Collider Codes – the experimentalist's standpoint

Jon Butterworth

Corfu, 12 Sept 2017

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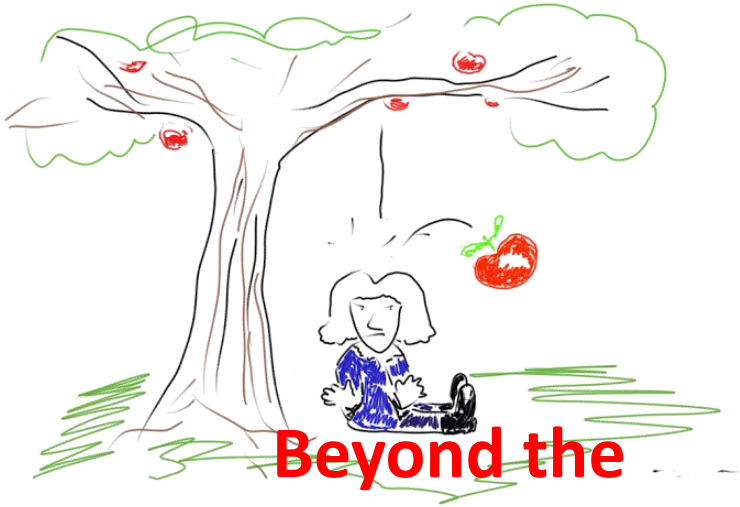
A personal view, I speak for no one but myself…

Dual/overlapping role of the LHC

- Searching for Physics Beyond the SM
  - Well motivated



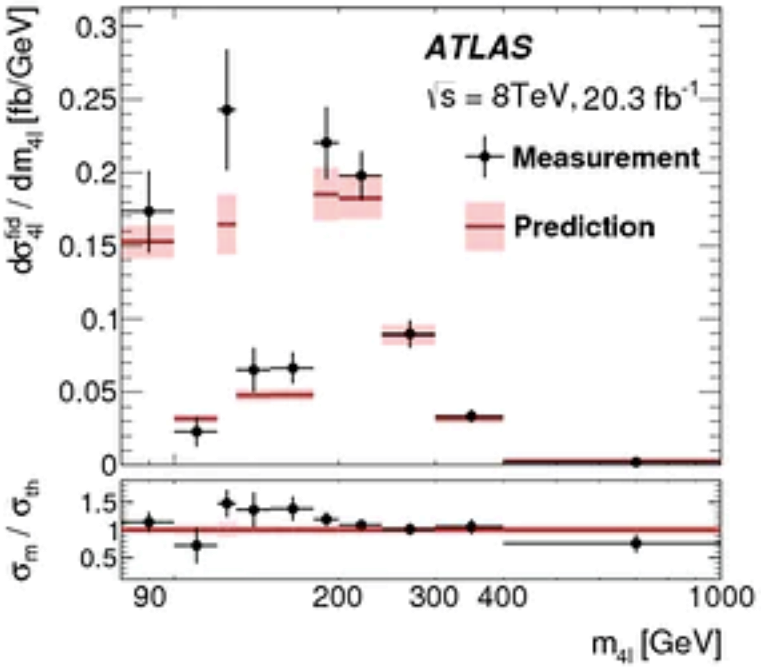
Beyond the Standard Model!

Beyond the Standard Model and General Relativity!

Dual/overlapping role of the LHC

- Searching for Physics Beyond the SM
  - Well motivated
- ~~Measure the Standard Model~~

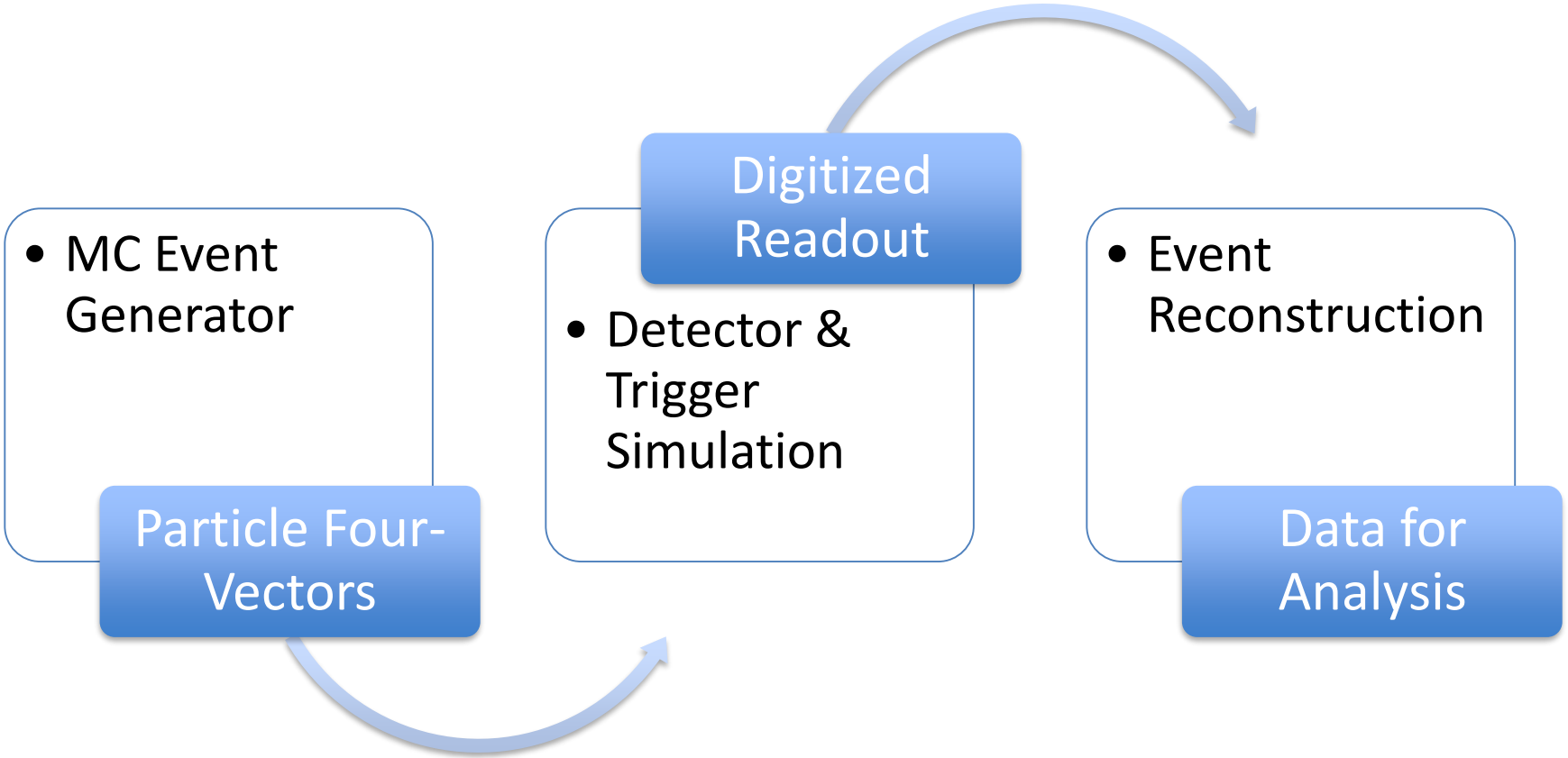
Measure what happens, and compare to the predictions of the Standard Model



