Measurement and Monte Carlo

or how to make (and use) an optimally useful measurement

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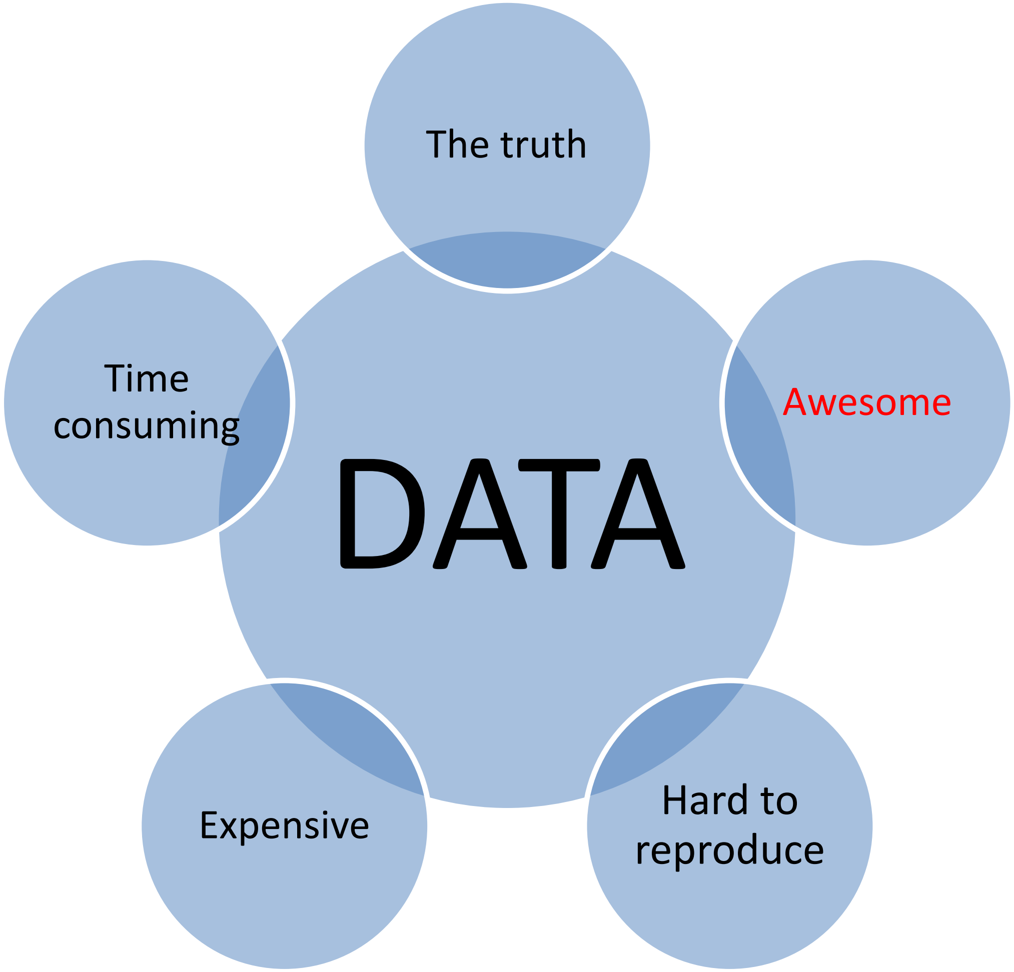
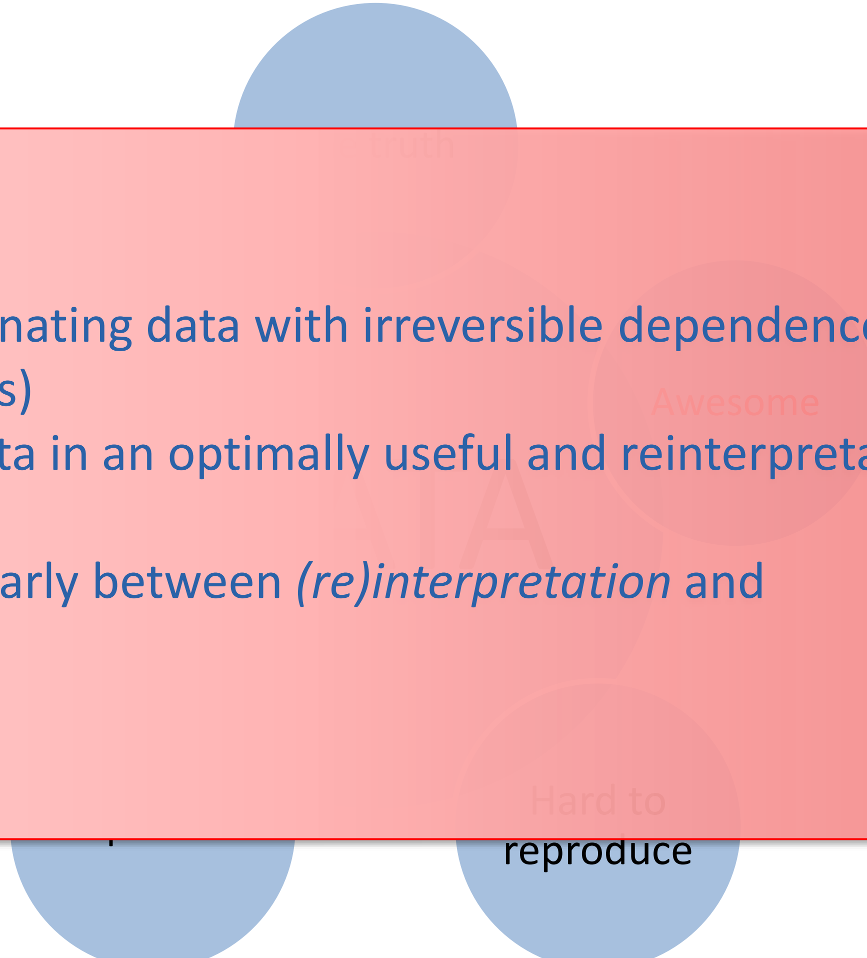
MCnet school, Online/Dresden/Karlsruhe, September 2021

Thanks to Emily Nurse and Andy Buckley


The truth
Time consuming
Awesome
DATA
Expensive
Hard to reproduce

- Avoid contaminating data with irreversible dependence on theory model(s)
- Publish the data in an optimally useful and reinterpretable way
- Distinguish clearly between *(re)interpretation* and *measurement*



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- Distinguish clearly between *(re)interpretation* and *measurement*

- Corollary: theory needs to predict what we actually measure

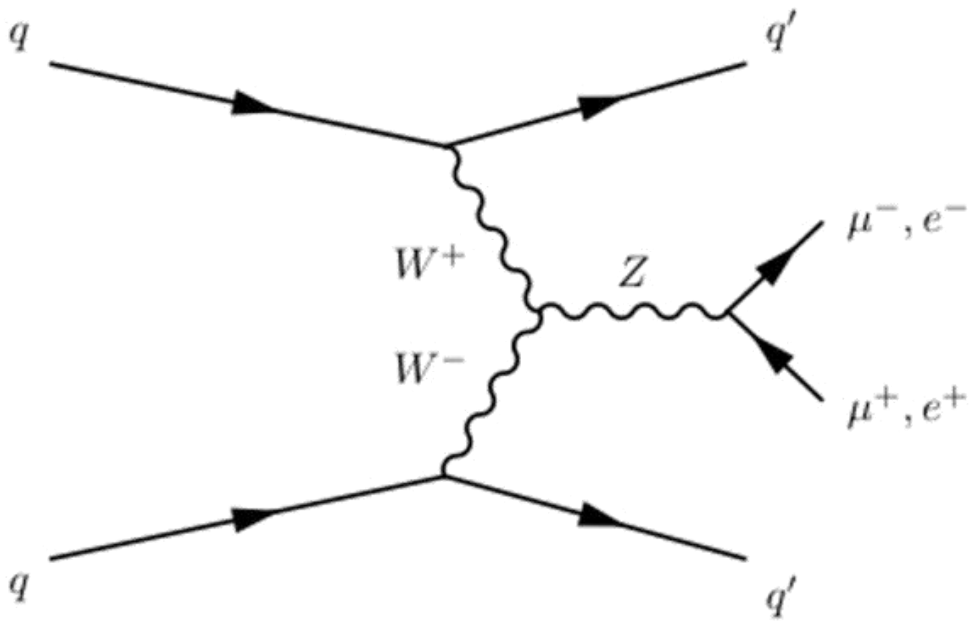
Overview

- What do we actually measure
- Monte Carlo Generators in data analysis
- "Detector effects" on various particles
- Making measurements as useful, and model-independent, as possible
  - Correcting for detector effects
  - The concept of a fiducial phase-space
  - What we mean by final-state particles (it is not always simple)
  - Background subtraction (or not)
- BSM studies

Lectures will focus on LHC with a bias towards ATLAS, but all principles are applicable elsewhere

What *do* we actually measure?

- Electronic signals in detectors due to interactions with traversing particles produced in collisions
- Signals from multiple sub-detectors are combined, and each collision "event" is reconstructed to give a list of identified particles/jets with kinematics

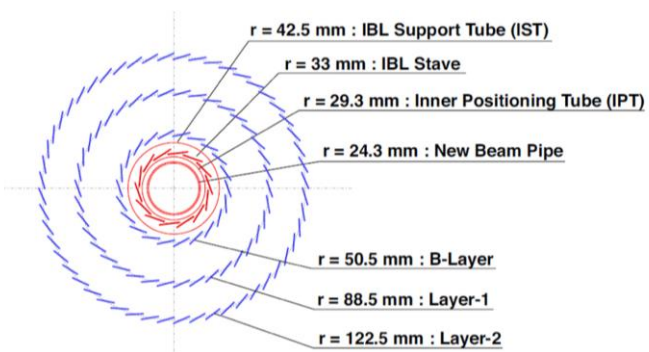


What *do* we actually measure?

