Rivet+Contur: constraining BSM physics with precision collider measurements

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COST School on Dark Matter & Hidden Sectors
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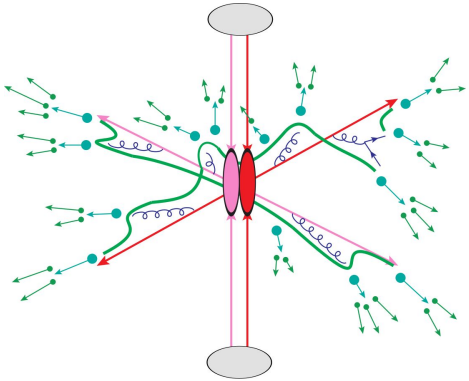
Outline

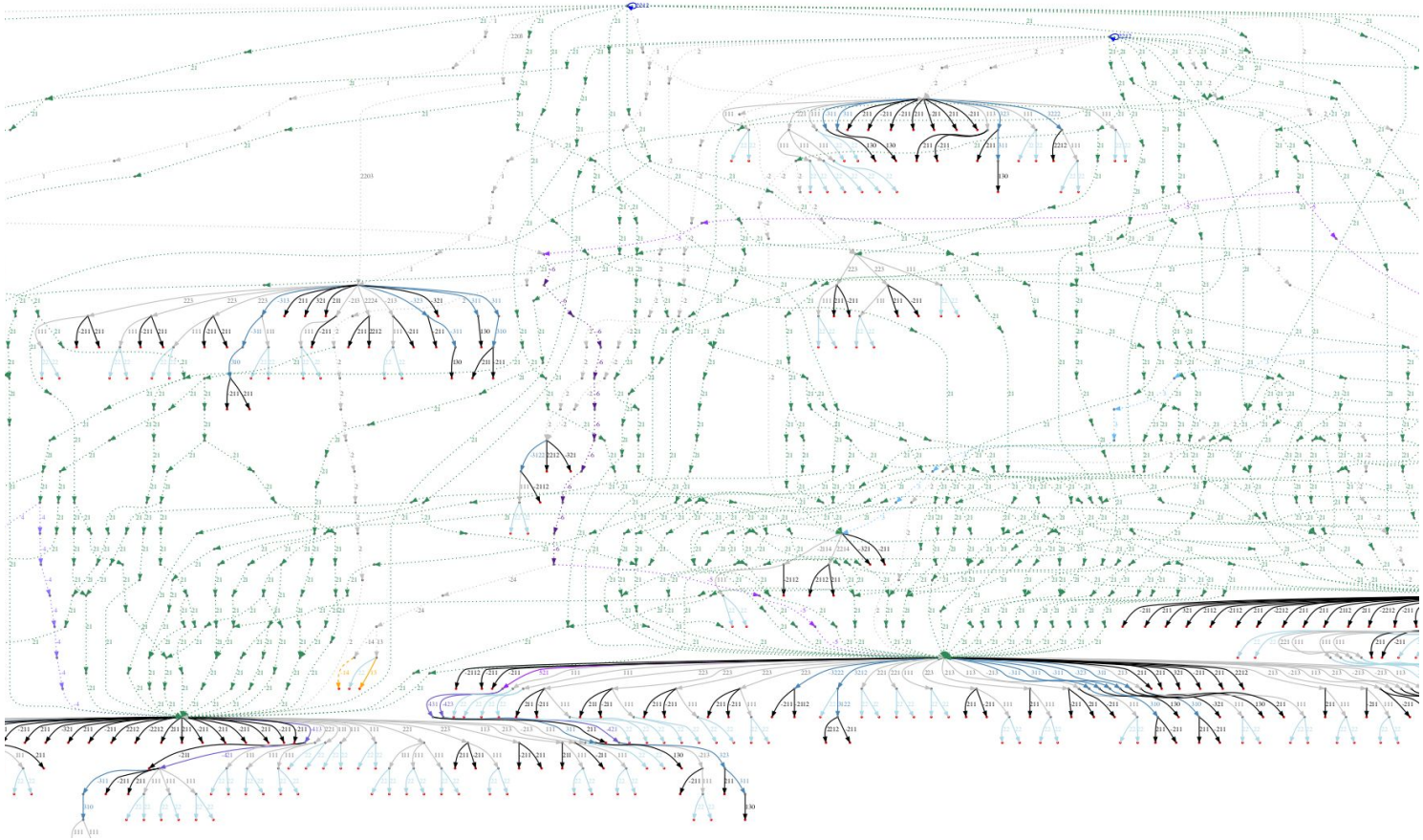
- The Rivet toolkit and project
- Generic analysis preservation
- Retooling for LHC precision
- BSM searches
- Contur
- Case studies
  - Simple vector DM
  - Vector-like quarks
  - Composite dark matter

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 / observable 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**

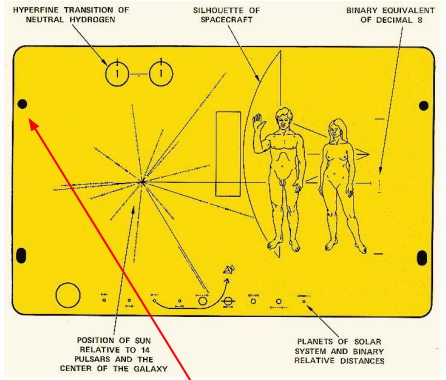


Just part of an *LO* pp event!



Design lessons learned

- **Runnable preserved analyses is a simple/obvious idea, with surprising impact. First implemented in HZTool**
  - Reproducing a key plot (or not) is *powerful*
  - ⇒ *understand physics, communicate issues, improve MCs*
  - *A common language for pheno and experiment*



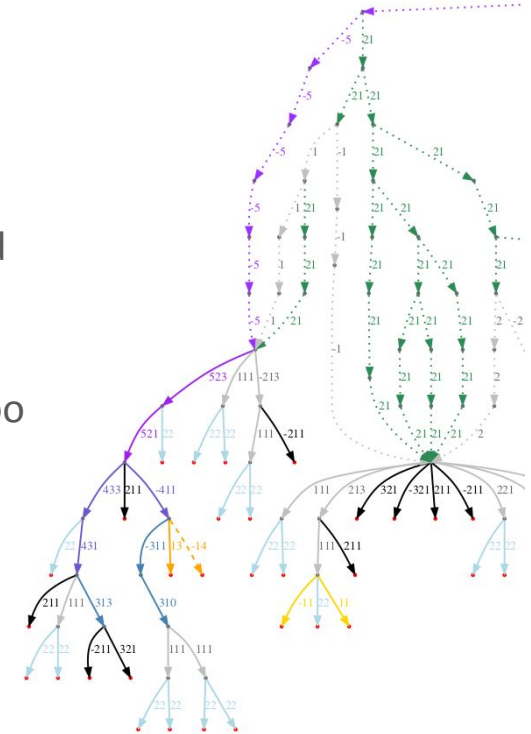
- **But…**
  - Partons, bosons, etc. direct from the event graph are frequently unphysical / depend on approximations / may not even exist!
  - Adding a new generator meant patching ~all analyses!
  - ⇒ predict “real” observables, from well-defined final states
  - experiment needs to be careful in how it defines “corrected” observables, too

- **Boring but important**
  - Standardisation: event format conventions, PDG particle numbering, etc.
  - Scalability: cache, not repeat, lots of expensive operations e.g. jet finding

Physically safe analysis methods

Physical insights from avoiding event-graph overinterpretation:

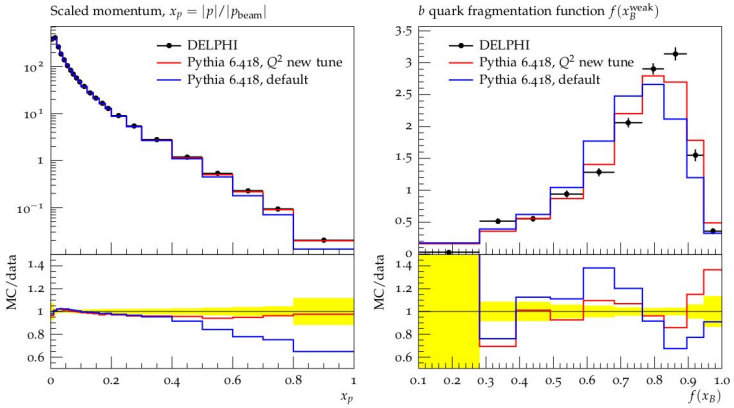
- **refining the "fiducial" idea, defining *unfolding targets***
- **Hadronisation as a "decoherence barrier"**
  use the natural dividing line between the quantum-interfering hard process & semi-classical decays: ~ no tempting partons!
- **Bringing truth tagging closer to reco**
  first releases used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

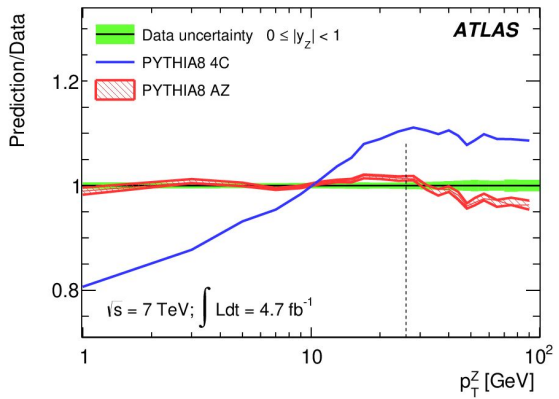


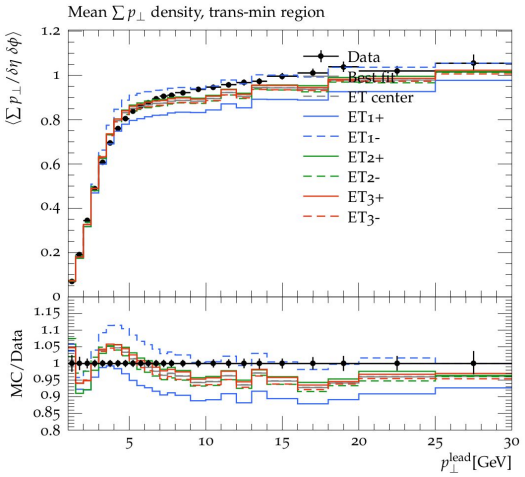
Early applications: tuning

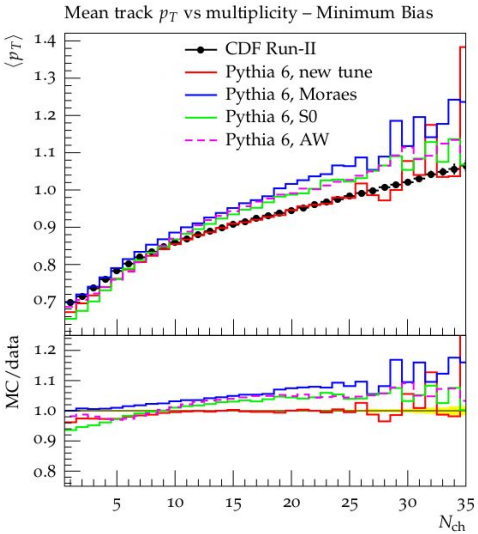
Event generators have dirty secrets. Usually in non-perturbative QCD ⇒ tuning

- “Professor” and ATLAS MC tunes, including the Pythia8 A14 and AZ
- Return to some of this with semi-visible-jet BSM models?





