Accelerating physics impact

The why & how of Rivet analysis preservation

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FNAL LPC seminar
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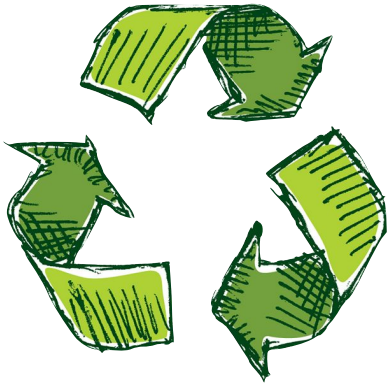
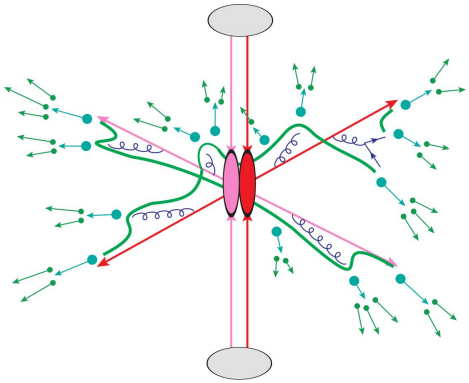
Outline

- **The Rivet toolkit and project**
- **Origins and generic analysis preservation**
- **Early developments**
  - Soft QCD & MC tuning
  - Refining fiducial definitions
- **Retooling for precision at the LHC**
- **Rivet for heavy ions and EIC**
- **Beyond the Standard Model: searches and Contur**
- **The future of Rivet**
- **Joining the party**



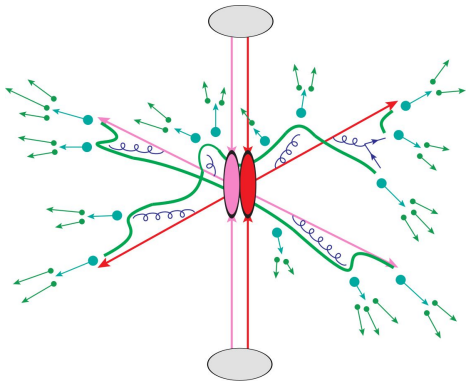
What is Rivet?

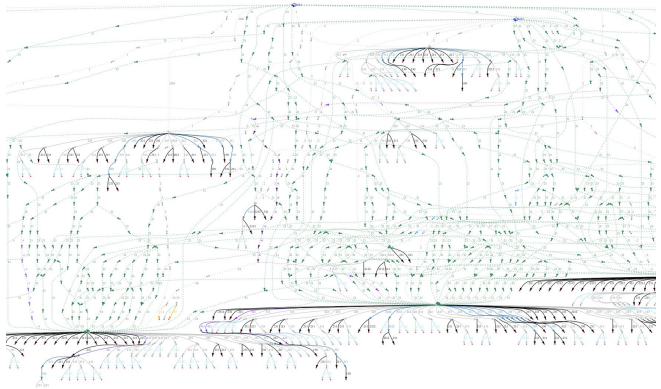
- **The “LHC standard” MC analysis toolkit**
- **More broadly a project to preserve the logic of HEP data analyses and further expt-pheno collaboration**
- **Containing:**
  - A good ol’ event loop
  - Physics object calculators
  - Fiducial / generator-independence emphasis
  - Integration with HepData
  - Transparent weight-stream handling
  - 1000+ analyses!
- **Rivet now sits at the centre of a web of analysis reinterpretation tools, linking experiment to theory**



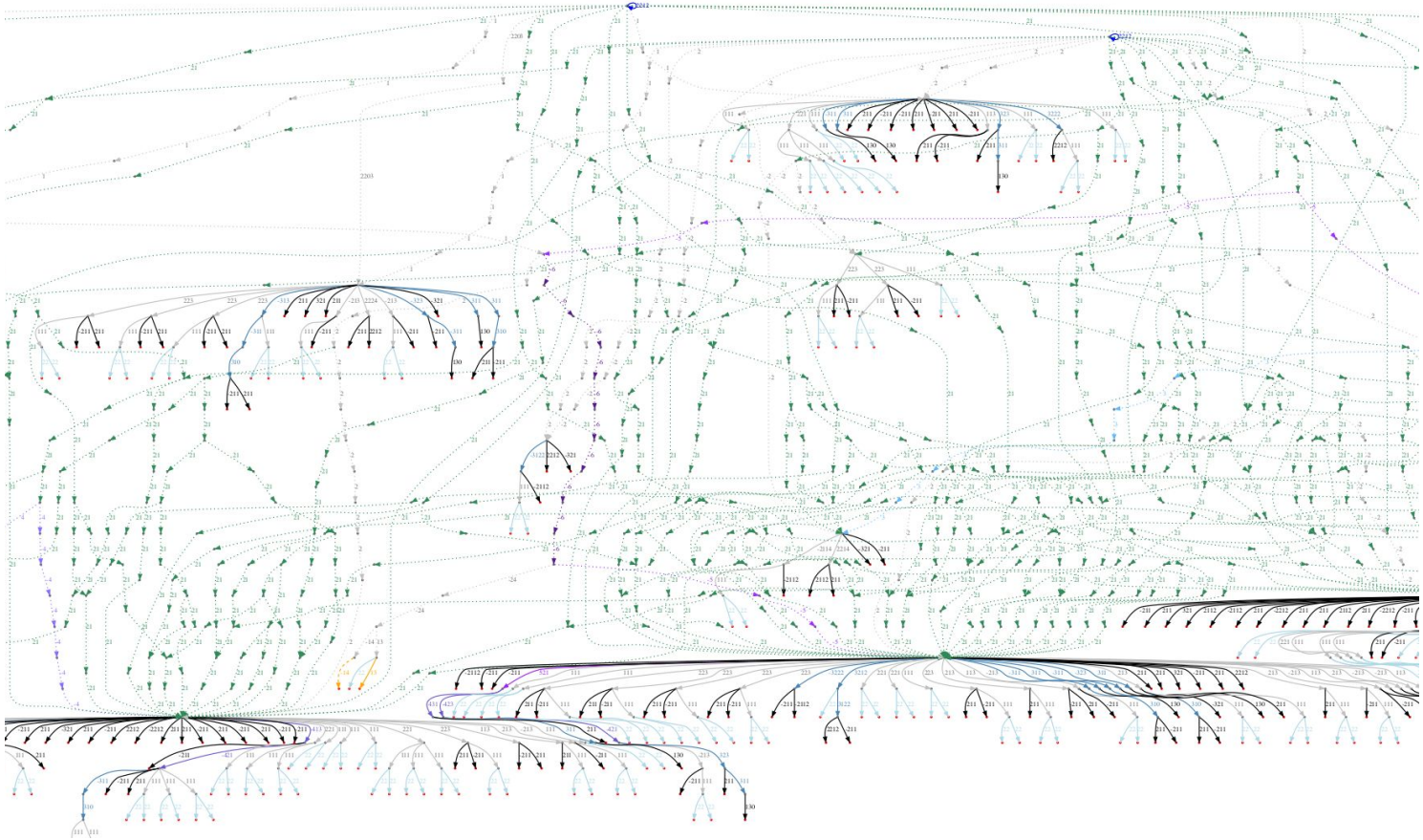
MC generation

- **MC generation is where theory meets experiment**
  - The fundamental pp collision, *sans* detector
- **Components of a fully exclusive SHG 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 basically hostage to shower MCs!**
  - The core mechanism for translating theory to experimental signatures, from QCD to BSM
  - Generally very complex modelling and output





Just part of a ttbar event!



