Accelerating impact with Rivet

Analysis prototyping, preservation & re-interpretation

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Workshop on Neutrino Event Generators
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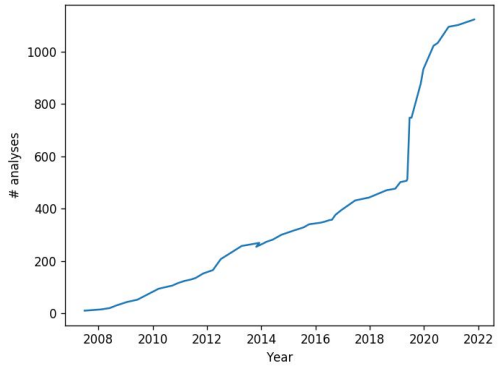
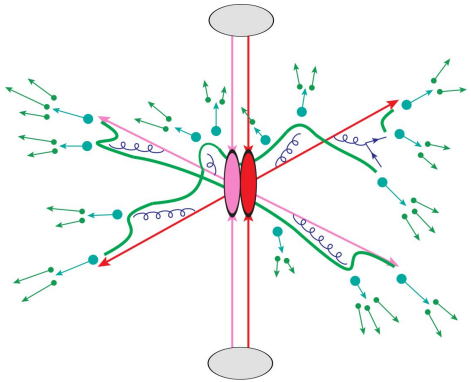
Rivet and neutrino physics?

- Honesty time: I'm not really here to "sell" Rivet to you for neutrino physics studies. It hasn't been a focus for us *at all!*
- (Not to say that it mightn't be useful, or have features that will become useful for neutrino MC studies… you are very welcome to try, and we'll help.)
- But I will explain some of the history of how we designed, re-designed, (etc.), and built a successful MC data-analysis and data-reinterpretation community at the LHC
- Hopefully this will turn out to be transferable expertise, and you can save some "not invented here" re-learning time
- But also, USE RIVET, obviously ;-)

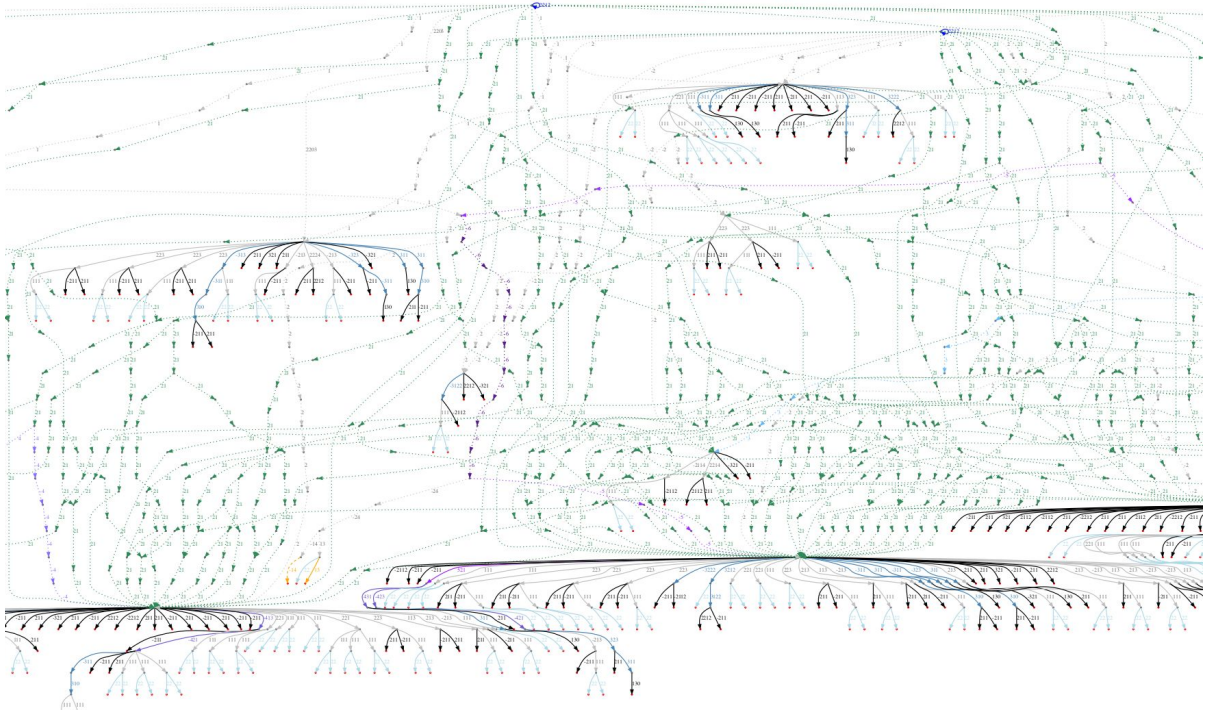
What is Rivet?

- **The "LHC standard" MC analysis toolkit**
- **More broadly a project to preserve the logic of HEP data analyses and further expt-pheno collaboration**
  ⇒ the MCnet CEDAR meta-goal
- **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? Event loops are trivial…**



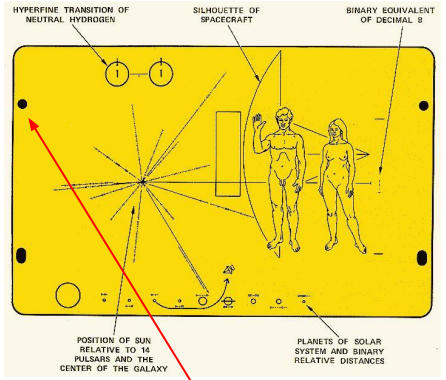


Because of this:



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

Lessons learned

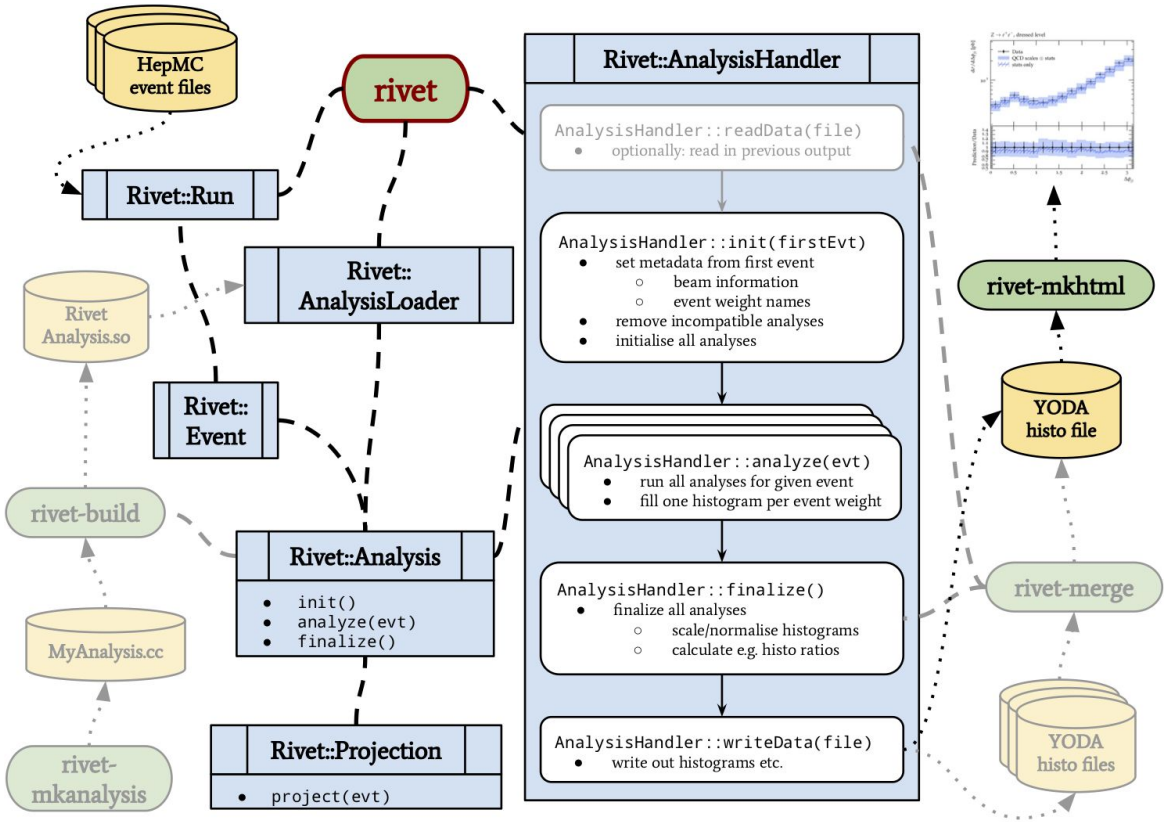


- **A simple/obvious idea, with surprising impact:**
  - **Reproducing a key plot (or not) is *powerful***
    - ⇒ *understand physics, communicate issues, improve MCs*
  - **A *common language* for phenomenology and experiment**
- **But…**
  - "Obvious" to use partons, bosons, etc. direct from the event 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

