Reinterpretation of current and future measurements

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What is reinterpretation?

- **First interpretation:** physics conclusions drawn from data observables in the experimental-analysis paper
  - Often models the analysis was *designed* to be sensitive to
- **Reinterpretation:** re-use of analysis data to draw conclusions about physics models it *wasn't* designed for
- **I.e. doing science!** Unclear why it has a special name…
- Borderline experiment/theory activity, vibrant collaborations across soft boundaries, e.g. [LHC Reinterpretation Forum]
- **Key to getting most science from our facility investment**
  - **Sustainability:** max physics/tCO_2 ⇒ **analysis life does not end with publication; data re-usability maximises long-term impact**


CERN-LPCC-2020-001, FERMILAB-FN-1098-CMS-T, Imperial/HEP/2020/RIF/01

Reinterpretation of LHC Results for New Physics: Status and Recommendations after Run 2

We report on the status of efforts to improve the reinterpretation of searches and measurements at the LHC in terms of models for new physics, in the context of the LHC Reinterpretation Forum. We detail current experimental offerings in direct searches for new particles, measurements, technical implementations and Open Data, and provide a set of recommendations for further improving the presentation of LHC results in order to better enable reinterpretation in the future. We also provide a brief description of existing software reinterpretation frameworks and recent global analyses of new physics that make use of the current data.

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Reinterpretation tools

- **Several main tools "on the market".** Rivet+Contur, MadAnalysis, SModelS, GAMBIT, CheckMATE
- **All "lightweight" analysis preservation/reuse approaches**
  - **SModelS** reinterprets search data direct from published simplified-model sensitivity maps
  - Others implement event loops, logic and simplified detector-effect modelling
  - **GAMBIT** tries to do everything: EW precision, flavour, astro, cosmo, … collider as last resort
  - **CheckMATE** has ~focused toward tests of long-lived particle models, via efficiency maps
  - By familiarity, I have to focus on "MC gen" collider-reinterpretation today

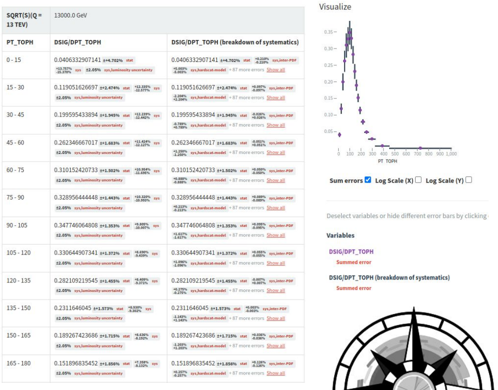
Reinterpretation tools (2)

- **Main data-source is HEPData.** Standard for LHC, less beyond
  - ➢ Stores numerical "primary data", i.e. histograms, event counts in signal regions, errors & correlations
  - ➢ Also "new" push to store experiments' theory estimates, especially super-expensive precision SM backgrounds

- **Statistical models:** HEPData, pyhf, Spey, HS3, (TACO) + ONNX
  - ➢ HEPData becoming more semantically aware of aux-file meanings: ability to query available resources (OpenMAPP)

- **Also "full-detail" analysis preservation** and reinterpretation using Docker/etc. containers: RECAST/Reana
  - ➢ See following talk by Nicole Skidmore

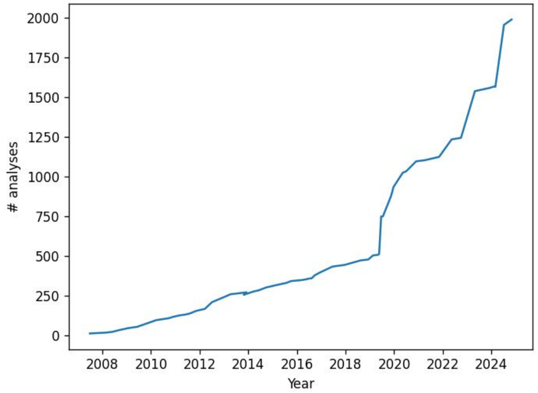
- **Focus here on Rivet**, for (my) familiarity but most ideas apply generally; different tools ⇒ different focuses

