Measurements and Model Independence at Colliders

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13 July 2016

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And something you can do with them once you have them

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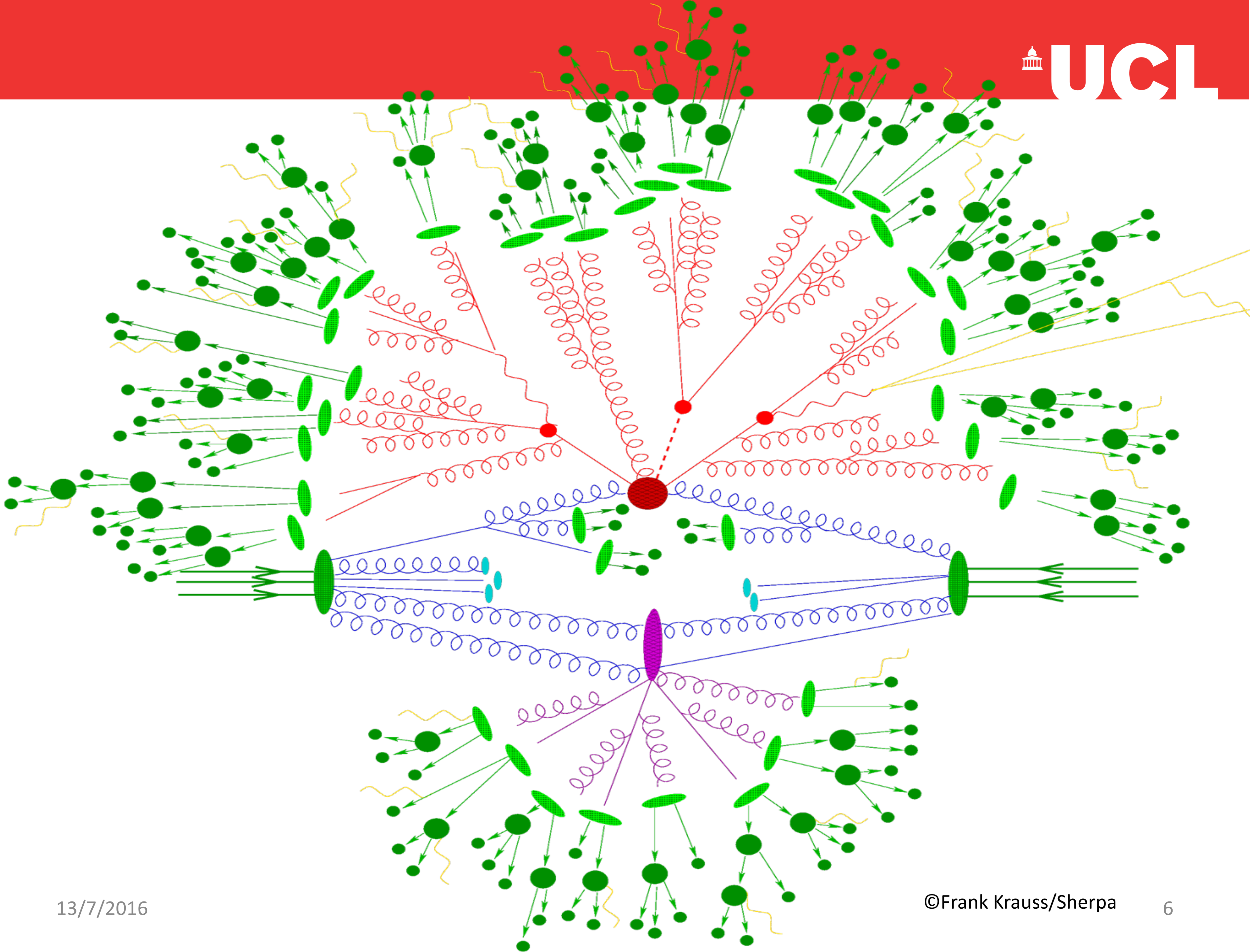
The Role of Generators & Simulation

- What are event generators for?
  - Event generators and theory
  - Event generators and simulation
- What do we actually *measure*?
  - The final state
  - “Truth” particle definitions
  - Fiducial or not?
- Real Examples

Event Generators and Theory

- Briefly:
  - In a collider or fixed-target experiment, the underlying theory (typically short distance physics), is usually embedded in a more complex “event”
  - This will include known and/or lower energy physics
  - See Torbjorn’s lectures …



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Event Generators and Theory

- Event generators can embed state-of-the-art calculation or the short-distance physics in a realistic and complete collision, and predict the final state
- Different levels of precision and modelling can be combined and tested

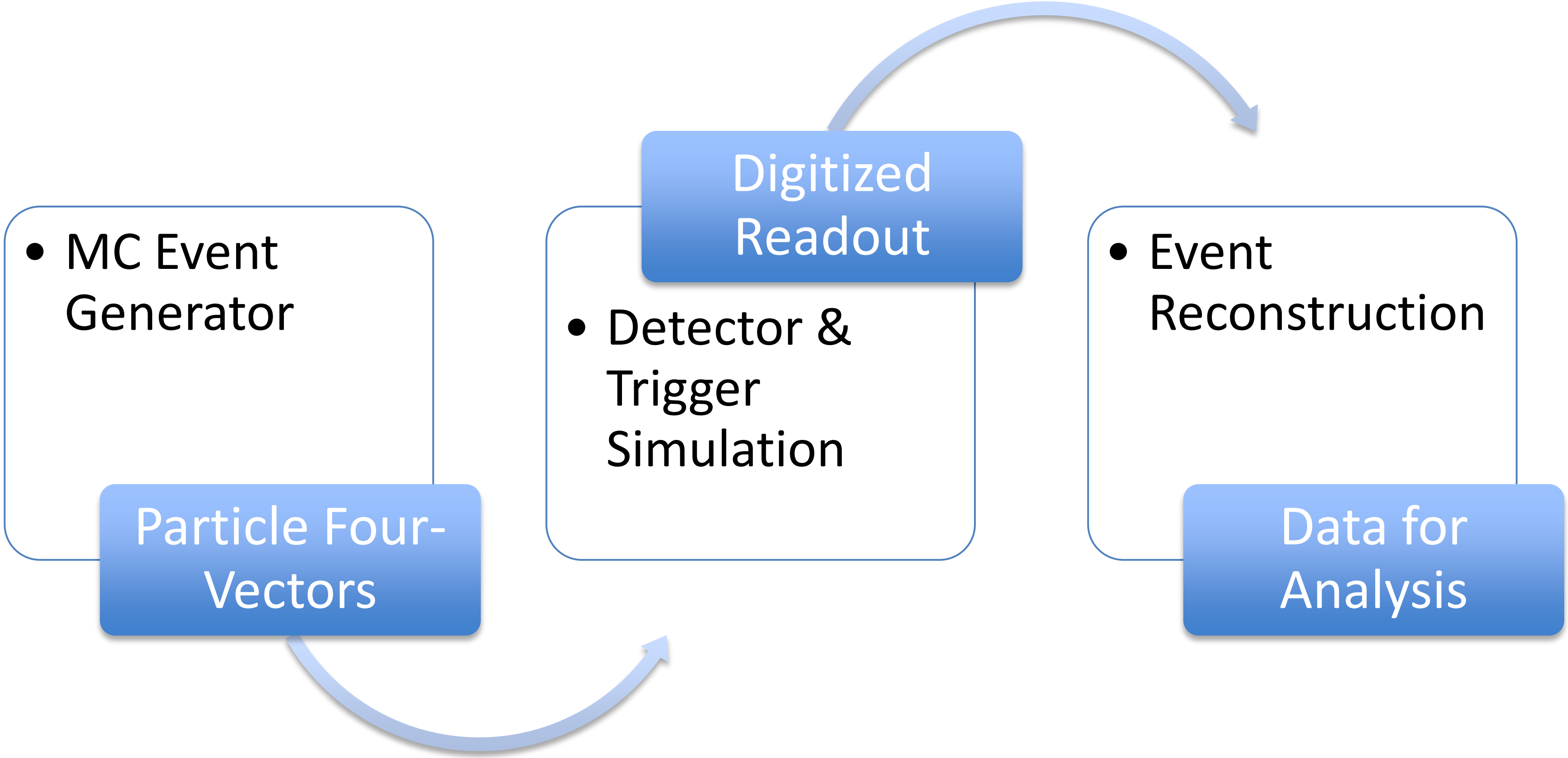
Event Generators and Simulation

- “Simulation” in the experimental context usually means “detector simulation”
- Detailed software model of detector(s) in GEANT
- Particles (from the generator) propagate step-by-step through
  - Electromagnetic fields: they can curve, radiate, pair-produce
  - Material (with which they interact): scattering, absorption, more pair-production, energy loss…
  - Time: That is, quasi-stable particles can be decayed (may include some short distance physics)

Event Generators and Simulation

- Simulation of readout
  - Digitisation, truncation, saturation etc
  - Pile up (in-time and out-of-time)
  - Trigger readout simulated seperately
- Provide “as data” input to reconstruction algorithms
- Retain knowledge of what “really” happened: MC truth

Simulation and Experiment



- MC Event Generator

Particle Four-Vectors

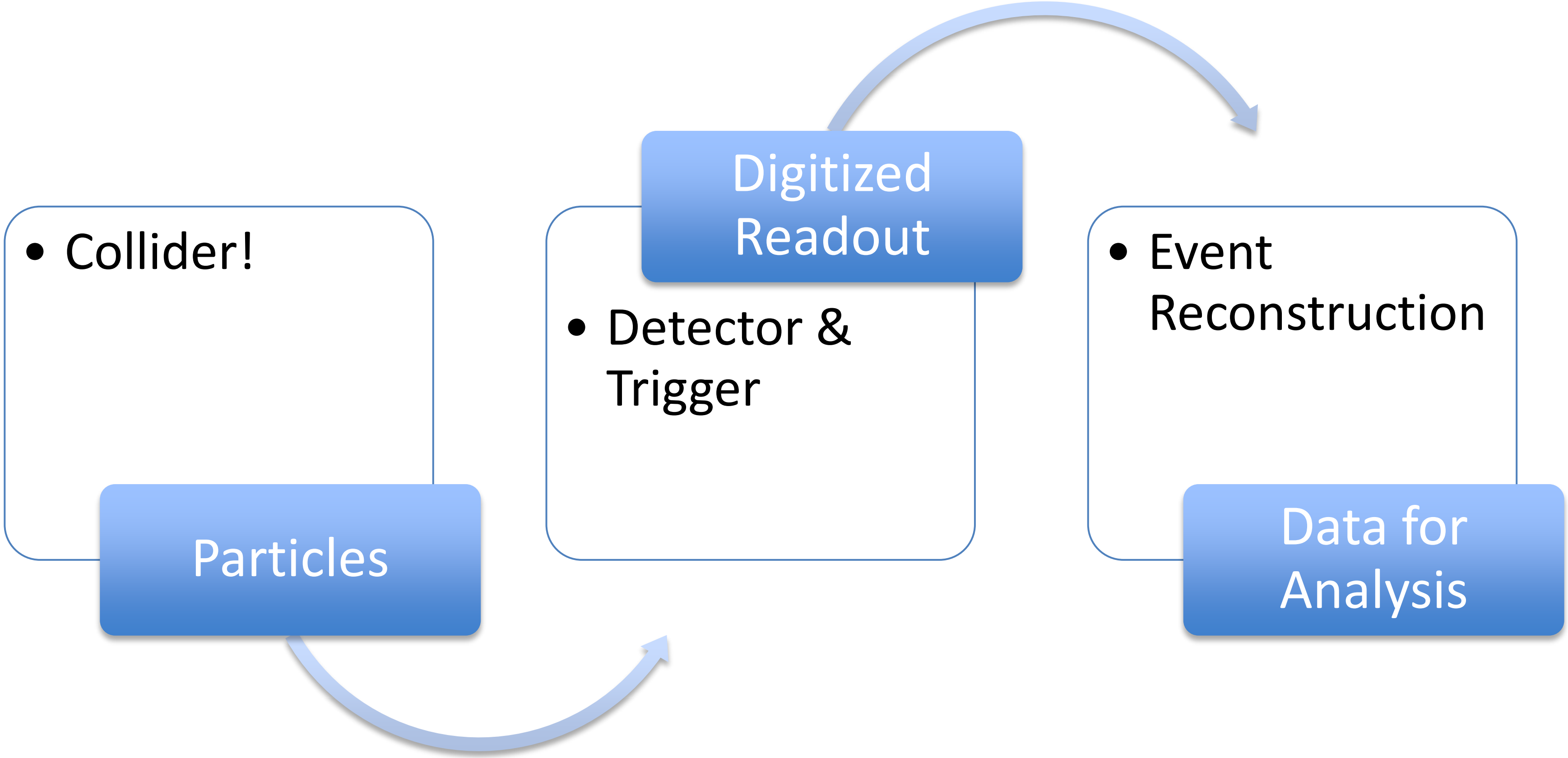
- Detector & Trigger Simulation

Digitized Readout

- Event Reconstruction

Data for Analysis

Simulation and Experiment



- Collider!