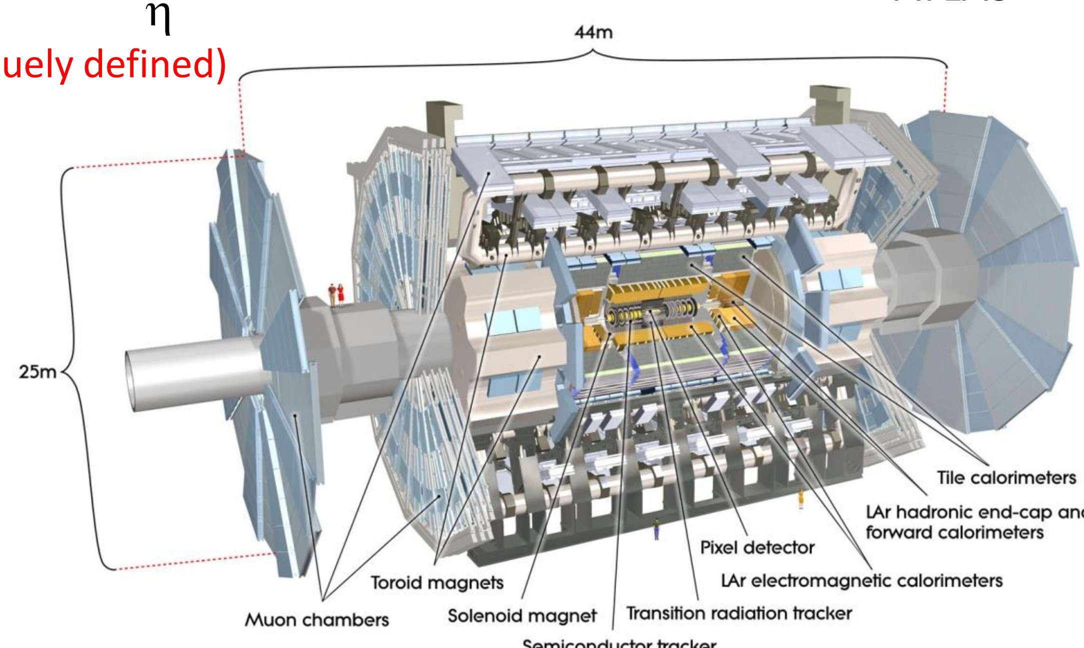
We only “see” *stable final-state* particles :

- **electrons:** stable
- **muons:** “stable” (τ_0 = 2.2ms, decays after ~1.2 km at 20 GeV)
- **taus:** unstable (τ_0 = 0.3 ps, decays after about 1mm at 20 GeV)
- **neutrinos:** stable (but invisible)
- **Quarks, gluons →**
  - “Stable” hadrons
  - unstable → jets, leptons, photons, stable hadrons…
- **Photons**: stable η
- **W, Z, H, top:** unstable (and not uniquely defined)

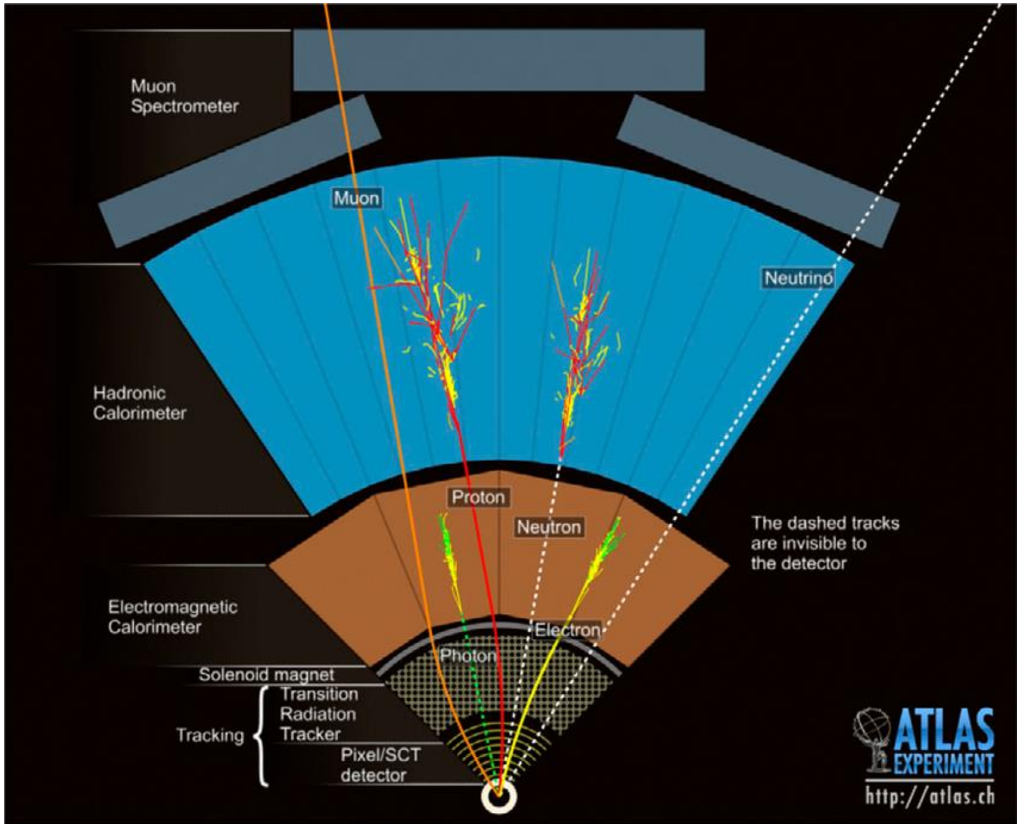
$d = \gamma\tau_0 v = c\tau_0 p/m$
m_μ = 0.1 GeV
m_τ = 1.8 GeV



ATLAS



What *do* we actually measure?



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- The kinematics of the identified particles are reconstructed and information about the event can be inferred
- But these measurements are *not exact,* they have an *experimental resolution*

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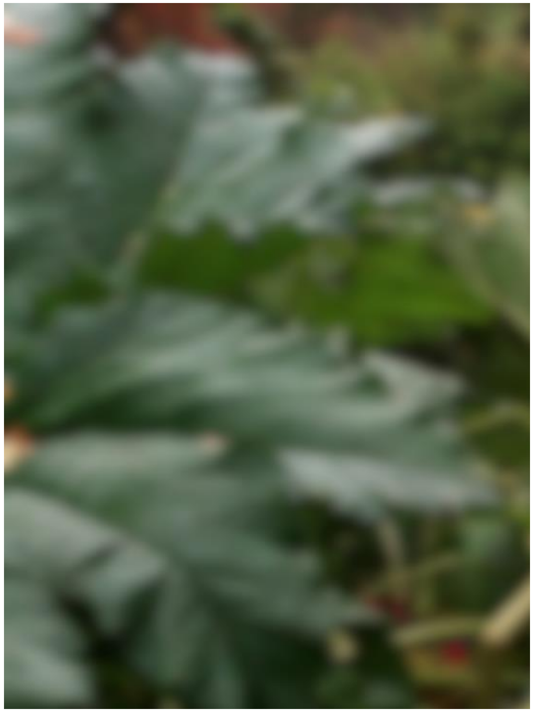