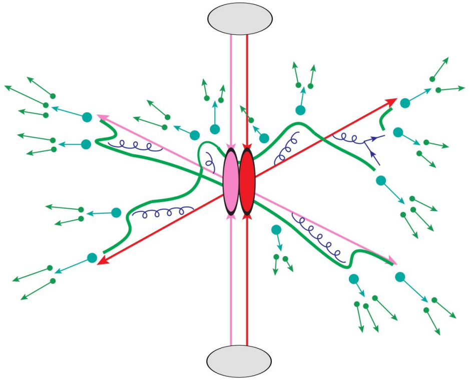


SQRT(S)(Q = 13 TEV)	13000.0 GeV	
PT_TOPH	DSIG/DPT_TOPH	DSIG/DPT_TOPH (breakdown of systematics)
0 - 15	0.0406332907141 ±+4.702% stat; +13.757% -15.370% sys; ±2.05% sys,luminosity uncertainty	0.0406332907141 ±+4.702% stat; +0.210% -0.210% sys,inter-PDF; +5.003% -5.003% sys,hardscat-model + 87 more errors Show all
15 - 30	0.119051626697 ±+2.474% stat; +12.335% -12.577% sys; ±2.05% sys,luminosity uncertainty	0.119051626697 ±+2.474% stat; +0.097% -0.097% sys,inter-PDF; -2.204% +2.204% sys,hardscat-model + 87 more errors Show all
30 - 45	0.199595433894 ±+1.945% stat; +12.239% -12.442% sys; ±2.05% sys,luminosity uncertainty	0.199595433894 ±+1.945% stat; -0.026% +0.026% sys,inter-PDF; -0.789% +0.789% sys,hardscat-model + 87 more errors Show all
45 - 60	0.262346667017 ±+1.683% stat; +11.424% -12.127% sys; ±2.05% sys,luminosity uncertainty	0.262346667017 ±+1.683% stat; -0.051% +0.051% sys,inter-PDF; +1.250% -1.250% sys,hardscat-model + 87 more errors Show all
60 - 75	0.310152420733 ±+1.502% stat; +10.954% -11.695% sys; ±2.05% sys,luminosity uncertainty	0.310152420733 ±+1.502% stat; +0.050% -0.050% sys,inter-PDF; +0.888% -0.888% sys,hardscat-model + 87 more errors Show all
75 - 90	0.328956444448 ±+1.443% stat; +10.320% -10.993% sys; ±2.05% sys,luminosity uncertainty	0.328956444448 ±+1.443% stat; +0.089% -0.089% sys,inter-PDF; +0.213% -0.213% sys,hardscat-model + 87 more errors Show all
90 - 105	0.347746064808 ±+1.353% stat; +9.805% -10.007% sys; ±2.05% sys,luminosity uncertainty	0.347746064808 ±+1.353% stat; +0.095% -0.095% sys,inter-PDF; +1.617% -1.617% sys,hardscat-model + 87 more errors Show all
105 - 120	0.330644907341 ±+1.372% stat; +8.690% -9.439% sys; ±2.05% sys,luminosity uncertainty	0.330644907341 ±+1.372% stat; +0.055% -0.055% sys,inter-PDF; +1.096% -1.096% sys,hardscat-model + 87 more errors Show all
120 - 135	0.282109219545 ±+1.455% stat; +8.409% -9.371% sys; ±2.05% sys,luminosity uncertainty	0.282109219545 ±+1.455% stat; -0.007% +0.007% sys,inter-PDF; +0.275% -0.275% sys,hardscat-model + 87 more errors Show all
135 - 150	0.2311646045 ±+1.573% stat; +8.930% -9.302% sys; ±2.05% sys,luminosity uncertainty	0.2311646045 ±+1.573% stat; +0.003% -0.003% sys,inter-PDF; -1.143% +1.143% sys,hardscat-model + 87 more errors Show all
150 - 165	0.189267423686 ±+1.715% stat; +8.636% -8.192% sys; ±2.05% sys,luminosity uncertainty	0.189267423686 ±+1.715% stat; +0.036% -0.036% sys,inter-PDF; -1.203% +1.203% sys,hardscat-model + 87 more errors Show all
165 - 180	0.151896835452 ±+1.856% stat; +7.358% -8.132% sys; ±2.05% sys,luminosity uncertainty	0.151896835452 ±+1.856% stat; +0.126% -0.126% sys,inter-PDF; +0.257% -0.257% sys,hardscat-model + 87 more errors Show all

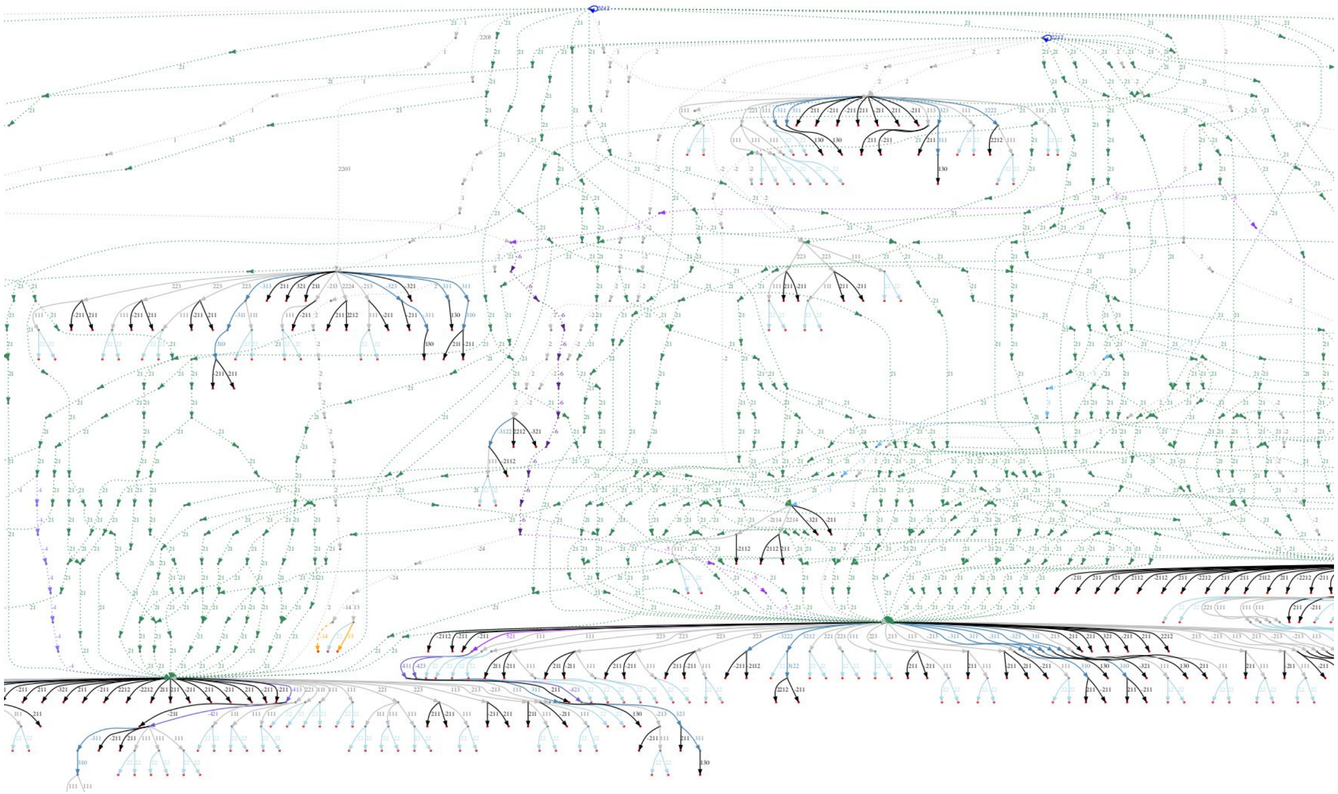
What is Rivet?

- ❖ **The “LHC standard” MC analysis toolkit**
- ❖ More broadly a project to preserve the logic of data analyses and encourage expt-pheno collaboration
- ❖ Package structure & key features:
  - ➢ C++ core with Python tools
  - ➢ Fiducial / generator-independence
  - ➢ Integration with HEPData
  - ➢ Automatic systematic-weights propagation
  - ➢ ~2000+ analyses written in “physicist C++”
- ❖ **Central to a community of analysis reinterpretation tools, linking experiment to theory**
- ❖ **But why? Event loops are trivial…**





Because “MC truth” events are not *true*!