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: Q^2 ~ 4 GeV^2 DIS; jets ~ 5 GeV p_T; diffraction
  - Many "state of the art" models only implemented in MCs, claiming to predict distributions in rather complicated observables/kinematics
  - 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: "take 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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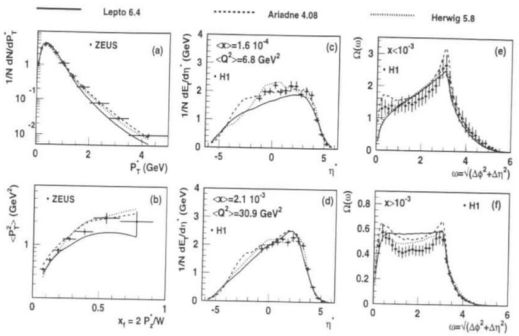


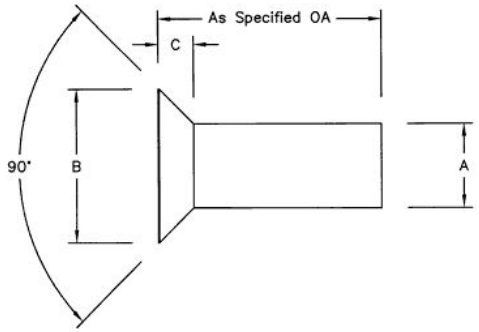
Figure 1: *The transverse momenta dN/dp_T (a) and the 'seagull' plot $\langle P_T^2 \rangle \times x_F$ (b) of single particles in the positive hemisphere of the hadronic center of mass. The transverse energy flow $dE_T/d\eta$ in a low (c) and high (d) x and Q^2 bin. The transverse energy-energy correlations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

Lessons learned from HZTool

- **A tool like this is a very valuable asset**
  - Reproducing or failure to reproduce a key plot is *powerful*
  - *Progress in understanding physics! Solve expt issues, get better pheno tools!*
  - *And a common "language" for phenomenologists and experimentalists*
- **Model independence**
  - Obvious to use partons, intermediate bosons, etc. direct from the event graph
  - Frequently unphysical, depend on the approximations used. May not even exist!
  - HZTool filled up with cryptic "if HERWIG, if PYTHIA, if …" code
  - Adding a new generator meant patching ~all analyses!
  - Predict "real" observables, from well-defined final states
- **Standardisation**
  - (physical) event format conventions, PDG particle numbering scheme, etc.
- **Scalability**
  - Lots of expensive operations are repeated: sharing calculations is essential

Rivet design concepts

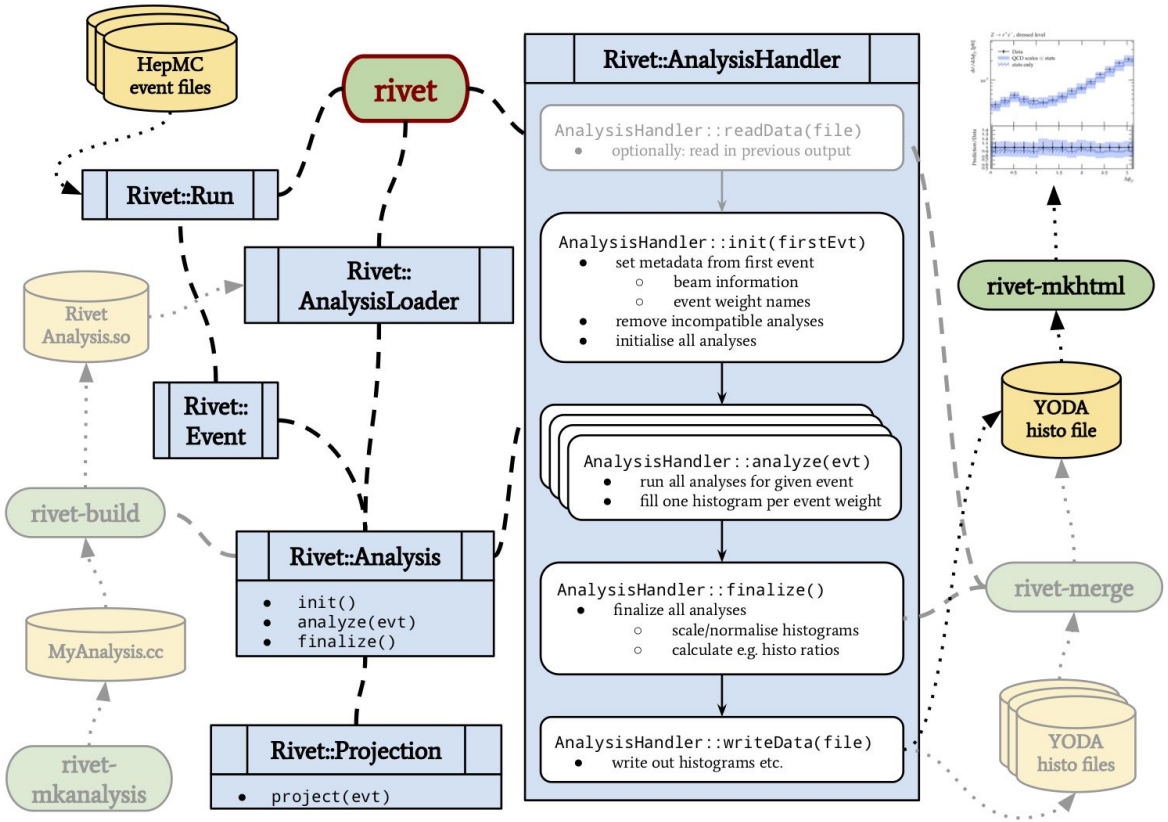
- **Ease of use**
  - **Big emphasis on "more physics, less noise"!**
  - Boilerplace analysis code, HepData sync "automatic"
  - Event loop and histogramming basically familiar
  - Lots of tools to avoid having to touch the raw event graph



- **Embeddable**
  - OO C++ library, Python wrapper, sane user-facing scripts
  - No generator dependence: communication through HepMC
  - Analysis routines separate and dynamically loadable via "plugins"
- **Efficient**
  - Avoid recomputations via "projection" result-caching system
- **Physical**
  - **Measurements primarily from final-state particles only**