MC event generators in Measurement

- Event generators simulate collision events based on an underlying theory combined with phenomenological models with parameters tuned to experimental data (usually for low-energy QCD effects)
- The output is a list of particles produced in the collision, together with kinematics (four vectors)
- *This part is experiment independent, depends only on incoming particle types and CoM energy*


```
HepMC::Version 2.06.09
HepMC::IO_GenEvent-START_EVENT_LISTING
E 0 -1 0 1.305047132963e-01 7.763841138914e-03 0 -5 234 10001 10003 0 9 3.301267434432e-06 8.978821408834e+02 7.930514580328e+02 7.930514580328e+02
7.930514580328e+02 7.105872898865e+02 4.000000000000e+00 7.930514580328e+02 6.298240114645e+03
N 9 "MEWeight" "MUR0.5_MUF1_PDF261000" "MUR1_MUF0.5_PDF261000" "MUR1_MUF1_PDF261000" "MUR1_MUF2_PDF261000" "MUR2_MUF1_PDF261000" "NTrials" "Weight"
"WeightNormalisation"
U GEV MM
C 1.982628645082e+02 1.982628645082e+02
F 3 21 1.355269110210e-01 1.127542580157e-03 8.823075221978e+01 1.355269110210e-01 2.792889203654e+01 0 0
V -1 0 0 0 0 0 1 1 1 1.000000000000e+00
P 10001 2212 0 0 6.499999932280e+03 6.500000000000e+03 9.382720033633e-01 4 0 0 -1 0
P 10002 2212 0 0 6.499999932280e+03 6.500000000000e+03 9.382720033633e-01 11 0 0 -4 0
V -2 0 0 0 0 0 1 1 1 1.000000000000e+00
P 10003 2212 0 0 -6.499999932280e+03 6.500000000000e+03 9.382720033633e-01 4 0 0 -2 0
P 10004 2212 0 0 -6.499999932280e+03 6.500000000000e+03 9.382720033633e-01 11 0 0 -3 0
V -3 0 0 0 0 0 0 5 1 1.000000000000e+00
P 10005 21 1.714330700467e+00 2.213281091146e-01 -9.575581739813e+02 9.575597341546e+02 -2.157918643758e-05 11 0 0 -6 2 1 655 2 656
P 10006 21 -1.757323314213e+00 -4.154628631199e+00 -4.924799664895e+01 4.945416360863e+01 -1.383649647574e-05 11 0 0 -9 2 1 657 2 654
P 10007 21 1.582987254987e+00 2.799715977806e+00 -2.760412681726e+02 2.760600043333e+02 3.814697265625e-06 11 0 0 -11 2 1 654 2 655
P 10008 2101 -1.321999312907e+00 1.020529656020e+00 -3.814444371002e+03 3.814444780601e+03 5.793299988339e-01 11 0 0 -12 1 2 657