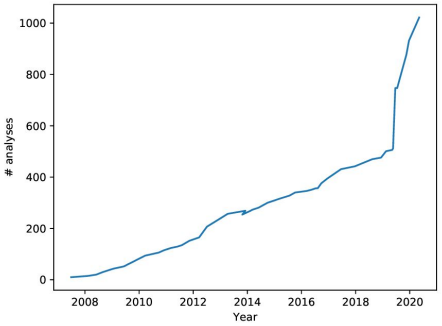




The state we're in

- **Version 3.1.0 crossed the 1000 analysis mark**

  A steady flow of analysis submissions, ~50/year, plus the occasional deluge from Herwig.



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

  preservation has to be part of "how we do science";
  still some way to go ⇒ coverage monitoring:

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

  systematics multiweights, "perfect merging", 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^- (≥ 12 GeV)	e^+e^- (≤ 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^- (≥ 12 GeV) | e^+e^- (≤ 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

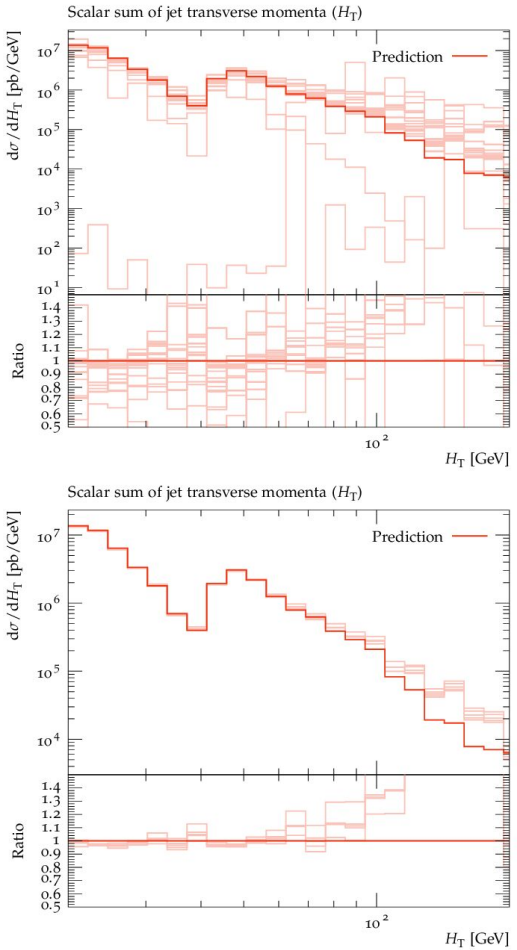
ATLAS: Measurement of isolated-photon plus two-jet production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
Inspire ID: 1772071 arXiv ID: 1912.09866 Report IDs: CERN-EP-2019-210
Links: Inspire CDS arXiv

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

Multiweights and re-entry

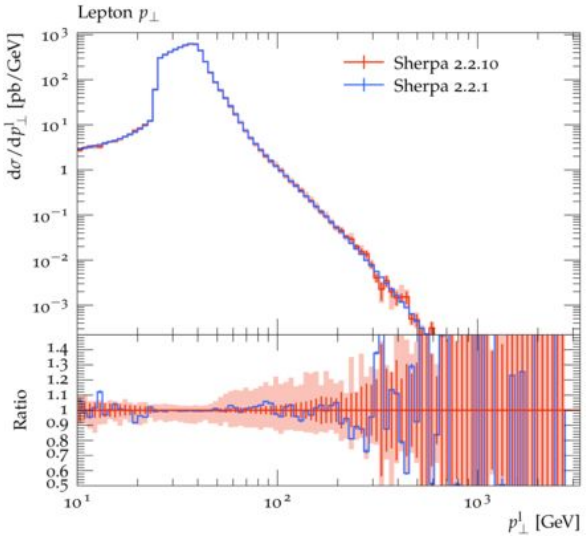
- **MC weight vectors allow expression of increasingly complex theory uncertainties.** But a burden for analysis chains: have to propagate and correctly combine O(200) weight streams!

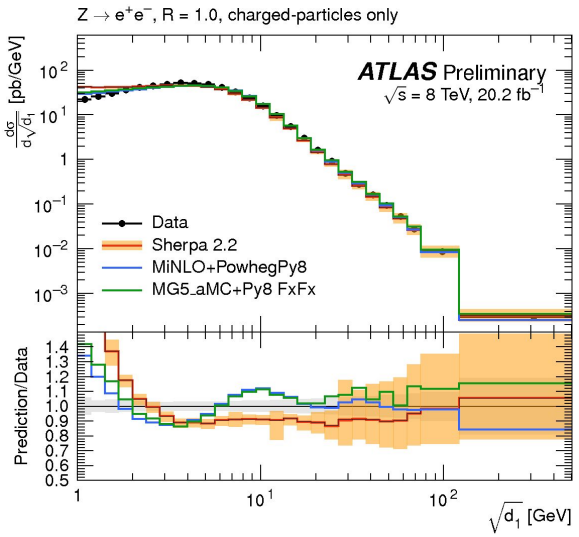
- **Rivet 3: automatic handling of weights**
  ⇒ data objects are secretly multiplexed!
  Not in full use for Contur interpretation yet, but already available
  Also ⇒ “re-entrant” perfect data-object merging

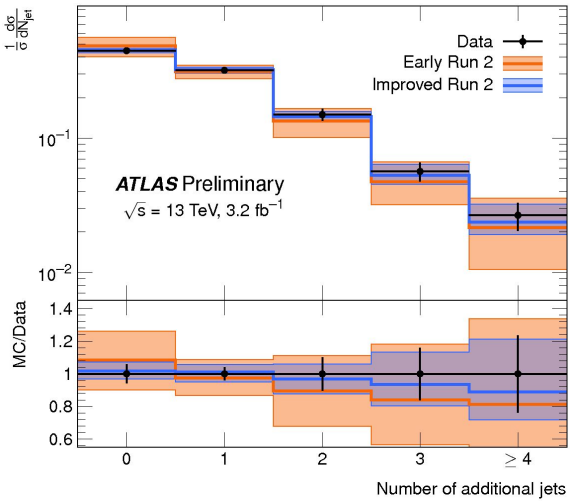


Rivet multiweights in action

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



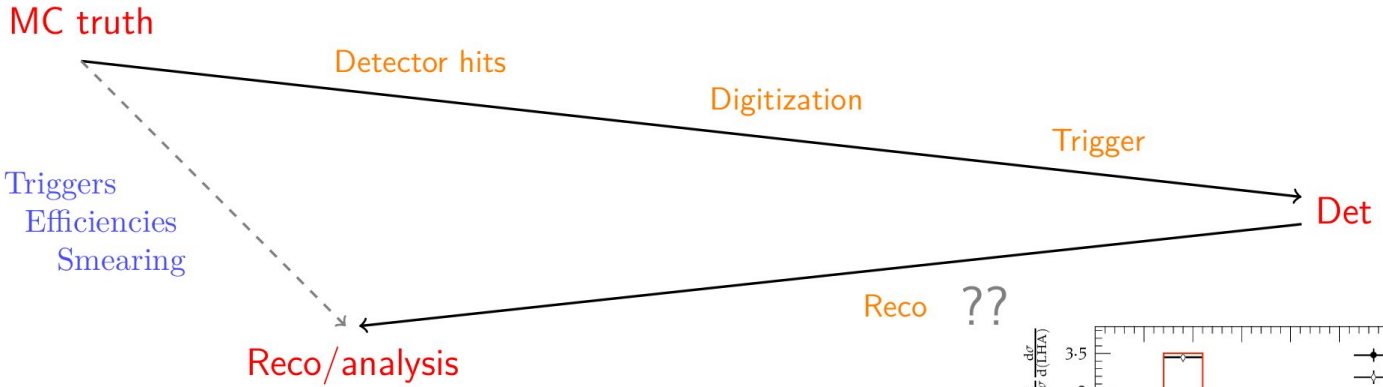




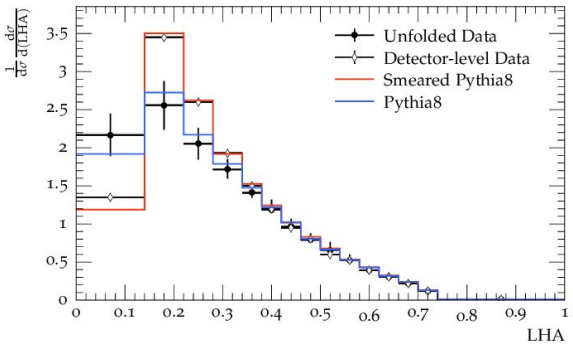
- Weight-naming standardisation underway via MCnet

Detector emulation (an aside from the precision…)

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

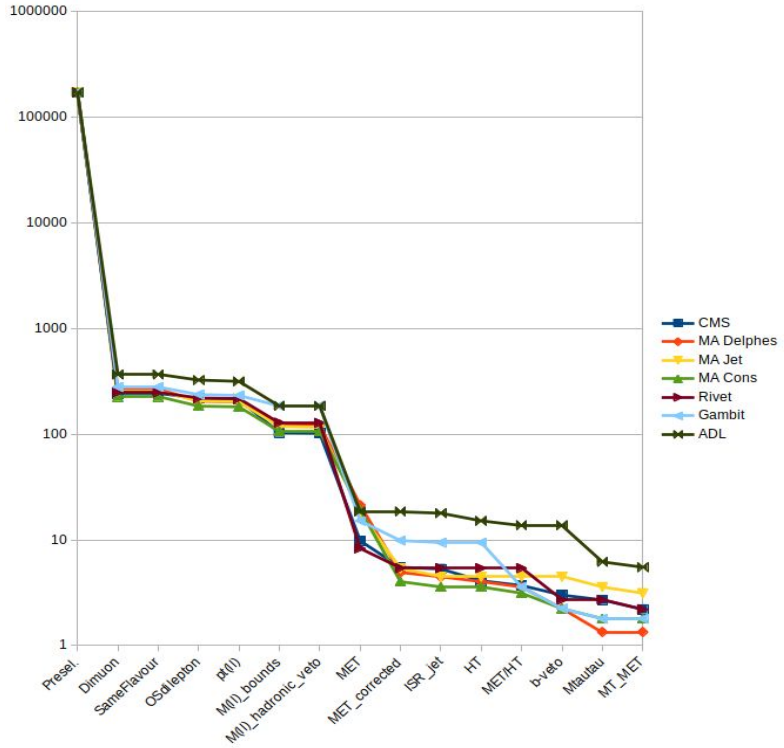


  - like Delphes, but more flexible & can be *analysis-specific* ⇒ MA5 "SFS" mode
  - flexibility allows e.g. "tuned" jet-substructure smearing, systematics studies, …



Rivet and BSM-search recasting

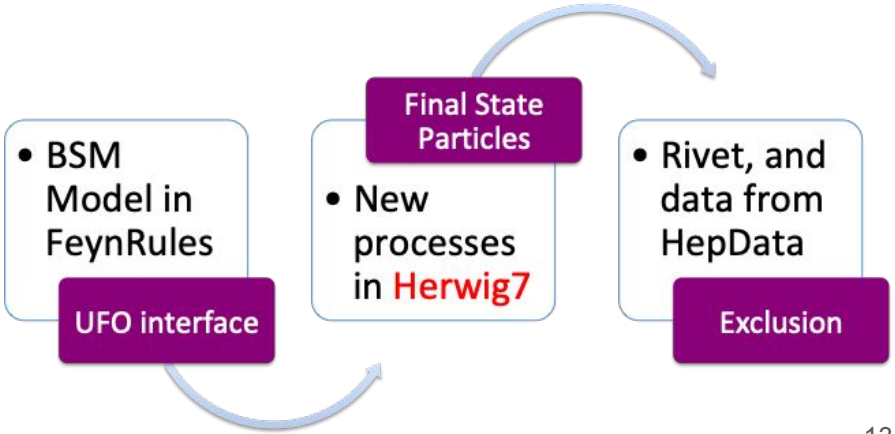
- **Rivet's main emphasis *isn't* BSM direct searches, but there's no reason not to.**
  - lots of experiment experience and support
  - efficient scaling-up to hundreds of analyses, with *phase-space specific* detector/efficiency functions
  - possible to do for BSM preservation what we did for measurement analyses?
  - more efficient route than e.g. RECAST for "simple" searches. Similar mechanism now in MA5
  - again, needs experiment buy-in



