Constraints on New Physics using LHC Measurements of the final state

Jon Butterworth

Birmingham, 24 May 2017

Dual/overlapping role of the LHC

- Searching for Physics Beyond the SM
  - Well motivated

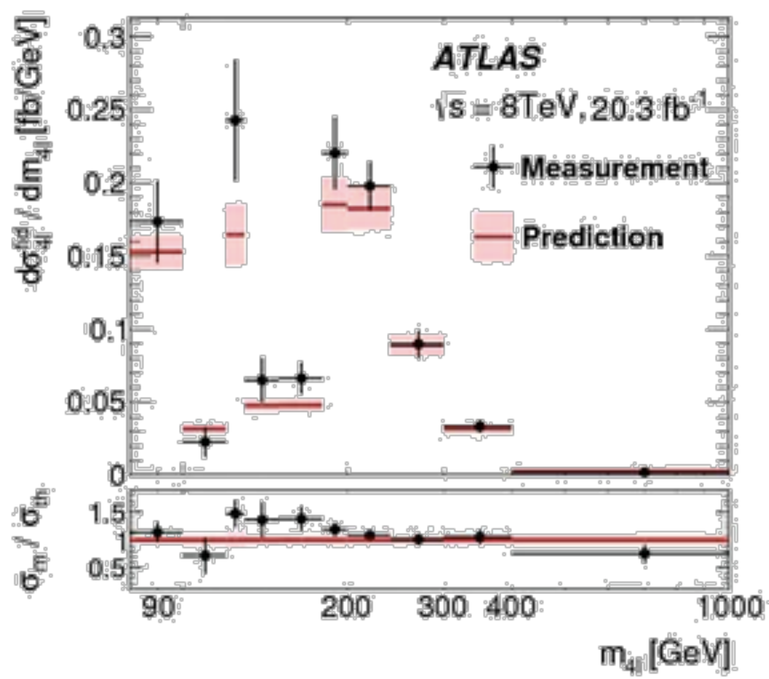
Beyond the Standard Model!

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



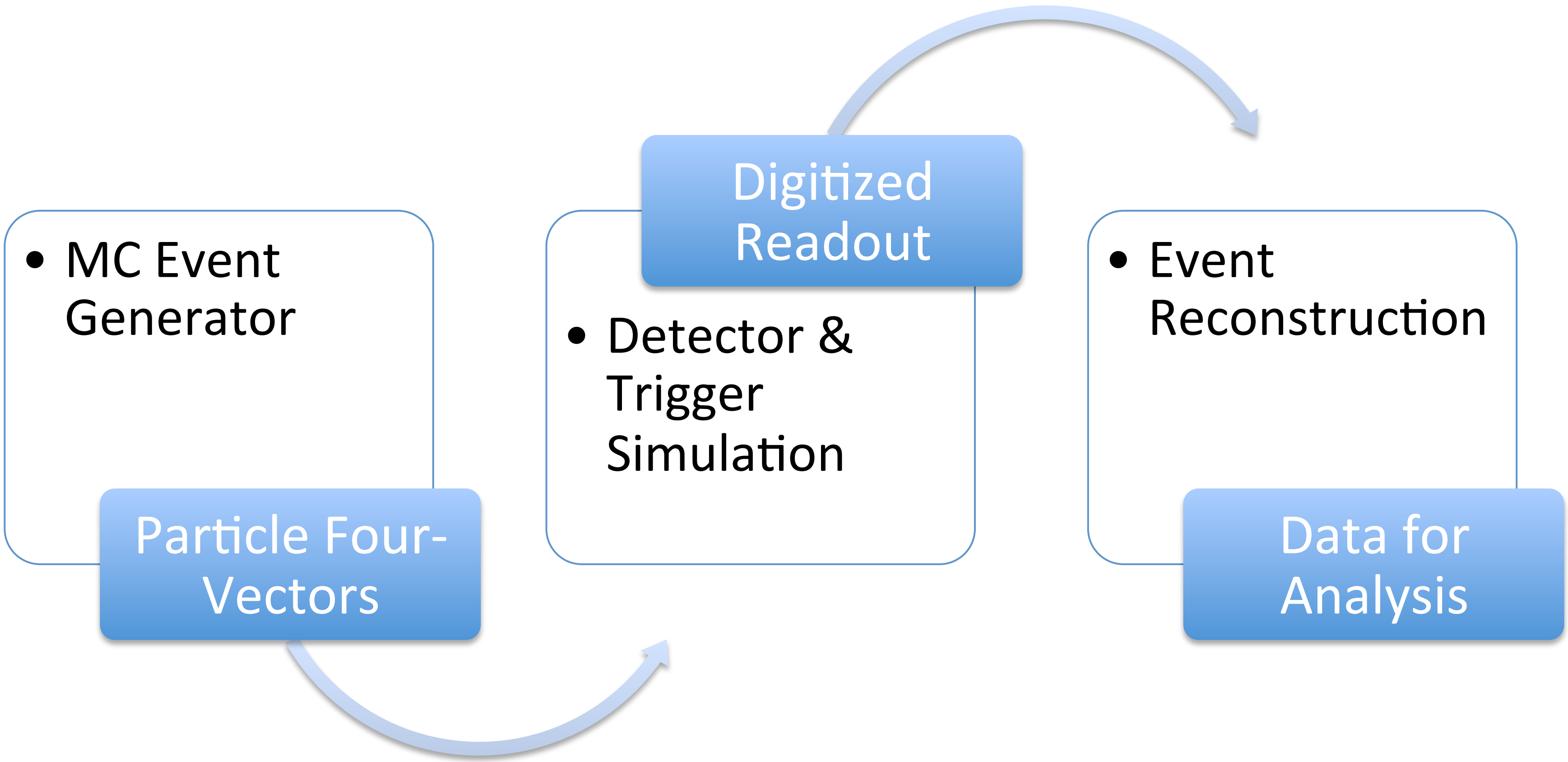
What do we actually *measure*?

- The final state!
  - Quantum mechanics says so
- Clearly we can't, even in principle, tell the difference between amplitudes with identical final states
- If your measurement can't be defined in such terms, you should worry!
  - Model dependence
  - Physical meaning!

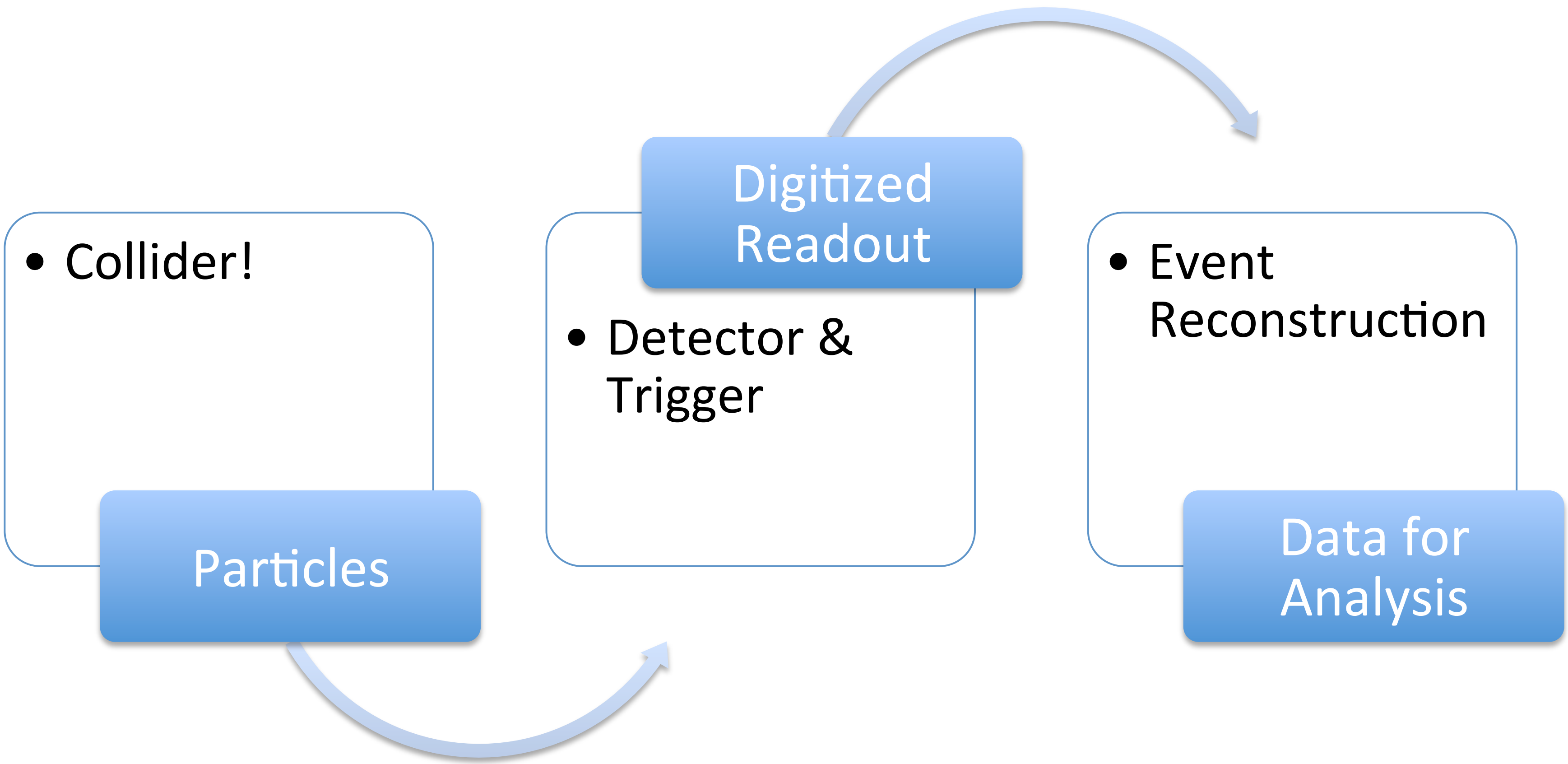
Tension between

- "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"

Simulation and Experiment



Simulation and Experiment



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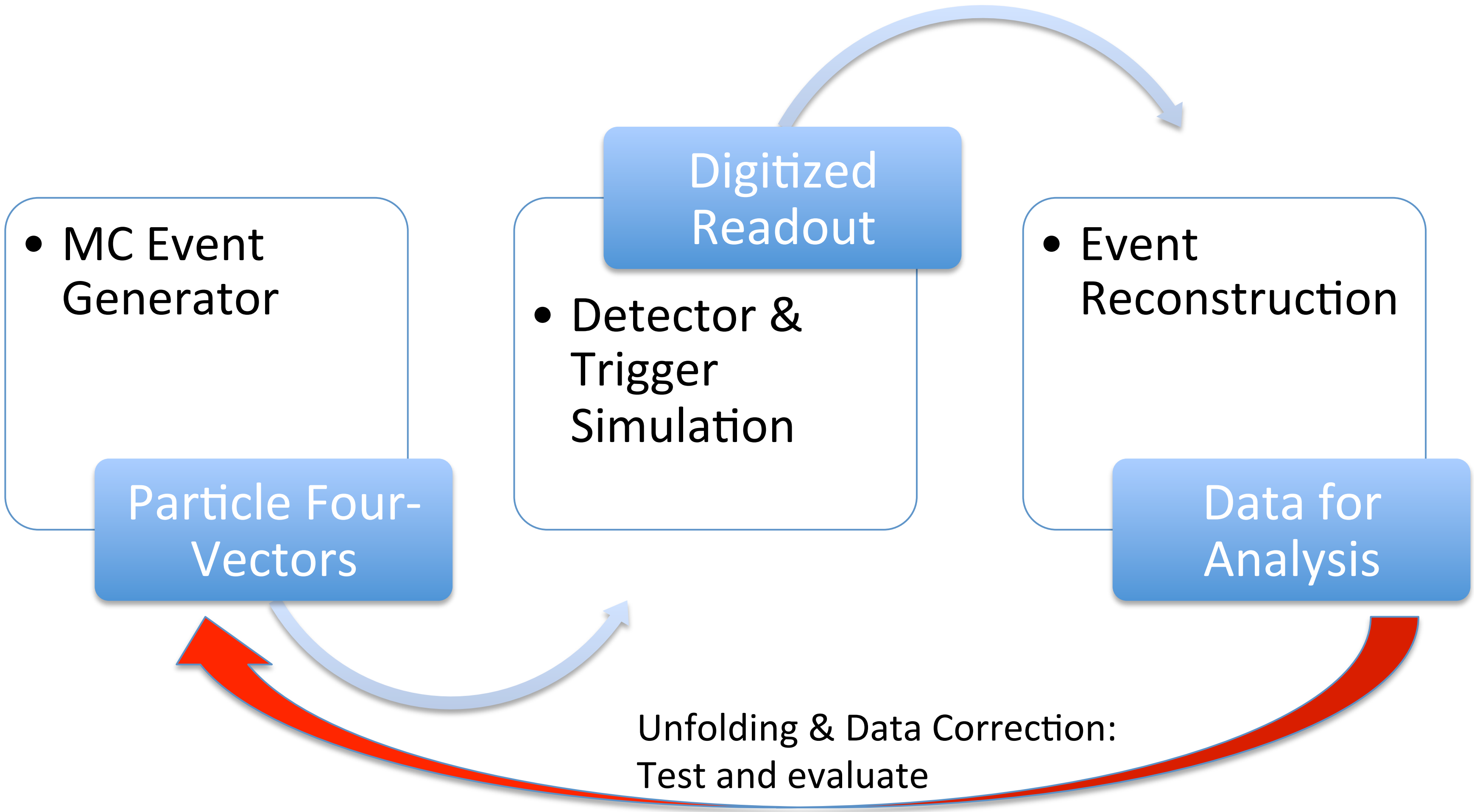
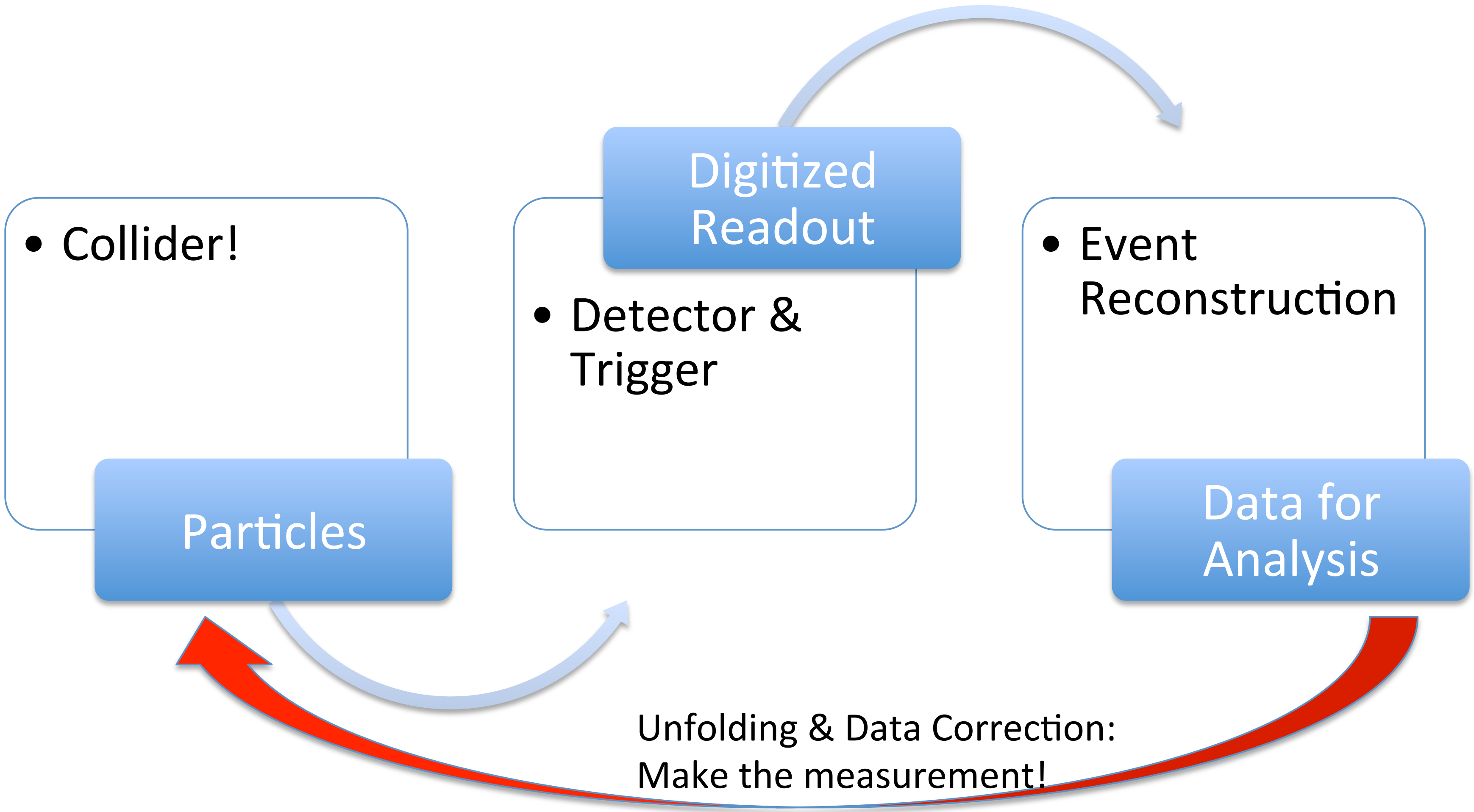


Simulation and Experiment



"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 mandate simulation of the full final state
  - Inclusive calculation is not enough on its own
  - MC generator are key tools

What is your final state?

