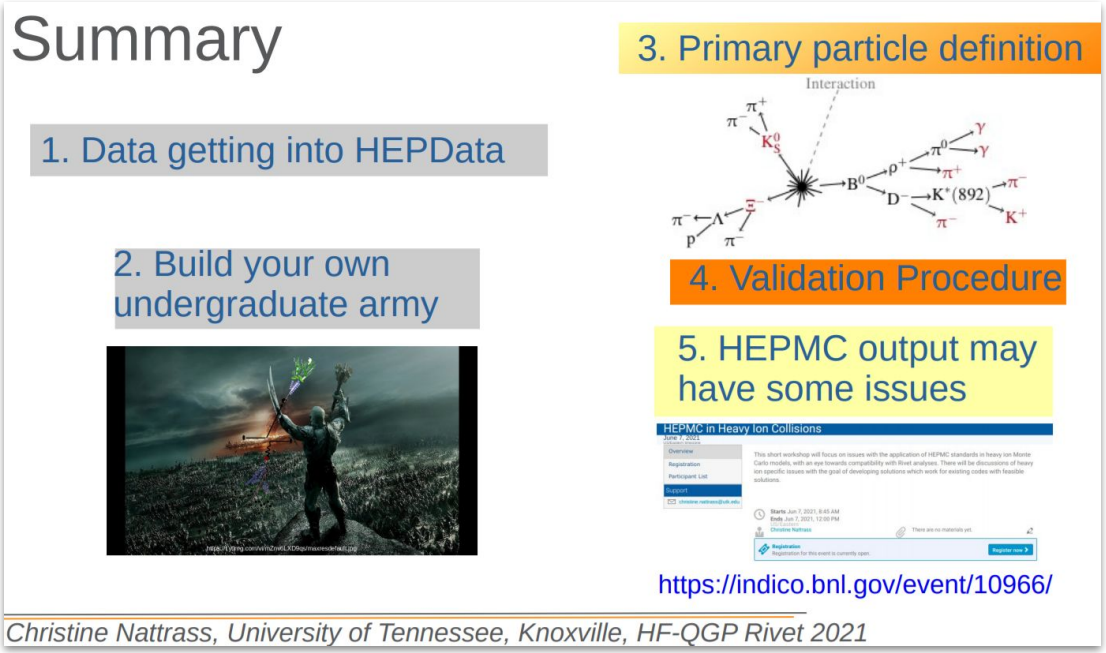
- "Adding heavy-ion support" sounds trivial!
- Actually nuanced ⇒ lots of structural impacts
  - HI observables often require centrality-fraction calibration curves: we need a 2-pass run.
  - Flow observables, event/event correlations… all centrality-binned!
  - Swappable definitions: few HI generators are general-purpose enough to do "everything"
- All supported "out of the box" since v3
  - Paper: https://arxiv.org/abs/2001.10737
  - Core development tool for Pythia/Angantyr: authors and ALICE (etc.) collaborators providing analyses
- Maybe some similar features are useful or needed?





HI *community engagement*

- **Great "spontaneous" engagement from within HI. Several productive workshops**

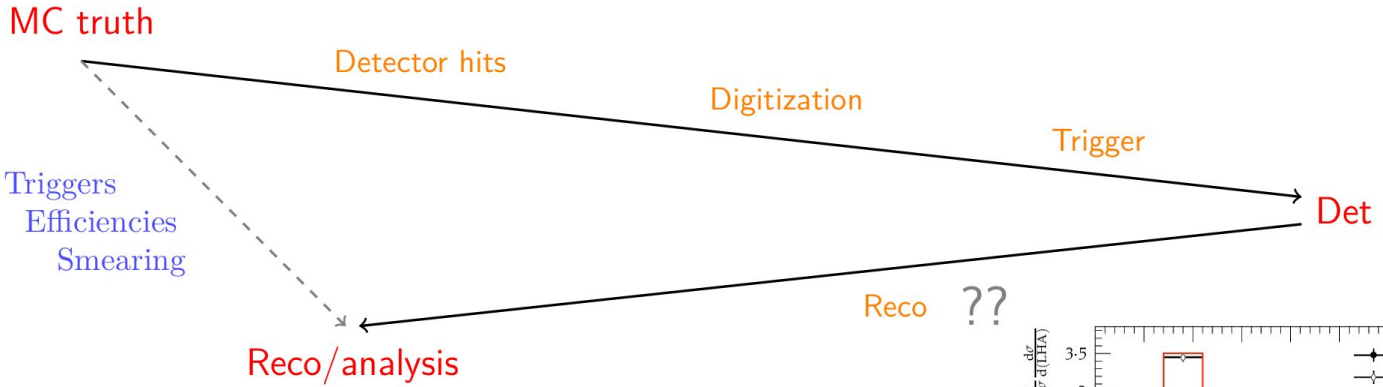


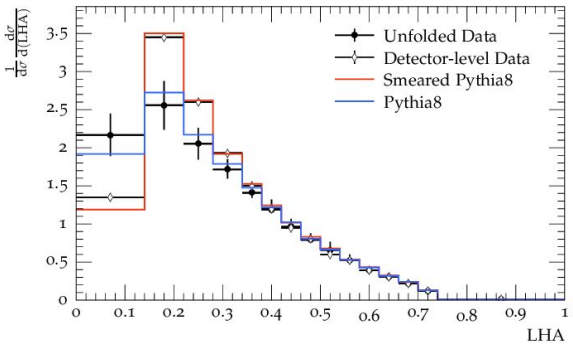
- HepData, Rivet
- Better ex/ph communication
- Faster model/data comparisons
- Addressing issues with formats and incomplete models
- Undergrad army!

Could this work in COMPASS?

Detector emulation (but unfold by preference!)

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



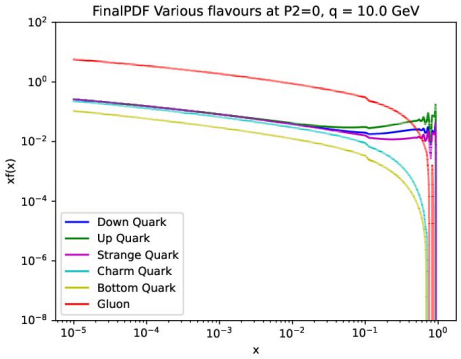


  - like Delphes, but more flexible & can be *analysis-specific* ⇒ MA5 "SFS" mode
  - flexibility allows e.g. "tuned" jet-substructure smearing, systematics studies, …

The future of Rivet

- **Vision: Rivet as a standard for "truth-level" observables**
- Eyes on future colliders, including EIC, cosmic-ray air showers … and nuclear physics, COMPASS? Happy to try!
- Not just standalone, but as a library in pheno & experiment frameworks, too: leverage analysis collection, standardise MC-observable definitions, seamless systematics handling, etc.
- Version 2 features include high-dimensional (and consistent) histogramming, HDF5 aux data, and ONNX machine-learning.
- 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.