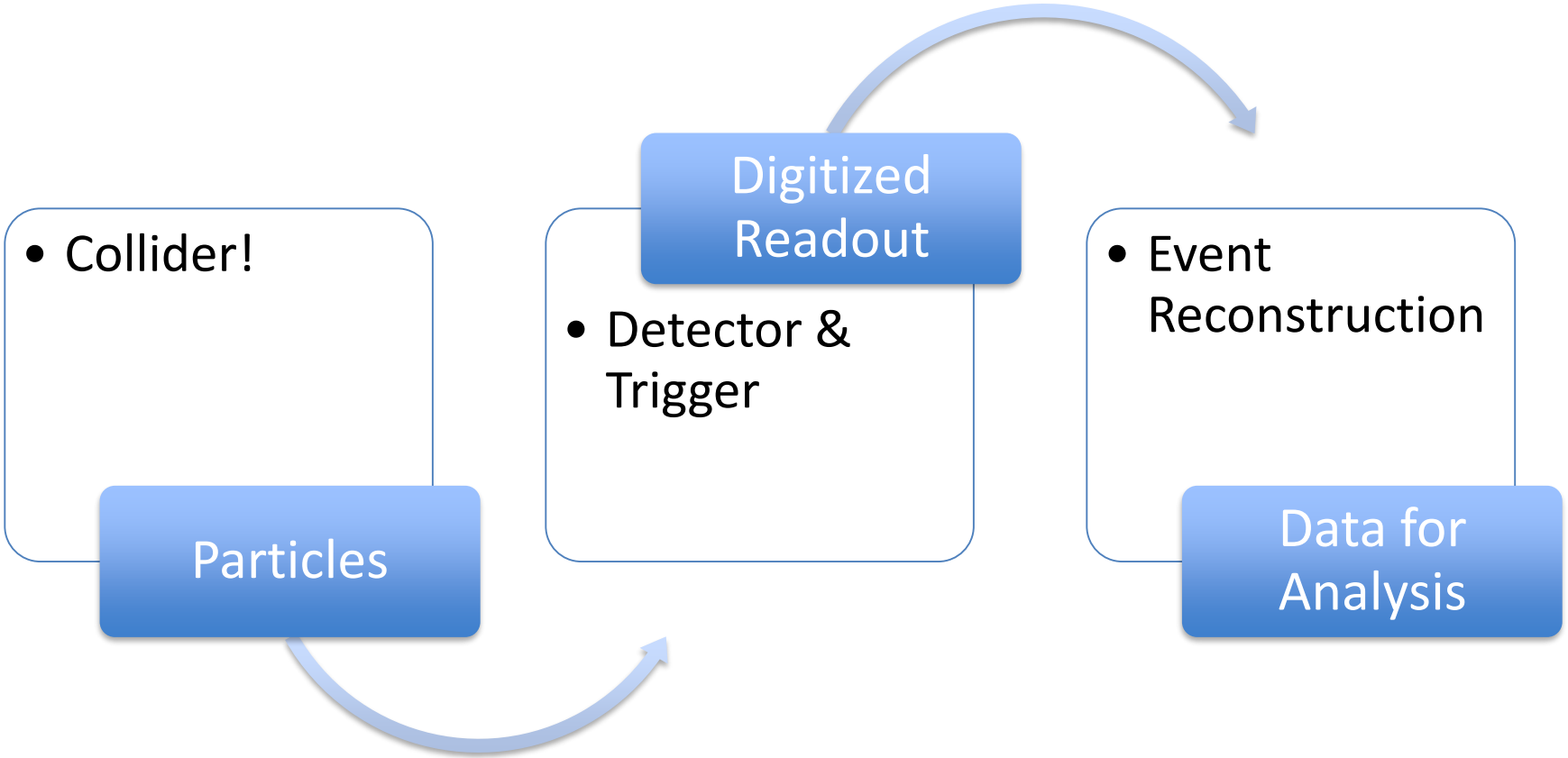
Tension between

- "universal measurement" with meaning beyond that particular experiment and "universal measurement" with meaning beyond that particular theory
  - "We counted charged particles in this particular region of phase space with these particular beams and this particular detector"
  - "We extracted the top mass under the assumption that this particular version of this MC is true"
- The best, most sensitive search for a very a very specific piece of BSM physics
- A search which is a general and model-independent as possible

Simulation and Experiment



Simulation and Experiment



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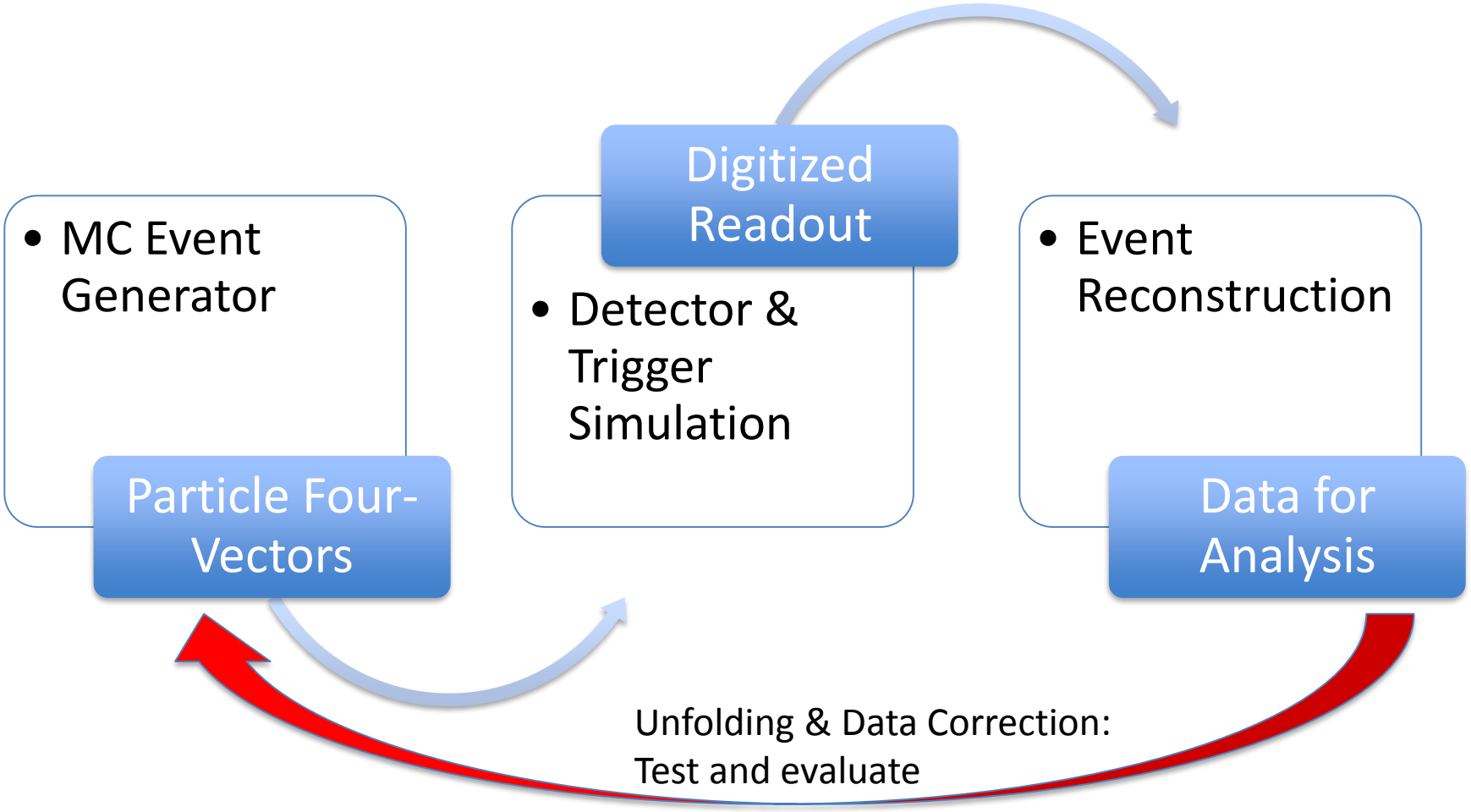

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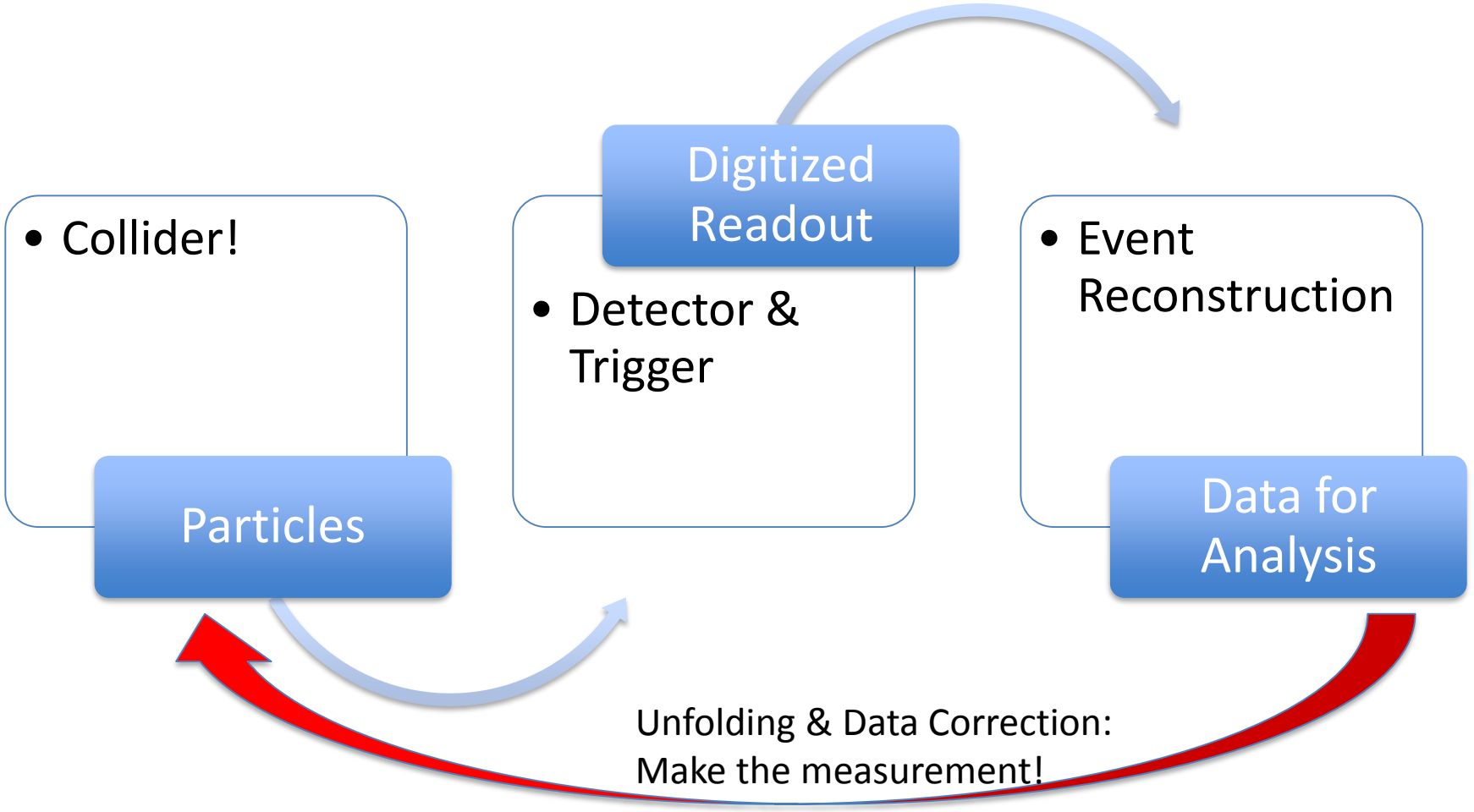