Les Houches 2019 CMS soft-lepton recasting-tools comparison

BSM from “Standard Model”

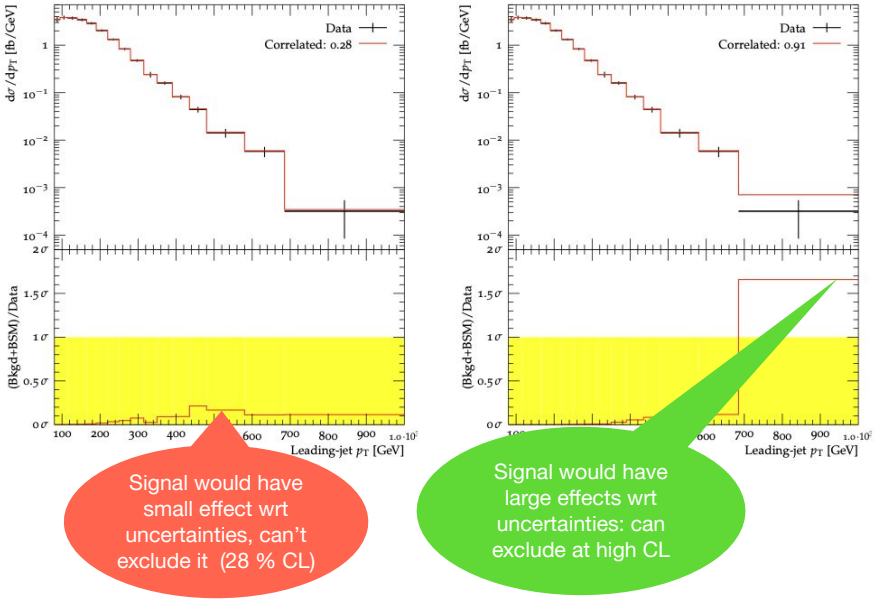
- **Not being focused on *direct* searches doesn’t mean no interest in BSM!**
- **Particle-level measurements *can* achieve high model-independence**
  - Define fiducial cross-section carefully: avoid SM assumptions (e.g. *v*) & uncertain subtractions
  - Publish and re-use control distributions: often “background only” for the model of immediate interest doesn’t mean that other BSM models can’t populate
  - Be careful to minimise model sensitivity in unfolding (and preserve the unfolding model, cf. fits)
- **The Contur idea**
  - 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 — arXiv:2102.04377**
  - Ok, not just! *How* you run matters
  - 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. Rivet3's "perfect merging"

HT Louie Corpe



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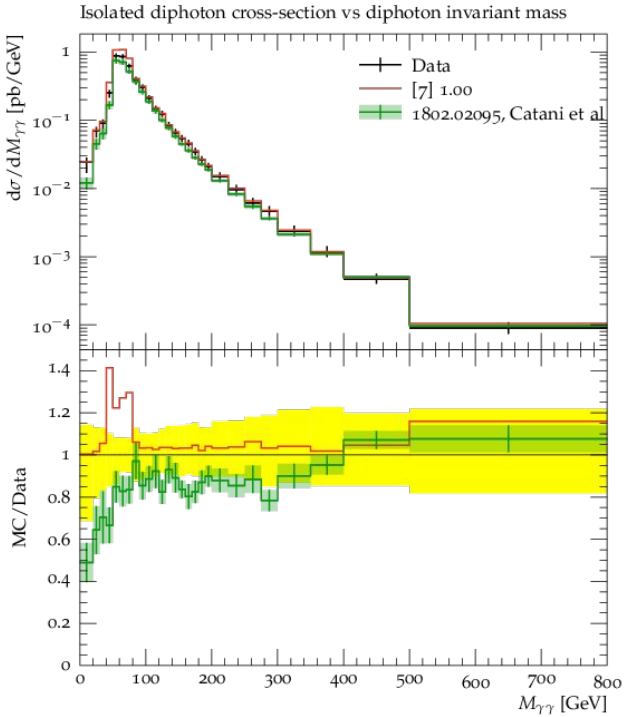

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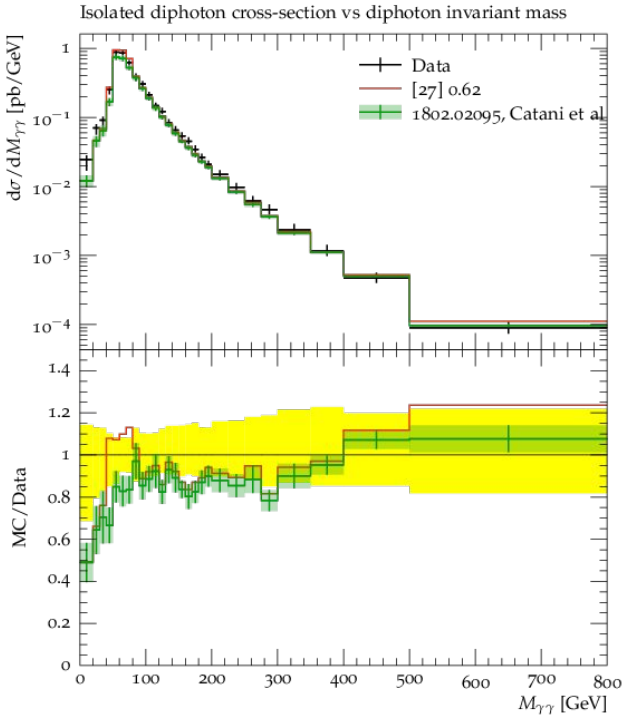
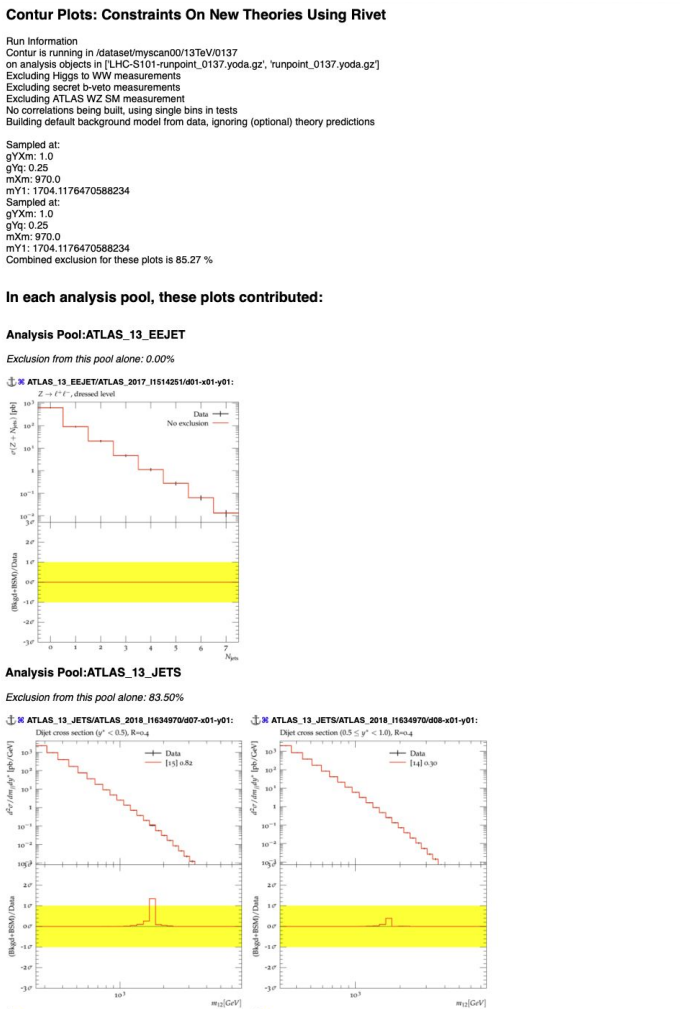


Contur workflow

- **MC gens:** historically Herwig+UFO, support now for MG5, Pythia, Powheg… anything that writes HepMC and can be run through Rivet
- **Stats:** Poisson LLR implemented, but reduces well to a simple (or correlated, even profiled) χ2 for unfolded measurements
- Can run Contur on any set of Rivet histograms for one BSM point.
  Web output cf. Rivet ⇒

  Or in a sampling / grid scan organised by contur-batch



Contur Plots: Constraints On New Theories Using Rivet

Run Information
Contur is running in /dataset/myscan00/13TeV/0137
on analysis objects in ['LHC-S101-runpoint_0137.yoda.gz', 'runpoint_0137.yoda.gz']
Excluding Higgs to WW measurements
Excluding secret b-veto measurements
Excluding ATLAS WZ SM measurement
No correlations being built, using single bins in tests
Building default background model from data, ignoring (optional) theory predictions

Sampled at:
gYXm: 1.0
gYq: 0.25
mXm: 970.0
mY1: 1704.1176470588234
Sampled at:
gYXm: 1.0
gYq: 0.25
mXm: 970.0
mY1: 1704.1176470588234
Combined exclusion for these plots is 85.27 %

In each analysis pool, these plots contributed:

Analysis Pool:ATLAS_13_EEJET

Exclusion from this pool alone: 0.00%

ATLAS_13_EEJET/ATLAS_2017_I1514251/d01-x01-y01:

Analysis Pool:ATLAS_13_JETS

Exclusion from this pool alone: 83.50%

ATLAS_13_JETS/ATLAS_2018_I1634970/d07-x01-y01:

ATLAS_13_JETS/ATLAS_2018_I1634970/d08-x01-y01:

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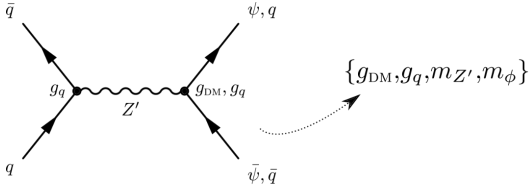
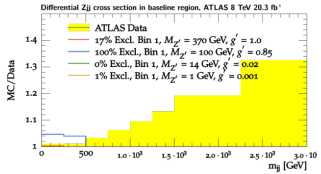
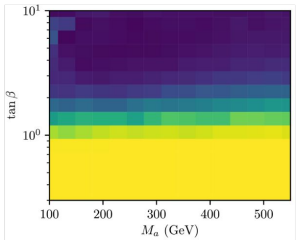
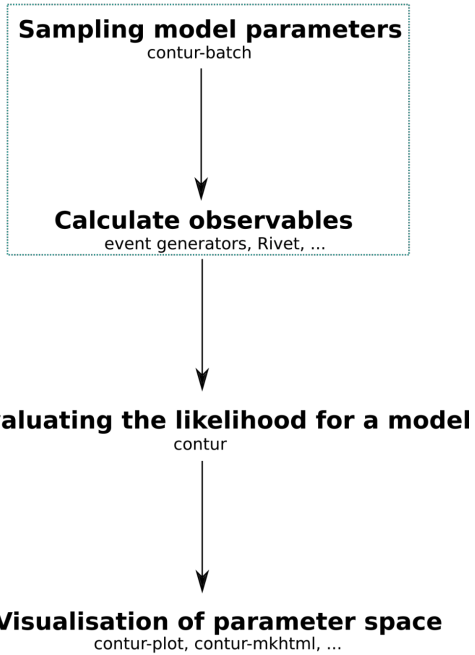