Particles

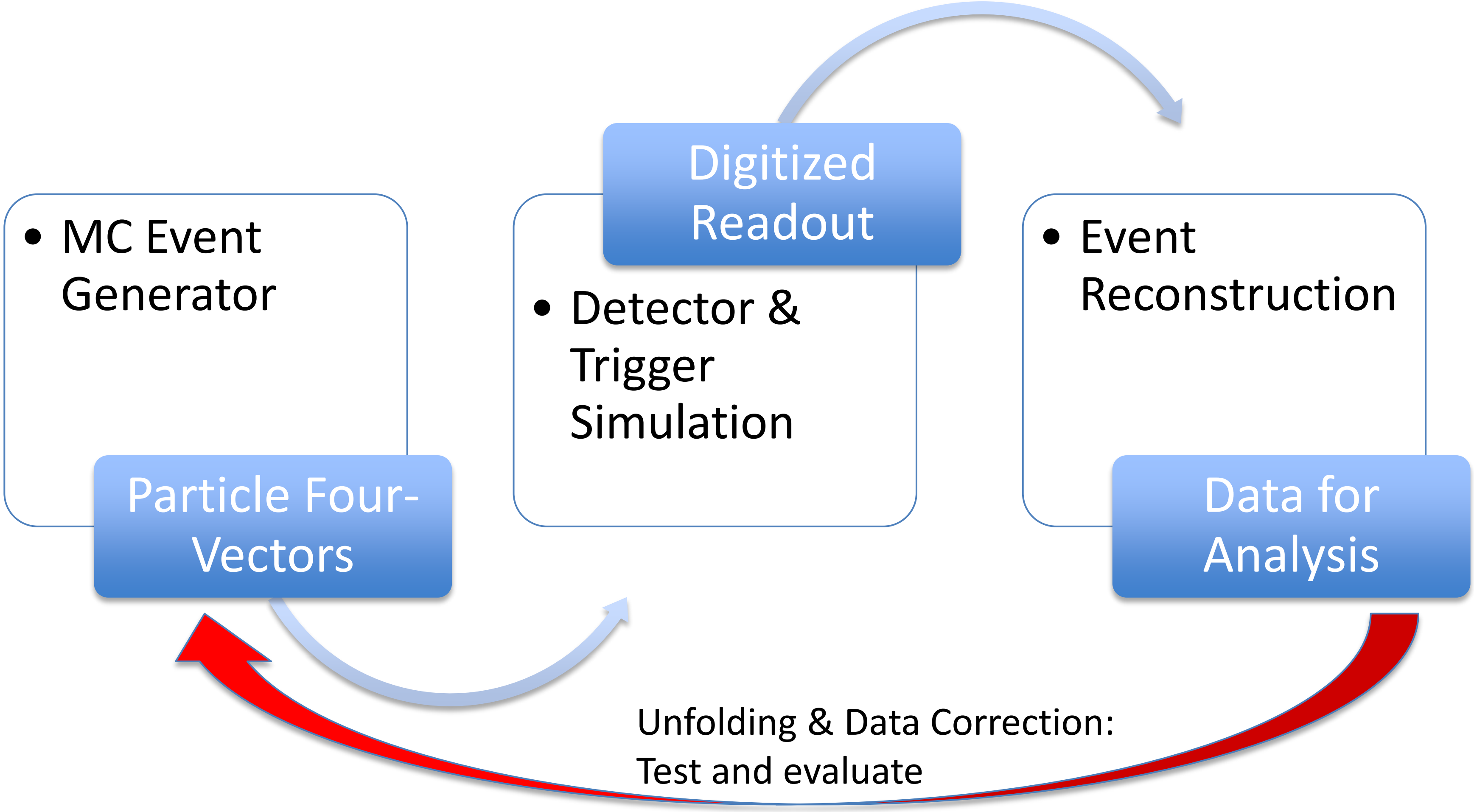
- Detector & Trigger

Digitized Readout

- Event Reconstruction

Data for Analysis

Simulation and Experiment



- MC Event Generator

Particle Four-Vectors

Digitized Readout

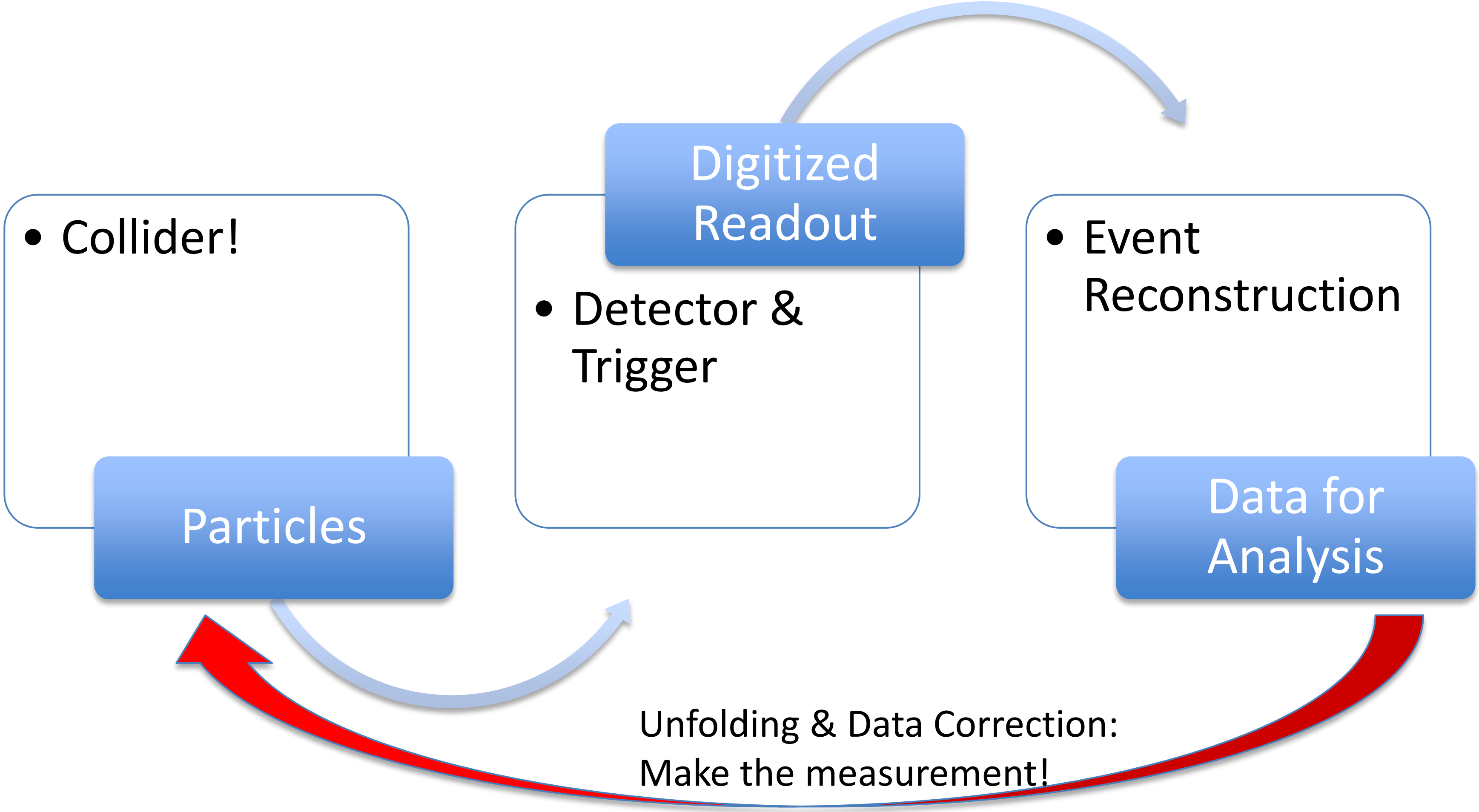
- Detector & Trigger Simulation

- Event Reconstruction

Data for Analysis

Unfolding & Data Correction:
Test and evaluate

Simulation and Experiment



- Collider!

Particles

Digitized Readout

- Detector & Trigger

- Event Reconstruction

Data for Analysis

Unfolding & Data Correction:
Make the measurement!

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”

What do we actually *measure*?

- Experimentalists: don’t publish a paper in which all the results are valid only in a particular theory or model
- Theorists: don’t trust them if they do (even if it is *your* theory or model!)
- At least the first stage of a measurement or search should be stated, in terms of “truth” final-state particle definitions where possible (and if it’s not possible… why not?)

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?)

What is your final state?

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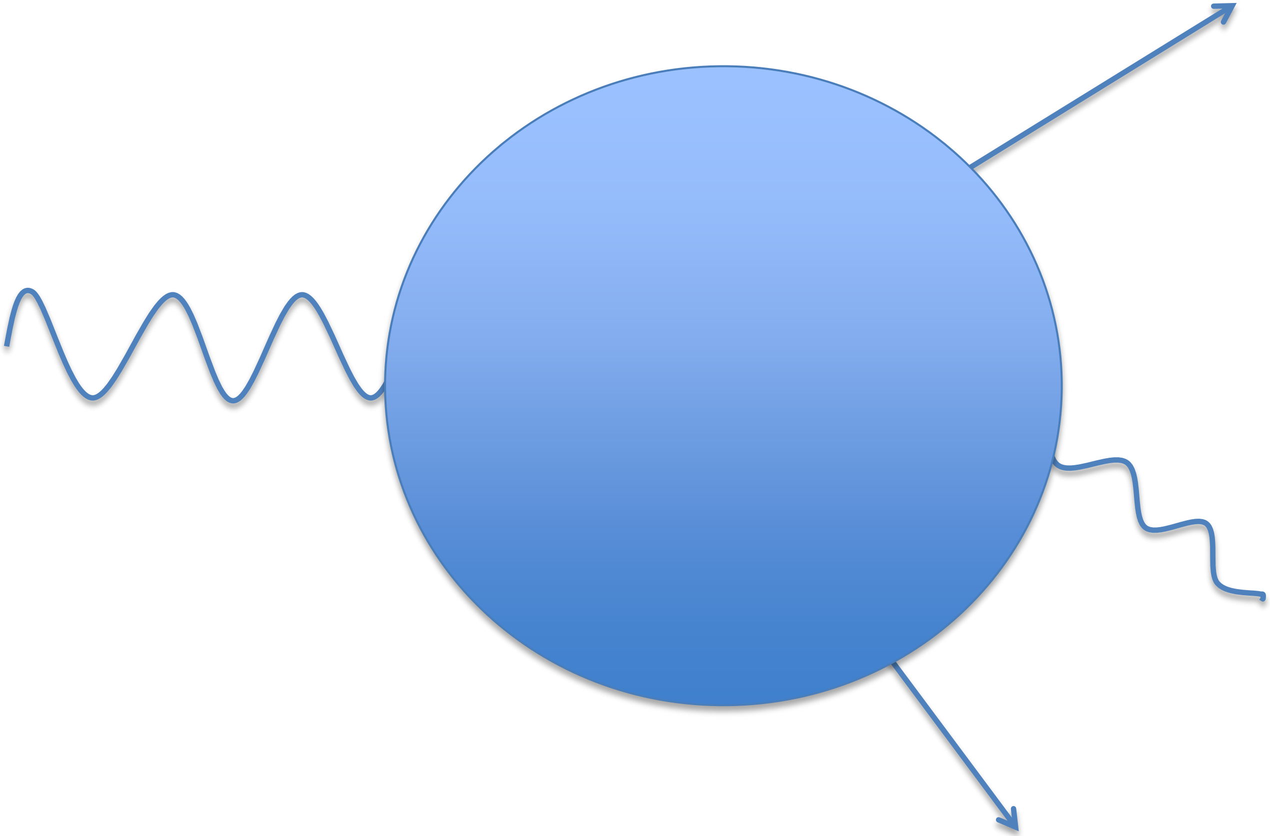
- Electrons, muons? (what about FSR?)

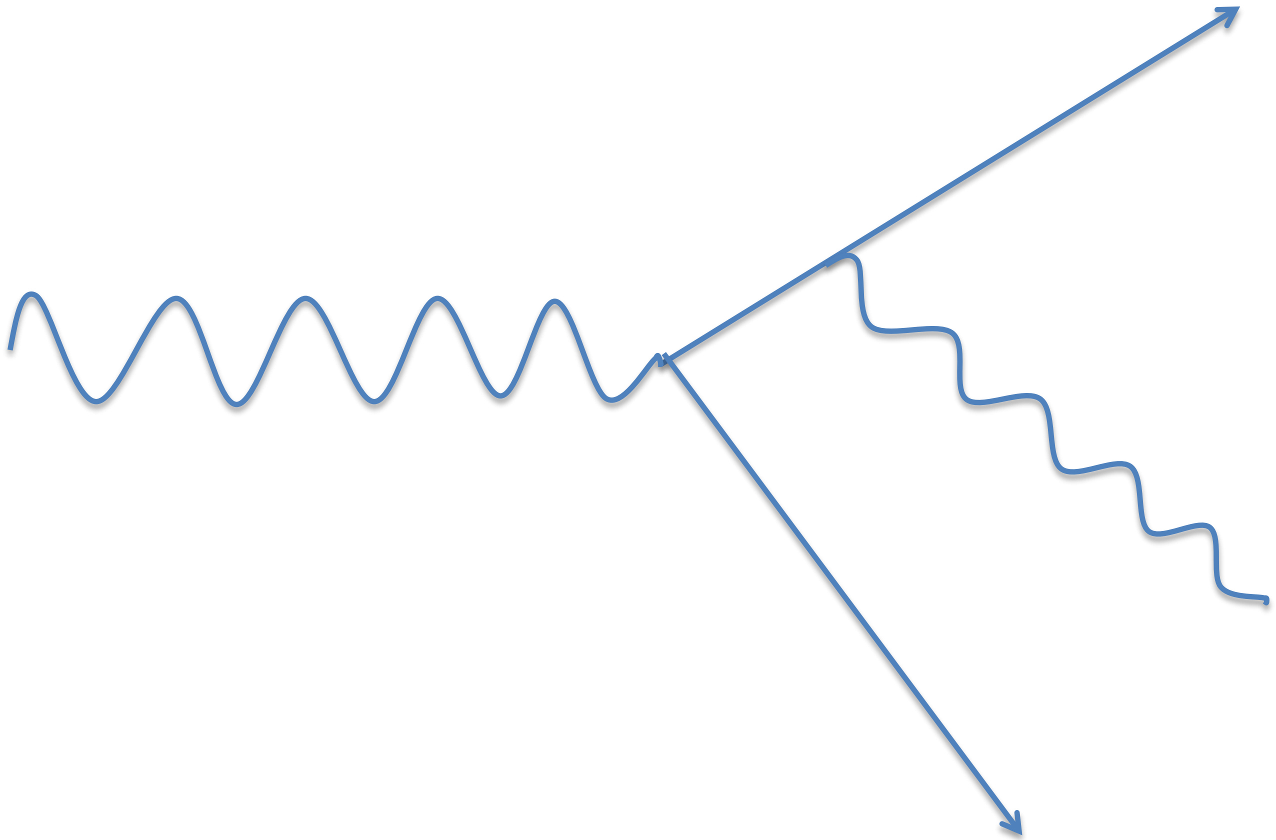
Important considerations (for searches too)

- 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

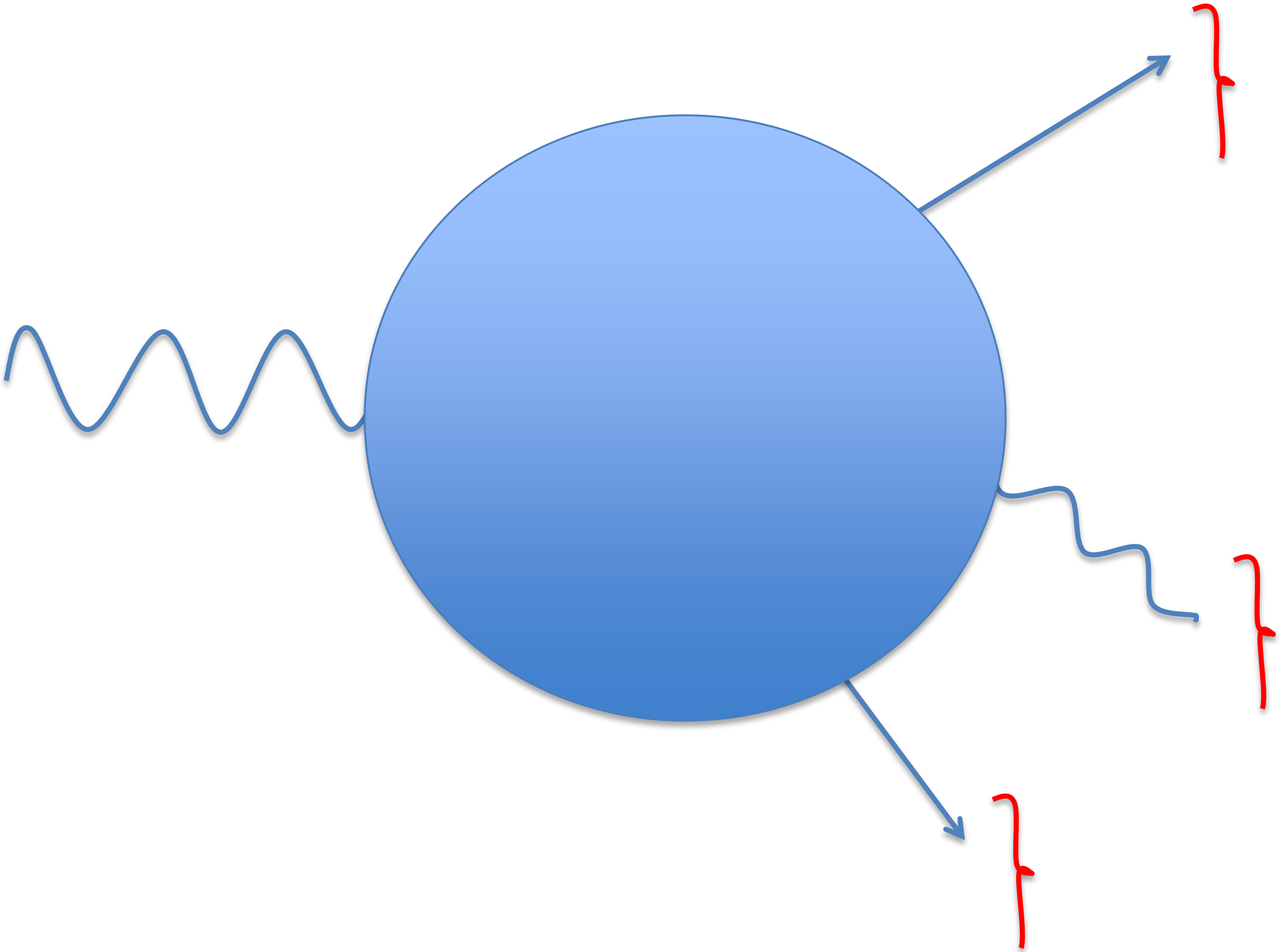


A Drell-Yan Diagram



- 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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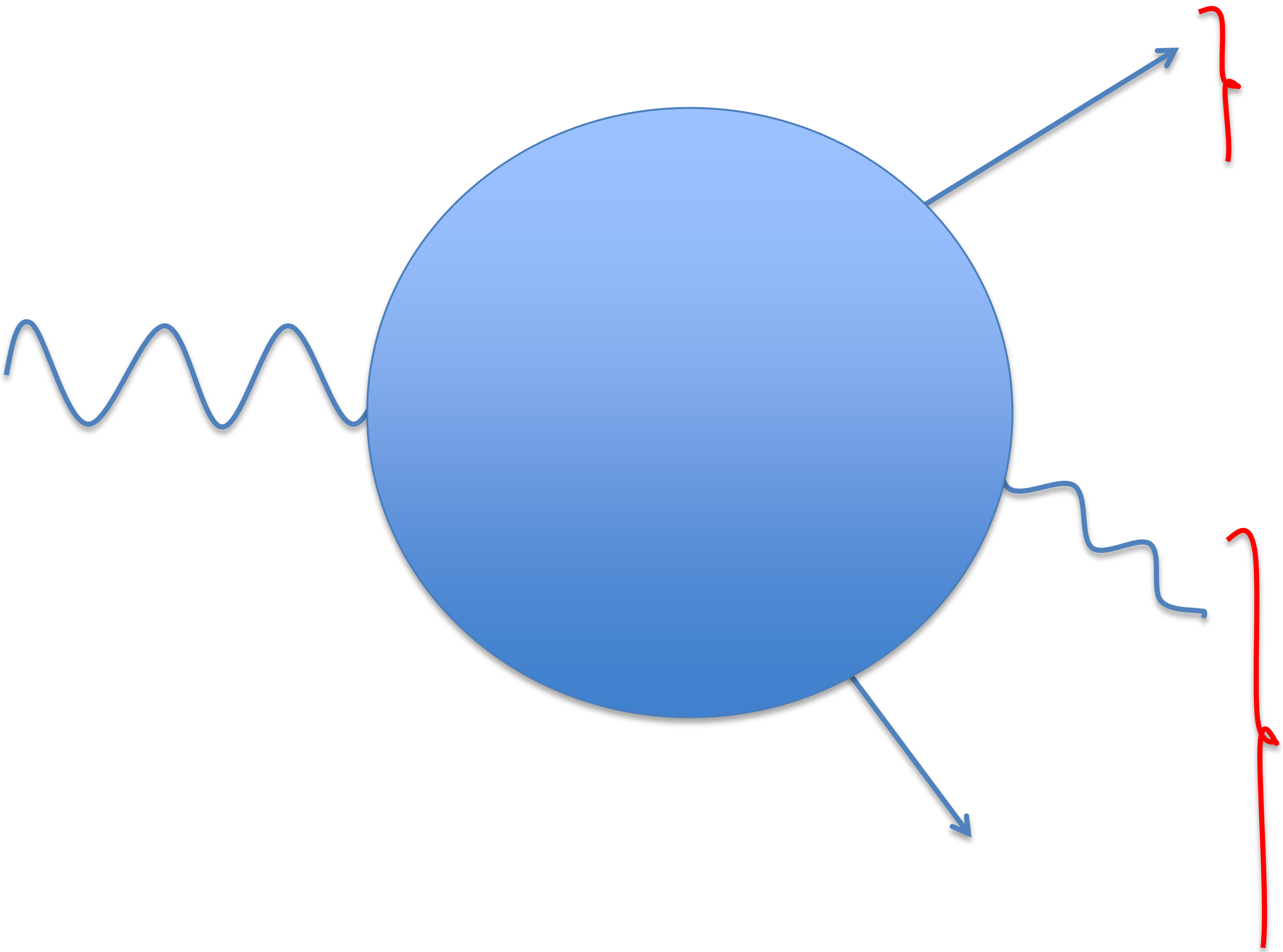
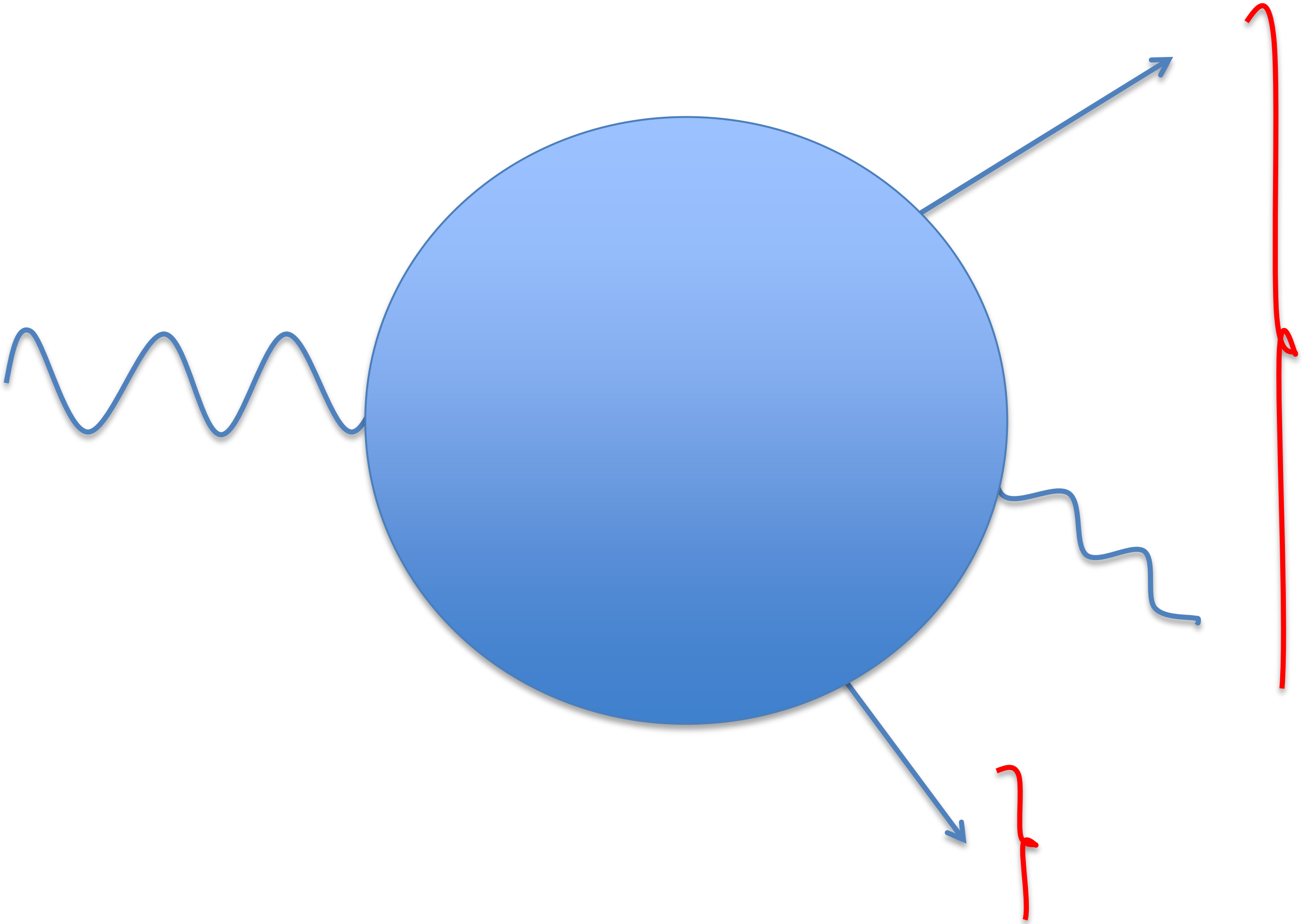
  - Large source of low-mass lepton pairs from Z resonance with a hard FSR photon
  - Present in detector
  - Present in dressed truth definition, which is much closer to what the detector sees in this case
  - Dressing with large cone… approaching Born but not asking about unphysical variables…