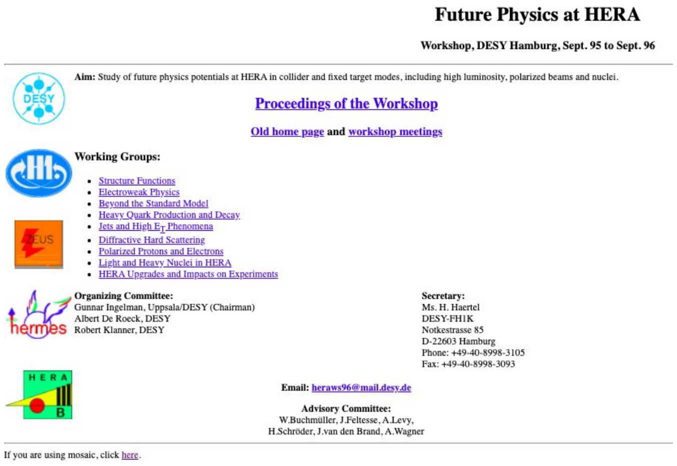
⇐ ~⅓ of an LO tt event

MC events are full of unphysical debug info, kinematic inconsistencies, *ad hoc* structures & representations, etc.!

Avoid physicists needing to rediscover graph algorithms, MC conventions, and 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"**
  - PPARC/STFC initiative, adopted by MCnet network



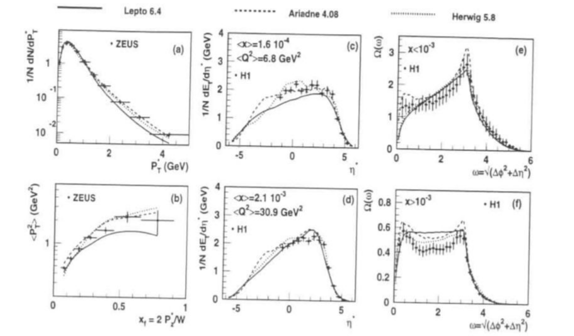
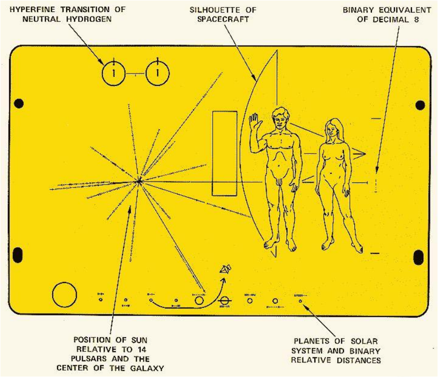


Figure 1: The transverse momenta dN/dp_T (a) and the 'seagull' plot $\langle P_T^2\rangle \times x_F$ (b) of single particles in the positive hemisphere of the hadronic center of mass. The transverse energy flow $dE_T/d\eta$ in a low (c) and high (d) x and Q^2 bin. The transverse energy-energy correlations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

Lessons learned

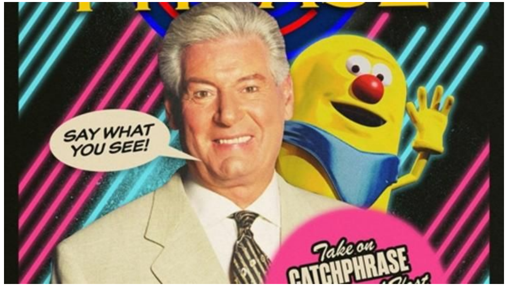
- **A simple/obvious idea, with surprising impact:**
  - Reproducing (or not) a key plot is *powerful*
  - A clear basis for concluding whether or not models agree with each other and with data. Numbers > adjectives!
  - **A *common language* for phenomenology and experiment**
- **Practicality forces good behaviour (a "Ulysses contract")**
  - It's "obvious" to use partons & bosons from the event graph
  - But they are frequently unphysical, approximate in various ways, and may not even exist!
  - Generality / compatibility with many generators means avoiding gen-dependence, and enforcing standards
  - **⇒ predict "real" observables, from well-defined final states**
    … AKA "fiducial analysis"
  - My bias: this should be our measurement gold-standard, increasingly including BSM-focused analyses in the HL era

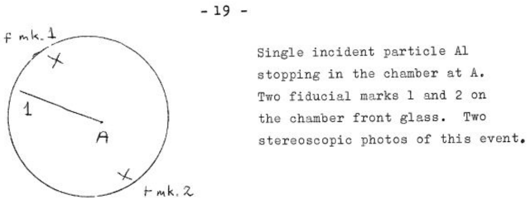


Pioneer plaque

Fiducial analysis

- **Another simple/obvious idea:**
  - **"Say what you see": don't report what you couldn't see!**
  - More specifically: *do* correct for detector biases, but minimise extrapolations beyond experiment acceptance
  - Done by aligning "unfolding target" (usually MC) definition with reco-level acceptances and selection cuts
  - Take "safe" shortcuts, e.g. use hadron decay histories in place of reco, but don't rely on partons from interfering amplitudes: hadronization is a decoherence barrier
  - Result is "best estimate of what could be seen by a perfect detector": don't fill unseen phase-space with model-dependent assumptions



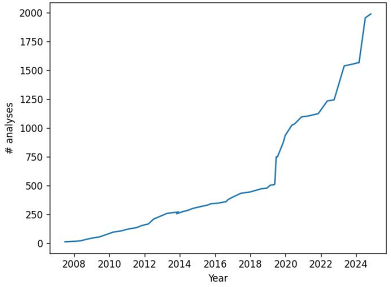


- **Analysis lifetime is maximised by not being model-specific**
  - E.g. HH-production signal-strength at HL-LHC has ~40% theory uncertainty from m_t scheme. No theory resolution in sight. But fiducial cross-section is unaffected