Getting & using Rivet

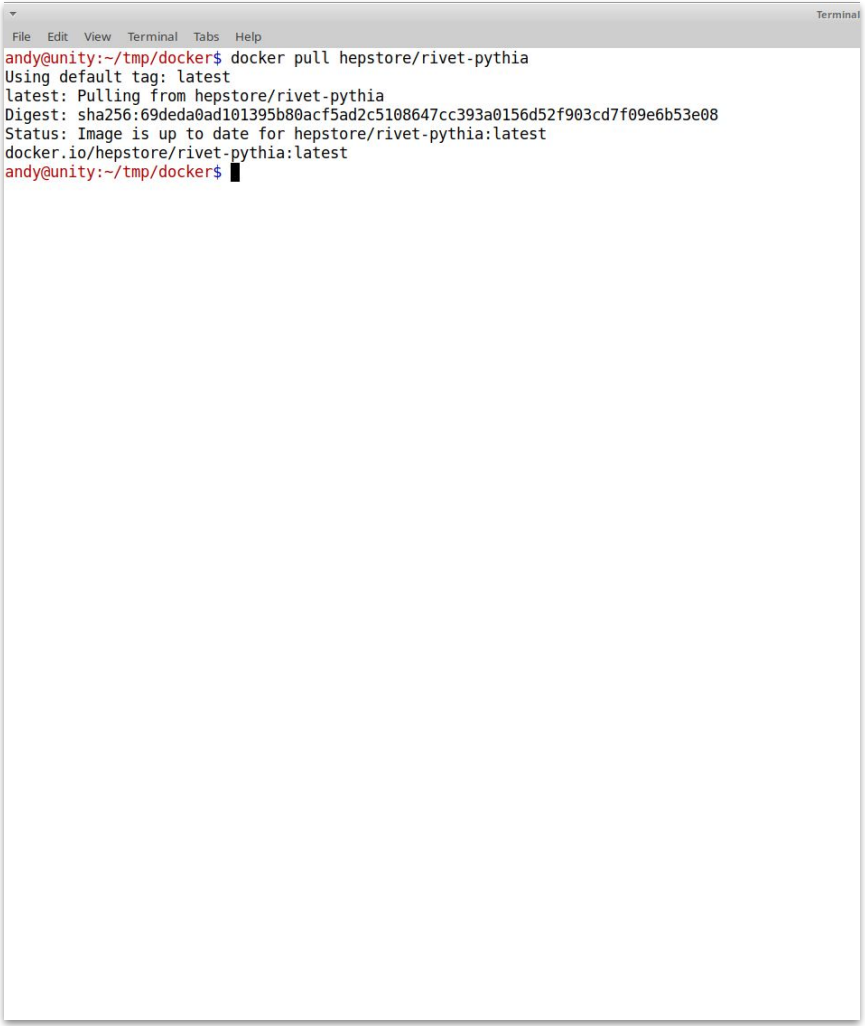
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



Getting & using Rivet

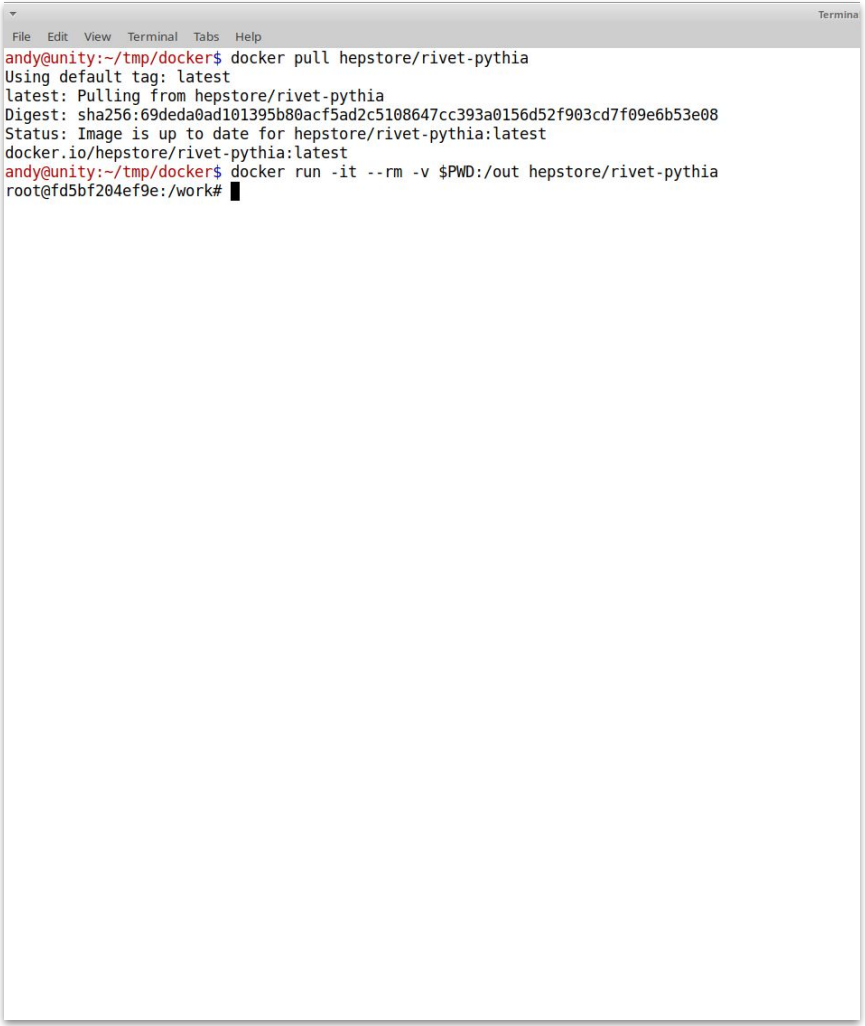
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



Getting & using Rivet

Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!