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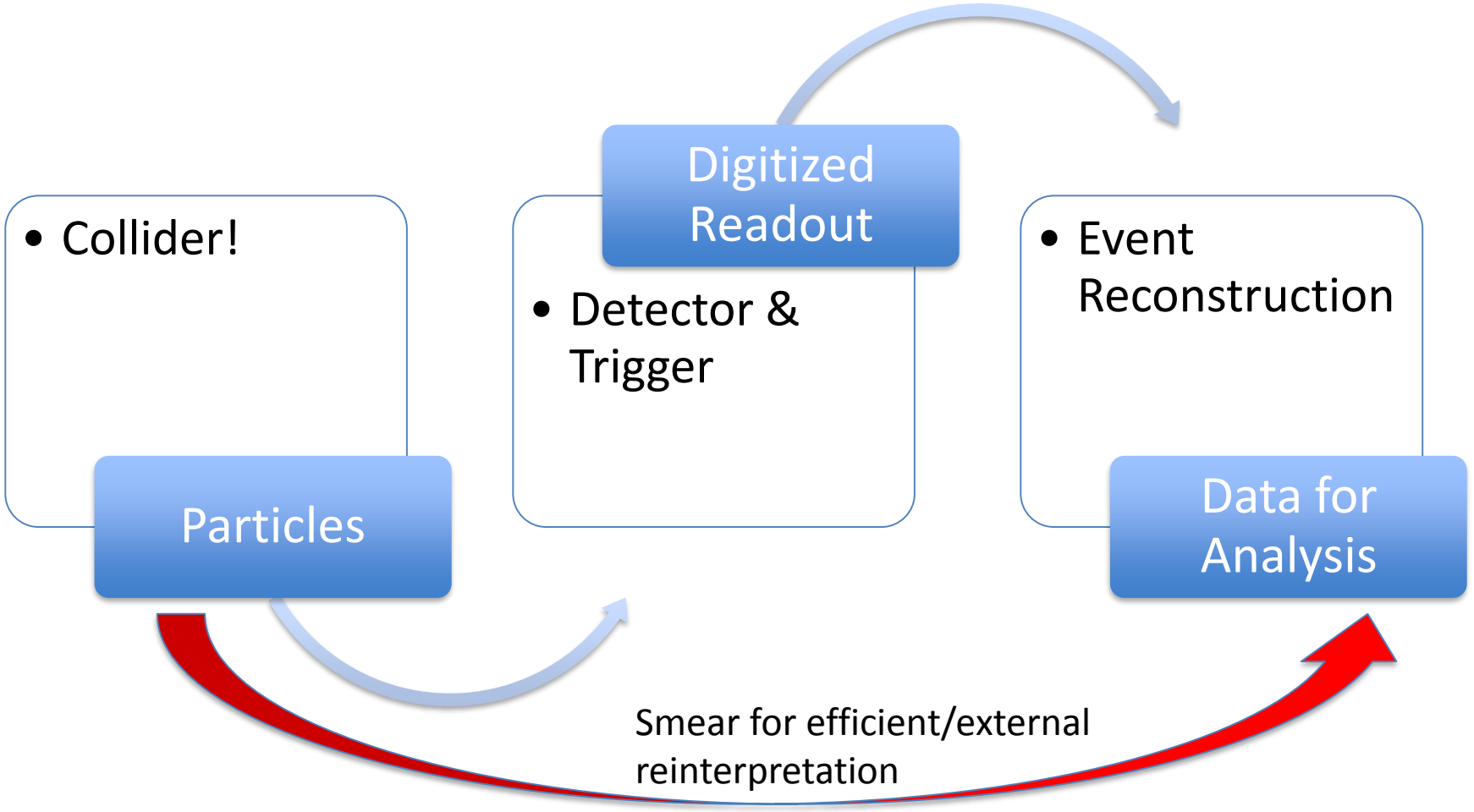
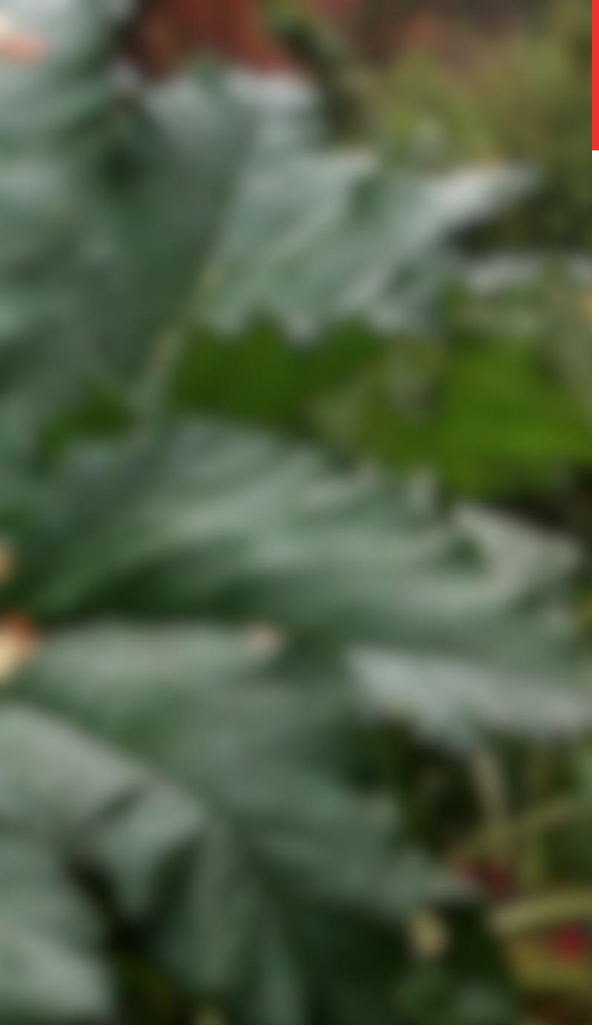


Important considerations for searches & measurements

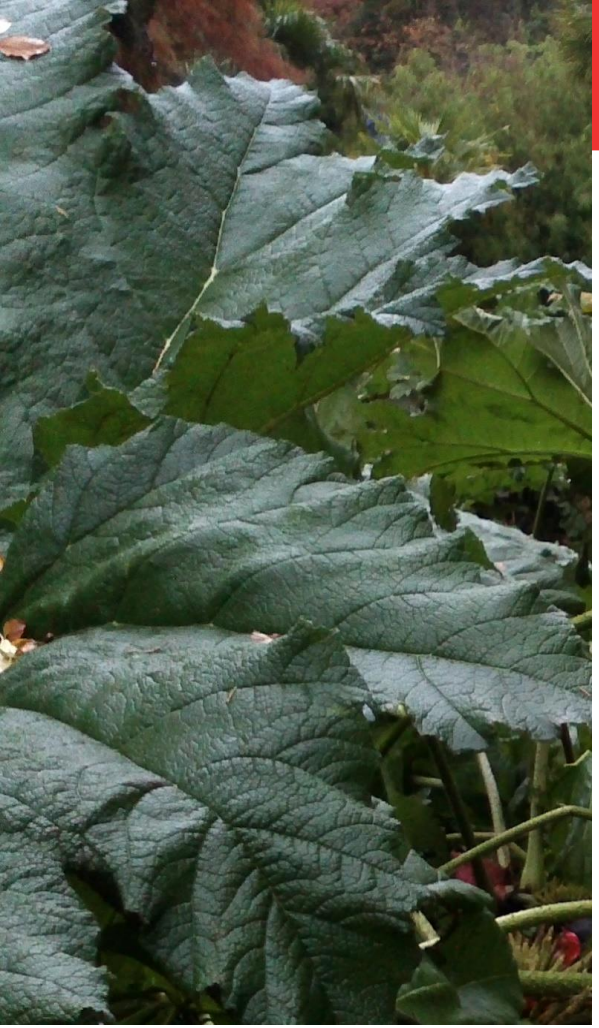
- What is your final state?
  - A common choice is place a lifetime cut at 10ps, and where necessary to draw further distinction, draw the line at hadronisation.
  - Stable objects (hadrons, leptons, photons) can be combined algorithmically to give well-defined objects (jets, dressed leptons, isolated photons, missing E_T…)
  - Remember, this is about defining “truth”, i.e. what we correct back to within some systematic uncertainty

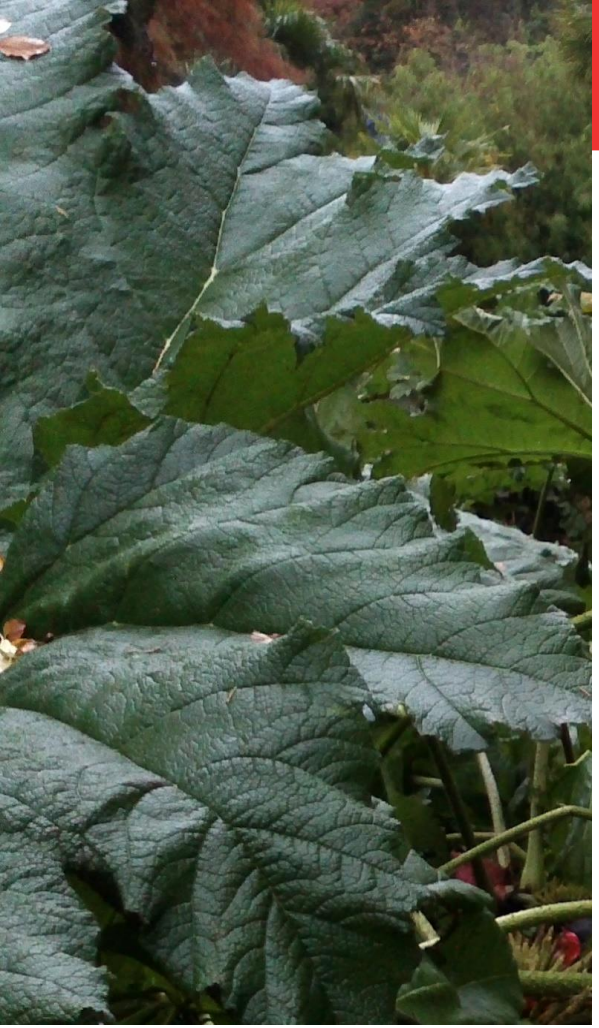
Fiducial or not?