- Quarks, gluons? (top?)
- W, Z, H?
- Taus?
- Hadrons? (lifetime cut? Do they propagate in B-field? In material?)
- Jets (what are the input objects?)
- Neutrinos? All of them? Missing E_T
- Photons? Isolated photons?
- Electrons, muons? (what about FSR?)

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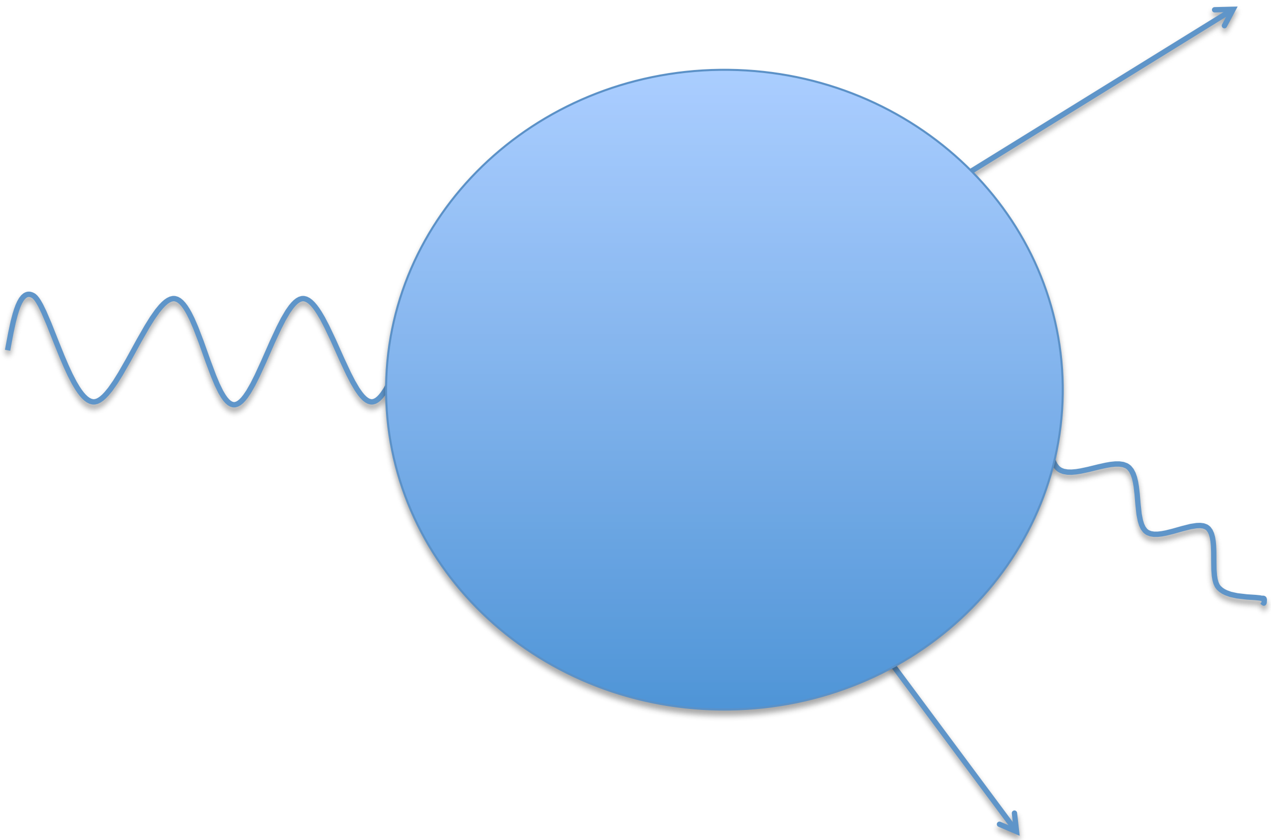
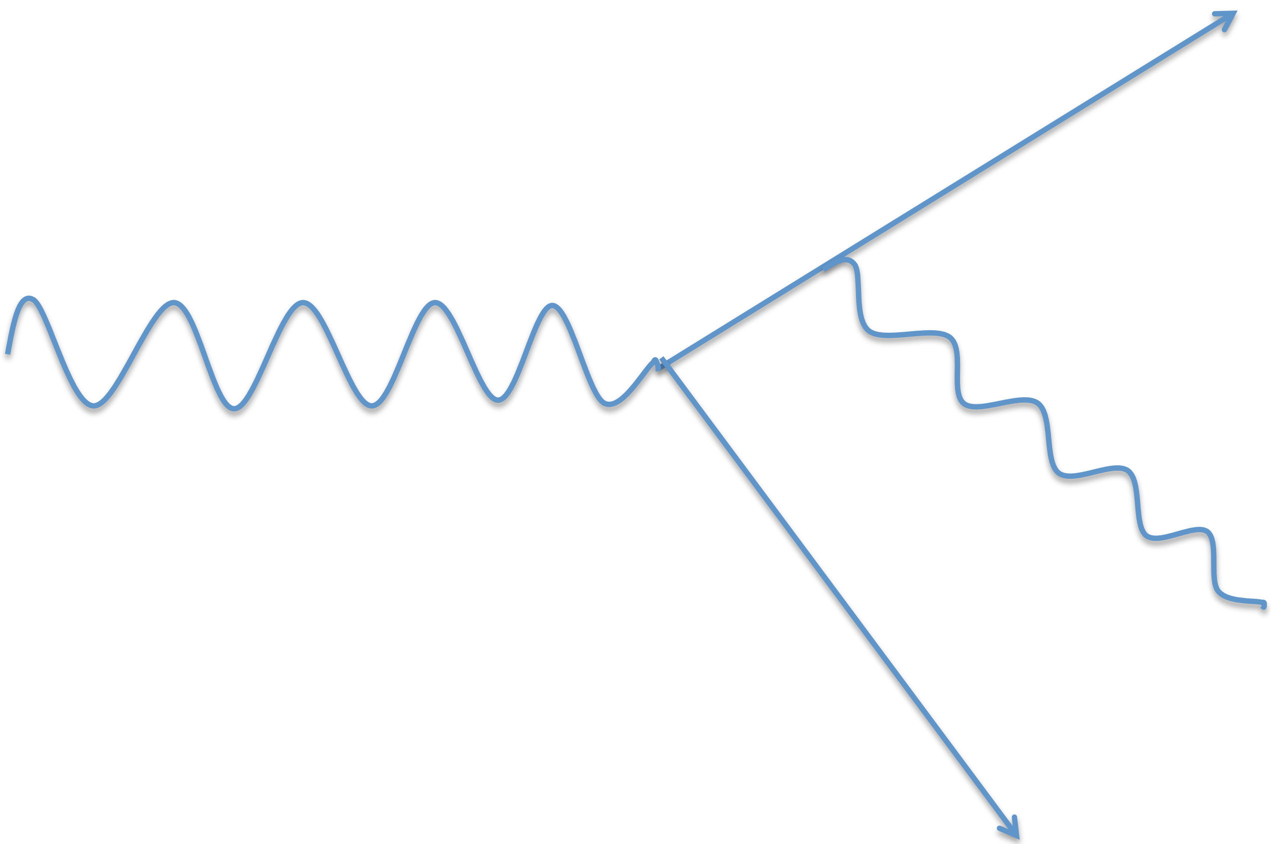
Important considerations (for searches too)

- 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

A Drell-Yan Event

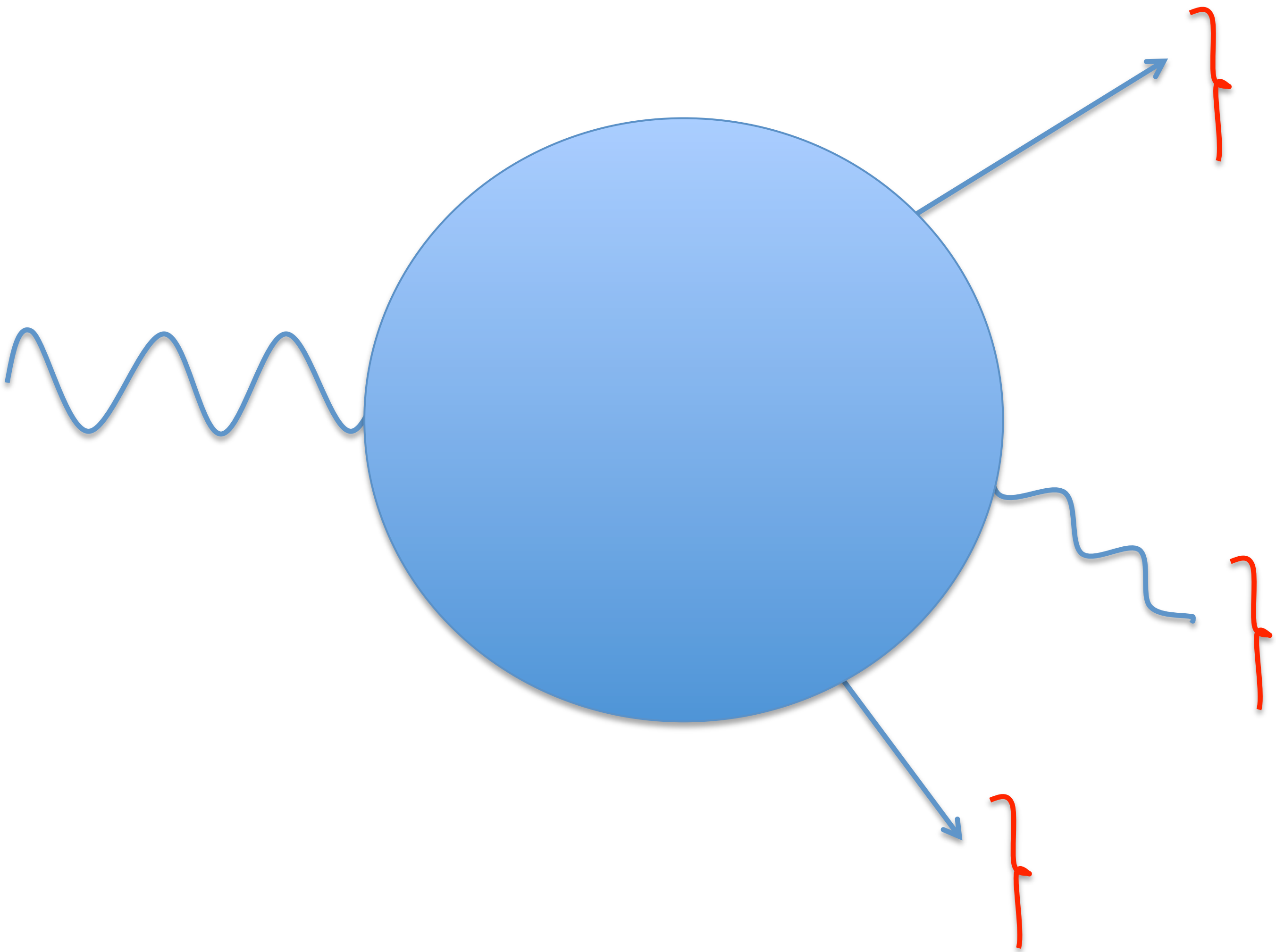


A Drell-Yan Diagram



- Consider low mass Drell-Yan (below Z peak)
  - Large source of low-mass lepton pairs from Z resonance with a hard FSR photon
  - Present in detector
  - Present in dressed truth definition, which is much closer to what the detector sees in this case

Dressed (small cone)



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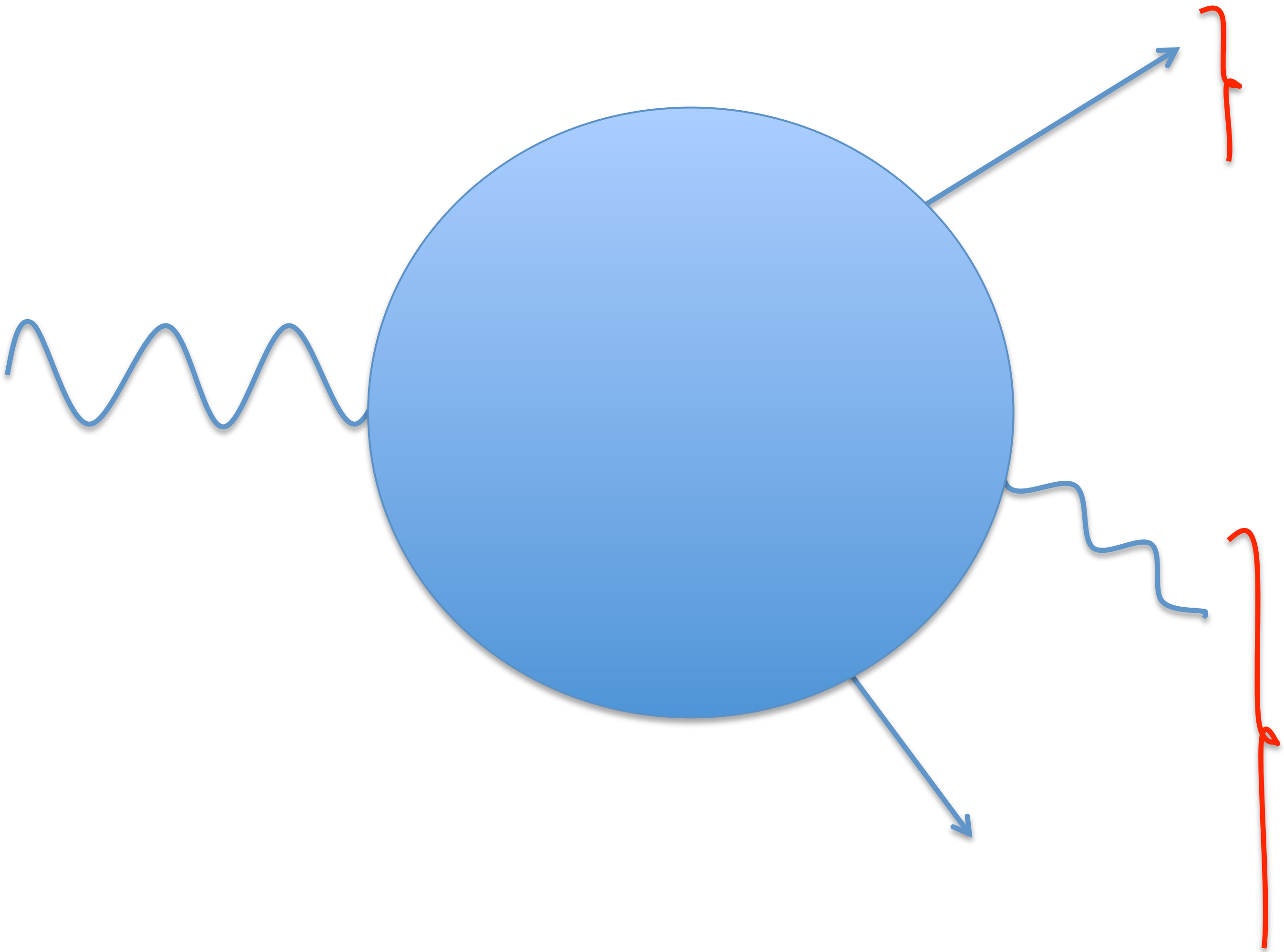
  - Dressing with large cone… approaching Born but not asking about unphysical variables…