Dressed (possibility) big cone

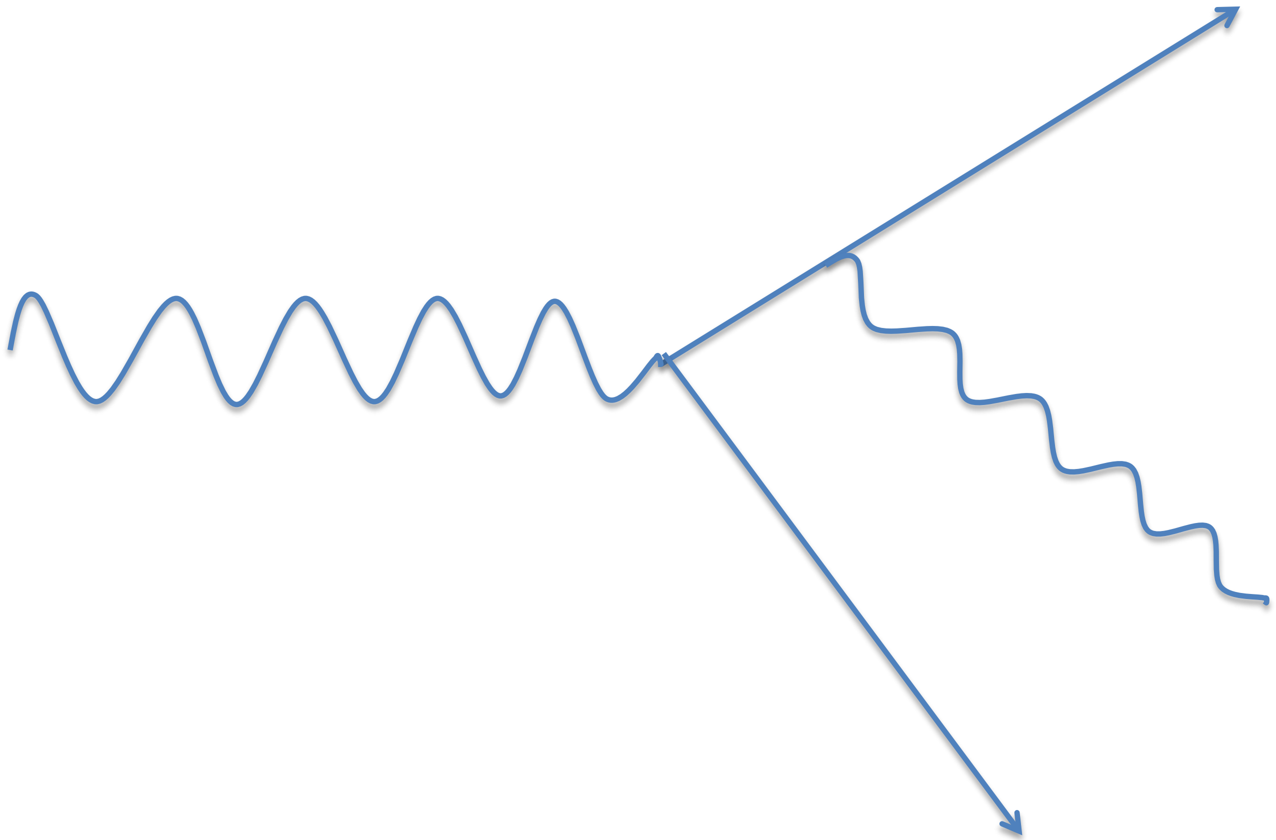


- Consider low mass Drell-Yan (below Z peak)
  - Large source of low-mass lepton pairs from Z resonance with a hard FSR photon
  - Present in detector
  - Present in dressed truth definition, which is much closer to what the detector sees in this case
  - Correction to “Born” level has to do this →

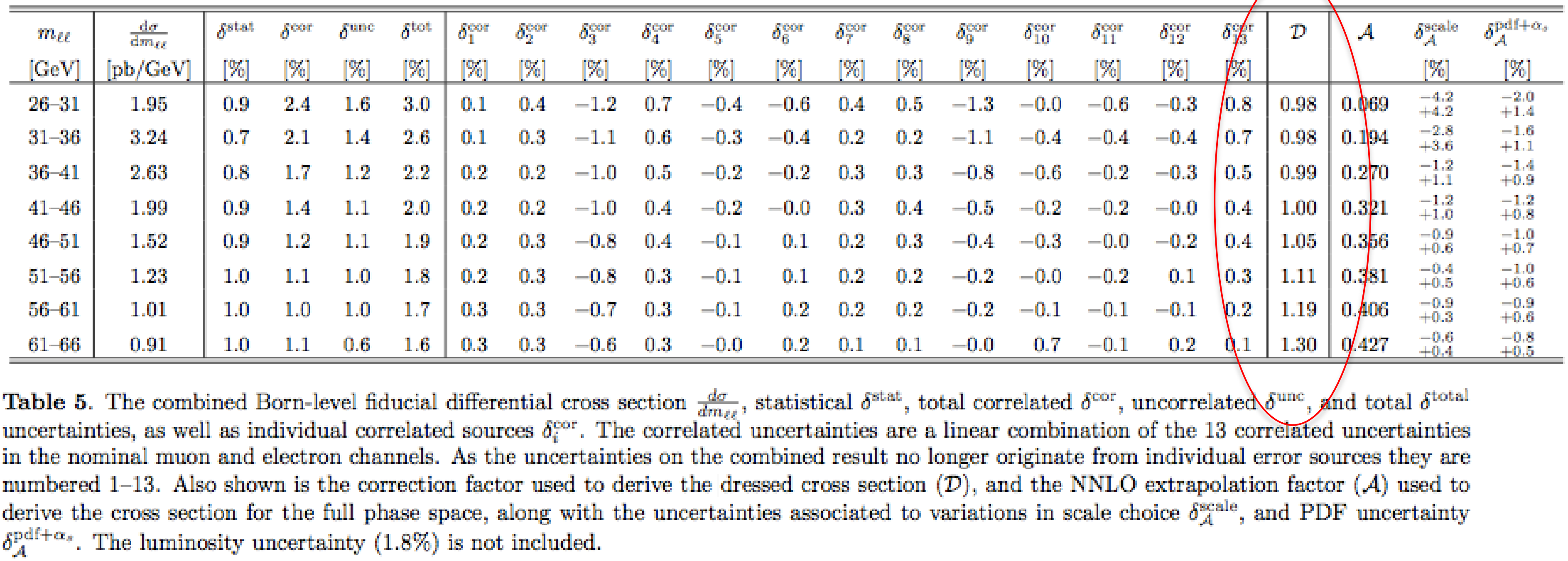
Born



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
  - 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^{cor}_1 [%]	δ^{cor}_2 [%]	δ^{cor}_3 [%]	δ^{cor}_4 [%]	δ^{cor}_5 [%]	δ^{cor}_6 [%]	δ^{cor}_7 [%]	δ^{cor}_8 [%]	δ^{cor}_9 [%]	δ^{cor}_{10} [%]	δ^{cor}_{11} [%]	δ^{cor}_{12} [%]	δ^{cor}_{13} [%]	$\mathcal{D}$	$\mathcal{A}$	$\delta^{scale}_{\mathcal{A}}$ [%]	$\delta^{pdf+\alpha_s}_{\mathcal{A}}$ [%]
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^{cor}_i. 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 $\delta^{scale}_{\mathcal{A}}$, and PDF uncertainty $\delta^{pdf+\alpha_s}_{\mathcal{A}}$. The luminosity uncertainty (1.8%) is not included.

ATLAS arXiv
arXiv:1404.1212

QED FSR effects

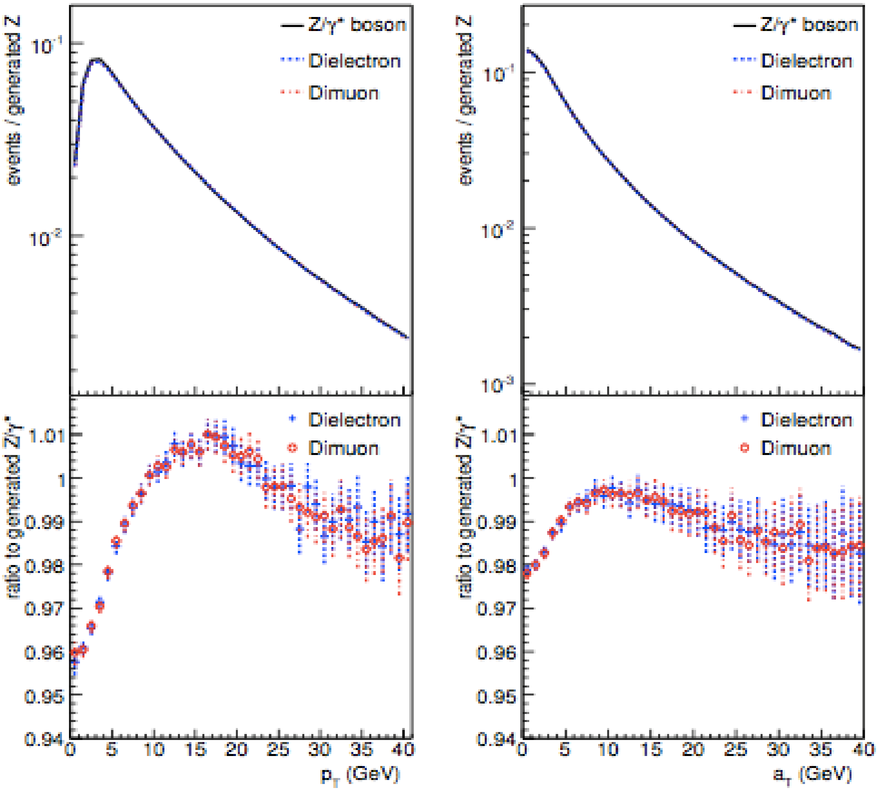


Fig. 46: The Z/γ^* p_T (left) and a_T (right) using the same treatment of electron and muon final states.

(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

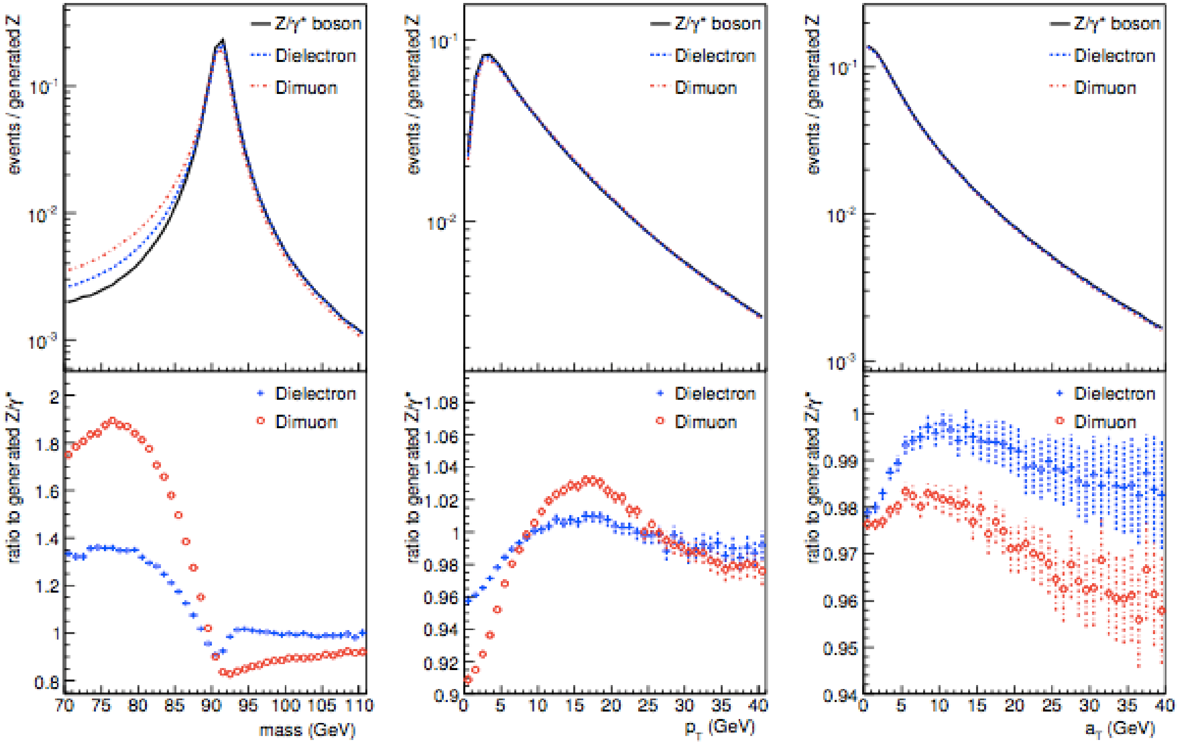


Fig. 44: Comparing the generated Z/γ^* to the observable (defined in the text). Left: the Z/γ^* mass; centre: the Z/γ^* p_T; right: the Z/γ^* a_T.

(Dressed electrons, cone 0.2.
Bare muons.)