The result

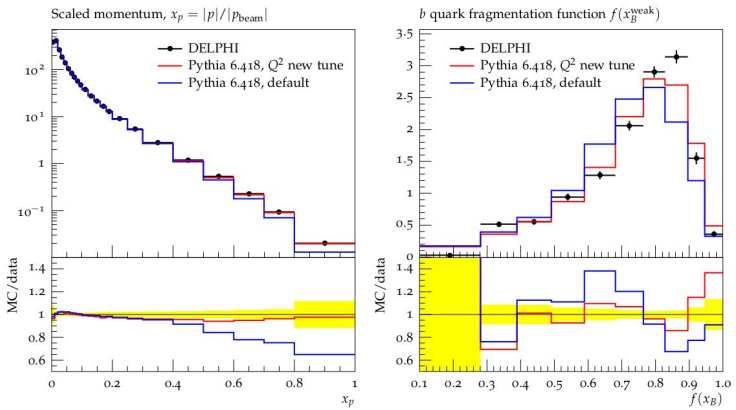
- As of Rivet v3.1.0 arXiv:1912.05451
- Streamlined set of tools from analysis coding to event processing to plotting (and other applications)
- And a key gateway to connect your analysis to theory (and back again)
- Let's review some of the early impacts…

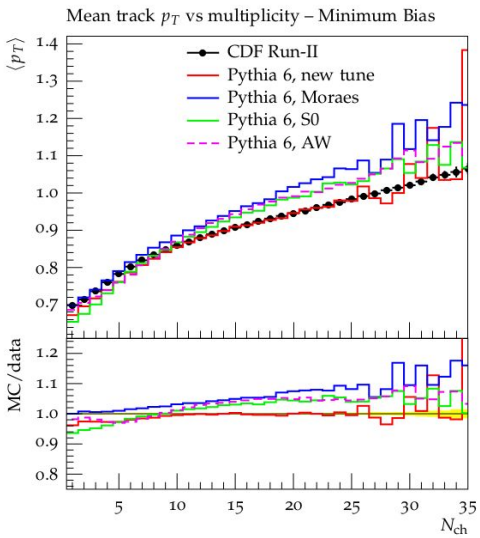


Event generator tuning

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

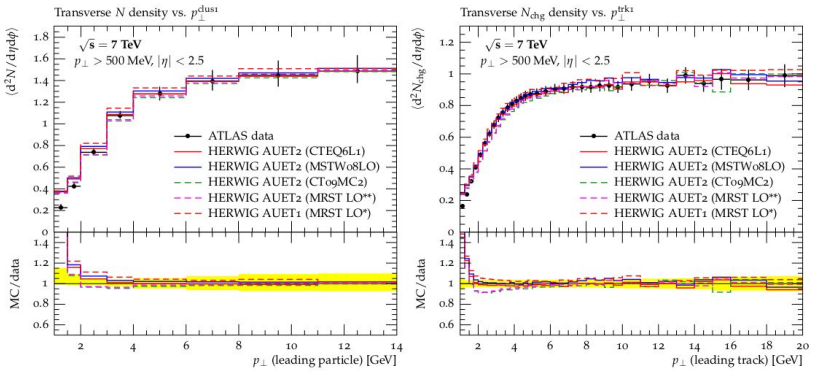


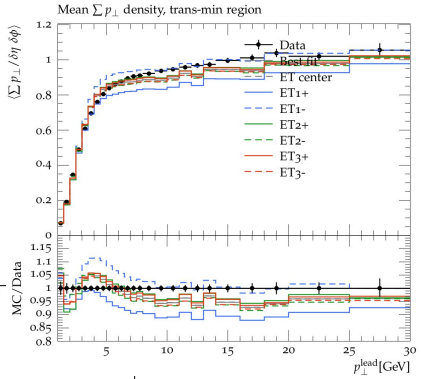


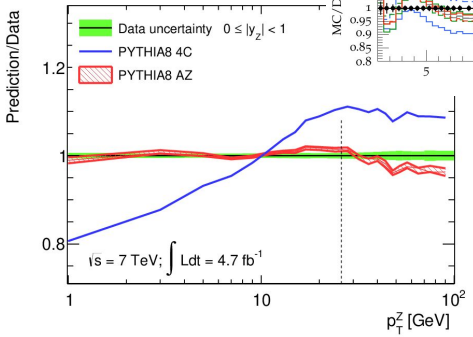
More tuning…

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 was an essential task: better tunes, better experimental analysis design
  - Rivet + Professor 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, …



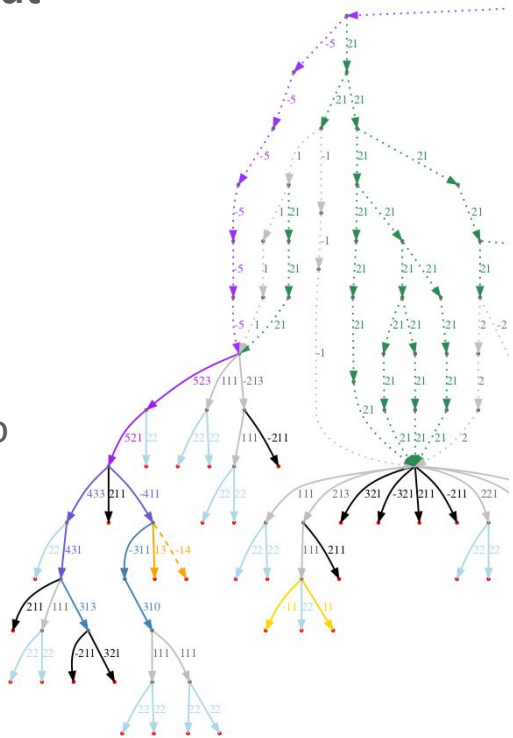




Physically safe analysis methods

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

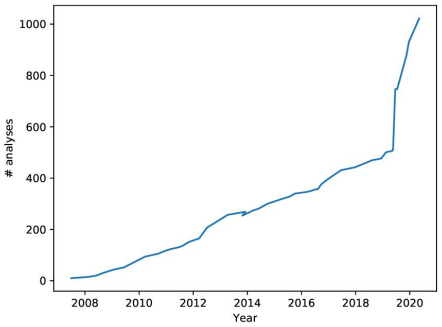
- **refining the "fiducial" idea, defining *unfolding targets***
- **Hadronisation as a "decoherence barrier"**
  use the natural dividing line between the quantum-interfering hard process & semi-classical decays: ~ no tempting partons!
- **Bringing truth tagging closer to reco**
  first releases used *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 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 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

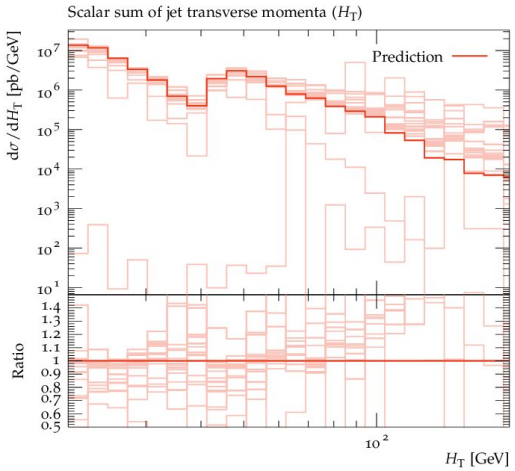
Inspire ID: 1772071 arXiv ID: 1912.09866 Report IDs: CERN-EP-2019-210