Dressed (possibility) big cone



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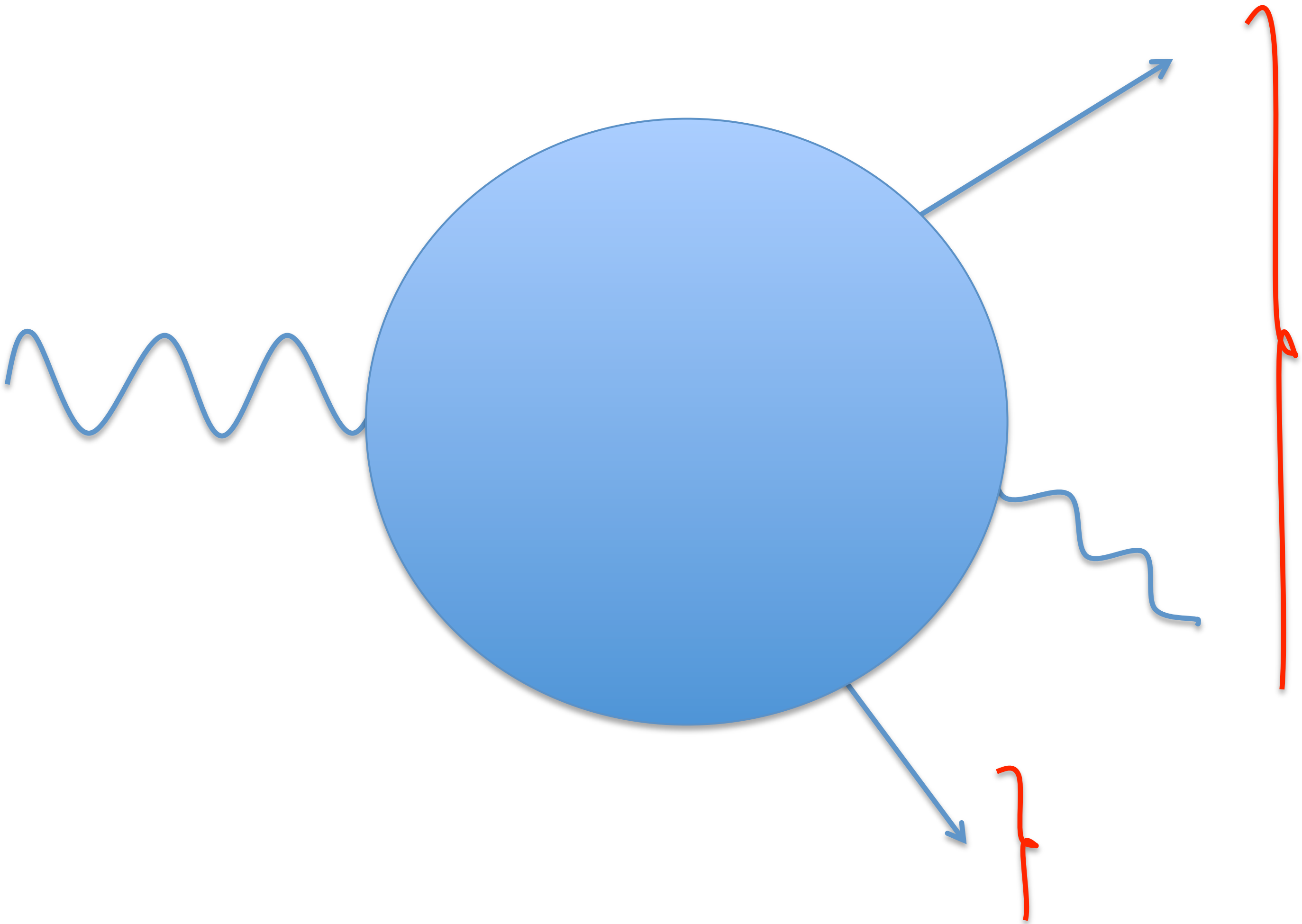
  - Correction to "Born" level has to do this →

Born



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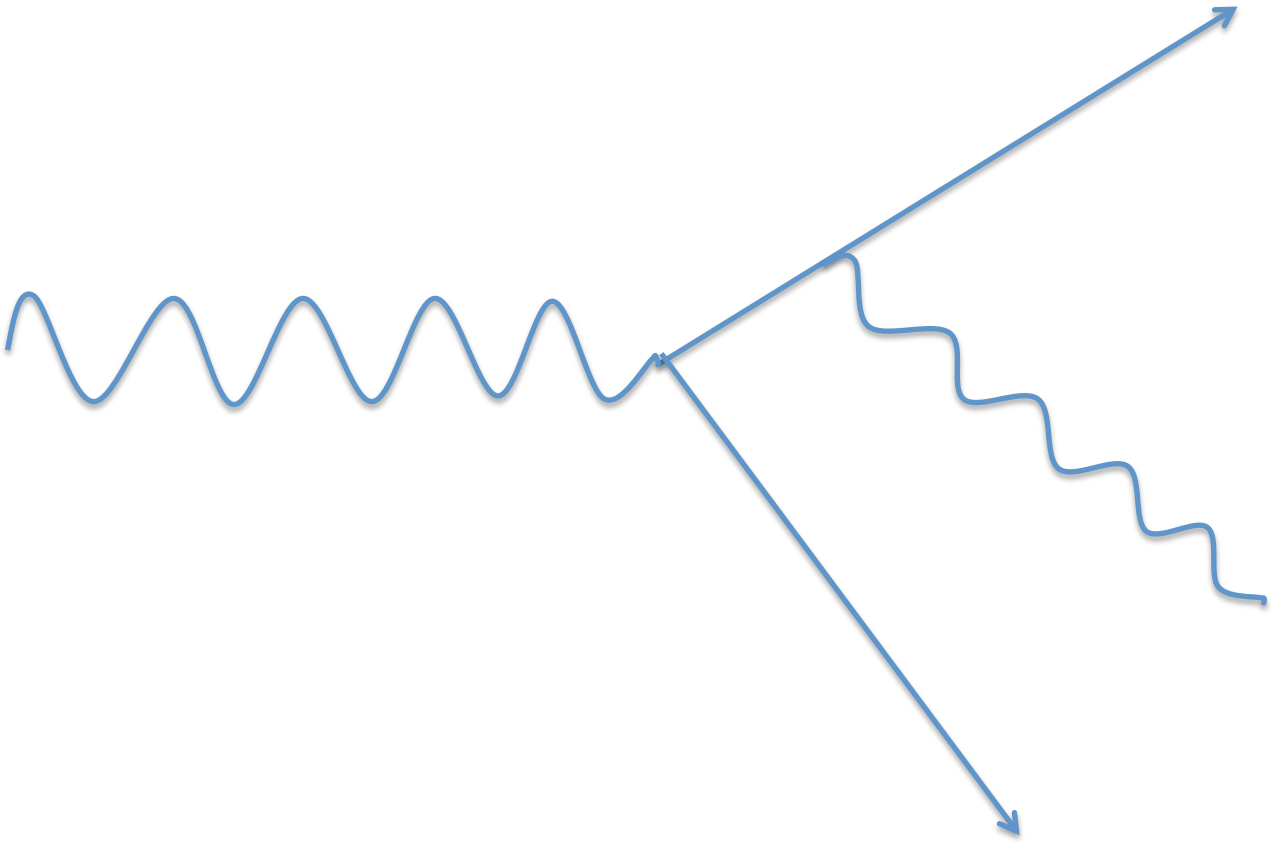

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  - Large source of low-mass lepton pairs from Z resonance with a hard FSR photon
  - Present in detector
  - Present in dressed truth definition, which is much closer to what the detector sees in this case
  - Correction to "Born" level
  - Low mass Drell-Yan near Z mass ~30% theory correction built into data

$m_{\ell\ell}$ [GeV]	$\frac{d\sigma}{dm_{\ell\ell}}$ [pb/GeV]	δ^{stat} [%]	δ^{cor} [%]	δ^{unc} [%]	δ^{tot} [%]	δ_1^{cor} [%]	δ_2^{cor} [%]	δ_3^{cor} [%]	δ_4^{cor} [%]	δ_5^{cor} [%]	δ_6^{cor} [%]	δ_7^{cor} [%]	δ_8^{cor} [%]	δ_9^{cor} [%]	δ_{10}^{cor} [%]	δ_{11}^{cor} [%]	δ_{12}^{cor} [%]	δ_{13}^{cor} [%]	$\mathcal{D}$	$\mathcal{A}$	$\delta_{\mathcal{A}}^{scale}$ [%]	$\delta_{\mathcal{A}}^{pdf+\alpha_s}$ [%]
26–31	1.95	0.9	2.4	1.6	3.0	0.1	0.4	−1.2	0.7	−0.4	−0.6	0.4	0.5	−1.3	−0.0	−0.6	−0.3	0.8	0.98	0.069	$^{-4.2}_{+4.2}$	$^{-2.0}_{+1.4}$
31–36	3.24	0.7	2.1	1.4	2.6	0.1	0.3	−1.1	0.6	−0.3	−0.4	0.2	0.2	−1.1	−0.4	−0.4	−0.4	0.7	0.98	0.194	$^{-2.8}_{+3.6}$	$^{-1.6}_{+1.1}$
36–41	2.63	0.8	1.7	1.2	2.2	0.2	0.2	−1.0	0.5	−0.2	−0.2	0.3	0.3	−0.8	−0.6	−0.2	−0.3	0.5	0.99	0.270	$^{-1.2}_{+1.1}$	$^{-1.4}_{+0.9}$
41–46	1.99	0.9	1.4	1.1	2.0	0.2	0.2	−1.0	0.4	−0.2	−0.0	0.3	0.4	−0.5	−0.2	−0.2	−0.0	0.4	1.00	0.321	$^{-1.2}_{+1.0}$	$^{-1.2}_{+0.8}$
46–51	1.52	0.9	1.2	1.1	1.9	0.2	0.3	−0.8	0.4	−0.1	0.1	0.2	0.3	−0.4	−0.3	−0.0	−0.2	0.4	1.05	0.356	$^{-0.9}_{+0.6}$	$^{-1.0}_{+0.7}$
51–56	1.23	1.0	1.1	1.0	1.8	0.2	0.3	−0.8	0.3	−0.1	0.1	0.2	0.2	−0.2	−0.0	−0.2	0.1	0.3	1.11	0.381	$^{-0.4}_{+0.5}$	$^{-1.0}_{+0.6}$
56–61	1.01	1.0	1.0	1.0	1.7	0.3	0.3	−0.7	0.3	−0.1	0.2	0.2	0.2	−0.2	−0.1	−0.1	−0.1	0.2	1.19	0.406	$^{-0.9}_{+0.3}$	$^{-0.9}_{+0.6}$
61–66	0.91	1.0	1.1	0.6	1.6	0.3	0.3	−0.6	0.3	−0.0	0.2	0.1	0.1	−0.0	0.7	−0.1	0.2	0.1	1.30	0.427	$^{-0.6}_{+0.4}$	$^{-0.8}_{+0.5}$

Table 5. The combined Born-level fiducial differential cross section $\frac{d\sigma}{dm_{\ell\ell}}$, statistical δ^{stat}, total correlated δ^{cor}, uncorrelated δ^{unc}, and total δ^{total} uncertainties, as well as individual correlated sources δ_i^{cor}. The correlated uncertainties are a linear combination of the 13 correlated uncertainties in the nominal muon and electron channels. As the uncertainties on the combined result no longer originate from individual error sources they are numbered 1–13. Also shown is the correction factor used to derive the dressed cross section ($\mathcal{D}$), and the NNLO extrapolation factor ($\mathcal{A}$) used to derive the cross section for the full phase space, along with the uncertainties associated to variations in scale choice $\delta_{\mathcal{A}}^{scale}$, and PDF uncertainty $\delta_{\mathcal{A}}^{pdf+\alpha_s}$. The luminosity uncertainty (1.8%) is not included.

ATLAS arXiv
arXiv:1404.1212

QED FSR effects

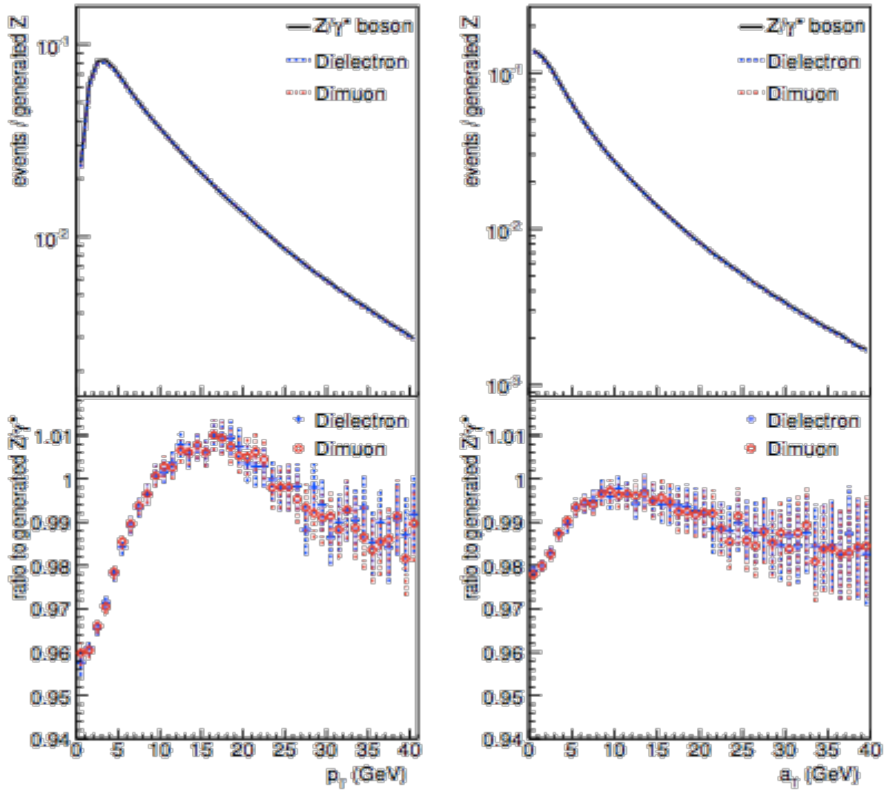

Fig. 46: The Z/γ^* p_T (left) and a_T (right) using the same treatment of electron and muon final states.

(Dressed electrons and muons, cone 0.2.)

From Les Houches 2009 **arXiv:1003.1643**

A. Buckley, G. Hesketh, F. Siegert, P. Skands, M. Vesterinen, T.R. Wyatt

QED FSR effects

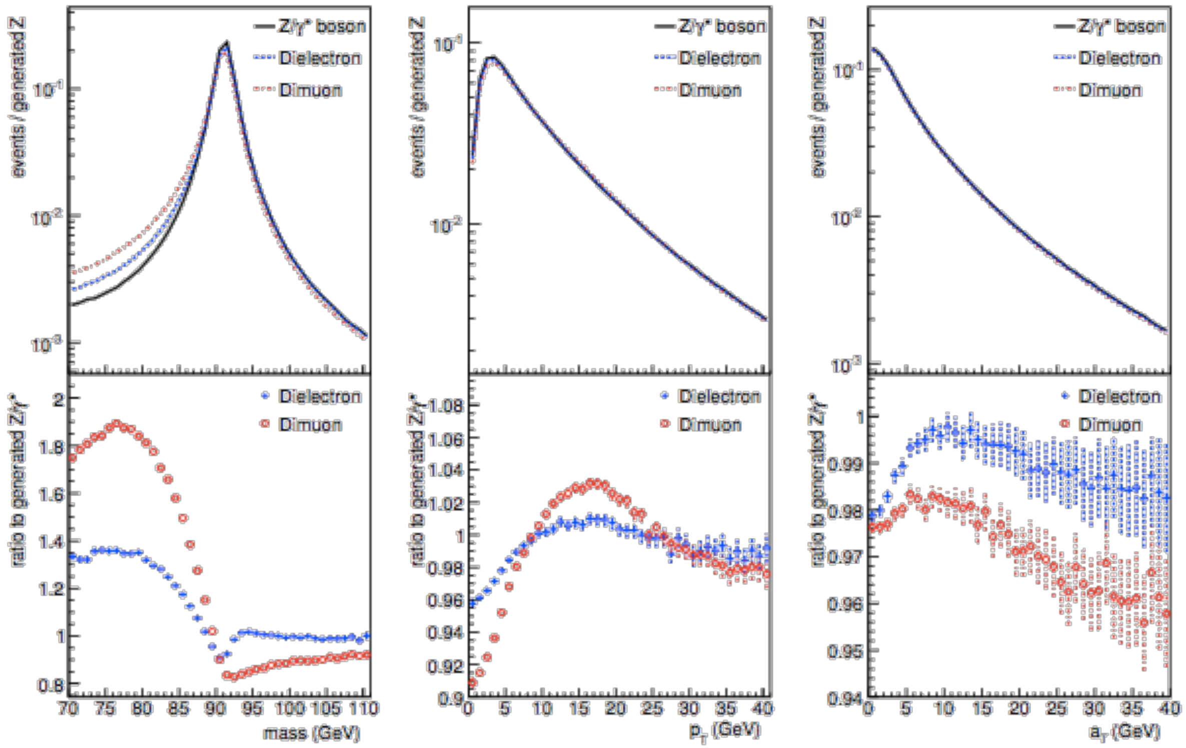

Fig. 44: Comparing the generated Z/γ^* to the observable (defined in the text). Left: the Z/γ^* mass; centre: the Z/γ^* p_T; right: the Z/γ^* a_T.

(Dressed electrons, cone 0.2. Bare muons.)

