MCnet CEDAR

Tools and e-infrastructure for MC event generation

Key4HEP/MCnet workshop, DESY, 5-6 Dec 2024

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Introduction

CEDAR was the name for the not-directly-MC-development bit of the MCnet European networks — including “user” connections to MC from both experiment and theory

The name and original direction are from a UK e-science project that pre-dated MCnet, and created Rivet, modern HepData, and HepForge

MCnet itself is a community organisation rather than funded network now — but see CERN/LPCC-funded studentships

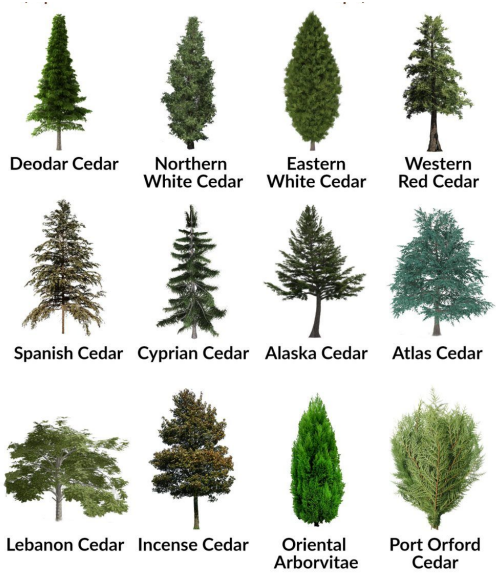
CEDAR remains active and current via

- tools projects, e.g. Rivet, YODA, Professor, Contur, LHAPDF, HepMC, etc.;
- MC standards development and coordination;
- and funded work on HEP computational efficiency, e.g. UK SWIFT-HEP

Main CEDAR activities

As a “project that doesn’t exist”, it’s hard to give an official task list! But…

- Systematics multi-weight propagation & weight standardisation
- Rivet analysis preservation and data reuse (cf. sustainability)
- Professor MC tuning, Contur analysis reinterpretation
- HepMC, heputils, etc.
- LHAPDF PDF library and interpolator
- SWIFT-HEP exascale and performance improvements
- ML preservation and OpenMAPP e-infrastructure
- new: reweighting extensions, specialist-decay interfacing, …



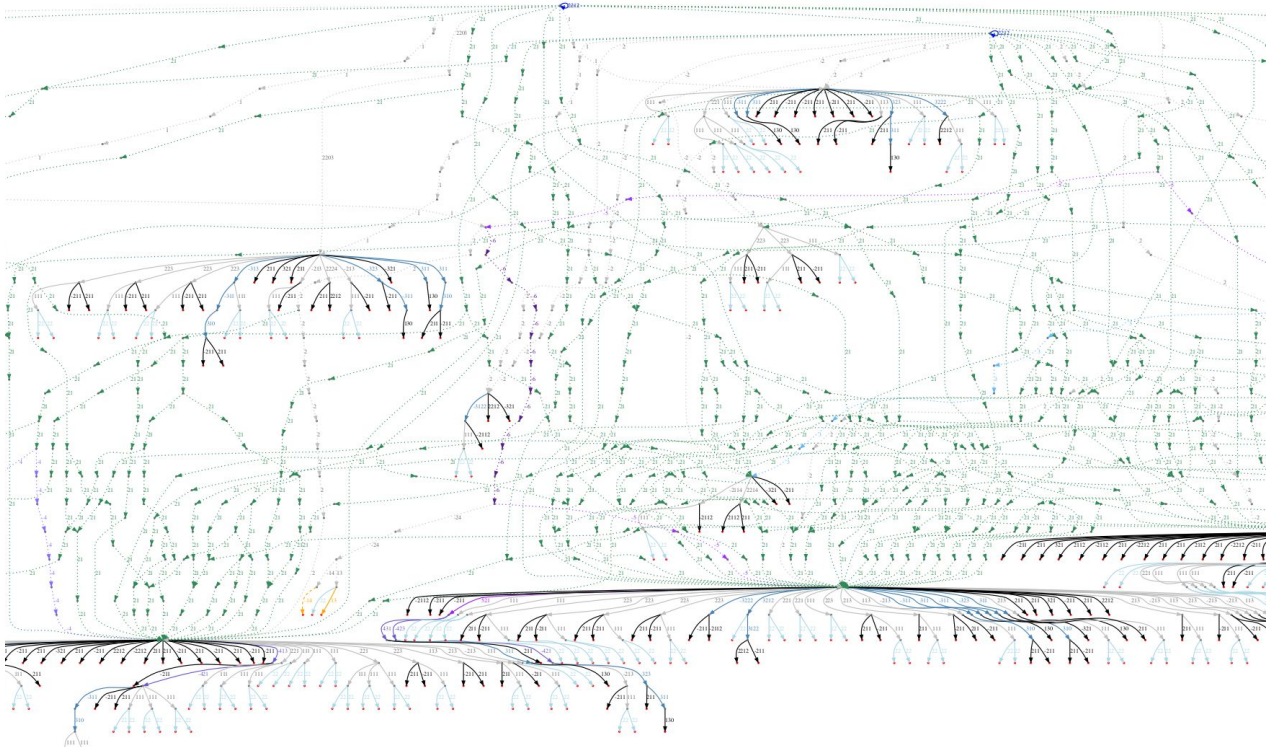
Also participation in MCnet governance, training activities e.g. MC schools, priority-setting and lobbying (e.g. for MC-expert and research-software career paths and funding)

HepMC3 (+ LHE, etc.)

Universal event-record library: graph representation and algorithms, plus I/O

Not 100% a CEDAR project: support status actually unclear!

v3 untangles many historic issues, adds extensibility, but performance needs focus and a tools infrastructure also needed



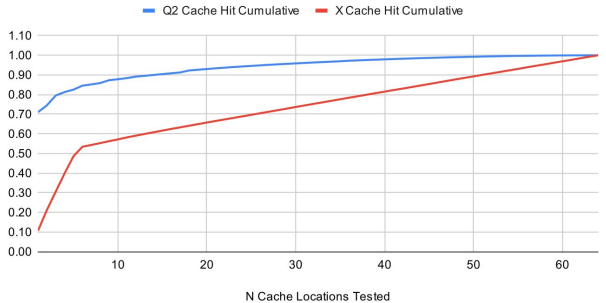
LHAPDF

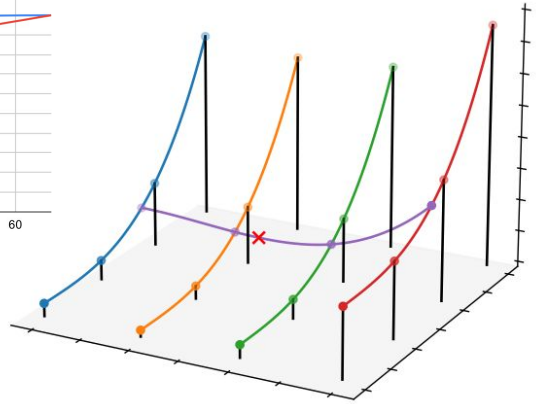
Updated, dynamic-memory evolution of the historic PDFLIB -> LHAPDF5 to meet Grid requirements

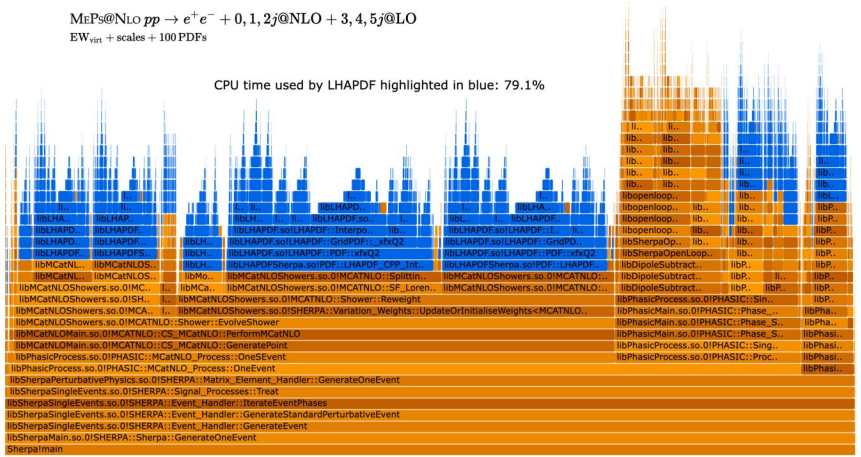
Re-engineered with single data format, no/minimal set-specific code

Interpolation via local polynomials: quite optimised but fundmentally limited. Higher derivatives not continuous
⇒ some issues for N3LO calculations

New spline interpolation and GPU implementation coming soon…



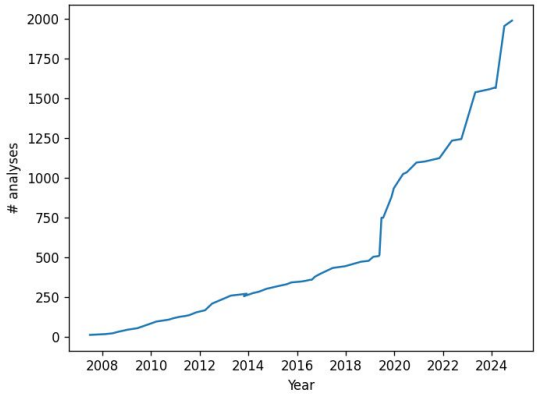




Rivet+YODA

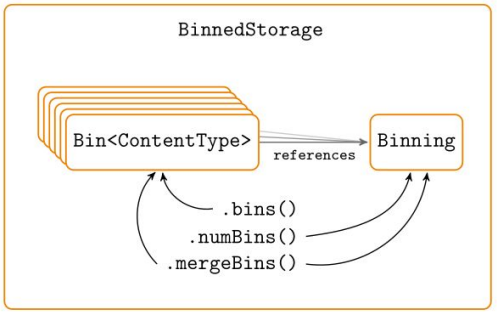
Rivet is a library / toolkit for MC event analysis, successor of DESY HZTOOL; developed for validation, extended many times