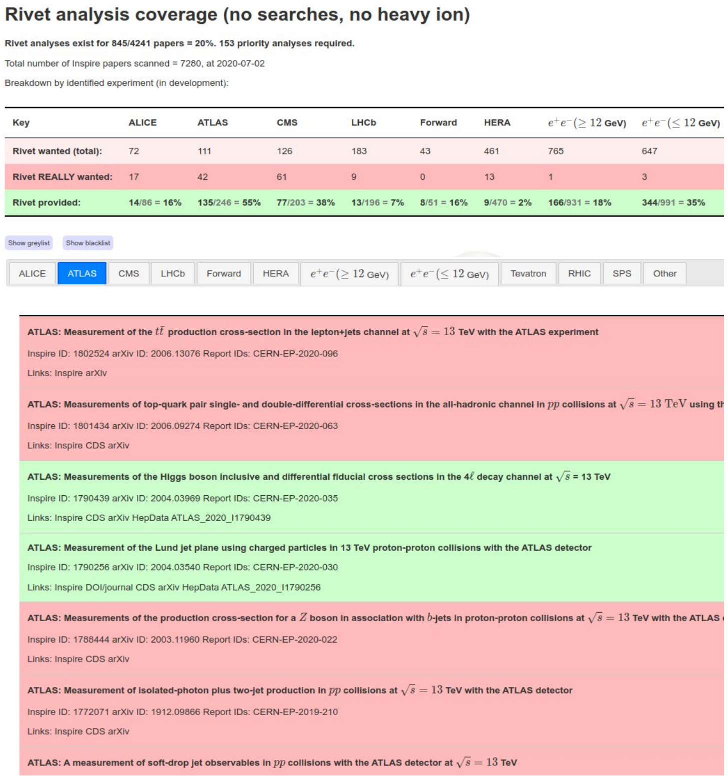
How’s it going?

- ❖ **Version 4.0.2 (Oct 2024) → 1,987 analyses!**

  A steady flow of analysis submissions until 2019, then increase + several deluges from MC gen teams



- ❖ **Official support from the (LHC) experiments is crucial**
  - ➢ Preservation of analysis logic in executable form has become standard for measurements
  - ➢ The original teams know logic best by far; papers are never quite complete/unambiguous
  - ➢ Still imperfect! We monitor paper coverage ⇒



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 $\sqrt{s} = 13\ \mathrm{TeV}$ 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

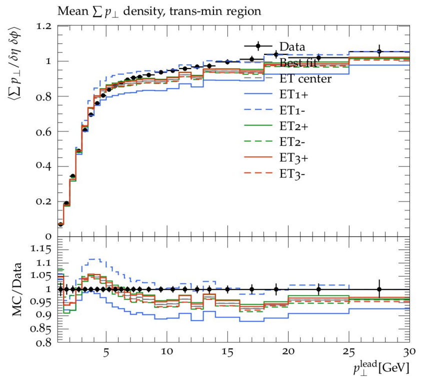
Inspire ID: 1772071 arXiv ID: 1912.09866 Report IDs: CERN-EP-2019-210

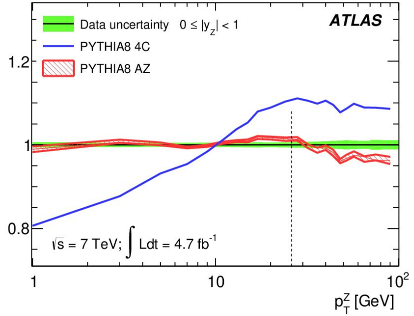
Links: Inspire CDS arXiv

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

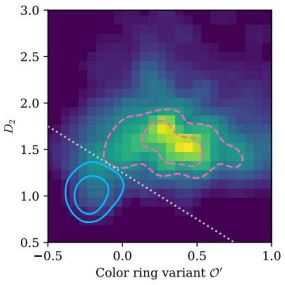
Applications: from tuning to BSM

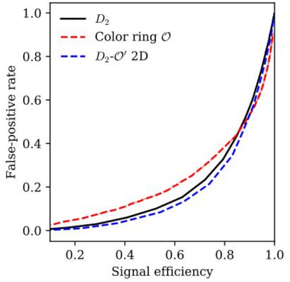
- **Pre-LHC huge QCD uncertainties: MC tuning via Rivet analyses**
- **Tunes revealed gaps in data and in modelling**
  - Better tunes ⇒ better analysis, better results ⇒ better MC
  - Impact: LEP and Tevatron analyses published for ~10 years suddenly got *used*! And cited…
    - ⇒ ATLAS and CMS tunes, tune uncertainties
    - ⇒ Rapid responses to preliminary data
  - Model development: matching & merging, addition of energy evolution & colour-reconnection to Herwig, …





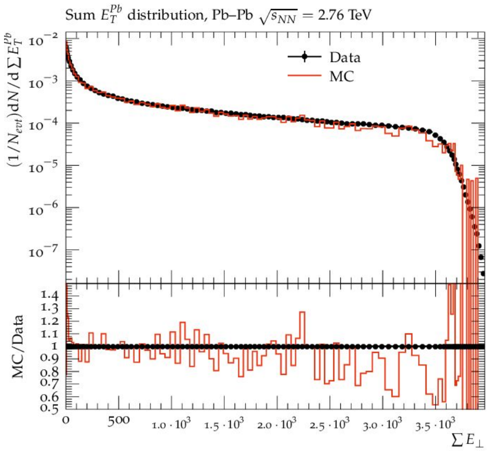
- **Recently, also use of Rivet's large analysis collection for *BSM & Higgs***
  - Same features that made analyses quick to use for tuning also useful in analysis prototyping and model scans