P 10009 2 -2.179953283341e-01 1.130548882582e-01 -1.402590739555e+03 1.402590761053e+03 -1.525878906250e-05 11 0 0 -12 1 1 656
V -4 0 0 0 0 0 0 5 1 1.000000000000e+00
P 10010 21 -1.776658431622e+00 2.479865383302e-01 9.401401408359e+02 9.401418522880e+02 -1.078959321879e-05 11 0 0 -6 2 1 659 2 661
P 10011 21 1.999658988953e+00 8.983465456712e-01 1.336251894549e+03 1.336253692735e+03 3.051757812500e-05 11 0 0 -9 2 1 658 2 659
P 10012 21 -1.730206524559e+00 6.026174210027e-02 4.297680545482e+02 4.297715415849e+02 -8.374976501503e-05 11 0 0 -11 2 1 660 2 658
P 10013 2203 1.736227309883e+00 -1.470428846972e+00 3.155057560022e+03 3.155058474679e+03 7.713299971049e-01 11 0 0 -12 1 2 660
P 10014 1 -2.290213426542e-01 2.638340208699e-01 6.386648994053e+02 6.386649949634e+02 7.629394531250e-06 11 0 0 -12 1 1 661
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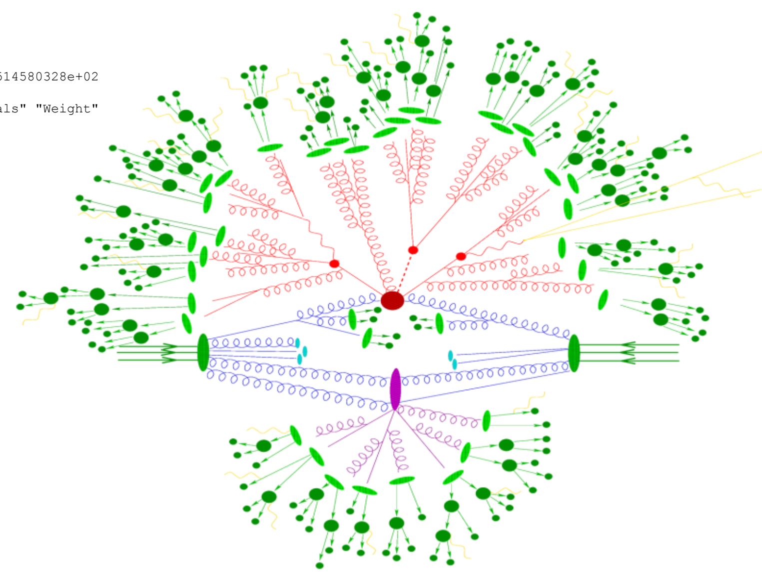
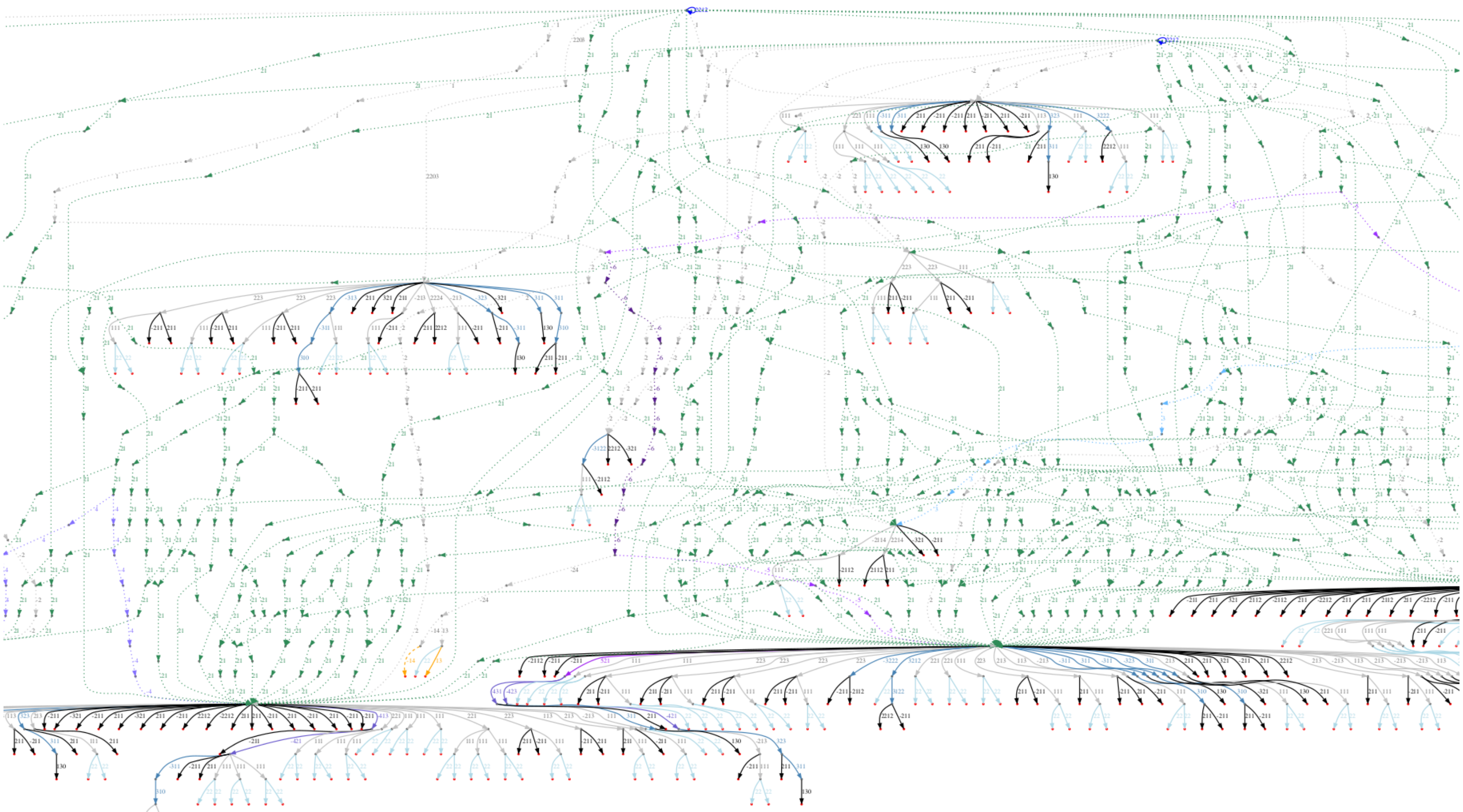


Picture from Sherpa authors

MC event generators in Measurement

MC event-record graphs are only partially physical! Which bits are safe?!



Picture from Sherpa authors

Monte Carlo detector simulation

- Often we also have to simulate the effect of our detectors
  - Special simulation codes based on GEANT
  - Generated particles pass step-by-step through material (with which they interact) and magnetic fields (where they curve and radiate)
- Digitization step simulates detector response in terms of electronic signals (same format as data)
- *The same reconstruction code as used in data can then be applied to the simulated events*
- *This part is experiment specific :* Detector simulation is *CPU intensive* and codes are often *not publicly available*
- *Generally will also include accelerator-specifics (pile up, beam backgrounds etc)*

Monte Carlo event generators in data analysis

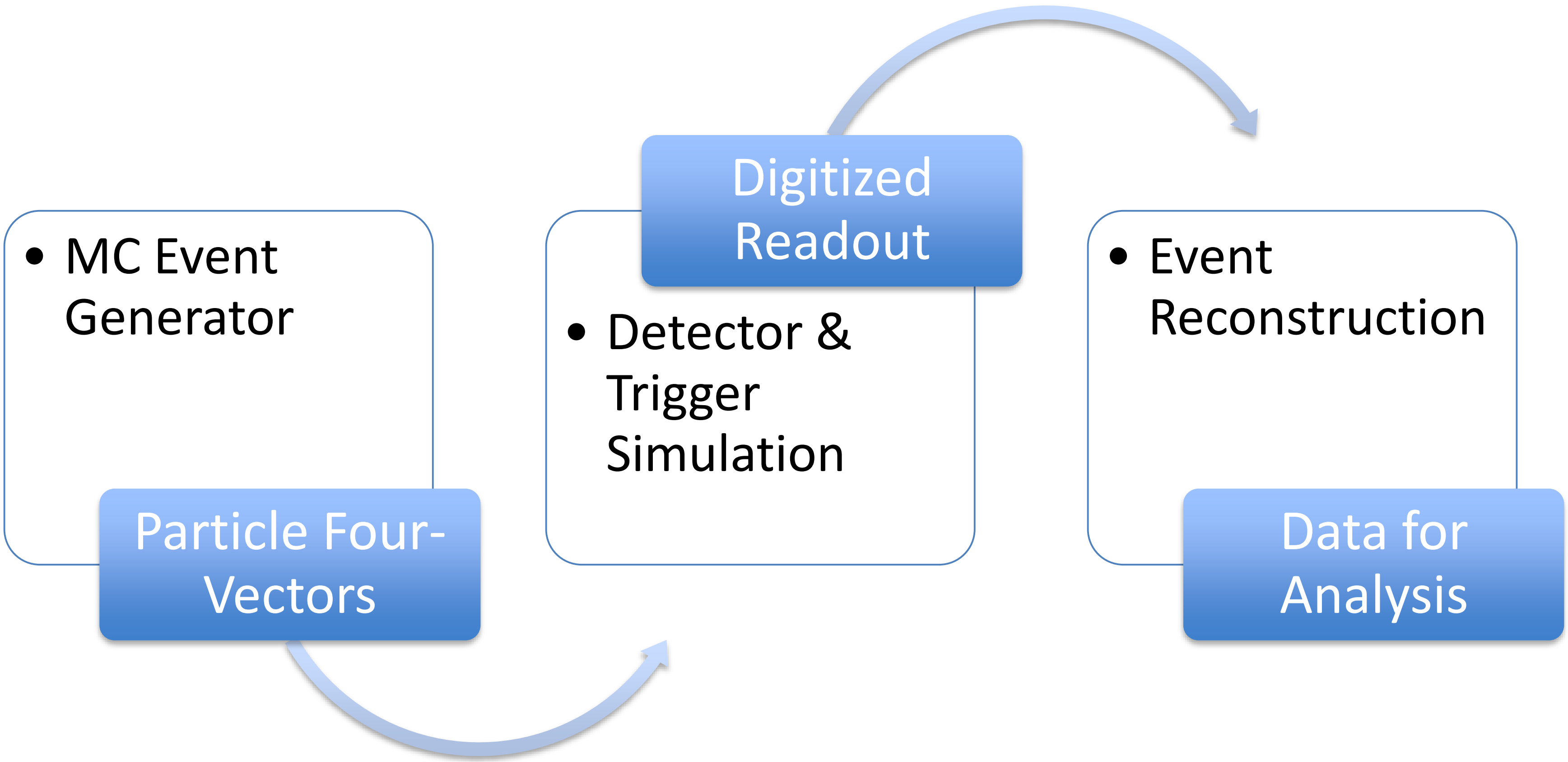
Generated events are used to:

Monte Carlo event generators in data analysis