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)



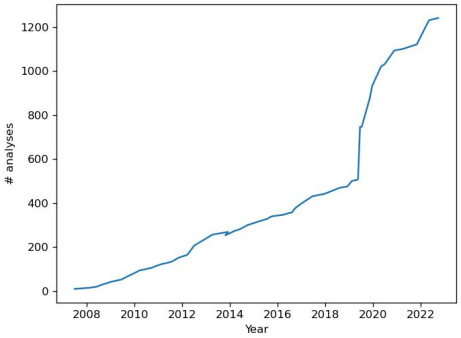
The state we're in

- **Version 3.1.7 (Oct 2022) ⟶ 1200+ analyses!**

  A steady 50/yr flow of analysis submissions, plus occasional deluges from MC gen teams

  ⇒ v3.1.8 imminent,

  ⇒ new major v3.2 asap

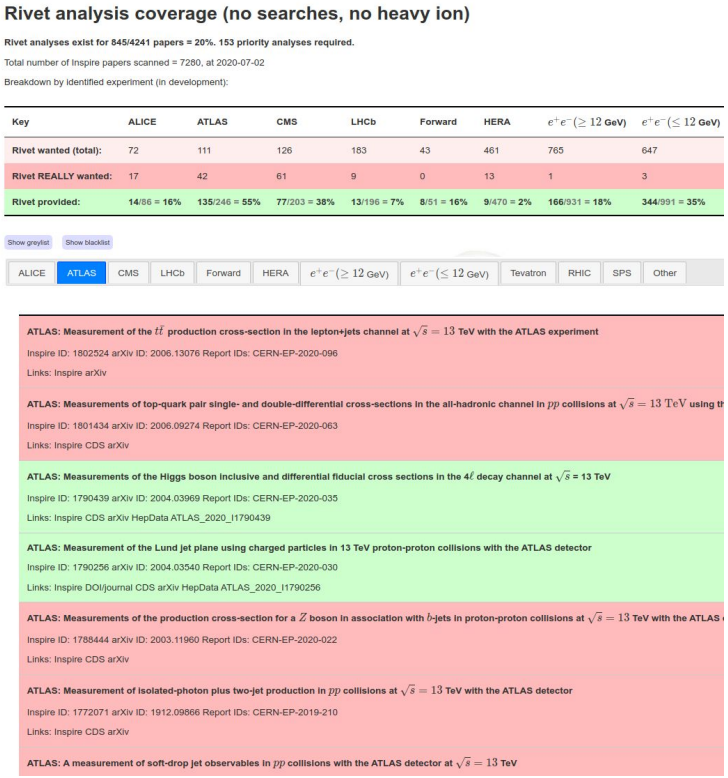


- **Official support from the (LHC) experiments is crucial**

  preservation = standard part of "how we do science", but still imperfect! We monitor paper coverage ⇒

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

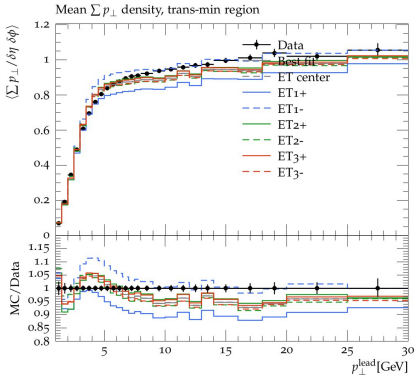
  systematics multiweights, "perfect merging", heavy ions, detector smearing functions, analysis options

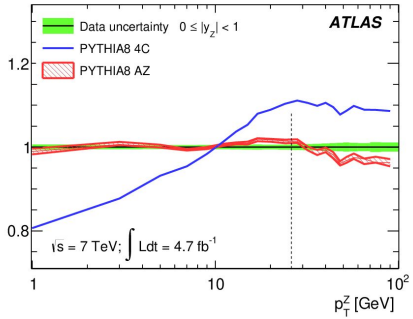


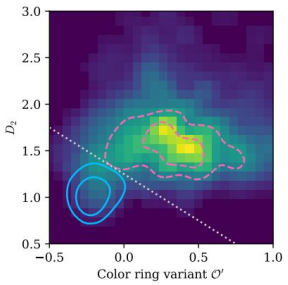
Applications: from tuning to…

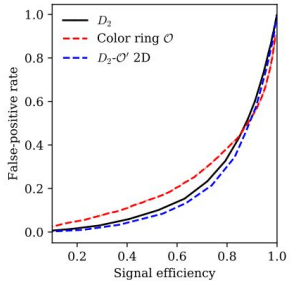
***First* "killer app": huge pre-LHC soft-QCD uncertainties:**

- **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… *(and GENIE tuning!)*
    - ⇒ 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



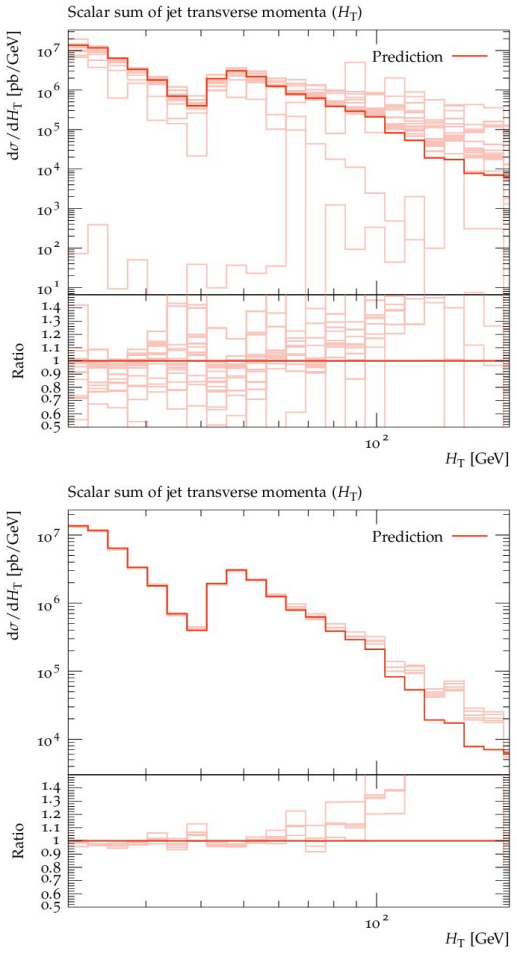






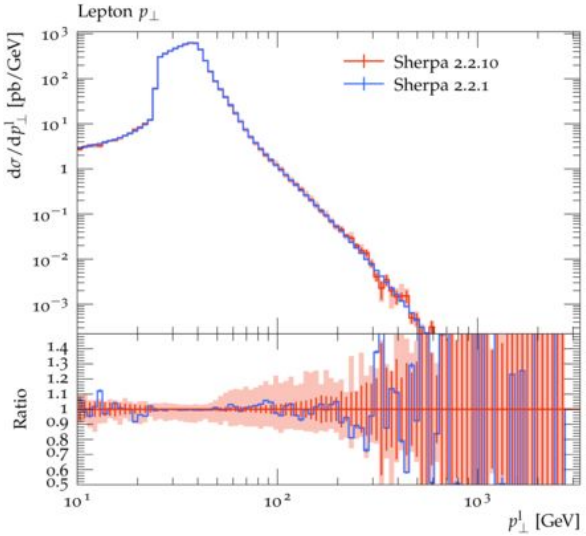
Multiweights and re-entry

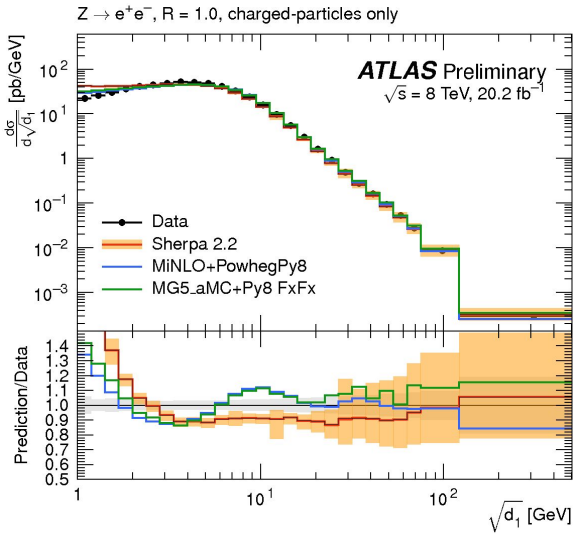
- **MC weight vectors allow expression of increasingly complex theory uncertainties.** But a burden for analysis chains: have to propagate and correctly combine O(200) weight streams!
- **Rivet 3: complex automatic handling of weights**
  ~invisible to users: data objects *look* like histograms etc. 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