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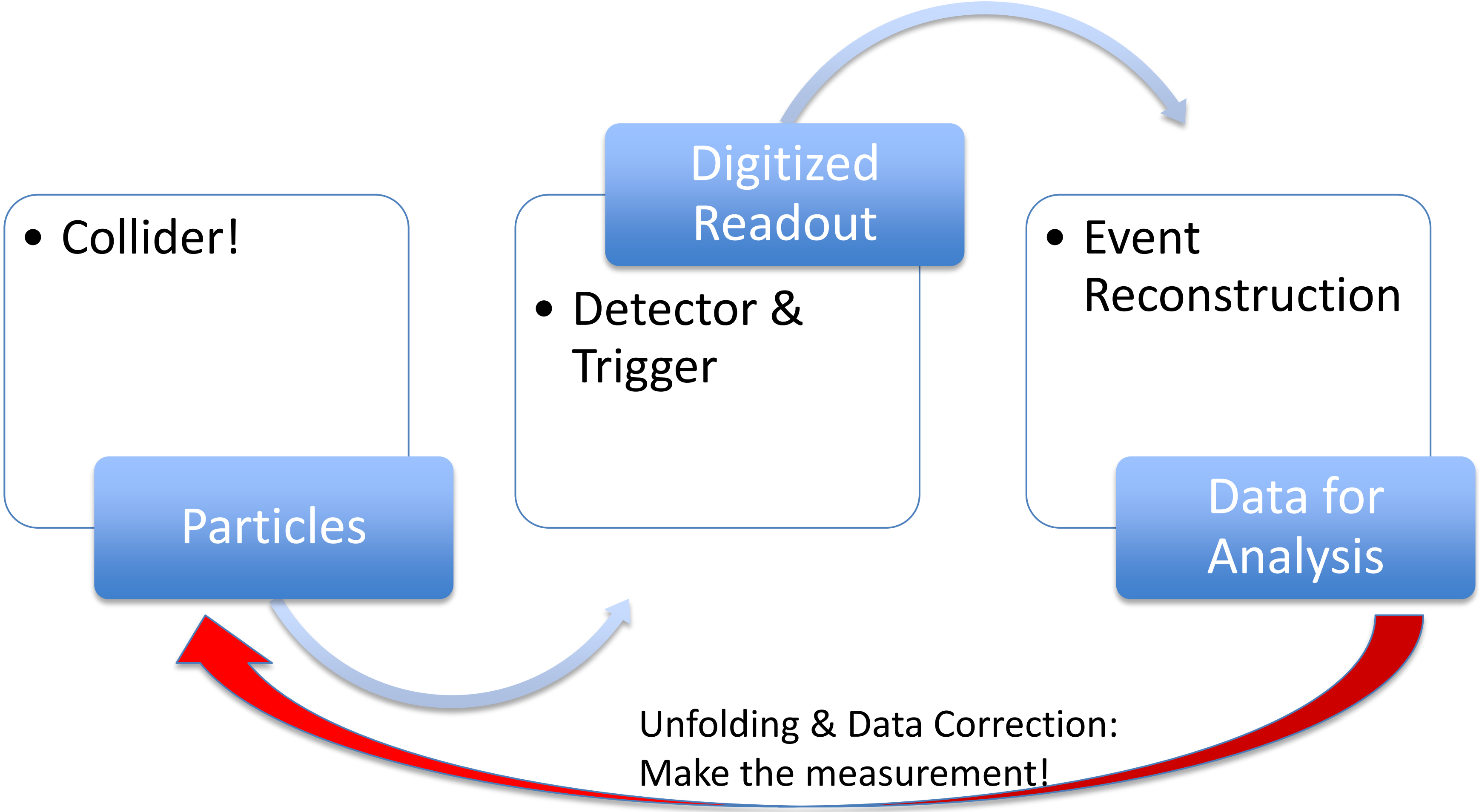
Key points from that example

- 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.

Simulation and Experiment



- Collider!

Particles

Digitized Readout

- Detector & Trigger

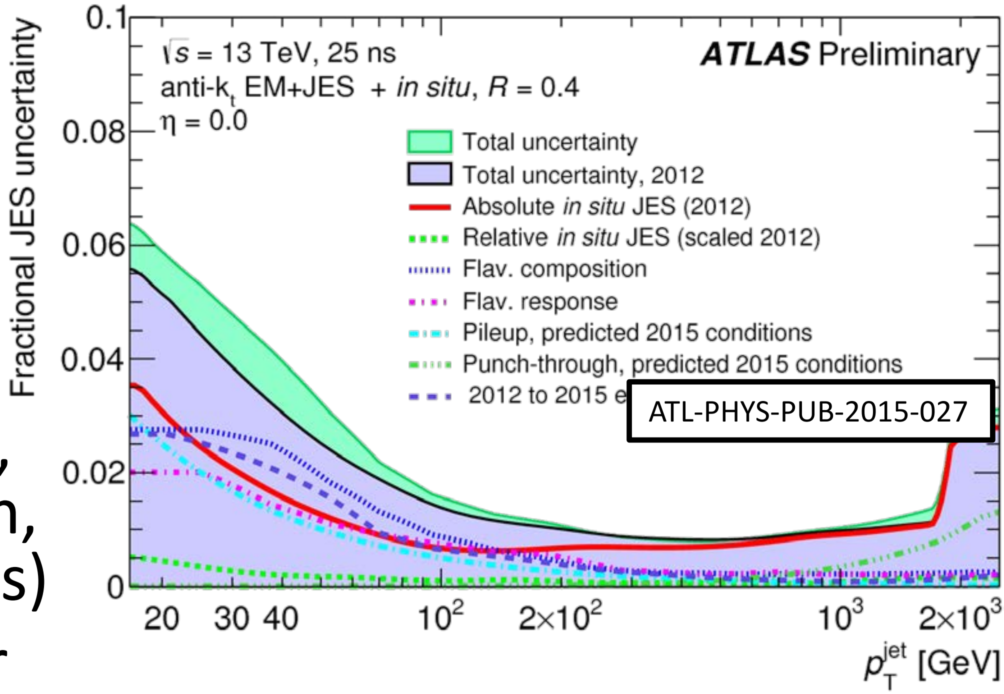
- Event Reconstruction

Data for Analysis

Unfolding & Data Correction:
Make the measurement!

Jet Energy Scale

- Calibration & uncertainty estimated with 2012 data
  - Uncertainty: ~1-6%, depends on p_T and η
- Uses
  - Test beam input
  - in-situ energy-balance (tracks; electrons, muons, photons for central region, central jets vs forward jets)
  - Used to improve detector software model
- Tested vs MC for 2015 data



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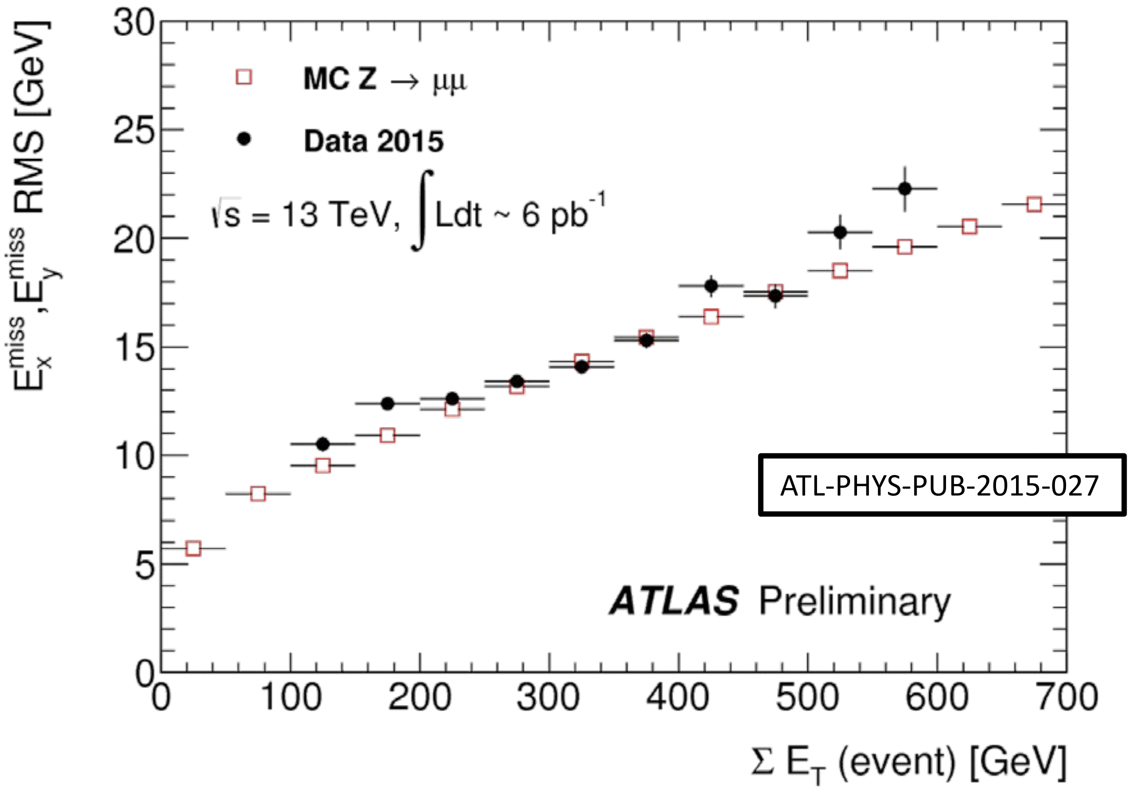
E_T^{miss} Resolution

- E_T^{miss} Resolution
  - measured in minimum bias & Z candidate events
  - Good agreement between data and MC



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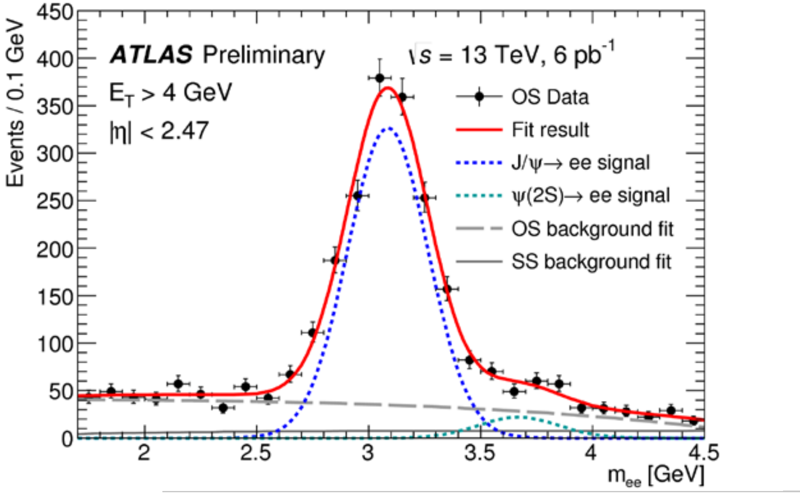
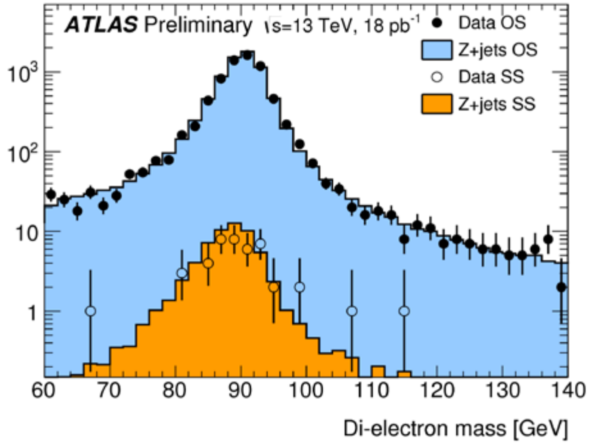
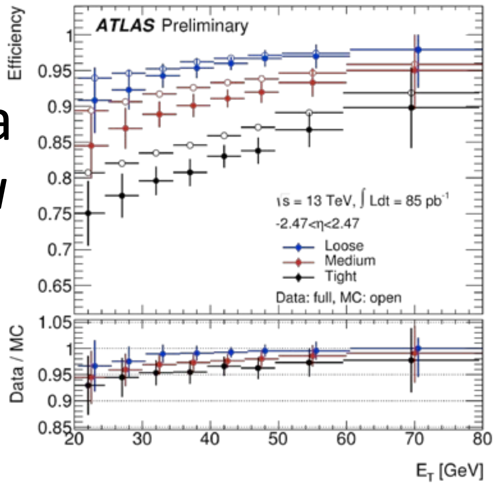
Electrons

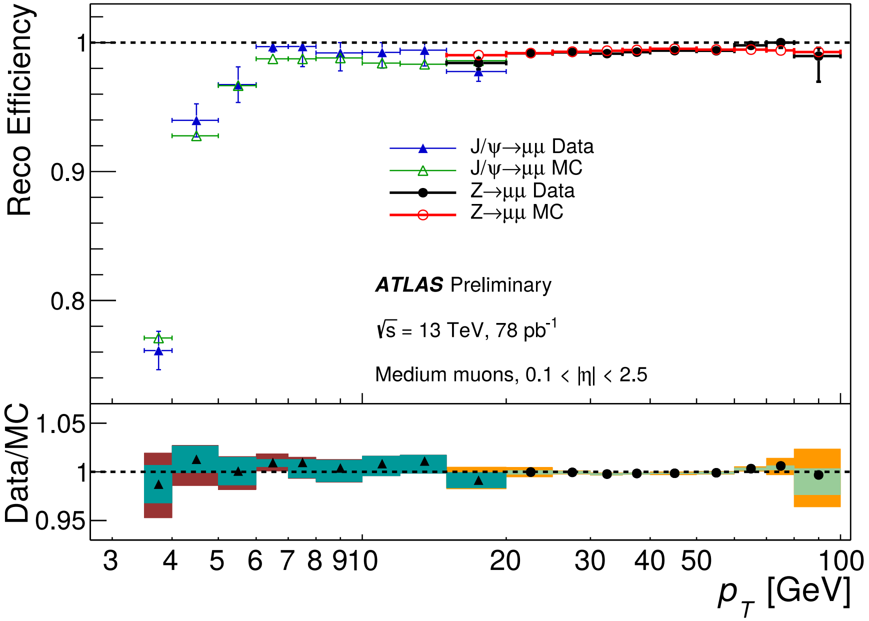
- Z and J/psi peaks used to evaluate electron energy scale & resolution
- Electron identification
  - Based on many variables combined in likelihood (details of detector)
  - Efficiencies 75% - 95%
  - Differences between data & MC corrected by *in-situ* calibration
  - Uncertainty ~2%



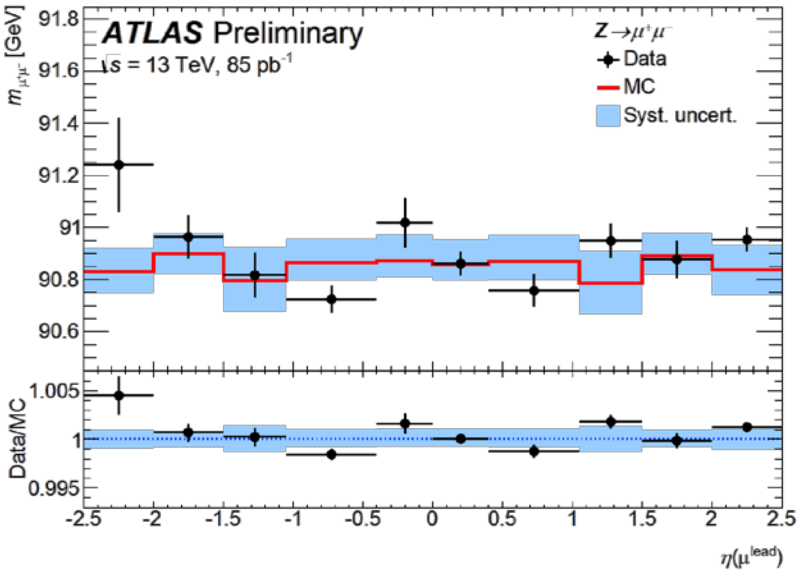


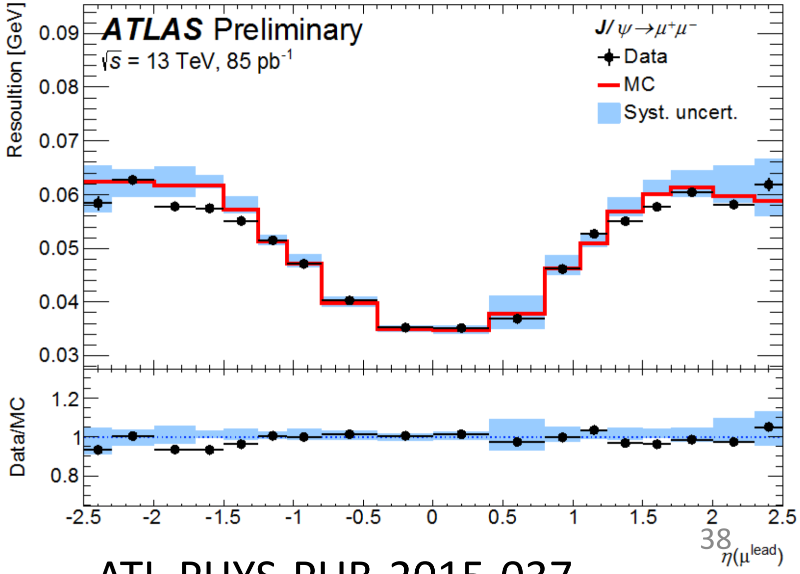


Muons



- High reconstruction efficiency
  - Well modeled by simulation
  - Uncertainty <1% for p_T>20 GeV
- Momentum scale already understood with precision of 0.2%
  - Resolution also understood to within 5% in this p range





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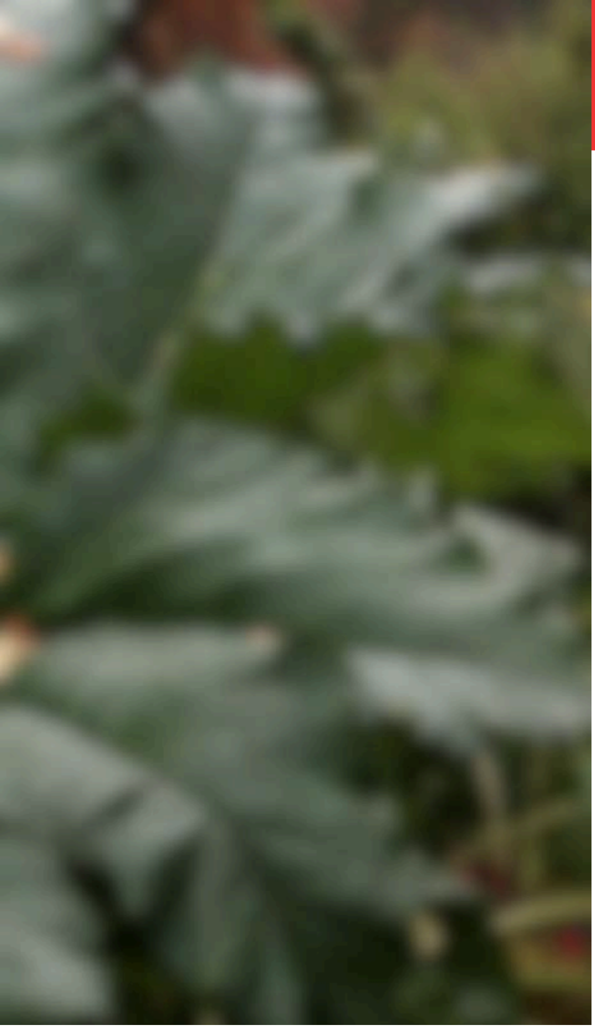
Fiducial or not?