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Key points from that example

- If in the future a better QED/EWK calculation is done (or a bug is found in the old one) the Born measure is no use, but the dressed one is unaffected (so long as the radiation in the dressing region is adequately described) and can be compared to the new theory.
- If you want to e.g. fit a PDF, correcting to Born level improves the correlation between dilepton mass and partonic x → easier to interpret.

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

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- Ideally of course, build an experiment which covers all the phase space of interest…

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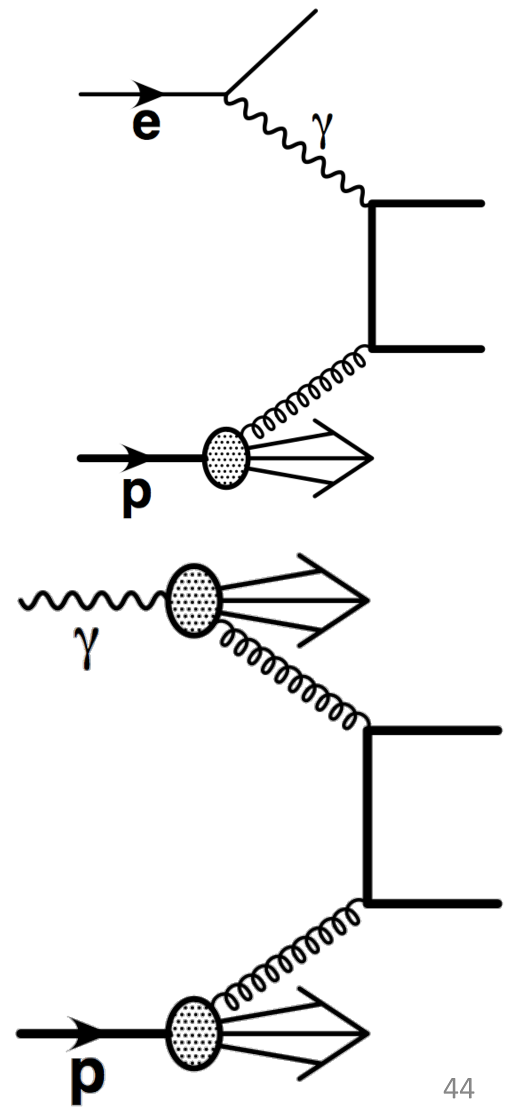
- Ideally of course, build an experiment which covers all the phase space of interest…
- Fiducial cross section should be defined in terms of the “ideal” or “true” final state

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

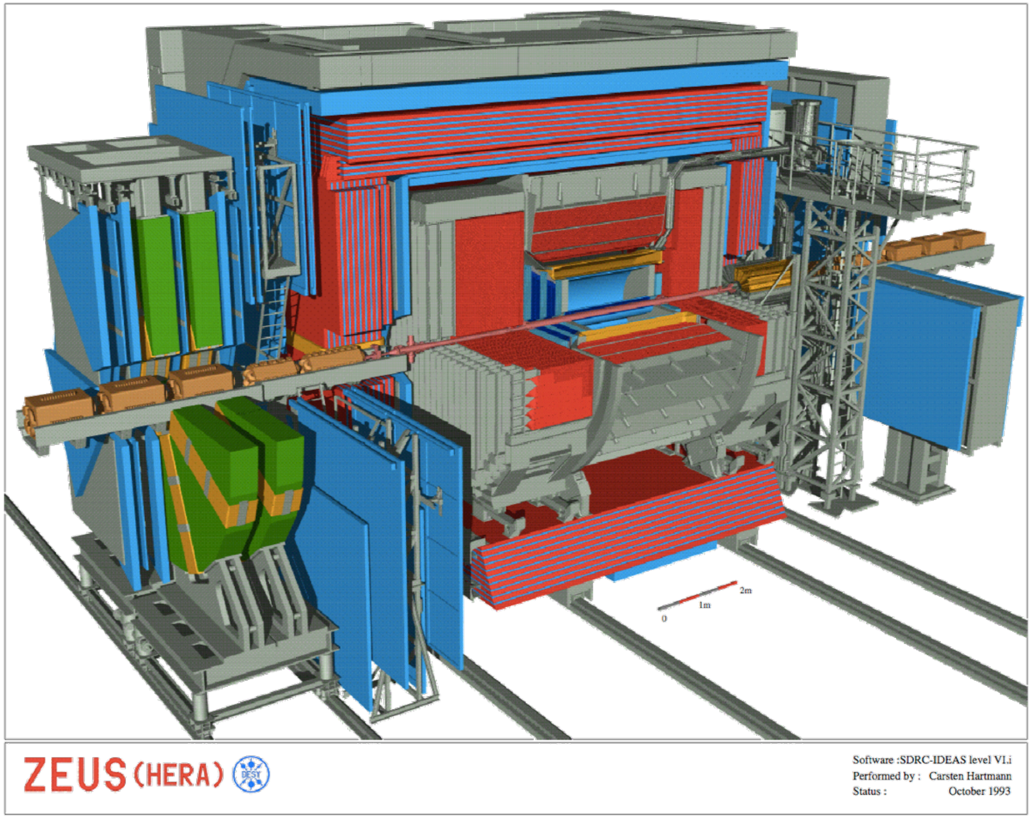
Real example: ZEUS charm photoproduction

- Electron-proton collider, proton energy 820 GeV, electron energy 27 GeV
  - →Mean photon energy ~10 GeV.
  - →Photon proton CM energy ~100 to 300 GeV
  - →Kinematics highly boosted in the proton direction



Real example: ZEUS charm photoproduction

- Tagging of charm via D*
  - →Highly dependent on track reconstruction, which has limited rapidity and p_T coverage.



Using the above quantities we measure an ep cross section for $D^{*\pm}$ production, $\sigma(ep \to D^{*\pm}X) \equiv \sigma(ep \to D^{*+}X) + \sigma(ep \to D^{*-}X)$, of:

$$\sigma(ep \to D^{*\pm}X) = 32 \pm 7(stat)^{+4}_{-7}(syst)\ \text{nb}$$

in the kinematic region $\{p_T(D^*) > 1.7$ GeV, $|\eta(D^*)| < 1.5\}$ and $115 < W < 275$ GeV. This cross section is valid for $Q^2 < 4$ GeV^2. The statistical error also includes the one due to the Monte Carlo statistics.

In order to quote a cross section for charm production we need to correct for the fraction of events in which a charm quark pair fragments into D^{*+} or D^{*-} as well as for the acceptance A_{ext} of the kinematic region $\{p_T(D^*) > 1.7$ GeV, $|\eta(D^*)| < 1.5\}$. The former is $(52.0 \pm 4.2)\%$ [33] and the latter is calculated by using PYTHIA with MRSD$'_{-}$/GRV HO to be $A_{ext} = 13.7\%$ for the region $115 < W < 275$ GeV. This extrapolation outside the kinematic region has a large uncertainty. In extrapolating $p_T(D^*)$, the uncertainty is mainly due to the strong dependence on the m_c value and for $\eta(D^*)$ it comes from the large differences between the different structure function parametrisations in the region $|\eta(D^*)| > 1.5$. As a consequence, the systematic error of the product $Acc \cdot A_{ext}$ is very large. We have fixed m_c to 1.5 GeV and quote the systematic error $\Delta(Acc \cdot A_{ext})$ coming from the different structure functions and using HERWIG (SF and MC in Table 1 respectively). Using a value of m_c of 1.35 GeV (1.8 GeV) results in a shift of $+25\%$ (-40%) of the estimated cross section.

Real example: ZEUS charm photoproduction

$\langle W \rangle$ (GeV)	N	Acc (%)	A_{ext} (%)	$\Delta(Acc \cdot A_{ext})$ SF	MC	$\sigma(ep \to ccX)$ (μb)	Integrated Φ	$\sigma(\gamma p \to ccX)$ (μb)
163 ± 16	21 ± 7	8.1	16.2	$^{+63}_{-49}\%$	$+54\%$	$0.23 \pm 0.08^{+0.23}_{-0.11}$	0.0367	$6.3 \pm 2.2^{+6.3}_{-3.0}$
243 ± 24	28 ± 8	22.4	8.8	$^{+92}_{-43}\%$	$+30\%$	$0.21 \pm 0.06^{+0.17}_{-0.10}$	0.0122	$16.9 \pm 5.2^{+13.9}_{-8.5}$
198 ± 20	48 ± 11	11.4	13.7	$^{+76}_{-43}\%$	$+48\%$	$0.45 \pm 0.11^{+0.37}_{-0.22}$	0.0488	$9.1 \pm 2.2^{+7.6}_{-4.4}$

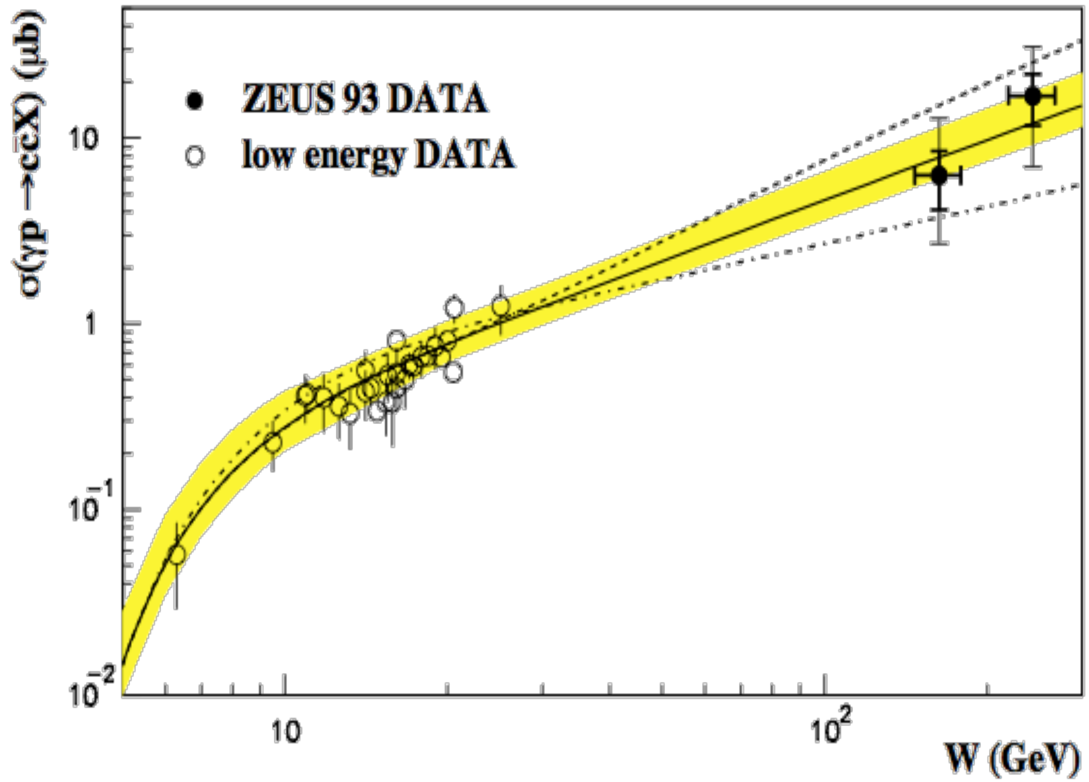
Table 1: Acceptances and cross sections

We therefore estimate the ep charm production cross section at $\sqrt{s} = 296$ GeV for $Q^2 < 4$ GeV^2 in the range $115 < W < 275$ GeV as:

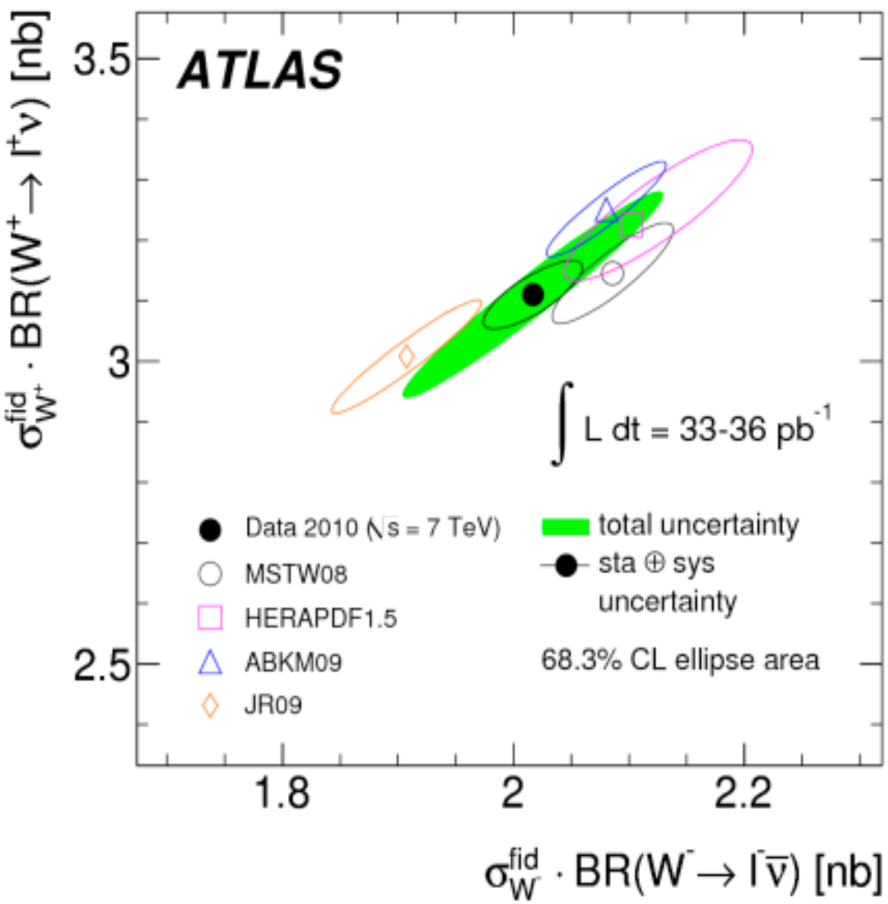
$$\sigma(ep \to c\bar{c}X) = 0.45 \pm 0.11^{+0.37}_{-0.22}\ \mu\text{b}.$$

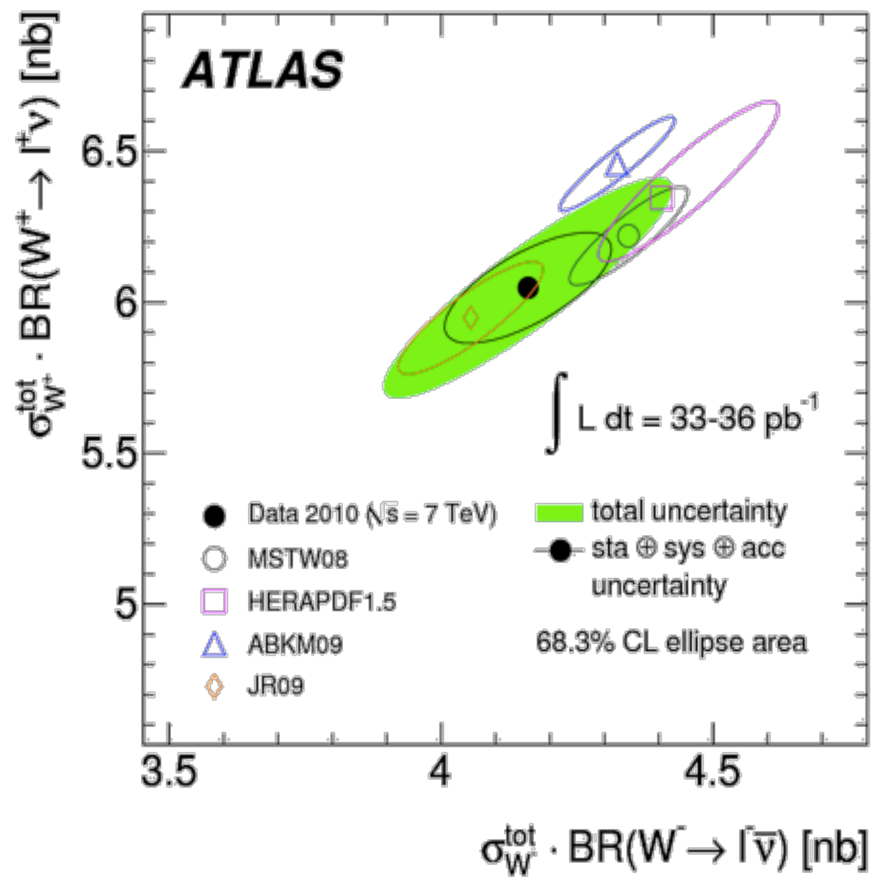
Real example: ZEUS charm photoproduction

- Large energy extrapolation
- Tiny acceptance → ~1.4% (and into tricky regions such as low p_T and high rapidity, hence high uncertainty)