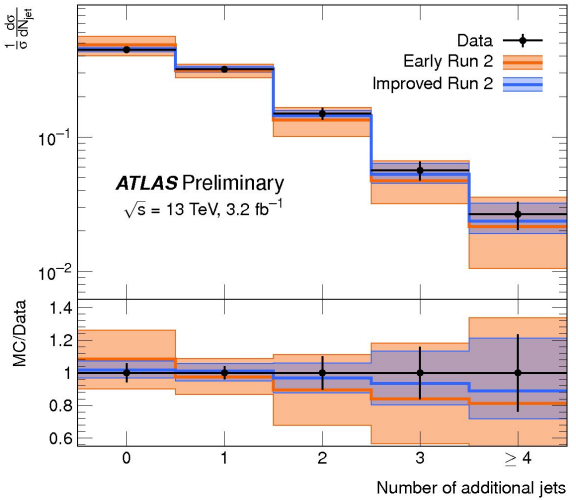


MC systematics bands via multiweights

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



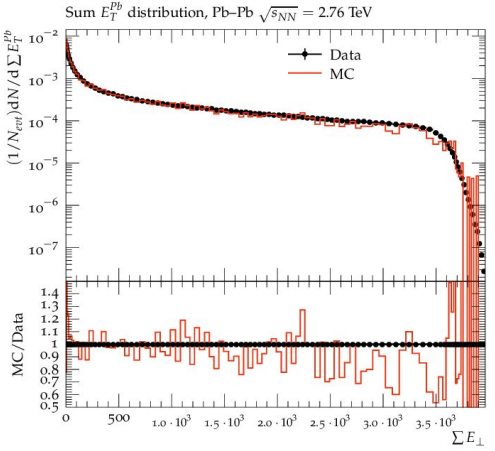


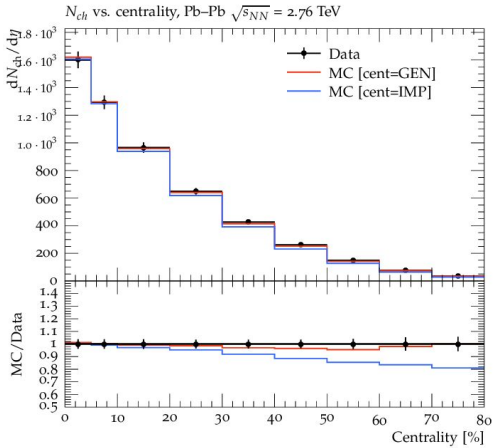


- Weight-naming standardisation: see arXiv:2203.08230

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
- HI experience ⇒ updated *pp* primary particle defns





HI *community engagement*

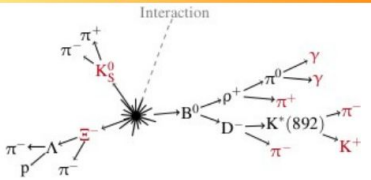
- **Great "spontaneous" engagement from within HI. Several productive workshops**

Summary

1. Data getting into HEPData

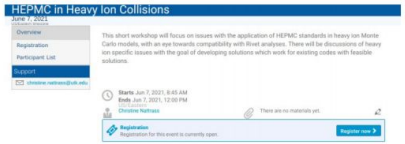
2. Build your own undergraduate army

3. Primary particle definition



4. Validation Procedure

5. HEPMC output may have some issues



https://indico.bnl.gov/event/10966/

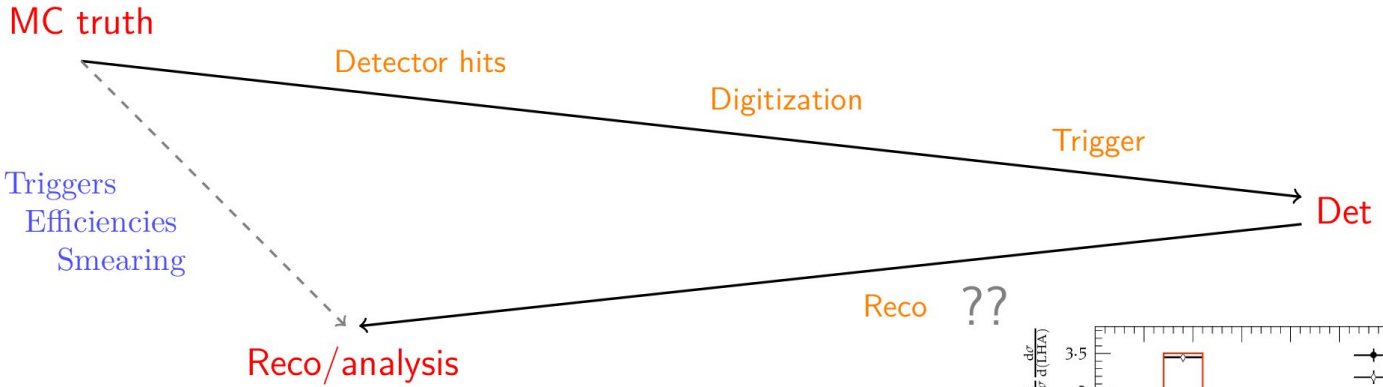
Christine Nattrass, University of Tennessee, Knoxville, HF-QGP Rivet 2021

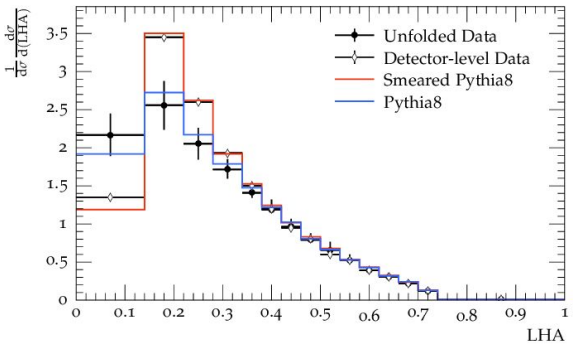
- HepData, Rivet
- Better ex/ph communication
- Faster model/data comparisons
- Addressing issues with formats and incomplete models
- Undergrad army!

Could this work in neutrino physics?