Getting & using Rivet

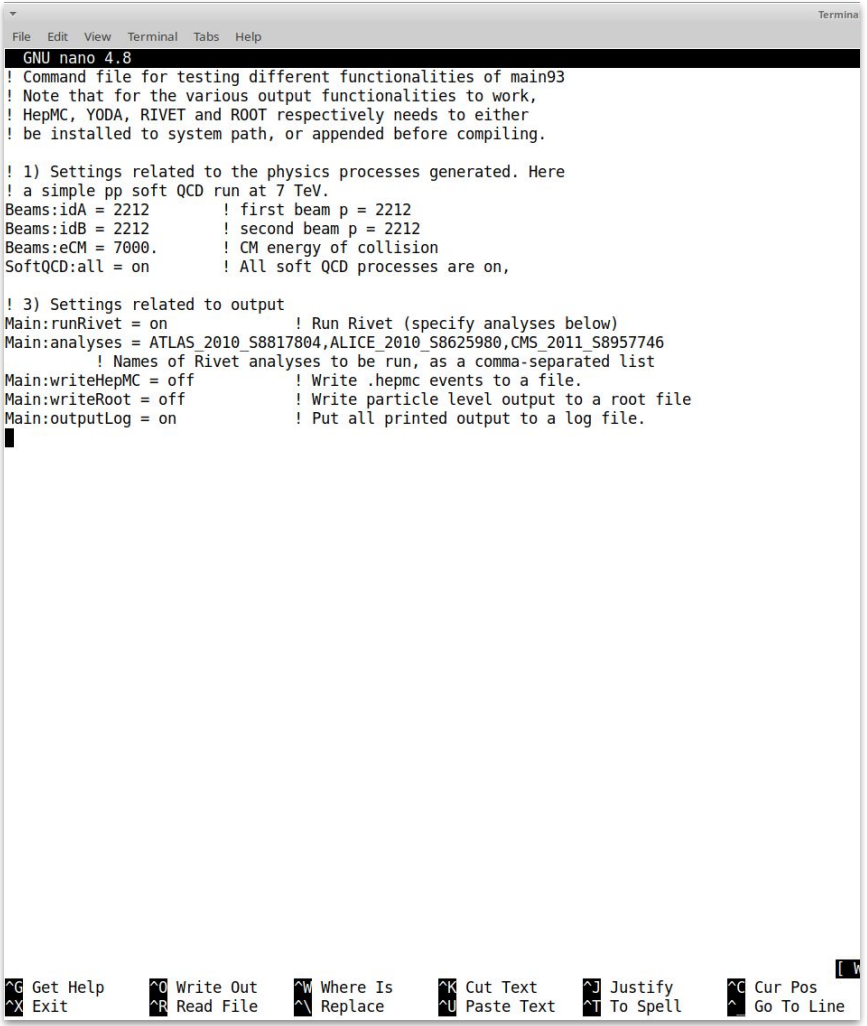
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



Getting & using Rivet

Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!

Getting & using Rivet

Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!

Getting & using Rivet

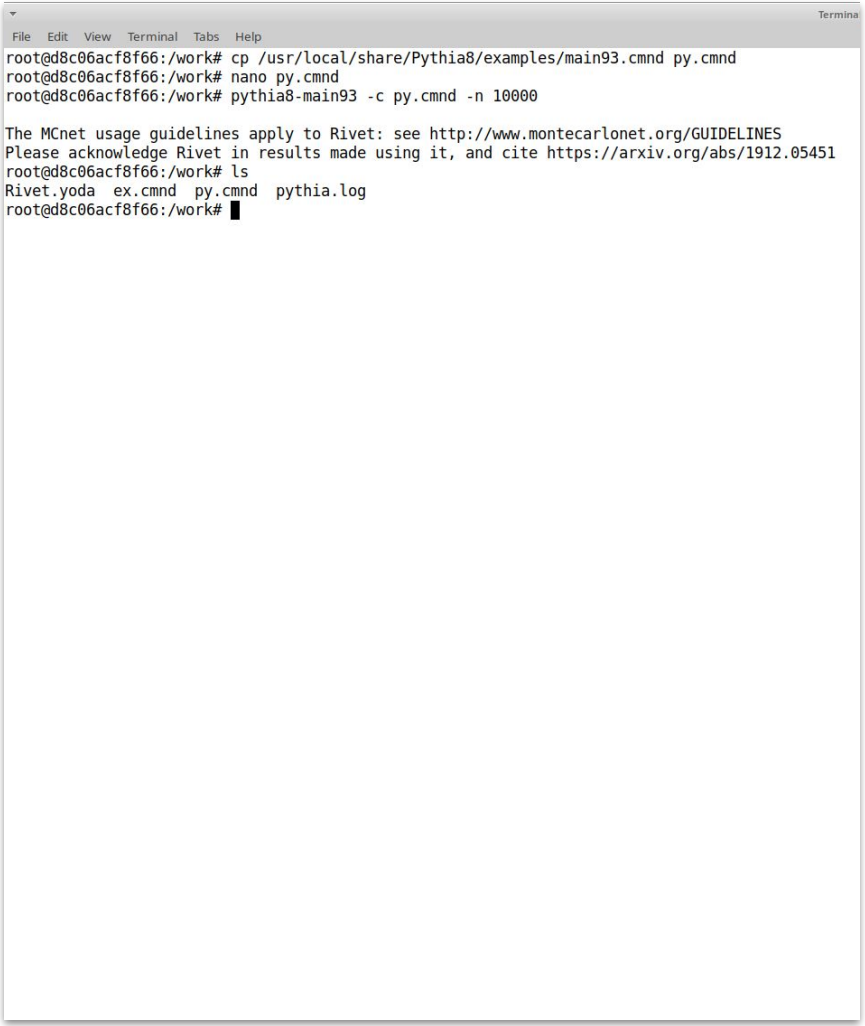
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