- Difference between “efficiency corrections” or “unfolding”, and “acceptance corrections”.
  - The first two generally mean correction for detector effects, which no one but the experimentalists can do.
  - The third means extrapolating into kinematic regions which have not been measured at all
- Beware of the third, especially as we go to higher energies…



Unfold





Increase acceptance

Increase acceptance

Extrapolate

But how reliably?

Concept of a “fiducial” cross section

- Defines a region in which acceptance is ~100%
- Implies that some kinematic cuts must be implemented in whatever theory the data are compared to (easy for MC, less so for some high-order calculations)

Inaccessible. Removed by kinematics cuts, and not part of the fiducial cross section

Concept of a “fiducial” cross section

- Defines a region in which acceptance is ~100%
- Implies that some kinematic cuts must be implemented in whatever theory is compared to (easy for MC, less so for some high-order calculations)
- Ideally of course, build an experiment which covers all the phase space of interest…
- Fiducial cross section should be defined in terms of the “ideal” or “true” final state

NB This has always been true, but becomes more relevant the more phase space you open. Hence at LHC, this now impacts electroweak-scale objects much more than it did at LEP or Tevatron

Tools needed to…

- Predict an exclusive final state
  - To “fold” with detector smearing and efficiency
  - To compare to unfolded fiducial cross sections
  - (To derive the unfolding correction)
- Well-defined theoretical framework
  - To allow comparisons between different measurement
  - To draw physics conclusions!

“Unfolding”

- Some people really don’t seem to like it…
- If the cross section is well-defined, unfolding and its uncertainties can be well-defined
  - Fiducial region, matches the experimental acceptance well
  - True final-state obects
- Both require simulation of the full final state
  - Inclusive calculation is not enough on its own
  - MC generator are key tools
- Standard unfolding tools, e.g.
  - RooUnfold https://arxiv.org/abs/1105.1160
  - SVD, …

Shopping List

- General purpose event generators
- Precision add-ons
- Common reconstruction tools
- Analysis preservation
- Data preservation
- Comparison tools

Shopping List

- General purpose event generators
  - Precision where available
  - Full final state, requires non-perturbative physics
    - PDFs
    - Hadronisation
    - Underlying event
    - Hadronic decays
    - …
  - Herwig, Pythia, Sherpa

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Shopping List

- General purpose event generators
- Precision add-ons
  - Very active area
  - NLO, NNLO
  - Loops and or high mulitplicities
  - Matching and merging → general purpose generators
  - Automation for new processes
  - MadGraph, MC@NLO, POWHEG &c, GoSam, OpenLoops, Whizard, BlackHat…

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Shopping List

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  - Fastjet
  - Rivet
  - MadAnalysis, Delphes
  - …

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- General purpose event generators
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- Common reconstruction tools
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- Data preservation
  - Journals
  - HEPDATA
  - CERN open data

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  - Professor, Gambit, Contur, SModelS, CheckMate, FastLim…
  - PDF fitters
  - Other Fitters: electroweak precision, SUSY, etc

Shopping List

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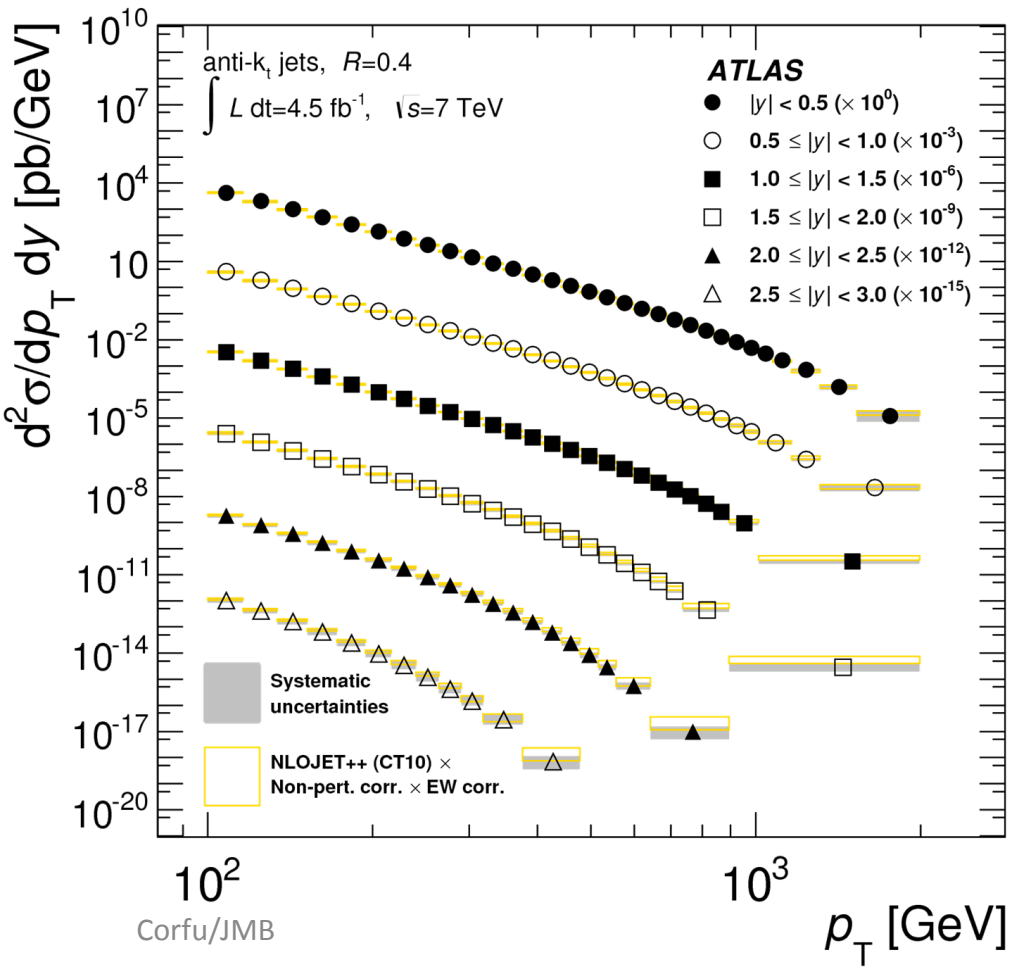
See for example MC4BSM at SLAC, May 2017:

https://indico.cern.ch/event/568875/timetable/

Precision ‘Standard Model’ Measurements

- They should not (and mostly do not) assume the SM
- They agree with the SM
- Thus they can potentially exclude extensions