- 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 the data are 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…

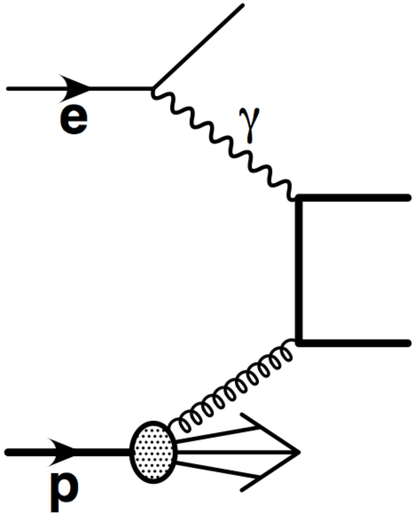
Concept of a “fiducial” cross section

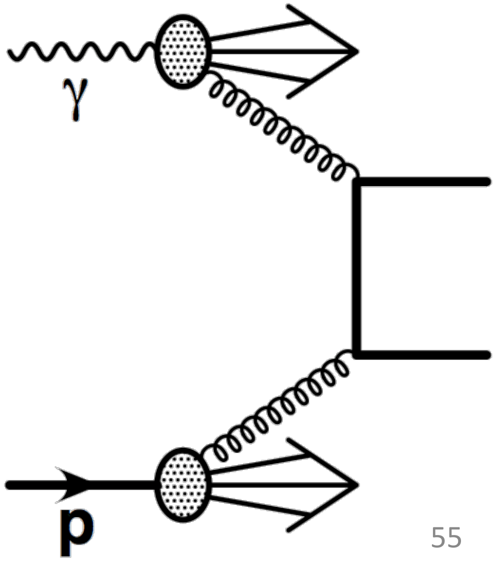
- Defines a region in which acceptance is ~100%
- Implies that some kinematic cuts must be implemented in whatever theory is compared to (easy for MC, less so for some high-order calculations)
- Ideally of course, build an experiment which covers all the phase space of interest…
- Fiducial cross section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

Real example: ZEUS charm photoproduction

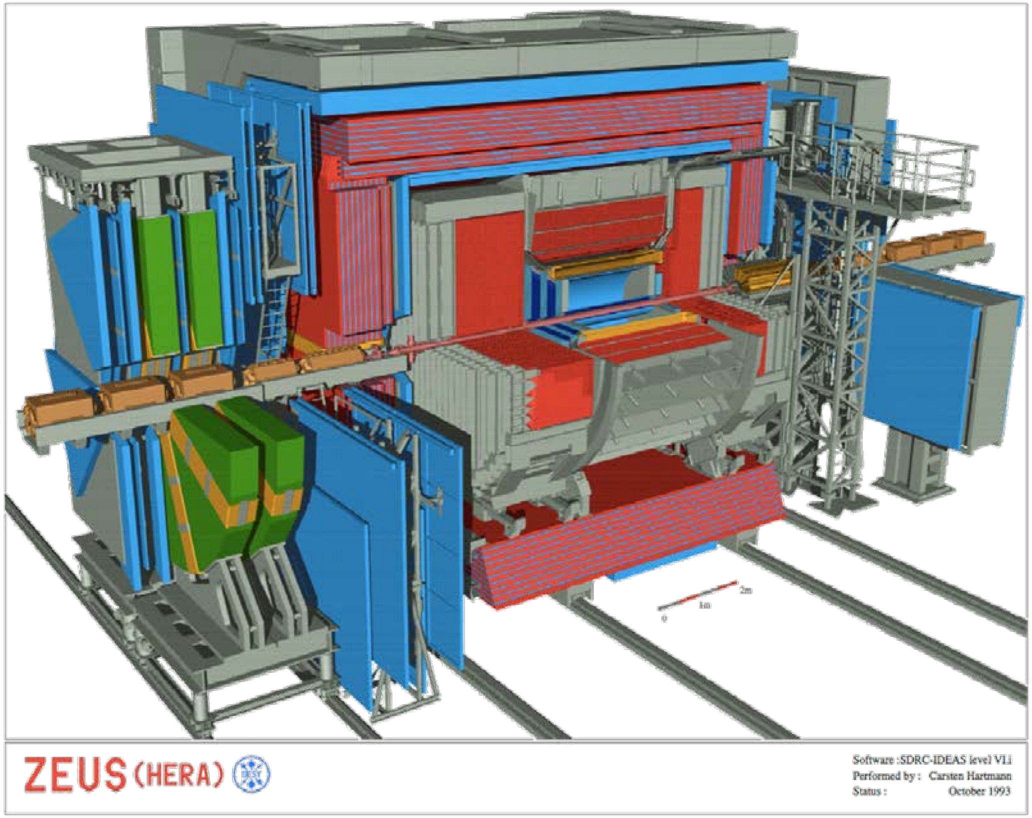
- Electron-proton collider, proton energy 820 GeV, electron energy 27 GeV
  - →Mean photon energy ~10 GeV.
  - →Photon proton CM energy ~100 to 300 GeV
  - →Kinematics highly boosted in the proton direction

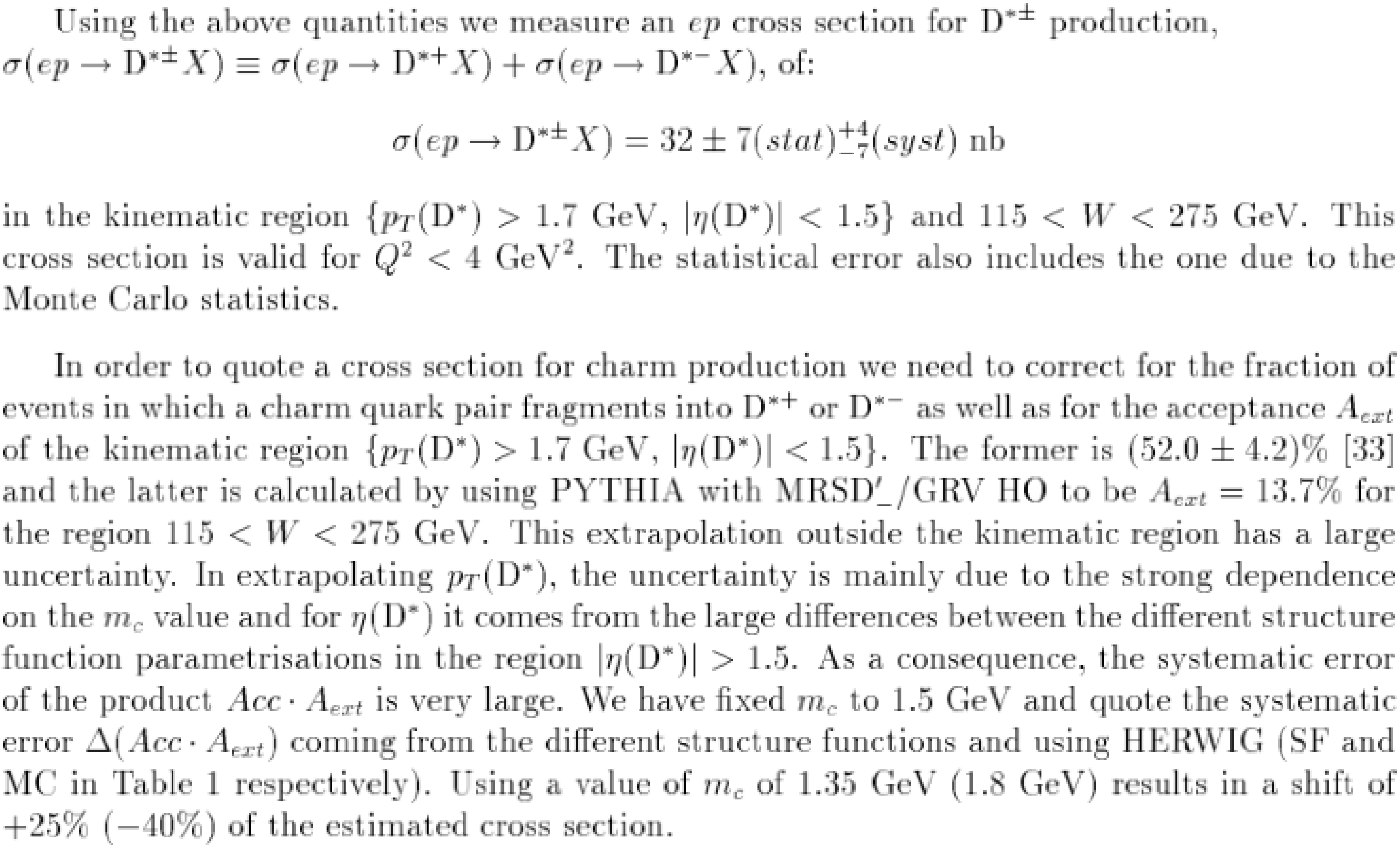




Real example: ZEUS charm photoproduction

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





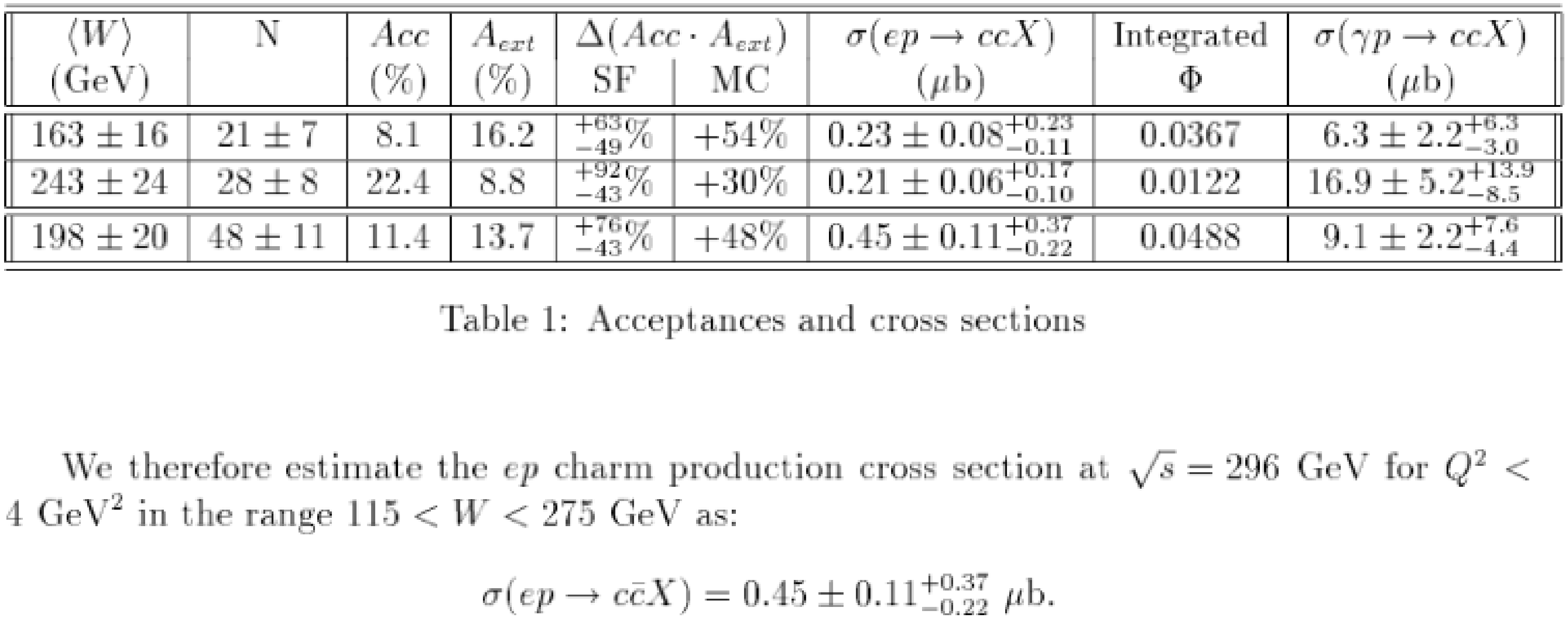
Using the above quantities we measure an ep cross section for $\mathrm{D}^{*\pm}$ production, $\sigma(ep \to \mathrm{D}^{*\pm}X) \equiv \sigma(ep \to \mathrm{D}^{*+}X) + \sigma(ep \to \mathrm{D}^{*-}X)$, of:

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

in the kinematic region $\{p_T(\mathrm{D}^*) > 1.7$ GeV, $|\eta(\mathrm{D}^*)| < 1.5\}$ 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 $\{p_T(\mathrm{D}^*) > 1.7$ GeV, $|\eta(\mathrm{D}^*)| < 1.5\}$. 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 $p_T(\mathrm{D}^*)$, the uncertainty is mainly due to the strong dependence on the m_c value and for $\eta(\mathrm{D}^*)$ it comes from the large differences between the different structure function parametrisations in the region $|\eta(\mathrm{D}^*)| > 1.5$. 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	$^{+63}_{-49}\%$	$+54\%$	$0.23\pm0.08^{+0.23}_{-0.11}$	0.0367	$6.3\pm2.2^{+6.3}_{-3.0}$
243 ± 24	28 ± 8	22.4	8.8	$^{+92}_{-43}\%$	$+30\%$	$0.21\pm0.06^{+0.17}_{-0.10}$	0.0122	$16.9\pm5.2^{+13.9}_{-8.5}$
198 ± 20	48 ± 11	11.4	13.7	$^{+76}_{-43}\%$	$+48\%$	$0.45\pm0.11^{+0.37}_{-0.22}$	0.0488	$9.1\pm2.2^{+7.6}_{-4.4}$

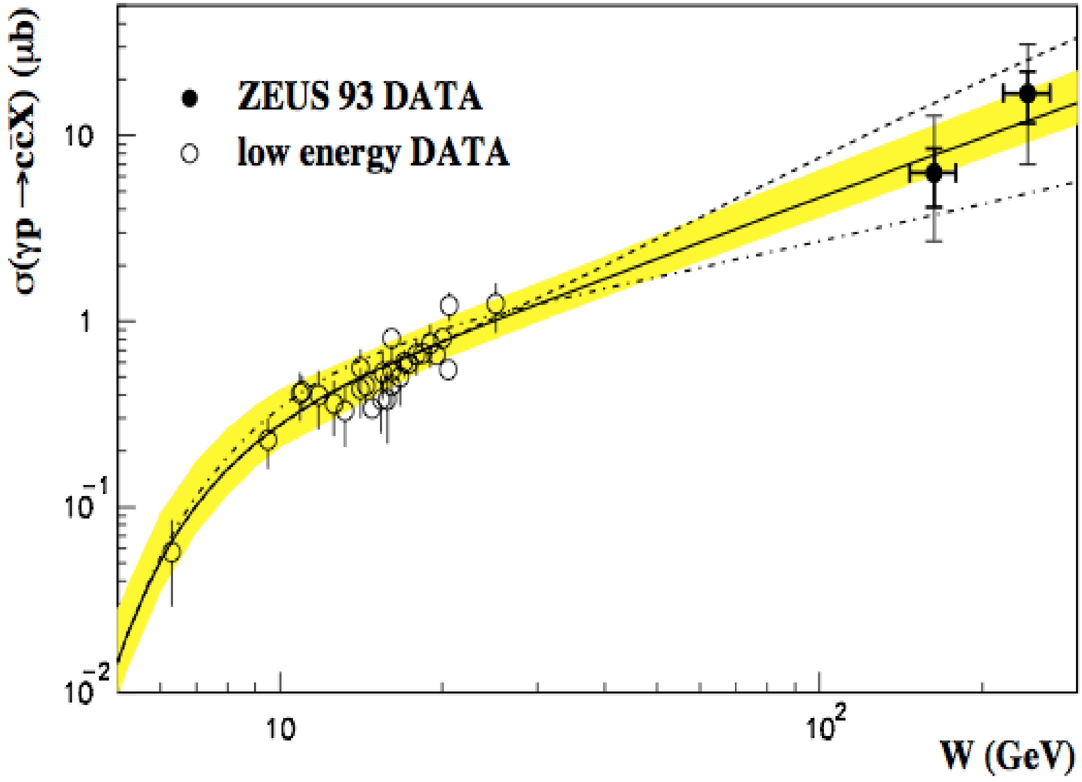
Table 1: Acceptances and cross sections

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:

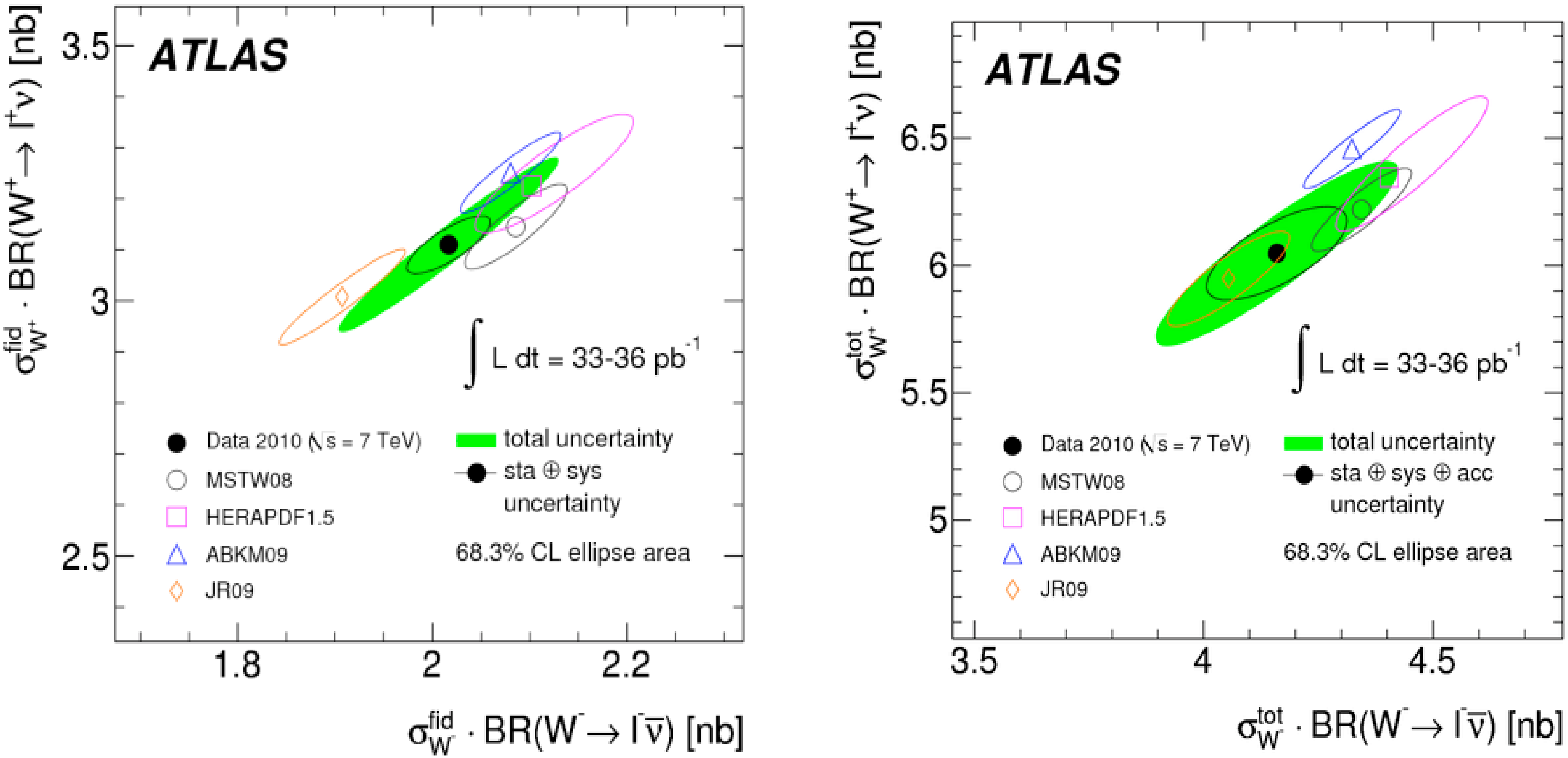
$$\sigma(ep\to c\bar{c}X)=0.45\pm0.11^{+0.37}_{-0.22}\ \mu\mathrm{b}.$$

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)

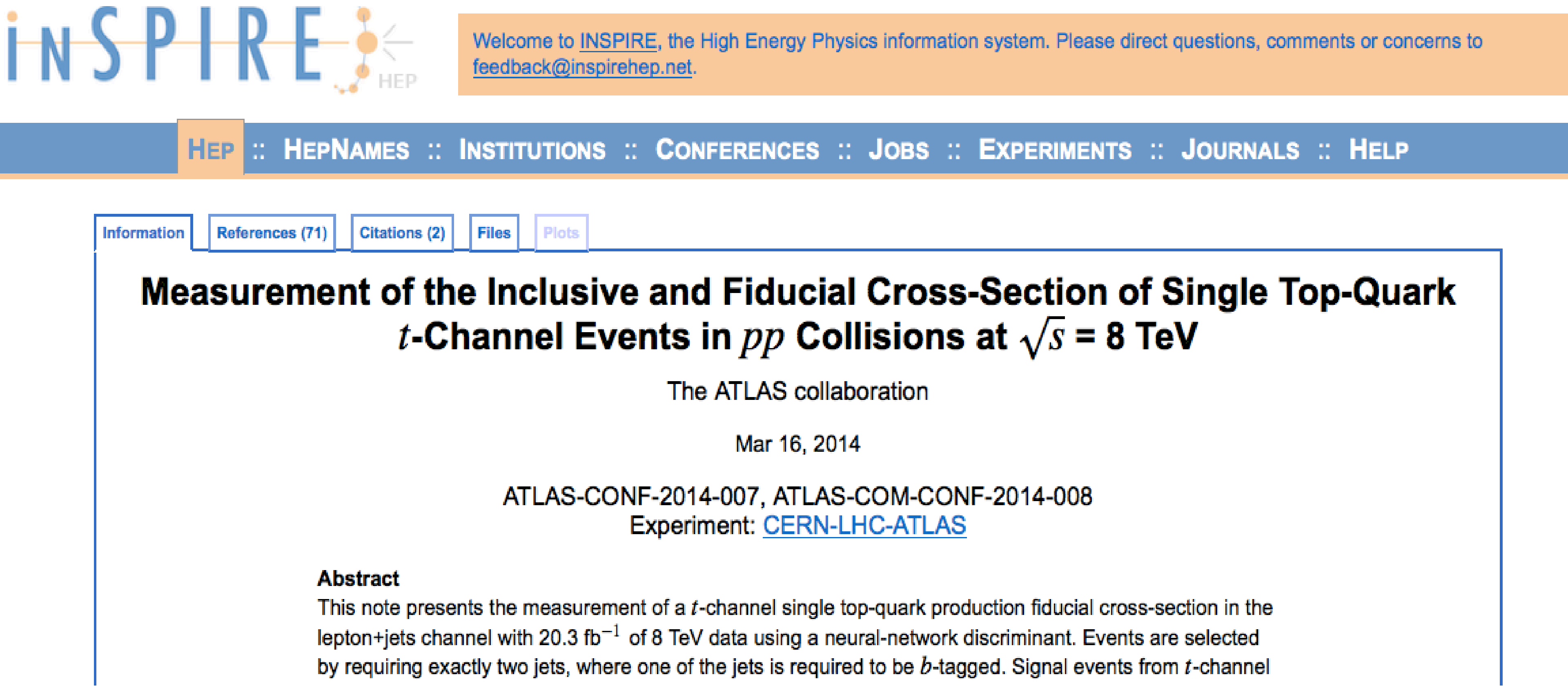


Real example: ATLAS W & Z cross sections (to e, μ), 7 TeV



Real example: ATLAS WW cross section (to e, μ), 7 TeV

- Efficiency/detector corrections to obtain fiducial cross section: 0.4-0.7 (defined in terms of lepton kinematics)
- Acceptance (accessible phase space compared to inclusive WW): 0.07-0.16
- That missing 90% is stuff we *don't measure*
- The efficiency/detector efficiency won't change much at 13 TeV, but the acceptance may well drop further



Welcome to INSPIRE, the High Energy Physics information system. Please direct questions, comments or concerns to feedback@inspirehep.net.

Measurement of the Inclusive and Fiducial Cross-Section of Single Top-Quark t-Channel Events in pp Collisions at $\sqrt{s}$ = 8 TeV

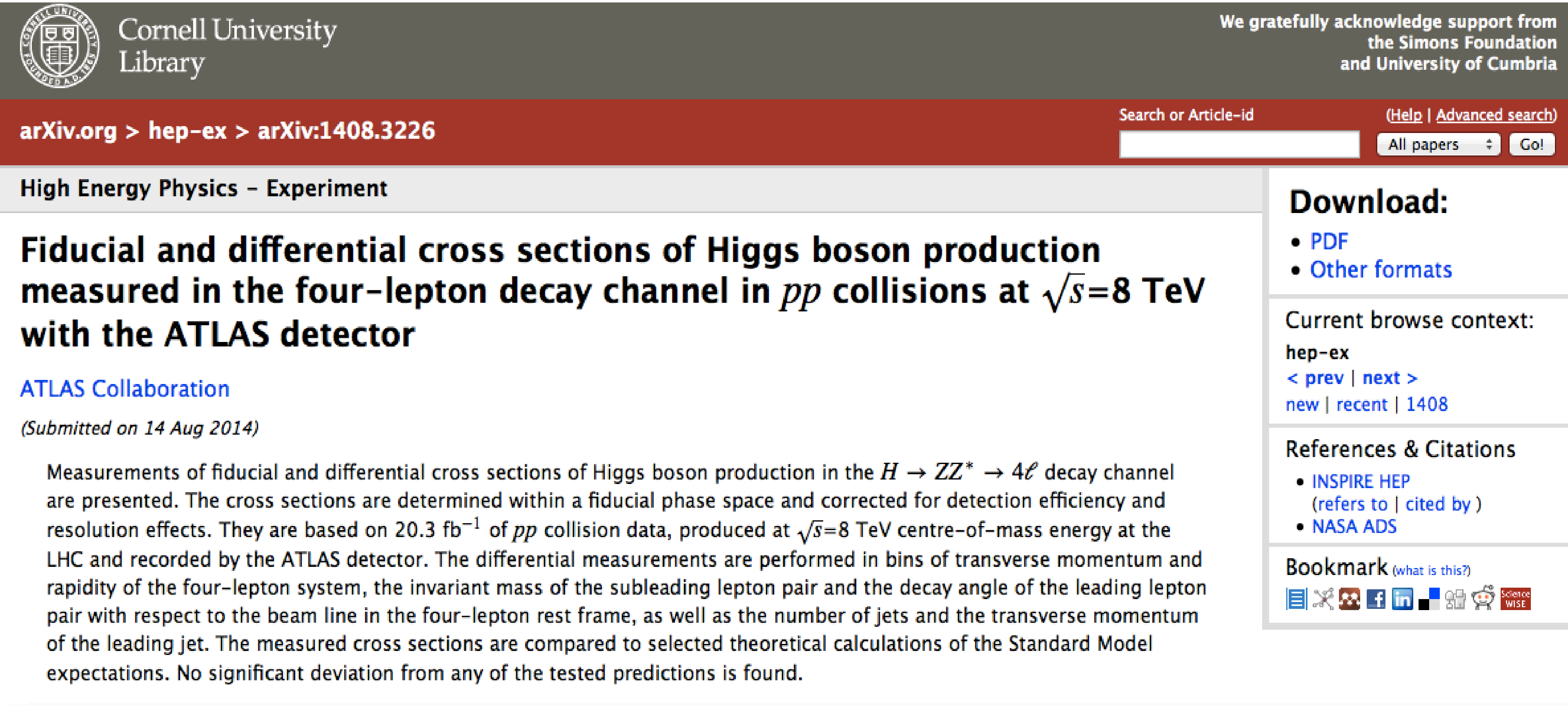
The ATLAS collaboration

Mar 16, 2014

ATLAS-CONF-2014-007, ATLAS-COM-CONF-2014-008
Experiment: CERN-LHC-ATLAS

Abstract

This note presents the measurement of a t-channel single top-quark production fiducial cross-section in the lepton+jets channel with 20.3 fb^{-1} of 8 TeV data using a neural-network discriminant. Events are selected by requiring exactly two jets, where one of the jets is required to be b-tagged. Signal events from t-channel



High Energy Physics – Experiment

Fiducial and differential cross sections of Higgs boson production measured in the four-lepton decay channel in pp collisions at $\sqrt{s}$=8 TeV with the ATLAS detector

ATLAS Collaboration

(Submitted on 14 Aug 2014)

Measurements of fiducial and differential cross sections of Higgs boson production in the $H \to ZZ^* \to 4\ell$ decay channel are presented. The cross sections are determined within a fiducial phase space and corrected for detection efficiency and resolution effects. They are based on 20.3 fb^{-1} of pp collision data, produced at $\sqrt{s}$=8 TeV centre-of-mass energy at the LHC and recorded by the ATLAS detector. The differential measurements are performed in bins of transverse momentum and rapidity of the four-lepton system, the invariant mass of the subleading lepton pair and the decay angle of the leading lepton pair with respect to the beam line in the four-lepton rest frame, as well as the number of jets and the transverse momentum of the leading jet. The measured cross sections are compared to selected theoretical calculations of the Standard Model expectations. No significant deviation from any of the tested predictions is found.

Garbage in, garbage out

THEORY in, THEORY out

… so the experiment is a waste of time

Measurements and Model Independence at Colliders

And something you can do with them once you have them

Jon Butterworth

University College London

Aachen Seminar

28 June 2016

Measurements and Model Independence at Colliders

And something you can do with them once you have them

Jon Butterworth

University College London

CTEQ/MCnet School, DESY

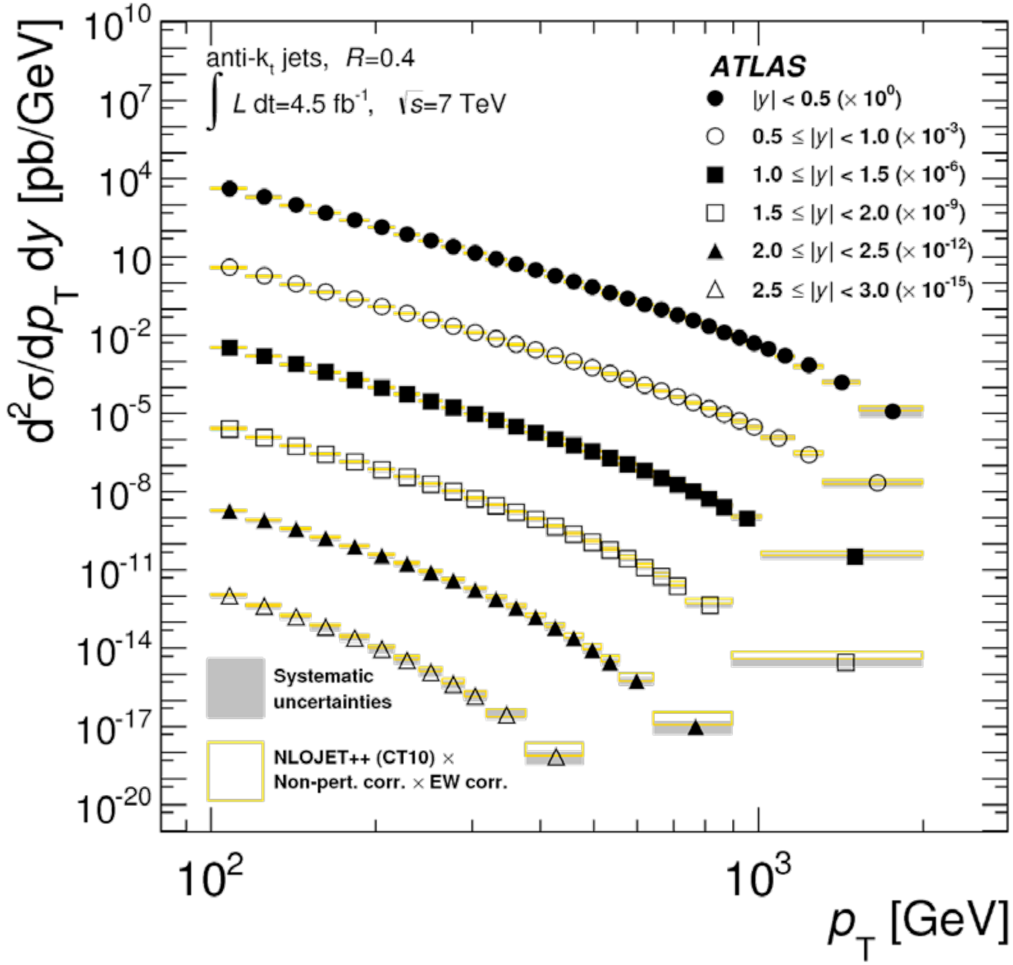
13 July 2016

Constraining BSM (Simplified) models with SM measurements

JMB, David Grellscheid (IPPP), Michael Krämer (Aachen), David Yallup

Precision ‘Standard Model’ Measurements

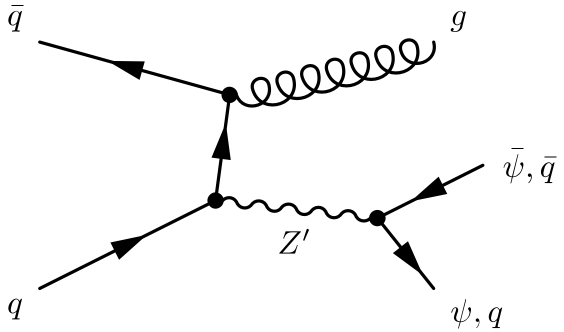
- They should not (and mostly do not) assume the SM
- They agree with the SM
- Thus they can potentially exclude extensions

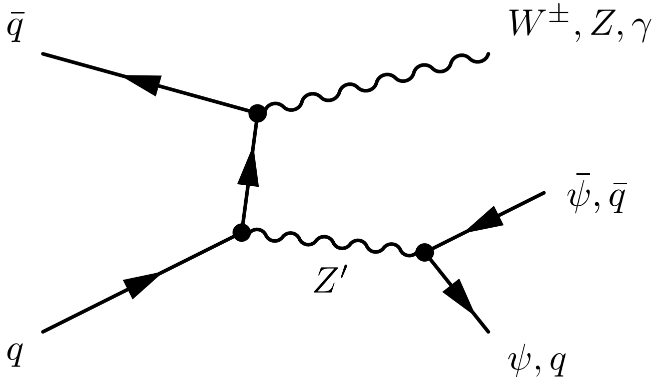


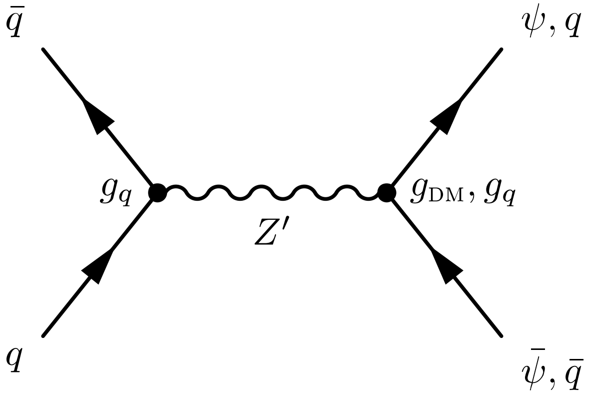
Simplified Model(s)

- 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.