Getting & using Rivet

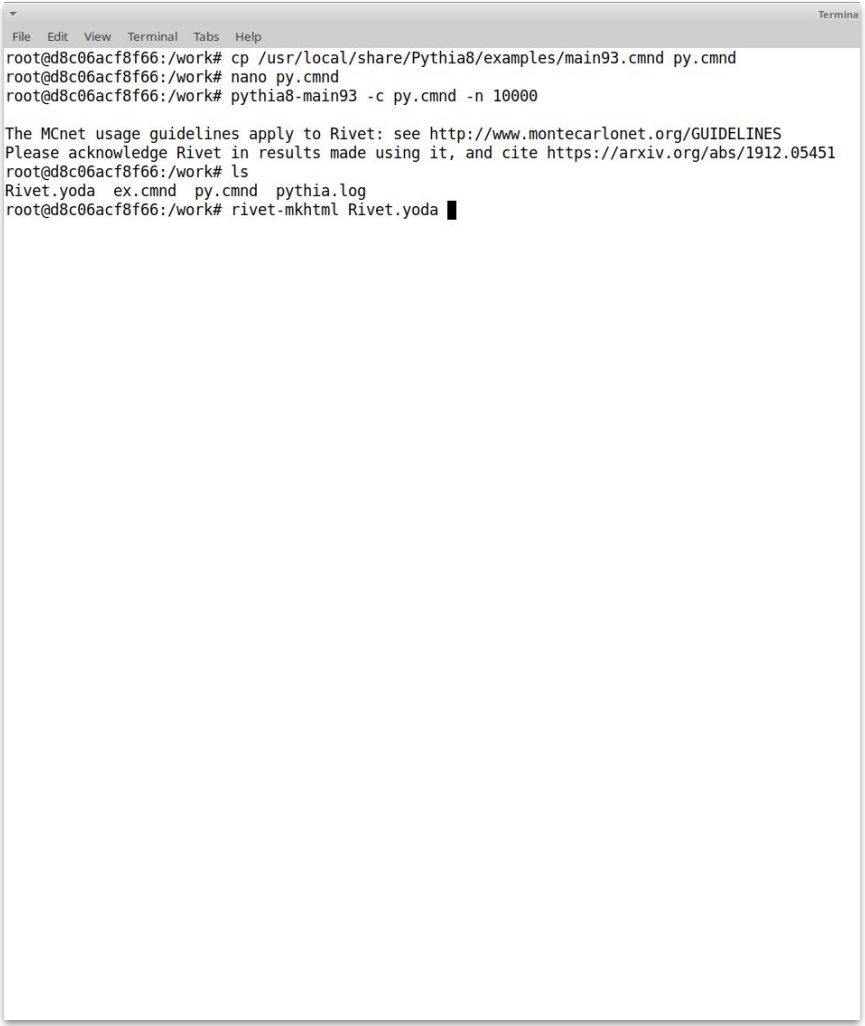
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



Getting & using Rivet

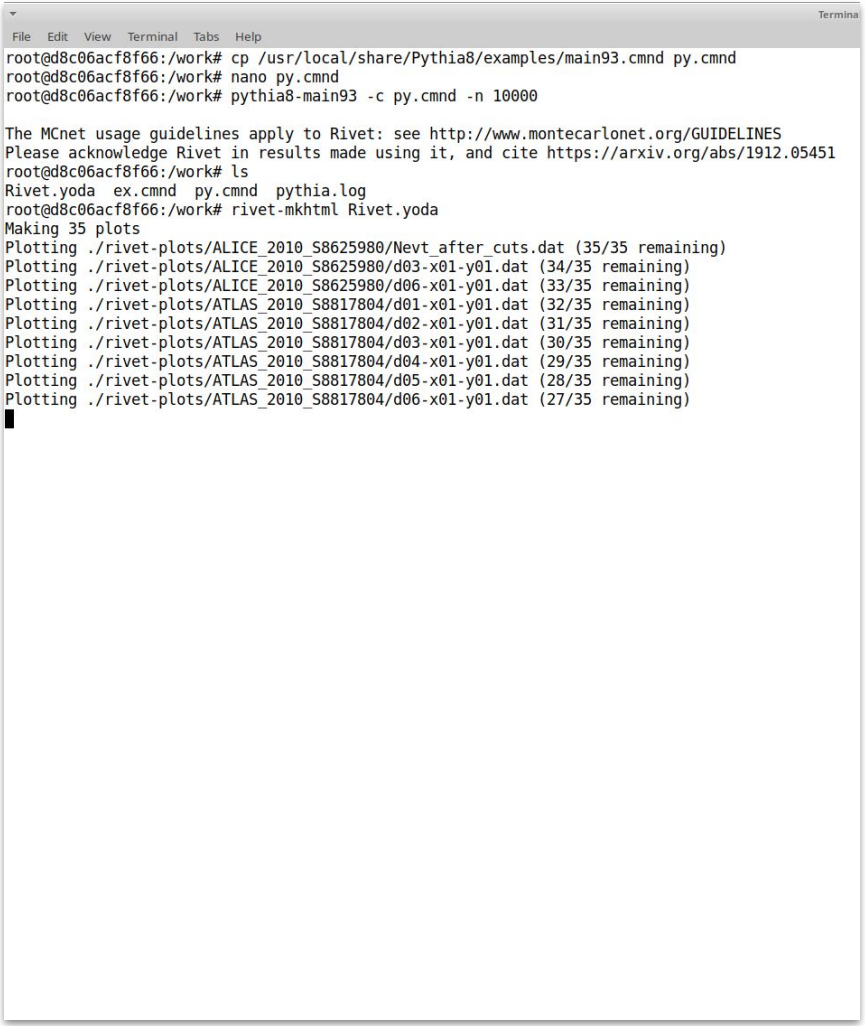
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



Getting & using Rivet

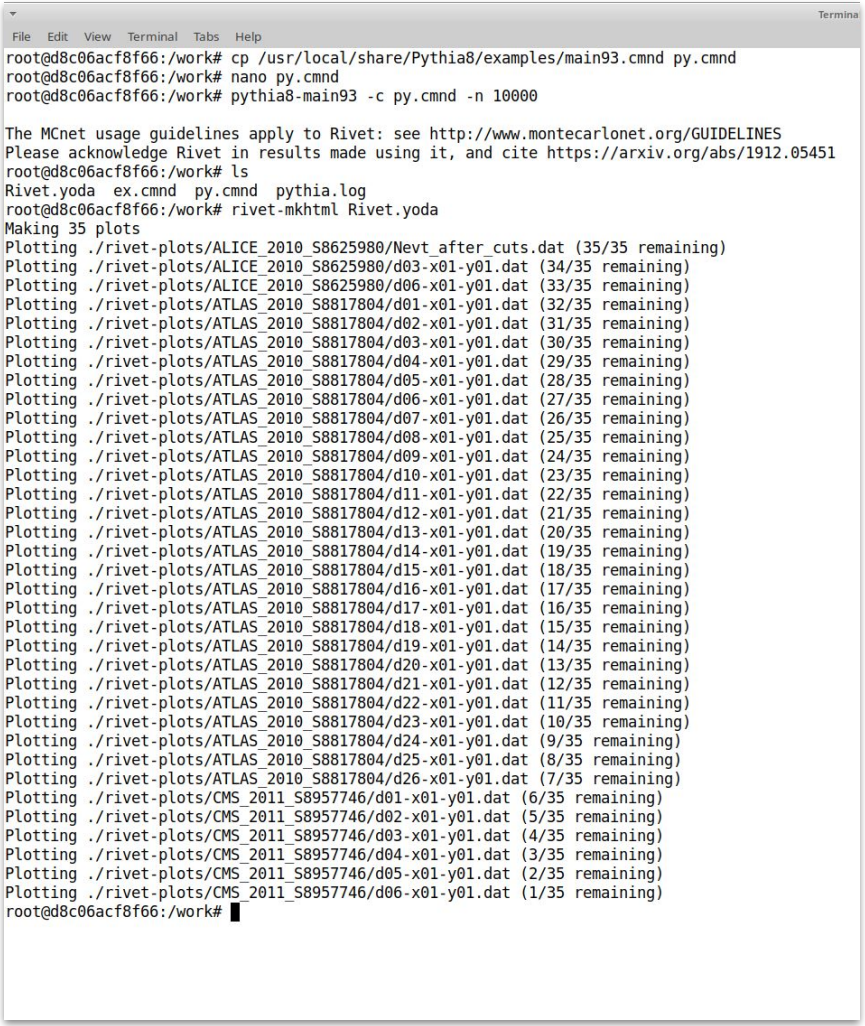
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