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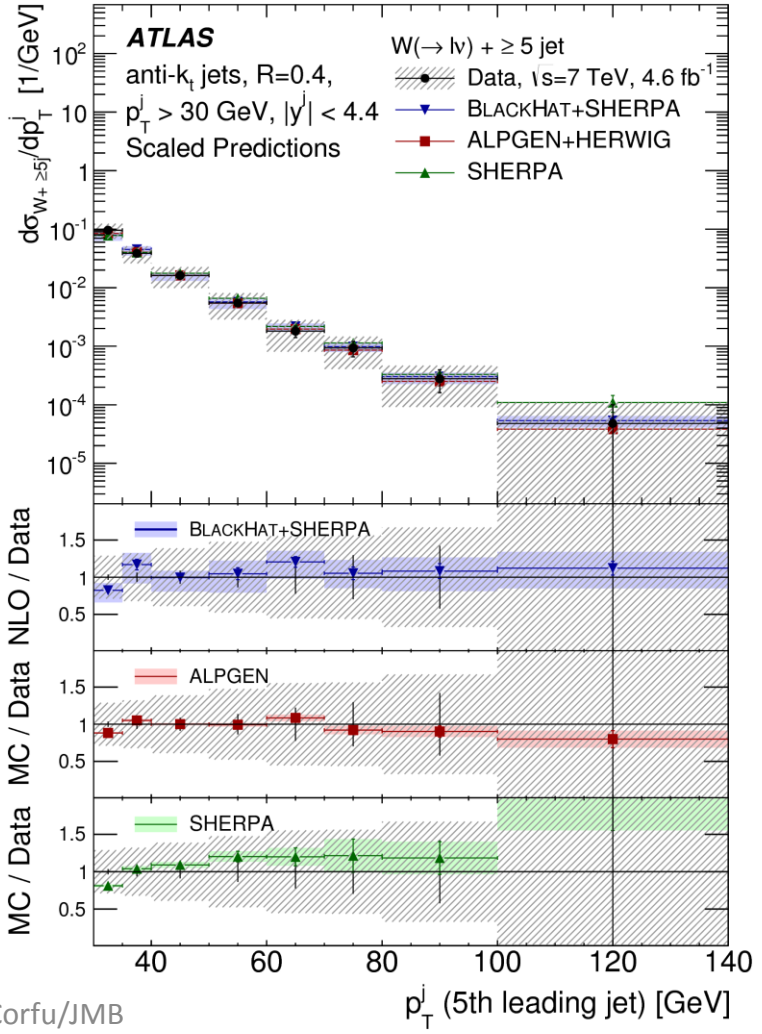
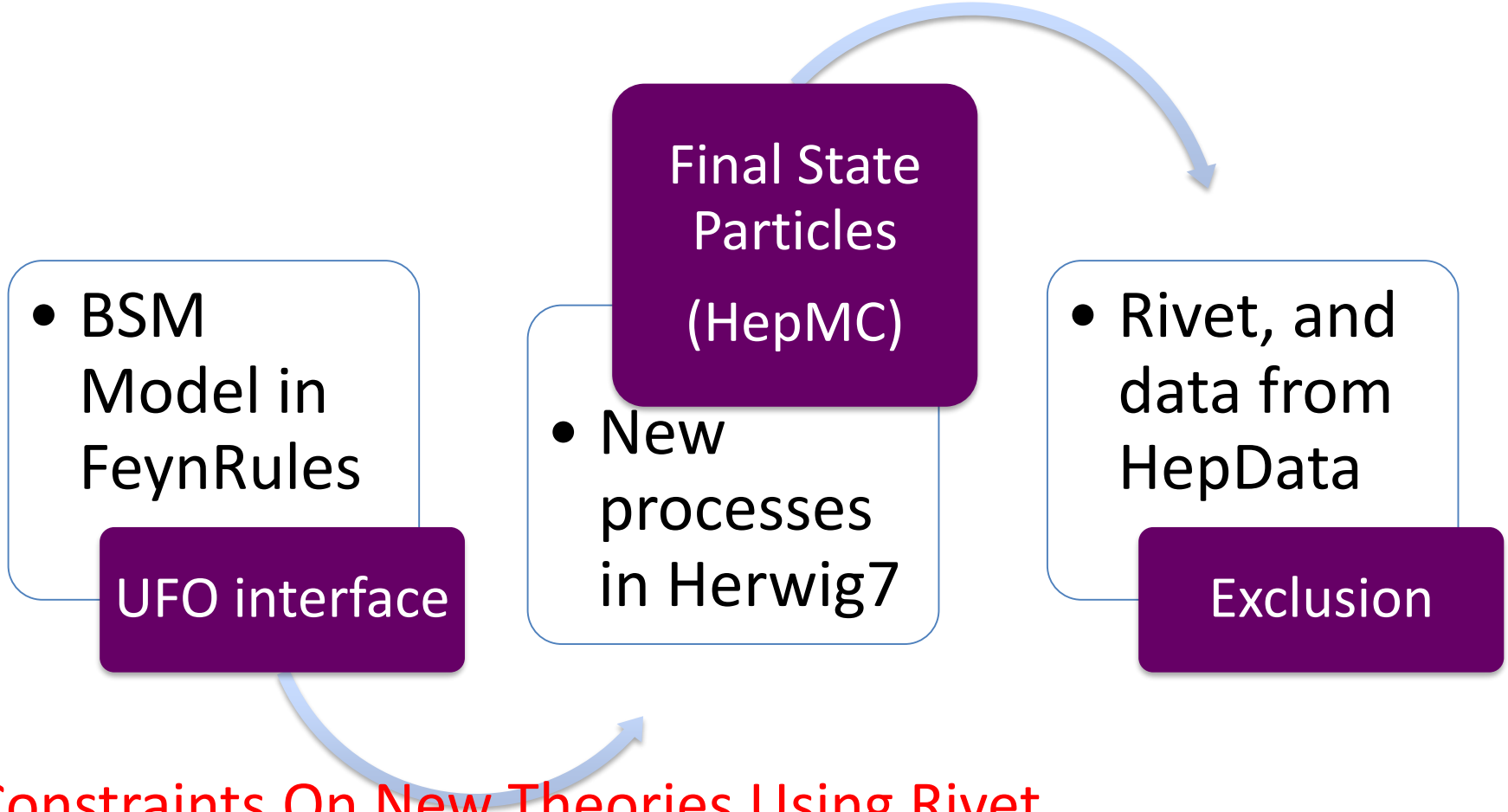


A (biased) example: Contur



Constraints On New Theories Using Rivet

arXiv:1606.05296 (JHEP 2017 078)
https://contur.hepforge.org/

Strategy

- Use measurements shown to agree with the Standard Model
  - Not a search! Guaranteed not to find anything
  - Measurements take longer, but more general and less model dependent
  - (Currently) assume the data = the background!
- Key for constraining new models if there is a signal (unintended consequences)
- Key for constraining scale of new physics if there is no signal

Statistics

- Construct likelihood function using
  - BSM signal event count
  - Background count (from central value of data points)
  - Gaussian assumption on uncertainty in background count, from combination of statistical and systematic uncertainties
  - BSM signal count error from statistics of generated events (small!)
- Make profile likelihood ratio a la Cowan et al (Asimov data set approximation is valid)
- Present in CL_s method (A. Read)
- Systematic correlations not fully treated - take only the most significant deviation in a given plot (conservative)

Dynamic data selection

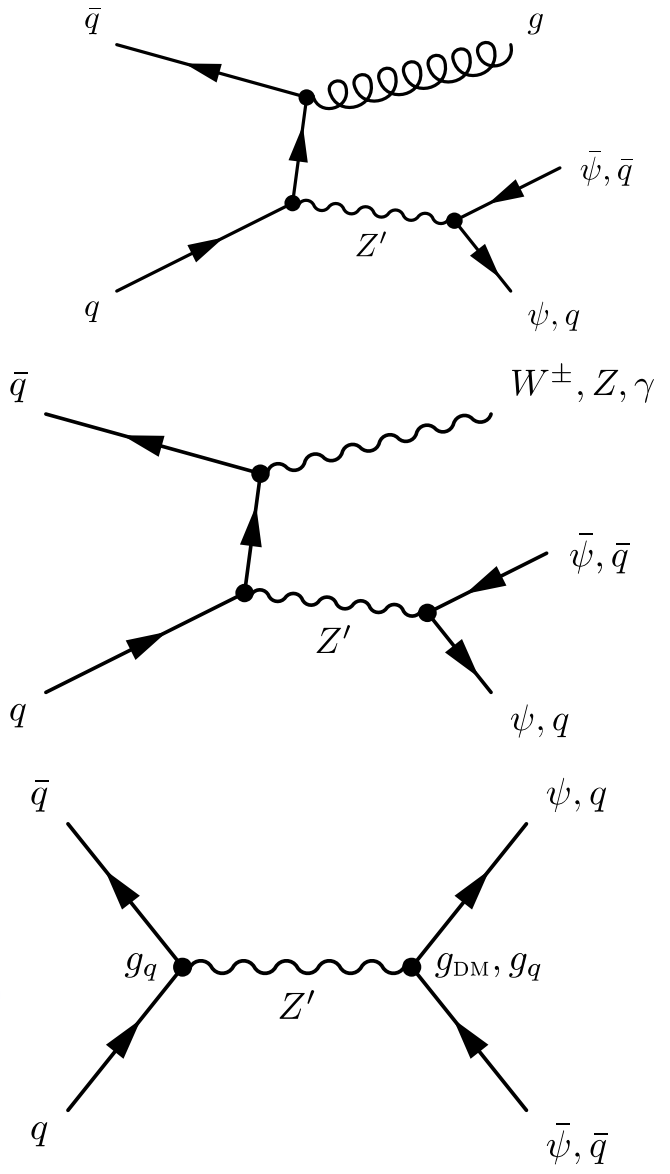
- SM measurements of fiducial, particle-level differential cross sections, with existing Rivet routines
- Classify according to data set (7, 8, 13 TeV) and into non-overlapping signatures
- Use only one plot from each given statistically correlated sample
- Jets, W+jets, Z+jets, γ (+jets), $\gamma\gamma$, WW, ZZ, W/Z+γ
  - "jets" includes heavy-flavour jets where available
  - No Missing E_T+jets (though one just published by ATLAS)
  - 8 TeV & 13 TeV now added
  - Also now using fiducial/differential/particle-level Higgs and top measurements
- Most sensitive measurement will vary with model and model parameters

CONTUR Category	Rivet/ Inspire ID	Rivet description
ATLAS 7 Jets	ATLAS_2014_I1325553 [28]	Measurement of the inclusive jet cross-section
	ATLAS_2014_I1268975 [30]	High-mass dijet cross section
	ATLAS_2014_I1326641 [32]	3-jet cross section
	ATLAS_2014_I1307243 [31]	Measurements of jet vetoes and azimuthal decorrelations in dijet events
CMS 7 Jets	CMS_2014_I1298810 [29]	Ratios of jet pT spectra, which relate to the ratios of inclusive, differential jet cross sections
ATLAS 8 Jets	ATLAS_2015_I1394679 [34]	Multijets at 8 TeV
ATLAS 7 Z Jets	ATLAS_2013_I1230812 [35]	Z + jets
CMS 7 Z Jets	CMS_2015_I1310737 [38]	Jet multiplicity and differential cross-sections of Z+jets events
CMS 7 W Jets	CMS_2014_I1303894 [37]	Differential cross-section of W bosons + jets
ATLAS W jets	ATLAS_2014_I1319490 [36]	W + jets
ATLAS 7 Photon Jet	ATLAS_2013_I1263495 [42]	Inclusive isolated prompt photon analysis with 2011 LHC data
	ATLAS_2012_I1093738 [44]	Isolated prompt photon + jet cross-section
CMS 7 Photon Jet	CMS_2014_I1266056 [45]	Photon + jets triple differential cross-section
ATLAS 7 Diphoton	ATLAS_2012_I1199269 [43]	Inclusive diphoton $+X$ events
ATLAS 7 ZZ	ATLAS_2012_I1203852 [39]	Measurement of the $ZZ(*)$ production cross-section
ATLAS W/Z gamma	ATLAS_2013_I1217863 [40]	W/Z gamma production

Simplified Model(s)

- Effective lagrangian including minimal new couplings *and* particles
- Our starter example: leptophobic Z' with vector coupling to u,d quarks, axial vector to a DM candidate ψ.