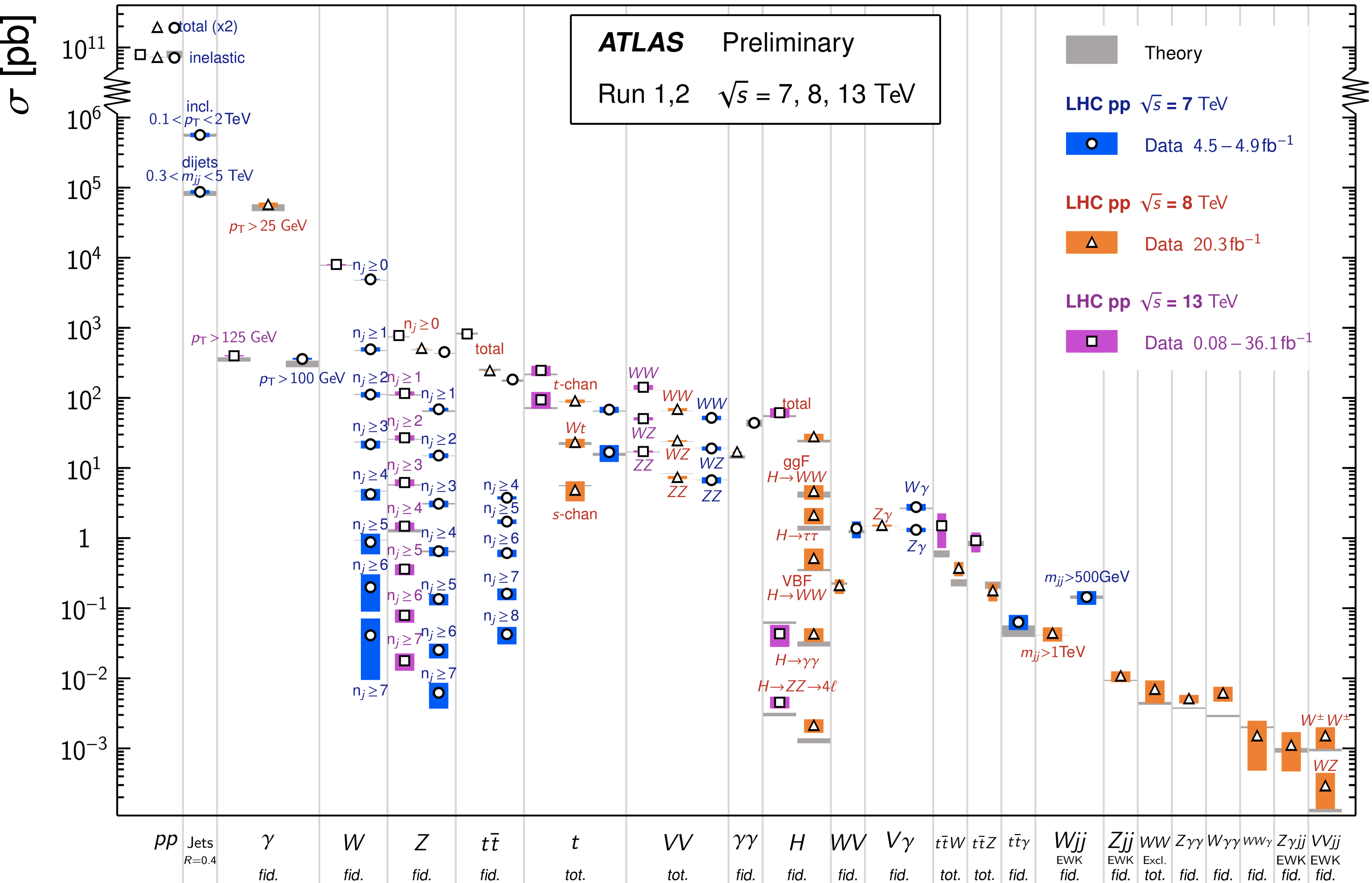
Real example: ATLAS W & Z cross sections (to e, μ), 7 TeV





Standard Model Production Cross Section Measurements

Status: May 2017

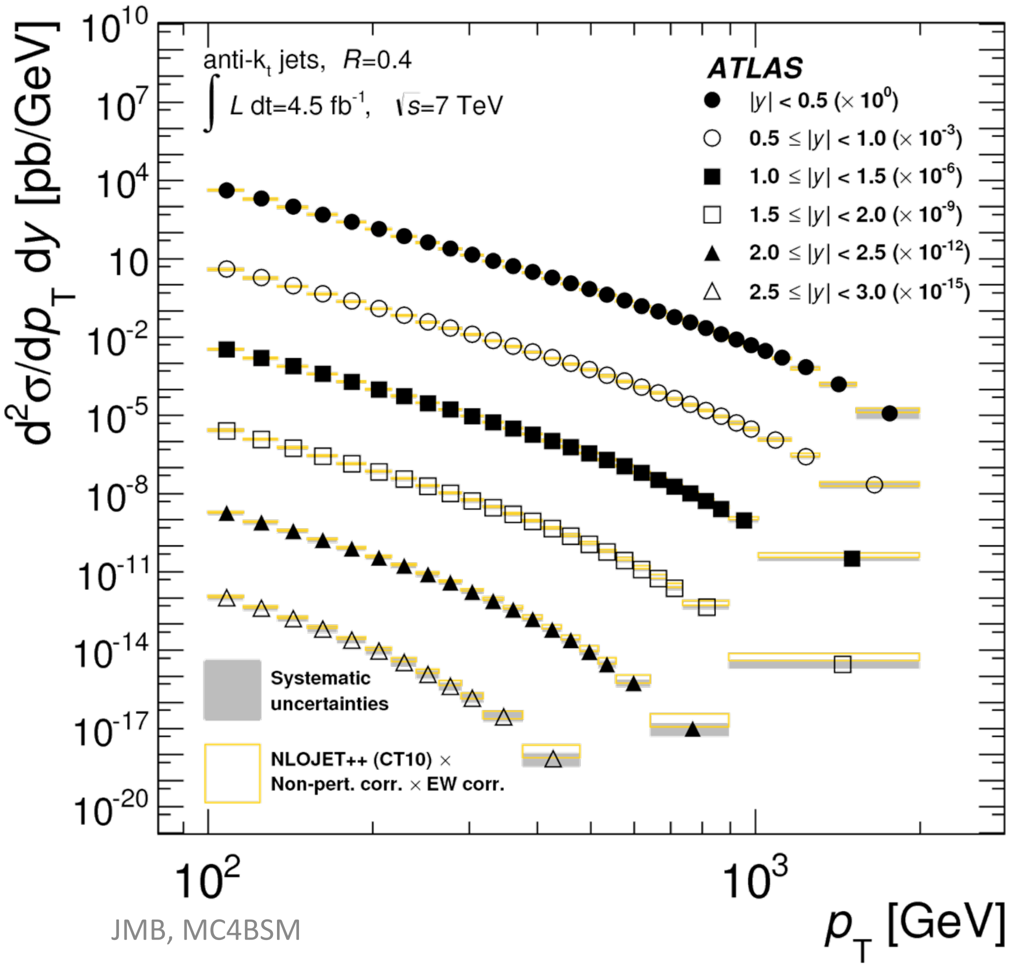


Something you can do once you have made your “minimally model dependent” measurements…

Jon Butterworth, David Grellscheid (IPPP), Michael Krämer, Björn Sarrazin (Aachen), David Yallup (UCL) arXiv:1606.05296 (JHEP 2017 078)

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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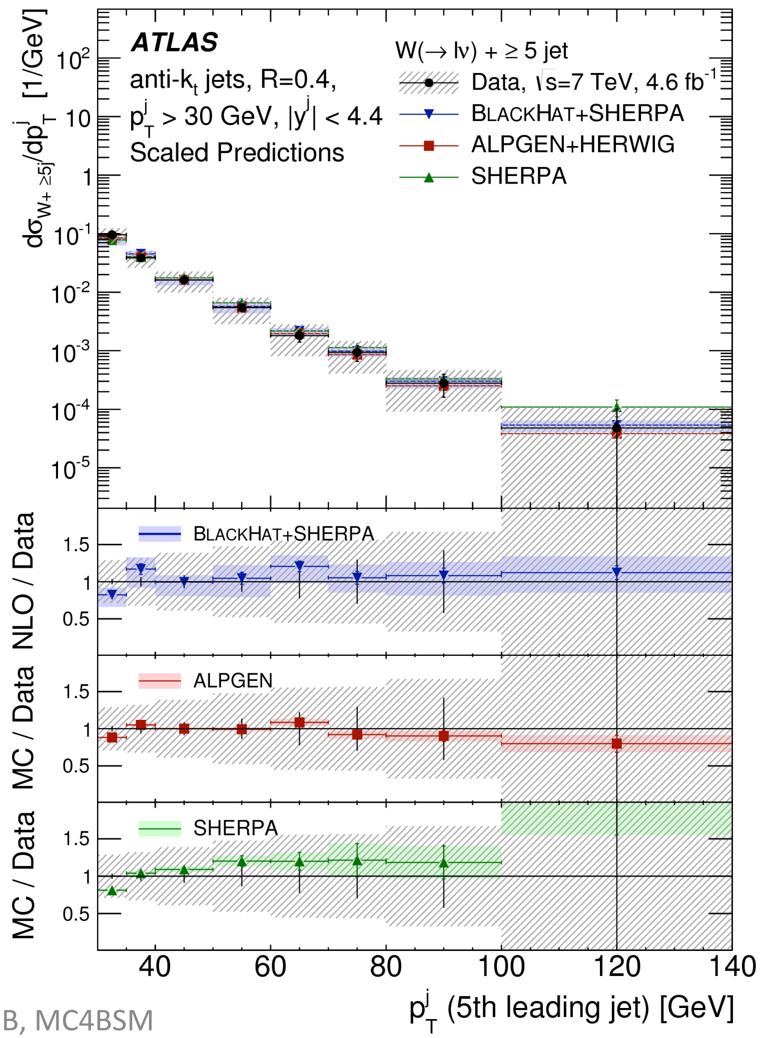
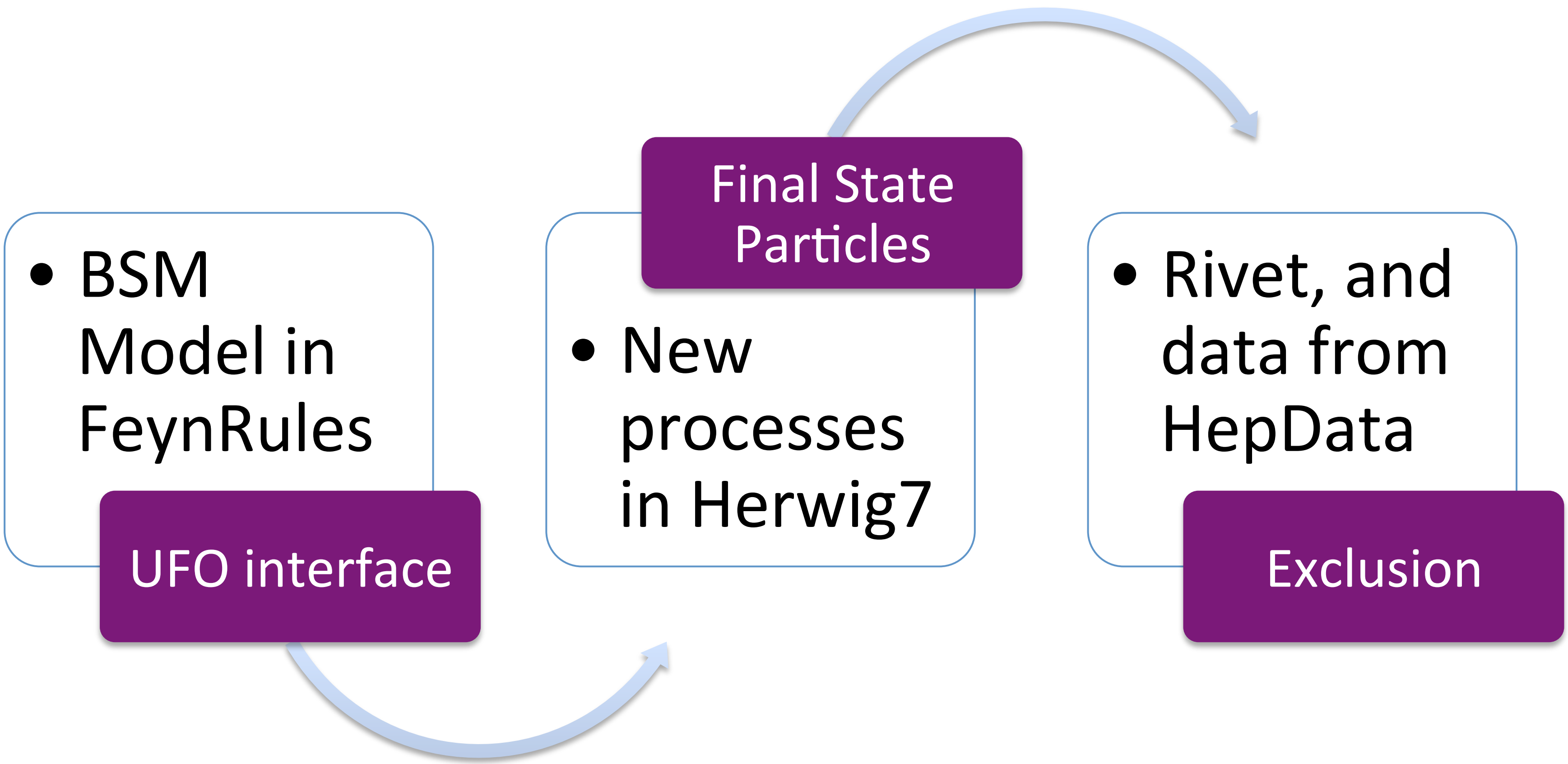


Key tools:


• BSM Model in FeynRules
UFO interface
• New processes in Herwig7
Final State Particles
• Rivet, and data from HepData
Exclusion