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"

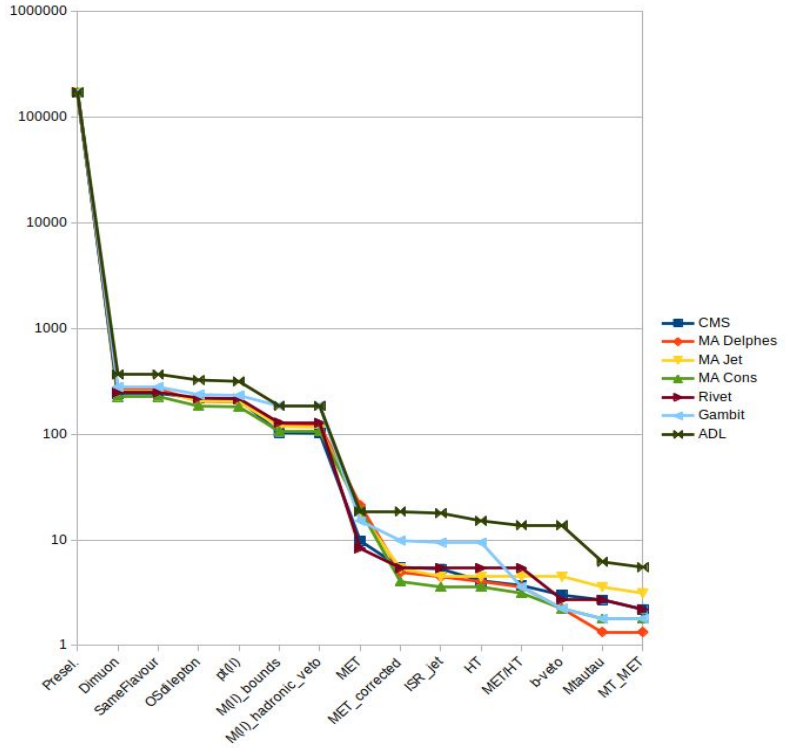




  - like Delphes, but more flexible & can be *analysis-specific* ⇒ MA5 "SFS" mode
  - flexibility allows e.g. "tuned" jet-substructure smearing, systematics studies, …

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

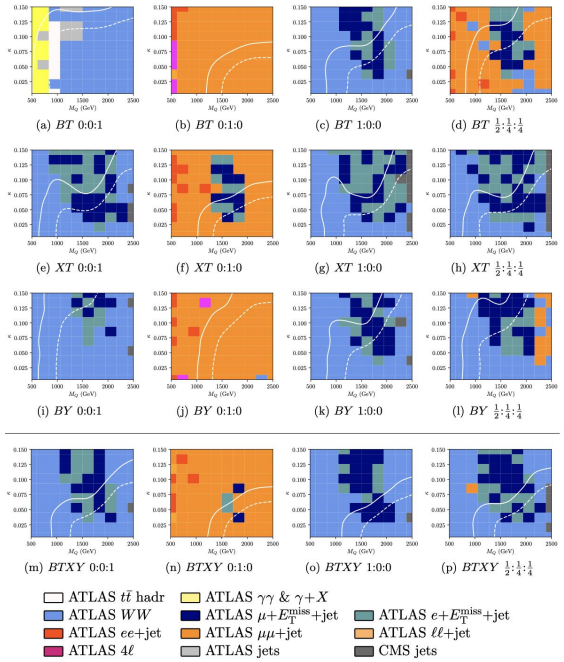
BSM from “Standard Model”

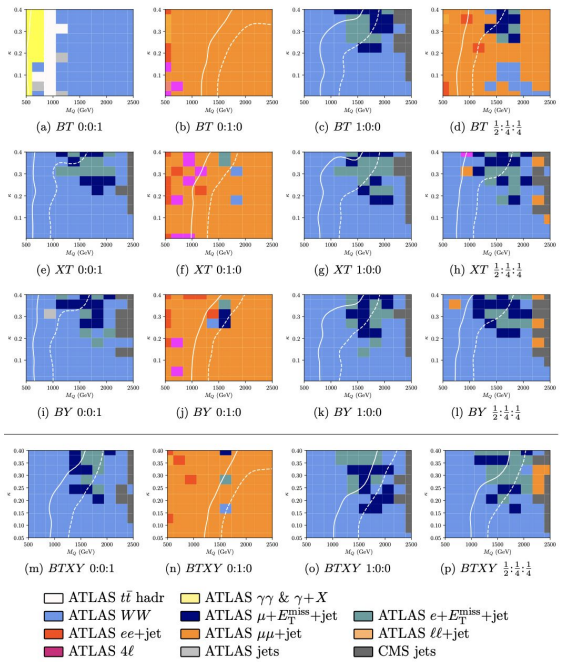
- **Not being focused on *direct* searches doesn’t mean no interest in BSM!**
- **Particle-level measurements *can* achieve high model-independence**
  - Careful definition of fiducial cross-section
  - Control distributions of “hidden variables” which are cut on
  - Reduce model sensitivity in unfolding
- **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

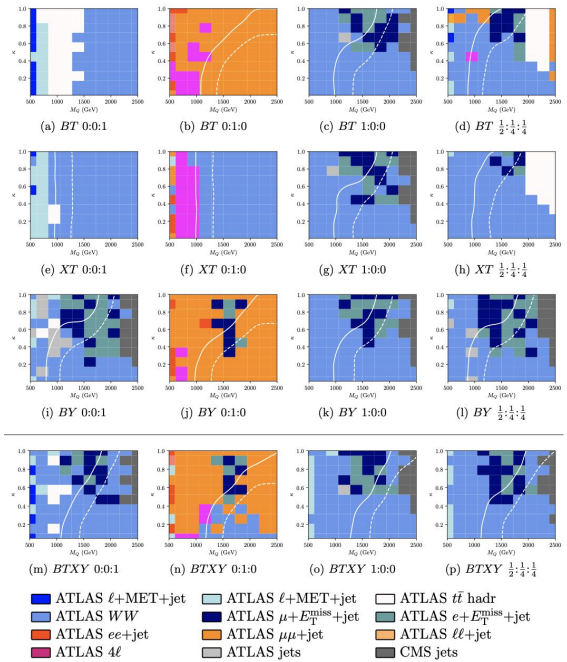
    a new result with Rivet code can be in Contur (or other) BSM fits within *hours*

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!







The future of Rivet

- **Vision: Rivet as a standard for "truth-level" observables, across (collider) physics**
  - ➢ Already used this way inside CMSSW truth definitions 🤯
- Eyes on future colliders, including EIC and nuclear physics, cosmic-ray air showers, … and neutrinos? 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.
- 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

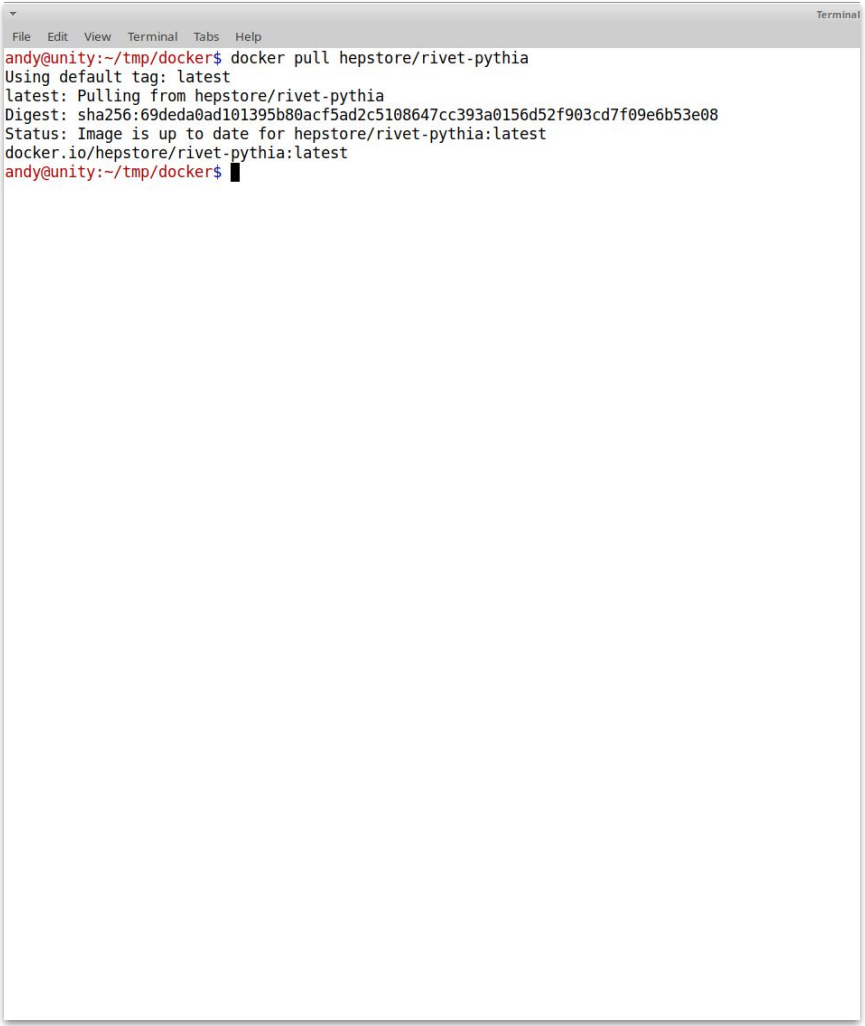
Lightweight analysis preservation is valuable… and easy to start

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!