- Current version = 4.0.2 (aim for 3-monthly release cycle)
- Just short of 2,000 included analyses (!)
- Transparent weight streaming, standard “truth” observables, automatic calculation-caching, and detector “smearing”
- Emphasis on ***fiducial analysis*** ⇒ the “modern way”!
- Official analysis logic preservation for LHC experiments



YODA: histogramming and stats library

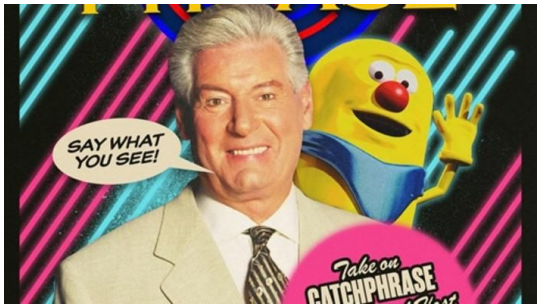
- smaller and more mathematically consistent than ROOT
- C++ and Python interfaces
- separates content from style, designed for reproducibility

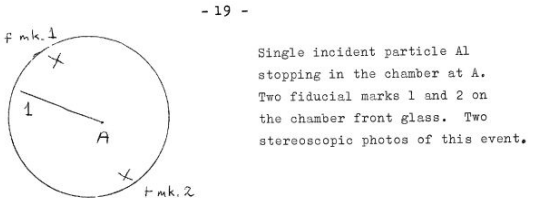


Fiducial analysis

A simple/obvious idea: 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

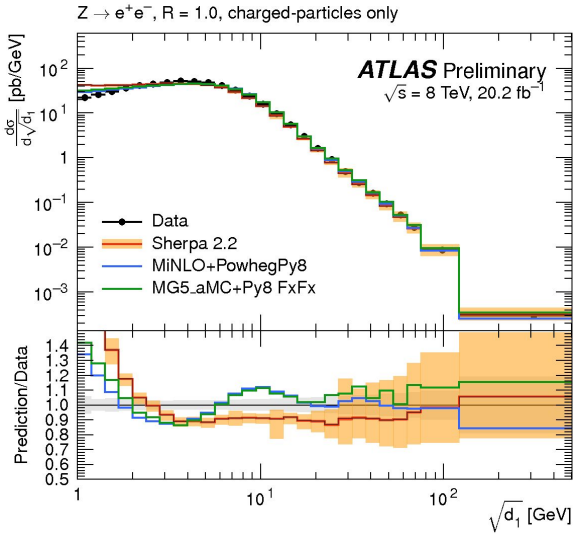
MC performance and scalability

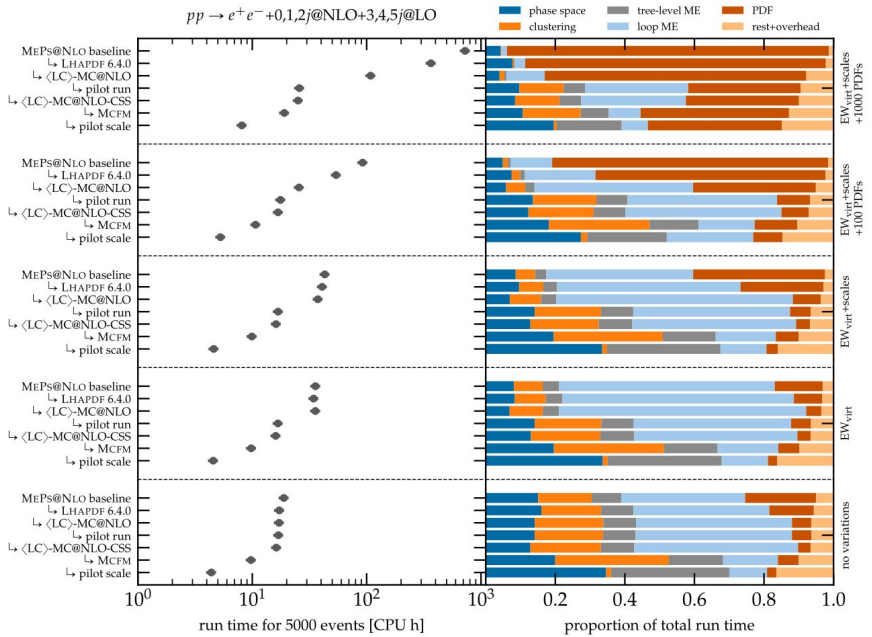
Multi-weighting methods and standardisation, cf. arXiv:2203.08230

SWIFT-HEP project has worked “with” CEDAR to improve precision MC-gen performance by factors > 10; future developments → HPC/Grid hybrid flow

And don’t forget (smart) weighting and enhancement as a strategy for efficiency!

⇒





Professor and Contur

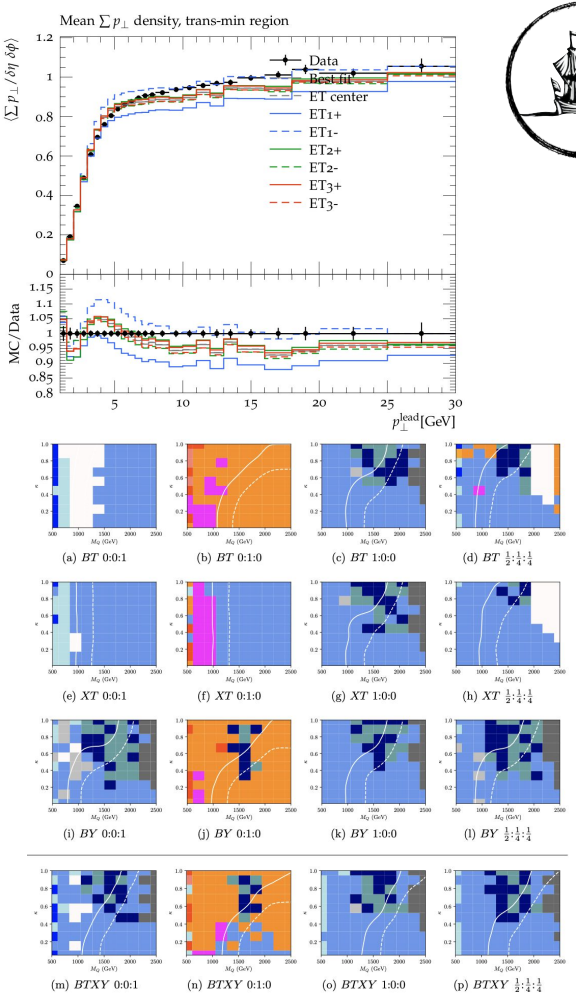
Two tools built on use of Rivet+YODA for physics studies:

Professor is a system for scalable objective tuning of MC generators (and any parametrised model that uses them, e.g. PDF-fitting)

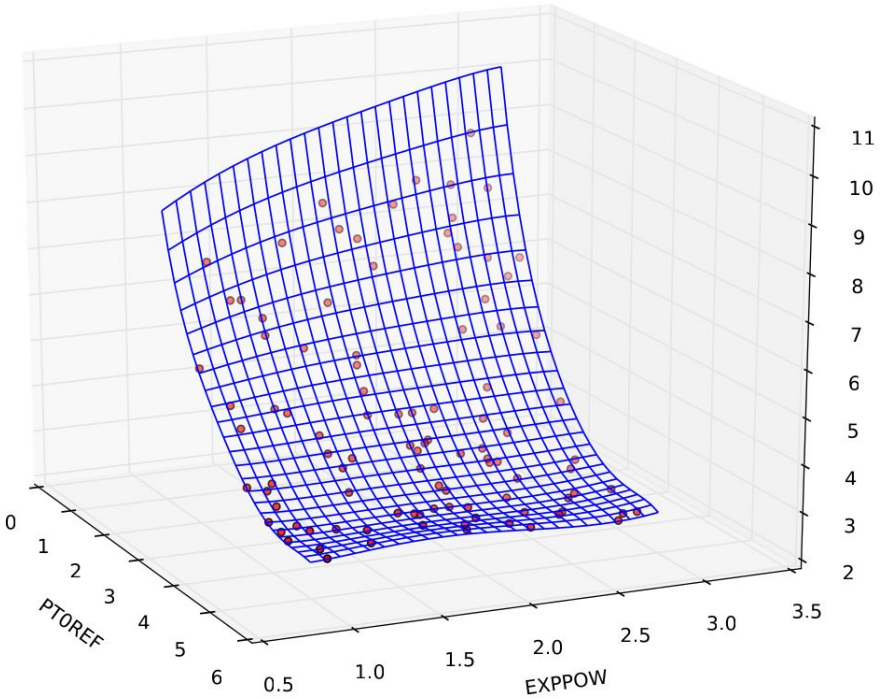
- the scalability refers to use of a priori scans to build fast surrogate models/losses that can be minimised
- used for majority of LHC-era MC tunes