Key tools: Constraints On New Theories Using Rivet

- BSM Model in FeynRules

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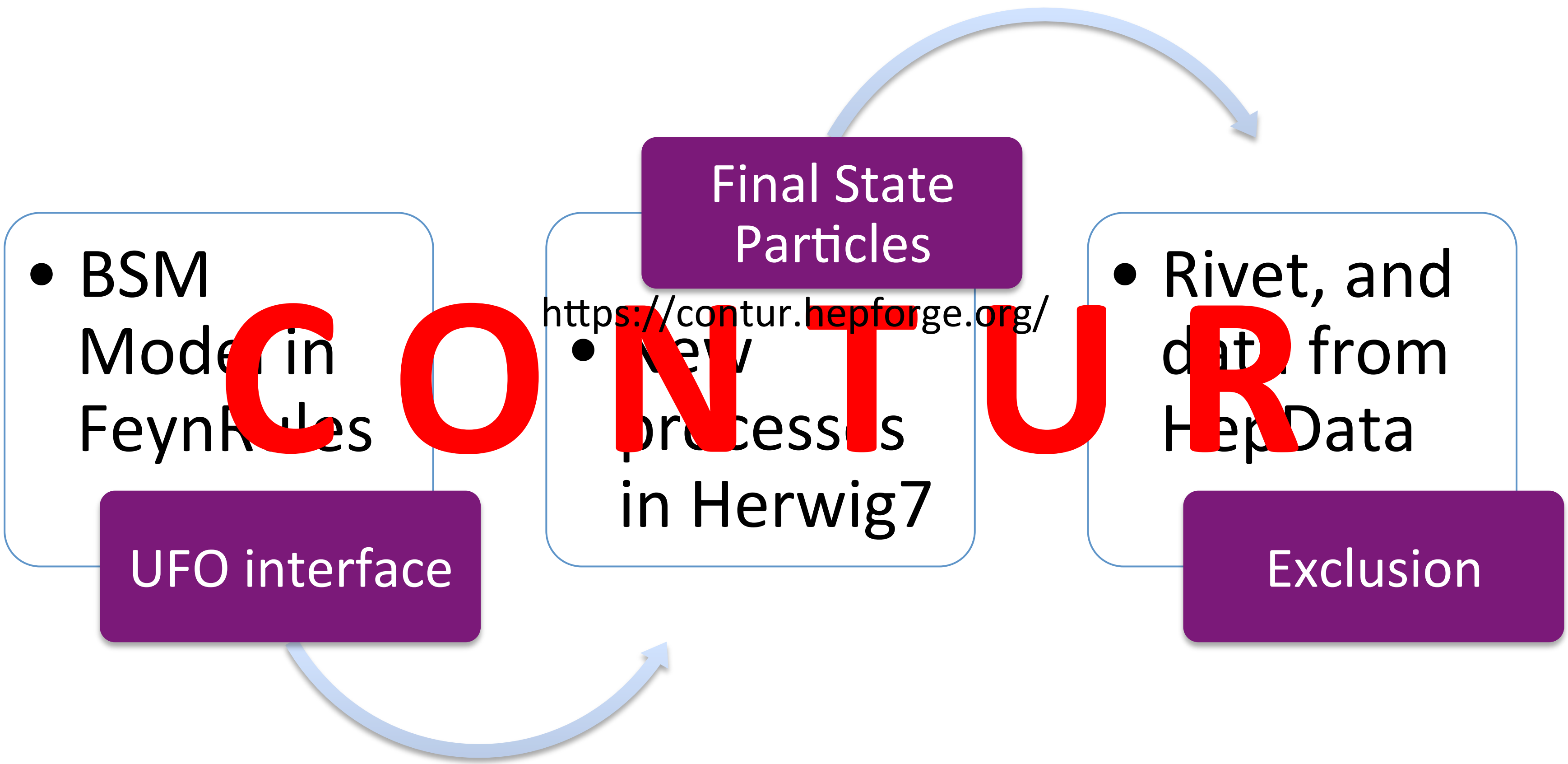
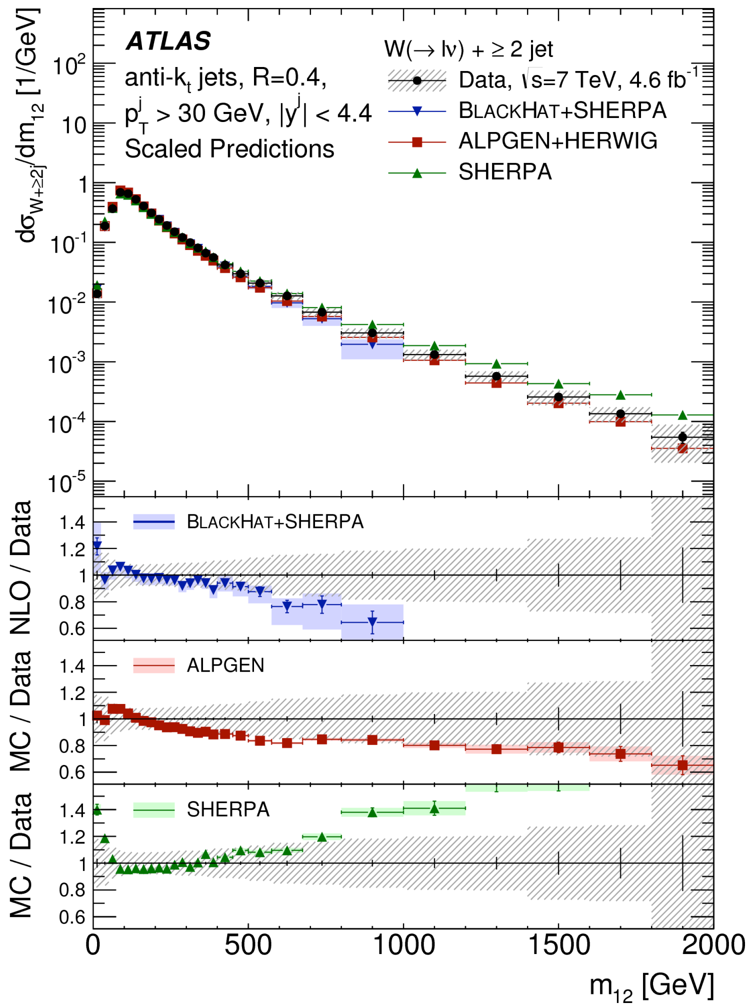


https://contur.hepforge.org/

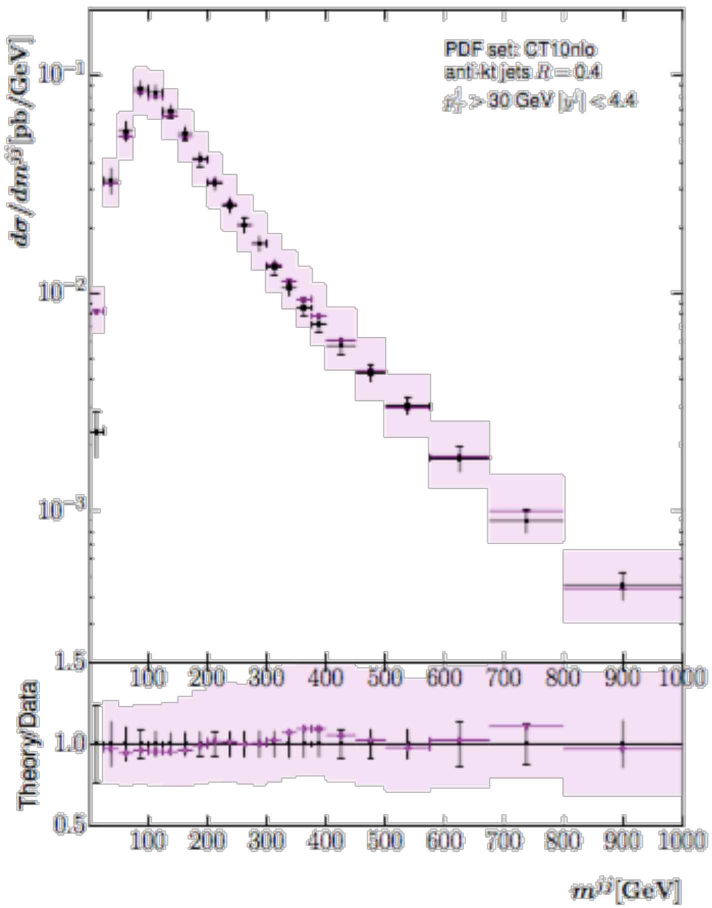
Strategy

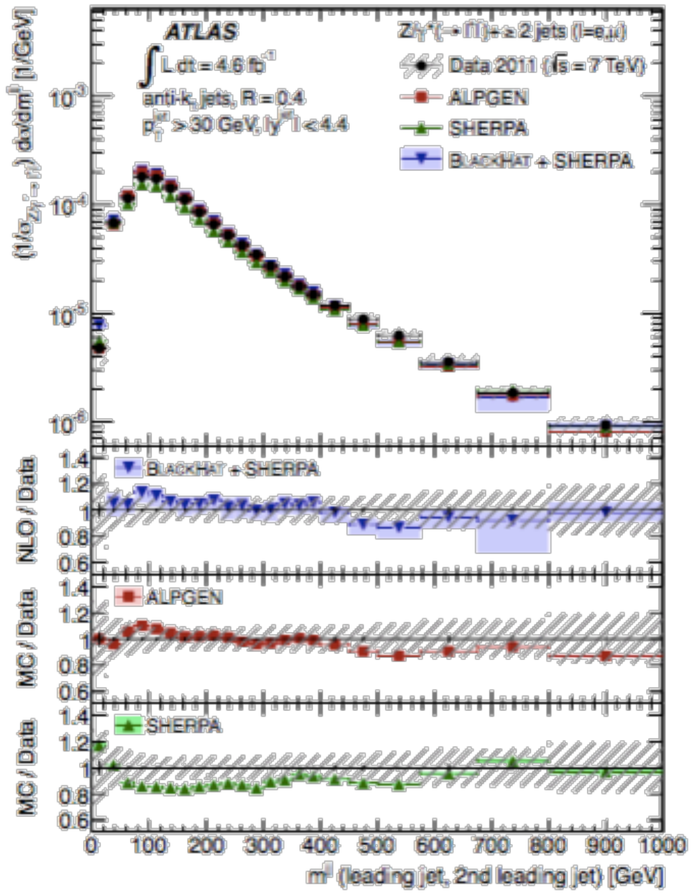
- Use measurements shown to agree with the Standard Model
  - Not a search! Guaranteed not to find anything
  - Measurements take longer, but more general and less model dependent
  - (Currently) assume the data = the background!

Will miss this kind of thing…



Although we probably want to miss it…





J. Andersen, J. J. Medley, J. M. Smillie, JHEP 1605 (2016) 136, arXiv:1603.05460 [hep-ph]

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

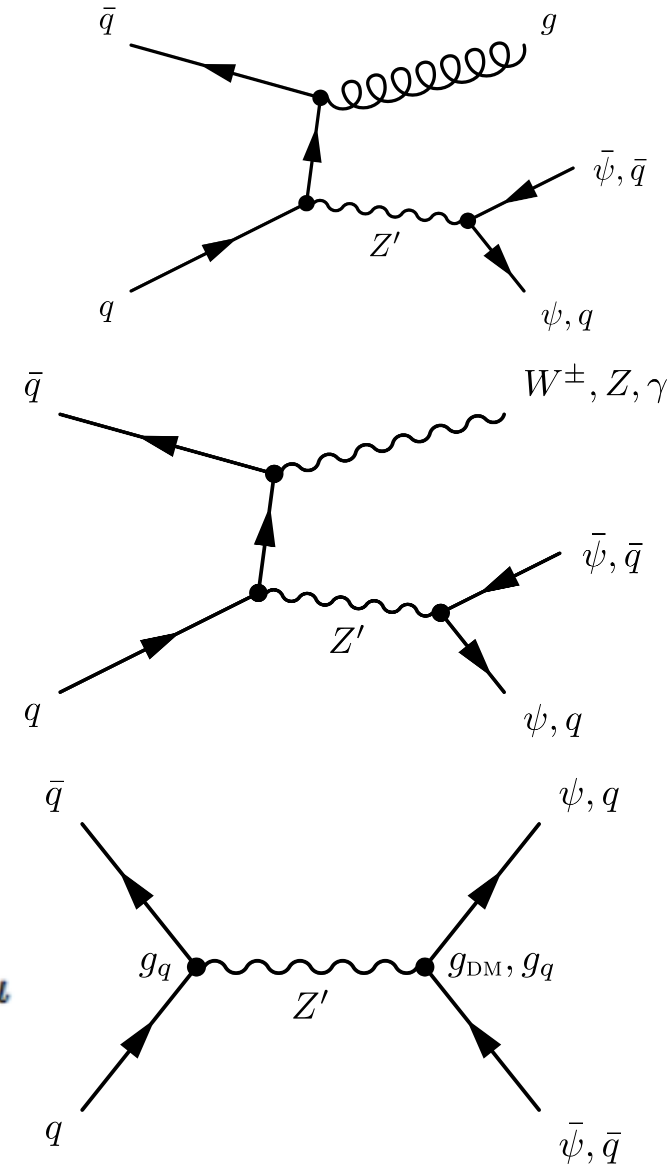
- SM measurements of fiducial, particle-level differential cross sections, with existing Rivet routines
- Classify according to data set (7, 8, 13 TeV) and into non-overlapping signatures
- Use only one plot from each given statistically correlated sample
- Jets, W+jets, Z+jets, γ (+jets), $\gamma\gamma$, ZZ, W/Z+γ
- Sadly no Missing E_T+jets, not much 8 TeV, no 13 TeV yet, though much is on the way… Also can use suitably model-independent Higgs and top measurements in future.
- 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.

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

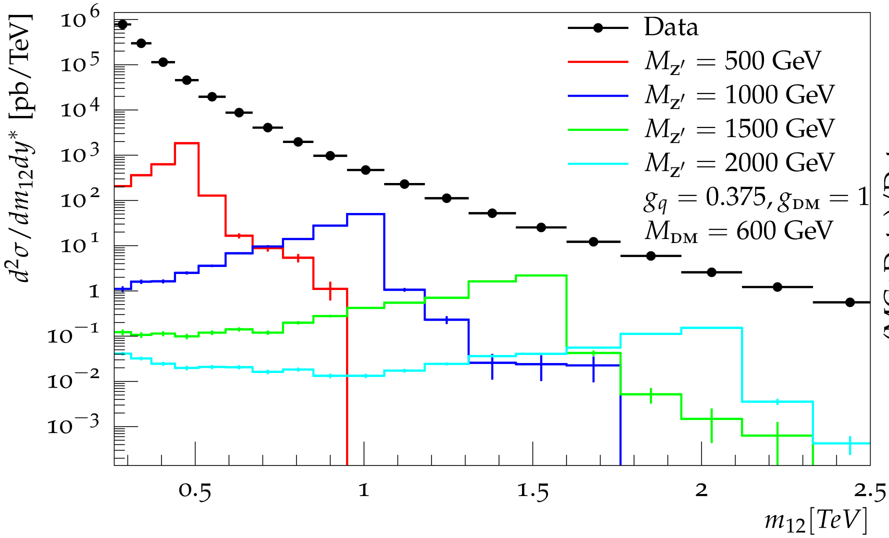


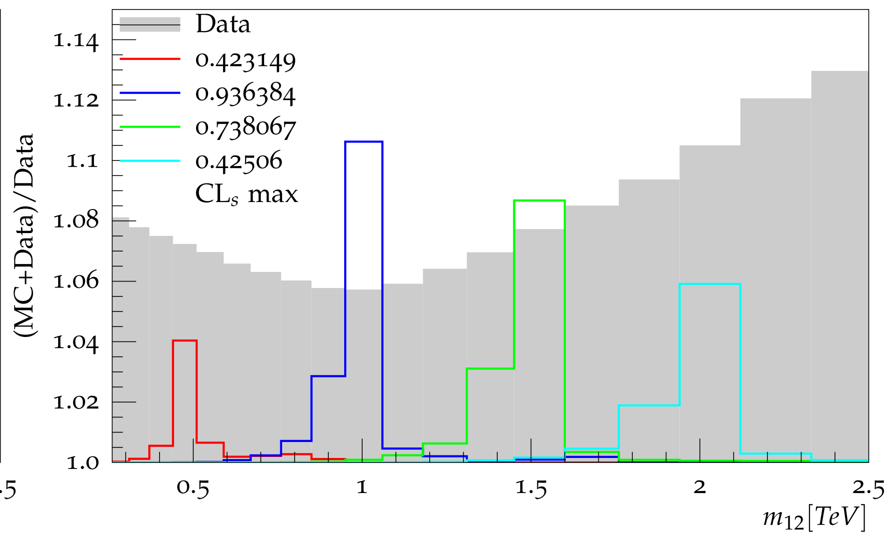
Parameter Choices

- 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 $g_q = 0.375$; $g_{DM} = 0.25$

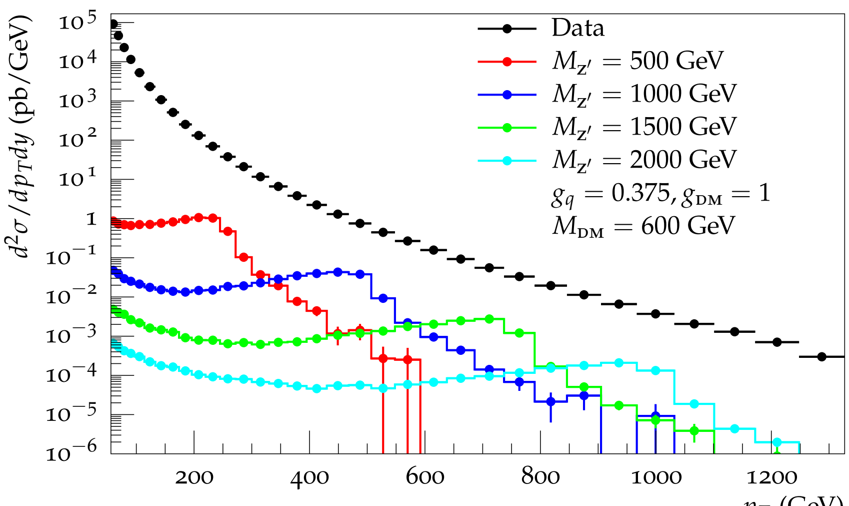
Data Comparisons

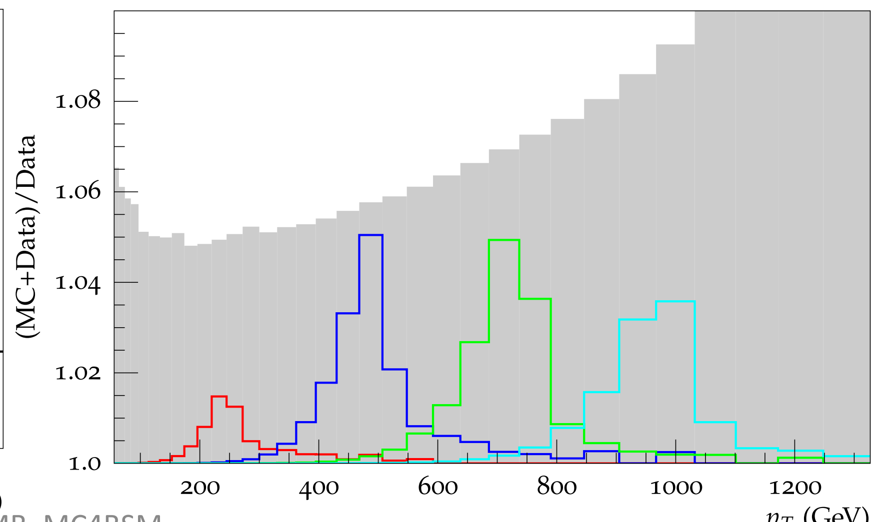
ATLAS Dijet double-differential cross sections ($y^* < 0.5$)