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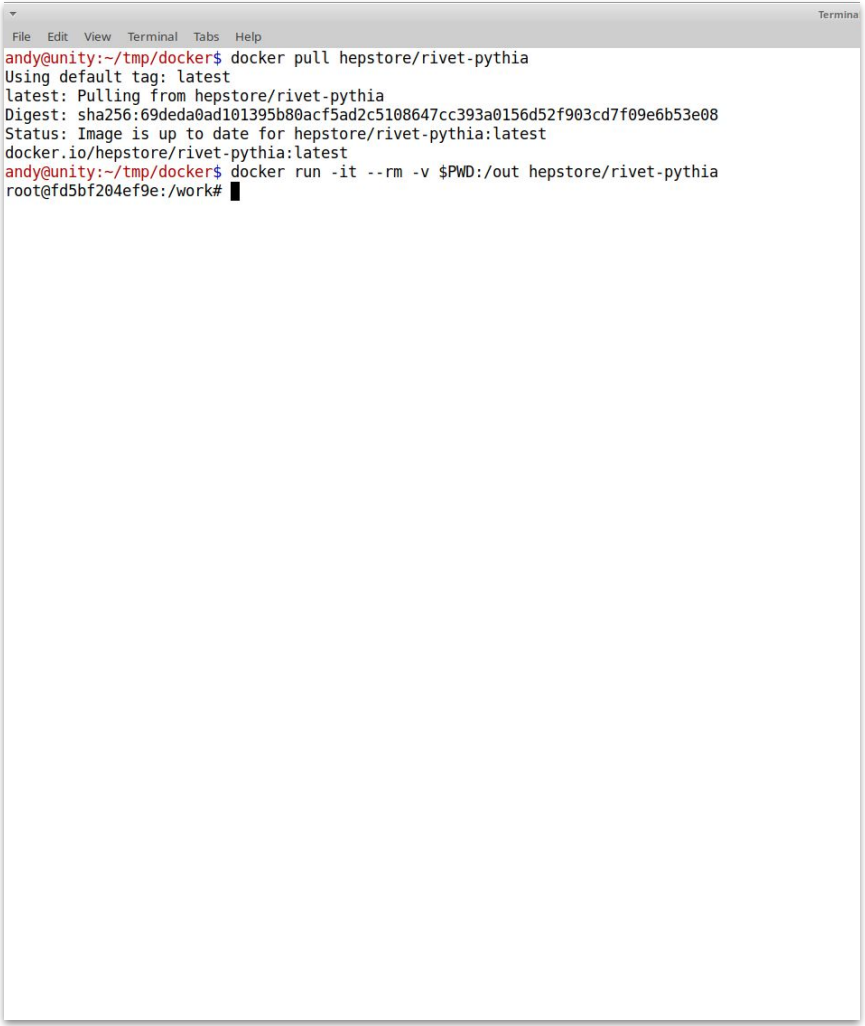

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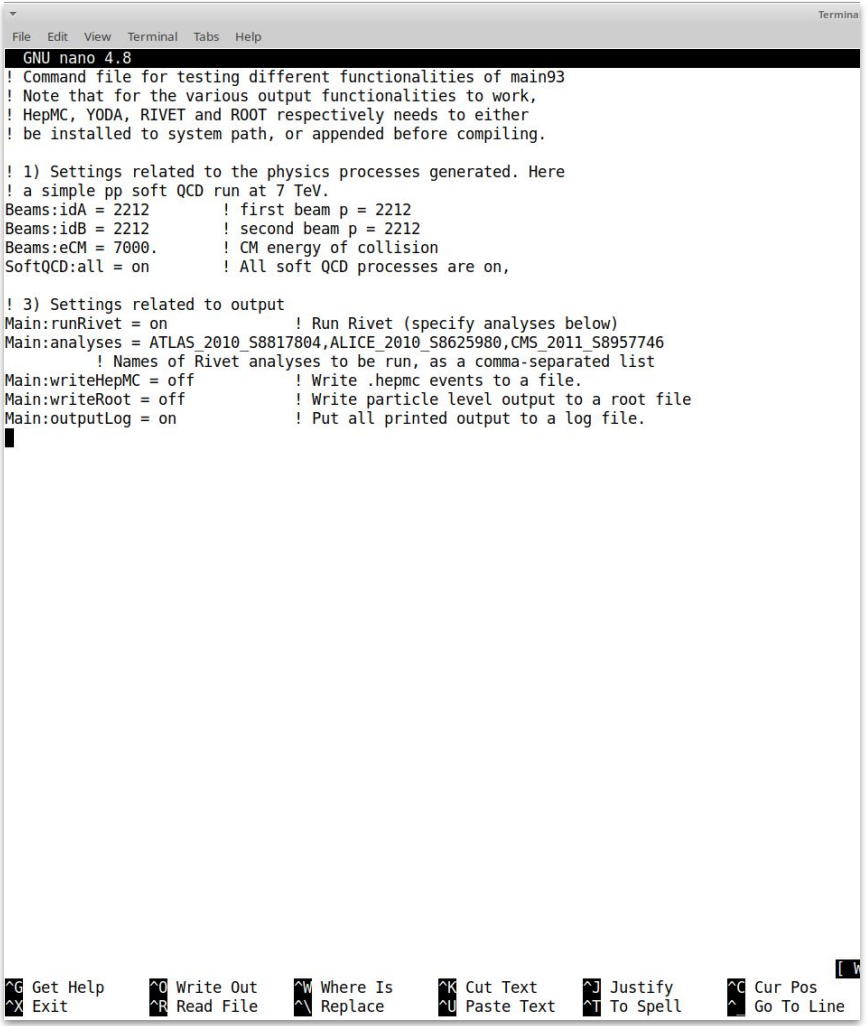

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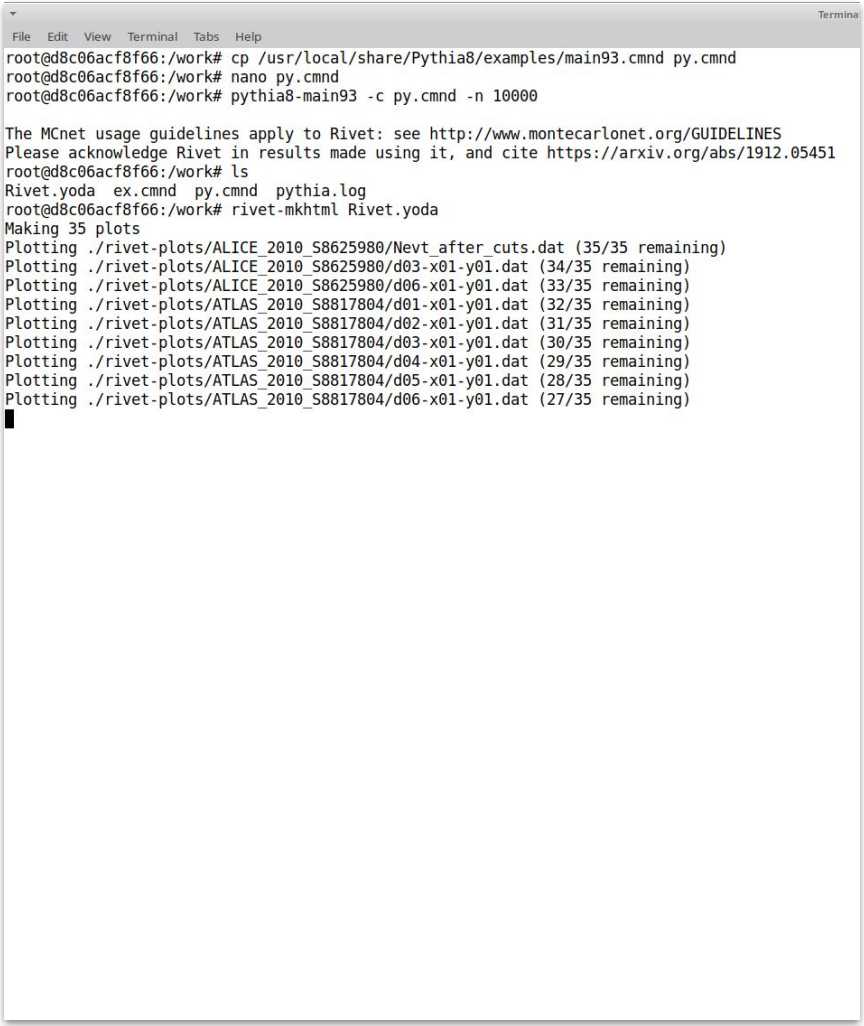