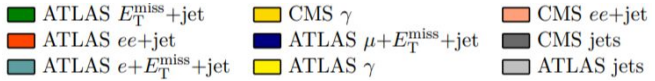
$$\mathrm{L}(\mu) = \mathrm{P}(n_{\mathrm{obs}} \mid \mu) = \frac{(\mu s + b)^{n_{\mathrm{obs}}}}{n_{\mathrm{obs}}!} e^{(\mu s + b)}$$



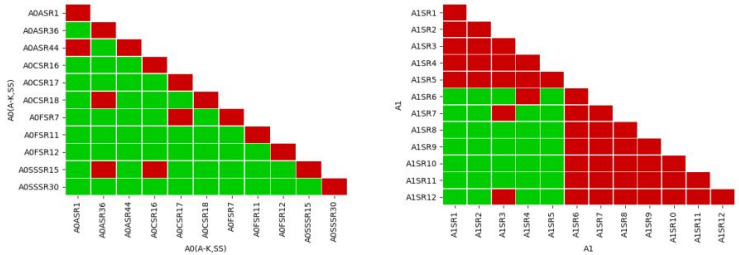


Independent signals

- **Much of Contur's power comes from signature *coverage***
  - Whatever your topology, chances are there's a measurement sensitive to it. For some models, one is already enough!
  - But these observables are not optimised to any BSM model ⇒ typically weaker than a dedicated (model-specific) search
    Secondary power comes from *combination*



  - Need to know which analyses are independent and can be trivially combined
    ⇒ group analyses in statistically orthogonal "pools". Use (expected) most-constraining pool element for setting limits; correlation data → "bigger elements" than single SRs



  - More ideas possible for assessing orthogonality or estimating correlation matrices [LH19]

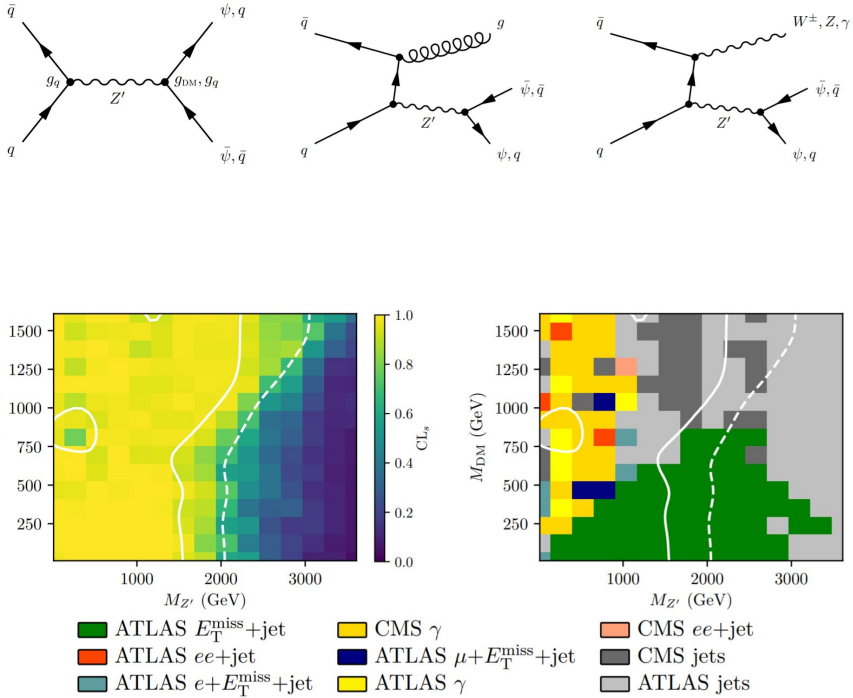
Contur BSM example 1

❖ Vector dark matter [JHEP 03 (2017) 078]

- ➢ Simple model of DM with vector mediator used as the canonical first real test of Contur
- ➢ Mix of BSM axial and SM vector couplings to avoid existing precision constraints

$$\mathcal{L} \supset g_{\mathrm{DM}}\,\overline{\psi}\gamma_\mu\gamma_5\psi\,Z'^\mu + g_q \sum_q \bar{q}\gamma_\mu q\,Z'^\mu$$

- ➢ Characterise model viability vs DM and mediator masses, and SM/BSM couplings
- ➢ MET+jet unsurprisingly dominates below M_{DM}-$M_{Z'}$ diagonal. Above is more interesting phenomenologically and benefits from Contur: *V*+jets fades into just-jets at high $M_{Z'}$
- ➢ Care needed with MET ≠ neutrinos, and *b*-veto

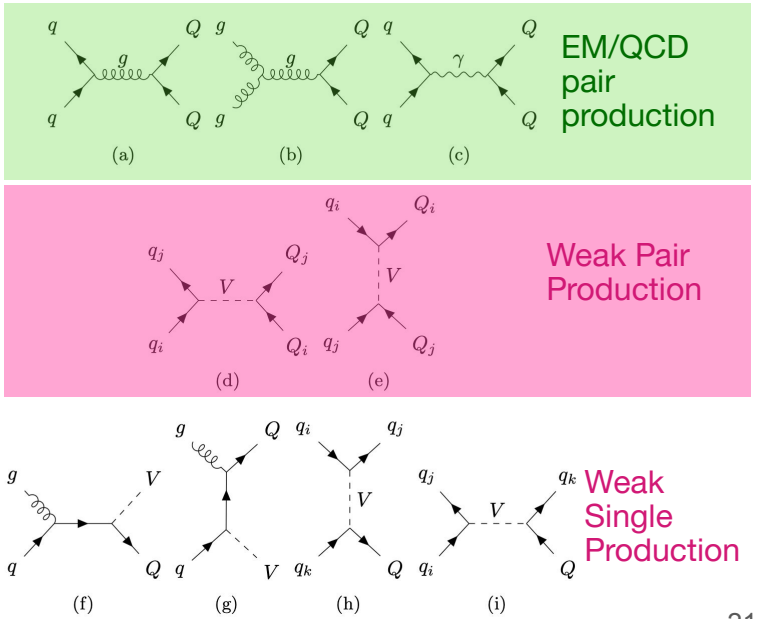


Contur BSM example 2

❖ **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!

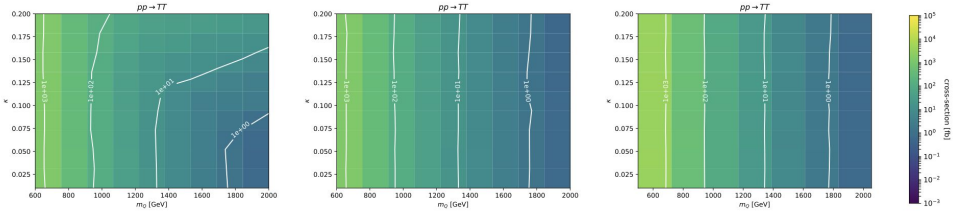
$$\mathcal{L} = \kappa_B \left[\sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{B}_{L/R} W_\mu^- \gamma^\mu u_{L/R}^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{B}_{L/R} Z_\mu \gamma^\mu d_{L/R}^i] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M_B}{v} [\bar{B}_{R/L}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



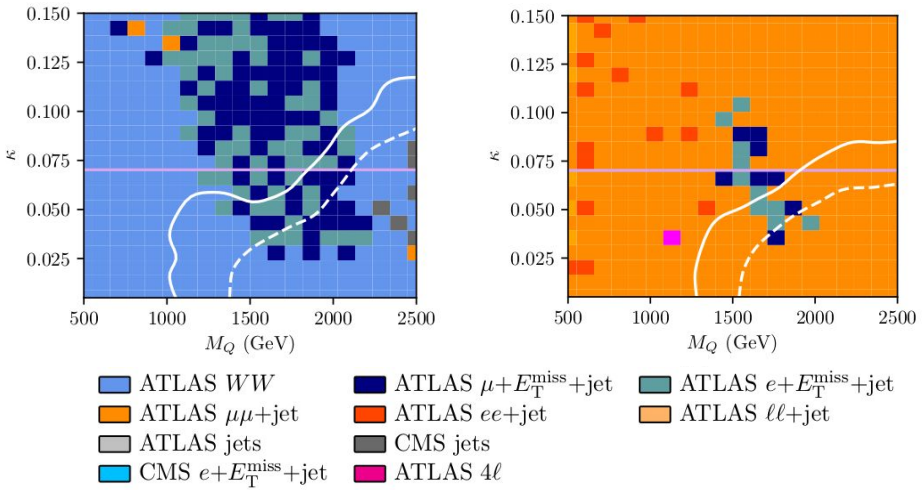
VLQ pheno with Contur: 1st gen

- 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, thanks to *W* and *H* decay channels
- “Injection” of ℓ+MET+jet sensitivity… why?

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 ℓ+MET+jet “injection”

- Check the single-point observable plots: the ℓ+MET+jet entry is from an unfolded VBF *Wjj* control region! Unfold your control regions, kids!

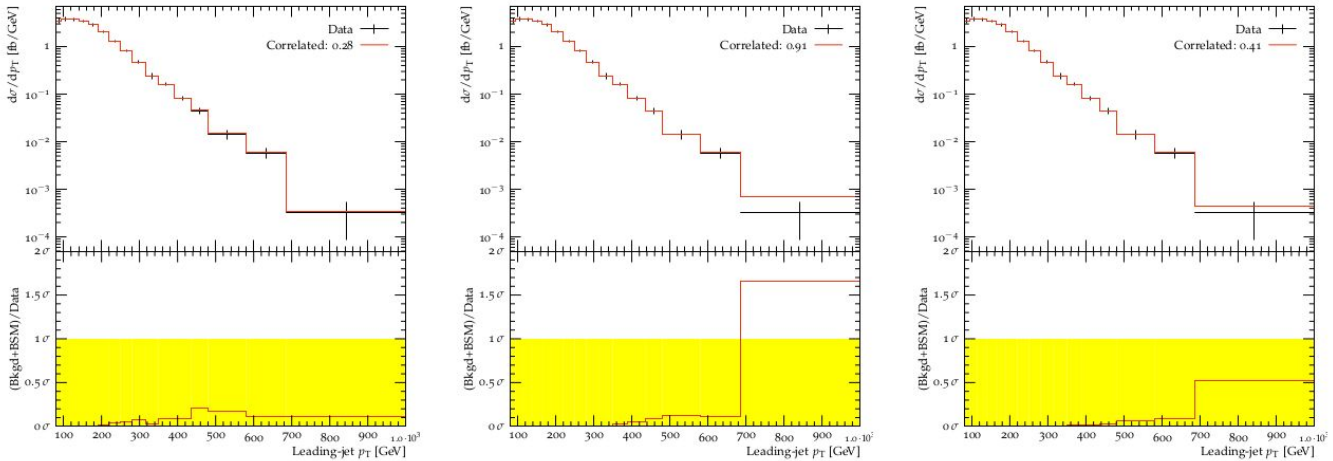
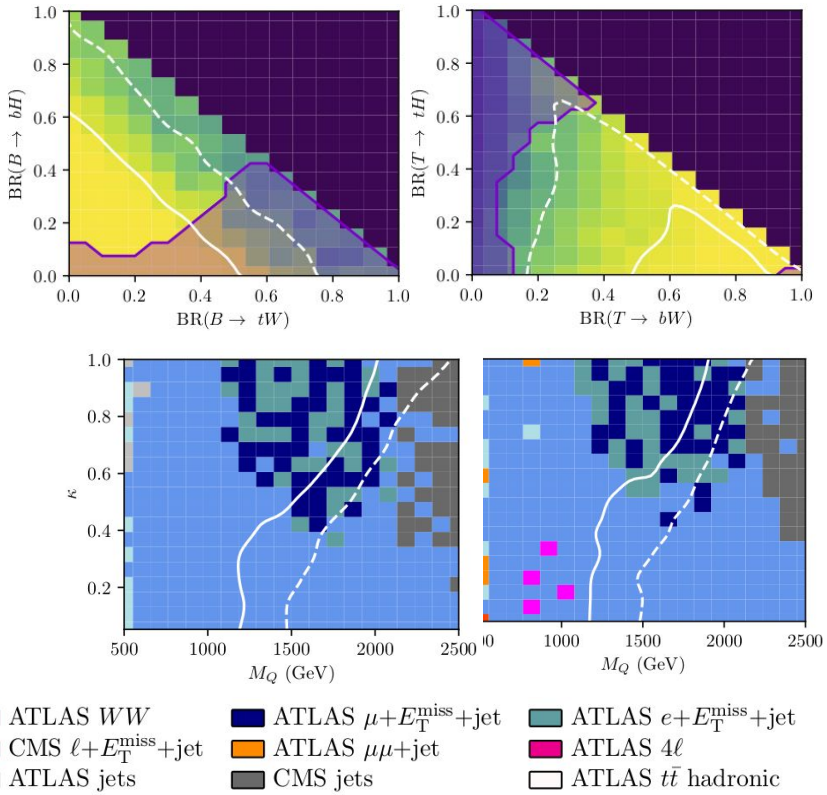