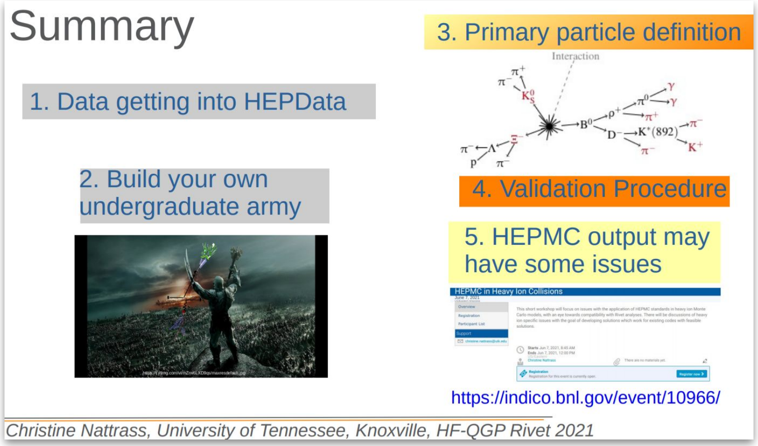




Heavy-ion preservation

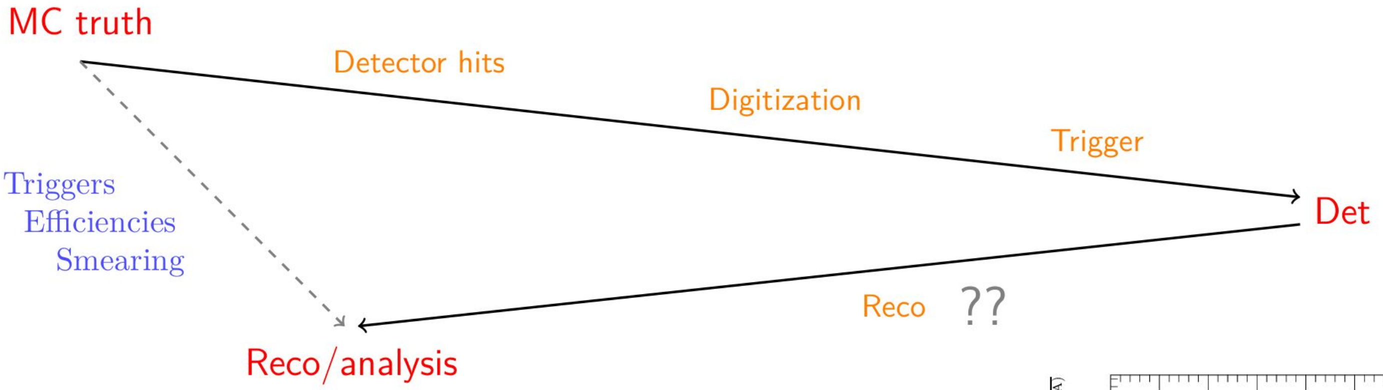
- **Heavy-ion physics is a "frontier":** high-complexity multi-scale event modelling, no current tools that can do everything → flexibility needed
- Again, a concrete tool through which to test against data sharpens discussions, provides a clear metric
- Some really nice community-led initiatives grew up around tools, spurred standardisations, collaboration between HEP/nuclear communities, and drive modelling developments:
- ⇒ more analyses finding there's *life after publication*



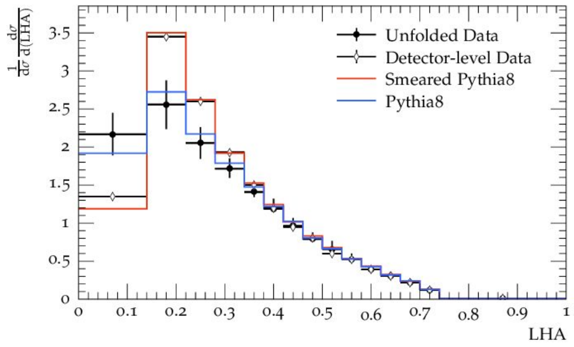


Detector emulation

❖ "Detector smearing" is valid for many reco-level analyses (also in GAMBIT, MA5): reco is calibrated back toward MC truth, so go direct and skip the unknowns

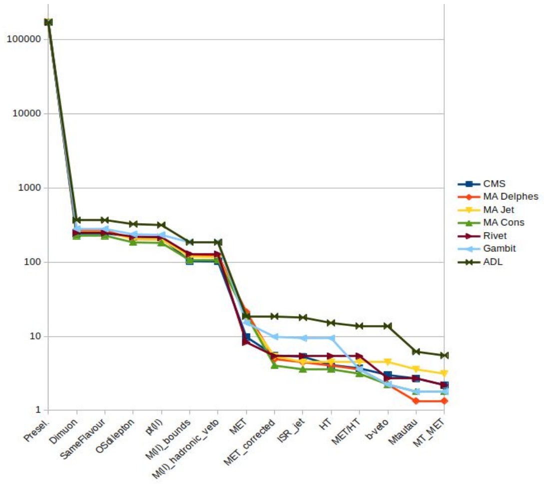


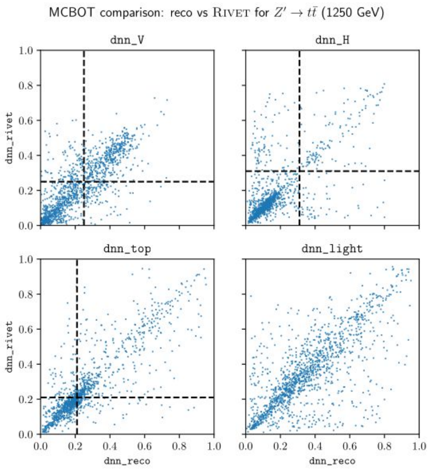
- ➢ capture key efficiencies cf. Delphes, but analysis-specific and less "simulation theatre"
- ➢ flexibility allows e.g. "tuned" jet-substructure smearing, systematics studies, whatever…



Reco-level search recasting

- **Lots of activity in reinterpretations of BSM-search analyses with detector emulation**
  - efficient scaling-up to hundreds of analyses
  - phase-space-specific detector/efficiency functions (or Delphes cards) found necessary
- **Precision maybe 10%-20%**
  - on fast-falling spectra, small effect on CL's
  - sufficient to highlight regions of interest in new models ⇒ point experiments to re-test
- **Machine-learning classifiers** *can* also be preserved and work well on smeared events
  - not always necessary: tagging algs can be parametrised, maybe MC-level NN
  - object robustness / truth equivalent matters