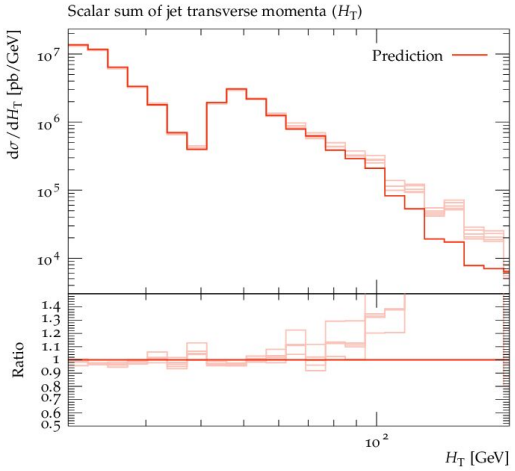
Links: Inspire CDS arXiv

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

Systematics “multiweights”

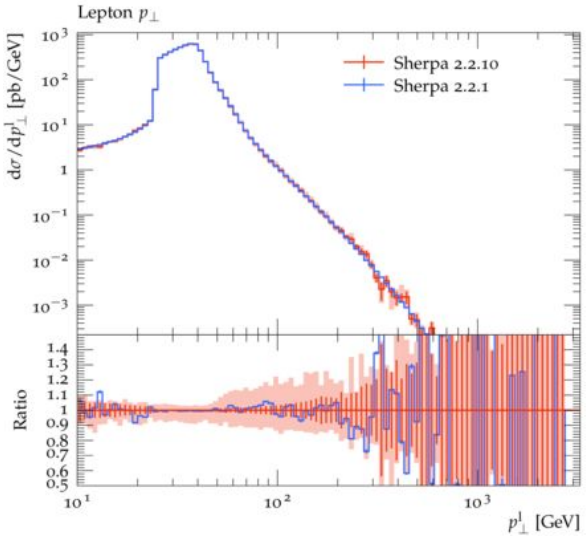
- **MC weight vectors allow expression of increasingly complex theory uncertainties.** But a burden for analysis chains: have to propagate and correctly combine O(200) weight streams!
- **Rivet 3: complex automatic handling of weights**
  ~invisible to users: data objects *look* like histograms etc.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