Figure 8: ATLAS 8 TeV Wjj forward-lepton control region leading-jet p_{T} distributions at three points on the 95% exclusion contour for $W{:}Z{:}H = 1{:}0{:}0$, respectively at M_Q values of (a) 1000 GeV, (b) 1750 GeV, and (c) 2250 GeV. The rise and subsidence of a 90% $\mathrm{CL_s}$ exclusion from a single Wjj bin is seen as the contour passes from below 1 TeV to above

VLQ pheno with Contur: 3rd gen

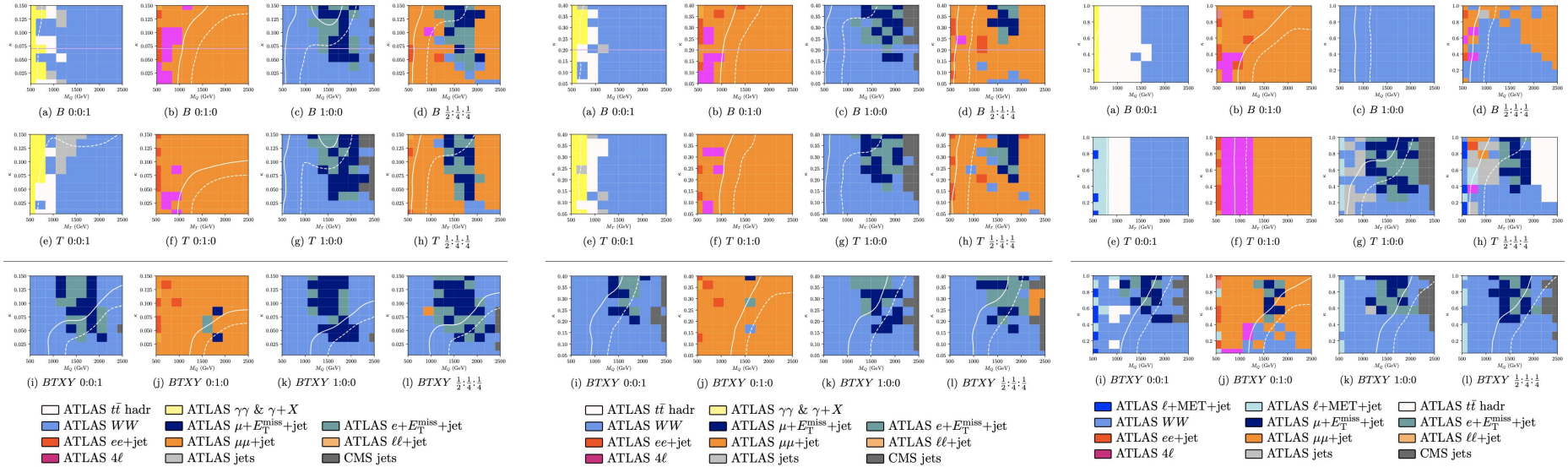
- In pure T, B pair-production mode, diboson and ℓ+MET+jet "SM" analyses ~cover or complement direct searches wonderfully
- In general, for *W:Z:H* = 0:1:0, *Tq* and *Xq* production killed by tiny top-quark PDF: pairs at low-m_Q, *Yq* at high-mass. Decays always have a *W* (directly or via $T \to tZ$) ⇒ 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

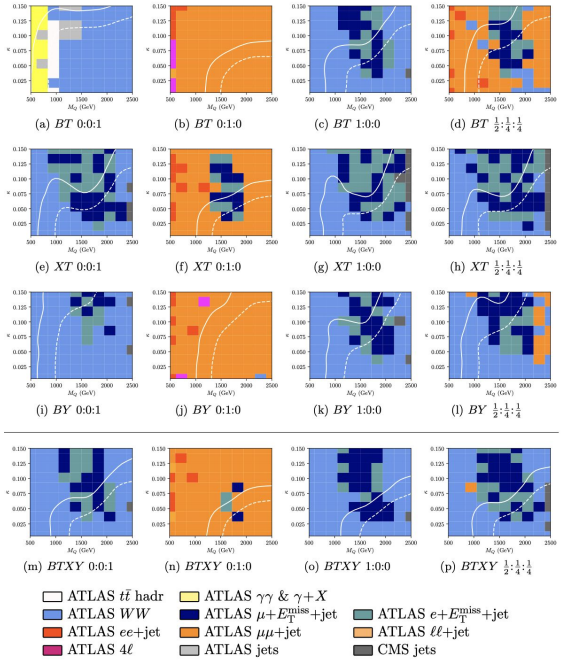
More realistic models… [singlets]

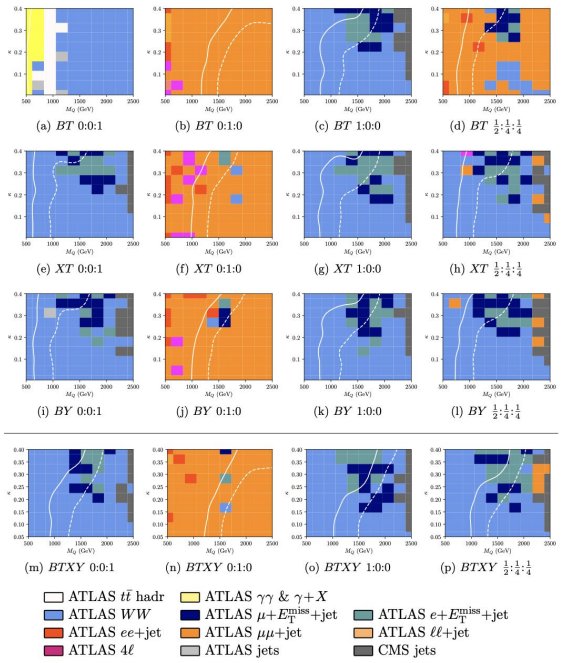
- Review requested a scan of realistic multiplets: 7 multiplets, each with 3 generational couplings, each with 4 W/H/Z-couplings, 300 points per scan, x 30,000 events!
- **~No problem! 1 month later…**

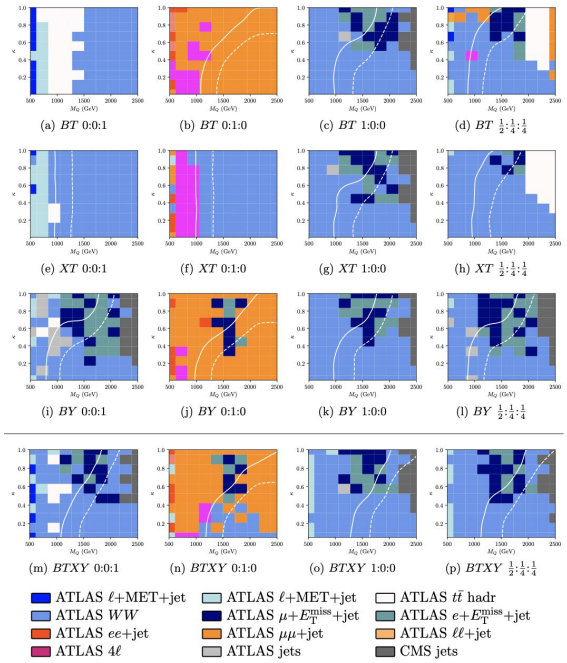


More realistic models… [doublets]

- 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!

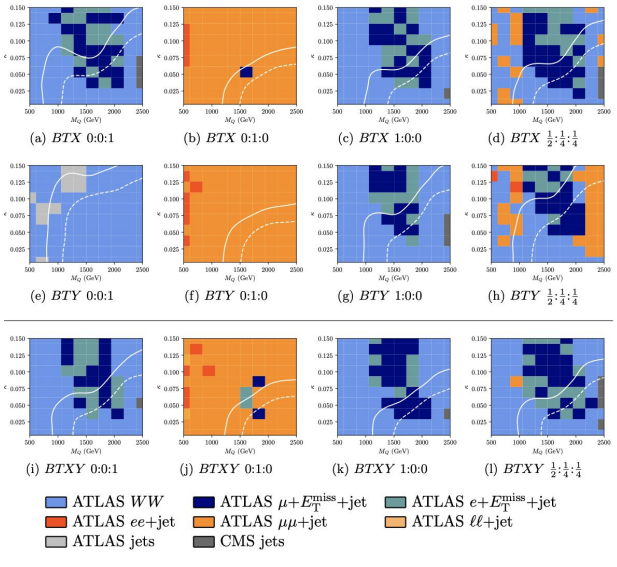


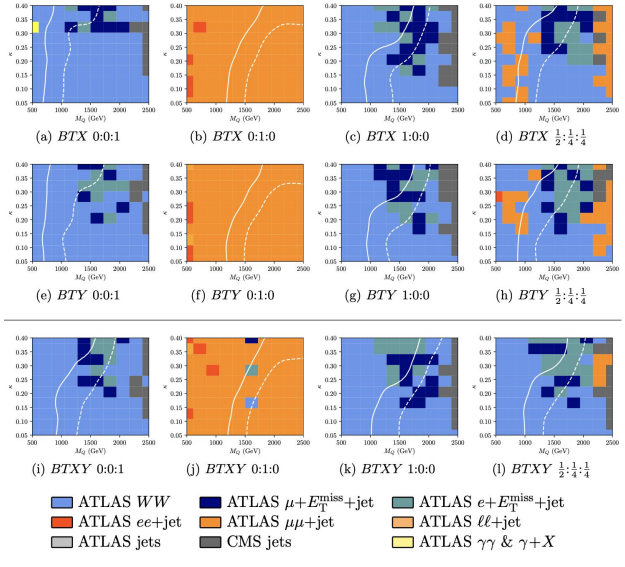


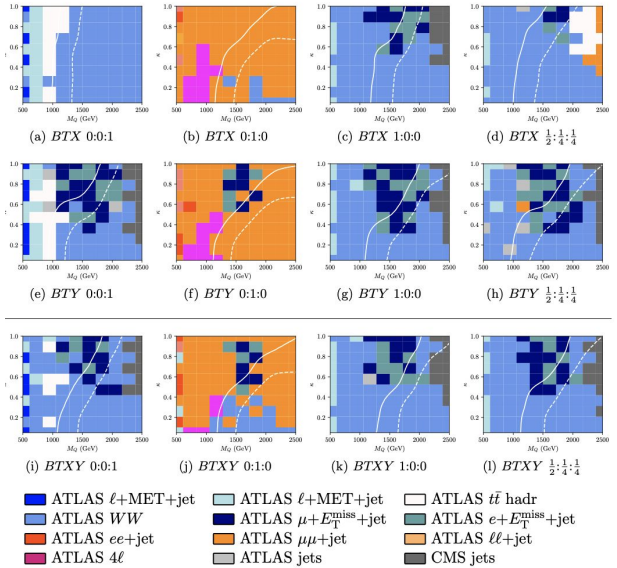


More realistic models… [triplets]

- 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!