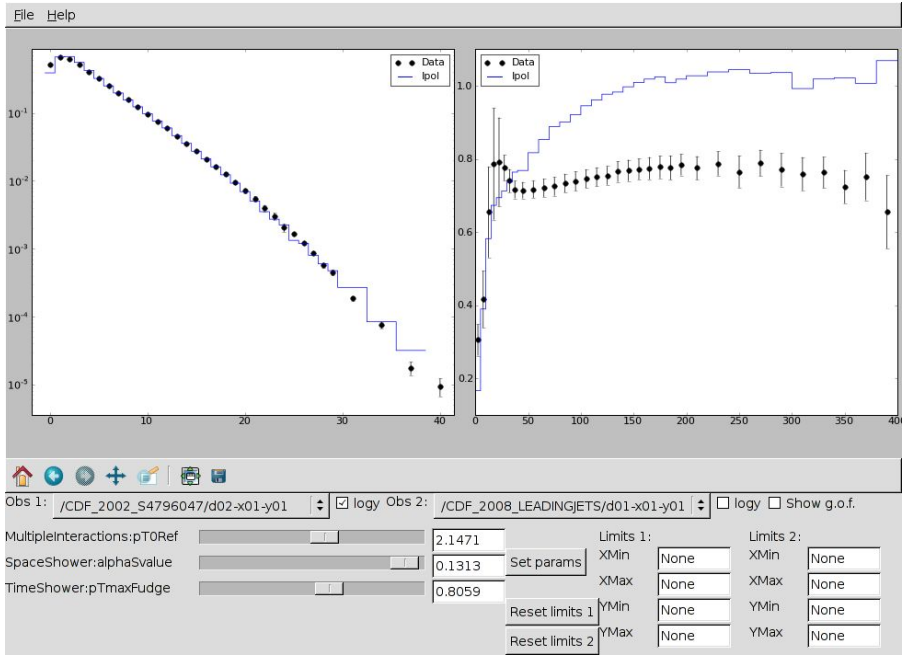
Contur is a toolkit using Rivet's analysis collection to place model-independent limits on new physics models, as a complement / precursor to dedicated searches

- now seeing active use in ATLAS BSM simulation

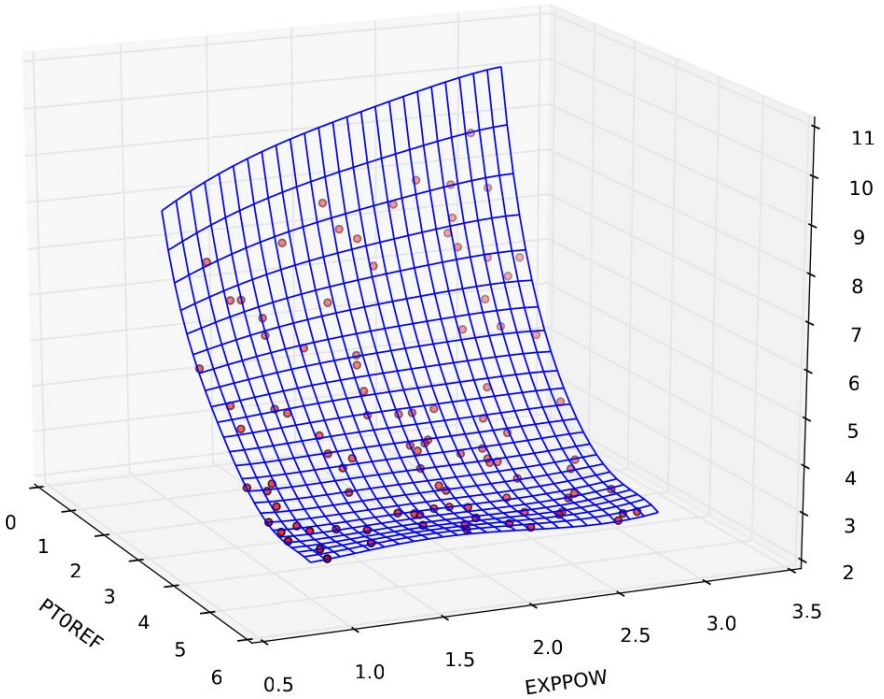


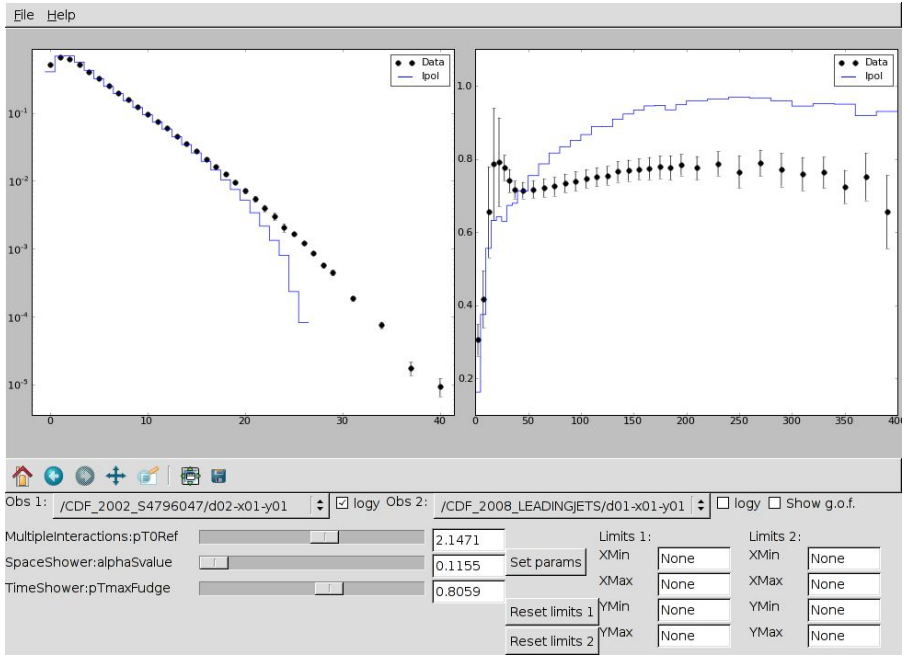
Professor examples





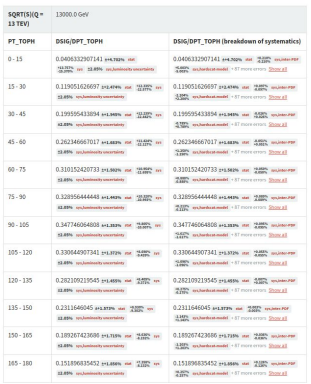
Professor examples

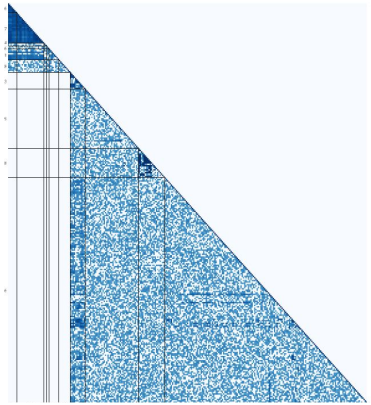


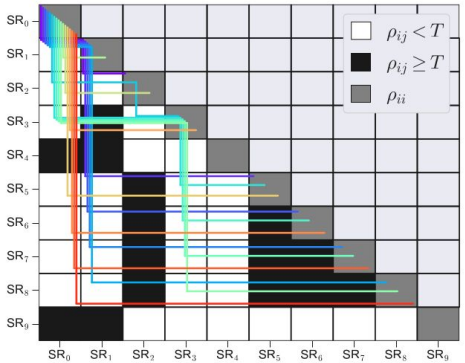


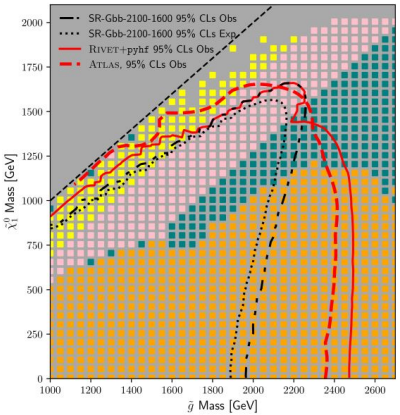
Reinterpretation

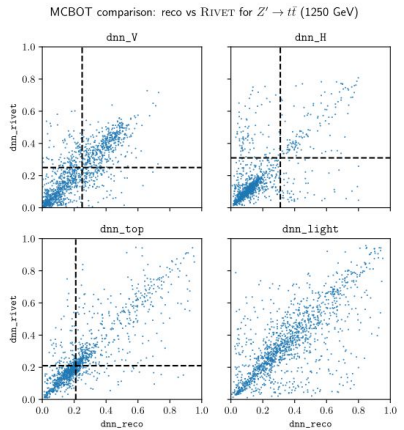
CEDAR tools central to analysis re-interpretation, and still on leading edge of tool and technique developments, e.g. Contur and TACO, and upgrading of “e-infrastructure” like HEPData via the OpenMAPP project











from Tomasz Procter thesis

Summary

CEDAR is an important part of MCnet's engagement with the LHC experimental and pheno communities

Several projects from small to medium size, and far more ideas than we have people to implement. A great way to get students started in MCnet work, or as a component of MC theory PhDs.

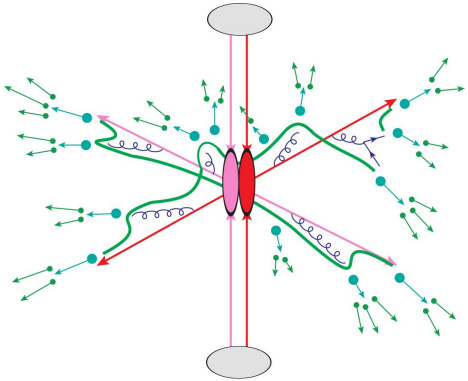
Activity in BSM analysis preservation, BSM recasting, statistics, tuning, PDFs, performance and more. Lots of expertise in MC mechanics, workflows, and tool-engineering.