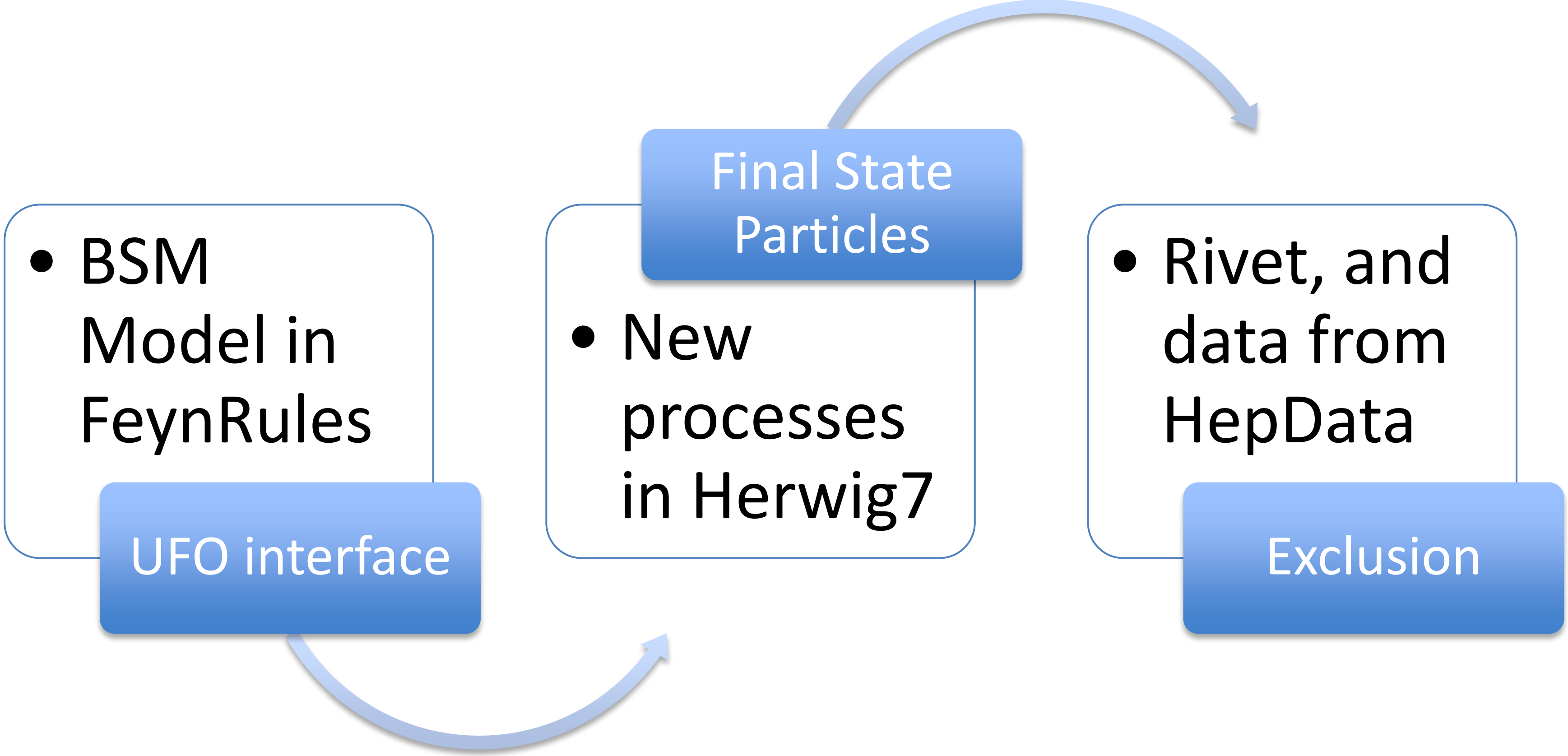
$$\mathcal{L} \supset g_{\rm DM}\,\overline{\psi}\gamma_\mu\gamma_5\psi\,Z'^\mu + g_q\sum_q \bar{q}\gamma_\mu q\,Z'^\mu$$







Key tools:



- BSM Model in FeynRules

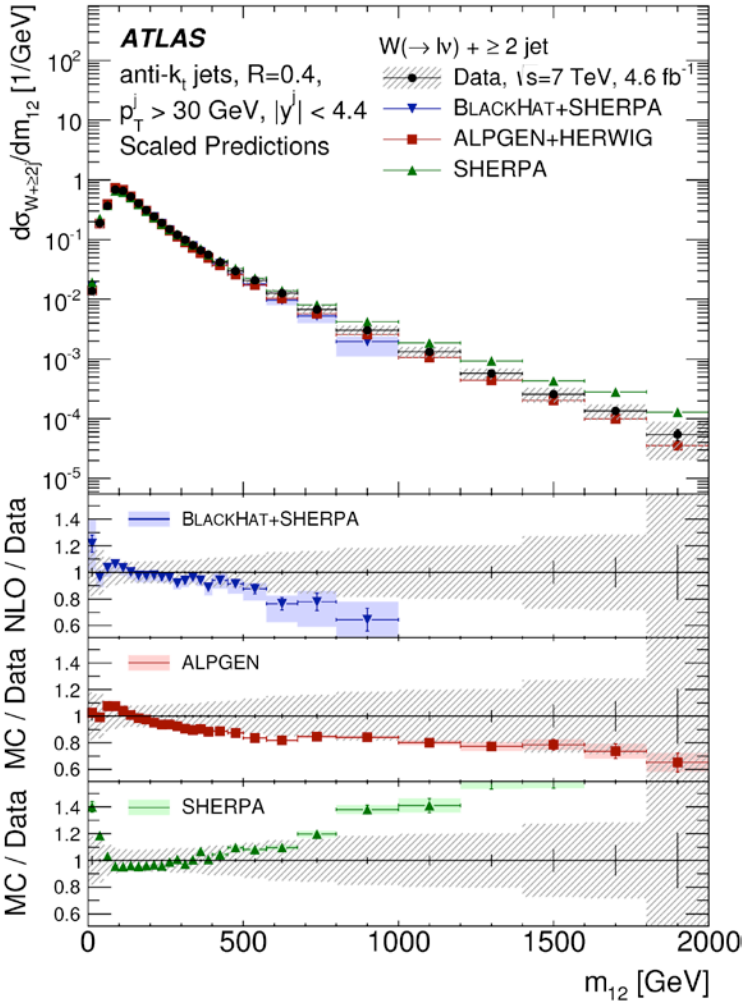
- New processes in Herwig7

- Rivet, and data from HepData

Strategy

- Use measurements shown to agree with the Standard Model
  - Not a search! Guaranteed not to find anything
  - Will be slower, but more comprehensive and model independent
  - Assume the data = the background!

Will miss this kind of thing…



Strategy

- Use measurements shown to agree with the Standard Model
  - Not a search! Guaranteed not to find anything
  - Will be slower, but more comprehensive and model independent
  - 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, 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

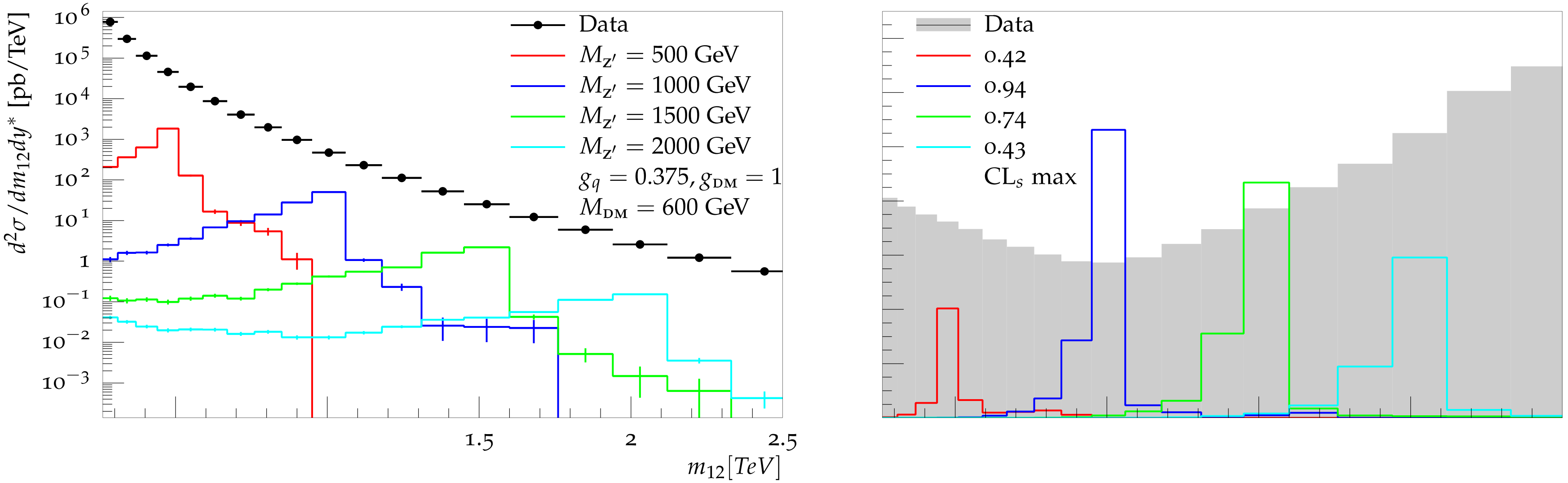
Contur Category	Rivet/ Inspire ID	Rivet description
ATLAS 7 Jets	ATLAS_2014_I1325553 [28]	Measurement of the inclusive jet cross-section
	ATLAS_2014_I1268975 [30]	High-mass dijet cross section
	ATLAS_2014_I1326641 [32]	3-jet cross section
	ATLAS_2014_I1307243 [31]	Measurements of jet vetoes and azimuthal 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

Parameter Choices

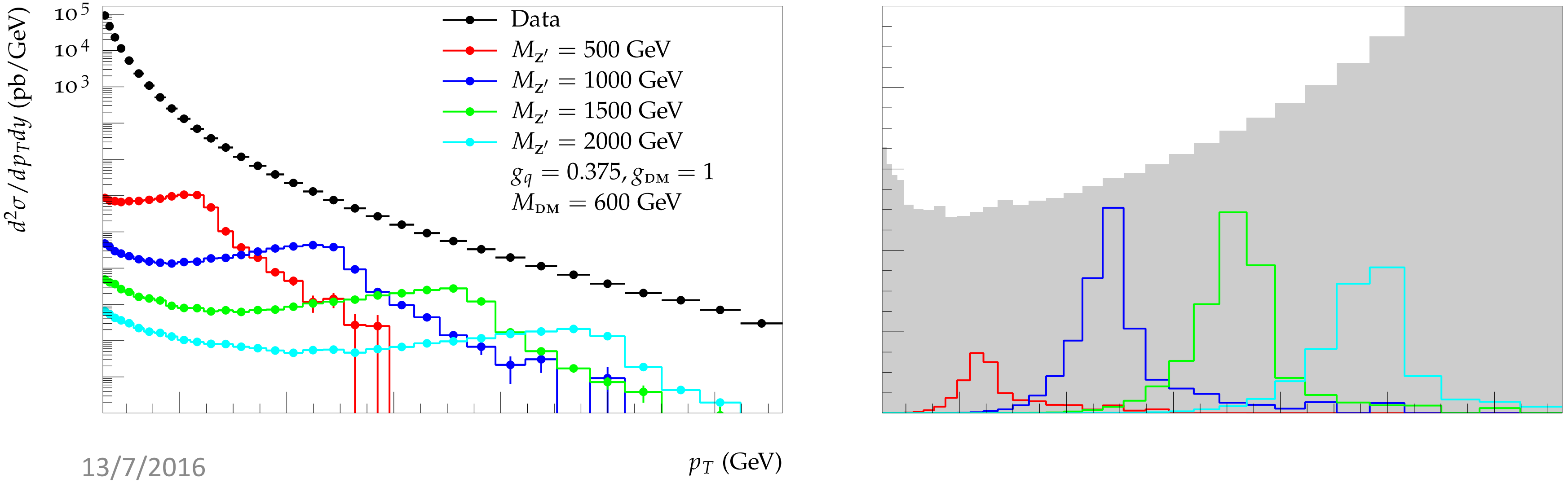
- Scan in M_{DM} and $M_{Z'}$
- Four pairs of couplings:
  - Challenging: $g_q = 0.25$; $g_{DM} = 1$
  - Medium: $g_q = 0.375$; $g_{DM} = 1$
  - Optimistic: $g_q = 0.5$; $g_{DM} = 1$
  - DM-suppressed $g_q = 0.375$; $g_{DM} = 0.25$

Data Comparisons

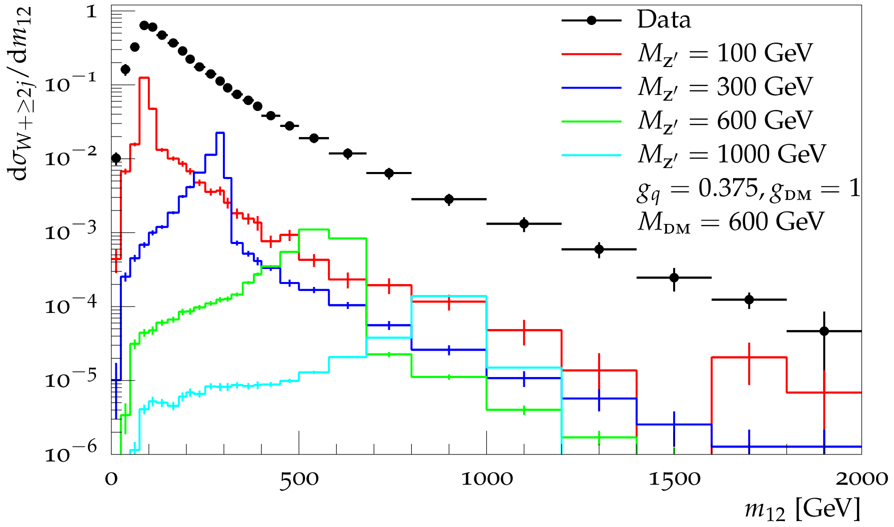
ATLAS Dijet double-differential cross sections ($y^* < 0.5$)

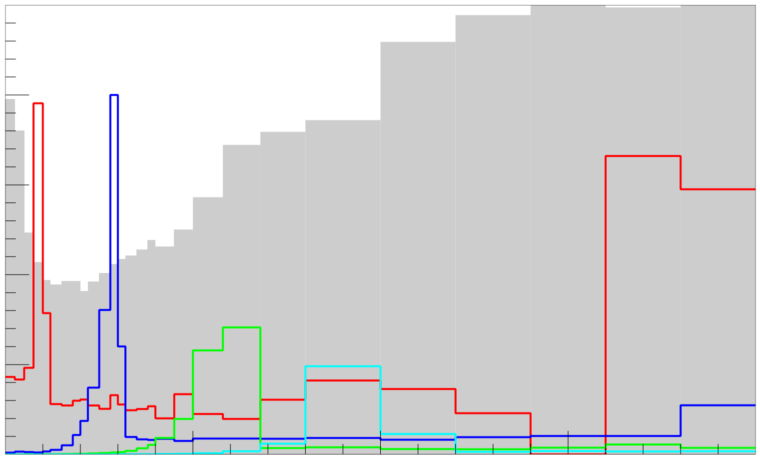


CMS inclusive jet double differential cross section ($|y| < 0.5$)