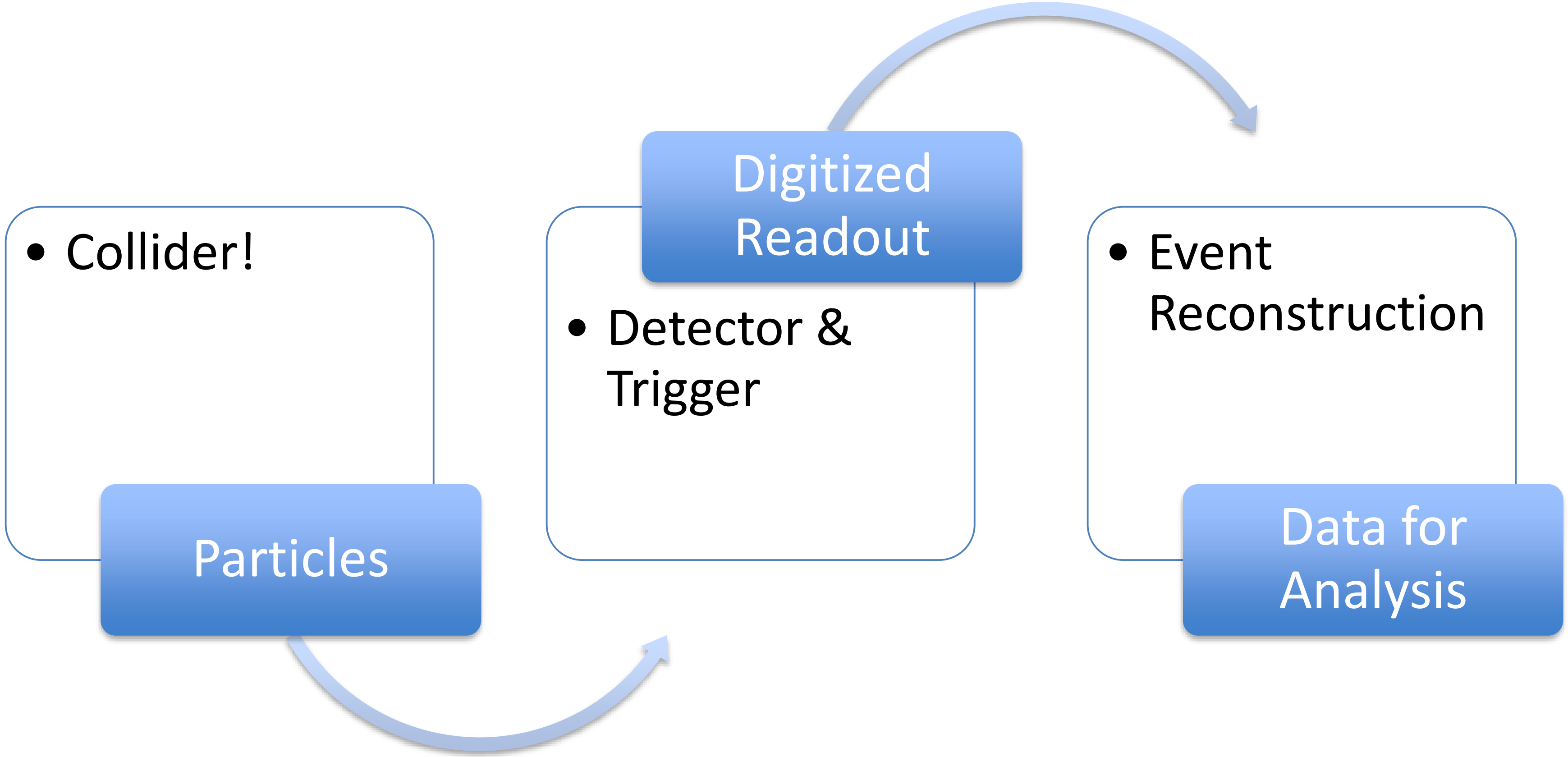
Generated events are used to:

1. Compare measured data to expectations from a given theory (SM or otherwise). Usually we ask “does the data agree with this theory?”
2. Subtract expected background processes from the data *(I will later discuss why this isn’t always the best idea)*
3. Correct for detector effects by comparing *truth-level* MC prediction with *reco-level* MC prediction *(more on this later)*
4. Plan the sensitivity of future experiments

Simulation and Experiment

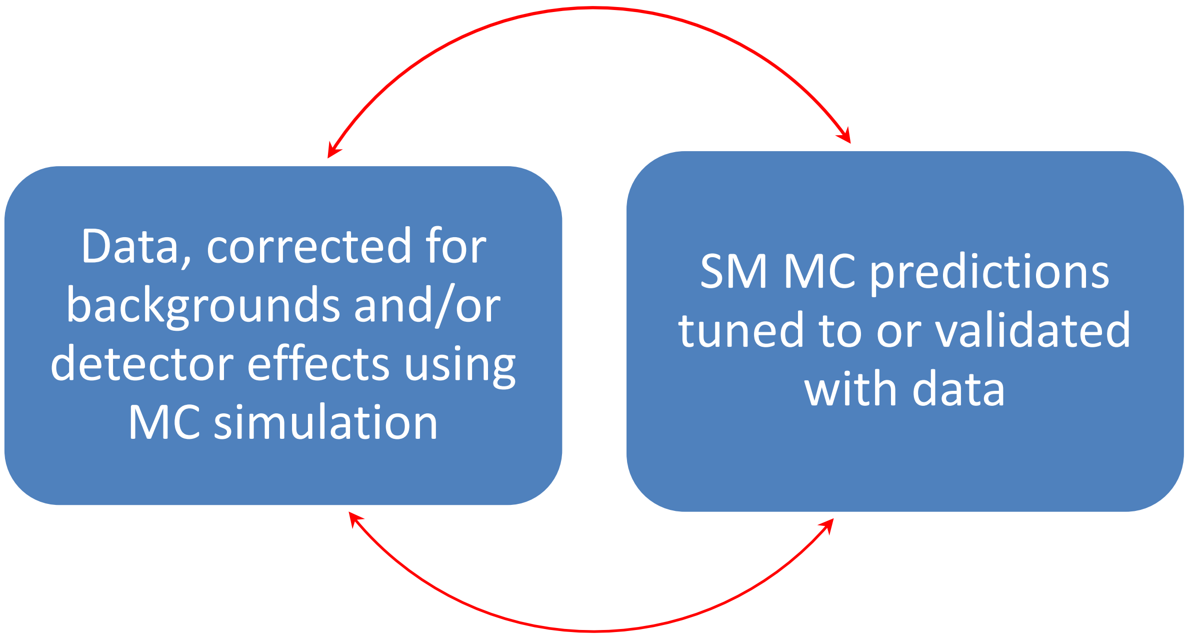


Simulation and Experiment



What do theorists want to do with our data?

Usually they ask "How well does the data agree with my prediction?" (where the prediction often comes as a set of final-state "truth" particles from MC generation)



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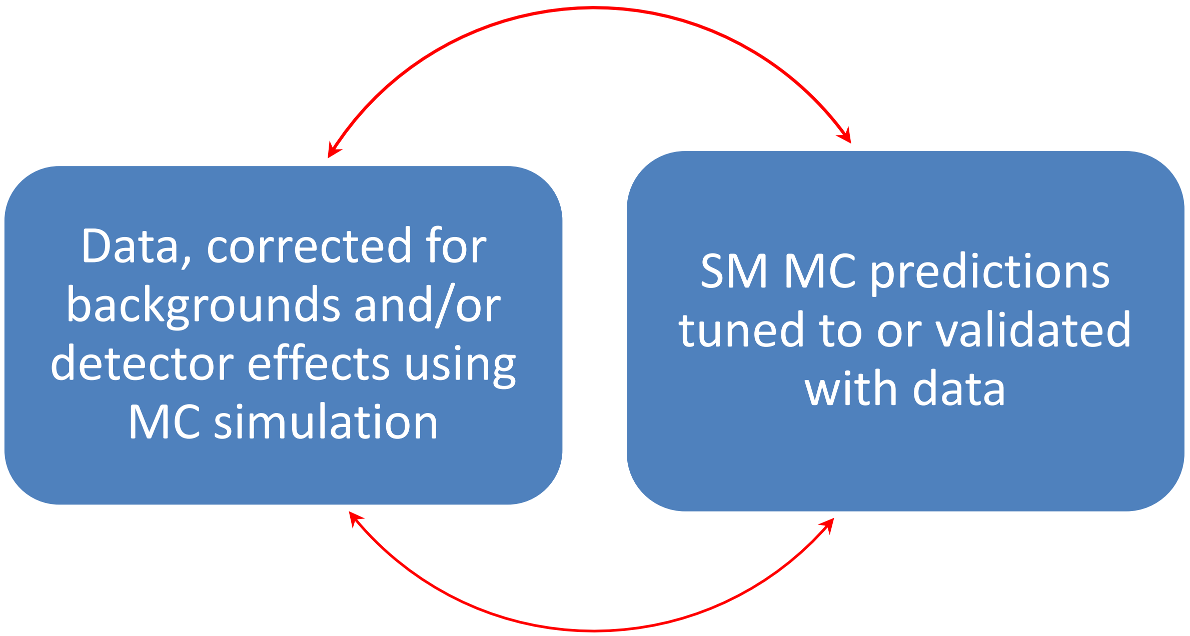


Careful! We don’t want the data to depend on the prediction we are constraining!

What do theorists want to do with our data?

Data, corrected for backgrounds and/or detector effects using MC simulation

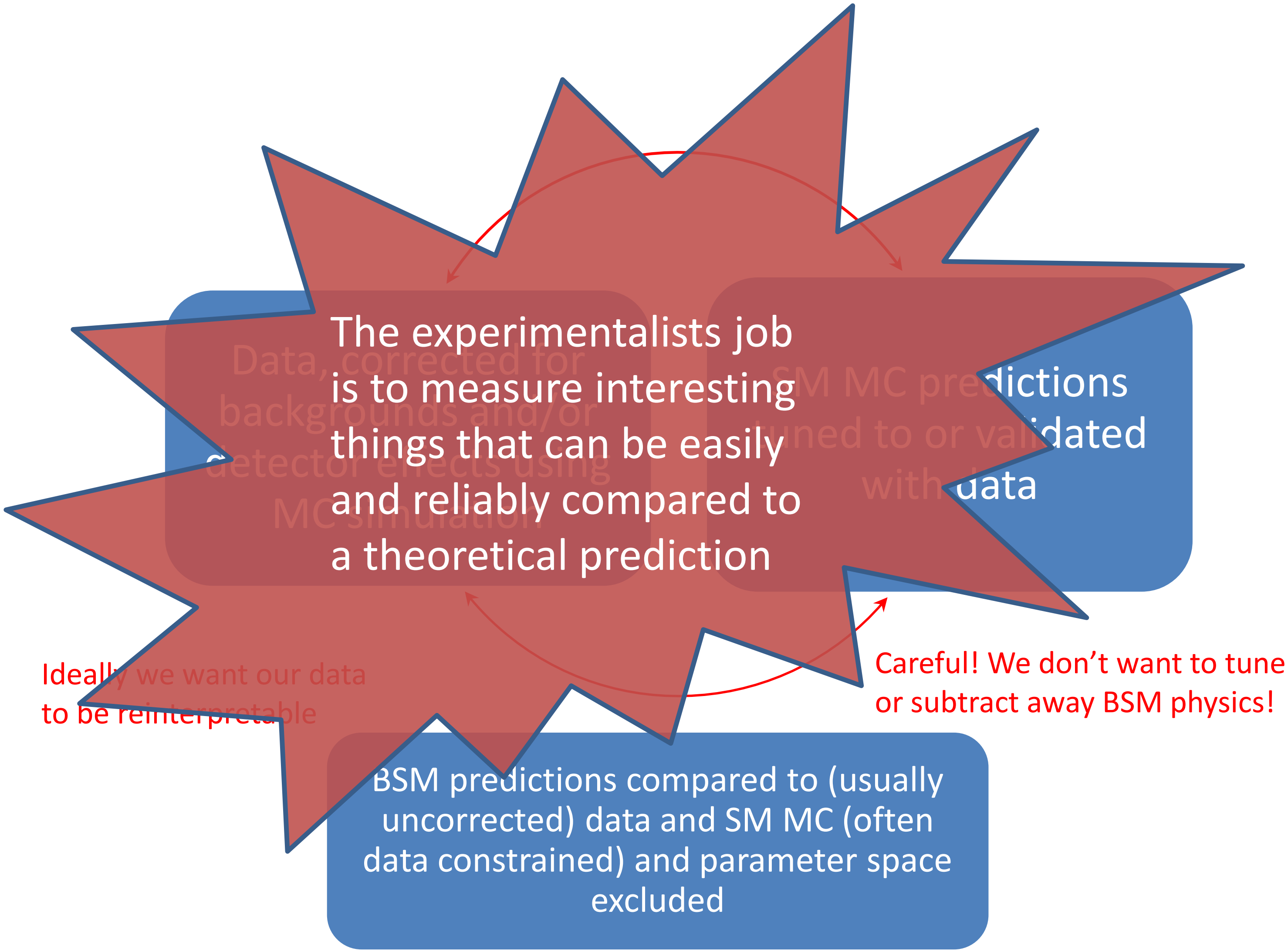
SM MC predictions tuned to or validated with data

Ideally we want our data to be reinterpretable

Careful! We don’t want to tune or subtract away BSM physics!

BSM predictions compared to (usually uncorrected) data and SM MC (often data constrained) and parameter space excluded

What do theorists want to do with our data?



Rivet

Robust Independent Validation of Experiment and Theory

- A system for validation of Monte Carlo event generators.
- Experimental results are included via HepData and an analysis routine is written that selects events and plots the relevant variables to compare to the data.
- Makes sure theorists are making the correct selection cuts when comparing to your data! > 1000 analyses preserved so far
- Incredibly useful for MC generator development, validation, and tuning, as well as testing BSM physics models

When you publish a result please make sure you provide a Rivet routine too!