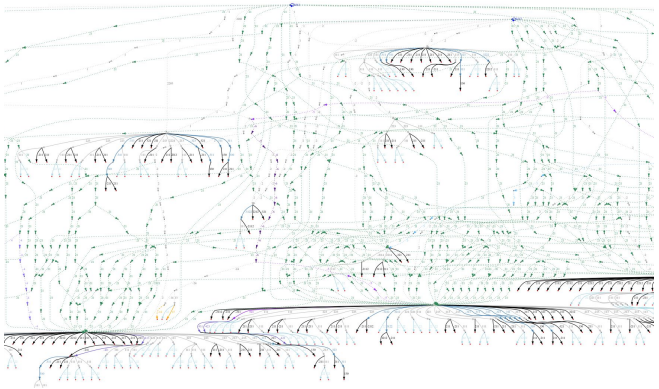
But we have big resources problems: need to find ways (more (co-)publications, career benefits, other rewards?) to incentivise students etc. to join projects… over to you!

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





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.

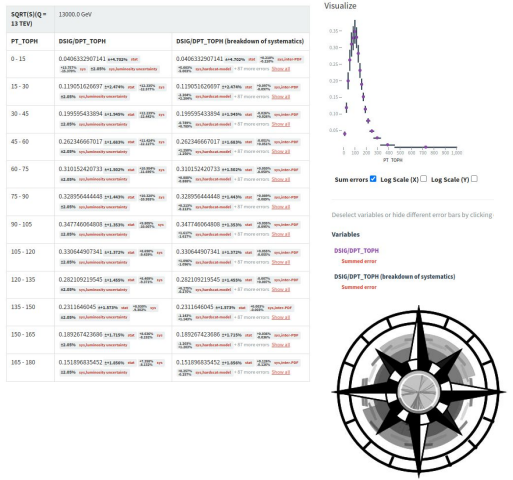
Waleed Abdallah,[1,2] Shehu AbdusSalam,[3] Azar Ahmadov,[4] Amine Ahriche,[5,6] Gaël Alguero,[7] Benjamin C. Allanach,[8,*] Jack Y. Araz,[9] Alexander Arbey,[10,11] Chiara Arina,[12] Peter Athron,[13] Emanuele Bagnaschi,[14] Yang Bai,[15] Michael J. Baker,[16] Csaba Balazs,[13] Daniele Barducci,[17,18] Philip Bechtle,[19,*] Aoife Bharucha,[20] Andy Buckley,[21,†] Jonathan Butterworth,[22,*] Haiying Cai,[23] Claudio Campagnari,[24] Cari Cesarotti,[25] Marcin Chrzaszcz,[26] Andrea Coccaro,[27] Eric Conte,[28,29] Jonathan M. Cornell,[30] Louie D. Corpe,[22] Matthias Danninger,[31] Luc Darmé,[32] Aldo Deandrea,[33] Nishita Desai,[34,*] Barry Dillon,[34] Caterina Doglioni,[35] Matthew J. Dolan,[36] Juhi Dutta,[1,36] John R. Ellis,[37] Sebastian Ellis,[38] Farida Fassi,[39] Matthew Feickert,[40] Nicolas Fernandez,[40] Sylvain Fichet,[41] Thomas Flacke,[42] Benjamin Fuks,[43,44,*] Achim Geiser,[45] Marie-Hélène Genest,[7] Akshay Ghalsasi,[46] Tomas Gonzalo,[13] Mark Goodsell,[43] Stefania Gori,[46] Philippe Gras,[47] Admir Greljo,[11] Diego Guadagnoli,[48] Sven Heinemeyer,[49,50,51] Lukas A. Heinrich,[11,*] Jan Heisig,[52,*] Deog Ki Hong,[53] Tetiana Hryn'ova,[54] Katri Huitu,[54] Philip Ilten,[55] Ahmed Ismail,[56] Adil Jueid,[57] Felix Kahlhoefer,[58,*] Jan Kalinowski,[59] Jernej F. Kamenik,[60,34] Deepak Kar,[61] Yevgeny Kats,[62] Charanjit K. Khosa,[63] Valeri Khoze,[64] Tobias Klingl,[19] Pyungwon Ko,[65] Kyoungchul Kong,[66] Wojciech Kotlarski,[67] Michael Krämer,[26] Sabine Kraml,[7,†] Suchita Kulkarni,[68,*] Anders Kvellestad,[69,70,*] Clemens Lange,[11,*] Kati Lassila-Perini,[71] Seung J. Lee,[72] Andre Lessa,[73,*] Zhen Liu,[74] Lara Lloret Iglesias,[49] Jeanette M. Lorenz,[75] Danika MacDonell,[76] Farvah Mahmoudi,[10,11,*] Judita Mamuzic,[77] Andrea C. Marini,[78] Pete Markowitz,[79] Pablo Martinez Ruiz del Arbol,[80] David Miller,[80] Vasiliki A. Mitsou,[77] Stefano Moretti,[81,82] Marco Nardecchia,[37] Siavash Neshatpour,[10] Dao Thi Nhung,[83] Per Osland,[84] Patrick H. Owen,[85,*] Orlando Panella,[86] Alexander Pankov,[87]

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

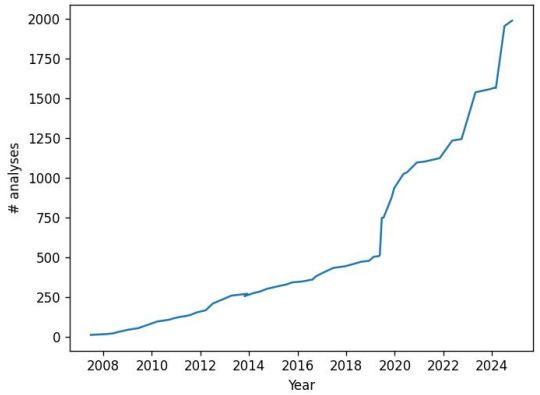
Reinterpretation tools (2)

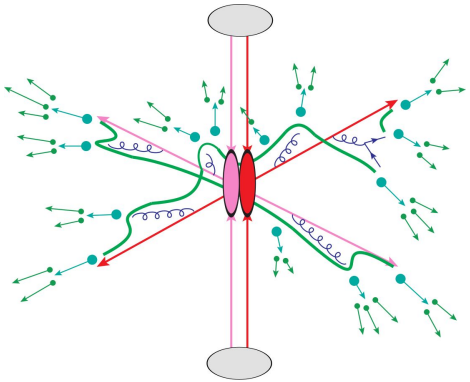
- **Main data-source is HEPData.** Standard for LHC, less beyond
  - Stores numerical "primary data", i.e. histograms, event counts in signal regions, errors & correlations
  - Also "new" push to store experiments' theory estimates, especially super-expensive precision SM backgrounds
- **Statistical 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
- **Focus here on Rivet**, for (my) familiarity but most ideas apply generally; different tools ⇒ different focuses



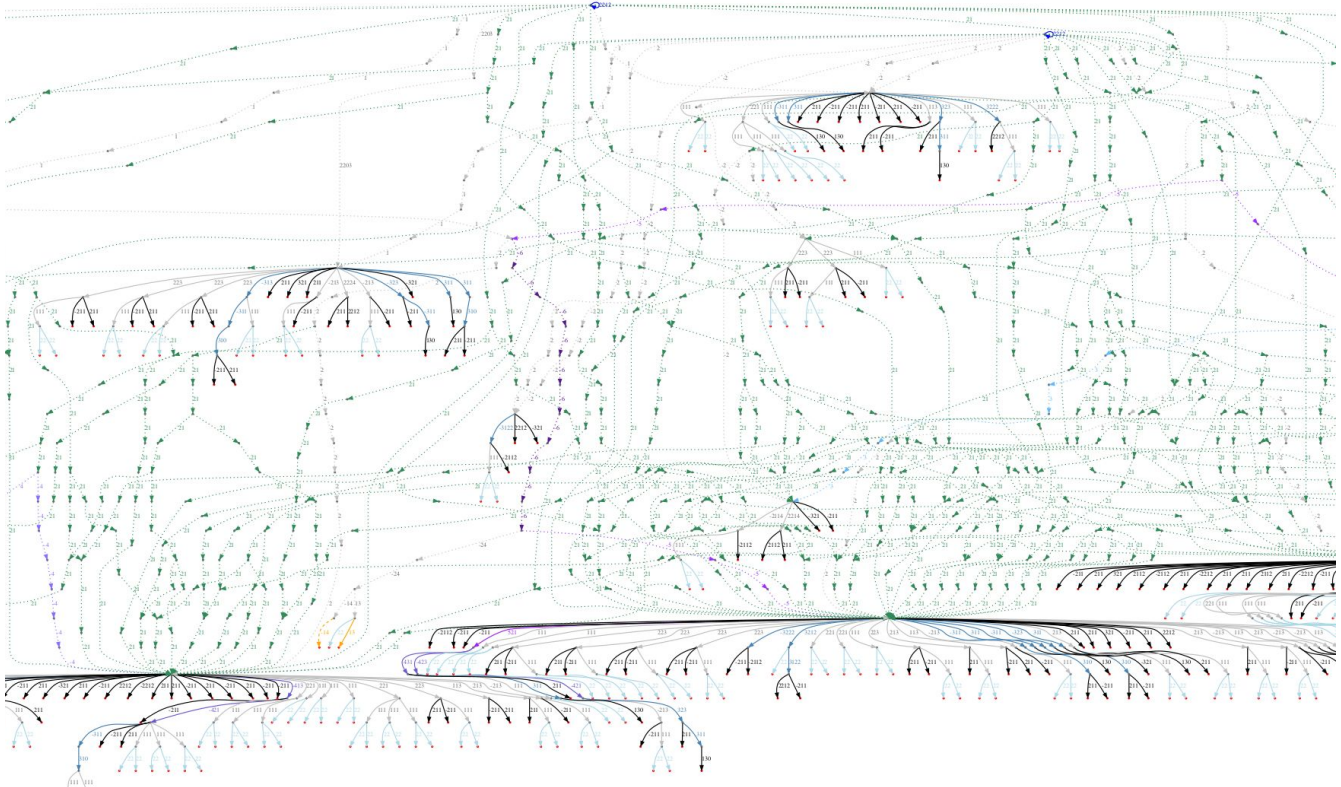
What is Rivet?