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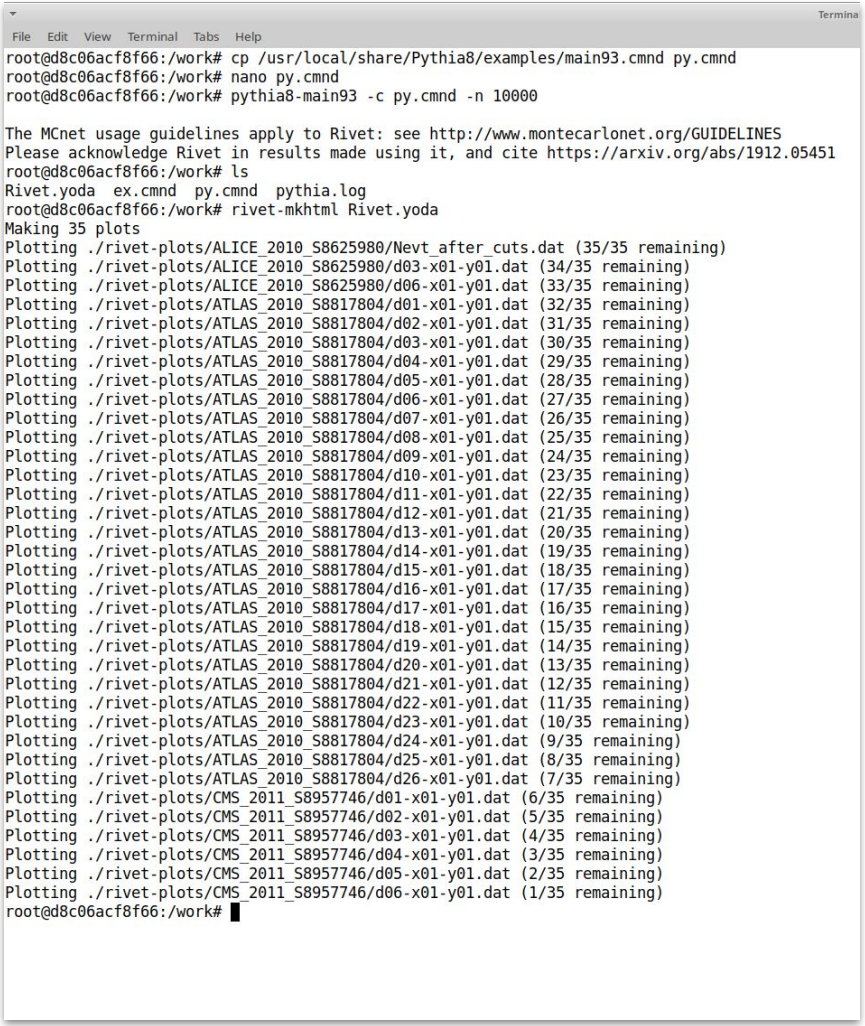

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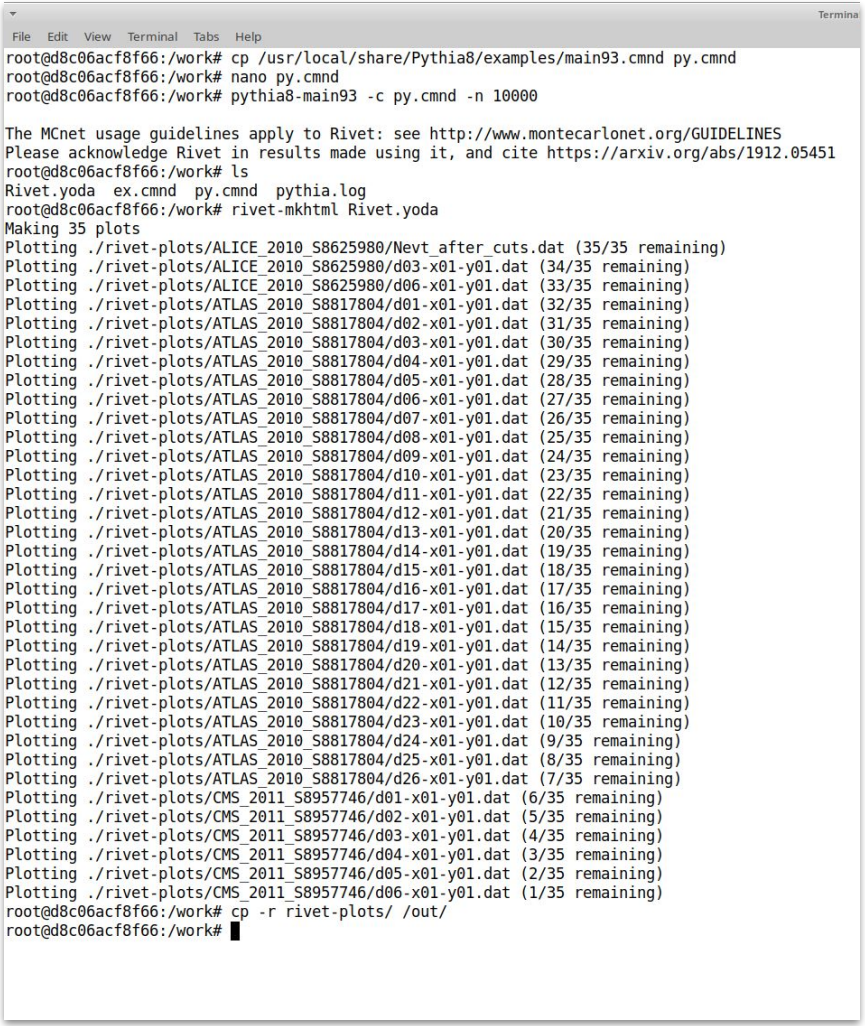

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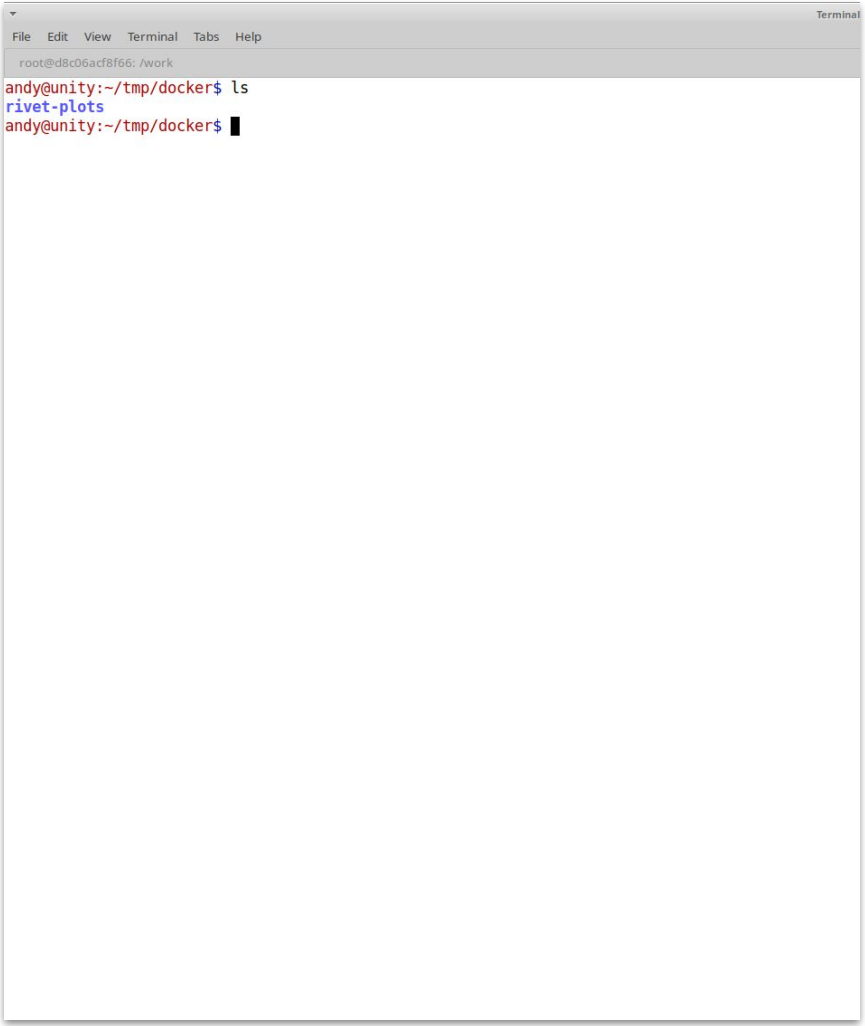