Rivet analysis coverage

Rivet analyses exist for 324/5731 papers = 6%. 185 priority analyses required.

Total number of Inspire papers scanned = 7216, at 2019-05-21

Breakdown by identified experiment (in development):

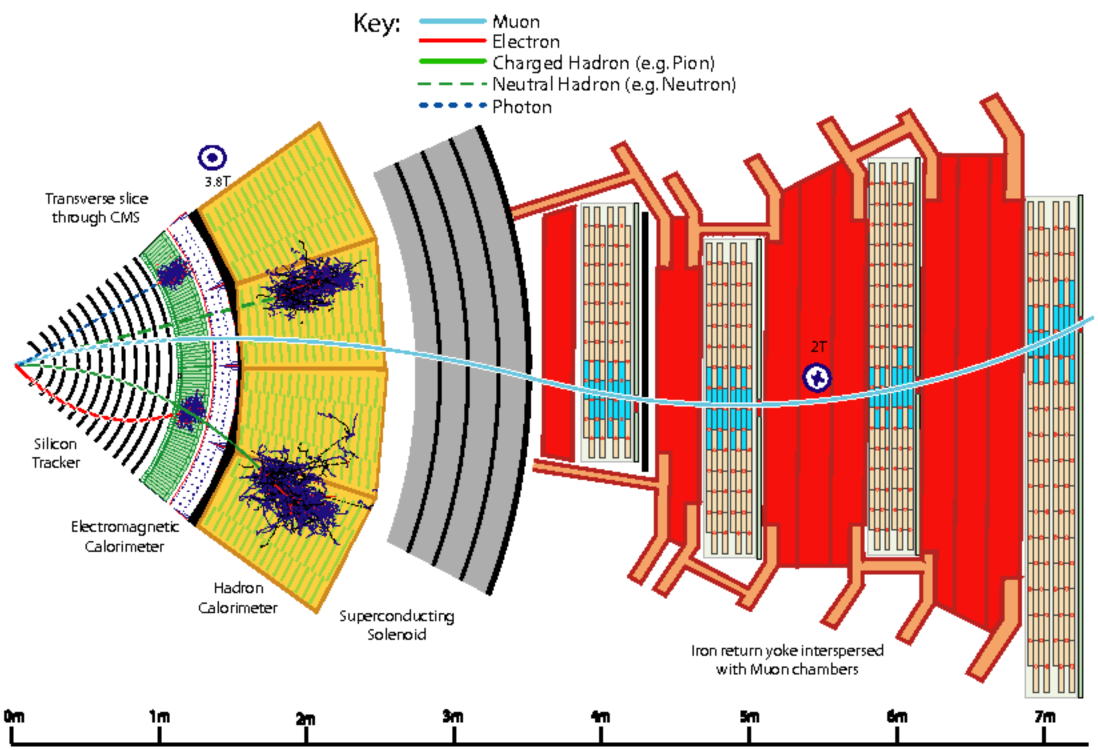
Key	ALICE	ATLAS	CMS	LHCb	B-factories	HERA	LEP	Other
Rivet wanted (total):	200	264	354	161	1498	446	1418	1066
Rivet REALLY wanted:	35	42	74	10	2	14	7	1
Rivet provided:	**20**/220 = **9%**	**149**/413 = **36%**	**77**/431 = **18%**	**11**/172 = **6%**	**14**/1512 = **1%**	**8**/454 = **2%**	**38**/1456 = **3%**	**7**/1073 = **1%**

https://rivet.hepforge.org

See Tomorrow's Rivet/Contur tutorial

Detector effects

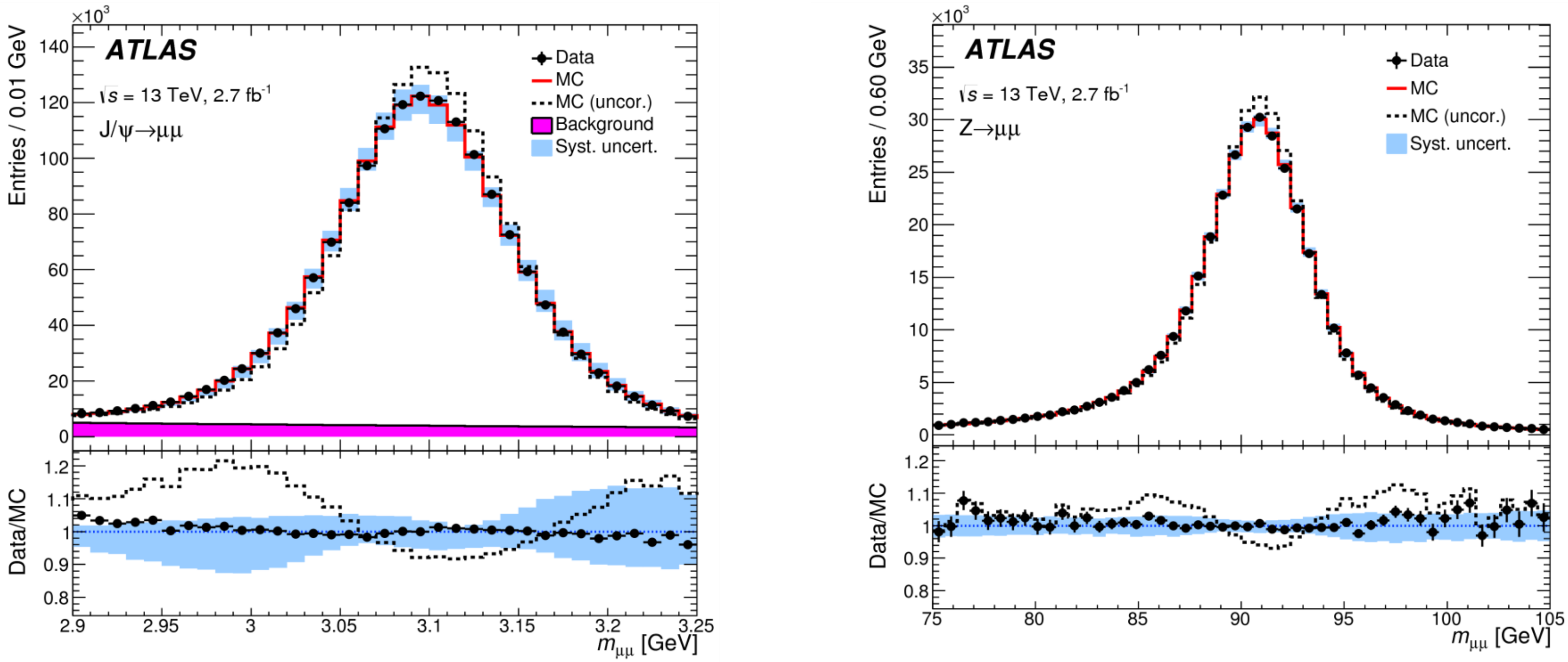
- Efficiencies: there is a non-zero probability that a particle passing through a detector will not be reconstructed
- Fake backgrounds: there is a non-zero probability that a particle will be reconstructed even though it wasn't really there
- Smearing: the measured energies, momenta, angles of the particles and jets will be smeared due to the intrinsic resolution of the detectors



We need to know what our detector is doing so we can account for it and in some cases reverse it

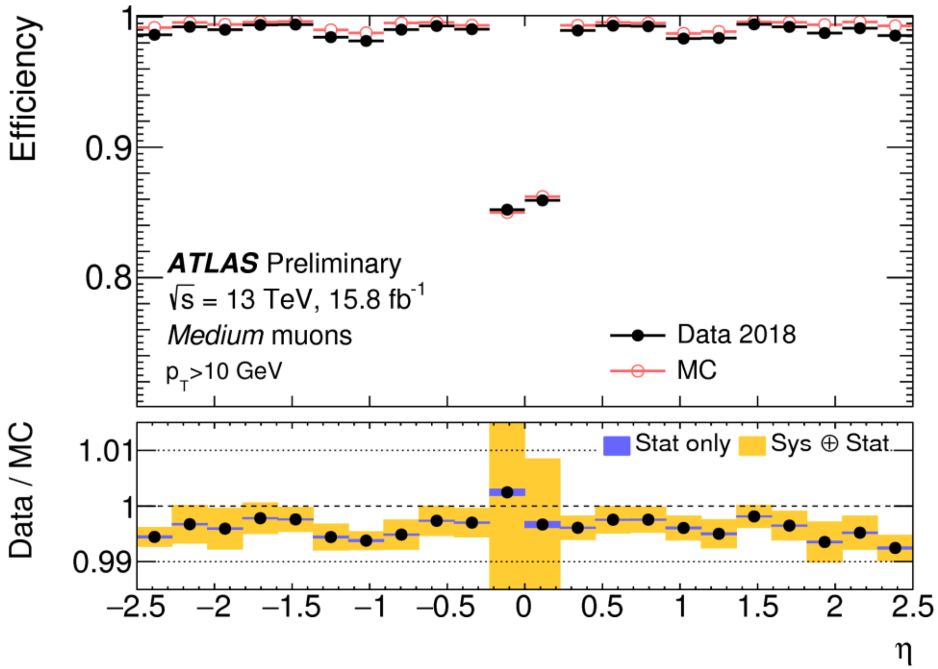
Detector effects: Muons

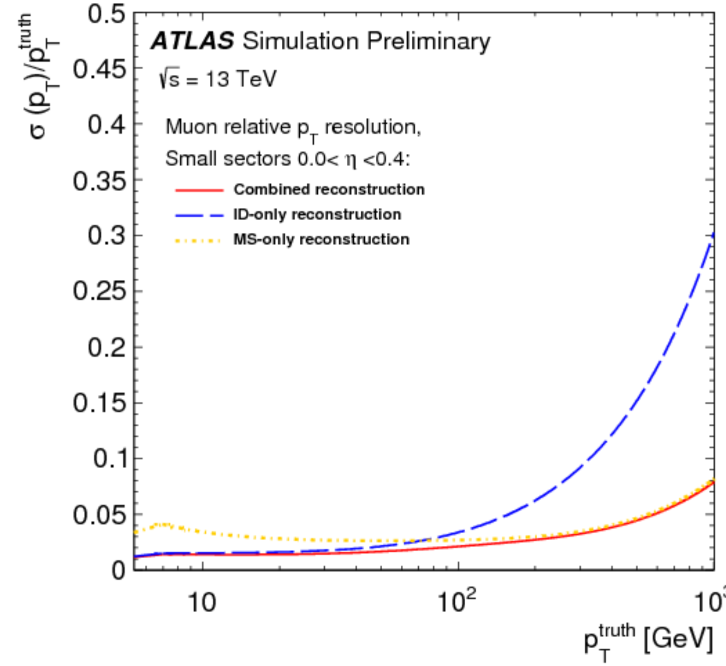
- Momentum measured in Inner Detector and Muon Spectrometers from charged particle tracks
- Usually isolation requirements
- Calibrated with $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ peaks



[Eur. Phys. J. C 76 (2016) 292]

Detector effects: Muons

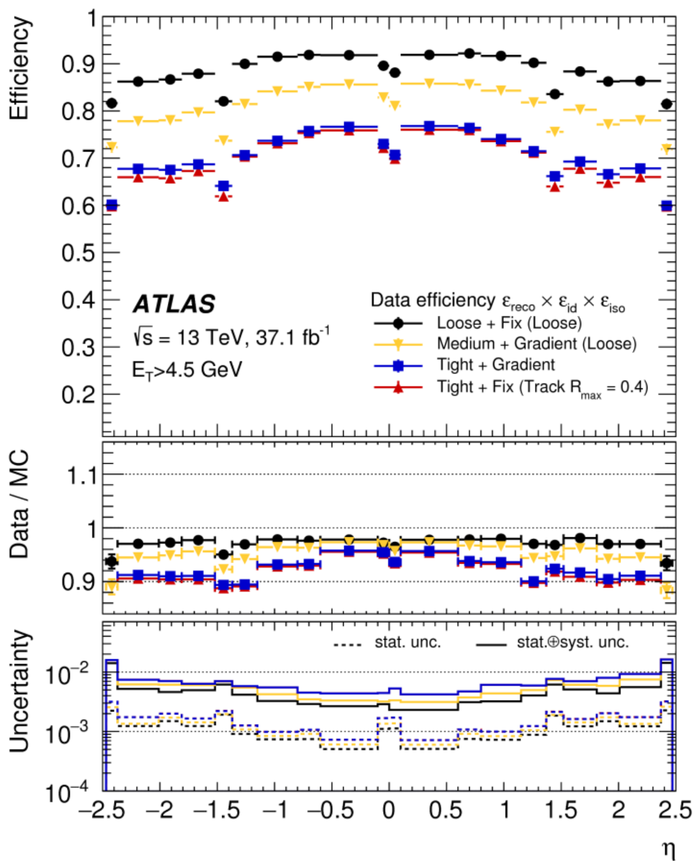




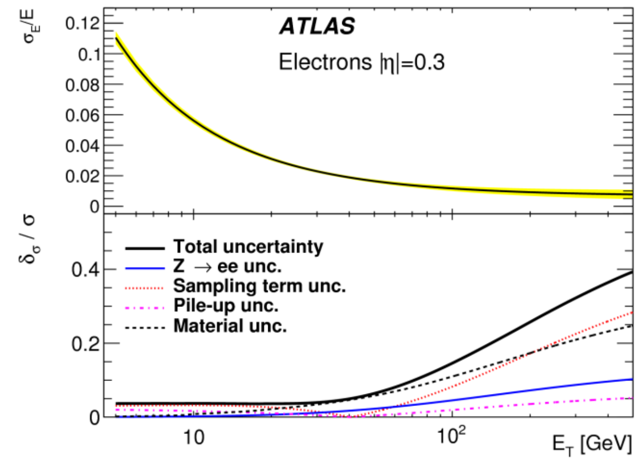
- High reconstruction efficiency
- Percent-level p_T resolution at low p_T (gets worse at high-p_T)

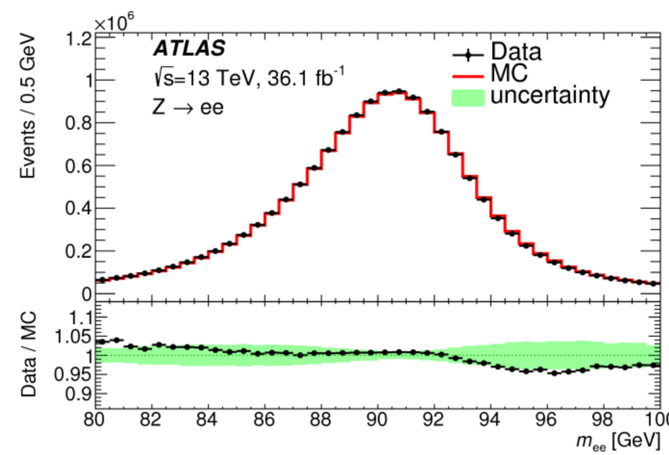
Detector effects: Electrons and Photons

- Calorimeter cluster measures energy, (electrons matched to Inner Detector track)
- Usually isolation requirements