- **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*!



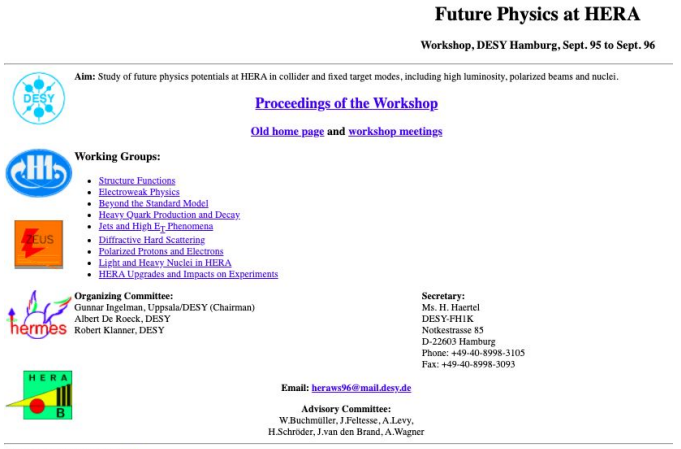
⇐ ~⅓ of an LO tt event

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



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
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Advisory Committee:
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H.Schröder, J.van den Brand, A.Wagner

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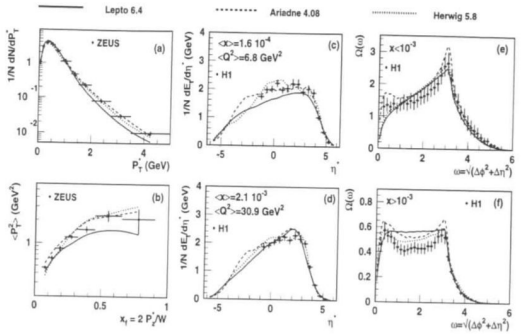
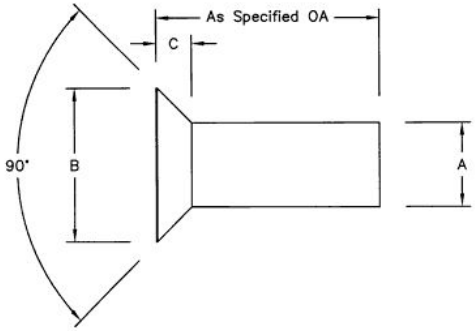


Figure 1: *The transverse momenta dN/dp_T (a) and the 'seagull' plot $\langle P_T^2 \rangle \times x_F$ (b) of single particles in the positive hemisphere of the hadronic center of mass. The transverse energy flow $dE_T/d\eta$ in a low (c) and high (d) x and Q^2 bin. The transverse energy-energy correlations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

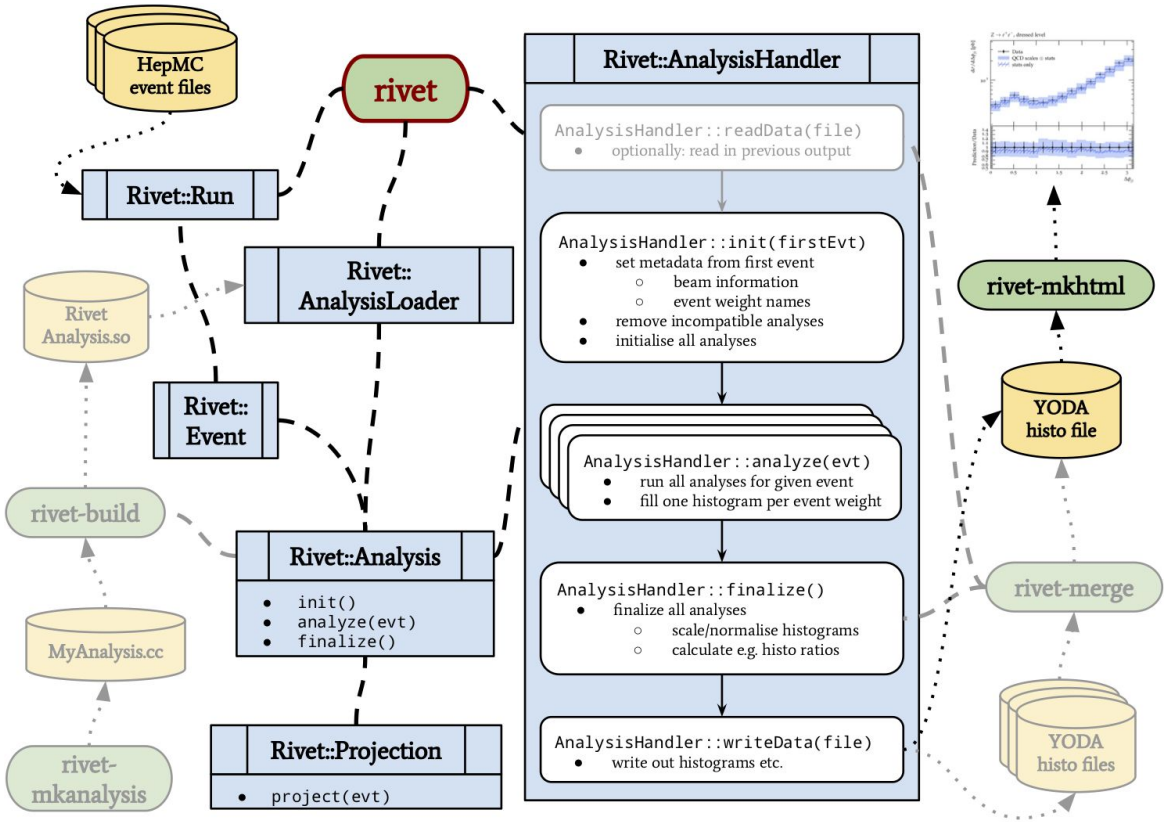
Designing Rivet

- **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**



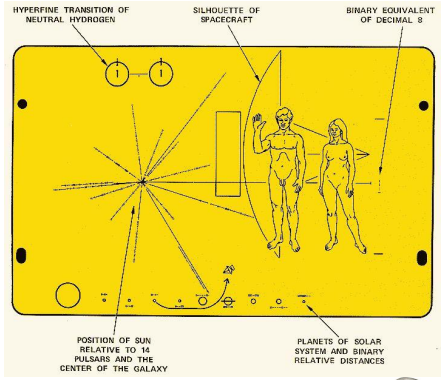
The result

- 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…



Lessons learned from HZTOOL

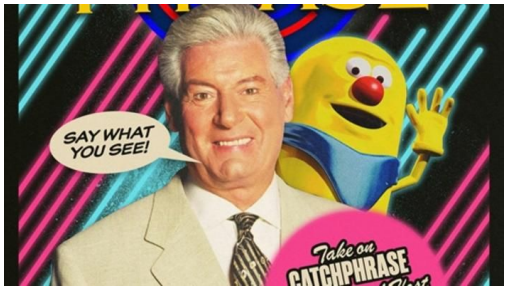
- **A simple/obvious idea, with surprising impact:**
  - Reproducing (or not) a key plot is *powerful*
  - A clear basis for concluding whether or not models agree with each other and with data. Numbers > adjectives!
  - **A *common language* for phenomenology and experiment**
- **Practicality forces 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

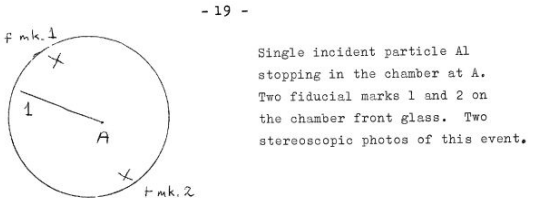


Pioneer plaque

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



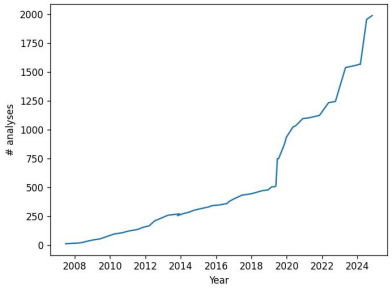


- **Analysis lifetime is maximised by not being model-specific**
  - E.g. HH-production signal-strength at HL-LHC has ~40% theory uncertainty from m_t scheme. No theory resolution in sight. But fiducial cross-section is unaffected

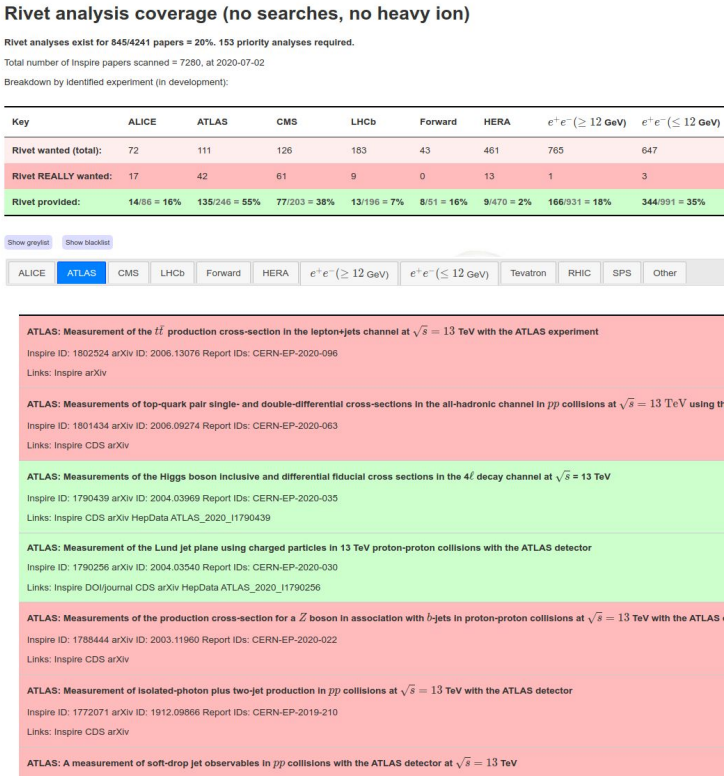
How's it going?