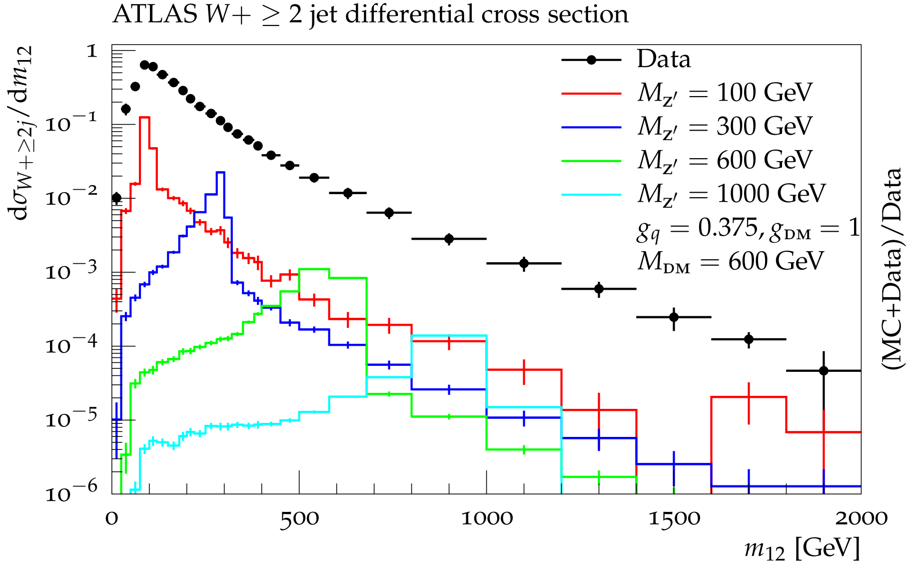


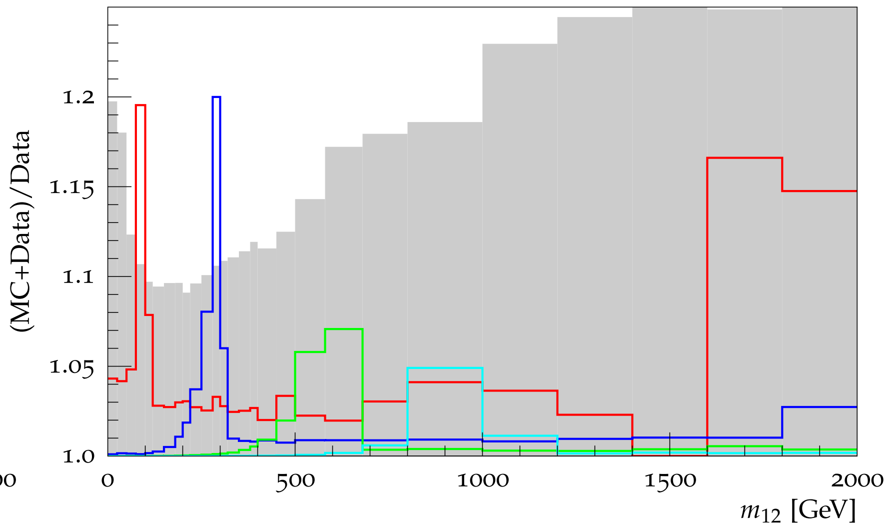
CMS inclusive jet double differential cross section ($|y| < 0.5$)

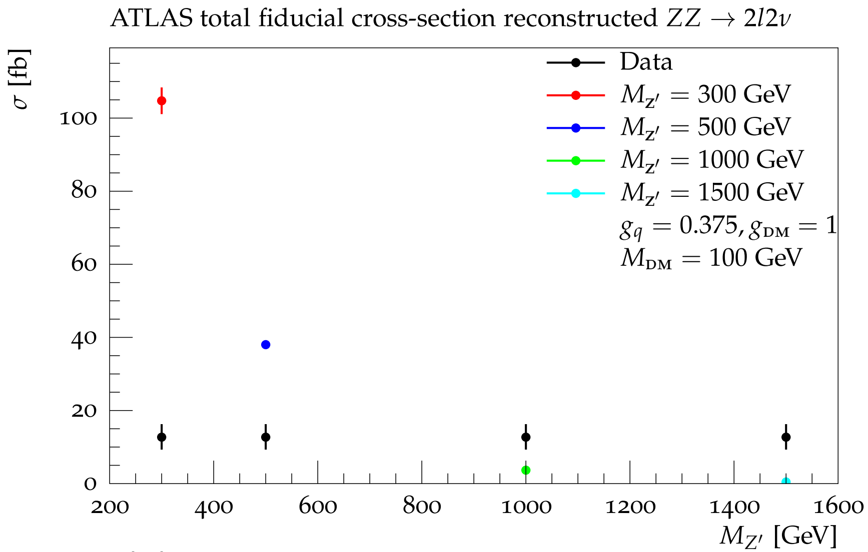


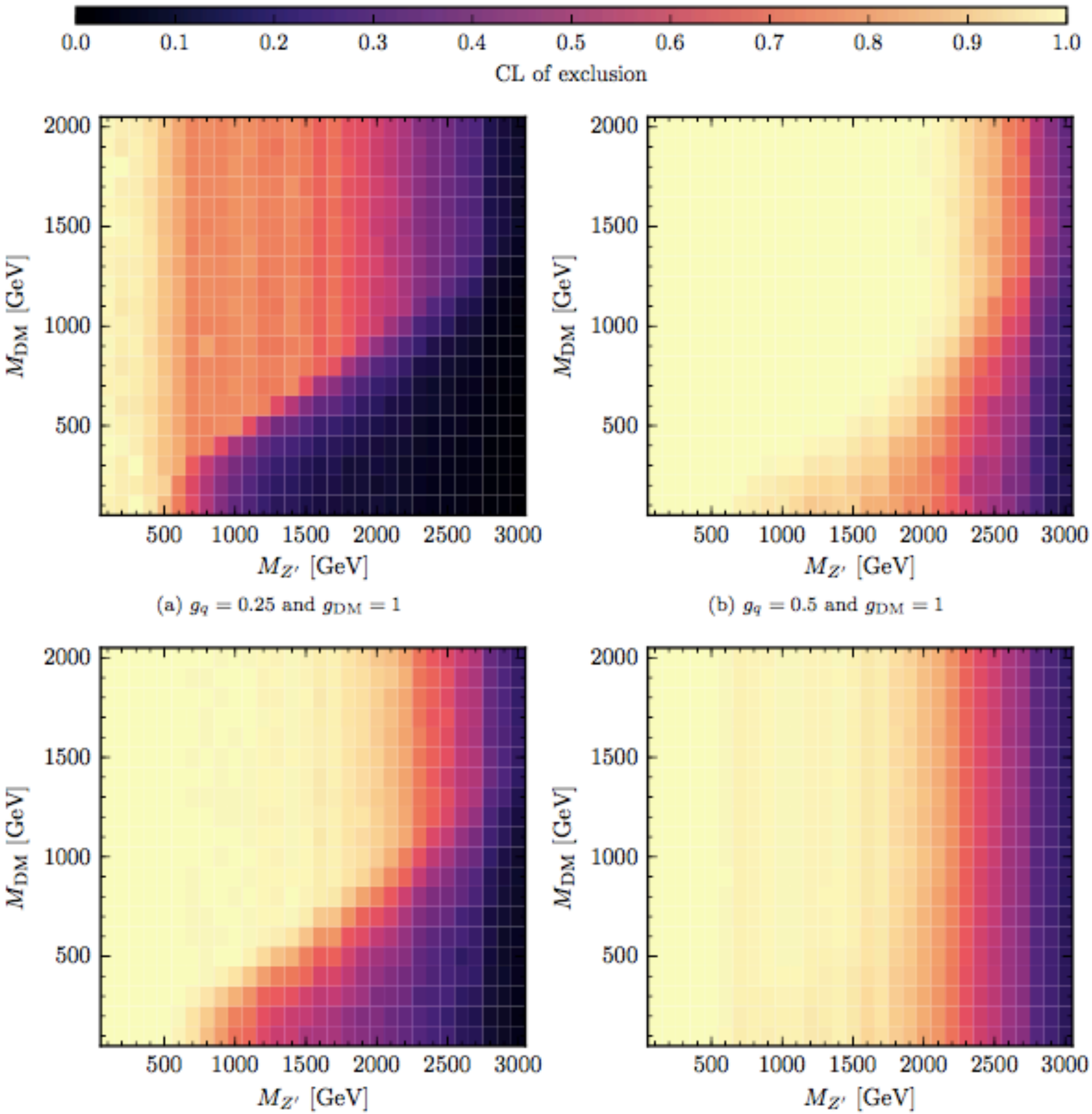


Data Comparisons







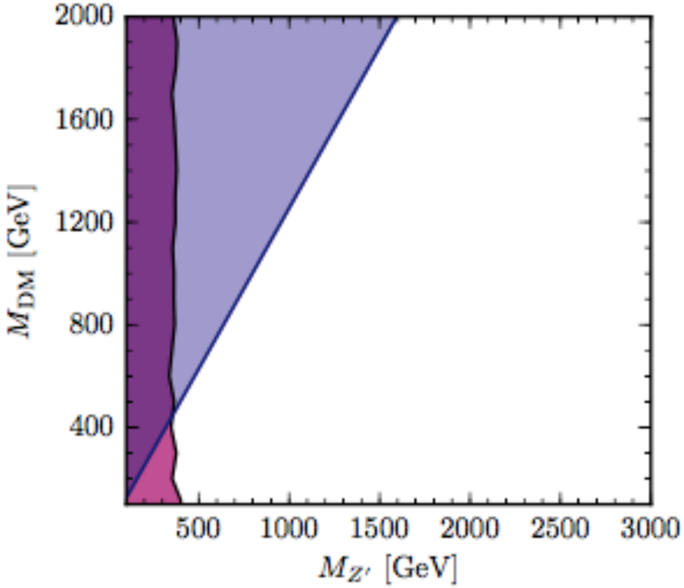


(a) $g_q = 0.25$ and $g_{\rm DM} = 1$

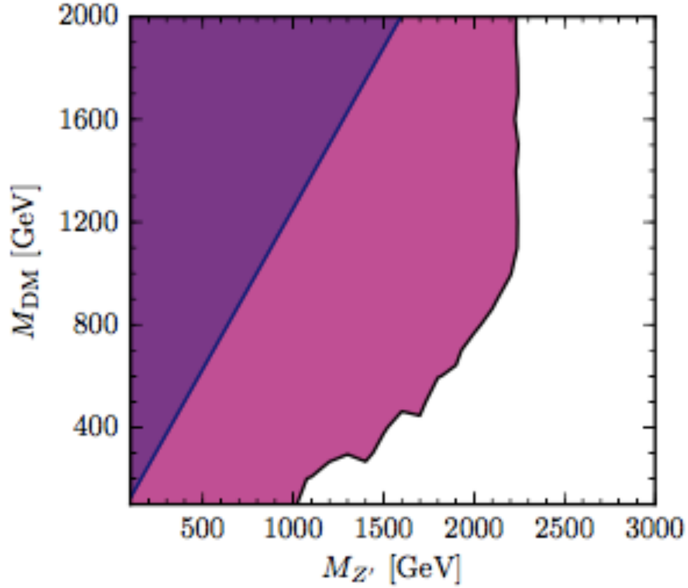
(b) $g_q = 0.5$ and $g_{\rm DM} = 1$

(c) $g_q = 0.375$ and $g_{\rm DM} = 1$

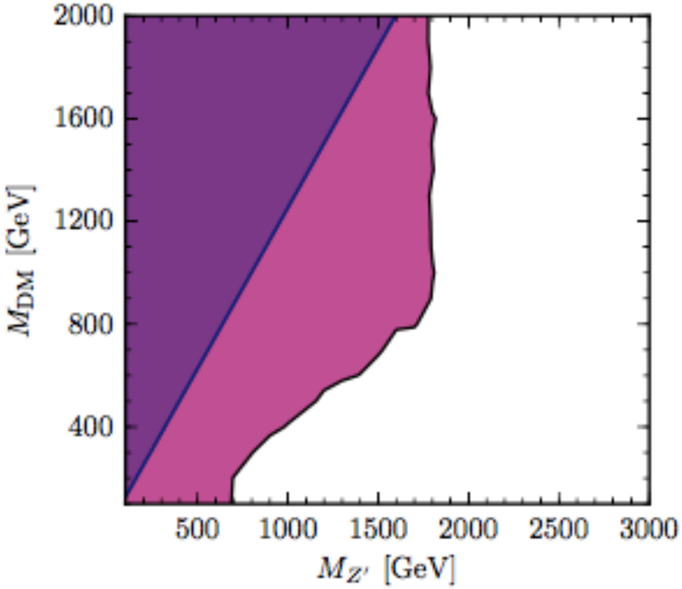
(d) $g_q = 0.375$ and $g_{\rm DM} = 0.25$



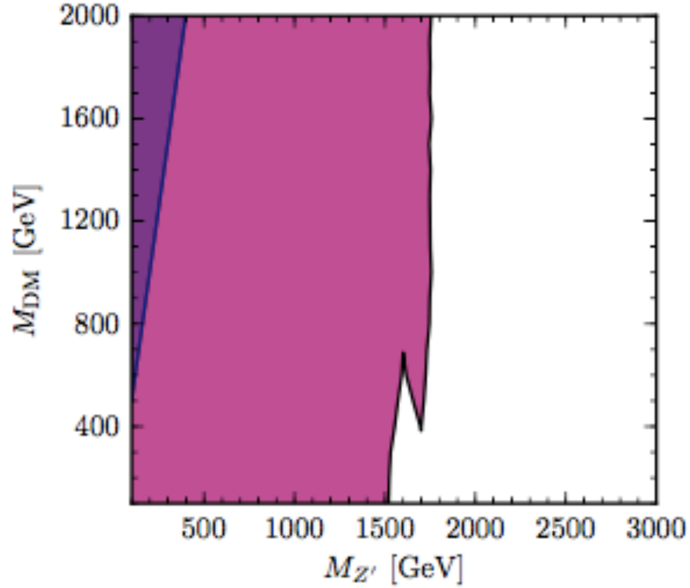
(a) $g_q = 0.25$ and $g_{DM} = 1$



(b) $g_q = 0.5$ and $g_{DM} = 1$



(c) $g_q = 0.375$ and $g_{DM} = 1$



(d) $g_q = 0.375$ and $g_{DM} = 0.25$

Low $M_{Z'}$, low coupling

- V+jets has unexpectedly good sensitivity at low $M_{Z'}$.
- How low in coupling g_{SM} does this go?
  - About 0.18

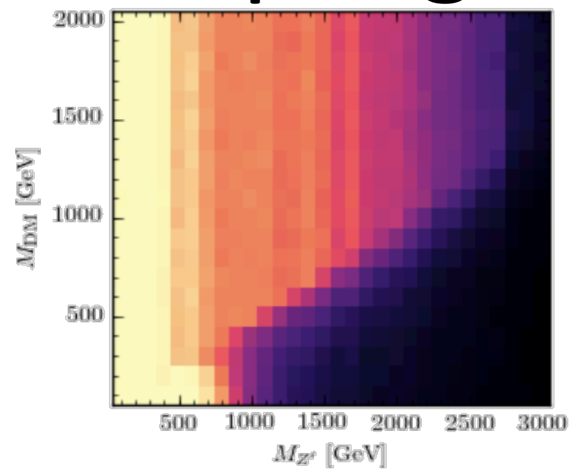


Figure 4: Exclusion heatmap for $g_q = 0.25$, $g_{DM} = 1.0$ from the CONTUR white paper.