Getting & using Rivet

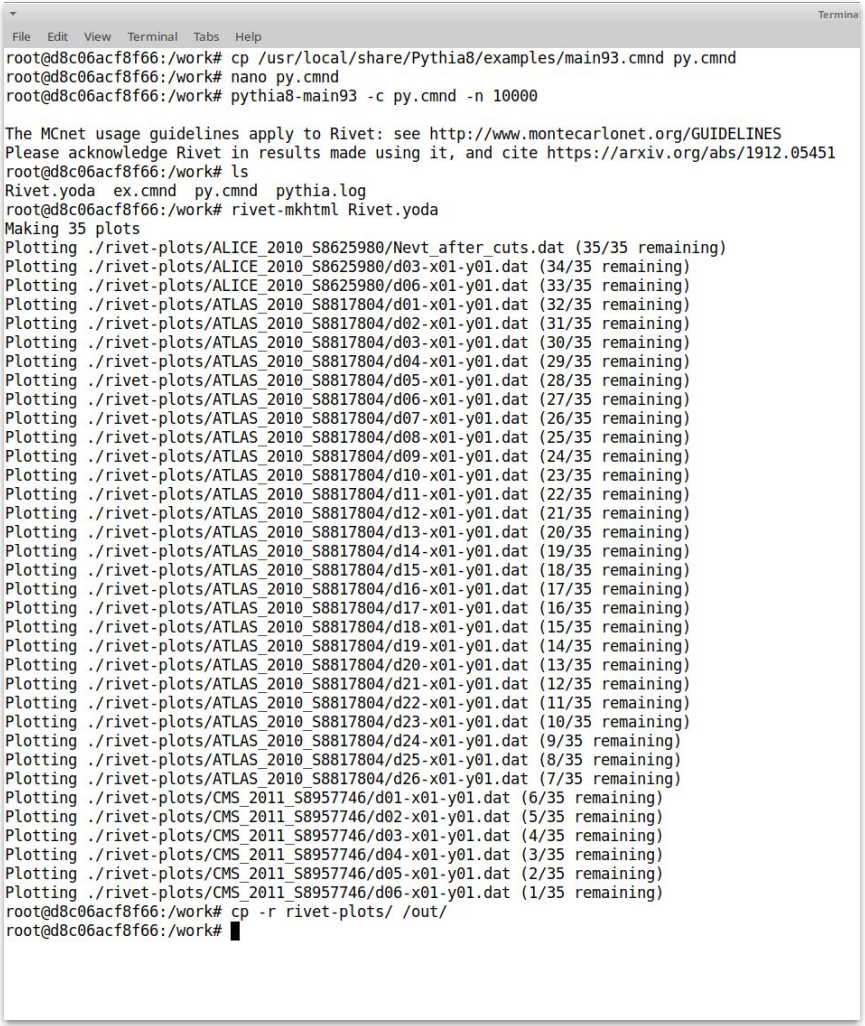
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



Getting & using Rivet

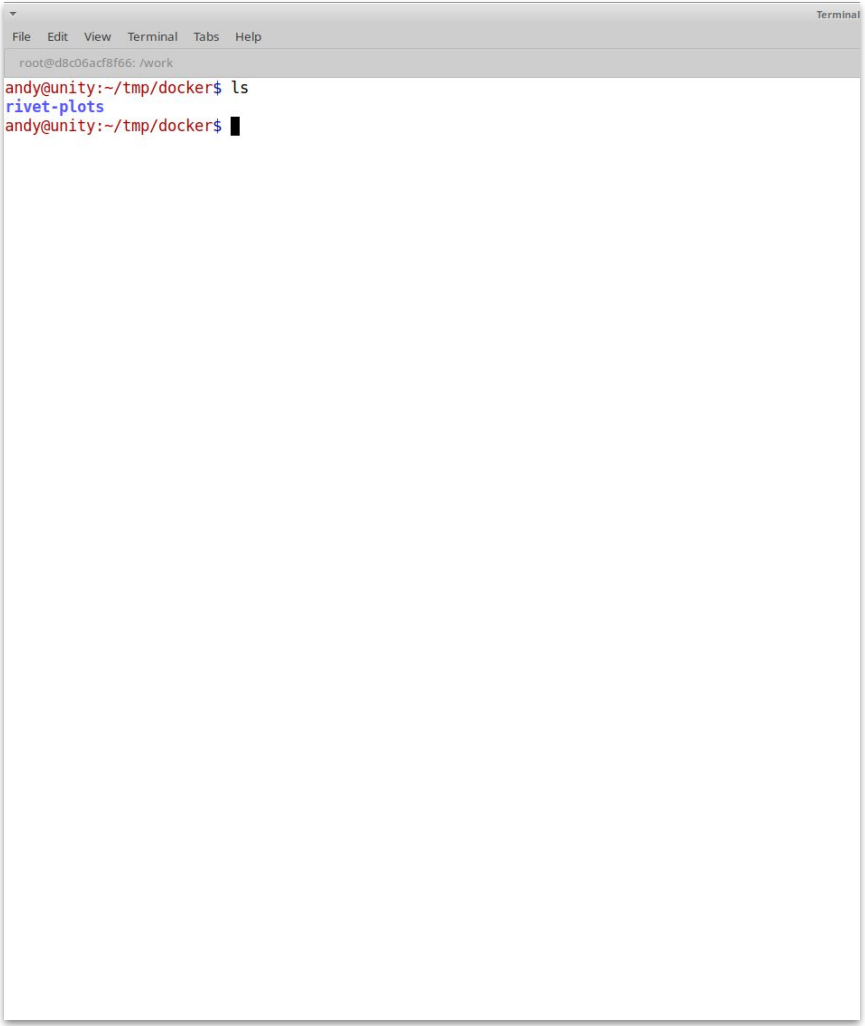
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



Getting & using Rivet

Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!