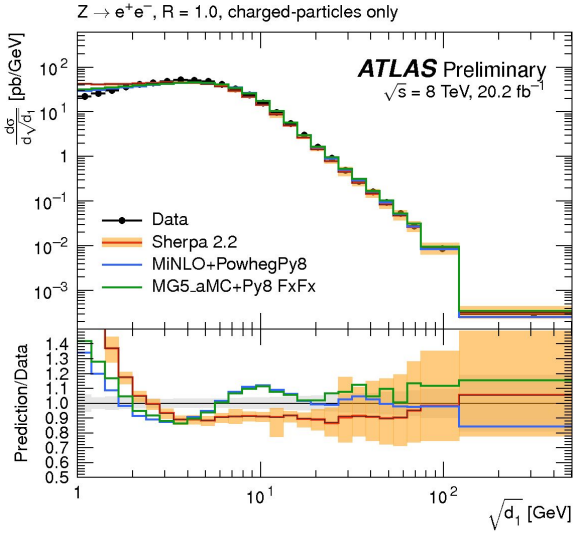


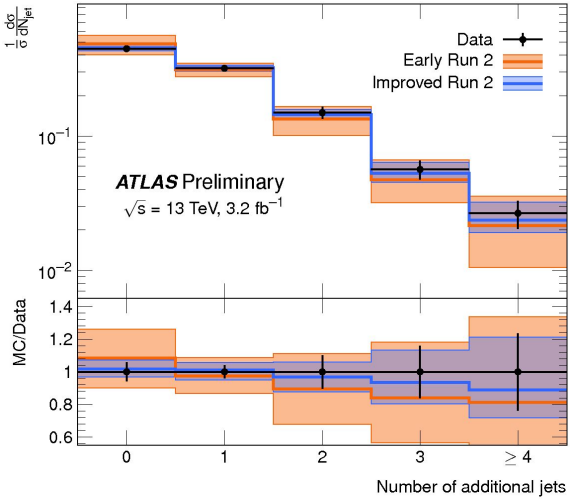


Rivet multiweights in action

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



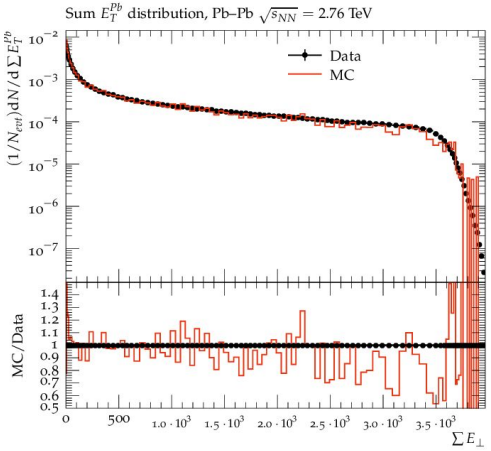


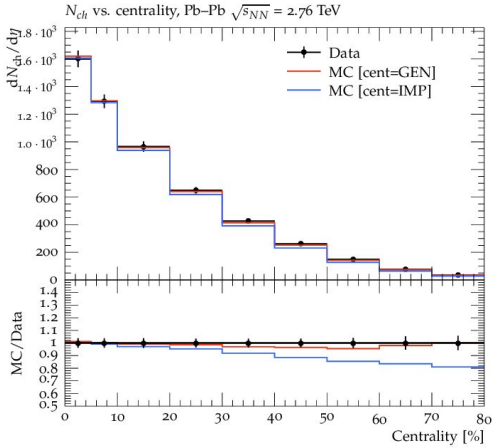


❖ Weight-naming standardisation underway via MCnet

Rivet and heavy-ion physics

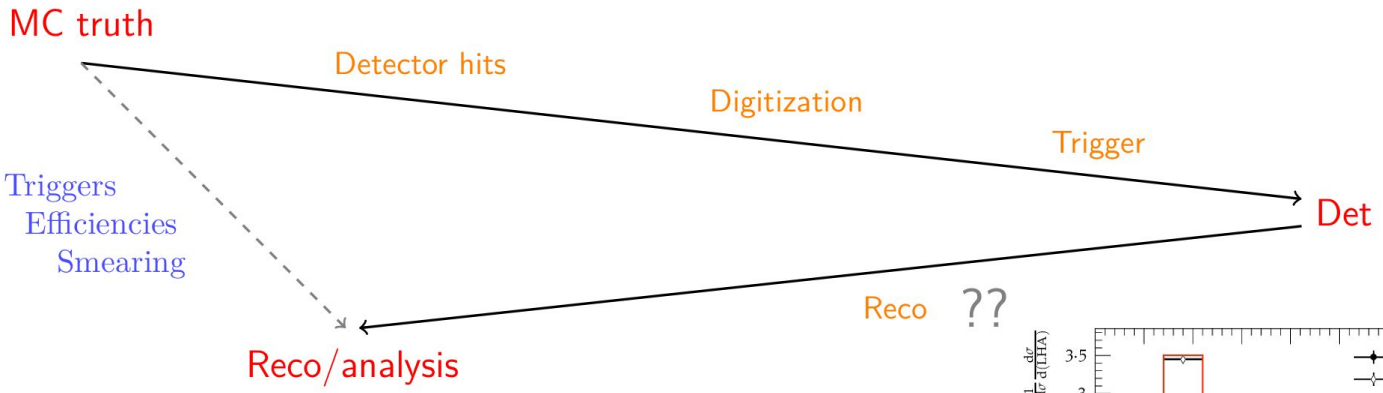
- **“Adding heavy-ion support” sounds trivial!**
- Actually a stern test, with far-reaching impacts.
  - HI observables often require centrality calibration curves: we need a 2-pass run. That wasn’t planned
  - And event/event correlations… centrality-binned!
  - Need swappable definitions: few HI generators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



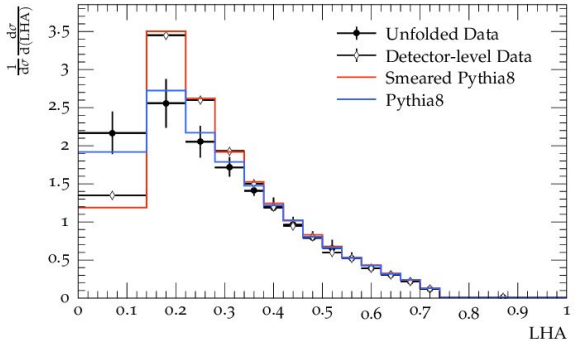


Detector emulation

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

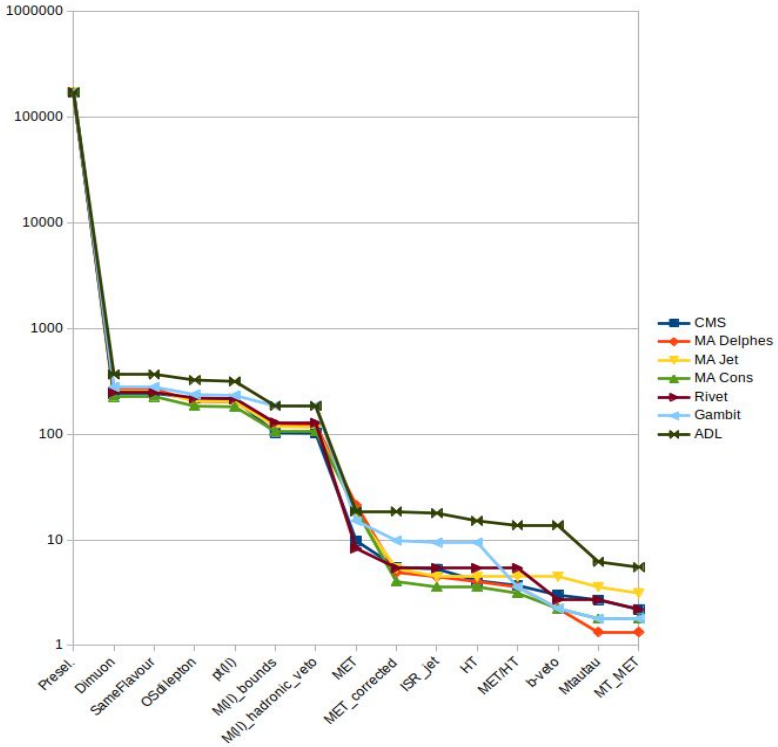


  - like Delphes, but more flexible & can be *analysis-specific* ⇒ MA5 "SFS" mode
  - flexibility allows e.g. "tuned" jet-substructure smearing:



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
  - but ours is best, obv… ;-)



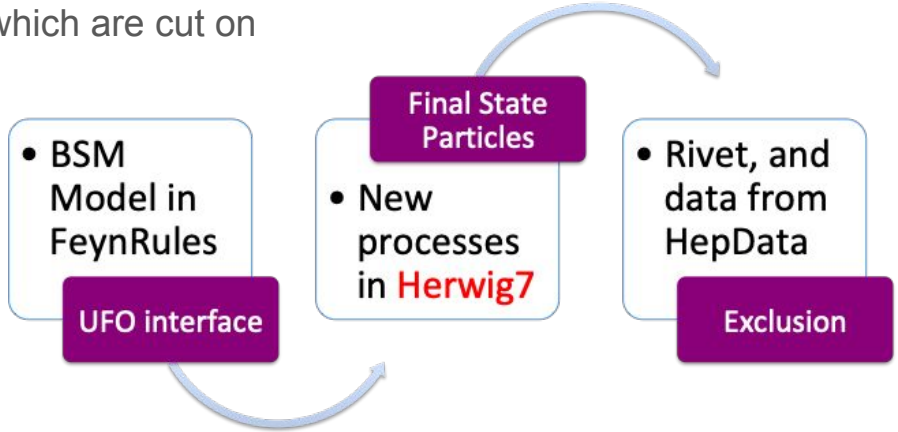
Les Houches 2019 CMS soft-lepton recasting-tools comparison

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; and…
- **Contur is getting particular uptake**
  - Inject signal to “SM” measurements:

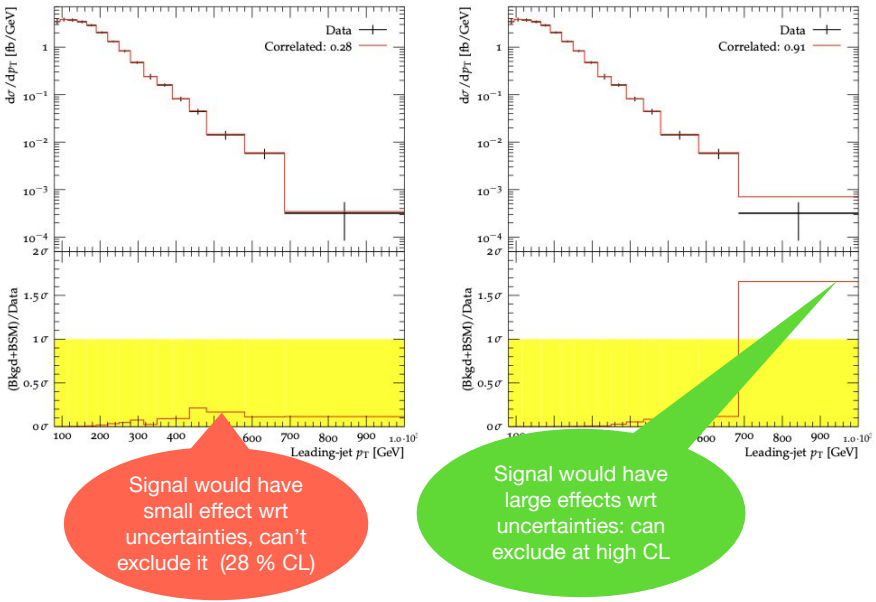
    if it’d be statistically distinct, the model is eliminated!
  - Rivet gives huge “synoptic” coverage:

    a new result with Rivet code can be in BSM fits within *hours*



Contur

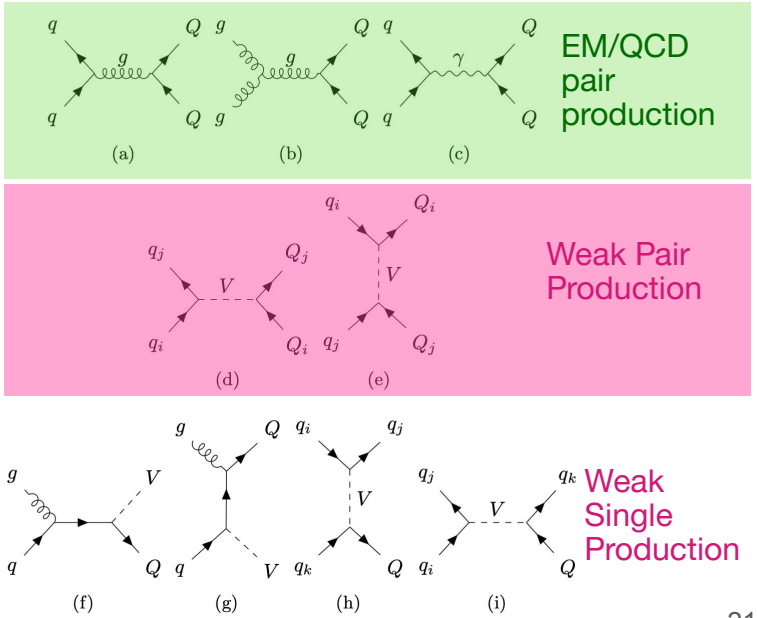
- **Contur is "just" a wrapper on Rivet**
  - Ok, not just! You need to know which analyses are "safe". Another reason for emphasis on final-states and *no cheating*
  - In absence of unambiguous BSM, make zeroth-order assumption that data = SM
  - Can be improved with high-precision SM theory predictions & 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
  -



Contur BSM example

- **Vector-like quarks** [SciPost Phys. 9, 069 (2020)]
  - Popular generic class of SM extensions, with new quark partners: $B^{-1/3}$, $T^{2/3}$, $X^{5/3}$, $Y^{-4/3}$
  - Couple to SM via usual quark EM & strong couplings, but
    B,T: interact with *W*, *Z* or *H* via modified weak coupling
    X, Y: interact only with *W* via modified weak coupling: $X \to Wt$, $Y \to Wb$ always
  - LHC searches mostly for 3rd gen, strong pair-production only!
  - 4 masses, 1 overall coupling κ,
    3 generational couplings ζ, 3 branching ratios ξ
    ⇒ rich collider phenomenology!

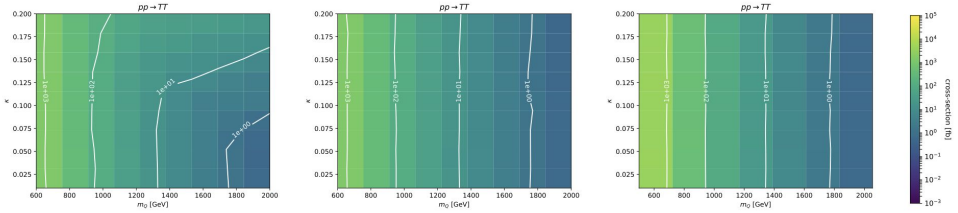
$$\mathcal{L} = \kappa_B \left[\sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{B}_{L/R} W_\mu^- \gamma^\mu u^i_{L/R}] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{B}_{L/R} Z_\mu \gamma^\mu d^i_{L/R}] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M_B}{v} [\bar{B}_{R/L} H d^i_{L/R}] \right]$$
$$+ \kappa_T \left[\sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W_\mu^+ \gamma^\mu d^i_{L/R}] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{T}_{L/R} Z_\mu \gamma^\mu u^i_{L/R}] - \sqrt{\frac{\zeta_i \xi_H^T}{\Gamma_H^0}} \frac{M_T}{v} [\bar{T}_{R/L} H u^i_{L/R}] \right]$$
$$+ \kappa_X \left[\sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{X}_{L/R} W_\mu^+ \gamma^\mu u^i_{L/R}] \right] + \kappa_Y \left[\sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{Y}_{L/R} W_\mu^- \gamma^\mu d^i_{L/R}] \right] + \text{h.c.},$$



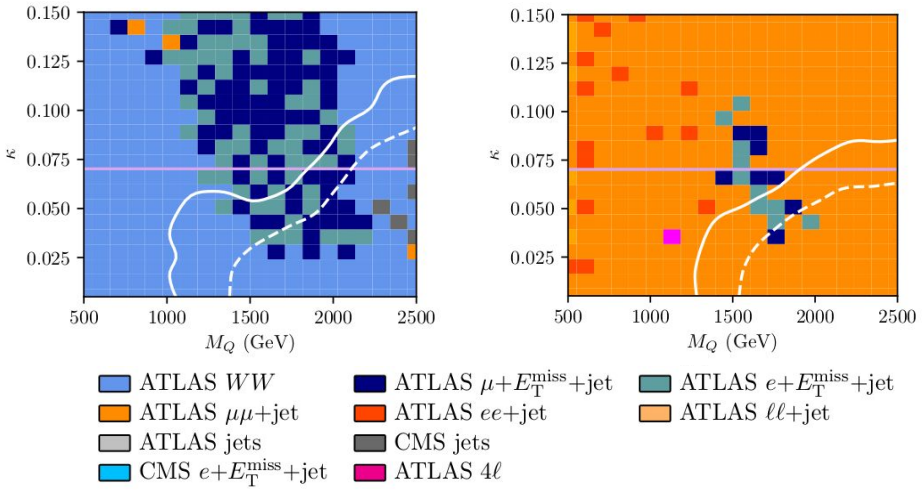
VLQ pheno with Contur: 1st gen

- Even pair-production has κ-dependence via weak production initiated by valence quarks
- Weak *Qq* single-VLQ production can dominate over pair-prod
- Different *W:Z:H* BFs for *T, B* activate different analysis pools "automatically" due to Rivet coverage
- *WW* diboson mostly dominates via *W*, *H*
- "Injection" of l+MET+jet events here from an unfolded VBF control region!