- **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 $\sqrt{s} = 13$ TeV using t
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

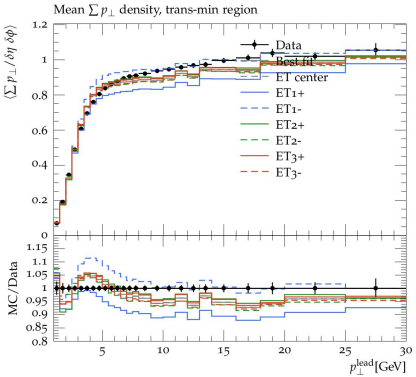
ATLAS: A measurement of soft-drop jet observables in pp collisions with the ATLAS detector at $\sqrt{s} = 13$ TeV

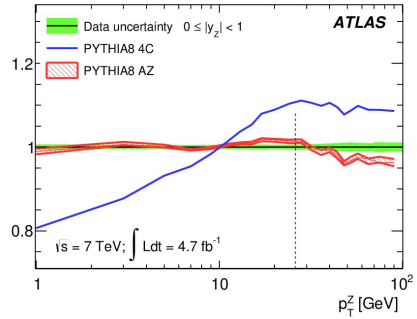
The future of Rivet

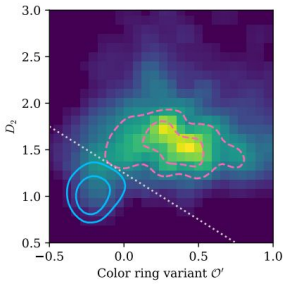
- **Vision: Rivet as a standard for "truth-level" observables, across collider physics**
- Not just standalone, but as a library in pheno & experiment frameworks, too: standard MC definitions (cf. CMS), seamless systematics handling, etc.
- At its core: a physics-oriented system for physicists to **compare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

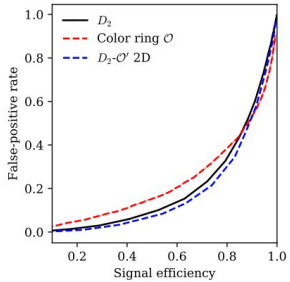
Applications: from tuning to BSM

- **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



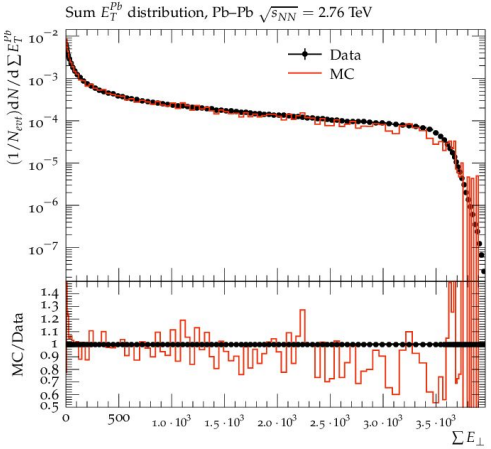


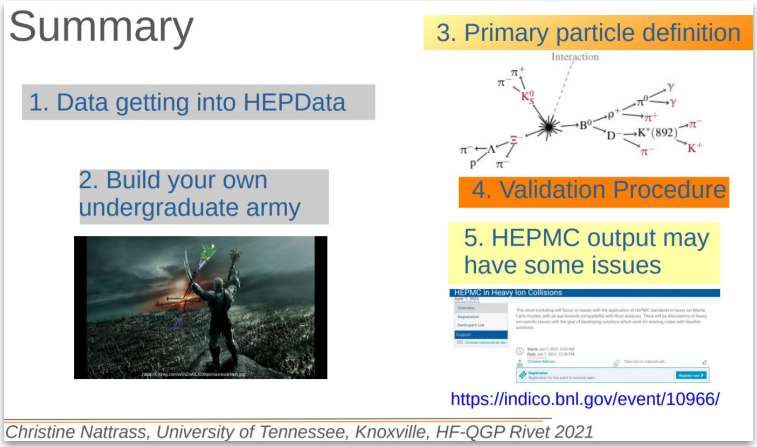




Heavy-ion preservation

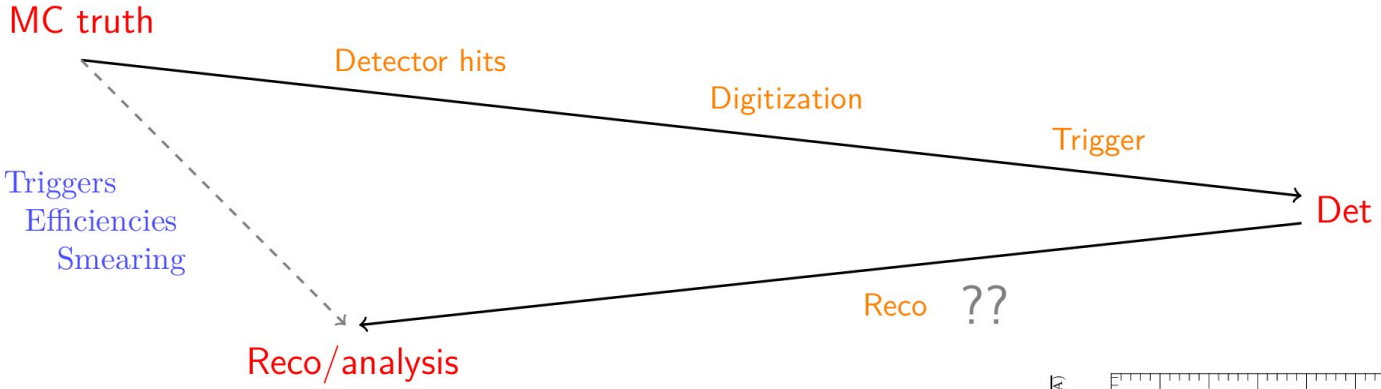
- **Heavy-ion physics is a "frontier":** high-complexity multi-scale event modelling, no current tools that can do everything → flexibility needed
- Again, a concrete tool through which to test against data sharpens discussions, provides a clear metric
- Some really nice community-led initiatives grew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



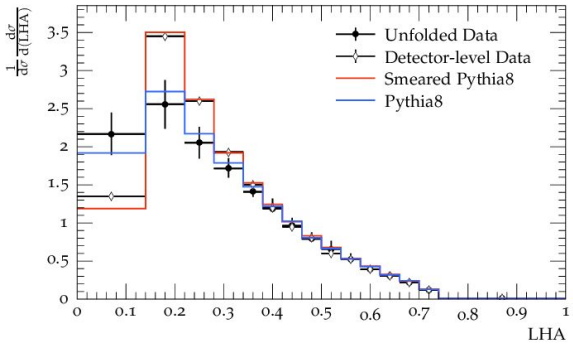


Detector emulation

- **"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**

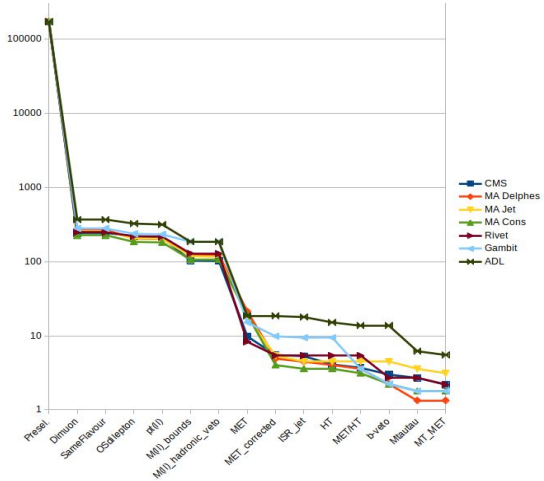


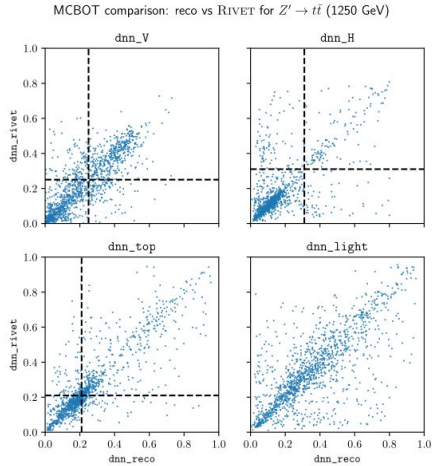
- capture key efficiencies cf. Delphes, but analysis-specific and less "simulation theatre"
- flexibility allows e.g. "tuned" jet-substructure smearing, systematics studies, whatever…