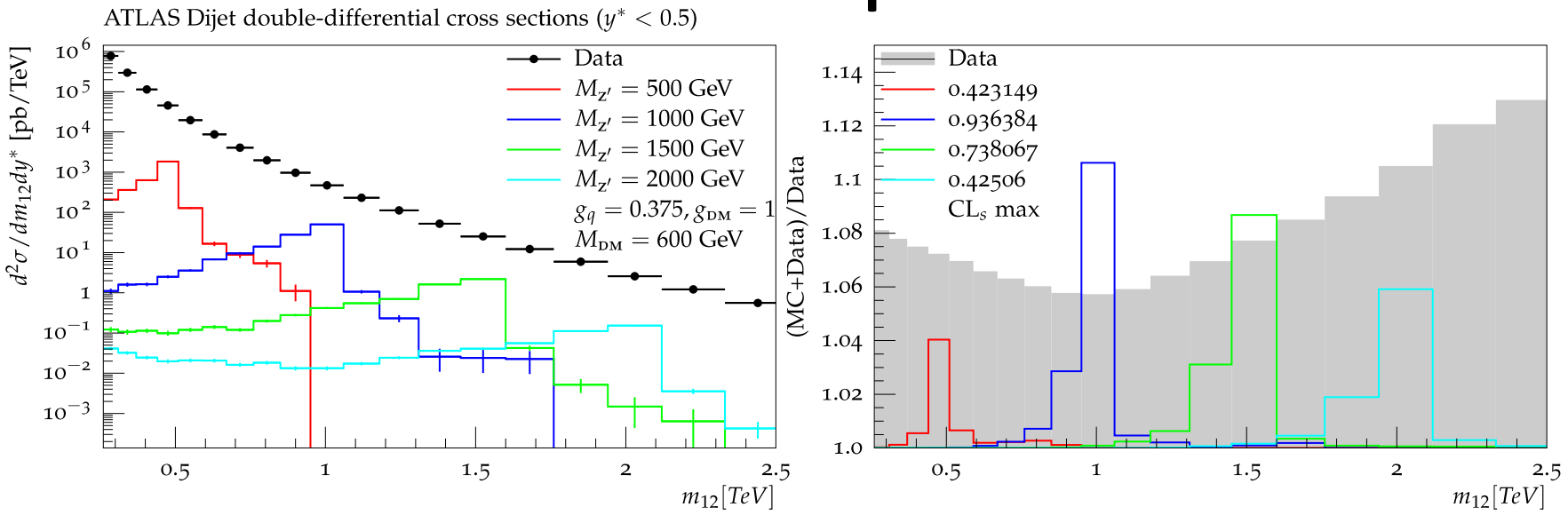
$$\mathcal{L} \supset g_{\mathrm{DM}}\,\overline{\psi}\gamma_\mu\gamma_5\psi\,Z'^\mu + g_q \sum_q \bar{q}\gamma_\mu q\,Z'^\mu$$

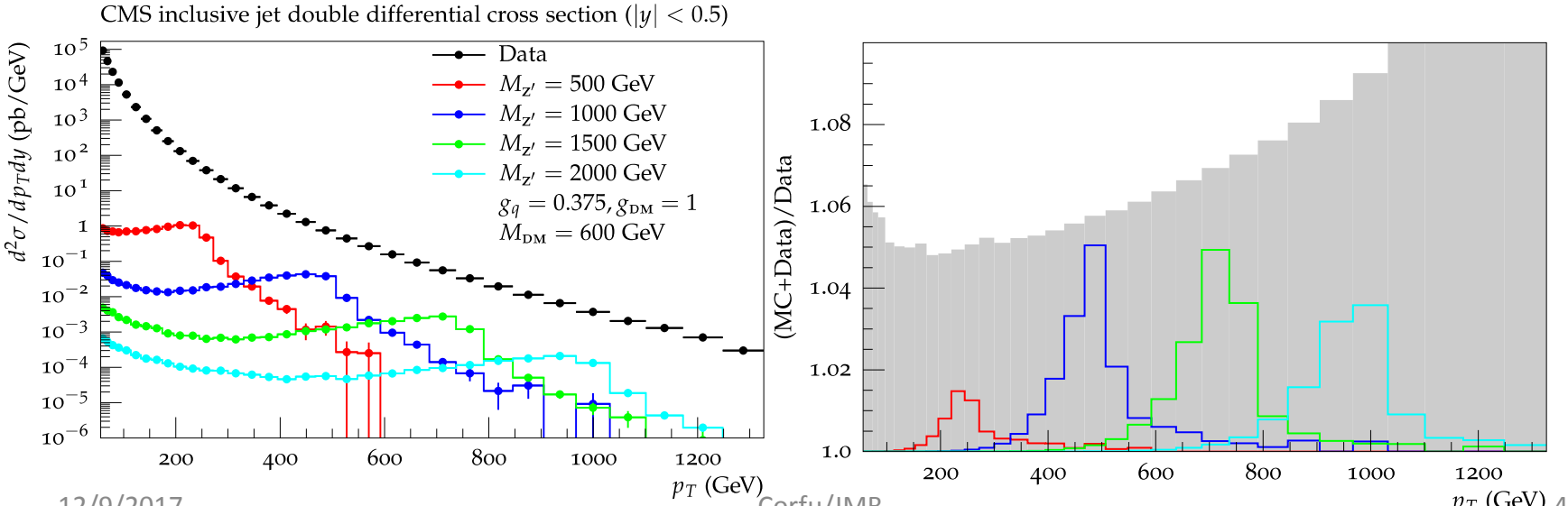


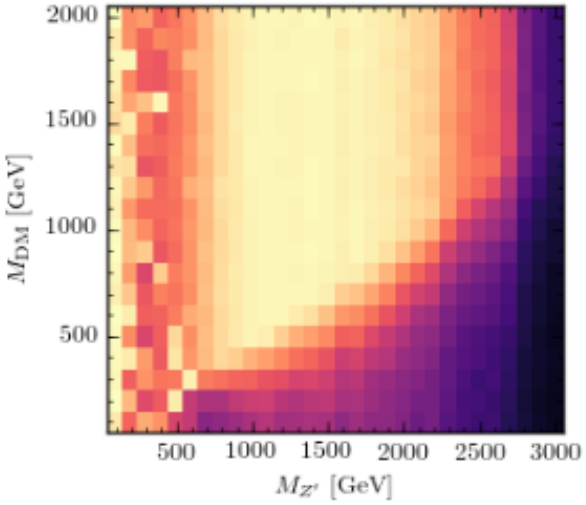
Parameter Choices

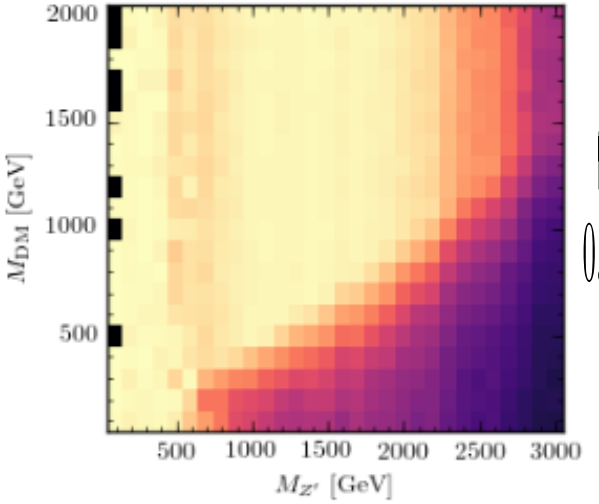
- Scan in M_{DM} and $M_{Z'}$
- Four pairs of couplings:
  - Challenging: $g_q = 0.25$; $g_{DM} = 1$
  - Medium: $g_q = 0.375$; $g_{DM} = 1$
  - Optimistic: $g_q = 0.5$; $g_{DM} = 1$
  - DM-suppressed $g_q = 0.375$; $g_{DM} = 0.25$