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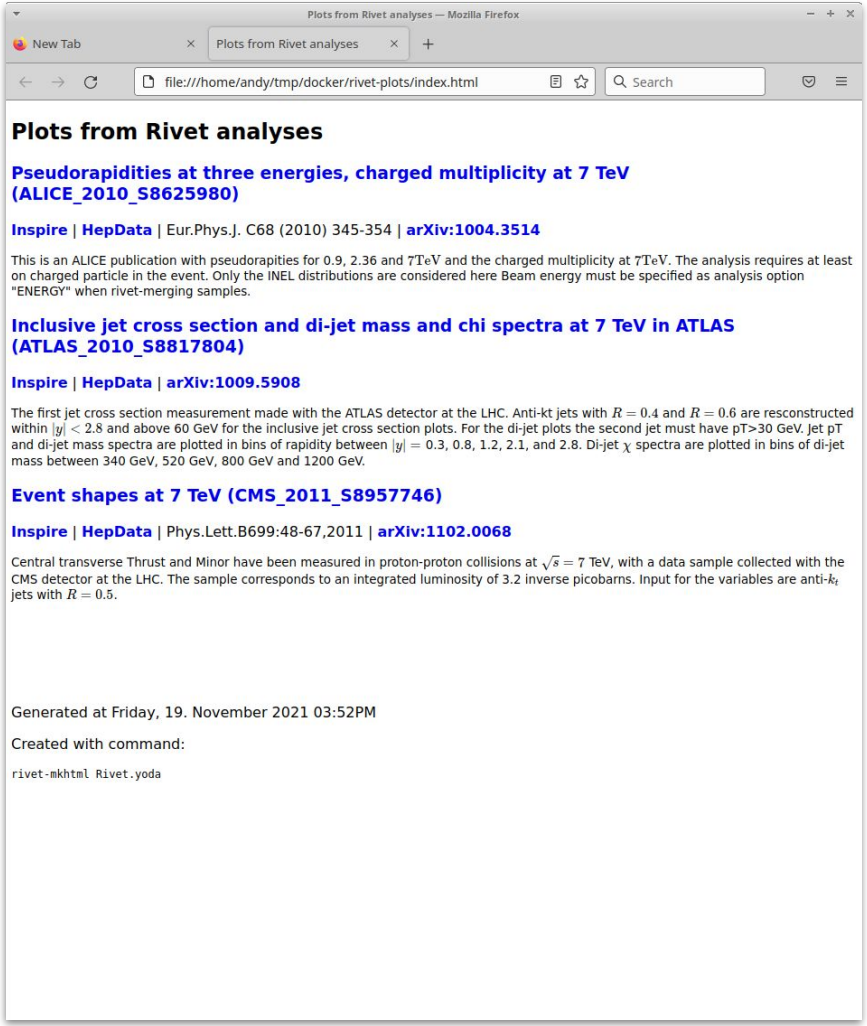

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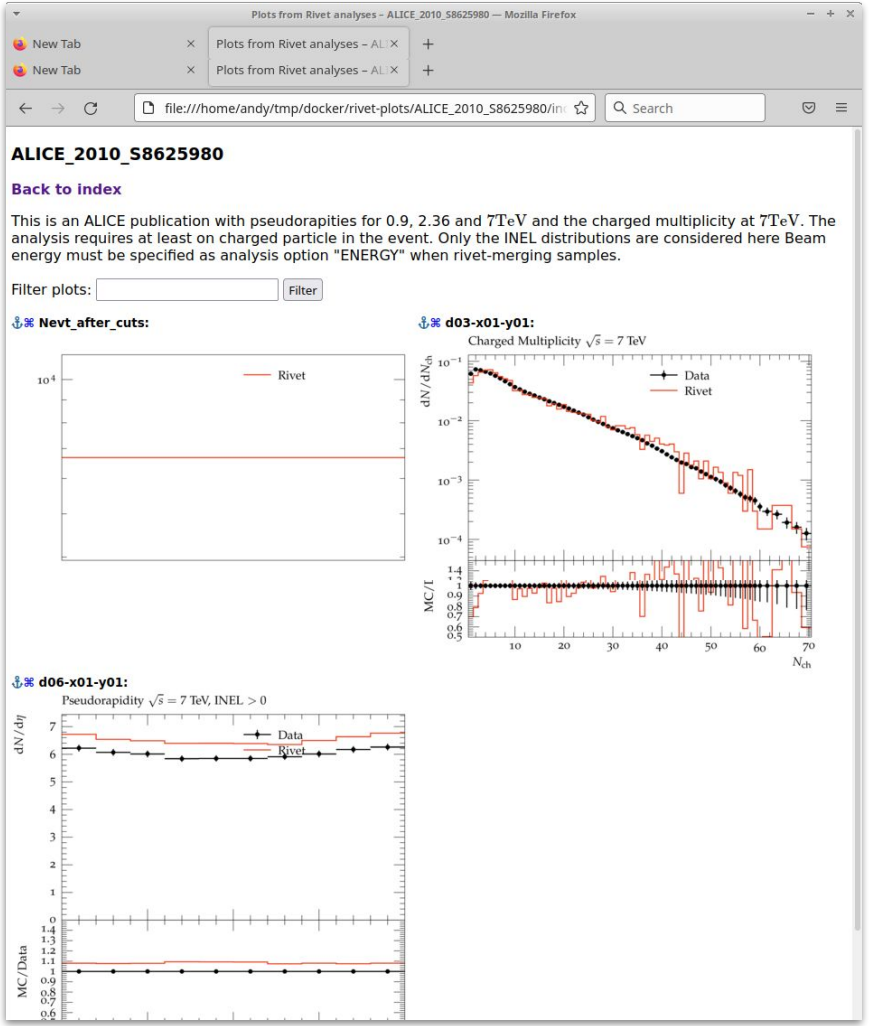


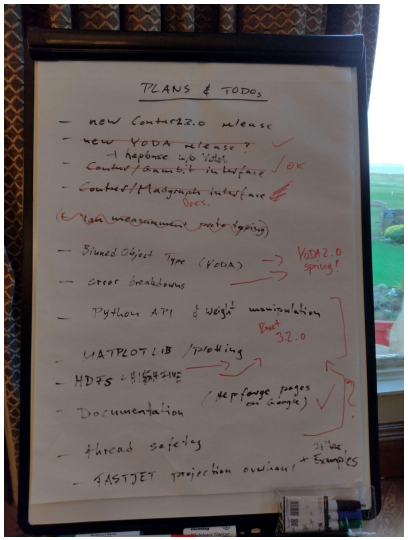
Summary / thoughts on engagement

- **Rivet arose from HERA experiment/theory collabs. Code is a powerful conduit for constructive discussion.**
- **Uptake by the LHC experiments: as "standard" as it gets**
- **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
  - *Do* sweat UI details: make the expt-theory connection through MC analysis a fun, physics-focused experience
  - Take long-term impact and re-use of analyses seriously
  - Connect good community/science behaviour to career rewards via extra collaborative papers, studies, exposure