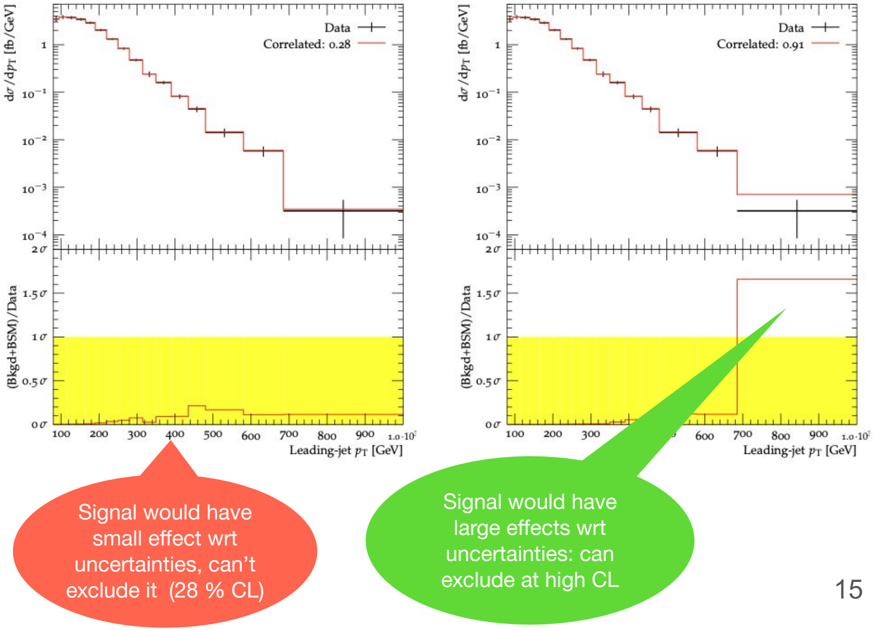




from Tomasz Procter thesis

BSM from “Standard Model”

- **Particle-level measurements *can* achieve high model-independence**
  - Careful definition of fiducial cross-section, reduce model sensitivity in unfolding
- **E.g. Contur injects BSM signal into “SM” measurements**
  - Many models already “dead” before a dedicated search ⇒ save *years* of effort (cf. ATLAS EXO)
  - Particularly strong for measurements with complex signatures: mixtures of leptons, jets, MET, …
  - But even e.g. model-independent unfolded MET+jet has near-search power
- **All at truth-level ⇒ *SPEED!***

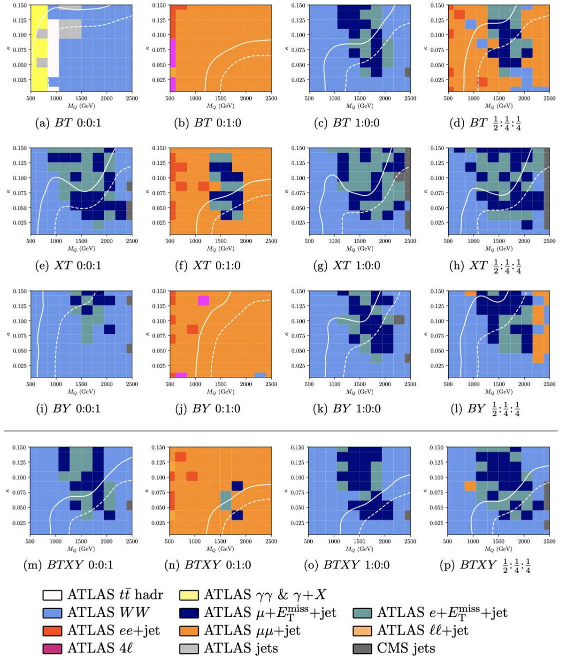


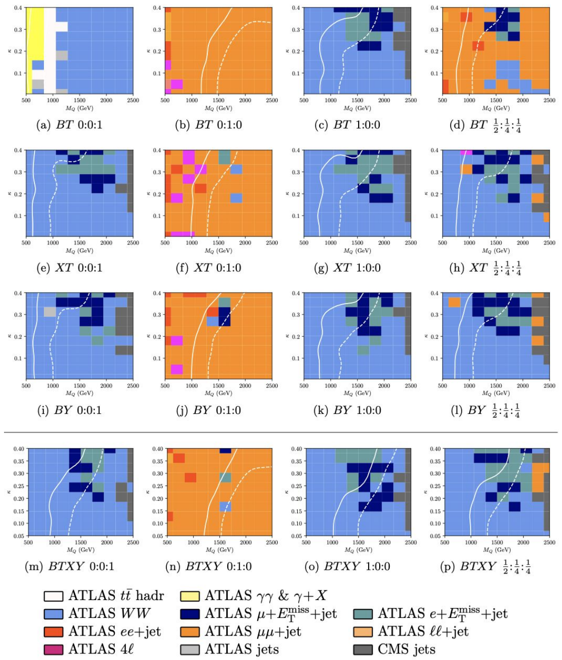
Try doing this with full-sim in finite time…

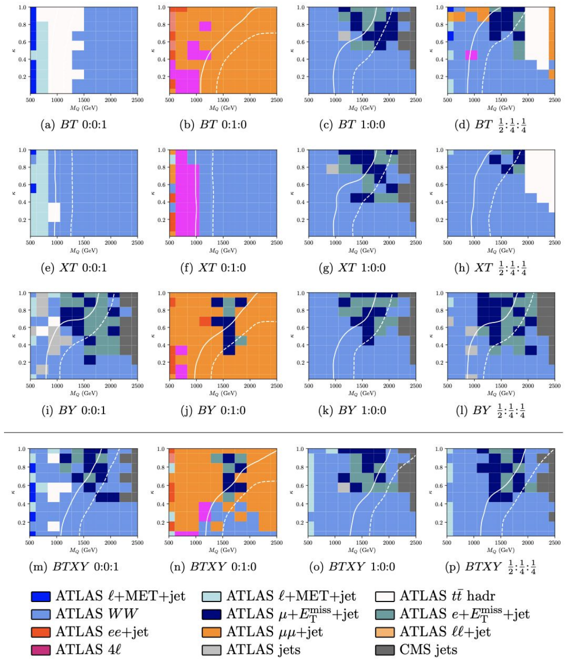
- Contur vector-like quark study on a scan of realistic VLQ multiplets:

  7 multiplets, each with 3 generational couplings, each with 4 W/H/Z-couplings,

  300 points per scan, x 30,000 events ⇒ 750M events!