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

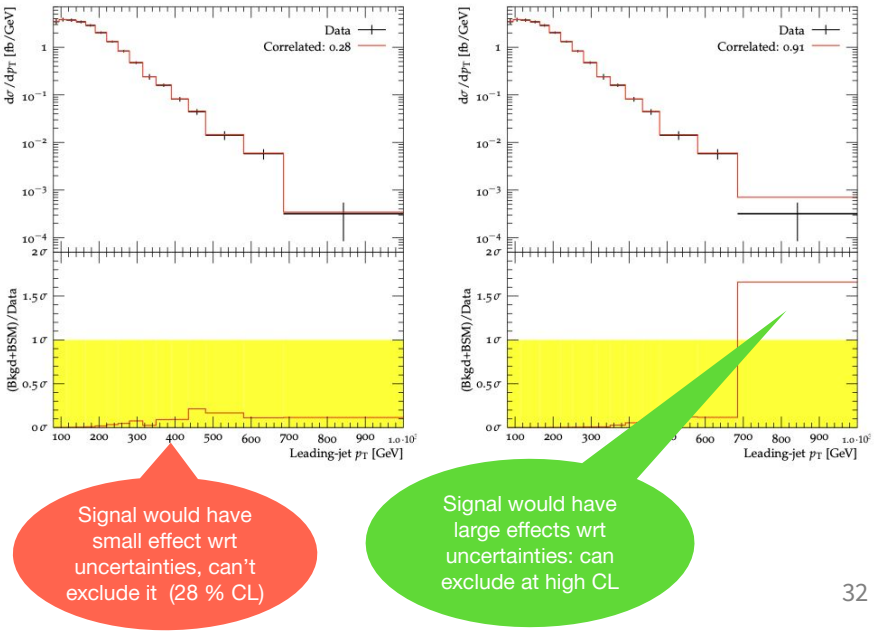




from Tomasz Procter thesis

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!***

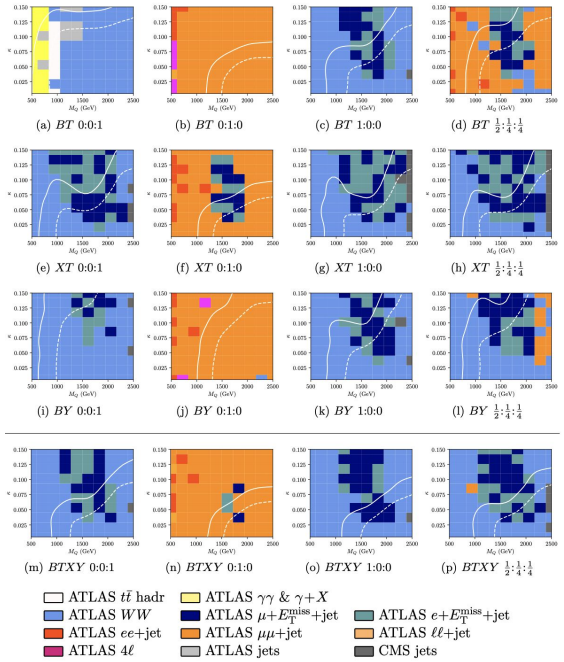


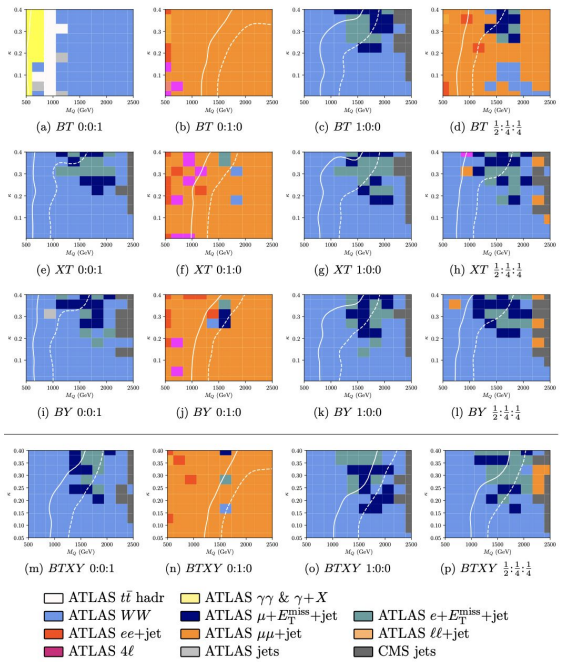
Try doing this with full-sim in finite time…

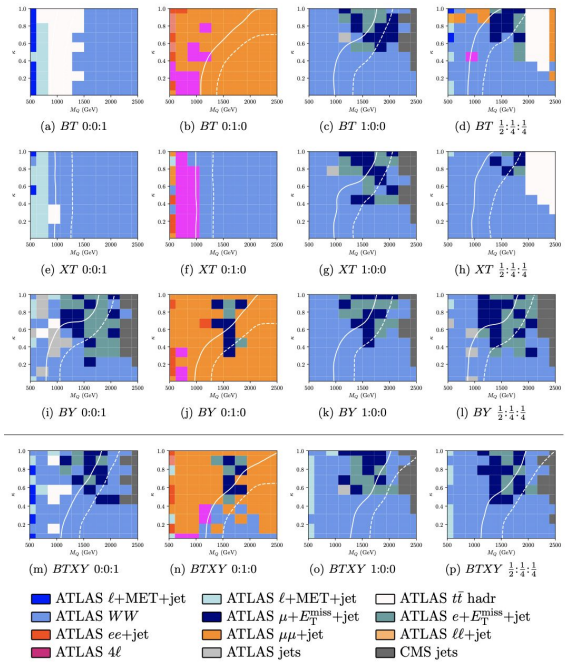
- Contur vector-like quark study on a scan of realistic VLQ multiplets:

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

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

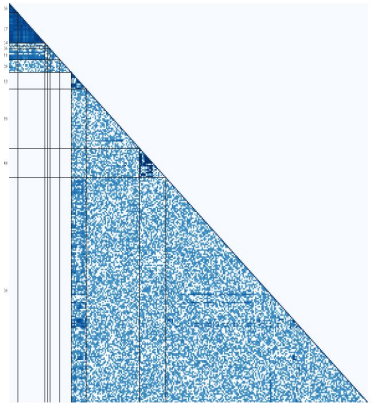




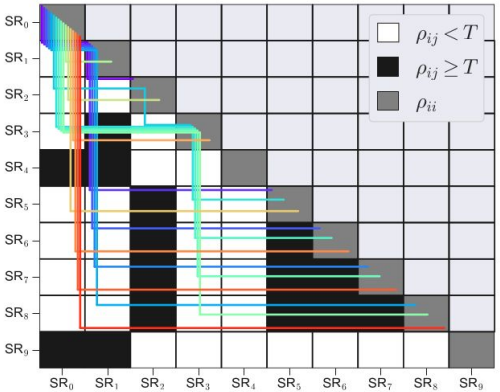


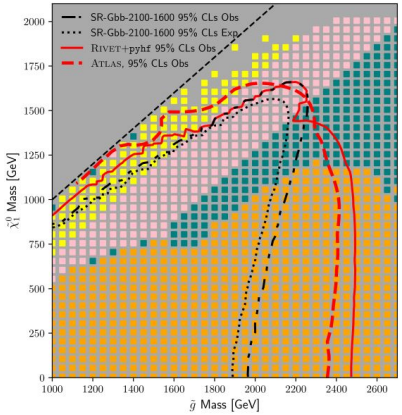
Analysis combinations

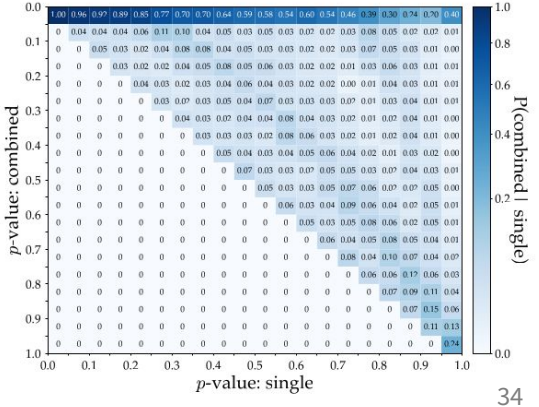
- **One last thing: cannot just naively add all ln*L*'s and draw a mega-limit!**
- Over many (many!) analyses, bins and signal regions, there will be acceptance overlaps ⇒ double-count exclusionary features
- Naive approach is to only use single best-expected bin: what a waste! Lots of exciting work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