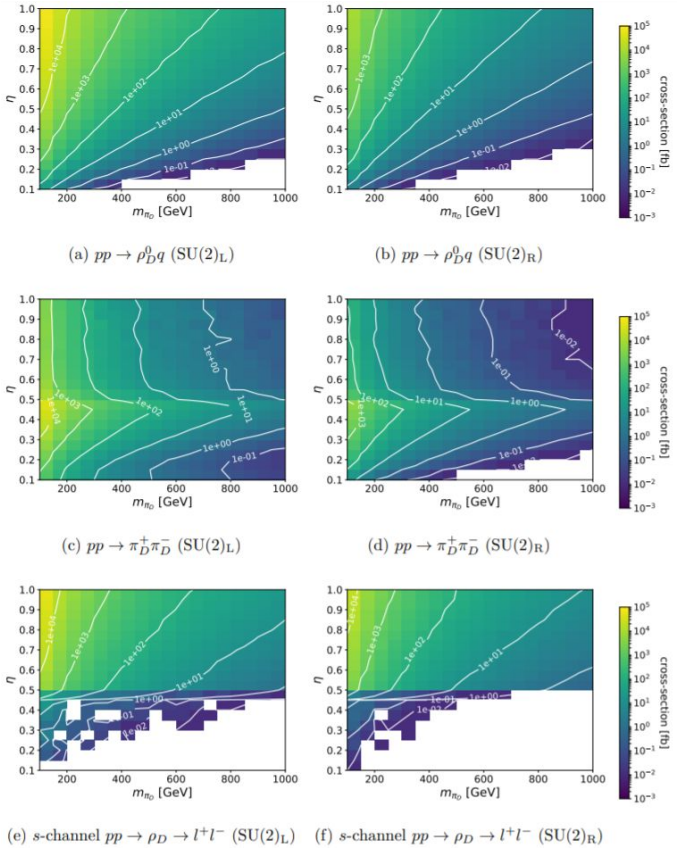




Speed is *good!*

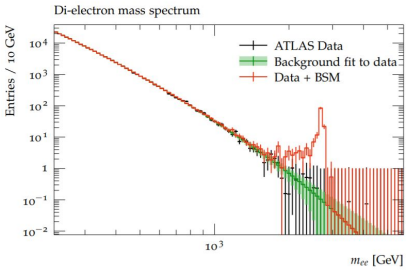
Contur BSM example 3

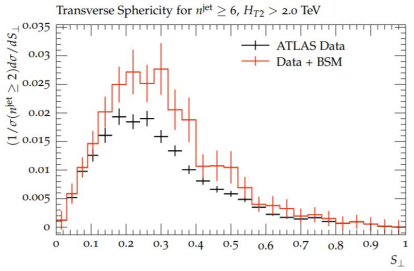
- **“Stealth” dark matter** [arXiv:2105.08494]
  - Complex family of DM models with strongly interacting dark sector
  - Dark confinement (assuming QCD-like SU(*N*) dynamics) produces dark hadron mass spectrum, with decays back to SM from selected states:
    ⇒ resonances, emerging jets, semi-visible jets
  - *A priori* constraints on models *really* weak!
  - Stealth DM in even-*N* models: scalar dark baryon is stable → DM candidate. Dark *ρ* and *π* mesons decay to SM particles. Characterise dark sector with $m_{\pi D}$ and $\eta = m_{\pi D}/m_{\rho D}$



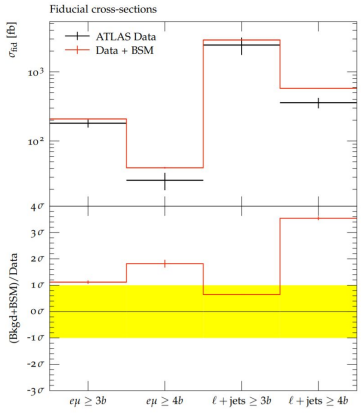
Contur stealth DM signatures

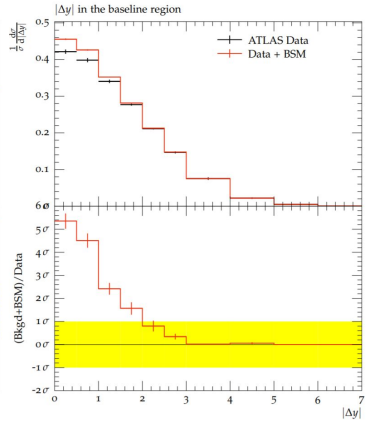
- **If $\eta > 0.5$, dark decay $\rho \rightarrow \pi\,\pi$ is forbidden: rho decays instead to SM lepton or quark pairs**
  - ➢ Dilepton signature peaking at rho mass, plus less distinct dijet and tt
  - ➢ Use Rivet-smeared ATLAS R2 dilepton resonance search!
- **If $\eta > 0.5$, dark $\rho \rightarrow \pi\,\pi$ dominates, and pheno gets complex**
  - ➢ Gaugephobic π: decay to 3rd gen quarks & multijet, V+jets signatures
  - ➢ Gaugephilic π: decays via V+H, V+jets 3rd gen quarks





η = 0.7 η = 0.45

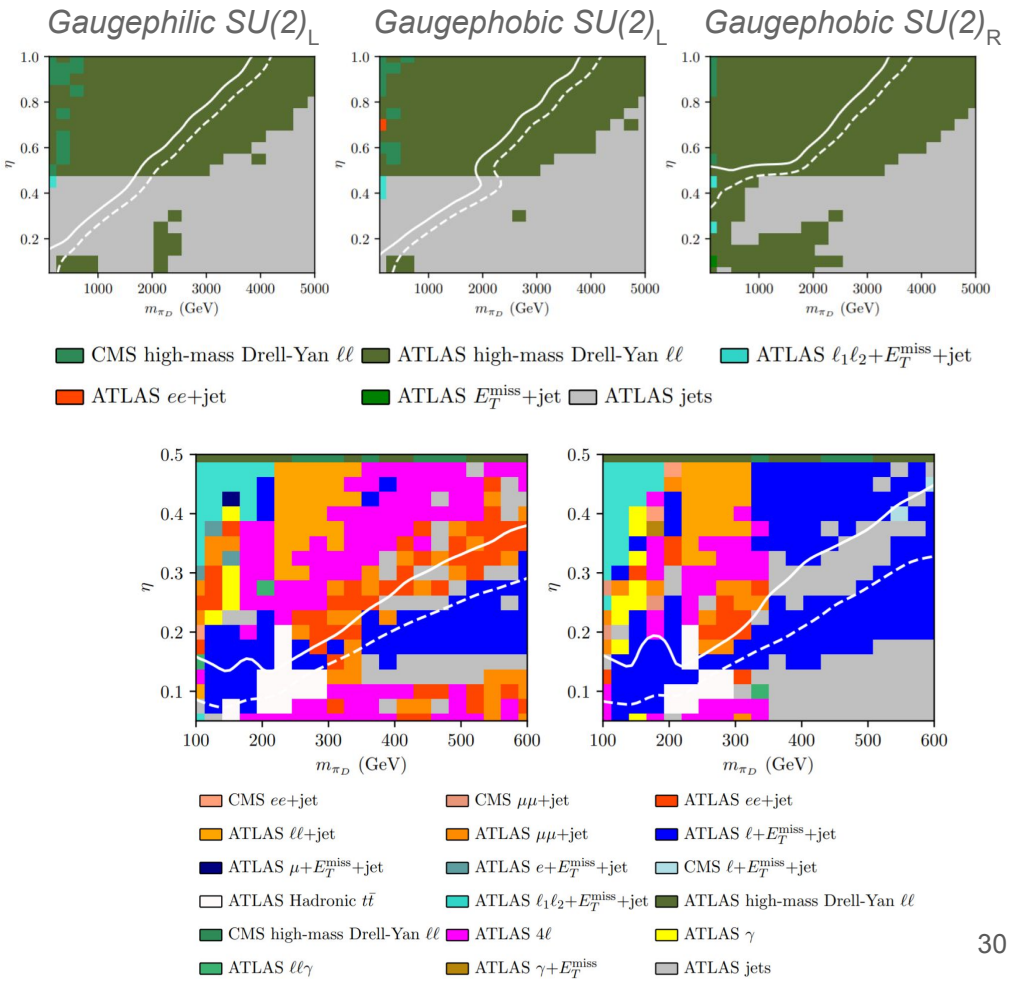




ttbb cross-secs *Dilepton+jets*

Stealth DM sensitivity

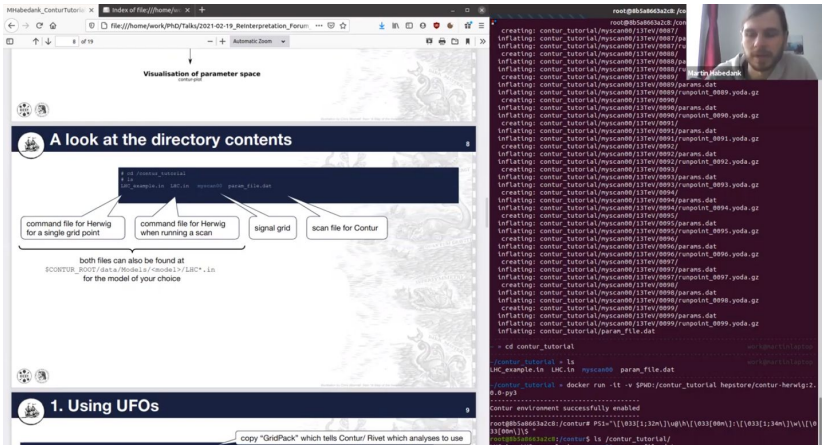
- Switch of sensitive mode when $\eta \rightarrow < 0.5$: dilepton-resonance sensitivity disappears
- Contur exclusions switch with little disruption (except for the gaugephobic $SU(2)_R$) to multijet event-shape observables
- Phenomenology of subleading pools for $\eta < 0.5$ is fascinating:
  - Non-resonant dileptons
  - $\pi_D \rightarrow \gamma\gamma$ in Higgs-mass window
  - tt and boosted hadronic top
  - 4ℓ via e.g. *ZHtb* and *hhVV*, …



Getting started with Rivet and Contur

- Being able to easily access Contur exclusions is key to it becoming a standard part of BSM operations
- Several dependencies: Rivet, generators, HepMC, Python packages…
- Easiest way is a pre-built Docker image:
- Tutorials available from the Rivet and Contur websites, and a video tutorial

```
andy@unity:~/.../contur-herwig$ docker pull hepstore/contur
Using default tag: latest
latest: Pulling from hepstore/contur
Digest: sha256:6345a0bd31e7c2eb772ae0751bce86b4612136eeef70ded3c1ddff0d1d9d05ed
Status: Image is up to date for hepstore/contur:latest
docker.io/hepstore/contur:latest
andy@unity:~/.../contur-herwig$ docker run -it --rm hepstore/contur
----------------------------------------
Contur environment successfully enabled
----------------------------------------
root@3522a2fc4127:/contur# exit
andy@unity:~/.../contur-herwig$ docker pull hepstore/contur-herwig
Using default tag: latest
```