Data Comparisons

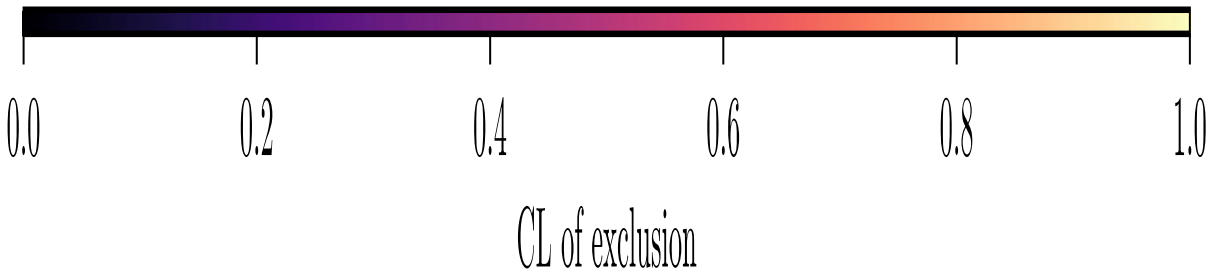








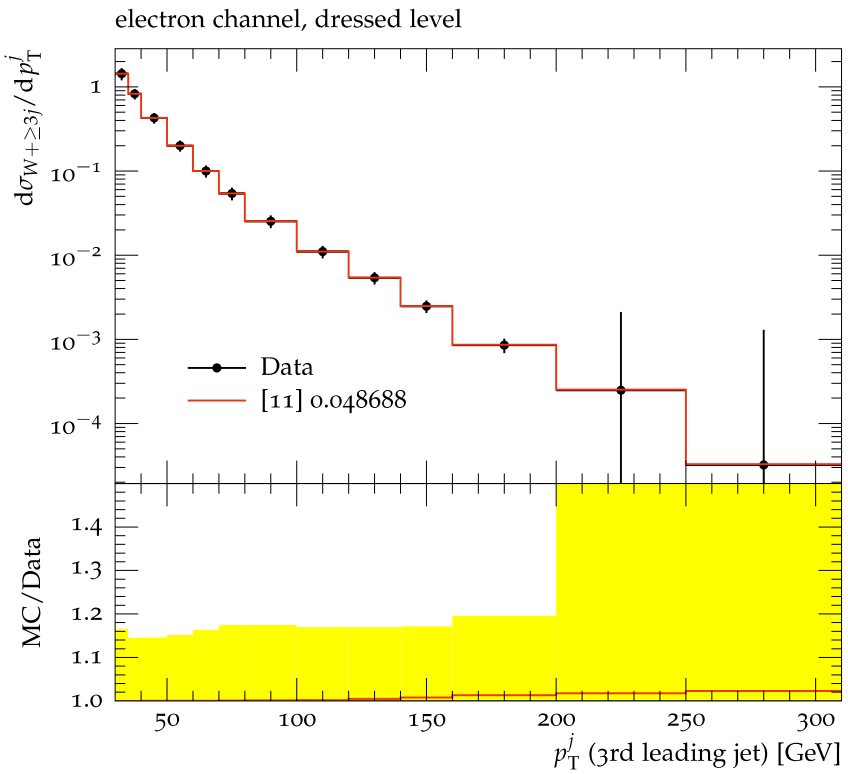
- Example Scan in M_{DM} and $M_{Z'}$
  - Medium: $g_q = 0.375$; $g_{DM} = 1$

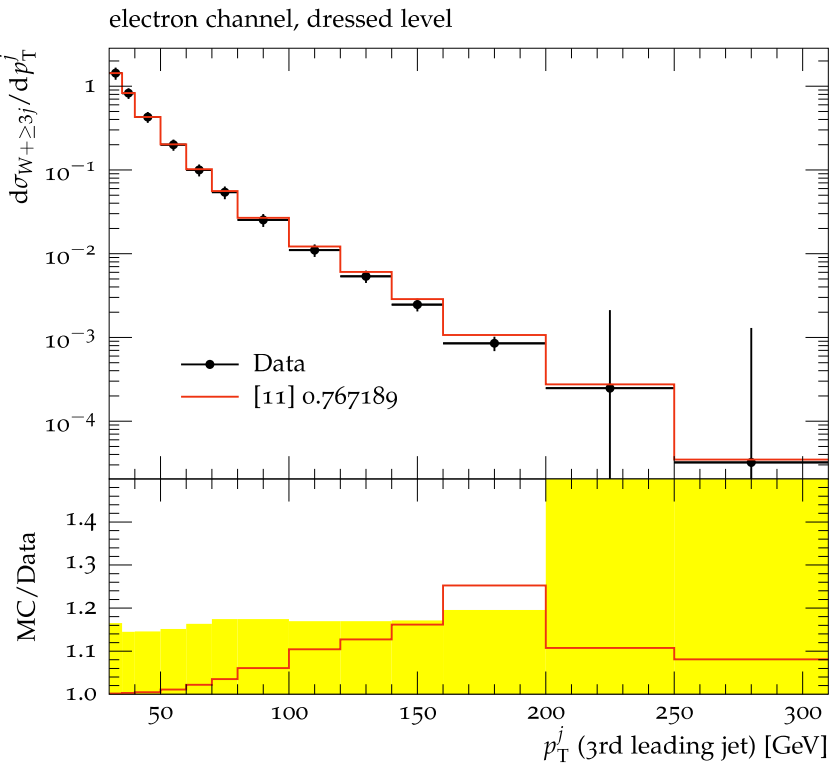


(Prelim plots from Kyeog Ro Lee, summer student))

Look at “all flavours” model

g_q = 0.375, M_{DM}=600 GeV, $M_{Z'}$=1 TeV (plots made in Les Houches…)

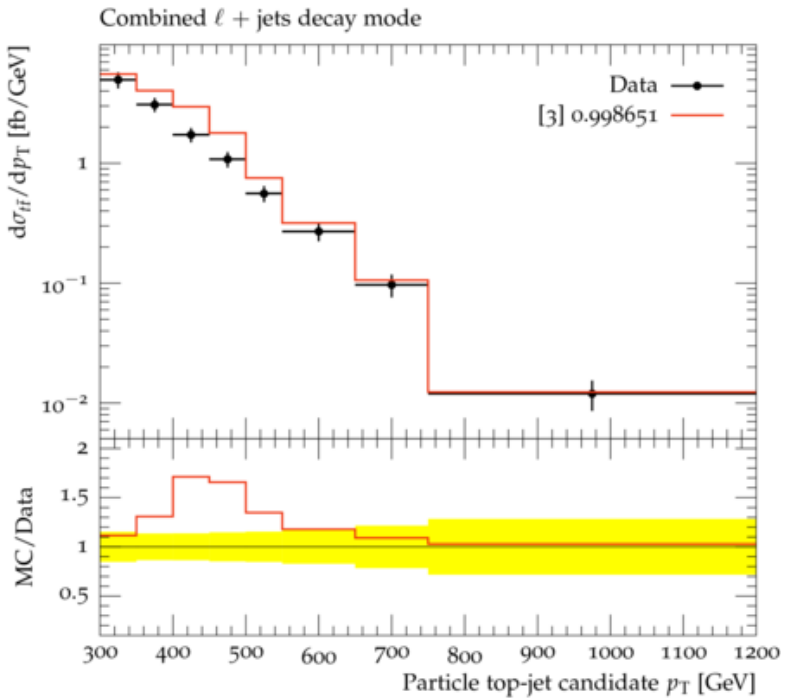


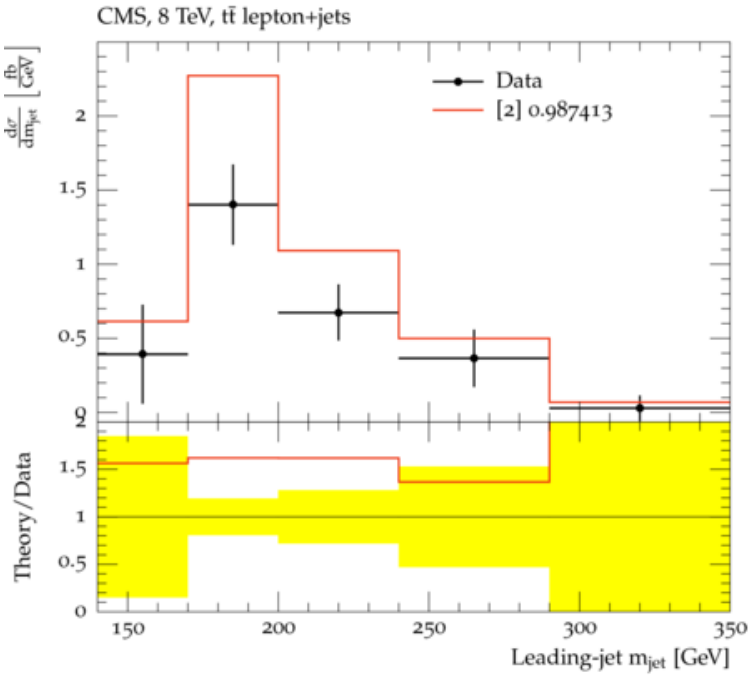


Look at “all flavours” model

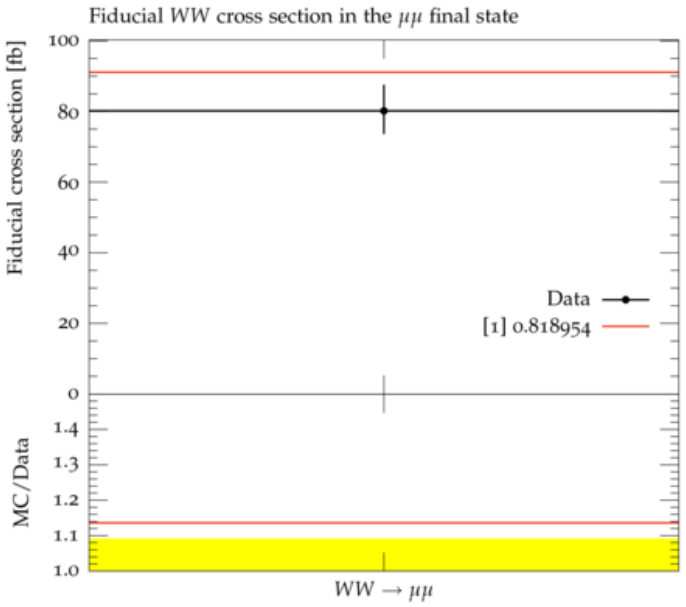
g_q = 0.375, M_{DM}=600 GeV, $M_{Z'}$=1 TeV