Backup slides

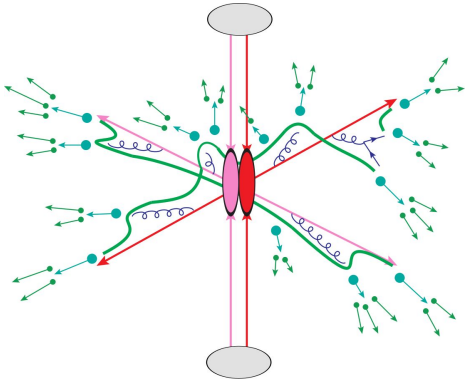
Practical tasks and challenges

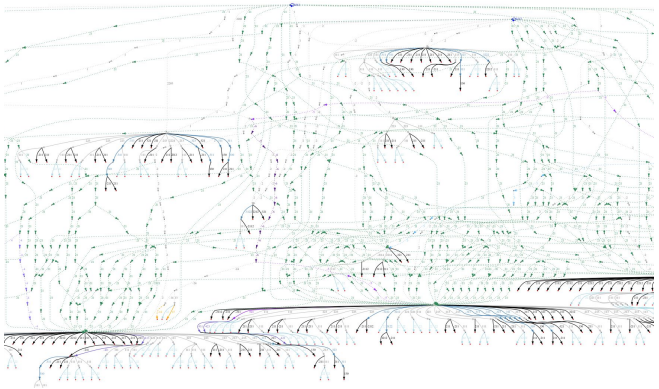
- **Tasks:**
  - Extension of HepData and other community infrastructure for ever-more precise data. Even our compressed data format is struggling with the volume of analyses and data
    GSoC+follow-up on generalised binned containers, static/dynamic object distinction, and multiweight-oriented data formats (HDF5)
  - Improved, modernised visualisation and exploration
    ⇒ matplotlib GSoC+follow-up to make public
  - Preserving MVAs: BDT and NN in vanilla C++? Or avoid?
- **Challenges:**
  - So much progress has happened at/because of in-person developer workshops ⇒ Covid had a big impact. Events in Dec 2020 and more recently have re-invigorated developments
  - Need to find ways to continue this without MCnet funding…



MC generation

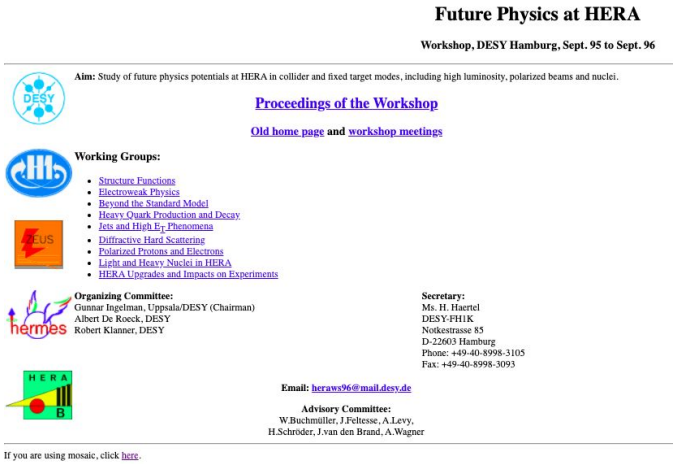
- **MC generation is where theory meets experiment**
  - The fundamental *pp, pA, AA* collision, *sans* detector
- **Components of an "exclusive" event-generator chain:**
  - QFT matrix element sampling at fixed-order in QCD
  - *Dressed* with approximate collinear splitting functions, iterated in factorised 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





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

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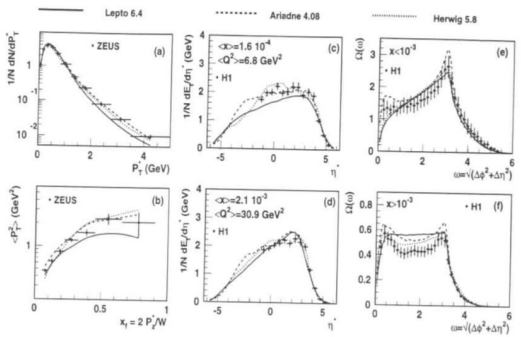
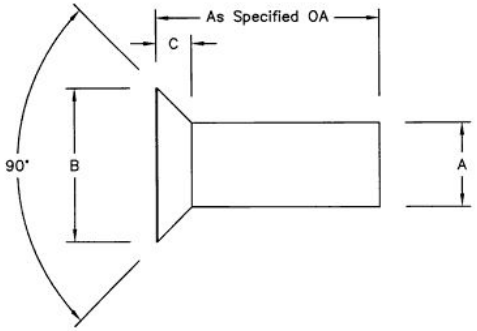


Figure 1: *The transverse momenta dN/dp_T (a) and the 'seagull' plot $\langle P_T^2 \rangle \times x_F$ (b) of single particles in the positive hemisphere of the hadronic center of mass. The transverse energy flow $dE_T/d\eta$ in a low (c) and high (d) x and Q^2 bin. The transverse energy-energy correlations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

Designing Rivet

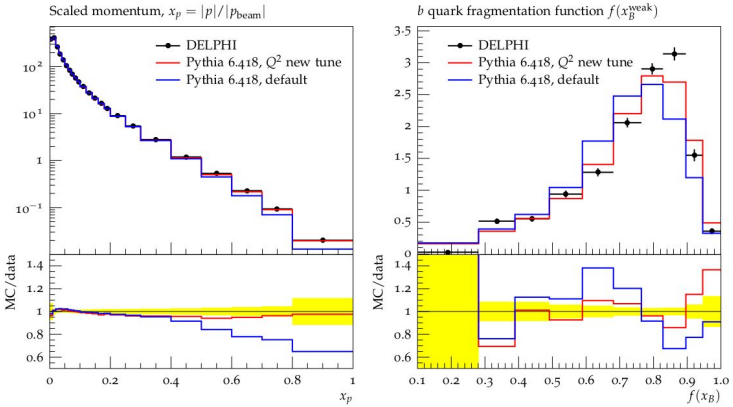
- **Ease of use**
  - **Big emphasis on “more physics, less noise”!**
  - Minimal boilerplate analysis code, HepData sync
  - Event loop and histogramming basically familiar
  - Tools to avoid having to touch the raw event graph
- **Embeddable**
  - OO C++ library, Python wrapper, sane user scripts
  - 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**

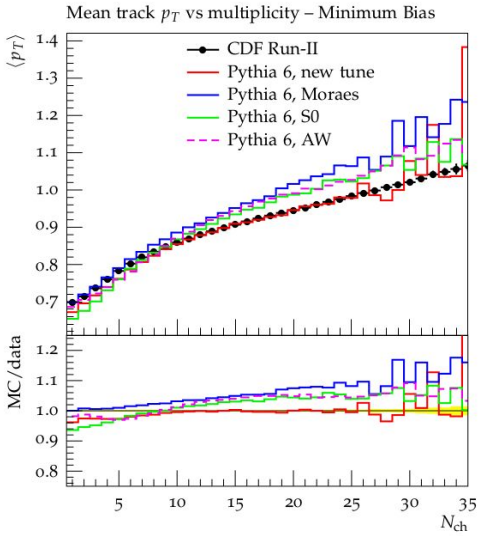


Event-generator tuning

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 param space… and then the argument is over
- **The "Professor" tunes, 2008; and…**

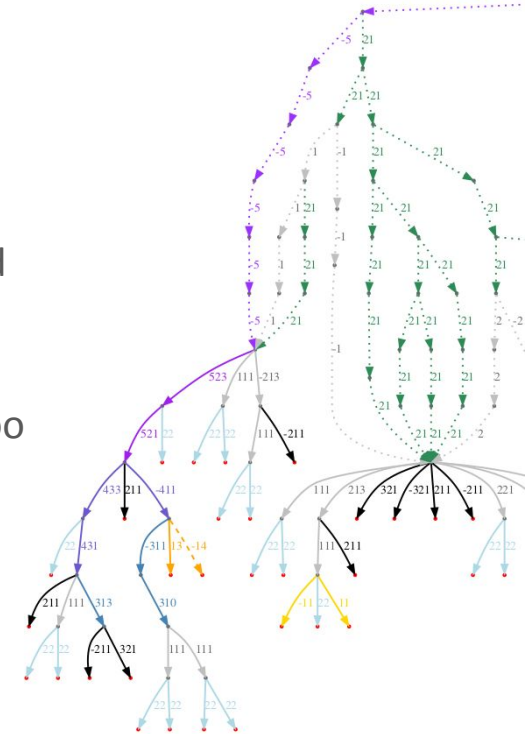




Physically safe analysis methods

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



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
  -