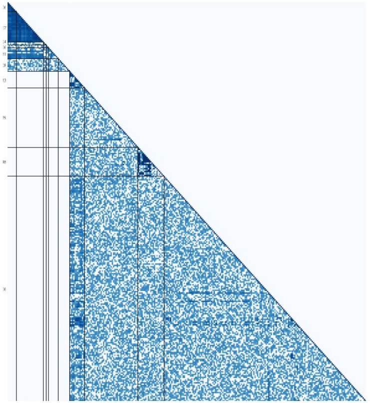




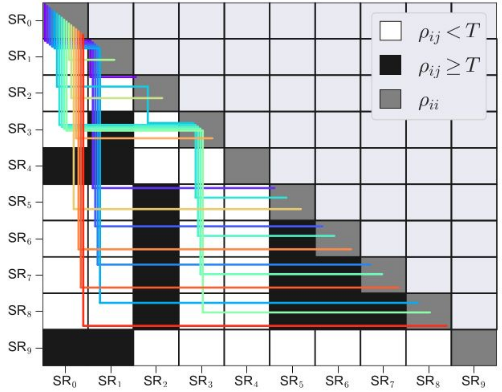


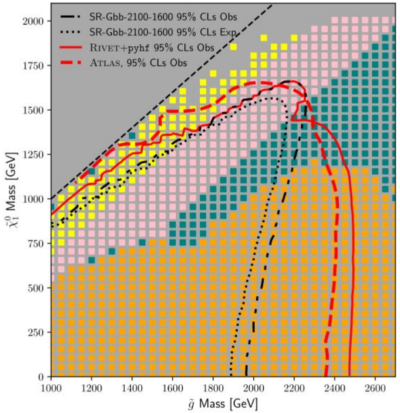
Analysis combinations

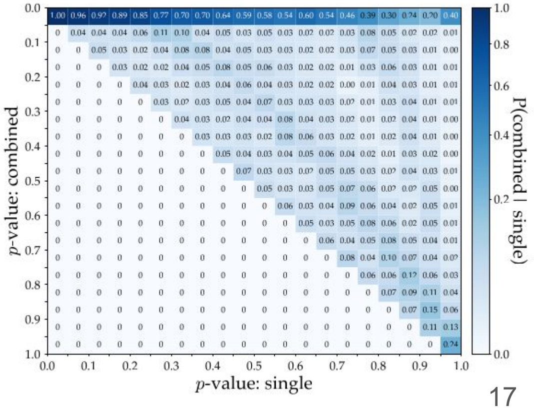
- **One last thing: cannot just naively add all ln$L$'s and draw a mega-limit!**
- Over many (many!) analyses, bins and signal regions, there will be acceptance overlaps ⇒ double-count exclusionary features
- Naive approach is to only use single best-expected bin: what a waste! Lots of exciting work on acceptance correlations, TACO WHDFS alg for best-expected combinations, and anomaly detection in development



from Jamie Yellen & Tomasz Procter theses

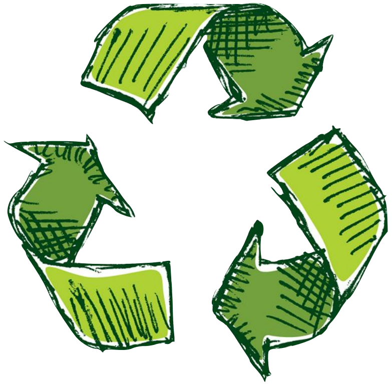






Summary

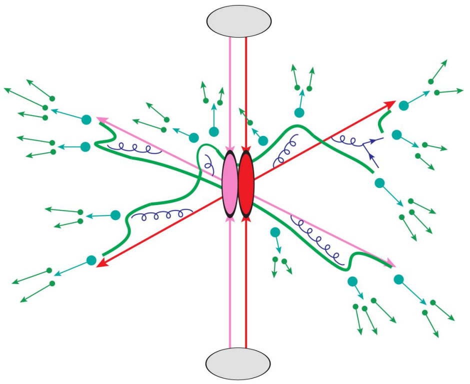
- **Reinterpretation is about enabling two-way communication between experiments and theory**
  - Testing & improving models, more impact, and avoiding wasted effort. Actual science aims, not proxies like publication
- **Preserving analysis logic, particularly in a publicly accessible and rapidly computable form *matters***
- **Several toolkits, with different focuses and strengths**
  - So far mainly collider-focused event-loops; the idea is more general. All analysis can & should be reusable and combinable
- **Incentives are needed**
  - Short-termism can discourage work for long-term impact
  - Get junior scientists enthused, build re-use culture & values
  - Reward good community/science behaviour ⇒ career rewards

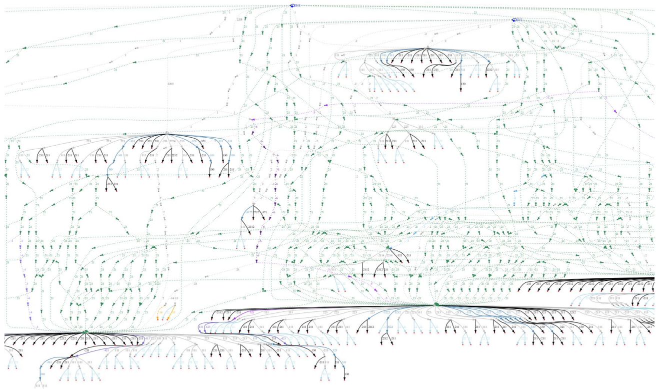


Backup slides

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

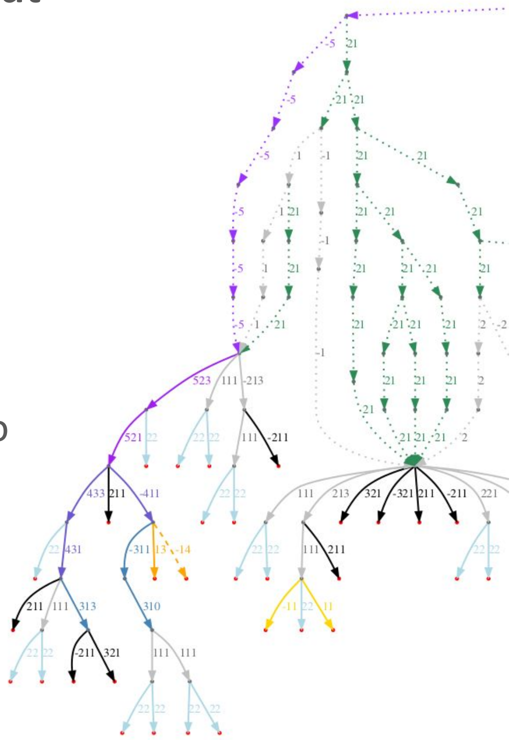




Physically safe analysis methods

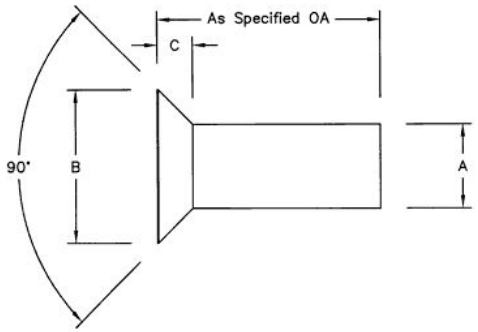
Avoiding unstandardised event-graph features was pragmatic, but led to some genuine physical insights:

- **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



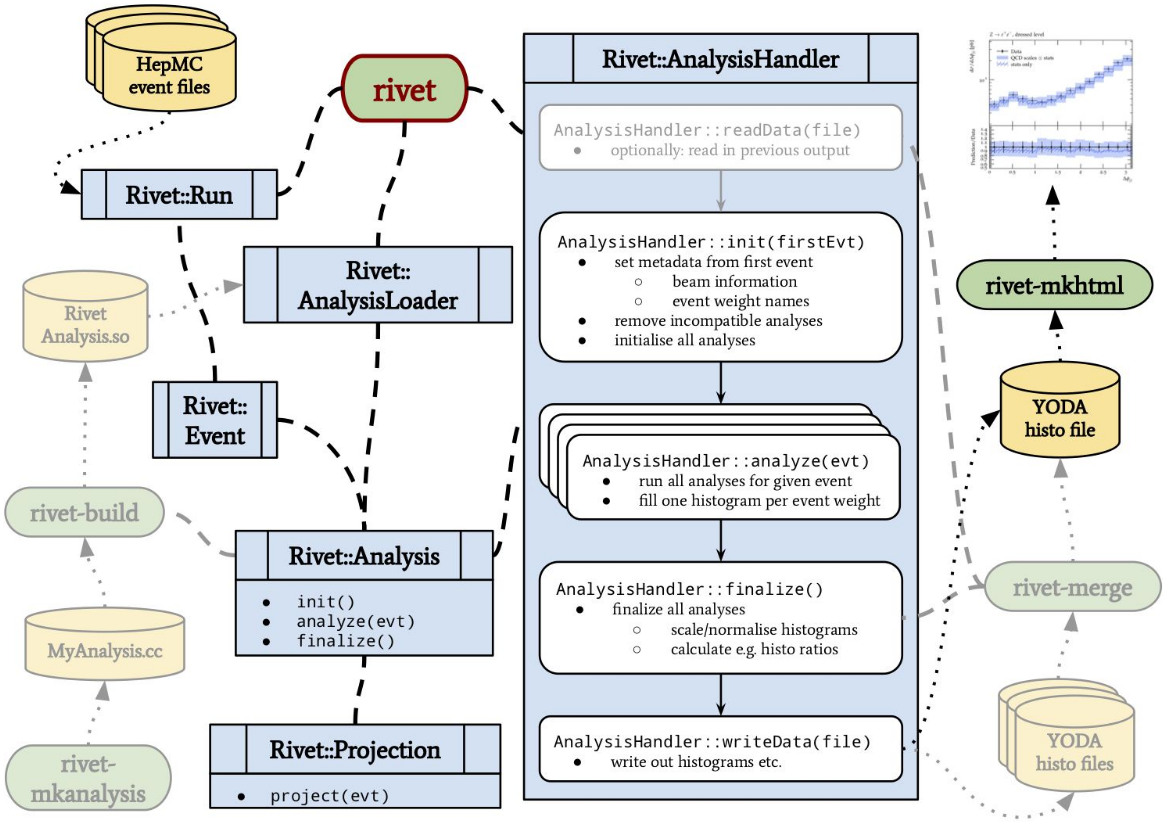
Designing Rivet

- **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**



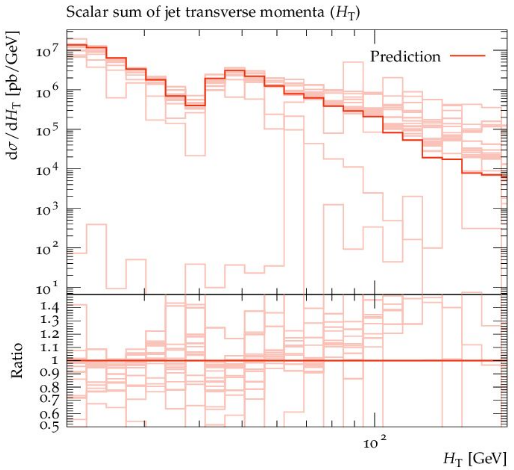
The result

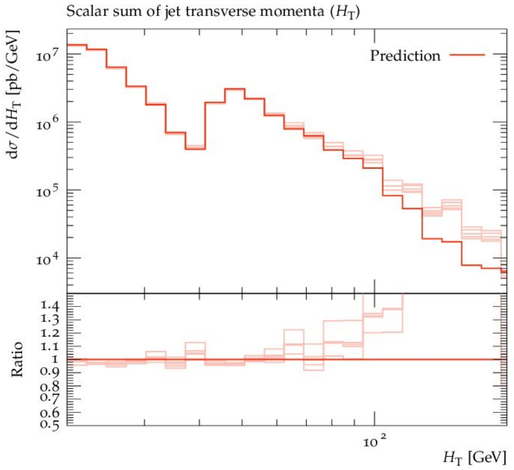
- **Rivet v3 structure**
  arXiv:1912.05451
- Streamlined set of tools from analysis coding to event processing to plotting (and other applications)
- And a key gateway to connect data analysis to theory (and back again)



Multiweights and re-entry

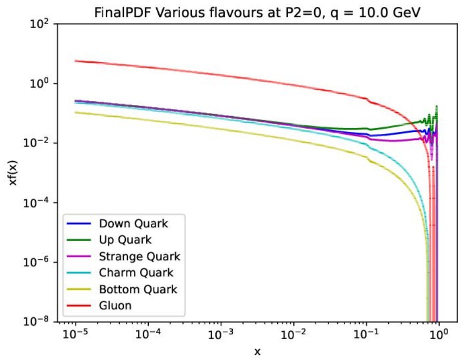
- **MC weight vectors allow expression of increasingly complex theory uncertainties.** But a burden for analysis chains: have to propagate and correctly combine O(200) weight streams!
- **Rivet 3: complex automatic handling of weights**
  ~invisible to users: data objects *look* like histograms etc.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





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, beyond? 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 4 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.