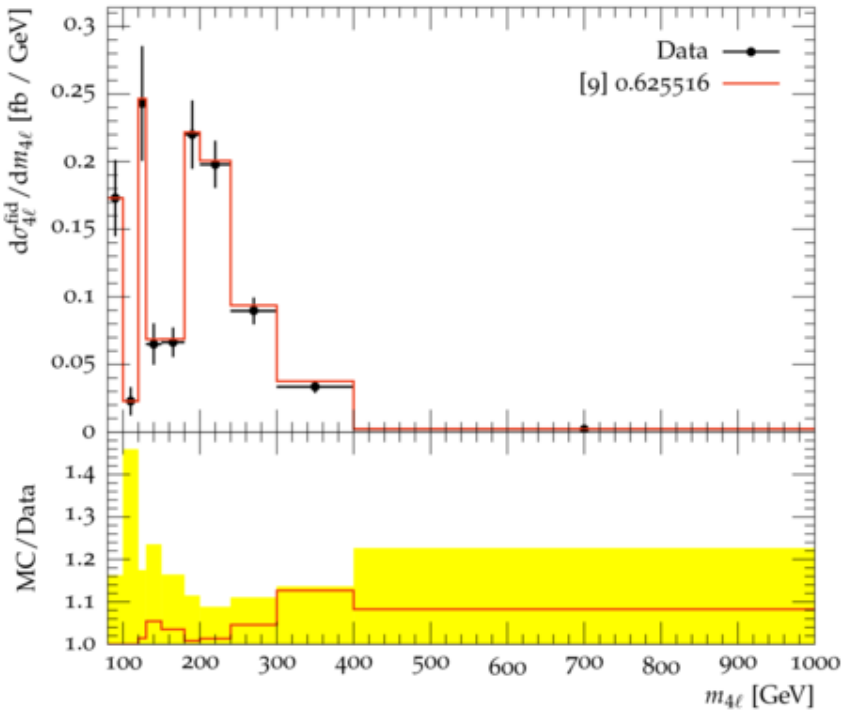
ATLAS & CMS
Boosted top
constraining DM
simplified model





- Les Houches studies of several new models underway within a few projects, aim for proceedings
- e.g 2 Higgs Double Model (Ken Lane *et al*) (Prelim/Work in progess)





WW & 4l measurements constraining 2HDM

Conclusions

- Particle-level measurements not only measure what is happening in our collisions, they constrain what is *not* happening.
- Limit-setting procedure developed; even with conservative treatment of correlations, limits are competitive with dedicated searches using comparable data-sets
- General framework developed:
  - consider all new processes in a given (simplified) model
  - consider all available final states. (e.g. V+jet shows previously unexamined sensitivity to the model considered)

Future work on Contur

- Highly scalable to other models & new measurements – plan continuous rolling development
- Include (latest) Standard Model predictions and uncertainties directly
- Treat correlations better, where available
- See and references therein, and contur.hepforge.org
- We want your UFO files…

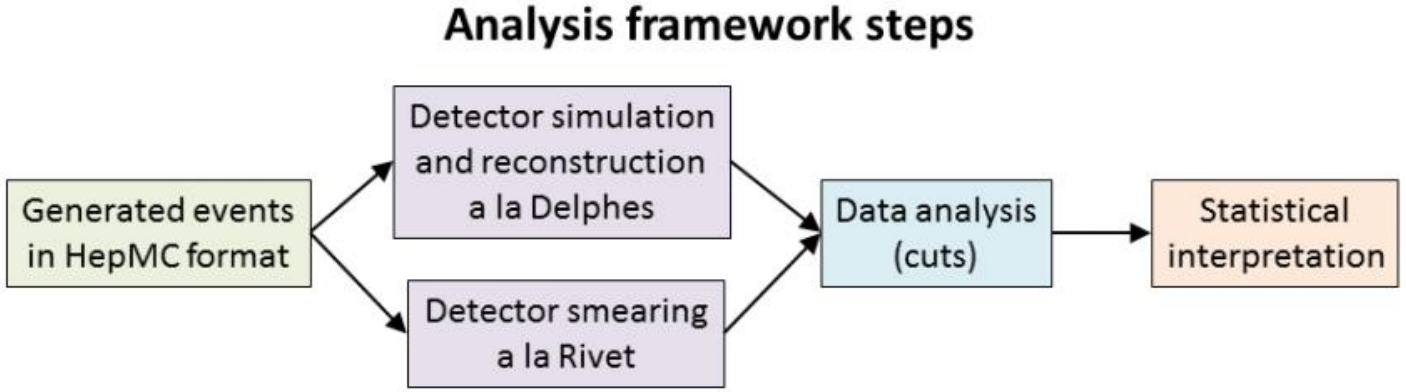
The Importance of Interfaces

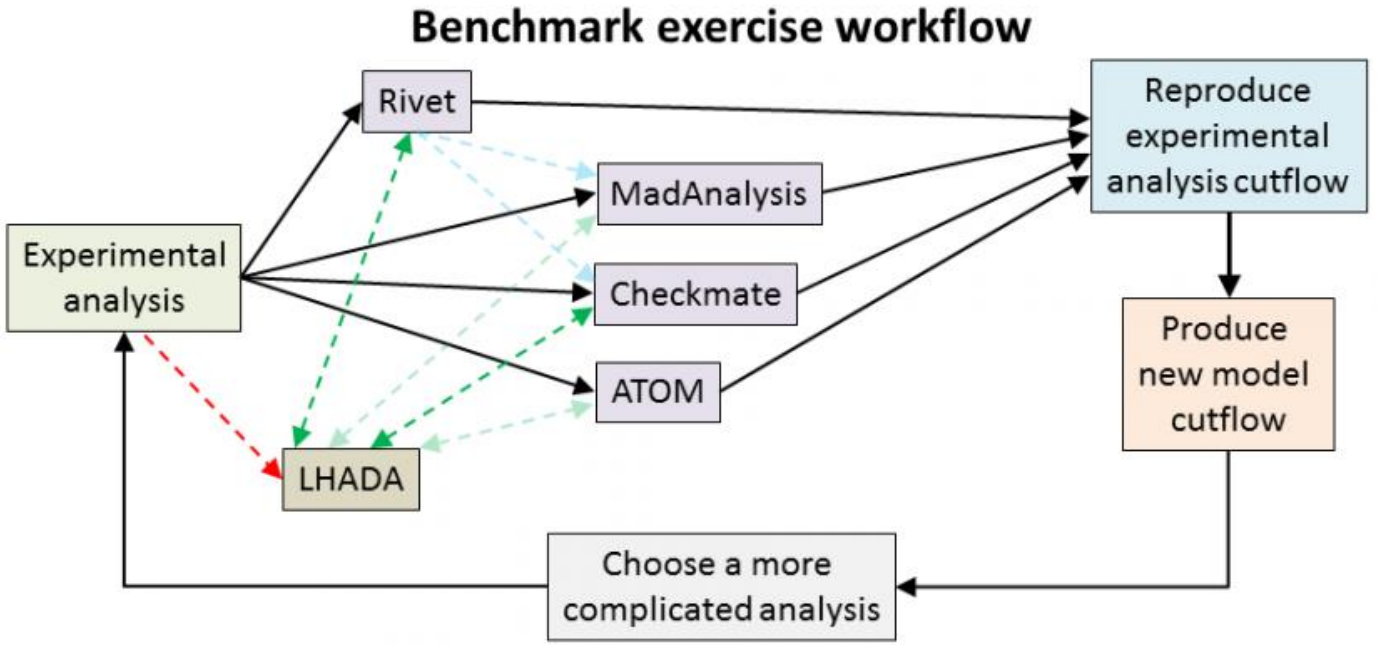
- LHEF
  - Les Houches Event Files standard format
  - parton-level output from ME generators → parton shower/hadronisation/full event simulation
  - Alwall et al, https://arxiv.org/abs/hep-ph/0609017
  - (also BLHA)
- HepEvt
  - Full final state from general-purpose event generator
  - Also used by GEANT4 material/detector simulation
  - http://hepmc.web.cern.ch/hepmc/
- UFO
  - Universal FeynRules Interface https://arxiv.org/abs/1108.2040
  - FeyRules model → general purpose generator

The Importance of Interfaces

- Yoda
  - Rivet/HepData/Plotting
- Root
  - Much experiment analysis, plotting
- Analysis/cut definitions?
  - MadAnalysis/Rivet/ATOM/Experiments…??
  - Exercise in Les Houches 2017 to benchmark/translate analyses, see what the issues are.

The Importance of Interfaces





Conclusion

- Wide range of tools available that cross between experiments, and between experiment and theory
- Great improvement on previous practice
  - Open source codes, common standards and interfaces, reproducibility, future-proofing, many-eyes…
- Risks of common-mode failure, “group think”
  - Mitigated by having diversity of packages from different authors, which can nevertheless interoperate to a large extent → interfaces, standards

Conclusion

- Significant and growing effort on "reinterpretation" of limits BSM models
- Within and beyond the experiments
- Aim for many advantages on the previous slide
  - Reproducibility, future-proof etc…
- Legacy of the LHC (including high lumi?)
- Watch this space (or get involved)
  - Next meeting FNAL, October 16-18:

    https://indico.cern.ch/event/639314/