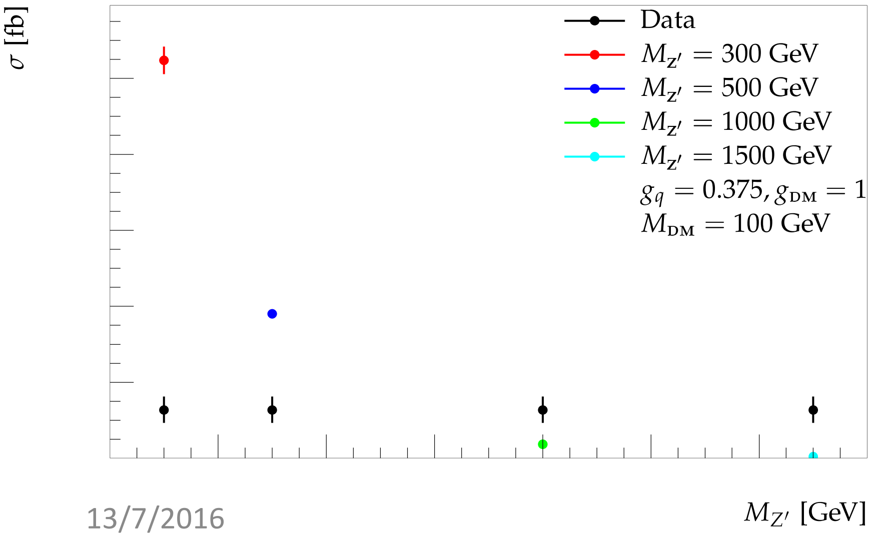


Data Comparisons

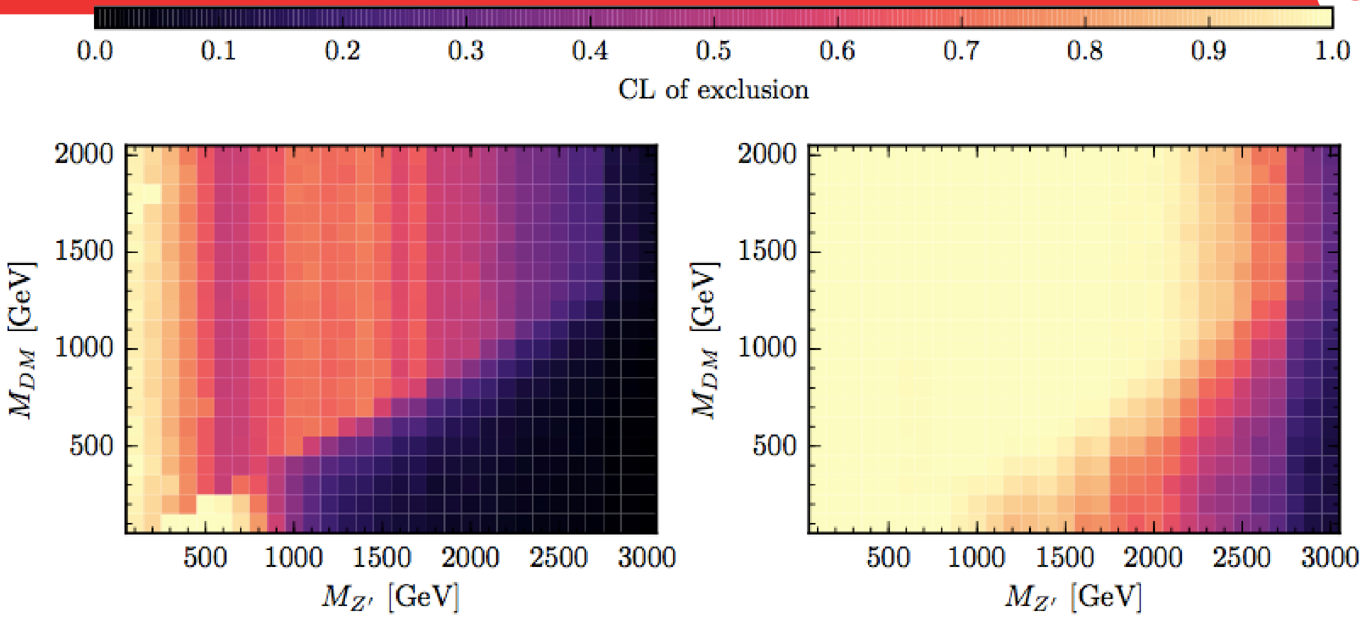

ATLAS $W+\geq 2$ jet differential cross section



ucial cross-section reconstructed $ZZ \rightarrow 2l2\nu$

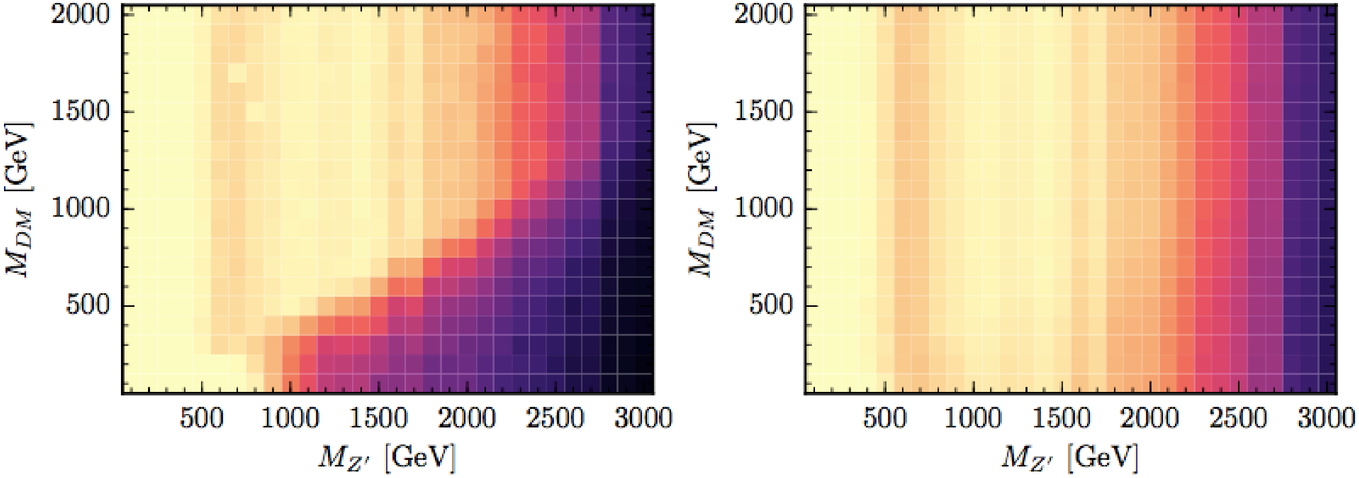


Heat Maps



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

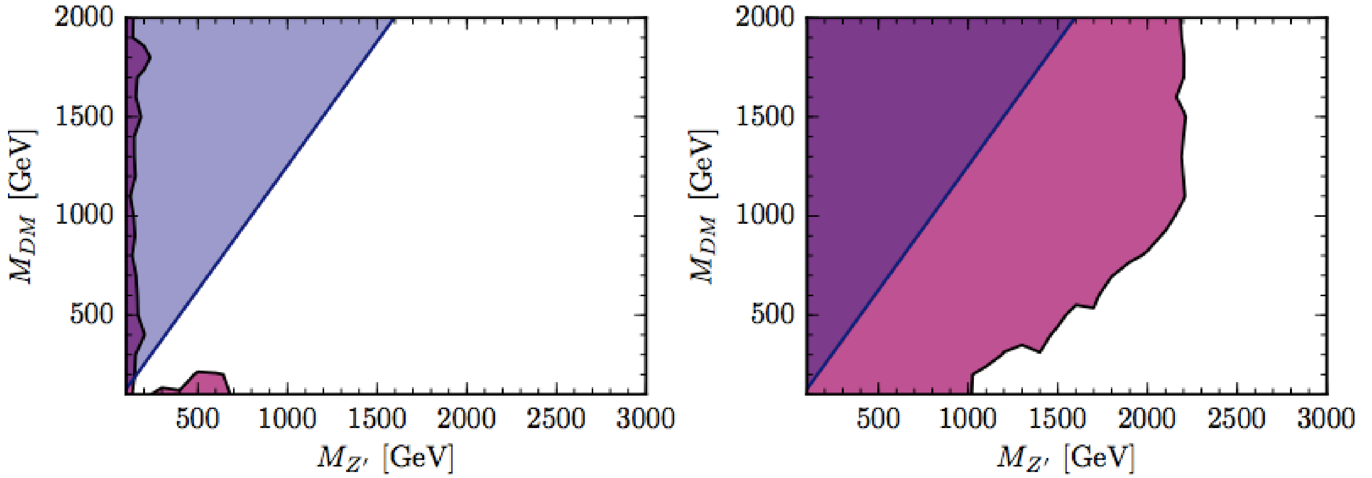
(b) $g_q = 0.5$ and $g_{\rm DM} = 1$



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

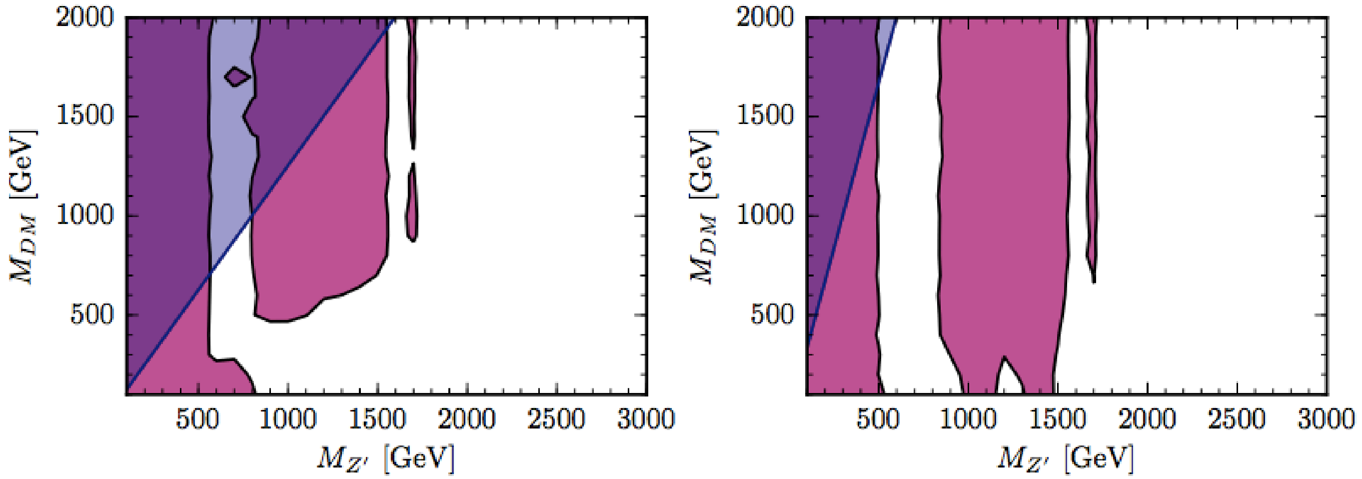
(d) $g_q = 0.375$ and $g_{\rm DM} = 0.25$

95% CL_s Contour



(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 $g_{\rm DM} = 1$

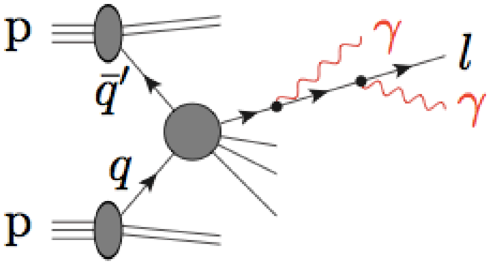
(d) $g_q = 0.375$ and $g_{\rm DM} = 0.25$

Figure 7: Contours in the $M_{Z'}$ and $M_{\rm DM}$ plane for the considered values of $g_{\rm DM}$ and g_q, indicating the excluded region at 95% confidence level. The triangular shaded area is the region in which perturbative unitary is violated by the model.

Conclusions

- Particle-level measurements can & should be made with a high degree of model-independence
  - Implies making choices on fiducial cut and careful definition of final state
- Such measurements not only measure what is happening in our collisions, they constrain what is *not* happening.
- Limit-setting procedure 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 (and references therein), & contur.hepforge.org

Collinear final-state radiation off leptons



Universal logarithmically enhanced corrections

$$\propto \alpha^n \ln^n(m_l^2/Q^2)$$

from final-state radiation

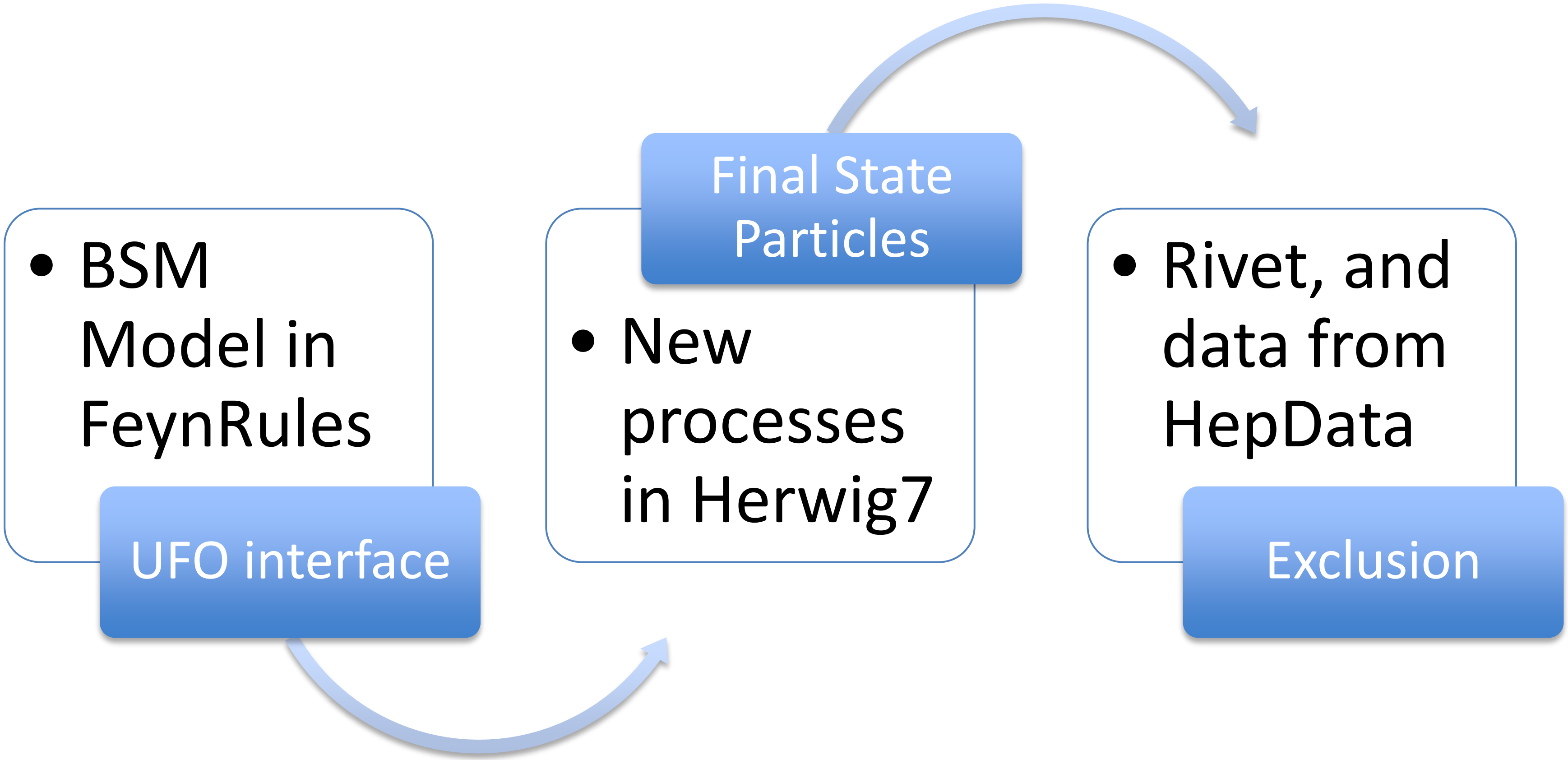
possible treatments:

- “bare leptons” (typical for muons, non-collinear-safe (NCS) case)
  photons are experimentally separated from leptons
  collinear singularities regularised by lepton mass
  ⇒ logarithmically enhanced corrections ⇒ large radiative tails
- “calorimetric/dressed leptons” (typical for electrons, collinear safe (CS))
  recombination of leptons with (collinear) photons (inclusive treatment)
  ⇒ mass-singular logarithms cancel, collinear-safe observables,
  predictions depend on photon-recombination scheme
- dedicated photonic parton showers, e.g. PHOTOS

  Placzek, Jadach ’03; Carloni Calame et al. ’04; Golonka, Was ’07

full FSR not universal, in general not separable from other EW corrections
combination of PHOTOS with full EW corrections difficult in practice

Key tools: Constraints On New Theories Using Rivet



- BSM Model in FeynRules

UFO interface

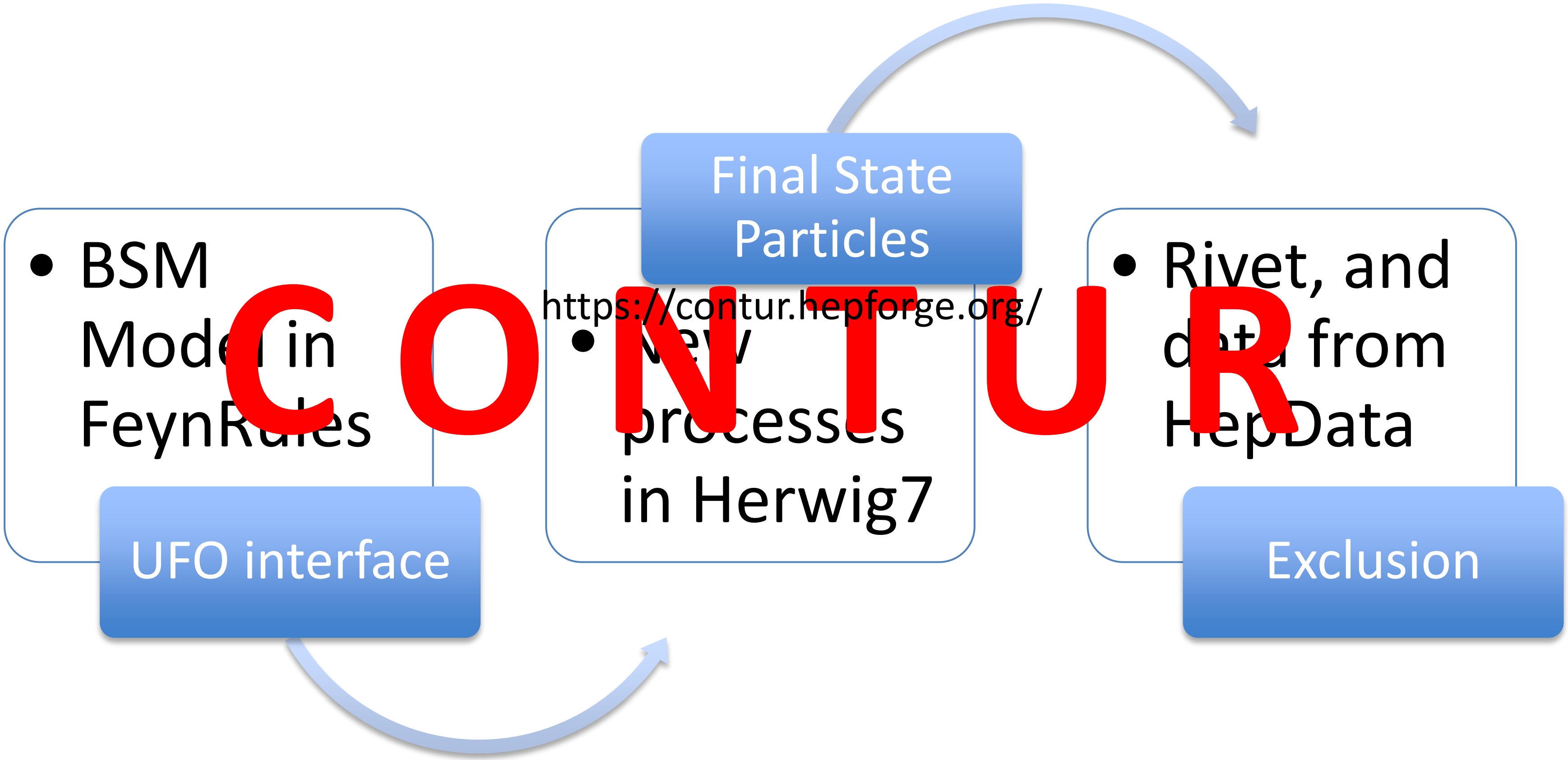
Final State Particles

- New processes in Herwig7

- Rivet, and data from HepData

Exclusion

Key tools: Constraints On New Theories Using Rivet



- BSM Model in FeynRules

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Exclusion

CONTUR

https://contur.hepforge.org/

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When is a lepton a lepton plus some photons?