Getting & using Rivet

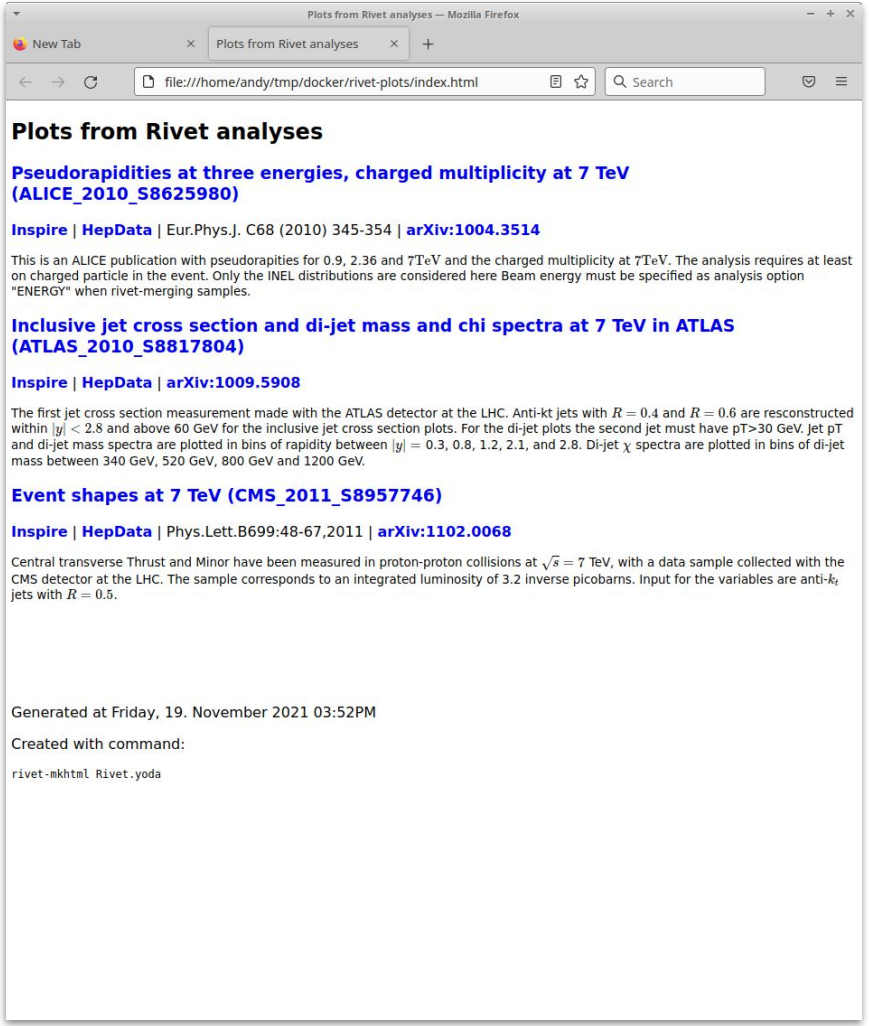
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



Getting & using Rivet

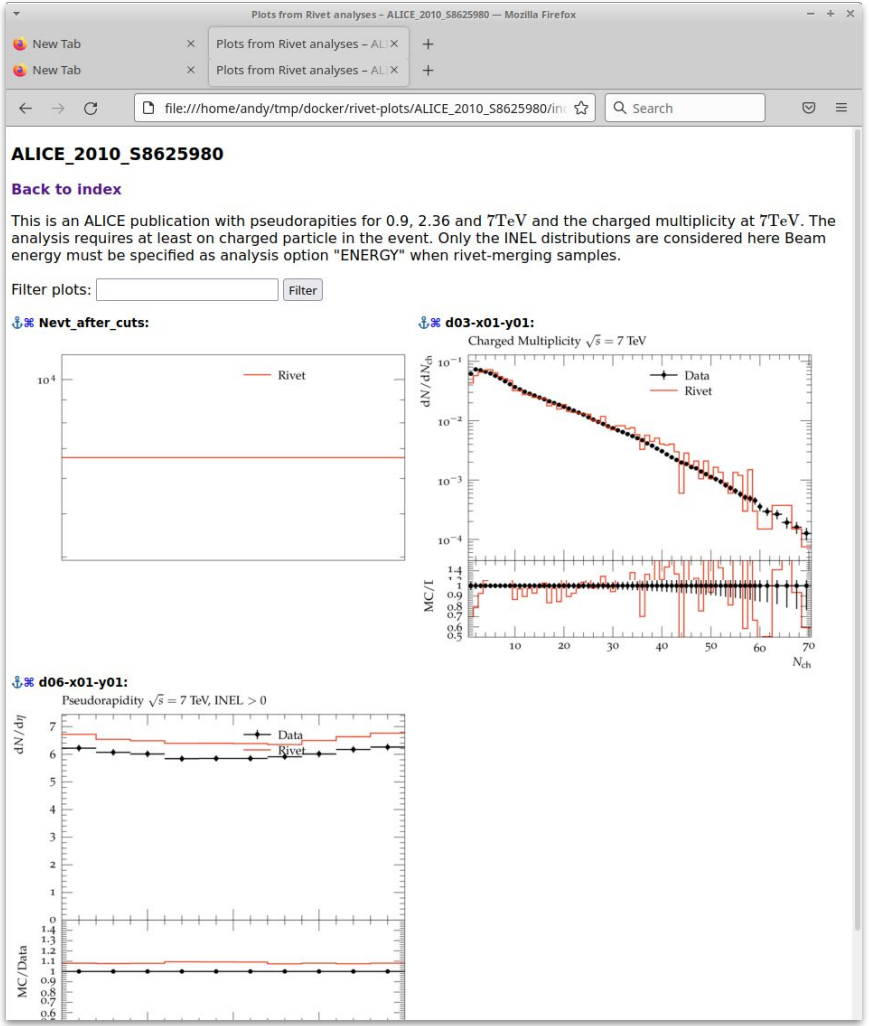
Lightweight analysis preservation is valuable… and easy to start