[arXiv:1902.04655](https://arxiv.org/abs/1902.04655)



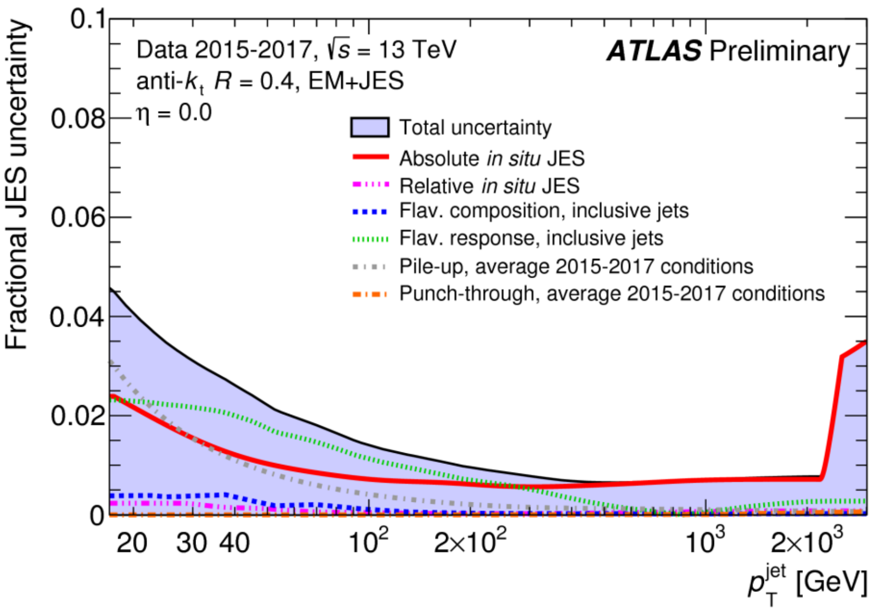


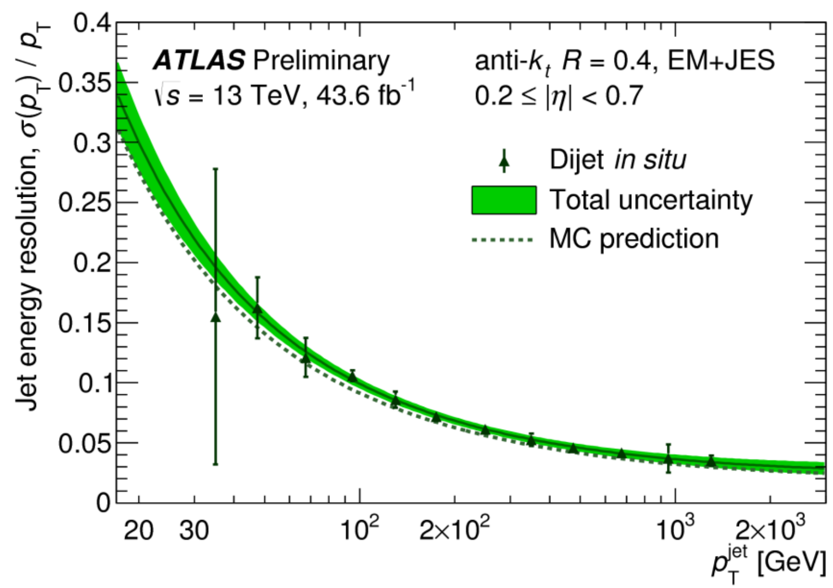
- High reconstruction efficiency
- Energy resolution: percent-level at high-energy, gets worse at low energy

Detector effects: Jets

- Partons lead to collimated hadrons which we form into “jets”
- Built with jet algorithms (usually anti-k_T) from calorimeter clusters / tracks
- Calibrated by balance with other calibrated objects (electrons, muons, photons) and forward jets balanced with central jets

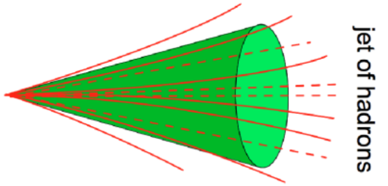
JETM-2018-006

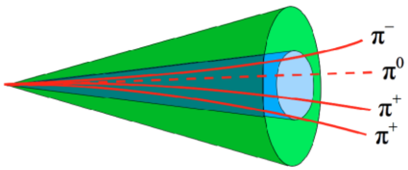


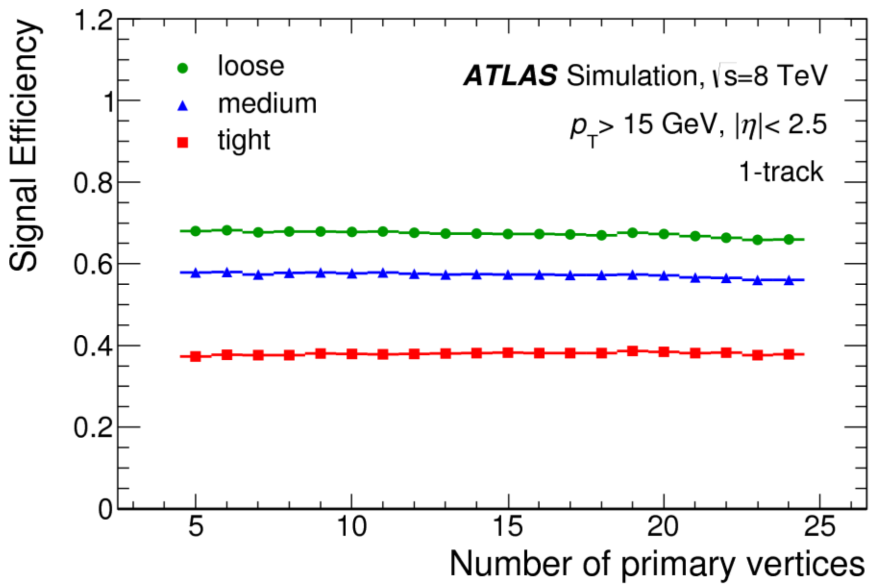


Detector effects: Taus (hadronic decays)

$\tau^{\pm} \rightarrow \pi^{\pm}\, \pi^{0}\, \nu$
$\tau^{\pm} \rightarrow \pi^{\pm}\, \nu$
$\tau^{\pm} \rightarrow \pi^{\pm}\, \pi^{0}\, \pi^{0}\, \nu$
$\tau^{\pm} \rightarrow \pi^{\pm}\, \pi^{\pm}\, \pi^{\square}\, \nu$
$\tau^{\pm} \rightarrow \pi^{\pm}\, \pi^{\pm}\, \pi^{\square}\, \pi^{0}\, \nu$
Recall, τ decays after ~1mm at 20 GeV







Eur. Phys. J. C75 (2015) 303

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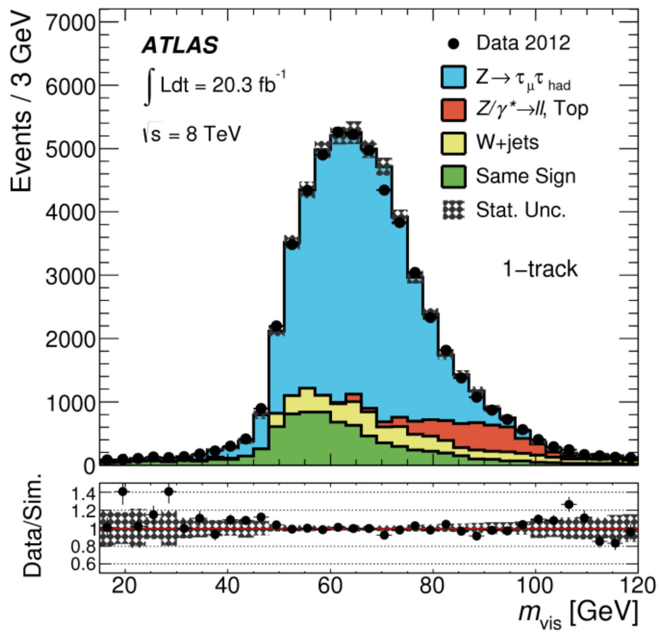
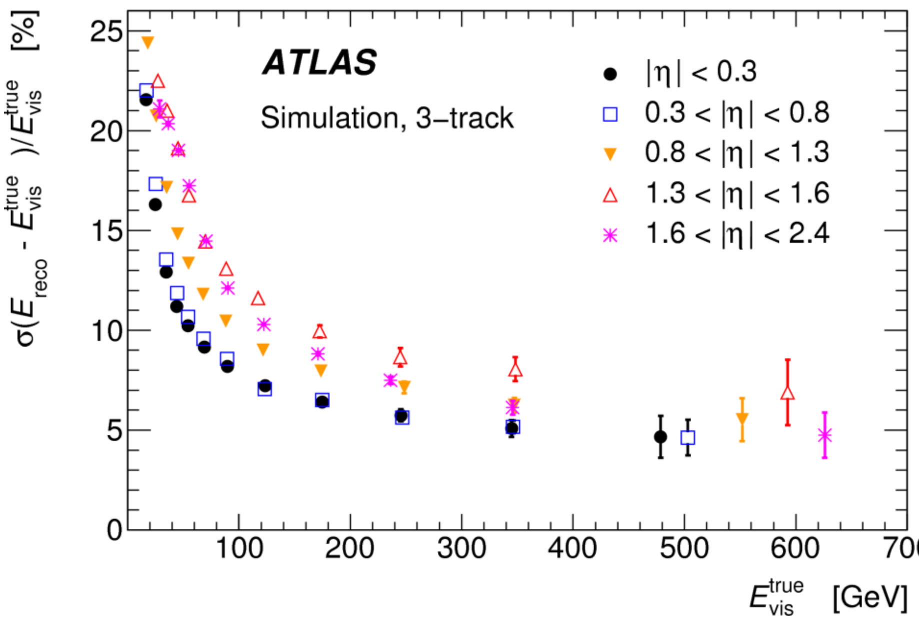
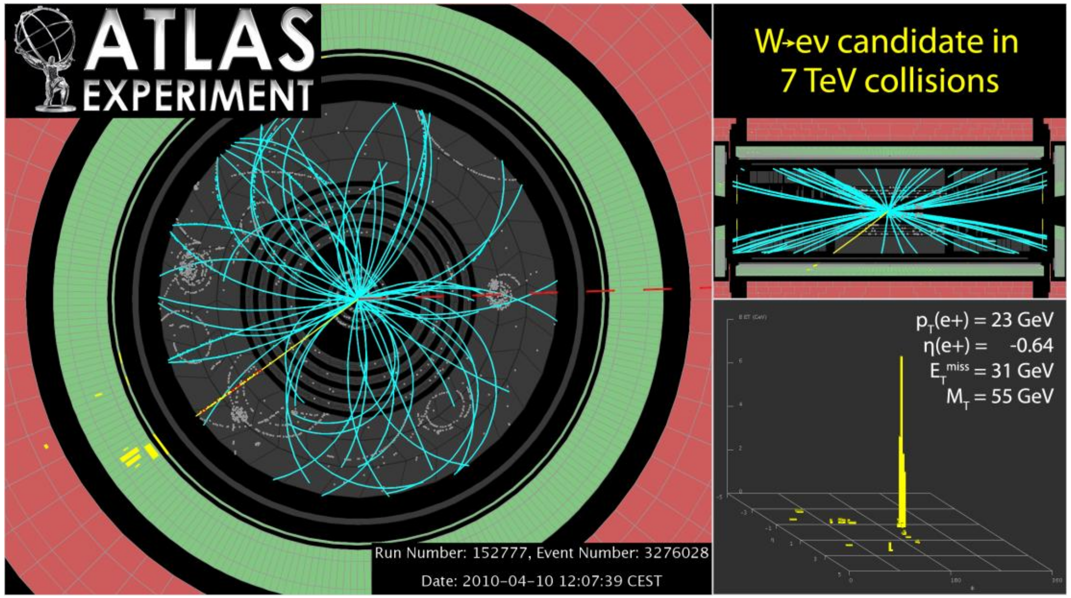


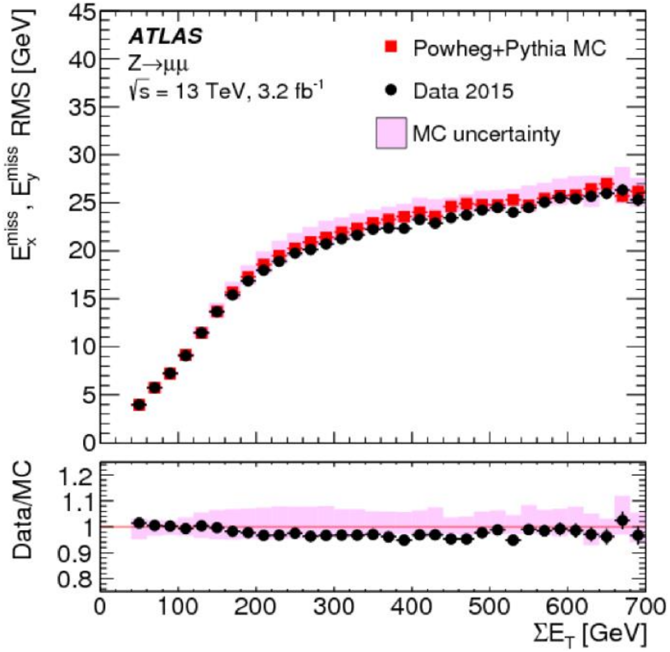


- Energy calibrated to *visible* decay energy (e.g. not including neutrino)
- Resolution of 5-25% depending on E and η

Detector effects: Neutrinos*, p_T^{miss} (or E_T^{miss})

$$\mathbf{E}_T^{miss} = \underbrace{\underbrace{-\sum_{\text{selected electrons}} \mathbf{p}_T^{e}}_{\mathbf{E}_T^{miss,e}} \underbrace{-\sum_{\text{accepted photons}} \mathbf{p}_T^{\gamma}}_{\mathbf{E}_T^{miss,\gamma}} \underbrace{-\sum_{\text{accepted }\tau\text{-leptons}} \mathbf{p}_T^{\tau_{had}}}_{\mathbf{E}_T^{miss,\tau_{had}}} \underbrace{-\sum_{\text{selected muons}} \mathbf{p}_T^{\mu}}_{\mathbf{E}_T^{miss,\mu}} \underbrace{-\sum_{\text{accepted jets}} \mathbf{p}_T^{jet}}_{\mathbf{E}_T^{miss,jet}}}_{\text{hard term}} \underbrace{\underbrace{-\sum_{\text{unused tracks}} \mathbf{p}_T^{track}}_{\mathbf{E}_T^{miss,soft}}}_{\text{soft term}}$$