Pair-prod cross-sections



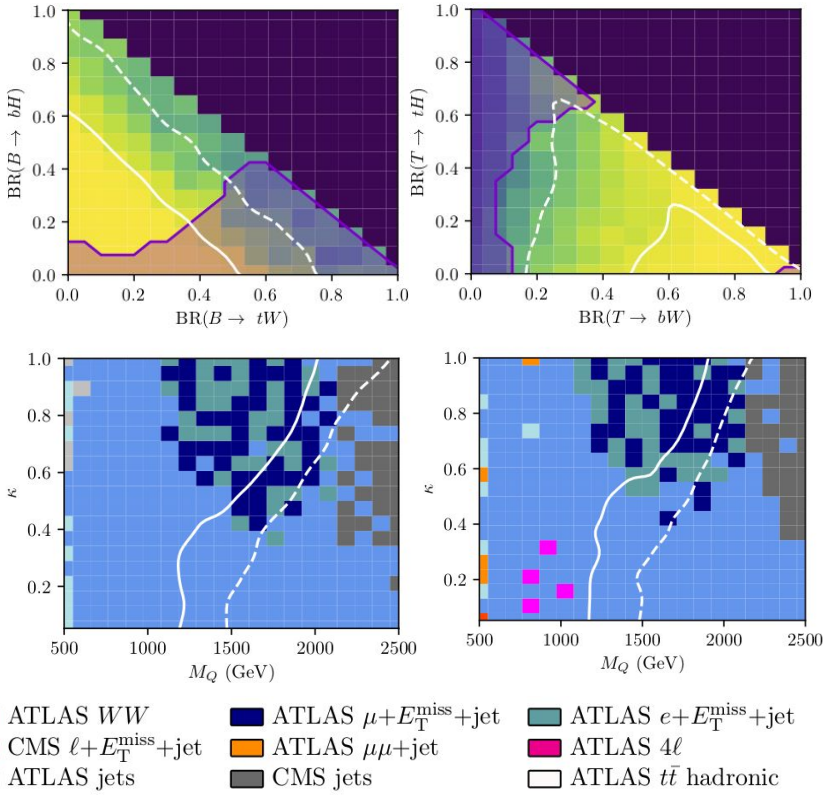
(a) T coupling to u, d only (b) T coupling to c, s only (c) T coupling to t, b only



Exclusions complementary to non-collider limits

VLQ pheno with Contur: 3rd gen

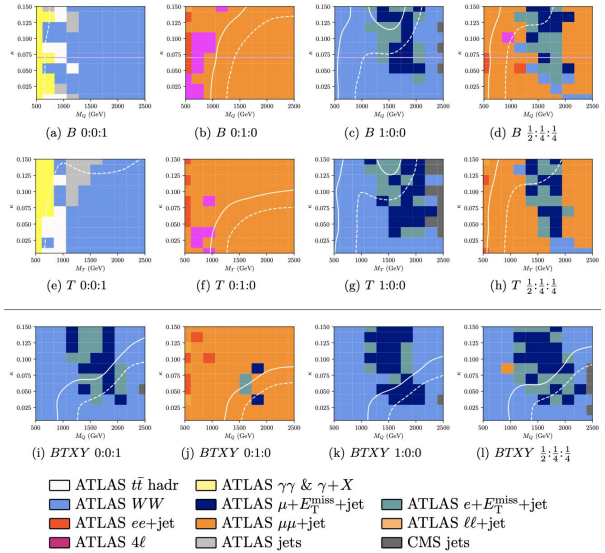
- In pure T, B pair-production mode, diboson and l+MET+jet "SM" analyses ~cover or complement direct searches wonderfully
- In general, for *W:Z:H* = 0:1:0, *Tq* and *Xq* production killed by tiny top-quark PDF: pairs at low-m_Q, *Yq* at high-mass. Decays always have a *W* (directly or via $T \to t\,Z$): l+MET pool always dominates
- Rivet+Contur "SM" routines give powerful sensitivity to VLQs, even far from the benchmark search modes

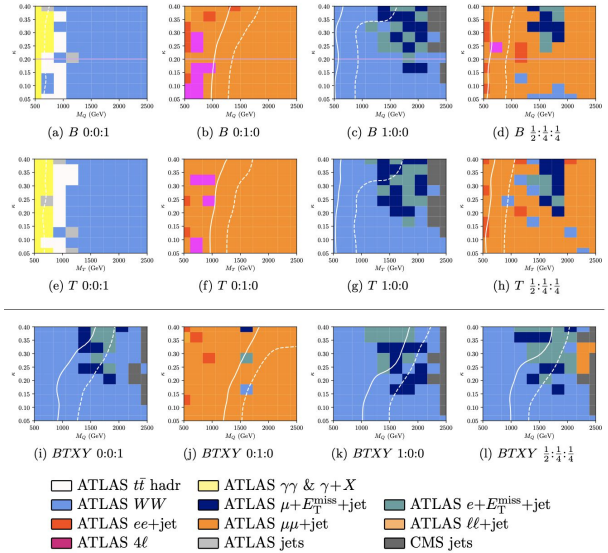


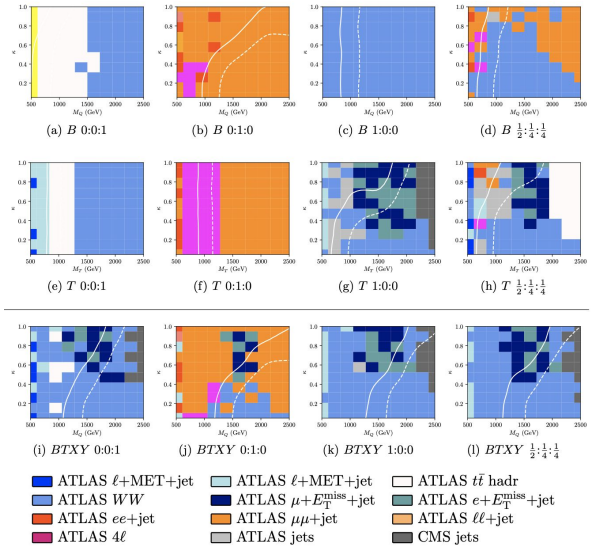
Generalising to 4 VLQs, still strong exclusions

More realistic models… [singlets]

- 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!
- **~No problem! 1 month later…**