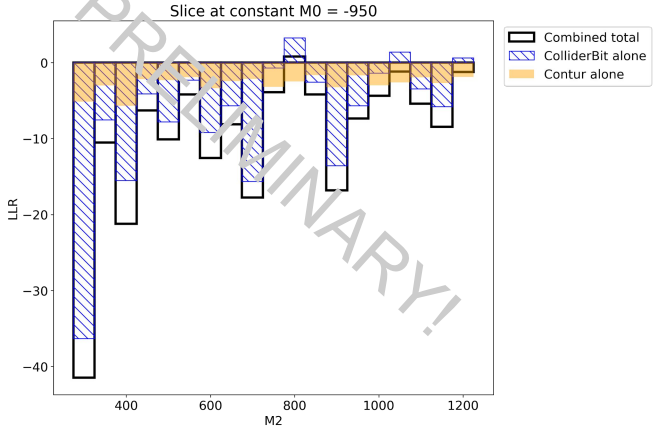


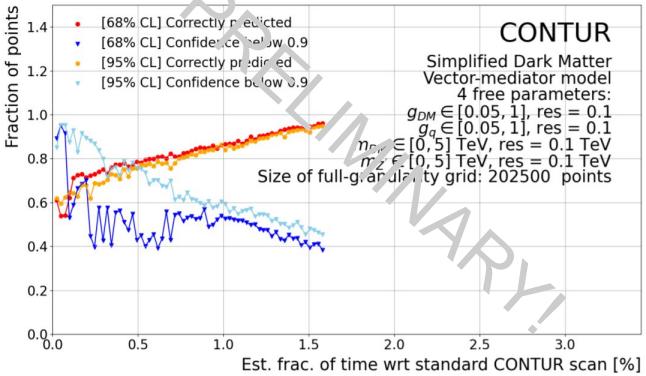
Next steps for Contur

- Present studies have focused on discrete sets of 2D grid scans. Trivial parallelism → 3D, maybe 4D, but higher dimensionalities need better sampling

- **1) Integrate into adaptive scans:** ongoing work with Gambit global fit. Has required re-engineering to avoid filesystem access. Extra LLR contribution worth the effort in marginal *and best-fit* points

- **2) Built-in optimal sampling with machine-learning:** Contur Oracle (see talk at upcoming Tools2021)





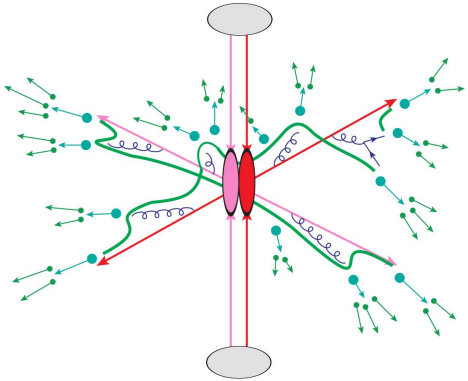
Summary

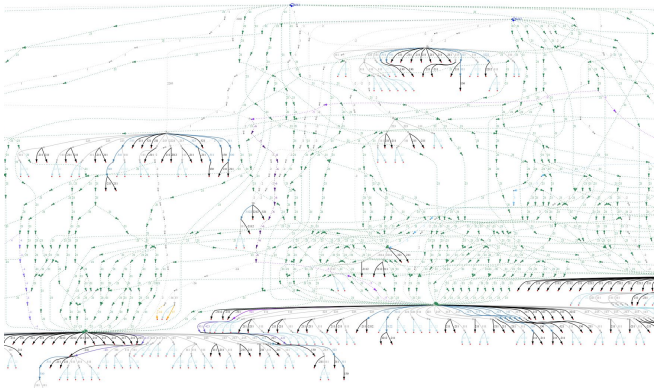
- Contur, based on Rivet, is a powerful new complement to dedicated searches, using the ever-growing collection of model-independent measurements. Synoptic pheno!
- Can help to avoid making difficult dedicated searches based on models already ruled out by (pretty) quick truth-level checks. Like all reinterpretation, more triage/signposting than definitive
- Need lots of experiment-implemented analyses in Rivet. Particularly CMS! An accelerator for analysis impact ⇒ lots of fun collaborations! (cf. new LPCC RAMP initiative: exposure for good practice)
- As we head into another LHC era, with more data (and metadata) the coverage will keep improving. Join in!

Backup

MC generation

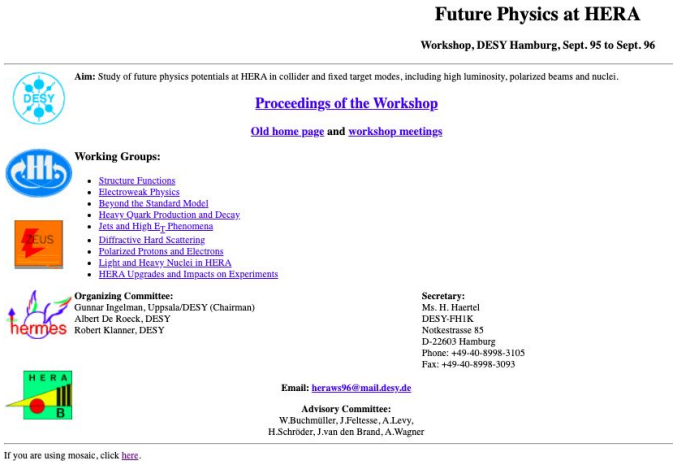
- **MC generation is where theory meets experiment**
  - The fundamental *pp (etc.)* collision, *sans* detector
- **Components of an "exclusive" event-generator chain:**
  - QFT matrix element sampling at fixed order in QCD etc.
  - *Dressed* with approximate collinear splitting functions, iterated in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





From HZTool to Rivet

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



Future Physics at HERA

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

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

Proceedings of the Workshop

Old home page and workshop meetings

Working Groups:

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

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

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

If you are using mosaic, click here.

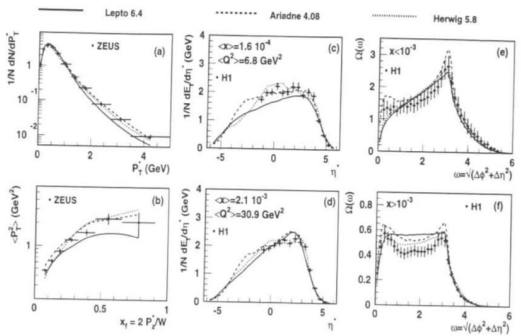
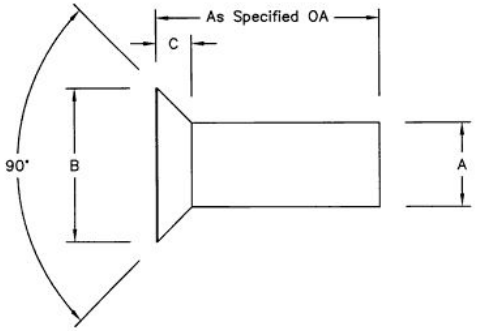


Figure 1: *The transverse momenta dN/dp_T (a) and the 'seagull' plot $\langle P_T^2 \rangle \times x_F$ (b) of single particles in the positive hemisphere of the hadronic center of mass. The transverse energy flow $dE_T/d\eta$ in a low (c) and high (d) x and Q^2 bin. The transverse energy-energy correlations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

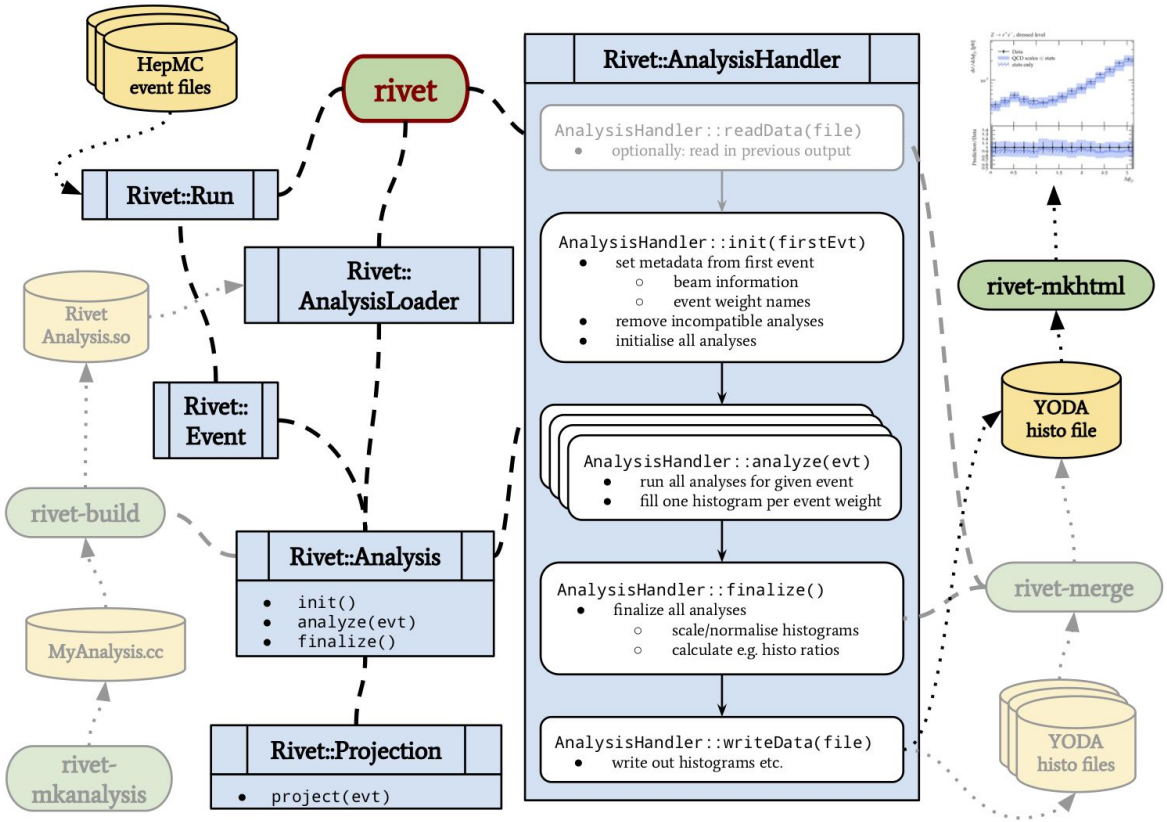
Designing the Rivet

- **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
  - Analysis routines factorised, and loaded as “plugins”
- **Efficient**
  - Avoid recomputations via “projection” caching system
- **Physical**
  - **Measurements primarily from final-state particles only**



The result

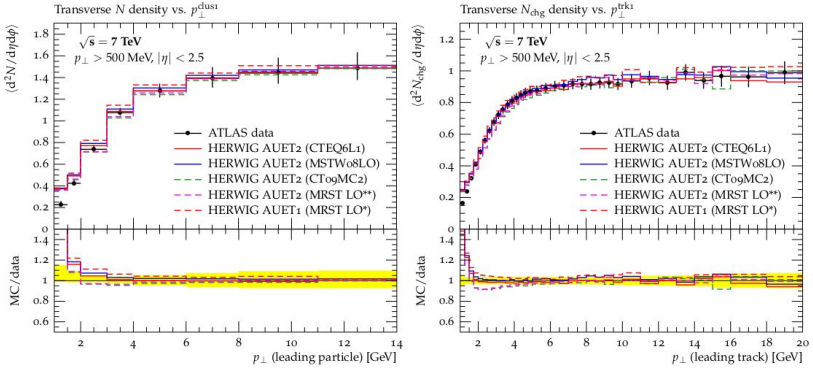
- **As of Rivet v3.1.0**
  arXiv:1912.05451
- Streamlined set of tools from analysis coding to event processing to plotting (and other applications)
- And a key gateway to connect your analysis to theory (and back again)
- Let's review some of the early impacts…