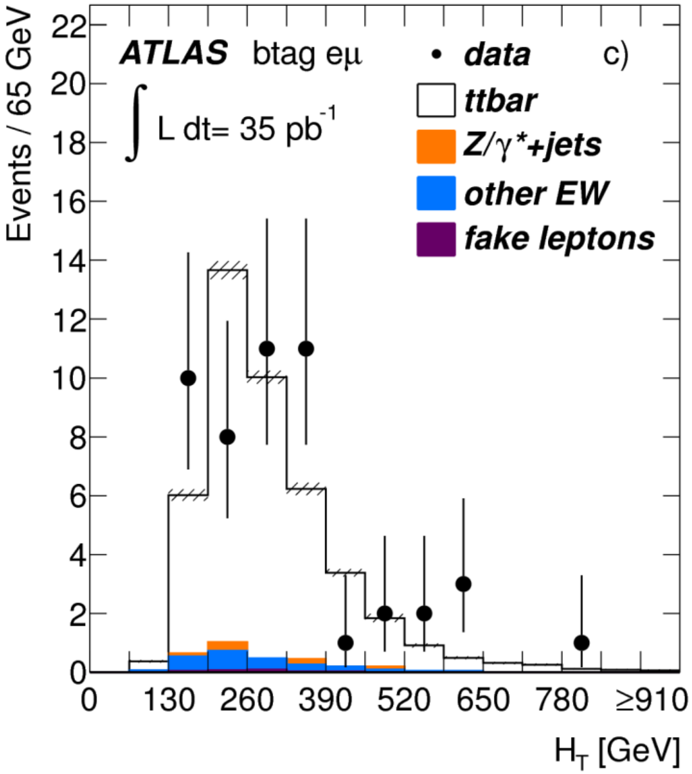
* Or other invisible particles

Recall: we often want to present the data corrected for detector effects so we can compare to final-state “truth-level” particles.

People outside the collaboration do not have access to CPU intensive simulation codes

Uncorrected distributions

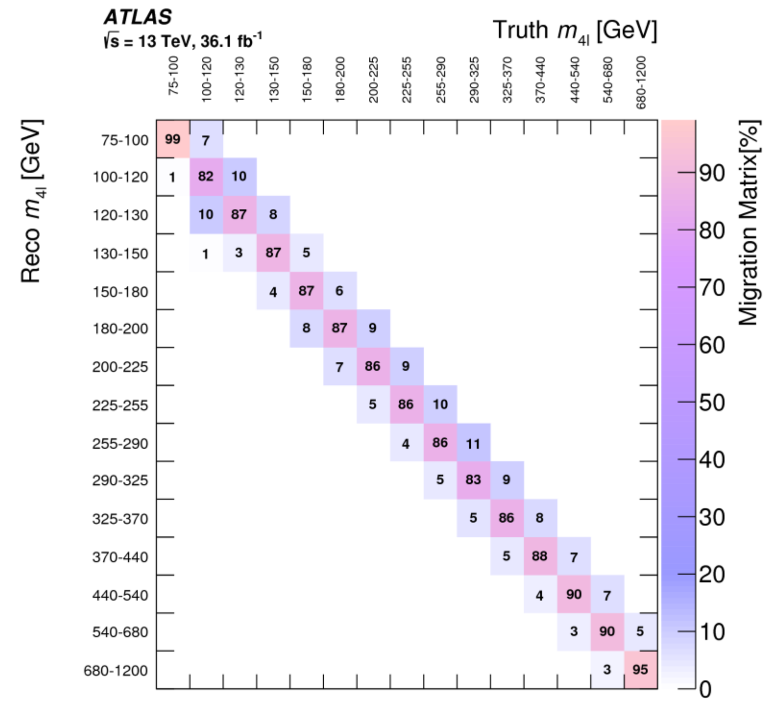
Phys. Lett. B707 (2012) 459



- Run 1 $t\bar{t}$ cross-section paper
- H_T distribution at *reco-level*
- This cannot be compared to any prediction other than the one used in the paper

Correcting for detector effects

- ✓ Correct for backgrounds from fake particles and sometimes those with similar final states (I will discuss later what to do with backgrounds leading to the *same* final state as the signal)
- ✓ Correct for the detector inefficiencies and scales and "unfold" resolution effects
- ✓ Assign systematic uncertainties to the corrected data to account for how well we understand the detector corrections



Only experimentalists can do this and so they should! Otherwise it is very hard to (re)-interpret an experimental result

Correcting for detector effects

- This is done using MC generators
- We must be careful as the corrections can depend on the underlying physics modelling.
- E.g.:
  - Bin migrations depend on underlying distribution
  - Efficiency corrections depend on kinematics of particles

✓ Validate / reweight underlying distributions by comparisons to data and assign appropriate systematic uncertainties

✓ Treat MC A versus MC B systematic uncertainties with caution

Simulation and Experiment

- MC Event Generator

Particle Four-Vectors

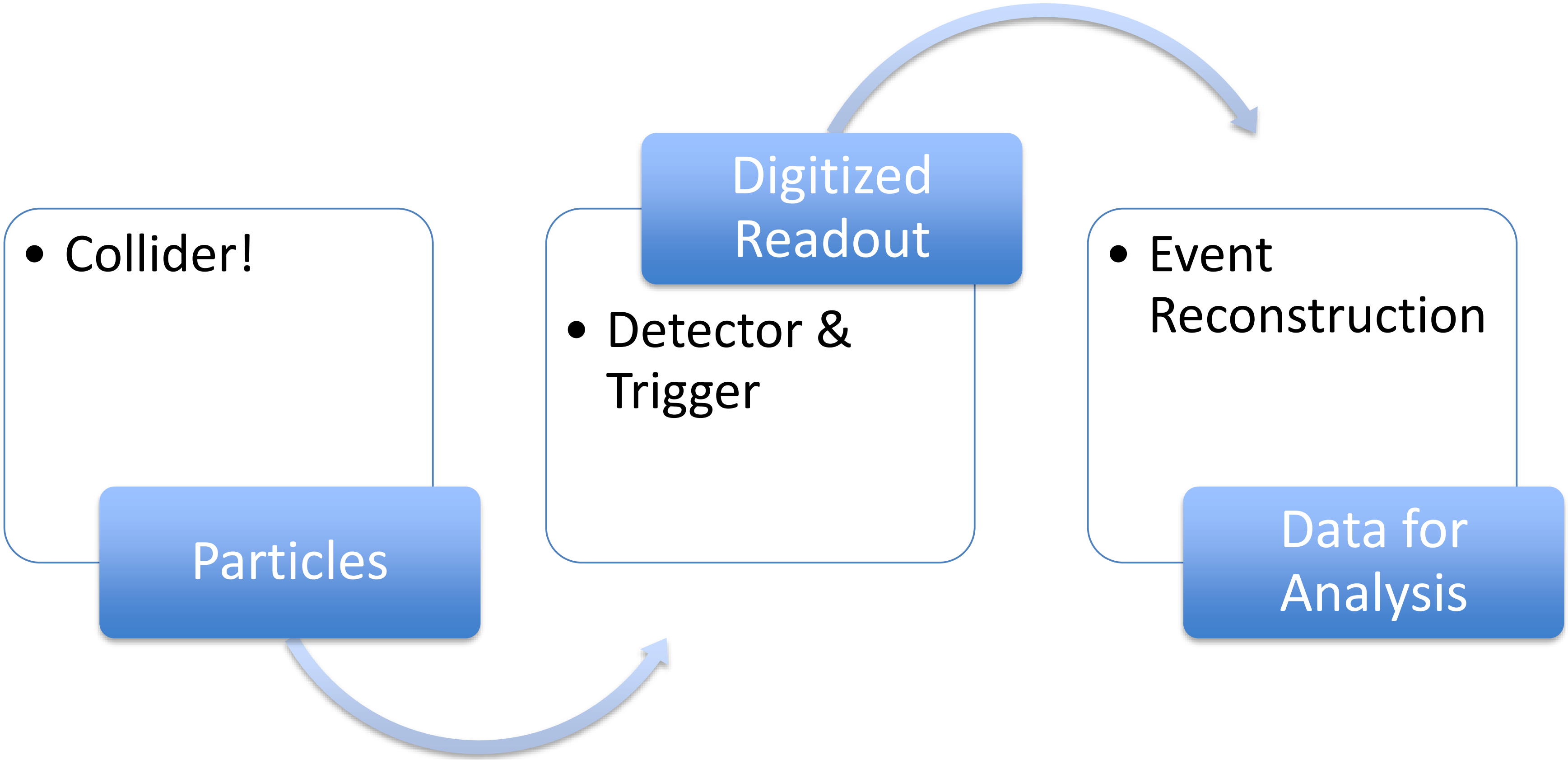
Digitized Readout

- Detector & Trigger Simulation

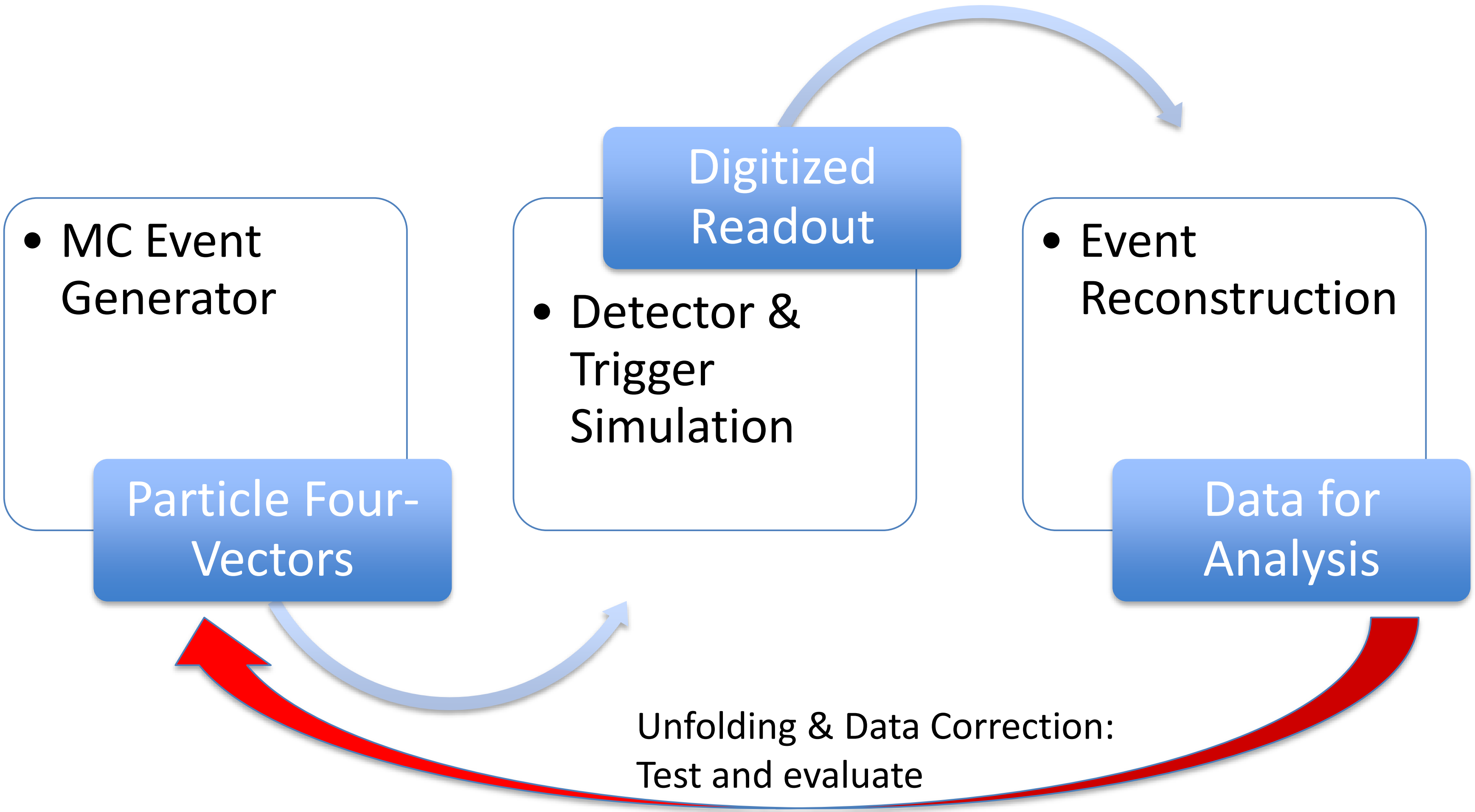
- Event Reconstruction

Data for Analysis

Simulation and Experiment



Simulation and Experiment



Simulation and Experiment