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

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



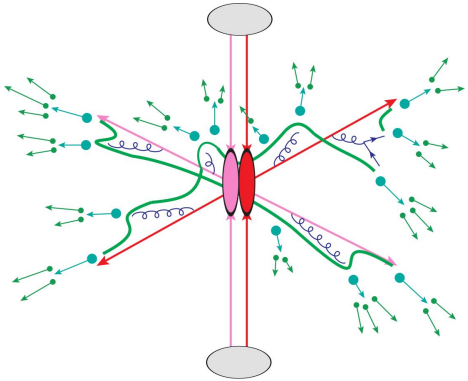
Summary / thoughts on engagement

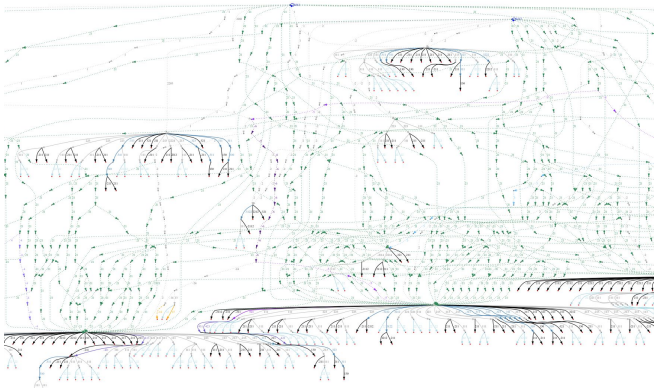
- **Rivet arose from HERA experiment/theory collabs. Code is a powerful conduit for constructive discussion.**
- **Preservation matters!**
- **Uptake by the LHC experiments: as "standard" as it gets**
  - But absolutely *not tied* to LHC!
- **An accelerator for analysis impact:** many exp/theory studies using Rivet as their common language. Impact on standards, e.g. event records, HepMC, weights…
- **Thoughts**:
  - Get junior scientists enthused, build vision/culture bottom-up
  - Build a rewarding expt-theory connection through MC analysis
  - Connect good community/science behaviour to career rewards via extra collaborative papers, studies, exposure

Backup slides

MC generation

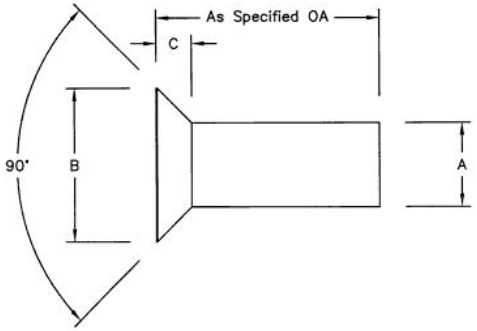
- **MC generation is where theory meets experiment**
  - The fundamental *pp, pA, AA* collision, *sans* detector
- **Components of an "exclusive" event-generator chain:**
  - QFT matrix element sampling at fixed-order in QCD
  - *Dressed* with approximate collinear splitting functions, iterated in factorised 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 hostage to shower MCs!**
  - The main mechanism for translating theory to experimental signatures, from QCD to BSM
  - Generally very complex modelling and output





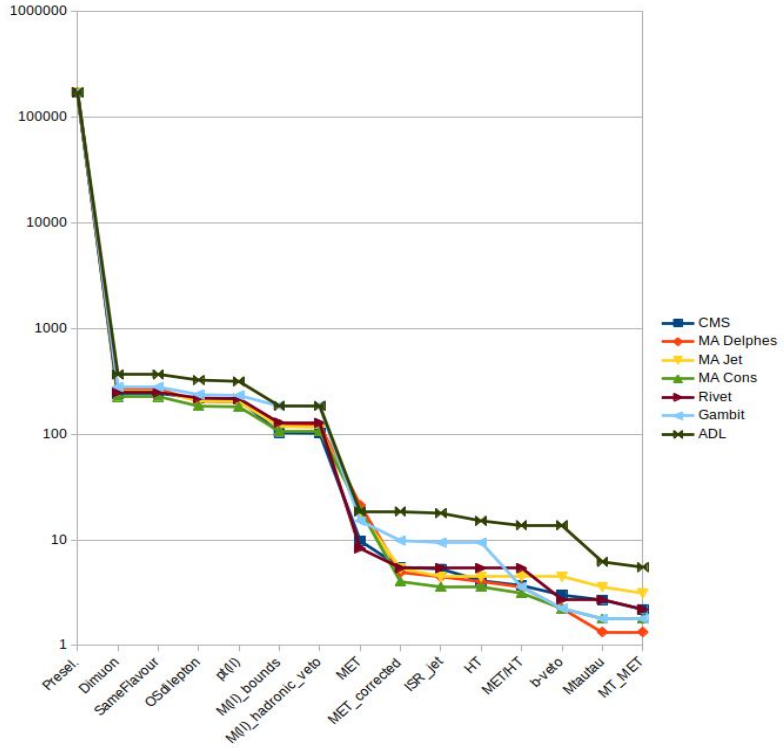
Designing Rivet

- **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
    - Note HepMC3 HI-support efforts
  - Analysis routines factorised: loaded as “plugins”
- **Efficient**
  - Avoid recomputations via “projection” caching system
- **Physical**
  - **Measurements primarily from final-state particles only**



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
- **Extra capabilities can lead to novel studies**
  - new areas, collaborations, interested users…



Les Houches 2019 CMS soft-lepton recasting-tools comparison

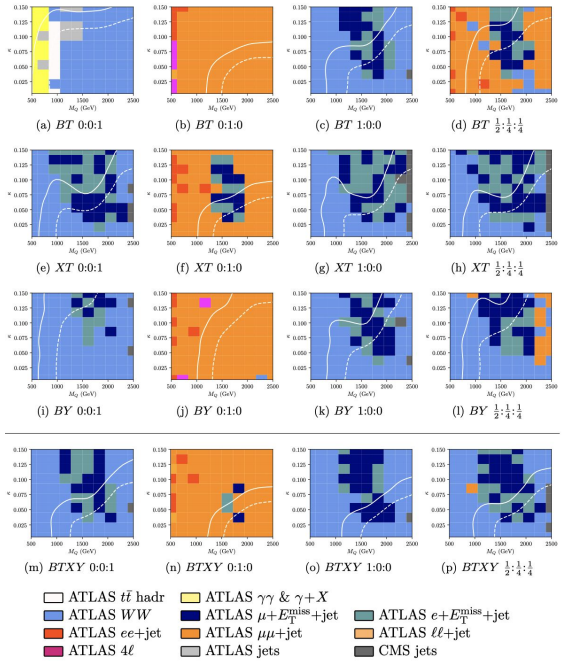
BSM from “Standard Model”