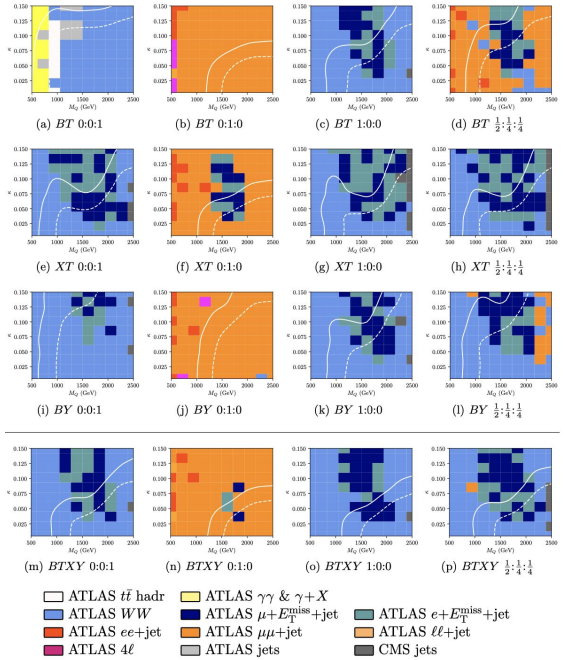


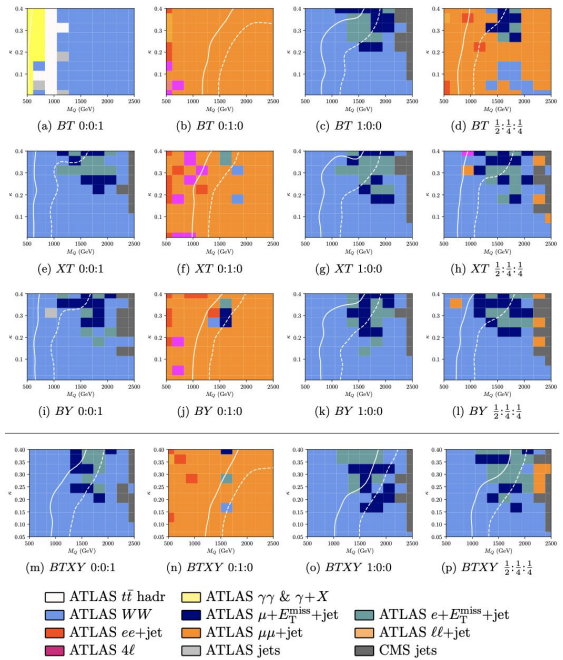


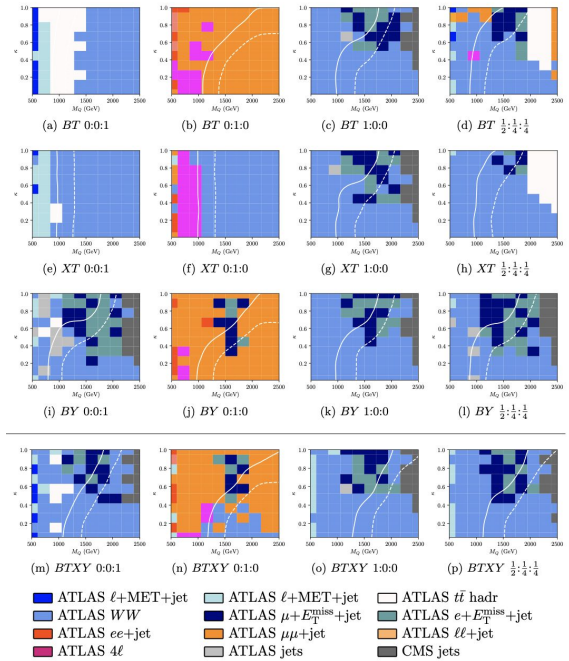


More realistic models… [doublets]

- 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!

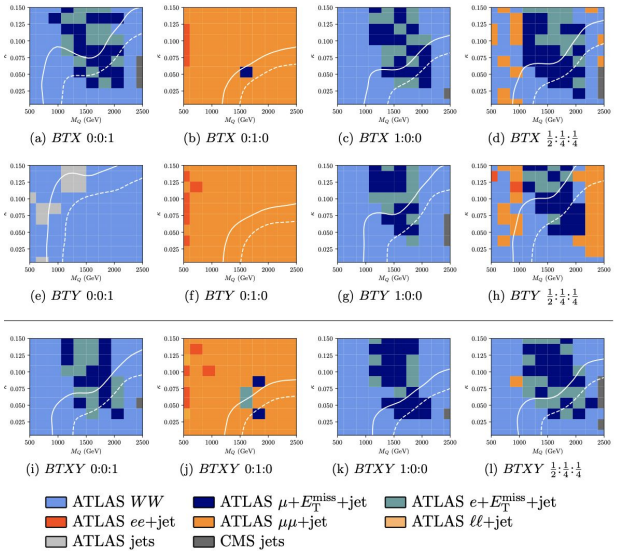


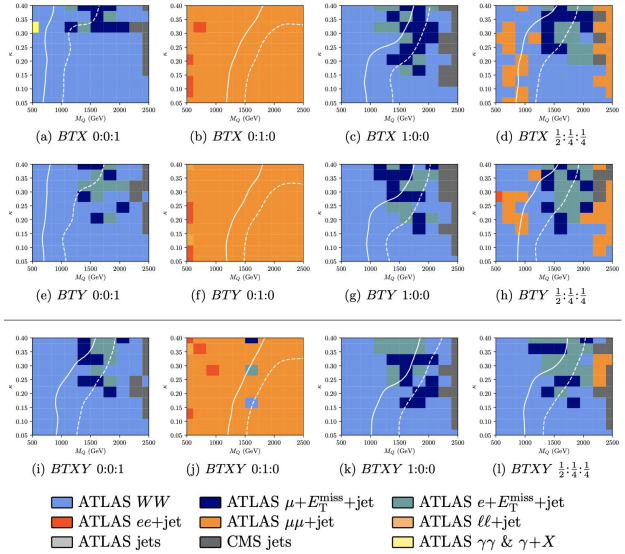


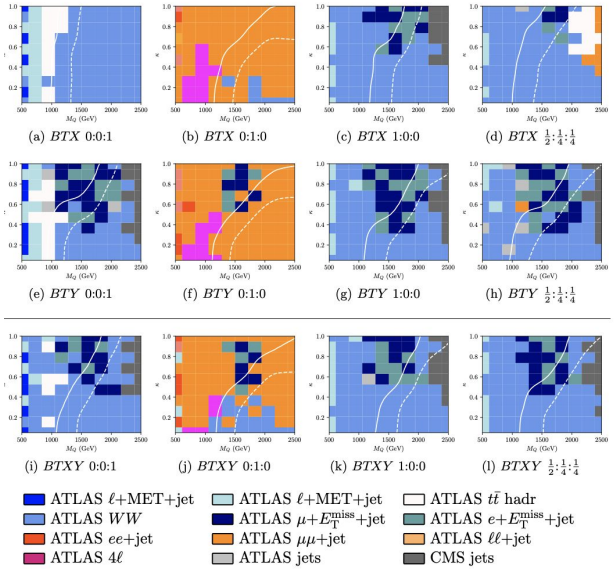


More realistic models… [triplets]

- 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!







Speed is *good!*

The future of Rivet

- **Our vision for Rivet is as a standard toolkit for "particle truth level" observables of all kinds, across collider physics**
- Not just standalone, but as a library that can be leveraged in pheno & experiment frameworks, too: standard MC definitions, seamless systematics handling, etc.
- At its core Rivet is 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 coherence and 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

And how!

I hope I've convinced you that lightweight analysis preservation isn't just some tech nerdery or admin overreach!

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 R3 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
  - Tuning
  - PDF studies, EFT, global BSM fits…
- 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 us!**