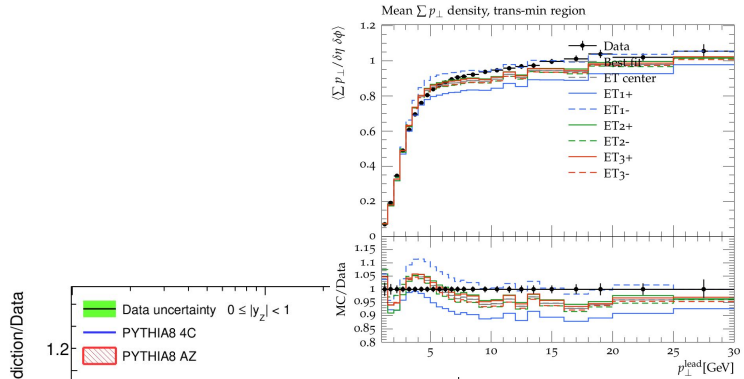


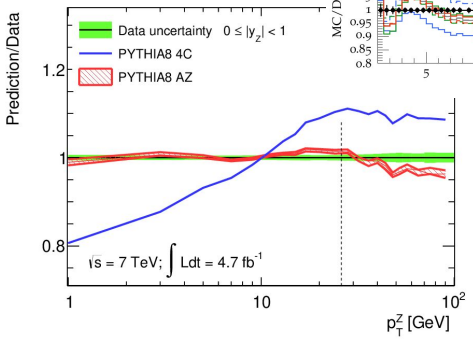
More tuning…

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 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, …

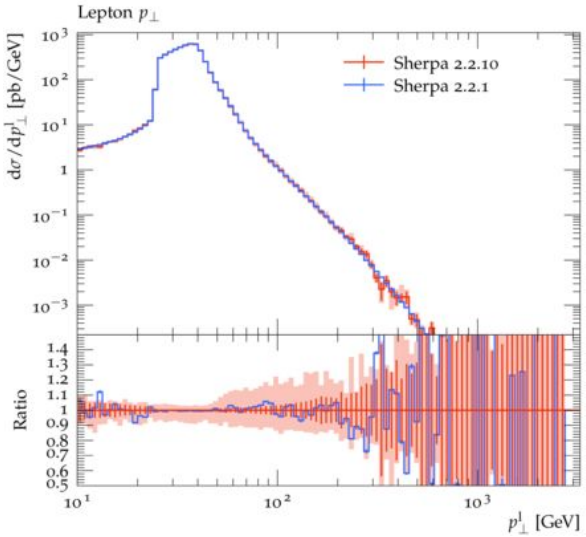


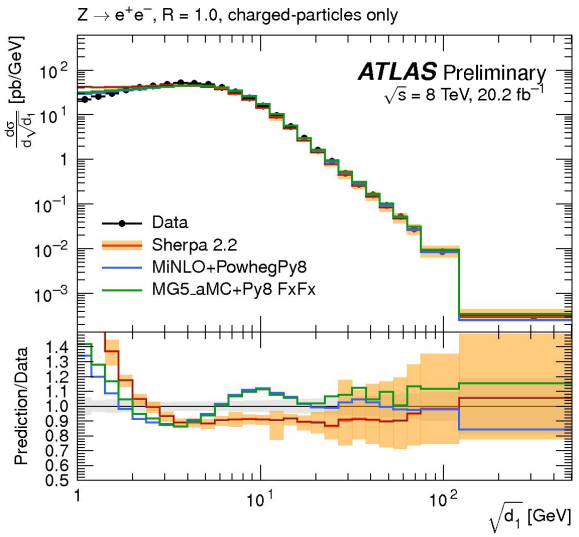


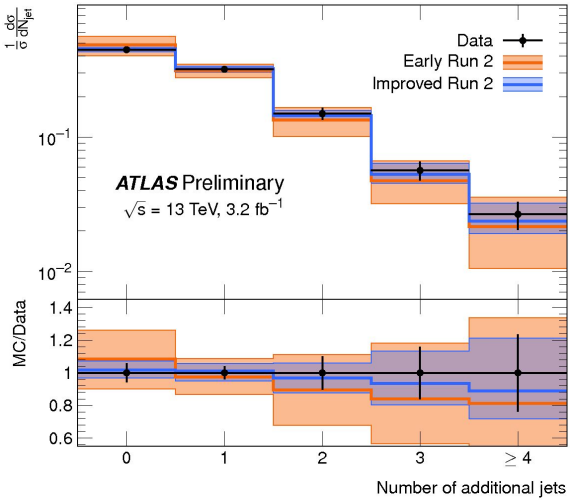


Rivet multiweights in action

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



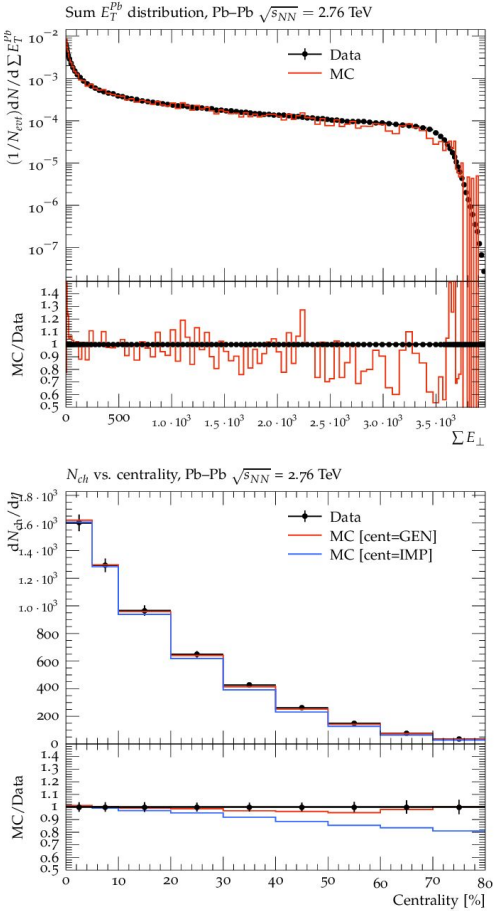




- Weight-naming standardisation underway via MCnet

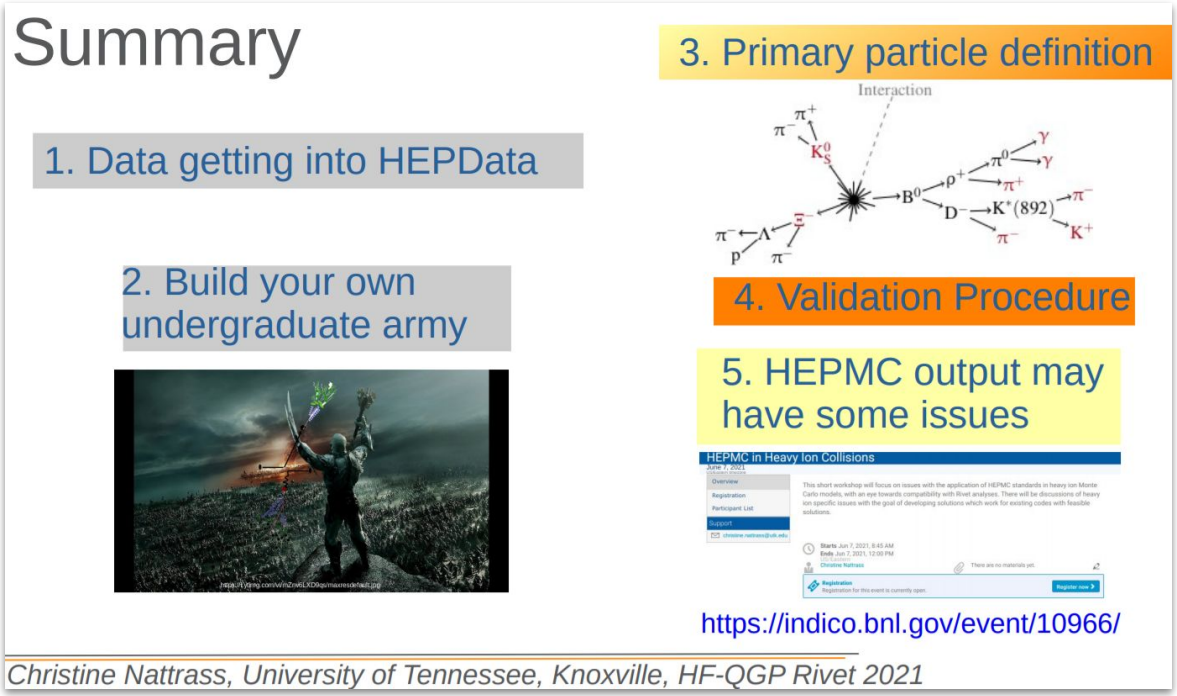
Heavy-ion physics preservation

- **“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*



Heavy-ion physics preservation

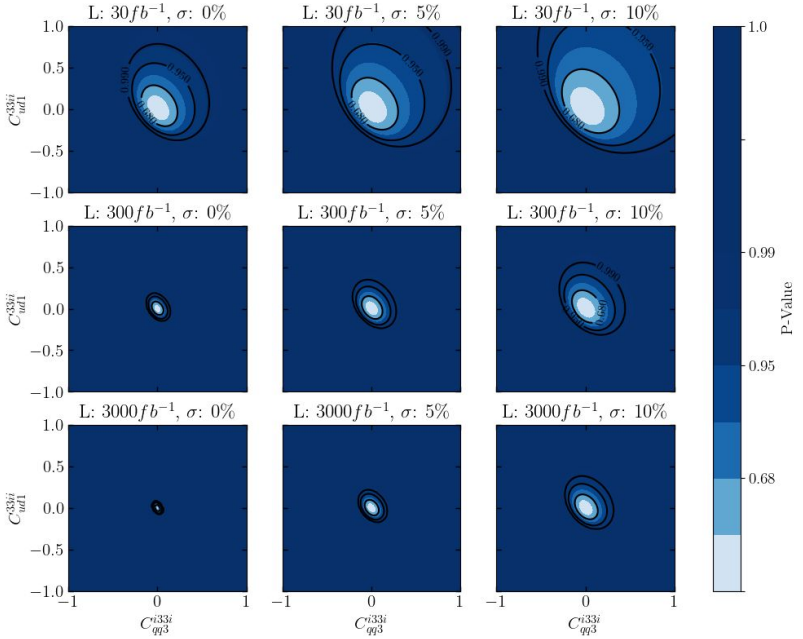
- **A genuinely exciting thing: HI culture is changing…**



- HepData, Rivet
- Better ex/ph communication
- Faster model/data comparisons
- Addressing issues with formats and incomplete models
- Undergrad army!
- https://indico.cern.ch/event/1022351/

Harder, faster, stronger… moar BSM

- Now extending beyond 1D and 2D grids:
  - ➢ Rivet (and Herwig) as a function
  - ➢ Embed into adaptive scans
  - ➢ Higher param dimensionalities
  - ➢ Including beyond colliders, e.g. Gambit
- Rivet as a tool to probe new-observable sensitivity, e.g. in EFT models (TopFitter)
- Bootstrapping for victory: estimating statistical and systematic correlations (with SModelS, MadAnalysis5)



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++

Getting started with Rivet

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
```