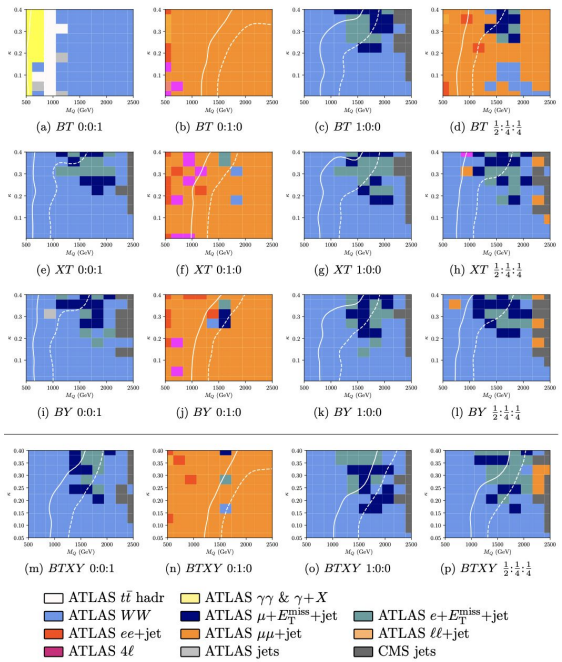
- **Not being focused on *direct* searches doesn’t mean no interest in BSM!**
- **Particle-level measurements *can* achieve high model-independence**
  - Careful definition of fiducial cross-section
  - Control distributions of “hidden variables” which are cut on
  - Reduce model sensitivity in unfolding
- **Rivet used directly in e.g.**
  - TopFitter top quark EFT fits;
  - at core of ATLAS *VH* EFT fits;
  - being integrated into Gambit global fits; and…
- **Contur is getting particular uptake**
  - Inject signal to “SM” measurements: if it’d be statistically distinct, the model is eliminated
  - Rivet gives huge coverage from “many angles”: views on not all, but most BSM signatures

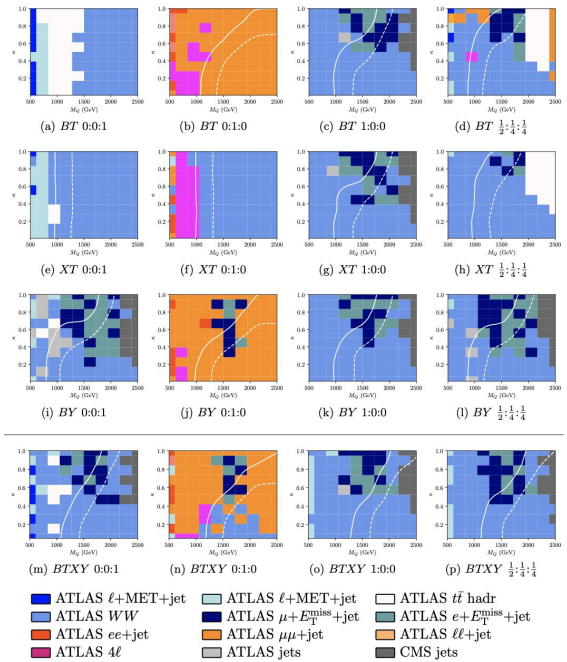
    a new result with Rivet code can be in Contur (or other) BSM fits within *hours*

Try doing this with full-sim recast in finite time…

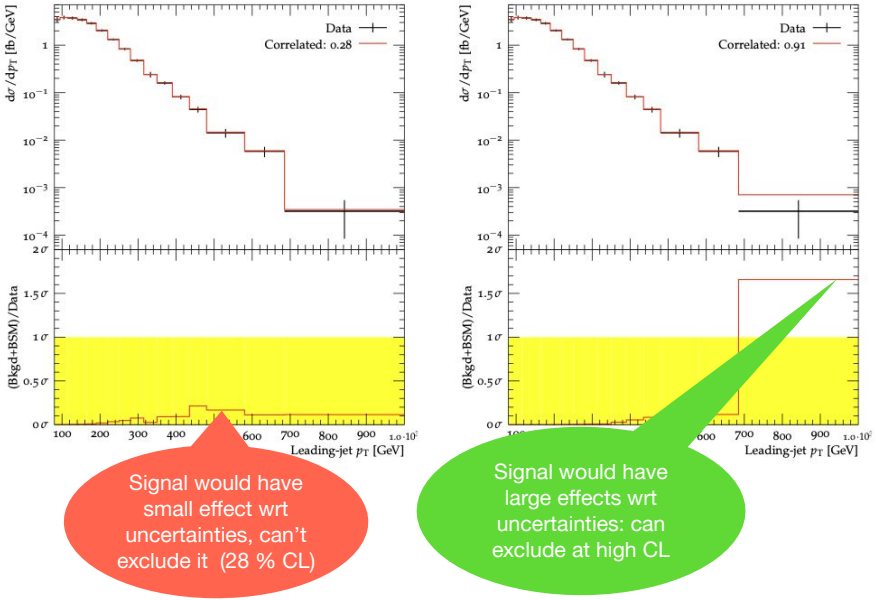
- Contur VLQ review requested a scan of realistic multiplets:
  - 7 multiplets, each with 3 generational couplings, each with 4 W/H/Z-couplings,
  - 300 points per scan, x 30,000 events ⇒ 750M events!







Contur

HT Louie Corpe

- **Contur is "just" a wrapper on Rivet**
  - Ok, not just! You need to know which analyses are "safe". Another reason for emphasis on final-states and *no cheating*
  - In absence of unambiguous BSM, make zeroth-order assumption that data = SM
  - Can be improved with high-precision SM theory predictions & uncertainties
  - Signal-injection ⇒ care with e.g. ratios & profiles… cf. Rivet "perfect merging"
  - Group analyses in stats-orthogonal "pools". Use (expected) most-constraining element in the pool for setting limits — use correlations when possible to make "bigger" elements
  -