from Jamie Yellen & Tomasz Procter theses







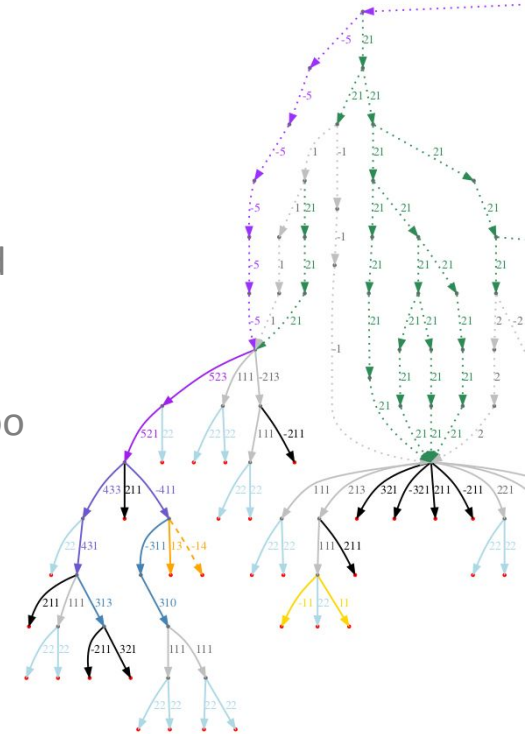
Reinterpretation summary

- **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

Physically safe analysis methods

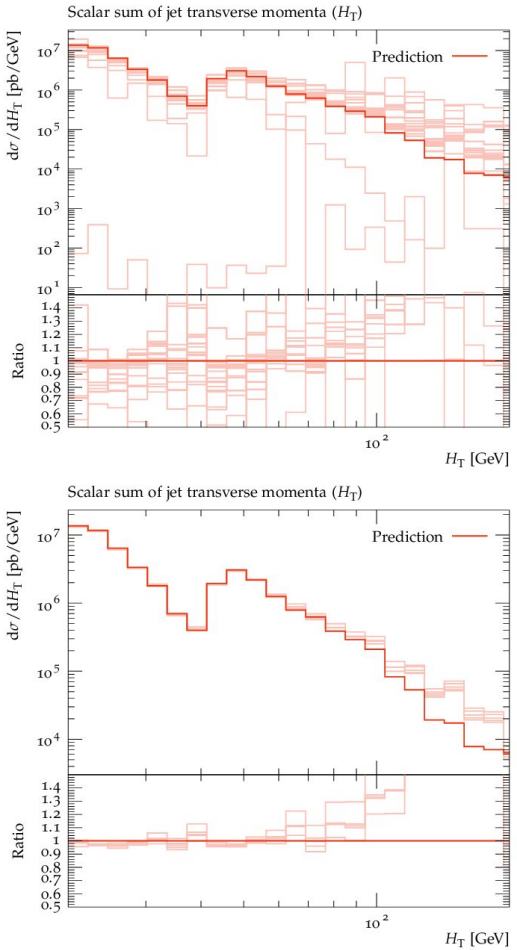
Avoiding unstandardised event-graph features was pragmatic, but led to some physical insights:

- **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



Multiweights and re-entry

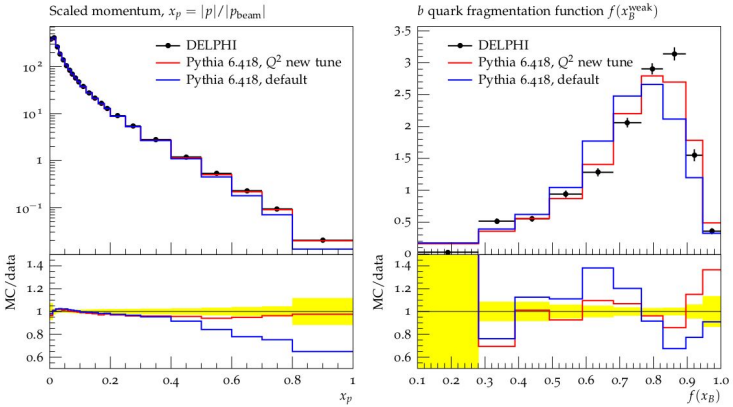
- **MC weight vectors allow expression of increasingly complex theory uncertainties.** But a burden for analysis chains: have to propagate and correctly combine O(200) weight streams!
- **Rivet 3: complex automatic handling of weights** ~invisible to users: data objects *look* like histograms etc. but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

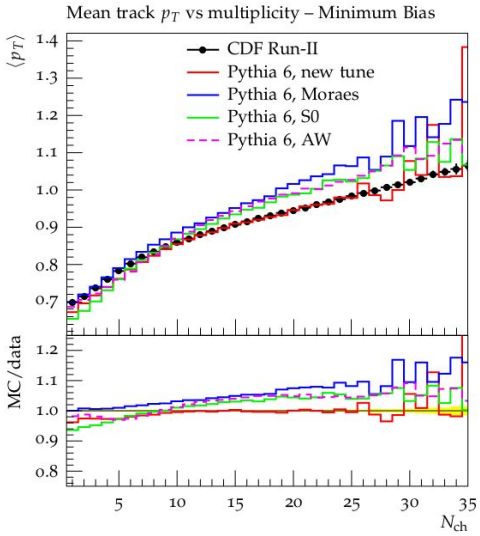


Event generator tuning

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…**





The Professor method

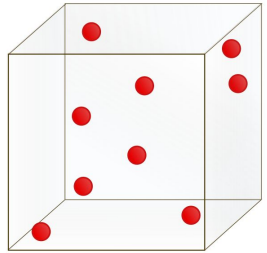
Tuning was historically brute force & inspiration

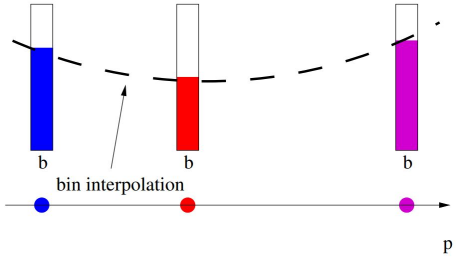
Professor method is an assistant, to aid convergence:

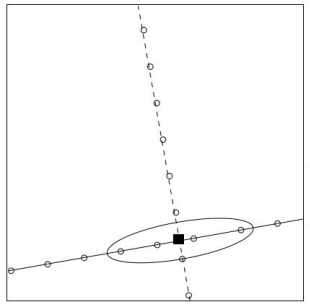
1. Sample (user-)param vectors $\boldsymbol{p}_n$ (from a hypercube/sphere)
2. Generate MC run-sets for beams, processes, etc. at each pt
3. Run *in parallel* on big batch/grid facilities, output histos
4. Build *surrogate models* $\text{bin}_b(\boldsymbol{p})$ from {$\boldsymbol{p}$}, e.g. conventionally a 3rd/4th-order polynomial in $\boldsymbol{p}$. *[Can also interpolate MC errs…]*
5. Use the surrogate models to make a surrogate GoF ⇒ optimize!

Expertise and inspiration still very useful!

What about machine learning? Sure, fine: easy adaptation. But if polynomials work — maybe via a change of variables — they are simple and robust



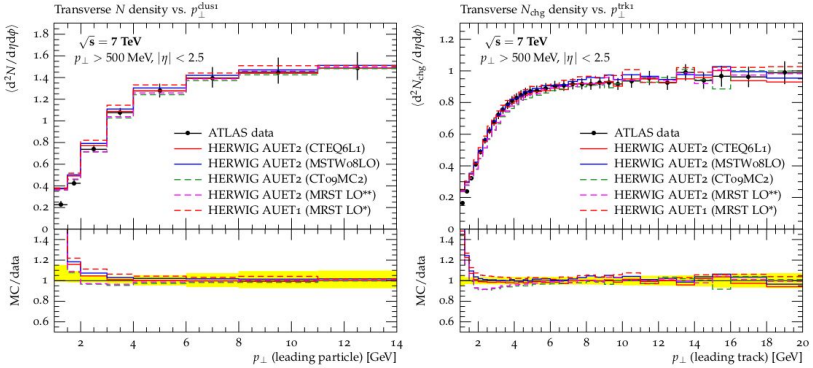


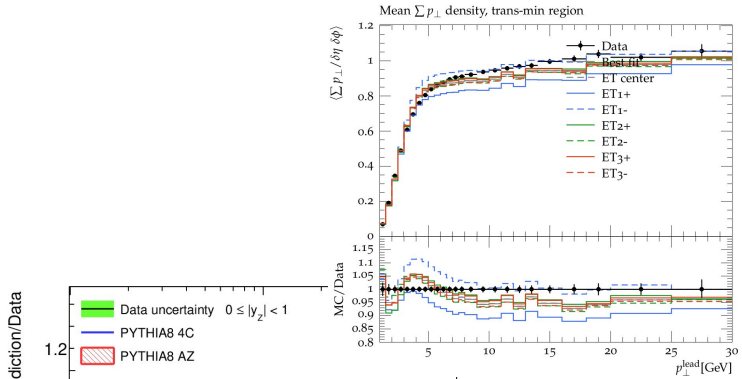


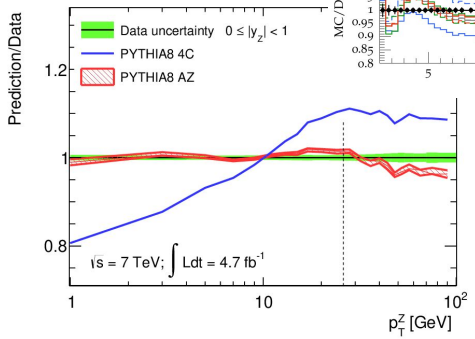
More tuning history

Pre-LHC, the soft QCD uncertainties were *huge*

- **Factor x 2 uncertainty on 7 TeV σ_{tot}!**
- **Feed in to underlying event, pile-up, etc.**
  - Tuning an essential task: better tunes ⇒ better analysis designs, better limits, …
  - Impact: LEP and Tevatron analyses published for ~10 years suddenly got used! And cited…
  - ATLAS AMBT, AUET, AZ, A14 etc. tunes + CMS
  - Rapid responses to preliminary data, changes of model (e.g. Py8 for ATLAS pile-up)
  - Model development: matching & merging, addition of energy evolution & colour-reconnection to Herwig, …







Tactics for tuning

- **Factorise parameter space**
  - Historically split hadron flavours and spectra, jet structure, event topologies, underlying event. Max O(10)
  - Approximate but practical. Can also automate some estimate of factorisation groupings through mutual sensitivities
- **Weighting, observable balance, and uncertainties**
  - Tuning naturally involves some data types more than others: balance?
  - Also, models not capable for fully describing all data bins: check envelopes, sensitivities, limit ranges… and *weight bins*
  - Custom goodness-of-fit function? Regularise, lose statistical interpretation?
  - "chi2" already does not behave classically: *eigentunes*, room for improvement
- **Future work**
  - Heavy flavour, matching/merging, including systematics via weights…