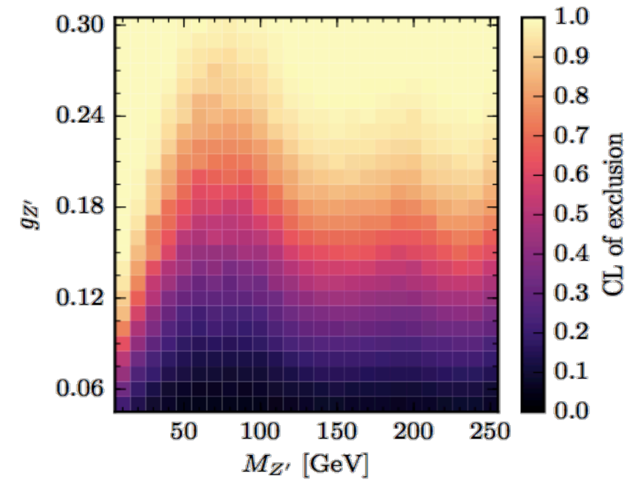


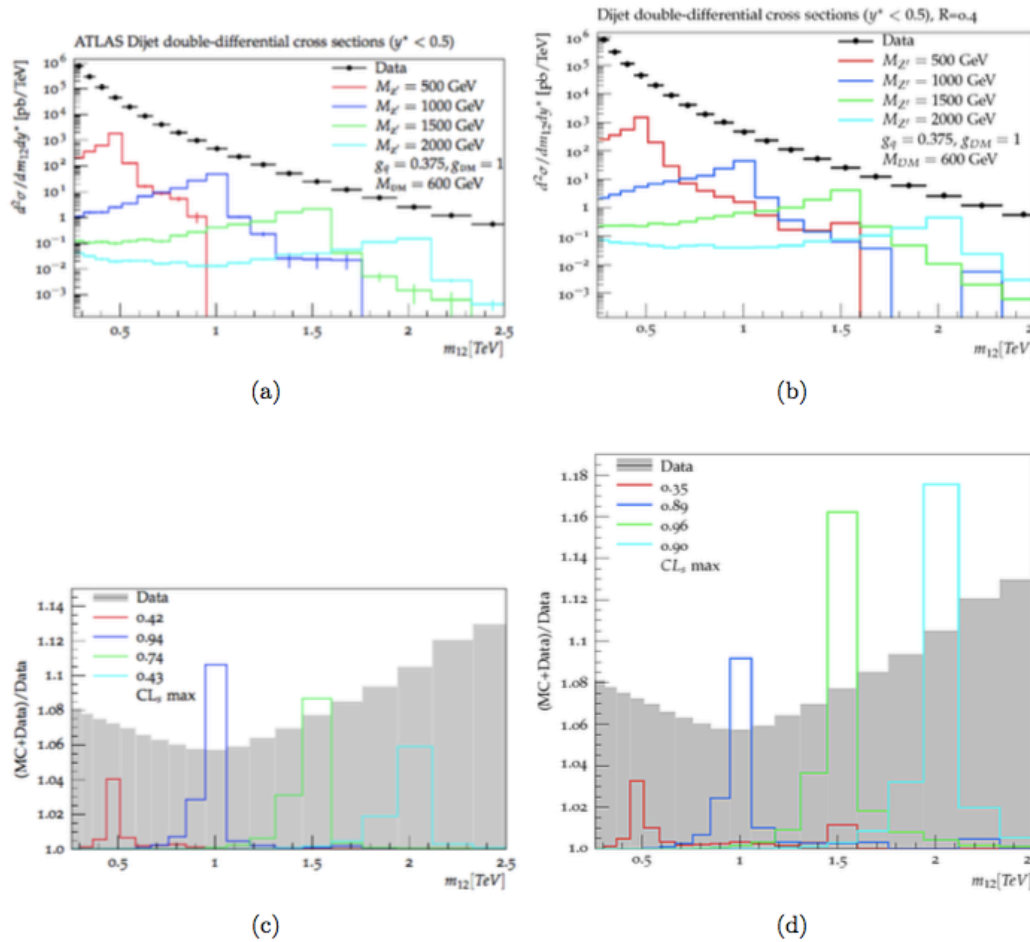
Figure 6: Exclusion heatmap for $M_{DM} = 600$ GeV and 500,000 events per .yoda file, using data from several 7 TeV and 8 TeV ATLAS and CMS analyses.

C. Donaldson (prelim.)

Look at “all flavours” model

C. Donaldson (prelim.)

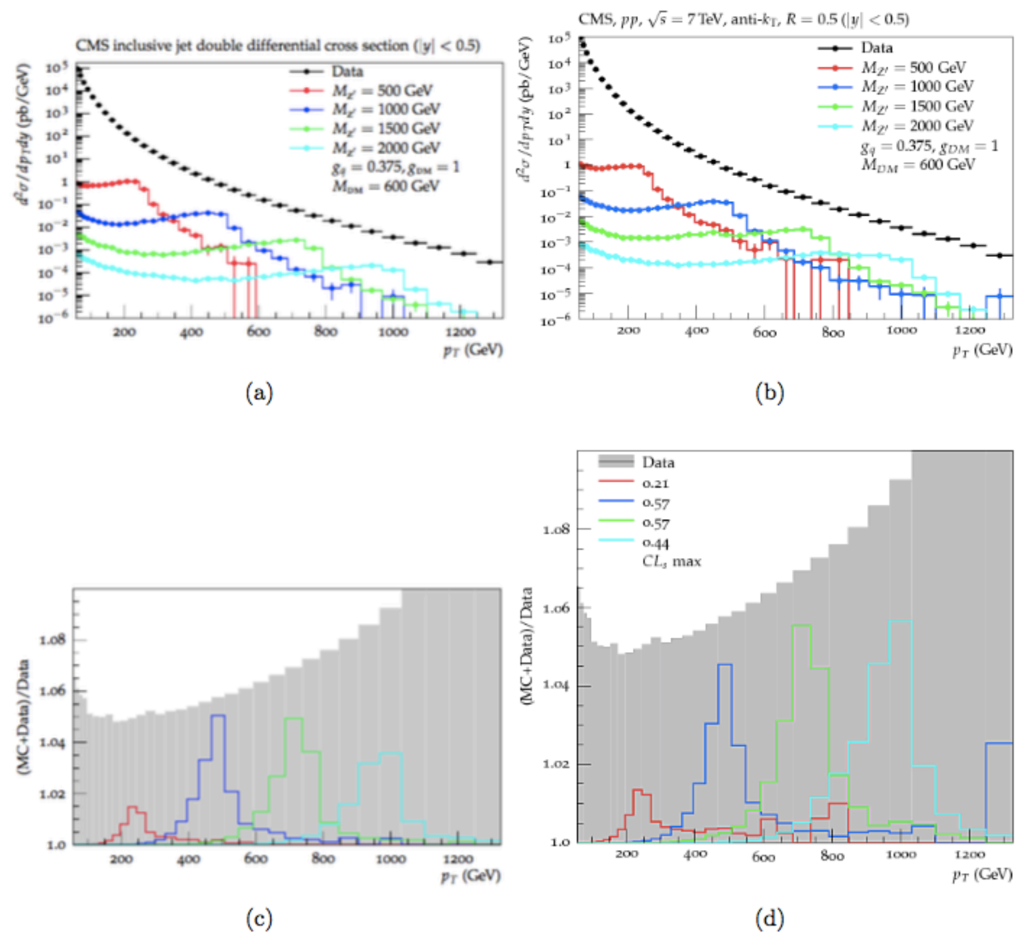
- $g_q = 0.375$



Look at "all flavours" model

C. Donaldson (prelim.)

- $g_q = 0.375$



Look at "all flavours" model

C. Donaldson (prelim.)

- Hadronic events

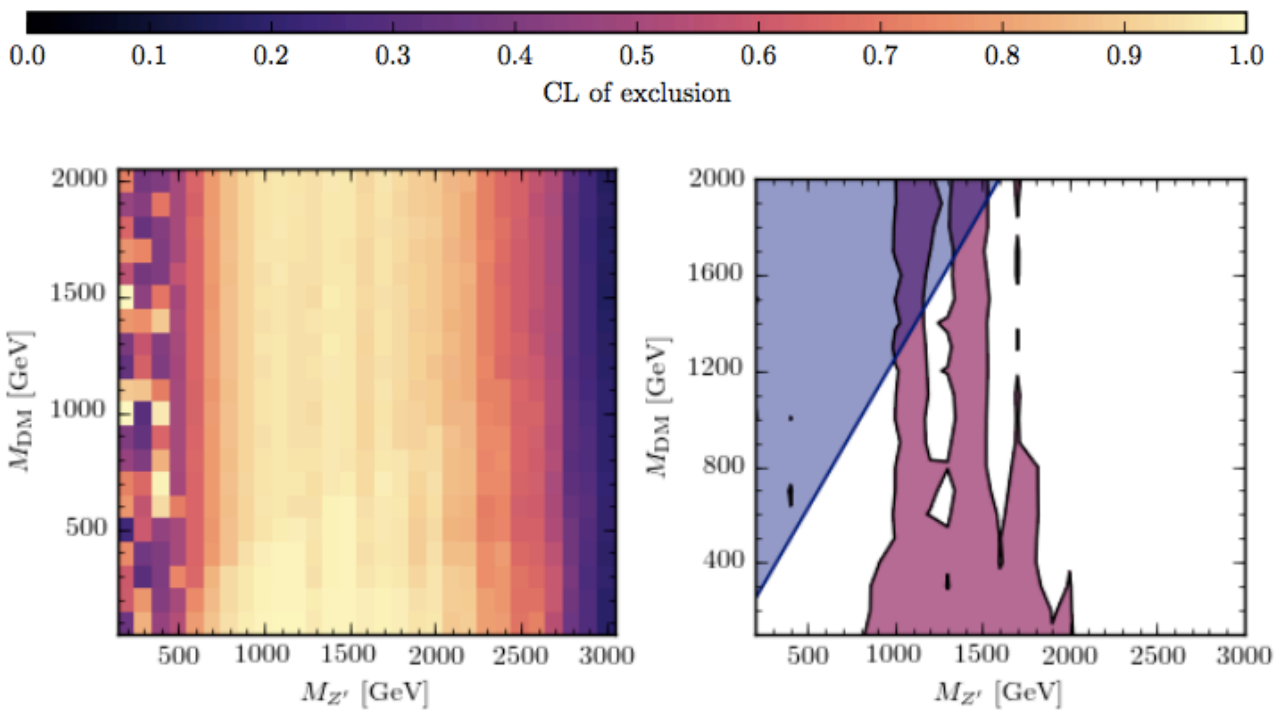


Figure 6: Heatmap and 95% contour for the HF model for the 7 TeV hadronic Rivet routines detailed in Table 3. Both plots are for fixed values of the couplings, where $g_q = 0.375$ and $g_{DM} = 1$. (a) shows the heatmap, and (b) shows the corresponding pink contour, which indicates the excluded region at 95% CL. The blue shaded triangular region in (b) shows the region in which perturbative unitary, as defined in Section 2.4, is violated.

Look at "all flavours" model

C. Donaldson (prelim.)

- "EW" events

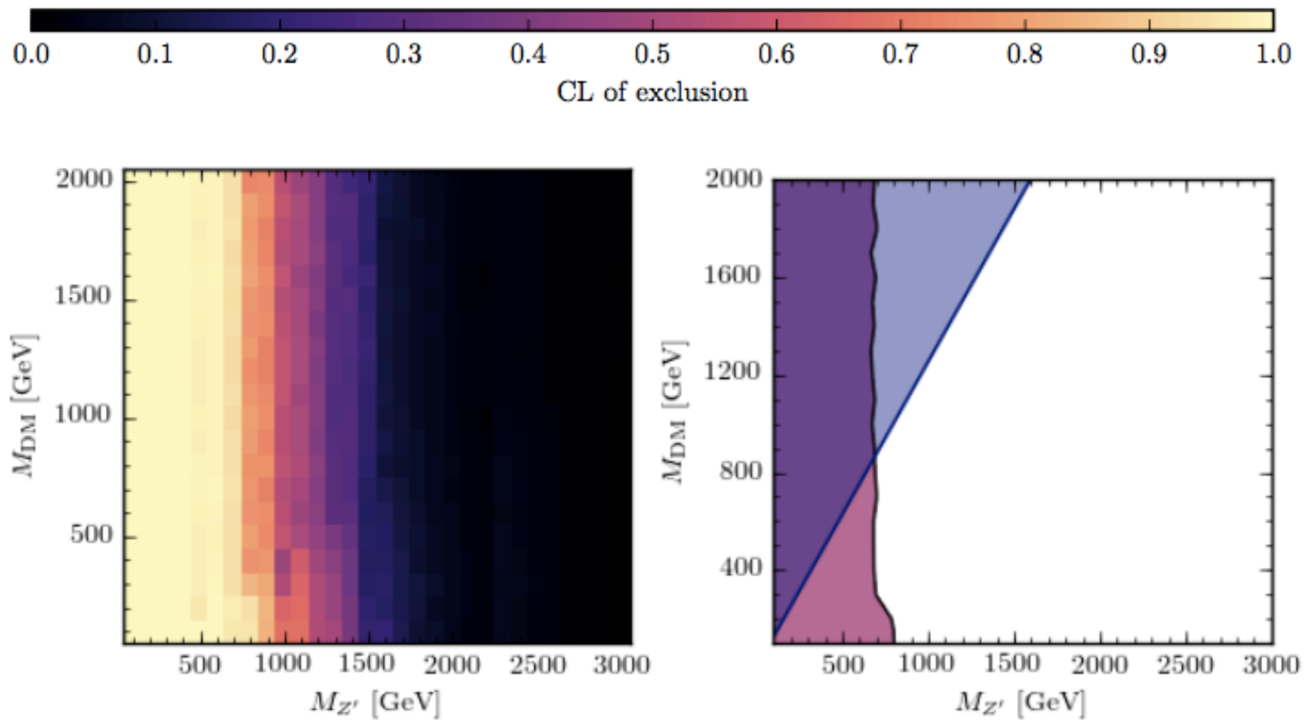


Figure 7: Heatmap and 95% contour for the HF model for the 8 TeV electroweak Rivet routines detailed in Table 4. Both plots are for fixed values of the couplings, where $g_q = 0.375$ and $g_{DM} = 1$. (a) shows the heatmap, and (b) shows the corresponding pink contour, which indicates the excluded region at 95% CL. The blue shaded triangular region in (b) shows the region in which perturbative unitary, as defined in Section 2.4, is violated.

Look at "all flavours" model

C. Donaldson (prelim.)

- All events

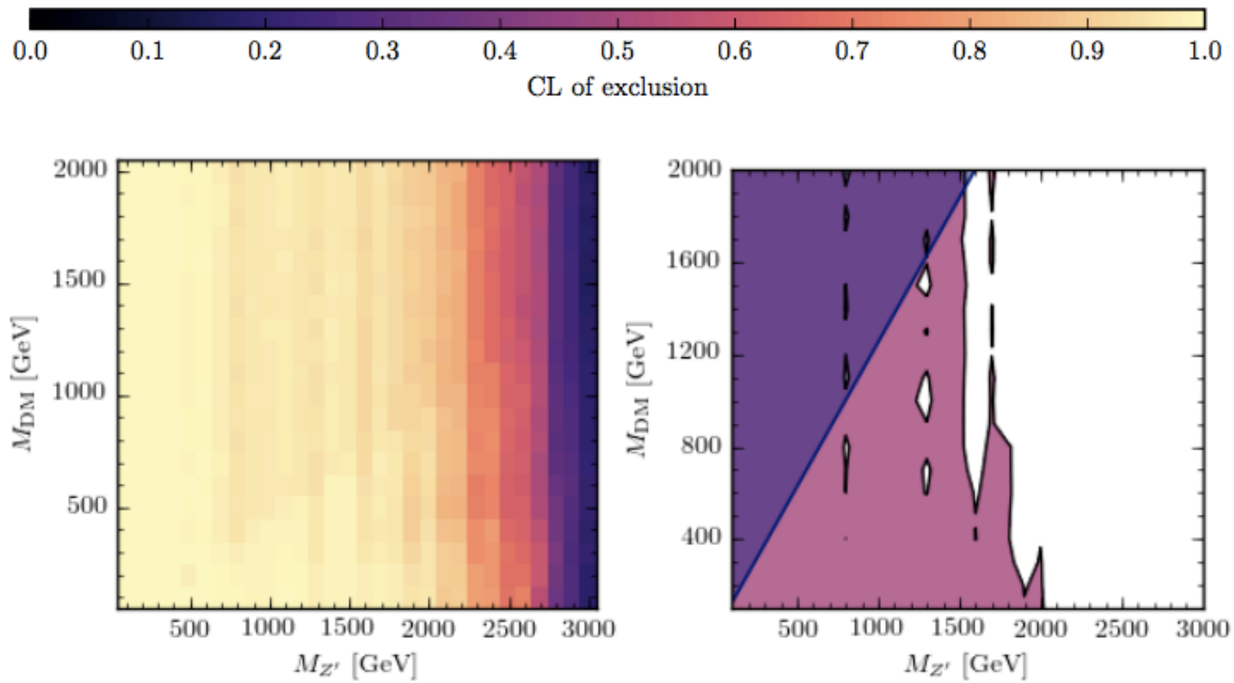


Figure 8: Heatmap and 95% contour for the HF model for all of the Rivet routines for 7 TeV electroweak, 7 TeV hadronic, and 8 TeV electroweak combined, as shown in Tables 2, 3, and 4. Both plots are for fixed values of the couplings, with $g_q = 0.375$ and $g_{DM} = 1$. (a) shows the heatmap, and (b) shows the corresponding contour, which indicates the excluded region at 95% CL. The blue shaded triangular region in (b) shows the region in which perturbative unitary, as defined in Section 2.4, is violated.

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 those from 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)
- Highly scaleable to other models & new measurements – plan continuous rolling development
- See arXiv:1606.05296 (JHEP 2017 078) and references therein, and hepforge.org/contur